

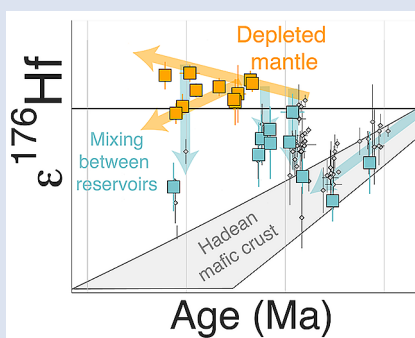
Onset of new, progressive crustal growth in the central Slave craton at 3.55 Ga

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Abstract



Ancient rock samples are limited, hindering the investigation of the processes operative on the Earth early in its history. Here we present a detailed study of well-exposed crustal remnants in the central Slave craton that formed over a 1 billion year magmatic history. The tonalitic-granodioritic gneisses analysed here are broadly comparable to common suites of rocks found in Archean cratons globally. Zircon Hf isotope data allow us to identify a major change positive ϵ_{Hf} starting at ~3.55 Ga. The crust production processes and spatial distribution of isotopic compositions imply variable interaction with older crust, similar to the relationships seen in modern tectonic settings; specifically, long-lived plate margins. A majority of the Slave craton might have been formed by a similar mechanism.

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Introduction

The growth and preservation of Earth's continental crust is an important planetary differentiation process. The Eo- to Mesoproterozoic is an important era when crustal preservation was just beginning to become successful. Crust from this period is the only vestige that remains to evaluate early geodynamics, the evolution of the atmosphere and ocean chemistry, and ultimately, the origin of life. Though many recent models suggest that a large fraction of the present crust formed in the Archean (e.g., Dhuime *et al.*, 2015), details of the timing of its extraction from the mantle and the mechanism of continental growth remain unclear, in part because of an incomplete rock record in many areas. Here we study an ancient crustal terrane that preserves an exceptionally long record of crustal production, allowing us to track the geodynamic processes of crust formation for over 1.5 Gyr.

Archean cratons are blocks of stable continental crust >2.5 billion years old, forming the cores of Earth's most ancient continents. The Slave craton of the Northwest Territories, Canada is an archetypal example, with extensive exposures of Meso- to Palaeoproterozoic rocks, making it ideally suited for tracing crust formation and reworking in the Archean.

The core of the Slave craton—the Central Slave Basement Complex (CSBC; Bleeker *et al.*, 1999a,b)—consists of extensive exposures of basement gneiss thought to extend

even farther beneath younger granitoids (Davis and Hegner, 1992; Thorpe *et al.*, 1992; Fig. 1). Although other cratons are also endowed with basement gneiss complexes (e.g., Moyen and Martin, 2012), the Slave craton is exceptional for the age range of exposed crust within a coherent geographic area. The detailed petrologic and tectonic framework for the formation of the Acasta Gneiss Complex (AGC) from 4.02 to 3.4 Ga (e.g., Reimink *et al.*, 2018 and references therein) can be used to explore how the younger, more geographically expansive, CSBC is related to the AGC in the subsequent billion years of crustal evolution. The new data presented here from both younger AGC samples (3.4–2.94 Ga) as well as a suite of 3.4–2.9 Ga CSBC samples, allow direct examination of the evolution of the broader Slave craton.

Geology and Geochemistry of the Slave Basement Gneisses

The definition of the CSBC (Bleeker *et al.*, 1999a) encompasses the zone of exposed basement gneisses in the central to south-central portion of the craton, including the Acasta Gneiss Complex. However, we refer to the CSBC and AGC independently to compare their formational mechanisms. The Acasta Gneiss Complex, on the westernmost margin of the Slave craton (Fig. 1), has received by far the most scientific interest due to the presence of the oldest known zircon-bearing

