

THE GEOLOGICAL SOCIETY

https://doi.org/10.1130/G49939.1

Manuscript received 10 December 2021 Revised manuscript received 7 February 2022 Manuscript accepted 10 February 2022

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Published online 26 April 2022

Plate tectonic-like cycles since the Hadean: Initiated or inherited?

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ABSTRACT

Interpretation of Earth's oldest preserved crustal archive, the Jack Hills zircon of Western Australia, has been controversial in terms of the onset of plate tectonics. We conduct timeseries analysis on hafnium isotopes of the Jack Hills zircon and reveal an array of statistically significant cycles that are reminiscent of plate-tectonic subduction. At face value, such cycles may suggest early Earth conditions similar to those of today-the uniformitarian hypothesis that plate tectonics was essentially operational since "day one". On the other hand, in the context of expected secular changes due to planetary evolution and geological observations, the cycles could instead imply that modern plate-tectonic subduction inherited mantle convective harmonics already facilitated by an early phase of stagnant-lid delamination-the "lid-toplates" hypothesis. Either way, any model for the nature of plate tectonics must incorporate conditions operating during Hadean time, either by initiation of plate tectonics then or by later inheritance of preexisting cycles of mantle convection.

INTRODUCTION

In 1981 CE, zircon grains as old as 3630 ± 40 Ma were discovered in an orthogneiss in the Mount Narryer region of the northern Yilgarn craton of Western Australia (de Laeter et al., 1981) (Fig. 1). At the Jack Hills locality ~60 km northeast of Mount Narryer (Fig. 1), zircon grains as old as 4276 ± 6 Ma and zircon yields five times higher than at Mount Narryer were discovered (Compston and Pidgeon, 1986). Subsequent to the initial Hadean zircon discovery, thousands of zircon from the Jack Hills have been analyzed for various geochemical purposes. The Jack Hills detrital zircon have now been dated to as old as 4404 ± 8 Ma (Wilde et al., 2001). While no consensus has been reached regarding the petrogenesis or tectonomagmatic setting of the Jack Hills zircon, a large compilation of zircon Hf isotopes (Wang and Wilde, 2018) confirms, and has reproduced, the upper bound of $\epsilon_{\! H\! f}$ data within two to three epsilon units (within uncertainty) of the chondritic uniform reservoir (CHUR) and

do not display demonstrable mantle depletion from ca. 4.4 to 3.5 Ga (Fig. 2A). The lack of clear mantle depletion, coupled with the radiogenic enrichment defining the lower bound of ε_{Hf} , implies the magmas in which these zircon formed were relatively low-volume melts that did not measurably change the composition of the mantle (Kemp et al., 2010).

We conducted time-series analysis on the Jack Hills detrital zircon. Early investigation into time-series analysis of Hf isotopes of zircon younger than 2.2 Ga suggests that while only periods >5 m.y. are significant due to nonuniform rates of magmatism, zircon, being well dated, is amenable to time-series analysis and yields statistically significant cycles reminiscent of plate-tectonic convection (Mitchell et al., 2019). Particularly strong cycles detected in the Hf isotopes of zircon have been discovered in global zircon data sets covering the past 2 b.y. including (in decreasing spectral power) the \sim 600 m.y. supercontinent cycle, the \sim 375 m.y. Wilson cycle of creation and destruction of an internal Atlantic-style ocean, the \sim 1.2 b.y. superocean cycle of the creation and destruction of an external Pacificstyle ocean, ~ 120 m.y. and ~ 60 m.y. cycles related to whole- and upper-mantle convection, respectively, and magmatic cycles with periods as short as ~ 10 m.y. (Mitchell et al., 2019). In Earth's modern mobile-lid (i.e., plate tectonic) geodynamic mode, the surface plates are involved in, and largely coupled to, mantle convection, where subduction-driven slab pull dominantly along the Pacific "Ring of Fire" coincides with basal traction forces associated with the girdle of mantle downwelling in between the two antipodal, large, low-shearwave-velocity provinces (Conrad et al., 2013). Whether such Hf cycles, or different ones, may be present in the well-sampled Jack Hills zircon can shed light on the nature of Hadean-Archean geodynamics.

