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Cluster analysis on a sphere: Application to magnetizations from metasediments of the Jack Hills, Western Australia

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ABSTRACT

Metasediments of the Jack Hills contain the oldest known terrestrial minerals in the form of zircons nearly 4.4 billion years old. Paleointensity data from these zircons provide evidence for a Hadean geodynamo as old as 4.2 billion years old. Given the importance of these zircons for constraining the earliest history of the core, it is vital to understand the fidelity of the zircon record. A fundamental aspect providing context for the preservation of primary magnetic signals is the nature of overprints predicted to have been imparted on rocks of the Jack Hills due to Archean to Proterozoic metamorphic events. To be viable magnetic records of a Hadean geodynamo, zircon magnetization directions should differ from these secondary magnetizations. To evaluate these secondary magnetizations, we report paleomagnetic analyses of a comprehensive sampling of 68 quartzite cobble-sized clasts from the Jack Hills metasediments ∼0.5 to 1.0 km from the Discovery Site (which has yielded the oldest zircons and paleofield estimates). While application of standard paleomagnetic tests suggests that the ensemble of cobble directions cannot be distinguished from those drawn from a random distribution, a new cluster analysis of directions on a sphere and non-parametric resampling approaches reveal significant directions amongst subsets of the data. One, isolated at the lowest temperature analyzed [200 to 300 °C, Declination (Dec.) = 316.8°, Inclination (Inc.) = −51.1°] appears to be dominated by the present day field. Another, isolated at higher (but still relatively low unblocking temperatures that we call "intermediate", of ∼350–500 °C, Dec. = 243.8°, Inc. = 9.5°) agrees with a magnetic overprint isolated from the secondary Cr–Fe mica fuchsite isolated from the Jack Hills Discovery site, passing a field test at the 80% confidence level. No evidence is found in our data, or in the data of others collected on similar Jack Hills lithologies, for a widespread 1 Ga remagnetization event. Instead, we interpret the most prevalent secondary magnetization of the quartzite (i.e., intermediate unblocking) and the fuchsite characteristic remanent magnetization to be ∼2.65 Ga in age, coincident with peak metamorphism (as high as ca. 475 °C) of the Jack Hills. The presence of this distinct secondary magnetization, its difference from that recorded by Jack Hills zircons at high unblocking temperatures, and the lack of a dominant remagnetization direction at high unblocking temperatures in the cobble data (the expected result for a primary magnetization), lends further support to the fidelity of the Hadean geomagnetic record. The presence of the secondary magnetization also lends support to the conclusion that most of the Jack Hills metasediments were deposited in the Archean, with only minor reworking and potential tectonic interleaving of Proterozoic components. Overall, the application of the new directional cluster analysis presented here has the potential to reveal magnetic directions in highly scattered data sets, typical of weakly magnetized coarse-grained sedimentary rocks

1. Introduction

Metasediments of the Jack Hills contain the oldest known terrestrial minerals in the form of zircons nearly 4.4 billion years old (Wilde et al., 2001; Valley et al., 2014). Paleointensity data from these zircons provide evidence for a Hadean geodynamo as old as 4.2 billion years old (Tarduno et al., 2015). A positive microconglomerate test conducted on 500 to 800 μm samples from oriented thin sections each centered on a large 200–300 μm zircon indicates that the zircons retain magnetizations at very high unblocking temperatures (ca. 550–580 °C), escaping remagnetization by later geological events. This conclusion is consistent with the peak metamorphic temperatures of ca. 475 °C (Rasmussen et al., 2010, 2011). Further support has been provided

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by recent documentation of the preservation of Li zonation in a zircon (Trail et al., 2016) that suggests the key Jack Hills Discovery site (also known as W74), from which the zircons yielding Hadean ages and magnetizations reported in Tarduno et al. (2015) were obtained, has not experienced amphibolite grade metamorphism (specifically, temperatures greater than 500 °C) since deposition.

While the microconglomerate test excludes chemical and thermal remagnetization of high unblocking temperature magnetizations (Tarduno et al., 2015), it is nevertheless useful to understand the magnetic overprinting history of the Jack Hills metasediments. In addition to providing further context for the zircon magnetizations, this history can provide clues to the tectonic evolution of the Jack Hills (Cottrell et al., 2016).

On the basis of the study of cobble-sized quartzite clasts from the Jack Hills (the first paleomagnetic study of the Jack Hills), Tarduno and Cottrell (2013) concluded that at highest unblocking temperatures, generally greater than 550 °C, a component of magnetization is present that cannot be distinguished from a random distribution using the classic test of Watson (1956). This was the first indication that the Jack Hills sediments might preserve a primary magnetization. The presence of a high unblocking temperature component in samples from the Tarduno and Cottrell (2013) collection was confirmed by independent measurements in a second laboratory [Lehigh University, reported in Dare et al. (2016)]. Remagnetization at ca. 1 Ga was first discussed by Tarduno and Cottrell (2013) but rejected because of the lack of directional evidence. Tarduno and Cottrell (2013) also observed a shallow magnetization at intermediate unblocking temperatures (300–500 °C), but this was observed in only about 20% of the samples (28 cobbles were analyzed).

