THE ARCHEAN GEOLOGY OF MONTANA

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ABSTRACT

The Archean rocks in the northern Wyoming Province of Montana provide fundamental evidence related to the evolution of the early Earth. This extensive record provides insight into some of the major, unanswered questions of Earth history and Earth-system processes: Crustal genesis—when and how did the continental crust separate from the mantle? Crustal evolution—to what extent are Earth materials cycled from mantle to crust and back again? Continental growth—how do continents grow, vertically through magmatic accretion of plutons and volcanic rocks, laterally through tectonic accretion of crustal blocks assembled at continental margins, or both? Structural reactivation—to what extent are ancient structures and fabrics of rocks reactivated to produce modern structures? Metallogenesis—are these ancient rocks potential sources or hosts for mineral deposits that occur across Montana? Uniformitarianism—did contemporary-style plate tectonics operate throughout all of geologic time back to the Archean–Hadean? Or are there variants to the model, e.g., plate tectonics vs. “flake” tectonics, subduction vs. sagduction, the role of plumes (i.e., “static lid” model) vs. plates (“mobile lid” model)? The answers to many of these questions can be garnered from the ~1.5 b.y. geologic record preserved in the Archean rocks of Montana.

The earliest history, documented in detrital zircons from quartzites, suggests that at 4.0 to 3.5 Ga (Ga, giga-annum; a billion years) crustal growth was dominated by plume-related tectonic processes that generated magmas derived from an early, depleting mantle and early mafic crust. Meta-igneous rocks, dominantly of the tonalite–trondhjemite–granodiorite (TTG suite) that crystallized at 3.5–3.1 Ga, occur in the Beartooth, Madison, Tobacco Root and Ruby Ranges, and represent the first major stage of formation of felsic continental crust produced by the onset of global plate tectonics in the contemporary sense, with magmagenesis in a subduction tectonic setting. Jackson (2005) characterized cratons as areas of thick, stable continental crust that have experienced little deformation over long (Ga) periods of time. In the Wyoming Province, the process of cratonization included the establishment of a thick tectosphere (subcontinental mantle lithosphere). The thick, stable crust–lithosphere system permitted deposition of mature, passive-margin-type sediments immediately prior to and during a period of tectonic quiescence from 3.1 to 2.9 Ga. These compositionally mature sediments, together with subordinate mafic rocks that could have been basaltic flows, characterize this period. A second major magmatic event generated the Beartooth–Bighorn magmatic zone at ~2.9–2.8 Ga. This event generated a voluminous (>106 km^3) TTG suite with subordinate calc-alkaline granitic rocks and high-Mg diorites that have strong affinities with modern-day magmatism in continental and oceanic arc settings.

The infrastructure on which this Mesoarchean continental arc developed is partially preserved in the eastern Beartooth Mountains. Supracrustal lithologies developed prior to 2.8 Ga were tectonically mixed with the older gneisses and the new TTG magmas in the mid-crust and subjected to upper-amphibolite to granulite facies metamorphism during the 2.8 Ga event. Tectonic thickening, including emplacement of an Alpine-style nappe, also occurred in the Neoarchean in the North Snowy Block.

The lowest grade Archean rocks are preserved in a sequence of metasedimentary rocks in the Jardine area of the South Snowy Block. These rocks were tectonically emplaced against the Beartooth Block prior to intrusion of 2.8 Ga epizonal granitic rocks. Less than 100 m.y. later, the Stillwater Complex (2.709 Ga) was intruded and possibly tectonically juxtaposed against the Beartooth Block. The contact aureole of the Stillwater Complex also has preserved sedimentary structures (Page, 1977), but detrital zircon populations demonstrate that these two metasedimentary sequences are unrelated. To the west, a third assemblage of low-grade metasedimentary rocks with preserved sedimentary structures (e.g., cross-beds in quartzites; Erslev, 1988), assigned to the Cherry Creek Metamorphic Suite (e.g., Peale, 1896; Heinrich and Rabbitt, 1960), occur in the southern Gravelly Range (although kyanite- and sillimanite-bearing schists occur in the northern part of the range). The depositional age of these rocks is interpreted to be 2.7 Ga based on U-Pb zircon ages of detrital zircons in quartzites and magmatic zircon ages in metadacitic interlayers. Other Late Archean rocks in the western Wyoming Province include sequences of quartzofeldspathic gneisses and associated metasupracrustal rocks also of ~2.7 Ga age that formed and are exposed in the southern Madison Range, Gravelly Range, Blacktail Range, and in the core of the Armstead anticline. A period of partial melting and deformation at ~2.55 Ga produced anatexis and emplacement of leucogranitic rocks in the Gallatin Canyon and Tobacco Root Mountains, and marked the last stage of tectonism in the North Snowy Block. On the western margin of the Wyoming Province, a high-grade metamorphic event at ~2.45 Ga overprinted the Archean crystalline rocks in the Ruby and Tobacco Root Mountains, and the Paleoproterozoic Great Falls Orogeny imparted a strong metamorphic and deformational overprint at ~1.79–1.83 Ga. Taken together, the Archean and earliest Paleoproterozoic basement of the northern Wyoming Province provide one of the best documented records of crustal genesis and episodic crustal evolution in the world.

INTRODUCTION

Many global models for the evolution of continents and continental crust suggest that the Archean Eon was the time when much, if not most, of the crust of the modern continents formed (Fyfe, 1978; Armstrong, 1981; McLellan and Taylor, 1982; Condie, 1986; Taylor and McLellan, 1995; Mueller and Nutman, 2017). A window into this time of earliest crust production and continent formation exists in Montana. Some of the oldest rocks in the world, dating back to 3.6 Ga (billion years ago) with zircons as old as 4.0 Ga, are exposed in the crystalline cores of mountain ranges of south-central Montana (Chamberlain and Mueller, 2018). These exposures are part of the Wyoming Province of Montana and Wyoming defined by Condie (1976), which formed the core of "nuclear North America." This crust–mantle system was cratonized by the end of the Archean, as evidenced by the interior of the province not being subjected to extensive penetrative deformation, metamorphism, or magmatism since that time. The modern Wyoming Province can be subdivided into three subprovinces: the Beartooth–Bighorn magmatic zone (BBMZ), the Montana metasedimentary terrane (MMT), and the southern accreted terranes (SAT; Mogk and others, 1992a; Chamberlain and others, 2003; Mueller and Frost, 2006). Overall, the Wyoming Province is host to "high-grade gneiss belts" (Windley, 1976; Windley and Smith, 1976), although metasedimentary rocks of lower metamorphic grade (greenschist facies) are locally present in the Jardine area of the South Snowy Block, in the Gravelly Range, and in the metasediments adjacent to the Stillwater Complex prior to formation of the contact aureole. Rock suites associated with greenstone belts (low-grade metaigneous and metasedimentary rocks) are scarce in the Montana part of the Wyoming Province and are only preserved in the Southern Accreted Terranes of Wyoming (Chamberlain and others, 2003; Frost and others, 2006a; Mueller and Frost, 2006) and remnants in the Wind River Canyon of the Owl Creek Mountains, Wyoming (Mueller and others, 1985).

The Archean rocks of the Wyoming Province are surrounded by Paleoproterozoic collisional orogens: the Great Falls Tectonic Zone on the north (O'Neill and Lopez, 1985; O'Neill and Berg, 1995), the Cheyenne Belt on the south (Karlstrom and Houston, 1984), and the Trans-Hudson orogen on the east (Klasner and King, 1986; Lewry and Stauffer, 1990; Baird and others, 1996). Relationships along the western margin are more complex and include: Archean crustal xenoliths of granulite facies metamorphic grade that represent the deep crust below the Snake River Plain (Leeman and others, 1985), the 2.45–2.55 Ga Farmington zone along the southwestern margin (Mueller and others, 2011), in the Tendoy Range (Mueller and others, 2016), and possibly some 2.7 Ga crust in the Grouse Creek Block (Foster and others, 2006; fig. 1). Along the southeastern margin, Worthington and others (2016) have proposed that the edge of the Archean Wyoming craton lies just east of the Big Horn Mountains, approximately 300 km west of previous interpretations. However, this interpretation conflicts with evidence of Archean basement in the eastern

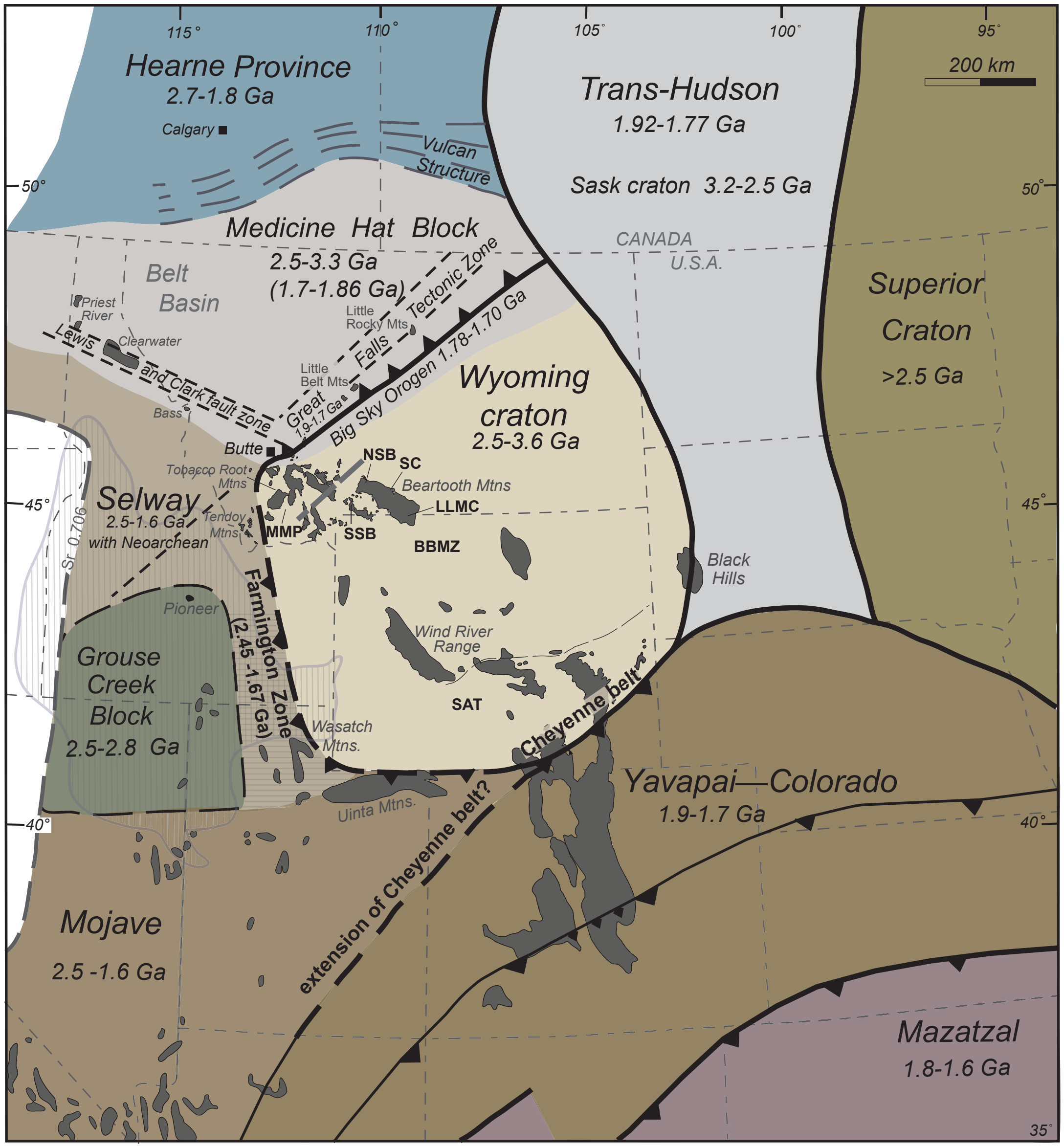

Figure 1. Tectonic index map of the Archean Wyoming Province (central light brown area; dark areas are exposures of Archean crystalline rocks). The Wyoming Province is surrounded by Paleoproterozic orogenic belts including the Great Falls Tectonic Zone to the northwest, the Farmington Zone to the west, the Cheyenne Belt to the southeast, and the Trans-Hudson Orogen to the east. NSB, North Snowy Block; SSB, South Snowy Block; BBMZ, Beartooth–Bighorn Magmatic Zone; MMT, Montana Metasedimentary Terrane; SAT, Southern Accreted Terrane; SC, Stillwater Complex; LLMC, Long Lake Magmatic Complex.

Wyoming craton including drillcore data (Peterman, 1981), Archean crustal xenoliths from the Montana Alkalic Province (Hearn and others, 1991; Barnhart and others, 2012; Mahan and others, 2012), and exposures of Archean rocks in the Black Hills (McCombs and others, 2004; Nabelek and others, 2006; Hrncir and others, 2017). These Paleoproterozoic orogens were mobilized during the amalgamation of the Wyoming Province, Medicine Hat Block, Hearne Province, and Superior Province to form the supercontinent Laurentia (Mueller and others, 2005; Foster and others, 2006). The extent and orientation of these Paleoproterozoic terranes are evident in aeromagnetic anomaly maps of the Precambrian basement of Montana (Sims and others, 2004). Subsequent to amalgamation of these terranes with the Superior Province to form Laurentia, much of the original Archean (including remobilized Archean) and Paleoproterozoic rocks (MMT) of the northwestern Wyoming Province were partially covered by the Mesoproterozoic Belt Basin and the entire Wyoming craton was blanketed by strata of the widespread Phanerozoic western miogeocline.

The Archean rocks of the northern Wyoming Province (NWP) exposed in Montana are distinctive in terms of: (1) their great antiquity; rocks as old as 3.6 Ga are exposed at the surface, detrital zircons have been analyzed with ages as old as 4.0 Ga, and some Sm-Nd model ages (time that an individual rock was extracted from the mantle) exceed 4.0 Ga; (2) unusually enriched $^{207}Pb/^{204}Pb$ signatures of magmatic rocks throughout the province indicate an origin from a source that was anomalously enriched (i.e., high U/Pb ratio) compared to the sources of crust in the adjacent Superior Province (Wooden and Mueller, 1988; Mueller and Wooden, 1988) and may have been part of an early "supercontinent" referred to as Itsaqia (Nutman and others, 2015); and (3) the crust of the northern Wyoming Province is underlain by a thick (up to 25 km) mafic lower crust that is unique among Archean cratons (Barnhart and others, 2012; Clowes and others, 2002; Gorman and others, 2002; Mahan and others, 2012; Snelson and others, 1998). This Archean crust is exposed through "deep-seated" Laramide faults (Late Cretaceous through early Tertiary; see Lageson and others, 2023) in the Beartooth, Bridger, Gallatin, Madison, Tobacco Root, Ruby, Blacktail, Highland, and Gravelly Ranges. These uplifts commonly provide spectacular exposures in three dimensions and often in high Alpine settings (fig. 2). Unfortunately, lateral continuity is lost among ranges because of Proterozoic and Phanerozoic cover rocks, making it difficult to correlate rock units across these ranges. Examples of deep-seated, ancient (>3.0 Ga) crystalline rocks are also found in numerous crustal xenolith locations in Cretaceous through Eocene volcanic rocks distributed across the Montana Alkalic Province (Barnhart and others, 2012; Gifford and others, 2014; Hearn and others, 1991; Mahan and others, 2012) and zircon xenocrysts in Cretaceous plutons (Foster and others, 2006; Gaschnig and others, 2013; Mueller and others, 1996a). Although there are significant differences in the lithologic assemblages, metamorphic and deformational histories, and isotopic ages of Archean crust exposed in the numerous ranges and sampled by xenoliths in Montana (Mogk and others, 1992a,b), these crustal components all contain ~2.7–2.8 Ga crust that exhibit these similar, highly radiogenic Pb isotopic compositions, indicating derivation from, or interaction with, an older, globally rare, high U/Pb reservoir (Wooden and Mueller, 1988; Mueller and Frost, 2006; Chamberlain and Mueller, 2018). Consequently, the Archean rocks of the BBMZ and MMT should not be considered allochthonous or exotic terranes. Although the interior of the craton has largely been unaffected by Paleoproterozoic events, the Archean rocks exposed along the margins of the craton have been partially, and in some cases extensively, reworked by Paleoproterozoic orogenic events involving tectonic convergence, collision, and/or accretion of exotic terranes (see Harms and Baldwin, 2020).

Figure 2. Archean basement rocks exposed along the Beartooth Highway. View to the northwest across the upper valley of Rock Creek with the "Bear's Tooth" just visible on the distant skyline. Photo credit: David Mogk.

