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Earth and Planetary Science Letters 137 (1996) 95–99

EPSL

Saw-toothed pattern of relative paleointensity records and cumulative viscous remanence

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Received 18 October 1995; accepted 23 October 1995

Abstract

Several studies of relative paleointensity data derived from marine sediments spanning the last 4 Myr display an asymmetrical "saw-toothed" pattern. Polarity reversals of the geomagnetic field are associated with low points in paleofield intensity, preceded by a long-term progressive decay of the field and followed by a rapid post-transitional recovery [1–3]. Since similar behavior is observed in far-flung sites whose rock magnetic records are different, it is argued that the world-wide "saw-toothing" represents geomagnetic field behavior [3]. We present an alternative explanation, calling on the effect of "hard" viscous remanence.

1. Introduction

Sedimentary sequences provide the only means of studying the long-term temporal evolution of the geomagnetic field in more or less continuous time series. The intensity of natural remanence (NRM) in sediments is thought to be linearly related to that of the geomagnetic field at the time of deposition [4], but it is also affected by the particular magnetic characteristics of the sediment, such as grain size, concentration, mineralogy (see e.g., [5]). A variety of normalization techniques have been tried in order to compensate for changes in the magnetic characteristics within the sedimentary sequence (see [5] for a recent review). In addition to this changing "magnetic activity" of a sequence, there is also the likelihood that the NRM has been affected by secondary magnetizations, such as viscous remanence (VRM). The usual methods for normalization, dividing the NRM by some bulk parameter such as anhysteretic remanence (ARM), both demagnetized to some level (usually by alternating field demagnetization), are rather poor in detecting possible contributions of VRM [6]. Viscous remanence acquired over long periods (millions of years) might be resistent to the usual demagnetization techniques and could pass unnoticed. Moreover, since VRM is time dependent, sediments from around the globe could well suffer similar VRM contamination, independent of detectable differences in mineralogy. Hence, agreement of various records on a global basis is a necessary, though not sufficient, criterion for reliability of relative paleointensity estimates. In this paper, we explore how unremoved long-term VRM might affect relative paleointensity records and show that it can result in a "saw-toothed" pattern reminiscent of recently published records of paleointensity for the last 4 Myr [1–3].

SSDI 0012-821X(95)00210-3

2. VRM model

Theories of magnetic remanence suggest that when a specimen with initial magnetization of M_0 is placed in zero field, the magnetization $M(t)$ will approach the equilibrium magnetization of zero by exponential decay [7,8]

$$M(t) = M_0 e^{-t/\tau} \tag{1}$$

where t is time and τ is a decay constant known as the relaxation time, dependent on a variety of factors such as saturation magnetization, grain volume, coercivity and temperature.

If a specimen with zero initial remanence is put into a magnetic field, we expect the magnetization $M(t)$ to grow to the equilibrium magnetization M_e by the complement of Eq. (1), that is:

$$M(t) = M_e(1 - e^{-t/\tau}) \tag{2}$$

The more general case in which the initial magnetization of a specimen is nonzero can be written as:

$$\begin{aligned} M(t) &= M_0 + (M_e - M_0)(1 - e^{-t/\tau}) \\ &= M_e + (M_0 - M_e) \cdot e^{-t/\tau} \end{aligned} \tag{3}$$

which grows (or decays) exponentially from $M_0 \to M_e$ as $t \to \infty$; the rate is not only controlled by τ, but also by the degree to which the initial magnetization is out of equilibrium. We assume that the initial remanence is a constant fraction of the equilibrium magnetization and depends linearly on the intensity of the paleofield.

In general, the magnetization at a given time will be the sum of a viscous remanence and the original remanence. Depending on the τ chosen, such a VRM could be a long-term (millions of years) "hard" contamination and would not be reflected in observations on laboratory time scales.

Some data sets appear to follow the relation $M(t) = S \cdot \log(t)$, but such a relation suggests infinite remanence at $t \to \infty$, and therefore cannot be true. Such behavior can generally only be observed over a restricted time interval and closely spaced, long-term observations only rarely show a strict $\log(t)$-behavior (see e.g., [9,10]). In reality, τ will not be uniform over all magnetic particles in the specimen, but will belong to some distribution $f(\tau)$. Theoretical explanations for the $\log(t)$ observations rely on choosing $f(\tau)$ to be uniform for $\log(\tau)$ and limiting the time span of observation (see e.g., [11]). We find that Eq. (3) satisfactorily models the viscous behavior of marine sediments typical of those used for paleointensity studies, choosing $f(\tau)$ to be normally or log-normally distributed (unpubl. data).

