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Pervasive remagnetization of detrital zircon host rocks in the Jack Hills, Western Australia and implications for records of the early geodynamo

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ABSTRACT

It currently is unknown when Earth's dynamo magnetic field originated. Paleomagnetic studies indicate that a field with an intensity similar to that of the present day existed 3.5 billion years ago (Ga). Detrital zircon crystals found in the Jack Hills of Western Australia are some of the very few samples known to substantially predate this time. With crystallization ages ranging from 3.0–4.38 Ga, these zircons might preserve a record of the missing first billion years of Earth's magnetic field history. However, a key unknown is the age and origin of magnetization in the Jack Hills zircons. The identification of >3.9 Ga (i.e., Hadean) field records requires first establishing that the zircons have avoided remagnetization since being deposited in quartz-rich conglomerates at 2.65–3.05 Ga. To address this issue, we have conducted paleomagnetic conglomerate, baked contact, and fold tests in combination with U–Pb geochronology to establish the timing of the metamorphic and alteration events and the peak temperatures experienced by the zircon host rocks. These tests include the first conglomerate test directly on the Hadean-zircon bearing conglomerate at Erawandoo Hill. Although we observed little evidence for remagnetization by recent lightning strikes, we found that the Hadean zircon-bearing rocks and surrounding region have been pervasively remagnetized, with the final major overprinting likely due to thermal and/or aqueous effects from the emplacement of the Warakurna large igneous province at ~1070 million years ago (Ma). Although localized regions of the Jack Hills might have escaped complete remagnetization, there currently is no robust evidence for pre-depositional (>3.0 Ga) magnetization in the Jack Hills detrital zircons.

1. The early geodynamo and the Jack Hills

The oldest known unmetamorphosed rocks indicate the existence of an active dynamo magnetic field with intensity 50–70% of the present day at 3.450 Ga (Biggin et al., 2011; Tarduno et al., 2010). Due to the lack of older low metamorphic grade rocks, the existence and intensity of the geodynamo during the first ~1 billion years of Earth history—the Hadean eon (>4.0 Ga) and subsequent Eoarchean era (3.6–4.0 Ga)—remain unknown. The early history of the field has important implications for planetary thermal evolution, the physics of dynamo generation, and the oxidation state of the atmosphere (Gomi et al., 2013; Gubbins et al., 2004; Lammer et al., 2008; Nimmo et al., 2004; Tarduno et al., 2014; Ziegler and Stegman, 2013).

The only materials of which we are aware that could possibly retain paleomagnetic records substantially predating 3.5 Ga are detrital zircon crystals found in upper greenschist facies metacon-

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glomerates from Erawandoo Hill in the Jack Hills of Western Australia (Holden et al., 2009). With U–Pb crystallization ages ranging from 3.05–4.38 Ga, these zircons are the oldest known Earthly materials. Ferromagnetic inclusions in these zircons have the potential to yield the oldest known records of the geomagnetic field.

The pebble metaconglomerates containing >4 Ga old zircons were deposited at 2.65–3.05 Ga (Rasmussen et al., 2010) and have been subsequently metamorphosed and heavily weathered (Spaggiari, 2007; Spaggiari et al., 2007). A key difficulty with establishing the age of the zircons' magnetization is that these post-depositional processes as well as analogous processes occurring after the zircons formed but prior to deposition in the final 2.65–3.05 metaconglomerate, could have completely remagnetized their inclusions without disturbing the zircons' U–Pb systematics (Mezger and Krogstad, 1997). Laboratory diffusion experiments indicate that a 1 billion year-thermal event at ∼750 °C, which exceeds the Curie points of common ferromagnetic minerals (≤675 °C), will produce just 1% Pb loss from a 100 μm radius non-metamict zircon (Cherniak and Watson, 2000). Therefore, a zircon's magnetization could be far younger than its crystallization age or even disturbance ages inferred from U–Pb discordance. Furthermore, even if could be established that the zircons have not been thermally remagnetized, they still might not retain an ancient magnetization if their ferromagnetic inclusions are secondary (Rasmussen et al., 2011).

A first step toward constraining the age of magnetization in the zircon grains is to establish whether their host conglomerates have been remagnetized since their deposition at 2.65–3.05 Ga. If the rocks have been thermally remagnetized to temperatures exceeding the Curie point of ferromagnetic inclusions in the zircons, this would require that the inclusions themselves were also completely remagnetized by the same event. Alternatively, if the host rocks have been primarily aqueously rather than thermally remagnetized, ancient magnetization might still be retained within primary ferromagnetic inclusions armored against penetrative fluid flow by the surrounding host zircon. Nevertheless, even this favorable case would still leave unknown whether the zircons were remagnetized following their crystallization but before deposition.