METHODS

This study uses the ε_{Hf} associated with 1041 discrete ages for 1643 Jack Hills detrital-zircon $\varepsilon_{\rm Hf}$ data from multiple sources (Bell et al., 2014, 2011; Harrison et al., 2008; Kemp et al., 2010; Wang and Wilde, 2018). The long-term hafnium isotope (ε_{Hf}) trend characterized by a linear regression with a slope of 0.006 ε_{Hf} units per million years was used for detrending in preparation for time-series analysis (Fig. 2A). This trend relates to the source of melting for Jack Hills magmatism, and its slope equates to a 176Lu/177Hf ratio of 0.025 (using the equation in Spencer et al. [2020]). This ratio is consistent with that of reworked mafic lithologies as proposed by Kemp et al. (2010). The secular melting trend (Fig. 2A), whatever the ultimate interpretation of its protolith, is subtracted in order to create the time series (Fig. 2B). Hf isotope values of zircon grains of the same age, within analytical

CITATION: Mitchell, R.N., et al., 2022, Plate tectonic-like cycles since the Hadean: Initiated or inherited?: Geology, v. 50, p. 827-831, https://doi.org/10.1130/G49939.1

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Figure 1. Geologic sketch map of the Narryer Gneiss Complex (Yilgarn craton of Western Australia), after Bell et al. (2011). Locations of the Jack Hills and Mount Narryer are indicated.

uncertainty, are averaged because time-series analysis requires discrete sampling. Our time-series analysis methods follow standard procedures that have previously been applied to Hf isotopes of zircon (Mitchell et al., 2019) and are detailed in the Supplemental Material¹.

¹Supplemental Material. Methods, supplemental Figures S1–S4 and Tables S1 and S2. Please visit https://doi.org/10.1130/GEOL.S.19491437 to access the supplemental material, and contact editing@ geosociety.org with any questions.

RESULTS

We report here that time-series analysis of the Jack Hills detrital zircon yields multiple statistically significant cycles that are essentially indistinguishable from modern convective cycles (Fig. 3; Table 1). For simplicity, the names of the modern tectonic cycles are used here nongenetically for cycles of similar period. A sensitivity test with conservative 5 m.y. age binning confirms the fidelity of cycles as short as ~40 m.y. (Fig. S1 in the Supplemental Material; Fig. 3B). But due to the antiquity of the Jack Hills zircon (and therefore larger analytical uncertainty), 60-90 m.y. is the shortest period to which we attribute significance. The size of the U-Pb age uncertainties at this age ($\sim 2\%$ of age, so \sim 76 m.y. for ca. 3.8 Ga) is therefore not a problem for the length of cycles that we interpret as significant. The only modern cycle not detected in the Jack Hills data is the \sim 1.2 b.y. superocean cycle (Li et al., 2019; Mitchell et al., 2019); however, this is not surprising given that the \sim 1.2 b.y. record of Jack Hills magmatism is too short to resolve it statistically. Nonetheless, the presence of the ~ 1.2 b.y. superocean cycle may be suggested in the \sim 1.2 b.y. duration of Jack Hills magmatism itself (Fig. 2); furthermore, the amplitude modulation of the wholemantle cycle (Fig. 3C) also suggests the presence of a \sim 1 b.y. cycle (Table 1; Fig. S2). Like in the modern ϵ_{Hf} record (Mitchell et al., 2019), the supercontinent cycle dominates the Jack Hills spectrum (Fig. 3A). To address the concern that zircon data density varies with time and thus sampling resolution can be relatively uneven (Fig. 2A), we show that even with a bootstrap

resampling of the data, the supercontinent cycle is still clearly present (Fig. 3D).

We next consider the conceivable geodynamic interpretations of this striking similarity between Hadean and modern magmatic systems. In modern magmatic arcs, most magmatic processes are controlled by plate subduction. Thus, negative-trending ϵ_{Hf} values (i.e., more crustal reworking) can be interpreted in terms of arc advance, and positive-trending ϵ_{Hf} values (i.e., more mantle-derived melting) can be interpreted in terms of arc retreat. The Australian Tasmanides, for example, show how cyclic $\epsilon_{\! Hf}$ variations can be interpreted in terms of alternating phases of arc advance and retreat (Kemp et al., 2009). Nonetheless, such subduction-related magmatic cycles can also be additionally facilitated, following flat-slab subduction, by delamination, which can also lead to magmatic "switch-on" and "switch-off" cycles (Li et al., 2012). Identifying ε_{Hf} cycles as due to mantle convection thus covers both cases of these cycles being driven dominantly by subduction or delamination, although in modern arcs it is clearly the former. Because the nature of Hadean geodynamics is basically unknown, interpreting the striking similarity between ϵ_{Hf} cycles in Hadean and modern magmatism requires considering two potentially dominant geodynamic modes in deep time: mobile-lid mantle convection driven by platetectonic subduction, or stagnant- and/or sluggishlid mantle convection driven by delamination.

