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Geomagnetic moment instability between 0.6 and 1.3 Ma from cosmonuclide evidence

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[1] The reliability of paleomagnetic records as proxies of the geomagnetic field intensity is still a matter of controversy since volcanic materials hardly provide continuous records, and marine sediments are suspected to carry a remanence biased by post-depositional realignments and/or by overprints. Such long standing debate emphasizes the need for the development of methods independent from paleomagnetism to decipher geomagnetic intensity variations. High resolution measurements of authigenic ^{10}Be/^{9}Be along with a detailed sedimentary record of directional and relative paleointensity variations evidence, over the 0.6–1.3 Ma time interval, frequent and recurrent excursions or short events in the late Matuyama and the early Brunhes epochs, among which two Brunhes-Matuyama reversal precursors and an intra-Jaramillo excursion. The results of this study confirm the idea of a highly unstable geomagnetic field as suggested by paleomagnetic evidences. *INDEX TERMS:* 1060 Geochemistry: Planetary geochemistry (5405, 5410, 5704, 5709, 6005, 6008); 1513 Geomagnetism and Paleomagnetism: Geomagnetic excursions; 1521 Geomagnetism and Paleomagnetism: Paleointensity; 1535 Geomagnetism and Paleomagnetism: Reversals (process, timescale, magnetostratigraphy); 3022 Marine Geology and Geophysics: Marine sediments—processes and transport; *KEYWORDS:* Geomagnetic excursions and reversals, paleointensity, geomagnetic moment, authigenic ^{10}Be/^{9}Be, cosmogenic isotope production, marine sedimentary archives. **Citation:** Carcaillet, J. T., N. Thouveny, and D. L. Bourlès, Geomagnetic moment instability between 0.6 and 1.3 Ma from cosmonuclide evidence, *Geophys. Res. Lett.*, *30*(15), 1792, doi:10.1029/2003GL017550, 2003.

1. Introduction

[2] Paleomagnetic studies carried on marine sediments document a strong variability of the geomagnetic dipole moment associated with polarity reversals and excursions [*Valet et al.*, 1994; *Guyodo and Valet*, 1999]. It has been suggested that over the last 4 Ma a saw tooth structure has determined the occurrence of reversals and the duration of stable polarity phases [*Valet and Meynadier*, 1993]. Alternative interpretations have suggested that viscous overprints carried by particles with long relaxation time artificially introduce the observed pattern [*Kok and Tauxe*, 1996; *Meynadier et al.*, 1998; *Kok and Tauxe*, 1999; *Valet and Meynadier*, 2001]. Since neither the volcanic paleomagnetic record, nor the high resolution near-seafloor magnetic anomalies record [*Gee et al.*, 2000] can reach an appropriate resolution and accuracy, the ongoing debate on continuous sedimentary records of paleointensity needs an independent approach to check the validity of sedimentary paleomagnetic signatures. Primarily controlled by variations of the magnetic cut-off rigidity, directly related to the intensity of the magnetic field [*Elsasser et al.*, 1956; *Lal*, 1992; *Masarik and Beer*, 1999; *Dunai*, 2001], the cosmonuclide production rate provides the appropriate approach [*Henken-Mellies et al.*, 1990; *Frank et al.*, 1997; *Baumgartner et al.*, 1998; *Masarik and Beer*, 1999].

2. Site Presentation

[3] The screening of the cosmonuclide producing primary cosmic ray particles by the horizontal component of the geomagnetic field being maximum near the equator, we focused on the 37.4 m long core MD97-2140 collected in the West Equatorial Pacific (02°02′59″N, 141°45′49″E, 2547 m water depth) with the Calypso corer during the IMAGES III campaign (1997) by the R. V. Marion Dufresne. The studied sedimentary sequence is composed of homogeneous grey to light grey hemipelagic clayey carbonate ooze. Its location, remote from variable terrigenous fluxes and its fairly high and constant sedimentation rate constitute the prerequisite conditions of an undisturbed and detailed cosmonuclide record. As emphasized by *Raisbeck et al.* [1979, 1985], bioturbation and/or reworking by bottom currents in low sedimentation rate sites can smooth over the cosmonuclide signatures, as it may have occurred in previous studies [*e.g., Raisbeck et al.*, 1979; *Henken-Mellies et al.*, 1990].