This contribution provides an overview of the long history of crustal evolution preserved in the Archean basement of Montana, presented in episodic stages of crustal evolution: (1) Early Archean (4.0–3.6 Ga) formation of earliest crust; (2) 3.6–3.2 Ga massive crust-forming event(s), which are recorded in the mostly plutonic rocks of the tonalite–trondhjemite–granodiorite (TTG) suite; (3) 3.2–2.8 Ga deposition and metamorphism of stable platform type supracrustal rocks in the MMT and eastern Beartooth Mountains; (4) ~2.8 Ga sodic-series magmatism in the BBMZ; (5) post-orogenic intrusion of the Stillwater Complex (~2.7 Ga); (6) 2.8–2.55 Ga tectonic juxtaposition of numerous units (e.g., North Snowy Block, South Snowy Block–Jardine), and (7) final magmatic growth (~2.7 Ga) and remobilization of older crust via anatexis and high-grade metamorphism along the western margin of the Wyoming Province ending ~2.55–2.45 Ga. In addition, the MMT in much of the northwestern part of the Wyoming Province has been overprinted by a major Paleoproterozoic tectonothermal event (Harms and others, 2004a,b; Mueller and others, 2004a, 2005) that has extensively reworked this Archean basement metamorphically and structurally in some locales (Cheney and others, 2004b; Harms and others, 2004; Roberts and others, 2002) and obscured much of the Archean geologic history of those areas. This chapter reviews the origins and evolution of this crust through the span of Archean time; the next chapters continue an overview of the Precambrian geology of Montana in reviews of the Paleoproterozoic history of this area (Harms and Baldwin, 2020), and formation of the Mesoproterozoic Belt Basin (Lonn and others, 2020).

Given the antiquity of these rocks, and the potential for numerous generations of magmatism, metamorphism, penetrative deformation, and provenance(s) of clastic sedimentary rocks, a geochronologic framework is essential to identify different crustal components and their role in the evolution of Archean continental crust. For this reason, this chapter is structured to address the timeline of major crust-forming and crust-modifying events in the Archean (table 1). Field, structural, petrologic, whole-rock elemental and isotopic geochemical, and geophysical analyses must also be integrated to determine the genesis and subsequent evolution of this ancient continental crust.

IN THE BEGINNING THERE WERE ZIRCONS (EARLIEST CRUST FORMATION, HADEAN TO EOARCHEAN, 4.0–3.5 GA)

The oldest evidence for Hadean and Eoarchean crust is preserved in detrital zircons in quartzites sampled across the northern Wyoming Province, including the Beartooth, Tobacco Root, and Ruby Ranges and spanning the BBMT and MMT (figs. 3, 4; Mueller and others, 1998). The U-Pb ages of these detrital zircons exceed the ages of the oldest rocks (3.5–3.6 Ga), with the oldest recording ages of 4.0 Ga, with minor concentrations of ages at 3.9, 3.7, and 3.5 Ga. Although the >3.5 Ga zircons are found throughout the NWP, they are dwarfed by the numbers of zircons produced during the major crust-forming event at 3.3–3.2 Ga (fig. 5; Mueller and others, 1998). In addition to the geochronologic data, Lu-Hf isotopic data from the oldest detrital zircons indicate that the earliest magmas were derived from an early, marginally depleted to undepleted mantle (fig. 6; Mueller and Wooden, 2012). The crust in which these oldest zircons originated has been interpreted as the result of plume-dominated crustal genesis (Bédard, 2006; Mueller and others, 2014b; Mueller and Wooden, 2012), perhaps similar to the plume-generated magmas at Tharsis on Mars (Reese and others, 2004). Although the source rocks and provenance of these oldest zircons have not been identified at the surface, they most likely were the result of episodic additions of Hadean to Eoarchean mafic proto-continental magmas. In this scenario, the original crust in this area formed by melting of primitive mantle under anhydrous conditions to yield mafic rocks with high U/Pb ratios that were rapidly recycled to produce more felsic magmas (e.g., TTG), probably associated with a zone of mantle upwelling or diapirism (similar to the modern Ontong–Java Plateau). These data also support the interpretation that there was extensive internal (closed system) melting and recycling of this crust and mantle lithosphere up to about 3.5 Ga, perhaps through melting of the lower parts of this proto-crust (including lithosphere) through processes referred to as “sagduction,” drip tectonics, or “crust–mantle overturn” (François and others, 2014) or simply radiogenic heat production, which was ~6x modern values in the Eoarchean (Brown, 2014). These data suggest that subduction-related magmatism did not play a significant role in crustal evolution in this region during the period 3.5–4.0 Ga.

Table 1. Chronologic framework of major Archean rock-forming and tectonic events.

Time Interval	Montana Metasedimentary Province	Beartooth–Bighorn Magmatic Zone
2.45 Ga	Granulite facies metamorphism, Tobacco Root and Ruby Ranges	
2.55 Ga	Leucogranites, Gallatin Canyon, Tobacco Root Mountains	Leucogranite North Snowy Block
2.6 Ga	Granodiorite, southern Madison Range; Teton and Wind River Ranges	
2.7 Ga	2.7 Ga gneiss Gravelly Range, Tendoy Mountains, Blacktail Range; deposition of Cherry Creek suite, Gravelly Range <2.7 Ga	2.709 Ga magmatic emplacement of Stillwater Complex
2.8-2.9 Ga		Calc–alkaline, continental arc magmatism in the Beartooth and Big Horn Mountains Psammitic to pelitic schists, orthoquartzites, BIFs; tectonically interleaved with older quartzofeldspathic gneisses;
3.2-2.8 Ga	Cratonization; stable platform sediments (marble, pelitic schists, orthoquartzites, BIFs), Tobacco Root and Ruby Ranges	Deposition of Jardine metasedimentary rocks >2.9 Ga, and protolith of Stillwater aureole rocks >2.7 Ga
3.5-3.2Ga	TTG gneisses in Madison, Tobacco Root, Bridger, Highland, and Ruby Ranges	TTG gneisses in enclaves in the Beartooth Mountains, tectonic slices in the North Snowy Block and Jardine areas
4.0-3.5 Ga	Detrital zircons preserved in quartzites as old as 4.0 Ga, but defining a continuum down to 3.5 Ga with small concentrations at 3.5, 3.7, and 3.9	

Note. BIFs, banded iron formations.

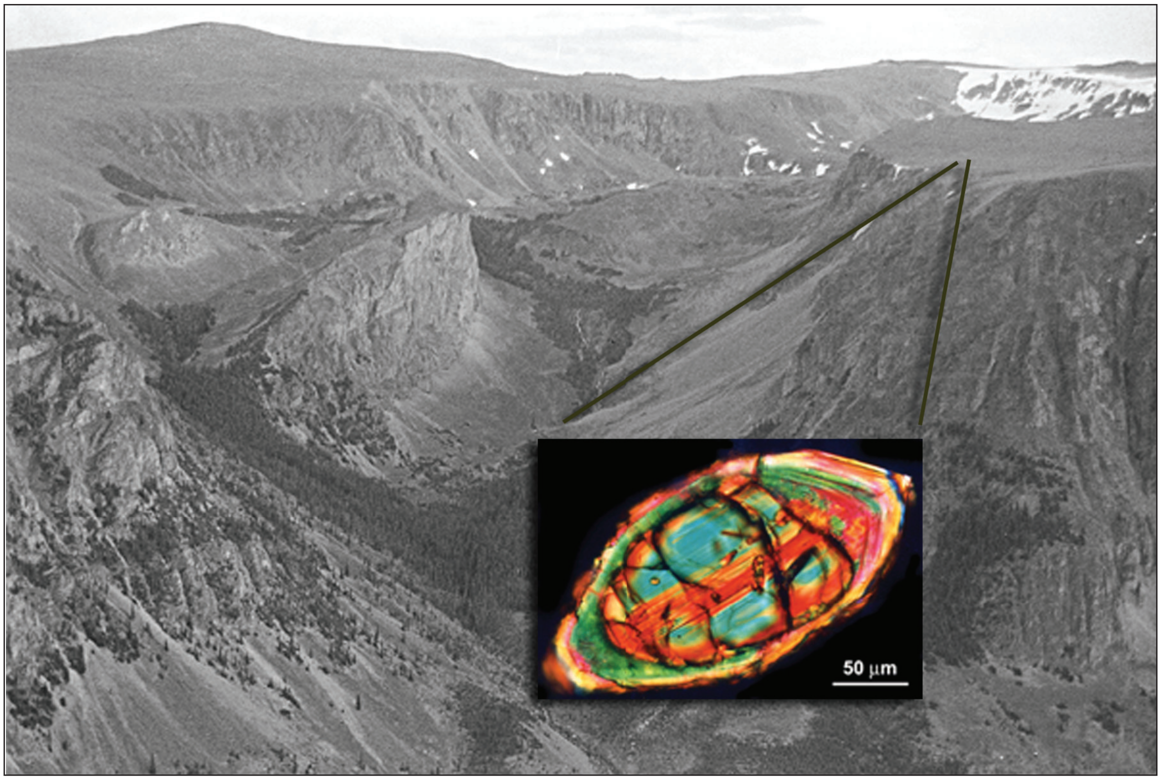

Figure 3. Detrital zircons provide a window into the Archean history of the continental crust. Zircons are recovered from quartzites, and imaging reveals rounded detrital cores and igneous or metamorphic overgrowths. Ages are determined by spot analyses of U-Pb isotope systematics using modern analytical methods such as secondary ion mass spectrometry or laser ablation inductively coupled mass spectrometry. Inset is a photomicrograph of a separated zircon grain with rounded detrital core and igneous or metamorphic overprint. Photo credit: Darrell Henry.

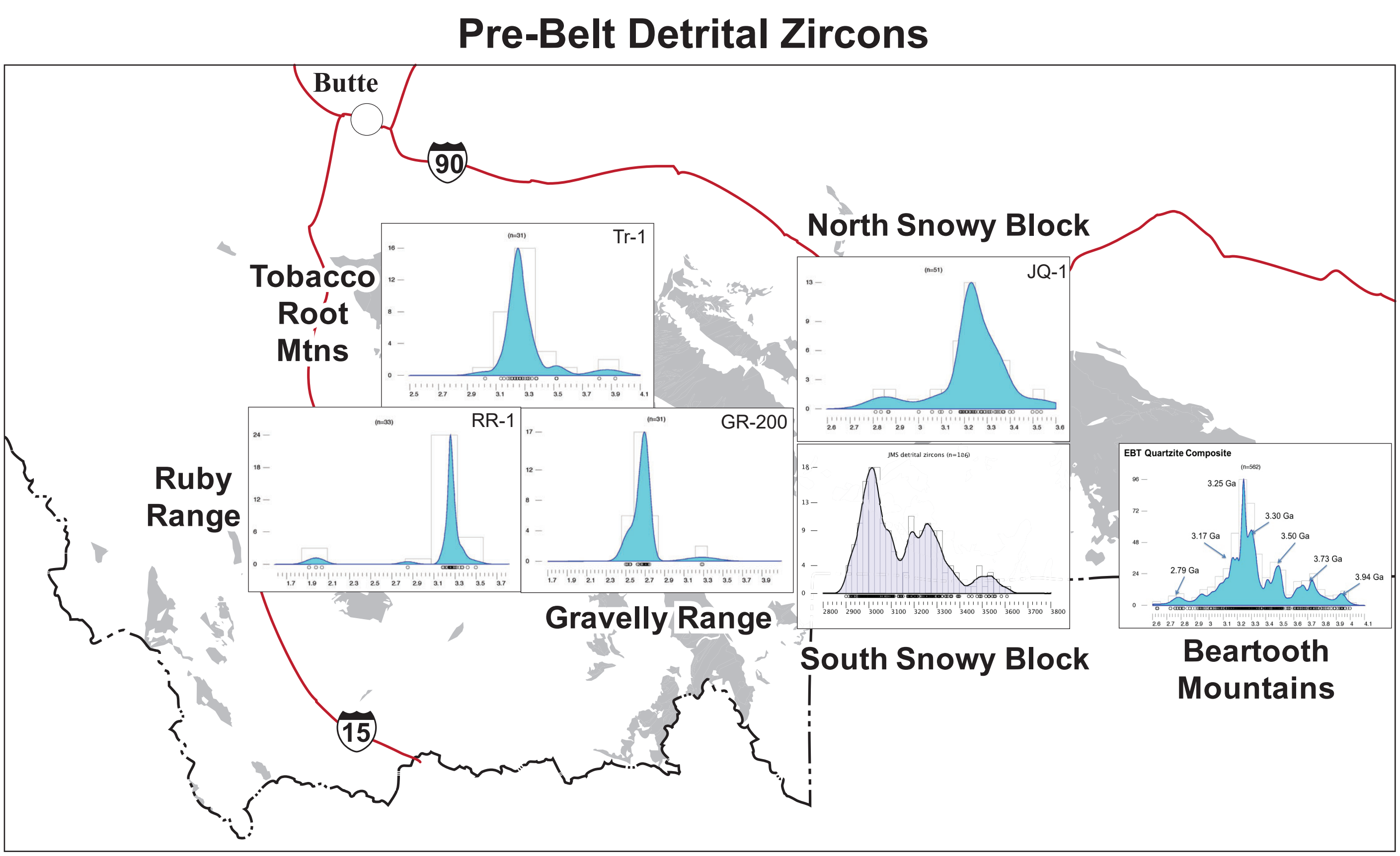

Figure 4. Distribution of detrital zircons from quartzites and their age spectra from Archean exposures from across southwest Montana using the kernel density estimator (KDE) algorithm of Vermeesch (2012).

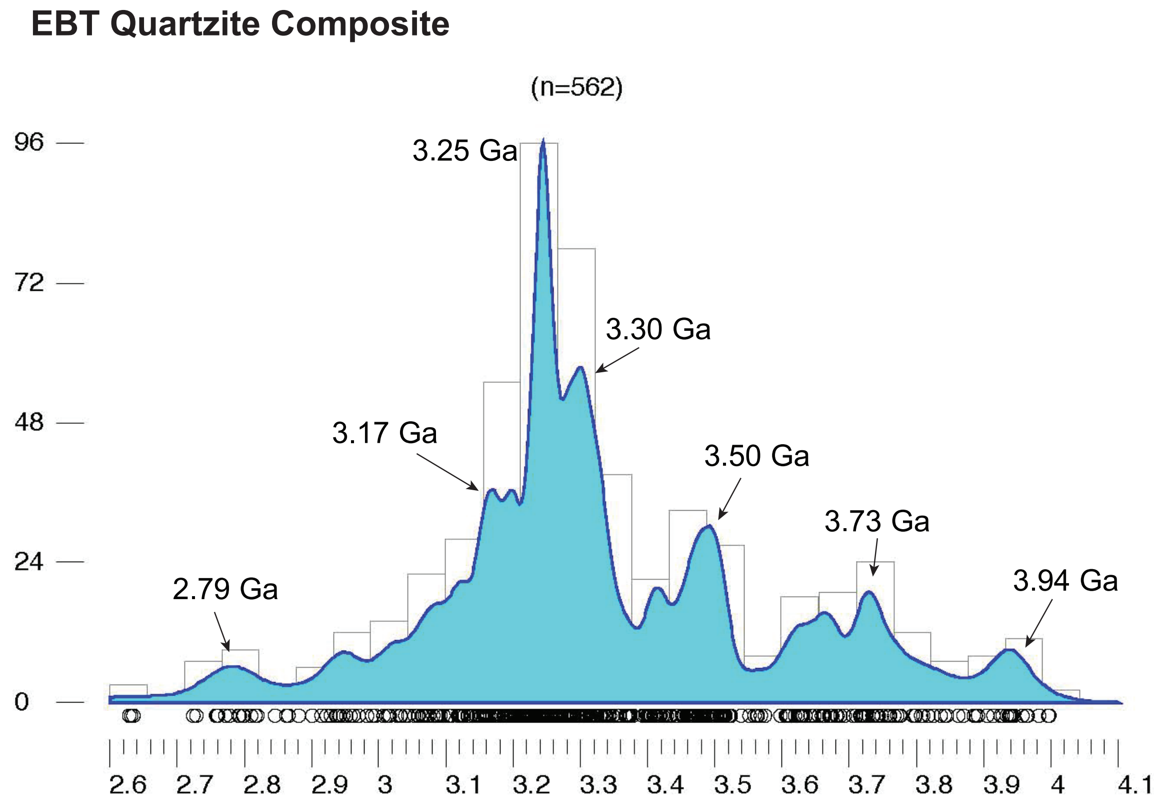

Figure 5. Composite age spectrum (KDE) from detrital zircons sampled from quartzites in the eastern Beartooth Mountains. Early crust-forming events likely occurred at ~3.9, 3.7, and 3.5 Ga, with a major crust-forming event recorded at ~3.2–3.3 Ga. The 2.79 Ga event is associated with emplacement of voluminous calc-alkaline magmas of the LLMC. Detrital zircon age spectra from other Archean exposures across southwest Montana also record a major crust-forming event at ~3.2–3.3 Ga (Mueller and others, 1998).