DISCUSSION

There are two end-member hypotheses for interpreting the similarity of Jack Hills



ern Australia) zircon time series. (A) ϵ_{Hf} array with a long-term linear trend used for detrending (see text for details; see Table S1 [see footnote 1] for raw data and references). Data density is visualized with a bivariate kernel density estimation (2D KDE). Depleted mantle models (upper dashed lines) are shown for the age of Earth and 3.8 Ga from Fisher and Vervoort (2018). The "maximum" line at the bottom of the data distribution with a 176Lu/177Hf ratio of 0.016 (lower dashed line) means the protolith cannot be any more mafic than 0.016: i.e., the upper range of average continental crust (176Lu/177Hf = 0.012-0.015: Griffin et al., 2004). CHUR-chondritic uni-

Figure 2. Jack Hills (West-

form reservoir. (B) $\Delta \epsilon_{\text{Hf}}$ (i.e., detrended ϵ_{HF} variation). The detrended array was then binned for discrete ages (Fig. 3A). The age of Earth's oldest rocks, Acasta Gneiss (northern Canada), is indicated. Statistically significant step change indicates increased ϵ_{Hf} volatility at ca. 4 Ga; uncertainties are 2σ .



magmatic cycles to those of modern magmatic systems driven by plate tectonics. The null hypothesis that must be tested before more complex scenarios are considered is the uniformitarian "day one" hypothesis that the similarity of ancient magmatic systems is due to the presence

TABLE 1. COMPARISON OF MODERN AND ANCIENT HF CYCLES

Cycle origin	Modern period (m.y.)*	Jack Hills period (m.y.)	Misfit (m.y.)
Superocean Supercontinent Wilson Whole mantle Upper mantle	1200 600 275 175 60	1030** 600 325 135 75 Net misfit	- -50 40 -15 -25

*Modern cycles are from Mitchell et al. (2019); **Not determined accurately enough to compare.

of plate tectonics in Hadean time. Although attractively simple, the uniformitarian hypothesis may be problematic considering secular trends in geological evolution (Herzberg et al., 2010; Keller and Schoene, 2012), in that it does not provide an explanation of how plate tectonics could have remained operationally constant despite dramatic changes in the geologic record-e.g., more frequent slab breakoff during subduction on a hotter early Earth would expectedly yield relatively shorter ϵ_{Hf} cycles (Moyen and van Hunen, 2012). As an alternative to the uniformitarian hypothesis, the crux of the "lidto-plate" hypothesis is that modern plate-tectonic cycles were inherited from stagnant- and/ or sluggish-lid convection in Hadean time. We next consider the evidence for and against these end-member hypotheses and suggest predictions of each model that may help resolve their relative importance in interpreting the Hadean and earliest Archean record.

Plate-Tectonic Model

The "day one" interpretation finds its origin in the very roots of geology: uniformitarianism, a philosophy indispensable in the establishment of geology as a science. According to the "day one" uniformitarian interpretation, the Jack Hills zircon formed in a geological setting similar to a modern plate-tectonic subduction zone (Harrison, 2009; Turner et al., 2020). Because the Hadean cycles (Fig. 3) are essentially indistinguishable from modern plate-tectonic cycles (Mitchell et al., 2019), the null hypothesis of uniformitarianism is difficult to reject. Furthermore, it is neither theoretically nor empirically implausible that some form of plate tectonics may have been fully operational on early Earth (Guo and Korenaga, 2020). The phasing of the supercontinent cycle is such that the Hadean was characterized by mantle-derived magmatism (Fig. 3C) akin to the stable tenure period of a supercontinent, when few collisional orogens exist and most subduction occurs along a well-developed, circum-supercontinent subduction girdle (Mitchell et al., 2019). Inferring subduction around a landmass of some size may support zircon fertility arguments for some appreciable volume of Hadean continental crust (Keller et al., 2017). Then, the cycle would have switched phase to more crustal reworking as the Archean began, possibly being consistent with increased preservational potential and the start of the rock record.

Lid-to-Plate Model

Arguments against the existence of plate tectonics from "day one" assert that the logic test should instead be whether plate tectonics is required to account for the Hadean-Archean geological record. The early rock record is dominated by tonalite-trondhjemite-granodiorite rocks (TTGs), which formed through partial melting of hydrated low-magnesium basaltic rocks (Johnson et al., 2013). Phase-equilibria modeling suggests that the protolith of early Archean TTGs formed at the base of thick, plateau-like basaltic crust (Johnson et al., 2017), consistent with the idea that early Earth was hotter than today (Herzberg et al., 2010), and, with multiple generations of melting and remelting, the arclike signature of trace elements does not require that TTGs formed in arcs (Johnson et al., 2017). These lines of evidence could collectively suggest that plate tectonics is not required for early Archean time and that the rock record can be explained by delamination occurring under a stagnant-lid and/or sluggish-lid convective regime (Johnson et al., 2013; Rozel et al., 2017). This line of reasoning is consistent with the evolutionary model and would suggest that modern plate-tectonic convective cycles are inherited from early stagnant-lid convective cycles—the "lid-to-plate" hypothesis (Beall et al., 2018). In the absence of subduction, $\varepsilon_{\rm Hf}$ cycles could have occurred as alternations between melting of thickened crust (crustal reworking) and mantle-derived melting following delamination of overthickened crust. Thus, under a stagnantlid regime, the "assembly" phase of the period similar to the supercontinent cycle could be associated with crustal thickening, and then the analogous "breakup" phase could be associated with foundering.

