The Plume to Plate Transition: Hadean and Archean Crustal Evolution in the Northern Wyoming Province, U.S.A.

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Abstract

The 2.8–4.0 Ga record of crustal evolution preserved in the northern Wyoming Province of western North America provides insight into the role of plume- and plate-regimes in the generation of Hadean and Archean continental crust, and the associated elemental depletion of the primitive mantle. The most complete record is exposed in the Beartooth Mountains (Montana-Wyoming), which lie within the Beartooth-Bighorn magmatic zone (BBMZ) sub-province of the Wyoming Province. The BBMZ (> 100,000 km^2) is characterized by a single, voluminous suite of Mesoarchean (~ 2.8–2.9 Ga) TTG (tonalite-trondhjemite-granodiorite) plutonic and metaplutonic rocks. In the Beartooth Mountains these Mesoarchean rocks are exposed along an ~ 100 km E-W cross-section, along which they intrude greenschist grade turbidites in the west (South Snowy block) and high grade, older gneisses in the east (Beartooth Plateau block). The most complete assemblage of pre-2.8 Ga crust is preserved as enclaves within the plutonic Mesoarchean rocks of the Beartooth Plateau block. These older gneisses consist of 3.1–3.5 Ga, tectonically interleaved

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meta-plutonic (principally TTG and associated migmatites) and metasupracrustal lithologies (e.g., quartzites, schists, banded iron formation, and a range of paragneisses).

The arc-like elemental abundances and enriched Pb and Nd isotopic systematics of the Mesoarchean magmatic suite and the 3.1–3.5 Ga older enclaves in conjunction with Lu-Hf data from 3.3 to 4.0 Ga detrital zircons suggest a model of crustal evolution that began with a Hadean, mafic proto-continent that likely developed over a zone of mantle upwelling. Lu-Hf systematics of the 3.6 to 4.0 Ga zircons suggest substantial recycling within the proto-continent in this interval, and that this recycling involved a low Lu/Hf (~0.1) system. A ubiquitous component of 3.2–3.4 Ga detrital zircons with more juvenile Hf isotopic compositions occurs throughout the northern Wyoming Province and suggests a major period of crustal growth and generation of TTG-suite rocks from more depleted sources. Following a period of relative quiescence (2.8–3.1 Ga) in the BBMZ, late Mesoarchean arc magmatism (TTG, adakites, etc.) largely reconstituted the older crust during a relatively brief period between 2.79 and 2.83 Ga; it has remained essentially undisturbed since that time.

Placing this history in a global context suggests that Hadean-Eoarchean crust formed in diachronous and spatially diverse environments that were both plume-like (e.g., Pilbara, northern Wyoming Province) and subduction-like (e.g., West Greenland). The relative importance of plume-type crustal growth declined and subduction-type growth increased through time as a consequence of a progressive decline in terrestrial heat production and mantle potential temperature, with a concomitant increase in hydrous mantle melting in subduction zones.

2.1 Introduction

One of the most poorly constrained and geochemically critical periods in earth history is the ~700 Ma between accretion (~4.5 Ga) and formation of the first well preserved felsic crust (~3.8 Ga). When considering the specific question of the formation of felsic crust, many authors have speculated about the nature of Hadean geodynamics and their relationship to modern geodynamic systems. Some hypotheses call upon extraterrestrial analogs (e.g., stagnant lid convection; Kamber et al. 2003; Debaille et al. 2013), while others call for modified versions of plate tectonics (e.g., thicker, more numerous, slower plates; faster plates, shallower subduction, etc.; Hargraves 1986; Abbott et al. 1994; Korenaga 2006; Herzberg and Rudnick 2012). These and many other studies (e.g., Wooden and Mueller 1988; Wyman and Kerrich 2002; Kamber et al. 2003; Smithies et al. 2005; Valley et al. 2005; Hamilton 2003; Harrison et al. 2008; Shirey et al. 2008; Wittig et al. 2008; Nutman and Friend 2009; Nebel-Jacobsen et al. 2010; Keller and Schoene 2012) have used both empirical and theoretical approaches to reach significantly different conclusions regarding the dominant geodynamic processes and related geochemical impacts associated with the creation of the earliest continental crust, sub-continental lithospheric mantle (e.g., tectosphere, keels, etc.), and elemental depletion of the primitive mantle.

In this contribution, we focus on the 4.0–2.8 Ga record of crustal evolution in the northern part of the Wyoming Province (NWP, Condie 1976; Wooden et al. 1988; Mogk et al. 1992; Figs. 2.1 and 2.2). Evidence from this crust supports the contention that Earth's earliest continents evolved in two separate, but contemporaneous, regimes: one driven by plate subduction and the other by mantle upwelling. Much as the planet forms crust today in both subduction and mantle plume