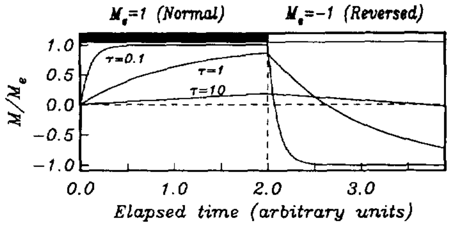

Fig. 1. Hypothetical specimens without initial remanence, with relaxation times of respectively 0.1, 1, and 10 arbitrary time units, acquire viscous magnetization until $t = 2$. The field then switches polarity, and magnetization grows in opposite direction.

Considering for the moment the simplest case of a single τ, we illustrate the effect of varying the value of τ in Fig. 1. Imaginary specimens with constant $M_0 = 0$ are placed in a magnetic field for 2 arbitrary time units. The magnetization approaches M_e according to Eq. (2). Note that relaxation times much longer than the time of observation result in apparently linear behavior. At $t = 2$, the field reverses, so that the equilibrium magnetization becomes $-M_e$. The magnetization acquired at $t = 2$ serves as initial remanence for the second part of the plot to calculate the decreasing $M(t)$ (for $t > 2$, according to Eq. 3). The rate of decay of the magnetization is much faster than the acquisition, because the magnetization at $t = 2$ is farther out of the equilibrium ($-M_e$). The parameters that control the rate at which VRM is acquired are thus τ, M_0 and the polarity (and intensity) of the magnetic field which in turn controls the sign (and magnitude) of M_e.

We turn now to the case in which a hypothetical specimen has an initial remanence $M_0 = 1$. The remanence acquired penecontemporaneously with deposition (M_0) is not in equilibrium with the prevailing field. We believe this to be generally true, because anhysteretic and thermal remanences are more likely to be closer to equilibrium and are several orders of magnitude larger than the (post-)depositional remanence acquired in the same field. Thus, after the physical orientation of the magnetic grains has ceased, the magnetization grows viscously by switching of the magnetic moments within grains

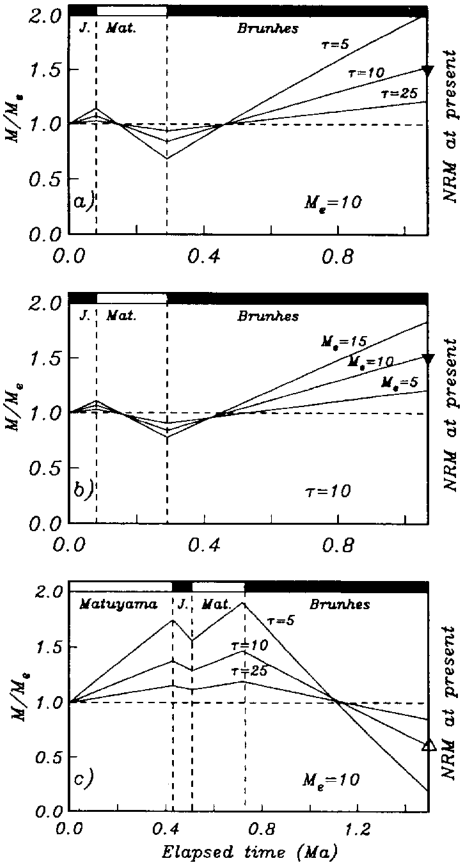

Fig. 2. (a) Relative paleointensities calculated for three values of τ and $M_e = 10$. Triangle indicates cumulative remanence at present for $M_e = 10$ and $\tau = 10$ Ma ($M_0 = 1$ for all simulations). (b) Same as (a) but now varying M_e with constant $\tau = 10$ Ma. (c) Same as (a) but deposited at 1.5 Ma in a reversed field.

and the magnetization approaches M_e. As a zero order approximation, we assume that the equilibrium magnetization (controlled by the mineralogy and the applied field) is of constant magnitude. In Fig. 2a we consider the evolution of NRM through time for a specimen which was deposited in the Jaramillo (1.07 Ma) and witnessed two subsequent field reversals. The VRM grows first parallel to M_0 until the first field reversal, followed by anti-parallel growth during the reversed Matuyama. During the Brunhes, the magnetization again grows parallel to the initial remanence, increasing to the present. We show curves using several values of τ assuming fixed $M_e = 10$. The NRM (= cumulative VRM plus M_0) at present for $\tau = 10$ Ma is shown as a triangle to the right.

