Did transit through the galactic spiral arms seed crust production on the early Earth?

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Abstract

Although there is evidence for periodic geological perturbations driven by regular or semi-regular extra-terrestrial bombardment, the production of Earth's continental crust is generally regarded as a function of planetary differentiation driven by internal processes. Here, we report time series analysis of the Hf isotopic composition of zircon grains from the North Atlantic and Pilbara cratons, the archetypes of Archean plate tectonic and non-plate tectonic settings, respectively. A ~170–200-million-year frequency is recognized in both cratons that matches the transit of the solar system through the galactic spiral arms, where the density of stars is high. An increase in stellar density is consistent with an enhanced rate of Earth bombardment by comets, the larger of which would have initiated crustal nuclei production via impact-driven decompression melting of the mantle. Hence, the production and preservation of continental crust on the early Earth may have been fundamentally influenced by exogenous processes. A test of this model using oxygen isotopes in zircon from the Pilbara Craton reveals correlations between crust with anomalously light isotopic signatures and exit from the Perseus spiral arm and entry into the Norma spiral arm, the latter of which well-matches the known age of terrestrial spherule beds. The data support

bolide impact, promoting the growth of crustal nuclei, on solar system transit *into* and *out of* the galactic spiral arms.

Introduction

Earth is unique amongst the known planets in having continents, whose formation has fundamentally influenced the composition of the mantle, hydrosphere, atmosphere, and biosphere. Cycles in the production of continental crust have long been recognised (Condie, 1998) and generally ascribed to the quasi-periodic aggregation and dispersal of Earth's continental crust as part of the supercontinent cycle (Murphy and Nance, 2003). However, such cyclicity is also evident in some of Earth's most ancient rocks that formed during the Archean (4000–2500 Ma) and Hadean (>4000 Ma) eons, when plate tectonics may not have operated. These frequencies are challenging to decipher in the early Earth given that the rock record becomes increasingly fragmentary with age.

One mechanism to assess the cyclicity of crust production and its drivers is through the isotopic records of rocks and constituent minerals (Puetz and Condie, 2019). Zircon U–Pb–Lu–Hf isotopic datasets are particularly well-suited to this endeavor as they retain a time-encoded proxy for the degree of source fractionation. Here, we investigate the cyclicity in the addition of new mantle-derived (juvenile) crust and its subsequent reworking through the Hf isotopic record of dated zircon grains from the Archean North Atlantic Craton (NAC) in West Greenland, and the Pilbara Craton in Western Australia. We complement this Hf data set with oxygen isotope compositions of dated Pilbara zircon.

The NAC is dominated by Mesoarchean (3200–2800 Ma) felsic (silica-rich) gneisses and ultramafic complexes, along with younger supracrustal sequences and late-tectonic felsic to mafic intrusions (Friend and Nutman, 2019). It is commonly considered to have formed through horizontal (subduction–accretion) processes, and to provide evidence for the operation of plate tectonics (a mobile-lid regime) by that stage in Earth history (Garde et al., 2020). By contrast, the older part of the Pilbara Craton in Western Australia consists of variably-metamorphosed Palaeo- to Mesoarchean ultramafic to felsic supracrustal successions surrounding 3600–3300 Ma (Smithies et al., 2009) granite domes, and is generally regarded to have formed through vertical (non-plate tectonic) processes in a single-plate (deformable stagnant lid) regime (Smithies et al., 2019).

Not all cratons were initiated at the same time, nor did they evolve at the same rate (Mole et al., 2019). Consequently, rather than using a global dataset, we examine the isotopic time series on a per craton basis. We fit quantiles (25th, 50th, 75th) to the NAC and Pilbara data sets using a moving 25 Ma bin. We interpret the 75th quantile to chart a more significant contribution from juvenile magmatism and the 25th quantile to mark a greater degree of crustal recycling, whereas the 50th quantile to reflect the average evolution. To further evaluate the zircon Hf time series, we use various spectral analysis approaches including periodograms and continuous wavelet transforms (CWT) (see DR1).

