

Creating Continents: Archean Cratons Tell the Story

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ABSTRACT

The record of the first two billion years of Earth's history (the Archean) is notoriously incomplete, yet crust of this age is present on every continent. Here we examine the Archean record of the Wyoming craton in the northern Rocky Mountains, USA, which is both well-exposed and readily accessible. We identify three stages of Archean continental crust formation that are also recorded in other cratons. The youngest stage is characterized by a variety of Neoproterozoic rock assemblages that are indistinguishable from those produced by modern plate-tectonic processes. The middle stage is typified by the trondhjemite-tonalite-granodiorite (TTG) association, which involved partial melting of older, mafic crust. This older mafic crust is not preserved but can be inferred from information in igneous and detrital zircon grains and isotopic compositions of younger rocks in Wyoming and other cratons. This sequence of crust formation characterizes all

cratons, but the times of transition from one stage to the next vary from craton to craton.

INTRODUCTION

Continental crust that formed in the Archean eon (2.5 billion years or older) makes up less than 3% of Earth's surface today, but all continents contain crust of this age (Fig. 1). These ancient crustal blocks, commonly covered by long, uninterrupted stratigraphic sequences, are known as cratons and comprise the oldest coherent lithosphere on Earth. They record little to no penetrative deformation, calc-alkalic magmatism, or metamorphism for hundreds of millions of years (Mueller and Nutman, 2017). Geophysically, cratons represent a coupled crust-mantle system in which Archean crust is underlain by a thick (>150 km) keel of cold, neutrally buoyant, sub-continental, depleted lithospheric mantle of comparable age (e.g., Pearson et al., 2021). Cratons preserve an important record of crust formation and

growth, provide the oldest record of processes that led to a differentiated Earth, and enable critical geologic observations for testing theoretical models of early Earth evolution (e.g., Korenaga, 2021). Although the timing of craton construction varies somewhat from craton to craton, we argue that most cratons are the cumulative result of three distinct stages of petrologic and geochemical evolution from which we infer the tectonic processes that formed them. Thus, cratons preserve a unique record of Earth's changing physiochemical conditions (e.g., global cooling) and tectonic regimes over the first two billion years of Earth's history. Starting with the youngest Archean rocks and working back in time, we use examples from the Wyoming craton to describe each stage in the development of a stable, Archean craton.

THE WYOMING CRATON

Although many cratons are in remote, relatively inaccessible locations with minimal

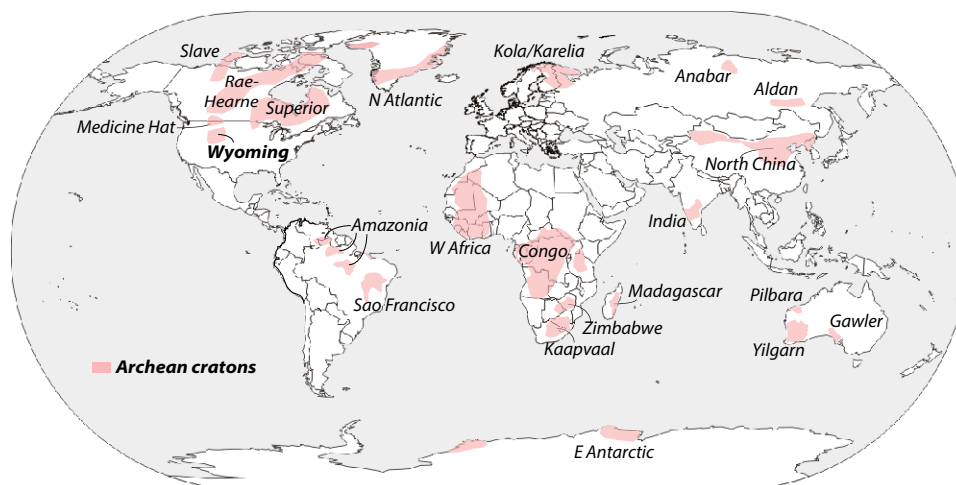


Figure 1. Global distribution of Archean cratons. Craton labeled "India" includes the Dhawar, Bastar, Bundelkhand, and Singhbham cratons. Modified from Bedle et al. (2021).

