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Statistical reanalysis of Archean zircon paleointensities: No evidence for stagnant-lid tectonics

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ABSTRACT

The initiation of mobile-lid plate tectonics on Earth represented a critical transition towards a more familiar world in terms of surface temperature stabilization, biogeochemical cycling, topography creation, and other processes. Zircon-based estimates of the geomagnetic field intensity have recently been cited as providing evidence for the lack of mobile-lid motion between 3.9 and 3.4 billion years ago (Ga). We reanalyze the published dataset of 91 zircon paleointensities from the Jack Hills (Australia) and Green Sandstone Bed (GSB; South Africa) localities within this time interval and, using both analytical and bootstrap resampling approaches, show that the small number of samples result in large uncertainties in implied paleolatitude. Specifically, in more likely scenarios that do not assume coherent motion for both localities, all latitudinal displacements on Earth are permitted within the 95 % confidence interval. We also examine the less likely scenario that the two landmasses shared a motion history, which increases the data density and presents the best-case scenario for constraining latitudinal motion. In this case, the 95 % confidence interval of the zircon paleointensity data is compatible with the displacements of between 35 % and 52 % of modern continental localities, all of which experience mobile-lid tectonics. Finally, generating expected paleointensity time series for modern continents undergoing mobile-lid motion shows that about two-thirds of these motions would not be resolved by zircon paleointensities, even in the best-case scenario of combining Jack Hills and GSB datasets. All of these analyses assume that these zircons retain a primary paleomagnetic signal, an assertion which is opposed by a number of published zircon magnetism studies. We conclude that Archean zircon paleointensities do not provide evidence for or against mobile-lid plate tectonics prior to 3.4 Ga. Future paleomagnetic investigation of tectonic regime on the early Earth should therefore focus on magnetization directions in well-preserved, oriented whole rocks.

1. Introduction

Plate tectonics encompasses a range of geophysical processes that exert fundamental controls on the stability of surface temperatures, the cycling of biologically important elements, and the creation of topographic relief (Walker et al., 1981; Sleep and Zahnle, 2001; Hao et al., 2020). Determining the existence of plate tectonics is therefore critical to understanding the conditions in which life first developed on Earth.

One of the most readily observable features of plate tectonics on the modern Earth is the continuous, relative motion between mostly rigid plates at rates typically 3–6 cm per year and up to 18 cm per year (Zahirovic et al., 2015). Although plate motion does not unambiguously indicate modern-style mobile-lid plate tectonics (Lenardic, 2018), any

observation of modern-like surface motion would imply some widespread crustal deformation mechanism that distinguished the early Earth from true stagnant-lid planets such as modern Venus and Mars. Taking advantage of the quantitative relationship between the time-averaged magnetic field inclination and latitude, paleomagnetic studies have measured the ancient magnetic field directions recorded in well-dated, whole rock samples to infer mobile-lid motion up to at least 3.25 billion years ago (Ga) (Brenner et al., 2022). Paleomagnetic studies on even older rocks have produced paleolatitudes that can be used to infer plate motion if new data at similar ages can be acquired (Biggin et al., 2011; Bradley et al., 2015). Using paleomagnetism to detect surface motion before approximately 3.5 Ga, however, has thus far been hindered by the lack of well-preserved rock units of the appropriate age.

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Dated detrital zircons provide a possible solution to this issue since they may contain inclusions of ferromagnetic minerals for paleomagnetic analysis (Sato et al., 2015; Fu et al., 2017). In the last decade, intensive paleomagnetic research has targeted detrital zircons with crystallization ages of up to 4.2 Ga from the Jack Hills of Australia and, more recently, the Green Sandstone Bed (GSB) in the Barberton greenstone belt of South Africa. In particular, one recent study explored the potential for zircon paleomagnetism to distinguish between mobile-lid and stagnant-lid tectonic regimes on the early Earth (Tarduno et al., 2023). The authors observed apparent stability in compiled zircon paleointensities between 3.4 and 3.9 Ga. Assuming a dipolar field geometry and, therefore, a simple relationship between latitude and local field strength, they concluded that the zircon paleointensities favor a stagnant-lid during this time interval. If true, this would imply that life on Earth originated under radically different geophysical and geochemical conditions compared to present-day.

We identify two major challenges for the use of detrital zircon paleomagnetism to understand crustal motion on the early Earth: (1) whether or not primary ferromagnetic minerals, which are the only carriers that potentially retain a thermoremanent magnetization from the time of zircon crystallization, survive in the zircons and (2) whether or not the available amount of zircon paleointensity data is sufficient to robustly assess plate motion.

First and more fundamentally, the existence of primary ferromagnetic carrier minerals in the available zircons remains highly controversial, with several studies concluding that all identified magnetic carriers in Jack Hills zircons formed during aqueous alteration events hundreds of million to billions of years after igneous crystallization (Weiss et al., 2018; Tang et al., 2019; Borlina et al., 2020; Taylor et al., 2023). Furthermore, the host rocks of the Jack Hills zircons have been pervasively remagnetized in multiple metamorphic and alteration events, which reveals potential time windows when alteration may have also occurred to the detrital zircons (Weiss et al., 2015).

Regarding GSB zircons, a separate study of 283 grains found that only three older than 3.5 Ga and larger than 70 µm that had a detectable magnetization, the strongest of which was 9.45×10^{-14} A m² (Fu et al., 2021). Moments of this magnitude are unsuitable or, at best, marginally acceptable for paleomagnetic recording due to the limited number of independent magnetized domains (Berndt et al., 2016; Lima and Weiss, 2016). This appears to contradict the finding of nine zircons in this age and size range with moment $\geq 1.0 \times 10^{-12}$ A m² among a set of ">1000" separated zircons in Tarduno et al. (2023). The origin of this discrepancy is currently unknown; however, its existence calls into question the reproducibility of any GSB zircon paleointensity results.

Although critical to the interpretation of any paleomagnetic results, we do not focus here on these ambiguities surrounding the age and origin of zircon paleomagnetic signals and, instead, summarize the existing evidence in Appendix A.

Instead, here we focus on the second, statistical problem. If the Jack Hills and GSB zircon paleointensities are robust despite the issues raised above and in Appendix A, a fundamental challenge arises from the modest number of zircons and whether such a limited dataset can produce robust inferences about plate motions. Most acutely, a total of only eight zircon paleointensities in the Tarduno et al. (2023) analysis fall within the time bins centered on 3.708, 3.808, and 3.908 Ga.

Even before doing a detailed analysis, there are reasons to suspect that a large number of paleointensities would be needed to reconstruct paleolatitude. Assuming a dipolar geomagnetic field, polar magnetic fields are stronger than those at the equator by a factor of two. Therefore, any paleointensity dataset used to constrain paleolatitude must, ultimately, quantify the time-averaged magnetic field with a confidence interval much smaller than this factor-of-two range. Given the many sources of variance for paleointensity measurements including instrument precision, non-ideal sample behavior, and paleosecular variations of the geodynamo, achieving this level of accuracy requires averaging across large sample sizes. At least in part for this reason, no paleomagnetic study prior to Tarduno et al. (2023) has, to our knowledge, used paleointensities as the sole basis for estimating paleolatitudinal motion.

Here we quantify the uncertainties on paleolatitudes inferred from the Hadean-Archean zircon paleointensity dataset. The text below is organized as follows. In Section 2.1, we briefly summarize the statistical analysis used in Tarduno et al. (2023), describing how they arrived at bounds of 48 and 53 for, respectively, the maximum permitted absolute and relative latitudinal motion. In Section 2.2, we follow the assumptions of Tarduno et al. (2023) as closely as possible, analyzing a combined paleointensity dataset containing Jack Hills and GSB zircons. We explain the differences in our statistical calculations, including the use of 95 % confidence intervals and a complementary set of empirical bootstrap analyses to verify these intervals. This section concludes that the maximum permitted latitudinal motion for a combined landmass is, instead of 48, in the range of 70 to 78 and that two-thirds of modern continents undergo motion compatible with the zircon paleointensity dataset, if these paleointensities are interpreted at face value.

In Section 2.3, we test the validity of combining Jack Hills and GSB zircon paleointensities into a single dataset as was done by Tarduno et al. (2023) and as we do in Section 2.2. This analysis shows that a latitudinal separation of up to 100 is permitted at 3.408 Ga (95 % confidence interval) and that any latitudinal separation is possible at ages \geq 3.608 Ga. Building on this insight that the two landmasses were capable of independent motion, in Section 2.4 we quantify the maximum permissible latitudinal motion for the two separate zircon datasets. We find that, in the 3.408 to 3.908 Ga interval, any amount of latitudinal motion is permissible within the 95 % confidence intervals implied by the data. Therefore, no conclusions regarding the operation of mobile-lid or stagnant-lid tectonics can be drawn from the zircon dataset.

Finally, in Section 3 we discuss additional uncertainties associated with using zircon paleointensities to reconstruct tectonic motion and examine whether acquiring larger zircon datasets in the future can mitigate the large uncertainties described in our analysis.

