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Detrital magnetite and chromite in Jack Hills quartzite cobbles: Further evidence for the preservation of primary magnetizations and new insights into sediment provenance

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ABSTRACT

The magnetization of zircons from sedimentary rocks of the Jack Hills (Yilgarn Craton, Western Australia) provide evidence for a Hadean to Paleoarchean geodynamo, 4.0 to 4.2 billion years old. These magnetizations pass a microconglomerate test, attesting to the fidelity of Jack Hills zircons as recorders of these most ancient magnetic signals. The lack of pervasive remagnetization of the Jack Hills is also documented through a positive conglomerate test conducted on cobble-sized clasts. A key element of the latter test is the preservation of a high unblocking temperature magnetization that can survive peak metamorphic temperatures. Rock magnetic studies suggest the mineral carrier is magnetite. Herein, we investigate the magnetic mineral carriers in cobble samples through scanning electron microscope and microprobe analyses, conduct an inter-laboratory paleomagnetic study to evaluate sensitivities required to evaluate the weak magnetizations carried by the Jack Hills sediments, and assess provenance information constrained by the opaque minerals. These data confirm magnetite as a detrital phase and the presence of high unblocking temperature magnetizations, further supporting the posit that the Jack Hills sediments can preserve primary magnetic signatures. We note that some of these magnetizations are near the measurement resolution of standard cryogenic magnetometers and thus exacting laboratory procedures are required to uncover these signals. In addition to magnetite, the cobbles contain an assemblage of Mg poor Cr–Fe chromites, Ni-sulfides and pyrrhotite that suggest a source in a layered intrusion different from the granitoid source of the zircons. Any Hadean rock fragment in these sediments, if present, remains elusive.

1. Introduction

The Jack Hills (JH) of Western Australia contain the oldest known terrestrial zircons, which are nearly 4.4 billion years old (Wilde et al., 2001; Valley et al., 2014). Studies using single silicate crystal paleointensity (SCP) techniques (Tarduno et al., 2006, 2007) suggest that some of these zircons record a geodynamo that is 4 billion years old, and perhaps older than 4.2 billion years old (Tarduno et al., 2015). The accuracy of this magnetic history is predicated on the preservation of a primary magnetization in the Jack Hills meta-sediments, which have seen metamorphic reheating of 420 to 475 °C at ∼2.6 Ga (Rasmussen et al., 2010, 2011). A "microconglomerate" test, in which the paleomagnetic directions from oriented zircons were measured, provides evidence that the magnetizations can see through later metamorphic events. Specifically, the microconglomerate test was conducted on ∼500–800 μm samples, each centered on a single large (200–300 μm) zircon (Tarduno et al., 2015). These measurements required the use of the ultra-high resolution 3-component DC SQUID magnetometer at the University of Rochester; this instrument offers an order of magnitude greater sensitivity than other high-resolution SQUID rock magnetometers. Thermal demagnetization using a CO_2 laser, which allows heating on short time scales that limit alteration (Tarduno et al., 2007), showed a characteristic remanent magnetization between 565 and 580 °C, carried by magnetic inclusions

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in the zircons. While the characteristic remanent magnetizations from individual samples were well-defined (generally by 4 heating steps), the ensemble of directions could not be distinguished from a random distribution, indicating a positive microconglomerate test.

The possibility of the preservation of primary magnetization by the JH sediments was also supported by a paleomagnetic study of cobble-sized quartzite clasts (Tarduno and Cottrell, 2013). Thermal demagnetization, using a conventional ASC Scientific TD-48 thermal demagnetization oven, and measurement using a 2G Enterprises 755 3-component DC SQUID magnetometer with high resolution sensing coils, yielded a characteristic remanent magnetization at high unblocking temperatures (>550 °C) indicative of a magnetite carrier. The presence of magnetite was further indicated by the observation of the Verwey transition (Verwey, 1939) – the crystallographic change from the monoclinic to the cubic phase in magnetite – in magnetic susceptibility versus temperature data.

The characteristic remanent magnetization from the cobbles also passed a conglomerate test indicating that a primary magnetization could be retained at high unblocking temperatures in the Jack Hills sediments. This observation can be further examined versus theoretical predictions of the influence of metamorphic reheating using Néel (1949, 1955) theory for single domain for thermoremanent magnetization. Specifically, the thermal relaxation time can be related to rock magnetic parameters as follows (Dunlop and Özdemir, 1997):

$$\frac{1}{\tau} = \frac{1}{\tau_0} exp\left[-\frac{\mu_0 V M_s H_K}{2kT}\left(1-\frac{|H_0|}{H_K}\right)^2\right] \quad (1)$$

where τ_0 ($\sim 10^{-9}$ s) is the interval between thermal excitations, μ_0 is the permeability of free space, V is grain volume, M_s is spontaneous magnetization, H_K is the microscopic coercive force, k is Boltzmann's constant, T is temperature, and H_0 is the applied field. This formulation was used by Pullaiah et al. (1975) to determine time-temperature relationships that can be in turn used to predict how secondary magnetizations might be acquired:

$$\frac{T_A ln(\tau_A/\tau_0)}{M_s(T_A)H_K(T_A)} = \frac{T_B ln(\tau_B/\tau_0)}{M_s(T_B)H_K(T_B)} \quad (2)$$

where the two relaxation times (τ_A, τ_B) correspond to temperatures (T_A, T_B) respectively, and $H_K >> H_0$. Equation (2) describes the tendency for the maximum metamorphic temperature to leak to a higher unblocking temperature range (Dunlop and Buchan, 1977; Dunlop, 1981). If we consider a peak metamorphic temperature of 420 °C, the lower bound constrained by the monazite-xenotime thermometry of Rasmussen et al. (2011), and a nominal reheating duration of 1 million years, SD unblocking temperatures up to ∼470 °C could be affected. The upper bound on metamorphic reheating (475 °C) with the same duration, suggests that SD unblocking temperatures up to ∼530 °C could be affected. A heating duration of 10 m.y. would result in an increase in these upper temperature bounds by only ∼10 °C. These temperature estimates are in agreement with the sharp break seen in demagnetization data at high unblocking temperatures, and the start of the definition of a characteristic remanent magnetization.

Recently Weiss et al. (2015) reported on a study which in part sought to resample the cobble-bearing conglomerate bed study investigated by Tarduno and Cottrell (2013). GPS coordinates suggest that the stratigraphic horizons studied by Weiss et al. (2015) differ from the one sampled by Tarduno and Cottrell (2013), but some samples may be within 30–40 m of stratigraphic distance. Weiss et al. (2015) interpret their data as indicating either failed or indeterminate field tests; they conclude that the Jack Hills rocks were pervasively remagnetized in a single magnetic direction at ca. 1070 Ma (Wingate et al., 2002), and that magnetite as reported by Tarduno and Cottrell (2013) from magnetic measurements is not intrinsic to the samples but is instead a product of laboratory alteration. There are several problems with these interpretations:

1. Weiss et al. (2015) were unable to isolate magnetizations from the critical unblocking temperatures above the peak metamorphic temperature (and its extension to higher unblocking temperatures predicted by theory as explained above.) Therefore, the magnetization isolated by Weiss et al. (2015) provides no information on the presence or absence of a magnetization that predates the episode of peak metamorphic reheating (∼2650 Ma).
2. If the Jack Hills sediments have been pervasively remagnetized, the remagnetization direction should be expressed as a single direction (after removal of viscous magnetizations) encompassing low to high unblocking temperatures, as predicted by theory for single domain magnetite grains, and by relaxation of multidomain magnetite grains; the high unblocking temperatures are missing in data presented by Weiss et al. (2015).

As part of our continuing efforts to investigate magnetic particles in the Jack Hills sediments, we present our first results of scanning electron microscope (SEM), energy dispersive X-ray spectroscopy (EDS) and electron microprobe (EMP) analyses, coupled with new paleomagnetic analyses of JH quartzite cobbles. These analyses provide important context for understanding the magnetizations held by zircons (which are not explicitly studied here).

The new analyses confirm the presence of magnetite as an intrinsic detrital oxide phase in Jack Hills quartzite cobbles, including a sample from an outcrop reported in Weiss et al. (2015). Our new paleomagnetic data (and prior analyses reported in Tarduno and Cottrell, 2013), indicate that a ca. 1070 Ma magnetization does not pervasively overprint the sediments of the Jack Hills. We also present new data from an independent laboratory calibration test that verify the unblocking temperature structure and directions reported by Tarduno and Cottrell (2013). Importantly, in these analyses the crucial high unblocking temperature component that Weiss et al. (2015) are unable to isolate is seen. We discuss why some laboratories and their associated experimental protocols cannot define magnetizations on the weakest terrestrial samples that are otherwise within the measurement range of SQUID rock magnetometers. We also provide guidelines (e.g., on appropriate sample sizes, atmosphere for thermal demagnetization, and required magnetometer sensitivity) for other laboratories seeking to investigate such samples with very weak intrinsic magnetizations.

The EMP data define a host of other magnetic oxides that we interpret as the source of a complex series of secondary magnetizations seen at low unblocking temperatures (Tarduno and Cottrell, 2013). We highlight the compositional distinctiveness of magnetic grains, and related non-magnetic sulfides for constraining provenance and addressing the question of whether a Hadean rock fragment is preserved in the Jack Hills sediments (Wilde and Spaggiari, 2007; Tarduno and Cottrell, 2013). A Hadean rock sample could provide insight into the early Earth's physical environment, salient processes, and the origin of life. We suggest that Cr–Fe spinels, Ni-bearing sulfides and some pyrrhotite grains form an assemblage derived from an ultramafic source. The very low Mg content of the spinels leads us to suggest that rather than a komatiitic source, this assemblage reflects erosion of a layered intrusion, fragments of which may be preserved as enclaves in gneiss of the Yilgarn craton. However, any Hadean rock fragment, if present, remains elusive.