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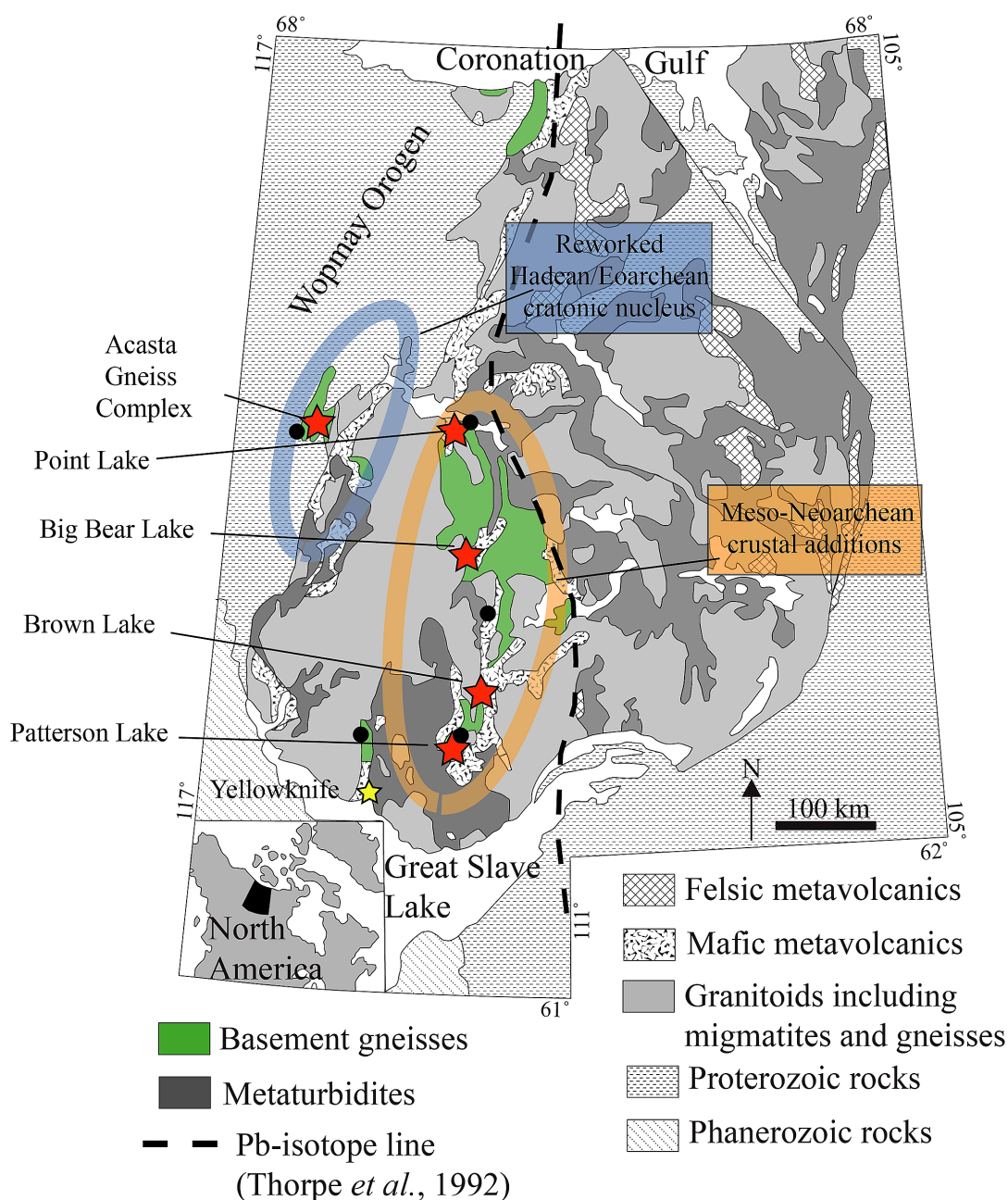


Figure 1 Geologic map of the Slave craton highlighting the major domains that contain basement gneisses. Map modified from St. Onge *et al.* (1988); Bleeker *et al.* (1999a,b). Major basement complexes are shown along with crustal province boundaries inferred from Nd and Pb isotope data (Davis and Hegner, 1992; Thorpe *et al.*, 1992). Red stars indicate key locations sampled in this study and coloured circles are locations where detrital zircons have been analysed for their U-Pb-Hf systematics as described in Figure 3 and the Supplementary Information.

rocks on Earth (*e.g.*, Bowring and Williams, 1999; Reimink *et al.*, 2016a). Recent petrologic and geochemical studies have documented systematic trends in the geochemical character of AGC rocks through time (*e.g.*, Reimink *et al.*, 2016b; 2018), which are used here to evaluate continued crustal growth in the broader Slave craton.