3. Synthesis of Paleomagnetic Results

[4] Paleomagnetic subsampling was performed by continuous measurements on U-channels of the natural remanent magnetization (NRM) with a DC SQUID magnetometer (2G-760R) equipped with an alternating field (AF) demagnetizer. The stability of the NRM was tested by stepwise AF treatments applied from 5 to 100 mT, revealing medium destructive fields of 20 to 30 mT. The main magnetic carriers were identified by hysteresis parameters and Curie T° determination as pseudo-single domain titanomagnetite (see electronic supplement)[1]. Stable directions of the characteristic remanent magnetization (ChRM) were isolated after removal of a soft viscous overprint at a 5 mT AF step.

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[1] Auxiliary material is available at ftp://ftp.agu.org/apend/gl/2003GL017550

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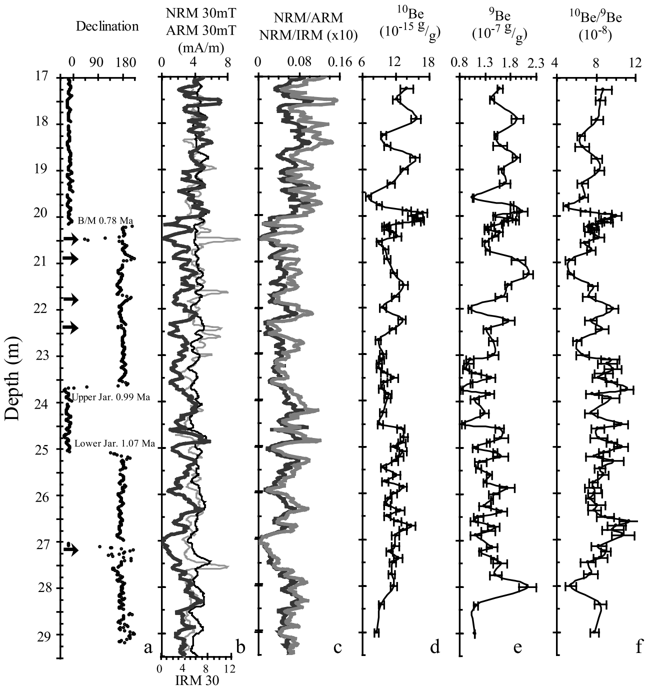

Figure 1. Paleomagnetic and beryllium isotope results vs depth of core MD97-2140. (a) Declination (°) (arrows indicate large amplitude declination swings); (b) Intensities of the NRM (mA/m), ARM (10^{-2} A/m) and IRM (10^{-1} A/m); (c) Relative paleointensities (NRM/ARM at 30 mT, 10 × NRM/IRM at 30 mT); (d) ^{10}Be concentrations (10^{-15} g/g) with error bars including statistical errors and instrumental uncertainties (see Methods); (e) ^{9}Be concentrations (10^{-7} g/g) with error bars expressing the statistical error of the fit of the standard addition lines (see Methods); (f) ^{10}Be/^{9}Be ratio (10^{-8}) with errors propagated from (d) and (e).

Except in the upper 12 m where sediments carried a secondary fabric induced by the coring, the average ChRM inclination (0°) is compatible with the axial dipole field hypothesis at the site latitude.

