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# Earth's Earliest Crust

Jonathan O'Neil<sup>1</sup>, Hanika Rizo<sup>2</sup>, Jesse Reimink<sup>3</sup>, Marion Garçon<sup>4</sup>, and Richard W. Carlson<sup>5</sup>

## ABSTRACT

The scarcity of rocks preserved from the first billion years (Gy) of Earth's history hinders our ability to study the nature of the earliest crust. Rare >4.0-Gy-old zircons confirm that felsic crust was present within 500 million years of Earth's formation. Given that most of that ancient crust has been destroyed, geochemical and isotopic tracers applied to rocks from the oldest sections of continents can be used to provide insights into the nature of the predecessor crust. Evidence from Earth's oldest rocks and minerals suggests multiple early mantle depletion episodes, possibly linked to the

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formation of an initial, dominantly mafic, crust. This early crust was the precursor to evolved rocks that now constitute considerable portions of Earth's oldest surviving crust.

**KEYWORDS:** Hadean; Archean; early crust; Earth's oldest rocks; crustal reworking; depleted mantle; isotope geochemistry

## **INTRODUCTION**

The Hadean Eon was named after Hades, the Greek god of the underworld, and viewed as a time when catastrophic events related to Earth's accretion prevented the survival of solid rocks on its surface. The Hadean encompasses almost 600 million years (My) of Earth's earliest history, from the Solar System formation 4.568 billion years ago (Ga), until the preserved rock record begins, currently defined by the International Commission on Stratigraphy at 4.031 Ga. However, the boundary marking the end of the Hadean at ~4 Ga is a moving target given the continuing discovery of increasingly old rock terranes. Our ability to investigate the earliest crust and the geological processes responsible for its formation is greatly hindered by the near absence of preserved Hadean rocks and minerals. Hadean and early Archean (4.0–2.5 Ga) rocks and minerals provide a sparse, potentially biased, geological record, making extrapolation to planetary-scale processes and features challenging. Nevertheless, these small remnants can record invaluable information about the nature of the early crust. Here, we review what is known so far about some of Earth's oldest rocks and focus on how geochemical and isotopic tracers can be used to better constrain the composition of our planet's most ancient crust and the impact of its formation on the early mantle.

## **WHAT REMAINS—THE OLDEST GEOLOGICAL RECORD**

The oldest known terrestrial materials are Hadean detrital zircons as old as ~4.4 Ga (e.g., Wilde et al. 2001), first reported from the Jack Hills in the Yilgarn craton (FIG. 1; Cavosie et al. 2019 for review), with additional Hadean detrital grains being discovered globally.

With a crystallization age of up to 4.03 Ga based on zircon U-Pb data (Bowring and Williams 1999), the Acasta gneisses, located in the Slave craton (FIG. 1), represent the oldest evolved rocks known on Earth. Potentially older rocks, however, are included in the Nuvvuagittuq greenstone belt in the Superior craton (FIG. 1), a volcano-sedimentary sequence mostly composed of mafic metavolcanic rocks. The Nuvvuagittuq belt is at least 3.75 Gy old, as constrained by zircon U-Pb ages in intruding

felsic rocks (Cates and Mojzsis 2007), but the  $^{146}\text{Sm}$ - $^{142}\text{Nd}$  isotopic systematics of its metavolcanic rocks (see *Toolkit*) suggest an older age of  $\sim 4.3$  Ga, yet still debated in the scientific community (O'Neil et al. 2019 for review).

The Eoarchean (4.0–3.6 Ga) geological archive is similarly sparse. The best-known assemblage of Eoarchean rocks is the Isua supracrustal belt within the Itsaq Gneiss complex in the North Atlantic craton of southwestern Greenland (FIG. 1; Nutman et al. 2021 for review). Often considered as the best-preserved remnant of ancient supracrustal rocks (rocks deposited on existing basement rocks of the crust), the Isua supracrustal belt comprises 3.7–3.8 Ga mafic metavolcanic and metasedimentary rocks, and orthogneisses as old as  $\sim 3.85$  Ga. On the Canadian side of the North Atlantic craton, the Saglek-Hebron complex (FIG. 1) also includes rare occurrences of Eoarchean rocks. The oldest rocks are  $\sim 3.9$  Ga tonalite-trondhjemite-granodiorites (TTG; Laurent et al. 2024 this issue), but the complex is dominated by  $\sim 3.75$  Ga orthogneisses (e.g., Wasilewski et al. 2021) with numerous enclaves of mafic metavolcanic, ultramafic, and metasedimentary rocks as old as  $\sim 3.8$  Ga (e.g., Morino et al. 2017).