Previous work on the CSBC focused on preliminary field characterisation, geochronology, and its structural evolution (*e.g.*, Isachsen and Bowring, 1997; Bleeker *et al.*, 1999a,b; Ketchum *et al.*, 2004). Many of the exposed rocks in the CSBC are deformed, masking primary field relationships. Multiple magmatic pulses have been clearly defined within the Slave basement gneisses (van Breemen *et al.*, 1992; Bleeker *et al.*, 1999a; Sircombe *et al.*, 2001; Ketchum *et al.*, 2004), with major events from 4.02–2.8 Ga defined by Bleeker and Davis (1999) and summarised by Sircombe *et al.* (2001). Distinct magmatic

pulses are evident at ~3.4–3.3 Ga, 3.26–3.2 Ga, 3.16–3.1 Ga, 3.06–3.01 Ga, 2.99–2.93 Ga, and 2.9–2.85 Ga. This nearly continuous record of magmatism makes the CSBC an excellent natural laboratory to study crust formation mechanisms over an important period of continent formation on Earth.

Results

Sample descriptions, whole rock compositions, and U-Pb-Hf data from individual analyses can be found in the Supplementary Information, along with intra-rock sample averages (*i.e.* averages from all magmatic zircons within a given sample) plotted in Figure 3.

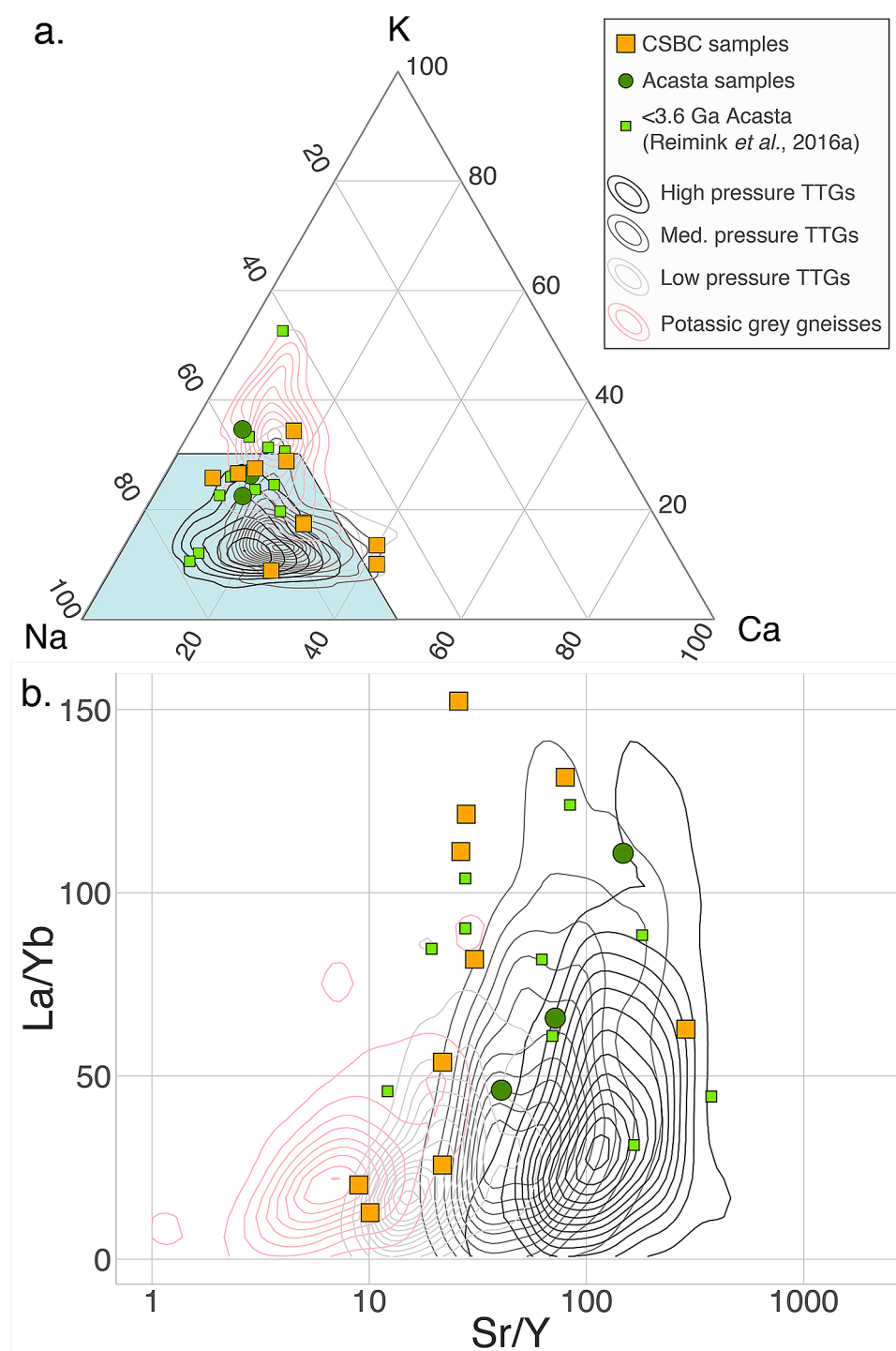


Figure 2 (a) Molar K-Na-Ca diagram. Orange squares are CSBC samples from this study. Green symbols are <3.6 Ga samples from the Acasta Gneiss Complex, small squares are samples measured by Reimink *et al.