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Magnetic properties of pelagic marine carbonates

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ABSTRACT

Pelagic carbonates are deposited far from continents, usually at water depths of 3000–6000 m, at rates below 10 cm/kyr, and are a globally important sediment type. Recent advances, with recognition of widespread preservation of biogenic magnetite (the inorganic remains of magnetotactic bacteria), have fundamentally changed our understanding of the magnetic properties of pelagic carbonates. We review evidence for the magnetic minerals typically preserved in pelagic carbonates, the effects of magnetic mineral diagenesis on paleomagnetic and environmental magnetic records of pelagic carbonates, and what magnetic properties can tell us about the open-ocean environments in which pelagic carbonates are deposited. We also discuss briefly late diagenetic remagnetisations recorded by some carbonates. Despite recent advances in our knowledge of these phenomena, much remains undiscovered. We are only at early stages of understanding how biogenic magnetite gives rise to paleomagnetic signals in sediments and whether it carries a poorly understood biogeochemical remanent magnetisation. Recently developed techniques have potential for testing how different magnetotactic bacterial species, which produce different magnetite morphologies, respond to changing nutrient and oxygenation conditions. Future work needs to test whether it is possible to develop proxies for ancient nutrient conditions from well-calibrated modern magnetotactic bacterial occurrences. A tantalizing link between giant magnetofossils and Paleogene hyperthermal events needs to be tested; much remains to be learned about the relationship between climate and the organisms that biomineralised these large and novel magnetite morphologies. Rather than being a well-worn subject that has been studied for over 60 years, the magnetic properties of pelagic carbonates hold many secrets that await discovery.

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1. Introduction

Carbonate sediments are deposited on the seafloor of ~50% of the world ocean (Fig. 1a). In addition, marine carbonates crop out on 10% of the global land surface (Blatt et al., 1980; Fig. 1a). The total world volume of hydrocarbons hosted by carbonates has been estimated at 50%, and the ease with which fluids can flow and react with carbonates has made them a common host of ore deposits (Blatt et al., 1980). Much of the carbon on Earth is stored in carbonate sediments, which makes these sediments a crucial part of the global carbon cycle (e.g., Archer et al., 2000). Carbonate sediments are, therefore, a globally important sediment type. In this paper, we focus on pelagic carbonates, which are defined as those deposited far from the continents, usually at water depths of 3000–6000 m, and at rates slower than 10 cm/kyr (Berner, 1980) with carbonate contents greater than 30%. Paleomagnetic studies have frequently targeted pelagic carbonate sediments, especially since development of superconducting rock magnetometers (Goree and Fuller, 1976), because they often contain high-fidelity records of the ancient geomagnetic field. Classic studies of marine carbonates demonstrated that the latitudinal distribution of ancient carbonate rocks mirrors that of modern carbonates once corrected for paleolatitude (e.g., Briden and Irving, 1964; Irving, 1964). They have also been used to demonstrate the geocentric axial dipole (GAD) field hypothesis (e.g., Opdyke and Henry, 1969), which is a cornerstone of paleomagnetism. Extensive studies of Mesozoic and Cenozoic Tethyan carbonates have made fundamental contributions to tectonic reconstructions (e.g., Channell and Tarling, 1975; Lowrie and Alvarez, 1975; VandenBerg et al., 1978), magnetobio-chronology (e.g., Alvarez et al., 1977; Lowrie and Alvarez, 1977a; Roggenthen and Napoleone, 1977; Lowrie and Alvarez, 1981; Lowrie et al., 1982; Napoleone et al., 1983; Speranza et al., 2005; Jovane et al., 2007; Coccioni et al., 2008; Jovane et al., 2009, 2013), and have provided evidence that led to the Cretaceous–Tertiary boundary impact hypothesis (e.g., Lowrie and Alvarez, 1977a; Alvarez et al., 1980). High-quality magnetic polarity records, which mirror the expected polarity pattern of the geomagnetic polarity timescale (GPTS), have also been reported from Cenozoic pelagic carbonates in the Atlantic (e.g., Tauxe et al., 1983; Mead et al., 1986; Tauxe and Hartl, 1997; Channell et al., 2003; Edgar et al. 2010), Indian (e.g., Touchard et al., 2003; Savian et al., 2013), Pacific (e.g., Valet and Meynadier, 1993; Schneider et al., 1997; Lanci et al., 2004, 2005; Channell et al., 2013; Guidry et al., 2013; Yamazaki et al., 2013) and Southern Oceans (e.g., Channell and Stoner, 2002; Roberts et al., 2003; Florindo and Roberts, 2005; Fuller et al., 2006; Florindo et al., in press).