[5] Declination variations document polarity reversals at ~20.18, 23.76 and 25.24 m (Figure 1a) as well as large amplitude swings at ~20.48 m, 20.90 m, 21.76 m, 22.38 m, 27.08 m, suggesting the occurrence of transient directional instabilities attributed to excursions. The declination reversals recorded at 20.18 m, 23.76 m and 25.24 m are identified as the Brunhes-Matuyama (B-M), Upper Jaramillo, and Lower Jaramillo polarity transitions, whose ages, according to the Geomagnetic Polarity Time-Scale (GPTS) [*Shackleton et al.*, 1990; *Hilgen*, 1991] are 0.78 Ma, 0.99 Ma and 1.07 Ma, respectively (Figure 1a). Between 25 and 20.5 m depth, these ages yield a constant sedimentation rate of 1.75 cm/ka that was then applied to the whole studied interval.

[6] This homogeneous sedimentary sequence is well-suited to decipher geomagnetic paleointensity variations, since concentration and grain size parameters (magnetic susceptibility, anhysteretic and isothermal R.M. and their ratio) fulfill the restrictive criteria generally required for NRM normalization [*Tauxe*, 1993]. Relative PaleoIntensity (RPI) variations reconstructed by normalizing the NRM intensity with the Anhysteretic R. M. (ARM) intensity and with the Isothermal R.M. (IRM) intensity (Figure 1b) exhibit similar profiles (Figure 1c). Highly variable RPI variations (Figure 1c) suggest a permanent instability of the geomagnetic moment intensity, which is markedly expressed as drastic drops at the time of reversals and excursions.

4. Beryllium Isotope Study

4.1. Methods

[7] Based on directional and RPI records, 72 subsamples of ~500 mg (dry sediment) were collected between 1725 and 2900 cm for beryllium isotope analyses using a regular 25 cm sampling interval, adequately reduced to 10 cm near and within paleointensity minimum intervals. ^{10}Be concentrations measured in marine sediments not only depend on ^{10}Be production rates but also on oceanic and sedimentary effects [*Anderson et al.*, 1990; *Bourlès et al.*, 1989; *Robinson et al.*, 1995; *Frank*, 2000]. To account for such disturbing effects on sedimentation rates as well as on chemical and granulometric composition of the sediments, the authigenic (i.e., adsorbed onto particles from the water column) ^{10}Be and ^{9}Be were extracted, since only soluble forms of both beryllium isotopes have been homogenized in the water column before deposition [*Robinson et al.*, 1995; *Bourlès et al.*, 1989]. A selective leaching technique [*Bourlès et al.*, 1989] has thus been used. Authigenic ^{9}Be concentrations have been measured by furnace atomic absorption spectrometry using the method of standard additions and a Zeeman effect background correction (Hitachi Z-8200). Uncertainties in ^{9}Be concentrations are based on the reproducibility of measurements where several analyses were performed on the same sample or estimated from the fit of the standard addition lines in the case of single measurements. After isotopic dilution with 0.3 mg of ^{9}Be, authigenic ^{10}Be concentrations were determined through measurements of the ^{10}Be/^{9}Be ratio performed at the Tandetron AMS facility in Gif-sur-Yvette [*Raisbeck et al.*, 1987; 1994]. The measured ratios were calibrated directly against ^{10}Be/^{9}Be of the National Institute of Standards and Technology standard reference material SRM 4325. The authigenic ^{10}Be uncertainties were estimated using a conservative 5% instrumental uncertainty together with one standard deviation statistics of the number of ^{10}Be events counted (less than ±3%). All authigenic ^{10}Be concentrations presented are decay corrected (Half life = 1.5 Ma).

4.2. Results

[8] The authigenic ^{10}Be and ^{9}Be records present similar fluctuations probably linked to variations in the terrigeneous input (Figure 1d, e). To account for this effect, authigenic ^{10}Be and ^{9}Be concentrations were expressed as authigenic ^{10}Be/^{9}Be ratios that appropriately account for transient variations of environmental parameters, and represent reliable proxies of the ^{10}Be production rates (Figure 1f) [*Robinson et al.*, 1995; *Bourlès et al.*, 1989]. These ratios exhibit a fluctuating pattern of medium amplitude onto which abrupt variations of large amplitude are superimposed.