* (2016b) and dark green circles are samples added in this study. Contour density fields are high pressure TTGs (black), medium pressure TTGs (medium grey), low pressure TTGs (light grey), and potassic Archean grey gneisses (pink). Data used to construct these fields are taken from Moyen (2011). The blue field outlines sodic trondhjemites. (b) La/Yb versus Sr/Y for rocks from the Slave basement gneisses. Symbols as in (a).

Juvenile Crustal Growth of the Slave Craton

Most of the rocks analysed here from the CSBC have elemental compositions similar to typical Archean grey gneiss suites (Moyen and Martin, 2012) and can be classified as TTGs (tonalite-trondhjemite-granodiorites). The sodic nature of these CSBC granitoids ($\text{Na}_2\text{O}/\text{K}_2\text{O}$ generally >1.3) and relative enrichments in the incompatible trace elements suggests a derivation by partial melting of hydrated basalt (as summarised in Moyen, 2011; Moyen and Martin, 2012). The La/Yb and Sr/Y

of sodic melts typically increase with more residual garnet and a greater depth of melting. CSBC rocks have a range in La/Yb and Sr/Y, but they fall within the range of Archean TTGs, typically comparable to the medium and high pressure TTGs (Fig. 2).

The Hf isotope data from AGC granitoid rocks are broadly similar to trends seen in previous Hf isotope studies of AGC zircons (*e.g.*, Iizuka *et al.*, 2009; Bauer *et al.*, 2017; Fig. 3). Notably, >3.6 Ga zircons from the AGC have significantly negative initial ϵHf values that fall along an evolution line suggestive of reworking of Hadean protocrust (*e.g.*, Bauer *et*

