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Reply to Comment on "Pervasive remagnetization of detrital zircon host rocks in the Jack Hills, Western Australia and implications for records of the early dynamo"

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Determining the history of Earth's dynamo prior to the oldest known well-preserved rock record is one of the ultimate challenges in the field of paleomagnetism. Tarduno et al. (2015) argued that detrital zircons contain records of an active dynamo dating back to 4.2 billion years ago (Ga), 700 million years earlier than previously identified (Biggin et al., 2011; Tarduno et al., 2010). However, this extraordinary claim requires evidence that the zircons have not been remagnetized during the intervening time since their formation. Weiss et al. (2015) argued that such evidence had yet to be provided, a conclusion that we find still firmly holds.

Although mineral thermometry by our group and others has shown that the Jack Hills zircons and their host rocks have not been heated above ∼500 °C since deposition at ∼3 Ga (Rasmussen et al., 2011; Trail et al., 2016), they could have been aqueously remagnetized by alteration of original ferromagnetic minerals or neoformation of new ferromagnetic minerals in cracks and voids after this time. Moreover, the thermal and aqueous remagnetization histories of the zircons prior to deposition at 3 Ga are un-

known. These uncertainties mean that the ages of magnetization in the zircons could be hundreds of millions or even billions of years younger than their crystallization ages.

Weiss et al. (2015) focused on whether rocks in the Jack Hills region, including those which host the oldest zircons, were remagnetized after deposition at ∼3 Ga. They conducted a total of 12 baked contact, fold, and conglomerate tests on 277 specimens, which is nearly an order of magnitude larger than all other paleomagnetic studies of oriented Jack Hills samples to date combined (Cottrell et al., 2016; Tarduno and Cottrell, 2013; Tarduno et al., 2015). Weiss et al. (2015)'s tests yielded either negative results, indicating substantial remagnetization in a north-down direction observed throughout the Jack Hills, or inconclusive results due to unstable magnetizations. These results are in stark contrast to two positive conglomerate tests reported by Tarduno and Cottrell (2013) and Tarduno et al. (2015). Another difference is that the dominant magnetization-carrying mineral observed by Weiss et al. (2015) in the Jack Hills metaconglomerates appears to be pyrrhotite (although they did observe magnetite in some samples and many samples also contained hematite and goethite) while the latter two studies observed dominantly magnetite.

Included in the Weiss et al. (2015) study were conglomerate tests on three individual block samples of pebble conglomerate

(EHJH5, EHJH6, and EHJH7) from the Hadean zircon original discovery outcrop at Erawandoo Hill. Claims by Bono et al. (2016) and Cottrell et al. (2016) that this was not our sampling site are without foundation, as described in the Supplementary Material (SM). From each EHJH block, Weiss et al. (2015) analyzed mm to cm-sized subsamples of the pebble-sized clasts and matrix taken from the decimeter-scale oriented parent block samples. They found that the dominant ferromagnetic mineralogy in most samples is likely pyrrhotite given the dominant unblocking temperature of ∼330 °C, the identification of the Besnus low-temperature magnetic transition, and quantitative microprobe measurements of Fe:S in sulfides (see SM). Note that by 330 °C, many of the samples still had moments of 10^{-9} A m^2, which is ∼1000 times above the sensitivity limit of the 2 G Enterprises Superconducting Rock Magnetometer in the Massachusetts Institute of Technology (MIT) Paleomagnetism Laboratory [e.g., Fu et al., 2012]; therefore, the observed lack of directional stability is due to demagnetization of the stable remanence by this temperature rather than magnetometer noise.

Crucially, Bono et al. (2016) accept the central conclusion of Weiss et al. (2015) that the null hypothesis that the remanence directions of the clasts in each block are random can be rejected at the 95% confidence level, meaning they fail the conglomerate test.[1] This means that the clasts in the Hadean zircon-bearing rocks were remagnetized after deposition up to the maximum observed unblocking temperatures of 320–500 °C [see Table S3 of Weiss et al., 2015]. As such, this result does not provide evidence that the zircon magnetization predates deposition at 3 Ga, much less show that the zircon magnetization is a primary record dating back to 4.2 Ga.

The primary subject of the Comment by Bono et al. (2016) is constraining when after deposition at 3 Ga remagnetization of the rocks occurred. Because this is of not much consequence for determining the timing of the earliest dynamo, we recommend that readers not interested in the details of paleomagnetic analysis now skip ahead to the third-to-last paragraph. Bono et al. (2016) focus on whether the three block means are too scattered for the remagnetization to be interpreted as originating from the emplacement of the Warakurna large igneous province (LIP). We agree that the use of a grand mean calculated from the mean directions of just three parent block samples has limited significance given the resulting large 95% confidence interval. Weiss et al. (2015) did not discuss this issue in detail because of its relative unimportance: the main point is that the conglomerate tests fail, which requires remagnetization after 3 Ga. The differences in the $N = 3$ block means and large confidence interval for their grand mean observed by Weiss et al. (2015) are not surprising given the very small N and the following expected error sources:

(a) multiple overlapping secondary and diachronous overprints, which are clearly visible from non-Fisherian streaking of some EHJH6 specimen directions between the ubiquitous north-down direction and a southwest-down direction. Interestingly, the latter direction is very close to the characteristic magnetization direction identified by Cottrell et al. (2016) in the matrix of a nearby Erawandoo Hill sample (Fig. 1A), supporting the possibility of multiple remagnetization events. Cottrell et al. (2016) proposed that this southwest-down direction is related to a metamorphic event at 2.65 Ga. However, the direction also corresponds with the Cambrian portion of Australia's apparent polar wander path (Durocher et al., 2003; Klootwijk, 1980; Mitchell et al., 2010) such that it could

be a remagnetization associated with the late stages of the Peterman–Paterson orogeny (Li and Evans, 2011).

(b) poorly isolated characteristic magnetization components for some samples due to unstable behavior during laboratory demagnetization [i.e., EHJH samples with high temperature (HT) components with maximum angular deviations exceeding ∼15° in Weiss et al. (2015), Table S2];

(c) block and specimen orientation errors, along with modest differential tilting of the three parent blocks over the last 1.1 billion years (which we estimate could collectively add differential rotations of up to 5–10°).

(d) Secular variation of the geomagnetic field. Note that despite what is implied by Bono et al. (2016), Weiss et al. (2015) did not propose that secular variation was the sole source of the scatter of the EHJH directions.

Although the mean directions of the three EHJH blocks are somewhat scattered (Fig. 1A, Table S2), they are oriented in approximately a similar direction as the north-down remagnetization directions observed elsewhere in the Jack Hills by Weiss et al. (2015) (Fig. 1B, Table S2). The grand mean of all of these remagnetization directions (from conglomerate test, baked contact test, fold test and other host rock sites) is indistinguishable at 95% confidence from that of the ∼1080 Ma Warakurna LIP in local coordinates (which we have recalculated using all available high-quality Warakurna sites from western Australia; Fig. S1 and Table S3) and indistinguishable at 95% confidence from the characteristic magnetization direction of a 1078.4 ± 4.4 Ma Jack Hills dike that was the subject of three baked contact tests by Weiss et al. (2015) (Fig. 1B and Table S2). It is the consideration of all these remagnetization directions together, which includes three different types of failed field tests, that led Weiss et al. (2015) to conclude that thermal or aqueous processing by the emplacement of the Warakurna LIP at ∼1080 Ma was the most likely last major remagnetization event in the region. Although Weiss et al. (2015) describe how remagnetization scenarios at different times also are conceivable, the evidence for a pervasive Warakurna LIP overprint in the region around the Hadean zircon outcrop is far from a "chimera" and instead quite compelling. In any case, we remind the reader that when remagnetization of the host rocks occurred does not really matter: the main point is that remagnetization occurred after 3 Ga.