topographic relief, the Wyoming craton is an exception. Archean rocks are exposed in Late Cretaceous to Eocene basement-involved uplifts that are readily accessible and expose kilometer-scale vertical, three-dimensional sections of Archean crust. The Wyoming craton preserves a four-billion-year record of geologic history, from the earliest events recorded in detrital and xenocrystic zircons dating back to ca. 4.0 Ga to magmatism associated with the Quaternary Yellowstone hotspot. The craton extends over an area >300,000 km² with crustal thickness up to 50 km (Fig. 2). The Archean rocks of the Wyoming craton are mostly quartzofeldspathic gneiss and granitoids with a paucity of mafic supracrustal assemblages. Geologic, petrologic, geochemical, and structural studies have led to the identification of three subprovinces: the Beartooth-Bighorn magmatic zone (BBMZ), dominated by ca. 3.5 to ca. 2.6 Ga granitoids and gneisses; the Montana meta-sedimentary terrane (MMT), an area of ca. 3.5 to ca. 2.7 Ga plagioclase-rich quartzofeldspathic gneisses intercalated with Neoarchean metasupracrustal rocks; and the Southern Accreted Terranes (SAT), which are composed of ca. 2.7 to 2.6 Ga juvenile graywacke, mafic rocks, and felsic intrusions (Mogk et al., 2022) (Fig. 2A). Seismic data suggest a >20-km-thick, high-density, lower crustal layer beneath much of the BBMZ and MMT. This layer is absent farther south beneath the SAT, where the Moho depth steps from ~60 km to ~40 km north to south across the BBMZ-SAT boundary (Fig. 2B). The lithosphere-asthenosphere boundary lies at ~200 km depth beneath the Wyoming craton (Bedrosian and Frost, 2022). Paleoproterozoic orogens surround the craton (Fig. 2A).

CONTINENT CREATION IN THREE STAGES

The End of Cratonization: Neoproterozoic Rock Assemblages Formed by Plate Tectonic Processes

The Neoproterozoic 2.8–2.5 Ga record of the Wyoming craton preserves evidence of the final stabilization of the craton via modern tectonic processes, including examples of continental magmatic arcs, high-pressure continent-continent collisional zones, accreted terranes, and strongly peraluminous leucogranites formed by partial melting of aluminous metasedimentary rocks.

Continental Arc Magmatism

Continental magmatic arcs form on continental crust above subducting oceanic lithosphere. They comprise voluminous

calc-alkalic magmas with relative depletions in high field-strength elements across the compositional spectrum. Voluminous continental arc batholiths first appear in the

