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A first-order correction to minimize environmental influence in sedimentary records of relative paleointensity of the geomagnetic field

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[1] We propose a simple method to minimize the residual environmental influence which may exist in paleointensity records obtained from sediments. It consists of adding, or subtracting, a fraction of the normalizer (κ , ARM, or IRM) to the normalized intensity record, so that the corrected record exhibits fluctuations uncorrelated with those of the normalizer. This method was tested with paleointensity records obtained from two cores taken at midlatitude in the South Indian Ocean cores, eastward of the Kerguelen plateau. For each core, correction increases the correlation between the three normalized intensity records, NRM/ κ , NRM/ARM, and NRM/IRM. It also reduces the coherence between paleointensity records and bulk magnetic parameters used as normalizers. Although it has to be used with caution, this correction may improve paleointensity records by reducing nongeomagnetic influence. It can also be used to detect intervals where paleointensity may be unreliable, i.e., intervals where large differences between uncorrected and corrected records are observed, before and after correction.

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1. Introduction

[2] Geomagnetic field paleointensity records are widely used to better understand the core dynamics and how the geomagnetic field is generated, to intercorrelate sediments deposited in environmental contexts [Guyodo and Valet, 1996, 1999; Laj *et al.*, 2000, 2004; Stoner *et al.*, 2000], and sediments with ice [Wagner *et al.*, 2001]. Because Earth's magnetic field partially deflects incoming cosmic rays, paleointensity records are also of great inter-

est for evaluating the past abundance of radiocarbon in the different natural reservoirs, and therefore in 14-C age determinations [Elsasser *et al.*, 1956; Mazaud *et al.*, 1991; Laj *et al.*, 2002]. Consequently, obtaining high-resolution records of past geomagnetic field intensity has become one of the major objectives of the paleomagnetists for the last 10 years. Efforts were put on sediments, because they can provide continuous records, despite only relative changes of past field intensity are obtained. In principles, paleointensity records are obtained

from sediments by dividing the intensity of the Natural Remanent Magnetization (NRM) left after removal of any viscous component by a normalizer, which represents the variability in the “magnetization potential” of the sediments [Johnson *et al.*, 1948]. The Anhysteretic Remanent Magnetization (ARM), the Isothermal Remanent Magnetization (IRM), and the low field susceptibility (κ) are used as normalizers [Johnson *et al.*, 1975; Hartl *et al.*, 1993; Harrison, 1966]. κ is determined by the amount, nature and size of the magnetic grains inside the sediment, but also by the paramagnetic fraction of the sediment, so that its use may be more delicate. Thus ARM and IRM, which depend solely on the ferro/ferri magnetic phase, are usually preferred to κ . Reliable paleointensity records can be obtained only if the magnetic characteristics of the natural field recorder exhibit limited changes down core, and criteria were proposed to select sediments suitable for paleointensity determination [King *et al.*, 1983; Tauxe, 1993]. The NRM must be carried by stable magnetite preferably in the grain size range of 1–15 μm , concentration variations of more than an order of magnitude should be avoided. However, our knowledge of the processes responsible for the magnetization of pelagic sediments is far from being complete, and a number of non-geomagnetic phenomena can affect the magnetic record in sediment, such as changes in grain size and mineralogy variations caused by climatic and environmental variations, and/or diagenetic processes in the sedimentary column [Tarduno and Wilkinson, 1996; Schwartz *et al.*, 1996; Smirnov and Tarduno, 2000]. Consequently, it is delicate to assess the exact accuracy of normalized records, and classical tests consist of comparing the records obtained with the 3 normalizers, which should give consistent results, and of calculating the coherence function between the normalized intensity record and the normalized, in order to detect environmental contamination [Tauxe, 1993; Tauxe and Wu, 1990]. Here we propose to reduce the non geomagnetic contribution which may exist in normalized intensity records by adding, or subtracting, a fraction of the normalizer, so that the corrected paleointensity and the normalizer records exhibit uncorrelated fluctuations.

2. Methodology

[3] Normalization of the cleaned NRM intensity by κ , ARM, or IRM, is classically used to correct for the variation in the amount of magnetic remanence

Figure 1. (a) ARM, IRM, and κ records of core MD94-103 versus depth. Marine Isotopic Stages (MIS) boundaries are indicated. (b) NRM/ARM, NRM/IRM, and NRM/ κ records before correction. (c) Paleointensity records after correction. Deglaciation is indicated by a rectangle.

carriers in the sediments. In the case of an ideal sediment, the normalizer activates the same grains that carry the NRM [Levi and Banerjee, 1976]. Taking ARM as the normalizer in the formula below, one can write

$$\text{IntN}(z) = \text{NRM}(z)/\text{ARM}(z) = a B(z), \quad (1)$$

where $B(z)$ is the actual paleofield intensity to be determined, z is the depth down core, $\text{IntN}(z)$ is the normalized intensity, $\text{ARM}(z)$ is the ARM value at depth z , and parameter a is a proportionality factor, not determined because sediments provide only relative paleointensities.