Other sections of early Archean rocks are included in the Yilgarn and Pilbara cratons in Western Australia, as well as the Kaapvaal craton in southern Africa (FIG. 1). The Narryer terrane of the Yilgarn craton includes rocks as old as 3.73 Ga within the Meeberrie gneiss and Manfred complex (Kemp et al. 2019 for review). The Warrawoona Group of the East Pilbara terrane, mainly composed of basaltic to komatiitic volcanic rocks, was deposited between 3.53 and 3.43 Ga, but gabbroic rocks from the Shaw granitic complex and TTGs from the Muccan granitic complex were dated at 3.59 Ga (Wiemer et al. 2018; Petersson et al. 2019). The oldest rocks of the Kaapvaal craton are 3.660 Ga TTGs in the Ancient Gneiss complex (e.g., Hoffmann and Kröner 2019). The slightly younger supracrustal rocks in the Barberton greenstone belt, South Africa, include volcano-sedimentary sequences in the Fig Tree and Moodies groups (3.26–3.22 Ga) that contain detrital zircons in the Green Sandstone Bed as old as 4.1 Ga (Byerly et al. 2018), as well as komatiites in the Onverwacht Group (3.45–3.48 Ga). Less well documented occurrences of Eoarchean rocks include the 3.85 Ga rocks from the Napier complex of Antarctica (Black et al. 1986), the 3.7 to 3.8 Ga rocks from the Anshan and Muzidian areas of the North China craton (Liu et al. 2008; Wang et al. 2023), and the 3.7 Ga Aktash gneisses from the Tarim craton, China (Ge et al. 2020) (FIG. 1).

## **NEW TOOLS TO DECIPHER THE HISTORY OF ANCIENT CRUST**

Most ancient crustal rocks have been subjected to complex thermal histories that have changed their original mineralogy and often their bulk chemical composition. Understanding the processes that formed these ancient rocks requires a combination of dating techniques that can distinguish crystallization ages from later events, along with chemical and isotopic approaches that help trace the nature of their sources. The tool of choice for geochronology has become U-Pb dating of zircon, while isotopic tracers based on the decay of  $^{147}\text{Sm}$  to  $^{143}\text{Nd}$ , or  $^{176}\text{Lu}$  to  $^{176}\text{Hf}$ , on whole rocks or the zircons themselves, are commonly used to constrain the age and composition of their source (see *Toolkit*).

Another recent advance has been the application of short-lived radionuclides, such as the decay of  $^{146}\text{Sm}$  to  $^{142}\text{Nd}$  (half-life of 103 My). Because the abundance of  $^{146}\text{Sm}$  became too low (or “extinct”) by  $\sim 4$  Ga, measurable variations in  $^{142}\text{Nd}$  due to  $^{146}\text{Sm}$  decay were no longer produced after the Hadean. Hence, variations in  $^{142}\text{Nd}$  provide a record of chemical fractionation between Sm and Nd before 4 Ga (FIG. 2). This tool is, therefore, ideal to highlight evidence of Hadean silicate differentiation preserved in younger rocks. Variations of  $^{142}\text{Nd}/^{144}\text{Nd}$  are typically expressed as  $\mu$ -values, representing parts per million deviations from a Nd standard with  $\mu^{142}\text{Nd} = 0$  (see *Toolkit*). Mantle-derived rocks with positive  $\mu^{142}\text{Nd}$  indicate a mantle source that was depleted in incompatible elements (higher Sm/Nd) in the Hadean, while negative  $\mu^{142}\text{Nd}$  imply a pre-4 Ga source enriched in incompatible elements (lower Sm/Nd; FIG. 2). More than 500 samples have now been analyzed for  $^{142}\text{Nd}$  and unequivocally show that most of Earth’s oldest preserved crust was derived from sources that had been chemically modified by events occurring in the Hadean, long before the preserved rock record began (FIG. 2).

## **CRUSTAL ANCESTORS—EARTH’S LOST ANCIENT CRUST**

Earth’s first crust may have been a crystallization product of an early largely molten phase (e.g., magma ocean), analogous to the ancient crusts of the Moon and Mars, but surviving remnants of such crust on Earth are unknown. Although small amounts of  $>4$  Ga terrestrial material confirm that Hadean crust existed on Earth, the extremely rare geological archive from this eon indicates that this early crust was either nearly entirely destroyed or of minimal volume. The processes responsible for its destruction remain debated, but include disruption of the early crust by meteoritic impacts or sinking into Earth’s interior through mechanisms proposed to range from lithospheric “drips” to processes similar to modern plate subduction. The presence of Hadean zircons that crystallized from felsic, TTG-like magmas shows the existence of at least some felsic, continent-like crust early in Earth history. Continental crust can survive at Earth’s surface for billions of years because of the relatively

low density of its Si-rich rocks, and because it is underlain by strong and buoyant residual mantle peridotite (e.g., Pearson et al. 2021). In contrast, under the current mode of plate tectonics, mafic oceanic crust is transient and survives for only 100–200 My before its subduction into the mantle; yet in the modern world, oceanic crust covers roughly two-thirds of Earth’s surface. The proportion of Earth’s crust in the Hadean that was continent-like or ocean-like is effectively unknown.

Beyond the rare Hadean materials, Archean rocks also record valuable information about the nature and age of their progenitors, although even here, the record is biased by what is preserved. Archean crust is dominated by felsic rocks such as TTGs and granites, along with Mg-rich rocks, referred to as “greenstones.” Because felsic magmas cannot be derived by melting of mantle peridotite, they are commonly interpreted to stem from melting of an older crustal ancestor. Moreover, the geochemistry of Archean TTGs, notably their high silica contents, low K/Na ratios, and depletion in heavy rare earth elements, indicate their formation from melting of a metamorphosed basaltic precursor. The extent of TTGs in many Archean cratons, therefore, strongly implies the presence of an older mafic crust of potentially widespread distribution.