Bono et al. (2016) accuse Weiss et al. (2015) of "gross (90°) errors in orientation and measurement misorientation." We offer two strong pieces of evidence that refute this groundless assertion:

(i) Weiss et al. (2015) obtained a Warakurna-like local magnetization direction from a dyke with a U–Pb emplacement age of ∼1080 Ma as well as from numerous surrounding sites that included failed conglomerate, baked contact, and fold tests (Fig. 1B). In fact, based on the paleomagnetic direction we measured for the dyke, we predicted that it would have an age of 1.1–1.2 Ga before actually acquiring a U–Pb date for the dyke. These results demonstrate that we can accurately orient and measure paleomagnetic samples.

(ii) Our failed conglomerate tests, which demonstrated nonrandom magnetization directions at each site, are statistically extremely unlikely to occur by chance if our samples had been misoriented (<1% for each of the EHJH5 and 6 tests, leading to a joint probability of $<10^{-4}$). In contrast, positive conglomerate tests like those reported by Tarduno and Cottrell (2013) and Tarduno et al. (2015) are the much more likely outcome when samples are misoriented. Given the ubiquity of north-down overprints in our samples, it remains puzzling that Tarduno and Cottrell (2013) did not observe such remanence directions in their conglomerate test samples. Note that the parent block for Tarduno et al. (2015)'s conglomerate test

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[1] Following Cottrell et al. (2016), we instead might say they pass the "inverse conglomerate test."
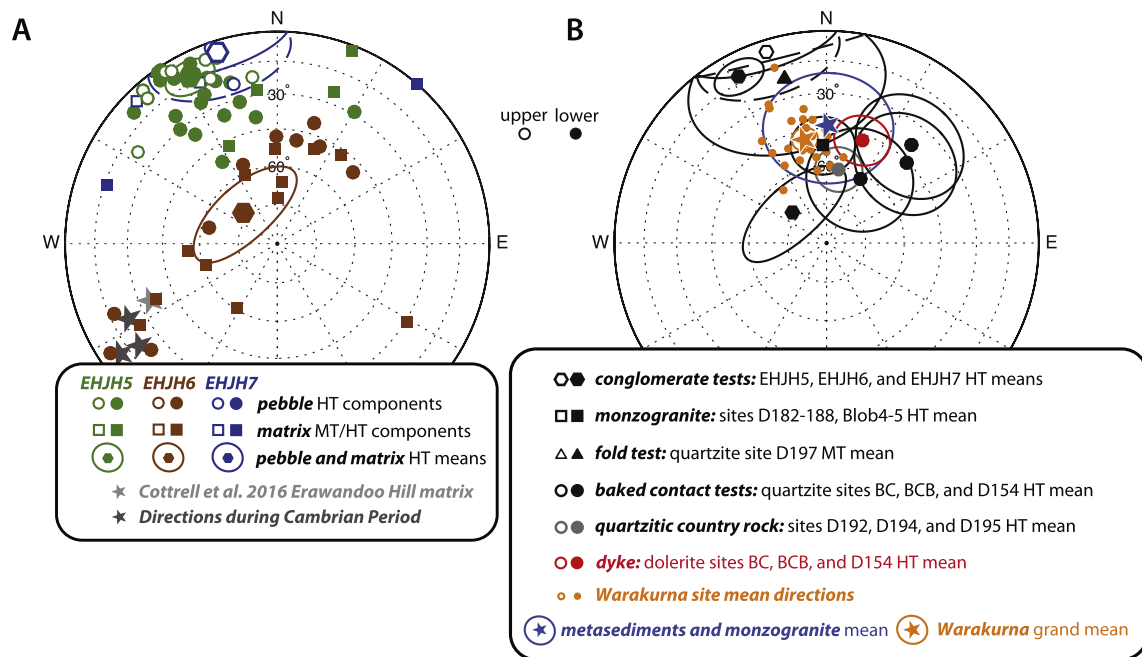
Fig. 1. Pervasive remagnetization of the Jack Hills and its relationship with the Warakurna LIP. Equal area stereonets show directions of high temperature (HT) and middle temperature (MT) components of natural remanent magnetization using data from Weiss et al. (2015). Open and closed symbols represent projections on upper and lower hemispheres, respectively. Peak unblocking temperatures for the MT and HT components range from 200–580 °C, with most sedimentary samples unblocking below ~330 °C [see Weiss et al., 2015]. Points with surrounding ellipses are mean directions and associated 95% confidence intervals. (A) Conglomerate tests on three blocks of pebble conglomerate from the Hadean-zircon site at Erawandoo Hill: EHJH5 (green), EHJH6 (brown), and EHJH7 (blue). Circles and squares represent magnetization components for clasts and matrix, respectively. For all clast subsamples, HT components are shown for all three sites, while for matrix subsamples, MT components are shown for EHJH5 and HT components are shown for EHJH6 and EHJH7. Hexagons and associated ellipses give HT means and 95% confidence intervals for each of the three blocks (Table S2). Light grey star denotes geographic mean of Erawandoo Hill matrix measured by Cottrell et al. (2016). Dark grey stars denote the directions in Jack Hills coordinates of poles from Australia's apparent polar wander path during the Cambrian at 520–510 million years ago (Billy Creek/Wirre-alpa/Arona Creek Limestone, Kangaroo Island Red Beds, and Lower Lake Frome Group) (Swanson-Hysell et al., 2012). (B) Evidence from rocks throughout the Jack Hills for remagnetization by the Warakurna LIP. Shown are means for the three EHJH conglomerate tests (hexagons) from (A) compared to means from the monzogranite intrusion (square), a quartzite fold test at site D197 (triangle), three quartzite baked contact tests associated with a 1.1 Ga dyke at sites BC, BCB, and D154 (black circles), and a distal baked contact test at country rock quartzite sites D192, D194 and D195 (grey circle) (Table S2). Small orange circles give the direction for site means of Warakurna LIP-associated sills, dykes, and dolerites in local Jack Hills coordinates (see Table S3 and Fig. S1 for details). The grand mean of all Jack Hills sites excluding the dyke (blue star) is indistinguishable from the dyke mean (red circle) (Table S2) and indistinguishable from the grand mean Warakurna LIP in local Jack Hills coordinates (orange star).

was an unoriented block sample (their Fig. S1), such that the absolute direction of overprints cannot be recovered.

Bono et al. (2016) state that our interpretation that the remagnetization of Erawandoo Hill likely resulted from the Warakurna LIP "sets an unfortunate precedent for the discipline." This hyperbole is ironic given that over the last 2–3 years, we have repeatedly requested the primary demagnetization data and samples for the Tarduno and Cottrell (2013) study from the U. Rochester group; however, they would not provide these data to us nor even to the *EPSL* editors when requested as part of this Comment and Reply. By comparison, our demagnetization data are available as an online supplement to Weiss et al. (2015) and were analyzed by Bono et al. (2016) as part of their Comment. Furthermore, we sent some of the standard cm-sized cobble specimens measured by Weiss et al. (2015) to J. Tarduno and R. Cottrell in September, 2014. The exchange of data and samples is critical for resolving the issues discussed in this Comment and Reply: to establish why Tarduno and Cottrell (2013) observed a positive cobble conglomerate test often with high fractional remanence remaining above 350 °C that is carried by magnetite (with no reported north-down overprint), while all of our conglomerate, fold, and baked contact tests either were negative (with pyrrhotite-dominated remagnetization in the north-down Warakurna LIP direction) or inconclusive. Access to the demagnetization data for Tarduno and Cottrell (2013) would allow us to assess the intensity, direction and thermal stability of magnetization overprints for the 20 out of their 28 samples whose demagnetization data do not appear in their manuscript

Figs. 5 and 6. Even the latter vector-component figures are difficult to interpret because the divisions on the published axes are not numbered. Exchange of samples would enable us to test whether the differences in results between the MIT and Rochester labs relates to differences in measurement techniques, sample lithologies and/or lightning remagnetization. Reproducibility tests like these form the basis of the scientific method.

