PALEOPROTEROZOIC GEOLOGY OF MONTANA

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ABSTRACT

The Paleoproterozoic Era (2.5–1.6 Ga) was a transitional period in Earth's evolution. It might be considered Earth's "teenage" period of development from its infancy in the Hadean and Archean to the planet we live on today. It was during early Paleoproterozoic time that the atmosphere became oxygenated; banded iron formations reached a peak in the Paleoproterozoic and became rare by the end of the era. Most agree that life, albeit single-celled, made the profound step to eukaryotism at about this time. Continents were unvegetated and unpopulated, but conventional sedimentary deposits accumulated all the same—including the products of silicate weathering. Carbonates became more commonplace in the Paleoproterozoic than they had been in the Archean. Plate tectonic processes that operate in the modern Earth were firmly established as driving the cycle of crustal consumption and renewal. Tonalite–trondhjemite–granodiorite plutonic systems were no longer the dominant rock suite as subduction modernized. And, in a remarkable phase of Earth history, during the period from ~2.0 to 1.7 Ga, small Archean cratons coalesced across collisional orogens and the interior of the ancestral North American continent was fused into being.

In southwest Montana, on the northern flank of the Wyoming Province, rocks spanning the Paleoproterozoic Era are preserved and exposed in the uplifted basement of the Laramide Rocky Mountain ranges, and likely underlie the Belt Basin and Phanerozoic rocks of the State. In this basement can be found evidence of the penultimate and final stages in the consolidation of the ancestral North American continent. There are two lithotectonic domains in the exposed Precambrian crystalline rocks of southwest Montana. Rocks of the Beartooth Mountains are part of the Beartooth–Bighorn magmatic zone at the core of the Wyoming Province. This domain has been essentially quiescent since a major Archean cratonizing period at ~2.8–2.6 Ga. Northwest of the Beartooth Mountains, all other crystalline basement exposures constitute the Montana metasedimentary terrane (MMT), in which is preserved a significant Paleoproterozoic history.

Rocks of the MMT record burial, metamorphism, deformation, and partial melting attributable to orogeny at both ~2.55 and ~2.45 Ga. This was superimposed on Archean quartzofeldspathic igneous and sedimentary protoliths, producing interlayered quartzofeldspathic gneiss and metasupracrustal suites. The quartzofeldspathic gneisses are polygenetic and likely include both paragneiss and orthogneiss, much of which probably originated in an arc setting. Most of the metasupracrustal rocks that predate the ~2.55 and ~2.45 Ga orogenic periods are marble-bearing sequences that also include pelitic schist, quartzite, amphibolite, and meta-banded iron formation. They record the presence of shallow-water depositional environments along a volcanically active continental margin of the northern Wyoming Province in the earliest Paleoproterozoic prior to the ~2.55 and ~2.45 Ga orogenic events.

Post-orogenic stability in the MMT was interrupted at 2.06 Ga, when probable rift-related mafic dikes and sills cross-cut the older gneisses.

North and west of "Giletti's line," a thermochronologic boundary within the MMT, rocks were profoundly affected by tectonism again at ~1.78–1.72 Ga in the Big Sky orogeny, during the final amalgamation of the Wyoming Province with adjacent Archean cratons to the north and east. The protoliths of metasupracrustal sequences that originated after 2.06 Ga extension and before the ~1.78–1.72 Ga Big Sky orogeny demonstrate the presence of a suprasubduction zone setting at the leading edge of the Wyoming Province above a south-dipping subducting slab. Mafic flows with hydrothermally altered mafic rocks and voluminous mudstone with interlayered mafic flows suggest a back-arc basin setting relative to active arc diorites located farther to the north and east; interlayered carbonates, mudstones, banded iron formation, and mafic flows to the southwest record the tectonically active, shallow-water continental margin of the northern Wyoming Province. These suites became juxtaposed against older quartzofeldspathic gneiss suites of the MMT when the subduction-related domains collapsed against and accreted to the Wyoming Province continental margin during the ~1.78–1.72 Big Sky orogeny. Collisional crustal thickening produced penetrative recrystallization and amphibolite to granulite facies metamorphism throughout the south-vergent orogenic core zone for which the Wyoming Province served as a foreland.

Remote sensing techniques have been coupled with xenolith, isotope, and inherited zircon studies in Phanerozoic igneous bodies in order to probe the covered basement of northern, eastern, and northeastern Montana. This has constrained the probable limits of the Wyoming Province and Medicine Hat Block Archean cratons. An accretionary network of Paleoproterozoic orogens that includes not only the Big Sky orogen, but also the Trans-Hudson/Dakotan orogen and Selway terrane, surrounds the Archean Wyoming Province and was the site of final consolidation of the craton in Montana.

INTRODUCTION

Exposed Precambrian crystalline rocks of southwest Montana record a complex and incompletely understood Paleoproterozoic history of episodic tectonothermal events that resulted in the amalgamation of crustal blocks along what had been the northwestern margin of the Wyoming Province at the close of the Archean. These events produced the final consolidation of continental crust that underlies the profound unconformity at the base of the Mesoproterozoic Belt Supergroup and Cambrian Flathead sandstone across much of the State. North and west of the Beartooth Mountains and the Archean gneisses that typify the Beartooth–Bighorn magmatic zone (BBMZ) of the Wyoming Province (Mogk and others, 2020), this Precambrian basement includes distinctive metasupracrustal suites that distinguish it as the Montana metasedimentary terrane (MMT; fig. 1; Mogk and others, 1992a). Within Montana, these metamorphic rocks can be found in the cores of the southern Madison, Henrys Lake, Gravelly, Blacktail, and Tendoy Ranges immediately adjacent to the BBMZ, across the Ruby, Greenhorn, Tobacco Root, Highland, northern Madison, and Gallatin Ranges farther to the northwest, and in more distant exposures in the Little Belt Mountains well to the north (fig. 1). Crystalline basement rocks are exposed in these ranges as a consequence of uplift associated with Mesozoic Sevier and Laramide compression along basement-involving thrust faults followed by normal faulting during the Cenozoic; elsewhere this basement lies buried beneath a Paleozoic and Mesozoic sedimentary blanket. Precambrian metamorphic suites of similar age and character to those of the MMT can be found in isolated exposures in neighboring Idaho and Washington (Foster and others, 2006; Vervoort and others, 2016) and in the Black Hills of South Dakota (fig. 2; Dahl and others, 1999). These rocks of the MMT are the principal recorders of the Paleoproterozoic geologic history of Montana.

The Wyoming Province

The Wyoming Province is one of the ancient building blocks of ancestral North America (Hoffman, 1988; Whitmeyer and Karlstrom, 2007), distinguished by a distinctive isotopic signature (Wooden and Mueller, 1988; Mogk and others, 1992b), and by its antiquity, its persistence, and its resistance to change during Phanerozoic time as an integrated domain of continental crust and associated lithosphere (Chamberlain and others, 2003; Mueller and Frost, 2006; Mogk and others, 2020). Exposed mostly in the Laramide ranges of Wyoming and southwest Montana (fig. 2), it may extend under much of the plains in those states. Evidence for crust as old as ~3.5 Ga is found locally within tonalite–trondhjemite–granodioritic (TTG) and granitic composition gneisses of southwest Montana and in the Bighorn Mountains in Wyoming (Mogk and others, 2020). The ancient crust of the Beartooth and Bighorn Mountains was cratonized by voluminous TTG and granitic plutonism during the period ~2.8–2.6 Ga, forging the BBMZ; in contrast, rocks to the northwest in Montana, in the MMT, largely escaped this plutonism (Chamberlain and others, 2003; Mogk and others, 2020). From this distinctive BBMZ core, the Wyoming Province grew over post-2.8 Ga Archean time by accretion along both its northwestern and southern margins, likely including convergence between the BBMZ and the MMT. Late Archean

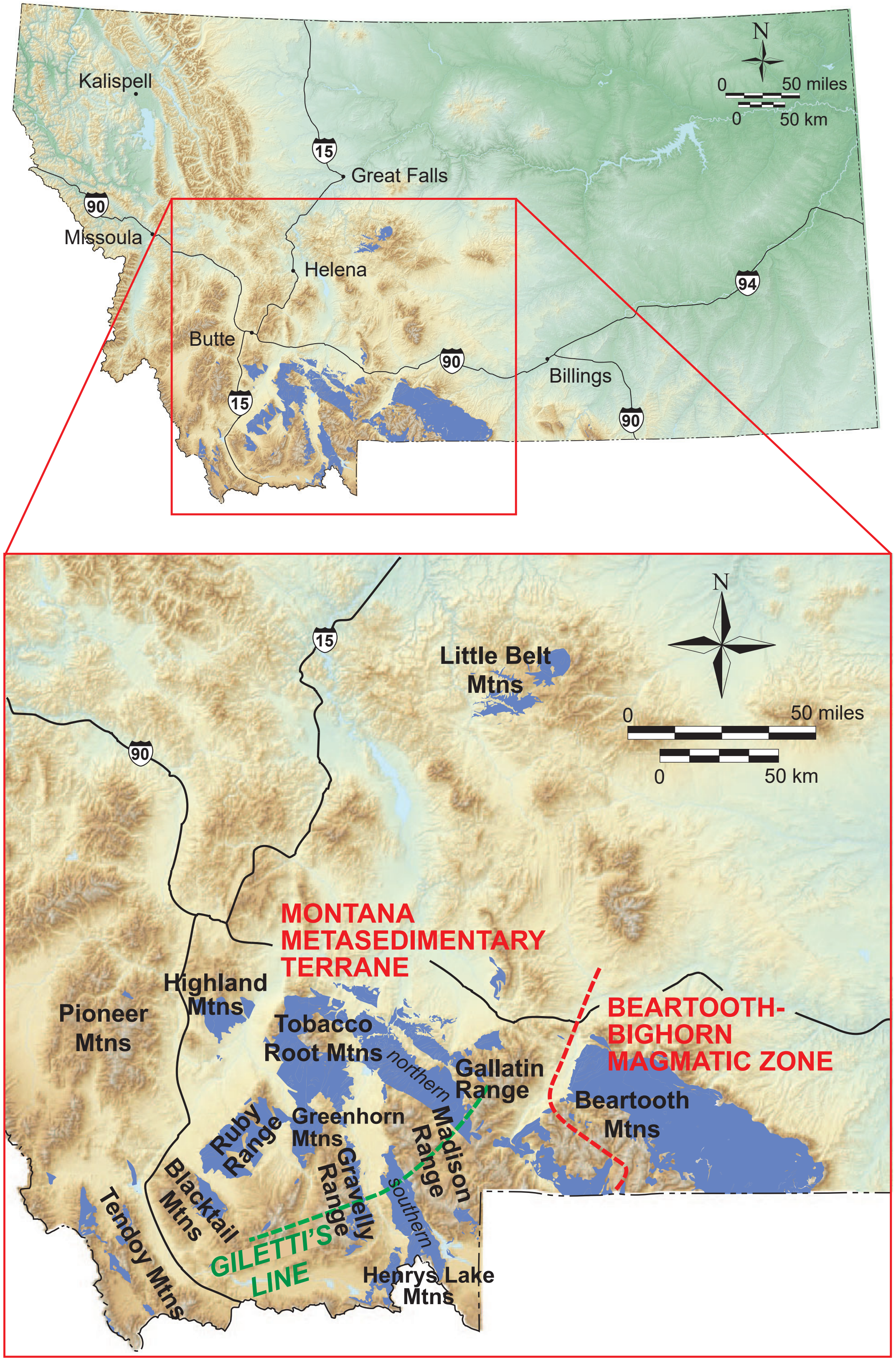


Figure 1. The distribution of exposed pre-Beltian, Precambrian crystalline rocks of Montana (blue shading), exposed in the Laramide and younger mountain ranges of southwest Montana, with significant tectonic domains and boundaries. Adapted from Vuke and others (2007).

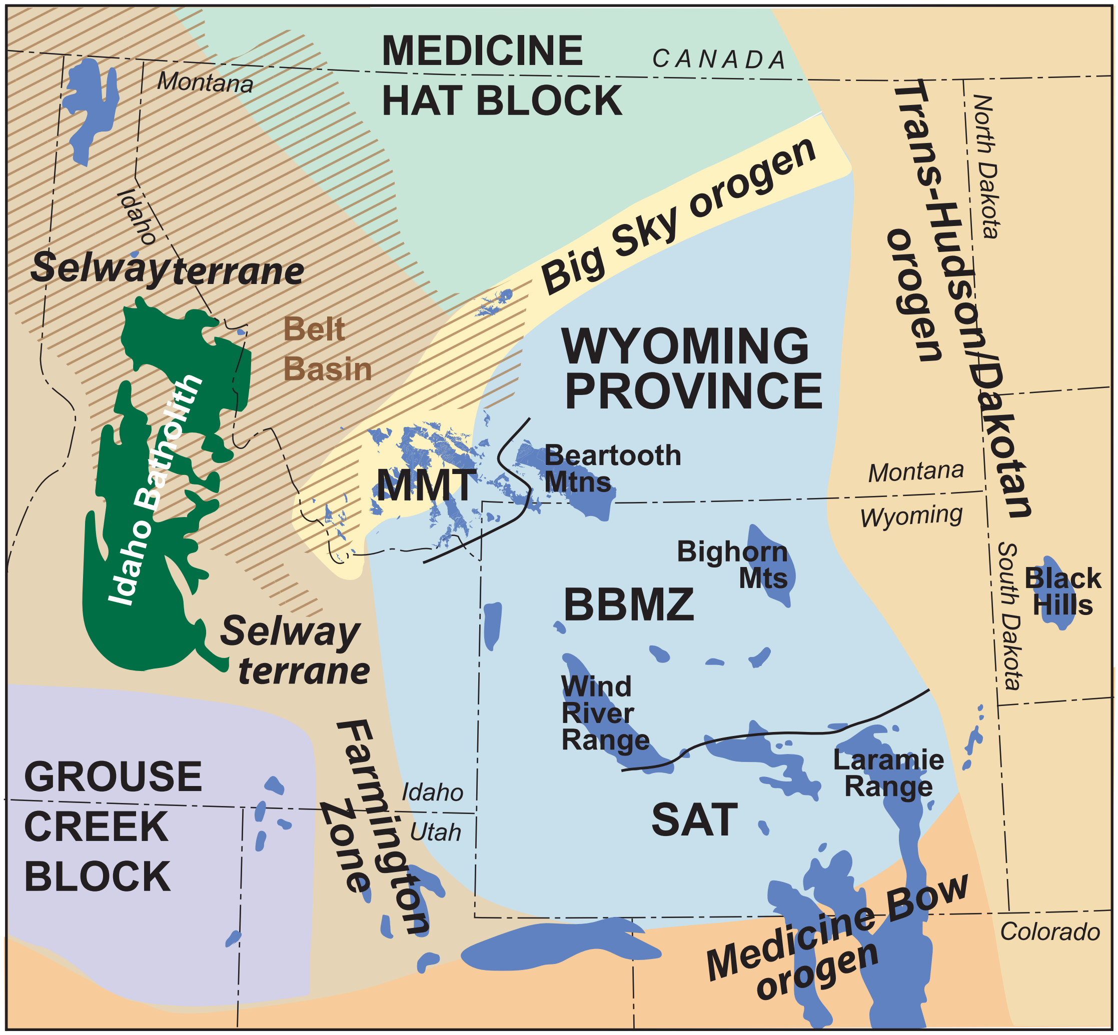


Figure 2. The Archean Wyoming Province (light blue) is surrounded by Paleoproterozoic accretionary margins: the Big Sky orogen and Medicine Bow orogen to the north and south, respectively, the Selway terrane to the west, and Trans-Hudson/Dakotan orogen to the east. The Wyoming Province can be subdivided into the Montana metasedimentary terrane (MMT), the Beartooth–Bighorn magmatic zone (BBMZ), and the southern accreted terranes (SAT) based on contrasting geologic histories. The Big Sky orogen (yellow/tan) encompasses that area of the MMT that was affected by deformation and metamorphism at ~1.8–1.7 Ga. Areas of exposed pre-Belt Precambrian crystalline rocks shown in dark blue (adapted from Vuke and others, 2007). The Medicine Hat Block (light blue-green) and Grouse Creek block (lavender) are peripheral Archean domains known only from drill core (Medicine Hat block) or limited exposures (Grouse Creek block). Significant post-Paleoproterozoic geologic domains are also shown: the Belt Basin in brown hachure and the Idaho Batholith in dark green. Figure adapted from Chamberlain and Mueller (2019); Foster and others (2006); and Mueller and Frost (2006).

greenstone-like belts of arc-related plutons and basins developed periodically along an active margin in the southern province; this domain constitutes the southern accreted terranes (SAT; fig. 2; Chamberlain and others, 2003; Mueller and Frost, 2006).