A combination of isotopic tracers applied to Archean rocks can shed light on what could have been Earth’s early crust by better constraining the age and composition of their crustal ancestors. For example, Hf isotopes in zircons have been widely used for this purpose. As zircons crystallize, they record the Hf isotopic composition of their host magma, reflecting that of the magma source at the time of crustal melting. Combining U-Pb with Hf and Nd initial isotopic variability allows determination of the compositional characteristics of the progenitor(s) and whether they formed in the Hadean or later. FIGURE 3 shows the evolution of Hadean mafic and felsic sources, along with the Hf-in-zircon isotopic compositions (expressed as  $\epsilon\text{Hf}$ , the deviation in parts per 10,000 of the sample relative to a chondritic reference value; see *Toolkit*) and  $\mu^{142}\text{Nd}$  values of some of the oldest TTG, focusing on terranes that recorded negative  $\mu^{142}\text{Nd}$  (i.e., a Hadean enriched source), and Eoarchean-Hadean detrital zircons. The trends defined by the Acasta gneisses, TTGs from the NE Superior craton, the Napier complex, and the Muzidian complex are consistent with melting of 4.25–4.35 Ga mafic crust. The detrital Jack Hills zircons show a wide range of initial  $\epsilon\text{Hf}$  compositions; however, a subset of the least altered Jack Hills zircons and detrital zircons from the Green Sandstone Bed in the Barberton greenstone belt show an evolution broadly following a slightly older mafic progenitor, perhaps as old as 4.45 Ga (FIG. 3). Like the Hf isotope record, the negative  $\mu^{142}\text{Nd}$  of many Eoarchean TTGs can be explained by the melting of a 4.25–4.35 Ga mafic crust, whereas a Hadean felsic precursor would have led to  $\mu^{142}\text{Nd}$  much lower than what has been observed for TTG—suggesting limited remelting of Hadean felsic crust to create preserved Eoarchean evolved rocks.

The combined record of Hf isotopes in zircons and  $\mu^{142}\text{Nd}$  of some of Earth's oldest crustal rocks thus points to the existence of an early, potentially wide-spread, mafic crust that served as their geological ancestor, and which appears to have not been directly preserved in the rock record. Moreover, given that TTGs are typically interpreted to represent 10%–50% partial melts of mafic amphibolite, this would imply the involvement of large volumes of mafic Hadean crust to produce the TTG-dominated Archean cratons. Although negative initial  $\epsilon\text{Hf}$  and  $\epsilon^{143}\text{Nd}$  (defined similarly to  $\epsilon\text{Hf}$ ) are common in many post-Eoarchean rocks, only some Neoarchean (2.8–2.5 Ga) TTGs from the NE Superior and Muzidian terranes currently display negative  $\mu^{142}\text{Nd}$ . As negative  $\mu^{142}\text{Nd}$  is a sign of Sm-Nd fractionation in the Hadean, these two terranes suggest the survival of some mafic Hadean crust for at least a billion years, some five times longer than the oldest modern oceanic crust. The signatures of this Hadean mafic crust seem to completely disappear as sources for crustal rocks younger than ~2.4 Ga (“enriched reservoir” in FIG. 2), implying the complete destruction of this early crust by that point in time, perhaps by subduction into the mantle.

## **PERSPECTIVE FROM THE SEDIMENTARY RECORD**

Terrigenous, fine-grained, clastic, sedimentary rocks concentrate the erosion products of land above sea level. They provide insights into the composition and history of Earth's earliest crust on the assumption that they depict a composite picture of large areas of ancient continental crust. The early Archean record for terrigenous sediment is sparse. It is therefore challenging to use this limited record to constrain the nature of the Hadean “lost” crust as discussed above. Later Archean terrigenous sequences are present in almost all cratons, making this archive particularly interesting for studying the nature and evolution of the global Archean crust. Sedimentary processes such as weathering, hydrodynamic sorting, and diagenesis can, however, significantly change the composition of sediments from source to sink and after deposition. The biggest challenge is thus to select and interpret the proper geochemical proxies to represent the composition and history of the eroded continental areas. The interpretation of the geochemical record preserved in the oldest sedimentary archive has been widely disputed, particularly regarding the relative proportions of felsic and mafic crust in the Archean.

From the pioneering work of Taylor and McLennan (1985) and subsequent studies (e.g., Tang et al. 2016), the Archean crust has long been thought to be dominantly basaltic, and that a major change, proposed to be the onset of plate tectonics, turned it to dominantly felsic at the end of the Archean. New insights may be obtained from re-evaluations of the meaning of trace element ratios in fine-

grained sedimentary rocks (e.g., Ptaček et al. 2020) that integrate both (i) the compositional evolution of igneous rocks through geological time (Keller and Schoene 2012) and (ii) the propensity of trace element ratios involving Cr and Ni to be biased by contributions from komatiite (a rare ultramafic volcanic rock type with unusually high Mg, Cr and Ni contents), the consequence of which is overestimation of the contribution to the sediment from mafic rocks. These studies concluded that the oldest emerged crust preserved in Archean sedimentary rocks was, on average, almost as felsic as today. FIGURE 4 shows an estimation of the SiO<sub>2</sub> content of continents through time, based on the composition of fine-grained sedimentary rocks. Because the Sm/Nd ratios and SiO<sub>2</sub> contents are well correlated in igneous rocks, the Sm/Nd ratio of fine-grained terrigenous sedimentary rocks through time provides a good compositional (SiO<sub>2</sub>) secular proxy for continents (Garçon 2021). From this perspective, the SiO<sub>2</sub> of continents appears to have been felsic (between 60 and 70 wt.%) throughout most of the Archean (FIG. 4). Additional evidence of a dominantly felsic crust above sea level as far as the sedimentary archive dates back was further provided by the record of Ti isotopes (Greber et al. 2017) and major element contents (Lipp et al. 2021) in ancient terrigenous rocks, all arguing for an average SiO<sub>2</sub> content > 60 wt.% for the emerged Archean crust.

