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Advances in the geology of the Tobacco Root Mountains, Montana, and their implications for the history of the northern Wyoming province

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ABSTRACT

Integrated studies by Keck Geology Consortium participants have generated many new insights into the Precambrian geology of the Tobacco Root Mountains. We have clarified the tectonic setting and origin of two suites of metamorphic rocks: (1) a quartzofeldspathic gneiss complex with associated metasupracrustal rocks (the combined Indian Creek and Pony–Middle Mountain Metamorphic Suites) that originated in a continental arc setting between 3.35 and 3.2 Ga with subsequent sedimentation and (2) mafic metavolcanic rocks with intercalated metasedimentary rocks (the Spuhler Peak Metamorphic Suite) from a suprasubduction zone ophiolite or backarc basin possibly of Proterozoic age. A poorly preserved metamorphic event at 2.45 Ga affected the former but not the latter, as did the intrusion of rift-related mafic dikes and sills at 2.06 Ga. Both suites were amalgamated, metamorphosed to at least upper amphibolite facies, subjected to simple shear strain and folded into map- and outcrop-scale sheath folds, and tectonically unroofed during the period 1.78 to 1.71 Ga. We name this event the Big Sky orogeny.

The Proterozoic geology of the Tobacco Root Mountains can be integrated with coeval features of the geology of the northern Wyoming province to outline a northeast-trending, southeast-vergent belt as the Big Sky orogen. The Big Sky orogen consists of a metamorphic hinterland flanked to the southeast by a foreland of discrete ductile shear zones cutting older basement, and to the northwest by arc-related metaplutonic bodies and the trace of a fossil subduction zone in the upper mantle. Archean blocks to the north of the Big Sky orogen may have been accreted as allochthonous terranes during collision and convergence.

The remarkable synchroneity of collision along the Big Sky orogen with tectonism in the Trans-Hudson orogen along the eastern margin of the Wyoming province and in the Cheyenne belt to the south of the province raise profound but unanswered questions about the process by which the Wyoming province was added to the rest of the ancestral North American craton.

Keywords: Archean, Proterozoic, Wyoming province, Great Falls tectonic zone, Tobacco Root Mountains.

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INTRODUCTION

The Wyoming province is a loosely defined craton underlying much of Montana and Wyoming, characterized by its Archean age and seemingly stabilized after a major crust-forming event at 2.6–2.7 Ga (Houston et al., 1993; Frost and Frost, 1993; Frost, 1993; Dutch and Nielson, 1990; Hoffman, 1988). It is flanked to the east and south by Proterozoic orogenic or accretionary belts—the Trans-Hudson orogen (Dahl et al., 1999; Dahl and Frei, 1998; Bickford et al., 1990) and the Cheyenne belt (Chamberlain et al., 1993; Houston, 1993; Premo and Van Schmus, 1989), respectively—that stand in geologic and chronologic contrast to the core of the Archean craton and define the boundaries of the Wyoming province. Knowledge of the Wyoming province comes from discontinuous exposures in basement-cored uplifts of Tertiary age in Wyoming and southern Montana. Even these few windows die out to the north, so that the view necessary to establish the northern limit of the Wyoming province is obscured (Fig. 1).

The Wyoming province consists of three domains that share a characteristic isotopic fingerprint (Frost, 1993; Mueller and Wooden, 1988; Wooden and Mueller, 1988) but are otherwise geologically distinct (Fig. 1). (1) To the south, the Wyoming greenstone province includes greenstone belt sequences like those typical of Archean cratons elsewhere (Hoffman, 1988), whereas the northern Wyoming province consists of (2) the Beartooth-Bighorn magmatic terrane, a largely tonalite-trondhjemite-granodiorite domain intruded by 2.6 Ga, and (3) the Montana metasedimentary terrane, dominated by quartzofeldspathic gneisses in which belts of distinct metasupracrustal sequences are preserved (Mogk and Henry, 1988; Mogk et al., 1992a, 1992b; Mueller et al., 1998; Wooden et al., 1988).

The Tobacco Root Mountains, a Laramide and younger topographic feature in southwest Montana, lie along the northern limit of exposure of Precambrian crystalline basement in the Wyoming province and are cored by metamorphic rocks included in the Montana metasedimentary terrane (Fig. 1). The Tobacco Root Mountains contain several high-grade metamorphic suites: the Pony–Middle Mountain Metamorphic Suite is dominated by quartzofeldspathic gneiss with minor amphibolite; the Indian Creek Metamorphic Suite comprises similar quartzofeldspathic gneisses and amphibolites but also includes mappable sequences of metasupracrustal rocks (marble, quartzite, aluminous schist, and iron formation); the Spuhler Peak Metamorphic Suite is a mineralogically distinctive sequence of mafic rocks with associated quartzite and aluminous schist; and the metamorphosed mafic dikes and sills (MMDS) crosscut and are locally numerous in the Pony–Middle Mountain and Indian Creek Metamorphic Suites but are not present in the Spuhler Peak Metamorphic Suite (Fig. 2).

Building on the work of Charles Vitaliano and his students in the 1970s (Vitaliano et al., 1979a; Vitaliano et al., 1979b; see reprinted map and text accompanying this volume), this Special Paper reports the results of integrated field and instrument-based petrologic, thermobarometric, kinematic, geochronologic, and geochemical studies in the Tobacco Root Mountains conducted under the auspices of the Keck Geology Consortium in the 1990s (Burger, 2004, this volume, Chapter 1). This work clarifies the origin of the suites of Precambrian metamorphic rocks in the Tobacco Root Mountains and, among other findings, demonstrates orogenic activity at both 2.45 and 1.78–1.72 Ga. In contrast to the Late Archean stabilization of the Wyoming province in general, recognition of these Paleoproterozoic events prompts an assessment of how the geologic history of the Tobacco Root Mountains can refine and redefine the nature of the northern Wyoming province.

PRECAMBRIAN GEOLOGIC HISTORY OF THE TOBACCO ROOT MOUNTAINS

A wide range of observations (documented in this volume and summarized in this chapter) indicates extensive reworking of preexisting rocks across the Tobacco Root Mountains between 1.78 and 1.72 Ga. The pressures and temperatures of metamorphism, the widespread distribution and extent of folding, simple shear and transposition of compositional layering, and the degree to which isotopic geochronometers were reset demonstrate an event that was orogenic in character and scope. Because the evidence for this orogeny and most of its known effects are found in Montana, we designate this the Big Sky orogeny.

The Big Sky orogeny so pervasively affected the rocks of the Tobacco Root Mountains that only glimpses of older geologic history are preserved. The vastness of the time span over which at least some metamorphic rocks of the Tobacco Root Mountains existed prior to the Big Sky orogeny (ca. 3.4 to 1.78 Ga, or over a quarter of Earth's history) also contributes to uncertainty. A complete, accurate reconstruction of the evolution of the Tobacco Root Mountains prior to the Big Sky orogeny is out of reach with the presently available observations. We present here the simplest, most straightforward geologic history that is consistent with all data (Fig. 3). Many other interpretations are possible, and future studies may prove some of them more tenable.

The post–1.7 Ga Precambrian history of the Tobacco Root Mountains is comparatively simple and quiescent. Mafic dikes, apparently generated in several different episodes, cut the metamorphic rocks and are not themselves metamorphosed (Wooden et al., 1978). Conglomerates of the LaHood Formation are juxtaposed with Precambrian crystalline rocks across a normal fault and record the initiation of the Belt basin and Belt Supergroup sedimentation in this area (Schmitt, 1988).

Origin of the Indian Creek Metamorphic Suite and the Pony–Middle Mountain Metamorphic Suite

The quartzofeldspathic gneiss and associated amphibolite of the Indian Creek and Pony–Middle Mountain Metamorphic Suites record the earliest stage in Tobacco Root Mountains geologic history. The nature of the protoliths of these metamorphic rocks and the setting in which they arose are of considerable importance to the Archean history of the northern Wyoming province. Yet, because all original contacts have been transposed

