

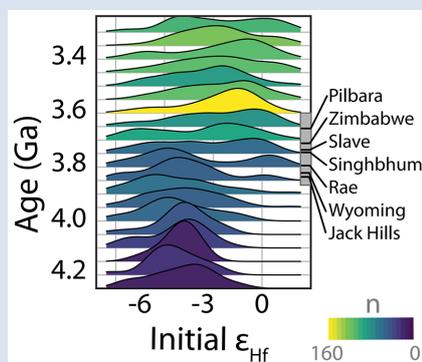
Hafnium isotopes in zircons document the gradual onset of mobile-lid tectonics

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Abstract



The tectonic regime of the early Earth has proven enigmatic due to a scarcity of preserved continental crust, yet how early continents were generated is key to deciphering Earth's evolution. Here we show that a compilation of data from 4.3 to 3.4 Ga igneous and detrital zircons records a secular shift to higher $^{176}\text{Hf}/^{177}\text{Hf}$ after $\sim 3.8\text{--}3.6$ Ga. This globally evident shift indicates that continental crust formation before $\sim 3.8\text{--}3.6$ Ga largely occurred by internal reworking of long-lived mafic protocrust, whereas later continental crust formation involved extensive input of relatively juvenile magmas, which were produced from rapid remelting of oceanic lithosphere. We propose that this secular shift in the global hafnium isotope record reflects a gradual yet widespread transition from stagnant-lid to mobile-lid tectonics on the early Earth.

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Introduction

On the modern Earth, continental crust is mostly generated at convergent plate margins through subduction-driven mantle melting. Due to the limited extent of the early rock record, it remains unclear whether a similar process was operative throughout Earth history or if there were major changes in the dominant mechanisms of continental crust production over time. On the basis of geological data and theoretical models, some workers have proposed that the earliest continental crust formed by remelting of long-lived mafic crust, either in local oceanic plateaus or in a global stagnant lid (Kemp *et al.*, 2010; Reimink *et al.*, 2014; van Kranendonk *et al.*, 2015). Determining whether protocrustal residence time varied regionally will shed light on the tectonic processes responsible for early crust production. Specifically, a uniformitarian view of continental crust production mechanisms is predicated on little change in the residence time of protocrust, whereas a non-uniformitarian view permits major changes that, in turn, would imply a transition in Earth's tectonic regime. A stagnant lid can only recycle mafic protocrust through volcanic burial, while a "mobile-lid" regime, with active subduction—possibly in a different style than modern plate tectonics—can rapidly

recycle mafic crust and transport surface-derived volatiles into the mantle.

Long-lived radiogenic isotope systems are powerful tracers of crustal evolution as they track crustal residence times and changes in magma source. Zircon is particularly useful because it preserves the original Hf isotope composition of the magma from which it is derived and, through the U-Pb decay system, precise information on the time of magma crystallisation. Crust has a lower Lu/Hf than residual mantle and therefore accumulates less radiogenic ^{176}Hf relative to the mantle, which is reflected in the resulting lower ϵ_{Hf} signature. Arrays of decreasing ϵ_{Hf} values with time suggest repeated reworking of pre-existing crust. Alternatively, shifts in Hf isotopic compositions reflect contributions from other sources such as the mantle, which often coincide with changes in crust production mechanisms.

The Hadean Earth may have been dominated by a ubiquitous mafic protocrustal lid (Kamber, 2007; Shirey *et al.*, 2008), but this view is based on only a few locales and therefore its global applicability has remained speculative. An extensive dataset is now available to assess the nature of the sources of Hadean and Archean magmas on a global scale. We compile the global Hf isotope record of 4.3–3.0 Ga zircons (including

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magmatic, xenocrystic, and detrital zircons; references in Methods, see Supplementary Information) of eight different Archean cratons. We compare the general ϵ_{Hf} -time evolution reflected in that dataset with a comparable dataset for the 4.02–3.4 Ga Acasta Gneiss Complex (AGC) of the Slave craton of Canada, a locale where zircon Hf isotope data is directly linked to parental whole rock geochemistry spanning 600 Myr of crust evolution. This comparison is necessitated by the nature of the extant data from other cratons, which are largely comprised of detrital zircons with only indirect links to their parental igneous rocks.

The Global Hf Isotope Dataset

The relatively well-characterised meta-igneous rocks of the AGC represent the earliest felsic rock record on Earth. We have previously summarised several decades of research in the AGC, linking the zircon and whole rock geochemical datasets, and have formulated a tectonic model for these rocks based on those datasets (Supplementary Information; Reimink *et al.*, 2019a). The zircons in 4.0–3.75 Ga AGC rocks show a trend towards decreasing ϵ_{Hf} values with time. In combination with whole rock compositional data, we interpret the ϵ_{Hf} trend to be a result of crustal magma generation by repeated, closed system melting of an ancient, long-lived mafic protocrustal nucleus at <~30 km depth, possibly in an oceanic plateau-like environment. AGC magmas produced after ~3.6 Ga (Fig. 1) show a distinct break in the trend to more negative ϵ_{Hf} values, instead displaying a broad range from juvenile values (+0.3) to those indicating contamination of magmas by older crust (-9.6). These Hf isotope data, along with other geochemical and isotopic data for these rocks, are interpreted to reflect a transition to a mobile-lid system, which brought young, surface-derived mafic crust to depths of melting beneath the evolving plateau. Partial melting of this mafic crust produced a pulse of felsic magmas with juvenile ϵ_{Hf} values that mixed with older extant crust in a tectonic setting broadly analogous to modern subduction systems. Continuation of this process formed the more extensive Slave craton basement east of the AGC (Reimink *et al.*, 2019b).

In many cratons, detrital zircons found in Archean sedimentary sequences deposited on top of older crustal nuclei are the only extant records of evolved crust older than 3.6 Ga (Fig. 1). Analysis of these detrital suites are poorly mixed, thus preserving a high degree of regional variation, indicating limited sediment transport distance and restricted provenance (*e.g.*, Sircombe *et al.*, 2001). This in turn suggests that the preserved continental detrital zircon suites represent erosion of several distinct, isolated terranes rather than of just one or two formerly contiguous terranes. Our compilation includes zircons of magmatic and detrital origins, likely providing a more complete global view of Archean processes.

The Slave craton can be used as a comparative framework to interpret the Hf isotope signatures of the global zircon archive. Notably, detrital zircons from the Slave craton sedimentary cover sequence exhibit similar ϵ_{Hf} -time trends as zircons recovered from the meta-igneous rocks of the Slave craton. This validates the use of detrital zircon suites for determining the geochemical character of their source rocks. Detrital and xenocrystic zircons (Fig. 1) from the Yilgarn, Singhbhum, Pilbara, Rae, W. Superior, Limpopo, and Wyoming cratons span the age range of from 4.3–3.0 Ga. Initial ϵ_{Hf} values of the 4.3–3.8 Ga zircon record are mostly negative and generally decrease with time. In contrast, between ~3.8–3.6 Ga, ϵ_{Hf} shifts to higher values in each terrane, requiring input from a juvenile source. This results in a bimodal distribution in ϵ_{Hf} probability density when zircon ϵ_{Hf} values are binned by

age (Fig. 2). These changes are also statistically significant, as shown by change-point analysis and moving averages (Supplementary Information). Occurring in every terrane and closely matching the Hf isotope evolution trends of the Slave craton, we suggest that this isotopic shift represents a global transition from crustal differentiation processes dominated by *in situ* reworking of older crust to those characterised by significant input of more juvenile crust.

The similarity of Hf isotope trends between the Slave record and the worldwide Hadean–Eoarchean detrital zircon record suggests that the processes recorded in the Slave craton were operating globally (Figs. 1, 2). The consistently negative ϵ_{Hf} values of Hadean detrital zircons indicate reworking of older mafic material ($^{176}\text{Lu}/^{177}\text{Hf}$ 0.022–0.015; Blichert-Toft and Albarède, 2008; Kemp *et al.*, 2010), which we propose reflects episodic shallow-level melting of an extensive and persistent stagnant mafic lid (Fig. 3). Mafic crustal reworking may have been focused in areas where the mafic protocrust was locally thickened *via* plume-like eruptions in a ‘heat-pipe’ regime (Moore and Webb, 2013), where heat is transported out of the mantle by volcanism from a restricted source area through an unbroken, stagnant lithosphere. Later in the Eoarchean (~3.8–3.6 Ga), the widespread shift to higher ϵ_{Hf} values likely occurred in response to a mobile-lid tectonic regime that melted surface-derived juvenile mantle (Fig. 3).

Rocks in SW Greenland-Labrador and northern Quebec have near-zero zircon ϵ_{Hf} at 3.7–3.9 Ga (*e.g.*, Næraa *et al.*, 2012; O’Neil *et al.*, 2013). No pre-3.94 Ga zircons have been found at either location, suggesting that felsic crust production in these terranes only began after ~3.9 Ga coinciding with the localised onset of the mobile-lid regime. Indeed, a subduction environment has been suggested to explain the lithologies and geochemistry of the Isua belt at ~3.8 Ga (*e.g.*, Friend and Nutman, 2010). There is also evidence for reworking of Hadean mafic crust to form Eoarchean felsic rocks at both of these locations (*e.g.*, Kamber, 2007; O’Neil *et al.*, 2013). Either of these interpretations is consistent with a Hadean stagnant-lid regime prior to crustal production and preservation in the SW Greenland and northern Quebec.

