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Anisotropy of thermoremanent magnetisation of Cryogenian glaciogenic and Ediacaran red beds, South Australia: Neoproterozoic apparent or true polar wander?

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ABSTRACT

Determining the effects of compaction-related inclination shallowing of remanence directions is crucial for ascertaining the validity of low palaeolatitudes for Neoproterozoic red beds in South Australia that are central to the debate concerning low-latitude Proterozoic glaciation. The inclination correction (or flattening) factor, f, is defined as $\tan(I_D)/\tan(I_F)$, where I_D and I_F are the inclinations of the measured detrital remanence and the ancient inducing field, respectively. The anisotropy can be estimated using anisotropy of magnetic susceptibility and the anisotropy of high-field isothermal remanence (hf-AIR). The elongation–inclination (E–I) method has also been used to infer inclination shallowing. We add the anisotropy of thermoremanent magnetisation (ATR) to these methods. For the late Cryogenian Elatina Formation arenites, which constitute the bulk of the Elatina data set, the inclination correction using $f = 0.738$ derived from ATR increases the palaeolatitude of the Elatina Formation from $6.5 \pm 2.2°$ to $8.8 \pm 3.2°$, which confirms that the Elatina glaciation occurred near the palaeoequator. Inclination corrections for the Ediacaran argillaceous Brachina and Wonoka formations, using $f = 0.35$–0.38 derived from ATR, are significantly greater than for the more arenaceous Elatina Formation, which increases their palaeolatitudes from ~12° to ~30°. Carbonates from the basal Ediacaran Nuccaleena Formation yielded $f = 0.8$ from ATR, which represents only a small palaeolatitude correction from 19° to 23°. The anisotropy results imply that the characteristic remanent magnetisations carried by all these units were acquired early as depositional remanent magnetisations, essentially at the time of deposition. The shift of the palaeopoles from argillaceous units indicating significantly higher palaeolatitudes introduces a distinctive loop into the late Cryogenian–Ediacaran–Cambrian pole path for Australia. This loop shows similarities with the North American pole path for this period, for which true polar wander (TPW) has been inferred. However, until ages of Neoproterozoic strata in South Australia are better constrained uncertainty persists on whether the similarities of the Australian and North American pole paths reflect TPW.

1. Introduction

The Cryogenian and Ediacaran of the Adelaidean (Neoproterozoic) in South Australia (Preiss, 1987, 2000) record two of the most intriguing periods in geological history, providing an almost continuous record of palaeolatitudinal trends, climate swings and evidence of the early evolution of complex life. The apparent low palaeolatitudes of Cryogenian glaciogenic deposits have been confirmed by many studies spanning two decades (Embleton and Williams, 1986; Schmidt et al., 1991; Schmidt and Williams, 1995; Sohl et al., 1999; Schmidt et al., 2009) and the immediately overlying carbonate deposits suggest rapidly changing environments (Williams, 1979; Kennedy, 1996; Giddings and Wallace, 2009; Schmidt et al., 2009). Palaeolatitudinal changes recorded by late Cryogenian and Ediacaran strata are critical to understanding such environmental changes in South Australia and globally. However, some have doubted the fidelity of magnetic recording by sedimentary rocks, and in particular whether compaction-related inclination shallowing might explain the low palaeolatitudes of Proterozoic glaciogenic deposits.

Studies of the remanence acquisition by sediments during sedimentary and diagenetic processes are as old as the science of palaeomagnetism. Depending on various physical properties such as grain size, grain-size distribution and grain shape, sediments are subject to inclination error during initial depositional processes and later compaction. Inclination error has been investigated in redeposition experiments for sediments carrying both magnetite and hematite (Johnson et al., 1948; King, 1955; Griffiths et al., 1960; Tauxe and Kent, 1984). It has been thought that inclination may partially or completely recover alignment with the field through bioturbation or diagenetic effects (Irving and Major, 1964; Irving, 1967; Kent, 1973). Over the last decade, however, it has been argued that anomalies in apparent polar wander paths (APWPs) and palaeoreconstructions result in part from inclination error (Van der Voo and Torsvik, 2004; Kent and Irving, 2010). The elongation–inclination (E–I) method of comparing directional distributions with geomagnetic

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models (Tauxe and Kent, 2004) has rekindled interest in the subject (Krijgsman and Tauxe, 2004, 2006). Results from laboratory estimates of inclination shallowing (Jackson et al., 1991; Garcés et al., 1996; Kodama, 1997; Tan and Kodama, 2002) have been found to be consistent with those from the E–I method (Kent and Tauxe, 2005; Tan et al., 2007; Tauxe et al., 2008).