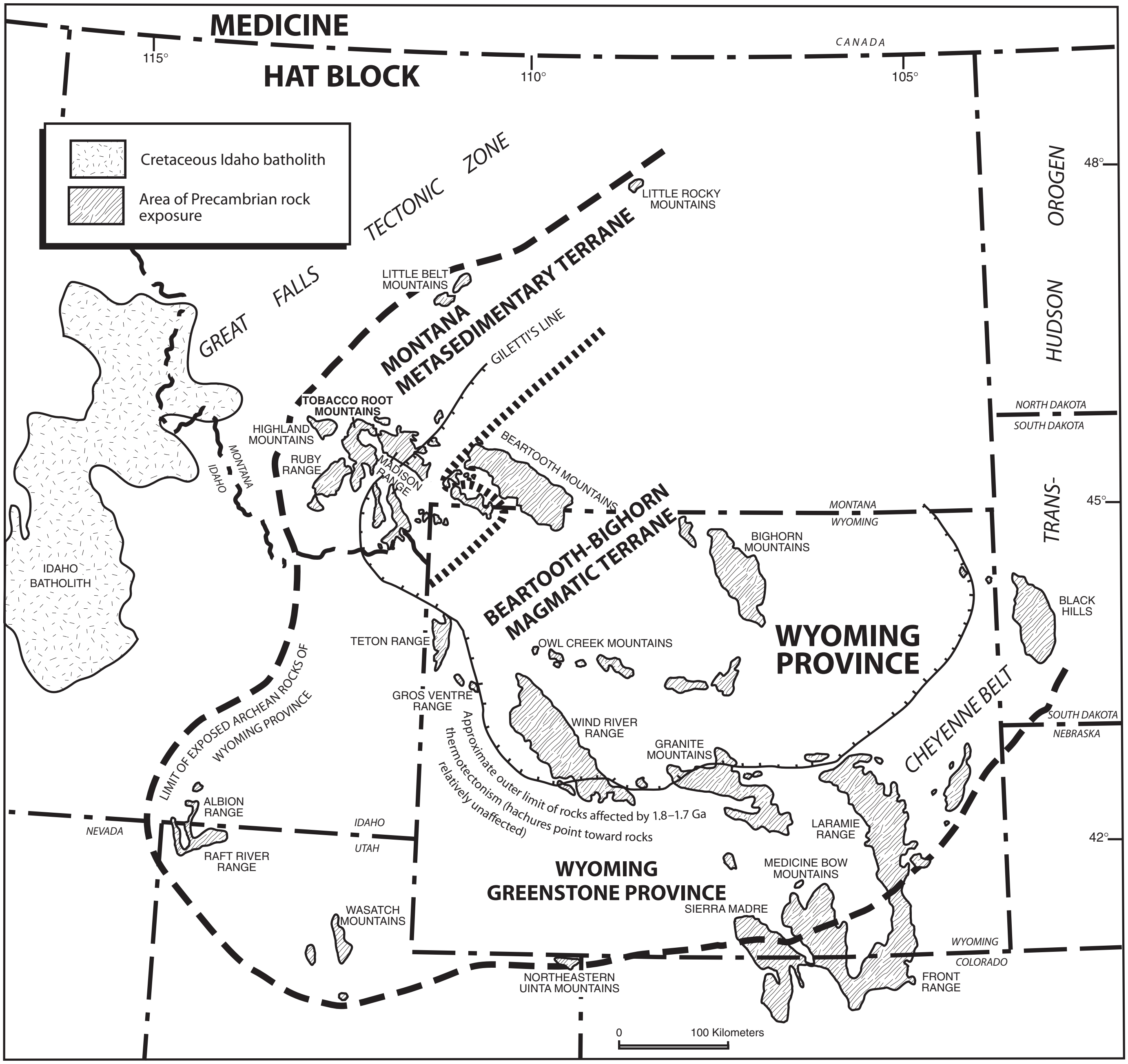

Figure 1. Map of exposed rocks of the Wyoming province and locations referred to in the text. Patterned areas are exposed Precambrian rocks; random dash area is the Idaho batholith; dashed line is the limit of Wyoming province exposure; striped line is the boundary between the Montana metasedimentary terrane and the Beartooth-Bighorn magmatic terrane (after Mogk, 1992); hachured line separates rocks affected by thermotectonism at 1.7–1.8 Ga from undisturbed Archean rocks, and corresponds to Giletti's line (Giletti, 1966) in the northern Wyoming province.

and all primary structures obliterated by extensive high-grade metamorphism both at 1.78 to 1.72 Ga and at 2.45 Ga, direct evidence as to the original character of the Indian Creek and Pony–Middle Mountain Metamorphic Suite rocks has been lost.

Our insights into this problem are provided mainly by major and trace element geochemistry (Mogk et al., 2004, this volume, Chapter 2). Elemental ratios of most Indian Creek and Pony–Middle Mountain Metamorphic Suite samples conform to norms for igneous rocks, but a significant minority indicates a sedimentary origin. Those samples of igneous origin are bimodal in composition: Felsic end members are dominantly calc-alkaline and mafic end members tholeiitic. Discriminant

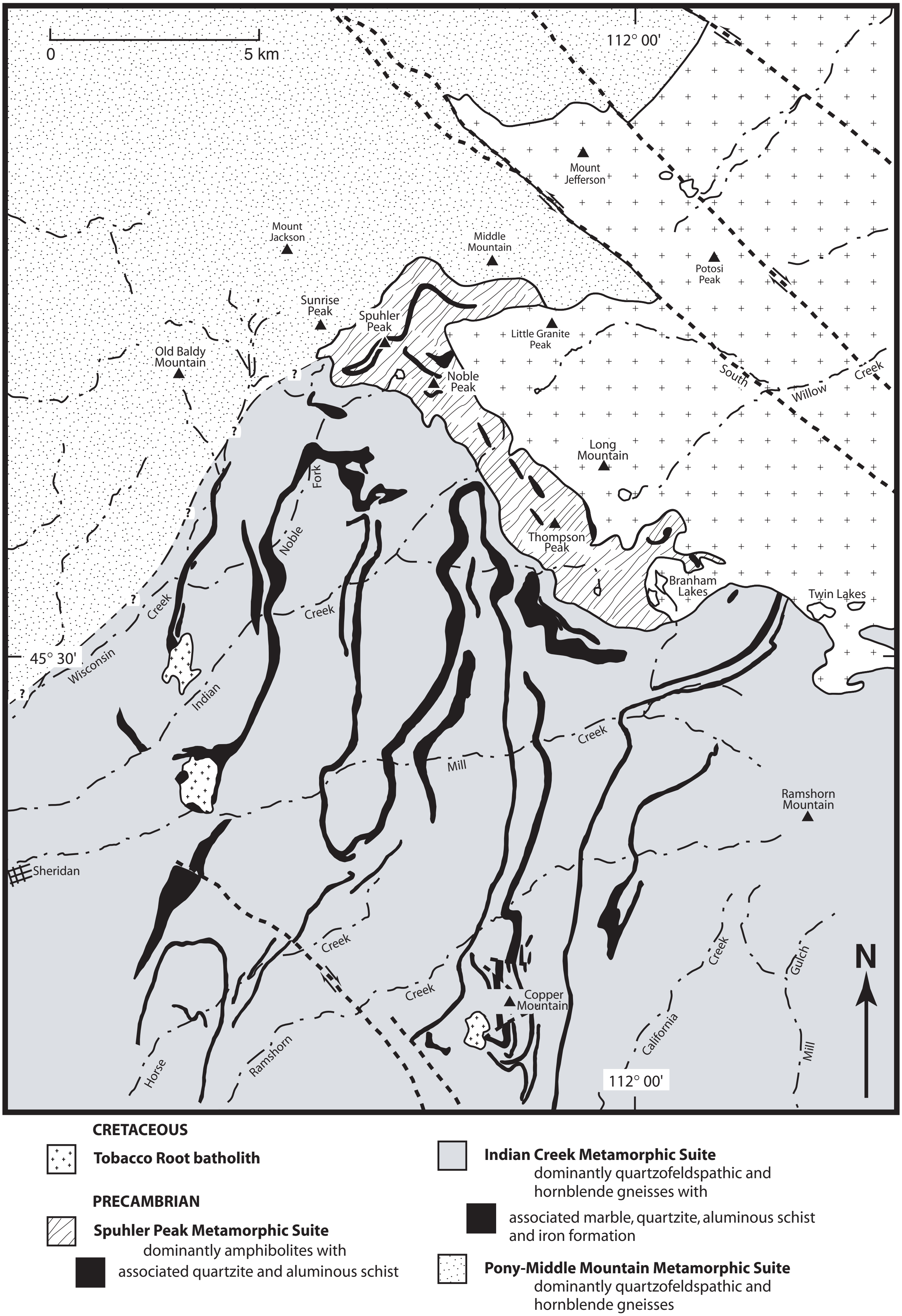
0
5 km
112° 00'
Mount Jefferson
Mount Jackson
Middle Mountain
Potosi Peak
Sunrise Peak
Spuhler Peak
Little Granite Peak
Old Baldy Mountain
Noble Peak
South
Willow
Creek
Long Mountain
Fork
Noble
Thompson Peak
Branham Lakes
Twin Lakes
Creek
Creek
45° 30'
Wisconsin
Indian
Creek
Mill
Ramshorn Mountain
Sheridan
Creek
Creek
Copper Mountain
Horse
Ramshorn
California
Creek
Gulch
Mill
N
112° 00'
CRETACEOUS
Tobacco Root batholith
PRECAMBRIAN
Spuhler Peak Metamorphic Suite
dominantly amphibolites with
associated quartzite and aluminous schist
Indian Creek Metamorphic Suite
dominantly quartzofeldspathic and hornblende gneisses with
associated marble, quartzite, aluminous schist and iron formation
Pony-Middle Mountain Metamorphic Suite
dominantly quartzofeldspathic and hornblende gneisses

Figure 2. Simplified geologic map of the Tobacco Root Mountains (after Vitaliano et al., 1979b, and O'Neill, 1983). The boundary between the Indian Creek Metamorphic Suite and the Pony–Middle Mountain Metamorphic Suite is schematic and based on the abundance of marble in the Indian Creek Metamorphic Suite.