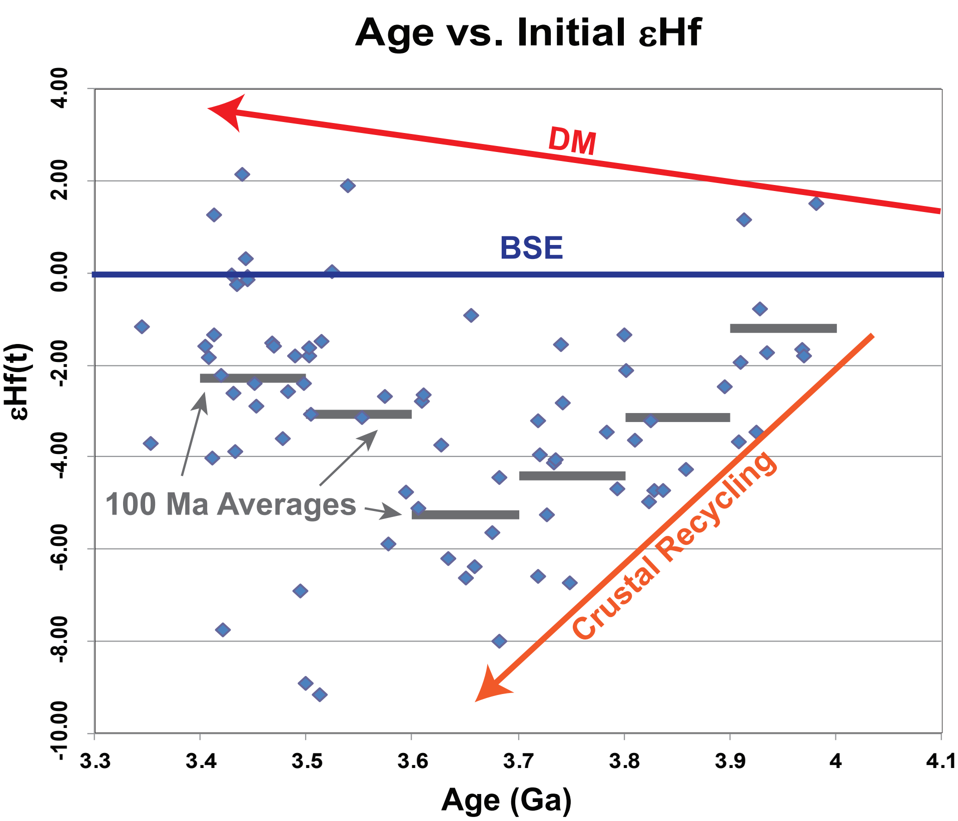

Figure 6. Individual zircon εHf data and 100 Ma averages (gray bars) plotted against $^{207}Pb/^{206}Pb$ age. Extrapolation of the crustal recycling line to depleted mantle (DM) at ~4.1 Ga does not require the older crust to be felsic or zircon bearing, but the low average Lu/Hf does likely mean that zircon was present in some lithologies. Higher values for zircons beginning at 3.5–3.6 Ga suggest higher proportions of juvenile contributions to younger crust. Typical error for extrapolated values is ~1.5 εHf (2σ). BSE, bulk silicate earth (modified from Mueller and Wooden, 2012).

THE BIRTH OF A CONTINENT (PALEOARCHEAN 3.6–3.1 GA)

A massive crust-forming event in the Wyoming Province initiated at ~3.6 Ga (Mueller and others, 1996b, 1998) and extended through ~3.1 Ga (Mueller and Frost, 2006). Magmatism was episodic over this interval, and produced large volumes of felsic magmas dominantly of the TTG suite (commonly referred to as "gray gneisses"); true granites are present, but are relatively rare. Representative U-Pb zircon ages from tonalitic, granitic, and mafic gneisses from the eastern Beartooth Mountains are presented in figure 7. Orthogneisses dominate over metasedimentary rocks across the northern Wyoming craton. This suite of TTG gneisses comprises the largest volume of rocks exposed in the MMP (fig. 8; Madison, Tobacco Root, and other Ranges) and in enclaves and pendants in 2.8 Ga magmatic rocks in the Beartooth Mountains. The oldest rocks exposed in the NWP are 3.5–3.6 Ga TTG gneisses with occurrences in the eastern Beartooth Mountains (Mueller and others, 2014b), North Snowy Block (Mogk and others, 1988; Mueller and others, 1996b), Spanish Peaks of the northern Madison Range (Weyand, 1989), and Tobacco Root Mountains (Mogk and others, 2004; Mueller and others, 2004a). Overall, these TTG rocks have typical chondrite normalized light REE (LREE) enrichment, some with positive Eu anomalies indicating concentration of plagioclase in the magmas; depleted heavy REE (HREE) element contents that indicate partial melting of mafic (amphibolite, granulite, eclogite) sources with residual amphibole/pyroxene/garnet-bearing lower crust; and primitive mantle normalized high field strength element (HFSE; e.g., Nb, Ta, Hf, etc.) depletion and large ion lithophile (LIL; e.g., K, Na, Rb) element enrichment similar to the patterns in modern arc magmatism (Mueller and others, 1993, 2004b, 2014b). The similarities of the major and trace element compositions of these rocks to modern day arc volcanic rocks indicate

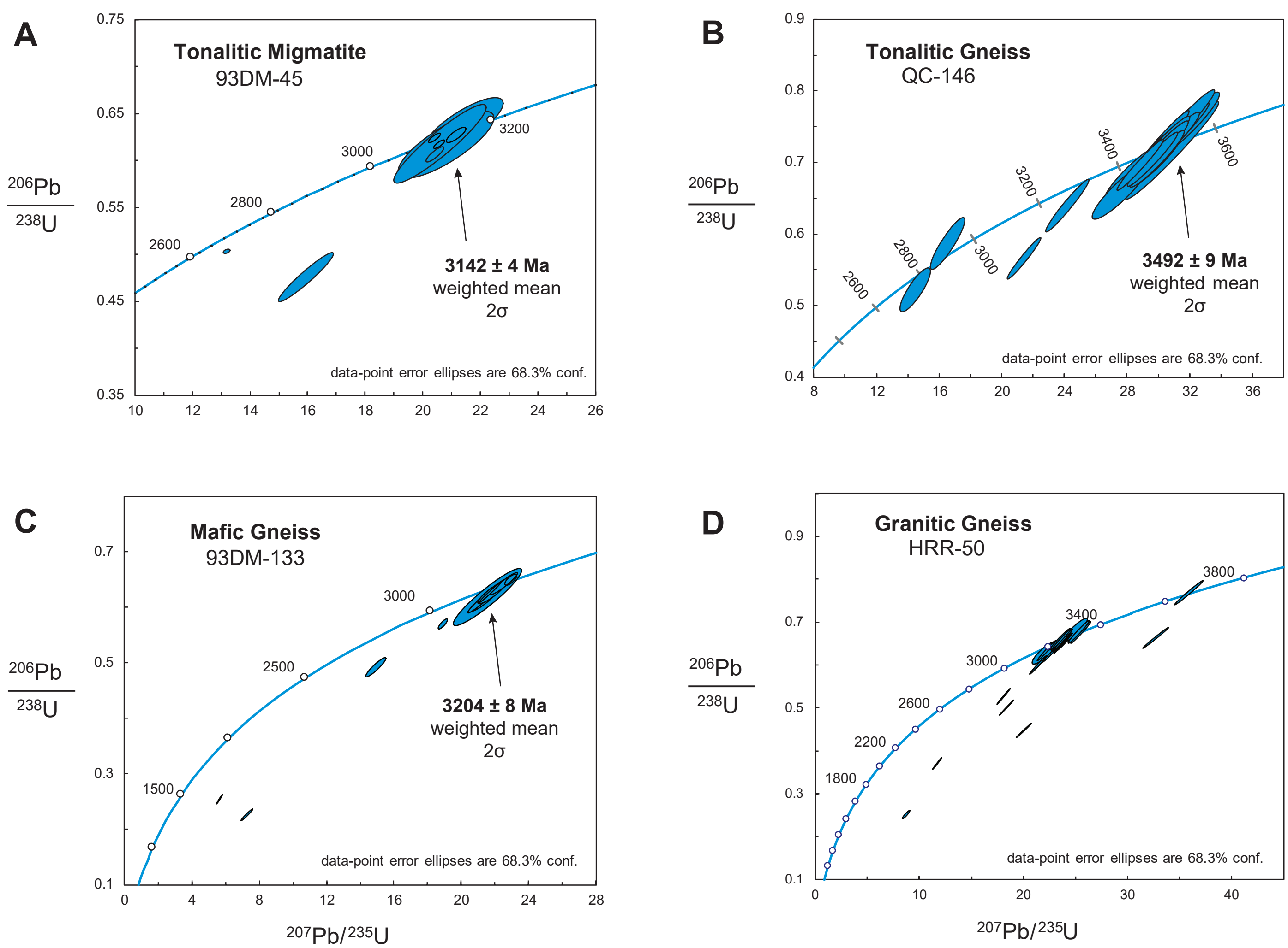

Figure 7. Representative U-Pb analyses of primary zircons from metaigneous rocks in the eastern Beartooth Mountains, with crystallization ages of 3.14–3.49 Ga. The ~2.8 Ga event is associated with emplacement of voluminous calc-alkaline magmas of the LLMC.

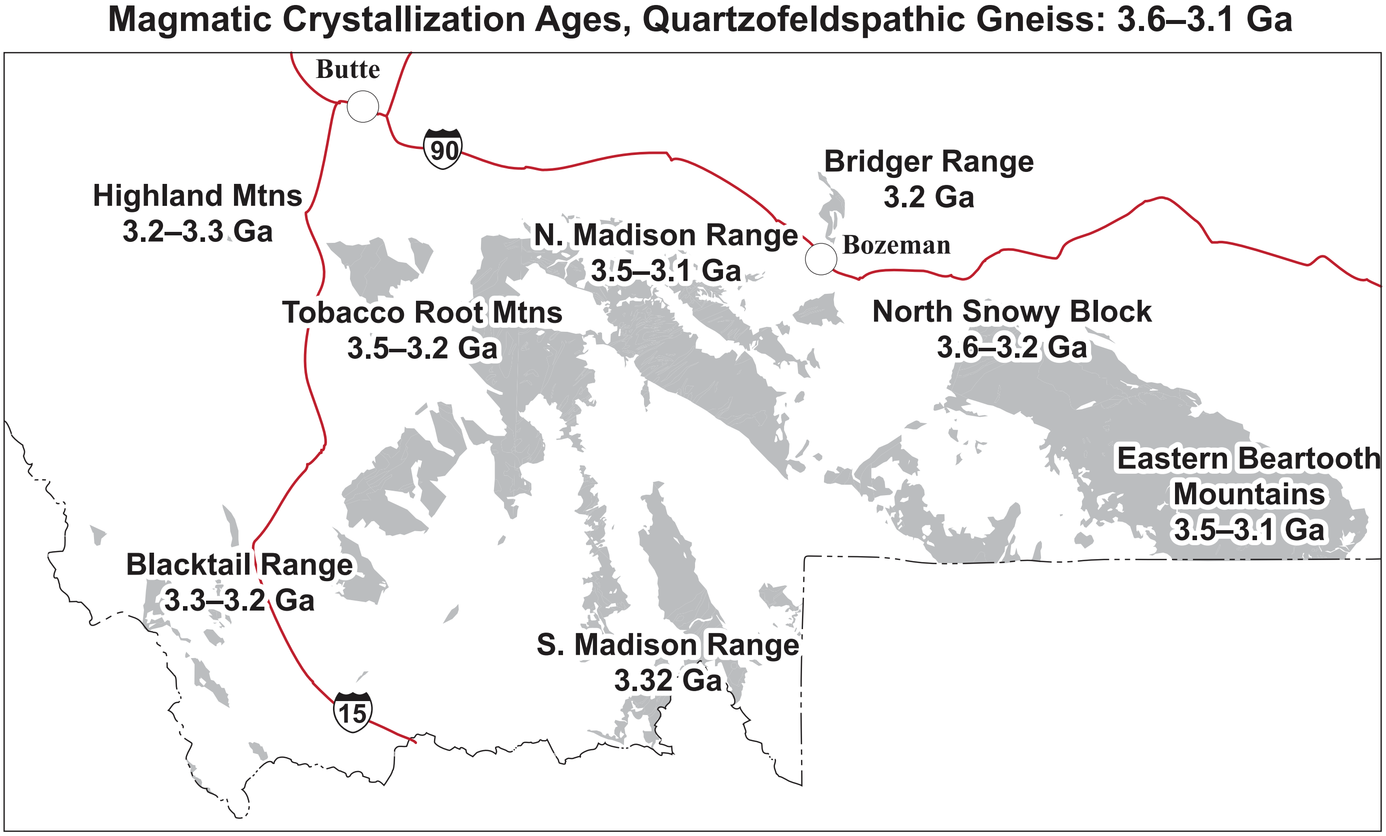

Figure 8. Occurrences of quartzofeldspathic gneisses with magmatic ages of 3.5–3.1 Ga in the Archean basement of southwest Montana.

their possible derivation in a subduction setting. Interaction with older crust is indicated by isotopic compositions that yield Eoarchean model ages and >3.2 Ga xenocrysts in Mesoarchean metaigneous rocks (Wooden and others, 1988; Mueller and others, 1993, 2004b).

In the *eastern Beartooth Mountains (EBT)*, these ancient gneisses are tectonically intercalated with metasedimentary and meta-igneous rocks, and occur as pendants up to kilometer-scale engulfed by voluminous 2.8 Ga magmatic rocks (fig. 9). In aggregate, rocks exposed in numerous locations in the eastern Beartooth Mountains (e.g., Quad Creek, Hellroaring Plateau, Wyoming Creek, Line Creek Plateau, Christmas Lake areas) have very similar elemental and isotopic geochemical signatures. Geochemical variation diagrams show the aggregate range of compositions observed in the eastern Beartooth Mountains and demonstrate that the mafic rocks generally follow a tholeiitic trend, the felsic to intermediate rocks follow a calc-alkaline trend, the quartzofeldspathic gneisses are weakly peraluminous, and trace element discrimination diagrams indicate formation in a volcanic arc or collisional tectonic setting (fig. 10). Zircons in the age range of 3.5–3.3 Ga have Lu-Hf systematics (εHf) that generally follow a trend to more positive values over time, indicating a period of increasing juvenile additions to the crust from the mantle (Mueller and Wooden, 2012; Mueller and others, 2014b). This is interpreted to represent the onset of subduction in the Wyoming Province and Earth history more generally, most likely producing numerous, episodic, and small-scale melting events (Mueller and others, 2009, 2013; Mogk and others, 2017).

In the *Spanish Peaks of the northern Madison Range* (fig. 11), quartzofeldspathic gneisses were originally mapped by Spencer and Kozak (1975) and more recently by Kellogg and Williams (2000). The establishment of geochemically evolved continental crust was concentrated in the Paleoarchean in the Spanish Peaks. Salt (1987) identified numerous sheet-like intrusions of gneisses (fig. 12), ranging in composition from hornblende monzodiorite to granite (fig. 13). Although closely related in space as interlayered magmatic bodies, these gneisses cannot be genetically related in a single magmatic cycle because of the great span of time recorded in their crystallization ages. Magmatism in the Spanish Peaks is episodic, spanning ~1 billion years, including a 3.53 Ga trachydacitic gneiss, production of a major pulse of TTG to granitic melts occurred between 3.35 and 3.21 Ga, and em-

Figure 9. A pendant of layered, tectonically mixed metasupracrustal rocks and 3.5–3.1 Ga TTG quartzofeldspathic gneisses (foreground) enclosed by 2.8 Ga calc-alkaline magmatic rocks (gray outcrops in the distance). This location is on Hellroaring Plateau, eastern Beartooth Mountains. Photo credit: Darrell Henry.

placement of later intrusions of granite (2.77 Ga) and a late-stage leucogranite (2.56 Ga; Salt, 1987; Weyand, 1989; table 2). The crust in the Spanish Peaks experienced high-grade metamorphism (upper amphibolite to transitional granulite facies) and penetrative deformation in the Paleoproterozoic, which transposed all structural elements into their current NE-trending fabric (Condit and others, 2015). The Spanish Peaks are also cut by numerous high-grade shear zones (Condit and others, 2015; Johnson and others, 2014; Kellogg and Mogk, 2009; Salt, 1987). The "gray gneisses" of the Spanish Peaks are the dominant rock type through the Gallatin River canyon. These rocks have experienced intense ductile shearing and migmatization (Mogk, 1992), and a U-Pb zircon age of 2.45 Ga has been determined for the granitic leucosomes (Mueller and others, 2011). In the adjacent Bridger Range, a bi-modal suite of quartzofeldspathic gneisses and amphibolites is exposed in the core of the Laramide block uplift (Lageson, 1989) with U-Pb zircon ages of ~3.2 Ga (Fussell and others, 2015, 2016).

The *Tobacco Root Mountains* contain a variety of quartzofeldspathic gneisses ranging in composition from tonalite to granite, with a distinctive suite of metasupracrustal rocks that include marble, quartzite, pelitic schists, banded iron formation, and related metabasites. This suite of crystalline rocks was variously mapped by Reid (1963), Vitaliano and others (1979), and James (1981). A comprehensive research program by the Keck Geology consortium (summarized in Brady and others, 2004) has documented the Paleoproterozoic "Big Sky Orogeny" (see also Harms and Baldwin, 2020), which imparted a very strong metamorphic and deformational overprint that makes it difficult to characterize the original Archean geology. Quartzofeldspathic gneisses are the dominant lithologies and include tonalitic to granitic compositions that range in age from 2.7 to 3.5 Ga (Mueller and Cordua, 1976; Mueller and others, 2004a; Krogh and others, 2011) on the basis of Rb-Sr whole-rock and U-Pb zircon ages. Geochemical analyses indicate the protoliths of the gneisses are a bi-modal magmatic association, formed in a continental arc or back-arc extensional setting, and that these rocks may have experienced potassic metasomatism prior to subsequent metamorphic and deformational events (Mogk and others, 2004).

