Low-latitude glaciation in the Neoproterozoic of Oman

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ABSTRACT

Although Earth is widely believed to have undergone a series of extreme low-latitude snowball glaciations during the Neoproterozoic (ca. 1000–543 Ma), only one reliable paleomagnetic result, from Elatina, South Australia, places glacial rocks close to the equator. We report new paleomagnetic data from the Neoproterozoic Huqf Supergroup of Oman that pass fold and reversal tests and yield a paleopole at 52.3°S, 074.4°E (N = 25 sites; \( \alpha_{95} = 7.3^\circ \)). This paleopole places the Muscat region of Oman at a latitude of 13° in the late Neoproterozoic and provides the first direct evidence that both glacial and overlying cap carbonate units were deposited in the tropics. The presence of glacial-interglacial cyclicity within the Huqf Supergroup indicates that areas close to the equator may have been largely free of ice at the time of deposition, a result that is inconsistent with the classic snowball Earth model. Our result precludes the possibility that contrasting lithologies mark a phase of rapid plate motion and provides the first evidence for low-latitude glaciation in Arabia. A series of magnetic reversals in the Fiq tillite and the overlying Hadash dolomite, in northern and central Oman, correlates well with a similar sequence in the Mirbat Formation in southern Oman and indicates that recovery from glacial conditions took place over long time scales (possibly >10^5–10^6 yr).

Keywords: Oman, Neoproterozoic, paleomagnetism, glaciation, Marinoan, Arabia.

INTRODUCTION

The late Neoproterozoic interval was marked by the most extreme climate change known in Earth’s history, possibly including several episodes of global refrigeration (e.g., Hoffman et al., 1998; Kennedy et al., 1998; Evans, 2000; Hoffmann et al., 2004). These have generally been grouped into two major glacial phases: the Sturtian, ca. 745 Ma to 670 Ma (Lund et al., 2000; Evans, 2000), but there is still considerable uncertainty about their precise chronology. Probable Marinoan glacial deposits in Australia have been dated as ca. 580 Ma, and have been correlated with the Gaskiers Formation of Newfoundland (Calver et al., 2004). In contrast, the Ghaub Formation of Namibia is dated as 635 ± 1.2 Ma, and is also bracketed as a Marinoan glaciation (Hoffmann et al., 2004). Thus the Marinoan glaciation event was either a long-lasting event of global significance, or incorporates multiple nonsynchronous smaller events, and many of the proposed correlations between different continents are incorrect (e.g., Hoffmann et al., 2004).

Nevertheless there is abundant stratigraphic evidence for major glaciations at that time, and several workers have argued for a completely frozen ocean during these events, temporarily arresting the hydrological cycle and potentially causing catastrophic extinction, in a so-called snowball Earth (Kirschvink, 1992; Hoffman et al., 1998; Hoffman and Schrag, 2002). The snowball Earth model predicts a long-lasting (~10^6–10^7 yr) ice-covered ocean, followed by a runaway greenhouse world in which cap carbonates are deposited in a relatively short period of time (10^3–10^4 yr). Evidence supporting low-latitude glaciation includes the ubiquitous occurrence of tillites in late Neoproterozoic sedimentary successions and the apparent conformity of these glacial deposits with overlying putative warm-water carbonates (Hoffman and Schrag, 2002). To date, however, there is only one paleomagnetic result, from the Elatina Formation of South Australia, that directly places the Marinoan glaciation in equatorial latitudes (Schmidt and Williams, 1995; Sohl et al., 1999; Evans, 2000).