[4] In the case of a nonideal sediment, the normalized intensity IntN is also affected by

Table 1a. Correlation Coefficients Obtained Before Correction of Core MD94-103 Paleointensity Records^a

MD94-103	NRM/ARM	NRM/IRM	NRM/k	CC With Normalizer
NRM/ARM	1	0.81	0.80	−0.28
NRM/IRM		1	0.98	−0.55
NRM/k			1	−0.54

^a Correlation coefficients (CCs) are calculated between the different paleointensity records and also between the paleointensity records and their normalizers.

nongeomagnetic contribution due to depositional and diagenetic processes in the sediment. Here, it is assumed here that this contribution can be related to the fluctuations of the bulk sediment magnetic parameter normalizer (κ , ARM, or IRM), which tracks the variations of the magnetic material in the sediment. If this nongeomagnetic contribution is small, a linear approximation can be considered, then the nongeomagnetic contribution to be added to equation (1) can be thus expressed as

$$e(\text{ARM}(z) - \text{MARM}), \quad (2)$$

where MARM is the mean value of ARM(z) measured down core. In this linear approach, the residual nongeomagnetic contribution is therefore maximal when ARM exhibits a maximal deviation from its mean value. When this nongeomagnetic term is considered, equation (1) becomes

$$\begin{aligned} \text{IntN}(z) &= \text{NRM}(z)/\text{ARM}(z) \\ &= aB(z) + e(\text{ARM}(z) - \text{MARM}), \end{aligned} \quad (3)$$

where e is a proportionality factor, to be determined. In the ideal case, e equals zero, and the normalized intensity is strictly proportional to the paleofield intensity (1). In cases where a nongeomagnetic contribution does exist, e is not equal to zero. As a consequence, IntN is not proportional to the paleofield, because of the presence of this nongeomagnetic term.

[5] Finally, (3) can be rewritten as

$$B(z) = (1/a)\{\text{NRM}(z)/\text{ARM}(z) - e(\text{ARM}(z) - \text{MARM})\}. \quad (4)$$

Since B(z) is the actual paleofield, the “correct” (or corrected) relative paleointensity record, IntCorr, is given by

$$\begin{aligned} \text{IntCorr}(z) &= aB(z) \\ &= \text{NRM}(z)/\text{ARM}(z) - e(\text{ARM}(z) - \text{MARM}). \end{aligned} \quad (5)$$

Parameter e is the unknown parameter. Here, e is determined by an iterative trial and error process, so that the fluctuations of the corrected paleointensity record, IntCorr, and the fluctuations of normalizer exhibit a correlation coefficient (CC) lower than 0.05. It is assumed that the geomagnetic field intensity has varied independently from magnetic mineral deposition, a commonly accepted hypothesis.

3. Examples

[6] The method was tested with two cores taken from the South Indian Ocean, eastward of the Kerguelen plateau. Both cores are located at latitudes around 45°South along the southern flank of the South Indian Ocean ridge. They were taken in a zone where a large thickness of magnetite-rich sediment eroded from the Kerguelen volcanic plateau and transported by the Antarctic Circumpolar Current (ACC) accumulated [Dezileau *et al.*, 2000; Mazaud *et al.*, 2002]. Core MD94-103 (45°35'S; 86°31'E) was taken by the Research vessel Marion-Dufresne during a PACIMA cruise at a depth of 3559 m. It covers the last climatic cycle. NRM, ARM and IRM records [Mazaud *et al.*, 2002] were obtained at the LSCE with u-channel technique using small access 2G pass-through magnetometers [Weeks *et al.*, 1993]. High-resolution bulk magnetic susceptibility (κ) was measured using a Bartington sensor loop in line with a track system also designed for u-

Table 1b. Correlation Coefficients Obtained After Correction of Core MD94-103 Paleointensity Records^a

MD94-103	IntCorr(ARM)	IntCorr(IRM)	IntCorr(k)	CC With Normalizer
IntCorr(ARM)	1	0.91	0.90	−0.045
IntCorr(IRM)		1	0.98	−0.042
IntCorr(k)			1	−0.041

^a CCs are calculated between the different paleointensity records and also between the paleointensity records and their normalizers.