We close this Reply by emphasizing what is the critical issue for establishing the existence of a Hadean dynamo from the Jack Hills zircons: determining whether or not the zircons were remagnetized *before* deposition at 3 Ga but still well after their formation at 4.4 Ga and later. Pre-depositional zircon remagnetization is a serious possibility for two reasons. First, it has not been demonstrated that the zircons' ferromagnetic inclusions are primary; in fact, a recent petrographic study showed that only ~12% of iron oxides in Jack Hills zircons are not spatially associated with cracks or annealed cracks (Bell et al., 2015). Second, it has not been demonstrated that the zircons escaped heating above the Curie point of their constituent ferromagnetic inclusions prior to deposition at 3 Ga. The slow diffusion of Pb in zircon means that a 10 million-year-long, ~820 °C thermal event, which far exceeds magnetite's 580 °C Curie point, will produce just 1% Pb loss from a 100 μm radius non-metamict zircon (Cherniak and Watson, 2000) (Fig. 2). Both of these points mean that a zircon's magnetization could be far younger than its U–Pb age or even disturbance ages inferred from U–Pb discordance.

In an effort to address this issue, Tarduno et al. (2015) argued that, if the zircons had experienced high-temperature metamor-
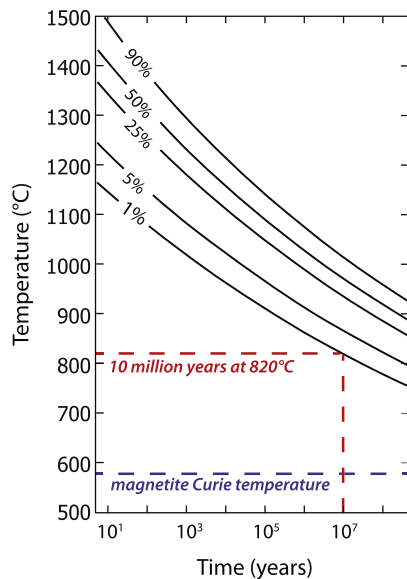
Fig. 2. Conditions for diffusional Pb loss in crystalline zircon. Shown are the time-temperature conditions for a thermal event that will lead to 1%, 5%, 25%, 50% and 90% Pb loss from a 100 μm radius grain. Blue line shows 580 °C Curie point of magnetite, while red lines show that a temperature event to 820 °C lasting for 10 million years will produce just 1% Pb loss. Such an event would be essentially undetectable by the U–Pb methods used by Tarduno et al. (2015). After Cherniak and Watson (2000).

phism, the Pb would be redistributed in an inhomogeneous fashion at the nm-scale, resulting in non-systematic Pb/U variations during secondary ion mass spectrometry (SIMS) depth profiling that they did not observe. The above statements misrepresent their SIMS capability in three ways: a) the sputtering process mixes near surface atoms at the ~10 nm-scale, b) the SHRIMP instrument they used cannot truly depth profile as sputtered atoms from both crater bottom and surface are simultaneously accelerated into the mass spectrometer, and c) the 7–13 μm diameter spot they used is orders of magnitude larger than would be needed to reveal such nm-scale heterogeneities, even if they existed. In any case, even if they were able to detect such inhomogeneities, the studies cited in Tarduno et al. (2015) [e.g., Davis et al., 2008 and Kusiak et al., 2013] show that their formation occurred during granulite facies metamorphism, indicating temperatures that greatly exceed magnetite's Curie point. Therefore, even if Tarduno et al. (2015) could have verified the absence of such Pb redistribution, it would fail to rule out complete thermal remagnetization prior to deposition.

In summary, neither the age of magnetization in the Jack Hills zircons nor the existence of a dynamo prior to 3.5 Ga has been established. Bono et al. (2016)'s focus on the events that remagnetized the zircon host rocks after deposition at 3 Ga does little to address this problem and is a diversion from the central point of Weiss et al. (2015): the conglomerate tests failed. Nevertheless, it remains possible that some Jack Hills zircons might have escaped complete remagnetization and retain paleomagnetic records back to the Hadean. We suggest that the best way to resolve the conflicting results from the MIT and Rochester laboratories is through the open exchange of key primary demagnetization data and samples and independent attempts to reproduce the measurements of the two labs on a controlled sample suite. To address the key issue of whether the zircons themselves contain primary remanence,

paleomagnetic investigations should be conducted on individual zircons that can be shown not to have been remagnetized since their formation. We invite Bono et al., as well as the wider community, to join us in this endeavor.

Appendix A. Supplementary material

Supplementary material related to this article can be found online at http://dx.doi.org/10.1016/j.epsl.2016.07.001.

References

Bell, E.A., Boehnke, P., Hopkins-Wielicki, M.D., Harrison, T.M., 2015. Distinguishing primary and secondary inclusion assemblages in Jack Hills zircons. Lithos 234–235, 15–26.

Biggin, A., de Wit, M., Langereis, C., Zegers, T., Voute, S., Dekkers, M., Drost, K., 2011. Palaeomagnetism of Archaean rocks of the Onverwacht Group, Barberton Greenstone Belt (southern Africa): evidence for a stable and potentially reversing geomagnetic field at ca. 3.5 Ga. Earth Planet. Sci. Lett. 302, 314–328.

Bono, R.K., Tarduno, J.A., Cottrell, R.D., 2016. Comment on: Pervasive remagnetization of detrital zircon host rocks in the Jack Hills, Western Australia and implications for records of the early dynamo, by Weiss et al. (2015). Earth Planet. Sci. Lett. 450, 406–408. http://dx.doi.org/10.1016/j.epsl.2016.06.006.

Cherniak, D.J., Watson, E.B., 2000. Pb diffusion in zircon. Chem. Geol. 172, 5–24.

Cottrell, R.D., Tarduno, J.A., Bono, R.K., Dare, M.S., Mitra, G., 2016. The inverse microconglomerate test: further evidence for the preservation of Hadean magnetizations in metasediments of the Jack Hills, Western Australia. Geophys. Res. Lett. 43, 4215–4220.

Davis, W.J., Rayner, N., Pestaj, T., 2008. When good zircons go bad—redistribution of radiogenic Pb in granulite grade zircon, Snowbird Tectonic Zone, Canada. In: Petrov, O., Shevchenko, S., Sergeev, S., Mordberg, L. (Eds.), 4th International SHRIMP Workshop. VSEGEI Press, Saint Petersburg, Russia, pp. 42–44.

Durocher, K.E., Kyser, T.E., Marlatt, J., Hanly, A., 2003. New ^{40}Ar/^{39}Ar ages from the central Paterson Orogen, Western Australia. Austr. J. Earth Sci. 50, 601–610.

Fu, R.R., Weiss, B.P., Shuster, D.L., Gattacceca, J., Grove, T.L., Suavet, C., Lima, E.A., Li, L., Kuan, A.T., 2012. An ancient core dynamo in asteroid Vesta. Science 338, 238–241.

Klootwijk, C.T., 1980. Early Palaeozoic paleomagnetism in Australia. Tectonophysics 64, 249–332.

Kusiak, M., Whitehouse, M.J., Wilde, S.A., Nemchin, A.A., Clark, C., 2013. Mobilization of radiogenic Pb in zircon revealed by ion imaging: implications for early Earth geochronology. Geology 41, 291–294.

Li, Z.-X., Evans, D.A.D., 2011. Late Neoproterozoic 40° intraplate rotation within Australia allows for a tighter-fitting and longer-lasting. Rodinia Geology 39, 39–42.

Mitchell, R.N., Evans, D.A.D., Kilian, T.M., 2010. Rapid early Cambrian rotation of Gondwana. Geology 38, 755–758.

Rasmussen, B., Fletcher, I.R., Muhling, J.R., Gregory, C.J., Wilde, S.A., 2011. Metamorphic replacement of mineral inclusions in detrital zircon from Jack Hills, Australia: implications for the Hadean Earth. Geology 39, 1143–1146.

Swanson-Hysell, N.L., Maloof, A.C., Kirschvink, J.L., Evans, D.A.D., Halversong, G.P., Hurtgen, M.T., 2012. Constraints on Neoproterozoic paleogeography and paleozoic orogenesis from paleomagnetic records of the Bitter Springs Formation, Amadeus Basin, Central Australia. Am. J. Sci. 312, 817–884.

Tarduno, J.A., Cottrell, R.D., 2013. Signals from the ancient geodynamo: a paleomagnetic field test on the Jack Hills metaconglomerate. Earth Planet. Sci. Lett. 367, 123–132.

