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RESEARCH **FOCUS**

Probing the complexities of magnetism in zircons from Jack Hills, Australia

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When and how did the early geodynamo originate and evolve, and how could its changing strength have influenced the earliest surface environments on Earth? These are unresolved questions of great importance in geoscience, relevant to issues as broad as planetary origins and the cradle of life in our Solar System. Paleomagnetic analyses on some of the world's oldest little-metamorphosed rocks demonstrate the existence of a ca. 3.5 Ga geodynamo with strength broadly comparable to that of today (Tarduno et al., 2014). In addition, at no point in the geological record is there any indication that geomagnetic field strength was persistently and substantially lower than its current range of values (Smirnov et al., 2016). Any search for a record of geodynamo origination must therefore extend to materials older than 3.5 Ga.

The Jack Hills, in the Yilgarn craton of Western Australia, contain the most extensive terrestrial Hadean (pre–4.0 Ga) record: hundreds of U-Pb–dated detrital zircon grains found within tectonically interleaved clastic successions of likely depositional ages ranging from 3.0–2.7 Ga to as young as Mesoproterozoic (Wang and Wilde, 2018). The successions have been substantially deformed and metamorphosed to amphibolite facies (Spaggiari et al., 2007), but the allure of obtaining relict Hadean geomagnetic field characteristics has drawn two groups of researchers to investigate Jack Hills paleomagnetism. One group reports evidence for a primary magnetic remanence in both cobble clasts and individual zircon grains (Tarduno and Cottrell, 2013; Tarduno et al., 2015; Cottrell et al., 2016; Dare et al., 2016; Bono et al., 2016, 2018), whereas another group interprets their own data, from a range of Jack Hills lithologies, as showing pervasive remagnetization subsequent to deformation of the clastic successions (Weiss et al., 2015, 2016).

Positive field stability tests on the ages of remanence in Jack Hills metasedimentary rocks are necessary to support a claim of Hadean magnetizations, but not sufficient: even a demonstrably pre-depositional magnetization could have been acquired as an overprint during the billion-year (or more) interval between zircon crystallization and sedimentation. Thus, an independent method of analysis is desirable for constraining that earlier history. In this issue of *Geology*, Weiss et al. (2018, p. 427) present a new facet of investigation into the Jack Hills paleomagnetism debate, focusing on high-resolution magnetic imaging of individual Jack Hills zircons. The study identifies significant concentrations of ferromagnetic minerals within grain cracks and on the zircons' exteriors. The authors argue that if the zircons had preserved primary magnetizations from the times of their initial crystallization, then the remanence signals should be sourced from ferromagnetic inclusions distributed through the interiors of the grains. Instead, the predominant distribution along cracks and grain boundaries provides evidence for secondary magnetic remanence carriers of younger ages. The study is innovative in its use of diverse microscopic imaging tools, including the novel method of quantum diamond microscopy (Glenn et al., 2017). Weiss et al. (2018) challenge proponents of a primary origin of Jack Hills zircons to demonstrate, beyond doubt, that their sources of ferromagnetic remanence reside deep within the internal fabrics of the zircon grains; and only then can the magnetic records be reliably considered of Hadean antiquity.

Resolution of the Jack Hills magnetism debate may require more investigations utilizing a diverse portfolio of laboratory methods, preferably on a common set of samples that are split into aliquots distributed to a number of independent laboratories (as suggested by Weiss et al. [2016]). Here, I also suggest a complementary line of research, based on the experience gained from decades' worth of paleomagnetic studies on other Archean cratons, such as Superior (Buchan et al., 2007; Evans and Halls, 2010) and Kaapvaal (Alebouyeh Semami et al., 2016). The steady construction of those cratons' apparent polar wander paths through Paleoproterozoic time has yielded a range of well-dated remanence directions that serve as references for identifying possible remagnetizations of Archean rocks. As an example, when analyzing the world's oldest (ca. 2.55 Ga) laterally extensive carbonate platform blanketing the Kaapvaal craton, de Kock et al. (2009) were able to link several remagnetization events to episodes of large igneous province emplacement and/or craton-marginal orogenic activity. In the Western Australian shield, only the Pilbara craton enjoys a semblance of apparent polar wander path construction through the Neoarchean-Paleoproterozoic interval (e.g., Evans et al., 2017).

By contrast, the Yilgarn craton, which hosts the Jack Hills, is constrained by only a few highly reliable paleomagnetic poles through the interval 3.5–1.0 Ga (Wingate et al., 2002; Smirnov et al., 2013; Pisarevsky et al., 2014), which for perspective, spans more than half of Earth history. It is thus difficult to assess any hypothesis of remagnetization in the Jack Hills region, because for most conceivable ages of overprinting, one observed magnetic remanence direction would appear nearly as viable as any other. Weiss et al. (2015) found broad agreement between their observed overprint directions and those of the well-constrained Warakurna large igneous province at 1.07 Ga; indeed, a Warakurna mafic dike intrudes the Jack Hills within a hectometer of the "Discovery Site" that has yielded many of the Hadean zircons and some of the paleomagnetic results. Perplexingly, the Warakurna overprint described by Weiss et al. (2015) represents, at most, a minor component of the other research group's dataset (Bono et al., 2018), which contains two other magnetic remanence directions interpreted as partial but not complete regional overprints—tentatively assigned to various ages by comparisons to an independent geochronologic study of the area (Rasmussen et al., 2010). At present, two principal questions remain unanswered in the Jack Hills debate: why do the two research groups observe markedly different results, and what is the complete thermal-magnetic history of the Jack Hills region? Differences in methodology and laboratory procedure may explain the first issue. Steady determination of younger paleomagnetic poles from the numerous mafic igneous rocks of the Western Australian shield can address the second question, and provide essential context for any magnetic investigation of its fragmentary earlier record.

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