Evidence of Hadean material is very subdued in the Archean sedimentary archives. Hadean detrital zircons appear absent from most Archean metasedimentary units, with a few exceptions (Green Sandstone Bed, South Africa; Jack Hills, Australia), and a record of Hadean mafic crust has not yet been found in Archean metasedimentary rocks. In fact, the available bulk-rock <sup>147</sup>Sm-<sup>143</sup>Nd, <sup>146</sup>Sm-<sup>142</sup>Nd, and <sup>176</sup>Lu-<sup>176</sup>Hf data for the oldest terrigenous rocks point to a very limited contribution from Hadean crustal sources, (e.g., Garçon 2021; Boyet et al. 2021). This suggests that the Hadean mafic crust was either mostly below sea level, hence unable to form sediments due to lack of subaerial erosion, or was progressively reworked into more felsic lithologies through intra-crustal differentiation, or was recycled and mixed away into the mantle early in the Archean.

## **THE MANTLE VIEWPOINT—EARLY SILICATE DIFFERENTIATION**

As the crust is primarily derived from partial melting of the mantle, a high mass ratio of crust to complementary melt-depleted mantle results in a residual mantle with a composition depleted in the most incompatible trace elements. Such signatures are commonly observed in samples of subcontinental mantle from beneath Archean cratons where Re-Os isotopes document a rough synchronicity of crust and lithospheric mantle formation, or at least preservation (e.g., Pearson et al. 2021). The broader influence of crust extraction from the mantle is evident in compositional and

isotopic data from modern mid-ocean ridge basalts. However, isotopic data in this case suggest ages between 1.5 and 2.0 Ga that are often interpreted as reflecting the average age of a relatively continuous process of crust extraction and recycling throughout Earth history (e.g., Armstrong and Hein 1972). The existence of preserved early Archean crust, along with corresponding evidence discussed below for ancient sections of melt-depleted mantle, shows that crust–mantle differentiation began very early in Earth history.

A still unresolved issue regarding our understanding of the early differentiation history of the mantle stems from the observation that Hf isotopes in many ancient zircons, particularly in Eoarchean rocks from Greenland, are indicative of derivation from sources with minimal, if any, previous fractionation of Lu from Hf (Guitreau et al. 2012). In contrast, whole-rock Sm-Nd systematics indicate derivation of the same rocks from sources that experienced prior depletion of incompatible elements. One explanation of this paradox is that whole-rock samples may have undergone post-crystallization events that potentially fractionated the parent and daughter elements, leading to the erroneous calculation of initial isotopic compositions. The Lu-Hf system in zircon is less sensitive to such issues given the very high Hf concentrations and low Lu/Hf ratios of zircon, making the diffusion of Lu and/or Hf into or out of zircon unlikely. While alteration is possible, the observation that both  $\mu^{142}\text{Nd}$  and initial  $\epsilon^{143}\text{Nd}$  are positive in many of the Eoarchean Greenland rocks, makes the whole-rock disturbance explanation unlikely, given the fact that post-magmatic parent-daughter elemental fractionation does not affect the  $^{142}\text{Nd}/^{144}\text{Nd}$  ratio after the extinction of  $^{146}\text{Sm}$ .

A potential explanation is that the ancient chemical depletion recorded by Nd isotopes is valid, but not the result of typical crust–mantle differentiation where the magnitudes and directions of Sm-Nd and Lu-Hf fractionation are strongly coupled. For example, crystallization of a terrestrial magma ocean involving lower-mantle mineral phases, such as bridgmanite, that fractionate high-field strength elements (like Hf) very differently than rare earth elements (such as Nd, Sm, and Lu) could decouple Lu-Hf and Sm-Nd evolution (e.g., Rizo et al. 2011). The observation of unfractionated initial Hf isotopic compositions in Eoarchean rocks, however, is not universal, so the full explanation of the cause of this apparent decoupling of Nd and Hf isotope systematics remains unclear.