We illustrate the effect of varying M_e while holding τ constant at 10 Ma in Fig. 2b. In Fig. 2c we show the evolution of cumulative remanence for a sample deposited 1.5 Myr ago (i.e., deposited during a reversed field). The VRM grows parallel to M_0 until the beginning of the Jaramillo at which point it begins to decay. In the reversed field after the Jaramillo, the remanence again grows until the Matuyama/Brunhes boundary. The Brunhes is sufficiently long for the remanence to decay to below M_0 and the NRM at present (elapsed time = 1.5 Ma) is shown by a triangle (for $M_e = 10$ and $\tau = 10$ Ma).

3. VRM in a reversing field

To calculate the remanence through a series of field reversals, we calculate the cumulative magnetization at present after $(n-1)$ polarity reversals, as the last term (M_n) of the sequence:

$$M_k = \left\{ \pm M_e + (M_{k-1} \mp M_e) \cdot e^{-\Delta t_k/\tau} \right\}_{k=1}^{n} \tag{4}$$

where term M_k is the magnetization acquired during the kth polarity interval with duration Δt_k, and M_0 is the initial magnetization. The ± and ∓ signs indicate the switching paleofield.

Now we wish to calculate the NRM at present for a hypothetical sequence spanning the last 4 Myr (Fig. 3a). We take $M_0 = 1$, $M_e = 10$ and $\tau = 10$ Ma, and use the time scale of reversals of [1] (see Table 1). The triangles indicate the points from Fig. 2b and c (deposited 1.07 and 1.5 Ma, respectively). Please note that the cumulative viscous remanence described here will "demagnetize" itself by the alternating paleofield (see [12]) and, given sufficient time, stabilize to some constant value.

As already mentioned, any real specimen will have a range of values of τ. Because of the exponential dependence of τ on grain volume and coercivity, small changes in these parameters can lead to enormous variations in τ [8]. These relaxation times will belong to some distribution $f(\tau)$, spanning perhaps from milliseconds to billions of years. So, with N values of τ_i for the relaxation times, Eqs. (3) and (4) become:

$$M(t) = M_e + \frac{M_0 - M_e}{N} \sum_{i=1}^{N} e^{-t/\tau_i} \tag{5}$$

and

$$M_k = \left\{ \pm M_e + \frac{M_{k-1} \mp M_e}{N} \sum_{i=1}^{N} e^{-\Delta t_k/\tau_i} \right\}_{k=1}^{n} \tag{6}$$

We have no a priori knowledge of $f(\tau)$. In fact, the conclusions drawn here do not depend on any particular type of distribution of τ and are valid for all those we considered (uniform, log-uniform, normal and log-normal). All that appears to be required is to have τ values in the range between about 1 and 100 Ma. Relaxation times shorter than about 1 Ma saturate quickly, generate square waves, and are also most likely to be demagnetized by normal laboratory cleaning fields (e.g., AF demagnetization to 20 mT), while the magnetization of grains with very long τ's remain close to M_0 (see Fig. 1).

Table 1
Time scale of reversals of Valet and Meynadier [1]

EVENT	Age (Ma)
Matuyama-Brunhes	0.780
Upper Jaramillo	0.990
Lower Jaramillo	1.070
Upper Olduvai	1.790
Lower Olduvai	1.950
Gauss-Matuyama	2.510
Upper Kaena	3.050
Lower Kaena	3.125
Upper Mammoth	3.225
Lower Mammoth	3.375
Gilbert-Gauss	3.600