Tarduno, J.A., Cottrell, R.D., Davis, W.J., Nimmo, F., Bono, R.K., 2015. A Hadean to Paleoarchean geodynamo recorded by single zircon crystals. Science 349, 521–524.

Tarduno, J.A., Cottrell, R.D., Watkeys, M., Hofmann, A., Doubrovine, P.V., Mamajek, E.E., Liu, D., Sibeck, D.G., Neukirch, L.P., Usui, Y., 2010. Geodynamo, solar wind, and magnetopause 3.4 to 3.45 billion years ago. Science 327, 1238–1240.

Trail, D., Cherniak, D.J., Watson, E.B., Harrison, T.M., Weiss, B.P., Szumila, I., 2016. Li zoning in zircon as a potential geospeedometer and peak temperature indicator. Earth Planet. Sci. Lett. 171. http://dx.doi.org/10.1007/s00410-00016-01238-00418.

Weiss, B.P., Maloof, A.C., Tailby, N., Ramezani, J., Fu, R.R., Hanus, V., Trail, D., Watson, E.B., Harrison, T.M., Bowring, S.A., Kirschvink, J.L., Swanson-Hysell, N.L., Coe, R.S., 2015. Pervasive remagnetization of detrital zircon host rocks in the Jack Hills, Western Australia and implications for records of the early geodynamo. Earth Planet. Sci. Lett. 430, 115–128.

Sampling site of EHJH blocks. B. Weiss and J. Kirschvink collected the three EHJH blocks in the Jack Hills in 2001 with R. Pidgeon, T. M. Harrison, and S. Mojzsis; the first is the co-discoverer of the Erawandoo Hill Hadean zircon original discovery outcrop (Compston and Pidgeon, 1986) and all three have studied the outcrop extensively (Bell et al., 2015; Compston and Pidgeon, 1986; Dunn et al., 2005; Grange et al., 2010; Harrison, 2009; Holden et al., 2009; Hopkins et al., 2008; Hopkins et al., 2010; Kemp et al., 2010; Mojzsis, 2007; Mojzsis et al., 2001; Pidgeon, 1992, 2014; Pidgeon and Wilde, 1998; Spaggiari et al., 2007; Trail et al., 2016; Trail et al., 2011; Turner et al., 2007; Turner et al., 2004; Watson and Harrison, 2005; Wilde and Pidgeon, 1990)] (Fig. S2 and Table S4). Furthermore, we have extracted >4 Ga zircons from blocks within 5 m of the EHJH6 and EHJH7 sites. This context negates the speculation of Bono et al. (2016) and Cottrell et al. (2016) that the EHJH samples are not from the Erawandoo Hill Hadean zircon outcrop.

Ferromagnetic mineralogy of Erawandoo Hill metaconglomerates. Weiss et al. (2015) provided five pieces of evidence for pyrrhotite as the dominant ferromagnetic mineral (along with some goethite and hematite) in both the clasts and much of the matrix of the Jack Hills metaconglomerates: (a) thermal demagnetization of three-axis isothermal remanent magnetization, showing a mineral with a Curie point of ~325°C and coercivity exceeding 0.36 T (their Figs. 2 and S2); (b) thermal demagnetization of natural remanent magnetization, showing maximum unblocking temperatures usually below 320-340°C; (c) identification of monoclinic pyrrhotite's 34 K Besnus transition in low-temperature magnetometry measurements (their Fig. 3H); (d) quantitative measurements of sulfides using wavelength dispersive spectroscopy showing Fe:S in the pyrrhotite field (their Fig. 4c); (e) backscattered electron microscopy imaging of iron sulfides identified with energy dispersive spectroscopy (EDS) (their Fig. 4a). Cottrell et al. (2016) also observed maximum unblocking temperatures of 320-340°C in the Erawandoo Hill metaconglomerate, but concluded that Cr-Fe spinels are the dominant remanence carrier. However, their compositional analyses only included EDS, such that they did not show quantitatively that the composition of the spinels is consistent with the observed unblocking temperatures. Given the aforementioned evidence for pyrrhotite and the fact that Cr-Fe spinels with ~325°C Curie points are only very rarely found to be dominant remanence carriers in terrestrial rocks (Moskowitz et al., 2015), we suggest that monoclinic pyrrhotite is a better candidate as the main remanence carrier in the samples of Cottrell et al. (2016).

Calculation of mean directions. As discussed in the main text, we calculate a mean for each EHJH5, EHJH6, and EHJH7 block. These consist of clast high temperature (HT) directions from EHJH5 and clast and matrix HT directions from EHJH6 and EHJH7. Following Weiss et al. (2015), we use the HT mean direction inferred for each clast that yielded multiple intra-clast specimens for EHJH5, while we considered each intra-clast specimen as a direction due to the small total number of specimens measured for EHJH7 (although using the clast means would not meaningfully change the results). Because a quantile-quantile test (Tauxe, 2010) shows that the EHJH6 directions are collectively non-Fisherian (Table S1), we calculate a mean direction

following Kent (1982) using PmagPy (Tauxe et al., 2016) (Table S2). As discussed in the main text, the directions of EHJH6 appear to be streaked between two directions that may be associated with multiple remagnetization episodes that are contributing to the distinct sample directions as well as the block mean. All the other Jack Hills combined sites shown in Fig. 1B have distributions consistent with being Fisherian (Table S1).