The Montana Metasedimentary Terrane

Although the presence of significant metasupracrustal suites is its defining characteristic, volumetrically the MMT is dominated by quartzofeldspathic gneisses (fig. 3). Quartzofeldspathic gneiss in the Tobacco Root Mountains has been mapped as the Pony series (Reid, 1957; Tansley and others, 1933) or Pony–Middle Mountain metamorphic suite (Burger, 2004) and as the Indian Creek metamorphic suite (Burger, 2004). Quartzofeldspathic gneiss north of the Johnny Gulch area in the northern Gravelly Range is contiguous with and analogous to the Indian Creek metamorphic suite (Berg, 1979; Kellogg and Williams, 2000). In the Blacktail, Tendoy, and Ruby Ranges, quartzofeldspathic gneiss occurs as the Dillon granite gneiss (Heinrich and Rabbitt, 1960; James, 1990). In the Highland Mountains, O'Neill and others (1996) mapped quartzofeldspathic gneiss and quartz–feldspar–biotite gneiss [Units X(A)q and X(A)qf, respectively, in O'Neill and others]. Similarly, quartzofeldspathic gneiss is abundantly represented in maps of parts of the northern (Spencer and Kozak, 1975) and southern (Erslev and Sutter, 1990) Madison Range. The quartzofeldspathic gneisses of the MMT are most likely polygenetic; within this broad lithotype there are TTG gneisses, bimodal gneisses, and potassium feldspar gneisses that likely include both ortho- and paragneiss. Suites of zircons recovered from quartzofeldspathic gneiss in the MMT include grains as old as 3.9 Ga—most are in the range of 3.2–3.4 Ga (Mogk and others, 2020). Together, these gneisses preserve an Archean history that is well documented elsewhere in this volume (Mogk and others, 2020).

Metasupracrustal rocks that are interleaved with these quartzofeldspathic gneisses across the MMT have a geologic significance that is larger than their more limited spatial distribution and volume might suggest. Metasupracrustal suites include greater or lesser amounts of marble, aluminous pelitic schist and gneiss, amphibolite, orthoamphibolite, quartzite, and iron formation (fig. 3). (We note that the presence of these suites defines the Montana *metasedimentary* terrane, but because of the ubiquitous presence of amphibolite, we think it is more accurate to emphasize their *metasupracrustal* nature.) These rocks hold the potential to constrain paleogeographic reconstructions of the tectonic environments that existed along the margin and/or to the northwest of the Archean core of the Wyoming Province during their deposition and leading up to their burial, metamorphism, and deformation.

Early attempts to synthesize these various metasupracrustal suites focused on constructing lithologic

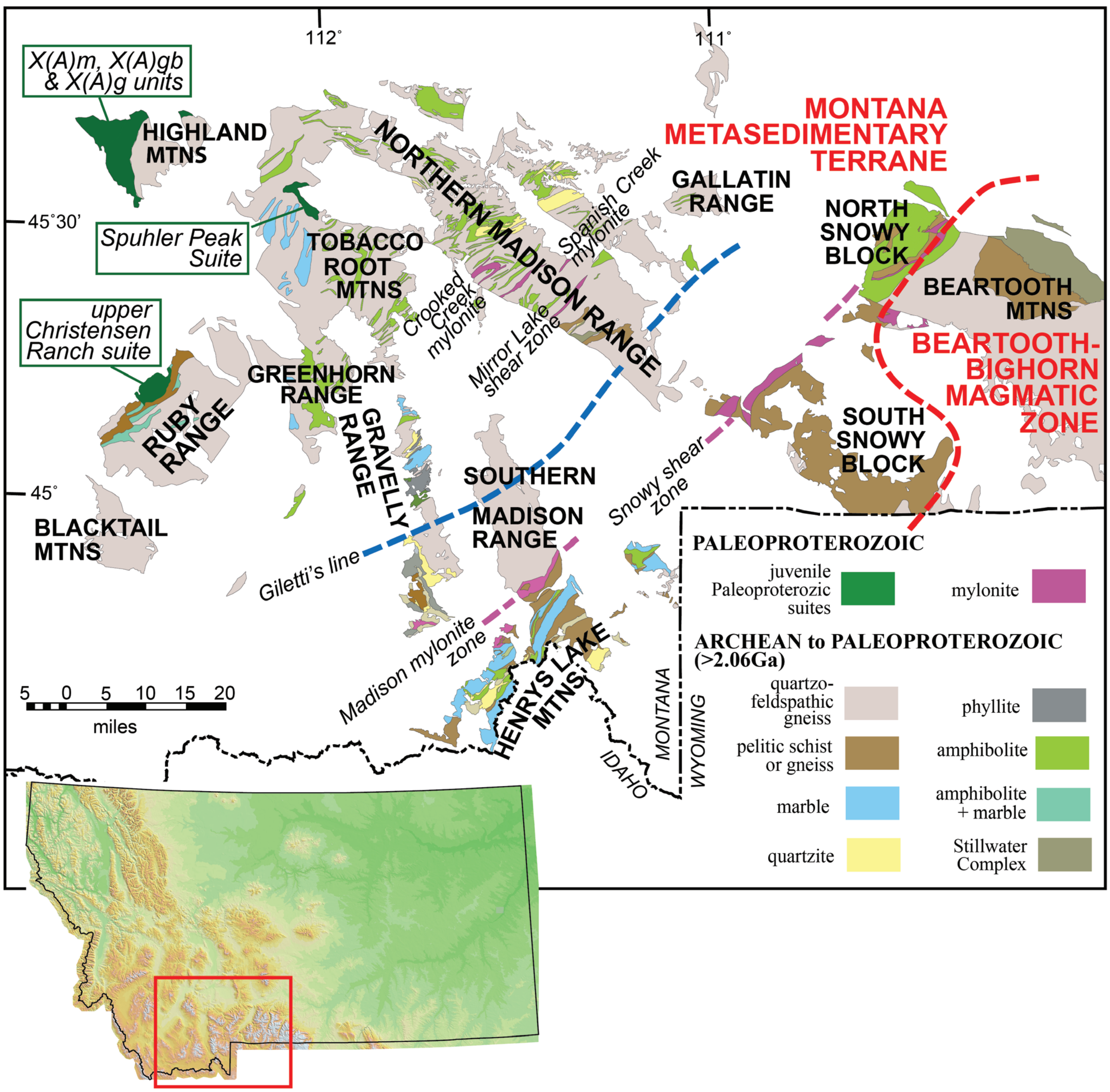


Figure 3. Lithotectonic map of the MMT in southwest Montana. Adapted from Vuke and others (2007) with permission to show the major metasupracrustal lithologic types and the distribution of quartzofeldspathic gneiss (undivided). Younger rocks not shown. Significant shear zones indicated by dashed purple lines; Giletti's line—a geochronological front—shown by the blue dashed line; the MMT–BBMZ boundary shown by a red dashed line. Red box in the inset Montana relief map indicates the area covered by the geologic map.

correlations using the presence or absence of marble. A marble-bearing suite in the central Gravelly Range was first fully described by Heinrich and Rabbitt in 1960, who maintained the name Cherry Creek group as defined by Peale in 1896. Subsequent to its original definition in the Gravelly Range, the name “Cherry Creek” was applied to marble-bearing units in the Tobacco Root Mountains (Winchell, 1914; Tansley and others, 1933; Reid, 1957), the Ruby Range (Perry, 1948; Heinrich and Rabbitt, 1960), and the southern Madison Range (Erslev, 1983; Erslev and Sutter, 1990). Marble-absent suites, some of which occur structurally below marble-bearing suites, have been called “pre-Cherry Creek” (Heinrich and Rabbitt, 1960; Garihan, 1979; Erslev, 1983; Erslev and Sutter, 1990). This usage seems to be anchored in a model of the Wyoming Province that presumes an evolution over time toward thicker continental crust and lithosphere that could support a stable marine platform, represented by the presence of marble. The more recent availability of a broad spectrum of geochronological tools has shown that this simple lithologic correlation does not reflect the significant variability of the metasupracrustal suites or their ages and origins, and should be abandoned (see also the discussion in Vitaliano and others, 1979b and in James, 1990). Geochronologic data have demonstrated that it is more fruitful to consider chronologic correlations and to think in terms of chronologic domains.

Giletti’s Line: Chronologic Correlations and Distinctions in the MMT

On the basis of biotite K-Ar dating, Giletti (1966) defined a NE–SW-trending chronologic boundary across the Precambrian basement rocks of southwest Montana (figs. 1, 3), south of which he found late Archean to early Proterozoic cooling ages; but to the north, ages consistently were ~1.6 Ga. Giletti interpreted this to reflect a regional Paleoproterozoic metamorphism. Thereafter, Rb-Sr whole-rock dating was applied to a suite of quartzofeldspathic gneiss samples from the Tobacco Root, Ruby, and Gallatin Ranges, and the South Snowy Block of the Beartooth Mountains (Mueller and Cordua, 1976; James and Hedge, 1980; Montgomery and Lytwyn, 1984), resulting in what should now be considered “errorchron” ages of ~2.6 and 2.75 Ga. This was widely assumed to be the metamorphic age of crystalline basement rocks throughout southwest Montana; Giletti’s younger dates were reinterpreted to reflect a thermal event that reset lower temperature chronometers but was not responsible for the formation of the rocks dated (James and Hedge, 1980) or for the growth of metamorphic minerals within them (Mueller and Cordua, 1976).

More recent and more robust geochronological studies have refined but not fundamentally changed the position of “Giletti’s line” and have reconfirmed his original interpretation. Giletti’s Paleoproterozoic K-Ar ages represent much more than just low-temperature resetting. We now know that rocks NW of Giletti’s line experienced displacement, penetrative deformation, and thorough metamorphism or remetamorphism that produced their constituent mineral parageneses in an orogenic event from approximately 1.8 to 1.7 Ga (Mueller and others, 1993, 2011, 2012; Roberts and others, 2002; Cheney and others, 2004b; Foster and others, 2006; Jones, 2008; Kellogg and Mogk, 2009; Krogh and others, 2011; Ault and others, 2012; Alcock and others, 2013; Condit and others, 2015; Baker and others, 2017; Baldwin and others, 2017; Hames and Harms, 2013). This orogeny has been variously called the Big Sky orogeny (Brady and others, 2004a), the Trans-Montana orogeny (Simms and others, 2004), and the Great Falls orogeny (Mogk, and others, 2020). Here, we elect to use Big Sky orogeny.

Additionally, both north and south of Giletti’s line, most rocks of the MMT preserve evidence of a tectonothermal event at either ~2.55 Ga or ~2.45 Ga—the former generally to the south of Giletti’s line, in close proximity to the BBMZ, and the latter generally to the north of Giletti’s line. Metamorphism and plutonism dated in the range ~2.55 to 2.45 Ga have been referred to as the Tendoy (Mueller and others, 2012; Baldwin and others, 2014; Baker and others, 2017) and Beaverhead (Jones, 2008) or Beaverhead–Tobacco Root (Krogh and others, 2011) orogenies. More work needs to be done to define the spatial and temporal distribution of end-Archean–earliest Paleoproterozoic metaplutonic events in southwest Montana. Here, we will focus only on well-documented ~2.45 Ga dates and will use the name “Beaverhead orogeny.”

The application of monazite geochronology, in particular, along with biotite and amphibole Ar^{40}/Ar^{39} analysis and garnet Lu-Hf dating, has allowed identification of two distinct suites north of Giletti’s line. The first, which is much more widespread, yields monazite ages of both ~2.45 Ga and ~1.8–1.7 Ga. Both marble-bearing and marble-absent metasupracrustal sequences have this geochronologic profile, including some of the most prominent and thick marble horizons in the MMT, such as the Indian Creek metamorphic suite in the Tobacco Root Mountains (Cheney and others, 2004b) and the lower part of the Christensen Ranch suite on the western side of the Ruby Range (Roberts and others, 2002; Baldwin and others, 2014, 2017). To the extent it can be dated with monazite, this age profile is also characteristic of quartzofeldspathic gneiss in the MMT (Cheney and others, 2004b; Jones, 2008; Baldwin and others, 2017). The protoliths of all of these sequences must predate 2.45 Ga.

In contrast, some metasupracrustal sequences north of Giletti's line yield only 1.8–1.7 Ga monazites, with no evidence of metamorphism at ~2.45 Ga (fig. 3). These are the Spuhler Peak suite in the Tobacco Root Mountains (Cheney and others, 2004b); mylonitic biotite gneiss, garnet-biotite gneiss, foliated orthogneiss, garnet-rich gneiss and schist, and igneous and metamorphic rocks, undivided [units X(A)m, X(A)gb, Xi, X(A)g, and Xs, respectively] as mapped by O'Neill and others (1996) in the Highland Mountains (Pearson and Cheney, 2008); the upper Christensen Ranch suite in the Ruby Range (Baldwin and others, 2017); and the Aspen pelitic gneiss in the Little Belt Mountains (fig. 3; Holm and Schneider, 2002; Mueller and others, 2002; Vogl and others, 2004). We consider these to have been juvenile late Paleoproterozoic units, with protoliths certainly younger than 2.45 Ga and most likely younger than 2.06 Ga, based on the absence of cross-cutting metamorphosed mafic dikes and sills (MMDS) that are prominent elsewhere in the MMT and have an intrusive age of 2.06 Ga (Mueller and others, 2004, 2005). These younger metasupracrustal sequences represent the depositional and eruptive settings that existed between 2.06 and 1.8 Ga in or adjacent to the northern Wyoming Province. We now recognize that both marble-bearing and marble-absent sequences occur in those metasupracrustal units that are older than the ~2.45 Ga tectonism as well as in those that are younger than 2.06 Ga. In comparison, however, quartzofeldspathic gneiss is rare, and marble-absent units dominate, in these younger, post-2.06 Ga metasupracrustal sequences.

In the central Gravelly Range, a distinct suite of uniquely low-grade metasupracrustal rocks lies north of Giletti's line and south of the Johnny Gulch area, adjacent to the type area of the Cherry Creek group. First mapped by Heinrich and Rabbitt (1960) and Hadley (1969a,b, 1980), then studied in greater detail by Vargo (1990), this suite is dominated by siliceous phyllite, but includes carbonaceous phyllite and chlorite phyllite, cross-bedded quartzite, iron formation, and a pillowed metabasalt metamorphosed to greenschist facies (Vargo, 1990). The rocks of this suite have resisted dating; neither the time of metamorphism nor the age of the protoliths has been determined. As a consequence, it cannot be assigned to either predate or postdate the effects of the ~2.45 Ga Beaverhead orogeny.

Much of Precambrian Montana lies hidden beneath its rich and productive blanket of Paleozoic and Mesozoic strata. Only the MMT of southwestern Montana allows direct observation and thereby provides the components from which to reconstruct the following Paleoproterozoic history of the state.

ARCHEAN QUARTZOFELDSPATHIC GNEISS AND METASUPRACRUSTAL SUITES OF THE MMT AND THE ROLE OF THE 2.45 GA BEAVERHEAD OROGENY

Interlayered quartzofeldspathic gneiss and metasupracrustal units form the dominant lithologic assemblage in the Precambrian crystalline basement of ranges throughout the MMT, and north of Giletti's line in particular (fig. 3). Notable examples where marbles, quartzites, banded iron formation, and amphibolites occur within quartzofeldspathic gneiss complexes are the Indian Creek metamorphic suite in the southern Tobacco Root Mountains (Burger, 2004; Mogk and others, 2004), the Dillon gneiss unit in the Ruby Range (Heinrich and Rabbitt, 1960; James, 1990), much of the northern Madison Range, including both the Jerome Rocks and Gallatin Peak terranes in the Spanish Peaks area (Spencer and Kozak, 1975; Mogk and others, 1992b; Kellogg and Mogk, 2009; Condit and others, 2015), and the "Cherry Creek" sequence, as defined by Erslev and Sutter (1990) in the southern Madison Range. Some regions of the MMT contain metaintrusive gneisses without significant (or any) associated metasupracrustal rocks. The Pony–Middle Mountain metamorphic suite in the northern Tobacco Root Mountains is a well-documented example (Mogk and others, 2004), as are the quartzofeldspathic gneiss and quartz–feldspar–biotite gneiss [map units X(A)q and X(A)qf, respectively, in O'Neill and others, 1996] in the core of the Highland Mountains (O'Neill and others, 1988, 1996), and the "Pre-Cherry Creek" central gneiss complex of Erslev and Sutter (1990) in the southern Madison Range.