Figure 2. Squared coherence obtained for core MD94-103 between paleointensity records and bulk magnetic records used as normalizers, before and after correction. Confidence levels are indicated by horizontal lines. 19 kyr periodicity is indicated by a vertical line.

channels. Like several other cores from this region eastward of the Kerguelen plateau, κ , ARM, and IRM exhibit higher values during Marine Isotopic Stages (MIS) 2, 4, and 6 than during the Holocene and MIS 5 [Dezileau *et al.*, 2000; Mazaud *et al.*, 2002]. It was interpreted as reflecting a stronger deposition of magnetic grains during MIS 2, 4, and 6 [Dezileau *et al.*, 2000]. Magnetic mineralogy analyses indicated pseudo mono-domain (titano)-magnetite grains as dominant carrier of the NRM, with Curie temperature close to that of magnetite and hysteresis determinations indicate limited grain size change, within accepted criteria for paleointensity determinations [Mazaud *et al.*, 2002]. This core provides a record of the Laschamp geomagnetic event in the South hemisphere [Mazaud *et al.*, 2002; Laj *et al.*, 2006], and a geomagnetic correlation to NAPIS-75, a paleointensity record obtained from the North Atlantic [Laj *et al.*, 2000] allowed to place core MD94-103 onto the Greenland GISP2 age model in the 30–50 kyr B.P.

Figure 3. (a) ARM, IRM, and κ records of core MD88-769. Marine Isotopic Stages (MIS) boundaries are also indicated. (b) NRM/ARM, NRM/IRM, and NRM/ κ records before correction. (c) Paleointensity records after correction.

interval [Mazaud *et al.*, 2002]. ARM, IRM, and κ exhibit similar variations, with abrupt change at the time of the last deglaciation (Figure 1a). NRM/ARM, NRM/IRM, and NRM/ κ also exhibit an abrupt change concomitant to that of the bulk magnetic parameters, which makes plausible the

Table 2a. Same as Table 1a, but With Core MD88-769

MD88-769	NRM/ARM	NRM/IRM	NRM/ κ	CC With Normalizer
NRM/ARM	1	0.64	0.72	−0.01
NRM/IRM		1	0.92	−0.43
NRM/ κ			1	−0.5

Table 2b. Same as Table 1b, but With Core MD88-769

MD88-769	IntCorr(ARM)	IntCorr(IRM)	IntCorr(κ)	CC With Normalizer
IntCorr(ARM)	1	0.80	0.90	−0.01
IntCorr(IRM)		1	0.93	0.03
IntCorr(κ)			1	−0.026

idea of some environmental influence in the records of normalized intensity.

[7] The above correction method was successively applied to the three normalized intensity records, NRM/ARM, NRM/IRM, and NRM/ κ . Corrected records (Figure 1c) do not largely differ from uncorrected ones (Figure 1b). However, the correction significantly reduces the amplitude of the variation at the deglaciation (Figure 1c). As illustrated by Figure 1 and by the correlation coefficients shown in Tables 1a and 1b, the correction has improved the consistency between the three paleointensity records obtained with the 3 normalizers. Coherence was also calculated between paleointensity and normalizer, before and after correction (Figure 2). To obtain temporal spectra, core MD94-103 was aged considering radiocarbon age determinations for the past 30 kyr B.P. [Sicre *et al.*, 2005] and a geomagnetic correlation to NAPIS-75 in the 30–50 kyr B.P. interval [Mazaud *et al.*, 2002]. It is observed that the correction significantly reduces the coherence between normalized intensity records and normalizer, in particular at Earth's precession periodicity (Figure 2). Finally, the corrected NRM/ARM record is compared to GLOPIS-75 [Laj *et al.*, 2004]. Despite differences at deglaciation time and around 25 kyr B.P., this record resembles the GLOPIS-75 stack, with a marked low corresponding to the Laschamp geomagnetic event (Figure 5a).