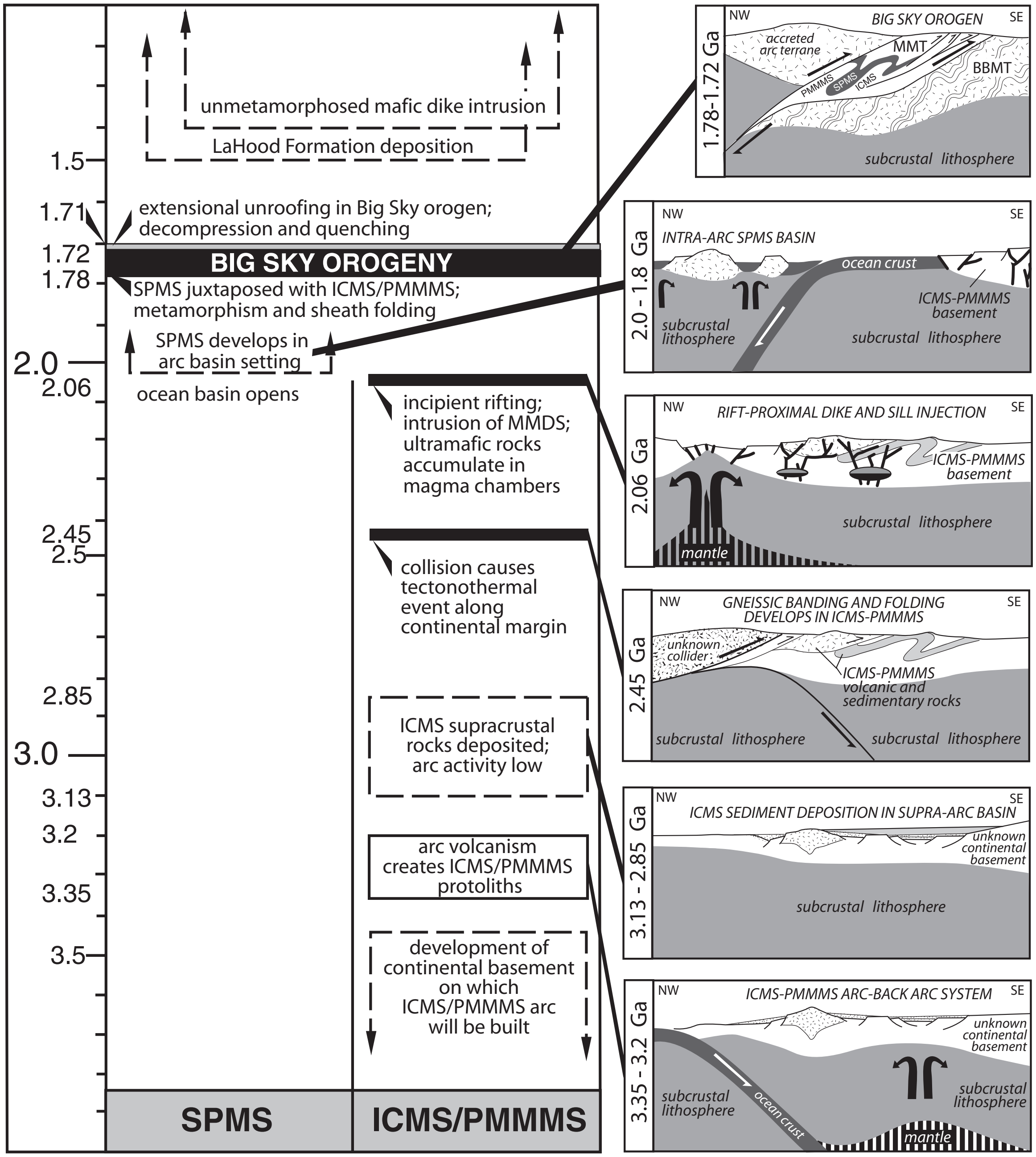

Figure 3. Time line of Precambrian tectonic evolution in the metamorphic suites of the Tobacco Root Mountains. Dashed lines are used where ages are approximate or constrained only by minima and/or maxima. Solid lines and bars indicate known ages. Schematic cross sections illustrate proposed tectonic settings of the Tobacco Root Mountains metamorphic suites at critical points in the time line. PMMMS—Pony–Middle Mountain Metamorphic Suite, SPMS—Spuhler Peak Metamorphic Suite, ICMS—Indian Creek Metamorphic Suite, MMDS—metamorphosed mafic dikes and sills, MMT—Montana metasedimentary terrane, BBMT—Beartooth-Bighorn magmatic terrane

diagrams suggest that the felsic gneisses have an arc affinity, whereas most mafic samples fall in ocean floor fields. Both have strongly negative ε_{Nd} (although the mafic samples are less so) suggesting contamination by older, evolved continental crust (Mueller et al., 2004, this volume, Chapter 9). Finally, samples whose geochemical characteristics indicate a sedimentary protolith are chemically similar to clastic rocks from continental arcs or active continental margin settings (Mogk et al., 2004, this volume, Chapter 2). In sum, these chemical characteristics point to a subduction-related continental arc setting, with intra-arc or backarc extension to generate mid-ocean ridge–like mafic rocks and produce metasomatic alteration that the rocks appear to have experienced (Mogk et al., 2004, this volume, Chapter 2).

The quartzofeldspathic gneisses and amphibolites that dominate the Indian Creek and Pony–Middle Mountain Metamorphic Suites have overlapping ranges of chemical characteristics (Mogk et al., 2004, this volume, Chapter 2). There is no obvious discontinuity between the quartzofeldspathic gneisses of the two suites in the field. Recognition of a map-scale fold involving both suites demonstrates that the two are laterally equivalent along structural strike and that quartzofeldspathic gneiss is continuous from one suite to the other (Harms et al., 2004, this volume, Chapter 10). On this basis, where no distinction need be made between the Indian Creek and Pony–Middle Mountain Metamorphic Suites we will refer to them together simply as the quartzofeldspathic gneiss suite.

We favor an extrusive or volcaniclastic, rather than plutonic, origin for most igneous arc rocks of the quartzofeldspathic suite (Mogk et al., 2004, this volume, Chapter 2). This interpretation is based on the following.

1. The dominance of tabular lithologic units and the interlayering of one unit with another. Strongly crosscutting geometries were not observed in the quartzofeldspathic gneiss. Although the original rock bodies have most certainly been flattened, transposed, and structurally repeated, the ubiquity and fine scale of interlayering argues for it as a primary feature. Interlayering of quartzofeldspathic gneiss of both igneous and sedimentary origin and interlayering of marble, quartzite, aluminous gneiss, and iron formation with the quartzofeldspathic gneiss are easiest to reconcile with a volcanic or volcaniclastic origin for the quartzofeldspathic gneiss.

2. The lithologic heterogeneity on all scales. This is in strong contrast to lithologic homogeneity over large areas that characterize metaplutonic rocks elsewhere in the northern Wyoming province (Mogk et al., 1992b; Wooden et al., 1988). An exception to this interpretation may be the potassium feldspar–megacrystic gneisses of the Pony–Middle Mountain Metamorphic Suite, which we believe are likely candidates for metaplutonic rocks.

At present, our best constraints indicate the quartzofeldspathic gneiss suite originated in a long-standing or repeatedly productive continental arc active between ca. 3.35 and 3.2 Ga. Igneous ages of 3.31 Ga, 3.21 Ga (U-Pb sensitive high-resolution ion microprobe [SHRIMP] dating by Mueller et al., 2004, this volume, Chapter 9) and 3.37 Ga (U-Pb upper-intercept age by Krogh et al., 1997) have been obtained from magmatic zircons separated from Indian Creek Metamorphic Suite samples. These magmatic ages are very similar to the intrusive age of quartzofeldspathic gneiss elsewhere in the Montana metasedimentary terrane (Mueller et al., 1993, 1996c). Whole-rock Rb-Sr ages of 2.75 Ga (James and Hedge, 1980) and 2.67 Ga (Mueller and Cordua, 1976), which were long-standing geochronologic benchmarks for the Tobacco Root Mountains, should now be abandoned in favor of the ages from these more robust dating techniques (see also Roberts et al., 2002). Except through its contribution to the Nd isotope systematics of the arc rocks (Mueller et al., 2004, this volume, Chapter 9) and to detrital zircon populations in Indian Creek Metamorphic Suite metasupracrustal rocks (Mueller et al., 1998), no direct evidence of the older continental basement onto which the 3.35–3.2 Ga continental arc was built has been found.

The obvious metasupracrustal rocks of the Indian Creek and Pony–Middle Mountain Metamorphic Suites—the marbles, quartzites, aluminous schists, and iron formation—represent a different paleoenvironment and, apparently, a different period than the quartzofeldspathic gneisses and amphibolites that envelope them. The presence of rock types such as marble and iron formation, and their lateral continuity, point to a stable depositional environment and periods of tectonic quiescence in and around the basin. Quartzite from the Indian Creek Metamorphic Suite metasupracrustal sequence has yielded detrital zircons ranging in age from 3.13 to 3.93 Ga (Mueller et al., 1998). This 3.13 Ga maximum age for the metasupracrustal rocks is younger than the youngest magmatic age from the quartzofeldspathic gneisses. Mueller et al. (2004, this volume, Chapter 9; 1998) highlight the absence of 2.75 to 2.85 Ga zircons representative of gneisses of that age that are widespread in the northern Wyoming province (Frost, 1993; Frost and Frost, 1993; Mogk and Henry, 1988; Wooden et al., 1988; Montgomery and Lytwyn, 1984). This, they argue, promotes a depositional age older than 2.85 Ga for the quartzite. Alternatively, the zircon age distribution could result from deposition after 2.75 Ga, but in an area either of very restricted provenance or outside the detrital range of the northern Wyoming province.

The Indian Creek and Pony–Middle Mountain Metamorphic Suites, therefore, incorporate two distinct stages in the early history of the Tobacco Root Mountains: long-lived (3.35–3.2 Ga) arc and backarc magmatism on an older continent, and sedimentation after 3.13 Ga. The metasupracrustal rocks may have originated independently and been tectonically juxtaposed with the quartzofeldspathic gneiss, possibly as an aspect of the 2.45 Ga tectonothermal event, or the metasupracrustal rocks may record the transition from an active arc margin to erosion of the arc and deposition in an epicontinental sedimentary basin.