The fidelity of the magnetic recording process in sediments and correction factors for calculating palaeolatitudes can be estimated using a number of laboratory parameters. Laboratory redeposition is more applicable to young sediments such as lacustrine and seafloor sediments. For ancient sediments it is not possible to emulate the compaction and diagenetic changes associated with lithification. Apart from redeposition experiments, other laboratory methods that are commonly employed in various magnetisation experiments with sediments are isothermal remanent magnetisation (IRM), anhysteretic remanent magnetisation (ARM) and thermoremanent magnetisation (TRM).

The anisotropy of acquisition of these various types of magnetisation can be determined by imparting magnetisation along a number of directions and measuring the resulting remanence vector each time. The caveat is that the initial magnetic state of a sample must be regained prior to subsequent acquisitions. Additionally, determining the anisotropy of anhysteretic remanence (AAR) in hematite-bearing sediments is impractical for most palaeomagnetic laboratories because the high fields needed to magnetise hematite and then demagnetise samples prior to each acquisition step are beyond those available using standard alternating-field demagnetisation capabilities. Similarly, determining the anisotropy of isothermal remanence (AIR) has been limited, although use of superconducting magnets and other large electromagnets capable of generating fields > 10 T has enabled high field AIR (hf-AIR) to be used with some success (Kodama and Dekkers, 2004; Bilardello and Kodama, 2009; Schmidt et al., 2009). However, mixed mineralogies add another degree of freedom that complicates interpretation of results.

Anisotropy of TRM can fail through thermochemical alteration of the magnetic minerals within samples at the high temperatures (> 660 °C) required to remove the remanence imparted at each TRM step. For this study we opted for full determination of the anisotropy of (partial) TRM, or pTRM, at many temperature steps, much like stepwise thermal demagnetisation, with the aim of detecting the onset of chemical alteration and thereby restricting our interpretation only to the pTRM acquisition steps free of discernible alteration.

2. Cryogenian and Ediacaran stratigraphy and geochronology

2.1. Stratigraphy

Neoproterozoic strata in the Adelaide Geosyncline region (Fig. 1) record two Cryogenian glaciations, the ~700–660 Ma Sturt glaciation (Coats and Preiss, 1987; Preiss et al., 2011) and the terminal Cryogenian (~635 Ma) Elatina glaciation (Fig. 2) (Coats and Preiss, 1987; Williams et al., 2008, 2011). The Elatina glaciation is recorded by permafrost regolith and periglacial aeolianite on the cratonic Stuart Shelf in the west, and glaciofluvial, deltaic, littoral, and marine-shelf glaciogenic deposits in the Adelaide Geosyncline, which is now represented by folded strata of the Flinders Ranges and Mount Lofty Ranges (Fig. 1). Palaeomagnetic and rock magnetic studies of glaciofluvial and deltaic red sandstones and tidalites from the Elatina Formation (Fig. 2) indicate the early acquisition of remanence and deposition within 10° of the palaeoequator (Embleton and Williams, 1986; Schmidt et al., 1991; Schmidt and Williams, 1995; Sohl et al., 1999; Schmidt et al., 2009). These findings have stimulated research worldwide on the nature of Cryogenian glaciations.