The crystalline rocks of the northern *Ruby Range* were mapped by Tysdal (1976) and an overview of the Precambrian metamorphic and structural history of the Ruby Range has been reported by Karasevich and others (1981). The lithologic assemblages include quartzofeldspathic gneisses and metasupracrustal rocks

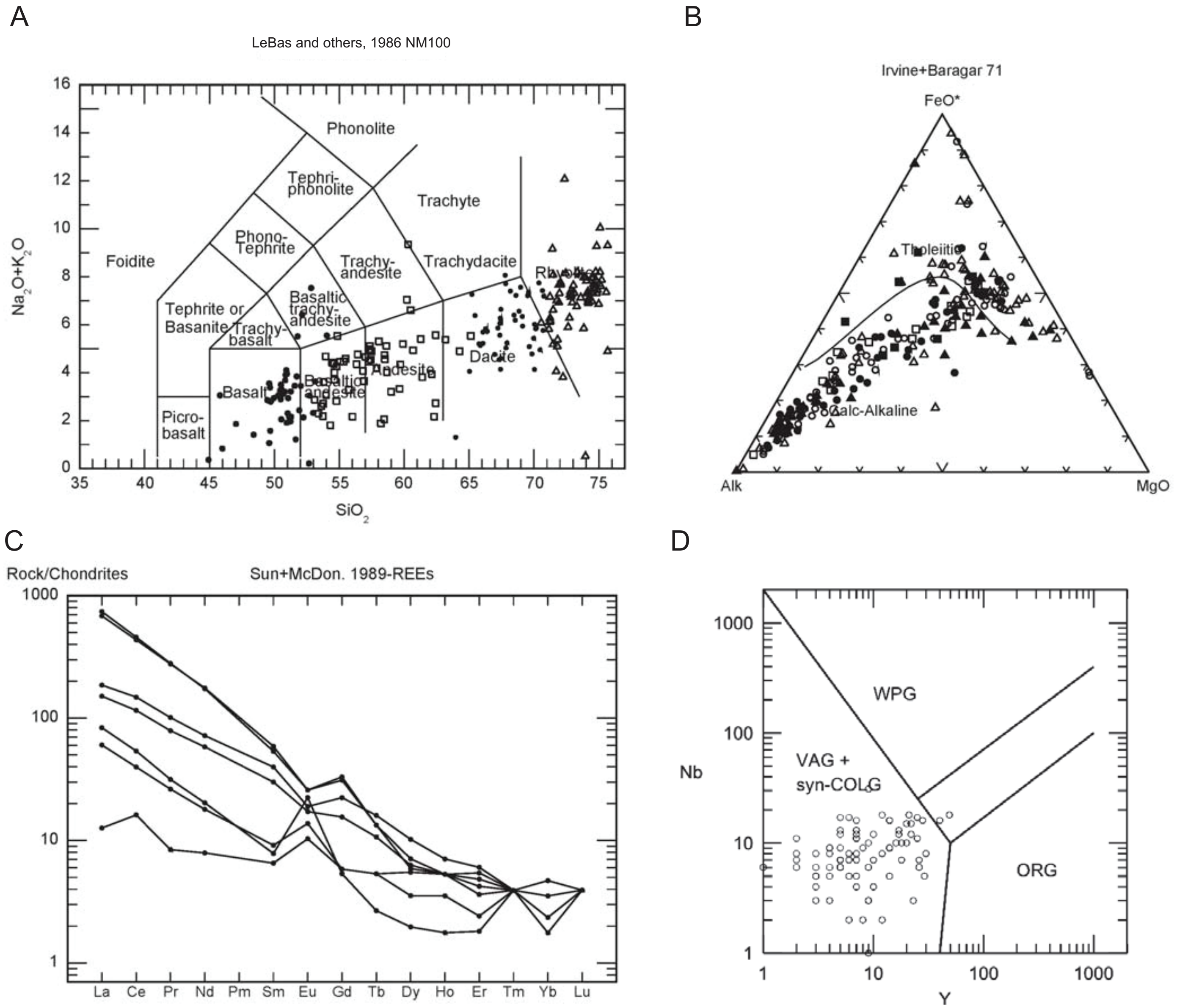

Figure 10. Geochemical variation diagrams. (A) Total alkali-silica diagram showing range of composition of 3.5–3.2 Ga gneissic rocks (after Le Maitre and others, 1989). (B) AFM diagram showing tholeiitic trend for mafic rocks and calc-alkaline trend for felsic rocks (after Irvine and Barager, 1971). (C) Chondrite-normalized rare earth element diagram showing LREE (low amu) enrichment, HREE (high amu) depletion, and some positive Eu anomalies indicating concentration of plagioclase in the melt after Sun and McDonough (1989). (D) Tectonic discrimination diagram showing geochemical affinities with volcanic arc granites after Pearce and others (1984).

(Dahl, 1979; Immega and Klein, 1976; James, 1992). Unfortunately, there are few isotopic data that reveal the age of the quartzofeldspathic gneisses, but the lithologic assemblages, compositions, metamorphic grade, and structural style of the gneisses are similar to those reported for the Indian Creek metamorphic suite in the nearby Tobacco Root Mountains (Harms and others, 2004a). High-grade metamorphism was reported as ~2.75 Ga based on Rb-Sr geochronology (James and Hedge, 1980; Karasevich and others, 1981), although more recent work by Roberts and others (2002) using ^{40}Ar–^{39}Ar biotite ages and four ^{207}Pb–^{206}Pb step-leach garnet analyses yield primarily Paleoproterozoic ages of 1.82–1.74 Ga (also reported by Alcock and others, 2013) and a "cryptic" 2.47 Ga metamorphic event. The marble sequences, although of probable Archean age, are host to significant talc deposits that formed in the Mesoproterozoic (Anderson and others, 1990).

Additional exposures of Precambrian basement in the Highland Mountains, adjacent to the Tobacco Root Mountains, was mapped by O'Neill and others (1996). These rocks have also been strongly reworked by Paleoproterozoic high-grade metamorphism, partial melting, and deformation, but the original age of the quartzofeldspathic gneisses is at least as old as 3.2 Ga, similar to most of the basement rocks of the adjacent Tobacco Root and Ruby Ranges (O'Neill, 1988, 1995;

Figure 11. Archean basement exposed in the Spanish Peaks of the northern Madison Range in the Bear Basin area. Most of the rocks on the skyline are varieties of 3.5–3.2 Ga quartzofeldspathic gneisses. Photo credit: Travis Courthouts.

Figure 12. Tonalitic gneiss intruded by sheets of younger granitic rocks that have been subsequently sheared into the regional foliation. Rock hammer for scale. Photo credit: David Mogk.

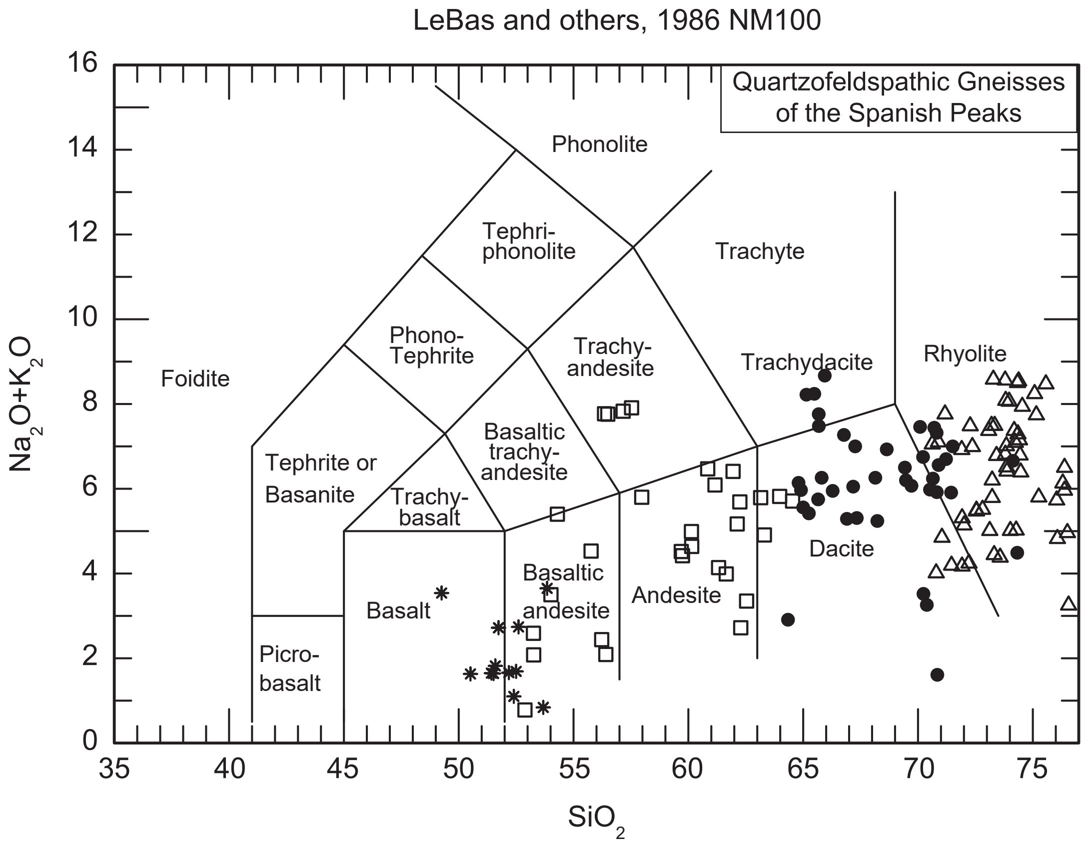

Figure 13. Total alkali–silica diagram showing the range of compositions of quartzofeldspathic gneisses in the Spanish Peaks (after Le Maitre and others, 1989).

O'Neill and others, 1988; Mueller and others, 2005).

In aggregate, the Paleoarchean rocks of the Wyoming Province in Montana are significant for a number of reasons:

(1) They represent the first major stage of formation of voluminous, felsic, continental crust in North America coincident with formation of the Slave Province (Reimink and others, 2019) and the Morton Gneiss of the Minnesota River Valley (Bickford and others, 2006; Satakoski and others, 2013). Globally, numerous models for crustal growth have been proposed, including early differentiation of virtually all of the continental crust by 3.9 Ga with subsequent steady-state recycling of this crust (Armstrong, 1981; Fyfe, 1978); a uniform growth rate of continental crust through time or an accelerating growth rate (Hurley and Rand, 1969); and episodic growth of the continental crust (Condie and others, 2009a; Taylor and McLennan, 1995; Veizer and Jansen, 1979). Evidence from the Wyoming Province supports this latter interpretation.

(2) The geochemical and isotopic signatures of these rocks (primarily the TTG suite) are interpreted to represent the onset of global plate tectonics (as understood in a contemporary sense, with magmagenesis in a subduction tectonic setting). Genesis of this oldest felsic crust at this time is referred to as the "plume to plate" transition (Mueller and others, 2014b).

(3) The detrital zircon record from Precambrian quartzites from across the Wyoming Province typically has a very strong maximum at 3.2–3.3 Ga. This attests to the large volumes of felsic crust that must have been produced at this time.

(4) The extensive Paleoarchean felsic crust provided the stable architecture for deposition of stable platform sedimentary sequences (next section), a second stage of magmatic arc development at 2.8 Ga in the BBMZ, and was cratonized such that it developed a thick tectosphere (rigidly connected crust and mantle lithosphere) that was first described in the Wyoming Province (Mueller and Rogers, 1973) and has influenced subsequent evolution and preservation of continental crust across the northern Wyoming Province (Mueller and others, 2004b; Pollack, 1986).

Table 2. Ages of quartzofeldspathic gneisses in the Spanish Peaks, Northern Madison Range.

Sample	Rock Type	Pb $^{207}/^{206}$ Age
BBGd	Granodiorite	3534 ± 11
SP-105	Granite/trondhjemite	3350 ± 14
BBT	Tonalite	3296 ± 06
SP-119	Tonalite	3289 ± 15
SP LSg		3273 ± 13
SP-79	Granite	3219 ± 25
SP Mzd	Quartz Monzodiorite	3208 ± 17
SP-130	Granite	2769 ± 10
SP-141	Leucogranite	2559 ± 12

A TECTONIC PAUSE (MESOARCHEAN, 3.1–2.9 GA)

The Mesoarchean included a time interval of relative tectonic quiescence from 3.1 to 2.9 Ga that accommodated the deposition of mature, stable platform type sedimentary rocks. These are now metasupracrustal rock assemblages, and include quartzites, pelitic and psammitic schists, marbles, and banded iron formations with subordinate mafic rocks that could have been basaltic flows. The protoliths of the metasupracrustal rocks are interpreted as mature sandstones to produce orthoquartzites, mudstones to produce the pelitic schists, and carbonate rocks to produce the marbles. Some of the quartzofeldspathic gneisses may also be paragneisses with either an arkosic or volcaniclastic protolith (e.g., Tobacco Root Mountains; Mogk and others, 2004). A long interval of tectonic quiescence is considered necessary to produce these stable platform type sedimentary sequences. These rock associations are spectacularly exposed as mappable units in the Montana Metasedimentary Terrane in the Madison (Kellogg and Williams, 2000), Tobacco Root (Vitaliano and others, 1979), and Ruby Ranges (Tysdal, 1976) in the western Wyoming Province, which was the basis for distinguishing the MMT (Mogk and others, 1992). In the eastern Beartooth Mountains, metasupracrustal rocks occur on a more limited basis as kilometer-scale pendants preserved in 2.8 Ga magmatic rocks mapped by Rowan (1969) and interpreted by Henry and others (1982) as xenoliths and pendants that were entrained in the younger (~2.8 Ga) intrusions of the voluminous magmatic rocks of the Long Lake Magmatic Complex (LLMC; see below). The youngest detrital zircons sampled from quartzites in all these occurrences are ~3.0 Ga old (Mueller and others, 1998), requiring that deposition in these basins must have been younger than this age.

In the eastern Beartooth Mountains, the metasupracrustal rocks include quartzites, pelitic schists, banded iron formations, metabasites, and minor ultramafic rocks; marbles are conspicuously absent. The metasupracrustal rocks are tectonically interleaved with slices of the Paleoarchean (3.6–3.1 Ga) quartzofeldspathic gneisses along high-grade shear zones (fig. 14). A “clockwise” P-T path has been interpreted for these rocks (fig. 15). The first stage of metamorphism (M1) is in the upper amphibolite to granulite facies (Henry and Daigle, 2018; Henry and others, 1982, 2015). Typical mineral assemblages are garnet–cordierite–sillimanite–biotite–K-feldspar in pelitic schists; hornblende–plagioclase ± garnet–clinopyroxene–orthopyroxene in mafic rocks; and magnetite–quartz–garnet–orthopyroxene ± clinopyroxene in banded iron formations. Peak metamorphic conditions have been calculated at 6–8 Kbar and up to 750–800^{o}C (Henry and others, 1982; Maas, 2004; Mueller and others, 2008; Will, 2013; Henry and Daigle, 2018; Guevara and others, 2017). Granulite facies assemblages are

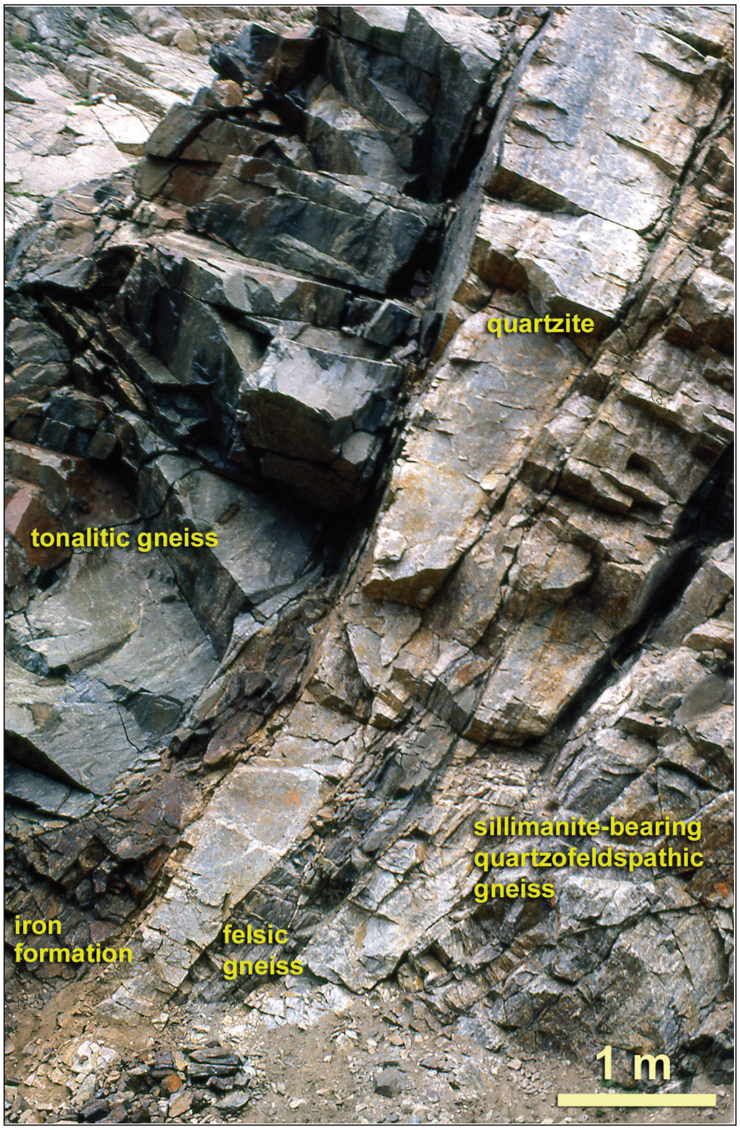

Figure 14. Metasedimentary rocks, including quartzite, banded iron formation (BIF), and minor pelitic schists are tectonically intercalated with quartzofeldspathic and tonalitic gneisses in the Quad Creek area of the eastern Beartooth Mountains. Photo credit: Darrell Henry.

overprinted (M2) with amphibolite facies assemblages (e.g., hornblende overgrowths on pyroxenes, 5–6 kbar and ~600°C). A late thermal overprint (M3) increased the temperature to ~750–800°C, and this is attributed to heating related to emplacement of the 2.8 Ga LLMC magmatic bodies (next section). This sequence of rocks must have (a) been deposited in a stable platform type setting <3.0 Ga ago; (b) gone through an orogenic cycle that brought the metasupracrustal rocks through the granulite/amphibolite facies (M1–M2) at crustal levels of ~20–25 km; this cycle is interpreted as the result of tectonic thickening based on the "clockwise" pressure–temperature path; and (c) the metasupracrustal rocks were tectonically juxtaposed with Paleoproterozoic (3.5–3.1 Ga) gneisses, and underwent a late heating metamorphic stage (M3) prior to and culminating in the intrusion of the suites of 2.8 Ga LLMC (see next section).