2. Reassessing the precision of time-binned Archean zircon paleointensities

2.1. Summary of tarduno et al. (2023) analysis

We first briefly summarize the statistical methodology used in Tarduno et al. (2023) (Table 1). After compiling a set of 102 Jack Hills and GSB zircon paleointensities (Tarduno et al., 2023; Source Data Fig. 3), these authors gathered 90 individual zircon paleointensities into six 100-million-year (My) bins centered at ages between 3.408 and 3.908 Ga. They then used several statistical tests to show that paleointensities recorded by the two zircon populations are indistinguishable at all times prior to 3.408 Ga. Although the authors cite differences in the magmatic source as evidence that the Jack Hills and GSB zircons are likely from independent plates, they nevertheless computed the mean and standard errors for paleointensities in each age bin using the combined zircon dataset. This 1-standard error interval was then used to bound the maximum permissible change in paleointensity (light purple shaded region in Tarduno et al. 2023, Fig. 4D). Finally, by assuming a perfectly dipolar geodynamo with a constant underlying time-averaged strength and adopting a paleolatitude of 24.5 for both localities at 3.4 Ga based on Tarduno et al. (2010), the authors argued that the maximum permissible change in latitude for either plate between 3.4 and 3.9 Ga is \sim 48 while the maximum relative change between the two landmasses is \sim 53. These values are sufficiently small such that they are likely incompatible with observed plate motion behavior in the past 600 My (Tarduno et al. 2023; Fig. 4E-F), thereby providing evidence for the lack of mobile-lid motion.

Table 1

Summary of differences in statistical approach between this work and Tarduno et al. (2023).

Procedure or parameter	This work	Tarduno et al. (2023)
Grouping of Jack Hills and GSB data	All analyses provided for both combined and separated datasets	Bounds on paleointensities and latitudinal motion derived only from combined dataset
Paleointensity bounds	95 % confidence intervals computed both analytically using Student's t-distribution and empirical bootstrap	One standard error, which, accounting for sample size, corresponds to 68 %, 67 %, 65 %, 58 %, and 61 % confidence intervals for the 3.408, 3.508, 3.608, 3.808, and 3.908 Ga bins, respectively
Paleointensity bound for 3.708 Ga bin, where $n = 1$	Provided empirical bootstrap confidence interval; analytical estimation not possible with $n = 1$	Interpolated from bounds for 3.608 and 3.808 Ga (Fig. 4D in article)
Bound on maximum latitudinal motion	95 % confidence intervals computed from resampling of paleointensities at a pair of ages such as 3.408 Ga and 3.808 Ga.	Estimated to be ~48 based on maximum range of latitudes that fall within one standard error in paleointensity
Bound on maximum differential motion between Jack Hills and GSB	95 % confidence intervals computed for latitudinal separation at 3.408 Ga and ratios of paleointensities for other ages	Estimated to be \sim 5 more than the maximum latitudinal motion (48 + 5=53), based on one standard error at approximately 3.408 Ga.

2.2. Combined Jack Hills and GSB dataset

We begin by following the analysis of Tarduno et al. (2023) as closely as possible, using the combined dataset of 91 zircons with ages between 3.358 and 3.958 Ga and differing from their analysis only in our calculation of statistical uncertainties.

We first check the consistency of our zircon binning results with Tarduno et al. (2023). The number of zircons in each of our age bins, which have the same center and width, are identical except for the 3.408 Ga bin, which has one extra zircon (Table S1). Although the reason for this discrepancy is unclear, it results in negligible differences between our analyses (Table 2). Otherwise, our calculated standard errors are identical to those in Tarduno et al. (2023) except for the 3.808 and 3.908 Ga bins, where they differ slightly from both Extended Data Table 3 and Fig. 4D in Tarduno et al. (2023) (Fig. 1A). Nevertheless, these differences in standard errors are only at the 0.1 μ T level. We therefore broadly confirm that Fig. 4D in Tarduno et al. (2023) and the attendant analyses are based on the 1-standard error intervals, consistent with the description provided in that publication.

Our analysis diverges from that of Tarduno et al. (2023) with regard to the calculation of confidence intervals (Table 1). Tarduno et al. (2023) used a 1-standard error interval to visualize the uncertain of the paleointensity mean and then used this interval to bound the limits of paleointensity change and, in turn, latitudinal motion (Fig. 4D in that work).

We find at least three issues with this approach. First, it is common to use at least a 2-standard error interval to denote uncertainty. In the best case of large sample sizes, the 1-standard error range corresponds to the 68 % confidence interval. Designating the paleointensities from an hypothetical mobile continent as "inconsistent" or not "compatible" with the observed means because they fall outside of a 68 % confidence interval [p. 535 in Tarduno et al. (2023)] is a much more relaxed criterion than commonly used in most research fields. In paleomagnetism, for example, the uncertainties of paleomagnetic poles are almost invariably represented using 95 % confidence intervals (Butler, 1998; Tauxe, 2010).

Table 2

Summary of age bin means, sample count, and analytical and empirical bootstrap confidence intervals for the combined dataset, Jack Hills, and GSB zircons.

	3.408 Ga	3.508 Ga	3.608 Ga	3.708 Ga	3.808 Ga	3.908 Ga
All zircon mean (µT)	10.4	9.5	8.5	8.6	8.9	7.9
All zircon N	50	24	9	1	3	4
2-standard error	1.5	2.5	3.3	-	2.8	2.4
95 % CI Student's t	1.6	2.6	3.8	-	6.1	3.9
95 % CI	-1.3 /	-1.8 /	-2.9 /	-6.0 /	-4.4 /	-4.0 /
Bootstrap	+1.4	+ 2.1	+ 3.6	+ 13.0	+ 6.7	+ 5.7
Jack Hills mean	11.0	11.1	8.1	-	10.8	9.0
Jack Hills N	33	14	8	0	1	2
Jack Hills 95 % Student's t	2.2	4.3	4.3	-	-	32.4
Jack Hills 95	-1.6 /	-2.4 /	-3.0/	_	-6.0 /	-51/
% Bootstrap	+ 1.8	+ 2.8	+ 3.8		+ 13.0	+ 8.7
GSB mean	9.3	7.2	11.6	8.6	7.9	6.8
GSB N	17	10	1	1	2	2
GSB 95 % Student's t	1.7	1.7	-	-	22.9	1.9
GSB 95 %	-2.2 /	-2.7 /	-6.0 /	-6.0 /	-5.1 /	-5.1 /
Bootstrap	+ 2.5	+ 3.4	+ 13.0	+ 13.0	+ 8.7	+ 8.7

Table 3

Ninety-five percent confidence interval of paleointensity ratios between the indicated age bins. For each comparison, 10^6 pairs of mean paleointensities, one from each age, are generated using analytical or empirical bootstrap uncertainties. The ratios of the higher to lower paleointensity are tabulated and sorted. The 95 % percentile highest value of each distribution is then given here for analytical (left in each entry) and empirical bootstrap (right) uncertainties. Values greater than 2 implies that all relative latitudes on Earth are permissible at 95 % confidence. For reference, the ratio between a dipolar magnetic field at 50, 60, and 70 latitude and that at the equator are 1.66, 1.80, and 1.91. Therefore, any bin comparison except between 3.408 Ga and 3.508 Ga can, at best, constrain latitudinal motion to less than ~50. No result is available from analytical analysis for comparisons involving the 3.708 Ga age bin because the uncertainty cannot be estimated from a single data point.

	3.508	3.608	3.708	3.808	3.908
3.408 3.508 3.608 3.708 3.808	1.45; 1.36	1.95; 1.77 1.84; 1.65	None; 4.03 None; 3.68 None; 3.43	2.10; 2.15 2.04; 2.01 2.29; 2.09 None; 3.71	2.08; 2.42 1.97; 2.23 2.05; 2.15 None; 3.61 2.42; 2.51

Second, for small numbers of observations, the 1-standard error range corresponds to even less than a 68 % confidence interval. The mean of *n* data points picked from a normally distributed underlying population follows a Student's t distribution with n - 1 degrees of freedom (Fisher, 1925; Ramsey and Schafer, 2002, pp. 34–35). The Student's t-distribution has significantly heavier tails compared to a normal distribution in the case of small *n*, resulting in larger ranges for a given confidence interval. The 1-standard error interval as used by Tarduno et al. (2023) for the 3.808 Ga age bin, for example, corresponds to a 58 % confidence interval because the age bin contains only three data points (Fig. 2A; Table 1).

The difference between multiples of the standard error and common confidence intervals diverges more dramatically for wider confidence intervals. For example, for the 3.808 and 3.908 Ga age bins, which contain 3 and 4 data points, the 95 % confidence intervals span 4.3 and 3.2 standard errors, respectively, instead of the familiar 2 standard errors associated with large *n* datasets.

Due to this dependence on *n*, we avoid using a fixed interval in terms



Fig. 1. Time series of mean zircon paleointensities showing updated confidence intervals. (**A**) Time series for the combined Jack Hills and GSB zircon dataset. Green intervals are computed 1-standard error shown to verify consistency with the Tarduno et al. (2023) confidence interval, reproduced here in light purple. We omit the range between 3.658 and 3.758 Ga due to insufficient data to establish uncertainty. Orange and black error bars represent 95 % confidence intervals derived from analytical and empirical bootstrap analysis, respectively. Light gray points are raw zircon paleointensities. (**B**) Paleointensities time series based on separate Jack Hills (blue) and GSB (red) datasets. Solid and dashed intervals denote analytical and empirical bootstrap methods, respectively.

of standard error and, instead, plot 95 % confidence intervals for each age bin mean according to Student's t-distributions (Figs. 1A, 2; Table 2). For the three age bins between 3.408 and 3.608 Ga, which contain between 9 and 50 zircons, our confidence intervals agree closely with those of Tarduno et al. (2023) with the only significant difference lying in the choice of plotting the 1 or 2-standard error range. However, for the 3.808 and 3.908 Ga age bins, our confidence intervals are 115 % and 60 % larger than the 2-standard error range, respectively.

