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Evaluating the paleomagnetic potential of single zircon crystals using the Bishop Tuff

Roger R. Fu[a,b,c,*], Benjamin P. Weiss[a], Eduardo A. Lima[a], Pauli Kehayias[d,e], Jefferson F.D.F. Araujo[a], David R. Glenn[d,e], Jeff Gelb[f], Joshua F. Einsle[g], Ann M. Bauer[a], Richard J. Harrison[g], Guleed A.H. Ali[b], Ronald L. Walsworth[d,e]

[a] *Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA, USA*
[b] *Lamont-Doherty Earth Observatory, Columbia University, Palisades, NY, USA*
[c] *Department of Earth and Planetary Sciences, Harvard University, Cambridge, MA, USA*
[d] *Harvard-Smithsonian Center for Astrophysics, Cambridge, MA, USA*
[e] *Department of Physics, Harvard University, Cambridge, MA, USA*
[f] *Carl Zeiss X-ray Microscopy Inc., Pleasanton, CA, USA*
[g] *Department of Earth Sciences, University of Cambridge, Cambridge, UK*

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ABSTRACT

Zircon crystals offer a unique combination of suitability for high-precision radiometric dating and high resistance to alteration. Paleomagnetic experiments on ancient zircons may potentially constrain the history of the earliest geodynamo, which would hold broad implications for the early Earth's interior and atmosphere. However, the ability of zircons to record accurately the geomagnetic field has not been demonstrated. Here we conduct thermal and alternating field (AF) paleointensity experiments on 767.1 thousand year old (ka) zircons from the Bishop Tuff, California. The rapid emplacement of these zircons in a well-characterized magnetic field provides a high-fidelity test of the zircons' intrinsic paleomagnetic recording accuracy. Successful dual heating experiments on eleven zircons measured using a superconducting quantum interference device (SQUID) microscope yield a mean paleointensity of 54.1 ± 6.8 μT (1σ; 42.6 ± 5.3 μT after excluding possible maghemite-bearing zircons), which is consistent with high-precision results from Bishop Tuff whole rock (43.0 ± 3.2 μT). High-resolution quantum diamond magnetic (QDM) mapping, electron microscopy, and X-ray tomography indicate that the bulk of the remanent magnetization in Bishop Tuff zircons is carried by Fe oxides associated with apatite inclusions, which may be susceptible to destruction via metamorphism and aqueous alteration in older zircons. As such, while zircons can reliably record the geomagnetic field, robust zircon-derived paleomagnetic results require careful characterization of the ferromagnetic carrier and demonstration of their occurrence in primary inclusions. We further conclude that a combination of quantum diamond magnetometry and high-resolution imaging can provide detailed, direct characterization of the ferromagnetic mineralogy of geological samples.

1. Introduction

Due to its resistance to metamorphism and weathering processes, the silicate mineral zircon ($ZrSiO_4$) preserves a unique record of the Earth's ancient past. Geochemical studies of zircons routinely provide important constraints on their crystallization environment (e.g., Watson and Harrison, 2005). Moreover, zircons often provide highly accurate radiometric formation ages due to their high initial U to Pb ratio.

Owing in part to these properties, detrital zircon crystals from the Jack Hills of Western Australia are the oldest preserved terrestrial material and have been dated up to 4.37 Ga (Froude et al., 1983; Harrison, 2009; Valley et al., 2014). These zircons provide one of the only known opportunities for direct experimental paleointensity characterization of the earliest geodynamo. Such direct constraints on the Earth's early magnetic field hold key implications for a broad range of geophysical problems. A delayed onset of the geodynamo may imply the persistence of a hot, molten lower mantle or the late initiation of plate tectonics (Labrosse et al., 2007; Nimmo and Stevenson, 2000; O'Neill and Debaille, 2014). On the other hand, an active dynamo during the earliest Hadean eon

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[*] Corresponding author.
E-mail address: rogerfu@fas.harvard.edu (R.R. Fu).

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may imply an important role for compositionally-driven convection in the core or a magma ocean overturn event (Elkins-Tanton et al., 2005; O'Rourke and Stevenson, 2016). At the same time, the intensity of the geomagnetic field may have exerted strong control on the rate of atmospheric loss (Kulikov et al., 2007).

Previous paleomagnetic experiments on Archean whole rock samples dating suggest the existence of an active geodynamo at 3.5 Ga of possibly lower than modern strength (Biggin et al., 2011; Hale and Dunlop, 1984; Hale, 1987; McElhinny and Senanayake, 1980; Tarduno et al., 2010; Yoshihara and Hamano, 2004). On the other hand, the abundance of nitrogen atoms in lunar soil has been interpreted to suggest the lack of a geodynamo at ∼3.9 Ga (Ozima et al., 2005). Most recently, a paleomagnetic study of Jack Hills zircons proposed that a geodynamo with lower than modern day intensity has existed since ∼4.2 Ga (Tarduno et al., 2015). However, a context study of the Jack Hills area has questioned the likelihood that a primary paleomagnetic record may be retained in Jack Hills zircons, such that the ages of their magnetizations are currently unknown (Weiss et al., 2015).

Despite the potential of zircon paleomagnetism to expand our understanding of the early geodynamo, the ability of single zircon crystals to record accurately ancient magnetic fields has not yet been tested against bulk rock measurements. Zircon is not ferromagnetic and cannot by itself record ambient magnetic fields. Primary Fe oxide inclusions observed in zircon (Timms et al., 2012) can potentially carry remanent magnetization. However, the magnetic recording properties of these and other possible ferromagnetic inclusions in zircon remain largely unknown. Detailed paleomagnetic and rock magnetic characterization of zircon is therefore necessary to establish the validity of any paleomagnetic record retrieved from zircon grains.

