Earth and Planetary Science Letters 419 (2015) 1–13

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Records of geomagnetism, climate, and tectonics across a Paleoarchean erosion surface

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ARTICLE INFO

Article history:
Received 22 August 2014
Received in revised form 23 February 2015
Accepted 5 March 2015
Available online 17 March 2015
Editor: T. Elliott

Keywords:
Archean
paleomagnetism
geomagnetism
Pilbara
Kaapvaal
Vaalbara

ABSTRACT

Paleomagnetism has provided key constraints on the evolution of Earth's climate, geomagnetic field, and continental geography through Phanerozoic and Proterozoic time. Extending these constraints into the Archean eon has been particularly challenging due to the paucity of the ancient rock record. Here we report paleomagnetic measurements on the NASA Astrobiology Drilling Project (ABDP)-8 core drilled through one of the world's least deformed and least metamorphosed Paleoarchean [3200–3600 million year old (Ma)] rock successions located in the East Strelley Belt of the eastern Pilbara Craton, Australia. Our results show that the ∼3350 Ma Euro Basalt preserves a shallow magnetic inclination that appears to have formed as a result of early seafloor hydrothermal alteration, suggesting that the evaporitic carbonate platform of the conformably underlying Strelley Pool Formation was deposited in a near-equatorial location. This is consistent with (although does not require) late Paleoarchean climatic zoning, low orbital obliquity, and a geocentric axial dipole (GAD) field geometry similar to that of the Phanerozoic. The Euro Basalt paleopole overlaps with previously published Paleoarchean poles from the East Pilbara craton and with time-equivalent poles reported from the Barberton Greenstone Belt of the Kaapvaal craton, supporting the existence of a Paleoarchean Vaalbara continental aggregation.

1. Introduction

Planetary orbital obliquity determines the distribution of insolation over Earth's surface. Modern Earth has a low obliquity (23°) that controls the Hadley cell circulation pattern, leading to moisture-rich tropics and carbonate platforms equatorwards of ∼30° latitude (Salby, 1996). Early paleomagnetic studies observed that carbonate platforms were deposited below ∼30° paleolatitude throughout much of the Phanerozoic era if a geocentric axial dipole (GAD) field geometry is assumed (Briden, 1970). This consistency helped establish the GAD hypothesis as a foundational principle in paleomagnetism for characterizing polar wander, continental reconstructions, and the unusual paleolatitudes of climate-sensitive rocks like glacial sediments associated with the hypothesized "Snowball Earth" events (Evans, 2006).

While Earth's geomagnetic field existed as early as ∼3450 Ma (Biggin et al., 2011; Tarduno et al., 2007, 2010; Usui et al., 2009), reconstruction of the earliest field geometry using globally-distributed paleomagnetic data is not feasible due severe under-sampling of Paleoarchean rocks. Furthermore, the climate pattern at this time would have depended on many unconstrained factors, including the configuration and proportion of land masses and oceans, the intensity of insolation, the planetary obliquity, and the temperature and composition of the atmosphere and ocean (Spiegel et al., 2009). Hence, there is little prospect of fully characterizing Earth's earliest climate zonation using traditional paleomagnetic methods. Nevertheless, the magnetization of very rare, well-preserved Paleoarchean volcanic rocks interbedded with chemical sediments can be used to test whether the basic conditions that have prevailed since ∼2000 Ma, including a GAD field geometry, obliquity <54°, and a latitudinally zoned climate (Evans, 2006), might have originated in much deeper time.

If the GAD hypothesis is assumed to hold for Paleoarchean time, then paleomagnetic data from this era can also be used to infer relative positions of some of the earliest known continental masses. In particular, they could be used to test the hypothesis that the Kaapvaal craton of South Africa and the East Pilbara craton of Western Australia are the partial remnants of a single Archean proto-continental mass, termed Vaalbara (Cheney et al., 1988). Such an association has long been suggested by the broad similarity between their Neoarchean supracrustal successions and associated intrusive suites. The earliest paleomagnetic tests of the

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http://dx.doi.org/10.1016/j.epsl.2015.03.008

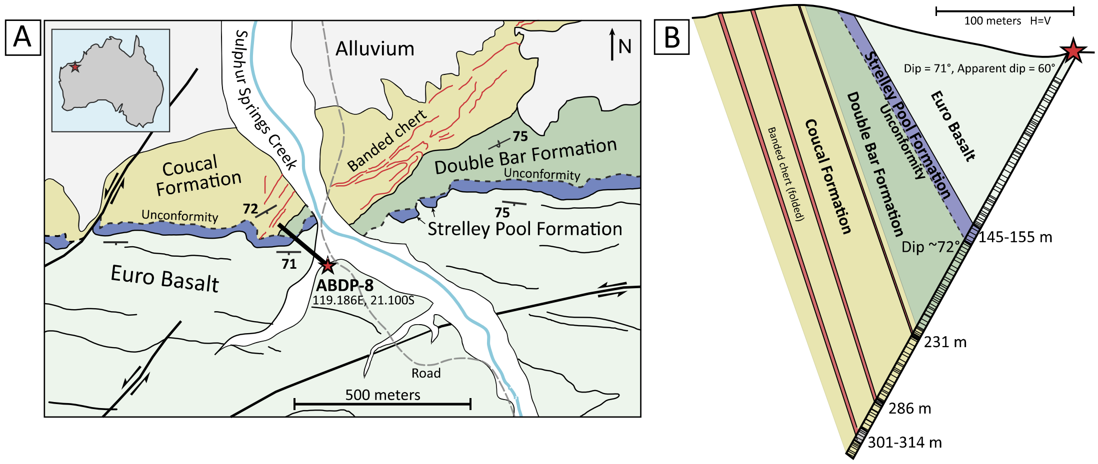

Fig. 1. Geological setting. (A) Generalized geological map of the study area (after Van Kranendonk (2000) and interpretation of satellite imagery). Star: ABDP-8 drill site located at 21.1000°S, 119.1864°E. Faults (bold arrows) and strikes and dips of bedding (bars with tick marks and dip angles) shown in selected locations. (B) Geometry of the ABDP-8 drill core and rock units at depth, with each of our subsamples indicated by a black band. C1, C2, and C3 are banded chert horizons mapped within the uppermost Coucal Formation to the northeast of the drill site.