A third issue with the confidence intervals presented in Tarduno et al. (2023) is that authors plotted the 1-standard error range as a continuous region in Fig. 4D. However, because the 3.708 Ga age bin contains a single data point, no inference for the confidence interval is possible. As such, a more accurate depiction of the uncertainty would leave the 3.658 to 3.758 Ga range unfilled (Fig. 1A), indicating that, based on the data, very large or small paleointensities cannot be rejected at any quantitative confidence. This technically permits all possible paleointensities and therefore paleolatitudes in this time interval, invalidating by itself the Tarduno et al. (2023) conclusion of no mobile-lid motion. Nevertheless, we do not use this age bin to bound latitudinal motion in our subsequent analysis in order to maintain comparability with Tarduno et al. (2023) and to assess an optimal scenario for bounding latitudinal motion.

As additional verification for out Student's t-distribution-based confidence intervals, we replicate the computed values using an empirical, non-parametric bootstrap resampling approach (Efron and Tibshirani, 1986), hereafter referred to as the "empirical bootstrap" method. Estimating the true underlying distribution for single zircon paleointensities is challenging due to the compounded effects of sample recording quality, sample cooling time, magnetic overprinting, and true geodynamo variations at multiple timescales. Fortunately, the relatively dense concentration of zircon paleointensities around 3.4 Ga provided in Tarduno et al. (2023) permits an empirical estimate of this distribution, if we interpret these paleointensities to be primary (Appendix A).

We therefore use the 41 Jack Hills and GSB zircon paleointensities between 3.38 and 3.42 Ga as the source distribution for bootstrap resampling, which implicitly assumes that plate motion within this 40 My interval is small compared to motions we attempt to resolve in the full 3.4–3.9 Ga interval. This assumption is likely true given, as the only quantitative plate motion constraint near this time period, the 0.55° per My latitudinal motion of the Pilbara after 3.35 Ga (Brenner et al., 2022), which corresponds to a 22 latitudinal shift in a 40 My interval. Such a shift is small compared to the median latitudinal displacement of 76 in modern plates over a 600 My interval (Tarduno et al., 2023). Comparison of this empirical bootstrap source distribution to those of modern paleointensity datasets from Western Europe and Hawaii since 10 Ma reveals, after normalization to a common mean, similar distribution morphologies indistinguishable at 95 % confidence interval according to a Kolmogorov-Smirnov test [Fig. S1; (Bono et al., 2022)]. This agreement suggests that the 3.4 Ga dataset of 41 zircons provides sufficient coverage of extreme values to be used as the source of empirical bootstrap resampling.

Drawing with replacement from this 3.4 \pm 0.02 Ga dataset, we generated 10⁵ bootstrap pseudosamples, each of which consisted of six age bins containing 50, 24, 9, 1, 3, and 4 paleointensities analogous to the actual zircon age bins (Table 2). We then computed the mean within each age bin of each pseudosample, allowing us to construct empirical confidence intervals for each age bin mean (Fig. 1A). The empirical bootstrap 95 % confidence intervals are close to those computed from the Student's t-distribution with three age bins agreeing within 15 % and all within 24 %. Critically, for the two oldest ages bins, which have small numbers of zircons, the bootstrapped and Student's t distributionderived intervals agree more closely with each other than with the raw 2-standard error interval (50 % and 51 % discrepancy between empirical bootstrap and 2-standard error compared to 10 % and 20 % discrepancy between empirical bootstrap and Student's t; Table 2). As such, the empirical bootstrap analysis corroborates the use of the Student's t distribution to describe the paleointensity means, as is expected from statistical theory (Fisher, 1925).

With these newly computed confidence intervals, we can compute the maximum latitudinal motion permitted by the zircon paleointensity data (Fig. 2B). To review (Section 2.1), Tarduno et al. (2023) used the 1-standard error interval of paleointensities to establish a 48 upper bound on latitudinal motion (Tarduno et al., 2023; Fig. 4D). This method effectively rejects plate motion trajectories corresponding to paleointensity changes that lie outside of a 58 % to 68 % confidence interval, depending on the age bin used (Table 1). Such a narrow confidence interval is rarely encountered in scientific hypothesis testing and would be overly exclusive in rejecting potential plate motions.

To compute a maximum permissible latitudinal motion in the 3.408–3.908 Ga interval using the more common 95 % cutoff, we compare the paleointensities at 3.408 and 3.808 Ga. Following Tarduno et al. (2023), we adopt a paleolatitude of 24.5 at 3.408 Ga to facilitate comparison with the earlier study. Further, the availability of an independent paleolatitude constraint, even if of questionable reliability (see Discussion), greatly strengthens the ability for zircon paleointensities to infer paleolatitudinal change because it effectively calibrates the



Fig. 2. Illustration of statistical methods used in this work and in Tarduno et al. (2023). (A) Comparison of confidence intervals. Tarduno et al. (2023) adopt a 1-standard error uncertainty interval for bounding paleointensity changes regardless of sample size while we adopt a 95 % confidence interval computed for each sample size. X-axis is in units of standard error, abbreviated "S.E.". "C.I." stands for confidence interval while the variable *k* denotes degrees of freedom for the Student's t distributions. (**B**) Steps we used to compute a confidence interval for latitudinal change. The same procedure was used to compute latitudinal difference between the Jack Hills and GSB at each age bin.

underlying dynamo strength. Removing such a constraint would permit only comparison of paleointensity ratios and are more permissive of large latitudinal changes (Table 3). This analysis therefore represents the best-case scenario for estimating latitudinal motion and distinguishing stagnant- and mobile-lid tectonics. Meanwhile, we use the 3.808 Ga mean for comparison because its significant uncertainty is suitable for estimating a maximum permissible latitudinal shift.

We use parametrized bootstrap resampling to generate paleointensity pairs at 3.408 and 3.808 Ga using Student's t-distributions with n-1 degrees of freedom (Figs. 2B,3). Assumption of a 24.5° paleolatitude at 3.408 Ga (see above) allows us to compute the paleolatitude at 3.8 Ga for each paleointensity pair. Further following Tarduno et al. (2023), we assume a dipolar geomagnetic field geometry and that the two paleointensities were recorded in different hemispheres and add the paleolatitudes to obtain the maximum total latitudinal displacement. Repeating this procedure 10^6 times generated a distribution of latitudinal displacements, from which we retrieved the 95-percentile highest value to define the single-sided 95 % confidence interval (Fig. 3).

One complexity of this analysis is that, due to the assumption of a paleolatitude at 3.408 Ga and the factor of two range in equator-to-pole field strengths, a significant fraction of bootstrapped paleointensity pairs do not nominally correspond to physical pairs of paleolatitudes. In other words, the 3.808 Ga paleointensity may be lower than the

predicted equatorial value or higher than the polar value for a given paleointensity at 24.5. Physically, we interpret the former scenario as a case where the continent remains near the equator at 3.808 Ga, resulting in small latitudinal motion in the 3.4–3.8 Ga interval. The cases where the 3.808 Ga paleointensity is higher than the polar value corresponds to motion of the continent to the polar regions, implying a latitudinal change of 24.5 + 90 = 114.5. Although the motion of a landmass beyond the pole is non-physical, higher-than-nominally-permitted paleointensities are both possible and expected due to the large scatter in zircon paleointensities. These outcomes must be retained in the analysis of confidence intervals because they are an accurate reflection of the uncertainties in paleointensities. Please see Appendix B for further discussion and a sensitivity test where we show that rejecting all paleointensities higher than the implied polar value does not change any conclusions.

Our parametrized bootstrap analysis results in a 95 % confidence upper bound of 70.1° for latitudinal motion, which is significantly larger than the 48 estimated by Tarduno et al. (2023) (Fig. 2A). In other words, there is a 95 % probability that a single plate containing both the Jack Hill and the GSB traversed less than 70.1° in latitude between 3.408 and 3.808 Ga, if the zircon paleointensities are assumed to be primary. Resampling using the empirical bootstrap method from the 3.4 ± 0.02 Ga paleointensities results in a similar 95 % upper bound of 77.6°



Fig. 3. Histograms of maximum permitted latitudinal motion comparing zircon-based constraints and past 0.6 Gy plate motions. Panels (A-C) show the distribution of latitudinal motion implied by 10⁶ resamplings of Student's t distributions describing the paleointensity of the indicated dataset between the indicated ages. Latitudes of 24.5, 36.9, and 24.5 are assumed for the combined dataset, the Jack Hills, and the GSB, respectively, at 3.408 Ga (see text). The apparent discontinuous behavior at the highest latitudinal displacement bin is caused by (1) the gathering of all trials where the older paleointensity exceeded the expected polar value for a given 3.408 Ga paleointensity and latitude into a single bin corresponding to the maximum possible displacement and (2) the shape of the latitude-paleointensity relationship resulting in a narrow range of paleointensities being mapped to a wide range of latitudes near the poles. Dashed lines show the 95th percentile value of latitudinal motion. (D) Maximum latitudinal displacement between 0.6 Ga and the present for 228 continental locations as compiled by Tarduno et al. (2023). Ninety-five percent confidence interval bounds from the zircon datasets in panels (A)-(C) are shown for comparison, along with the 48 bound reported in Tarduno et al. (2023).

(Fig. 3A). The slightly higher outcome from this analysis is due to the asymmetric bootstrap source population, which results in a wider tail at the high end of 3.808 Ga paleointensities.