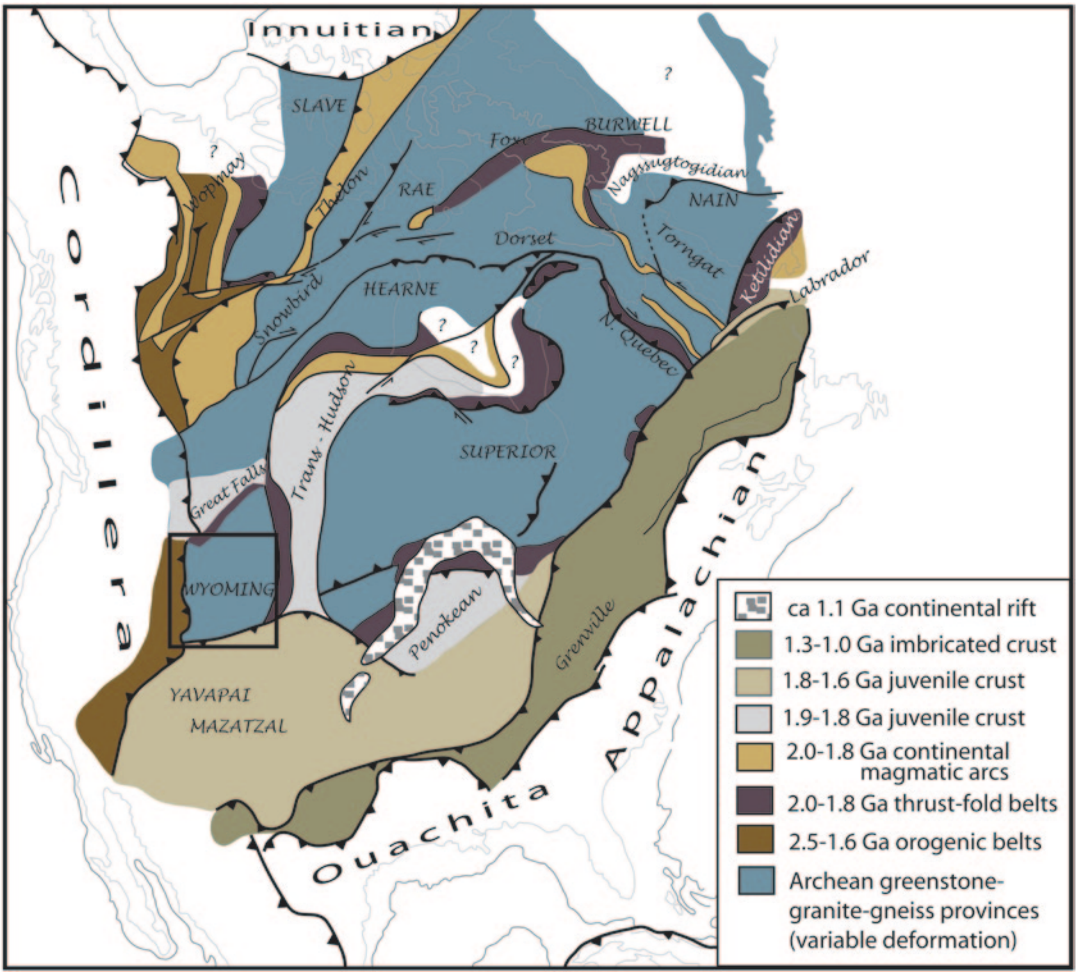

Fig. 2.1 Precambrian age-provinces of North America showing location of Wyoming Province (after Hoffman 1989)

systems, so it likely was in the Hadean-Eoarchean. The primary difference compared to tectonics on the modern Earth is the relative contributions of the two mechanisms, i.e., a higher proportion of subduction-derived crust today compared to the early Earth (e.g., Smithies et al. 2005; Van Kranendonk 2011; Mueller et al. 2010).

2.2 The Northern Wyoming Province

The northern part of the Wyoming Province comprises two primary subdivisions (Mogk et al. 1992; Chamberlain et al. 2003; Mueller et al. 2005; Mueller and Frost 2006; Fig. 2.2): (1) the BBMZ (Beartooth-Bighorn magmatic zone) extends over an area of more than 100,000 km^2 and is composed primarily of Mesoarchean metaplutonic rocks of the TTG (tonalite-trondhjemite-granodiorite) association, but contains enclaves of older rocks (as old as 3.5 Ga in the Beartooth Range); and (2) the MMT (Montana metasedimentary terrane) contains a range of Neoarchean metasedimentary associations interleaved with older (3.2–3.5 Ga) gneisses (e.g., Mueller et al. 1993, 1996, 2004; Krogh et al. 2011). A third tectonic domain, the GFTZ (Great Falls tectonic zone), is comprised primarily of MMT lithologies overprinted in the Paleoproterozoic (~1.8 Ga) during suturing of the NWP to the Medicine Hat block. Numerous authors (O'Neil and Lopez 1985; Mueller et al. 2002, 2005; Roberts et al. 2002;