[8] The second core, MD88-769, was taken in the same sedimentary formation, but eastward from MD94-103 during the ASPARA cruise of the R.V. Marion-Dufresne. NRM, ARM and κ were also measured at the LSCE with u-channel technique. MIS were clearly identified, and the bulk magnetic parameters exhibits variations similar to those of core MD 94-103 (Figure 3a). However, core MD88-769 is located at a greater distance from the erosion sources, the Crozet-Kerguelen plateau, than core MD94–103. Consequently, core MD88–769 is characterized by a sedimentation rate of about 6.5 cm/kyr, lower than that of core MD94–103, of about 20 cm/kyr [Mazaud *et al.*, 2002]. As for core MD94–103, above correction was successively applied to the three normalized intensity records, NRM/ARM, NRM/IRM, and

NRM/ κ . Figures 3b and 3c show the relative intensity profiles obtained before and after correction, respectively. A better consistency between the 3 normalized relative intensity profiles is obtained after correction (Figure 3). Correction increases the correlation between normalized intensity records and normalizers (Tables 2a and 2b). NRM/ARM

Figure 4. Squared coherence obtained for core MD88-769 between paleointensity records and bulk magnetic records used as normalizers, before and after correction. Confidence levels are indicated by horizontal lines. 19 kyr periodicity is indicated by a vertical line. No correction was necessary for the NRM/ARM record (see text and Tables 2a and 2b).

Figure 5. (a) Comparison between the paleointensity record of core MD94-103 (corrected NRM/ARM) and the GLOPIS-75 stack. (b) Comparison between the paleointensity record of core MD88-769 (NRM/ARM) and the GLOPIS-75 stack.

record is not changed (CC between NRM/ARM and ARM is below 0.05 before correction; see Tables 2a and 2b), but NRM/IRM and NRM/ κ records are corrected so that they closely resemble the NRM/ARM record. Coherence spectra between normalized intensities and normalizers were calculated, before and after correction (Figure 4). Age model was derived for this core by correlating its susceptibility signal to the susceptibility signal of core MD94-103. The correction reduces the coherence between NRM/IRM and IRM, and between NRM/ κ and κ . MD88-769 record resembles GLOPIS-75 record (Figure 5b). A less marked minimum in intensity is visible at the Laschamp geomagnetic event. Core MD88-769, however, has a sedimentation rate lower than that

of cores used in the GLOPIS-75 stack, so that its geomagnetic signal is more smoothed than the GLOPIS-75 stack.

4. Discussion and Conclusion

[9] We have tried to reduce the nongeomagnetic influence in normalized intensity records by considering a linear correction, in which a fraction of the normalizer is added, or subtracted, to the normalized intensity record. It can be seen as a principal component analysis, in which the corrected record is a linear combination of two initial records, the normalized intensity and the normalizer. In the two examples discussed above, correction reduces the coherence between paleointensity

records and their normalizers. It also improves the correlation between the paleointensity records obtained with the different normalizers. Because κ , ARM, and IRM differently record magnetic mineralogy and grain size changes, improvement in correlation between NRM/ARM, NRM/IRM, and NRM/ κ , is a strong indication that the correction was able to reduce the nongeomagnetic contribution remaining in each normalized intensity record, so that the three corrected records converge toward the actual (relative) paleointensity of the geomagnetic field.

[10] The proposed correction method, however, has to be used with caution. Only one parameter, e , is adjusted in order to reduce the correlation coefficient (CC) between the paleointensity record and the normalizer. CC is an indicator of the global correlation and does not document the spectral distribution of the coherence. Thus it is strongly recommended to calculate the coherence function between the normalizer and the paleointensity, before and after correction in order to check how the coherence is modified at the different frequencies by the proposed correction. Because a linear approximation is adopted for the correction, it can be only used for cores with limited changes in mineralogy and grain size, thus fitting selection criteria for paleointensity determinations. Also, because of its simplicity, the proposed correction cannot be used for artifacts like those involving convolution, such as smoothing and delayed remanence acquisition. Complication also occurs if the mineralogy exhibits complex variations, so that different corrections have to be envisaged for different depth intervals. Also, the time interval over which the correlations are calculated should be large enough, so that independence between climatic and geomagnetic fluctuations is statistically realized. For instance, in the case of core MD94–103, a calculation restricted to the last deglaciation would lead to overcorrection, in which any trend in paleointensity during the deglaciation would be eliminated. In a conservative approach, this method can be also used to detect intervals where relative paleointensity records may be unreliable, i.e., intervals where large differences between uncorrected and corrected records are observed, and/or intervals where the correction fails to reconcile the 3 normalized records, as this is for example the case for core MD88–769 in the 3.8–5.0 m interval. Comparisons with other methods will be of great interest, such as that of *Brachfeld and Banerjee* [2000] based on the use of grain size estimates and of *Hofmann et al.*

[2002, 2005], in which environmental influence is reduced by minimizing the differences between several paleointensity records obtained from a limited geographic area, so that they recorded the same geomagnetic changes.

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