Palaeogeography, Palaeoclimatology, Palaeoecology 418 (2015) 75–89

Contents lists available at ScienceDirect

Palaeogeography, Palaeoclimatology, Palaeoecology

journal homepage: www.elsevier.com/locate/palaeo

Challenging the sensitivity limits of Paleomagnetism: Magnetostratigraphy of weakly magnetized Guadalupian–Lopingian (Permian) Limestone from Kyushu, Japan

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ARTICLE INFO

Article history:
Received 5 July 2014
Received in revised form 14 October 2014
Accepted 28 October 2014
Available online 4 November 2014

Keywords:
Paleomagnetism
Limestone
Permian
Kiaman superchron
Illawarra Reversal
Mass extinction

ABSTRACT

Despite their utility for bio- and chemostratigraphy, many carbonate platform sequences have been difficult to analyze using paleomagnetic techniques due to their extraordinarily weak natural remanent magnetizations (NRMs). However, the physical processes of magnetization imply that stable NRMs can be preserved that are many orders of magnitude below our present measurement abilities. Recent advances in reducing the noise level of superconducting magnetometer systems, particularly the introduction of DC-SQUID sensors and development of a low-noise sample handling system using thin-walled quartz-glass vacuum tubes, have solved many of these instrumentation problems, increasing the effective sensitivity by a factor of nearly 50 over the previous techniques of SQUID moment magnetometry.

Here we report the successful isolation of a two-polarity characteristic remanent magnetization from Middle–Late Permian limestone formed in the atoll of a mid-oceanic paleo-seamount, now preserved in the Jurassic accretionary complex in Japan, which had proved difficult to analyze in past studies. Paleothermometric indicators including Conodont Alteration Indices, carbonate petrology, and clumped isotope paleothermometry are consistent with peak burial temperatures close to 130 °C, consistent with rock magnetic indicators suggesting fine-grained magnetite and hematite holds the NRM. The magnetic polarity pattern is in broad agreement with previous global magnetostratigraphic summaries from the interval of the Early–Middle Permian Kiaman Reversed Superchron and the Permian–Triassic mixed interval, and ties the Tethyan–Panthalassan fusuline zones to it. Elevated levels of hematite associated with the positive $\delta^{13}C_{carb}$ of the Kamura event argue for a brief spike in environmental oxygen. The results also place the paleo-seamount at a paleolatitude of ~12° S, in the middle of the Panthalassan Ocean, and imply a N/NW transport toward the Asian margin of Pangea during Triassic and Jurassic times, in accordance with the predicted trajectory from its tectono-sedimentary background. These developments should expand the applicability of magnetostratigraphic techniques to many additional portions of the Geological time scale.

1. Introduction

A fundamental goal of stratigraphy is to establish interbasin correlations with globally-isochronous time horizons, including the critical stratotype horizons, and to correlate these to the magnetic reversal patterns of the Geomagnetic Reversal Time Scale (GRTS), which should be essentially isochronous on a global scale. Most of the global stratotype sections and points (GSSPs) have been defined in fossiliferous, shallow marine carbonate platform sequences due to their proven ability to record pristine biological and geochemical records of Earth history. Unfortunately, it is well known that biostratigraphically-defined zone boundaries are often diachronous, and local oceanographic and geological effects can influence geochemical proxies for chemostratigraphic correlation.

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http://dx.doi.org/10.1016/j.palaeo.2014.10.037
0031-0182/

Efforts to use paleomagnetic techniques for unraveling magnetic polarity patterns in many GSSPs, however, have often proven frustrating. Prominent examples include the original definition of the Silurian–Devonian stratotype at Klonk, in the Czech Republic, where the metamorphic grade appears to have been too high to retain primary paleomagnetism (Ripperdan, 1990), and several Ordovician GSSPs on Anticosti Island, Canada (Ripperdan, 1990; Seguin and Petryk, 1986), where many of the pale carbonates were found to be too weakly magnetized to measure and demagnetize reliably using the conventional techniques of 25 years ago. From these studies it was simply not known whether the rocks had concentrations of magnetic minerals too small to produce a measureable moment, or if diagenetic processes and hydrocarbon migration had destroyed those that were there initially.

It has long been known that the physical processes of aligning magnetic minerals during the formation of sedimentary rocks can preserve stable magnetic components that are many orders of magnitude below the measurement ability of the best superconducting rock (moment) magnetometers (Kirschvink, 1981), even those using the enhanced sensitivity of DC-biased superconducting quantum interference devices (DC-SQUIDs) (Weiss et al., 2001). In fact, the situation is much worse than this sensor noise limit, as the intrinsic magnetic moment of most of the sample holders used in paleomagnetic studies (background noise) is typically several orders of magnitude higher than the sensor limit. DC-SQUID sensors in the commercially available 2G Enterprises™ rock magnetometers typically have r.m.s. magnetic moment noise levels of a few tenths of a pAm^2 (a few $\times 10^{-10}$ emu), whereas most sample holders measure at a few tens of pAm^2 (10^{-7} emu), several orders of magnitude higher. Recently, the introduction of acid-washed, thin-walled quartz-glass tubing for supporting samples with a vacuum has lowered this noise greatly by minimizing the amount of extraneous matter in the sense region of the SQUID magnetometers (Kirschvink et al., 2008). Coupled with a computer-controlled pick-and-place sample changing system, this permits the large numbers of precise demagnetization experiments needed for magnetostratigraphic studies to be performed rapidly.

