Earth and Planetary Science Letters 453 (2016) 96–107

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

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When and why sediments fail to record the geomagnetic field during polarity reversals

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ARTICLE INFO

Article history:
Received 8 April 2016
Received in revised form 10 June 2016
Accepted 28 July 2016
Available online 24 August 2016
Editor: B. Buffett

Keywords:
geomagnetic reversals
magnetization acquisition
rock magnetism
sediment
demagnetization

ABSTRACT

We present four new records of the Matuyama–Brunhes (M–B) reversal from sediments of the Equatorial Indian Ocean, West Equatorial Pacific and North Atlantic Oceans with deposition rates between 2 cm/kyr and 4.5 cm/kyr. The magnetic measurements were performed using 8 cc cubic samples and provided well-defined reverse and normal polarity directions prior and after the last reversal. In three records stepwise demagnetization of the transitional samples revealed a succession of scattered directions instead of a well-defined characteristic component of magnetization. There is no relationship with changes in magnetic mineralogy, magnetic concentration and magnetic grain sizes. This behavior could be caused by weakly magnetized sediment. However the transitional samples of two cores have almost three orders of magnitude stronger magnetizations than the non-transitional samples that yielded unambiguous primary directions in the other two cores. Moreover a similar proportion of magnetic grains was aligned in all records. Therefore, the large amount of magnetic grains oriented by the weak transitional field did not contribute to improve the definition of the characteristic component. We infer that the weakness of the field might not be only responsible. Assuming that the transitional period is dominated by a multipolar field, it is likely that the rapidly moving non-dipole components generated different directions that were recorded over the 2 cm stratigraphic thickness of each sample. These components are carried by grains with similar magnetic properties yielding scattered directions during demagnetization. In contrast, the strongly magnetized sediments of the fourth core from the West Equatorial Pacific Ocean were exempt of problems during demagnetization. The declinations rotate smoothly between the two polarities while the inclinations remain close to zero. This scenario results from post-depositional realignment that integrated various amounts of pre- and post-transitional magnetic directions within each sample. The present results point out the impossibility of extracting reliable information on geomagnetic reversals from low-medium deposition rate sediments with the current sampling techniques. Among other features, they put in question the relationship between reversal duration and site latitude.

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1. Introduction

Most paleomagnetic records of reversals has been published during the past 40 years from sedimentary sequences with accumulation rates mostly varying from 2 to 5 cm/kyr and in some very rare cases up to 10–12 cm/kyr. Despite the existence of a large database, no consensus has emerged yet concerning the structure and geometry of the transitional field, and reversal models remain controversial (Clement and Constable, 1991; Bogue and Merrill, 1992; Jacobs, 1994; Roberts, 1995; Merrill and McFadden, 1999; Constable, 2003; Amit et al., 2010; Valet and Fournier, 2016). Among various issues, a typical example was the controversy concerning the apparent tendency of virtual geomagnetic pole (VGP) paths to be confined within two preferred longitudinal bands. The longitudinal confinement of some VGP paths is puzzling when faced to the large dispersion of the transitional VGPs derived from high resolution records. This situation leads us to question the meaning of the magnetic signal recorded by sediments during reversals. This is also justified by our limited knowledge of the processes involved in sediment magnetization (see e.g. Katari and Bloxham, 2001; Tauxe et al., 2006; Shcherbakov and Sycheva, 2010; Spassov and Valet, 2012; Roberts et al., 2013). A first unknown is that magnetization depends on time required for locking-in the orientation of magnetic grains present at the same level. A second parameter is the fidelity of magnetic alignment in presence of low field intensity and a third one, barely considered, is the

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http://dx.doi.org/10.1016/j.epsl.2016.07.055
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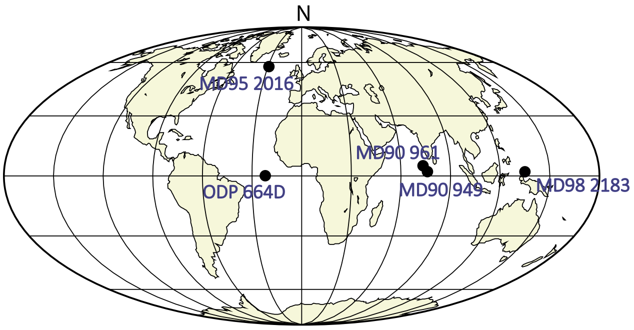

Fig. 1. Geographic locations of the four studied cores and of ODP Hole 664D.

ability of sediment magnetization at accounting for rapid field changes. It is puzzling that most transitional demagnetization diagrams are of low quality and in fact rarely discussed in detail, while they may reveal interesting information. The first question that comes to mind concerns the reproducibility of the results. Reversal records from very nearby sites (Valet et al., 1988; Van Hoof and Langereis, 1992; Van Hoof et al., 1993) have been shown to be coherent with each other, but they were recorded in similar environments, and therefore may be potentially biased by the same artifacts. The non-dipole field is reorganized substantially over a period of approximately 1 kyr (Lhuillier et al., 2011). Therefore, temporal and spatial variability of the non-dipolar field may generate different transitional field behavior at relatively distant sites. Assuming an accumulation rate of 5 cm/kyr, no more than two 8 cc cubic paleomagnetic samples describe a 1 kyr long transitional period. No critical evaluation has been proposed so far concerning the meaning of sedimentary reversal records with accumulation rates of the order of 4–5 cm/kyr because emphasis was placed on the importance of building up a large dataset. In summary, we are faced to a situation in which a large number of results has been published, while tools are missing to evaluate the fidelity of the records. In fact, we do not really know what is the potential of sediments to document polarity transitions.