The Huqf Supergroup of Oman (Fig. 1) preserves a continuous Neoproterozoic to younger Paleozoic sedimentary sequence that contains evidence for at least two large glacial events; i.e., the tillites of the Ghubrah and Fiq Formations. The age of the Huqf Supergroup is constrained by a U-Pb zircon age from an ash unit in the lower part of the group, which has been dated at 711.8 ± 1.6 Ma (Allen et al., 2002), whereas at the top of the unit a date of 544.5 ± 3 Ma suggests deposition into the Early Cambrian (Amthor et al., 2003). The Ghubrah therefore fits in the Sturtian glacial bracket, between 750 and 695 Ma, and is thought to correlate with other glaciogenic sections, such as the Pocatello Formation of Idaho (Fanning and Link, 2004). The Fiq Formation unconformably overlies the Ghubrah and Saqla Formations in Oman. It has previously been assigned a Marinoan age, based on carbon isotope comparisons with other sec-
The glaciomarine Fiq diamict incorporates marine interglacial cycles (Leather et al., 2002; Kellerhals and Matter, 2003), and is overlain by a dolostone cap carbonate, the Hadash Formation. This grades into the Masirah Bay Formation, a silty carbonate, which is abruptly overlain by the Khufai limestone. In south Oman, the Mirbat Formation, comprising diamict, overlain by a thin carbonate and turbiditic siltstones and sandstones, is also included in the Huqf Supergroup. Although predominantly unaltered, the Huqf Supergroup has undergone some tectonism. In the Jebel Akhdar in northern Oman (Fig. 1B), much of the folding is Cretaceous in age, with some evidence for early Paleozoic deformation (Blendinger et al., 1990; Gass et al., 1990). In the Huqf region of eastern Oman (Fig. 1D), strike-slip faulting began in the late Precambrian and continued through much of the Paleozoic (Husseini and Husseini, 1990). In south Oman (Fig. 1C), the Mirbat Formation shows little sign of deformation.

PALEOMAGNETIC RESULTS

Drilled cores and hand samples for paleomagnetic analysis were collected from a total of 44 sites across Oman in the 3 main locations of the Huqf Supergroup (Fig. 1). In the Fiq Formation, six sites (20 samples) were sampled, mostly located in sandstone interbeds within the tillite. Where possible, samples of tillite clasts were also collected. The Hadash Formation was sampled at 21 sites (60 samples) and the Masirah Bay Formation at 5 sites (36 samples). In the Mirbat Formation, samples of the dolostone, tillite, and siltstone were collected from 12 sites (31 samples). Where possible, samples were taken from either side of local fold structures. The samples were cut into 2.5-cm-diameter cores. Measurements of natural remanent magnetism (NRM) were carried out in a field-free room with a 2G cryogenic magnetometer: 404 specimens were demagnetized by using standard progressive thermal and alternating field techniques. During thermal treatment, the samples were systematically reoriented to detect spurious, laboratory-induced magnetization. In order to identify the characteristic remanent magnetism (ChRM), the components of demagnetization for each specimen were analyzed by the least-squares methods (Kirschvink, 1980).

Magnetic behavior and NRM intensity varied both between and within lithologies. Typically, the fine red siltstone units of the Fiq and Mirbat Formations have the highest initial NRM, ~30 mA/m. The dolostones of the Hadash and lower Mirbat Formations and the carbonate silts of the Masirah Bay units range between 0.5 mA/m and 30 mA/m. Although in many specimens patterns of demagnetization were too poor to confidently assign a trend, in more than 30% of specimens, stable components of magnetization were revealed: a low-stability component A with a maximum unblocking temperature ($T_{ub}$) of 400 °C, and a higher-stability component B, with a maximum $T_{ub}$ of ~600 °C (Fig. 2; GSA Data Repository Table DR11 presents the site mean data and associated statistical parameter). Component A is identified in 28% of specimens. In some specimens, it is the ChRM, present to peak temperature and trending toward the origin on orthogonal demagnetization plots. Component A points down at a shallow angle in a northerly direction. After tilt correction, the $\alpha_90$, a cone of 95% confidence describing the spread of a set of data, increases slightly, whereas $k$, the precision parameter, decreases. Component A therefore fails a fold test, indicating that it was imprinted after folding. In some specimens, a similar low-temperature component is identified pointing south and up. When inverted, this fits with component A, passing a reversal test. The direction of component A is statistically indistinguishable from the present earth field in Oman and is therefore interpreted as a magnetism of recent origin, probably a chemical remanent magnetization acquired during weathering over at least the past 780 k.y., since the time of the last magnetic reversal.

Component B is identified in 21% of samples, commonly between 400 and 600 °C, and in some cases at lower temperatures, always as a ChRM. Component B points either at a shallow angle upward and to the north, or in the opposing direction, down and southward. After bedding correction, the dispersion of the data decreases significantly, and the data pass both the McElhinny (1964) fold test and the Enkin (2003) fold test at the 95% confidence level (Fig. 2). Given that a number of sites contained only a few specimens, we also ran the fold test excluding those sites with fewer than three specimens. The results were similar, but with positive fold tests using both the McElhinny (1964) and Enkin (2003) tests. Given that the earliest folding in Oman is Cambrian–Ordovician in age (Blendinger et al., 1990; Gass et al., 1990), this result indicates that component B is either primary or an early magnetic reset acquired prior to folding.