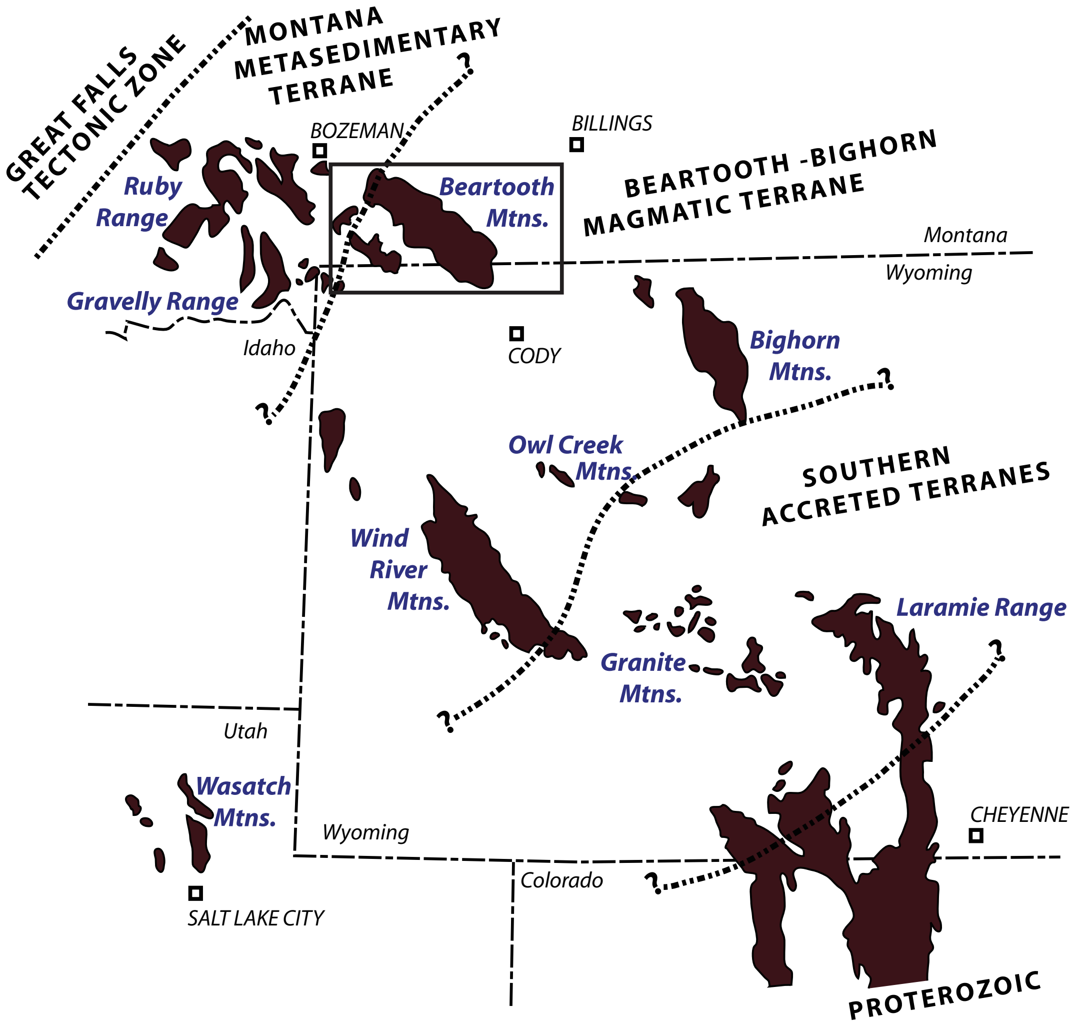

Fig. 2.2 Outline of major exposures of crystalline basement and generalized approximate sub-province boundaries in the Wyoming Province: Southern accreted terranes; Beartooth-Bighorn magmatic zone; and Montana metasedimentary terrane (Mogk et al. 1992; Chamberlain et al. 2003)

Brady et al. 2004; Foster et al. 2006, 2012) have discussed the evolution of the GFTZ and its impact on the MMT, so it will not be addressed here.

The most voluminous rocks formed during the Hadean-Archean in the northern Wyoming Province are the Mesoarchean TTG gneisses (metagranitoids) that dominate the BBMZ. The metagranitoids of the BBMZ are linked by several important characteristics in addition to their primary Mesoarchean age: (1) uniquely enriched Pb isotopic compositions (elevated $^{207}Pb/^{204}Pb$ for a given $^{206}Pb/^{204}Pb$) and negative initial Nd isotopic compositions; (2) current exposures and parageneses that reflect amphibolite to granulite grade metamorphism, indicative of upper- to mid-crustal conditions; and (3) seismic images that show a continuity of relatively thick crust (~50 km) with a distinctive, thick (10–25 km), high velocity lower crust (Vp > 7 km/sec), and (4) a mantle keel of > 250 km thickness (e.g., Wooden and Mueller 1988, Mueller and Wooden 1988; Frost 1993; Frost et al. 1998; Henstock et al. 1998; Clowes et al. 2002; Gorman et al. 2002; Chamberlain and Mueller 2007; Yuan and Romanowicz 2010; Tian and Zhao 2012).