[9] After transfer to an age scale, authigenic ^{10}Be/^{9}Be variations (Figure 2a) are compared to the MD97-2140 RPI record (Figure 2b) and to two RPI reference records: Californian margin ODP site 1021 [*Guyodo et al.*, 1999]

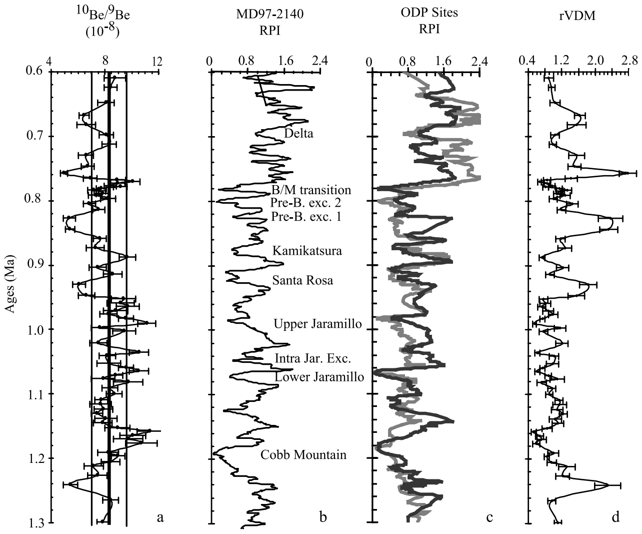

Figure 2. Authigenic ^{10}Be/^{9}Be, cosmogenic derived rVDM, and RPI records vs ages. (a) ^{10}Be/^{9}Be (10^{-8}); vertical lines are mean value and mean value $\pm 1\sigma$; (b) Relative paleointensity along MD97-2140 with identification of reversals and excursions; (c) Relative paleointensity along ODP 1021 (black curve) [*Guyodo et al.*, 1999] and ODP 848 and 851 (grey curve) [*Valet and Meynadier*, 1993]. Time scales of these records were adjusted by allowing slight readjustment of main features to the MD97-2140 time scale in order to better evidence the similarity between the 3 presented records; (d) M/M$_0$ derived from authigenic ^{10}Be/^{9}Be; error bars propagated from 2a.

and Equatorial Pacific ODP sites 848–851 [*Valet and Meynadier*, 1993] (Figure 2c). Significant ^{10}Be/^{9}Be increases (i.e., exceeding the critical value set at "average $+1\sigma$") coincide with, or lag, magnetic reversals. A 97% increase occurs at 0.77 Ma (i.e., slightly after the B-M [transition, this delay (0.01 Ma)], most likely results from a delayed acquisition of post-depositional remanent magnetization (PDRM) due to a significant lock-in depth (18 cm).

[10] A 55% increase at ~0.99 Ma coincides with the Upper Jaramillo and a 31% increase at ~1.06 Ma coincides with the Lower Jaramillo. A significant ^{10}Be/^{9}Be increase at ~1.03 Ma correlate to a low RPI event within the Jaramillo event at 1.04 Ma; another increase at 1.16–1.17 Ma correlates to a RPI low at 1.18 Ma, associated with a transient full reversal. Again, the delay (0.01–0.02 Ma) most likely results from a delayed PDRM acquisition due to a lock-in depth of at least 18 cm.

[11] Two low RPIs at 0.8 and 0.82 Ma, concomitant with excursional signatures, are associated with less significant ^{10}Be/^{9}Be increases overprinted on the general trend leading to the ^{10}Be/^{9}Be maximum of the B-M boundary. Low RPIs at 0.88 and 0.91–0.92 Ma are expressed by a single significant ^{10}Be/^{9}Be peak at 0.885 Ma.