Using the Tarduno et al. (2023) compilation of maximum latitudinal motions for randomly sampled continental locations within the past 600 My, we find that 35 % and 52 % of localities fall within our 95 % confidence interval for the analytical and empirical bootstrap analyses, respectively (Figs. 3D, 4D). In other words, 35 %–52 % of modern landmasses, all of which undergo plate tectonic motion, traverse an

equal or smaller range of latitudes in 600 My than is permitted for the Archean zircon-bearing plate at 95 % confidence based on paleointensity data. Such an outcome does not reliably reject the hypothesis of present-day-like mobile-lid behavior for the sampled Archean plate. For comparison, a limit of 48 as computed by Tarduno et al. (2023) is higher than the motion of ~11 % of modern plates (Source Data Extended Data Fig. 5 in that work).

If we compare age bin pairs that do not include 3.408 Ga or exclude the claimed paleolatitude constraint for 3.408 Ga (see Discussion), then no quantitative paleolatitude change constraints are possible. Instead, the only observable is the paleointensity ratio (Table 3). Given the uncertainties on the mean paleointensity in each age bin, the paleointensity ratio between two age bins defines a distribution. If the 95 % confidence interval of this distribution includes the full range between 1 and 2 (or, equivalently, >5 % of the distribution is greater than 2), then all possible relative locations on the Earth's surface are allowed within the 95 % confidence interval, since the difference in field intensity between the pole and the equator is 2. For further comparison, the ratio between the paleointensity at 50° latitude and the equator is 1.66, and the ratio decreases for 50⁻separations away from the equator. Therefore, the ratios tabulated in Table 3 indicate that all age pairs that involve the 3.708, 3.808, and 3.908 Ga intervals permit motion between any two latitudes, since the 95 % confidence interval includes 2. Only the 3.408 to 3.508 Ga comparison can constrain the latitudinal motion to less than 50°.

As a complementary method for comparing the motions of modern plates with those inferred from Jack Hills and GSB zircons, we used the GPlates program (Müller et al., 2018) to output the 0-500 Ma latitudinal motions of nine cratons representative of the major Phanerozoic landmasses while adopting the reconstruction of Merdith et al. (2021) (Fig. 5; see Appendix C for detailed description of methodology). After converting latitudinal motions to relative changes in paleointensity and smoothing with a 100 My moving window to allow direct comparison to the binned zircon paleointensity dataset, we find that six out of the nine blocks remain within the 95 % confidence interval of combined Jack Hills and GSB zircon paleointensities at all times between 3.408 and 3.908 Ga. In other words, the expected paleointensity changes associated with the latitudinal motion of two-thirds of these landmasses cannot be resolved by zircon paleointensities sampled with the same density and quality as presented in Tarduno et al. (2023). The same result holds when using the analytical or bootstrapped uncertainties (Fig. 5). This analysis confirms our earlier conclusion that a substantial fraction of modern plate motion trajectories is compatible with 95 % confidence bounds resulting from the combined zircon paleointensity data. Therefore, these data cannot be interpreted as substantial evidence against the existence of mobile-lid plate tectonics prior to 3.4 Ga.

As an additional insight from this analysis, comparing unsmoothed paleointensity time series for each continental block showed that five out of nine unsmoothed time series were compatible with the zircon data, in contrast to six out of nine for the 100 My smoothed curves. Meanwhile, seven out of nine were compatible for the 200 My smoothed datasets (Fig. S3). This behavior is expected since averaging across time would tend to decrease the amplitudes and attenuate the apparent horizontal velocities of continental motion. The fact that the result changes substantially among these smoothing scenarios demonstrates that even binning in 100 My intervals can potentially bias the analysis towards the non-detection of mobile-lid motion. Even so, we base our main analysis on 100 My age bins due to the already low data density and to maintain comparability with Tarduno et al. (2023).

2.3. Testing for coherent motion between the Jack Hills and GSB blocks

The above analysis that combines the Jack Hills and GSB zircons into a single dataset results in the narrowest possible confidence intervals for paleointensity in each age bin. However, such a time series is only relevant for constraining latitudinal motion if the two localities shared a single plate. In fact, there is no substantial evidence that the Jack Hills and GSB were once located on the same plate. Tarduno et al. (2023), for example, cites petrological evidence that the two localities are at least separated enough to be sampling distinct petrogenetic environments. Most notably for the 3.408 Ga age bin, Hf isotopic composition and δ^{18} O at this age are clearly different between the two localities, requiring two different petrogenetic environment (Bell et al., 2011, 2014; Drabon et al., 2022).

Here we use the paleointensity data to evaluate whether the assumption of coherent motion, and therefore the concatenation of the two zircon datasets, can be justified. Although Tarduno et al. (2023) used a Welch's *t*-test, a Kolmogorov-Smirnov test, and a Mann-Whitney test to show that Jack Hills and GSB paleointensities are indistinguishable prior to 3.408 Ga, these failures to reject the null hypothesis of a common distribution do not require that the two blocks share a common motion. In other words, the lack of detectable difference based on a particular dataset cannot be interpreted as evidence that the difference, if any, is below the resolving power of the dataset. We therefore quantify the resolving power of the zircon dataset by computing the maximum Jack Hills-GSB separations permitted at each age bin.

Tarduno et al. (2023) estimated a 5° difference between the two landmasses at 3.408 Ga using the combined zircon dataset and 1-standard error intervals. As argued in Section 2.2, this is much narrower confidence interval (68 %; Table 1) than commonly reported in paleomagnetic studies. Further, as seen in Fig. 4D of Tarduno et al. (2023), this value was based on the combined Jack Hill and GSB dataset. For resolving the difference in latitude of the two sites, the paleointensities from each should be group separately, after which their means should be compared with each other.

We therefore first separate the 50 zircons in the 3.408 age bin into subsets of 33 and 17 samples belonging to the Jack Hills and GSB, respectively. As in Tarduno et al. (2023) and Section 2.2 above, we assume a paleolatitude of 24.5 for the GSB and use the mean paleointensity difference between the two localities at this time to compute a Jack Hills latitude. The resulting best-guess paleolatitude for the Jack Hills is 36.9. Resampling the paleointensity of each locality using analytical and empirical bootstrap-derived uncertainties (see Section 2.2 for explanation of the two methods; Fig. 1B) yields 95 % confidence intervals of 36. $9^{+30.5}_{-22.2}$ and $36.9^{+39.1}_{-23.1}$, respectively. These latitude ranges each span 69 % and 73 % of the Earth's surface, implying only a very weak constraint on the true paleolatitude of the Jack Hills at 3.408 Ga. If the Jack Hills and GSB were located in opposite hemispheres, these bounds would imply an upper bound to their latitudinal separation of $36.9 + 39.1^\circ + 24.5 = 91.9^\circ$ and $36.9 + 39.1^\circ + 24.5 = 100.5^\circ$, respectively.

No independent latitude constraints are available for any other age bin. We are therefore left with only the paleointensity ratio instead of absolute paleolatitudes to estimate the latitudinal separation. Technically, without an anchoring paleolatitude for either landmass, even two equal paleointensities can imply a 180 separation if the landmasses were located at opposite poles. Therefore, unlike in the case involving the 3.408 Ga age bin where an anchoring latitude exists, we do not assume location in opposite hemispheres in this analysis to explore the minimum uncertainty scenario for constraining latitudinal separation.

Due to the existence of several age bins where one locality has only a single data point, we use the empirical bootstrap method to generate sets of 10^5 paleointensity pairs and compute the ratios between the higher and lower paleointensities in each pair. The location of one landmass at the equator and the other at the pole would result in a paleointensity ratio of 2, under the assumption of a dipolar field. Therefore, if the 95 % confidence interval of the paleointensity ratio includes the full range between 1 and 2, any latitudinal separation on Earth cannot be rejected at the $p \leq 0.05$ level. We find that this is the outcome for all age bins other than 3.408 Ga, implying that the data cannot reject any latitudinal separation for the two landmasses ≥ 3.508 Ga (Fig. 6). In summary, the



Fig. 4. Histograms of maximum permitted latitudinal motion comparing zircon-based constraints and past 0.6 Gy plate motions. Panels are same as Fig. 4 except the paleointensity pairs represented in Panels (A)-(C) are generated using an empirical bootstrap approach instead of analytically.

zircon paleointensities permit latitudinal separations between the Jack Hills and GSB of up to 91.9 to 100.5 at 3.408 Ga and any separation at earlier ages. This result stands in contrast to the maximum latitudinal separation of \sim 53 reported by Tarduno et al. (2023).

2.4. Latitudinal motion bounds for separate Jack Hills and GSB motion

Having shown in the previous section that no evidence exists in support of a shared motion for the Jack Hills and GSB blocks between 3.908 and 3.408 Ga, we compute the maximum permitted latitudinal motion separately for each zircon dataset. As in Section 2.2, we computed empirical bootstrap-based and, where at least two zircons are available, Student's t-distribution-based confidence intervals for mean paleointensities, resulting in large uncertainties for ages greater than 3.608 Ga (Fig. 1B).

Assuming as before that the GSB had a paleolatitude of 24.5 at 3.408 Ga and comparing to the 3.808 Ga paleolatitude includes 90%, which confidence interval of the 3.808 Ga paleolatitude includes 90%, which corresponds to a latitudinal displacement of 114.5 assuming a change of hemisphere (Figs. 3C, 4C). This implies that motion between 24.5 and the opposite hemisphere pole is permitted within the 95% confidence

interval and that, therefore, any amount of latitude change on the Earth's surface is compatible with the paleointensity data. Using analytic or empirical bootstrap confidence intervals for this analysis yields the same conclusion.