Cryptic Tectonothermal Event at 2.45 Ga

Geochronology provides evidence for what was at least a thermal event in the area occupied by the Pony–Middle Mountain and Indian Creek Metamorphic Suites at 2.45 Ga. Monazites of this age are found in aluminous gneisses in both suites (Cheney et al., 2004b, this volume, Chapter 8). Spot analyses of zircon rims ($^{207}Pb/^{206}Pb$ SHRIMP dating by Mueller et al., 2004, this volume, Chapter 9) and lower-intercept ages from discordant zircon populations (Krogh et al., 1997) in quartzofeldspathic gneisses of the Indian Creek Metamorphic Suite also indicate metamorphic growth or disturbance of zircon at 2.4 Ga. Patchy Ca and Fe zoning in the cores of some Indian Creek and Pony–Middle Mountain Metamorphic Suite garnets may be relicts of this earlier metamorphism (Cheney et al., 2004a, this volume, Chapter 6).

No 2.45 Ga igneous rocks have been identified so far within the quartzofeldspathic gneiss suite (Mueller et al., 2004, this volume, Chapter 9). Inherited zircons that range in age from ca. 2.2 to 3.0 Ga, including several at 2.4 Ga (single zircon, $^{207}Pb/^{206}Pb$ SHRIMP dating), however, have been recovered from the Cretaceous Tobacco Root batholith (Mueller et al., 1996a, 1996b), which cuts the center of the Tobacco Root Mountains (Fig. 2). Mueller et al. (1996a) interpret the zircons as coming directly from magmatic rocks, rather than being second-cycle components of clastic rocks, and point out that plutonic rocks of that age must be preserved at some depth below the range.

Other observations hint that the event at 2.45 Ga was tectonic as well as thermal, and that the arc, backarc, and basinal deposits of the Indian Creek and Pony–Middle Mountain Metamorphic Suites were consolidated into continental crystalline basement by burial, deformation, and metamorphism at that time, implying renewed plate convergence and/or collision. MMDS bodies cut well-developed and folded gneissic fabrics in both the Indian Creek and Pony–Middle Mountain Metamorphic Suites (Brady et al., 2004a, this volume, Chapter 5; Harms et al., 2004, this volume, Chapter 10)—metamorphic fabrics that must, consequently, be older than the 2.06 Ga intrusive age of the MMDS suite (Mueller et al., 2004, this volume, Chapter 9) and have been of high enough grade to survive Big Sky metamorphism at 1.78 Ga. Because it requires the fewest separate metamorphic events, we propose that the 2.45 Ga monazite grew during the development and deformation of the pre-MMDS gneissic banding. This correlation, however, is not strictly required by the data in hand. Both porphyroblasts and matrix in the Pony–Middle Mountain and Indian Creek Metamorphic Suites contain 2.45 Ga monazite, many of which do not have 1.78 Ga rims, but, in the Indian Creek Metamorphic Suite, rocks that have 2.45 Ga monazite most typically also have 1.78 Ga grains. These aspects of the character and distribution of the older monazites suggest that they were profoundly resistant to change even when conditions produced new monazite growth at 1.78 Ga. This being the case, we cannot rigorously or unequivocally relate the 2.45 Ga monazites to the growth of any metamorphic minerals around them, as the latter might or might not have crystallized at 1.78 Ga while the former were clearly unaffected.

Evidence for a thermal or tectonothermal event at 2.45 Ga in the northern Wyoming province is not limited to the Tobacco Root Mountains. Hornblende, biotite, and muscovite $^{40}Ar/^{39}Ar$ plateau ages of 2.4–2.5 Ga in the southern Madison Range are interpreted to reflect the primary cooling history of that area (Erslev and Sutter, 1990). Xenoliths from the Idaho batholith contain zircons with upper-intercept ages of 2.34 Ga (Bickford et al., 1981).

Origin of the Metamorphosed Mafic Dikes and Sills—Mafic Magmatism and Continental Rifting

The Indian Creek and Pony–Middle Mountain Metamorphic Suites are host to metamorphosed mafic dikes and sills (MMDS), many of which retain relict igneous textures (Brady et al., 2004a, this volume, Chapter 5), but all contain metamorphic minerals that reflect the pressure and temperature conditions of the Big Sky orogeny (Cheney et al., 2004a, this volume, Chapter 6), including metamorphic zircons (Mueller et al., 2004, this volume, Chapter 9). Originally there probably were more crosscutting dikes than are seen today, as many have been transposed to layer-parallel geometries by Big Sky deformation (Harms et al., 2004, this volume, Chapter 10).

One representative MMDS body in the Pony–Middle Mountain Metamorphic Suite was sampled for geochronology and yielded a population of prismatic, low-discordance zircons that give what is interpreted to be an intrusive age of 2.06 Ga (Mueller et al., 2004, this volume, Chapter 9). Consistency of major and trace element composition among the many dikes analyzed geochemically argue that all are part of a single magmatic suite intruded into both the Indian Creek and Pony–Middle Mountain Metamorphic Suites together (Brady et al., 2004a, this volume, Chapter 5). However, because multiple sets of dikes of differing Proterozoic ages are known from the Wyoming and other Archean cratons (Frost and Frost, 1993; Krogh et al., 1987; Aspler and Chiarenzelli, 1998, and references therein), and from the post–1.7 Ga history of the Tobacco Root Mountains themselves (Wooden et al., 1978), it is possible that the MMDS suite might include undated bodies of ages other than 2.06 Ga.

Continental rifting at 2.06 Ga is the most likely context for MMDS intrusion. Major element compositions of MMDS rocks indicate a subalkaline, tholeiitic basalt protolith. Their rare earth element (REE) patterns are similar to those of basalts intruded into continental rift settings today (Brady et al., 2004a, this volume, Chapter 5). Discriminant diagrams based on largely immobile elements are inconclusive as to the setting of origin of the MMDS bodies (Hess and Vitaliano, 1990). The sharp contacts of the MMDS bodies, their planar geometries, and the relict chilled margin textures observed indicate that the original dikes and sills cut cool, relatively brittle, continental crust of the Indian Creek and Pony–Middle Mountain Metamorphic Suites. Thus, MMDS-related rifting disrupted the craton that was established or enlarged by collision at 2.45 Ga and stabilized before 2.06 Ga. We speculate that at some distance from the present Tobacco Root Mountains the rifting process went to completion and ocean crust was formed. This new, ca. 2.0 Ga continental margin would subsequently become the locus of collision during the Big Sky orogeny.

Comparison of major element ratios in MMDS rocks indicates that significant fractional crystallization, notably of orthopyroxene but of plagioclase and clinopyroxene as well, occurred in their source reservoir over the course of intrusion of the suite (Brady et al., 2004a, this volume, Chapter 8). Orthopyroxene-rich cumulates created in this way may have been the parents of the relatively silica-rich meta-ultramafic rocks that are present locally in the Indian Creek, Pony–Middle Mountain and Spuhler Peak Metamorphic Suites (Johnson et al., 2004, this volume, Chapter 4).

Origin of the Spuhler Peak Metamorphic Suite

The Spuhler Peak Metamorphic Suite is dominated by hornblende amphibolites and orthoamphibole-garnet gneiss. Geochemical analysis indicates these metamorphosed mafic rocks originated as tholeiitic basalt and hydrothermally altered equivalents, respectively (Burger et al., 2004, this volume, Chapter 3). Trace element chemistry appears arc-related and unlike mid-oceanic-ridge basalt. The scattered metamorphosed ultramafic bodies in the Spuhler Peak Metamorphic Suite do not appear to be ophiolitic either; their geochemistry suggests they are the result of fractional crystallization and were neither komatiites nor mantle peridotites (Johnson et al., 2004, this volume, Chapter 4). A suprasubduction zone ophiolite, backarc, or intra-arc oceanic basin setting of origin for the Spuhler Peak Metamorphic Suite would provide both the observed arc signature and the context for widespread hydrothermal alteration of tholeiitic basalt as required by the prominence of orthoamphibole-garnet rocks.

Interlayered aluminous, siliceous schist and quartzite in the Spuhler Peak Metamorphic Suite reflect the introduction of detritus to—or in the case of quartzite, possibly chemical sedimentation in—the suite's basin (Burger et al., 2004, this volume, Chapter 3). Marbles are notably absent from the suite. These sedimentary components are consistent with a backarc basin setting but do not preclude other interpretations.

The maximum age of the Spuhler Peak Metamorphic Suite is constrained by the few low-discordance, clearly detrital zircon grains that have been recovered from a quartzite in the suite. These range from 3.39 to 3.02 Ga (U-Pb SHRIMP dating); the absence of 2.75–2.85 Ga grains is, again, noteworthy (Mueller et al., 2004, this volume, Chapter 9).

The lithologic contrast between the Spuhler Peak Metamorphic Suite and adjacent quartzofeldspathic gneiss suites (the Indian Creek and Pony–Middle Mountain Metamorphic Suites) has focused attention on the nature of this contact. While the Spuhler Peak Metamorphic Suite experienced all phases of the Big Sky orogeny together with the quartzofeldspathic gneiss suite, there is no evidence that it underwent metamorphism at 2.45 Ga (Cheney et al., 2004b, this volume, Chapter 8) and, like Gillmeister (1972), we observed no MMDS bodies in the Spuhler Peak Metamorphic Suite (Brady et al., 2004a, this volume, Chapter 5). It is clear that the Spuhler Peak Metamorphic Suite was not in contact with the quartzofeldspathic gneiss suite in the period 2.45 to 2.06 Ga and was in contact by 1.78 Ga. But what kind of contact developed in that interval? Two models have been proposed; the implications of each are different and striking.