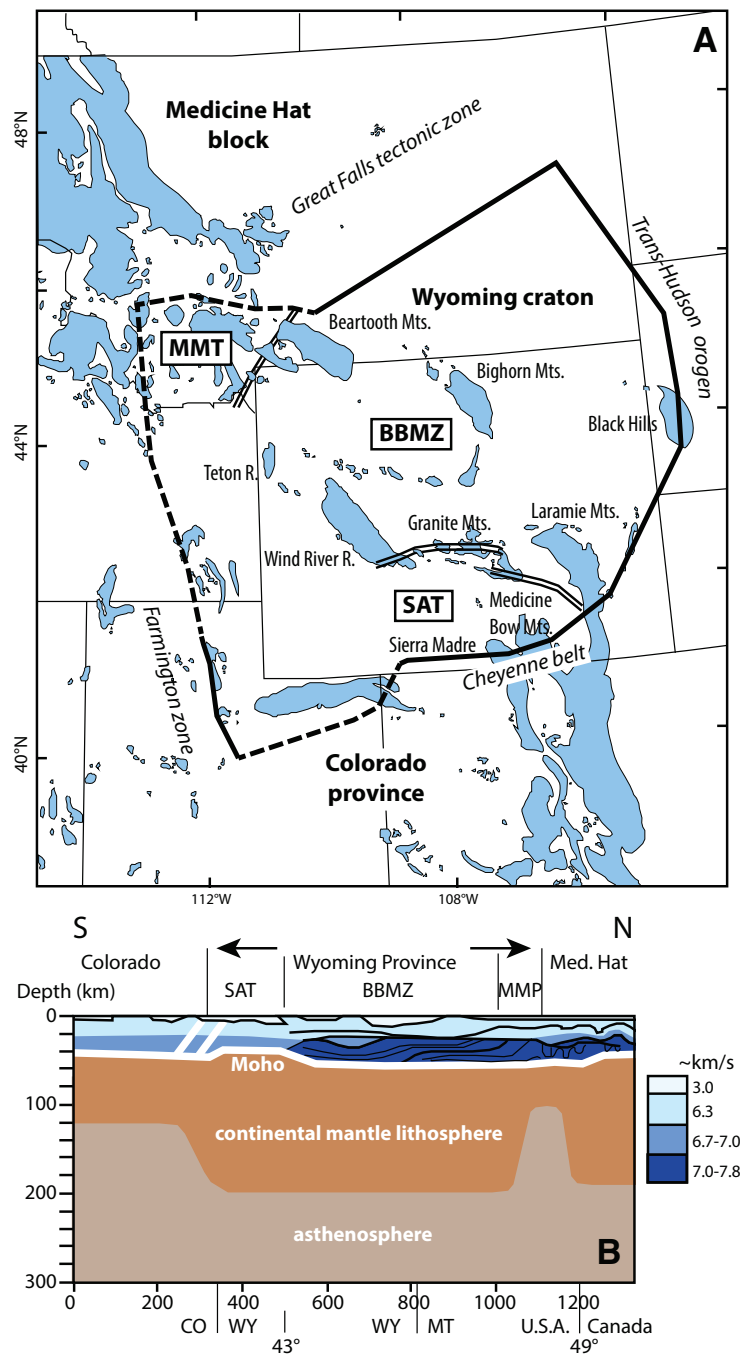


Figure 2. (A) Simplified geologic map of the Wyoming Province showing Precambrian outcrop in blue. Thick black lines indicate interpreted extent of the Wyoming Province. Double black lines mark the boundaries between subprovinces. BBMZ—Beartooth-Bighorn magmatic zone; MMT—Montana metasedimentary terrane; SAT—Southern Accreted Terranes. Modified from Bedrosian and Frost (2022). (B) Schematic cross section south-north along the Deep Probe seismic refraction/wide-angle reflection experiment (Snelson et al., 1998; Gorman et al., 2002). Crustal structure interpreted from seismic data shows greater lithospheric thickness beneath the Wyoming and Medicine Hat cratons compared to Colorado province and Paleoproterozoic Great Falls orogen that lies between the two cratons. Province boundaries and approximate thickness of the lithosphere are interpreted from electrical and seismic data by Bedrosian and Frost (2022).

Wyoming craton in the Bighorn Mountains (2.86–2.84 Ga; Frost and Fanning, 2006) and Beartooth Mountains (2.83–2.79 Ga; Mueller et al., 2010). These batholiths range in composition from gabbro and diorite to granite, and like modern continental arcs, are magnesian and calc-alkalic (Figs. 3A–3C). Initial whole rock Nd isotopic compositions from these batholiths are intermediate between depleted mantle values and values of older continental crust (Fig. 4). The incorporation of juvenile material, either from depleted mantle or juvenile crust, indicates these continental arc batholiths record both continental growth and crustal recycling, similar to modern continental arcs.

High-Pressure Collisional Tectonics

Continent-continent collisions are a hallmark of modern plate tectonics. These collisional events produce thrust-oriented deformation zones that join terranes of distinctive ages, lithologies, and metamorphic grade. Peak metamorphism is generally at high-pressure granulite conditions (pressures >10 kbar and temperatures of >700 °C), conditions that are rare prior to the Neoarchean (Brown and Johnson, 2018). One of the best examples of Archean rock assemblages interpreted to have formed by Himalayan-style continent-continent collisional tectonics is preserved in the northern Teton Range, where two distinct gneiss units with contrasting geologic histories were juxtaposed at 2.68 Ga along mylonitic ductile shear zones that exhibit discontinuities in metamorphic grade that reach granulite facies (Frost et al., 2016; Swapp et al., 2018). Decompression melting after peak metamorphism produced leucogranites along the boundary between the gneiss units (Frost et al., 2016). These observations suggest a clockwise *P-T* path for the northern Teton Range, similar to high pressure granulite *P-T* paths recognized in the Himalayas (Fig. 5).