Although paired zircon Hf–O isotope signatures are commonly used to infer tectonic regime changes (*e.g.*, Dhuime *et al.*, 2012), in the case we address here, the O isotope system would not be sensitive to a shift between stagnant- and mobile-lid tectonics as both regimes largely involve direct remelting of basaltic source rocks. Heavy zircon $\delta^{18}\text{O}$ values most distinctly track weathered sedimentary input to the magmatic system, whereas partial melting of mafic crust hydrated by surficial waters will leave a more subdued isotopic imprint. Notably, there would be no expected difference in oxygen isotope composition between melts of long-lived mafic protocrust and melts of juvenile chondritic protocrust recycled in a mobile-lid regime. The lack of O isotope sensitivity within the processes of interest is shown by the fact that locations with substantial zircon O isotope datasets, such as the Jack Hills region, are indistinguishable from those found in the AGC (Reimink *et al.*, 2020), and no significant O isotope change occurs synchronously with a substantial Hf isotope shift.

Various geochemical datasets may suggest systematic change in the net growth rate of continental crust *ca.* 3.0 Ga (Dhuime *et al.*, 2012), or even 3.2 Ga (Næraa *et al.*, 2012). These apparent changes in net crustal growth have been suggested to be the result of modern style tectonics during the Mesoarchean. Though the statistical reliability of the observed 3.0 Ga crustal growth shift is not certain (Korenaga, 2018) and other global zircon based datasets have suggested geodynamic changes and net continental growth in the Eoarchean (Iizuka



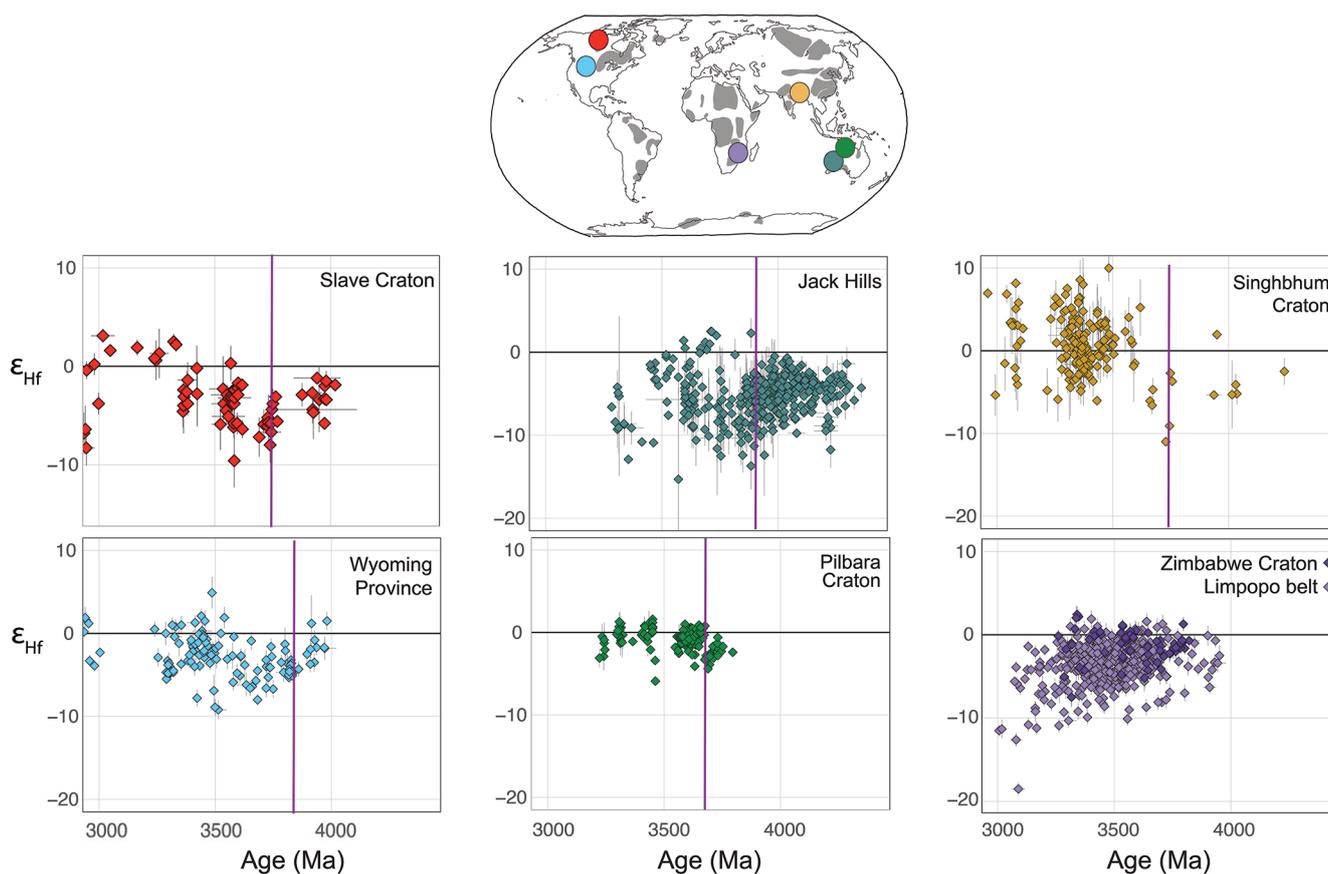


Figure 1 Zircon U-Pb-Hf isotope datasets from globally distributed Archean cratons. The purple lines show the change-point analysis inflection point shifts, which are often older than the first appearance of juvenile ϵ_{Hf} values and the loss of Hadean protocrustal signals. While the Limpopo belt does not clearly document a similar trend, detrital zircons from the Zimbabwe Craton do (Fig. S-11; Bolhar *et al.*, 2017).

et al., 2017), our interpretations are not inconsistent with a separate tectonic change at ~ 3.0 Ga. This dataset is diagnostic of a change from long-lived protocrust to shorter-lived crust generated in a mobile-lid setting ~ 3.8 Ga, a change likely to result in more rapid continental crust generation than a stagnant-lid regime. This mobile-lid setting could have operated through the Archean until ~ 3.0 Ga, when the Earth transitioned to a modern style tectonic regime (Dhuime *et al.*, 2012) or stabilised cratonic nuclei, driving the rise of continental reworking in collisional zones.

The analysis presented here does not necessarily suggest modern style plate tectonics, but is consistent with a more general “mobile-lid tectonics,” which may take many forms. A transition to “mobile-lid tectonics” is also a critical turning point in the broader differentiation of the Earth. Later Nd and Hf isotope records (Shirey *et al.*, 2008; Fisher and Vervoort, 2018) are critical for parsing the evolution of the depleted mantle with time, which is reflective of crustal extraction and dependent on the volume of crust removed and preserved within continents. This suggests that more voluminous crust production *via* mobile-lid tectonics initiated in the Eoarchean, consistent with the onset of discernible depleted mantle signatures in the Palaeoarchean (Fisher and Vervoort, 2018).

The Geodynamics of the Early Earth

Our analysis indicates that the Eoarchean is marked by a global change in terrestrial geodynamics, most likely a transition from stagnant-lid to mobile-lid tectonics. Though mobile-lid

tectonics can produce decreasing negative ϵ_{Hf} trends with time by supercontinent amalgamation, pre-3.6 Ga felsic rocks are mostly intermediate tonalites, which are not a common magma type produced in continent-continent collisions. Thus, we can rule out large scale continental reworking during this time period. A stagnant lid can potentially produce the long crustal residence times indicated by the Hf isotope trends. However, rates of volcanic burial must be less than estimated in the heat pipe model of Moore and Webb (2013); in this model Hadean resurfacing rates of $\sim 1\text{--}2$ mm/yr are needed for volcanic heat loss to balance mantle heat production by radionuclides. Such high burial rates would bury crust sufficiently deep to induce melting and felsic crust production (30 km) in only 15–30 Myr. This is too rapid to produce the negative ϵ_{Hf} trajectories seen in the global zircon record, implying that muted stagnant-lid volcanic fluxes may be necessary to preserve Hadean protocrust until the Eoarchean. Alternatively, a global ~ 4.4 Ga stagnant lid may have been melted by punctuated heat pipe volcanism (*e.g.*, Kemp, 2018). Furthermore, crustal reworking must be confined to laterally limited regions, as a fully global process would produce felsic crust covering the entire surface, which in turn would make the eventual initiation of mobile-lid tectonics difficult (van Hunen and Moyen, 2012).