Additional Considerations

There is a notable step-change increase in $\epsilon_{\rm Hf}$ volatility, fluctuating $\pm 10~\Delta\epsilon_{\rm Hf}$ (i.e., detrended ϵ_{HF} variation) during Hadean time and $\pm 20 \Delta \varepsilon$ Hf during Archean time (Fig. 2B), that may offer an additional clue to help discern between the competing interpretations. We apply an algorithm (Spencer et al., 2019) that tests for heteroscedastic behavior, i.e., changes in mean value and/or data dispersion; if there is no statistically significant change, then the algorithm would simply assign one mean value with constant variation to the entire data set. In fact, the Archean increase in $\Delta \epsilon_{\rm Hf}$ variance is characterized by a statistically significant step change in the data at ca. 4 Ga (Fig. 2B), but interestingly there is no change in the mean ε_{Hf} value. The uniformitarian hypothesis cannot easily explain this secular change, with the only conceivable uniformitarian explanation being that the step change indicates a transition from localized to more widespread subduction. Bandpass filtering of the \sim 60–90 m.y. cycle attributed to uppermantle convection independently corroborates the step change (Fig. 2B), suggesting again that the increase in amplitude is not so much a trend as a punctuated event occurring at ca. 3.8 Ga, after which the amplitude doubles (Fig. 3C). This rather sudden transition in the increasing amplitude of upper-mantle convection coincides with, perhaps not coincidentally, Earth's oldest preserved rocks, the ca. 4 Ga Acasta Gneiss of northern Canada (Bowring and Williams, 1999), and the 3.9-3.5 Ga tectonic cycle documented in the Itsaq Gneiss Complex of Greenland (Nutman, 2006) (Fig. 3C). According to the inheritance interpretation, preservation of the first continental material and the increased amplitude of ϵ_{Hf} variability both occurring at ca. 3.9 Ga could represent the transition from the dominance of delamination to that of subduction, i.e., from stagnant- and/or sluggish-lid to plate-tectonic convection (Bauer et al., 2020; Brown et al., 2020). Thus, one way to test between the two hypotheses presented here lies in the interpretation of the increased amplitude of ε_{Hf} variability at ca. 3.9 Ga. Perhaps the most compelling case for the lid-to-plate interpretation of the $\epsilon_{\!\rm Hf}$ cycles comes from their underlying trend line implying crustal reworking of a single mafic source (Fig. 2A), where such steady crustal evolution of a long-lived mafic crust is easy to envision in a pre-tectonic regime only involving delamination, but not subduction that would involve the reworking of more evolved rocks. Reconciling our results of essentially constant cyclicity with these additional constraints that appear to require a transition from stagnant-lid to plate-tectonic convection thus suggests that the two modes of mantle convection have strikingly similar tempos, which can be tested by numerical modeling.

Implications

Identifying cycles in Jack Hills zircon geochemistry akin to modern tectonic cycles argues for a fundamental advance in our understanding of early Earth geodynamics, indicating either the early operation of plate tectonics or that the dynamics of modern plate-tectonic convective subduction were in fact inherited from ancient stagnant-lid convective delamination. Early plate tectonics would imply that stagnant- and/ or sluggish-lid convection and delamination have always been secondary to the dominance of plate-tectonic convection and subduction. On the other hand, if Hadean cycles were due to stagnant- and/or sluggish-lid convection, then given the similarity with modern systems, such inherited mantle convection patterns played a key role in the development of plate tectonics. Either way, an understanding of the dynamics of plate tectonics must be rooted in Hadean time, either by an early initiation of plate tectonics or by its later inheritance of mantle convective cycles.

ACKNOWLEDGMENTS

Funding was provided by the National Natural Science Foundation of China (grants 41890833 and 41888101) and the Key Research Program of the Institute of Geology and Geophysics, Chinese Academy of Sciences (grant IGGCAS-201905) to R.N. Mitchell and an Australian Research Council (ARC) Laureate Fellowship grant to Zheng-Xiang Li (FL150100133). The manuscript benefited from constructive reviews from Fabio Crameri and two anonymous reviewers, as well as the insightful editorial guidance of Urs Schaltegger. This is a contribution to International Geoscience Programme (IGCP) 648 (Supercontinent Cycles and Global Geodynamics) and Deep-time Digital Earth (DDE).

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Printed in USA