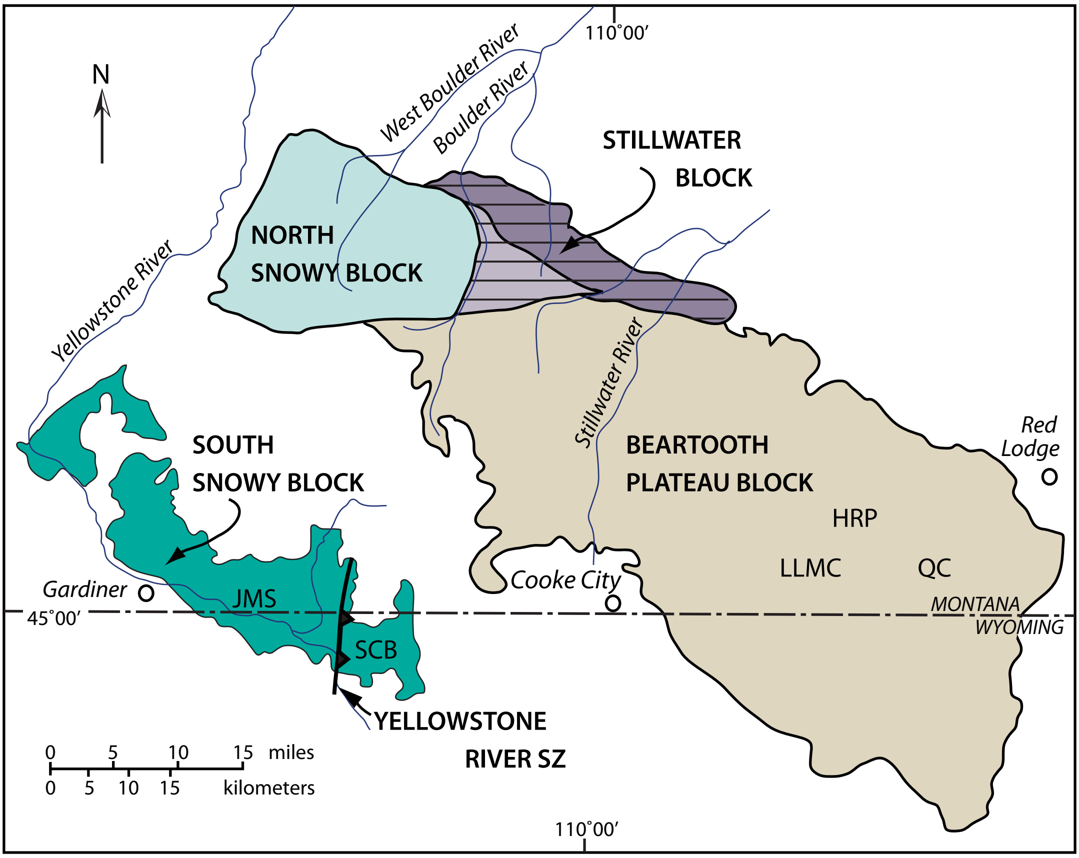

Fig. 2.3 Outline of the Beartooth uplift with individual blocks labeled. The *darker color* in the Stillwater block is the Stillwater Layered Igneous Complex (2.7 Ga). The LLMC and its temporal equivalents occur throughout the Beartooth Plateau and South Snowy blocks. See text for discussion of SCB (Slough Creek batholith), JMS (Jardine Metasedimentary Sequence), and Yellowstone River shear zone (SZ); *white areas* indicate Phanerozoic cover

These geochemical and geophysical characteristics are all applicable to crust comprising the Beartooth Mountains (Montana-Wyoming). Although Mesoarchean crust is contiguous throughout the Beartooth Mountains, this crust can be divided into several blocks with distinct geology (Fig. 2.3). This contribution will focus on two of the major blocks: the Beartooth Plateau and South Snowy blocks. The Beartooth Plateau block comprises most of the southeastern part of the Range and is lithologically dominated by Mesoarchean TTG plutonic and metaplutonic igneous rocks typical of the BBMZ. This association is exemplified by the 2.79–2.83 Ga Long Lake magmatic complex (LLMC; Fig. 2.3; Mueller et al. 2010). The LLMC contains enclaves of older, high-grade, metamorphic rocks (to 3.5 Ga); some of which contain detrital zircons to 4.0 Ga (Mueller et al. 1998; Valley et al. 2005; Mueller and Wooden 2012; Maier et al. 2012). The South Snowy block comprises most of the southwestern part of the Range. It is similar to the Beartooth plateau block in terms of its plutonic components, which were emplaced coevally with the LLMC, but distinct because these plutons intruded and partially assimilated metasedimentary rocks of greenschist-to-amphibolite grade (Mogk et al. 2012). Consequently, the South Snowy and Beartooth Plateau blocks expose a cross section of crustal levels that reflect the development of a Mesoarchean marginal arc built on Eoarchean-Hadean crust.

Beartooth Plateau Block Early work by Poldervaart and students (e.g., Eckelmann and Poldervaart 1957; Harris 1959; Larsen et al. 1966; Rowan 1969; Skinner 1969; Spencer 1969; Butler 1969) described and mapped the varied lithologies and structures throughout the Beartooth Plateau block. They interpreted the quartzofeldspathic gneisses as classic products of "granitization". Application of modern analytical approaches, primarily ion probe (specifically SHRIMP) for U-Pb geochronology and ICP techniques for trace elements, however, has led to the recognition and characterization of a very different history for these Archean rocks (e.g., Mueller et al. 2010; Mueller and Wooden 2012). The Hadean-to-Archean geologic evolution of the Beartooth Plateau block is discussed below in three general sections: (1) the earliest or "pre-rock" record interpreted from the chemical and isotopic compositions of detrital zircons; (2) the transitional period from ~3.1 to ~3.6 Ga that is dominant in the detrital zircon record; and (3) the well-characterized evolution of the 2.8 Ga, arc-related, magmatic and deformational event.

1. The earliest record of crustal evolution preserved in the Wyoming Province is derived from detrital zircons from the Beartooth Plateau block (Fig. 2.3; Mueller et al. 1992; Mueller et al. 1998; Mueller and Wooden 2012; Maier et al. 2012). These zircons occur in quartz-rich metasedimentary rocks that are intercalated within multilithologic metamorphic assemblages intruded by the prevalent Mesoarchean plutonic rocks of the LLMC (Mueller et al. 1998, 2010). Lithologies include quartzofeldspathic gneisses, metapelites, banded iron formation, migmatites, quartzites, and mafic and ultramafic amphibolites (Henry et al. 1982; Mueller and Wooden 2012; Maier et al. 2012).