Accreted Terranes

Juxtaposition and accretion of disparate terranes is another process typical of modern plate tectonics. In the Wyoming craton, Neoarchean metaigneous rocks of oceanic affinity and immature metasedimentary rocks occur as allochthonous units along the southern margin of the BBMZ in the southern Wind River, Granite, Sierra Madre, and Medicine Bow Mountains. They accreted to the BBMZ at 2.65–2.63

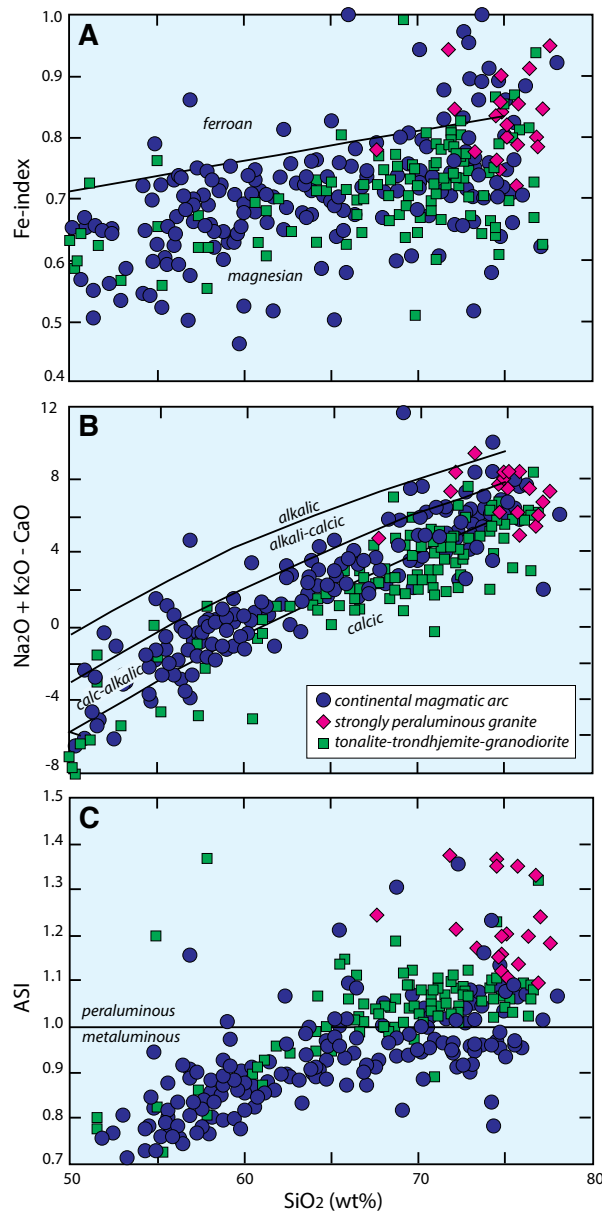


Figure 3. Fe-index, $\text{Na}_2\text{O} + \text{K}_2\text{O} - \text{CaO}$, and alumina saturation index (ASI) diagrams for Archean rocks from the Wyoming craton, including Long Lake Magmatic Complex and Louis Lake continental arc batholiths (navy circles); Bear Mountain and Rocky Ridge strongly peraluminous granite gneiss (pink diamonds); and trondhjemite-tonalite-granodiorite gneiss (green squares). Data sources: Frost and DaPrat (2021); Frost et al. (1998, 2006b, 2017); Gosselin et al. (1990); Mueller et al. (2010); and Wooden et al. (1988).

Ga, prior to the emplacement of the Louis Lake batholith (Frost et al., 2006a; Souder and Frost, 2006). Neoarchean accreted terranes have been described from other cratons, including Superior (Jaupart et al., 2014), Slave (Davis et al., 1994), and North China (Kusky et al., 2016).

Strongly Peraluminous Leucogranites

Strongly peraluminous granites have an aluminum saturation index (ASI) of greater than 1.1; contain aluminous phases such as muscovite, cordierite, or garnet; and are commonly interpreted to be derived from aluminous sedimentary sources. Partial melting of such sources can produce granite with the strongly peraluminous compositions

characteristic of collisional orogens (e.g., the Himalayas; Nabelek, 2020). Strongly peraluminous granites first become globally abundant in the Neoarchean (e.g., Bucholz and Spencer, 2019). In the Wyoming craton, two Neoarchean intrusive suites composed entirely of strongly peraluminous granite formed at 2.60 and ca. 2.64 Ga (Fig. 3; Frost and DaPrat, 2021; Gosselin et al., 1990). These ages suggest a relationship to the collision of the Wyoming and Superior provinces and creation of supercraton Superia (Ernst and Bleeker, 2010). Older (ca. 3 Ga) strongly peraluminous granites are present in other cratons, but most appear in the Neoarchean; e.g., in the Wyoming, Superior, Slave, and Yilgarn cratons (see Bucholz and Spencer, 2019, for a review).