To the west, in the Tobacco Root Mountains, the distinctive metasupracrustal suite of marble, pelitic schists, quartzites, banded iron formations (BIFs), and metabasites are interpreted also as having been deposited in a passive margin or stable platform setting during a period of tectonic quiescence. The age of deposition is unknown, but it must have been after ~3.1 Ga (the age of the youngest detrital zircons in quartzites), and the original sedimentary rocks are interpreted to be unconformable relative to the underlying quartzofeldspathic gneisses (3.5–3.1 Ga) (Mogk and others, 2004). The Tobacco Root Mountains are also host to the Spuhler Peak Formation, which is interpreted as a tectonically emplaced suite of mafic volcanic rocks with compositions similar to Archean tholeiites with arc-related affinities. These mafic rocks were most likely deposited in a marine environment with minor intercalated clastic sedimentary material

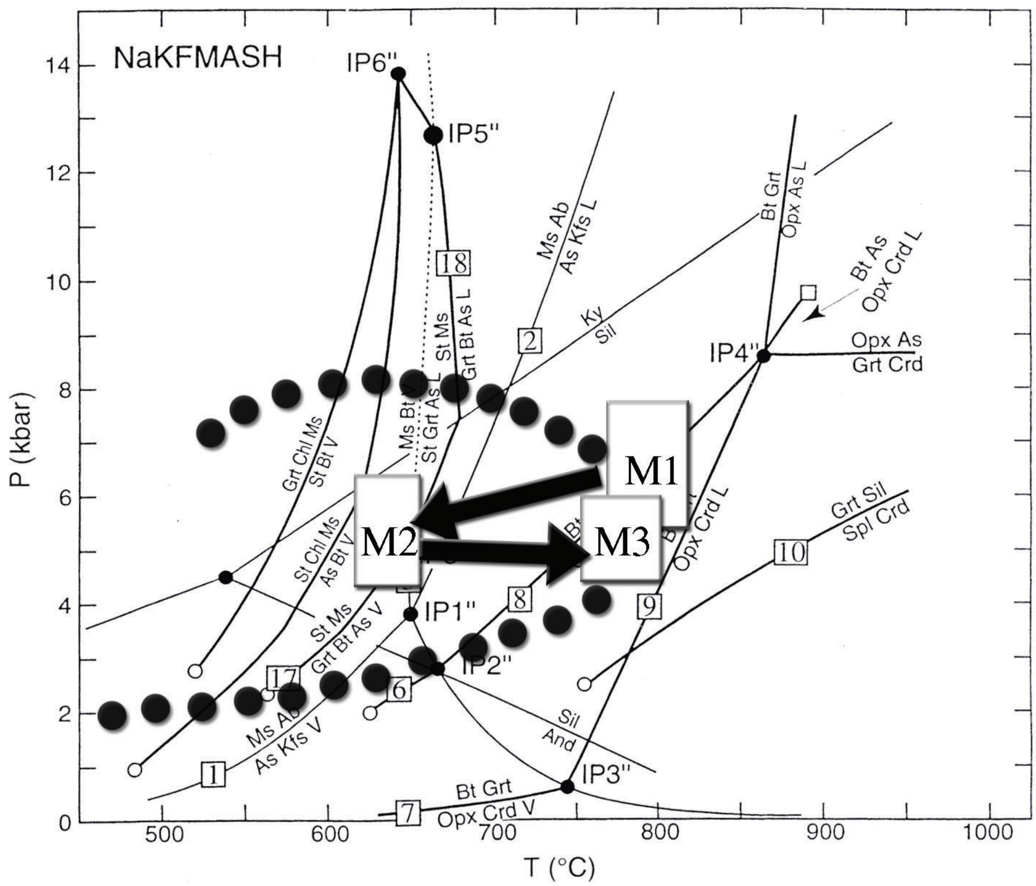

Figure 15. Pressure–temperature path calculated for metasedimentary rocks of the eastern Beartooth Mountains, based on numerous independent geothermometers and geobarometers, and textural relations of metamorphic reactions. Abbreviations of minerals involved with metamorphic reactions: Ky, kyanite; Sil, sillimanite; Chl, chlorite; Ms, muscovite; Bt, biotite; St, staurolite; Gt, garnet; Cd, cordierite; Opx, orthopyroxene; V, water vapor; L, melt.

(Burger and others, 2004; Cummings and McCulloch, 1992). The age of the Spuhler Peak Formation is uncertain, but Mueller and others (2004a) report that the youngest detrital zircon in quartzites from this unit is 3.2 Ga (although a single zircon yielded an age of 2.45 Ga). An Archean age is also inferred based on Sm-Nd model ages of mafic rocks and the age distribution of zircons from the quartzite, similar to patterns in other Archean quartzites across the Wyoming Province. Primary relations of the basement rocks in the Tobacco Root Mountains are largely obscured by multiple high-grade metamorphic events, which may include ~2.7 Ga (Rb-Sr ages, Mueller and Cordua, 1976; James and Hedge, 1980), 2.45 Ga (Cheney and others, 2004a,b; Roberts and others, 2002), and 1.78 Ga penetrative deformation (Harms and others, 2004a) during the Big Sky phase (~1.78 Ga) of the Paleoproterozoic Great Falls Orogeny (1.9–1.7 Ga; Mueller and others, 2004; Cheney and others, 2004a,b).

THE LATE ARCHEAN: CRUSTAL GROWTH THROUGH MAGMATIC AND TECTONIC ACCRETION (2.8–2.6 GA)

The Late Archean was a time of continued crustal growth in the NWP through discrete episodes of magmatism (2.8, 2.7, 2.6 Ga; fig. 16), and tectonic juxtaposition of allocthonous crustal blocks (Mogk and Henry, 1988; Mogk, 1988; Mogk and others, 1988). The BBMZ was originally defined by the occurrence of voluminous magmatic rocks of the TTG and calc-alkaline suites exposed in the Beartooth and Bighorn Mountains (Mogk and others, 1992). In the Beartooth Mountains, the Beartooth Plateau Block, North Snowy Block, South Snowy Block, and Stillwater Complex (fig. 17) all record different styles of Late Archean crustal evolution. In the western Wyoming Province, Late Archean magmatic rocks occur in discrete areas in the Gravelly Range, southern Madison Range, Blacktail Range, and in the core of the Armstead Anticline (fig. 16).

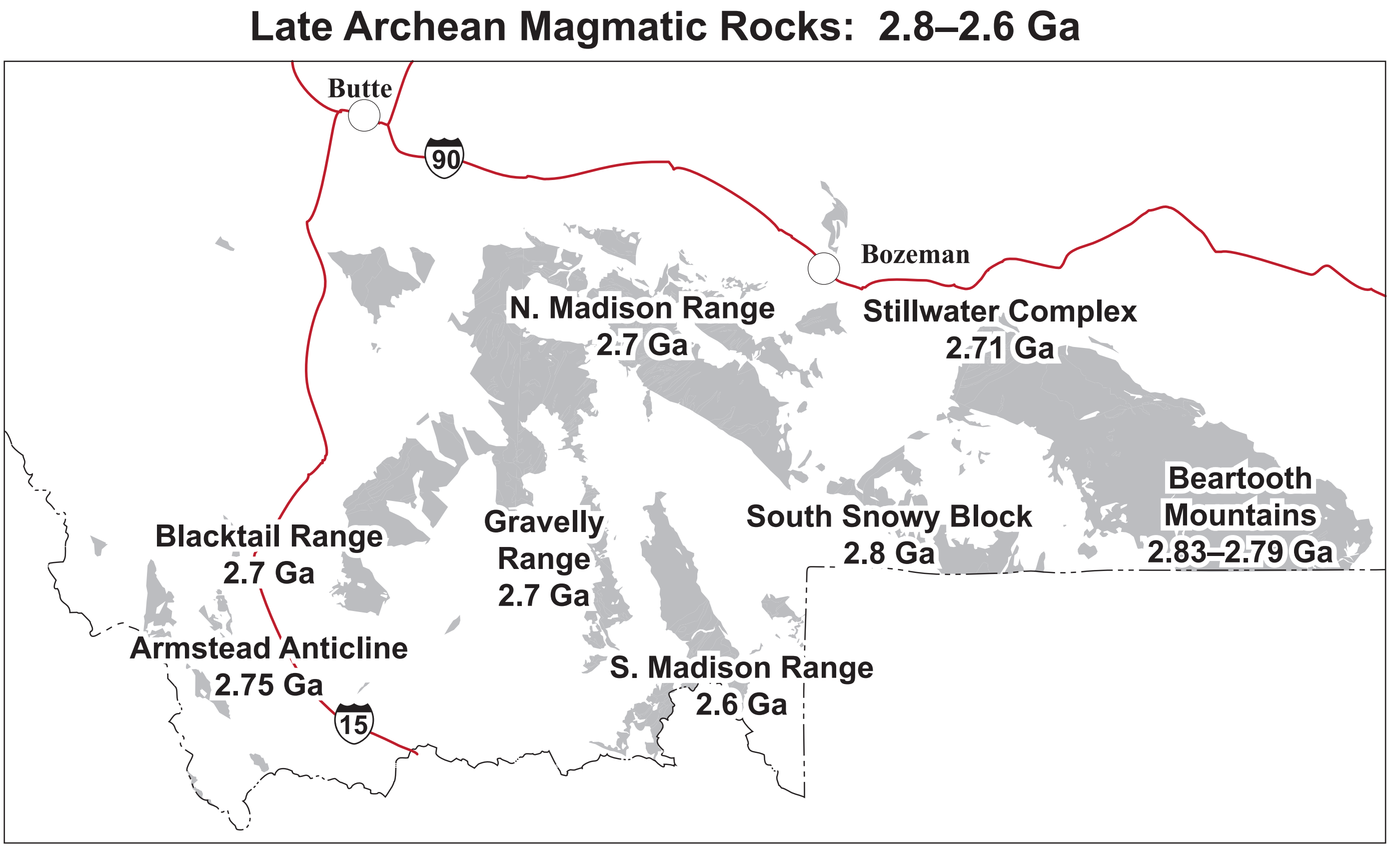

Figure 16. Occurrences of igneous rocks with crystallization ages of 2.8–2.6 Ga in the Archean basement of southwest Montana.

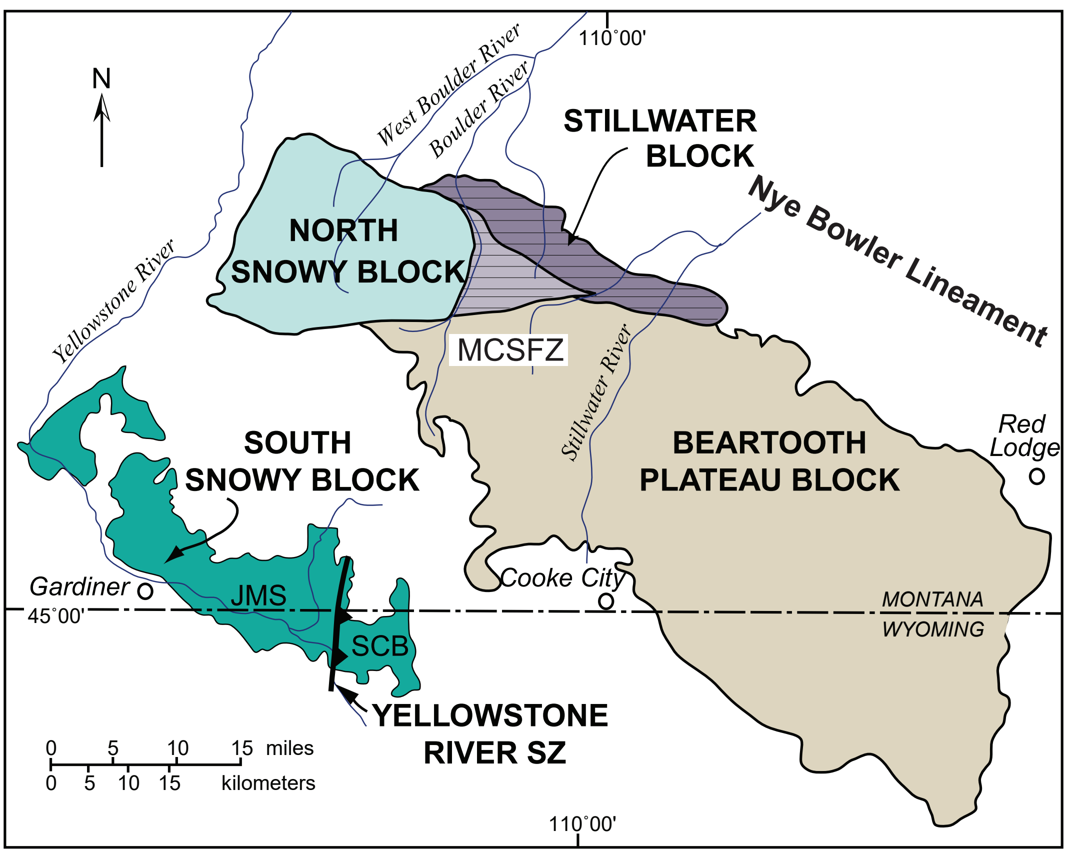

Figure 17. Index map of Late Archean crustal components in the Beartooth Mountains. Details of the geologic relations of each area are discussed in the text. Locations of the North Snowy Block, Stillwater Block, and Beartooth Plateau Block are identified. JMS, Jardine Metasedimentary Suite; SCB, Slough Creek Block, MCSFZ, the Mill Creek Stillwater Fault Zone. The Yellowstone River shear zone is marked by the thrust fault symbol (saw teeth on the hanging wall). The lined unit in lighter pink north of the MCSFZ is the Stillwater contact aureole. The Nye–Bowler lineament is NW–SE trending north of the Beartooth Block.

BEARTOOTH–BIGHORN MAGMATIC ZONE (BBMZ; ~2.8 GA)

The quartzofeldspathic rocks of the Beartooth Mountains have played a significant role in the history of geologic thought on the origin of continental crust through the early work by Arie Poldervaart, students, and colleagues (Butler, 1966, 1969; Casella, 1964, 1969; Eckelmann and Poldervaart, 1957; Harris, 1959; Larsen and others, 1966; Poldervaart and Bentley, 1958; Rowan, 1969; Skinner, 1969; Bowes and Skinner, 1969; Rowan and Mueller, 1971). This group described and mapped the varied lithologies and structures throughout the Beartooth Plateau Block. Poldervaart originally focused on this region because he felt it was a classic example of granitization; i.e., he interpreted the quartzofeldspathic gneisses as classic products of "granitization" by metasomatic fluids and the rounded detrital zircon cores (Eckelmann and Poldervaart, 1957) as evidence of "chemical resistors" to the fluids that infiltrated the quartzites to produce the quartzofeldspathic gneisses. Application of modern analytical approaches, primarily ion probe (SHRIMP) and more recently LA-ICP-MS methods for U-Pb geochronology and ICP techniques for trace element geochemical analysis, however, has led to the recognition of the predominantly intrusive origins (with partial assimilation of the metasupracrustal rocks) of these Archean magmatic rocks (e.g., Mueller and others, 1982; Wooden and others, 1982).

The BBMZ in Montana and Wyoming is dominated by Mesoarchean metaplutonic rocks of the TTG igneous suite. In terms of volcanic equivalents, the magmatic rocks of the LLMC range in composition from basaltic to rhyolitic, and significantly contain large volumes of rocks of andesitic and dacitic composition. These rocks were intruded as numerous sheet-like bodies at mid-crustal levels (Henry and others, 1982; fig. 18). Trace element patterns, including high field strength element depletion, light REE enrichment, negative Eu anomalies, and depletion of heavy REEs, are consistent with magmagenesis in a subduction setting, as also suggested by trace element discrimination diagrams (fig. 19). U-Pb geochronology of zircons shows that the numerous compositional varieties of magmatic rocks of the LLMC overlap in time (i.e., they do not follow a simple liquid line of descent from mafic to felsic) during the limited period of magmatism of 2.83–2.79 Ga (fig. 20). Sm-Nd, U-Pb, and Lu-Hf systematics indicate there is a significant component of recycled older crust mixed with primitive melts from the depleted mantle (Wooden and Mueller, 1988). Mueller and others (2010, 2014b) interpreted the assemblage of magmatic rocks in the eastern Beartooth Mountains as the product of simultaneous melting of disparate mantle and lower crustal rocks to generate the diverse array of rocks observed. Additional geochemical and isotopic evidence of magmagenesis in a continental marginal subduction environment has been presented by Mueller and others (1983, 1988, 2008), Mueller and Wooden (1988), and Wooden and Mueller (1988).