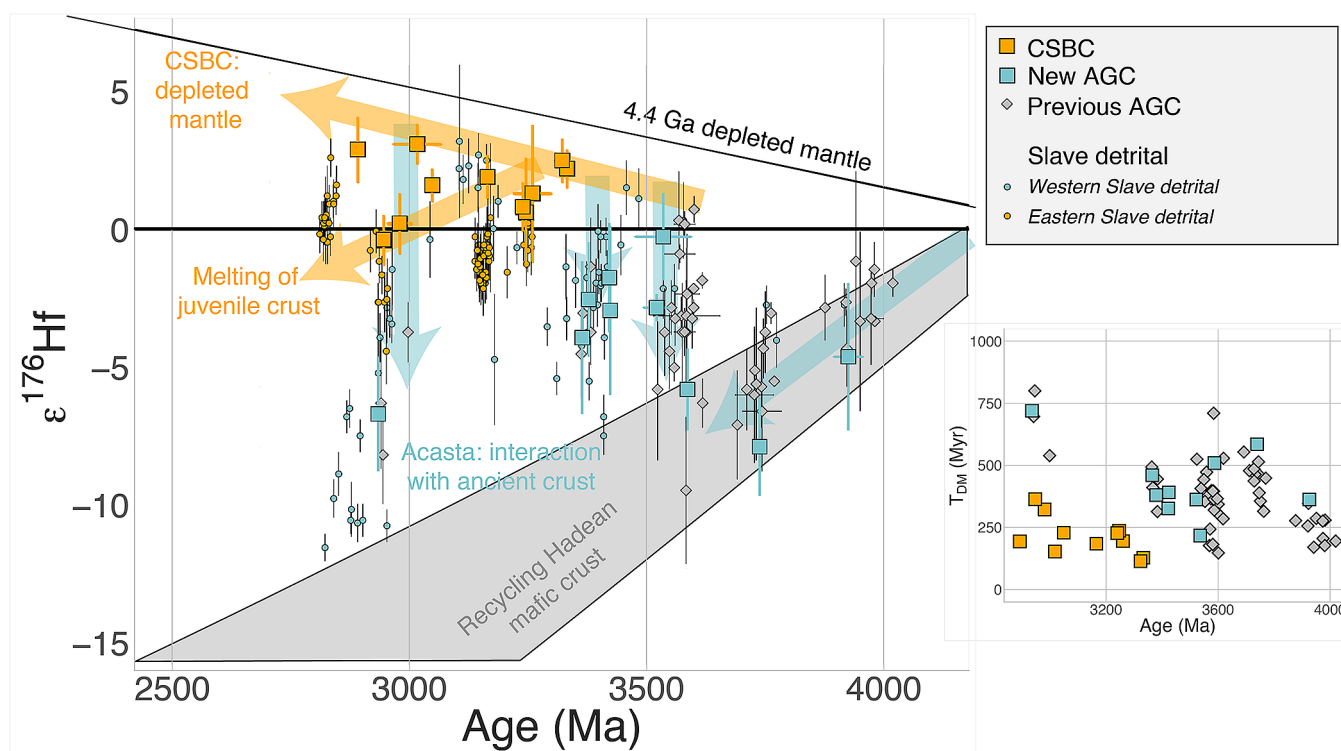


Figure 3 Zircon Hf isotope data from Slave basement gneisses. Orange symbols are analyses from the CSBC, blue are new analyses from the AGC, grey diamonds are a compilation of Acasta Hf isotope data (sources in the text), and small circles are single detrital zircon analyses from sediments of the Slave Craton Cover Group sequence (Pietranik *et al.*, 2008). Note that detrital zircon analyses are grouped by sediment location (see Supplementary Information). Grey field is the evolution of Hadean mafic protocrust, while orange and blue lines show our interpretations (sloped lines for time-integrated isotope evolution, vertical lines for mixing) for systematic petrogenetic differences between the two portions of the Slave basement gneisses. The Archean depleted mantle evolution line shown here is the connector line between a chondritic source at 4.4 Ga and modern MORB ϵ_{Hf} values of +17. Calculated with respect to this model evolution for the depleted mantle, the inset shows the maximum crustal residence times (depleted mantle model ages calculated using a source $^{176}\text{Lu}/^{177}\text{Hf}$ of 0.015, and then subtracting the U-Pb crystallisation age from this model age) for all Slave craton Hf isotope data. The transition from long to short crustal residence times occurs at 3.6 Ga.

al., 2017). In contrast, younger AGC granitoids that formed between 2.95 and 3.6 Ga have higher ϵ_{Hf} that is clearly offset from the Hadean protocrust reworking trend (Fig. 3) suggesting that these new crustal additions involved mixing between recently-mantle-derived crustal magmas and Hadean protocrust. Magmatic assimilation of ancient crust is the preferred mechanism for isotopic mixing in this case, supported by the presence of >3.6 Ga xenocrystic zircons found in 3.6 Ga magmatic rocks (*e.g.*, Iizuka *et al.*, 2007; Reimink *et al.*, 2016a).