One might argue that we should calculate a grand EHJH5-7 mean using all of 62 specimens from all blocks rather than the approach here of calculating a grand mean from the 3 EHJH block means. This alternate approach would produce a mean very similar to that originally reported by Weiss et al. (2015) but with a much smaller confidence interval. We chose not to follow this approach since Fig. 1A shows that there are clear systematic directional offsets between the three blocks. In any case, both approaches yield the same overall result that the metasediment and monzogranite grand mean is within error of the Warakurna LIP mean (Fig. 1B).
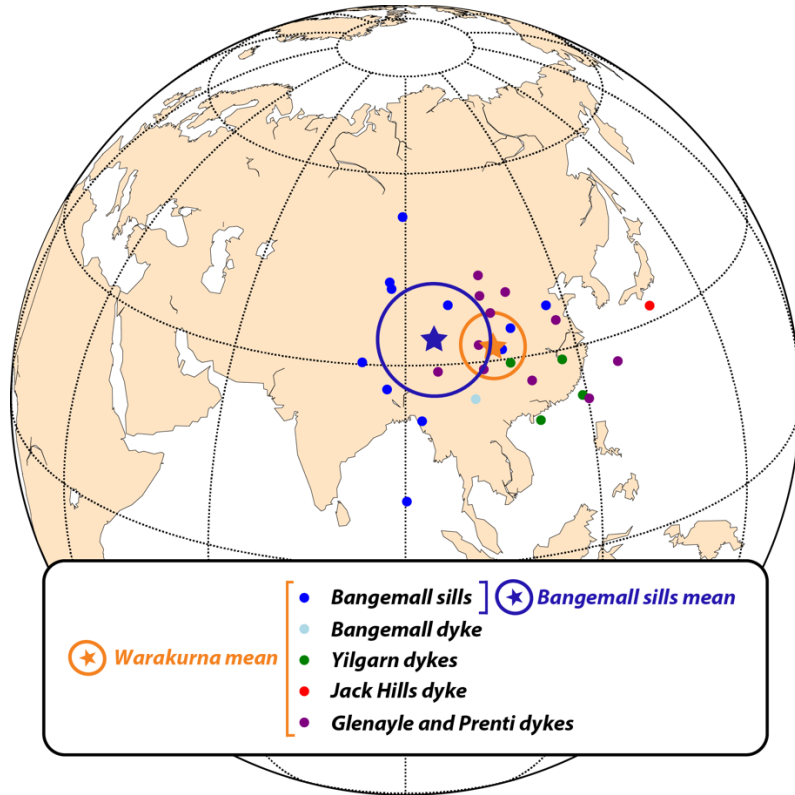
Fig. S1. Virtual geomagnetic poles (VGPs) inferred from 1.1 Ga western Australian dykes and sills associated with the Warakurna LIP. Data and references are provided in Table S3 with the following identification numbers: Bangemall sills (blue circles) = 1-11, Bangemall dyke (light blue circle) = 12, Yilgarn dykes (green circles) = 13-16; Jack Hills dyke = 17, Glenayle and Prenti dykes (purple circles) = 18-28. Stars show mean poles for all Warakurna rocks (orange) and mean pole for just Bangemall sills (blue) [the latter was used as the Warakurna mean direction in Weiss et al. (2015)]. The Jack Hills dike VGP is at the edge of the population of Warakurna VGPs likely due to secular variation.
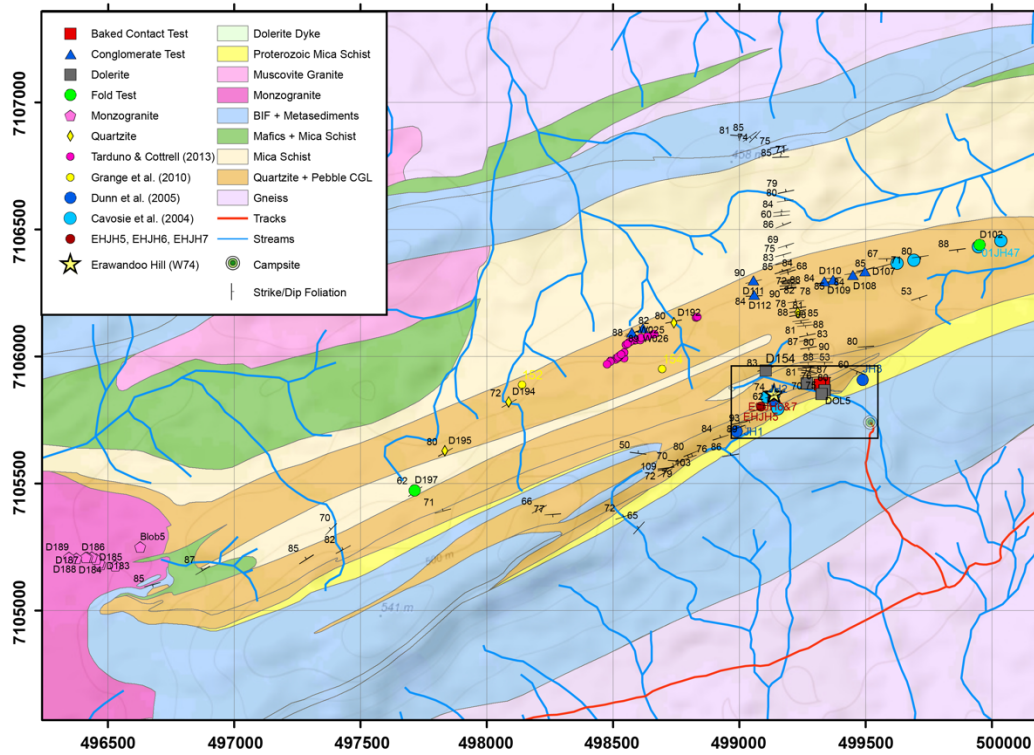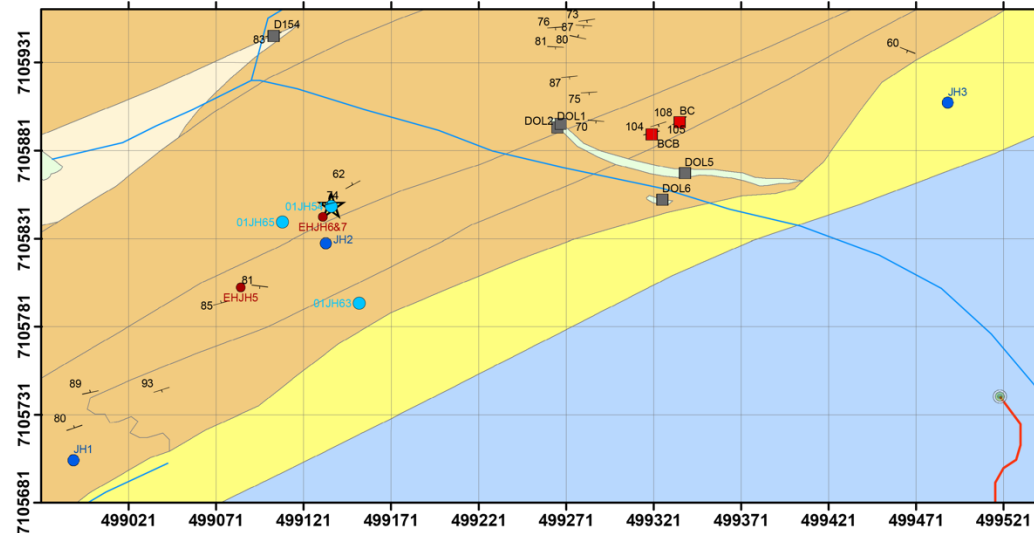
Fig. S2. Generalized geological map of the central-west Jack Hills after Spaggiari (2007). Lithologies are denoted by light shaded colors. Our baked contact, fold, and conglomerate test sites are noted. Yellow star denotes discovery site of Hadean (i.e., >4 Ga) zircons (W74, on Erawandoo Hill). Sampling locations of Cavosie et al. (2004), Dunn et al. (2005), and Grange et al. (2010) are denoted by small light blue, dark blue and yellow circles. Sampling localities for individual cobbles sampled by Tarduno and Cottrell (2013) are shown by small magenta circles. All geological contacts are estimated. Stratigraphic up direction frequently is ambiguous within the quartzites and conglomerates, but is usually toward the southeast. Short lines show strike direction with dip toward short perpendicular line and dip angle given in degrees. Magnetic

declination was set to 0°; the estimated local magnetic declination was 0.4°. Projection is with the Universal Transverse Mercator grid in the World Geodetic System 1984 standard. Elevation difference between contour lines (grey) is 50 m. Global Positioning System coordinates for our sites are given in Table S4. (A) Overview map. Spacing between gridlines is 500 m. (B) Zoom into Erawandoo Hill Hadean zircon original discovery outcrop [boxed region in (A)]. Spacing between gridlines is 50 m. Hadean zircons previously have been isolated from sites JH1, JH2 and JH3 by Dunn et al. (2005), site 152 by Grange et al. (2010), and from sites 01JH36, 01JH54, 01JH65, and W74 by Cavosie et al. (2004). The positions of the three EHJH sites plotted differ by ~200 m from those in Weiss et al. (2015) Fig. 1 due to a minor datum conversion error in the latter study. The original plotting positions of these sites were nevertheless within just 16-61 m of the Hadean zircon site JH1.

Tables

Table S1. Tests for Fisher distribution of overprint directions in the Jack Hills.

Sites	N	M_u	Fisherian?	M_e	Fisherian?
Conglomerate test HT (block EHJH5)	30	1.168	yes	0.544	yes
Conglomerate test HT (block EHJH6)	22	1.369	no	0.865	yes
Conglomerate test HT (block EHJH7)	10	0.773	yes	0.793	yes
Dike (dolerite from sites BC, BCB, and D154)	12	0.704	yes	1.003	yes
Monzogranite HT (sites D182-188, Blob4, and Blob5)	19	1.070	yes	0.874	yes
Country rock HT (sites D192, D194, and D195)	10	1.168	yes	0.685	yes
Baked contact test HT (site D154)	10	0.832	yes	0.667	yes
Baked contact test HT (site BC)	10	0.914	yes	0.731	yes
Baked contact test HT (site BCB)	12	0.975	yes	0.902	yes

Note: The first column gives the site name, the second column gives the number of directions, the third and fifth columns give the statistics that test for uniform distribution in declination and exponential distribution in inclination, respectively, around the mean, the fourth and sixth columns show whether a Fisher distribution can be rejected with 95% confidence based on each statistic (i.e., M_u and M_e exceed critical values of 1.207 and 1.094, respectively). Using measurements from Weiss et al. (2015). Note that the EHJH5, EHJH6, and EHJH7 values differ from those reported by Bono et al. (2016).

Table S2. Mean overprint directions for Jack Hills rocks.

