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Quantifying magnetite magnetofossil contributions to sedimentary magnetizations

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ABSTRACT

Under suitable conditions, magnetofossils (the inorganic remains of magnetotactic bacteria) can contribute to the natural remanent magnetization (NRM) of sediments. In recent years, magnetofossils have been shown to be preserved commonly in marine sediments, which makes it essential to quantify their importance in palaeomagnetic recording. In this study, we examine a deep-sea sediment core from offshore of northwestern Western Australia. The magnetic mineral assemblage is dominated by continental detritus and magnetite magnetofossils. By separating magnetofossil and detrital components based on their different demagnetization characteristics, it is possible to quantify their respective contributions to the sedimentary NRM throughout the Brunhes chron. In the studied core, the contribution of magnetofossils to the NRM is controlled by large-scale climate changes, with their relative importance increasing during glacial periods when detrital inputs were low. Our results demonstrate that magnetite magnetofossils can dominate sedimentary NRMs in settings where they are preserved in significant abundances.

1. Introduction

Magnetotactic bacterial magnetosomes are permanent nanomagnets that, when arranged in chains, provide a means for the bacteria to orient themselves using Earth's magnetic field (Blakemore, 1975; Blakemore et al., 1980; Kirschvink, 1980a; Simmons et al., 2006). After death, these magnetically ideal single domain (SD) magnetosomes can be incorporated into the sedimentary matrix as magnetofossils. They then have the potential to contribute to sedimentary magnetizations if they maintain an existing alignment (or become aligned after burial) with the ambient geomagnetic field (Kirschvink, 1979; Stolz et al., 1986; Tarduno et al., 1998; Abrajevitch and Kodama, 2009) and if they avoid diagenetic dissolution through burial in anoxic environments (Karlin and Levi, 1983; Canfield and Berner, 1987). Their ideal SD size means that such magnetofossil-based magnetizations should provide a stable, but potentially nonlinear, record of geomagnetic field variations (Tauxe, 1993; Roberts et al., 2012).

Early studies identified magnetofossils in marine sediments and demonstrated that both chains and dispersed particles could carry stable laboratory-induced remanences (Kirschvink and Chang, 1984; Petersen et al., 1986; Stolz et al., 1986; Hesse, 1994). In some sediments, specific magnetofossil-rich horizons have elevated natural remanent magnetization (NRM) intensities with SD-like demagnetization characteristics, which suggests that magnetofossils contribute to their palaeomagnetic record (Tarduno et al., 1998; Abrajevitch and Kodama, 2009). These observations have led to the hypothesis that a biogeochemical remanent magnetization (BgRM), acquired by geomagnetically-aligned magnetosome chains preserving their orientation in the sedimentary record, can contribute to sedimentary NRMs. The consequences of BgRM acquisition would be especially important if the bacteria lived below the surface mixed sediment layer (e.g., Tarduno et al., 1998) and produced an NRM contribution that is offset from the palaeomagnetic signal carried by detrital particles. Alternatively, if magnetotactic bacteria lived in the water column or uppermost part of the sediment column, the post-mortem magnetofossil remains would be reoriented by both geomagnetic torques and a variety of sedimentary processes in the same manner as detrital magnetic particles. These magnetofossils would therefore contribute to a depositional (or postdepositional) remanent magnetization rather than a BgRM.

Testing the contribution of magnetofossils to the palaeomagnetic record has been a challenge until recently because of a lack of rock magnetic techniques that could be used to detect magnetofossils effectively. Instead, time-consuming magnetic extractions and transmission electron microscope (TEM) imaging were necessary to identify magnetofossil particles (e.g., Petersen et al., 1986; Hesse, 1994), which limits the number of samples that can be investigated.

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Developments in magnetic "remote sensing" have revealed that magnetofossils are much more widespread in the geological record than was thought previously (Egli, 2004; Egli et al., 2010; Roberts et al., 2012). Mathematical unmixing of laboratory-induced remanence curves demonstrates that a variety of sediment types contain apparent magnetofossil components with narrow size distributions and coercivities consistent with magnetite (Kruiver et al., 2001; Egli, 2004; Abrajevitch and Kodama, 2009). First-order reversal curve (FORC) measurements provide a joint measure of the coercivity and interaction field distribution for fine magnetic particle systems (Pike et al., 1999). Thus, FORC diagrams have high diagnostic power, and allow identification of different domain states of particles within mixed magnetic mineral assemblages (Roberts et al., 2000). FORC distributions from magnetosome chains have a clear SD signature with a wide distribution of coercivities, but minimal interactions (Pan et al., 2005; Chen et al., 2007; Carvallo et al., 2009; Roberts et al., 2012; Li et al., 2012). Egli et al. (2010) developed a high-resolution FORC measurement protocol that allows proper quantification of the distribution produced by non-interacting SD particles, the so-called "central ridge" in a FORC diagram. Magnetosomes are flux linked and in combination behave as a single elongated SD particle (Dunin-Borkowski et al., 1998; Muxworthy and Williams, 2006, 2009), so that intact magnetofossil chains will contribute to the FORC central ridge signature. High-resolution FORC distributions are, therefore, an important diagnostic tool for detecting magnetofossils.