1. Gillmeister (1972) interpreted the Spuhler Peak Metamorphic Suite to have been deposited on the quartzofeldspathic gneiss suite across an unconformity. This is consistent with the observation that MMDS bodies do not cross the Spuhler Peak Metamorphic Suite contact and with the persistence of a quartzite in the Spuhler Peak Metamorphic Suite along the contact, presumably a basal clastic deposit. One weakness of this model is that it does not account for the lack of feeder dikes within the Indian Creek or Pony–Middle Mountain Metamorphic Suites for the voluminous mafic layers in the Spuhler Peak Metamorphic Suite. Also, in this model, the Spuhler Peak Metamorphic Suite arc and related backarc spreading system would have developed on a basement of quartzofeldspathic gneiss. The absence of a calc-alkaline component in Spuhler Peak Metamorphic Suite metabasalts (Burger et al., 2004, this volume, Chapter 3) makes such a continental setting problematic. Finally, if the Spuhler Peak Metamorphic Suite accumulated unconformably on the quartzofeldspathic gneiss suite, then it must be younger than the 2.06 Ga MMDS intrusions and older than the onset of the 1.78 Ga Big Sky orogeny, that is, wholly Proterozoic. The detrital zircon population of interlayered quartzite requires, in turn, that either sediment supply to the arc-related Spuhler Peak Metamorphic Suite basin was shielded from the nearby Beartooth-Bighorn magmatic terrane, where 2.75–2.85 Ga rocks are common, or the Tobacco Root area, including the Indian Creek and Pony–Middle Mountain Metamorphic Suites, was not adjacent to the Beartooth-Bighorn basement before the Big Sky orogeny.

2. Burger (1969) mapped a fault at the base of the Spuhler Peak Metamorphic Suite because of apparent discordance in structure and metamorphic grade between it and the quartzofeldspathic gneiss suite and because a high-strain zone is coincident with the contact. Our work does not substantiate Burger's original criteria: the grade of Big Sky metamorphism is consistent across all the metamorphic suites of the Tobacco Root Mountains (Cheney et al., 2004a, this volume, Chapter 6); the discordant geometry of Indian Creek Metamorphic Suite folds along the contact may be only an apparent truncation; and high-strain zones are present both along and away from the Spuhler Peak Metamorphic Suite contact (Harms et al., 2004, this volume, Chapter 10). Nevertheless, the Big Sky orogeny is a likely context for tectonic juxtaposition of the Spuhler Peak Metamorphic Suite and the quartzofeldspathic gneiss suite because it was accompanied by substantial simple shear strain across the Tobacco Root Mountains (Harms et al., 2004, this volume, Chapter 10). If the Spuhler Peak Metamorphic Suite was faulted against the quartzofeldspathic gneiss suite, the age of the suite must be older than the Big Sky orogeny but otherwise is constrained only by the detrital zircons recovered to date. The suite could be Archean and older than the 2.75–2.85 Ga Beartooth-Bighorn magmatic terrane crust

not represented by detrital zircons, but we consider the length of time between the origin of the Spuhler Peak Metamorphic Suite in this case and its amalgamation with the rest of the Wyoming province during the Big Sky orogeny over a billion years later to be problematic in light of the transient nature of plate boundaries, arcs, and ocean crust. Conversely, as there is no direct evidence for an Archean age, the Spuhler Peak Metamorphic Suite could be Proterozoic, having developed in an arc-backarc basin system exotic to the northern Wyoming province. The culmination of subduction in this Proterozoic ocean would be the collision that accreted the Spuhler Peak Metamorphic Suite to its present position relative to the quartzofeldspathic gneiss suite and produced the Big Sky orogeny.

Our work in the Tobacco Root Mountains did not, in fact, produce any observation that unequivocally requires or explicitly contradicts either the unconformity or the fault model for the Spuhler Peak Metamorphic Suite contact. A Proterozoic age for the Spuhler Peak Metamorphic Suite is a significant departure from long-standing views as to the antiquity of the rocks in the Tobacco Root Mountains, but we find that the model of tectonic juxtaposition of a Proterozoic Spuhler Peak Metamorphic Suite has the fewest objectionable elements and matches the most observations. For this reason we consider the suite to be an allochthonous terrane within the Big Sky orogen.

The Big Sky Orogeny

Mineral assemblages, mineral textures, and mineral chemistry in all four metamorphic suites in the Tobacco Root Mountains record progressive metamorphism along a clockwise path through pressure-temperature space that reflects stages in the Big Sky orogeny between 1.78 and 1.71 Ga (Fig. 4) (Cheney et al., 2004a, this volume, Chapter 6, 2004b, this volume, Chapter 8; Brady et al., 2004b, this volume, Chapter 7). Metamorphism started with a higher-pressure, higher-temperature (>1.0 GPa and >700 °C) phase (M1). The higher-pressure (M1) start of the metamorphic path is demonstrated predominately in aluminous orthoamphibole-bearing lithologies from the Spuhler Peak Metamorphic Suite, but it is also preserved locally in similar rock types in the Indian Creek Metamorphic Suite, demonstrating that M1 conditions were experienced across the Tobacco Root Mountains at the onset of the Big Sky orogeny. If, as we propose, the Spuhler Peak Metamorphic Suite is a Proterozoic suite with no previous metamorphism, then peak pressures exceeding 1.0 GPa experienced by the suite must have been achieved by tectonic overburden constructed during the Big Sky orogeny, presumably as a consequence of convergence at that time, and therefore suggest crustal thickness in the orogen in excess of 40 to 50 km. Juxtaposition of the Spuhler Peak Metamorphic Suite with the Indian Creek and Pony–Middle Mountain Metamorphic Suites would have occurred as part of this tectonic stacking, although it is not clear from the present geometry in the Tobacco Root Mountains whether the Spuhler Peak Metamorphic Suite was obducted onto the quartzofeldspathic gneisses or was partially subducted beneath them as the Big Sky orogeny commenced (Harms et al., 2004, this volume, Chapter 10).

From the maximum pressures of metamorphism, the Tobacco Root Mountains underwent modest decompression while heating

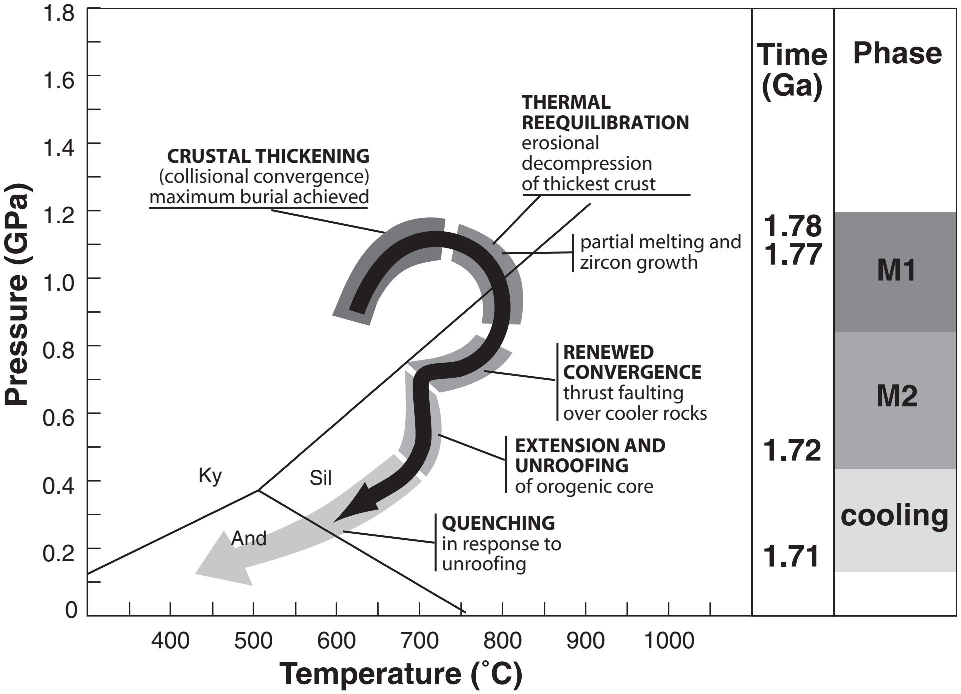

Figure 4. Pressure-temperature-time path for all three metamorphic suites of the Tobacco Root Mountains and the MMDS during the Big Sky orogeny correlated to metamorphic phases and to tectonic stages in the development of the orogen. The numerous mineral stability fields that constrain the pressure-temperature path are given in Cheney et al. (2004a, this volume, Chapter 6; see their Figure 21); only the aluminosilicate stability fields (Holdaway, 1971) are shown here for reference (Ky—kyanite; Sil—sillimanite; And—andalusite).

to a thermal maximum of ~800 °C (Cheney et al., 2004a, this volume, Chapter 6). We suggest this occurred as geotherms reestablished themselves in the thickened crust while erosion was focused at high elevations in the new orogen. No igneous rocks generated during the Big Sky orogeny have been identified in the Tobacco Root Mountains. Leucosome, however, is widely observed. We interpret it to be the result of partial melting that is best linked to the maximum temperatures of metamorphism along this decompressing arc of the pressure-temperature loop (Cheney et al., 2004a, this volume, Chapter 6). Low-discordance, low-Th/U, metamorphic zircon recovered from leucosome gives an age of 1.77 Ga (U-Pb SHRIMP dating) for this stage of the orogeny (Mueller et al., 2004, this volume, Chapter 9). The localization of this leucosome in dilatant zones associated with boudins and folds, the latter of which, in particular, characterize mesoscopic deformation in the Tobacco Root Mountains, links the time of deformation to the maximum temperature and pressure phase (M1) of the Big Sky orogeny (Harms et al., 2004, this volume, Chapter 10; Mueller et al., 2004, this volume, Chapter 9). Mesoscopic folds are part of a pervasive structural pattern of north-dipping fabric, north-plunging lineation, and a map-scale sheath fold of the Spuhler Peak Metamorphic Suite, flanked by the Indian Creek and Pony–Middle Mountain Metamorphic Suites, which we interpret to be the result of intense, regional, simple shear (Harms et al., 2004, this volume, Chapter 10) that accompanied crustal thickening and M1 metamorphism.