ALLOCHTHONOUS UNITS ALONG THE WESTERN BBMZ

The western margin of the Beartooth Mountains is defined by a fundamental discontinuity in the Archean basement between the BBMZ and the MMT (fig. 1). Two significant rock suites in the North and South Snowy Blocks have been interpreted as allochthonous units (Mogk and others, 1988; Mogk, 1988) that were emplaced into their current tectonic setting in the BBMZ during the Late Archean (fig. 17).

The North Snowy Block

The North Snowy Block was mapped in detail by Reid and others (1975) and reinterpreted by Mogk and others (1988) to be a zone of tectonic mixing of numerous allochthonous units. These units include six major lithologic suites of Archean age: (1) a bi-modal TTG gneiss–amphibolite complex (as old as 3.5 Ga; Mueller and others, 1996b); (2) the Pine Creek Nappe complex, a kilometer-scale, recumbent thrust-nappe with amphibolite core (Barney Creek amphibolite), and symmetrically disposed George Lake Marble and Jewel Quartzite; (3) a metasupracrustal–migmatite complex that consists of a quartzite–amphibolite unit with lit-par-lit injections of granitic rocks; (4) the phyllitic Davis Creek Schist; (5) the Mt. Cowen granitic augen gneiss; and (6) a leucogranite sill (Mogk and others, 1988). The detrital zircons in the quartzite of the Pine Creek Nappe are dominantly in the range of 3.2 to 3.4 Ga (Mueller and others, 1998), and the amphibolite in the core of the nappe has a U-Pb zircon age of 3.2 Ga (Mogk and others, 1988). These units have been tectonically juxtaposed and preserve different metamorphic grades and fabrics, except for the late, leucogranitic sill (2.55 Ga). The metamorphic grade increases upsection from the greenschist facies phyllitic schist in the east, through

A

B

Figure 18. Field relations showing (A) intrusion of granite into metaigneous rocks of intermediate composition in the Long Lake area of the Beartooth Mountains (rock hammer for scale) and (B) partial assimilation of blocks of intermediate gneiss in a matrix of younger granitic intrusive rocks (rock hammer for scale). Photo credits: David Mogk.

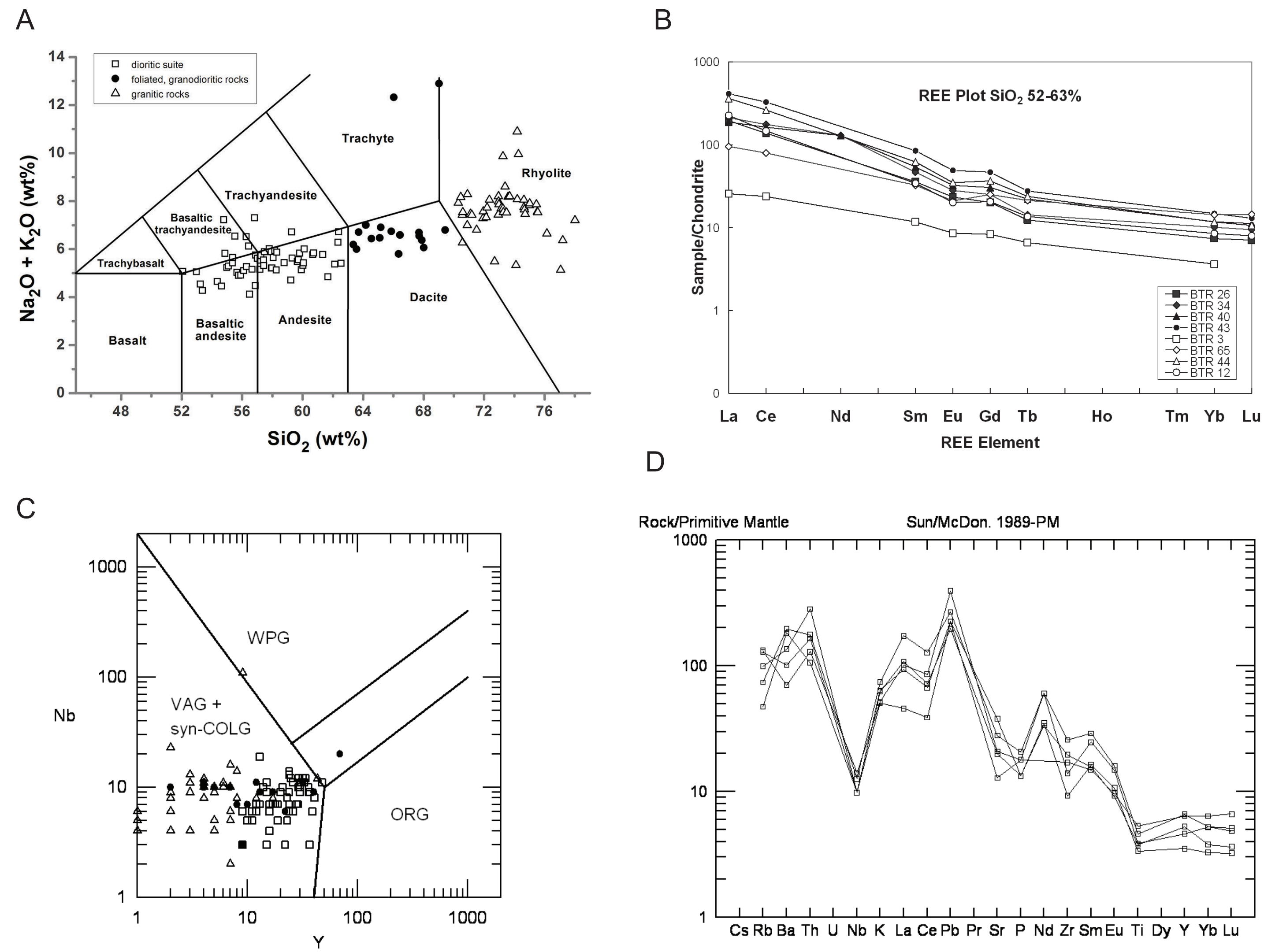

Figure 19. Geochemical variation diagrams of the 2.8 Ga Long Lake Magmatic Complex. (A) Total alkali–silica diagram showing range of compositions of the LLMC (after Le Maitre and others, 2002); (B) REE diagrams for the granitic and granodioritic rocks of the LLMC (after Wooden and others, 1992); (C) tectonic discrimination diagram demonstrating geochemical affinity with volcanic arc granites (after Pearce and others, 1984); (D) Primitive mantle-normalized “spider diagram” showing high field strength element (HFSE) depletion commonly observed in modern subduction settings (after Sun and McDonough, 1989).

the epidote–amphibolite facies of the trondhjemitic gneiss, amphibolite facies of the Pine Creek Nappe, and to the uppermost unit of migmatized gneisses. The leucogranitic sill is interpreted to reflect the last major Archean deformation event in this area. The Pine Creek Nappe is significant because it has all the characteristics of modern Alpine nappes (recumbent, isoclinal folding, strongly attenuated lower limb, mylonitic fabrics in quartzite developed at the lower contact with TTG gneiss), and has been interpreted as one of the oldest documented examples of horizontal tectonics often associated with modern plate tectonics (Mogk and others, 1988; fig. 21).

The South Snowy Block

The South Snowy Block contains a distinct metasedimentary sequence (Jardine sequence) that was originally mapped with accompanying petrologic and geochemical data by Casella and others (1982). The petrology and geochemistry of these rocks were also described by Thurston (1986). The rock types include varieties of phyllites, biotite schists, quartzites, rare metaconglomerates, and banded iron formations. Primary sedimentary structures, such as compositional layering and graded bedding, low-angle cross stratification, rip-up clasts, and channel scour deposits are commonly preserved (fig. 22). Protoliths of these rocks are interpreted as graywackes and mudstones, and partial Bouma sequences are present, suggesting deposition by turbidity currents. An early stage of isoclinal folding is attributed to soft sediment deposition in a turbidite setting (Fereday and others, 2011), and two stages of open and crenulation folding have been defined (Jablinski and Holst, 1992), forming a Ram-

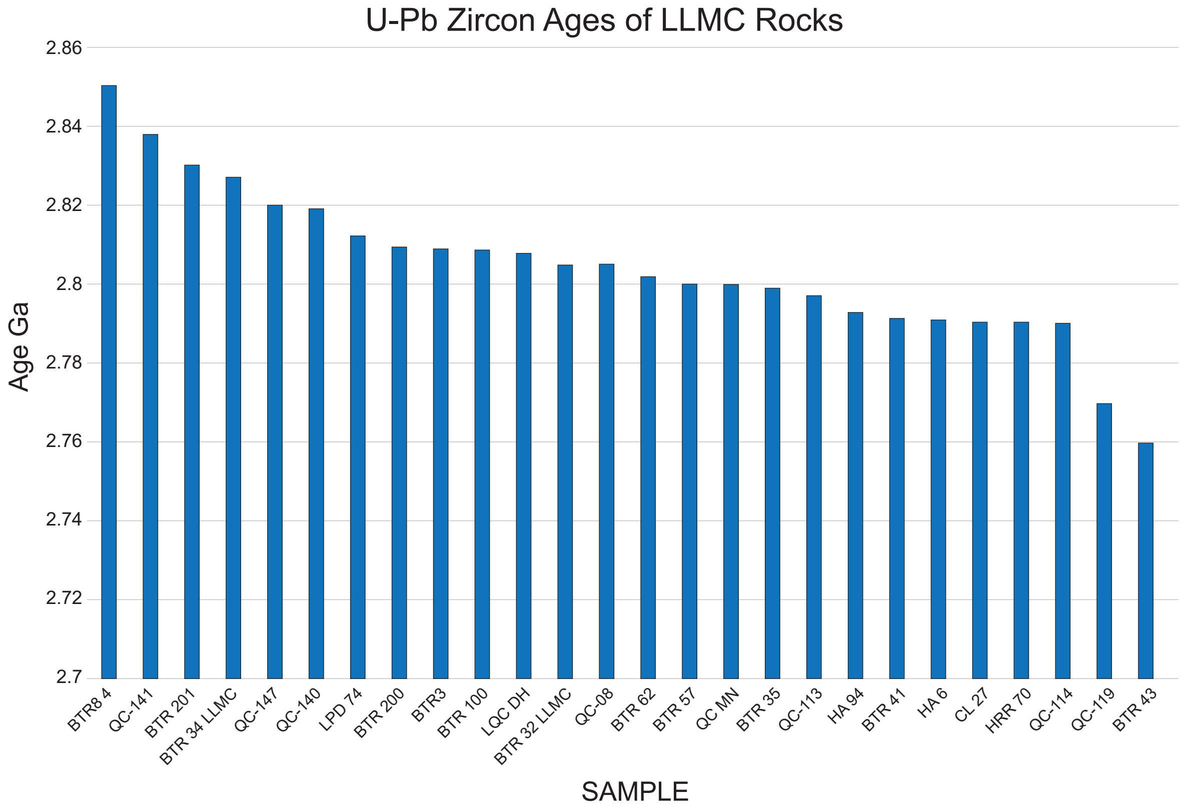

Figure 20. Distribution of crystallization ages (U-Pb zircon) for magmatic rocks of the LLMC.

sey-type 1 dome and basin structure. The banded iron formations are host to the gold mineralization of the Jardine Mine (Hallager, 1984; Smith, 1996). Metamorphism of this sequence is anomalously low grade compared to most Archean metasedimentary sequences in the Wyoming Province and produced phyllitic schists in the west (near Gardiner, MT) and andalusite–staurolite–garnet–biotite schists to the east near Tower Junction in Yellowstone National Park (Osborne and others, 2011). Peak metamorphic conditions are 3.8 Kbar and 550^{o}C. Detrital zircon U-Pb data from a quartzite near Jardine have a maximum frequency at ~3.2 and 3.0 Ga with subsidiary concentrations at 3.5 Ga and a minimum age of 2.9 Ga, a pattern not observed in any of the other quartzites across the Wyoming Province. Significantly, there are no zircons of 2.8 Ga age, so these sediments could not have been derived from the adjacent Beartooth massif (Goldstein and others, 2011; fig. 23).

Two epizonal, bulbous plutons, the Crevice Stock and Hellroaring Stock, intrude the Jardine metasedimentary rocks (Brookins, 1968; Montgomery and Lytwyn, 1984; Philbrick and others, 2011). These have peraluminous affinities, have an estimated depth of crystallization of 10–12 km (3–4 Kbar), and have primary U-Pb zircon ages of ~2.8 Ga—the same as the main Beartooth magmatic event, and the minimum age of tectonic juxtaposition of the Jardine metasediments against the BBMZ (Mueller and others, 2014a; Philbrick and others, 2011). A major shear zone, the Yellowstone River Shear Zone (fig. 14), separates the Jardine metasedimentary sequence on the west from the meta-igneous rocks to the east (Marks and others, 2012). The 2.8 Ga magmatic rocks (LLMC) of the Beartooth Mountains also extend into the Slough Creek area of Yellowstone Park (Berndt and others, 2012; Grip and others, 2012; Mavor and others, 2012; Mueller and others, 2014a). These magmatic rocks crystallized under mesozonal conditions (~8 Kbar; Berndt and others, 2012), and have been thrust over the metasedimentary rocks (3.8 Kbar maximum), a structural throw of over 10 km across the Yellowstone River shear zone. A tectonic slice of 3.2 Ga TTG gneiss and younger leucogranites is also exposed in the shear zone (Lexvold and others, 2011; McKinney and others, 2012). The Jardine metasedimentary sequence is interpreted as exotic to the Beartooth Mountains and to blocks of basement rocks in surrounding ranges based on its unique detrital zircon pattern and anomalously low metamorphic grade (Mogk, 1988). The crosscutting Crevice and Hellroaring Plutons share geochemical affinities with the LLMC of the

Figure 21. The Pine Creek Nappe, North Snowy Block. The tree line marks the thrust contact between the overlying nappe and underlying 3.2–3.5 Ga TTG gneiss. The bottom limb of the nappe is attenuated quartzite and marble, the core of the nappe is amphibolite (darker layer), and the upper limb of marble (directly under the cloud) and quartzite (lightest unit in the saddle to the right) is on the skyline. Photo credit: David Mogk.

A

B

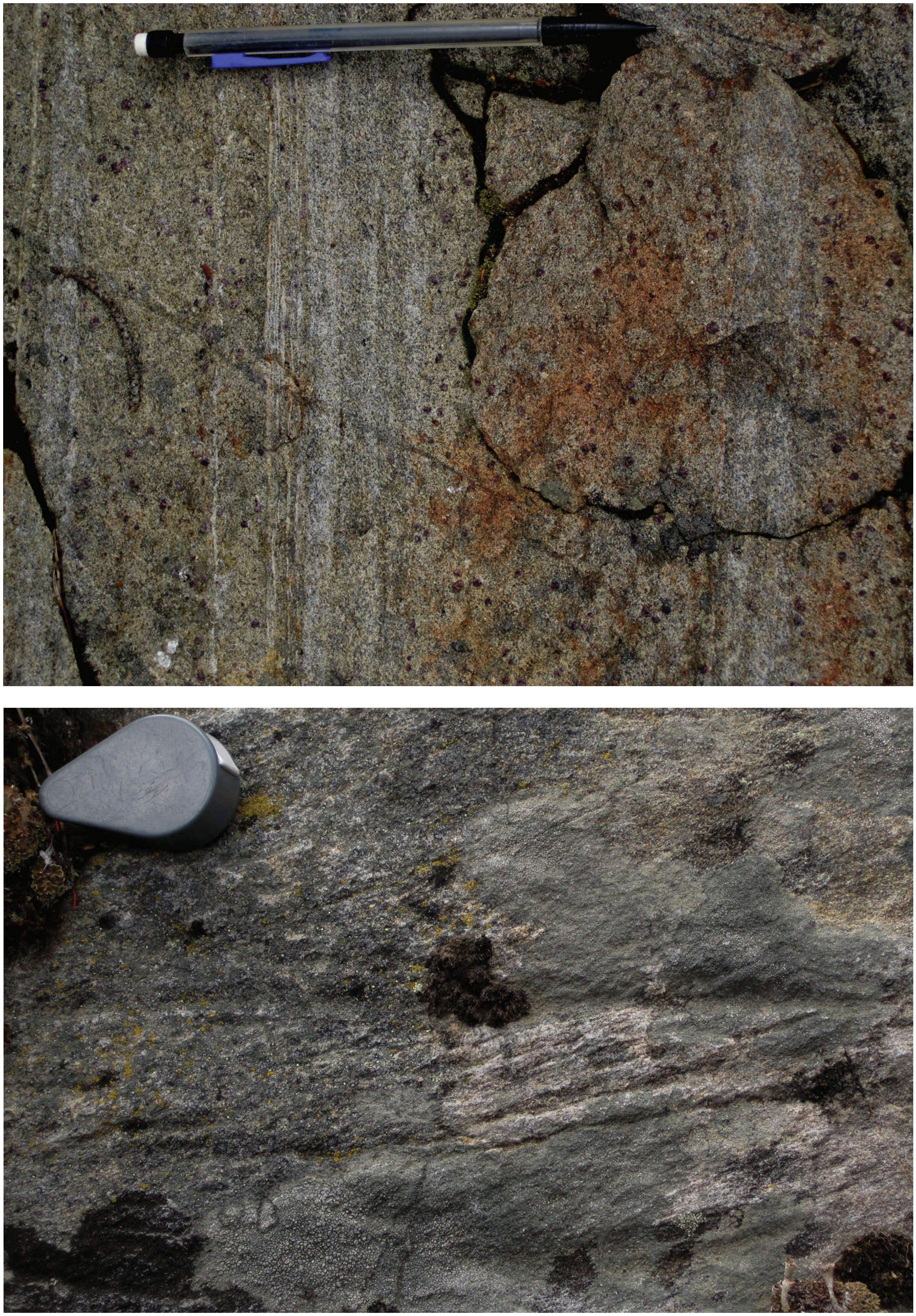

Figure 22. Sedimentary structures preserved in the Jardine metasedimentary sequence: (A) Graded bedding interpreted as part of a turbiditic Bouma sequence and (B) Cross-bedding in quartzite. Photo credits: Darrell Henry.