While rock magnetic data can provide strong evidence for the presence of magnetofossils, their interpretation is not unique. TEM observations can support the presence of magnetofossils, which have specific compositions, crystal structures, a limited size spectrum and a restricted range of characteristic morphologies (Petersen et al., 1986; Tarduno et al., 1998; Kopp and Kirschvink, 2008). Although magnetic particle extraction and TEM imaging are time consuming, analysis of a small number of samples can provide sufficient evidence to interpret more rapidly acquired rock magnetic data in terms of magnetofossil identification. Using a combination of TEM and rock magnetic techniques, recent work has provided strong support for the common occurrence of magnetofossils in a variety of marine sediments (Roberts et al., 2011, 2012; Chang et al., 2012; Larrasoaña et al., 2012; Yamazaki, 2012; Yamazaki and Ikehara, 2012).

Now that the experimental tools needed to identify magnetofossils are available, it is important to quantify their contribution to sedimentary NRMs. In this study, we present results from a Quaternary marine sediment core in which magnetofossils appear to be ubiquitous and where their relative contribution to the NRM is primarily modulated by detrital input from the nearby Australian continent. When the relative magnetofossil abundance is high, the sedimentary magnetization becomes more SD-like in its characteristics, therefore providing strong support for a dominant contribution of magnetofossils to the NRM. With the assumption of a two end-member mixing system, the magnetofossil contribution to the overall sedimentary NRM can be determined as a function of age.

2. Geological setting

Core MD00-2361 (113°28.63′E, 22°04.92′S) was recovered ~41 km off the coast of northwestern Western Australia at a water depth of 1805 m during the *Marion Dufresne* TIP 2000 expedition (Fig. 1). The summer climate of this region is dominated by the Australian monsoon, with large rainfall episodes causing rivers to flood and transport large volumes of sediment to the ocean (Gingele et al., 2001a). Satellite images have revealed sediment-laden river plumes extending 200–300 km offshore during the northern Australia wet season (Gingele and De Deckker, 2004). The position of core MD00-2361 is ~160 km from the

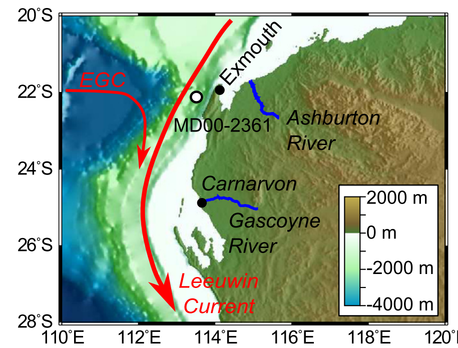

Fig. 1. Indian Ocean bathymetry and location of sediment core MD00-2361 (open symbol) offshore of northwestern Western Australia. The near-surface Eastern Gyral Current (EGC) and Leeuwin Current (red arrows) are adapted from Tomczak and Godfrey (1994). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

mouth of the Ashburton River (Fig. 1), in a location expected to receive suspended riverine sediment advected southward by the Leeuwin Current (Spooner et al., 2011, Fig. 1). During the winter months, northwestern Western Australia is dry and the rivers have a reduced carrying capacity, or in some cases they dry out completely (Gingele et al., 2001a). During such dry periods aeolian dust is transported eastward along the so-called Indian Ocean dust path and contributes to the terrigenous flux that reaches the Indian Ocean (Bowler, 1976; McTainsh, 1989; Hesse and McTainsh, 2003). The relative contributions of riverine and aeolian sediment fluxes that reach the Indian Ocean from northwestern Western Australia have been shown to vary on glacial–interglacial time scales. During glacial periods, northwestern Western Australia was relatively cold and arid, with increased aeolian fluxes and reduced riverine fluxes (Hesse, 1997, 2003). In contrast, interglacial periods were characterized by warm and wet conditions with increased river transport and reduced aeolian activity (Gingele et al., 2001b).

3. Materials and methods

Core MD00-2361 is 42 m long; we have analyzed the uppermost 16.5 m of the core in this study. We analyzed 11 continuous 1.5-m long u-channel samples from the upper portion of the core. A detailed late Quaternary palaeoceanographic reconstruction, based on the upper 13.6 m of core MD00-2361, has been published by Spooner et al. (2011).

Magnetic measurements were made at 1-cm intervals with a 2-G Enterprises narrow-access pass-through cryogenic magnetometer (Weeks et al., 1993) at the National Oceanography Centre, Southampton, UK. NRMs were demagnetized in 12 steps up to a maximum field of 100 mT with an alternating field (AF) demagnetizer that is arranged in-line with the magnetometer. NRM demagnetization data were analyzed with the UPmag software of Xuan and Channell (2009) and characteristic remanent magnetization (ChRM) directions were defined using the principal component analysis approach of Kirschvink (1980b). Isothermal remanent magnetizations (IRMs) were imparted to the u-channel samples with a 2-G Enterprises off-line pulse magnetizer. The IRM at 900 mT is assumed to represent the saturation isothermal remanent magnetization (SIRM).

Subsamples were taken from the u-channels at 10 cm stratigraphic intervals, and were crushed gently and air-dried. Hysteresis and backfield demagnetization measurements were performed using a Princeton Measurements Corporation vibrating sample magnetometer at the Research School of Earth Sciences, Australian National University. First-order reversal curve (FORC) diagrams (Pike et al., 1999; Roberts et al., 2000) were measured for a selection