The higher-pressure–higher-temperature (M1) arc of the Big Sky metamorphic path was followed by differential reequilibration at lower temperatures and pressures (M2) via nearly isobaric cooling (from ~750 to 700 °C at ~0.7–0.8 GPa), leading to isothermal decompression (from ~0.7 to <0.6 GPa at ~700 °C) (Cheney et al., 2004a, this volume, Chapter 6). The occurrence and conditions of M2 metamorphism are well established by garnet-amphibole thermobarometry (Cheney et al., 2004a, this volume, Chapter 6) in metamorphosed mafic rocks in all four Precambrian suites (Indian Creek, Pony–Middle Mountain, and Spuhler Peak Metamorphic Suites and MMDS). Friberg (1994) and Hess and Vitaliano (1990) also documented pressure and temperature conditions similar to our M2 phase. We suggest isobaric cooling indicates that the Tobacco Root Mountains metamorphic suites and their tectonic overburden were carried piggyback in the hanging wall of a large-scale thrust fault over cooler rocks formerly at higher crustal levels, increasing total crustal thickness in the Big Sky orogen beyond 40–50 km. Isothermal decompression points to gravitational instability and orogenic collapse triggered by this crustal-scale thrust faulting.

Monazite, which is present both as inclusions in various porphyroblasts and within the matrix of metamorphic rocks in the Tobacco Root Mountains, shows dominant growth at 1.78 Ga and continued growth until 1.72 Ga (Cheney et al., 2004b, this volume, Chapter 8). We interpret this age range to represent the M1-to-M2 metamorphic period. Comparison with the 1.77 Ga zircon age of partial melting and pervasive deformation suggests 1.78 Ga monazite growth was associated with the early, higher-pressure portion of the metamorphic path. Monazites as young as 1.753 Ga are present in kyanite (Cheney et al., 2004b, this volume, Chapter 8); the pressure-temperature path must have crossed the kyanite-sillimanite reaction after that time (Fig. 4).

^{40}Ar/^{39}Ar ages of 1.71 Ga from hornblende in the Spuhler Peak and Indian Creek Metamorphic Suites (Brady et al., 2004b, this volume, Chapter 7) confirm cooling through the hornblende closure temperature (~500 °C) immediately after final growth of monazite and upper amphibolite-facies M2 metamorphism. This is a record of rapid quenching following M2 isothermal decompression, which is consistent with tectonic unroofing of the deeper parts of the Big Sky orogen, including the Tobacco Root Mountains. No extensional structures have been identified within the Tobacco Root Mountains (Harms et al., 2004, this volume, Chapter 10). This is not unexpected given the uniformity of metamorphic grade observed throughout the Spuhler Peak, Indian Creek, and Pony–Middle Mountain Metamorphic Suites and MMDS (Cheney et al., 2004a, this volume, Chapter 6) and the consistent time of cooling demonstrated across the Tobacco Root Mountains and adjacent ranges (Brady et al., 2004b, , this volume, Chapter 7, and references therein). The Tobacco Root Mountains must have been positioned in the footwall plate of any detachment systems active during decompression and rapid cooling.

ARCHITECTURE OF THE BIG SKY OROGEN ACROSS THE NORTHERN WYOMING PROVINCE

Nearly four decades ago, Giletti (1966) compiled K-Ar age data for the northern Wyoming province and revealed a domain of ca. 1.6 Ga ages separated from much older, Archean rocks to the south across a northeast-trending line that has become known as “Giletti’s line” (Fig. 5). He interpreted the Proterozoic ages as reflecting a regional metamorphism that reset the Ar system in rocks originally metamorphosed much earlier, typically ca. 2.4–2.6 Ga. Later, Erslev and Sutter (1990) and O’Neill (1998) went on to suggest that a northeast-trending Proterozoic orogen underlies the northern Wyoming province and that Giletti’s K-Ar boundary separates a reset hinterland to the northwest from a cooler, undisturbed foreland to the southeast in that south-vergent orogen. Evidence for 1.8–1.6 Ga thermal disturbance in much older metamorphic rocks has subsequently been documented in the North (Reid et al., 1975) and South (Montgomery and Lytwyn, 1984) Snowy Blocks of the Beartooth Mountains, along Giletti’s line, and in the Stillwater Complex (Houston et al., 1993) south of the line. These additional geochronologic data refine the position of Giletti’s line but do not fundamentally change his, or Erslev and Sutter’s and O’Neill’s vision. The geology of the Tobacco Root Mountains reported in this Special Paper makes clear the importance of a 1.78 to 1.71 Ga orogeny north of Giletti’s line and replaces the long-standing view (held since James and Hedge [1980] and Mueller and Cordua [1976]) that metamorphism in this region was entirely or primarily Archean. Despite limited and discontinuous exposures of Precambrian basement, with a wide range of other geologic, geochronologic,

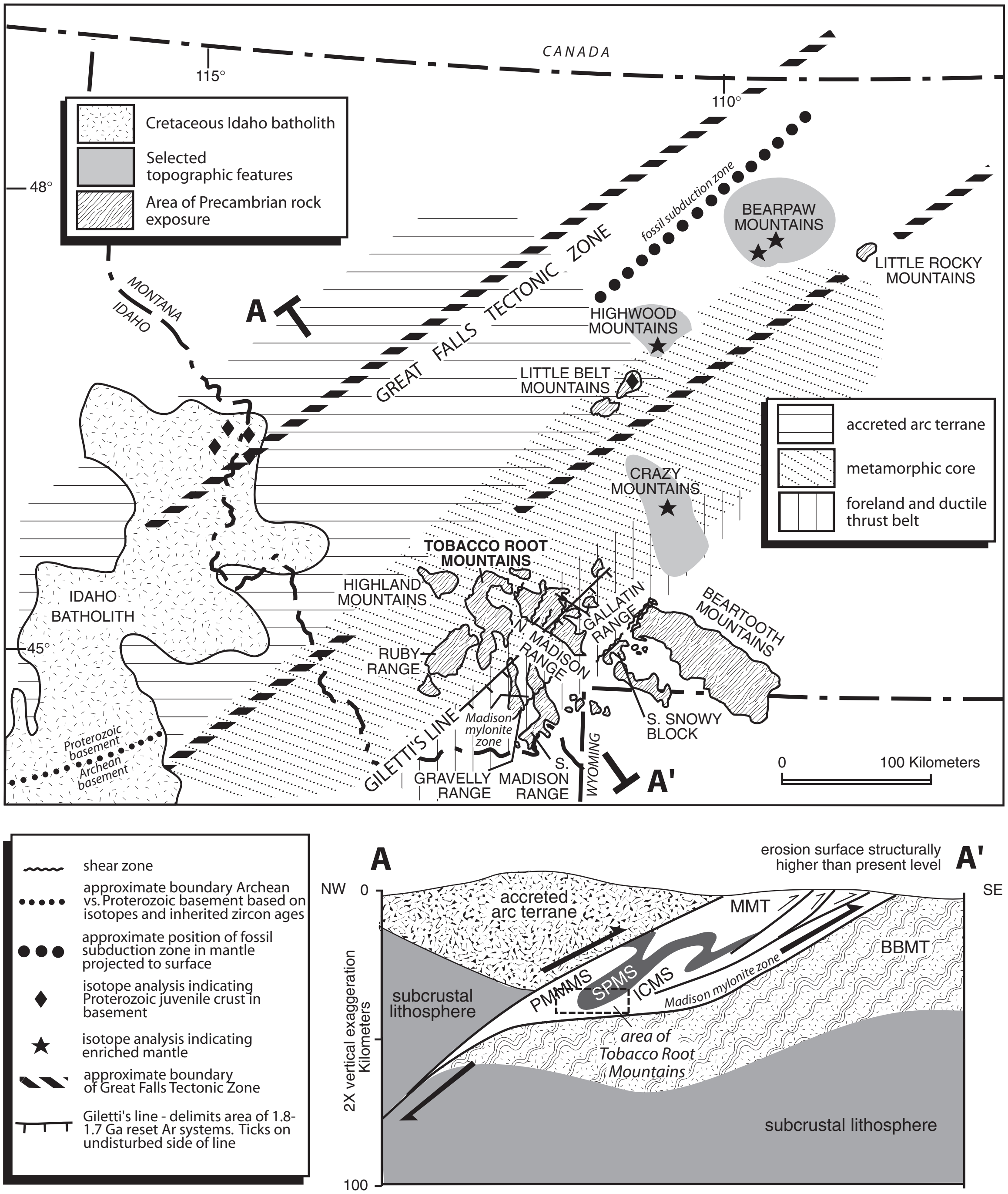

Figure 5. Architecture of the Big Sky orogen in map and cross section. Geochemical, geophysical, and geologic observations cited in the text outline a northeast-trending metamorphic core zone (dotted diagonal ruling, map view) of the orogen that is flanked to the southeast by a foreland of discrete, southeast-vergent, ductile thrust faults (vertical ruling, map view) and to the northwest by a fossil subduction zone and accreted, juvenile, Proterozoic arc terrane (horizontal ruling, map view). See also O'Neill's (1998) Figures 1 and 2. PMMMS—Pony–Middle Mountain Metamorphic Suite, SPMS—Spuhler Peak Metamorphic Suite, ICMS—Indian Creek Metamorphic Suite, MMT—Montana metasedimentary terrane, BBMT—Beartooth-Bighorn magmatic terrane.

geochemical, and geophysical advances in the northern Wyoming province, it is now possible to outline the broad characteristics of this orogen in space and time (see also O'Neill, 1998) (Fig. 5). Major components include

- a ductilely deformed metamorphic core,
- a supracrustal foreland cut by discrete shear zones south of the metamorphic core,
- a north-dipping fossil subduction zone north of surface exposures of Precambrian rocks, and
- a loosely defined domain of juvenile plutonic rocks indicating accretion of an arc along the northern margin of the orogen.