Sites	δ (°)	i (°)	α₉₅ (°) or η, ζ (°)	N	Reference
Conglomerate test HT (block EHJH5)	332.3	12.3	7.9	30	Weiss et al. (2015)
Conglomerate test HT (block EHJH6)	312.0	72.5	10.5, 24.8	22	Weiss et al. (2015), This study
Conglomerate test HT (block EHJH7)	342.6	-6.2	21.1	10	Weiss et al. (2015)
Dike (dolerite from sites BC, BCB, and D154)	19.3	47.5	10.1	12	Weiss et al. (2015)
Monzogranite HT (sites D182-188, Blob4, and Blob5)	358	51.9	11.7	19	Weiss et al. (2015)
Country rock HT (sites D192, D194, and D195)	9.3	61.2	8.8	10	Weiss et al. (2015)
Fold test at site MT (site D197)	345.8	21.0	32.0	5	Weiss et al. (2015)
Baked contact test HT (site D154)	45.0	45.5	19.5	13	This study
Baked contact test HT (site BC)	28.0	62.0	20.2	10	This study
Baked contact test HT (site BCB5)	40.9	38.7	20.2	12	This study
*Grand mean of metasediments and monzogranite**	*0.8*	*43.9*	*23.1*	*9*	*This study*

Note: The first column lists the site or block, the second and third columns are the declination and inclination of the mean direction (Kent mean for the EHJH6 block and Fisher means for all other sites), the fourth column gives the of the sizes of the 95% confidence interval semiaxes of the Kent ellipse for the EHJH6 block and the radius of the Fisher circle for all other sites, the fifth column gives the number of directions, and the sixth column lists the reference for the reported mean. HT component ranges are defined in Weiss et al. (2015).
*Using all site means in this table except that of the dike.

Table S3. Site mean directions for igneous rocks associated with the Warakurna LIP.

ID	Site	Site λ (°)	Site θ (°)	Dip Direction (°)	Dip (°)	N	δ_{geo} (°)	i_{geo} (°)	k	α_{95} (°)	δ_{tilt} (°)	i_{tilt} (°)	VGP λ (°)	VGP θ (°)	Reference	δ_{geo} at JH (°)	i_{geo} at JH (°)
1	BBS-1	-23.5	116.6	88	13	9	344.9	48.4	75	5.6	359.8	48.7	36.8	116.4	Wingate et al. (2002)	359.5	45.6
2	BBS-3	-23.7	116.6	353	4	5	336.4	37.7	108	6.6	337.2	33.9	42.3	86.9	Wingate et al. (2002)	337.3	30.0
3	BBS-5	-23.8	116.7	134	1	5	328.5	50.5	610	2.8	328.5	51.5	26.5	87	Wingate et al. (2002)	329.0	49.0
4	BBS-6	-23.8	116.7	320	2	8	337.4	37.1	41	8.2	337	35.2	41.3	87.3	Wingate et al. (2002)	337.1	31.7
5	BBS-7	-23.8	116.6	41	60	6	267.9	49.3	37	10.1	352.4	50.6	34.4	108.8	Wingate et al. (2002)	352.3	47.9
6	BBS-8	-23.9	116.9	29	29	6	312.1	57.7	257	3.8	343.7	42.9	38.7	97.9	Wingate et al. (2002)	344.0	39.9
7	BBS-9	-23.9	116.8	233	19	6	344.7	40.9	97	6.2	327.2	45.2	30.3	82.7	Wingate et al. (2002)	327.7	42.6
8	BBS-10	-23.4	116.2	28	43	6	268.1	65.3	575	2.6	350.2	53.8	31.5	106.7	Wingate et al. (2002)	349.8	50.8
9	BBS-12	-23.8	116.6	34	80	5	244.8	22.6	195	4.9	331	58	21.9	92.6	Wingate et al. (2002)	331.6	55.9
10	BBS-15	-23.9	116.6	205	74	4	2.8	5.1	20	18.1	319.9	65.2	10.1	90.2	Wingate et al. (2002)	320.9	63.7
11	BBS-25	-23.7	115.6	38	79	11	111.3	-37.5	40	6.9	164.1	-19.9	52.6	89.3	Wingate et al. (2002)	343.5	14.9
12	BBS-dyke	-22.2	116.3			9	341.9	60	159	4.1			24.7	101.3	Wingate et al. (2002)	342.2	56.4
13	MKTI	-26.2	117.3			7	359.1	54.7	102	6			29.4	107.8	Wingate et al. (2004)	350.4	53.2
14	MKTJ	-26.2	117.0			6	2.6	60	49	9.7			20.5	111.5	Wingate et al. (2004)	353.0	61.8
15	MKTK	-26.2	117.1			7	352.9	61.8	27	11.7			22.9	119.2	Wingate et al. (2004)	2.8	60.0
16	MKTM	-23.2	117.7			8	350.1	53.2	143	4.6			28.6	116.9	Wingate et al. (2004)	360.0	54.7
17	JH dike	-26.2	117.0			11	19.3	47.5	18	10.1			32.2	137	Weiss et al. (2015)	19.3	47.4
18	A	-25.4	122.3	35	2	7	345.3	43.8	99	6.1	346.7	42.5	37	105.6	Wingate (2003)	350.0	44.2
19	B	-25.0	121.6			6	333.4	49.6	75	7.8			29	95.4	Wingate (2003)	338.9	50.3
20	C	-25.1	121.7			8	345.3	40.6	85	6			39.7	104.1	Wingate (2003)	349.3	40.4
21	D	-25.2	121.9			10	346.5	36.2	190	3.5			42.8	104.5	Wingate (2003)	350.3	36.1
22	E	-25.1	122.0			6	340.2	52.4	446	3.2			28.9	103.1	Wingate (2003)	345.5	52.8
23	FG	-25.2	122.2	5	5	8	344.6	61.4	90	5.9	347.3	56.7	26.4	111	Wingate (2003)	353.3	56.5
24	H	-25.2	122.5			5	357.1	61.4	109	7.4			22.2	120.2	Wingate (2003)	4.0	60.5
25	I	-25.2	122.5			8	5.0	57.7	208	3.9			26.3	126.9	Wingate (2003)	11.1	56.1
26	J	-25.3	122.1	35	5	6	336.4	51.2	38	11	341.3	48.4	32.5	102.7	Wingate (2003)	346.2	48.8
27	K	-24.9	121.6			6	356.1	49.7	15	17.9			34.4	117.5	Wingate (2003)	0.5	48.4
28	L	-26.5	122.8	35	4	4	346.1	42.3	34	16	348.7	39.6	39.8	109.2	Wingate (2003)	353.5	41.2
	Warakurna LIP grand mean					28			35.3	4.7			32.2	105.2	*This study*	348.2	48.6

Note: The first column gives identification number (see Fig. S1), the second column gives the site names, the third and fourth columns give the site latitudes and longitudes, the fifth and sixth columns give the stratum dip directions and dips for rocks with paleohorizontal indicators, the seventh column gives the number of directions, the eighth and ninth columns give the geographic (i.e., in situ) declination and inclination of the Fisher mean directions, the tenth column gives the estimates of the Fisher precision parameter, the eleventh column gives the semiaxes of the 95% confidence interval for the mean direction, the twelfth and thirteenth columns give the tilt-corrected declination and inclination of the Fisher mean directions (where applicable), the fourteenth and fifteenth columns give the latitude and longitude of the associated virtual geomagnetic pole (VGPs) that have been variably tilt-corrected following the VGPs used in Wingate et al. (2002), Wingate (2003), and Wingate et al. (2004), the sixteenth column gives the references for the data, and the seventeenth and eighteenth columns give the directions of the VGPs calculated for local Jack Hill coordinates (i.e., at Erawandoo Hill).

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Table S4. Universal Transverse Mercator GPS coordinates for the sampling sites in Fig. S2 and in Weiss et al. (2015) Fig. 1. Datum surface is the World Geodetic System 1984, zone 50S.