The most direct methods for establishing whether rocks retain ancient magnetization are paleomagnetic field tests (Graham, 1949). The basis of the fold test (McElhinny, 1964) is that magnetization that predates (postdates) folding will be less (more) directionally scattered in bedding-corrected coordinates. Similarly, in the baked contact test (Buchan, 2007), country rocks located outside the remagnetization aureole of a younger igneous intrusion and that have magnetization predating (postdating) the intrusion will be magnetized in a different direction from (similar direction to) that of the intrusion. In the conglomerate test, magnetization in clasts of a conglomerate that predates (postdates) deposition of the conglomerates will be collectively randomly (nonrandomly) oriented (Watson, 1956). A robust conglomerate test will also demonstrate that the magnetization within individual clasts is consistently oriented in order to exclude the possibility that random clast magnetization directions resulted from fine-scale heterogeneous remagnetization of the conglomerate after deposition.

Recently, Tarduno and Cottrell (2013) reported a paleomagnetic conglomerate test on a quartz-cobble metaconglomerate from the Jack Hills. They identified a high-temperature magnetization component in 27 cobbles that thermally demagnetized from ∼540 °C and 580 °C and was randomly oriented to >95% confidence. They proposed that this positive conglomerate test indicates that the host rocks had not been thermally remagnetized to >540 °C since their deposition. However, this conglomerate test has several limitations, the most important of which are:

(i) The test was conducted 0.6 km from Erawandoo Hill, with the intervening stratigraphy obscured by cover and containing bedding-parallel faults and shear zones (Spaggiari, 2007; Spaggiari et al., 2007). Therefore, the thermal history of the cobbles might differ greatly from that of the >4.0 Ga zircon-bearing Erawandoo Hill conglomerate.

(ii) The abundance of zircons with ∼1700 Ma ages [with one grain as young as 1220 Ma (Grange et al., 2010)] in similar, nearby cobbles means that the conglomerate test may only constrain remagnetization events following as much as 1400 million years after the deposition of the Erawandoo Hill Hadean-zircon bearing conglomerate and after many of the major metamorphic events known to have affected the region.

(iii) For most samples, no overprinting magnetization was identified with a direction unambiguously corresponding to known metamorphic events as indicated by Australia's polar wander path. Such overprint are expected if the cobbles are as old as the 2.65–3.0 Ga Erawandoo Hill conglomerate and have the capability of retaining stable magnetization.

More importantly, this single conglomerate test also leaves the many other rich opportunities for constraining the zircon's magnetization age—fold tests, baked contact tests, and conglomerate tests on other lithologies—unexplored. With this motivation, we conducted two trips to the Jack Hills in 2001 and 2012 to acquire samples for paleomagnetic conglomerate, baked contact, and fold tests and geochronometry that address these limitations. Our goal was to establish the intensity and timing of metamorphic and alteration events to constrain the remagnetization processes experienced by the zircons' host rocks directly at Erawandoo Hill and the surrounding region. Here we report the results of paleomagnetic and radioisotopic analyses of these samples and their implications for the preservation of ancient paleomagnetic records in the Jack Hills zircons.

2. Geology of the Jack Hills

The host rocks of the ancient detrital zircons in the Jack Hills are part of an apparently ∼2 km thick sedimentary succession in fault contact with the surrounding granites and granitic gneisses of the Archean Narryer Terrane (Maas et al., 1992; Spaggiari, 2007; Wilde, 2010) (Fig. 1). The supracrustal rocks are steeply dipping, recumbently folded and thought to pinch out at depth in contact with underlying granite. There are four main sedimentary associations: (1) Archean chert and banded iron formation along the northern and southern margins of the belt, (2) Archean pelitic schists, (3) mature Archean clastic sandstones, quartzites, and conglomerates that include the 2.65–3.05 Ga Hadean detrital zircon host rocks, and (4) Proterozoic quartz-rich rocks (Eriksson and Wilde, 2010; Spaggiari et al., 2007; Wilde and Pidgeon, 1990). The contacts between and within these four associations are often shear zones and/or are obscured by cover. The Hadean detrital zircons have been found almost exclusively within ∼1 km of Erawandoo Hill, mainly in a metaconglomerate containing metamorphically elongated and flattened, cm-sized quartzitic pebbles set in a sandy matrix (Spaggiari, 2007; Spaggiari et al., 2007).

Because the 2.65–3.05 Ga depositional age of the Hadean zircon-bearing sediments postdates the surrounding ∼3.10–3.73 Ga gneisses and porphyritic granitoid rocks (Pidgeon and Wilde, 1998; Spaggiari et al., 2008), the detrital zircon host rocks largely avoided high-grade metamorphism associated with these intrusions. The zircon host rocks nevertheless experienced multiple episodes of thermal metamorphism and aqueous alteration. In particular, quartz–biotite–chloritoid assemblages in siliciclastic rocks indicate upper greenschist facies metamorphism, while grunerite in surrounding banded iron formation and calcic plagioclase–hornblende