Compelling evidence for the existence of a Hadean depleted mantle comes from Eoarchean and Paleoarchean (3.6–3.2 Ga) rocks from several Archean cratons (e.g., Rizo et al. 2011; Morino et al. 2017; Maltese et al. 2022). Although these rocks formed after the extinction of  $^{146}\text{Sm}$ , they contain excesses in  $^{142}\text{Nd}$  that can only be produced in high Sm/Nd reservoirs formed in the Hadean. By coupling the initial  $\epsilon^{143}\text{Nd}$  and  $\mu^{142}\text{Nd}$  in the same rocks, the differentiation age and the degree of

depletion of the mantle source involved in their formation can be estimated, as shown in FIGURE 5. With mantle differentiation ages ranging from 4.2 to 4.5 Ga coupled with variable  $^{147}\text{Sm}/^{144}\text{Nd}$  ratios in the source, the data suggest that multiple episodes, or gradual, depletion were likely recorded in Earth's Hadean mantle. Moreover, while the degree of source depletion suggested by the mafic-ultramafic Archean rocks is similar to the present-day mantle source of mid-ocean ridge basalts, as reflected by the comparable  $^{147}\text{Sm}/^{144}\text{Nd}$  source ratio, the Hadean depleted reservoirs recorded by the felsic TTGs appear to be more depleted (i.e., higher Sm/Nd). Possible processes generating these depletion events include episodic early crust extraction and/or solidification of Earth's magma ocean(s) producing depleted mantle domains (FIG. 5).

Excesses in  $^{142}\text{Nd}$  have been observed in rocks from only a limited number of terranes, suggesting either poor preservation of such terranes, that early mantle depletion may not have occurred on a global scale, or that the database remains limited. If this early depletion was the result, at least in part, of the extraction of Earth's first crust, then the volume of early crust may have been either small or eradicated by the efficient recycling of such crust back into the mantle. Abundant ancient basaltic crust characterized by incompatible element enrichment is, however, likely required as a source for the formation of the voluminous TTG found in ancient terranes—so the record of positive (depleted mantle-like) and negative (enriched ancient mafic crust)  $^{142}\text{Nd}$  signals may both reflect crust–mantle differentiation. Finally, evidence from  $^{142}\text{Nd}$  for an early depleted mantle is subdued in rocks younger than 3.4 Ga (e.g., Bennett et al. 2007), perhaps due to the recycling of the incompatible element-enriched crust and mixing with its complementary depleted components in the mantle.

## **CONCLUDING REMARKS**

Recent advances using the newest geochemical and isotopic tools provide insight into the geological ancestry of Archean cratons to better understand Earth's earliest crust and mantle. Although the crystalline and sedimentary records may depict different views of the nature of the dominant crustal progenitor of Archean cratons, crust–mantle differentiation, at least to some extent, clearly occurred in the Hadean. Contrary to the etymology of the word Hadean, crust existed on Earth before 4 Ga, and the rare remnants of surviving ancient crust are now beginning to yield information on the nature of Earth's earliest crust.

## **ACKNOWLEDGEMENTS**

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Figure 1: Location of some of Earth's oldest rocks and Archean cratons discussed here.