4.3. A Cosmonuclide Derived Relative Virtual Dipole Moment Record

[12] A relative Virtual Dipole Moment (rVDM) record (Figure 2d) has been derived from the authigenic ^{10}Be/^{9}Be using the simple and direct physical relationship between the cosmogenic production rate and the geomagnetic moment: $P/Po = (M/Mo)^{-1/2}$ [*Elsasser et al.*, 1956], where P is the measured ^{10}Be/^{9}Be ratio, Po the record ^{10}Be/^{9}Be average value, and M/Mo the rVDM. Comparison of this rVDM record with the RPI record from the same core and those from the two other sites in the Pacific region showed that the lowest rVDM phases correspond to the low RPI phases associated with the previously cited geomagnetic reversals.

[13] The early Brunhes epoch starts with the maximum rVDM value at 0.76 Ma rapidly followed by a return to low rVDM at ~0.7 Ma expressed in all RPI records and assignable to the Delta excursion [*Creer et al.*, 1980]. Similarly, the evolution toward the rVDM high at ~0.67 Ma is expressed in all RPI records. Finally the rVDM decreasing trend from 0.65 to 0.6 Ma is in agreement with two of the RPI records.

[14] The occurrence of a B-M precursor suggested by studies of marine [*Kent and Schneider*, 1995; *Hartl and Tauxe*, 1996] and loess sequences [*Sun et al.*, 1993] is generally considered as an artifact of the remanence acquisition. Nevertheless, both data sets, RPI and cosmogenic derived VDMs, evidence two successive drops at 0.80 and 0.82 Ma that are precursors of the B-M transition, the oldest one being dated at 0.821 ± 0.013 Ma [*Quidelleur et al.*, 2002]. Moreover, these data sets firmly evidence a progressive rVDM decrease leading to the minimum rVDM of the B-M transition.

[15] In the low rVDM interval documented between 0.85 and 0.92 Ma, two excursions named Kamikatsura and Santa Rosa have been reported [*Doell et al.*, 1968; *Champion et al.*, 1988] and dated at 0.886 ± 0.003 Ma and 0.922 ± 0.012 Ma, respectively [*Singer et al.*, 1999].

[16] Between 0.99 and 1.07 Ma (i.e., during the Jaramillo normal event) rVDMs remain low and exhibit a significant decrease at 1.04 Ma. This feature is assignable to a short polarity reversal described in a continental sedimentary sequence of New Zealand and dated prior to 1.05 ± 0.05 Ma [*Pillans et al.*, 1994]. More recently, the occurrence of an intra-Jaramillo excursion was supported by directional and paleointensity data recorded in North Atlantic marine sequences [*Channell et al.*, 2002] and in a loess sequence of Northern China [*Guo et al.*, 2002].

[17] A paleointensity drop between 1.10 and 1.12 Ma assignable to the Punaruu event, a short reversal dated at 1.105 ± 0.005 Ma [*Singer et al.*, 1999], does not appear during the long lasting rVDM decreasing trend preceding the Lower Jaramillo transition.

[18] The oldest period of low rVDM ranging from 1.15 to 1.21 Ma is associated with a sharp declination shift assignable to the Cobb Mountain event [*Mankinen et al.*, 1978] dated at 1.181 ± 0.007 Ma [*Renne et al.*, 1998]. The duration (0.08 Ma) and amplitude of rVDM and RPI decreasing trends leading to this short event constitute one of the most prominent feature of the whole record.

5. Conclusion

[19] By an independent approach this cosmonuclide record validates the relative paleointensity records and reveals a dominantly weak and highly variable VDM regime over the 1.3–0.6 Ma interval. Two major and long lasting (at least 50 ka) periods of decreasing VDM lead to the Brunhes-Matuyama polarity transition and to the Cobb

Mountain short event. The B-M transition is preceded by two VDM lows, confirming the occurrence of pre-transitional excursions, and is followed by a rapid but transient recovery to high VDM values. Other VDM lows are associated with the Upper and Lower Jaramillo transitions and with several excursions.

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