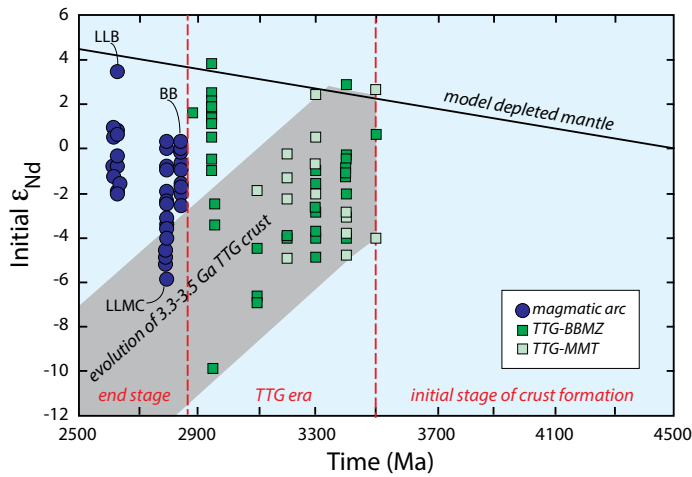


Figure 4. Initial Nd isotopic compositions of continental arc batholiths (Long Lake Magmatic Complex [LLMC], Louis Lake [LLB], and Bighorn batholith [BB]) and trondhjemite-tonalite-granodiorite (TTG) from the Wyoming craton. Data sources: Frost et al. (1998, 2006b, 2017); Mueller et al. (2010); P. Mueller, personal commun. (2022).

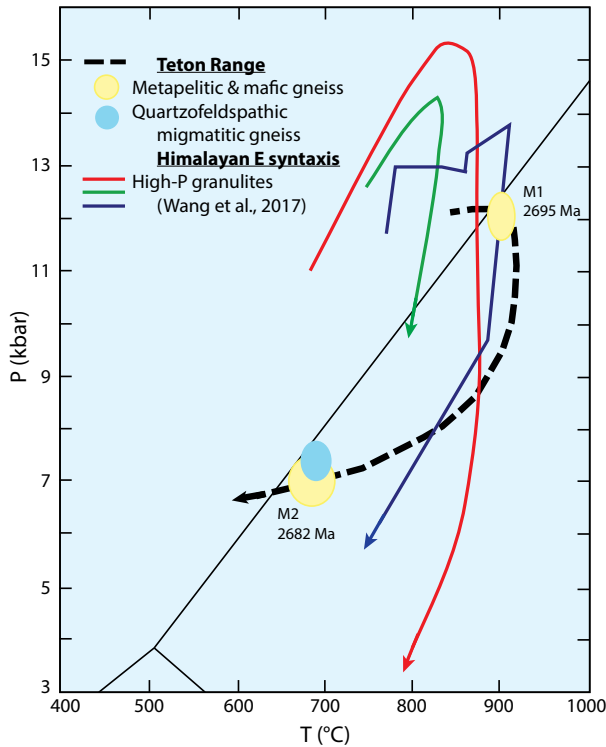


Figure 5. Comparison of the pressure-temperature-time (P - T - t) path inferred for the northern Teton Range (thick black dashed line) from Swapp et al. (2018) and P - T - t paths for high-pressure granulites from the eastern syntaxis of the Himalayas compiled by Wang et al. (2017) (red, green, and blue lines). Teton Range P - T conditions determined for the metapelite and mafic gneiss package are indicated by yellow ovals, and P - T conditions determined for the quartzofeldspathic gneiss package are indicated by blue ovals.

The oldest TTG associations in the Wyoming craton include 3500–3450 Ma trondhjemitic gneisses from the Beartooth and Granite Mountains (Frost et al., 2017; Mueller et al., 1996, 2014). Similar ages and compositions have been identified throughout the BBMZ and MMT, with a major event at ca. 3.3–3.2 Ga (Mogk et al., 2022). These rocks formed episodically over a protracted period of some 600 million years in Wyoming to produce an extensive continental nucleus. The slightly younger granodiorites in Wyoming’s gray gneiss terranes have been interpreted to result from partial melting of older TTG, forming more potassic and silicic compositions (Frost et al., 2017).