U-Pb ages determined for detrital zircons via ion microprobe (SHRIMP) are dominated by 3.2–3.4 Ga grains in all samples (Mueller et al. 1998). Detrital grains younger than 3.1 Ga were not documented, which implies deposition after 3.1 Ga, but before unroofing of the extensive 2.8 Ga plutonic rocks. The critical observations noted in previous work on detrital zircons from these rocks and pertinent to Hadean and Mesoarchean crustal evolution include: (1) zircons > 3.5 Ga are relatively abundant (~25 % of the zircons analyzed by Mueller et al. 1998) and ages extend in a continuum from ~3.3 Ga to 4.0 Ga (Mueller et al. 1998); (2) O-isotopic compositions of zircons from a sub-set of these same quartzites have δO^{18} values that are: (i) only slightly elevated relative to zircons from mantle-derived melts, (ii) similar to those in the ancient 4.0–4.4 Ga zircons from Australia (Jack Hills), and (iii) consistent with very limited intracrustal recycling of surface materials into the magmas from which the zircons originally crystallized (Valley et al. 2005); and (3) Hf isotopic data for several multi-grain zircon separates from these rocks (Stevenson and Patchett 1990) implied the presence of older Archean crust in the Beartooth area.

More recently, Mueller and Wooden (2012) reported extensive U-Pb, trace element, and Lu-Hf data for 3.3–4.0 Ga detrital zircons from quartzites within these metamorphic enclaves. In that study trace-element analyses were performed at the same locations within individual zircons that were used for the U-Pb geochronologic analyses. Analyses of Lu-Hf systematics were then made at the same locations used for U-Pb and/or trace element measurements in order to maximize the probability that all measurements were made on material in the same domain of the zircon (identified using cathodoluminescense). These analyses revealed a clear pattern of continuously decreasing minimum εHf values (parts in 10^4 deviation from the chondritic reservoir of Bouvier et al. 2008) in each 100 Ma segment between 4.0 and 3.6 Ga (Fig. 2.4). Subsequent to about 3.5–3.6 Ga, the minimum εHf values begin to increase, reaching a maximum at ~3.3 Ga. Utilization of the recently proposed BSE (bulk silicate earth) Lu-Hf parameters of Bizzaro et al. (2012), rather than those of Bouvier et al. (2008), would alter the absolute values of εHf, but would not change the pattern of decreasing values with decreasing age in Fig. 2.4.

The most important aspect of the positive correlation of initial εHf and age in Fig. 2.4 is that a single evolution line conforms to the minimum εHf values of individual zircons for the period from 3.6–4.0 Ga. Using these minimum values along with the constraint that there was no crust

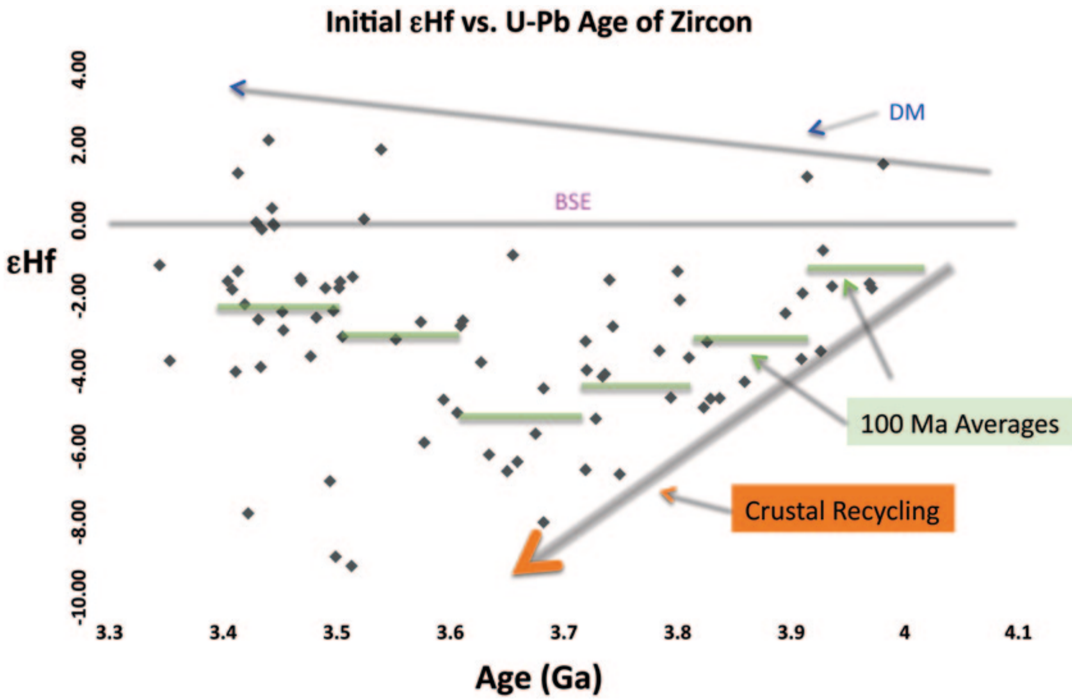

Fig. 2.4 Age ($^{207}Pb/^{206}Pb$ of zircon) vs. initial εHf showing the continuity of ages for detrital zircons during the 3.3–4.0 Ga period, the consistently decreasing values of εHf from 4.0 to 3.5 Ga, and the increasing initial εHf values post-3.5 Ga. The line along the lower limit of εHf values corresponds to a Lu/Hf ratio of 0.09. DM line is from Mueller et al. (2008) and CHUR/BSE from Bouvier et al. (2008). Horizontal bars are the averages of the initial εHf values for each 100 Ma increment. After Mueller and Wooden (2012)