A first basic approach might be to compare distinct records of the same reversal from nearby and distant locations. This would allow us to check for their consistency by combining their magnetic characteristics and their resolution. This paper analyzes four distinct records of the last reversal (Matuyama–Brunhes, M–B). Three records were obtained at equatorial sites from sediments deposited in distinct environmental conditions, and the last one comes from a high latitude North Atlantic Ocean site.

2. Core locations and samplings

Three cores were taken at the equator in the Indian and Pacific oceans. Cores MD90-949 and MD90-961 were collected during the Seymama cruise of the French R.V. Marion Dufresne in 1990 at nearby sites that differ by only 3° in latitude and longitude. Core MD90-949 (2°06.90′N 76°06.50′E) is 28 m long and was taken at 3600 m water depth. Sediment is dominated by nanofossil ooze. The site of core MD90-961 (05°03.71′N, 73°52.57′E) is located to the east of the Maldives Platform (Fig. 1). Beryllium and paleointensity measurements have documented the field intensity changes across the last reversal recorded by this sediment (Valet et al., 2014). Lithology is composed of calcareous nanofossil ooze with abundant foraminifera. The 37 m long core MD97-2183 (2°00.82′N, 135°01.26′E) was also taken by the R-V Marion-Dufresne in the western Pacific ocean and consists of hemipelagic clay with calcareous and siliceous microfossils. Previous measurements of U-channels taken from the entire core by Yamazaki and Oda (2004) helped to determine the position of the last reversal. Lastly, core MD95-2016 was obtained at high latitude (57.42°N, 370.8°E) in the North Atlantic ocean (Fig. 1) and is dominated by brown gray clay. Note that all four cores were obtained using the same coring system on board the R.V Marion-Dufresne, and therefore no large difference between records should be imputed to the coring technique. All cores were sampled using 8 cm^3 cubic plastic boxes taken adjacent to each other and in a few cases with a 1 cm overlap. No U-channel has been used to avoid additional smearing of the signal that considerably bias the transition records (Valet and Fournier, 2016).

Except in core MD95-2016, previous magnetic measurements performed on U-channels indicated the depth of the last reversal in each core (Yamazaki and Oda, 2004; Valet et al., 2014). Sediment thickness above the last reversal gives the average deposition rate at each site during the past 800 kyr. The lowest accumulation rate $v = 2.8$ cm/kyr was found at site MD90-949 and provides a resolution as low as 0.714 kyr per sample. The Indian Ocean sediment core MD90-961 has the fastest deposition rate of 4.8 cm/kyr so that each typical 2 cm thick sample integrates 0.42 kyr of geomagnetic history. Its proximity to core MD90-949 gives the opportunity of comparing two records with different resolution. Based on the B–M stratigraphic position, the average accumulation rate of the sediment from core MD97-2183 is 4.3 cm/kyr. However, the time-depth correspondence derived from the record of relative paleointensity proposed by Yamazaki and Oda (2004) suggests 3.8 cm/ka for the Brunhes chron and 7 cm/ka for the past 200 ka that, according to the authors, could reflect oversampling during coring. These two values give a field integration between 0.48 kyr and 0.52 kyr within a 2 cm sample. Lastly, core MD95-2016 from North Atlantic has an accumulation rate of 4 cm/kyr yielding a maximum resolution of 0.5 kyr per sample. Interestingly, these last three records are characterized by similar resolution. Rapid variations in deposition rates cannot be excluded, but they would be without major relevance to the conclusions and observations of the present study.

3. Demagnetization characteristics

All samples were stepwise demagnetized by alternating fields at small increments of 2 to 5 mT (depending upon evolution of their magnetic moment) until complete demagnetization between 60 and 80 mT. They were measured in four different positions using a 2G cryogenic magnetometer. In order to fully describe the evolution of demagnetization within each sequence, we show on purpose all demagnetization diagrams of the samples close to and within each transitional interval. They have been plotted in Figs. 2 and 3 using the PaleoMac software (Cogné, 2003). Further information is given in Figs. S1–S3 that show the evolution of the directions on stereoplots and the evolution of the magnetic moments after each demagnetization step. The name of each sample is given in centimeters and corresponds to its stratigraphic depth downcore. Declinations were corrected from core orientation by adjusting the mean normal declinations of the Brunhes chron to zero. Despite many demagnetization steps and care taken at isolating the characteristic component of magnetization, most demagnetization diagrams of samples close or within the transitional interval are of much poorer quality than the normal or reverse polarity samples. Below we describe the demagnetization characteristics of the samples with intermediate directions between the two polarities in each core. They are highlighted in Figs. 2 and 3.

The declination of samples between 2153 cm and 2150 cm in core MD90-949 (Figs. 2 and S1) jumps from south to north. The demagnetization diagrams show that after removing a soft overprint with positive inclination, the successive directions are highly scattered and located in two opposite quadrants of the demagnetization diagram. There is a scattered succession of directions dominated by either reverse or normal polarity. No transitional di-

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