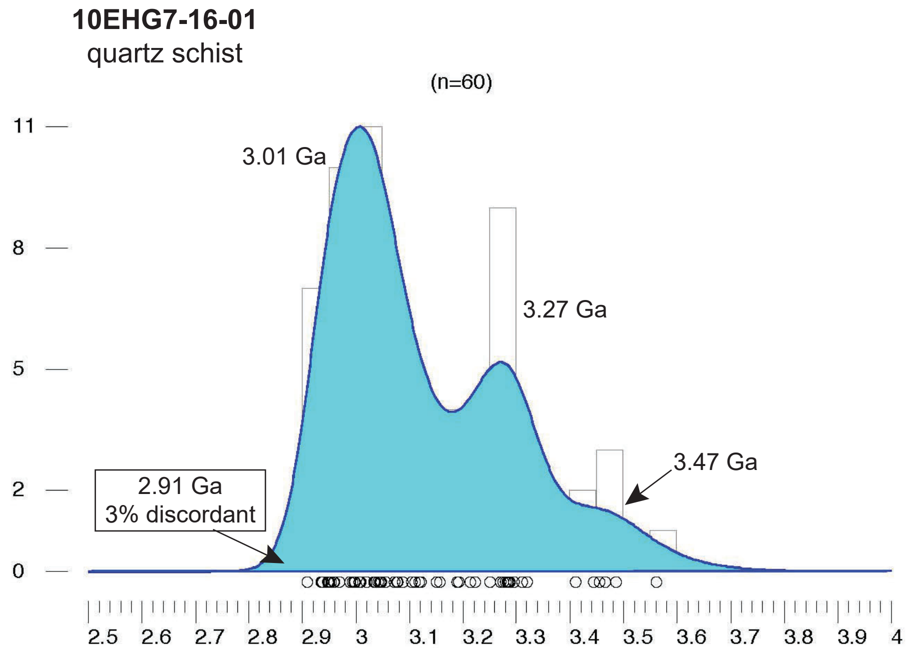

Figure 23. Detrital zircon U-Pb age spectrum from quartzite from the Jardine metasedimentary sequence (*n* = 60; grains <10% discordant).

Beartooth Mountains, including the enriched Pb isotopic signature of all Late Archean magmatic rocks of the Wyoming Province (Mueller and others, 2014b). These plutons place a minimum age of ~2.8 Ga for the tectonic emplacement of the Jardine metasediments against the Beartooth Plateau Block. The evolution of the Precambrian rocks of northern Yellowstone Park has been summarized by Mogk and others (2012).

STILLWATER COMPLEX (2.7 GA)

The significance of the Stillwater Complex as an iconic mafic–ultramafic layered intrusion and as host to the only Pt-Pd mine in the United States has been addressed in chapters by Boudreau and others (2020) and Gammons and others (2020). We include the Stillwater Complex in this chapter on Archean rocks because of its significance for the tectonic evolution of the Archean basement of Montana. Geissman and Mogk (1986) interpreted the Stillwater Complex as an allochthonous unit that was tectonically emplaced against the Beartooth massif along the Mill Creek–Stillwater fault zone (Wilson, 1936) in the late Archean. In its current structural position, the layering of the Stillwater Complex is steep to near vertical and locally overturned. Some of this tilting is certainly the result of Laramide faulting, but there must also be a Precambrian component of tilting because there is a high-angle unconformity of lower Cambrian rocks that are near horizontal, and in contact with steeply dipping underlying Stillwater Complex rocks. Early attempts to date the Stillwater Complex using K-Ar and Rb-Sr (e.g., Kistler and others, 1969; Nunes and Tilton, 1971) gave unreasonably old ages and/or large uncertainties. A Rb-Sr whole-rock isochron approach to the aureole rocks gave an age of 2.76 Ga (Mueller and Wooden, 1976), indistinguishable from the then-accepted age of the country rock. Subsequently, both Sm-Nd mineral isochron approaches and U-Pb zircon ages ranged from 2.701 ± 0.008 to 2.713 ± 0.003 Ga (DePaolo and Wasserburg, 1979; Nunes, 1981; Premo and others, 1990), and are within error of the most recently reported age of 2.709 Ga using high-precision zircon and baddeleyite U-Pb methods (Wall and Scoates, 2016). The Stillwater Complex must have crystallized in a near-horizontal orientation and during a time of tectonic quiescence to permit the development of rhythmic compositional layering; inch-scale layers extend for kilometers across the complex. The Stillwater Complex has not been subjected to the regional high-grade metamorphism and penetrative deformation experienced by the crystalline rocks of the Beartooth Mountains to the south. However, there has been some later hydrothermal alteration of the complex that may be, in part, Paleoproterozoic based on K-Ar ages, and in part related to Laramide faulting (Thacker and others, 2017). This evidence suggests that the high-grade regional metamorphism and deformation must have mostly ended prior to emplacement of the complex.

There is a well-developed contact metamorphic aureole at the base of the Stillwater Complex. These metasedimentary rocks did not experience regional penetrative deformation, and primary sedimentary structures are locally preserved (Page, 1977, 1979; Page and Koski, 1973; Page and Nokleberg, 1974; Page and Zientek, 1985). Although previously correlated with the low-grade Jardine metasedimentary sequence, the Stillwater aureole quartzites have detrital zircon age spectra that are distinct, indicating disparate source areas (fig. 24). Diagnostic contact metamorphic mineral assemblages include orthopyroxene–cordierite and anthophyllite–cordierite pelitic hornfels and fayalite–magnetite–quartz assemblages in banded iron formations, and a thoroughly recrystallized blue quartzite unit (Frost, 1982; Labotka and Kath, 2001; Page, 1977; Thomson, 2008; Vaniman and others, 1980). Calculated peak metamorphic conditions are ~2–3 Kbar and 800°C. In terms of regional tectonics, this is significant because the regionally metamorphosed crystalline rocks of the Beartooth massif on the south side of the Mill Creek–Stillwater fault zone in the Lake Plateau area have peak metamorphic conditions of 6–8 Kbar and 650°C (Richmond and Mogk, 1985). This break in metamorphic grade suggests that there is a pressure difference of at least 3 Kbars (~10 km vertical offset) between the Stillwater aureole and regional rocks of the Beartooth massif across the Mill Creek Stillwater fault zone (fig. 17). The tectonic setting of the Stillwater Complex has not been widely addressed, but Geissman and Mogk (1986) interpreted emplacement in an extensional half graben (similar to the Duluth Complex) that formed via wrench faulting along splays of the Nye–Bowler lineament in thick, tectonically stable Archean basement (fig. 17).

LATE ARCHEAN ADDITIONS TO AND MODIFICATIONS OF CONTINENTAL CRUST IN THE WYOMING CRATON (~2.7 GA)

The Wyoming Province continued to evolve in the latest Archean–earliest Proterozoic through (a) deposition and possible accretion of primarily low-grade metasedimentary sequences, and (b) addition of magmatic bodies (fig. 16).

The Precambrian rocks of the Gravelly Range have been mapped by numerous groups (Hadley, 1969; Hadley and others, 1980; Sumner and Erslev, 1988; Vargo, 1990; Witkind, 1972). The Gravelly Range contains the type section of the Cherry Creek Metamorphic Suite (CCMS). Peale (1896) and Heinrich and Rabbitt (1960) described the metasupracrustal units in the Gravelly Range as consisting of dolomitic marble, pelitic schists and phyllites, quartzites, banded iron formation, metabasites, and quartzofeldspathic gneisses. A mylonitic granitic gneiss has been dated at 2.7 Ga (U-Pb zircon; D'Arcy and others, 1990). In the northern part of the Gravelly Range, the CCMS experienced amphibolite–facies metamorphism (garnet–sillimanite and garnet–kyanite–staurolite assemblages;

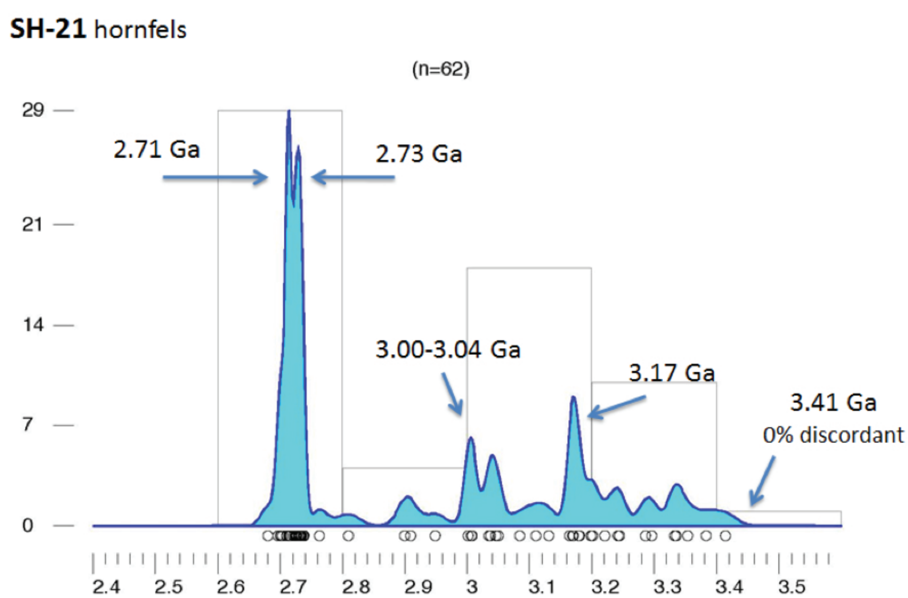

Figure 24. Groupings of detrital zircon ages (>2.8 Ga) and contact metamorphic ages of zircons that grew in the contact aureole of the Stillwater Complex (~2.71 Ga; *n* = 62; grains <10% discordant).

Heinrich and Rabbitt, 1960), whereas south of Ruby Creek (and the Yellowstone Talc Mine; see Berg and Gammons, 2020) the country rocks are of a distinctly lower metamorphic grade (greenschist to epidote-bearing amphibolite facies) and include phyllites and fine-grained schists (with finely interlayered quartzite, marble, BIF, and minor mafic amphibolite; Vargo, 1990). The CCMS is of major tectonic significance because it has long been used to correlate the Precambrian metasupracrustal rocks across the ranges of southwestern Montana, largely based on the distribution of marble units (Tansley and others, 1933; Winchell, 1914). Determining the age of the CCMS has proven to be elusive, but this sequence has been interpreted as a Late Archean stable platform assemblage (Gibbs and others, 1986). Detrital zircons from quartzites in the CCMS yield minimum ages in the range of 2.5–2.7 Ga, which we interpret as being derived, in part, from the immediately underlying mylonitic gneisses; smaller populations of zircons represent older source areas as previously described across the Wyoming Province (Mueller and others, 1998). In addition, a metavolcanic layer in the southern Madison Range ascribed to the CCMS by Mueller and others (1993) is also 2.7 Ga. A granodiorite sill intrudes correlative rocks to the CCMS in the southern Madison Range, and yielded an age of 2.58 Ga (Mueller and others, 1993). The interpretation of an "unconformable relation" between the CCMS and the "pre-Cherry Creek gneisses" was proposed by Erslev (1982), who reported a basal conglomerate in CCMS rocks that contained clasts of pre-Cherry Creek gneisses, and a relict granulite metamorphism and deformation in the gneisses that are not evident in the CCMS rocks. The U-Pb zircon age of ~2.7 Ga from the metavolcanic rock reported by Mueller and others (1993) could represent the time of deposition of these rocks in the Gravelly and southern Madison Ranges. Based on these observations, we conclude that the CCMS rocks (a) were deposited in a Late Archean, tectonically quiescent passive margin or interior basin, (b) were unconformably deposited on ~2.7 Ga and older gneisses, but prior to the ~2.58 Ga age of the sill, (c) the metamorphic grade is anomalously low for most of the CCMS rocks compared with other metasupracrustal sequences in southwest Montana, (d) the detrital zircon age distribution is distinct compared with other quartzite units in the northern Wyoming Province (compare with Mueller and others, 1988), and (e) it is inappropriate to correlate other metasupracrustal rocks in surrounding ranges (e.g., Tobacco Root Mountains, Ruby Range) with the "type" CCMS of the Gravelly Range. An alternate interpretation of a Paleoproterozoic deposition age of the CCMS was suggested by O'Neill (1998) and O'Neill and Christiansen (2004). O'Neill (1995) interpreted the CCMS as "…thrust faulted and folded, weakly metamorphosed sandstone, shale and iron-formation deposited in an Early Proterozoic foredeep" and based this hypothesis on a model from the Superior Province by Hoffman and others (1989).

The southern Madison Range is also host to a generation of Late Archean granitic orthogneisses (and a hornblende-bearing variant) with U-Pb zircon ages of 2.75–2.67 Ga, respectively, that intruded the older 3.1–3.3 Ga TTG suites (Mueller and others, 1993). A younger granodioritic gneiss crystallized at ~2.6 Ga, and this gneiss has trace-element abundances that are more suggestive of crustal melts than subduction activity and higher initial Sr isotopic ratios that suggest more involvement of older crust in their petrogenesis. An andesitic metavolcanic rock that was sampled in a low strain zone of the Madison mylonite zone (Erslev, 1983) is intercalated with biotite schists that have been correlated with the CCMS, and has a U-Pb zircon age of 2.67 Ga, thus confirming an Archean age of these metasupracrustal rocks (Mueller and others, 1993). It is interesting to note that magmatic rocks of this age also are present in the Teton and Wind River Ranges in more southerly regions of the Wyoming Province (Bagdonas and others, 2016; Frost and others, 1998, 2000, 2006a,b, 2016; Frost and Fanning, 2006).

Other exposures of ~2.7 Ga gneisses along the western margin of the Wyoming Province have been described:

(1) In the Blacktail Range, Clark (1987) identified quartzofeldspathic gneisses ranging in composition from granitic to tonalitic with subordinate dioritic compositions, and interpreted these as orthogneisses. The gneisses are intercalated with minor amphibolites, ultramafic rocks, calcareous gneisses and marbles, pelitic schists, and quartzites. These gneisses are actually the type section of the "Dillon Gneiss" (Heinrich, 1950; Scholten and others, 1955). Wilhelmi and others (2017) obtained U-Pb zircon ages of the orthogneisses in the range of 2.74–2.77 Ga, with some inherited zircons with ages of ~3.2 Ga. Migmatitic units record a period of high-grade metamorphism and anatexis at 2.55–2.45 Ga.

(2) The age of the quartzofeldspathic gneisses of the Armstead anticline near the Clark Canyon Reservoir have been determined by Mueller and others (2012) to be 2.73 Ga, with metamorphic overprints of 2.45 and 1.8 Ga. The primary crystallization age of these rocks (~2.70–2.77 Ga) is distinctly younger than the vast majority of Archean basement exposed in the Tobacco Root, Highland, and Ruby Ranges, but may represent recycling of this older basement based on the presence of some inherited zircons, Sm-Nd model ages, and distinct negative Eu anomalies (Mueller and others, 2012).

Along the northern margin of the Wyoming Province, exposures of Precambrian rocks in the Little Rocky Mountains contain a variety of quartzofeldspathic gneisses, amphibolite to transitional granulite facies metabasites, and minor pelitic schists. These rocks were originally confirmed as Archean (Peterman, 1981b) based on Rb-Sr whole-rock data (2,750 Ma). Gifford and others (2018) obtained U-Pb zircon ages on the gneisses in the range from 2.4 to 3.3 Ga, with most ages 2.6 to 2.8 Ga. This sequence of rocks has been interpreted as representative of the Medicine Hat Block, rather than the Wyoming Province, based on differences in the distribution of ages and geochemical characteristics. The Little Rocky Mountain exposures and crustal xenoliths (as discussed below) provide some of the only windows to Archean crystalline rocks that may be exotic to the Wyoming Province as a result of emplacement during the Paleoproterozoic collision along the Great Falls Tectonic Zone.