To better isolate the remagnetization history, Cottrell et al. (2016) sampled fuchsite, a secondary chrome mica from the Discovery Site. Fuchsite grains commonly contain relict Cr–Fe spinels capable of recording magnetizations at unblocking temperatures that should have been reset by peak metamorphic conditions. Indeed, the fuchsite was found to record a well-defined magnetization between ca. 270 and 340 °C that was interpreted to record the geomagnetic field as viewed from the Yilgarn Craton at ca. 2.65 Ga, imparted during peak metamorphic reheating.

Herein, we revisit the question of low to intermediate unblocking temperature magnetizations recorded by the cobble-sized cobbles of the Jack Hills. To determine whether a larger sample set might reveal a more coherent pattern of overprint, the initial 28 samples of Tarduno and Cottrell (2013) were supplemented by the collection of 40 new cobbles. We present new thermal demagnetization results, and subsequent analyses.

The high degree of directional scatter motivated the development of a new method of analysis of directional data on a sphere. This new approach reveals directions that are not obvious from application of the iconic randomness tests of Watson (1956). Specifically, the direction of magnetization recorded by the fuchsite of the Discovery site is also present at intermediate unblocking temperatures in the Jack Hills cobbles. This indicates that the most important overprint direction in the Jack Hills sediments is that carried by the fuchsite and the intermediate unblocking temperature component of the Jack Hills cobbles, possibly imparted at ∼2.65 Ga. The difference between this magnetic direction and directions isolated at high temperatures from oriented single zircons yields further support for select Jack Hills zircons as magnetic recorders and the presence of a Hadean geomagnetic field (Tarduno et al., 2015). The isolation of this ancient remagnetization direction at the Discovery Site and in a long transect of cobble-bearing sediments supports the conclusion that most of the Jack Hills metasediments have Archean depositional ages, with only minor reworking and possible tectonic interleaving of younger Proterozoic components.

2. Field collection and sampling

Quartzite cobbles were sampled from the same horizon reported on by Tarduno and Cottrell (2013) in 2012 as part of a long term study of the magnetic component structure of these rocks and magnetic provenance (Fig. 1; Supplementary Fig. SM1.1 and Table SM1.1), representing the graduate thesis studies of M.S. Dare and R.K. Bono. Procedures follow those of Tarduno and Cottrell (2013) with the following revisions. Tarduno and Cottrell (2013) focused on cobbles with a minimum of flattening with the reasoning that these cobbles would have undergone rolling, minimizing penetrative deformation (Ramsay and Huber, 1987). To increase the sample size, some more flattened cobbles were sampled, and beds off strike from the Tarduno and Cottrell (2013) were sampled. In addition, to increase the diversity of clasts as part of a study of magnetic provenance (Dare et al., 2016), a few irregularly shaped clasts having sedimentary banding were sampled. Laboratory sampling of each cobble follows procedures outlined in Tarduno and Cottrell (2013). Cobbles were split using diamond saws and the interior of each was inspected to find an optimal location (least recrystallization and weathering) for an ∼3–6 cc cube (∼10 g) for paleomagnetic analysis (see Supplementary Fig. SM1.2). A photographic catalog of every field sample (except JC23 and JC24 where laboratory photographs are provided in lieu of field photographs, which were not taken because of low light) for this study and that of Tarduno and Cottrell (2013) is provided in Supplementary Materials SM2.

3. Thermal demagnetization

Thermal demagnetization experiments were conducted in air using a magnetically shielded (∼10 nT), ASC Scientific Thermal Demagnetizing Oven (TD-48), heating samples in a step-wise fashion from 100 to 600 °C, typically in 25 °C increments. For each temperature step, sample order within the demagnetizing oven was preserved; samples were rotated 180° between each step in the oven. Paleomagnetic measurements were done using a liquid helium cooled 2G Enterprises 3-component DC SQUID (model 755) magnetometer at the University of Rochester, which is equipped with high resolution sensing coils and a 4.2 cm room-temperature access bore. The 4.2 cm access bore is necessary to accommodate samples that are large enough to bear sufficient magnetic material. This ensures that the SQUID magnetometer can reliably measure the magnetically weak, bulk sedimentary rock samples [see Dare et al. (2016), for more discussion on SQUID magnetometer sensing limitations]. The demagnetizing oven and magnetometer are housed within a magnetically shielded room with an ambient magnetic field of <200 nT.

4. Analyses

4.1. Temperature intervals and principal component fits

We follow the nomenclature outlined in Tarduno and Cottrell (2013) for assigning unblocking ranges, with "low" temperature, LT, (typically between 200–300 °C, $n = 46$), "intermediate" temperature, IT, (∼350–500 °C, $n = 55$), and "high" temperature, HT, (∼550–580 °C, $n = 54$) unblocking temperature components (Fig. 2). Six cobbles with smooth, linear decay trends were interpreted to record lightning strikes and excluded from further analysis. Select unblocking components have been reported previously in Tarduno and Cottrell (2013) and Dare et al. (2016). A summary of the LT, IT and HT unblocking components is presented