Name	Easting (m)	Northing (m)	Reference	Original System	Notes
EHJH5	499084	7105804	Weiss et al. (2015)	AGD84	Pebble conglomerate tests Hadean (i.e., >4 Ga) discovery site on Erawandoo Hill
EHJH6,7	499131	7105844	Weiss et al. (2015)	AGD84	Pebble conglomerate test Hadean discovery site on Erawandoo Hill
01JH54	499137	7105849	Cavosie et al. (2004)	WGS84, 50S	Hadean detrital zircon site
01JH63	499153	7105793	Cavosie et al. (2004)	WGS84, 50S	Proterozoic detrital zircon site
01JH65	499109	7105839	Cavosie et al. (2004)	WGS84, 50S	Hadean detrital zircon site
01JH32	499626	7106365	Cavosie et al. (2004)	WGS84, 50S	
01JH33	499692	7106380	Cavosie et al. (2004)	WGS84, 50S	
01JH36	499947	7106428	Cavosie et al. (2004)	WGS84, 50S	Hadean detrital zircon site
JH1	498989	7105703	Dunn et al. (2005)	AGD94	Hadean detrital zircon site
JH2	499134	7105827	Dunn et al. (2005)	AGD94	Hadean detrital zircon site
JH3	499488	7105908	Dunn et al. (2005)	AGD94	Hadean detrital zircon site Proterozoic detrital zircon site
152	498140	7105889	Grange et al. (2010)	WGS84	Hadean detrital zircon site Proterozoic detrital zircon site
154	498694	7105949	Grange et al. (2010)	WGS84	
JT10	498835	7106156	Tarduno and Cottrell (2013)	WGS84	Cobble conglomerate test
JT8,9	498827	7106151	Tarduno and Cottrell (2013)	WGS84	Cobble conglomerate test
JC16	498664	7106089	Tarduno and Cottrell (2013)	WGS84	Cobble conglomerate test
JC15	498658	7106088	Tarduno and Cottrell (2013)	WGS84	Cobble conglomerate test
JC17	498635	7106079	Tarduno and Cottrell (2013)	WGS84	Cobble conglomerate test
JC14	498610	7106074	Tarduno and Cottrell (2013)	WGS84	Cobble conglomerate test
JC13	498607	7106064	Tarduno and Cottrell (2013)	WGS84	Cobble conglomerate test
JC12	498592	7106065	Tarduno and Cottrell (2013)	WGS84	Cobble conglomerate test
JC11	498585	7106063	Tarduno and Cottrell (2013)	WGS84	Cobble conglomerate test
JC19	498567	7106057	Tarduno and Cottrell (2013)	WGS84	Cobble conglomerate test
JC18	498563	7106055	Tarduno and Cottrell (2013)	WGS84	Cobble conglomerate test
JC21	498557	7106051	Tarduno and Cottrell (2013)	WGS84	Cobble conglomerate test
JC20	498550	7106046	Tarduno and Cottrell (2013)	WGS84	Cobble conglomerate test
JC10	498544	7106014	Tarduno and Cottrell (2013)	WGS84	Cobble conglomerate test
JC9	498544	7105993	Tarduno and Cottrell (2013)	WGS84	Cobble conglomerate test
JC1	498539	7106007	Tarduno and Cottrell (2013)	WGS84	Cobble conglomerate test
JC25	498532	7106007	Tarduno and Cottrell (2013)	WGS84	Cobble conglomerate test
JC22	498526	7106002	Tarduno and Cottrell (2013)	WGS84	Cobble conglomerate test
JC23	498527	7105999	Tarduno and Cottrell (2013)	WGS84	Cobble conglomerate test
JC2	498523	7105998	Tarduno and Cottrell (2013)	WGS84	Cobble conglomerate test
JC24	498520	7105998	Tarduno and Cottrell (2013)	WGS84	Cobble conglomerate test
JC8	498517	7105993	Tarduno and Cottrell (2013)	WGS84	Cobble conglomerate test
JC3a,b	498512	7105993	Tarduno and Cottrell (2013)	WGS84	Cobble conglomerate test

JC4	498509	7105987	Tarduno and Cottrell (2013)	WGS84	Cobble conglomerate test
JC5	498488	7105983	Tarduno and Cottrell (2013)	WGS84	Cobble conglomerate test
JC6	498489	7105980	Tarduno and Cottrell (2013)	WGS84	Cobble conglomerate test
W74	499137	7105850	Weiss et al. (2015)	WGS84, 50S	Hadean zircon discovery site on Erawandoo Hill
BC	499336	7105897	Weiss et al. (2015)	WGS84, 50S	Dolerite baked contact test
BCB	499320	7105890	Weiss et al. (2015)	WGS84, 50S	Dolerite baked contact test
Blob4	496529	7105176	Weiss et al. (2015)	WGS84, 50S	Monzogranite
Blob5	496628	7105250	Weiss et al. (2015)	WGS84, 50S	Monzogranite
D102	499952	7106439	Weiss et al. (2015)	WGS84, 50S	Fold test
D107	499498	7106336	Weiss et al. (2015)	WGS84, 50S	Cobble conglomerate test
D108	499450	7106321	Weiss et al. (2015)	WGS84, 50S	Cobble conglomerate test
D109	499371	7106303	Weiss et al. (2015)	WGS84, 50S	Cobble conglomerate test
D110	499337	7106296	Weiss et al. (2015)	WGS84, 50S	Cobble conglomerate test
D111	499056	7106301	Weiss et al. (2015)	WGS84, 50S	Cobble conglomerate test
D112	499059	7106244	Weiss et al. (2015)	WGS84, 50S	Cobble conglomerate test
D145	499232	7106174	Weiss et al. (2015)	WGS84, 50S	Quartzite
D154	499104	7105946	Weiss et al. (2015)	WGS84, 50S	Dolerite baked contact test
D182	496471	7105181	Weiss et al. (2015)	WGS84, 50S	Monzogranite
D183	496466	7105187	Weiss et al. (2015)	WGS84, 50S	Monzogranite
D184	496453	7105202	Weiss et al. (2015)	WGS84, 50S	Monzogranite
D185	496436	7105210	Weiss et al. (2015)	WGS84, 50S	Monzogranite
D186	496419	7105209	Weiss et al. (2015)	WGS84, 50S	Monzogranite
D187	496412	7105209	Weiss et al. (2015)	WGS84, 50S	Monzogranite
D188	496375	7105205	Weiss et al. (2015)	WGS84, 50S	Monzogranite
D189	496346	7105208	Weiss et al. (2015)	WGS84, 50S	Monzogranite
D192	498741	7106132	Weiss et al. (2015)	WGS84, 50S	Quartzite
D194	498087	7105820	Weiss et al. (2015)	WGS84, 50S	Quartzite
D195	497834	7105628	Weiss et al. (2015)	WGS84, 50S	Quartzite
D197	497715	7105472	Weiss et al. (2015)	WGS84, 50S	Fold Test
DOL1	499266	7105894	Weiss et al. (2015)	WGS84, 50S	Dolerite
DOL2	499268	7105896	Weiss et al. (2015)	WGS84, 50S	Dolerite
DOL5	499339	7105868	Weiss et al. (2015)	WGS84, 50S	Dolerite
DOL6	499326	7105853	Weiss et al. (2015)	WGS84, 50S	Dolerite
W025	498575	7106095	Weiss et al. (2015)	WGS84, 50S	Cobble conglomerate test
W026	498622	7106113	Weiss et al. (2015)	WGS84, 50S	Cobble conglomerate test

Note: First column gives the site name, the second column gives the northing, the third column gives the easting, the fourth column gives the reference, the fifth column gives the original datum (AGD84 = Australian Geodetic Datum 1984 and WGS84 = World Geodetic Datum 1984) in which the site coordinates were measured in the field [for Weiss et al. (2015)] or reported (for other studies), and the final column gives additional site information.   Site coordinates for all sites other than those of Weiss et al. (2015) were gleaned from published papers and were not provided formally approved by those authors. Transformations between geographic and Universal Transverse Mercator coordinate systems with different datum planes introduce some position error, but all points listed in this table should be within 2 m of the published locations.

Supplementary References

Bell, E.A., Boehnke, P., Hopkins-Wielicki, M.D., Harrison, T.M., 2015. Distinguishing primary and secondary inclusion assemblages in Jack Hills zircons. Lithos 234-235, 15-26.