Within the zircon, garnet, and monazite they contain, the interlayered gneiss and metasupracrustal suites retain evidence for a tectonothermal event at ~2.45 Ga. North of Giletti's line, these suites have been thoroughly reworked during the Big Sky orogeny. As a consequence, it can be challenging to discriminate those geologic features that are a consequence of the ~2.45 Ga event versus those of the ~1.8–1.7 Ga Big Sky orogeny. The following aspects, however, can be deduced.

- North of Giletti's line, metasupracrustal rocks of appropriate composition contain ~2.45 Ga monazite as cores within younger (1.8–1.7 Ga) rims and as small relict grains within a rock's matrix (Cheney and others, 2004b; Baldwin and others, 2014, 2017). Based on the ages of the monazites they contain, the main rock-forming, metamorphic minerals reflect Big Sky orogeny metamorphic conditions (Cheney and others, 2004a,b); nevertheless, the preserved ~2.45 Ga monazites indicate that metamorphism during that earlier time frame must have been sufficient to drive monazite growth reactions. Similarly, rims of ~2.45 Ga zircon on older, Archean grains or as metamorphic grains in quartzofeldspathic gneiss (e.g., Mueller and others, 2004, 2011, 2012), and inherited 2.42 to 2.47 Ga zircons in the Boulder Batholith (Lund and others, 2002), indicate conditions amenable to zircon growth.
- South of Giletti's line, schists in the southern Gravelly Range and Henrys Lake Mountains (O'Neill and Christiansen, 2004) contain relict kyanite (Dickoff and Harms, 2007). In the southern Madison Range, Erslev and Sutter (1990) obtained metamorphic conditions of ~650˚C and 6 kbar for peak metamorphism in cordierite-bearing rocks. We provisionally attribute these conditions to the ~2.45 Ga Beaverhead orogeny, although both dating and thermobarometric analyses south of Giletti's line are few and not linked to the same rocks.
- A distinctive garnet leucogneiss (fig. 4) that is widespread within the Dillon gneiss unit of the Ruby Range has a ~2.45 Ga intrusive and metamorphic age (Alcock and others, 2013; Baker and others, 2017; Baldwin and others, 2017; Harms and Baldwin, 2019). An intrusive age of ~2.44 Ga was determined from zircon in quartzofeldspathic orthogneisses in the Tendoy Range as well (Kellogg and others, 2003; Pearson and others, 2017). Smaller, cross-cutting mafic bodies in the Tobacco Root Mountains (Krogh and others, 2011) and the northern Madison Range (Condit and others, 2015) also intruded at this time. Crust and mantle partial melt production appear to have been a component of the ~2.45 Ga event.
- Gneissic banding is cross-cut by metamorphosed mafic dikes in the Tobacco Root and Highland Mountains (Brady and others, 2004b), demonstrating that the gneissic fabric must be older than the dike intrusive age of 2.06 Ga

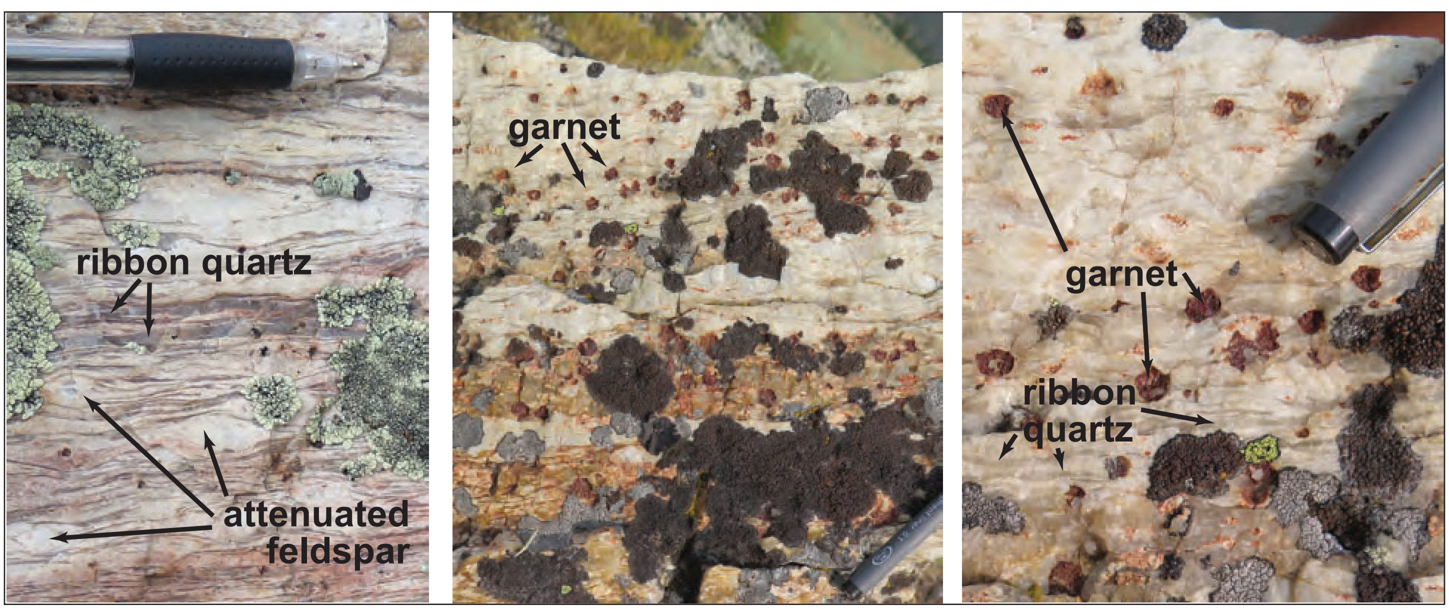


Figure 4. Garnetiferous leucogneiss, commonly mylonitic, cross-cuts the Dillon gneiss and the lower Christensen Ranch group in the Ruby Range. With both crystallization and metamorphic ages contemporaneous with the ~2.45 Ga Beaverhead orogeny, this leucogneiss demonstrates that crustal thickening and metamorphism were sufficient to produce crustal melt during that tectonic event.

(figs. 5, 6; Mueller and others, 2004, 2005). Although the gneissic fabric has not itself been directly dated, a conservative interpretation is that in at least some cases the fabric formed during the 2.45 Ga event, then became locally or regionally transposed during the Big Sky orogeny (Harms and others, 2004a).

In sum, it appears that orogenic processes such as metamorphism, new mineral growth, the development of a high-grade fabric, and the production and intrusion of melt bodies were widespread across the MMT at ~2.45 Ga and support the model of a ~2.45 Ga Beaverhead orogeny.

The protolith ages of quartzofeldspathic gneisses of the MMT, and of the interlayered metasupracrustal components in particular, can only be constrained to be older than 2.45 Ga; how much older than 2.45 Ga is not clear. We emphasize again the polygenetic character of the quartzofeldspathic gneiss suites and caution against assuming they share common history in pre-2.45 Ga time. Zircons recovered from quartzofeldspathic gneiss units predominately fall in the age range

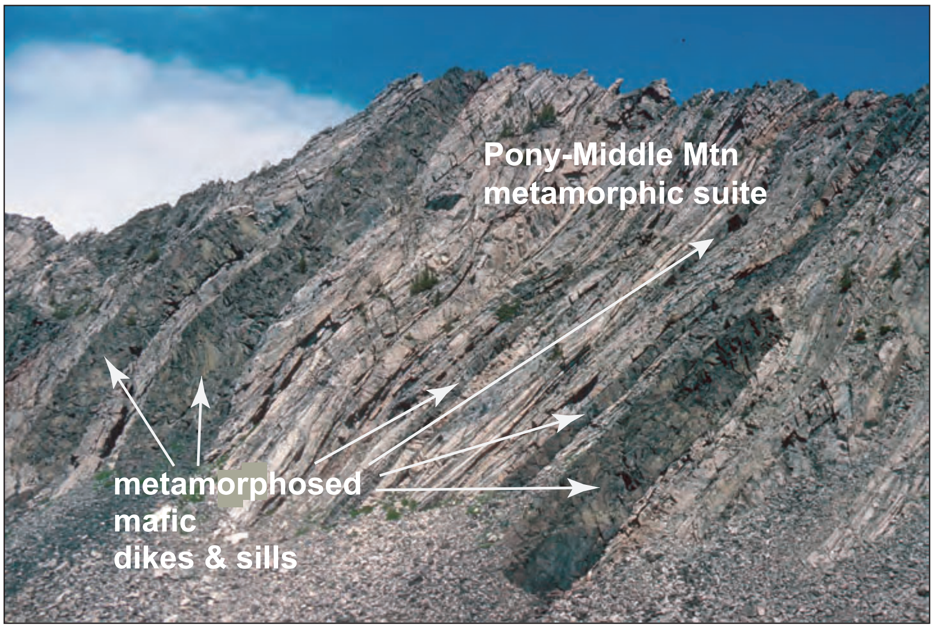


Figure 5. Ridgeline above Sunrise Lake in the Tobacco Root Mountains, where prominent metamorphosed mafic dikes and sills (MMDS) are nearly concordant with banded quartzofeldspathic gneiss of the Pony–Middle Mountain metamorphic suite. Field of view is approximately 100 m wide. Photograph by John Brady, used with permission.

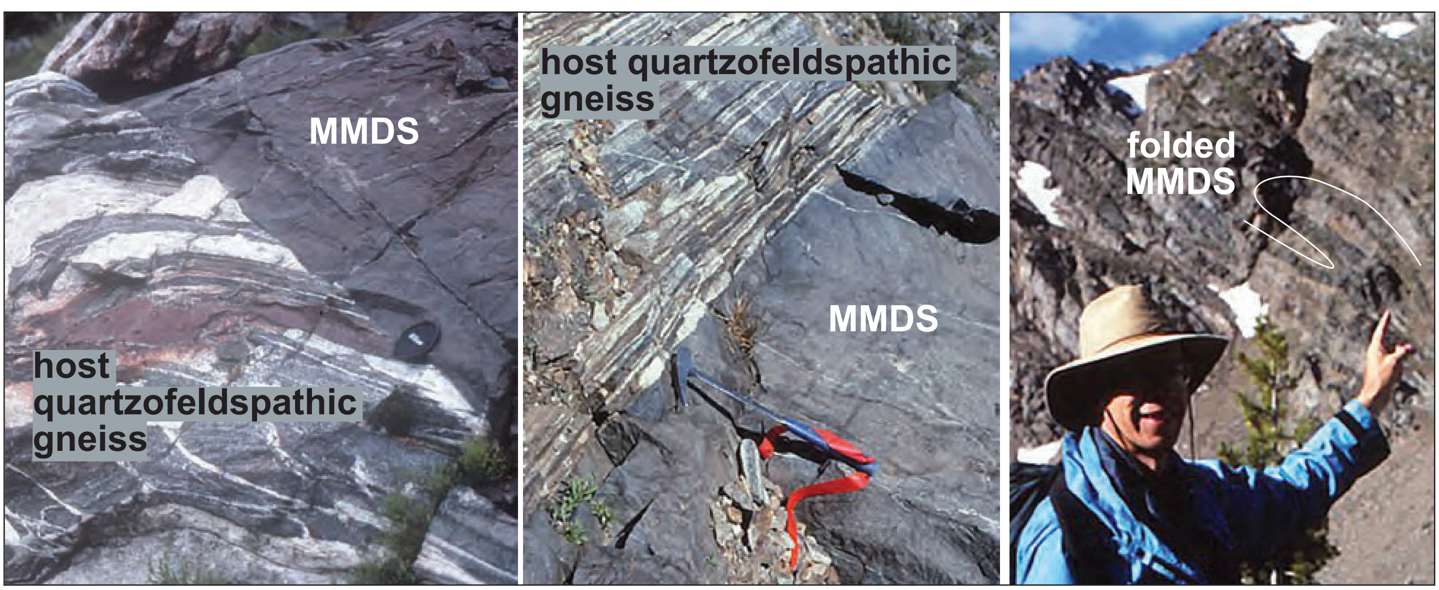


Figure 6. Metamorphosed mafic dikes and sills (MMDS) have a range of contact relationships to host quartzofeldspathic gneiss of the Indian Creek and Pony–Middle Mountain suites in the Tobacco Root Mountains. Dikes cross-cut gneissic fabric at a high angle in some places (left); have been rotated into near parallelism with gneissic banding in high strain zones (center), producing “pseudo-sills”; and can be isoclinally folded along with the host gneiss (John Brady’s index finger points to the MMDS fold nose, outlined in white, in the photo on the right).

3.2–3.4 Ga (Mueller and others, 1993, 2004) and may represent significant crust formation during that time. The most straightforward interpretation of the metasupracrustal suites is that they were deposited on a basement of quartzofeldspathic gneiss, and thus are younger than 3.2 Ga. Condit and others (2015) report field evidence documenting a depositional relationship in the Bear Basin area of the northern Madison Range. Presumably-detrital zircons recovered from quartzite in the Ruby Range are as young as 2.85 Ga (Mueller and others, 1998) and require a <2.85 Ga age for at least those metasupracrustal rocks. Finally, great antiquity of the metasupracrustal suites seems inconsistent with the absence of evidence for any metamorphic or tectonic effect in the >400-million-year period between the age of the youngest detrital zircons and the Beaverhead orogeny at 2.45 Ga. Thus, it seems possible that some or all of the metasupracrustal suites could have been relatively youthful prior to their involvement in the Beaverhead orogeny, a conclusion also reached by Roberts and others (2002). Nevertheless, we find no compelling reason to assume that pre-2.45 Ga marble-bearing sequences in the MMT are all correlative and recommend that application of the term "Cherry Creek" beyond the rocks actually at Cherry Creek in the Gravelly Range be discontinued.

What can be inferred from the protoliths of the metasupracrustal suites: the interlayered limestone, sandstone, iron formation, and ubiquitous basalt? These sedimentary rock types suggest a shallow water setting, implying deposition on a continent or along its margins. The presence of basalt, however, is not typical of Phanerozoic stable continental shelves. If latest Archean tectonic environments functioned similarly to those in the Proterozoic and Phanerozoic, the metasupracrustal assemblage is more consistent with settings such as island arcs with fringing carbonate platforms or rift-related attenuated continental crust. These settings suggest a tectonically active margin along the NW flank of the Wyoming Province prior to the ~2.45 Ga Beaverhead orogeny, and the collapse and consolidation of those domains at ~2.45 Ga, possibly resulting from collision. This raises the possibility that some of the quartzofeldspathic gneiss + metasupracrustal rock suites of the MMT may not, in fact, have been native to the Wyoming Province prior to 2.45 Ga.

2.06 Ga MAFIC DIKES

Quartzofeldspathic gneiss complexes in both the Tobacco Root and Highland Mountains are cut by a suite of metamorphosed mafic dikes and sills, the MMDS unit of Brady and others (2004b), also discussed by Hanley and Vitaliano (1983; figs. 5, 6), that give a Pb^{207}/Pb^{206} zircon intrusive age of 2.06 Ga (Mueller and others, 2004, 2005). In the Tobacco Root Mountains these bodies cross-cut gneissic banding in both the Indian Creek and Pony–Middle Mountain suites (Brady and others, 2004b; Harms and others, 2004a); in the Highland Mountains, they can be found within the quartz–feldspar–biotite gneiss and the quartzofeldspathic gneiss in the core of the range [map units X(A)qf and X(A)q in O'Neill and others, 1996; Castro and others, 2014]. Ranging in width from only several centimeters at their thinnest to 5–10 m wide at their thickest, these bodies are generally too small to appear on published maps; in the absence of detailed descriptions, it is not clear how widespread they may be within the basement gneisses of the MMT. In contrast, excellent spatial coverage of observations has failed to locate any MMDS bodies within either the Spuhler Peak suite in the Tobacco Root Mountains (Burger and others, 2004) or those metasupracrustal units that mantle the quartzofeldspathic core of the Highland Mountains (the mylonitic biotite gneiss [X(A)m], garnet biotite gneiss [X(A)gb], foliated orthogneiss (Xi), garnet rich gneiss and schist [X(A)g], and igneous or metamorphic rocks, undivided (Xs) of O'Neill and others, 1996) despite the juxtaposition of these units with areas of quartzofeldspathic gneiss that do host the mafic intrusive bodies.