For this study, sites with a negative inclination and declination close to north are as-
signed a normal polarity, and south-down vectors are assigned a reversed polarity. This assumes that Arabia was in the Southern Hemisphere in the late Precambrian, an argument consistent with Gondwana assembly. A Northern Hemisphere location would simply involve switching these polarity assignments. The south-down directions cluster well with the north directions after inversion, implying at least one reversal. Figure 3 shows a composite magnetostratigraphy based on reversals identified in the combined north Oman sections and the Mirbat Formation. In north Oman, a reverse polarity horizon is identified in the Fiq Formation in a site in Wadi Mistal, ~400 m below the base of the Hadash Formation; ~300 m higher in the unit, a site in Wadi Saha demagnetizes with normal polarity, indicating a reversal in the upper part of the Fiq Formation. Component B in the Hadash Formation is predominantly of reverse polarity. However, above the solid dolomite, in the lowermost of four dolomite-silt interbeds, a reversed polarity horizon is present in Wadi Bani Awd. In the Huqf region, where the dolomite is thinner, one site 2 m from the base of the outcrop is normal. This pattern is mirrored by the Mirbat dolomite with reversals at the base, and one normal polarity horizon in the lowermost of two dolomite-silt interbeds. A normal polarity horizon is identified ~150 m from the base of the middle Mirbat member, in site Mir03, with a similar normal horizon in one site, Msb04, in the Huqf region. All sites above this, in the middle Mirbat Formation, have reverse polarity. The presence of reversals at the same stratigraphic level in distinct basins is a strong indication, when combined with the fold test, that the magnetization was acquired during deposition, and as such, we interpret component B as a primary component of magnetization.

**DISCUSSION AND CONCLUSIONS**

Given that our sampling sites extend over 6° of latitude we report our result in terms of a mean pole. A comparison of the corresponding paleopole for component B (52.3°S, 74.4°E; N = 25 sites; k = 16.7; α95 = 7.3°), rotated into African coordinates, with those of a similar age from other elements of Gondwana (taken from Meert, 2003), also rotated into African coordinates, is presented in Figure 4A. If the various elements that made up Gondwana had been assembled at this time the poles should also converge. Geological evidence suggests that the collision between Arabia and North Africa had occurred by the Cambrian (Meert, 2003). The disparity between the Neoproterozoic Gondwana poles and the paleopole from this study suggests that the eventual collision between Arabia and North Africa took place after ca. 600 Ma (Davies et al., 1980; McWilliams and McElhinny, 1980; Schmidt and Williams, 1996; Sohl et al., 1999; Meert, 2003). The distribution of paleopoles also implies that the paleogeography at the time was characterized by a series of separate land masses, rather than one large supercontinent (Fig. 4B).

This result provides a high-reliability datum for low-latitude (~13.0°) calculated for a location at Muscat, Oman) glaciation and supports extensive late Neoproterozoic cooling. Our result is the first to directly indicate that deposition of both the tillite and the overlying cap carbonate took place at the same latitude in the tropics. We note, however, that magnetic reversals are present in both the tillite and the overlying cap carbonate. The identification of a sharply defined reversal toward the top of the cap carbonate may indicate that deposition of this unit could have taken place over time scales of at least 10^5–10^6 yr, or, alternately, there are significant variations in the rates of deposition between the solid dolomite lower in the Hadash Formation and the overlying dolomite-silt interbeds that form the upper part of the Hadash Formation. Similar reversals have been described for the Puga cap carbonate in the Amazon craton (Trindade et al. 2003), though these have proved controversial because the mean direction is close to the present earth field for the area and there are no field tests to constrain the age of magnetization.

Sedimentary cyclicity in the low-latitude Fiq Formation is comparable with modern glacial-interglacial alternations, and the presence of wave ripple marks indicates open-ocean deposition (Leather et al., 2002; Kellershohn and Matter, 2003). This implies that tropical latitudes were not continuously covered by ice during the Marinoan snowball episode, meaning that both CO_{2} and methane could be freely released from the oceans to the atmosphere at this time, consistent with some less extreme climate models (Crowley et al., 2001).

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