The Tobacco Root Mountains are presently the best-documented part of the metamorphic core zone and provide the best evidence for the evolution of the orogen over time. On this basis, we extend the name "Big Sky orogeny" from the Tobacco Root Mountains across the northern Wyoming province and apply it to the whole Proterozoic orogenic belt.

Metamorphic Core Zone

The core of the Big Sky orogen lies along a northeast-trending belt of ca. 1.8–1.7 Ga upper amphibolite facies metamorphism that not only includes the Tobacco Root Mountains but extends from the Ruby and Highland Ranges to the Little Belt Mountains. It may also encompass metamorphism and/or deformation in the northern Madison and Gallatin Ranges. The ~300 km along-strike exposed length of this belt is modest compared with the high grade of metamorphism and intensity of ductile deformation and shear observed in the Tobacco Root Mountains and with the magnitude of Proterozoic crustal thickening we have proposed. The Big Sky metamorphic core zone may reasonably be expected to continue in the subsurface perhaps as far southwest as the root of the Idaho batholith and northeast to the Trans-Hudson orogen.

Garihan (1979) and O'Neill et al. (1988) report amphibolite- and upper-amphibolite-grade, migmatitic, aluminous gneiss, hornblende gneiss, and quartzofeldspathic gneiss that are mylonitized and folded in the crystalline core of the Ruby and Highland Mountains. Step-leach ^{207}Pb/^{206}Pb analysis of garnet, a method that probably yields a maximum age (Dahl et al., 2000), gives an age of metamorphism of younger than 1.82 Ga in the Ruby Range and younger than 1.79 Ga in the Highland Range (Roberts et al., 2002). Cooling through the hornblende and biotite blocking temperatures occurred between 1.74 and 1.71 Ga (^{40}Ar/^{39}Ar dating) (Roberts et al., 2002; Brady et al., 2004b, this volume, Chapter 7) and provides a minimum metamorphic age in the Highland and Ruby Ranges.

To the northeast, in the core of the Little Belt Mountains, an intrusive age of ca. 1.86 Ga has been determined by U-Pb zircon geochronology for various granitoid gneisses and establishes a maximum age for their deformation and metamorphism (Mueller et al., 1997, 2002; Vogl et al., 2002). Catanzaro and Kulp (1964) analyzed concordant monazite of similar age (ca. 1.9 Ga) from a migmatite. A garnet step-leaching age of 1.86 Ga (Dahl et al., 2000) provides another, again maximum age constraint on metamorphism. Hornblende and biotite ^{40}Ar/^{39}Ar plateau ages of 1.79–1.77 Ga on the same rocks can be interpreted as the close of deformation and metamorphism (Holm and Schneider, 2002).

The metamorphic history of the Gallatin Range seems very similar to that in the Tobacco Root Mountains. Mogk (1990, 1992) demonstrates a clockwise pressure-temperature path from upper amphibolite or granulite conditions, followed by isothermal decompression. The age of metamorphism and deformation in the Gallatin Range, however, has previously been interpreted as Archean, based on the mid-Archean age of deformed sills interpreted as synkinematic (Mogk, 1990, 1992). Similarly, northeast-striking, northwest-dipping shear zones in the northern Madison and Gallatin Ranges have also been considered Archean because they are crosscut by unfoliated granites dated at 2.55 Ga based on the upper intercept of discordant zircons (Mogk et al., 1992a). We suggest both these ages bear reexamination. The metamorphic facies, structures, and fabrics in the Madison and Gallatin Ranges are parallel to and compatible with those of the 1.78–1.72 Ga Big Sky orogen in the Tobacco Root Mountains, and may also have originated at that time.

Foreland

The Madison mylonite zone in the southern Madison Range (Erslev and Sutter, 1990) is a wide, northeast-striking, northwest-dipping shear zone that roughly parallels Giletti's line (Fig. 5). It is interpreted as a thrust fault because it places higher-grade rocks over lower-grade rocks (Erslev and Sutter, 1990). The Ar system for rocks within the zone appears to have been disturbed at ca. 1.8 Ga, whereas rocks outside the zone give 2.4–2.5 Ga plateau ^{40}Ar/^{39}Ar ages (Erslev and Sutter, 1990), demonstrating that the Madison mylonite zone was active during the Big Sky orogeny. Particularly in comparison to the more penetrative deformation in the Tobacco Root Mountains to the northwest, we follow Erslev and Sutter (1990) and interpret the Madison mylonite zone as a component of the cooler, more cratonward part of the Big Sky orogen, where deformation and thermal disturbance was restricted to discrete shear zones.

The Madison mylonite zone is roughly parallel to a number of northeast-striking shear zones within the Montana metasedimentary terrane that juxtapose rocks of different geologic character and/or metamorphic grade, including a mylonite zone in the North Snowy Block that is typically cited as the suture between the Montana metasedimentary terrane and the Beartooth-Bighorn magmatic terrane in the northern Wyoming province (Mogk et al., 1988; Mogk and Henry, 1988; Mogk et al., 1992b; Reid et al., 1975), and shear zones that cut the northern Madison and Gallatin Ranges (the Mirror Lake and Big Brother shear zones of Mogk et al., 1992b). If proven to be Proterozoic, these shear zones constitute a belt of ductile thrust faults between the Big Sky metamorphic core to the northwest and Giletti's line to the southeast that straddles the transition from the infrastructural hinterland to the supracrustal foreland of the orogen.

In outlining his very similar model for a Proterozoic orogen in the northern Wyoming province, O'Neill (1998) suggested that low-grade metasedimentary rocks in the southern Gravelly Range originated as foreland basin deposits localized and overridden by the ductile thrust faults of the southern and northern Madison ranges. As these rocks remain undated, O'Neill's (1998) interpretation is speculative but promising; detrital zircon analysis should substantiate whether or not this basin received sediment shed from the rising core of the Big Sky orogen.

Fossil Subduction Zone

Where it crossed Montana (~110° W longitude), the "Deep Probe" seismic refraction line imaged two north-dipping reflectors between 50 and 100 km in depth, interpreted as the remnants of ancient subduction zones, the more southerly of which projects to the surface along the trend of the Big Sky orogen (Gorman et al., 2002; Henstock et al., 1998). Tomography defines a northeast-striking velocity anomaly in the deeper mantle (100 to 500 km in depth) also below the northern Wyoming province, which may be the result of subduction to that depth (Dueker et al., 2001). While Gorman et al. (2002) interpret the north-dipping mantle reflectors as Archean, we suggest they are better correlated in space and time with the Proterozoic Big Sky orogen (see also Mueller et al., 2004, this volume, Chapter 9). No younger subduction zones in this location and orientation are permissible by the Late Proterozoic through Phanerozoic geologic history of the Cordilleran miogeocline (Bond and Kominz, 1984; Sloss, 1988). The position and attitude of these mantle structures are compatible with an arc collision overriding the northern Wyoming province from north to south as the culmination of north-dipping subduction before 1.78 Ga. The reflectors may mark the location of a cryptic suture, where an ocean that opened following 2.06 Ga rifting associated with MMDS bodies in the Tobacco Root Mountains was consumed. The Spuhler Peak Metamorphic Suite may have originated in or around the arc associated with this subduction zone before being emplaced to the south in the Tobacco Root Mountains as an allochthonous terrane.

Pb, Sr, and Nd isotopic analysis of mantle-derived xenoliths in Eocene minette dikes in the Highwood Mountains (Carlson and Irving, 1994), and of Tertiary alkalic rocks in the Crazy Mountains (Dudas et al., 1987), have been interpreted to reflect a mantle enrichment event, probably brought about by subduction at ca. 1.5–1.8 Ga beneath these areas. The xenoliths from the Highwood Mountains carry 1.8 Ga zircons and 1.78 Ga monazites (Carlson and Irving, 1994). Alternatively, the isotopically enriched character of the Highwood Mountains xenoliths (O'Brien et al., 1995) and of minette bodies and encased xenoliths in the Bearpaw Mountains (MacDonald et al., 1992) have been correlated with what is considered to be a characteristic isotopic profile of the Archean Wyoming province (Frost, 1993; Mueller and Wooden, 1988; Wooden and Mueller, 1988), which suggests that the subcontinental lithosphere of the Wyoming province extends at least that far north of the surface expression of the craton. Either interpretation of the isotope data is consistent with north-dipping subduction closing an ocean basin and drawing the Wyoming craton down to the north below a south-vergent collisional orogen.