For the Jack Hills dataset, the paleolatitude of the Jack Hills at any point in the 3.408–3.908 Ga interval is not independently known. We therefore conduct the same paleointensity ratio analysis as we used earlier to quantify the Jack Hills-GSB separation (Section 2.3). We find that the 95 % percentile values for the paleointensity ratio are 2.05, 2.42, and 2.55 for intervals between 3.408 Ga and 3.608 Ga, 3.808 Ga, and 3.908 Ga, respectively (Fig. 7). Because these values are larger than 2, any latitudinal change is permitted between these times for the Jack Hills, resulting in no evidence for or against plate motion.

Finally, repeating this analysis while adopting a paleolatitude of 36.9[°] for the Jack Hills at 3.408 Ga (see Section 2.3) results in the same conclusion that all possible latitudinal motions are permitted within the 95 % confidence interval for the 3.408–3.908 Ga window (Figs. 3B, 4B). Although, as outlined in Section 2.3, this paleolatitude is highly uncertain, we undertook this analysis to explore the most favorable scenario for limiting possible latitudinal motion.

3. Discussion

Our statistical analyses above generally show that zircon paleomagnetism cannot meaningfully constrain the latitudinal motion or relative latitudinal separation of the Jack Hills and GSB landmasses prior to 3.408 Ga. Where possible, we have adopted the assumptions that yielded the strongest possible constraints on paleogeography, such as combining the two zircon datasets and adopting a paleolatitude for the GSB at 3.408 Ga. Here we discuss the validity of these assumptions and other potential sources of uncertainty inherent to detrital zircon paleointensities.

The assumption of a 24.5° paleolatitude at 3.408 Ga, derived from the Hooggenoeg Formation of the Barberton greenstone belt (Tarduno et al., 2010), is questionable because it assumes that the location of the Barberton greenstone belt at \sim 3.4 Ga corresponds to that of the GSB. While the GSB sediment was deposited at 3.31 Ga in what is now the Barberton greenstone belt, its zircon signature is remarkably different from that of surrounding igneous rocks and sedimentary rocks and many zircons show evidence for intense rounding, indicating that they were likely derived from a different source terrane, possibly after long-distance transport (Drabon et al., 2017; Lowe et al., 2021; Drabon and Lowe, 2022). Therefore, the paleolatitude of the Barberton greenstone belt may have been different to that of the GSB source terrane. Even if the GSB zircons shared a 3.4 Ga paleolatitude with the Barberton greenstone belt, the value of 24.5 was based on two samples and the direction is similar to a regional overprint consistent with the recent magnetic field (Tarduno et al., 2010; Biggin et al., 2011). This paleolatitude assumed by Tarduno et al. (2023) is therefore of low reliability and has not been included in subsequent compilations of high-quality paleomagnetic poles (Evans et al., 2021). As discussed earlier, dropping the assumption of a paleolatitude further weakens the ability for zircon paleointensities to record latitudinal motions (Table 3).

A related, fundamental weakness of using detrital zircons to infer paleogeography is that it assumes a modest transport distance for the zircon grains. In reality, zircons can be transported for 100 s to > 1000 kms between independently moving blocks and experience one or more episodes of sedimentary recycling, resulting in even larger separations between the site of igneous formation and that of deposition (Prave, 1996; Basei et al., 2008; Gehrels and Pecha, 2014; Lehmann et al., 2016; Nieminski et al., 2019).

Additional uncertainties arise from this specific zircon dataset. The zircons in the Tarduno et al. (2023) compilation were selected based on their natural remanent magnetization exceeding a minimum threshold of $\sim 9 \times 10^{-13}$ Am². Because natural remanent magnetizations for a given sample population are expected to be stronger if they formed in a

stronger ambient field (Tauxe, 2010; Chapter 10), the Tarduno et al. (2023) paleointensities may oversample high paleointensities compared to the true underlying distribution, resulting in unaccounted for biases in the subsequent statistical analysis. The use of an explicit magnetization intensity cutoff in paleointensity studies is, as far as we are aware, unprecedented due to the likelihood of introducing such a bias.

Even if the sample selection were unbiased, the paleointensity protocol used for all GSB zircons and 25 out of 44 original Jack Hills zircons (Tarduno et al., 2015) were based on the so-call "565°C" paleointensity method, where a single ratio between the natural remanent magnetization and a full thermoremanent magnetization remaining after heating to 565°C is converted into a paleointensity. Such single ratio paleointensities, as opposed to those based on a linear fit to an array of data in partial thermoremanence - natural remanence space (also known as Arai plots), preclude the use of common quality checks such as for laboratory heating alteration and non-linearity of the data array. These zircon paleointensities are subject to a range of additional uncertainties arising, for example, from multidomain behavior. This is especially relevant as even submicron-sized magnetite that are invisible to optical microscopy screening (Tarduno et al., 2015) display characteristic "concave up" behavior in Arai diagrams (Levi, 1977), biasing paleointensities towards higher or lower values, depending on the demagnetization step(s) used to compute the paleointensity. Observation of the full dataset in Arai diagram space can allow recognition and, to some extent, correction of this bias (Leonhardt et al., 2004; Wang and Kent, 2013; Smirnov et al., 2017); however, such information is not available for the 565°C method. Although Tarduno et al. (2015) compared paleointensities from the 565°C and the traditional Thellier-Coe protocols, 8 out of 18 565°C method paleointensities deviate by at least a factor of 2 (Fig. S3 in Tarduno et al. (2015)).

An additional, fundamental assumption of using paleointensities to constrain tectonic motion is that the geodynamo was nearly dipolar in the Eoarchean. The modern geodynamo exhibits a very weak latitudeintensity relationship, which is, in fact, dual-valued with polar values dropping below those of mid to high latitudes (Lawrence et al., 2009; Muxworthy, 2017). Significant non-dipolar components of the geodynamo likely persisted through Earth history (Biggin et al., 2020), although studies disagree on the sign and magnitude of these components (Panzik and Evans, 2014; Veikkolainen et al., 2017; Veikkolainen and Pesonen, 2021). We therefore find that the dipolar geodynamo assumption is reasonable given the available information, although future studies have a high likelihood of demonstrating significant non-dipolar components.

The large uncertainty intervals produced by our analysis stem fundamentally from the small number of zircon paleointensities; the intrinsic degree of scatter in the paleointensities does not appear to be anomalously high compared to other paleointensity datasets (Fig. S1). Would collecting a larger number of zircon paleointensities result in stronger constraints on Archean tectonic style? Using the empirical bootstrap method, we can project the bounds on maximum latitudinal motion for a hypothetical dataset size. Taking the example of GSB motion between 3.408 and 3.808 Ga (Fig. 3C, 4C), a set of 80 zircons each at the two time bins would be needed to achieve a 95 % upper bound of ~48° cited in the original Tarduno et al. (2023) study as evidence for a stagnant-lid, although this value still encompasses 11 % of <600 Ma latitudinal motions (Tarduno et al. 2023, Source Data Extended Data Fig. 5). To exclude 95 % of modern motions would require an upper bound of 40, which would require on the order of 500 zircons in each time bin, assuming the bin means do not shift significantly and that all zircons record a primary paleointensity. Given that the current dataset of two GSB paleointensities in the 3.808 Ga interval required more than 1000 separated zircons (Tarduno et al., 2023), even a sample size of 80 would require order 40,000 separated zircons, which would be extremely difficult to achieve due to the effort involved and, more fundamentally, the very limited availability of zircon-bearing GSB outcrops. Of the three known localities of the GSB, two are located on highly



Fig. 5. Comparison between uncertainties of the Archean zircon paleointensity dataset and the motion of Phanerozoic landmasses. Orange data points represent the age bin means and 95 % confidence intervals from the empirical bootstrap method. We plotted these confidence intervals instead of the analytically ones because these are available for all age bins, including 3.708 Ga, which is based on a single zircon. Planerozoic paleointensities curves were first generated as relative intensity time series based on paleolatitudes from Merdith et al. (2021) and then scaled to find the best fit to the zircon paleointensities. Phanerozoic landmasses are labeled as follows: AMZ=Amazonia, BAL=Baltica, CNG=Congo, DHA=Dhawar, MBL=Marie Byrd Land, NCH=North China, SIB=Siberia, SUP=Superior, YIL=Yilgarn.

exposed ridges, making only one locality, which contains only a single meter-scale fallen block of GSB material, suitable for paleomagnetic analysis. Finally, the above calculation is already optimistic because a separate study of 283 GSB zircons concluded that zero samples in any age bin yielded a paleomagnetic signal (Fu et al., 2021).

4. Conclusion

Our statistical reanalysis shows that published Archean zircon paleointensities support only weak inferences about the Earth's early tectonic regime, even with the most favorable assumptions. In the most optimal and unlikely scenario of coherent Jack Hills and GSB motions that justifies combining all zircon paleointensities into a single dataset, the 95 % confidence interval of latitudinal motions between 3.408 and 3.808 Ga includes values up to 70.1° or 77.6°, depending on the methodology used (Figs. 3A-4A). The maximum motion of 35 % to 52 % of modern continental localities during the past 600 My fall within this bound (Figs. 1, 3D-4D). Considering all possible comparisons between age bins, only the 3.408 and 3.508 Ga pair contains sufficient data to constrain latitudinal displacement to less than 50° at 95 % confidence interval while all latitudinal motions are permissible for any age bin pairs containing 3.708, 3.808, or 3.908 Ga (Table 3).