MMDS have distinctive characteristics (Brady and others, 2004b) that help distinguish them from Mesoproterozoic to Neoproterozoic mafic dikes that also occur within basement rocks of southwest Montana (Wooden and others, 1978; Harlan and others, 1996, 2005). They cut surrounding gneisses with sharp contacts, suggesting a cold host at the time of intrusion. Many MMDS retain relict microscopic and macroscopic igneous textures, including chilled margins. Nevertheless, MMDS consist of the metamorphic mineral assemblage garnet + clinopyroxene + hornblende + plagioclase (Brady and others, 2004b; Castro and others, 2014) and generally have a modest metamorphic mineral alignment. Some MMDS bodies cross-cut gneissic banding at a high angle, but most are only slightly oblique to the fabric of their host, and a few are folded along with the encompassing gneiss (fig. 6). Together, the mineralogy and geometry of the MMDS are interpreted to reflect metamorphism, deformation, flattening, and transposition subsequent to intrusion at 2.06 Ga.

Rocks of the MMDS retain an original tholeiitic bulk chemistry and have modestly enriched REE patterns that are 10–100 times chondrite (fig. 7; Brady and others, 2004b; Krogh and others, 2011; Castro and others, 2014). This chemistry is consistent with, but not definitive of, a continental rift setting of origin for the MMDS magmas. As we discuss later in this paper, a high-seismic velocity layer in the lower crust beneath the northern Wyoming Province may be attributable to rift-related mafic underplating at ~2.1 Ga (Barnhart and others, 2012). Inherited zircon in the age range ~2.1 to 2.45 Ga recovered from Mesozoic–Cenozoic intrusive rocks in southwestern-most Montana and adjacent Idaho (see the summary in Foster and others, 2006) may indicate the presence of crustal fragments that rifted away from the ~2.45 Ga Beaverhead orogen and the Wyoming Province during the 2.06 Ga event and were subsequently reassembled during the Big Sky orogeny. Taken together, the evidence suggests that there was rifting in the northern Wyoming Province at 2.06 Ga, which appears to have produced mafic intrusions over a broad, cratonic extensional domain. If so, it would have reestablished an open continental margin on the northwestern flank of the Wyoming Province subsequent to the Beaverhead orogeny, setting the stage necessary for the culminating Big Sky collisional event at ~1.8–1.7 Ga.

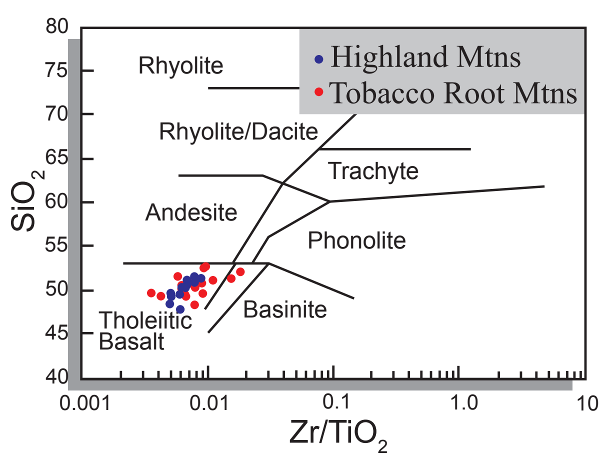
This suite of observations is interpreted to reflect the following history for the MMDS and for those parts of the Wyoming Province they intrude.

- At 2.06 Ga, MMDS intruded cold basement gneisses in what were originally high-angle, cross-cutting relationships.
- Intrusion occurred during a period of continental rifting, reestablishing the NW margin of the Wyoming Province following collisions and accretions associated with the ~2.45 Ga Beaverhead orogeny. Mafic magmatism may have been accompanied by underplating of the northern Wyoming Province continental crust.
- The host gneisses and the MMDS were subjected to metamorphism, deformation, and transposition during the regional ~1.8–1.7 Ga Big Sky orogeny, which resulted in the observed low-angle obliquity and metamorphic mineralogy of the MMDS.

Thus, the MMDS provide a benchmark that serves to distinguish some of the pre-1.8 Ga characteristics of the MMT and to segregate suites whose protoliths most likely originated subsequent to 2.06 Ga.

LATE PALEOPROTEROZOIC PALEOGEOGRAPHY

Although most of the MMT north of Giletti's line preserves evidence of significant thermotectonic events at both ~2.45 Ga (Beaverhead orogeny) and ~1.8–1.7 Ga (Big Sky orogeny), several spatially limited but nevertheless important metasupracrustal suites were metamorphosed only during the Big Sky orogeny (fig. 3): (1) the metaintrusive and metasupracrustal rocks of the Little Belt Mountains; (2) the mylonitic biotite gneiss, garnet–biotite gneiss, foliated orthogneiss, garnet-rich gneiss and schist, and igneous and metamorphic rocks, undivided [map units X(A)m, X(A)gb, Xi, X(A)g, and Xs, respectively, in O'Neill and others, 1996] in the Highland Mountains; (3) the



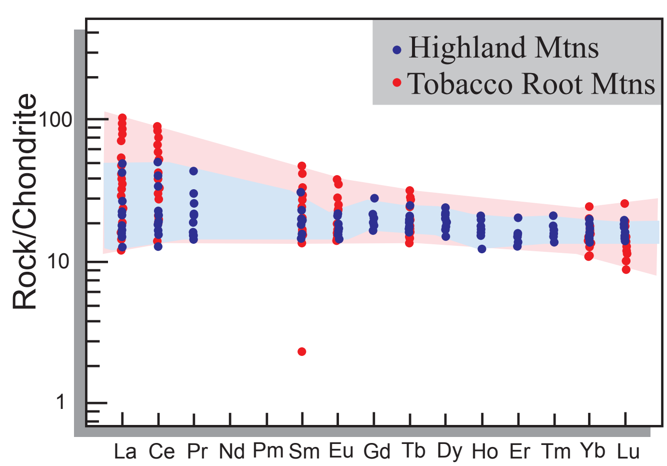


Figure 7. Geochemical characteristics of metamorphosed mafic dikes and sills (MMDS) within the quartzofeldspathic gneisses of the Tobacco Root (red dots) and Highland Mountains (blue dots). Both major and trace element compositions are consistent with modestly enriched mantle melts and permissive of a continental rift setting. Data from Brady and others (2004b) and Castro and others (2014). Diagrams drawn from Sun and McDonough (1989) and Winchester and Floyd (1977).

Spuhler Peak metamorphic suite in the Tobacco Root Mountains; and (4) the structurally higher part of the Christensen Ranch suite in the Ruby Range. Metasedimentary units in these suites have yielded monazites exclusively in the general age range ~1.8–1.7 Ga. Except in the Little Belt Mountains, each of these suites is juxtaposed directly against quartzofeldspathic gneiss and metasupracrustal complexes that (1) are intruded by 2.06 Ga metamorphosed dikes and sills; and/or (2) preserve ~2.45 Ga monazite, garnet, and zircon chronometers. The most straightforward explanation for this contrast is that these four suites were juvenile late Paleoproterozoic units prior to the Big Sky orogeny, that is, that they accumulated at some time in the period 2.06 to 1.8 Ga and thereby postdated both the Beaverhead orogeny and rift-related mafic intrusion. Notably, the four younger suites are nearly devoid of marbles and of quartzofeldspathic gneiss and so do not reflect the continental characteristics of the more ancient suites with which they are juxtaposed. Together, these four younger suites constrain the tectonic paleogeography of the northern Wyoming Province prior to the Big Sky orogeny.

The Little Belt Arc

A variety of metaintrusive gneisses have been mapped as informal units constituting the basement of the Little Belt Mountains—including the Pinto and Ranger diorites, Helispot granite, and Grey and Augen gneisses—accompanied by small screens of amphibolite and pelitic schist such as the Aspen gneiss (Weed, 1899; Vogl and others, 2004). As a suite, these metaplutonic rocks are calc-alkaline in bulk chemistry, and have trace element patterns and primitive initial Nd isotopic ratios consistent with genesis in a subduction setting (fig. 8; Mueller and others, 2002; Vogl and others, 2004). Concordant and upper-intercept U-Pb zircon ages derived from the metaplutonic rocks range from ~1.87 to 1.79 Ga (Mueller and others, 2002; Vogl and others, 2004). These are interpreted as intrusive ages that span at least some part of the period of subduction and arc activity. Cordierite-bearing equilibrium metamorphic assemblages (e.g., sillimanite + biotite + garnet + cordierite + quartz + K-spar + plagioclase) in host metapelitic rocks constrain very high-temperature, low-pressure metamorphic conditions (Vogl and others, 2004; Swanson and others, 2010) consistent with metamorphism within an arc setting. Monazites from these metapelitic rocks yield ages ranging from 1.91 Ga to 1.82 Ga (Dahl and others, 2000; Swanson and others, 2010), demonstrating that metamorphism was contemporaneous with arc plutonism. We interpret rapid cooling at 1.775 Ga, documented by nearly concordant Ar^{40}/Ar^{39} cooling ages of hornblende and biotite from several metaplutonic rocks (Holm and Schneider, 2002), as recording the time of arc cessation as a consequence of the inception of collision associated with the Big Sky orogeny.

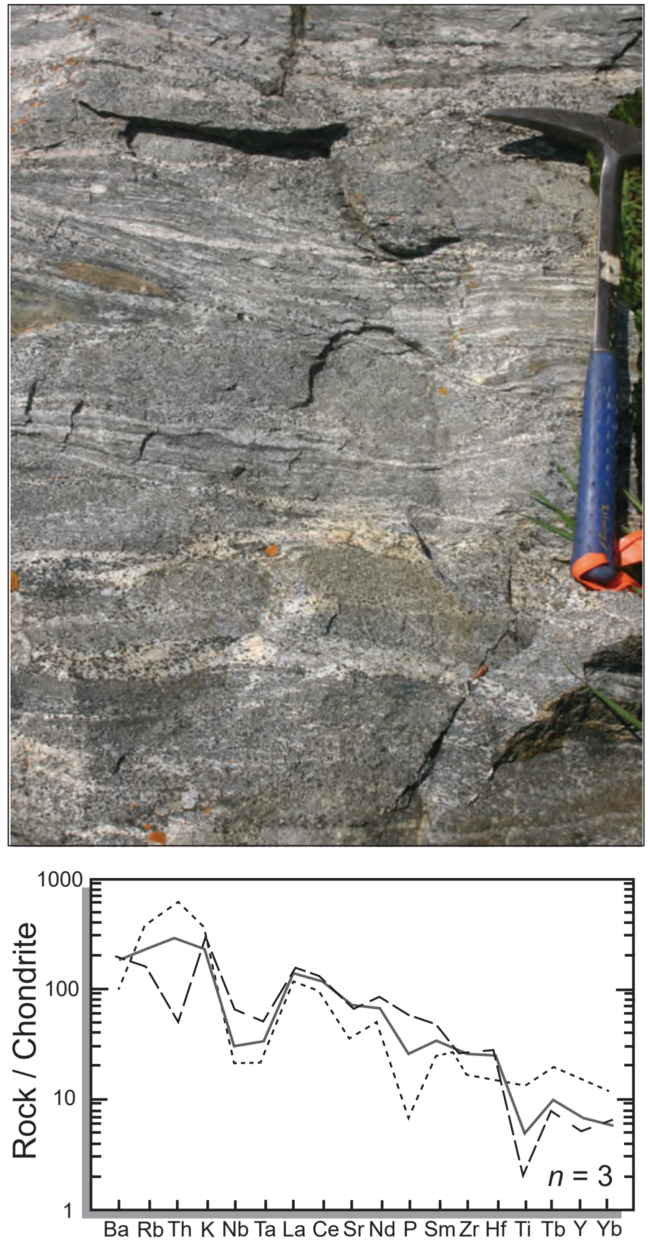


Figure 8. Dioritic gneisses of the Little Belt Mountains (top photograph) have trace element profiles (bottom) characteristic of a juvenile arc-related protolith. Geochemical data from Mueller and others (2002); diagram drawn from Thompson and others (1984).

Foster and others (2006) obtained both concordant and upper intercept zircon crystallization ages of ~1.89–1.86 Ga from spatially limited exposures of dioritic and quartzofeldspathic basement orthogneiss in the Pioneer Mountains and Biltmore Anticline in southwestern-most Montana. We correlate these rocks with coeval gneiss in the Little Belt Mountains, extending the Little Belt arc domain some 200+ km along the former margin of the Wyoming Province (fig. 9A).

The Highland Mountains Back-Arc Basin

In the Highland Mountains, Precambrian crystalline rocks occur in a structural dome that forms the core of the range (O'Neill and others, 1988, 1996). Quartzofeldspathic gneisses cut by MMDS lie in the center of that dome, where they are flanked by metasupracrustal rocks, most of which are biotite–sillimanite–garnet–potassium feldspar–plagioclase–quartz schists and gneisses and their mylonitic equivalent (mapped as garnet biotite gneiss [X(A)gb] and mylonitic biotite gneiss [X(A)m] by O'Neill and others, 1996). These aluminous schists and gneisses have yielded only ~1.8–1.7 Ga monazites (Pearson and Cheney, 2008). Throughout their outcrop area, the pelitic schists and gneisses are associated with abundant 1- to 5-m-thick, laterally continuous, concordant layers of hornblende–plagioclase–quartz ± garnet ± clinopyroxene ± biotite amphibolite (Rioseco and others, 2016).

This suite is best interpreted to represent what was, prior to the Big Sky orogeny, a basin filled with fine-grained, aluminous clastic material, richly interlayered with basalt flows, sills, and/or dikes. The absence of either quartzites or marbles in this extensive unit indicates the basin of deposition did not include shallow-water, passive, continental margin environments. Major and trace element analyses of the amphibolites indicate their basaltic protolith was subalkaline and tholeiitic; on discriminant diagrams based on immobile trace elements, these rocks typically span fields associated with mid-ocean ridge basalts, back-arc basins, and arc tholeiites (fig. 10; Rioseco and others, 2016). Taking this into account, the most likely basin of accumulation for the sedimentary and volcanic protoliths of the aluminous schists [X(A)gb and X(A)m of O'Neill and others, 1996] and interlayered amphibolites of the Highland Mountains was a suprasubduction zone back-arc basin.

Back-Arc Ocean Crust of the Spuhler Peak Metamorphic Suite in the Tobacco Root Mountains

The distinguishing lithologies of the Spuhler Peak metamorphic suite in the Tobacco Root Mountains, contrasting sharply with surrounding quartzofeldspathic gneisses, were first introduced by Tansley and others in 1933, and mapped as a separate unit by Burger (1967) and again by Vitaliano and others (1979a,b). The Spuhler Peak metamorphic suite is dominated by hornblende amphibolite and distinctive orthoamphibole–garnet gneiss with much less significant aluminous schist and quartzite; minor metaultramafic bodies are present; marble is absent (Burger and others, 2004).

The Spuhler Peak suite is in contact with quartzofeldspathic gneiss of the Indian Creek metamorphic suite that has been intruded by 2.06 Ga MMDS. In places, MMDS bodies are very close to the basal contact of the Spuhler Peak but do not cross that contact, nor do they intrude units of the Spuhler Peak anywhere (Brady and others, 2004b; Burger and others, 2004). Although Mogk and others (2020) interpret the Spuhler Peak suite as Archean based on Sm-Nd model ages, we find it more likely that the suite is <2.06 Ga in age and that it was a juvenile suite in the late Paleoproterozoic. Ion microprobe analyses of monazite in both orthoamphibole–garnet gneiss and aluminous schist give $^{207}Pb/^{206}Pb$ ages that range from 1.78 to 1.72 Ga; older monazites are not present (Cheney and others, 2004b).

On the basis of major and trace element geochemical analyses, Burger and others (2004) determined that the hornblende amphibolites of the Spuhler Peak metamorphic suite had tholeiitic basalt protoliths with trace element concentrations consistent with an arc-related origin (fig. 11), and that the orthoamphibolites were derived from hydrothermally altered mafic volcanic rocks genetically related to the protolith of the hornblende amphibolite. They estimate that 90% of the Spuhler Peak suite consisted of mafic volcanic rocks prior to metamorphism, with minor intercalated siliceous (either chert or sandstone) and muddy sediments. Together, these characteristics are best fit by suprasubduction, intra-arc or back-arc ocean crust with active spreading centers as the origin of the Spuhler Peak metasupracrustal suite prior to the Big Sky orogeny (Burger and others, 2004; Harms and others, 2004b).