The Elatina Formation is disconformably to unconformably overlain by the Early Ediacaran Nuccaleena Formation 'cap carbonate' (commonly < 10 m thick) at a basin-wide sequence boundary that marks the base of the Wilpena Group (Fig. 2) (Forbes and Preiss, 1987; Preiss, 2000; Williams et al., 2008; Schmidt et al., 2009; Williams et al., 2011). The succeeding formations of the group form two major upward-shallowing/coarsening cycles. The lower cycle commences with interbedded mudstone and dolostone that pass upwards to red brown and olive green siltstone and mudstone and local reddish sandstone of the marine-shelf Brachina Formation (500–1200 m thick). The Brachina coarsens upwards to the deltaic and shallow-marine ABC Range Quartzite (mostly ~500 m thick, but > 2000 m in the west) at the top of the cycle. Red and green mudstones of the transgressive, marine-shelf Bunyeroo Formation (400–700 m thick) herald the second major cycle. The regressive marine-shelf Wonoka Formation (~500–700 m thick) is a grey, green, brown and reddish mixed carbonate/fine-grained siliciclastic unit (Haines, 1988). The marginal-marine and estuarine Bonney Sandstone (255 m thick) conformably follows the Wonoka and the cycle is completed by the mostly shallow-marine Rawnsley Quartzite (413 m thick) at the top of the Wilpena Group. The famous metazoan Ediacara biota occurs in the Ediacara Member near the base of the Rawnsley Quartzite (Preiss, 1987, 2000).

The Adelaidean on the Stuart Shelf and in the Adelaide Geosyncline is disconformably overlain by Cambrian sediments. Strata in the Adelaide Geosyncline were deformed during the early Palaeozoic (514–490 Ma) Delamerian Orogeny (Drexel and Preiss, 1995; Foden et al., 2006).

2.2. Geochronology

Few ages are available for late Neoproterozoic strata in South Australia. A tuff in the Sturtian Wilyerpa Formation yielded a U–Pb zircon age of ~659 Ma (Fanning and Link, 2008) and black shale from the Tindelpina Shale Member gave a Re–Os age of 643.0 ± 2.4 Ma (Kendall et al., 2006). A U–Pb zircon age of 657 ± 17 Ma for the Marino Arkose Member of the Wilmington Formation (Ireland et al., 1998), a partial equivalent to the interglacial Enorama Shale, may date coeval volcanism (Preiss, 2000). A Th–U–total Pb diagenetic age of 680 ± 23 Ma for authigenic monazite from the Enorama Shale (Mahan et al., 2010) is compatible with the U–Pb zircon ages for the Wilmington and Wilyerpa formations but conflicts with the Re–Os age for the Tindelpina Shale Member.

The Elatina glaciation has not been dated directly but has been equated with the Ghaub glaciation in Namibia, where associated volcanic rocks yielded a U–Pb zircon age of 635 ± 1.2 Ma (Hoffmann et al., 2004). The Elatina glaciation has also been equated with the Nantuo glaciation in China, which has a minimum U–Pb zircon age of 635.2 ± 0.6 Ma (Condon et al., 2005) and yielded a U–Pb zircon age of 636 ± 4.9 Ma for a tuff near its base (Zhang et al., 2008). Ages of 635 Ma for the Elatina glaciation and 643 Ma for the Tindelpina Shale Member seem incompatible, because they would require exceptionally high rates of sedimentation for the > 4 km interglacial succession in the Adelaide Geosyncline. Although it is unclear whether Cryogenian glaciations correlate globally (Allen and Etienne, 2008), an age near 635 Ma is tentatively taken for the Elatina glaciation pending corroborating data.

Only Rb–Sr whole-rock shale isochrons and ages for detrital grains are available for the Ediacaran in South Australia. The Brachina Formation yielded a Rb–Sr isochron of 609 ± 64 Ma and the Yarloo Shale on the Stuart Shelf, the equivalent to the Bunyeroo Formation, gave a Rb–Sr isochron of 593 ± 32 Ma (Compston et al., 1987). The youngest of eleven $^{40}Ar/^{39}Ar$ ages for detrital muscovite from the Bonney Sandstone was 601 ± 17 Ma (Haines et al., 2004). A U–Pb zircon age of 556 ± 24 Ma for the Bonney Sandstone (Ireland et al., 1998) provides a maximum age for the overlying Rawnsley Quartzite (Preiss, 2000). The Ediacara biota are closely comparable with taxa of the 555 ± 0.3 Ma 'White Sea Association' in Russia (Martin et al., 2000), which implies an age of ~555 Ma for the Ediacara Member of the Rawnsley Quartzite.