We can only speculate on how the Earth might have transitioned between stagnant- and mobile-lid modes. Cooling of the Earth could promote the formation of weak plate boundaries necessary for subduction initiation, while allowing subducting slabs to remain strong and coherent (van Hunen and van den Berg, 2008; Sizova *et al.*, 2010). The formation of proto-continents or large oceanic plateaus could

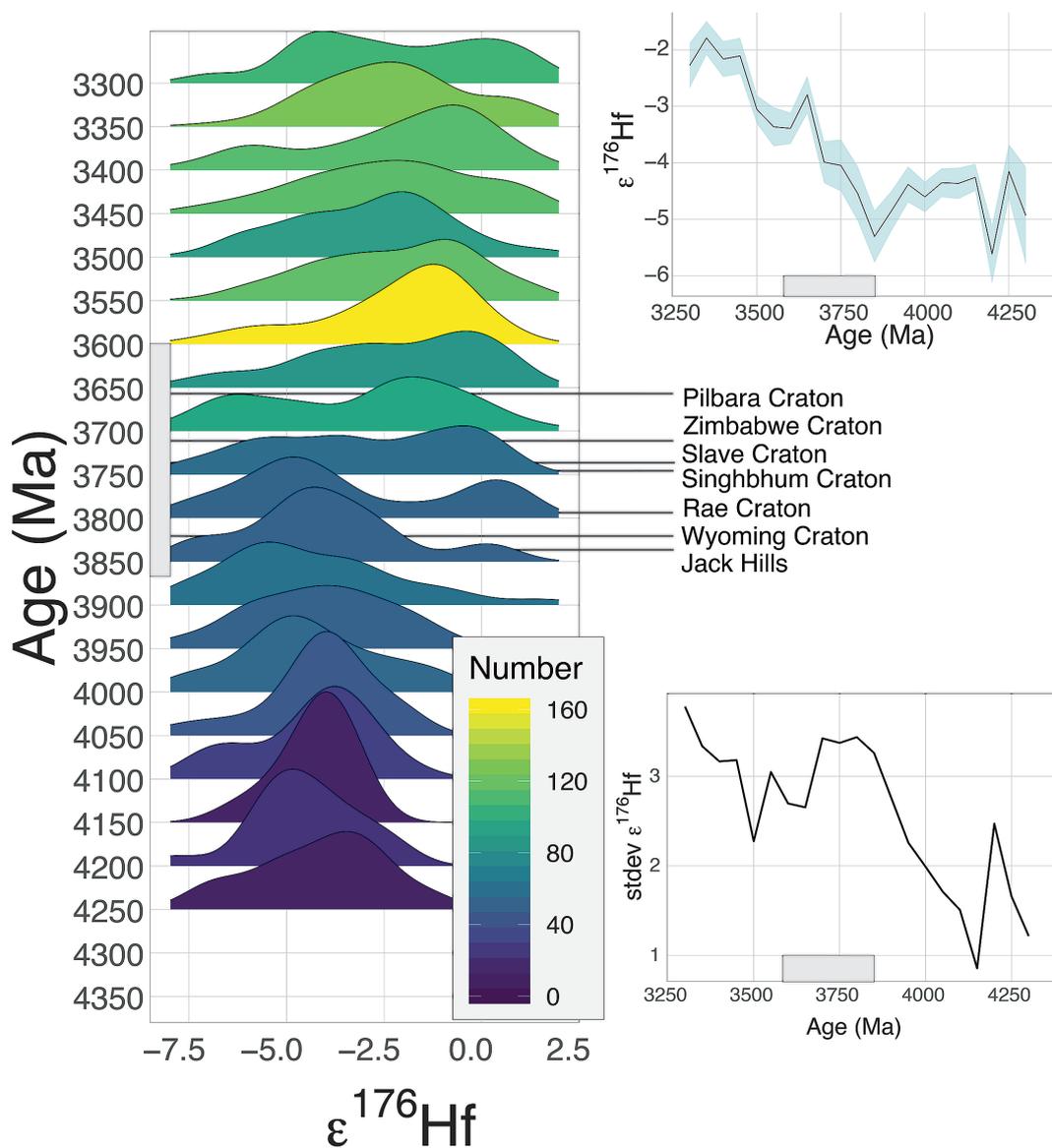


Figure 2 Stacked probability density plot of the global zircon age- ϵ_{Hf} compilation, with 50 Myr age bins. Colours indicate n for each bin. The timing of change-point shifts for cratons are labeled. The upper inset shows the moving average and 2 s.e. within this population; the lower shows the moving standard deviation.

also focus stresses and initiate subduction at their margins (Nair and Chacko, 2008; Gerya *et al.*, 2015). However, given our incomplete understanding of the lithospheric rheology responsible for the operation of modern plate tectonics, geodynamic predictions for the early Earth remain highly uncertain (Foley, 2018). The establishment of modern plate tectonics may have been a multi-stage process, with a transitional regime of subduction initiation and failure *en route* to the stabilisation of continuous subduction (O'Neill *et al.*, 2018).

Zircon Hf isotope data indicate that the transition from strongly negative to more juvenile ϵ_{Hf} values occurred at slightly different times in various cratons but within a ~ 200 Myr period globally from ~ 3.8 – 3.6 Ga (Figs. 1,2). This constraint could be important for a general understanding of the transition between stagnant- and mobile-lid regimes during the Archean, as different mechanisms will result in a variation in the predicted timespan for this global change. For instance, regime transformation is unlikely to be due to a global mantle overturn event, which would produce a geographically widespread change over a shorter time interval. Additionally, recent

modelling results indicate that it is geodynamically plausible for different regions of the Earth to experience the onset of mobile-lid tectonics at different times (Capitanio *et al.*, 2019).

The shift to a mobile-lid tectonic regime likely produced deeper volatile cycling by subducting plates. Changes in volatile recycling rates to the mantle will have resulted in compositional changes to the atmosphere and hydrosphere with dramatic implications for terrestrial habitability. Therefore, this tectonic shift in the early Archean may have ushered Earth's surface environs into a habitable regime with more efficient volatile recycling, promoting the sustained evolution of complex life. Future work should focus on finer resolution geodynamic models to explain the timing and nature of a transition from stagnant- to mobile-lid tectonics and a more precise accounting of the onset of juvenile magmatism in different locations. Our compilation suggests a substantial geodynamic change in the Eoarchean, which would have increased continental crust growth rates. This change may explain the lack of significant volumes of continental crust preserved on Earth prior to 3.9 Ga.

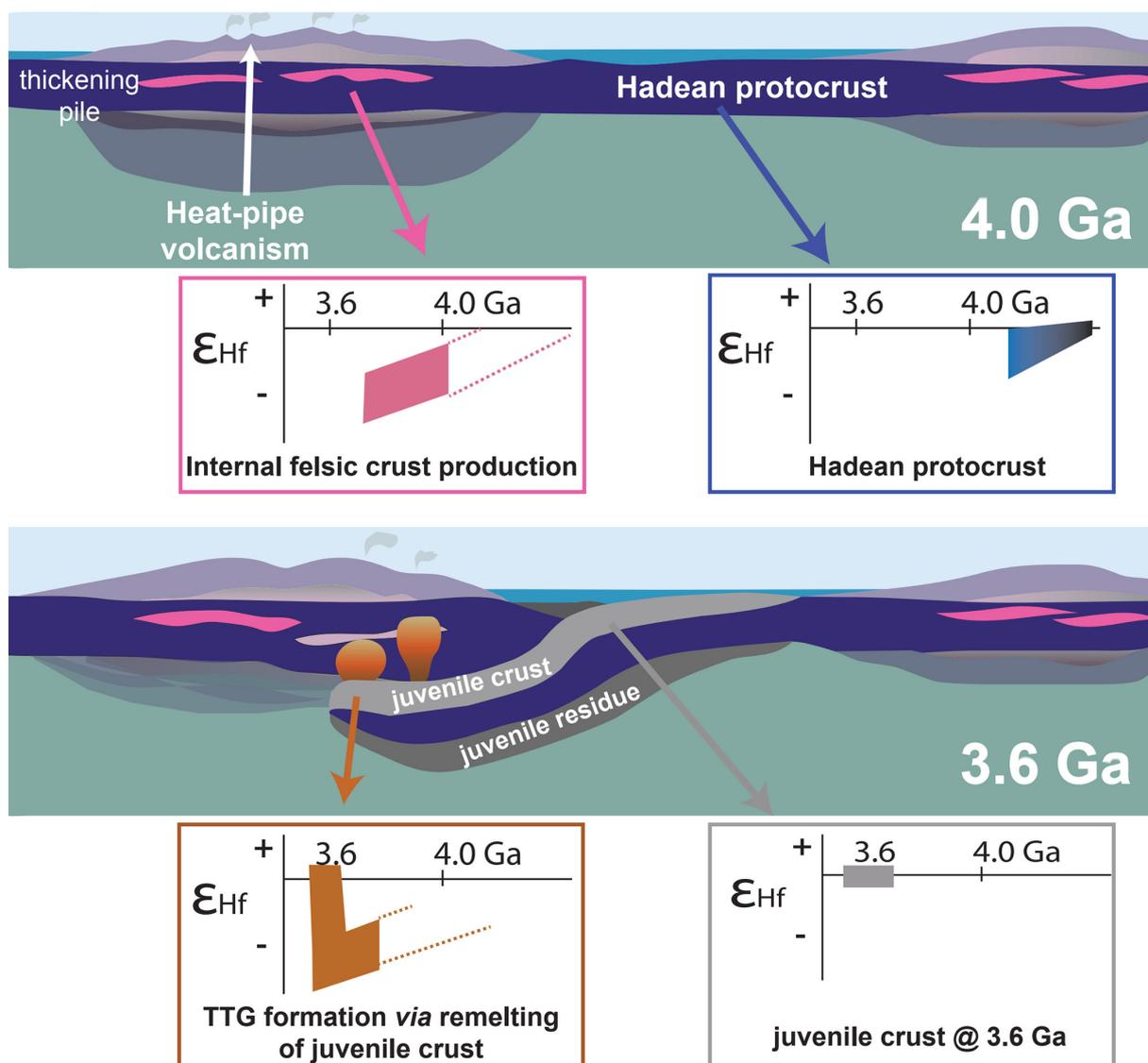


Figure 3 Schematic of global crust formation at ~4.0 and ~3.6 Ga; insets depict expected Hf isotope signatures of magmas.