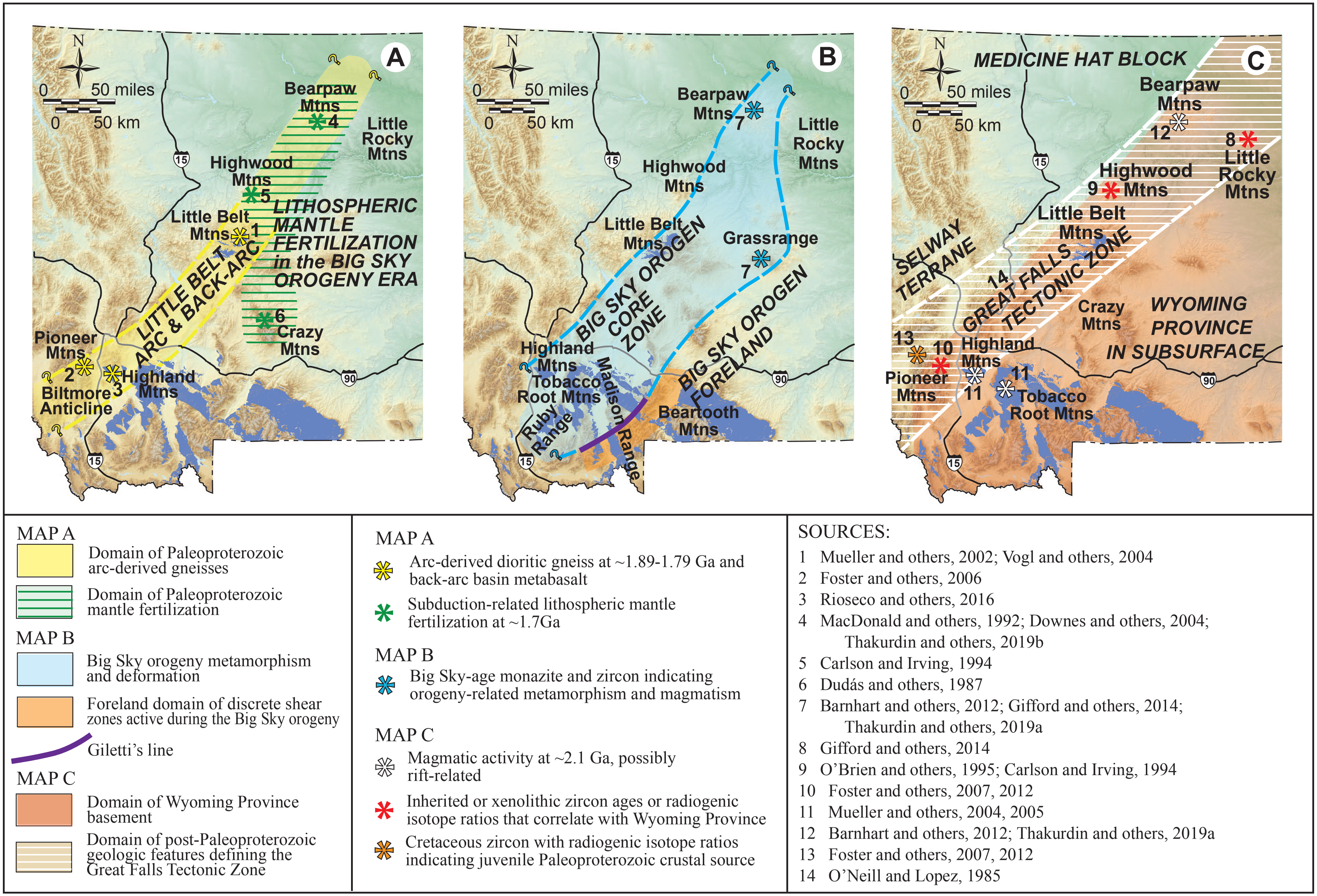


Figure 9. The subsurface distribution and character of Paleoproterozoic rocks has been assessed through the isotope geochemistry and geochronology of mantle and crustal xenoliths and through radiogenic isotopes in Cenozoic intrusive rocks in the ranges of central Montana. When integrated with observations on exposed Precambrian rocks (dark blue shaded areas), the Big Sky orogen and Wyoming Province basement can be delimited. Base maps modified from Vuke and others (2007). Sources of the data are given in the figure.

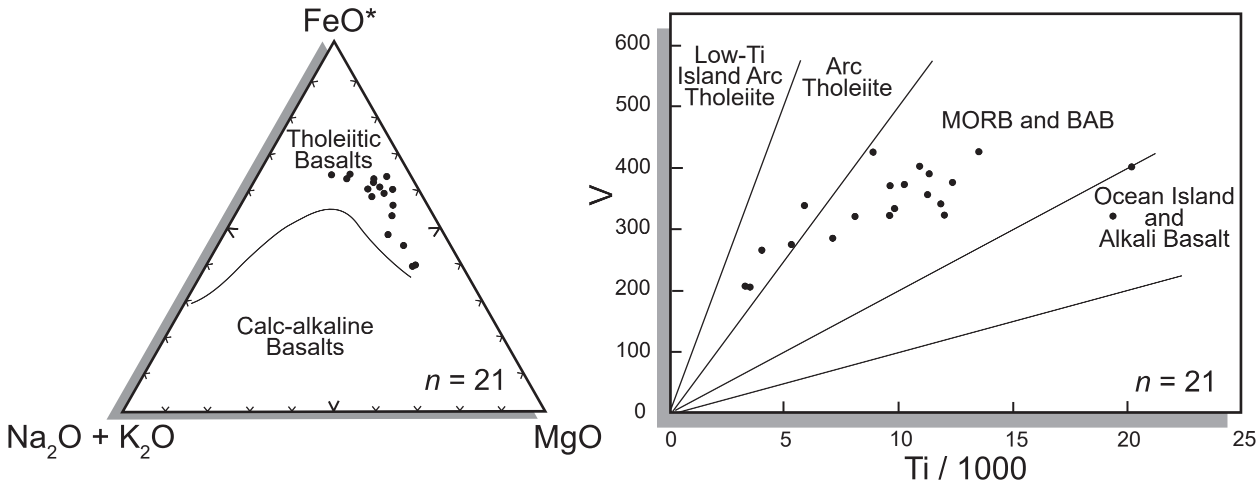


Figure 10. Geochemical characteristics of amphibolite layers within the biotite–sillimanite–garnet pelitic schists and gneisses [X(A)m and X(A)gb units of O'Neill and others, 1996], which mantle quartzofeldspathic gneisses in the core of the Highland Mountains structural dome, are consistent with an origin as basalt flows in a back-arc basin. Data from Rioseco and others (2016). Diagrams drawn from Irvine and Baragar (1971) and Shervais (1982). Discriminant diagram (right) based on elements largely immobile during metamorphism.

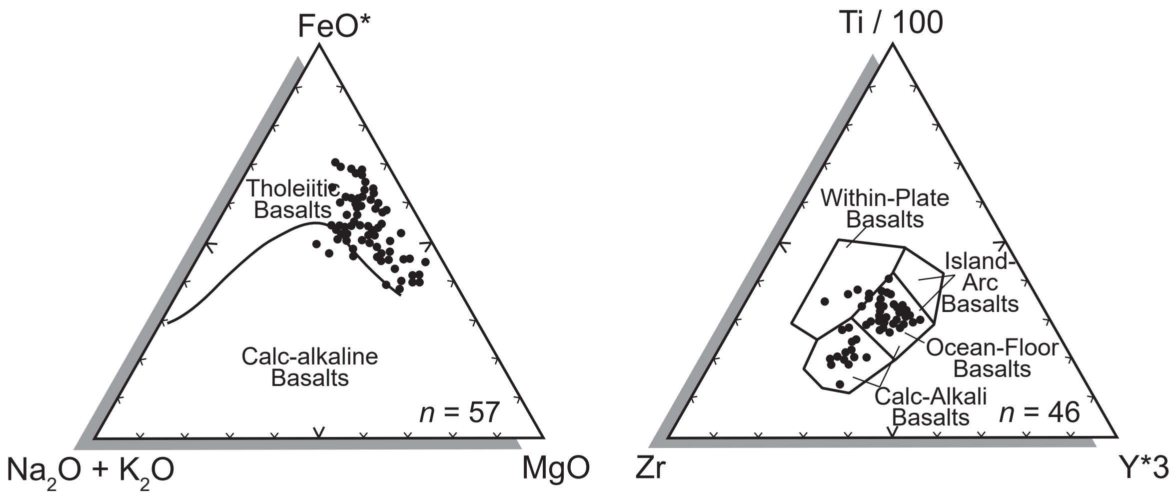


Figure 11. Both major and trace element composition of amphibolites within the Spuhler Peak suite of the Tobacco Root Mountains are indicative of ocean crust basalts. Data from Burger and others (2004). Diagrams drawn from Irvine and Baragar (1971) and Pearce and Cann (1973).

The Upper Christensen Ranch Suite in the Ruby Range

The Christensen Ranch metamorphic suite of the western Ruby Range is a west-dipping homoclinal sequence of metasupracrustal rocks that includes massive marble layers, calc-silicate, quartzite, iron formation, pelitic schist and gneiss, hornblende amphibolite, orthoamphibole schist, and minor quartzofeldspathic gneiss (Dahl, 1979; James, 1990). Recent geochronological analyses reveal that the suite is composed of two chronologically distinct units: a lower Christensen Ranch suite in which both ~2.45 Ga and ~1.8–1.7 Ga monazites occur, and an upper Christensen Ranch suite in which only ~1.8–1.7 Ga monazites can be found (Baldwin and others, 2014, 2017; Cramer and others, 2013). The monazite age spectrum of the lower Christensen Ranch suite is analogous to that of the structurally underlying Dillon gneiss (Baldwin and others, 2017). Both the lower Christensen Ranch suite and the Dillon gneiss host a well-dated 2.45 Ga leucogneiss (fig. 4; Baker and others, 2017; Baldwin and others, 2017) that cross-cuts metasedimentary unit boundaries, whereas the upper Christensen Ranch suite does not contain this leucogneiss, demonstrating the antiquity of the former and the distinctly different, younger history of the latter. Both the upper and lower Christensen Ranch suites contain prominent marble sections, as well as amphibolites, which suggests a continental shelf or margin in an active tectonic setting for the origin of each, a setting that must have existed prior to the Beaverhead orogeny at 2.45 Ga in the case of the lower Christensen Ranch suite, and one that existed after that tectonism and before the 1.8–1.7 Big Sky orogeny in the case of the upper Christensen Ranch suite.

Proterozoic Paleogeographic Reconstruction

It seems clear that the late Paleoproterozoic metaplutonic rocks of the Little Belt Mountains represent a subduction-related arc, but the polarity of that arc is less evident. Initial interpretations placed the ancient Wyoming Province continental crust on the subducting plate and the Little Belt arc to the NNW of the plate boundary (Erslev and Sutter, 1990; O'Neill, 1998; Harms and others, 2004b; Mueller and others, 2004, 2005; Vogl and others, 2004; Whitmeyer and Karlstrom, 2007). This model is consistent with the absence of ~1.8–1.7 Ga arc-related plutons within the MMT that would be evidence of southeast-directed subduction beneath the craton, and with the idea that thick, refractory lithosphere associated with the Archean Wyoming Province might act as a barrier to a southward-subducting plate (Mueller and others, 2004, 2005). Furthermore, a N–S deep seismic refraction profile identified the presence of a shallowly north-dipping reflector at ~50 to 100 km depth that projects to the surface just north of the Little Belt Mountains (Gorman and others, 2002). This has been interpreted as a fossil subduction zone, frozen within the North American lithosphere of the present (Gorman and others, 2002; Harms and others, 2004b; Mueller and others, 2005).

A significant shortcoming of this model is the absence of evidence for a sedimentary sequence within the MMT consistent with a classically understood passive continental margin that would identify the northern margin of the Wyoming Province prior to northward subduction below the Little Belt arc—one that might have developed over the lengthy period from 2.06 to 1.8 Ga. Instead, the tectonic characteristics of the late Paleoproterozoic juvenile suites of the Little Belt, Highland, Tobacco Root, and Ruby Ranges suggest a plate tectonic paleogeography driven by southward subduction to the north of and beneath the Little Belt arc, with (1) a northern arc that was distal relative to the Wyoming Province, (2) an active, rifted continental platform that was proximal to the Wyoming Province, and (3) an intervening back-arc basin with back-arc oceanic crust and sediments (fig. 12; Harms and Baldwin, 2019). Trace element and radiogenic isotope analyses of ultramafic xenoliths and of the alkali igneous rocks that contain them in the Highwood (Carlson and Irving, 1994), Bearpaw (MacDonald and others, 1992; Downes and others, 2004; Thakurdin and others, 2019b), and Crazy Mountains (Dudás and others, 1987) indicate the lithospheric mantle beneath those locations experienced subduction-related fertilization and enrichment at ~1.7 Ga. The Highwood and Bearpaw Mountains are along structural strike to the northeast of the Little Belt arc and may reflect arc-related processes, but the Crazy Mountains lie well to the southeast, across structural strike (fig. 9A). Mantle fertilization in that setting seems to require that subducting lithosphere extended from the arc, beneath the leading edge of the Wyoming Province during the Big Sky orogeny. Perhaps thick Archean lithosphere beneath the Wyoming Province did resist this southward subduction, which led to trench fallback and the opening of the back-arc basin.

The north-dipping, upper-mantle reflector at mid-lithospheric depth north of the Little Belt Mountains (Gorman and others, 2002) remains unexplained in this model. There may have been a second,

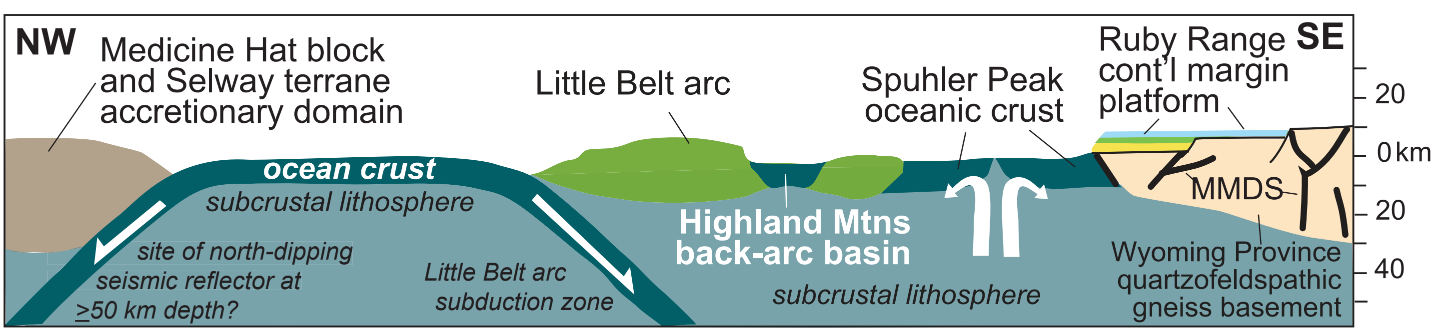


Figure 12. Schematic cross-section interpreting the pre-collision paleogeography of tectonic domains represented by juvenile Paleoproterozoic suites of the MMT. Southward-dipping subduction beneath the continental margin of the Wyoming Province, represented by the upper Christensen Ranch group in the Ruby Range today, opened a back-arc basin (Spuhler Peak and Highland Mountains suites) southeast of the Little Belt arc. A north-dipping, deep lithospheric seismic reflector observed in the subsurface north of the international border today (Gorman and others, 2002) may indicate that a second, north-dipping subduction system also operated to close the ocean basin between the Medicine Hat Block and the Little Belt arc.

north-dipping subduction zone beneath encroaching Archean cratons of southern Canada as part of a larger accretionary domain in the Paleoproterozoic (fig. 12), or the reflector might be a consequence of the ~2.45 Ga Beaverhead orogeny rather than the Big Sky orogeny. Because the seismic feature cannot be dated, all interpretations are speculative.