The CSBC represents the major volume of the preserved Slave cratonic nucleus. Zircons from CSBC granitoids have positive initial ϵ_{Hf} values, distinct from AGC rocks of similar age, indicating derivation from a source that evolved with higher-than-chondritic Lu/Hf. Our Hf isotope data suggest that these CSBC granitoids represent largely new crustal additions from the mantle and did not interact with >3.6 Ga material to any significant extent. We interpret negative ϵ_{Hf} values within the CSBC to be due to internal reworking of older (*ca.* 3.35 Ga) silicic material, however, there is no indication within the CSBC data that much older, AGC-aged rocks, were present in that area. This differs significantly from the original interpretation of a previous study (Pietranik *et al.*, 2008) that used detrital zircons from the sedimentary sequence deposited directly on the CSBC rocks. These detrital zircon grain U-Pb-Hf data were grouped from across the entire craton, lumping terranes together to infer episodic mafic crust extraction and protracted reworking (Pietranik *et al.*, 2008). However, when the detrital zircon data are subdivided by terranes, the U-Pb-Hf data from these grains matches our new data well, supporting our interpretations (Figs. 3, S-1).

Isotopic Structure of the Slave Craton and the Transition to Short-lived Protocrust

The new AGC data are consistent with a previous model suggesting that >3.7 Ga rocks in the AGC were derived by melting of long-lived Hadean protocrust (*e.g.*, Iizuka *et al.*, 2009; Guitreau *et al.*, 2014; Bauer *et al.*, 2017; Reimink *et al.*, 2018), which has been documented in several other ancient gneiss localities (*e.g.*, Kemp *et al.*, 2010; O'Neil *et al.*, 2013). Rocks of the AGC that were produced from melts of this protocrust have major element compositions representative of shallow-level differentiation, both by fractional crystallisation and shallow-level melting (*e.g.*, Reimink *et al.*, 2014, 2016a,b, 2018). In contrast, the positive initial ϵ_{Hf} values in the CSBC show that this geographically dominant swath of evolved crust was not derived by the remelting of long-lived Hadean mafic crust. Instead, the vast majority of the pre-2.9 Ga Slave craton was progressively, and rapidly, derived from mantle sources throughout the Mesoproterozoic without significant interaction with older crust. What isotopic variation is present can be easily explained by a small amount of assimilation of the older generation of CSBC crust (*ca.* 3.3–3.4 Ga).

Prevailing models for Archean TTG petrogenesis (*e.g.*, Moyen and Martin, 2012) dictate that rocks of these compositions were not direct mantle melts but instead formed by partial melting of mantle-derived basalts, thus requiring some, albeit short, intervening crustal residence history in the isotopic evolution from their mantle source. Maximum crustal residence times can be estimated by calculating the difference between the age of the rock and the depleted mantle model ages for the Hf isotope data (using an average Lu/Hf ratio for

mafic crust and a model depleted reservoir). These residence times depend on the assumed Hf isotope evolution of both the crustal precursor and the depleted mantle, so they should be considered relative values rather than absolute time intervals. Nevertheless, the relatively brief protocrustal residence prior to melting to produce the CSBC TTGs is distinctly different from the >400 Myr protocrustal residence times documented in several Hadean-Eoarchean crustal blocks described above, including the AGC (Fig. 3, inset). The relatively rapid reworking of mafic protocrust in the CSBC is similar to that seen in parts of many Neoproterozoic terranes and the modern plate tectonics dominated Earth.

Implications for Craton Formation Mechanisms

Magmatic events occurred in both the CSBC and the AGC during similar times (3.4–3.3 Ga and 2.95 Ga), and produced rocks with similar elemental compositions (Fig. 2). The Hf isotope distinction between these two crustal blocks, where rocks from the CSBC have higher initial ϵ_{Hf} values than their AGC counterparts (Fig. 3), is important for evaluating crustal production mechanisms. In the AGC area, Hadean-Eoarchean crust was involved in the formation of Mesoarchean granitoids whereas CSBC rocks were mostly derived from newly formed sources whose isotopic compositions were similar to some models for Archean depleted mantle compositions (*i.e.* positive ϵ_{Hf} values).