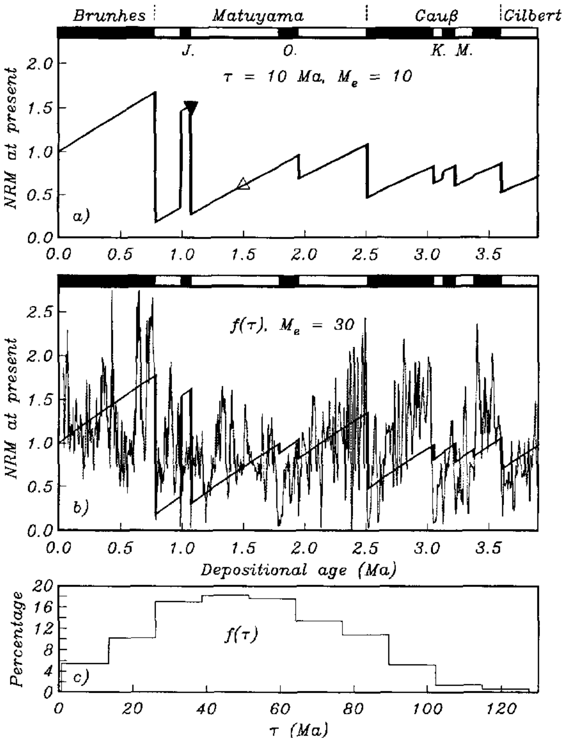

Fig. 3. (a) NRM at present as a function of depositional age using the geomagnetic reversal time scale of Table 1. $J.$ = Jaramillo; $O.$ = Olduvai; $K.$ = Kaena; and $M.$ = Mammoth. The values from Fig. 2 (shown as triangles) are also included. (b) Model of a normal distribution of τ with a mean of 50 Ma, and a standard deviation of 25 Ma ($N = 500$) (heavy line). Also shown are the sedimentary data of Valet and Meynadier [1] normalized by their mean value. (c) Histogram of τ values used.

4. Results

In Fig. 3b, we show a representative curve using a normal distribution of τ (shown in Fig. 3c). We compare our synthetic cumulative remanence model with patterns of relative paleointensity observed in sedimentary sequences from the equatorial Pacific taken during Leg 138 of the Ocean Drilling Program [1]. The cumulative remanence models do a fair job in duplicating global trend of the long-term "saw-toothing" of the sedimentary data (normalized by the mean), particularly for the period 2–4 Ma. The fit for the period 0–2 is less good, but the saw-toothed behavior is also less well expressed in the sedimentary data.

Valet and Meynadier [1] pointed out that in their relative paleointensity data, the "jump" associated with reversal boundaries (the magnitude of the recovery in intensity after a polarity reversal) was proportional to the duration of the subsequent polarity interval. Therefore, according to the authors, the Earth's magnetic field might have some "memory" of a powerful jump and resulting in a long interval of stable polarity. Since our models, with M_0 and M_e constant, show similar jumps, we argue that jumps in the measured data could be the result of the cumulative VRM acquired and lost over the subsequent parallel and anti-parallel polarity intervals.

The geomagnetic field intensity has not been of constant intensity over the last 4 Myr, nor can the distribution τ_i be assumed constant throughout such a period. On the other hand, since we are dealing with deep-sea sediments, the particles are essentially of similar origin and volume, so a rather narrow distribution around an unknown mean τ is expected. The success of our model lies in the fact that (1) the average field intensity has been approximately constant [13], (2) a constant distribution of τ probably sufficiently well characterizes the entire record (magnetic uniformity is a necessary criterion for acceptable sedimentary material in relative paleointensity studies [5] and the Leg 138 sediments were screened for this), (3) the contribution of grains with short τ's has been erased by demagnetization to ~ 20 mT (as was done by Valet and Meynadier [1]), and very long τ's hardly contribute to a magnetization acquired in a few million years. Naturally, if we allow M_0 and M_e to vary freely through time, we could model the trend of the observed data exactly. What impresses us, however, is the degree to which a rather simple model can explain the major features of the data.

5. Conclusions

In conclusion, we have a presented a plausible mechanism by which saw-toothed patterns in relative paleointensity records result from unremoved contributions from viscous remanence. The model calls on acquistion of cumulative viscous remanence and explains saw-toothing at reversal boundaries. Whereas we have not proved that saw-toothing is in fact caused by "hard" long-term VRM as opposed to being of geomagnetic origin, we have certainly provided grounds for suspicion.

Acknowledgements

We wish to acknowledge the helpful comments of Cor Langereis, Mark Dekkers, Tom Mullender, Thom Pick, Dave Dunlop, Rob Coe, and J.-P. Valet, J.-P. Valet and L. Meynadier for access to some of their data, and Chet Baker for the inspiration. The research was supported by The Netherlands Geosciences Foundation (GOA/NWO) and the US National Science Foundation (NSF). LT gratefully acknowledges partial support from the Universiteit Utrecht. [*RV*]

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