Zircon hafnium isotope time series

The 50th quantile of the NAC Hf data tracks along a ^{176}Lu/^{177}Hf ratio of 0.01 until 3200 Ma, when average values deviate towards more radiogenic signatures (Fig. 1A). A periodogram highlights frequency bands with >95% significance at ~198 Myr, ~113 Myr, several around ~74 Myr, and 54 Myr, and a band at ~680 Myr that is above the noise model (Fig. 2A). Wavelet analysis of the various quantile time series reveal broadly similar frequencies including a quasi-continuous band at ~200 Myr (Fig. 1B, C, D), and a ~170 Myr frequency considering only the >3200 Ma segment (DR1). All quantiles show more frequency structure in the pre-3200 Ma component of the record, with longer wavelengths dominating the post-3200 Ma segment.

By contrast, the Pilbara Hf time series (3800–2825 Ma) initially tracks values close to the chondritic uniform reservoir (CHUR), then becomes more variable with some super-chondritic values after

3500 Ma (Fig. 1E). Spectral analysis of the 50th quartile fit highlights frequency bands at >95% significance at ~114 Myr, ~80 Myr, and ~55 Myr, and bands at ~415 Myr and ~168 Myr that are above the noise model (Fig. 2B). Wavelet analysis of the various quantile time series have comparable bands with a continuous frequency at ~170 Myr (Fig. 1F, G, H). The frequency response of the Pilbara zircon Hf timeseries is similar to the CWT pattern in the pre-3200 Ma NAC.

Periodicities superimposed onto Earth systems

Various periodicities are thought to be superimposed onto the Earth system through processes acting across varying temporal and spatial scales, including planetary, solar system, and even galactic. These include a ~800 Myr resonance between tidal and free oscillations of the core, a 500–300 Myr supercontinent cycle, a ~200 Myr galactic year, and a ~30 Myr impact cycle (Rampino et al., 2019). Other long period geological cycles have been proposed from studies of large igneous provenances (LIPs) and mantle plumes (Prokoph et al., 2013).

The zircon Hf time series analysis for both the NAC and Pilbara cratons show frequency components in the ~170–200 Myr range, which are similar to those reported from timeseries analysis of LIPs, interpreted as a proxy for mantle plumes (Ernst and Buchan, 2002) (Fig. 2C). However, the Milky Way Galaxy appears to have four major spiral arms, which implies spiral arm passages also occur approximately every ~170–200 Myr (Rampino, 1997) as both arm and solar system orbit the galactic center at different rates. During this passage the solar system will transit through dense interstellar clouds and be subject to variable galactic tides (Fig. 3A). Perturbations of the Oort cloud (Fig. 3B) due to oscillations of the solar system around its galactic plane, and interactions between spiral arms with other areas of enhanced star formation during galactic transit, have been directly linked by some to the flux of meteorite impacts on Earth (Goncharov and Orlov, 2003).

Earth is subject to impacts from near Earth objects (NEOs), primarily derived from the main asteroid belt, and comets (Ivanov, 2008). While the former is inferred to result in much more frequent impacts (Granvik et al., 2018), the latter would result in two orders of magnitude more energy released into the crust on collision for comparable size impactors (Nuth et al., 2018). More energetic impacts excavate and uplift a greater volume of material, with impact melt production a function of energy and momentum (Schmidt and Housen, 1987). Comets would be the most likely impactor to carry a resolvable low frequency periodic signal as they are most susceptible to perturbations from outside the solar system (Rampino, 1997). Independent of impact energies, NEOs responsible for >20km craters occur every 0.75 Myr, which renders them unresolvable in the Hf isotope record (Ivanov, 2008).The lower forcing frequency coupled with the higher impact velocities of comets creates a detection bias in the Hf isotope record, despite NEOs as the expected dominant impactors.