Several Archean granite-greenstone terranes appear to have been generated by some form of so-called ‘vertical tectonics’ either by a density inversion formed by erupted mafic rocks lying on top of partially molten, granitic, mid-crust (*e.g.*, Collins *et al.*, 1998), or by melting at the base of a thickened oceanic plateau (*e.g.*, Smithies *et al.*, 2003). When mafic rocks are erupted through pre-existing continental rocks, as in the gravitational instability model, there is typically a significant amount of crustal assimilation and the mafic rocks record this in their isotopic systematics. Yet, the CSBC felsic rocks that were produced over a ~500 Myr interval show initial Hf isotopic compositions paralleling the isotopic evolution of a modelled depleted mantle that began forming at 4.4 Ga. Though the exact Hf isotope evolution of the depleted mantle is uncertain, there is no indication in the younger TTGs for involvement of significantly older crustal basement, either by long-term storage of mafic crust or by assimilation of pre-existing crustal sections in the CSBC. In contrast, crustal residence times recorded in areas where melting at the base of an oceanic plateau is invoked, such as the Pilbara craton, extend up to a billion years, and crust formed in this manner has depleted mantle model ages reflecting this ancient parentage (*e.g.*, Smithies *et al.*, 2003). This feature is notably absent in all of the CSBC Hf isotope dataset.

The isotopic differences and spatial extent of newly created crustal rocks between the CSBC and AGC areas are similar to those found in modern plate margin provinces where new crust is being created adjacent to, but spatially distinct from, older continental crust. On the modern Earth, major zones of continental growth occur at the edge of pre-existing continental crust. When subduction zones are developed along continental margins, the new magmas produced in these settings often show isotopic signatures that systematically vary from primitive mantle-like near the subduction zone to more isotopically evolved compositions toward the continental mass (*e.g.*, the $^{87}\text{Sr}/^{86}\text{Sr} = 0.706$ line in the Western US; Kistler and Peterman, 1973). Indeed, the CSBC rocks have trace element compositions compatible with a subduction zone (*e.g.*, enrichment in large-ion lithophile elements and depletion in high

field strength elements; Fig. S-2), and such signatures have been used to argue for evidence of plate margin settings in the Archean, though this is far from resolved (*e.g.*, Moyen *et al.*, 2012). In fact, this subduction-accretion process was invoked to explain isotopic trends in ~2.6 Ga granites in the Slave craton (Davis and Hegner, 1992) that mimic the trends of the 3.4–2.9 Ga Slave craton gneisses.

By 3.7 Ga, the Acasta area had stabilised as an evolved continental nucleus produced by reprocessing of Hadean-aged protocrust (*e.g.*, Reimink *et al.*, 2016b; 2018). At 3.55 Ga new crustal rocks were created in the AGC from a source containing juvenile, mantle-derived input. The spectrum of initial ϵ_{Hf} in these rocks is interpreted to be due to variable interaction between juvenile magmas and the rocks of the ancient continental nucleus *via* assimilation. This process clearly occurred as older zircons occur as xenocrysts in ~3.6 Ga samples. We also infer that assimilation generated the isotopic spread in the AGC at 3.4 and 2.95 Ga. During this same time, the majority of the CSBC crust was being constructed entirely from mantle sources, *i.e.* sources with no evidence of significant crustal prehistory. Because no substantially older crustal nucleus existed in the CSBC, the magmas that built this crust retained the depleted mantle isotopic signature. Furthermore, throughout this process, even the latest magmatic rocks were not assimilating and interacting with previously formed CSBC basement, suggesting lateral, rather than vertical, growth of the crust. Processes akin to modern subduction provide one mechanism to generate these isotopic and petrologic characteristics of the Slave basement gneisses, and indeed, models have suggested that subduction can initiate on the margins of plume-derived magmatic systems (*e.g.*, Geyra *et al.*, 2015). This is perhaps the mechanism that generated the 3.75–3.6 Ga transition in the AGC. Similar geodynamic changes have been invoked for other locations on Earth at different times (*e.g.*, Næraa *et al.*, 2012), suggesting that such transitions were not contemporaneous global changes, but occurred in different places at different times. Nevertheless, the CSBC represents a clear example of Mesoarchean crust that was formed by addition of new, juvenile, mass to the continent.

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Additional Information

Supplementary Information accompanies this letter at <http://www.geochemicalperspectivesletters.org/article1907>.



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