The current consensus is that formation of TTG magmas requires melting a hydrated mafic source at pressures greater than 12 kb (e.g., Moyen and Martin, 2012; Rapp and Watson, 1995), implying a thick mafic crust similar to modern oceanic plateaus. The geodynamic setting that would promote partial melting of both mantle and crustal sources to produce voluminous TTG remains unresolved, with stagnant lid, mobile lid, and plume-based tectonics all proposed (e.g., Moyen and Martin, 2012). In the Wyoming craton, Nd and Hf isotopic values of TTG exhibit a range of initial compositions that largely plot below model depleted mantle values (Figs. 4 and 7). These data indicate that the TTG suite cannot be formed solely by rapid, sequential melting of mantle-derived magmas that would produce positive initial Nd and Hf isotopic compositions as in an oceanic arc, but instead is derived from a variety of both isotopically juvenile and older, isotopically evolved sources. This suggests that by the time the TTG era began, Earth had already differentiated into two or more silicate reservoirs, including a depleted mantle and an evolved crust. Hf and Nd isotopic data from the Wyoming craton show that this differentiation occurred before the oldest TTG gneisses formed (ca. 3.5 Ga).

Archean gray gneiss terranes comprise the bulk of most cratons and have survived for three billion years or more, suggesting that the formation of a thick, buoyant, and rigid lithospheric keel plays an important role in their survival. This cratonic mantle lithosphere is interpreted to have formed by the extraction and ascent of partial melts enriched in Fe/(Fe + Mg), Ca, and Al into the crust, leaving a residual lithospheric mantle that is less dense and more buoyant than fertile mantle. The extraction of partial

The Trondhjemite-Tonalite-Granodiorite Era: Establishing Survivability

The survival of any individual craton depends on reaching a certain size (volume) and density. Globally, continental crust older than 2.9 Ga is dominated by the trondhjemite-tonalite-granodiorite (TTG) suite (Fig. 6) comprised of weakly peraluminous, magnesian, and calcic K-feldspar-poor quartzofeldspathic gneisses (Fig. 3) with

typically younger granodiorite and minor mafic and ultramafic rock. These suites first appear in significant volumes on different cratons over a period of some 300 million years, from 3.8 to 3.5 Ga (e.g., Nutman et al., 2015). In Wyoming and globally, the characteristic light rare-earth-element (LREE)-enriched REE patterns with little to no Eu anomaly and very low heavy rare earth elements (HREE) distinguish them from modern rocks.

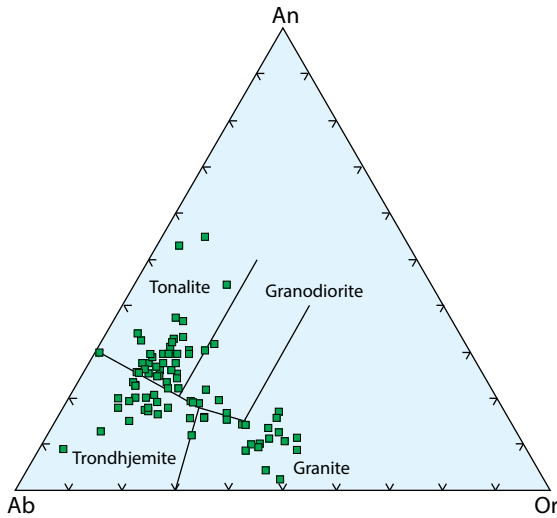


Figure 6. Normative An-Ab-Or compositions of trondhjemite-tonalite-granodiorite from the Wyoming craton. Data sources: Frost et al. (2017) and Wooden et al. (1988).

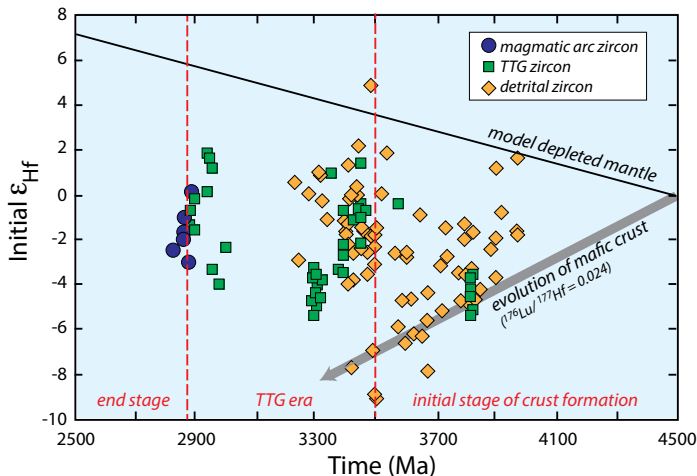


Figure 7. Initial Hf isotopic compositions of detrital zircon (diamonds), igneous and xenocrystic zircon from trondhjemite-tonalite-granodiorite (TTG; squares), and igneous zircon from magmatic arc rocks (circles) from the Wyoming craton. Data sources: Frost et al. (2017) and Mueller and Wooden (2012).