Relative to the juvenile late Paleoproterozoic suites, quartzofeldspathic gneiss + metasupracrustal suites of the MMT form a regional basement, having been consolidated at or by 2.45 Ga, although modified at 2.06 Ga. The nature of the contacts between these two fundamentally different domains has been debated for decades. Some interpretations call for unconformable, depositional contacts (e.g., Gillmeister, 1972; Karasevich and others, 1981); others argue that the suites have been tectonically juxtaposed (e.g., Burger, 1967; O'Neill and others, 1988; Harms and others, 2004b). The following observations constrain the parameters of this debate.

- In the Highland Mountains, two distinctive rock units lie along the contact between the juvenile, back-arc basin suite of sillimanite–biotite–garnet schists and gneisses with interlayered amphibolite and the underlying quartzofeldspathic gneiss dome.

  (1) O'Neill and others (1996) identified a thin but persistent, heterogeneous suite of distinctive metasupracrustal rocks, their garnet-rich gneiss and schist map unit [X(A)g], that traces the contact at a number of locations. Migmatitic sillimanite–biotite–garnet gneiss, quartzite, hornblende amphibolite, orthoamphibole–kyanite gneiss, and rare marble, iron formation, and serpentinite all occur within this unit, which is typically less than 150 m thick (Matthews and Cheney, 2006). Monazites recovered from this unit are all in the ~1.8–1.7 Ga range (Pearson and Cheney, 2008), suggesting that this distinctive suite is coeval with, and represents the base of, the Highland Mountains back-arc basin deposits. This unit may have developed extrusively and depositionally astride the rifting basement of the Wyoming Province. However, immediately adjacent quartzofeldspathic gneisses do not contain cross-cutting mafic bodies of appropriate age to have fed the extrusive protoliths of the basin's many amphibolite layers, and the amphibolite chemistry is not consistent with a continental setting of origin (fig. 10). The heterolithic character of this distinctive suite is notable; it may represent an olistostromal deposit or mélange.

  (2) Leucocratic quartz–feldspar dikes and sills, commonly mylonitic, are also associated with this contact and pervasively invade both the juvenile late Paleoproterozoic units and the underlying quartzofeldspathic basement. The volume of these intrusions is sufficient to warrant subdivision as a map unit of igneous and metamorphic rocks, undivided (Xs), and as individual bodies of granite, aplite, and pegmatite (Xg) by O'Neill and others (1996). One of these dikes has given a ~1.75 Ga U-Pb zircon age (Vogl, 2007). We interpret these bodies as neosome emplaced into a dilatant zone created by displacement between the overlying juvenile, back-arc basin suites and the quartzofeldspathic basement.

- In the Tobacco Root Mountains, neither the Indian Creek nor the Pony–Middle Mountain quartzofeldspathic gneiss suites hold mafic intrusive bodies that might have fed the voluminous mafic protoliths of the Spuhler Peak suite (Burger and others, 2004; Harms and others, 2004b), nor do the amphibolites of the Spuhler Peak reflect a continental setting of origin (Burger and others, 2004), suggesting tectonic juxtaposition of the two. On the other hand, Burger and others (2004) document the presence of a discontinuous but persistent thin quartzite at the base of the Spuhler Peak suite that might represent a basal clastic deposit above an unconformity. The preponderance of 3.0–3.3 Ga zircons recovered from this quartzite is similar to other Wyoming Province quartzites, but the absence of 2.7–2.9 Ga grains is not (Mueller and others, 2004), leaving paleogeographic interpretations based on detrital zircon patterns equivocal. Mueller and others (2004) suggest a temporally and physically restricted, rift-like basin setting within the Wyoming Province for this quartzite.

- Despite the profound chronologic contrast recorded by monazite populations, there is seeming lithostratigraphic continuity between the lower (pre-2.45 Ga) and upper (juvenile late Paleoproterozoic) halves of the Christensen Ranch metamorphic suite in the western Ruby Range. If there is a depositional contact between the upper and lower sequences, resumption of a volcanically active, shallow continental shelf or margin setting must have occurred in the Ruby Range domain following the Beaverhead orogeny. A rifting event at 2.06 Ga might have provided the necessary framework. On the other hand, James's (1990) geologic map of the Christensen Ranch suite demonstrates the presence of map-scale, refolded, isoclinal folds in the upper Christensen Ranch suite that are not present in the lower part of the suite. This necessitates a major, pre- or syn-Big Sky orogeny detachment horizon between the lower and upper Christensen Ranch suites.

Owing to the intensity of reworking and recrystallization during the Big Sky orogeny, the nature of the contact between juvenile Paleoproterozoic supracrustal suites and their older gneissic basement cannot yet be definitively established. We know of no observations that unequivocally require or explicitly contradict either the unconformity or the fault model for these contacts, and recognize that some or all may be unconformities that later served as surfaces of detachment and displacement. Nevertheless, we consider the present juxtaposition of juvenile late Paleoproterozoic suites with the significantly older quartzofeldspathic basement, in one way or another, to have been the consequence of collision, convergence, and crustal thickening associated with the Big Sky orogeny and recognize that the mafic metaextrusive components of these suites are now detached from what had been their underlying source domains.

THE BIG SKY OROGEN

The Big Sky orogeny was originally defined on the basis of penetrative metamorphism and deformation dated to the period ~1.78–1.72 Ga, as preserved in basement rocks in the Laramide ranges of southwest Montana (Brady and others, 2004a); this area can be considered the core zone of the Big Sky orogen (fig. 9B). Both autochthonous Archean Wyoming Province suites and obducted, allochthonous late Paleoproterozoic juvenile assemblages occur within the metamorphic core of the orogen and were affected by its processes. Observations made in this core zone constrain the magnitude and duration of Big Sky orogenic tectonism. To the south, the core zone is bounded by Giletti's line, south of which, regionally, rocks retain their pre-Big Sky orogeny metamorphic minerals, fabrics, and chronologic settings. Instead, one or more discrete shear zones were active during the time of the Big Sky orogeny. These can be interpreted as the mid-crustal expression of a foreland zone in the orogen (fig. 9B). Due to the absence of Laramide basement uplifts, the northern limit of the Big Sky orogen is only indirectly constrained. O'Neill and Lopez (1985) identified a broad, linear domain of Mesoproterozoic and much younger high-angle faults, sedimentological boundaries, and intrusive bodies that stretches across Montana, trending northeast, roughly parallel to Giletti's line, which they named the Great Falls tectonic zone (fig. 9C). With the exception of the Little Belt Mountains (Mueller and others, 2002), surface exposures within the Great Falls tectonic zone are Mesoproterozoic or younger; nevertheless, O'Neill and Lopez associated the Great Falls tectonic zone and its recurrent activity with an inherited basement zone of crustal weakness that they suggested lies at the NW boundary of the Wyoming Province. Like O'Neill and Lopez, we consider that the surface features of the Great Falls tectonic zone mark the subsurface location of the suture between the upper and lower plate domains of the Big Sky orogeny collision (fig. 9C).

The Metamorphic Core

In contrast to quartzofeldspathic gneisses, the varied lithologies of metasupracrustal rocks in the MMT north of Giletti's line provide ideal mineral assemblages from which to constrain the timing, conditions, and evolution of metamorphism during the Big Sky orogeny. Regionally, the metamorphic core of the orogen reached upper amphibolite to lower granulite facies.

Big Sky orogeny metamorphism has been documented in greatest detail in the Tobacco Root Mountains, where Cheney and others (2004a) established a well-constrained PT path (fig. 13). The minerals on which their analysis was based can be definitively associated with the Big Sky orogeny based on the age of monazite inclusions (Cheney and others, 2004b). In the Tobacco Root Mountains, mineral assemblages establish a clockwise PT path for metamorphism in which peak pressures of >1 GPa are indicated by kyanite + orthopyroxene, followed by peak temperatures of ~800°C established from pelitic rocks in which sillimanite replaced kyanite (Cheney and others, 2004a). Peak temperatures were sufficient to drive partial melting; limited neosome can be found in structurally dilatant pockets within the metamorphic fabric (Mueller and others, 2004,

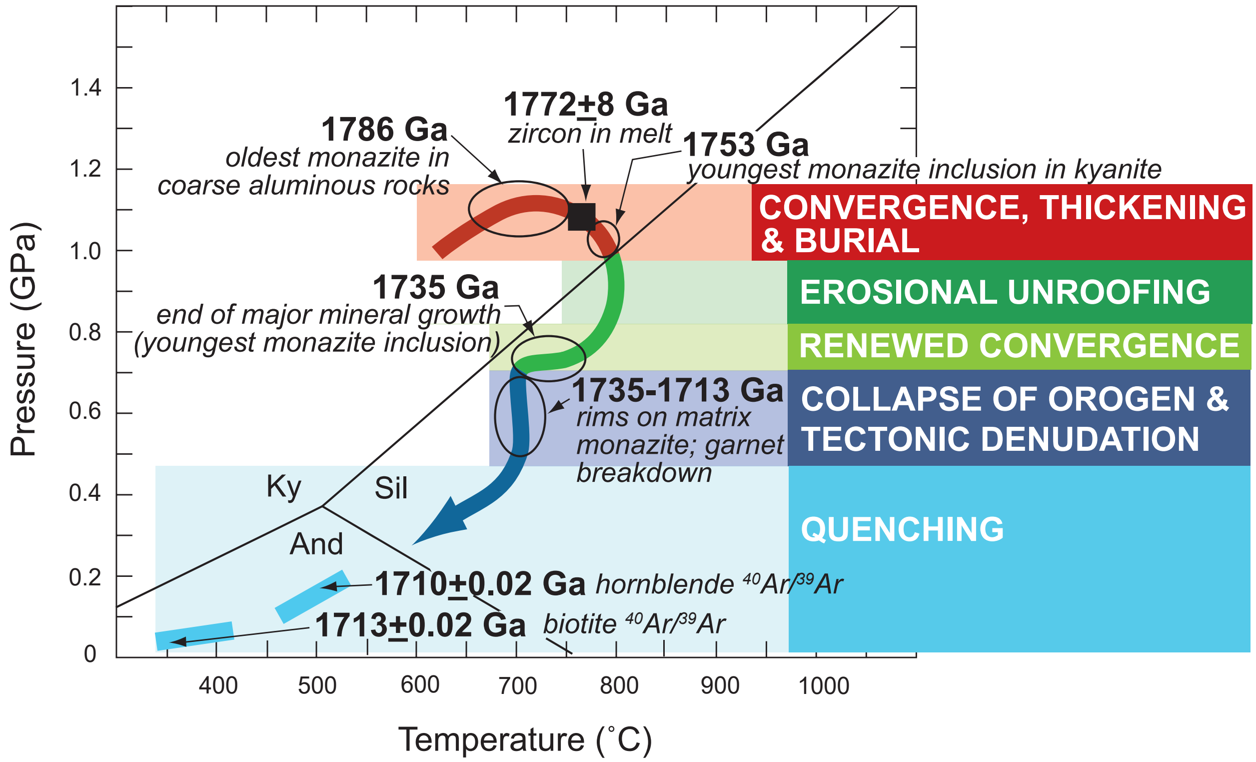


Figure 13. The pressure–temperature–time (PTt) path of metamorphism in the Tobacco Root Mountains constrains the tectonic evolution of that part of the Big Sky orogen. Data from Cheney and others (2004a,b; thermobarometry and monazite ages), Brady and others (2004c; $^{40}Ar/^{39}Ar$ ages), and Mueller and others (2004, 2005; zircon age). Adapted from Harms and others (2004b).

2005). Following the metamorphic peak, rocks of the Tobacco Root core underwent a three-stage cooling and decompression process: initial isobaric cooling was rapidly followed by isothermal decompression as recorded by a number of cordierite-bearing textures (Cheney and others, 2004a). Finally, slow stabilization of post-metamorphic pressures and temperatures can be documented by $^{40}Ar/^{39}Ar$ cooling analyses (Brady and others, 2004c).

"Peak" metamorphic conditions that have been determined in other parts of the Big Sky orogen core zone are consistent with the PT path established for the Tobacco Root Mountains (fig. 14). These are:

- ~1.2 GPa and 800˚C (Ault and others, 2012) and ~8.5 GPa and 700˚C (Kellogg and Mogk, 2009) in the northern Madison range;
- ~0.9 GPa and 700–725˚C in the southern part of the Madison range (Condit and others, 2015);
- ~0.85–0.95 GPa and 710–840°C in the Highland Mountains (Reioux, 2014; Klein and others, 2010);
- ~7.5–10 GPa and 700–850˚C (Cramer and others, 2013) or ~745–675˚C (Dahl, 1979) in the Ruby Range, where sillimanite is the dominant aluminosilicate and cordierite rimming garnet is abundant; and
- a clockwise pressure–temperature path from upper amphibolite or granulite conditions, followed by isothermal decompression determined in the Gallatin Range (Mogk, 1992). This metamorphism has not, however, been directly dated.

As suggested by Condit and others (2015), these results can be interpreted to record a north-to-south reduction in the pressures of metamorphism consistent with greater depths of exposure to the north, but because different bulk rock compositions and modes of analysis were used in these studies, the variations in calculated metamorphic pressures and temperatures could be more apparent than real.

In so far as this metamorphism was imposed on supracrustal suites that include prominent marbles of presumably shallow-water origin (the upper Christensen Ranch suite), we can estimate that the supracrustal rocks capped a continental crust not less than 25 km thick prior to collision. During the course of the Big Sky orogeny, these rocks were buried by an estimated 25 km of tectonic overburden to generate the observed minimum pressures of metamorphism. Thus the core zone of the Big Sky orogen represents a compressive domain where tectonic shortening produced a >50-km-thick crustal welt (Harms and others, 2004b).

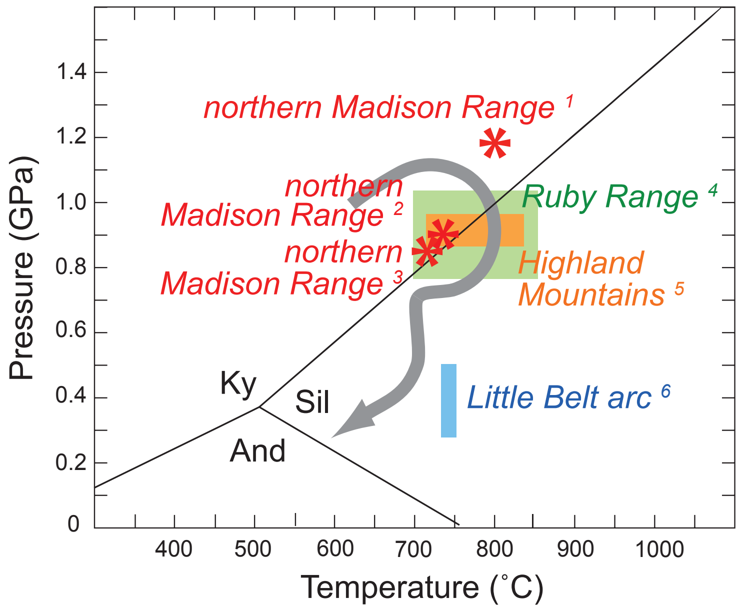


Figure 14. Pressure and temperature constraints across the metamorphic core of the Big Sky orogen are consistent with the PT path (gray curve) determined for the Tobacco Root Mountains (Cheney and others, 2004a). Metamorphic conditions in the Little Belt arc were substantially different and reflect metamorphism in a high T–low P arc environment preserved by shallow crustal emplacement into the Big Sky orogen. Data from: (1) Ault and others (2012); (2) Condit and others (2015); (3) Kellogg and Mogk (2009); (4) Cramer and others (2013) and Dahl (1979); (5) Reioux (2014) and Klein and others (2010); and (6) Vogl and others (2004) and Swanson and others (2010).

The grade of metamorphism in the Little Belt Mountains stands in contrast to the rest of the MMT and the Big Sky orogen core zone north of Giletti's line (fig. 14). There, pelitic rocks host spinel + cordierite assemblages, indicating peak conditions of ~750˚C and 0.3–0.5 GPa (Vogl and others, 2004; Swanson and others, 2010). This metamorphism is interpreted to have been the consequence of arc activity prior to the onset of the Big Sky orogeny. The Little Belt arc would have escaped higher-grade recrystallization during the peak of Big Sky orogeny metamorphism by occupying the highest structural level in the developing orogen.