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Author Contributions

AB and JRR formulated the idea and compiled the data. All authors aided in data interpretation and manuscript preparation. **Competing interests:** The authors declare no competing interests.

Additional Information

Supplementary Information accompanies this letter at <http://www.geochemicalperspectivesletters.org/article2015>.



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Supplementary Information

The Supplementary Information includes:

- Supplementary Discussion
- Figures S-1 to S-12
- Supplementary Information References

Supplementary Discussion

Restricted sourcing of detrital zircons in Archean cover group sequences

Our hypothesis of a global shift in tectonic regime relies on the globally representative nature of the compilation of detrital zircon suites that we have considered. In this section, we show that the current understanding of the sedimentary sequences containing ancient detrital zircons indicates restricted sourcing and small catchment size, which in turn strongly suggests that the detrital zircon suites considered here were derived from different terranes rather than sourced in a single, ancient terrane.

The sedimentary rocks that host Eoarchean-Hadean detrital zircons evaluated here are typically quartzites and conglomerates, which in places are interlayered with banded iron formations (Froude *et al.*, 1983; Bleeker *et al.*, 1999; Sircombe *et al.*, 2001; Thern and Nelson, 2012). Though many of these terranes have only recently been recognised to contain very old zircons, the Jack Hills and Slave craton zircon suites have been studied for decades and can aid in the interpretation of our global compilation. The Jack Hills detrital zircon suite is hosted in the Jack Hills greenstone belt, found along the southern edge of the Narryer Terrane in the Yilgarn Craton. The vast majority of analytical work focused on the Jack Hills detrital zircons has been dedicated to a relatively restricted outcrop (~2 m²), sample locality W74. A broader analysis of detrital zircons from the Yilgarn Craton (Thern and Nelson, 2012) indicates a substantial amount of regionality in the detrital zircon source terranes from sequence to sequence. Thern and Nelson (2012) concluded that even when considering samples containing >3.9 Ga zircons, distinct source terranes were required to explain the detrital zircon age distributions. Additionally, significant differences exist between the Jack Hills and Acasta Gneiss Complex (AGC) ϵ_{Hf} -age distributions; in general, the Jack Hills zircons are commonly older and have, on average, lower ϵ_{Hf} values than Acasta zircons at the same age. Therefore, the Yilgarn detrital zircons were not sourced from the AGC, and instead point to a slightly older crustal precursor.

The AGC is located on the western margin of the Slave craton and is only a small portion of the larger Slave craton basement gneiss assemblage, termed the Central Slave Basement Complex (CSBC; Bleeker *et al.*, 1999). Notably, the AGC is the only portion of the broader CSBC that is known to contain >3.4 Ga crust. A thin sedimentary cover group sequence, the Central Slave Cover Group, was deposited directly on top of CSBC and AGC basement rocks between 2.85 and 2.80 Ga (Ketchum *et al.*, 2004). This sequence contains detrital zircons that have been analysed for U-Pb (Sircombe *et al.*, 2001) and Hf-isotope systematics (Fig. 1c; Pietranik *et al.*, 2008). Significant differences in the U-Pb age distributions were documented between distinct locations across the



craton, and Sircombe *et al.* (2001) concluded that the sedimentary input in any one location had a limited diversity, leading to unimodal U-Pb age signatures. Grain size analysis of the detrital zircons substantiated this hypothesis. Whereas Pietranik *et al.* (2008) interpreted the Hf-isotope signatures (collected from the same grains as Sircombe *et al.*, 2001) from across the Slave craton as a whole, Reimink *et al.* (2019) focused on regional differences. The latter authors analysed the basement gneiss samples in the core of the Slave craton for their zircon Hf-isotope compositions and found that they had much more positive initial ϵ_{Hf} values (at the same age) than the concurrent magmatic generations of the AGC (Fig. 1a,c). They compared their basement gneiss samples to the detrital zircon U-Pb-Hf data from the cover group sequences and found that the detrital zircons found in sediments compare well with the basement gneisses directly beneath the sediments (Reimink *et al.* 2019; Fig. S-1). In other words, zircons from any individual sedimentary sample record the age- ϵ_{Hf} signature of proximal basement gneisses and not the entire craton.

Although most sedimentary packages containing Eoarchean-Hadean detrital zircons have not been studied in great detail, the two locations that have been studied in the most detail (the Yilgarn and Slave cratons) indicate that the sedimentary systems present during this time in Earth history had relatively restricted sedimentary input and localised sources. This conclusion is in line with limited freeboard in the Archean (*e.g.*, Flament *et al.*, 2008), leading to small basins and restricted sedimentary input. Therefore, it is unlikely that all detrital zircon suites in the current database were sourced from one ancient continental nucleus. The fact that several cratons contain Eoarchean-Hadean detrital zircons with negative initial ϵ_{Hf} values indicates that these signatures of long protocrustal residence times are representative of global crust formation processes during this time period, and consistent with a stagnant-lid regime.

Summary of the petrology and geochemistry of the Acasta Gneiss Complex

The AGC, which is located on the western margin of the Slave craton, has seen decades of geochronological, geochemical, and petrologic work, with dozens of publications contributing datasets relevant to the interpretations cited in this paper. Several of the authors of the present manuscript recently wrote a review chapter on the AGC that summarises this wealth of data and derives a tectonic model for the formation of the AGC from 4.02–3.4 Ga (Reimink *et al.*, 2018b). We point the reader to this chapter for a full discussion of data and references that contributed to the petrologic and tectonic model cited in the present study but summarise key components below.

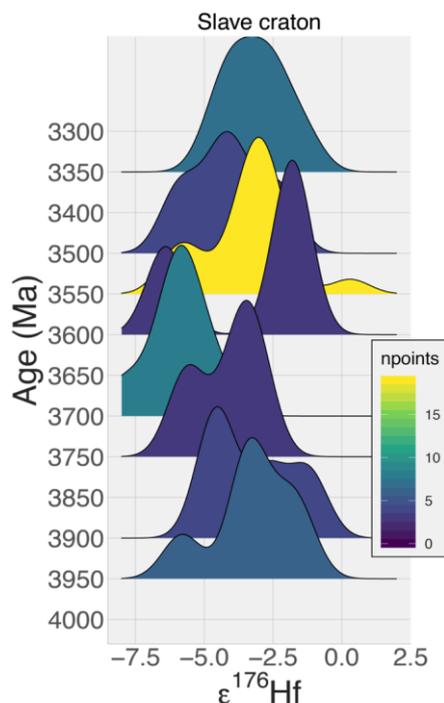


Figure S-1 Stacked probability density estimates for the Slave craton dataset, with the data binned in 50 Myr age bins and plotted separately.

The oldest rocks of the AGC (4.02 Ga) are iron-enriched tonalites with relatively flat REE patterns (low La/Yb) and negative Eu-anomalies. These geochemical signatures suggest formation by shallow-level fractional crystallisation of basaltic magma. Later

AGC magmas (3.96–3.75 Ga) include gabbros and generally more evolved tonalites and granodiorites but share the flat REE patterns and negative Eu anomalies of the oldest rocks. These later magmas formed by relatively shallow-level partial melting of hydrated mafic rocks. Granitoids formed at ~3.6 Ga, when ϵ_{Hf} values shift from negative to near zero (Fig. 1) and have fundamentally different compositional characteristics—they are more silicic, have steeper REE patterns (high La/Yb), and variable Eu anomalies. The petrological and geochemical characteristics of ~3.6 Ga AGC rocks suggest formation via partial melting of hydrated basalt at great depth, well within the garnet stability field (>40 km). Moreover, the elevated $\delta^{18}\text{O}$ values of zircon in this suite of AGC granitoids indicate that the magma source rocks had interacted with surface waters before deep burial.

As discussed in the main text, the isotopic record provides strong evidence that AGC rocks older than 3.7 Ga were formed by repeated reworking of Hadean protocrust, whereas < 3.6 Ga rocks require input from a relatively juvenile source. Both the Hf-isotope and ^{142}Nd -isotope systems show this distinct change in magma signatures after 3.6 Ga (Amelin *et al.*, 2000; Iizuka *et al.*, 2009; Reimink *et al.*, 2016; Bauer *et al.*, 2017; Reimink *et al.*, 2019; Roth *et al.*, 2014). Combined with the change in melting depth, these observations indicate a fundamental shift in the processes of TTG production at ~3.6 Ga in this region. The input of relatively juvenile material ~3.6 Ga in the AGC, which is also documented in global zircon Hf isotopic record, shows Hf isotope evidence of interaction with Hadean material. Along with the AGC zircon oxygen isotope record, this requires the input of surface-derived material at depth underneath a pre-existing crustal nucleus.