Vaalbara hypothesis had to rely on comparisons of inferred paleolatitude alone (Zegers et al., 1998), but publication of more reliable Neoarchean paleomagnetic poles from both terranes has made a direct plate-tectonic restoration more feasible (de Kock et al., 2009 and references therein). Furthermore, selected ∼3450 Ma Paleoarchean poles were considered by Biggin et al. (2011) to be consistent, broadly, with either the Zegers et al. (1998) or de Kock et al. (2009) Vaalbara reconstruction models, under alternative assignments of geomagnetic polarity for those poles. While the paleomagnetic record from the Kaapvaal Paleoarchean has improved markedly in recent years (Biggin et al., 2011), the time-equivalent dataset from the East Pilbara craton remains small and relatively unreliable.

Remanent magnetization in well-preserved rocks from the East Pilbara craton therefore has great potential for directly testing multiple hypotheses of uniformitarian conditions in Paleoarchean time. With these goals in mind, we examined the ABDP-8 core drilled near Sulphur Springs Creek in Western Australia (Fig. 1A). The ABDP-8 core has two major advantages over outcrop samples: 1) it is unaffected by the modern oxidative weathering and lightning strikes that have largely remagnetized surface exposures of low grade Paleoarchean rocks (e.g., Strik et al., 2003; Carporzen et al., 2012), and 2) it provides a semi-continuous stratigraphic time sequence through two of the oldest known but minimally metamorphosed rock sequences in the world.

The East Strelley Belt contains the only exposures of the Coonterunah Subgroup of the Warrawoona Group, the oldest known supracrustal rocks in Australia (Buick et al., 1995). The base of the Coonterunah Subgroup consists of the undated tholeiitic basalts and komatiites of the Table Top Formation, which grade upward into 3515 ± 3 Ma rhyolites, dacites and andesites of the Coucal Formation (Buick et al., 1995; Green et al., 2000). Thin, banded cherts that occur near the top of the Coucal Formation are silicified ashes that can be traced for several kilometers (Smithies et al., 2007). The Coucal Formation is overlain by tholeiitic basalts of the Double Bar Formation; a felsic volcanic near the top of this formation has a reported age of 3498 ± 2 Ma (Nelson, 2002). The Coonterunah Subgroup was intruded by the ≥3468 ± 4 Ma Carlindie Granitoid Complex, causing greenschist facies metamorphism (amphibolite facies near the intrusive contact) accompanied by open folding (Buick et al., 1995) and development of a weak foliation (Blewett, 2002). Deformation after ∼3426 Ma led to emergence and erosion of the upper Warrawoona Group section, producing a regional paleo-exposure surface (Buick et al., 1995), upon which the >3350 Ma Strelley Pool Formation was deposited during a magmatic hiatus (Allwood et al., 2006; Hickman, 2008). The overlying Kelly Group consists of komatiites and tholeiitic pillow basalts of the 3350–3335 Ma Euro Basalt, which are conformably overlain by the 3325–3315 Ma felsic volcanics of the Wyman Formation and the Charteris Basalt (Thorpe et al., 1992). In the East Strelley Belt, an unconformity beneath sediments of the ca. 3190 ± 10 Ma Soanesville Group locally eroded the Kelly Group above the Euro Basalt as well as the entire Sulphur Springs Group. Southward shallowing of dips away from the Carlindie Granitoid Complex is evidence for progressive doming that commenced soon after emplacement of the Euro Basalt and continued through deposition of the De Grey Supergroup (Van Kranendonk, 2000). Bedding orientations within the East Strelley Belt were probably further modified during regional transpression on the neighboring Lalla Rookh – Western Shaw structural corridor at ∼2940 Ma (Van Kranendonk and Collins, 1998) and during minor late Archean doming that cannot be constrained in age or precise geometry due to subsequent erosion of rocks younger than ∼2.8 Ga.

The ABDP-8 core transects greenschist facies rocks of the Coucal Formation (120 m of stratigraphy) and Double Bar Formation (50 m of stratigraphy) (Fig. 1B), the angular unconformity and a thin sequence of sedimentary rocks of the Strelley Pool Formation (25 m of stratigraphy), and the Euro Basalt (140 m of stratigraphy). While rocks in the greater East Strelley Belt have experienced metamorphic grades of prehnite–pumpellyite to lowermost amphibolite facies (Green et al., 2000) at temperatures between ∼250 and ∼500 °C (Harnmeijer, 2009), at the ABDP-8 site the metamorphic grades are lower to mid-greenschist beneath the angular unconformity and prehnite–pumpellyite above.

2. Sampling and lithological characteristics

We acquired 185 samples at approximately equal intervals from the ABDP-8 quarter core housed at Arizona State University (ASU) using a 2.54 cm diameter diamond drill bit mounted on a drill press. The mineralogies of representative specimens were characterized using scanning electron microscopy and energy dispersive spectroscopy analyses on polished end chip surfaces using a JEOL JXA-733 Superprobe housed in the MIT Electron Microprobe Facility. Volcanic rocks of the Euro Basalt consist of the mineral assemblage albite–actinolite–epidote–pumpellyite with a variably developed propylitic overprint characterized by a chlorite, quartz, and carbonate minerals. Accessory minerals occur as