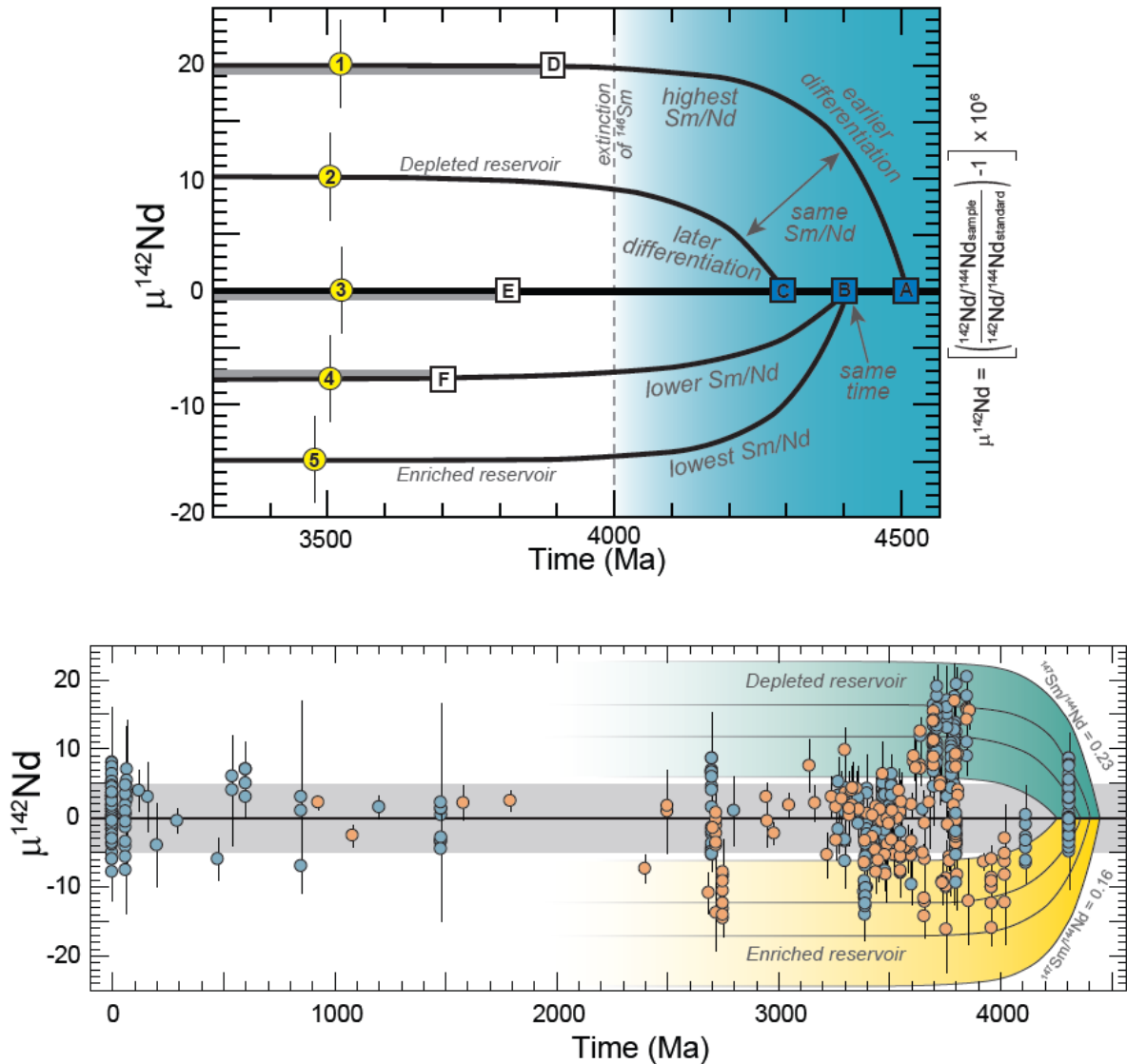


Figure 2: **(TOP)** Cartoon illustrating how  $\mu^{142}\text{Nd}$  traces Hadean silicate differentiation. Yellow circles show  $\sim 3.5$  Ga samples with different  $\mu^{142}\text{Nd}$ . Squares represent differentiation events occurring in the Hadean (blue) and after 4 Ga (white). Reservoirs formed from events A, B, and C have a common precursor with  $\mu^{142}\text{Nd} = 0$ . Events A and C show equal extent of Sm-Nd fractionation of a depleted reservoir at different times, producing the sources of rocks 1 and 2 with distinct positive  $\mu^{142}\text{Nd}$ , where the earlier source evolves to higher  $\mu^{142}\text{Nd}$ . Event B produces coeval enriched reservoirs with different Sm/Nd ratios, sourcing rocks 4 and 5 with distinct negative  $\mu^{142}\text{Nd}$ , where the more enriched reservoir generates the rock with lower  $\mu^{142}\text{Nd}$ . Differentiations D, E, and F occur after  $^{146}\text{Sm}$  is extinct, producing reservoirs (grey lines) with the same  $\mu^{142}\text{Nd}$  as their respective sources. Rocks

1, 3, and 4, derived from sources produced by post-4 Ga events, have different  $\mu^{142}\text{Nd}$  due to the distinct Hadean evolution of their precursors.

**(BOTTOM)** Compilation of terrestrial  $^{142}\text{Nd}$  data. Nuvvuagittuq samples are plotted as initial  $\mu^{142}\text{Nd}$  at their interpreted Hadean ages. Mafic-ultramafic and felsic rocks are shown with blue and orange symbols, respectively. The typical external precision of the standard is represented by the grey bar. Evolution lines (thin black lines) for the depleted and enriched reservoirs have  $^{147}\text{Sm}/^{144}\text{Nd}$  ratios of 0.23 and 0.16, respectively, derived at 4.45, 4.40, 4.35, and 4.25 Ga, from a reservoir with chondritic Sm/Nd and present-day  $\mu^{142}\text{Nd} = 0$ . Data sources are provided in the online supplement.