The Timing of Metamorphism

Because of the interplay of monazite and garnet during both metamorphic growth and breakdown (Kohn and Malloy, 2004; Williams and others, 2006), the application of monazite geochronology has driven significant advances in dating the stages of evolution of the Big Sky orogeny. Again, the most comprehensive study to date is that of Cheney and others (2004b) in the Tobacco Root Mountains. Their results constrain the following stages of the orogeny (fig. 13):

- 1786 Ma—onset of metamorphism based on the oldest monazite dated (a matrix grain);
- 1786–1753 Ma—ascending arm of the clockwise PT path constrained by monazite inclusions in garnet, kyanite, and cordierite;
- 1753 Ma—metamorphic conditions moved into the sillimanite stability field based on the youngest kyanite inclusion found;
- 1753–1732 Ma—decompression arm of the clockwise PT path demonstrated by monazite included in garnet;
- 1732 Ma—end of main phase of metamorphic mineral growth corresponding to the youngest monazite inclusion; and
- 1732–1715 Ma—a period of isothermal decompression and garnet breakdown that produced rims on matrix monazites.

The work of Cheney and others (2004a,b) has given a clear sense of the multiple stages of the orogeny, but we caution against strict application of these specific dates or rates outside of the Tobacco Root Mountains or direct comparison to the results of other monazite studies because: (1) like all orogenies, the Big Sky orogeny was likely time-transgressive (Condit and others, 2015); (2) cordierite is not present in pelitic rocks in all ranges, suggesting that not all parts of the orogen shared a phase of rapid decompression; and (3) the different monazite analytical techniques employed in different studies can produce disparate dates. Nevertheless, monazite ages that are broadly consistent with the pressure–temperature–time (PTt) path assembled in the Tobacco Root Mountains have been obtained from most other ranges north of Giletti's line (fig. 15;

Jones, 2008; Pearson and Cheney, 2008; Alcock and others, 2013; Cramer and others, 2013; Baldwin and others, 2014; Condit and others, 2015). Step leaching (Roberts and others, 2002) and Lu-Hf (Baker and others, 2017) dating methods applied to metamorphic garnet in the Ruby, Tobacco Root, and Highland mountain ranges have also yielded ages that are consistent with the PTt path established with monazites in the Tobacco Root Mountains.

Zircon geochronology applied to bodies of neosome generated during peak temperature conditions can also be integrated into the Big Sky orogeny PTt path. Leucocratic neosome has been dated in the Tobacco Root (Mueller and others, 2004, 2005) and Highland Mountains (Mueller and others, 2005; Vogl, 2007). These analyses consistently give ages of 1.75 or 1.76 Ga, which corresponds well to the shift of metamorphic conditions from kyanite to sillimanite stability documented by monazites in the Tobacco Root Mountains (figs. 13, 15; Cheney and others, 2004b).

Structural Character

Geothermobarometry and monazite geochronology consistently demonstrate that rocks of the MMT north of Giletti's line achieved the temperatures necessary to recrystallize their major rock-forming minerals during the Big Sky orogeny. Mineral alignment fabrics in the MMT north of Giletti's line should be understood as a feature of the ~1.8–1.7 Ga orogeny. Fabric and compositional layering are almost universally concordant, indicating that the main phases of mineral growth did not outlast deformation.

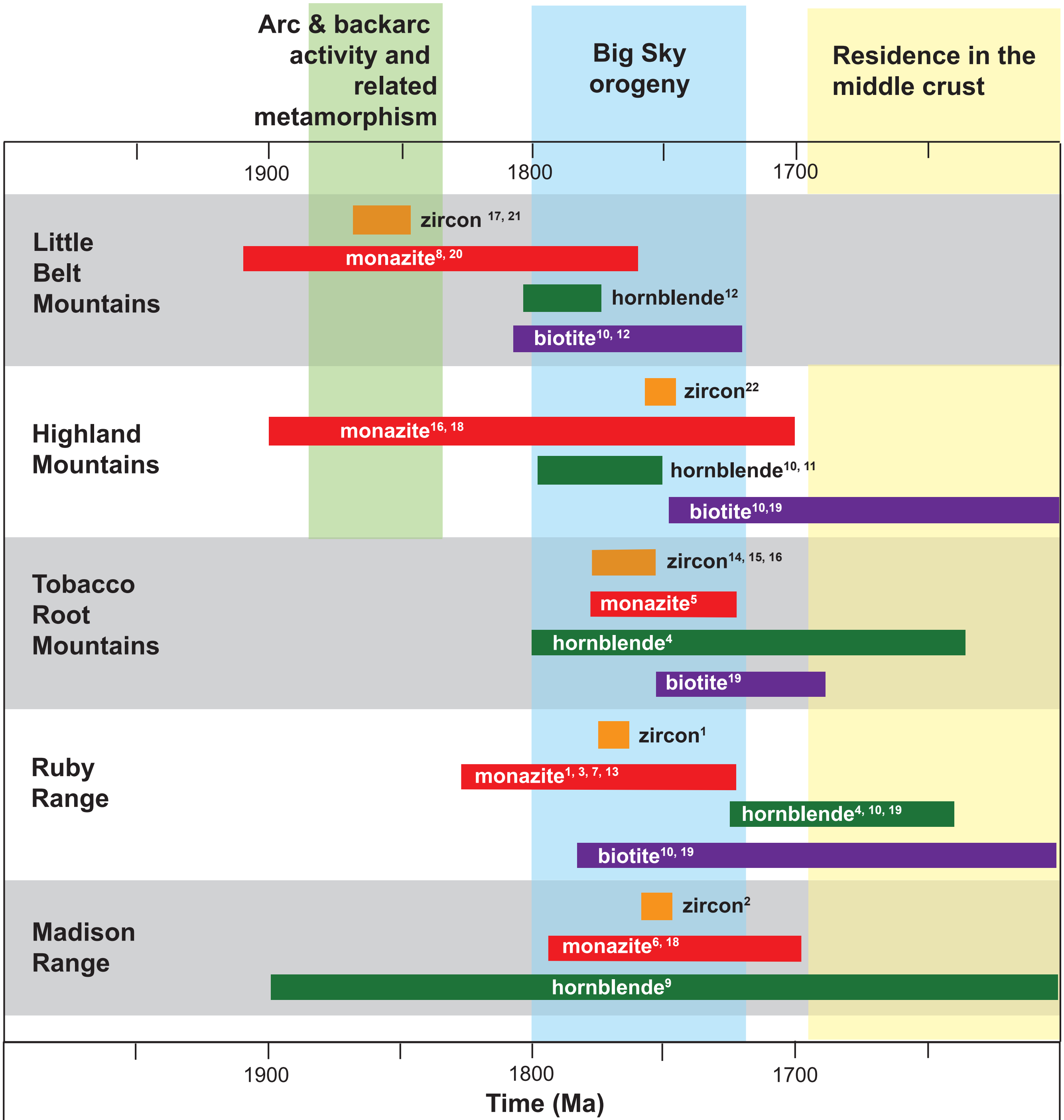
In the Tobacco Root Mountains, outcrop-scale folds are ubiquitous (Harms and others, 2004a); this is less true in the Highland Mountains and Ruby Range where units are more massive and there are fewer sequences of rocks of differing rigidity that are interlayered on an outcrop scale. On the other hand, map-scale folds have been documented in the northern Madison Range (Spencer and Kozak, 1975; Kellogg and Mogk, 2009) and the Ruby Range (James, 1990); in the Tobacco Root Mountains a map-scale sheath fold encloses the Spuhler Peak metamorphic suite (Vitaliano and others, 1979a,b; Harms and others, 2004a). Map scale folds are typically isoclinal, such that there must exist large domains of overturned sequences. Recognizing this, interpreting sequences of rocks in terms of an original protolith stratigraphy is unwarranted.

Mylonitic fabric is common in all the ranges. At this point, no systematic, regional assessment of the sense or direction of shear responsible for the mylonitization has been conducted. High strain zones that transpose gneissic banding and cross-cutting MMDS alike are documented in the Tobacco Root Mountains and must postdate the 2.06 Ga intrusion of the MMDS (Harms and others, 2004a). Prominent northeast-striking, northwest-dipping shear zones occur in the Crooked Creek, Mirror Lake, and Spanish Creek areas of the northern Madison Range and in the Gallatin Range (fig. 3) and have been interpreted as contemporaneous with, or as predating, either or both of the Beaverhead and Big Sky orogenies based on textural relationships with dated intrusive rocks (Mogk and Mueller, 1987; Mogk, 1992; Mogk and others, 1992b; Kellogg and Mogk, 2009; Johnson and others, 2014). The penetrative nature of Big Sky orogeny metamorphism and distributed shear across the region, however, suggest the potential for reactivation or displacement on these shear zones during the Big Sky orogeny and recommend reexamination of field relationships and geochronologic interpretations.

In sum, metamorphism during the Big Sky orogeny appears to have been accompanied by fabric-parallel simple shear, isoclinal folding, and displacement of rock units across the core zone of the orogen.

The Foreland

A critical step in understanding the geologic evolution of SW Montana was made when Erslev and Sutter (1990) characterized the Madison mylonite zone in the southern Madison Range (figs. 3, 9B). This broad, steeply NW-dipping zone juxtaposes quartzofeldspathic gneiss and metasedimentary rocks they called "pre-Cherry Creek" to the north, in the hanging wall, against a marble-bearing suite they correlated to the type Cherry Creek to the south (Erslev and Sutter, 1990). Lying well south of Giletti's line, rocks surrounding the Madison mylonite zone give $^{40}Ar/^{39}Ar$ cooling ages of around 2.5 Ga, whereas within the mylonite zone minerals suffered Ar loss at ~1.8 Ga (Erslev and Sutter, 1990). Erslev and Sutter (1990) interpreted the Madison mylonite zone as a south-directed, foreland ductile thrust fault associated with a compressional orogen represented by the rocks of the MMT north of Giletti's line. Subsequent models for the geologic evolution of the MMT in SW Montana have adopted this southerly vergent geometry (O'Neill, 1998; Roberts and others, 2002; Harms and others, 2004b; Sims and others, 2004; Condit and others, 2015).



SOURCES:

1 Alcock and others, 2013
2 Ault and others, 2012
3 Baldwin and others, 2014
4 Brady and others, 2004c
5 Cheney and others, 2004b
6 Condit and others, 2015
7 Cramer and others, 2013
8 Dahl and others, 2000
9 Erslev and Sutter, 1990
10 Hames and Harms, 2013
11 Harlan and others, 1996
12 Holm and Schneider, 2002
13 Jones, 2008
14 Krogh and others, 2011
15 Mueller and others, 2004
16 Mueller and others, 2005
17 Mueller and others, 2002
18 Pearson and Cheney, 2008
19 Roberts and others, 2002
20 Swanson and others, 2010
21 Vogl and others, 2004
22 Vogl, 2007

Figure 15. Geochronological synopsis and tectonic correlation of the Big Sky orogen, by range. Horizontal color bars represent ranges of ages determined for each mineral species. Zircon ages are magmatic. Monazite ages include both U-Pb and U-Th-Pb dates. Hornblende and biotite ages are $^{40}Ar/^{39}Ar$ dates and include both total fusion and plateau ages. Sources of the data are given in the figure.

Northwest-dipping shear zones (collectively known as the "Snowy shear zone") that are on strike with the Madison mylonite zone occur in the North and South Snowy Blocks of the Beartooth Mountains (fig. 3; Erslev 1992; Mogk and others, 1992a,b, 1988; Montgomery and Lytwyn, 1984; Reid and others, 1975). In the North Snowy Block, sheared rocks give a K-Ar age of ~1.78 Ga (Reid and others, 1975), whereas based on the ages of adjacent rocks, Mogk and others (1988) interpret the juxtaposition of tectonic slices to have occurred between ~2.75 and 2.55 Ga. Erslev (1992) provided kinematic evidence that shearing in the South Snowy Block included an extensional component, in contrast to the convergent Madison mylonite zone. The relationship of these shear zones to the development of the cooler, more craton-ward part of the Big Sky orogen awaits clarification.

O'Neill (1998) suggested that low-grade metasedimentary rocks in the southern Gravelly Range, described in detail by Vargo (1990), originated as foreland basin deposits preserved between ductile shear zones within the surrounding higher-grade schists and gneisses. As these rocks are undated, O'Neill's (1998) interpretation is speculative. If correct, the entrapment of these rocks would document significant thick-skinned crustal duplication north of Giletti's line. For the most part, however, the current level of exposure both north and south of Giletti's line lies well beneath that which would preserve direct evidence of a contemporaneous thin-skinned thrust belt or foreland basin to the Big Sky orogen.

The Suture Zone

The Montana Alkalic Province comprises a distinctive suite of primarily Paleocene to Eocene dikes, sills, pipes, and other intrusive and extrusive bodies derived from lithospheric mantle melt (Marvin and others, 1980); these igneous bodies carry evidence of the lithospheric mantle from which their magma was derived and of the deep continental crust through which the magma passed, in the form of radiogenic isotope compositions, xenoliths, and zircons the xenoliths contain. Numerous chronologic and geochemical analyses of these rocks provide the evidence from which the following generalizations can be drawn.

- Ancient crust and associated mantle lithosphere that can reasonably be correlated with the BBMZ of the Wyoming Province extends to the north and northeast of exposed basement in southwest Montana (fig. 9C). (1) In the Little Rocky Mountains, blocks of Precambrian gneisses that are preserved within Tertiary alkaline intrusive rocks yield magmatic zircons with crystallization ages of ~3.3 Ga and ~2.8–2.6 Ga (Gifford and others, 2018), an age spectrum very similar to peaks of crust formation in the BBMZ (Mogk, and others, 2020). (2) Distinctive radiogenic isotope ratios characteristic of the Wyoming Province (Wooden and Mueller, 1988) have been determined in Eocene alkalic rocks (O'Brien and others, 1995) and mantle xenoliths (Carlson and Irving, 1994) from the Highwood Mountains (fig. 9C).
- In the Bearpaw Mountains (fig. 9C), mantle xenoliths retain evidence of monazite and zircon growth at ~2.1 Ga (Barnhart and others, 2012; Thakurdin and others, 2019a). This can provisionally be correlated to rift-related mafic intrusions of that age (the MMDS) within exposed parts of the MMT domain and may suggest establishment or reestablishment of the northern margin of the Wyoming Province in the area of the Bearpaw Mountains at that time.
- Deep-crustal xenoliths in Eocene intrusions in the Bearpaw Mountains and Grass Range area have evidence of metamorphism and plutonism during the time of the Big Sky orogeny, preserved in ~1.8–1.7 Ga monazites (Barnhart and others, 2012) and 1.87–1.76 Ga presumably magmatic zircons (Gifford and others, 2014; Thakurdin and others, 2019a). This extends the core zone of the Big Sky orogen in the subsurface, along structural strike, well to the northeast of its exposures in southwest Montana (fig. 9B).

This evidence constrains the location of the suture between exotic crust that would have been part of the subducting plate leading into the Big Sky orogeny and the upper plate of the subduction and collision system, represented by the Wyoming Province along with its fringing arc and back-arc basin.

In so far as the deep crustal basement has contributed to the character of Mesozoic plutons that it hosts, radiogenic isotope ratios and derived model ages, as well as inherited zircon analyses, allow the fundamental crustal boundary between Archean Wyoming Province basement versus juvenile Paleoproterozoic crust and/or lithosphere to be traced to the southwest of the Montana Alkalic Province. Foster and others (2007,

2012) document the influence of this boundary on the Cretaceous Pioneer Batholith just to the southwest of the Highland Mountains (fig. 9C). Based on the Hf composition of magmatic and inherited zircon, the eastern part of this composite body incorporated material from evolved, Archean continental crust, whereas the western magmas absorbed juvenile, predominately Paleoproterozoic crust (Foster and others, 2012) and zircons in the ~1.9–1.8 Ga age range (Foster and others, 2007).

Based on the distribution of these paleogeographic constraints, the Little Belt arc and the juvenile back-arc system preserved in the Highland and Tobacco Root Mountains today must have been displaced well to the ESE from the suture at the site of subduction, tectonically overriding quartzofeldspathic basement of the northern Wyoming Province during the Big Sky orogeny.

Evolution of the Big Sky Orogen

Integrating petrologic, structural, and geochronologic data yields a detailed profile of the stages and processes involved in this Paleoproterozoic orogeny (fig. 15), and leads to the conclusion that this orogen can be understood in the same terms and with the same tectonic models that are routinely applied to Phanerozoic orogens.