melt also would deplete the mantle of water and heat-producing elements, leaving it cold, strong, and viscous relative to the surrounding mantle (e.g., Jordan, 1988). Isotopic systematics of lithospheric mantle xenoliths and young igneous rocks from a number of cratons, including Wyoming, suggest that the keel formed contemporaneously with the overlying crust (e.g., Pearson et al., 2021). Such keels are present beneath most cratons and protect the cratonic lithosphere from erosion by the convecting mantle (Bedle et al., 2021). We suggest that the thick, rigid, and strong subcontinental lithosphere formed during the TTG-forming stage is a necessary precondition for the survival of the craton and subsequent production of Neoproterozoic rock

assemblages by modern-style plate-tectonic processes observed in Wyoming and other cratons (e.g., Iaccheri and Kemp, 2018).

The Initial Stage: Formation and Influence of Earth's First Mafic Crust

Globally, very little crust older than 3.8 Ga survives, but what does remain marks the beginning of the TTG era on the planet. The oldest known rocks are the 4.03–4.00 Ga TTG gneisses of the Acasta terrane in the Slave craton of northern Canada (Bowring and Williams, 1999). Early Eoarchean rocks (3.9–3.8 Ga) are sparse but more widespread. Older Earth materials are limited to a few, scattered occurrences of Hadean detrital zircon grains dated at 4.0–4.4 billion years

from a number of cratons, including Yilgarn, Kaapvaal, Sao Francisco, North China, and Enderby Land (Carlson et al., 2019, and references therein). The presence of these zircon grains indicates that melts saturated in zircon must have been present, although the limited number and occurrences of detrital zircon grains of this age suggest felsic rocks were sparse or did not survive later tectonism. In the northern Wyoming craton, the ages of detrital zircon grains of 4.0–3.2 Ga suggest that early crust-forming events occurred at ca. 3.7 and ca. 3.5 Ga (Maier et al., 2012; Mogk et al., 2022; Mueller et al., 1998). Eoarchean zircon xenocrysts (ca. 3.8 Ga) have also been reported from the Granite Mountains (Frost et al., 2017) and the Wind River Range (Aleinikoff et al., 1989) in the southern BBMZ.

Hf isotopic data from these ancient detrital and xenocrystic zircon grains provide important constraints on the timing, composition, and evolution of both Wyoming's and Earth's first crust. Initial Hf isotopic ratios from the Wyoming craton define an array of increasingly negative ϵ_{Hf} with time, a trend that is consistent with intra-crustal recycling of Hadean to Eoarchean mafic crust (Mueller and Wooden, 2012; Fig. 7). Initial ϵ_{Hf} data of zircon grains from many cratons define similar arrays (e.g., Mulder et al., 2021). Mafic crust would not likely contain significant zircon, but it may have contained small volumes of zircon-bearing plagiogranite, as does modern oceanic crust (Grimes et al., 2011). Pb isotopic compositions of some Archean rocks also preserve evidence of a mafic protocrust. In some cratons, including Wyoming, high initial $^{207}\text{Pb}/^{204}\text{Pb}$ isotopic ratios of younger Archean rocks with low U/Pb ratios require involvement of Pb from an ancient high U/Pb (high- μ) reservoir that was isolated from the mantle in the Eoarchean or earlier (Frost et al., 2006b; Mueller et al., 2014). Other cratons with suggestions of high- μ character include the western Slave, North Atlantic, Yilgarn, and Zimbabwe (Kamber, 2015).