As a complementary test, direct comparison of Archean zircon paleointensities and their uncertainties to expected paleointensity variations produced by mobile-lid motion of modern continents in the past 600 My shows that the motion of six out of nine tested continents would be unresolvable at 95 % confidence (Fig. 5).

More realistically, given their distinct petrogenetic environments and the lack of any independent information to support their presence on the same tectonic block [see discussion above and in Tarduno et al. (2023)], the Jack Hills and GSB zircon paleointensities should be analyzed separately to constrain the motion of each landmass. If a paleolatitude of 24.5 is assumed for the GSB (Tarduno et al., 2023), the paleointensity data imply that the Jack Hills were located as much as 100.5 from the GSB at 3.408 Ga. The same data provide no constraint on the latitudinal separation at older times (Fig. 6). Computing maximum permissible latitudinal change between 3.408 and 3.908 Ga for the two



Fig. 6. Paleointensity constraints on the relative position of the Jack Hills and the GSB at different ages. Paleointensity pairs used to compute the ratios were generated using the empirical bootstrap method using the mean and number of zircons from each landmass at each indicated age. A ratio of ≥ 2 indicates that the corresponding latitudinal difference is ≥ 90 , implying that the permitted range spans all possible relative motions on Earth. The 3.708 Ga age bin is missing due to lack of Jack Hills data. PINT stands for paleointensity.

localities separately shows that all possible latitudinal changes are permitted within the 95 % confidence interval (Figs. 3, 4, 7).

Superseding all of the analysis presented above, however, is the more foundational uncertainty regarding the primary or secondary nature of paleomagnetic signals in the Jack Hills zircons and the apparent irreproducibility of strong magnetizations in the GSB zircons [Appendix A; (Weiss et al., 2018; Tang et al., 2019; Borlina et al., 2020; Fu et al., 2021; Taylor et al., 2023)]. Unless this controversy is eventually settled decisively in favor of a primary origin for zircon magnetizations, any conclusions drawn from this ambiguous dataset should not be used to address a question as consequential as the origin of plate tectonics on Earth.



Fig. 7. Histograms of higher to lower paleointensity ratios for paleointensity pairs resampled using the empirical bootstrap method for Jack Hills zircons at the indicated ages. As in Fig. 6 and Table 3, a ratio of \geq 2 indicates a latitudinal difference of \geq 90, implying latitudinal separations that span more than the Earth's surface. The 3.708 Ga age bin is missing due to lack of data. PINT stands for paleointensity.

CRediT authorship contribution statement

Roger R. Fu: Conceptualization, Investigation, Formal analysis, Writing – original draft, Writing – review & editing. **Nadja Drabon:** Writing – review & editing, Writing – original draft. **Benjamin P. Weiss:** Writing – review & editing, Conceptualization. **Cauê Borlina:** Writing – review & editing, Writing – original draft, Conceptualization. **Heather Kirkpatrick:** Writing – review & editing, Writing – original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No original data was used for the research described in the article.

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Supplementary materials

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Supplemental materials for:

Statistical reevaluation of Archean zircon paleointensities: No evidence for stagnant-lid tectonics.

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Appendix A: Summary of evidence presented to support a primary or secondary origin for magnetization in Jack Hills zircons.

1. Selection criteria for zircons

The Jack Hills zircons analyzed at the Rochester and the MIT Paleomagnetism Laboratories underwent somewhat different selection criteria. Zircons analyzed at Rochester have "one dimension greater than ~150 µm" and "NRM intensities >10⁻¹² Am²". Further, each zircon was "examined in detail using a light microscope to search for visible fractures or large inclusions" (Tarduno et al., 2015). The zircons that pass these criteria then had "surface contaminants... mechanically removed", were "cleaned in distilled water and IPA", and, "for some crystals [underwent] a dilute HCl cleaning". Zircons were only dated after paleointensity experiments were completed.

Jack Hills zircons in the MIT laboratory were extracted using heavy-mineral density separation and handpicked with a nonmagnetic tweezers. Following extraction, 3754 zircon grains were washed with HCl to remove potential secondary minerals coating the grains and mounted in nonmagnetic epoxy (Weiss et al., 2018; Borlina et al., 2020). Zircon grains were then dated using U-Pb chronometry. Grains older than 3.5 Ga were analyzed with backscattered scanning electron (BSE) microscopy, cathodoluminescence (CL) imaging and Li-ion imaging. Grains that showed U-Pb discordance < 10%, lack of visible cracks, metamictization and secondary deposits in the BSE images, and Li zoning < 20 μ m in the Li maps (suggesting that the zircon grains have no experienced temperatures >550 °C since formation) were targeted for paleomagnetic studies. We note that Borlina

et al. (2020) did not use the magnetic moment as part of the selection criteria since this could exclude zircon grains that recorded a weak or inactive and bias any paleointensity results towards stronger values.

Although many details differ, the most potentially consequential differences in the zircon selection and treatment procedures are (1) optical microscopy screening at the Rochester Laboratory and (2) more aggressive acid washing at the Paleomagnetsim Laboratory. Given the sub-micrometer size of ferromagnetic particles in the Jack Hills zircons of both purported primary and secondary origins (Tang et al., 2019; Tarduno et al., 2020), is not clear how optical screening can rule out the existence of secondary minerals. The pathways to metamictization-caused and other void spaces within the Jack Hills zircons are potentially nanoscale (Tang et al., 2019), which cannot be imaged except with high magnification electron microscopy.

2. The grain population characterized using quantum diamond microscopy

Magnetic field mapping using the quantum diamond microscope (QDM) has been used to locate the magnetic signals in Jack Hills zircons. A first study of 381 Jack Hills zircons by Weiss et al. (2018) showed that at least 72% of IRM-carrying and 67% of NRMcarrying zircons exhibited magnetization only on outer grains surfaces and internal fractures. Later works used QDM imaging on a zircons that displayed stable NRM thermal demagnetization behavior to locate ferromagnetic inclusions and applied high resolution electron microscopy and atom probe tomography to show that these inclusions are secondary in nature and formed at least several 100 My after igneous crystallization (Tang et al., 2019; Borlina et al., 2020; Taylor et al., 2023).

Several critiques of these analyses have been published. Most prominently, several publications have repeatedly asserted that the QDM could detect only isothermal remanent magnetization (IRM) instead of NRM (Tarduno et al., 2020, 2023). This claim is false as Weiss et al. (2018) obtained NRM maps of 22 zircons, nine of which showed ferromagnetic signal [Figs. DR4 and DR5 in Weiss et al. (2018)]. Later QDM analysis of Barberton Greenstone Belt zircons detected NRM signal as weak as 6×10^{-14} A m² and ruled out at high confidence the presence of stronger NRMs in the 10^{-12} to 10^{-11} Am² range as compiled by Tarduno et al. (2023)

The zircons subjected to high resolution imaging and geochronology analysis in Tang et al. (2019) and Taylor et al. (2023) were indeed remagnetized with a 0.25 T IRM before QDM analysis because the NRM was already removed during the thermal demagnetization process. If indeed a population of primary magnetite carrying NRM existed alongside secondary grains that did not carry NRM, as suggested by Tarduno et al. (2020, 2023), we would expect that both populations would respond to a 0.25 T IRM and that regions of high IRM intensity would contain grains from both populations. However, Tang et al. (2019) imaging experiments in the highly magnetized regions did not find any ferromagnetic grains that were not associated with porous metamict regions, dislocation-induced pathways, and/or fractures (Tang et al. 2019; Figs. 1-3).

Although, strictly speaking, the absence of evidence for primary grains does not rule out their existence, the fact that abundant secondary ferromagnetic inclusions were revealed in the Tang et al. (2019) analysis shows that primary grains, if they exist, can only constitute a small fraction of the total ferromagnetic population.

Given the complex geologic history of Jack Hills zircons and the broad interest in implications about the early geodynamo and tectonic regime, we submit that any reliable results must rule out the possibility of secondary magnetizations at high confidence. That is, simply leaving open the possibility of surviving primary ferromagnetic grains is insufficient; rather, study authors must demonstrate that the probability of significant secondary contribution to the paleomagnetic signal is small.

Specifically, given the high abundance of secondary ferromagnetic inclusions found in most Jack Hills zircons based on their association with outer surfaces, metamict regions, and fluid pathways, claims of a primary paleomagnetic signal must not only show that some primary grains survive, but that they dominate over any secondary populations. The published evidence that at least ~70% of Jack Hills zircons have magnetizations mainly concentrated on outer surfaces, fractures, and metamict zones (Weiss et al., 2018) should motivate studies claiming detection of primary paleomagnetic signals to demonstrate specifically that each zircon in their analysis is free from such secondary sources and are, instead, dominated by primary ferromagnetic inclusions.

3. The age and origin of detected ferromagnetic inclusions

The burden of proof, as usual for paleomagnetic studies, should be on the proposition that primary ferromagnetic grains exist in the sample. The QDM and electron microscopy-based studies cited above have shown that highly magnetic regions in two Jack Hills zircons with stable NRM components contain undetectable concentrations of primary magnetic material (see above; Tang et al., 2019). Instead, as described above, detected Fe-oxide phases occurred exclusively in pore spaces within metamict zones and near identifiable fluid channels such as dislocation. These spatial associations provide strong evidence of the inclusions' secondary origin, especially because porosity-inducing damage in the metamict zones require 100s of My to accumulate, therefore necessitating a significant time delay between zircon crystallization and Fe-oxide mineralization. Furthermore, direct age dating of Pb- and Fe-rich nanoclusters within zircon material retrieved from a highly magnetic region of a stable NRM-carrying Jack Hills zircon revealed ages of <2 Ga for Fe mineralization (Taylor et al., 2023). Together, these studies prove that, despite targeting only zircons that carry stable magnetization components, all detected ferromagnetic grains have a demonstrably secondary origin.