- The pre-Big Sky orogeny paleogeography consisted of an arc/back-arc system above a south-dipping subduction zone, NNW (current coordinates) of an attenuated and rifted margin of the Wyoming Province (fig. 12).
- Cessation of arc volcanism after ~1.8 Ga (fig. 15) marks the start of collapse of this system, presumably due to the arrival of a crustal block at the Little Belt subduction zone—most likely the Medicine Hat Block of southern Alberta (Whitmeyer and Karlstrom, 2007).
- Collision, collapse, and southward obduction of the Little Belt arc and its back-arc basin and of continent-proximal shallow-water deposits onto the older margin of the continental Wyoming Province was driven by continued convergence between the Medicine Hat Block and the Wyoming Province, drawing the northern edge of the Wyoming Province craton to the suture zone. The climax collision of the two cratons caused shortening and thickening of previously attenuated Wyoming Province continental crust and imbricated crustal panels with obducted, juvenile supracrustal suites during the period ~1.78–1.73 Ga. This crustal-scale shortening would have produced the tectonic overburden necessary to generate the upper amphibolite to granulite facies metamorphism observed today, producing the clockwise PT path in the orogen's metamorphic core, accompanied by the development of metamorphic fabric, regional shear strain, localized high strain zones, and map-scale isoclinal and sheath folds. The peak pressures of metamorphism observed in juvenile metasupracrustal rocks, such as the Spuhler Peak metamorphic suite, indicate burial by at least 25 km of tectonic overburden, which suggests a total crustal thickness >50 km in the Big Sky orogen core zone. This burial produced conditions sufficient to generate crustal partial melt; pockets of neosome can be observed across the Big Sky orogen core zone, but most of any melt produced must have migrated away as Big Sky orogeny-age granitic bodies of any significant size are notably absent.
- Isobaric cooling took place as the core zone was thrust southward over cooler basement rocks with the development of thick-skinned ductile thrust faults such as the Madison mylonite zone.
- Immediately following crustal thickening, and perhaps triggered by overthickening and facilitated by the development of crustal melt, extension and tectonic exhumation of the metamorphic core zone occurred, recorded as isothermal decompression over the period ~1.73–1.71 Ga. The surfaces on which extension may have occurred have yet to be identified.

Post-Big Sky Orogeny Cooling and Thermal Relaxation

Following Giletti (1966), both K-Ar and $^{40}Ar/^{39}Ar$ geochronology have been widely applied to assess the lower temperature thermal history of the Wyoming Province in Montana. Brady and others (2004c) provided a regional review of those data, which we synopsize here in figure 15. The prevailing characteristic of $^{40}Ar/^{39}Ar$ ages from the MMT north of Giletti's line is the broad range of cooling ages preserved. Older ages overlap with the period of metamorphism as documented by monazite growth in each range, yet the youngest $^{40}Ar/^{39}Ar$ ages are as much as 100 million years younger than the youngest monazite ages from the same area. We suggest that this reflects a prolonged period of stability and residence in the middle crust, within the thermal range for Ar diffusion, as a consequence of post-orogenic quiescence and slow erosive exhumation. Following Hames and Harms (2013), we suggest that the spread of younger ages results from Ar diffusion across grains of variable dimensions rather than resetting by multiple thermal events. This period of stability persisted until the early stages of extension and dike intrusion associated with the genesis of the Belt Basin.

EVIDENCE FOR THE PROTEROZOIC GEOLOGY OF BURIED CRYSTALLINE BASEMENT STATEWIDE

Montana's extensive cover of Phanerozoic sedimentary rock in the plains, the Mesoproterozoic to Neoproterozoic Belt Basin in the northwest (fig. 2), and the widespread Mesozoic to Cenozoic plutonic and extrusive overprints in the southwest leave most of the State's Precambrian crystalline basement and the geologic history it contains occluded from direct observation. How much of the State is underlain by the Wyoming Province as defined by its ancient Archean components and distinctive isotopic signature? What is the distribution of late Paleoproterozoic juvenile crust and how spatially extensive were the effects of the Big Sky orogeny? How does that orogen relate to other mobile belts surrounding the Wyoming Province? Potential field anomaly patterns, seismic profiles, xenoliths, inherited zircons, and drill cores have all been employed to scope the broad contours of the State's basement in order to address questions such as these. From these studies, the subsurface building blocks of Montana's basement prove to be the Wyoming Province and the Medicine Hat Block cratons, along with the surrounding Trans-Hudson/Dakotan orogen, the Big Sky orogen and its suture zone as represented by the Great Falls tectonic zone, and the Selway terrane (fig. 2), all three of which appear to have had a significant Paleoproterozoic history.

The distribution of the Wyoming Province in the subsurface of southwestern, southern, and eastern Montana may be outlined on the basis of broad magnetic anomalies associated with granitic versus gneissic basement (Sims and others, 2001, 2004) and by its exceptionally thick crust (~50 km) and lithosphere, as determined by both active and passive source, 2D and 3D seismic analyses, and magnetotelluric data (Gorman and others, 2002; Yu and others, 2018; Meqbel and others, 2014). Xenoliths in the Montana Alkalic Province provide evidence of Wyoming Province crust and lithosphere beneath the Highwood, Bearpaw, Little Rocky, and Crazy Mountains (fig. 9C). The isotopic composition of zircon in the Mesozoic Pioneer Batholith (Foster and others, 2006, 2012) constrains the northern limit of the Wyoming Province in the southwest part of the State. Similarly, along trend in neighboring Idaho, Sm-Nd and Pb isotopes define a boundary across the Idaho Batholith that divides Archean basement to the southeast from juvenile Proterozoic basement to the northwest (Fleck and Wooden, 1997; Fleck and Gunn, 1991; Leeman and others, 1991; Toth and Stacey, 1992). Inherited zircons within the northwestern batholith are largely limited in age to 1.82–1.75 Ga (Mueller and others, 1995; Foster and Fanning, 1997) and represent the presence of Big Sky orogeny-age juvenile crust at depth.

To the north of the Big Sky orogen suture zone, in southern Alberta and adjacent north-central Montana, basement rocks are assigned to the Medicine Hat Block (figs. 2, 9C; Ross, 2002). The Medicine Hat Block is known only through rocks recovered from deep drillholes in Canada, where zircon ages suggest meta-plutonic events in the age range 2.6–2.7 Ga and at 3.3 Ga (Villeneuve and others, 1993; Ross, 2002). Whether or not that history applies to the Montana part of the Medicine Hat Block is unknown. The overlap of Medicine Hat Block zircon ages with known times of tectonism in the Wyoming Province has promoted some interpretations of the Medicine Hat Block as a northward extension of the Wyoming Province, such that the Big Sky Orogen would not mark a true suture zone (Boerner and others, 1998; Buhlmann and others, 2000; Lemieux and others, 2000). A north–south-trending deep seismic refraction profile ("Deep Probe") revealed the presence of a ~25-km-thick, high-seismic velocity layer in the lower crust beneath most of the Wyoming Province (the "LCL," in some cases referred to as the "7.X layer"), and extending into southern Alberta beneath the Medicine Hat Block (Gorman and others, 2002). The LCL both shallows (Gorman and others, 2002) and changes its velocity (Snelson and others, 1998) beneath the Great Falls tectonic zone, however, which suggests to Chamberlain and others (2003) that there are two genetically unrelated lower crustal bodies juxtaposed across the suture of the Big Sky orogen. These observations could be reconciled if the Medicine Hat Block is a fragment of the Wyoming Province that was rifted away at 2.06 Ga and then returned to the Wyoming Province by collision at the time of the Big Sky orogeny. The LCL has been attributed to mafic underplating, either associated with rifting at ~2.1 Ga (Barnhart and others, 2012) or with subduction and collision at ~1.8–1.7 Ga (Gorman and others, 2002). Alternatively, the LCL has been interpreted as an Archean feature (Snelson and others, 1998; Gilbert, 2012; Chamberlain and Mueller, 2019). There is evidence, however, that Laramide and younger tectonics have both been influenced by basement structures (Chamberlain and others, 2003; Foster and others, 2006; Gilbert, 2012; Worthington and others, 2016) and have significantly modified the crust and lithospheric thicknesses of the Wyoming Province (Humphreys and others, 2015; Dave and Li, 2016). We should entertain multiple hypotheses when seeking to associate deep structures like the LCL with surface geology.

The Trans-Hudson orogen defines the western boundary of the Archean Superior Province in Canada and marks the ~1.85–1.78 Ga collision zone between the nucleus of the Laurentian continent and smaller Archean cratons to the west (Hoffman, 1988; Whitmeyer and Karlstrom, 2007; Corrigan and others, 2009). Strong, linear, potential field anomaly patterns have been used to define the lateral continuity of the Trans-Hudson orogen, which stretches from the shores of Hudson's Bay in Canada—where it is exposed at the surface—to the central plains in the U.S. (Thomas and others, 1987; Villeneuve and others, 1993). Whether or not the amalgamation of the Superior and Wyoming Provinces across the Trans-Hudson orogen beneath northeastern-most Montana was synchronous with collisions farther north in Canada is a matter of some debate (Dahl and others, 1999; Mueller and others, 2005; Killan and others, 2016). The Big Sky orogen in the basement beneath the Great Falls tectonic zone is less clearly expressed by potential field anomalies, but NE-trending anomalies appear to truncate against or to merge with those in the Trans-Hudson orogen in the eastern part of the State (Thomas and others, 1987; Lemieux and others, 2000; Sims and others, 2004), suggesting that the Trans-Hudson orogen in Montana postdates the Big Sky orogeny despite the pre-Big Sky orogeny age of the Trans-Hudson orogen in Canada. A COCORP reflection profile across northeastern-most Montana and western North Dakota imaged east-dipping reflectors between the Trans-Hudson orogen and Superior Province, whereas surface geology in Canada indicates a west-dipping boundary (Nelson and others, 1993). These discrepancies led Chamberlain and others (2002) to propose that a distinct "Dakotan" orogen lies to the east of the Wyoming Province. On the basis of (1) shallowing of the Moho; (2) absence of the LCL; (3) presence of a west-dipping reflector; (4) modeled gravity profiles; and (5) a change in orientation of linear magnetic anomalies, Worthington and others (2016) propose that the eastern margin of the Wyoming Province lies just east of the Bighorn Mountains in Wyoming. This separates the basement rocks of the Black Hills in South Dakota from the Wyoming Province, as a crustal fragment enclosed within a wide Paleoproterozoic Dakotan orogen (fig. 2).

A broad domain underlain by Paleoproterozoic crust and lithosphere—the Selway terrane of Foster and others (2006; fig. 2)—lies to the west and southwest of exposed Precambrian basement in the Laramide ranges of southwest Montana. This domain underlies the Belt Basin, the Montana thrust belt, and the Idaho–Bitterroot, Boulder, and Pioneer Batholiths (Foster and others, 2006). Both whole-rock and zircon isotope analyses conducted on Mesozoic and Cenozoic plutons to the WNW of the trend of the Little Belt arc indicate no involvement of mantle or crust older than ~2.45 Ga, and the most significant contribution to have been from crust of ~1.8–1.7 Ga age (Mueller and others, 1995; Foster and others, 2012). Inherited zircon cores, where spot-dated, and upper intercept ages when whole zircons were analyzed, consistently give ~1.7 ages (Bickford and others, 1981; Toth and Stacey, 1992; Foster and Fanning, 1997). The Selway terrane basement represents a significant area of juvenile Paleoproterozoic lithosphere that was tectonically active during the time of the Big Sky orogeny, suggesting that the northern Wyoming Province and Big Sky orogen lay at the southern edge of a broad, Paleoproterozoic accretionary domain, comparable in size and character to large Phanerozoic orogenic systems such as the North American Cordillera, in which there may have been multiple subduction zones and arcs in operation simultaneously (Harms and others, 2004b).

The antiquity and Paleoproterozoic stability of the BBMZ part of the Wyoming Province contrasts sharply with the tectonically active Paleoproterozoic character of the MMT and the domains surrounding the Wyoming Province in Montana—the Trans-Hudson/Dakotan orogen, Big Sky orogen, and the Selway terrane. Paleoproterozoic orogenies accomplished the consolidation of Montana's basement and exerted a controlling influence on the controlling influence on the post-Paleoproterozoic geologic evolution of the State (Foster and others, 2006; O'Neill and Lopez, 1985).

SUMMARY

Late Mesozoic to early Cenozoic Laramide block uplifts in southwestern Montana provide a window into the Precambrian basement of Montana through which we can reconstruct the growth and stabilization of the North American continent, a process that occurred by the collision and amalgamation of smaller Archean cratons, including the Wyoming Province, across Paleoproterozoic orogenic belts during a singular, remarkable phase of Earth history.

The northern margin of the Wyoming Province was the site of repeated Paleoproterozoic tectonism that resulted in additions to, possible removal of, and ultimate cratonization of that proto-continental margin. Earliest Paleoproterozoic time saw tectonothermal events, the Beaverhead and/or Tendoy orogenies at ~2.45 and ~2.55 Ga that probably resulted in growth of the northwest flank of the Archean Wyoming Province. A period of extension, failed rifting, or rifting at 2.06 Ga modified that collisional domain and reestablished it as a continental margin. By ~1.87 Ga, southward subduction below the Wyoming Province had begun along the Little Belt arc, opening a fringing back-arc basin along the flank of the Wyoming Province. Spuhler Peak ocean crust formed in that basin, and mudstones with basalt flows now in the Highland Mountains accumulated within it. The process of back-arc rifting produced shallow-water continental margin sedimentary rocks interrupted by mafic flows on the continental edge of the Wyoming Province, represented by the upper Christensen Ranch metamorphic suite in the Ruby Range. Probable collision of the Medicine Hat Block drove the collapse of this active plate-boundary system and its displacement across the Wyoming Province continental margin, folding and tectonically stacking that crust to thicknesses of 50 km or more, and causing the deformation and metamorphism that defines the ~1.78–1.72 Big Sky orogeny (Cheney and others, 2004a,b; Brady and others, 2004a; Harms and others, 2004b).

The Big Sky orogen is one of several nearly contemporaneous orogenic belts responsible for the final consolidation of Archean cratons into the stable core of what is North America today (Hoffman, 1988). All younger accretionary margins and collisional orogens have rimmed this stable core but have not significantly modified it (Whitmeyer and Karlstrom, 2007). The period from ~1.8 to 1.6 Ga seems to mark a fundamental transition in continental evolution. Nevertheless, the Big Sky orogen can be understood in the same framework as many Phanerozoic orogenic belts. Rocks in the ranges north of Giletti's line represent the metamorphic core zone of this orogen, experiencing significant burial and thickening by ductile shear and map-scale sheath and isoclinal folding (Harms and others, 2004a). This produced upper amphibolite to granulite facies metamorphism that proceeded along a clockwise PT path—punctuated by a period of isobaric cooling (Cheney and others, 2004a) as the core zone was displaced over an older and colder Wyoming Province foreland domain along discrete shear zones such as the Madison mylonite zone (Erslev and Sutter, 1990). The core zone then experienced isothermal decompression (Cheney and others, 2004a) as peak temperatures produced crustal melt, facilitating extensional collapse and unroofing of the overthickened core zone (Harms and others, 2004b).

The Big Sky orogen lies at the southeast margin of a broader, contemporaneous accretionary zone stretching into Idaho and eastern Washington (Foster and others, 2006). Paleoproterozoic collision along the Big Sky orogen and within this larger orogenic domain ultimately enclosed the Wyoming Province into the ancestral core of the North American continent.

ACKNOWLEDGMENTS

We are grateful to have had a decades-long collaboration with John Brady, Bob Burger, and Jack Cheney; our work would not have been started or sustained without them. Mike O'Neill, Dave Mogk, Paul Mueller, Jeff Vervoort, and Jim Vogl have been generous with their knowledge and experience; they have helped shape our ideas but should not be held responsible for how those ideas developed. John Brady and Kevin Chamberlain reviewed and improved this contribution; we thank them for their efforts.

This synthesis draws from the research work of nearly 100 undergraduate student-scholars at Amherst and Smith Colleges and across the Keck Geology

Consortium—too numerous to name but each remembered and appreciated. Over the years, funding has been provided by the Trustees of Amherst and Smith Colleges, the Keck Geology Consortium, the University of Montana, the National Science Foundation, and the U.S. Geological Survey EDMAP program. Finally, we are grateful to the citizens of southwest Montana who have generously allowed us to poke around their land for many field seasons.

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