significantly older than ~4.0 Ga in the system (i.e., the evolution line should not intersect the primitive or depleted mantle curves much older than the age of the oldest zircon, 4.0 Ga), yields a slope corresponding to a Lu/Hf ratio of ~0.10. This is a critical value for four reasons: (1) Using the most negative values provides the best approximation of the evolution of pre-existing crust (i.e., closest to 100% crustal melt), (2) It is only slightly above the value for current, average continental crust (0.081) proposed by Rudnick and Gao (2003), (3) It suggests a similar evolution path to the older zircons from the Jack Hills (e.g., Harrison et al. 2008; Kemp et al. 2010), and (4) It is lower than the typical values for modern arc or MORB magmas (~0.20; e.g., Pfander et al. 2007; Porter and White 2009; Wilbold et al. 2009; Arevalo and McDonough 2010; Nebel et al. 2011).

The difference between modern arc, MORB, and crustal Lu/Hf values is expected in light of the continual depletion in incompatible elements, including HFSE (high field-strength elements), characteristic of the evolution of the depleted mantle (e.g., Salters and Stracke 2004). Consequently, the modeled Lu/Hf value of ~0.1 for the period from 3.5–4.0 Ga in the NWP strongly suggests the source rocks for these zircons were derived from a more primitive (much less depleted) mantle than modern MORB or arc melts, or that garnet formed in the residuum of these melts and led to lower Lu concentrations (and lower Lu/Hf ratios). Trace element data for these zircons, however, suggest it is unlikely that parent magmas were in equilibrium with garnet (Mueller and Wooden 2012).

A second significant aspect of these data is that they define an overlapping continuum of ages with no significant peaks. Although the lack of discernable age-concentrations may reflect inadequate sampling for the time interval, the lack of strong age-concentrations is similar to the data from the Jack Hills (e.g., Harrison et al. 2008), but contrasts with other ancient detrital zircon suites such as those from the Rae Province, Canada (Hartlaub et al. 2006); Tanzania (Kapete et al. 2012); and the Limpopo Belt (Zeh et al. 2008) that also show continua of ages, but with discernable age-concentrations. The presence or absence of discernable concentrations (peaks) in the age spectra has implications for whether magmatic additions to individual segments of Hadean-Eoarchean crust followed a pattern of long-term episodicity similar to the patterns derived from younger detrital zircon suites that have been interpreted to reflect episodic plate tectonic-driven orogeny on the 100 Ma time-scale (e.g., Condie 2000) or to extended periods of diapiric upwelling. Although extended episodes of mantle upwelling (>100 Ma) are rare on Earth today, numerical simulations by Robin and Bailey (2009) show that repeated diapiric upwellings and associated density driven overturns of Hadean-Eoarchean crust can be expected to occur at intervals of as few as 10 Ma, which would yield a record that would be difficult to discern from an absolute continuum of ages. Similarly, Moyen and van Hunen (2012) suggest that Archean plate tectonics was characterized by short-lived subduction cycles of only a few million years, which could also produce an essentially continuous record.

2. The transition from the positive age-εHf relationship defined by the 3.6–4.0 Ga detrital zircons to the negative age-εHf from 3.2–3.5 Ga marks increasing contributions from more depleted (juvenile) sources to crustal growth. Gneissic and migmatitic rocks (TTG suite) and a range of metasupracrustal rocks (meta-igneous and metasedimentary) that formed during this transitional period are preserved at varying scales within the ~2.8 Ga LLMC, particularly in the Beartooth Plateau block. In the Beartooth Plateau block these metamorphosed supracrustal rocks include metabasites, peraluminous gneisses (migmatites), meta-ironstones, meta-ultramafic rocks, pelitic to psammatic schists, and quartzites, in addition to metaplutonic quartzofeldspathic gneisses (e.g., James 1946; Henry et al. 1982; Maier et al. 2012). The individual lithologies have been tectonically mixed along high-grade ductile shear zones, and multiple stages of disharmonic folding developed prior to emplacement of the LLMC. Many of these lithologies preserve petrologic evidence of one, and possibly two, stages of granulite facies metamorphic events with an amphibolite facies overprint that is commonly associated with local mylonitization (Fig. 2.5).

Ages for these pre-2.8 Ga rocks throughout the Range are difficult to determine because of the multiple metamorphic events and complex paragenetic sequences (e.g., Mogk and Henry 1988; Mueller et al. 1996). Quartzofeldspathic gneisses and migmatites that have been examined for their U-Pb zircon systematics suggest a range of ages from 3.5 Ga to 3.1 Ga (Fig. 2.6). Whole-rock Sm-Nd data yield a range of depleted mantle model ages (T_{dm}) that are often older than the intrusion age of individual lithologies with a maximum of 4.1 Ga (Fig. 2.7). Uranogenic common Pb (^{207}Pb-^{206}Pb) isotopic ratios show a general correlation on an isochron diagram along a reference line corresponding to an age of ~3.2 Ga (Fig. 2.8). This "age" is clearly the result of mixing among rocks of different ages as well as partial re-equilibration during metamorphism(s), but still provides a strong indication that these rocks are older than 2.8 Ga. The combination of the Pb-Pb array, which lies above the average crust of Stacey and Kramers (1975), and Sm-Nd whole-rock data (T_{dm} much older than crystallization age in some cases) shown in Figs. 2.7 and 2.8 indicate that some of the rocks that formed in the 3.1–3.5 interval interacted strongly with even older crust, while others did not (Wooden and Mueller 1988; Chamberlain and Mueller 2007).