FINAL ARCHEAN TO PALEOPROTEROZOIC TECTONOTHERMAL EVENT, 2.55–2.45 GA

The last record of Archean (to earliest Paleoproterozoic) tectonism and magmatism in the northern Wyoming Province occurred ~2.55–2.45 Ga ago and involved (a) reworking of older units through local anatexis and (b) overprinting by regional tectonothermal events along the western margin of the Province (fig. 25). The nature of the 2.45–2.55 Ga high-grade tectonothermal event is poorly understood, but produced local zones of upper amphibolite to granulite facies metamorphism and local anatectic melts across the western half of the Wyoming Province in Montana. In the North Snowy Block, a leucogranite sill produced a U-Pb zircon age of 2.55 Ga, which is interpreted as the stitching pluton emplaced along

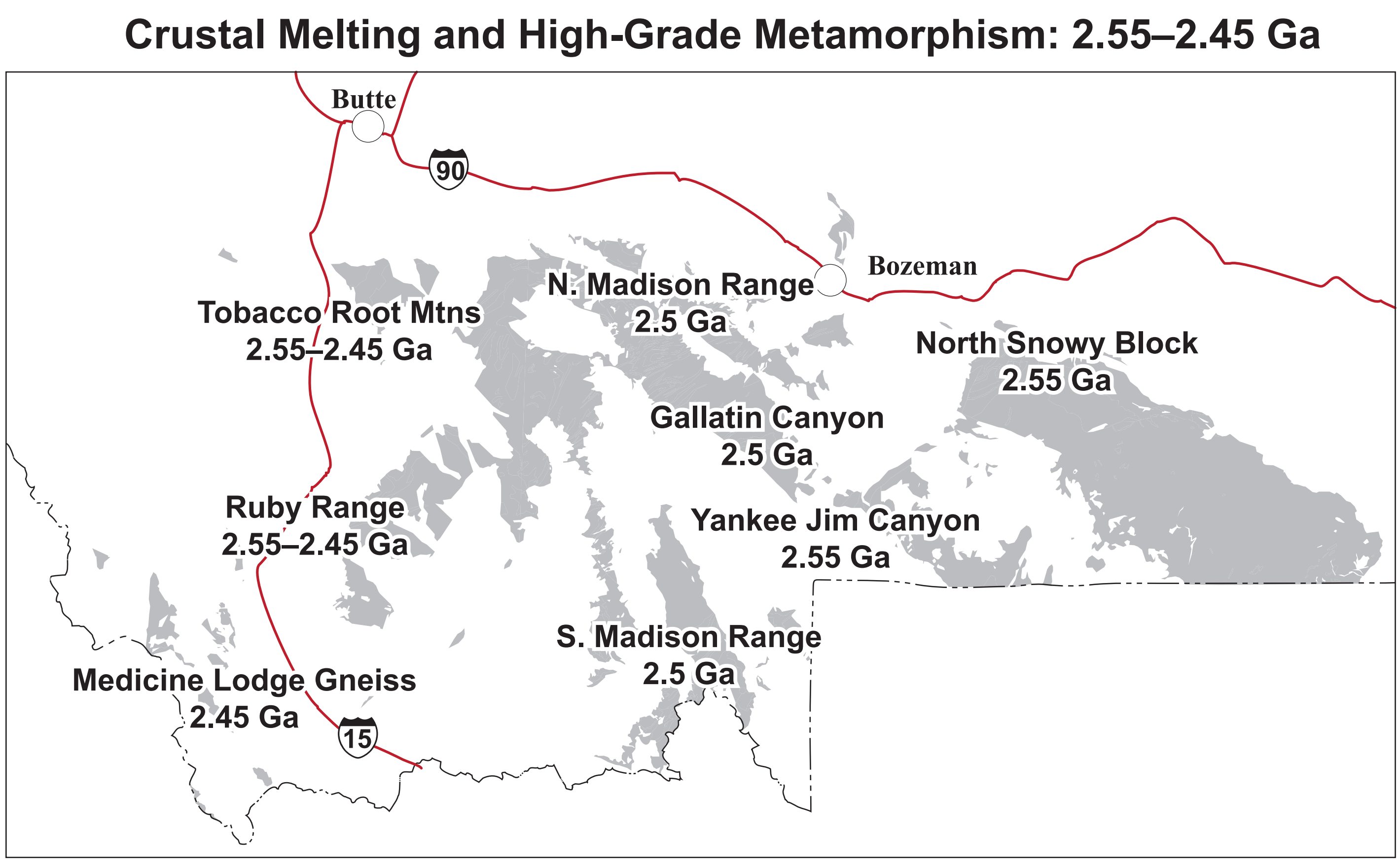

Figure 25. Occurrences of basement rocks that have experienced local anatexis and/or high-grade metamorphism in the interval 2.55–2.45 Ga ago.

shear zones that represent the last Archean tectonism in the region (Mogk and others, 1988). Similarly, a leucogranite with a U-Pb zircon age of 2.55 Ga in the Spanish Peaks area of the northern Madison Range represents the last Archean magmatic event in this area (Weyand, 1989). These leucogranites have been interpreted as crustal melts produced as a result of post-collisional, adiabatic decompression melting. Anatectic melts with U-Pb zircon ages of 2.42 Ga have been identified in the Gallatin River canyon (Mueller and others, 2011), formed by partial melting of the ~3.2 Ga TTG gneisses (Mogk, 1992). A gneiss from the Tendoy Mountains has a primary zircon age of 2.45 Ga (Kellogg and others, 2003; Mueller and others, 2016). As more geochronologic and thermochronologic data emerge, there is a growing recognition of a tectonothermal event at ~2.45 Ga that is recorded in the western Wyoming Province, e.g., reported for the Ruby Range (Roberts and others, 2002), Tobacco Root Mountains (Cheney and others, 2004a; Brady and others, 2004), Blacktail Range (Wilhelmi and others, 2017), Medicine Lodge Gneiss (Mueller and others, 2012, 2016), and as far south as the Wasatch Range of Utah (Mueller and others, 2011).

ARCHEAN CRUSTAL XENOLITHS

Further evidence of the extent, composition, and architecture of the Archean basement of Montana can be found in suites of crustal xenoliths recovered from igneous units in the Montana Alkalic Province within the Great Falls Tectonic Zone (Irving and Hearn, 2003) and from lavas of the Snake River Plain. Gifford and others (2014) reported on a diverse suite of quartzofeldspathic gneiss xenoliths that have ages of ~2.5 Ga and 1.8 Ga. Significantly, this suite of xenoliths is interpreted to have a source from the Medicine Hat Block that was juxtaposed with the Wyoming Craton during the Paleoproterozoic along the Great Falls Tectonic Zone (see Harms and Baldwin, 2020). Other locations of documented Archean xenoliths of felsic to intermediate composition gneisses have been reported from the Sweetgrass Hills, Highwood Mountains, and Bears Paw Mountains (Barnhart and others, 2012; Blackburn and others, 2011; Bolhar and others, 2007; Davis and others,1995; Mahan and others, 2012).

DENOUEMENT: THE END OF THE (ARCHEAN) EON

A major period of tectonic quiescence of ~500 Ma followed the 2.45 Ga event, recognized globally as a crustal age gap (Condie and others, 2009b). The onset of Paleoproterozoic tectonism along the Great Falls Tectonic Zone and Trans Hudson orogen (see Harms and Baldwin, 2020) thoroughly reworked the Archean basement rocks along the margins of the Wyoming Province because of the intensity of metamorphism and deformation, making it difficult to discern earlier stages of Archean tectonomagmatic events. This tectonism is recorded in the arc magmatism of the Little Belt Mountains ~1.86 Ga (Mueller and others, 2002; Vogl and others, 2002; Foster and others, 2006) and as metamorphic and deformational reworking of Archean crust throughout much of southwest Montana. Termed the “Big Sky Orogeny” (1.78–1.72 Ga) based on studies in the Tobacco Root Mountains (e.g., Brady and others, 2004; Harms and others, 2004b; Roberts and others, 2001), it has been applied to rocks in the Ruby Range, Highland Mountains, and Tendoy Range. This event has also overprinted Archean rocks of the southern Madison Range (Madison mylonite zone; Erslev, 1983; Erslev and Sutter, 1990), the northern Madison Range in the Spanish Peaks area (Condit and others, 2015, 2018), and is recognized through reset K-Ar biotite ages in the Gallatin Range (Giletti, 1966, 1971) and North Snowy Block (Reid and others, 1975). These Paleoproterozoic modifications largely impacted the margins of the Wyoming Province, but the interior of the Wyoming craton was largely unaffected.

SUMMARY

The Archean basement of the northern Wyoming Province in Montana has recorded a long and glorious history of genesis and evolution of the continental crust and its attendant mantle keel. A model for the earliest stages of crustal genesis and evolution is presented in figure 26. Major geologic events include:

- Formation of the earliest crust from the mantle occurred at 4.0 Ga and is represented by detrital zircons in quartzites in the Precambrian basement across the northern Wyoming Province. These crustal rocks are interpreted to have been of largely mafic composition produced in an Archean plume analog. This upwelling mantle regime may have rapidly

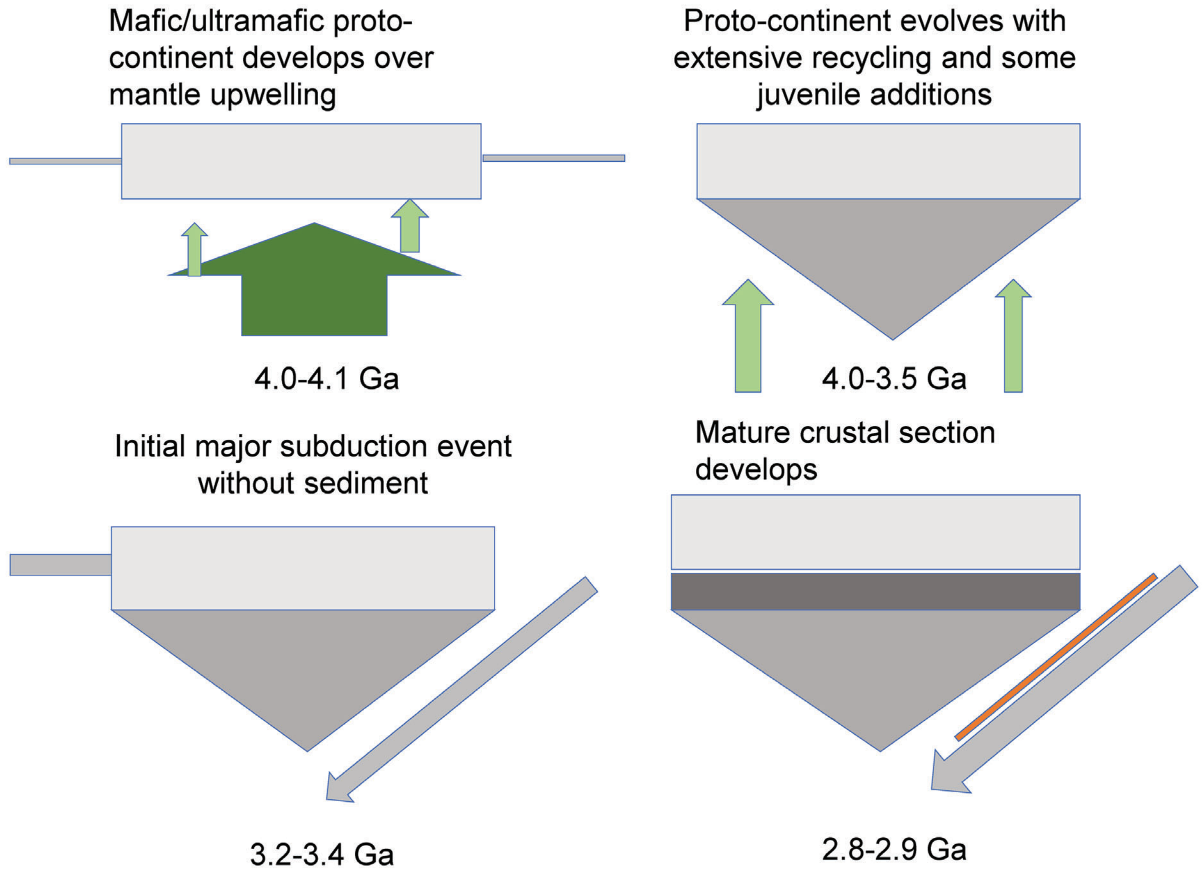

Figure 26. A model of genesis and evolution of Archean continental crust, northern Wyoming Province. Separation of initial mafic/ultramafic crust ~4.0 Ga ago over a mantle plume. Recycling of this crust with minor juvenile additions ~4.0–3.5 Ga. Partial melting of initial mafic crust (with garnet present) as a result of subduction (with little sediment involvement) to produce the oldest TTG suite ~3.5–3.2 Ga ago. After a period of tectonic quiescence (and deposition of stable platform sediments), a second subduction event that included partial melting of metasedimentary rocks, produced a second magmatic arc in the BBMZ.

generated more felsic crust via re-melting and recycling of the original mafic crust, which may be the primary source of the oldest zircons. This interval of original crust and mantle lithosphere differentiation extended to 3.5 Ga. Other non-subduction models for early crustal genesis include stagnant-lid and heat pipe models that have been proposed for other Archean crust (e.g., Moore and Webb, 2013; Harris and Bédard, 2014; Bédard, 2018). This is also the time when the high U/Pb character of the craton was established because high U/Pb ratio magmas occur most often in anhydrous mantle melting environments as opposed to the more hydrous conditions in subduction zones (Mueller and others, 2010, 2014b)

- The oldest rocks exposed at the surface are ~3.6 Ga TTG gneisses, which ushered in an extended period of formation of felsic continental crust (3.6–3.0 Ga), with peak production at 3.2–3.3 Ga across the entire northern Wyoming Province (Beartooth, Madison, Tobacco Root, Ruby Ranges). These rocks typically have trace element contents consistent with formation in an arc environment, and εHf and whole-rock Pb isotopic data indicate an increasing component of juvenile material was added to the crust between 3.5 and 3.2 Ga. The 3.2 Ga episode provides the first evidence of subduction-type tectonics in the geologic record of the northern Wyoming Province. Magmatism was episodic and occurred over a long period of time (~400 Ma). The northern Wyoming Province began an extended period of progressive cratonization at the end of this crust-forming event, establishing a thick tectosphere that only permitted tectonic remobilization along the margins in the Paleoproterozoic Great Falls Tectonic Zone, Cheyenne Belt (Wyoming), Trans-Hudson Orogen; and Farmington Zone (Utah) (also see Harms and Baldwin, 2020). This thick, stable crust permitted deposition of mature platform-type sedimentary rocks. Moreover, establishment of this first generation of silicic continental crust provided the foundation on which the 2.8 Ga BBMZ magmatic arc was built.

- Between ~3.2 and 2.9 Ga in the Beartooth Mountains, a period of tectonic quiescence allowed the formation of stable platform type sedimentary environments. In the eastern Beartooth Mountains, these rocks were tectonically mixed with the older gneisses and metamorphosed to upper amphibolite to granulite facies during the Beartooth Orogeny (~2.8 Ga). This metamorphism was accompanied by emplacement of the ~2.8 Ga LLMC, which contributed to the thermal budget of this metamorphic event. To the west, in the Tobacco Root Mountains and Ruby Range, metasupracrustal rocks including marble, pelitic schist, quartzite, banded iron formation, and related metabasites have also been interpreted as having protoliths deposited in a stable platform type environment. This sequence of rocks was interpreted as being in an unconformable relationship with the underlying 3.5–3.2 Ga quartzofeldspathic gneisses, based on youngest detrital zircon U-Pb ages in the associated quartzites (Mogk and others, 2004). One cycle of metamorphism and anatexis may have occurred ~2.7 Ga ago (Mueller and Cordua, 1976; James and Hedge, 1980). These metasupracrustal rocks in the western Wyoming Province were subjected to episodes of high-grade Paleoproterozoic metamorphism and deformation that has obscured evidence of early metamorphic cycles. This overprinting most likely occurred in two separate episodes, one at ~2.45 Ga based on ^{207}Pb–^{206}Pb step-leach garnet ages (Roberts and others, 2002) and ages of monazite inclusions in garnets (Cheney and others, 2004a) and the second in the Big Sky phase of the Great Falls Orogeny at 1. 78 Ga (Cheney and others, 2004a; Harms and Baldwin, 2020).
- A second major magmatic event generated the Beartooth–Bighorn magmatic zone at ~2.9–2.8 Ga. This event generated the voluminous calc-alkaline granitic and intermediate composition (TTG) rocks of the Beartooth and Big Horn Mountains. These rocks have strong geochemical affinities with modern-day magmatism in a continental arc setting and help define the BBMZ.
- The Neoarchean intrusion of the Stillwater Complex at 2.709 Ga marked the cessation of regional penetrative deformation and metamorphism in the eastern part of the northern Wyoming Province.
- However, in the western Wyoming Province, minor blocks of ~2.7 Ga quartzofeldspathic gneisses formed in the southern Madison Range, Blacktail Mountains, Gravelly Range, and Armstead Anticline areas. Granodioritic magmas were produced in the southern Madison Range at 2.7 and 2.6 Ga. Deposition of the Cherry Creek Metasedimentary Series must have occurred in this time frame, based on the minimum age of detrital zircons in quartzites from this sequence, and the age of an interlayered metavolcanic unit (~2.7 Ga).
- A last gasp of tectonism in the Neoarchean to earliest Paleoproterozoic produced minor amounts of leucogranites at ~2.55 Ga in the North Snowy Block, Gallatin Canyon, and Tobacco Root Mountains, and a high-grade metamorphic event associated with some magmatism has been documented at 2.45 Ga in the Ruby, Tobacco Root, Tendoy, and Highland Ranges.

Exposures of Archean basement of the northern Wyoming Province preserve one of the best documented records of continental crustal formation in the world. The Precambrian geologic record in this area spans roughly the first third of Earth's history and contains evidence of the earliest stages of crustal genesis. Subsequent stages of crustal evolution provide evidence of magmatic and tectonic processes that further contributed to, and modified, this ancient continental crust. These rocks provide the foundation for understanding the continued geologic history of this area in the Proterozoic and Phanerozoic as documented in the following chapters of this volume.

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