The source to these 3.75–3.96 Ga rocks was significantly older crust, as indicated by the increasingly negative zircon ϵ_{Hf} values as well as low whole-rock $\mu^{142}\text{Nd}$ (Fig. 2 in Reimink *et al.*, 2018a). In contrast, the ~3.6 Ga rocks were generated by a mixture of a relatively juvenile source and older evolved crust, with direct assimilation indicated by the presence of >3.7 Ga xenocrystic zircons in 3.6 Ga rocks (Iizuka *et al.*, 2006; Reimink *et al.*, 2016a). At ~3.6 Ga, variable interaction with the older, pre-existing crustal nucleus is evidenced by the spread in ϵ_{Hf} (~10 ϵ_{Hf} units) as well as the existence of older xenocrystic zircons within the ~3.6 Ga magmatic suite (Reimink *et al.*, 2016a; Iizuka *et al.*, 2007). The combination of the Hf- and O-isotope data are inconsistent with continued thickening of a single Hadean protocrustal block. Rather, the transition in Hf isotope compositions at ~3.6 Ga requires an external, younger source and the O-isotope data an efficient mechanism for the transit of surficial material to great depth. We have proposed that the geochemistry of 4.0 to <3.6 Ga AGC rocks documents a transition from repeated reworking of an ancient, long-lived protocrustal nucleus to a mobile-lid system that transported young, surface-derived crust to depth beneath the nucleus (Reimink *et al.*, 2018a).

Statistical and visual evaluation of the regional and global trends

We have applied several statistical and visualisation approaches to test the temporal changes in Hf isotope composition inferred from the global Hadean and early Archean zircon record. We present the data as stacked probability density estimates, and then evaluate the binned age statistics and the change point analysis of the mean values of these datasets with time. These are discussed in detail below.

First, to evaluate changes in ϵ_{Hf} values with time, we have taken regional and global data sets and subdivided them into 50 Myr age bins. The ϵ_{Hf} values (without uncertainties) were then plotted as a probability density estimator using the `geom_density_ridges` density estimator in the R software program (package: `ggplot2`). This approach can identify age intervals with distinct changes in ϵ_{Hf} distributions, and in particular highlight distribution changes that may be missed when considering a moving mean. For instance, Figure S-1 shows density estimators from each 50 Myr age bin for the Slave craton dataset. Note that the heights of each density curve are normalised to have the same area under each curve. Therefore, sharp peaks in the probability distribution are likely due to small numbers of data in a particular region. The colours under each curve correspond to the number of data points in each age bin.

The trend of decreasing ϵ_{Hf} values with decreasing age can readily be seen in the 4.0–3.7 Ga age interval and a bimodal ϵ_{Hf} distribution appears at ~3.6 Ga. These trends match the distribution of data in the age- ϵ_{Hf} plot for the Slave craton and show the utility of using stacked distribution plots for datasets that are over plotted (*i.e.*, crowded) in X-Y space, such as the global compilation of age- ϵ_{Hf} data.

In Figure S-2 we show stacked probability density estimators for all individual detrital datasets, along with the global compilation. Though several of the datasets (*e.g.*, Singhbhum, Rae, Limpopo) have only a few data points in the oldest population of zircons, the global compilation robustly documents the transition from the progressively lower ϵ_{Hf} trend to more juvenile ϵ_{Hf} values in the 3.8–3.6 Ga interval. The bimodal distributions of ϵ_{Hf} data in the 3.8–3.6 Ga interval show the arrival of a juvenile source into Earth's felsic crustal system, and the diminishing presence of Hadean crustal sources.



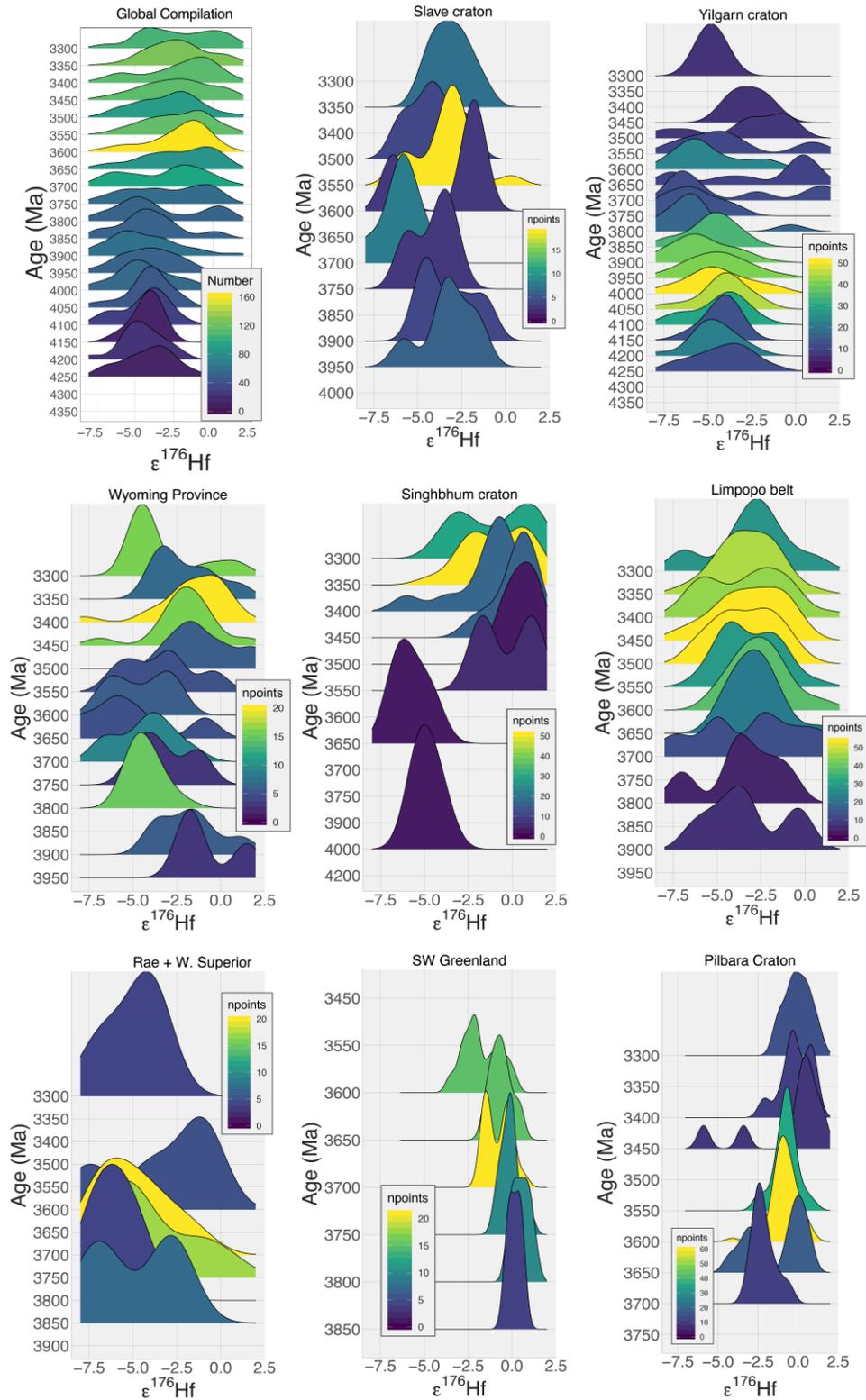


Figure S-2 Stacked probability density plots showing zircon ϵ_{Hf} values binned in 50 Ma age intervals. Location labels correspond to the plots beneath them and the bandwidth is chosen automatically for the probability densities, which applies to each density curve in an individual plot.



Binned age statistics

A common way to evaluate changes in a time-series analysis is to look at changes in the mean and standard deviations of samples through time. Using the same age bins (50 Myr) and the global compilation dataset, we can see changes in the mean ϵ_{Hf} value within each age bin. Note, however, that changes in the mean will be naturally subdued and mean values will not be representative of an actual source composition, particularly in the presence of bimodal distributions. This is particularly true in the 3.8–3.6 Ga interval, where the global compilation has a bimodal distribution (Fig. 2).

In Fig. S-3a, the mean ϵ_{Hf} from each age bin is plotted, with the blue error envelope representing the two standard errors about the mean. An increase in mean ϵ_{Hf} values begins at ~3.8 Ga, with the mean gradually shifting to higher ϵ_{Hf} values over the next ~500 Myr. In Fig. S-3b, the standard deviation of each age bin is plotted against age. A step increase in the standard deviation occurs, this time in the 3.9–3.7 Ga age interval. This is an expected result if another source, with a different Hf-isotope composition, is introduced into the system. This observation is not, in and of itself, diagnostic of a new source, as the standard deviation of the global Hf-isotope system is expected to increase over time simply as various reservoirs have more time to evolve to more extreme values, generating a larger spread in ϵ_{Hf} . However, the correspondence of this increase with the increase in mean ϵ_{Hf} value, with the arrival of a new source shown by bimodality in ϵ_{Hf} distributions in Fig. S-2, and the threshold analysis, discussed below, is entirely consistent with our analysis.