Lowrie and Heller (1982) and Freeman (1986) reviewed the magnetic properties of marine carbonates and outlined many details concerning their magnetic stability, magnetic properties, and magnetic mineralogy. Our understanding of the magnetic properties of pelagic carbonate sediments has undergone a recent revolution (e.g., Roberts et al., 2011, 2012; Larrasoaña et al., 2012; Yamazaki, 2012; Yamazaki and Ikehara, 2012; Channell et al., 2013) through use of techniques that enable better discrimination of the sources of fine-grained magnetic particles in sediments. In this paper, we summarise these developments and document the magnetic properties observed in globally distributed pelagic carbonates. Despite the substantial recent advances in our understanding of the magnetic properties of marine carbonates, many issues remain unresolved. We outline some of these important issues in the hope that concerted research will be undertaken to resolve these outstanding problems.

2. Formation, preservation and distribution of pelagic marine carbonates

Carbonate formation in marine environments is controlled by water temperature and concentration of dissolved CO_2. Carbonates will only precipitate in waters that are low in CO_2; because CO_2 is more soluble in cooler waters, carbonate is more likely to form in tropical seas (± 30° latitude). Likewise, carbonate precipitation is favoured thermodynamically at high temperatures and low pressures, which makes low latitude surface waters an ideal environment for carbonate precipitation. However, even if carbonate precipitates in surface waters, it might not survive export from the photic zone to the seafloor. There is a well-known relationship between water depth and carbonate deposition; the so-called carbonate compensation depth (CCD) results from the effect of pressure on calcite solubility (Archer, 1996), and is the depth at which the amount of $CaCO_3$ delivered from above is equal to the amount removed by dissolution. The lysocline occurs at shallower depths than the CCD and is the depth at which carbonate dissolution rapidly increases; it separates the upper waters in which planktonic calcareous skeletons are well preserved from the lower waters where they are more poorly preserved. The position of the CCD is variable in space and time because of deep-sea acidification that results from remineralisation of organic matter as it settles from the photic zone. This effect means that the Atlantic Ocean, which has recently ventilated deep waters with high pH, supports carbonate preservation at greater water depths (average of ~5500 m) than the Pacific Ocean (average of ~4500 m) where deep water is acidified by organic matter respiration (Archer, 1996). The global distribution of carbonate in seafloor sediments (Fig. 1a) is, therefore, a function of water temperature, water depth (pressure), pH, and relative dilution by terrigenous sediment components (Archer et al., 2000).

Many carbonates form on shallow water platforms at low latitudes, where water depths are typically <20 m. Modern shallow water carbonates account for only 5% of the global distribution of carbonate sedimentation, while 95% occurs on oceanic slopes and on the deep seafloor (Blatt et al., 1980). While many of the magnetic mineral types discussed in this paper also occur in shallow water carbonates (carbonate platforms, atolls or reefs), we focus explicitly on carbonate sediments deposited in open-ocean pelagic environments because of their greater comparative geographic and stratigraphic importance. Pelagic carbonate sediments are primarily oozes that consist of the remains of planktonic foraminifera and coccolithophores, although aragonite (from pteropods and heteropods), which is more soluble than calcite, can contribute to the carbonate fraction of sediments deposited at intermediate depths such as those near mid-ocean ridge crests. Calcareous nannofossils (produced by coccolithophores) have contributed to