Earth and Planetary Science Letters 367 (2013) 123–132

Contents lists available at SciVerse ScienceDirect

Earth and Planetary Science Letters

journal homepage: www.elsevier.com/locate/epsl

Signals from the ancient geodynamo: A paleomagnetic field test on the Jack Hills metaconglomerate

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ARTICLE INFO

Article history:
Received 21 November 2012
Received in revised form
6 February 2013
Accepted 7 February 2013
Editor: L. Stixrude
Available online 27 March 2013

Keywords:
paleomagnetism
geodynamo
Jack Hills
Archean
Hadean

ABSTRACT

The oldest history of Earth's magnetic field cannot be directly read from extant bulk rocks because of subsequent metamorphism at temperatures close to or exceeding the Curie temperature of common magnetic minerals. The Jack Hills metasediments of Western Australia, which have seen lower peak metamorphic temperatures, contain zircons as old as ~4.4 billion-yr-old. To assess whether these sediments can retain an ancient signal of the geodynamo, we present a paleomagnetic conglomerate test on a cobble-bearing Jack Hills unit. Thermal demagnetization reveals a distinct magnetic component with high unblocking temperatures between ~550 and 580 °C that passes the conglomerate test, indicating magnetization prior to deposition of the conglomerate. This result, together with rock magnetic data, indicates that the high unblocking temperature component is carried by magnetite which records magnetization in an ambient field, and the simplest explanation is that a dynamo was present. Existing geochronological data imply that the clasts could contain mixtures of minerals extending to ages only slightly older than the maximum depositional age at 3.05 billion-yr-ago. However, the positive conglomerate test reported here indicates that the Jack Hills metasediments have the potential to record Paleorchean to Hadean magnetic fields, on a clast or sub-clast mineral scale.

1. Introduction

The onset and nature of the geomagnetic field is important for understanding the evolution of the core, atmosphere and life on Earth (Tarduno et al., 2010). Specifically, the geomagnetic field shelters the atmosphere from erosion by the solar wind. In the case of the early Earth, the magnetic field would have had to balance the greatly enhanced solar wind pressure associated with the young rapidly rotating Sun (e.g. Wood, 2007). The interplay between the magnetic field and radiation from the young Sun controls the loss of light elements (e.g. Kulikov et al., 2007; Lichtenegger et al., 2010) and ultimately water and therefore can be thought of as a fundamental stage in the development of a habitable planet.

Trying to recover the record of the dynamo from the most ancient geological record, however, is a daunting task. The best preserved Paleoarchean units have seen at least greenschist grade metamorphism. If the magnetic constituents of rocks were comprised solely of ideal, single-domain (SD) particles, the problem of low grade metamorphism would be easier to approach. In this case, some portion of the hypothetical SD-grain population would be overprinted, and the remainder untouched; this would be manifested by a demagnetization temperature at which secondary magnetic components are removed (called the "unblocking temperature") somewhat exceeding the peak metamorphic temperature (e.g. Dunlop and Özdemir, 1997).

However, real rocks do not contain just SD magnetic particles. In particular, larger multidomain (MD) grains are easily reset during low grade metamorphic conditions; such secondary magnetizations can contaminate the overall magnetization up to the Curie temperature of the relevant magnetic mineral carrier (usually magnetite). In addition to these thermal effects, greenschist metamorphism can be associated with the formation of new magnetic minerals, either directly during the peak heating of the metamorphic event, or sometime afterwards through the further lower-temperature alteration of non-magnetic minerals formed during metamorphism. An example of the latter process is the formation of magnetite from serpentinite accompanying metamorphism of mafic–ultramafic rocks; this mechanism is ubiquitous in Archean komatiites (e.g. Yoshihara and Hamano, 2004).

To address these issues, several works have employed the single crystal paleointensity (SCP) approach (Tarduno et al., 2006; Tarduno, 2009). Single silicate crystals can host minute magnetic inclusion with ideal single-domain-like behavior (Cottrell and Tarduno, 1999; Dunlop et al., 2005; Feinberg et al., 2005). Isolating

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http://dx.doi.org/10.1016/j.epsl.2013.02.008

such crystals allows one to eliminate the effects of non-magnetic phases (e.g. clays) that can alter in the laboratory creating new magnetic phases; it also provides a way of avoiding the influence of multidomain grains. The silicate host may also act to protect the inclusions from alteration on geologic time scales.

Applying the SCP approach, Smirnov et al. (2003) reported paleointensity values from ~2.5 billion-yr-old dikes from the Karelia Craton. These data suggest that the field had a strength similar to that of the present-day field. Some paleointensity results from nearly coeval whole rock samples yield lower values, less than 25% of the modern field value (Macouin et al., 2003). Smirnov and Tarduno (2005) interpreted these results, which are otherwise derived from data of high technical quality, to the influence of a thermochemical remanence acquired during slow cooling of the dikes sampled. These, and other alteration effects tend to lower paleointensity estimates derived from whole rocks (Tarduno and Smirnov, 2004).

Again using the SCP approach, Tarduno et al. (2007) reported values within 50% of the present-day field from ~3.2 Ga plutons of the Barberton Greenstone Belt of the Kaapvaal craton of southern Africa. The oldest paleointensity estimate currently available based on a thermoremenent remanent magnetization are derived from 3.4 to 3.45 dacites of the Barberton and Nondweni Greenstone Belts (both on the Kaapvaal Craton). The SCP method yields values that are within 70% to 50% of the present-day field strength (Tarduno et al., 2010).