Bono, R.K., Tarduno, J.A., Cottrell, R.D., 2016. Comment on: Pervasive remagnetization of detrital zircon host rocks in the Jack Hills, Western Australia and implications for records of the early dynamo, by Weiss et al. (2015). Earth Planet. Sci. Lett., submitted.

Cavosie, A.J., Wilde, S.A., Liu, D., Weiblen, P.W., Valley, J.W., 2004. Internal zoning and U–Th–Pb chemistry of Jack Hills detrital zircons: a mineral record of early Archean to Mesoproterozoic (4348–1576 Ma) magmatism. Precambrian Res. 135, 251-279.

Compston, W., Pidgeon, R.T., 1986. Jack Hills, evidence of more very old detrital zircons in Western Australia. Nature 321, 766-769.

Cottrell, R.D., Tarduno, J.A., Bono, R.K., Dare, M.S., Mitra, G., 2016. The inverse microconglomerate test: Further evidence for the preservation of Hadean magnetizations in metasediments of the Jack Hills, Western Australia. Geophys. Res. Lett. 43, 4215–4220.

Dunn, S.J., Nemchin, A.A., Cawood, P.A., Pidgeon, R.T., 2005. Provenance record of the Jack Hills metasedimentary belt: Source of the Earth's oldest zircons. Precambrian Res. 138, 235-254.

Grange, M.L., Wilde, S.A., Nemchin, A.A., Pidgeon, R.T., 2010. Proterozoic events recorded in quartzite cobbles at Jack Hills, Western Australia: New constraints on sedimentation and source of >4 Ga zircons. Earth Planet. Sci. Lett. 292, 158-169.

Harrison, T.M., 2009. The Hadean crust: Evidence from >4 Ga zircons. Annu. Rev. Earth Planet. Sci. 37, 479-505.

Holden, P., Lanc, P., Ireland, T.R., Harrison, T.M., Foster, J.J., Bruce, Z., 2009. Mass-spectrometric mining of Hadean zircons by automated SHRIMP multi-collector and single-collector U/Pb zircon age dating: The first 100,000 grains. Int. J. Mass Spectrom. 286, 53-63.

Hopkins, M., Harrison, T.M., Manning, C.E., 2008. Low heat flow inferred from >4 Gyr zircons suggest Hadean plate boundary interactions. Nature 456, 493-496.

Hopkins, M.D., Harrison, T.M., Manning, C.E., 2010. Constraints on Hadean geodynamics from mineral inclusions in >4 Ga zircons. Earth Planet. Sci. Lett. 298, 367-376.

Kemp, A.J.S., Wilde, S.A., Hawkesworth, C.J., Coath, C.D., Nemchin, A., Pidgeon, R.T., Vervoort, J.D., DuFrane, S.A., 2010. Hadean crustal evolution revisited: New constraints from Pb–Hf isotope systematics of the Jack Hills zircons. Earth Planet. Sci. Lett. 296, 45-56.

Kent, J.T., 1982. The Fisher-Bingham distribution on the sphere. J. R. Stat. Soc. B 44, 71-80.

Mojzsis, S.J., 2007. Sulfur on the early Earth, in: van Kranendonk, M.J., Smithies, R.H., Bennett, V.C. (Eds.), Earth's Oldest Rocks. Elsevier, Amsterdam, pp. 923-970.

Mojzsis, S.J., Harrison, T.M., Pidgeon, R.T., 2001. Oxygen-isotope evidence from ancient zircons for liquid water at the Earth's surface 4,300 Myr ago. Nature 409, 178-181.

Moskowitz, B.M., Jackson, M., Chandler, V., 2015. 11.05 Geophysical properties of the near-surface Earth: Magnetic properties, in: Schubert, G. (Ed.), Treatise on Geophysics, Second ed. Elsevier, Amsterdam.

Pidgeon, R.T., 1992. Recrystallisation of oscillatory zoned zircon: Some geochronological and petrological implications. Contrib. Mineral. Petrol. 110, 463-472.

Pidgeon, R.T., 2014. Zircon radiation damage ages. Chem. Geol. 367, 13-22.

Pidgeon, R.T., Wilde, S.A., 1998. The interpretation of complex zircon U–Pb systems in Archaean granitoids and gneisses from the Jack Hills, Narryer Gneiss Terrane, Western Australia. Precambrian Res. 91, 309-322.

Spaggiari, C.V., 2007. Structural and lithological evolution of the Jack Hills Greenstone Belt, Narryer Terrane, Yilgarn Craton, Western Australia, Perth, p. 49.

Spaggiari, C.V., Pidgeon, R.T., Wilde, S.A., 2007. The Jack Hills greenstone belt, Western Australia Part 2: Lithological relationships and implications for the deposition of ≥ 4.0 Ga detrital zircons. Precambrian Res. 155, 261-286.

Tarduno, J.A., Cottrell, R.D., 2013. Signals from the ancient geodynamo: A paleomagnetic field test on the Jack Hills metaconglomerate. Earth Planet. Sci. Lett. 367, 123-132.

Tauxe, L., 2010. Essentials of paleomagnetism. University of California Press, Berkeley

Tauxe, L., Shaar, R., Jonestrask, L., Swanson-Hysell, N.L., Minnett, R., Koppers, A.A.P., Constable, C.G., Jarboe, N., Gaastra, K., Fairchild, L., 2016. PmagPy: Software package for paleomagnetic data analysis and a bridge to the Magnetics Information Consortium (MagIC) Database. Geochem. Geophys. Geosyst. 17, 10.1002/2016GC006307.

Trail, D., Cherniak, D.J., Watson, E.B., Harrison, T.M., Weiss, B.P., Szumila, I., 2016. Li zoning in zircon as a potential geospeedometer and peak temperature indicator. Earth Planet. Sci. Lett. 171, doi:10.1007/s00410-00016-01238-00418.

Trail, D., Watson, E.B., Tailby, N.D., 2011. The oxidation state of Hadean magmas and implications for Earth's atmosphere 4350 Myr ago. Nature 480, 79-82.

Turner, G., Busfield, A., Crowther, S.A., Harrison, T.M., Mojzsis, S.J., Gilmour, J., 2007. Pu-Xe, U-Xe, U-Pb chronology and isotope systematics of ancient zircons from Western Australia. Earth Planet. Sci. Lett. 261, 491-499.

Turner, G., Harrison, T.M., Holland, G., Mojzsis, S.J., Gilmour, J., 2004. Extinct [244]Pu in ancient zircons. Science 306, 89-91.

Watson, E.B., Harrison, T.M., 2005. Zircon thermometer reveals minimum melting conditions on earliest Earth. Science 308, 841-844.

Weiss, B.P., Maloof, A.C., Tailby, N., Ramezani, J., Fu, R.R., Hanus, V., Trail, D., Watson, E.B., Harrison, T.M., Bowring, S.A., Kirschvink, J.L., Swanson-Hysell, N.L., Coe, R.S., 2015. Pervasive remagnetization of detrital zircon host rocks in the Jack Hills, Western Australia and implications for records of the early geodynamo. Earth Planet. Sci. Lett. 430, 115-128.

Wilde, S.A., Pidgeon, R.T., 1990. Geology of the Jack Hills metasedimentary rocks, in: Ho, S.E., Glover, J.E., Myers, J.S., Muhling, J.R. (Eds.), Third International Archaean Symposium (Perth) Excursion Guidebook. University of Western Australia Extension Publication, Perth, pp. 82-95.

Wingate, M.T.D., 2003. Age and Palaeomagnetism of the Dolerite Intrusions of the Southeastern Collier Basin and the Earaheedy and Yerrida Basins Western Australia, Geological Survey of Western Australia, Record 2003/3, Perth, p. 34.

Wingate, M.T.D., Pirajno, F., Morris, P.A., 2004. Warakurna large igneous province: A new Mesoproterozoic large igneous province in west-central Australia. Geology 32, 105-108.

Wingate, M.T.D., Pisarevsky, S.A., Evans, D.A.D., 2002. Rodinia connections between Australia and Laurentia: no SWEAT, no AUSWUS? Terra Nova 14, 121-128.