Impact-generated melt production is also affected by the target temperature, which would be greater for an equivalent size impact on a warmer young Earth with steep thermal gradient and high internal temperatures (Potter et al., 2012). We posit that melts from energetic comet impact would form buoyant crustal nuclei that in turn would support crustal growth through hosting the products of later differentiation. This process must have been independent of the prevailing geodynamic settings since, for the NAC and Pilbara Cratons (e.g. subduction vs. stagnant lid tectonics), similar frequencies in their zircon Hf isotope time series are preserved, suggesting a common driving process. Additionally, the zircon Hf isotopic record tracks a similar frequency, throughout the entire Archean, to that advocated for Palaeozoic impact induced extinctions (Shoemaker, 1998). Arguably, the extension of this frequency into deep time points to a large-scale and relatively constant driver over most if not all our planet's history.

Models of early Earth crust generation emphasize melting of hydrated basaltic rocks to produce Tonalite–trondhjemite–granodiorites (TTGs). Smithies et al., (2021) suggested TTG magmas could be generated, both, via a bottom up process facilitated by mantle-derived water, and later in the Palaeoarchean, via a top down processes derived from sinking of greenstones. Models of impacts on the early Earth suggest production of large felsic shallow impact melt pools (Grieve et al., 2006). Hence, impacting critically fits into this formative history through providing buoyant seeds that would act as nucleation points for later TTGs generated via either mantle or greenstone extraction, simply as a function of having greater preservation potential.

A test using $\delta^{18}O$ in zircon

To better understand any link between the periodicities identified in the zircon Hf isotope time series and external forcing we develop a model for the motion of the solar system within the Milky Way Galaxy that we use to estimate mass distribution relative to our solar system. We then compare this to the compiled zircon oxygen record of the Pilbara Craton (Johnson et al., 2022; Fig. 4A, B).

Previous models have assumed a solar system orbit, relative to the spiral arms (i.e. galactic period), of 752 Myr, based on the average time between Superchrons, the periods during which Earth's magnetic field remained stable (Gillman and Erenler, 2019). The best fit galactic period to our data is 748 Myr, resulting in a duration of 187 Myr between passages through the spiral arms.

Oxygen isotopes in zircon crystals formed within and inherited by igneous rocks in the Pilbara Craton define a secular trend that further constrains crust production (Smithies et al., 2021)(Johnson et al., 2022). Zircon oxygen isotopes start with, on average, $\delta^{18}O$ values lighter than mantle values prior to 3400 Ma. Between 3400 and 3100 Ma zircon $\delta^{18}O$ values are mainly within the mantle field, but thereafter extend to heavy $\delta^{18}O$ values consistent with widespread reworking of supracrustal material (Fig. 4A). A continuous ~200 Myr frequency is evident in CWT analysis of a LOWESS (Locally weighted scatterplot smoothing) fit to the zircon oxygen data (Fig. 4B), with departures to light oxygen isotope values in zircon at ~3560 Ma and ~3430 Ma (Fig. 4A).

Zircon with isotopically-light oxygen is commonly associated with volcanic calderas and shallow extensional systems. Impacts can also establish light signatures through generation of both large volumes of hydrothermally altered crust and widespread post impact shallow melt pools (Grieve et al., 2006). Giant impacts may also drive decompression melting of the mantle (Shibaike et al., 2016). Notably, whilst the record of preserved crust provides very little material (other than zircon) to relate to the ~3560 Ma light oxygen isotope departure, the ~3430 Ma excursion corresponds to the age of spherule beds in Australia and South Africa that are direct evidence of large impacts (Byerly et al., 2002). Similar frequencies may also be expected for plume-driven models of early continental growth (Reimink et al., 2014), however, the close temporal association with spherule beds favours an impact-driver. The ~3560 Ma light zircon oxygen signature occurs on the predicted exit from the Perseus arm, whereas the younger ~3430 Ma excursion corresponds to entry into the Norma arm (Fig. 3A).