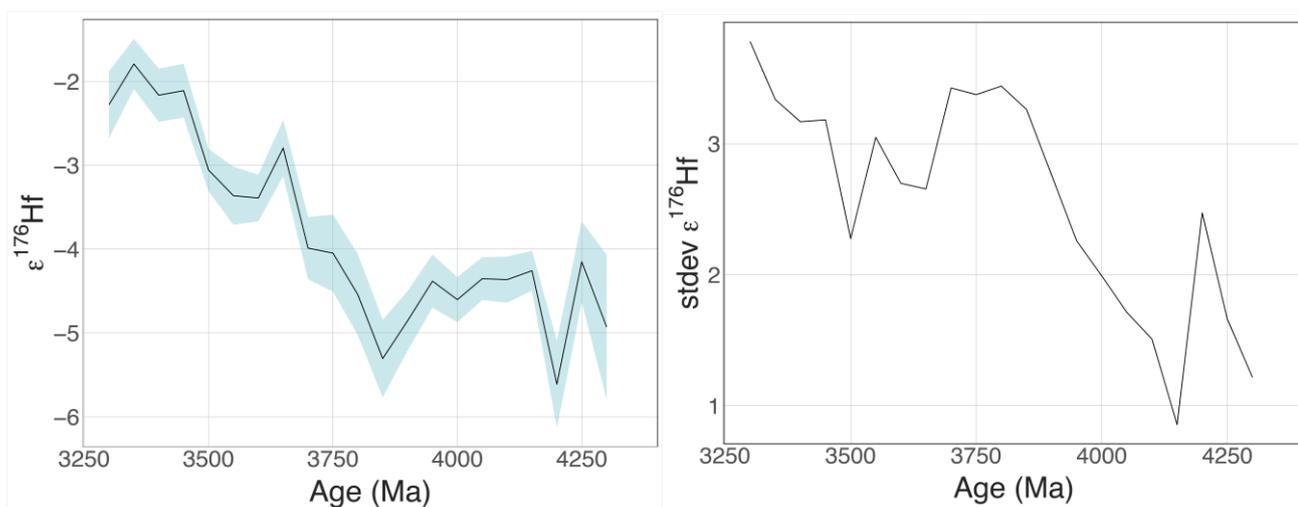


Figure S-3 (a) The mean ϵ_{Hf} (blue band is 2SE about the mean) at 50 Myr age bins for global detrital and magmatic zircons considered in this study. (b) The moving standard deviation of zircon ϵ_{Hf} values within each age bin.

Change-point analysis

Change-point analysis is a widely used statistical technique that is commonly employed to search for changes in means or variance of time-resolved data sets. We employ change point analysis, using the `chgnpt` package in R (Fong *et al.*, 2019). This particular implementation of change-point analysis, or more precisely threshold regression analysis, allows for hypothesis testing using several threshold regression models, including the so-called “segmented” threshold effect, which is most applicable to the types of data and underlying processes that we are attempting to evaluate. We chose this strategy as it appears to be the best method for detecting changes in source composition in age- ϵ_{Hf} data sets, where we are looking for shifts in isotopic composition that reflect large-scale changes in the source to the zircons and their parental magmas, be it older crustal material or a depleted mantle component. Therefore, we are attempting to discern changes in the slope of an underlying fit line which can represent the source to felsic rocks through time and its evolution in Hf-isotope space. Note, however, that a fit line may not always represent a real reservoir that is evolving along a Lu/Hf trajectory but may instead represent a systematic change in the mean due to the input from a new source. For instance, while we interpret the slope of a regression line through the oldest Slave craton data (Fig. S-4) to represent a real reservoir evolving towards negative ϵ_{Hf} (low Lu/Hf reservoir), the slope of the next trajectory line, after the threshold change, is not representative of a real source as it would require a highly depleted mantle that evolved from a low ϵ_{Hf} value at 3.6 Ga, an unlikely process.



Using the example of the Slave craton data, we can see the outputs from the threshold regression analysis. The first panel shows the input age- ϵ_{Hf} dataset for the Slave craton (data sources discussed in previous sections). The red line is the regression corresponding to the threshold change indicated by the threshold regression model. The second panel shows the likelihood of change from the restricted regression models with fixed change points, with real data points plotted as well. The bottom panel shows a histogram of the frequency of threshold estimates in a bootstrapped model of the existing dataset. Notably, this threshold regression analysis indicates that a significant change in the mean ϵ_{Hf} of the Slave craton data occurred in the 3.7-3.75 Ga interval. This agrees with our interpretation that the 3.6 Ga event in the Slave represents the arrival of a new, more juvenile, source to magmatism in the AGC (*e.g.*, Reimink *et al.*, 2018a and references therein).

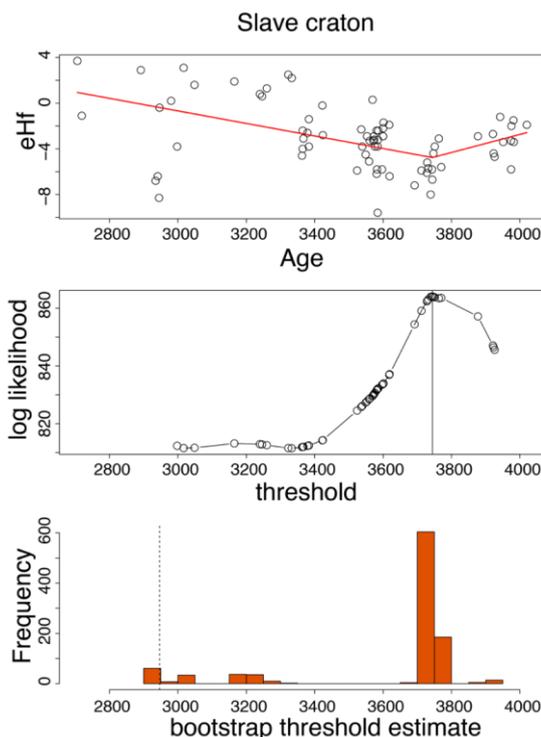


Figure S-4 Changepoint analysis for the Slave Craton.

Global compilation

The threshold regression model suggests a major change at 3.8-3.9 Ga in the global compilation of zircon ϵ_{Hf} . This change appears to be significantly older than the change at \sim 3.6 Ga documented in the Slave craton and other regions. However, as discussed in the main text, grouping all regions in one, global, analysis will necessarily ‘smear out’ any transition that does not occur at precisely the same time. For example, the earliest of two transitions toward higher ϵ_{Hf} values within the Yilgarn craton occurs near 3.85 Ga (Figs. S-7, S-10), while it occurs in the Slave \sim 3.6 Ga. An analysis of the combined datasets will be biased towards the dataset with more analyses, in this case the Yilgarn craton which hosts the Jack Hills zircons.

Additional ‘smearing’ of any transition will be caused by variability in mantle extraction ages of different regions. Again, we can look to the Yilgarn and Slave datasets, where the oldest components of the Slave have chondritic model ages \sim 4.2 Ga, whereas in the Jack Hills, the chondritic model ages are closer to 4.4 Ga. Combining these two regions will provide a mixed population, and smear any clear change point analysis results. Nevertheless, even when combining all regions to produce a global, but mixed, dataset, threshold regression models indicate a systematic change in zircon ϵ_{Hf} values in the 3.7-4.0 Ga interval.

In the following plots (Figs. S-5 through S-12), each location is evaluated using the same threshold regression analysis. Some cratons (Wyoming, Yilgarn) have threshold regression results very similar to the Slave craton and the global compilation, while others (Singhbhum, Rae, Limpopo) do not show the same clear transitions. The lack of transitions detected by the threshold regression analysis could be caused by many factors including, limited data in the age interval of interest (Rae), more prominent



transitions at younger ages (Singhbhum), or denser data populations at younger ages (Limpopo). Note that in the case of the Singhbhum craton, a clear trend nearly identical to the Slave craton is seen when the threshold analysis is applied only to analyses >3.4 Ga.

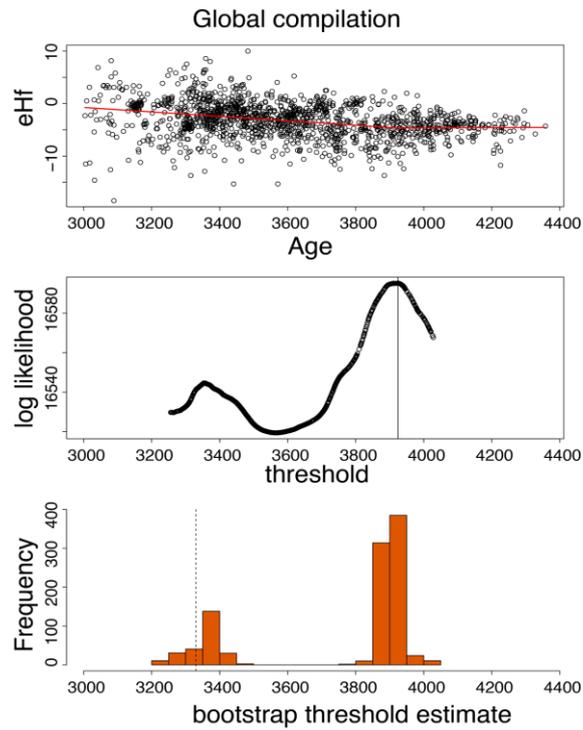


Figure S-5 Change-point analysis of the global zircon age- ϵ_{Hf} data compilation.