A similarly conceived study using nano-magneto-optical Kerr effect (MOKE) and scanning electron microscopy claims to have located an inclusion in a Jack Hills zircon that contains a primary ferromagnetic inclusion [Fig. 5 in Tarduno et al. (2020)]. As discussed above, we submit that simply the existence of a single primary ferromagnetic inclusion in a single Jack Hills zircon is insufficient to demonstrate the likely primary origin of the bulk NRM of the zircon in which it has been found, much less that of other analyzed zircons, especially given the much larger number of demonstrably secondary inclusions that have been found in zircons that satisfy more stringent acid-washing and paleomagnetic signature selection criteria (Weiss et al., 2018; Tang et al., 2019; Taylor et al., 2023). Therefore, even if the primary nature of this inclusion described in Tarduno et al. (2020) is assumed, we advocate for further, intensive investigation to establish that primary ferromagnetic inclusions constitute a significant portion of paleomagnetic sources found in Jack Hills zircons.

In any case, we find at least four major difficulties with the published evidence for the primary nature of the inclusion analyzed by Tarduno et al. (2020). First, the primary nature of the inclusion is apparently only established by the absence of connecting fractures in a single imaging plane. As higher-resolution transmission electron microscopy in Tang et al. (2019) shows, channels that direct metamorphic fluids to void spaces can be nanoscale and unresolvable at the resolution used in the Tarduno et al. (2020) analysis. Fractures that connect the inclusion to the outside environment may have also existed at depth within the sample or have been removed during excavation to expose the inclusion.

Second, the enclosing walls of the inclusion exhibit angular facets, some of which are in direct contact with enclosed void space. The authors claimed that these spaces were gas-filled during igneous crystallization [p. 2313 in Tarduno et al. (2020)]; therefore, the zircon walls that crystallized around these gas-filled volumes are expected to have rounded, convex morphologies characteristic of fluid inclusions and vesicles observed in other zircons (Thomas et al., 2003) and in a wide variety of igneous settings. On the other hand, included minerals, if euhedral, imprint facets onto the walls of the inclusion, which, in the event that the included phase is dissolved during metasomatism, retain the angular geometry of the original mineral. Figure S2 shows four Jack Hills Hadean zircons with published inclusion assemblages (Hopkins et al., 2008, 2010; Holden et al., 2009). We note that inclusions within these grains conform to the shape of the host-grain vacancy. Both a younger Jack Hills zircon (Harrison et al. (2017); Fig. 3 -RSES77-5.7, 4.06 ± 0.1 Ga) and younger phanerozoic zircon [Appalachian zircon and Peninsular Ranges zircon (Bell, 2016; Bell et al., 2019)] similarly do not show empty space around inclusions. In short, the angular morphology of the studied inclusion, even in the presence of interior voids, provides strong evidence for a pseudomorphic replacement origin, implying that the crystals observed inside the modern zircon are part of a later generation that post-dates igneous formation and subsequent dissolution of a primary, volume-filling phase.

A third and related problem with the cited evidence for a primary inclusion origin is the association between two purported potassium feldspar and one quartz inclusion with the void space. Tarduno et al. (2020) appear to be ambiguous in the interpretation of this void space, writing that they "interpret these as primary melt inclusions," but, simultaneously, stating that "vapor-phase magnetite can be one of the included phases." In the case of a fluid inclusion, which have been reported in zircon, the obvious lack of glass or its alteration products rules out this hypothesis. Regarding the possibility of a primary gas-phase inclusion (i.e., vesicle), we are not aware of any vesicles reported as demonstrably primary inclusions in zircons. Even if gas bubbles existed in the parent melt during Jack Hills zircon crystallization, interpretation of the observed polymineralic association as primary would require a group of three euhedral grains to agglomerate together, coalesce with a trapped gas bubble, and become included in a growing zircon while the gas phase casts a faceted shape into the surrounding zircon. We find this chain of events unlikely and advocate for future investigations that can provide examples in any modern zircons of faceted, void-containing primary inclusions.

As a fourth and final difficulty with the Tarduno et al. (2020) interpretation, the mere presence of minor Fe on one of the purported potassium feldspar crystals does not imply the existence of magnetite. Tarduno et al. (2020) cited two references for "vapor phase" magnetite that may have been deposited on the host feldspar crystal. However, these

references describe magnetite formation during metamorphic alteration of carbonate in a martian meteorite and condensation of magnetite in fumaroles at Earth surface pressure (Symonds, 1993; Bradley et al., 1996). Neither case is relevant to primary crystallization in a magma chamber environment. Further, the NanoMOKE data were taken in an artificial magnetic field of 0.5 T (Tarduno et al., 2020), implying that the signal from the inclusion may arise from ferromagnetic, superparamagnetic, or paramagnetic sources. In short, neither the NanoMOKE or compositional data provide specific evidence for ferromagnetic magnetite nor do they quantify whether ferromagnetism in the inclusion, if any, is strong enough contribute meaningfully to the overall zircon magnetization.

Finally, we reiterate our point above that, even ignoring these ambiguities in the identification of a primary ferromagnetic inclusion, it is insufficient to show simply that some primary ferromagnetic inclusions exist in Jack Hills zircons. Given the abundant, conclusively secondary ferromagnetic inclusions that have been documented (Weiss et al., 2018; Tang et al., 2019; Borlina et al., 2020; Taylor et al., 2023), a strong argument for the primary origin of zircon paleomagnetic signal must show that primary ferromagnetic minerals dominate over the well-established secondary population.

4. The validity of microconglomerate tests

In addition to presenting the purported evidence for primary ferromagnetic inclusions in Jack Hills zircons, Tarduno et al. (2020) also described an updated microconglomerate test where oriented, 0.5 mm-scale volumes of Jack Hills metaconglomerate containing zircons were analyzed to assess the presence of predepositional remanence. This result represents the refinement of earlier published experiments that used similar oriented specimens to claim the existence of a randomly oriented magnetizations blocked above 560°C (Tarduno et al., 2015) and, for contrast, unidirectional magnetization carried by secondary fuchsite grains blocked below 340°C (Cottrell et al., 2016).

In response to the original microconglomerate test reported in Tarduno et al. (2015), Weiss et al. (2018) presented QDM magnetic field maps of zircon-bearing thin sections that showed grain boundaries containing highly magnetic sources [Fig. DR7 in Weiss et al. (2018)]. Although these maps were made on IRM-carrying sections, they demonstrated that abundant ferromagnetic sources existed in interstitial accessory phases in the Jack Hills metaconglomerate within 100 μ m of zircons despite the nominally weak expected magnetization of a quartz-dominated sandstone. Tarduno et

al. (2020) responded to this criticism by separating a single piece of quartz adjacent to one zircon and measuring it separately on a SQUID microscope. This analysis showed that the quartz grain was much less magnetic than the 500 μ m-sized, zircon-containing microconglomerate "clast" sample.

This result is perfectly consistent with the QDM magnetic field maps presented in Weiss et al. (2018), which showed that the majority of quartz grains adjacent to zircons were indeed non-magnetic. However, assignment of the total signal to a zircon-quartz aggregate to the zircon itself requires that all non-zircon materials are non-magnetic, not only that one such grain is non-magnetic. As shown in the Weiss et al. (2018) QDM maps, the inclusion of a single highly magnetic zone in the vicinity of the zircon would be sufficient to overwhelm the paleomagnetic signature of the zircon itself. The Tarduno et al. (2020) extension to the microconglomerate test therefore does not demonstrate that the microconglomerate "clast" signals originate from zircon grains. The zircon itself still constitutes a small volume fraction of each oriented "clast" sample, which consists mainly of quartz and accessory phases that have not been individually verified to be magnetically subordinate to the zircon. A more valid microconglomerate test would require isolation of actual, oriented zircon grains or magnetic field microscopy at much high spatial resolution than that shown in the Tarduno et al. (2020) SQUID microscope data such that ferromagnetic sources can be identified at the sub-zircon scale.

Further, a truly robust microconglomerate test would require the sub-sectioning of single zircons to demonstrate the internal unidirectionality of remanence. Secondary remanence acquired over long timespans, heterogeneously among different grain populations, or simply in materials with poor ambient magnetic field-recording capacity is known to result in randomly oriented magnetizations at fine scales. This has been observed in the Jack Hills pebble conglomerate itself, where Weiss et al. (2015) showed that, among 15 cobbles that contain high temperature magnetizations, only 7 are homogeneously magnetized within the cobble [Fig. S8 in Weiss et al. (2015)]. Other studies have shown routine occurrence of characteristic remanent magnetization directions that are well-defined in single samples, but are random within sedimentary horizons that are expected to preserve a single paleofield direction [e.g., (Tauxe et al., 1994; Fuentes et al., 2019)]. These inconsistencies may arise from spatially heterogeneous remagnetization which, based on mineralogical evidence for secondary ferromagnetic phases as detailed above, may be applicable to Jack Hills zircons. Stable yet directionally incoherent within-clast magnetizations at the sub-millimeter scale have also been

observed in carbonaceous chondrites, also due to the spatially heterogeneous response to chemical alteration (Fu et al., 2014, 2021). To address this potential cause for a false-positive conglomerate test, a number of paleomagnetic studies have sub-sampled clasts to demonstrate internal consistency (Biggin et al., 2011; Weiss et al., 2015; Panzik et al., 2016).