Links to vertical oscillations of the solar system to perturbations of Oort cloud comets by the galactic tide or nearby passing stars have been made (Levison et al., 2004). The motion of the Sun modulates the strength of these perturbations as they are influenced by the local stellar density. However, the observed anisotropy in the perihelia of long-period comets does not support galactic tide oscillations as the sole source of such perturbations (Delsemme, 1987), and single encounters with a nearby star will not cause significant perturbation of the Oort cloud unless passing very close (<0.5 pc)(Torres et al., 2019). The higher densities of stars in spiral arms increases the probability of multiple stellar encounters, which also increases across the time spent in the arm, which may explain impacts around the *exit* of spiral arms.

A proposed mechanism for clustering of impacts when *entering* a spiral arm may be attributed to perturbation of the Oort cloud induced by Giant Molecular Clouds (GMC). Encounters with GMC are known to cause disturbance and, in extreme cases, cause comets to be lost to interstellar space (Jakubík and Neslusan, 2008). Compression of gas passing across a galactic arm causes the formation of a GMC, with subsequent gravitational collapse initiating star formation (Dobbs et al., 2014). As GMC have lifetimes (10–50 Myr) less than the duration of passage through a spiral arm, they are unlikely to perturb the Oort cloud during its *exit* of a spiral arm.

Galactic driver

Long period variations in the flux of comet impacts to Earth likely influenced crust production through a variety of mechanisms. On the early Earth, giant impacts may have been the trigger for production of Earth's first crustal nuclei via impact-induced melting and magmatic differentiation (Grieve, 1980). Younger impacts may have enhanced or modified processes of crust formation and destruction operating in different modes, at different times and locations. Clearly, the role of impacts in crust production will have changed with time owing to the exponential decline in average projectile size and particle density in the early solar system (Marchi et al., 2014), but also as the dominant tectonic mode on Earth transitioned into widespread subduction, as evident in the increasing average crustal residence in Pilbara magmas after 3200 Ma (Fig. 1).

Isostatic adjustments triggered by giant meteorite impacts (Fig. 3C) are predicted to result in extensive decompression melting of the mantle to produce thick plateau-like mafic–ultramafic pre-cratonic nuclei (Jones et al., 2003). Meteorite impacts also cause intense fracturing and brecciation of bedrock (Riller et al., 2018), and facilitate the development of prolonged hydrothermal circulation (Kring et al., 2020) (Fig. 3D). Such circulation promotes enhanced fluid–rock interaction, including significant shifts in $\delta^{18}O$ values, and supports partial melting, both in the immediate aftermath of impacting and developing a fertile melt source long after the event. Once initial mantle melt segregation occurred, it would be inevitable that such impact induced buoyant felsic seeds would have had a lower propensity to be recycled than their dense mafic counterparts. Whilst endogenous processes (e.g. plate tectonics) have been important in the establishment and maintenance of Earth's major geochemical reservoirs, the wider galactic environment may have seeded cratonic nuclei via impacting, that ultimately grew to the continental crust we live on.

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Captions

Fig. 1: (A) Zircon εHf evolution plot of the North Atlantic Craton with quantile fits. (B-D, F-H) Continuous wavelet spectrums for 25th, 50th, 75th fits. Region of edge effects indicated by the black line. (E) Zircon εHf evolution plot of the Pilbara Craton.

Fig. 2: (A) Periodogram for zircon εHf time series (50th quantile) from the: North Atlantic Craton, (B) Pilbara Craton. Green line: 95% significance level above the noise model. Red line: red noise model.

Fig. 3: (A) Milky Way Galaxy. Arm and solar system rotate clockwise at different rates. The + number denotes the number of times Earth has passed through that arm. (B) Model of the Oort cloud. (C) Schematic reconstruction of early Earth impact process (D) seeding crustal nuclei.

Fig. 4: (A) Continuous wavelet spectrum for LOWESS fit to Pilbara zircon oxygen isotope time series (B) Igneous zircon oxygen isotope evolution plot for the Pilbara Craton. Spherule beds; orange circles. Error bars at 2σ level. Dashed blue line; average crustal residence age.

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Contributions

CLK conceived the research and CLK and PS prepared the first draft of the manuscript with input from TE and TJ. All co-authors assisted in reviewing and editing the revised manuscript.

Competing interests

The authors declare no competing interests.