In aggregate, the rocks that formed during this transitional period (3.1–3.5 Ga) range in composition from basaltic to rhyolitic (Irvine and Baragar 1972; Fig. 2.9). The mafic rocks (48–52 % SiO_2) follow a tholeiitic trend (Fig. 2.10) and are both olivine- and quartz-normative. Tectonic variation diagrams reveal chemical affinities with calc-alkaline basalts and island arc tholeiites (Mullen 1983; Fig. 2.11). Rocks of intermediate composition (52–63 % SiO_2) include both tholeiitic and calc-alkaline varieties, whereas felsic rocks (>63 % SiO_2) are calc-alkaline. Most of the felsic gneisses are weakly peraluminous

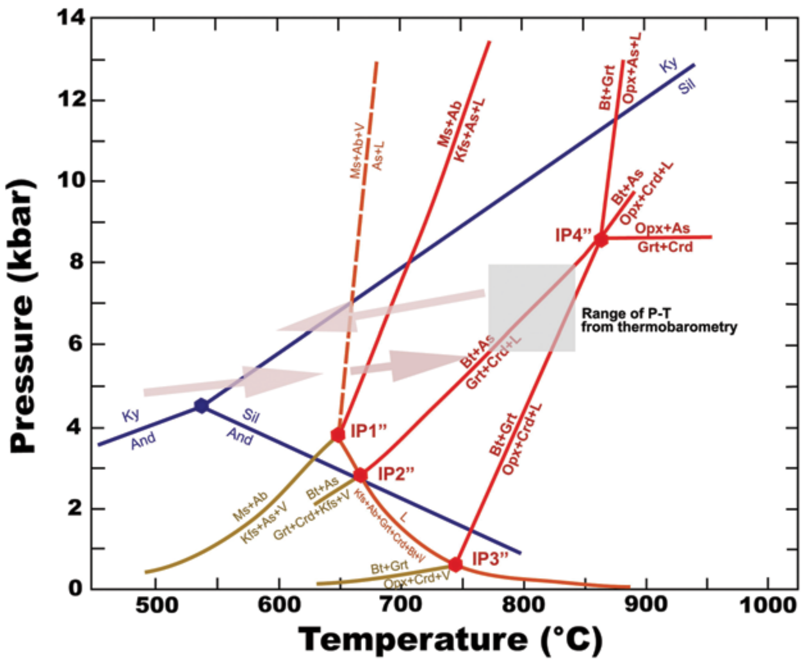

Fig. 2.5 Petrogenetic grid adapted from Spear et al. (1999) showing dehydration reactions (*gold*), water-saturated melting reactions (*orange*), dehydration melting reactions (*red*), and aluminosilicate polymorph boundaries (*blue*) in pressure-temperature space. The *gray-pink* arrows suggest the approximate pressure/temperature path experienced by these rocks. The *gray* box indicates the results and standard deviation of the geothermobarometry for peak metamorphic conditions