We chose the Middle–Late Permian limestone from Kamura in Kyushu, Japan, to test the suitability of these new sample-measuring techniques because previous rock magnetic work (Yokoyama et al., 2007) demonstrated that these rocks contained fine-grained magnetite and hematite, but in concentrations making the NRM difficult to analyze. Most of the Jurassic accretionary complex in SW Japan that contains exotic Permian limestone blocks suffered at most lower greenschist facies metamorphism around 140 Ma (Isozaki et al., 1990), usually characterized by the mineral paragenesis of pumpellyite–actinolite, except some locally baked domains in close contact with the Cretaceous–Paleogene granitic intrusions. Although the Kamura area in central Kyushu is located near an active volcanic region, there are ample indications from the local geology that these rocks were never affected significantly by thermochemical alteration. The studied interval straddles the Middle–Late Permian boundary (Isozaki and Ota, 2001; Ota and Isozaki, 2006) and thus records the end-Guadalupian mass extinction event (Jin et al., 1994; Stanley and Yang, 1994) and possibly the top of the Kiaman Reversed Superchron, known as the 'Illawarra Reversal' (Cottrell et al., 2008; Courtillot and Olson, 2007; Gialanella et al., 1997; Gradstein et al., 2012; Irving, 1964; Isozaki, 2009; Opdyke et al., 2000), offering the possibility of enhancing the correlation between the two time scales. In particular, the first appearance of a solid Normal interval is critical in identifying the Illawarra Reversal that is expected within Wordian (Middle Guadalupian) time.

Application of these new techniques to the Kamura limestone reveals the presence of a stable, 2-polarity characteristic NRM that is broadly consistent with past studies of the geomagnetic polarity chronology for late Permian Time, including the top of the Kiaman Superchron. The characteristic direction, and the match to the reversal chronology, indicates that the Kamura atoll was located at about 12° South latitude in the Panthalassic Ocean. A minimum of 3000 km of N/NW transport would have been required for it to dock against the Eastern margin of Pangea during Jurassic time. The present result also has profound implications to the bio- and chemostratigraphic correlation between the mid-superoceanic paleo-atoll limestone and continental shelf carbonates around Pangea.

2. Geological setting

2.1. Tectono-sedimentary background

The Permian and Triassic limestone at Kamura (Takachiho town, Miyazaki prefecture; Fig. 1) in Kyushu forms a part of an ancient mid-oceanic atoll complex primarily developed on a mid-oceanic paleo-seamount (Isozaki, 2014; Isozaki and Ota, 2001; Kasuya et al., 2012; Ota and Isozaki, 2006; Sano and Nakashima, 1997). This limestone occurs as a several kilometer-long, lensoid allochthonous block within the Middle–Upper Jurassic disorganized mudstone/sandstone of the Jurassic accretionary complex in the Chichibu belt, southwest Japan, with remarkably little internal deformation (Fig. 2). The orientation of the late Paleozoic to early Mesozoic subduction zone beneath the Asian blocks (Isozaki, 1997a,b) implies that the seamount originated to the east (Pacific side) with respect to Asia, i.e., somewhere in the superocean Panthalassa, and accreted to the Asian margin in the Jurassic, approximately 100 million years later. The limestone blocks in the Kamura area retain parts of the primary mid-oceanic stratigraphy (ca. 135 m in thickness), and range from Wordian (middle Guadalupian) to Norian (Upper Triassic) time with several sedimentary breaks in the Triassic part (Isozaki, 2014; Kambe, 1963; Kanmera and Nakazawa, 1973; Kasuya et al., 2012; Koike, 1996; Ota and Isozaki, 2006).

2.2. Lithostratigraphy and paleoenvironments

The Iwato Formation consists of ca. 100 m-thick, dark gray to black bioclastic limestone. Bioclasts include fragments of bivalves, calcareous algae, crinoids, fusulines and other small foraminifera, indicating Guadalupian age. The lower part of the Iwato Formation comprises wackestone with a black, organic-rich matrix and yields abundant large bivalves (Family Alatoconchidae) and large-tested fusulines (e.g., *Neoschwagerina, Yabeina, Lepidolina*). The upper part comprises peloidal wackestone. Black organic matter probably of microbial origin is concentrated in peloids. Megafossils are absent in this interval, except for very rare rugose coral (*Liangshanophyllum*) from the uppermost part. All black limestones are free from dolomitization.

The overlying Mitai Formation consists of nearly 40 m-thick, light gray bioclastic dolomitic limestone. Bioclasts are derived from calcareous algae, crinoids, ostracodes, gastropods, bivalves, crinoids, brachiopods, coral, fusulines and small foraminifera of the Tethyan affinity, and indicate Lopingian age. The limestones are mostly grainstone/wackestone with lesser amounts of lime–mudstone that are fossiliferous, mostly massive, partly including 1 cm-thick, continuous to discontinuous bands with concentrations of peloids and algae. Crystals of secondary dolomite are generally concentrated around bioclasts (and avoided in the paleomagnetic sampling). The lowermost 1 m-thick bed is characterized by white bands containing abundant dolomitized dasycladacean algae.

All the Tethyan fusuline assemblages and associated fossils from the Iwato and Mitai formations indicate that the seamount was located in a low-latitude domain in the superocean Panthalassa under a tropical climate (Isozaki, 2006, 2014; Isozaki and Aljinovic, 2009; Kasuya et al., 2012).

2.3. Bio- and chemostratigraphy

Conodonts, the index fossils with the highest resolution for the Permian, have unfortunately not been found in the Permian Iwato and Mitai formations where our paleomagnetic samples come from, as the sedimentary facies was too shallow to host conodont animals. Fusulines are the most abundant among fossils, and they provide a basis for