Accreted Arc

If the Big Sky orogen is a consequence of north-dipping subduction, a Proterozoic arc should have formed north of the orogen and the subduction zone. Major and trace element geochemistry, isotope geochemistry, and the lack of inherited zircons indicate the arc affinity and juvenile character of granitoid gneisses in the Little Belt Mountains (Mueller et al., 2002). With an intrusive age of ca. 1.86 Ga (U-Pb and Pb-Pb zircon dating by Mueller et al., 1996b, 2002), these rocks would have originated in an arc that was active prior to and at the inception of the Big Sky orogeny, timing that is consistent with an arc-continent collisional orogeny. On this basis, the basement of the Little Belt Mountains should be considered a suspect terrane with respect to the Big Sky orogen.

Precambrian basement in the Little Belt Mountains is the northernmost outlier of the Wyoming province and so may be the only surface exposure of the outboard realm of the Big Sky orogen. Other evidence for the character of this domain must be more indirect. The Mesozoic Idaho batholith straddles the southwest extension of the Big Sky orogen's metamorphic core and any outboard terranes that may be to the north. On the basis of Sm-Nd and Pb isotopes in Mesozoic and Cenozoic igneous rocks, Fleck and others (Fleck and Wooden, 1997; Fleck and Gunn, 1991) and Leeman et al. (1991) locate a northeast-trending boundary between Archean basement to the southeast and Proterozoic basement to the northwest that crosses the central Idaho batholith. Pb isotope ratios in the northern batholith suggest the presence of juvenile igneous crust beneath and around the northern Idaho batholith (Toth and Stacey, 1992). Inherited zircons from the northern Idaho batholith that are largely limited in age to 1.82–1.75 Ga (U-Pb, single zircon SHRIMP dating by Mueller et al. [1995] and Foster and Fanning [1997] that corroborates older, upper-intercept zircon dating by Bickford et al. [1981] and Toth and Stacey [1992]), very similar to the Sm/Nd model age determined for the batholith (Mueller et al., 1995), date that juvenile basement. These studies locate the southwestern extension of the boundary between autochthonous, Wyoming province basement of the Big Sky orogen and an accreted, Proterozoic juvenile arc terrane to the north.

Late Extensional Tectonics

The Snowy shear zone cuts across the north edge of the South Snowy Block of the Beartooth Mountains (Erslev, 1992). It is along strike from the Madison mylonite zone and parallel with the Madison mylonite zone and other ductile shear zones of the foreland belt, which suggests the Snowy shear zone may have been active during the Big Sky orogeny as well (suggested also by Erslev, 1992). The Snowy shear zone, however, has been interpreted as a ductile normal fault based on the offset in metamorphic grade observed across the fault (Erslev, 1992). If these timing and kinematic interpretations are correct, the Snowy shear zone would represent one of the extensional structures on which late-stage collapse and tectonic unroofing in the Big Sky orogen occurred, as recorded by the pressure-temperature history of the Tobacco Root Mountains.

THE GREAT FALLS TECTONIC ZONE AND THE NORTHERN BOUNDARY OF THE WYOMING PROVINCE

The Great Falls tectonic zone in Idaho and Montana was identified by O'Neill and Lopez (1985) on the basis of a linear array of faults that appears to have been active from the Proterozoic to the present and that coincides both with a belt of Mesozoic to Tertiary intrusives and with the trend of geophysical anomalies. The Great Falls tectonic zone is a broad northeast-trending swath that is parallel with and partly overlaps the distribution of the Big Sky orogen, lying along the suture between reworked Wyoming province basement in the Big Sky orogen and accreted juvenile arc rocks (Fig. 5). On this basis, we suggest that the Big Sky orogeny is the Proterozoic stage of the long history of repeated activity that defines the Great Falls tectonic zone (see also O'Neill, 1998).

Since its identification, interest in the Great Falls tectonic zone has focused principally on whether it marks the northern boundary of the Wyoming province (Boerner et al., 1998; Eaton et al., 1999; Holm and Schneider, 2002; Lemieux et al., 2000; Mueller et al., 2002). In assessing the nature of the Great Falls tectonic zone, much attention has been paid to the absence of gravity or electromagnetic signatures expected for a plutonic belt or accretionary sediment wedge that would have been generated by subduction before closure along a boundary. This has led some to look farther north, across the Medicine Hat block to the Vulcan structure, for the limit of the Wyoming province and to attribute the Great Falls tectonic zone to intraplate deformation (Boerner et al., 1998; Eaton et al., 1999; Buhlmann et al., 2000; Gorman et al., 2002; Lemieux et al., 2000). We know of no way other than arc-continent collision to produce a tectonic belt with the characteristics of the Big Sky orogen as we now understand them and conclude that closure of an ocean basin must have occurred (see also Mueller et al., 2002). This model does not, however, obviate the possibility that the Medicine Hat block, or perhaps all of the Hearne province, was related to the Wyoming province prior to rifting at ca. 2.06 Ga so that the northern limit of the Wyoming province was well to the north at that earlier time. The Hearne province, Medicine Hat block, and Wyoming province do share distinct crustal structure (Buhlmann et al., 2000; Gorman et al., 2002; Henstock et al., 1998; Lemieux et al., 2000) and Archean ages (Ross et al., 1991). Nor does the character of the Big Sky orogen eliminate the possibility that the Vulcan structure is also a Proterozoic collision orogen. Both the Medicine Hat block and the Vulcan structure appear to have been tectonically active between 1.7 and 1.85 Ga, as revealed by crustal xenoliths and basement rocks from deep drill cores (Lemieux et al., 2000; Ross et al., 1995, 1991), and the granitoids of the Rimbey belt north of the Vulcan structure are similar in age and arc-character to juvenile plutonic rocks we suggest lie just north of the Big Sky orogen (Ross et al., 1991). If the Big Sky orogen was a broad accretionary orogen, comparable in across-strike width to the Mesozoic Cordillera of western Canada (see also Ross, 2002), it may have ranged from a foreland along Giletti's line, across a metamorphic belt at the collisional suture in the northern Wyoming province, to a series of accreted terranes that could include the Medicine Hat block and remaining Hearne province, with convergent belts both inboard and outboard of each collider. A Proterozoic orogen of this scale would account for the dominance of 1.7–1.9 Ga detrital zircons in the Late Proterozoic Windermere sediments that accumulated in rift basins along the Cordilleran margin in southern British Columbia (Ross and Parrish, 1991).

IMPLICATIONS FOR THE ASSEMBLY OF THE NORTHERN WYOMING PROVINCE AND THE NORTH AMERICAN CRATON

The geologic history of the Tobacco Root Mountains and the Big Sky orogen provides a new context in which to understand the northern Wyoming province but also raises questions that cannot be addressed with our present knowledge. We hope the models introduced here will help focus future work on the following critical issues.

1. What is the relationship of the Big Sky orogen to the Montana metasedimentary terrane? Although rocks older than 1.78 Ga are preserved in many parts of the Montana metasedimentary terrane so that the terrane certainly carries an older history, the Montana metasedimentary terrane and Big Sky orogen are nearly coincident. The Archean history of the Montana metasedimentary terrane is unlike that of the Beartooth-Bighorn magmatic terrane (Mogk et al., 1992a, 1992b; Mogk and Henry, 1988). Juxtaposition of the two is believed to have occurred at ca. 2.55 Ga (Mogk et al., 1992a, 1992b; Mogk and Henry, 1988), but shear zones that define the boundary between the Montana metasedimentary and Beartooth-Bighorn magmatic terranes were, at least in part, active during the Big Sky orogeny and served to transport rocks of the Montana metasedimentary terrane south over the Beartooth-Bighorn magmatic terrane platform. Can any linkages between the Montana metasedimentary and the Beartooth-Bighorn magmatic terranes prior to the Big Sky orogeny be unequivocally demonstrated? The time of accretion of the Montana metasedimentary terrane bears careful reconsideration.

2. What is the relationship of the Big Sky orogen along the northern margin of the Wyoming province to collision and accretion along the eastern and southern margins of this Archean craton? How was the Wyoming province sutured with adjacent Archean cratons? Gravity and magnetic anomaly trends on which the location of the southern Trans-Hudson orogen is

based appear to truncate anomalies associated with the Great Falls tectonic zone (Dutch and Nielson, 1990; Hoffman, 1988; Thomas et al., 1987), and yet the age of the Trans-Hudson belt is traditionally considered to be 1.85–1.80 Ga (Bickford et al., 1990), at least 10–20 million years older than the Big Sky orogen. If Dahl and colleagues (Dahl and Frei, 1998; Dahl et al., 1999) are correct in their interpretation of Proterozoic Black Hills geology, then the time of tectonism in the southern Trans-Hudson orogen may be revised to be contemporaneous with instead of older than the Big Sky orogeny. If not, reinterpretation of the geophysical anomalies is required. In either case, there is remarkable synchroneity between collisional activity along the southern margin of the Wyoming province in the Cheyenne belt (Chamberlain et al., 1993; Houston, 1993; Premo and Van Schmus, 1989) and the development of the Big Sky orogen as we have documented it in the Tobacco Root Mountains (see also Mueller et al., 2002). These timing relationships constrain the process or processes by which the Precambrian basement of the North American craton was assembled, and the orchestration of those processes, and must be of fundamental importance to general models of crustal evolution.

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