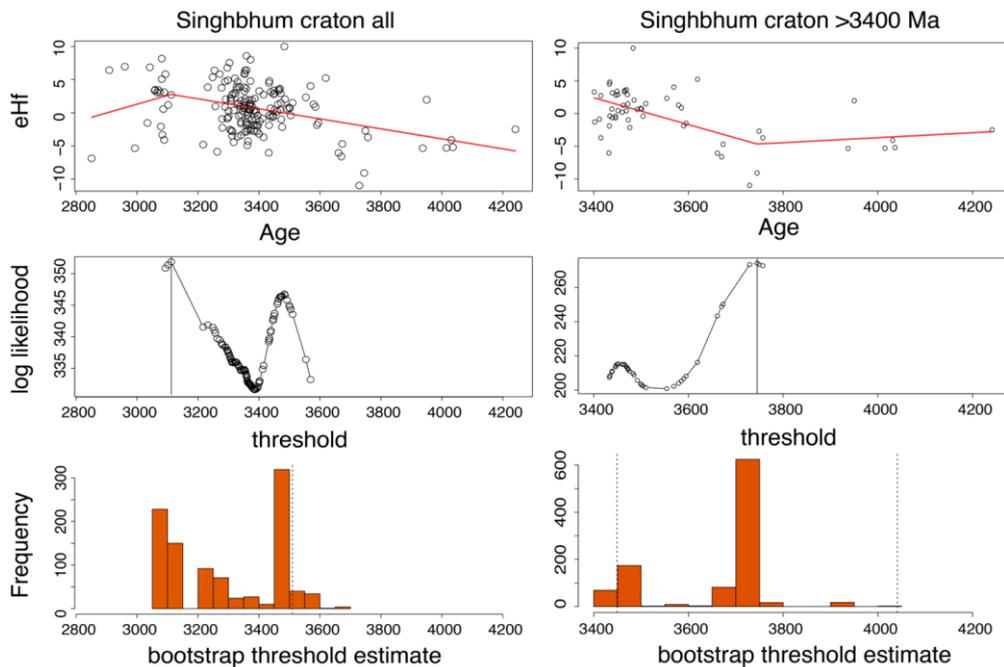


Figure S-6 Change-point analysis of the Singhbhum craton (at left: all timepoints; at right: >3400 Ma).



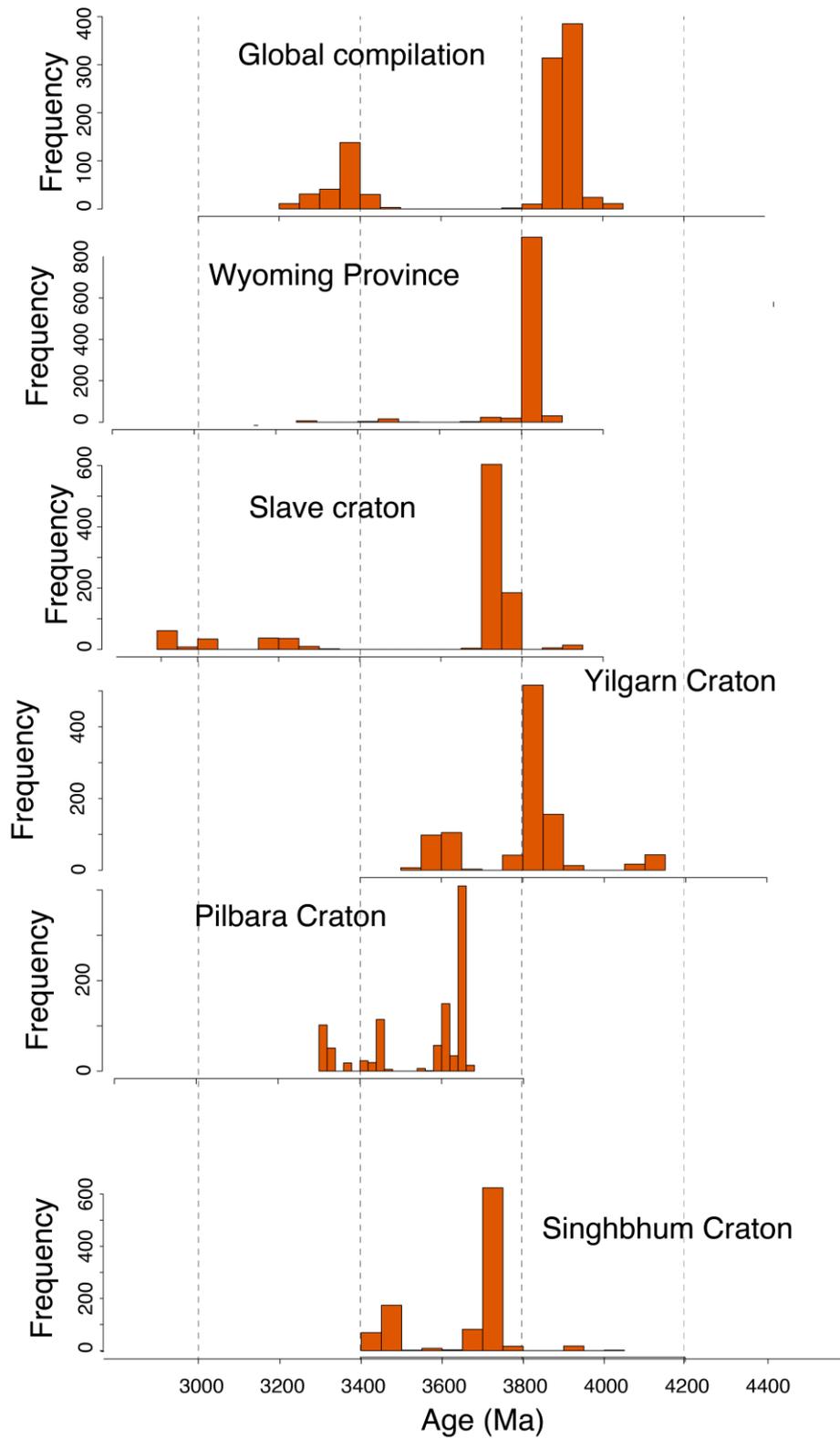


Figure S-7 Compilation of bootstrapped threshold estimates from the changepoint results for several cratons.



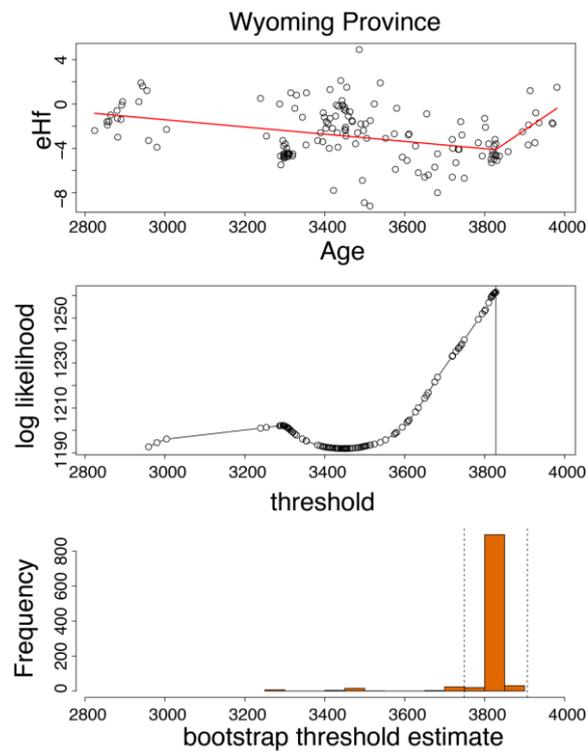


Figure S-8 Changepoint analysis of the Wyoming Province zircons.

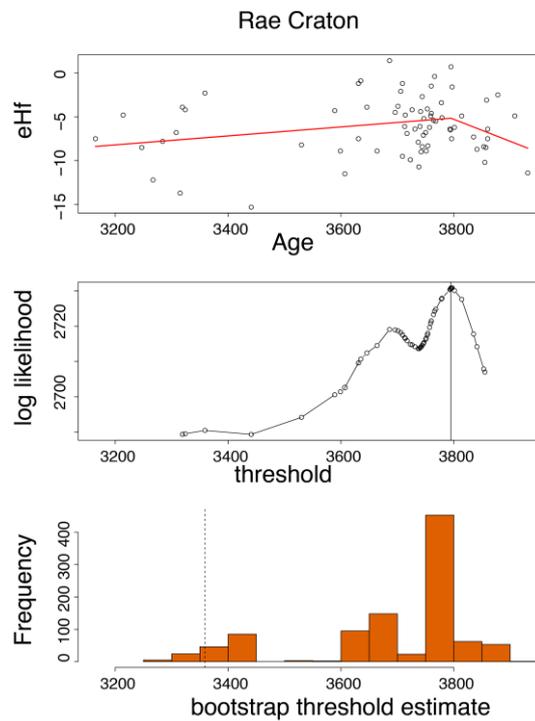


Figure S-9 Changepoint analysis for the Rae Craton and Western Superior Craton zircons.



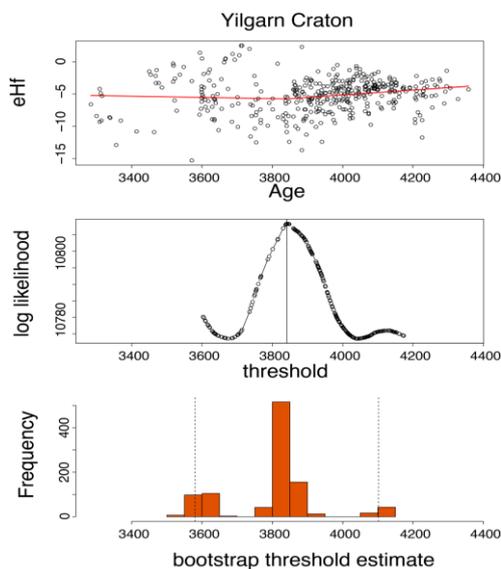


Figure S-10 Changepoint analysis for the Yilgarn craton zircons.