Without published data showing random magnetization components in isolated zircons instead of surrounding ferromagnetic phases, the inverse microconglomerate test showing that secondary fuchsite grains carry a unidirectional magnetization that fail the conglomerate test (Cottrell et al., 2016) are not relevant to discussion of zircon-hosted magnetizations.

5. The validity of bulk sample field tests

A series of papers led by both the Rochester and MIT paleomagnetism laboratories have reached starkly different conclusions about the paleomagnetic record carried by the host metaconglomerate unit in the Jack Hills and surrounding rocks (Tarduno and Cottrell, 2013; Weiss et al., 2015; Dare et al., 2016). We provide only a short summary of the controversy here, primary because the outcome of these paleomagnetic studies cannot conclusively determine the primary or secondary nature of magnetization in individual zircons. For example, a failed cobble conglomerate test of the zircon-hosting quartzites may only mean that other ferromagnetic phases in these rocks were chemically remagnetized without disturbing the zircons. Conversely, a passing cobble conglomerate test does not rule out chemical remagnetization of zircon-included ferromagnetic phases or remagnetization prior to deposition at ~3.0 Ga (Trail et al., 2016). Nevertheless, the paleomagnetic of surrounding rock units may offer circumstantial insights into the origin of Jack Hills zircon magnetism.

Because Hadean to Eoarchean Jack Hills zircons discovered to date have been separated from the quartzite cobbles within a clast-supported metaconglomerate unit, a paleomagnetic conglomerate test of these cobbles is the most relevant field test that can be performed using bulk (i.e., non-single grain; centimeter-scale) samples. Tarduno and Cottrell (2013) first reported a passing conglomerate test based on high-temperature magnetizations blocked between 550°C and 580°C in 27 cobbles. However, a similar set of experiments undertaking by Weiss et al. (2015) failed to reproduce this result, finding instead that, out of a total of 35 cobbles, only 15 carry any high-temperature, origintrending magnetization that can be plausibly interpreted as pre-depositional. Further, only seven of these cobbles carry internally unidirectional magnetization as expected for a pre-depositional remanence. At least three of these uniformly magnetized cobbles likely carry lightning overprints due to the lack of low temperature overprinting components. In summary, the Weiss et al. (2015) conglomerate test analyzed a larger number of cobbles, including for internal consistency, to reveal far fewer examples of plausible pre-depositional magnetization. These recovered directions are too few to be used in a statistically viable conglomerate test. The cause of this apparent fundamental discrepancy in conglomerate test results is currently unknown, although several hypotheses have been put forth. Although the Weiss et al. (2015) study included a larger range of sampling sites, including some in a parallel bed ~500 m north of the Hadean-Eoarchean zircon-bearing locality, both studies included pebbles from apparently the same outcrops ~400 m west of the zircon source. Other suggestions including lightning contamination of the Tarduno and Cottrell (2013) or demagnetization of the MIT samples in a reducing Ar atmosphere (Dare et al., 2016) are either unlikely or factually untrue. We reiterate that the solution to the conglomerate test discrepancy is unlikely to resolve the fundamental controversy over the origin of paleomagnetic signals in individual zircons, although a future, third-party investigation of the cobble conglomerates that, like Weiss et al. (2015), includes analysis of intra-clast magnetization consistency, would likely provide the most direct and insight evidence for understanding the preservation of predepositional magnetization.

Appendix B: Sensitivity analysis for the treatment of high resampled paleointensity values

As described in the Main Text, a complication of using paleointensities to constrain a change in paleolatitude is that, if the latitude of one landmass (or the same landmass at one age) is independently known, then the lowest (equatorial) and highest (polar) paleointensities possible under that dynamo condition are implicitly specified. Therefore, some paleointensities for the other landmass or age may fall outside of the possible range between the equator and pole. In the Main Text, we argued that this is to be expected given the large sources of variance in the problem; therefore, paleointensities higher than the implied polar value were interpreted as the location of the landmass near the poles in combination with a random variation that resulted in an even-higher value.

As a sensitivity test, we revisit this treatment of high resampled paleointensities. We find that excluding these nominally non-physical resampled paleointensities results in 95% upper bounds of 71.3° and 82.4° for the combined dataset using analytical and empirical bootstrap methods, respectively (compared to 70.1° and 77.6°). For separately considered Jack Hills and GSB datasets, these new bounds become 101.5° and 102.3° and 83.4° and 90.0°, respectively. In all but one case, these bounds include >50% of modern plate displacements (Figs. 3D, 4D) and in the one case where the bound does not (71.3°), the value is still larger than that produced by the same analysis including all resampled paleointensities. We therefore conclude that the treatment of resampled paleointensities higher than the nominal polar values does not affect the outcomes of any analyses.

Appendix C: Choice of modern landmasses for comparison of latitudinal motion

As described in the Main Text, we used the GPlates program (Müller et al., 2018) to extract the latitudinal motion of nine representative landmasses during the past 0.5 Gy (Fig. 1). Of these nine blocks, we selected Amazonia, Baltica, Congo, Marie Byrd Land, Superior, and Yilgarn because they are representative of the motions of their encompassing continents, the cores of which remained relatively intact during the analyzed time interval. The choice of tracked crustal blocks for eastern Eurasia is more subjective due to the multi-stage amalgamation of this landmass throughout the Phanerozoic. We selected the Dharwar to track the motion. For Siberia and the components of the united China block, we chose Tungus and North China, respectively. Although these landmasses were represented by several more crustal blocks during the Phanerozoic, Tungus remains at the heart of the large Siberia block while North China, although separated from multiple other China blocks prior to the Jurassic, remains within ~30° latitude of South China.

We then map these latitude trajectories to paleointensities assuming a dipolar geodynamo. Moving window smoothing with 100 My and 200 My kernels are applied at this point for the smoothed time series. Reconstructions over the past 600 My and 700 My, respectively, were required to generate these smoothed datasets. In the case of Marie Byrd Land, a quantitative reconstruction was available only back to 610 Ma and that time series was truncated in the 200 My smoothing case. Finally, we scale the resulting curve to fit the combined zircon paleointensity time series by minimizing the squares of residuals. This last step is necessary since the baseline intensity of the 3.9-3.4 Ga dynamo is unknown compared to that of the present day. We note that by scaling the relative paleointensity curve for each modern landmass by a single, time-independent value does not implicitly assume that the geodynamo has maintained a single time-averaged value over the past 500 My. Rather, our use of the Phanerozoic paleolatitude reconstructions is to obtain typical latitudinal motions in a mobile-lid plate tectonics world. We then use these to estimate the relative paleointensity changes of these landmasses if they had existed in the Archean. We are therefore adopting the same implicit assumption as Tarduno et al. (2023) that the time-averaged field between 3.4 and 3.9 Ga remained constant.

Further, for a given dynamo strength, the actual latitude of modern landmasses affects how latitudinal motion is mapped to paleointensity. We intend to compare the empirical range of latitudinal motion-induced paleointensity changes without specifying that the zircon-bearing Archean continent must have similar absolute latitudes compared to any modern landmasses. We therefore treat the paleointensity time series of the nine Phanerozoic blocks as sets of relative intensity changes.

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Figure S1: Comparison between paleointensities of zircons with age between 3380 and 3420 Ma and paleointensities with paleointensity quality criteria (Q_{Pl}) greater than or equal to 2 from two data-rich modern regions. The modern paleointensities have been renormalized to a common mean as the Archean dataset. The three datasets are consistent with drawing from a single underlying distribution according to a two-sample Kolmogorov-Smirnov test.



Figure S2: Backscatter electron images of published Jack Hills zircons. Grain RSES96-15.10 (4282 \pm 6 Ma, 2 σ ; Holden et al. 2009) displays a xenotime (secondary; left side along crack) inclusion and a rutile+quartz inclusion (right side) (Hopkins et al. 2008; 2010). Grain RSES130-8.5 (4228 \pm 10 Ma (2 s.e.); Holden et al. 2009) displays a small muscovite inclusion (Hopkins et al. 2008; 2010). Grain RSES113-13.18 (4250 \pm 13 Ma (2 s.e.); Holden et al. 2009) displays a small quartz inclusion (Hopkins et al. 2008; 2010). Grain RSES113-13.18 (4250 \pm 13 Ma (2 s.e.); Holden et al. 2009) displays a small quartz inclusion (Hopkins et al. 2008; 2010). Grain RSES113-13.18 (4250 \pm 13 Ma (2 s.e.); Holden et al. 2009) displays a small quartz inclusion (Hopkins et al. 2008; 2010). Grain RSES96-8.15 displays a quartz/muscovite inclusion bordering on edge of grain (right side) (Hopkins et al. 2008, 2010). Gray elipsoids are ablation pits from previous ion probe analyses.



Figure S3: Comparison between the predicted paleointensity changes arising from mobile-lid motion for nine modern cratonic blocks and age binned Archean zircon paleointensities. In contrast to the 100 My moving mean smoothed data in Main Text Fig. 5, panels (A) and (B) show unsmoothed and 200 My moving mean smoothed paleointensity curves. Modern landmasses are labeled as follows: AMZ=Amazonia, BAL=Baltica, CNG=Congo, DHA=Dhawar, MBL=Marie Byrd Land, NCH=North China, SIB=Siberia, SUP=Superior, YIL=Yilgarn.