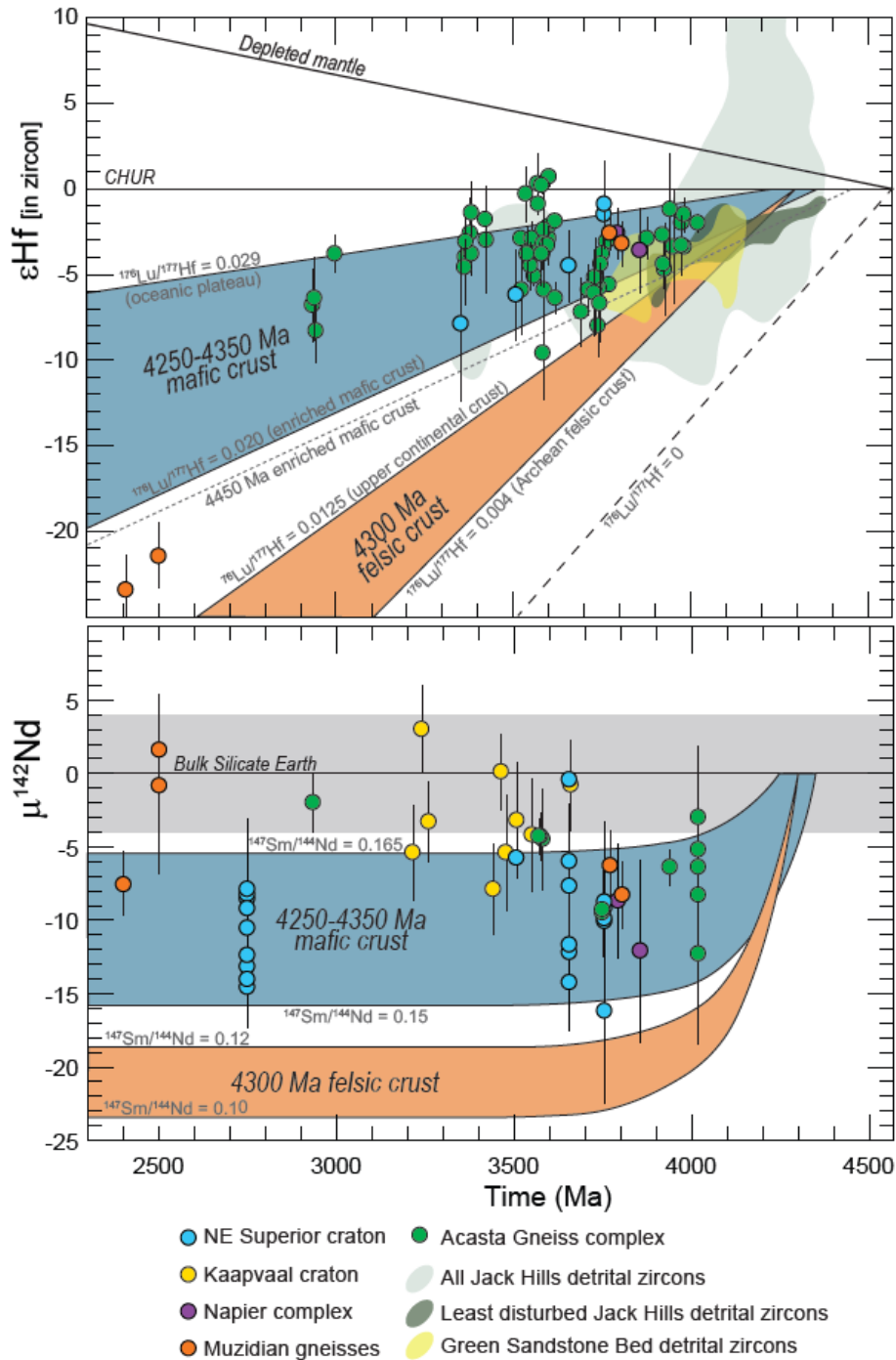


Figure 3: Initial  $\epsilon_{\text{Hf}}$ -zircon and  $\mu^{142}\text{Nd}$  for some of Earth's oldest TTGs and early Archean to Hadean detrital zircons, focusing on samples that record negative  $^{142}\text{Nd}$ . Each zircon- $\epsilon_{\text{Hf}}$  data point represents the average composition of several zircons from the same magmatic sample, calculated at the rock crystallization age. Irregular fields are for detrital zircons. The Green Sandstone Bed field only includes  $>3.80$  Ga zircons. The Jack Hills lighter grey field includes all analyses. The least-altered

Jack Hills zircons are shown by the darker grey field. Data points for  $\mu^{142}\text{Nd}$  are for individual whole-rock samples. K-rich granitic samples are not included as they may result from multiple crustal reworking episodes. The  $^{176}\text{Lu}/^{177}\text{Hf}$  and  $^{147}\text{Sm}/^{144}\text{Nd}$  ratios of the modeled crusts are shown in grey. Data sources are provided in the online supplement.