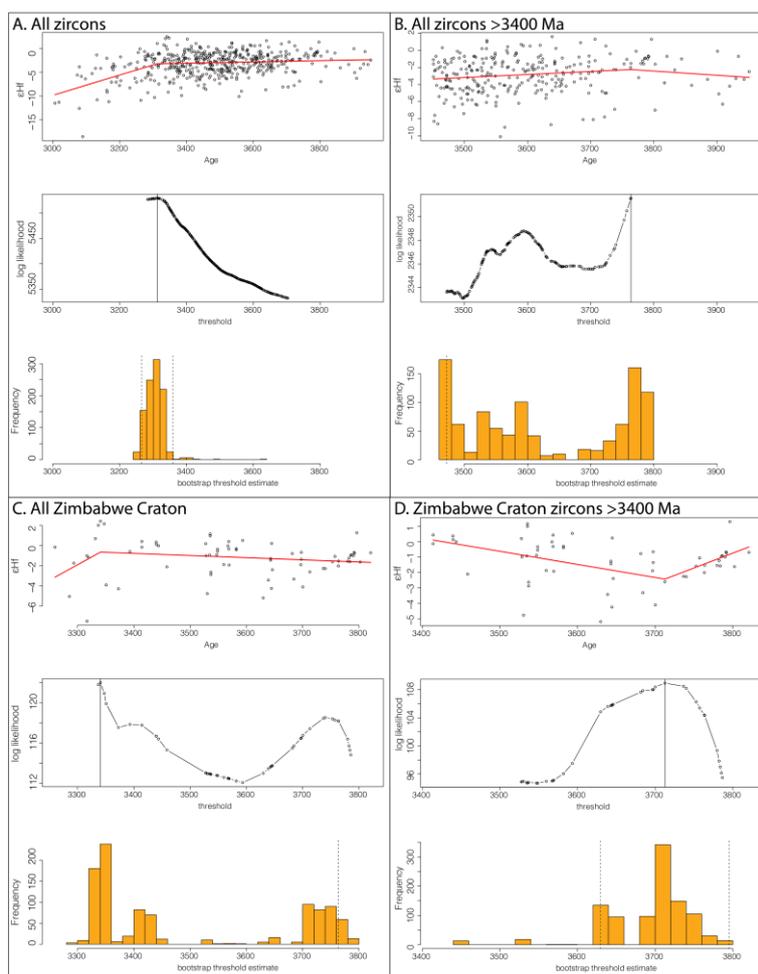


Figure S-11 Changepoint analysis for the combined Limpopo Belt (Zeh *et al.*, 2014) and Zimbabwe Craton (Bolhar *et al.*, 2017) detrital zircons, which may have had a related source. Panel A shows the changepoint analyses for the full dataset, which is dominated by low ϵ_{Hf} zircons <3200 Ma. Panel B shows the >3.4 Ga subset of all analyses. Panel C shows only those analyses from the Zimbabwe Craton, and a major peak in changepoint likelihood at ~3750 Ma, though not the dominant changepoint. Panel D shows the oldest (>3400 Ma) subset of the Zimbabwe Craton zircons, with a distinct changepoint similar to the Slave craton datasets.



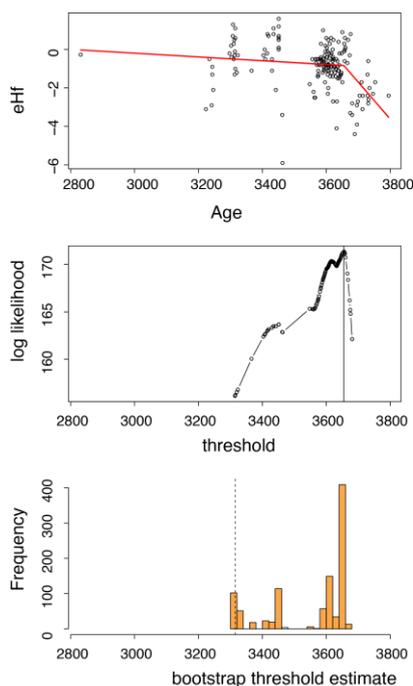


Figure S-12 Changepoint analysis for the Pilbara craton zircons.

Other Archean detrital and metaigneous zircon datasets

The similarity of Hf-isotope trends between the AGC and the Hadean–Eoarchean detrital zircon record makes a compelling case that the processes recorded in the AGC during this time were operating at a global scale. Here we compare the AGC zircon Hf isotope record with three additional terranes. The North Atlantic Craton zircon Hf isotope record is consistent with juvenile compositions from 3.9–3.7 Ga, similar to the evolution of the SW Greenland and the Nuvvuagittuq greenstone belts. There is also limited zircon ϵ_{Hf} data from the Ancient Gneiss Complex, southern Africa. These rocks do not appear to contain Hadean material and the oldest rocks (~3.66 Ga) have negative ϵ_{Hf} values, consistent with remelting or assimilation of older (but likely not Hadean) material. At ~3.5 Ga, there is input of relatively juvenile material, corresponding to a diminution of isotopic signals of the oldest crustal materials in this region in the <3.5 Ga magmatic generations. Notably, neither of these terrains contain identified >3.9 Ga zircon material and compare well with locations such as SW Greenland. They may simply not preserve a heritage of stagnant-lid crust production and instead only record felsic crust production at the onset of juvenile growth in a plate-margin setting.

We would also like to acknowledge here that the similarities between the Acasta Gneiss Complex ϵ_{Hf} -time trends and those of the Rae and W.Superior cratons and Limpopo Belt are more difficult to evaluate (the statistical change point analysis of these cratons is presented in S-9 and S-11). An important point, however, is that the Rae and West Superior regions have very few data. The Limpopo Belt dataset has significant scatter in each age interval, however, when Zeh *et al.* (2014) used oxygen isotopes and CL imaging to filter the dataset, the remaining number of analyses is prohibitively small. It is therefore our opinion that these terranes must be further analysed in detail, and our manuscript provides a testable model to motivate this future work.

Methods

Zircon Hf-isotope data were compiled from the following references, divided by location. All initial ϵ_{Hf} values were calculated using the ^{176}Lu decay constant of Scherer *et al.* (2001) and the CHUR Lu-Hf parameters of Bouvier *et al.* (2008).

The Acasta Gneiss Complex data plotted here is taken from Reimink *et al.* (2016a), Amelin *et al.* (1999), Iizuka *et al.* (2009), Reimink *et al.*, (2016b), Bauer *et al.* (2017), Reimink *et al.* (2019), Amelin *et al.* (2000), Iizuka and Hirata (2005), and the subset of zircon data from Guitreau *et al.* (2012) which matches the corresponding whole rock Hf isotope systematics. Sample SAB-96-55 of the Acasta Gneiss Complex dataset of Bauer *et al.* (2017) was excluded from the figures in this paper because subsequent zircon U-Pb analysis has revealed further complexity in the age interpretation and assignment. The Central Slave Basement Complex data



comes from Reimink *et al.* (2019), and the detrital Slave data from Pietranik *et al.* (2008).

The Jack Hills and Narryer Gneiss Terrane dataset includes detrital zircons from the Jack Hills (Amelin *et al.*, 1999; Kemp *et al.*, 2010; Amelin *et al.*, 2000; Bell *et al.*, 2014; Harrison *et al.*, 2008) as well as metaigneous zircons from the Narryer gneisses (Kemp *et al.*, 2010).

Some of the zircon Hf isotope results from the Nuvvuagittuq Greenstone Belt of northern Quebec (O'Neil *et al.*, 2013) are plotted as modes of Hf isotope composition instead of weighted means, as presented in the original publication. The uncertainty bars on those samples represent the range in measurements and do not represent the analytical uncertainty. The remaining data are from Augland *et al.* (2015).

Zircons from SW Greenland are from orthogneisses (Amelin *et al.*, 2000 and 2011; Fisher and Vervoort, 2018; Hiess *et al.*, 2009 and 2011; Kemp *et al.*, 2009; Næraa *et al.*, 2012), felsic volcanics (Hiess *et al.*, 2011; Kemp *et al.*, 2009), and metasediments (Næraa *et al.*, 2012). The uncertainties presented for the results of Amelin *et al.* (2000) are the 2SD of the weighted means. The age interpretations in Fisher and Vervoort (2018) are in part from Bennett *et al.* (1993) and Nutman *et al.* (2000) and unpublished data from G.E. Gehrels.

U-Pb and Lu-Hf isotope signatures of detrital zircons from a quartzite from the Rae Craton and a metagraywacke from the Assean Lake area, NW Superior Province, are from Hartlaub *et al.* (2006).

Zircon ϵ_{Hf} signatures from detrital zircons of the Wyoming craton are from quartz-rich metasediments of the Beartooth Mountains, Wyoming (Mueller and Wooden, 2012) and magmatic zircons from orthogneisses of the Sacawee Block of the Granite Mountains, Wyoming (Frost *et al.*, 2017). The results from (Frost *et al.*, 2017) are plotted at the measured zircon U-Pb ages in correspondence with how they were presented in that publication; the uncertainties have not been plotted but the 2σ vary between 6 and >100, with a typical value of ~20 Myr.

Magmatic zircons from the Singhbhum craton are from granitoids (Dey *et al.*, 2017), the Older Metamorphic Tonalitic Gneiss and Palaeoarchean TTGs (Chaudhuri *et al.*, 2018). Detrital zircons are from a modern river sediment (Miller *et al.*, 2018). Detrital zircons from quartzites of the Limpopo Belt are from Zeh *et al.* (2014). The xenocrystic zircons from the Pilbara craton are from Petersson *et al.* (2019) and other datasets compiled in that work.

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