A recent rock magnetic characterization of detrital zircons from the Tanzawa tonalitic pluton, Japan, measured the ratios of natural remanent magnetization (NRM) to thermoremanent magnetization (TRM) in 12 zircons and inferred a mean paleointensity of 74 μT, which overestimates paleofields expected for the sample location based on geomagnetic dipole field intensity records (8–31 μT) by a factor of 2 to 9 (Sato et al., 2015). When filtered to include only samples with high TRM acquisition capacities, the mean paleointensity of eight zircons (41 μT) is broadly consistent with actual geomagnetic fields. However, because no physical relationship was established between rock magnetic properties and the accuracy of paleointensities of individual zircons, the filtering criterion used cannot be extended reliably to future paleointensity studies. Furthermore, because the Sato et al. (2015) study only compares mean recorded fields over the span of several million years, it does not resolve whether discrepancies between individual zircon paleointensities and mean field values are due to paleosecular variations or an inability of zircons to record accurately ambient magnetic fields.

A more robust evaluation of zircon's paleomagnetic recording potential therefore requires detailed paleomagnetic experiments on mineralogically well-characterized zircons with simple geologic histories that acquired NRM in a well-constrained magnetic field. At the same time, zircons erupted in ash flows are preferable to deep-sourced plutonic zircons as the latter experienced prolonged cooling histories, which complicates the comparison of recovered paleointensities directly to known geomagnetic field intensities.

The Bishop Tuff is an extensive sequence of rhyolitic ash fall tuffs and ignimbrites in eastern California (Hildreth, 1979; Wilson and Hildreth, 1997). The melts that gave rise to the Bishop Tuff are characterized as evolved silicic magma bodies with high H_2O content (Anderson et al., 1989; Bindeman and Valley, 2002; Wallace et al., 1999). On the basis of inclusion assemblages, trace element concentrations, oxygen isotopic compositions, and Ti-in-zircon thermometry, the Jack Hills zircons are likewise considered to have crystallized from felsic magmas with substantial water content (Hopkins et al., 2010; Mojzsis et al., 2001; Watson and Harrison, 2005; Wilde et al., 2001). The composition of Bishop Tuff zircons may therefore be analogous to that of the Jack Hills samples, although their precise crystallization sequences may have differed given the uncertainties in the crystallization setting of the latter (e.g., Darling et al., 2009; Hopkins et al., 2010; Kemp et al., 2010; Nutman, 2006; Rasmussen et al., 2011). The emplacement of the Bishop Tuff occurred in a period of less than a few years at 767.1 ka, which postdates the Bruhnes–Matuyama reversal (Crowley et al., 2007; Singer et al., 2005; Snow and Yung, 1988; Wilson and Hildreth, 1997). Paleomagnetic records from the deposit were therefore not subject to viscous overprinting in a reversed geomagnetic field or post-depositional metamorphism. Meanwhile, the cooling period of TRM acquisition, likely on the order of tens to a few hundred years (Riehle et al., 1995), was too short to result in internal heterogeneities within the deposit due to paleosecular variation.

A previous paleomagnetic study of the Bishop Tuff showed that densely welded ignimbrite samples contain a primary TRM most likely carried by primary low-Ti titanomagnetite (Gee et al., 2010). Thellier–Thellier paleointensity experiments performed on 89 whole rock samples showed that 52% yielded reliable estimates of the paleomagnetic field intensity. The narrow range of paleointensity values derived from samples recovered from diverse locations and stratigraphic heights (43.0 ± 3.2 μT) confirms that cooling through the temperatures of NRM acquisition occurred sufficiently fast to avoid recording paleosecular variation. Because of the mineralogical properties described above, the simple geologic history, and the availability of detailed characterization of the paleofield intensity during emplacement, Bishop Tuff zircons offer a unique opportunity to evaluate the quality of primary paleomagnetic recording in zircon.

In this study, we conducted thermal and AF paleointensity experiments and characterized the ferromagnetic mineralogy of zircons from the Bishop Tuff. We chose zircons taken from sites adjacent to the locations of samples suggested by Gee et al. (2010) to carry primary TRMs. To acquire paleomagnetic data from single zircons, we developed and describe here novel techniques that permit thermal demagnetization and measurement of samples with starting NRM magnitude as low as 5×10^{-14} $\mathrm{A\,m^2}$. This sensitivity represents a gain of greater than one order of magnitude for samples subject to thermal demagnetization compared to previous techniques (Fu et al., 2014b; Tarduno et al., 2015). Comparison between single zircon and whole rock thermal paleointensities shows that the two data sets agree to within uncertainty. Results from our magnetic and electron microscopy and X-ray tomography suggest that stable magnetization in Bishop Tuff zircons is carried by Fe-oxides associated with apatite inclusions.

2. Samples and methods

We collected samples from an exposure of the Bishop Tuff from the Owens River Gorge. The sampling location (37.51189°N, 118.57129°W) is approximately 50 m north and 32 m up-section from the base of the ∼150 m thick Gorge Section F (GF) studied by Gee et al. (2010). All of our zircons are therefore found within the dense welded ignimbrite unit Ig1Eb (Wilson and Hildreth, 1997), which oxygen isotopic data indicate experienced limited to no post-depositional hydrothermal alteration (Holt and Taylor, 1998). Assuming that the flow unit was deposited isothermally, its mass density provides an emplacement temperature estimate of ∼660 °C (Gee et al., 2010), although the uncertainty on this temperature estimate is not well-understood. Variations in observed ignimbrite density ∼25 m up-section from our sampling locality may imply non-uniform deposition temperatures; how-