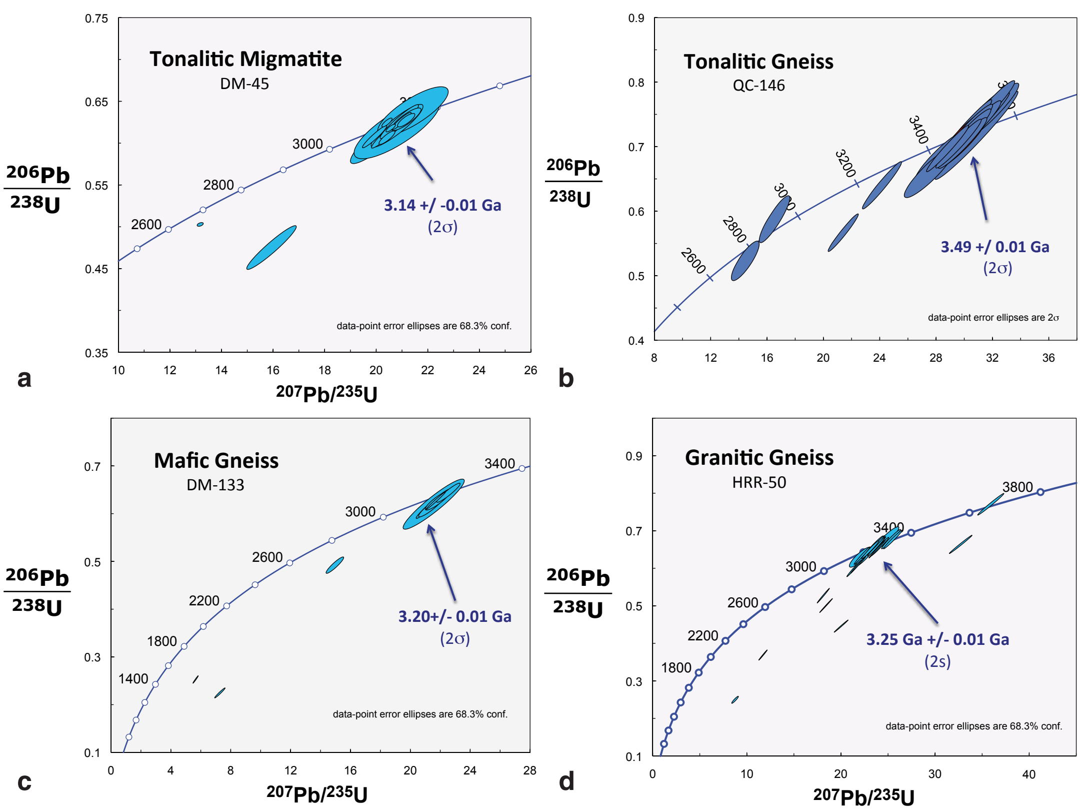

Fig. 2.6 U-Pb concordia plots for four pre-2.8 Ga gneisses: **a** tonalitic gneiss, **b** tonalitic migmatite, c mafic gneiss, and **d** granitic gneiss. All from the Beartooth Plateau block and determined using the SHRIMP-RG ion microprobe. Pb-loss is evident in all samples, and xenocrysts > 3.6 Ga in (d)

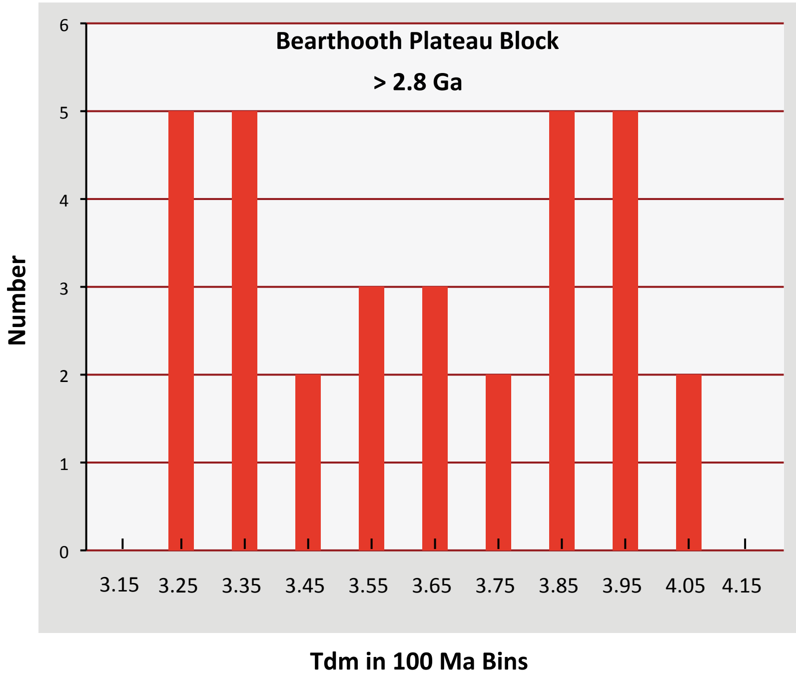

Fig. 2.7 Distribution of Tdm (Sm-Nd depleted mantle model ages; DePaolo 1981) for pre-LLMC lithologies from the Beartooth Plateau block

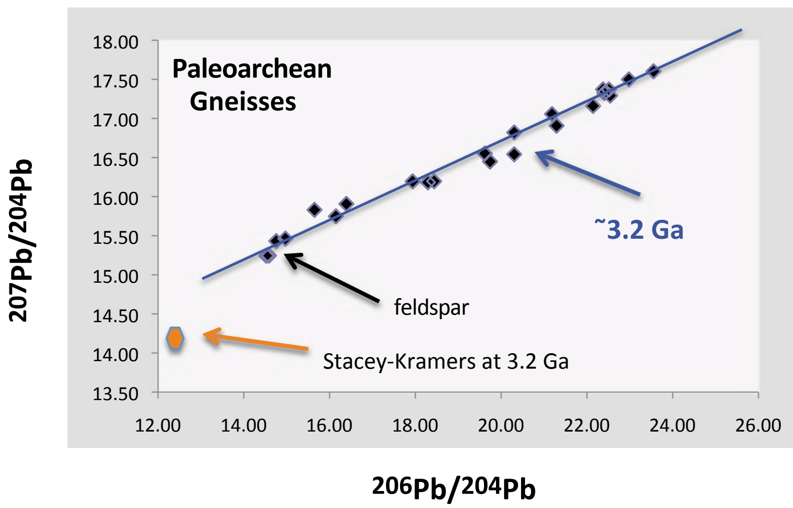

Fig. 2.8 Plot of common, uranogenic, whole-rock Pb isotopes and one feldspar from pre-LLMC rocks from the Beartooth Plateau block. Bulk-rock compositions range from 56 to 78 wt.% SiO_2

(normative corundum < 2 %). The protoliths of the felsic gneisses are difficult to determine due to the lack of original minerals and potential redistribution of elements during metamorphism, but the majority of these rocks appear to have an igneous origin (Fig. 2.12; Leyreloup et al. 1977). Tectonic variation diagrams reveal that the felsic gneisses have compositions of volcanic arc or syn-collisional granites (Fig. 2.13; Pearce et al. 1984). We do not imply that all of these rocks are genetically related due to the uncertainty of their ages of formation; however, their compositions collectively do fall within the range of rocks from well-characterized, contemporary, tectonic environments.

3. The Mesoarchean TTG rocks and granites (Wooden et al. 1988a, b; Mueller et al. 2010) that volumetrically dominate the Beartooth Mountains are the basis for designating this region as part of the BBMZ (e.g., Mogk et al. 1992;

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