The geomagnetic field may be truly ancient, starting shortly after core formation. However, several authors have offered a different viewpoint. A null or weak field at 3.8–3.9 Ga is predicted from a hypothesis seeking to explain lunar nitrogen values through transport from Earth's atmosphere by the solar wind (Ozima et al., 2005). A delayed onset of the geodynamo, to ages as young as 4.0–3.4 Ga, has been predicted from a model for cooling of a dense liquid layer at the base of the early Earth's magma ocean (Labrosse et al., 2007). Aubert et al. (2010) discuss two Earth thermal evolution models. In one, called the "low power model", a present-day CMB heat flow of 3 TW predicts a dynamo for all of Earth's history. In contrast, a higher choice of CMB heatflow (11 TW) suggests onset of the geomagnetic field sometime between 4.0 and 3.5 Ga.

The implications of these competing presence/absence models of the dynamo for shielding of the early Earth's atmosphere could not be more different. The oldest available paleointensity data at 3.45 Ga already point to the vulnerability of Earth's atmosphere against solar activity. Although the estimated magnetopause standoff distance is some 5 Earth radii (Tarduno et al., 2010) – a value that Earth has experienced on hour to day time scales during the most extreme modern coronal mass ejection events (CME) – this would have been the typical value for the early Earth. Hence, a CME would have further compressed the magnetosphere and possibly led to exosphere heating to the extent that hydrodynamic escape of volatiles including water would have occurred (Tarduno et al., 2010). If Earth had no magnetic field prior to the 3.5–4.0 Ga interval, these effects would have been extreme, implying a significant modification of the early Earth's hydrosphere by the solar wind. Thus, determining the absence/presence of the geomagnetic field prior to 3.45 Ga is of central importance for understanding the thermal evolution of Earth, surface conditions and the atmosphere.

But there are few areas of terrestrial rocks known with ages >3.45 Ga that have been spared metamorphism to amphibolite-facies; the thermal and associated chemical transformations remove these rocks from further paleomagnetic considerations. The most notable exception is the Pilbara Craton of Western Australia, but Pilbara rocks could potentially extend the record known from the Kaapvaal Craton only by a few tens-of-millions of years.

However, there is another recorder: rock clasts and silicate crystals composing the clasts eroded from older rocks (lost to us by erosion) that compose younger sedimentary units. Arguably the most famous of these are the Jack Hills metasediments of Western Australia, which host zircons up to ~4.4 billion-yr-old (Wilde et al., 2001). Rock clasts, quartz grains hosting magnetite inclusions composing clasts, or the zircons themselves (which can host magnetite inclusions, Tarduno et al., 2006; Nelson et al., 2010), could potentially record the earliest Archean to Hadean geodynamo. A prerequisite to any such examination is a paleomagnetic test (Graham, 1949) used to judge whether a given conglomerate can retain a magnetization older than the depositional age. If magnetizations from individual clasts define a common direction, that direction must be a secondary magnetization. If the magnetizations are random, the clasts could retain a magnetization older than the age of deposition of the conglomerate.

The oldest conglomerate test reported to date has been the study of a ~3416 Ma conglomerate of the Barberton Greenstone belt by Usui et al. (2009). In that study, dacite clasts yielded two distinct components of magnetization. One was retrieved at relatively low unblocking temperatures and yielded a common direction indistinguishable from a young ca. 180 Ma overprint direction. A higher unblocking temperature component, however, was randomly distributed, indicating that a primary magnetization could be preserved, a finding subsequently supported by SCP analyses of the conglomerate source rocks (Tarduno et al., 2010). Below we discuss the setting of

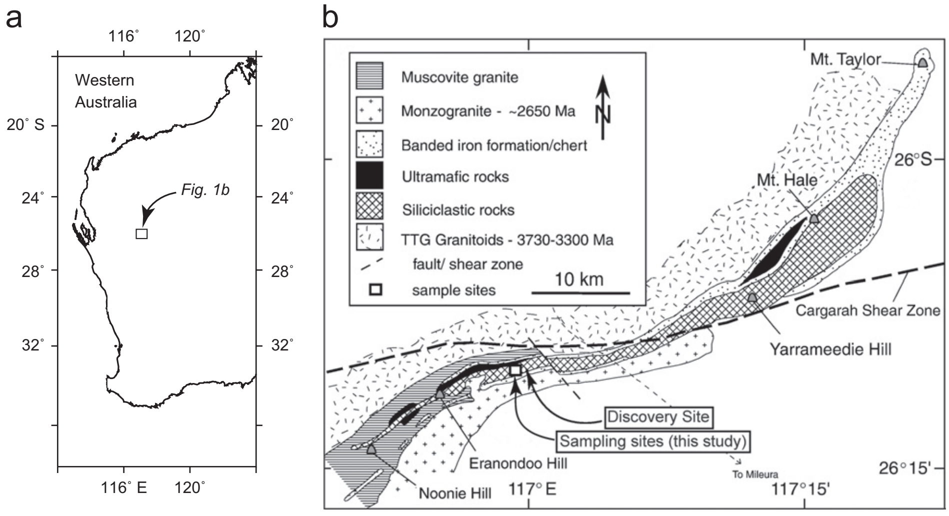

Fig. 1. Location of the Jack Hills metasediments. Maps after Grange et al. (2010) and Spaggiari et al. (2007).