In summary, although crust older than 4 Ga appears largely absent from the rock record, indirect evidence from the oldest detrital zircon grains, early TTG crust, and the Pb isotopic compositions of some Archean crust suggest the presence of a Hadean mafic crust. This early crust was thick and hot enough to partially melt at depth to form at least small volumes of tonalitic and trondhjemitic melts from which the oldest zircons crystallized. Because

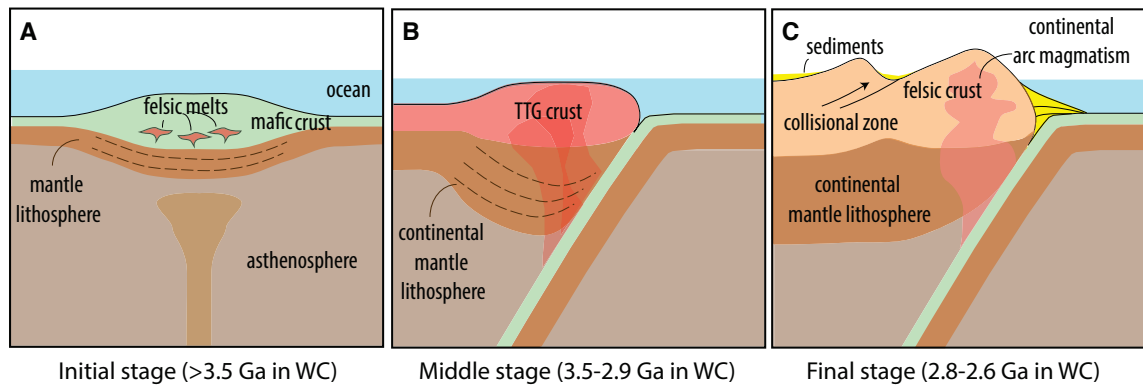


Figure 8. Summary cartoon showing the three stages of craton creation and stabilization, with the times at which these stages operated in the Wyoming craton (WC). (A) Initial stage in which thickened mafic crust, possibly formed over a mantle plume, partially melts at depth to form small volumes of zircon-bearing felsic melt. (B) Middle stage in which a trondhjemite-tonalite-granodiorite (TTG) crust forms from both mantle and crustal sources. Subduction is one potential mechanism for transporting mafic crust to depth for partial melting. (C) Final stage of Archean crustal evolution in which continental freeboard has increased and evidence of magmatic arcs, continent-continent collisions, and terrane accretion is abundant.

upwelling, decompressing, and partially melting mantle could form a thick mafic crust much like oceanic plateaus form above mantle plumes on Earth today, early global tectonics may have been dominated by vertical motion in the mantle (e.g., Korenaga, 2021; Mueller and Nutman, 2017).

DISCUSSION AND CONCLUSIONS

By studying the Archean record of the Wyoming and other cratons, we can identify three stages of crust formation that produced differentiated, thick, stable cratons.

- The first mafic crust formed early in Earth's history (Fig. 8A) and became thick enough in the late Hadean-Eoarchean that lower portions reached their melting temperatures, creating some felsic melt from which zircon crystallized. The Lu-Hf systematics of those zircon grains indicate that this mafic crust rapidly evolved to be isotopically distinct from contemporary mantle. In a number of cratons, including Wyoming, it has been shown that this early crust also had higher U/Pb than contemporary mantle or modern continental crust. As such, elevated initial $^{207}\text{Pb}/^{204}\text{Pb}$ ratios in younger rocks with low U/Pb are a fingerprint for the presence of Hadean mafic crust.
- Between 3.8 and 3.5 Ga the early mafic crust was augmented with TTG magmas in many cratons. Both Hadean mafic crust and mantle sources were involved in the production of large volumes of these TTG magmas. This process left a residual, melt-depleted, rigid, buoyant mantle lithosphere, which formed a thick, stable keel beneath the felsic TTG crust and enabled

its survival through many later geodynamic cycles (Fig. 8B).

- The formation of this thick cratonic lithosphere enabled the third stage of continent formation, in which recognizably modern plate-tectonic processes operated. Starting at ca. 2.8 Ga, a number of rock assemblages characteristic of plate-tectonic environments are preserved in the Wyoming craton, including continental arc batholiths, assembly of contrasting continental blocks across continent-continent collision zones, accretion of exotic terranes, and production of strongly peraluminous granite from chemically mature aluminous metasedimentary rocks (Fig. 8C). As with the onset of TTG formation, this final plate-tectonic stage appears to have begun at somewhat different times on different cratons.

In summary, the Archean rock record of Wyoming and other cratons suggests that by 3.5 Ga Earth had developed distinct geochemical reservoirs and that by 2.5 Ga Earth's continental crust had recorded many essential characteristics of modern plate-tectonic processes.

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