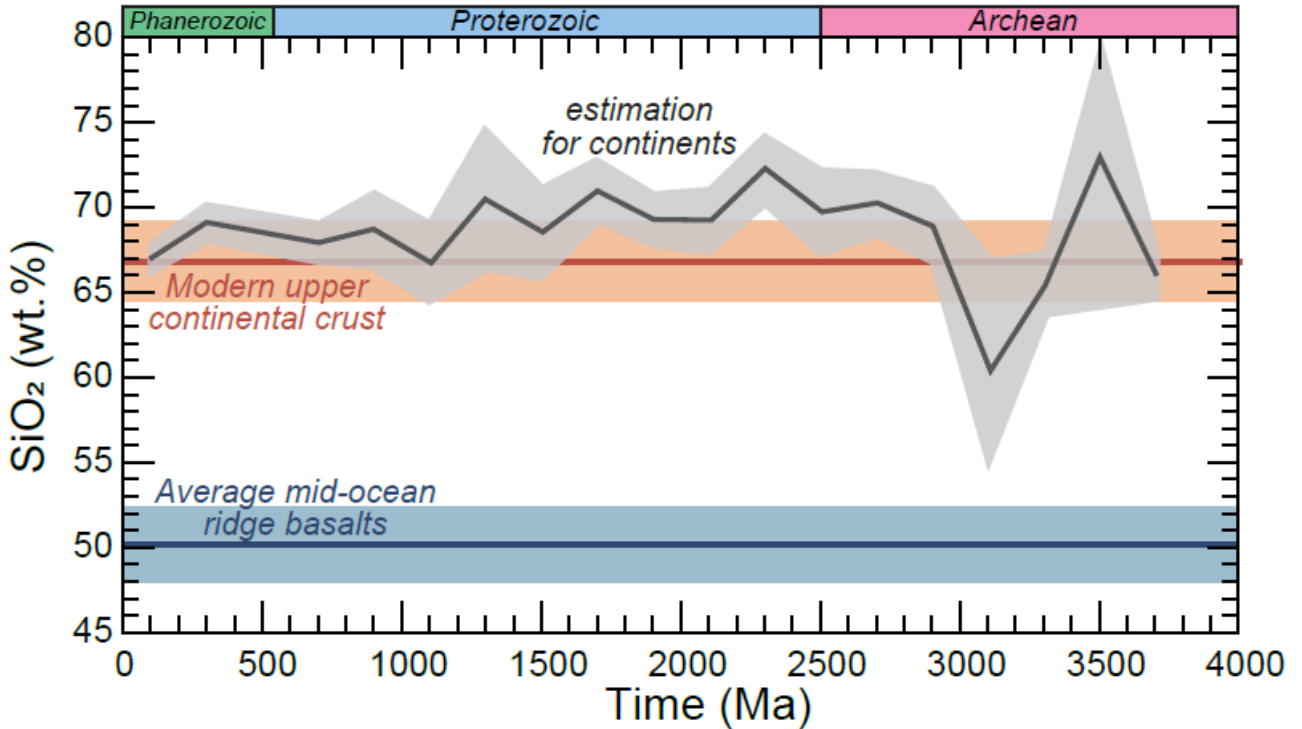


Figure 4: Estimated average  $\text{SiO}_2$  of continents through time based on the correlation of the Sm/Nd ratios of fine-grained terrigenous sedimentary rocks and  $\text{SiO}_2$  of igneous rocks. MODIFIED FROM GARÇON (2021). Data sources for upper continental crust and mid-ocean ridge basalt compositions are provided in the online supplements.

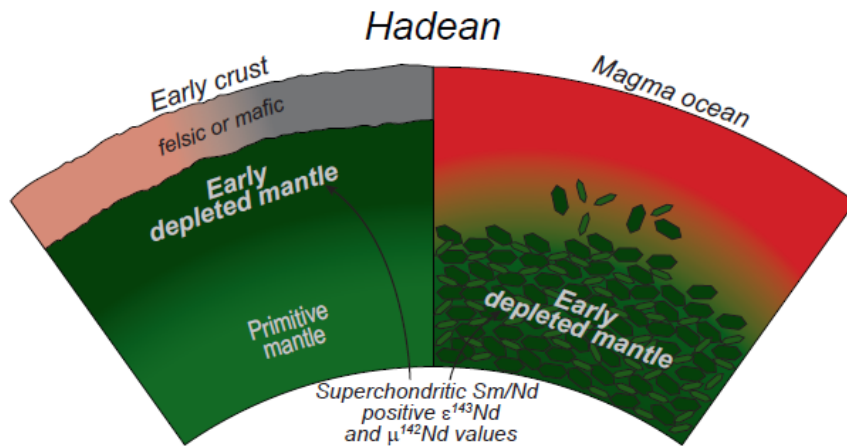
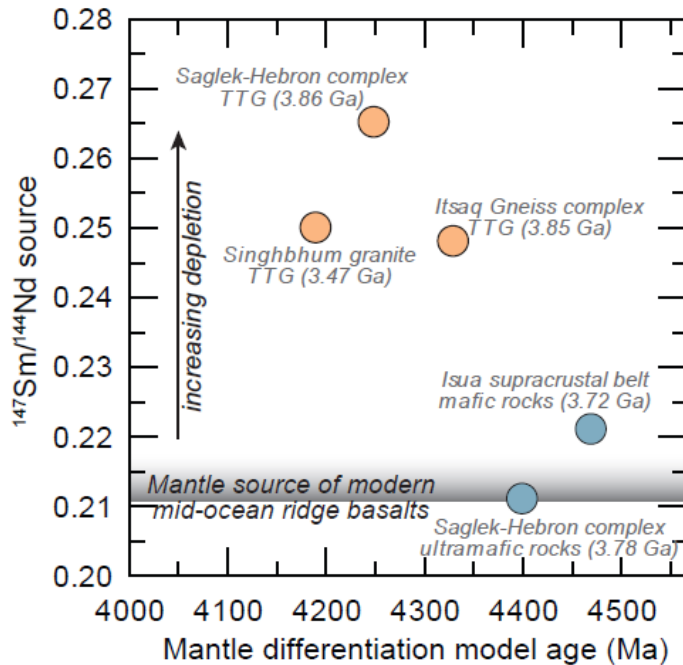


Figure 5: **(TOP)** Sm/Nd ratios versus differentiation age for sources of Paleoarchean to Eoarchean suites of rocks for which initial  $^{143}\text{Nd}$  and  $^{142}\text{Nd}$  data are available, and for rocks that have been interpreted as not significantly affected by post-magmatic processes. Mantle differentiation ages and Sm/Nd of the sources are calculated from coupled  $^{143}\text{Nd}$ - $^{142}\text{Nd}$  isotopic compositions. Data for mafic and ultramafic rocks include suites of samples. TTG data are individual samples. All samples yield positive  $\mu^{142}\text{Nd}$ , indicative of a Hadean depleted source. The variation in source Sm/Nd and ages spanning most of the Hadean suggests that no single event, but rather a combination of several or more-or-less continuous events, is responsible for the early depletion of the mantle. Ages in brackets

are the rock crystallization ages. Data sources are given in the online supplements, including the composition used to calculate  $^{147}\text{Sm}/^{144}\text{Nd}$  for the mantle source of mid-ocean ridge basalts.

**(BOTTOM)** Cartoon illustrating possible mechanisms responsible for the Hadean depletion of the mantle, such as episodic or progressive extraction of Earth's earliest crust (regardless of its composition) or the formation of depleted mantle domains following magma ocean solidification.

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