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VISCOUS DEMAGNETIZATION AND THE LONGEVITY OF PALEOMAGMETIC POLARITY MESSAGES

by

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TECHNICAL REPORT

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VISCOUS DEMAGNETIZATION AND THE LONGEVITY OF PALEOMAGNETIC POLARITY MESSAGES

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Abstract. Viscous decay of magnetic polarity messages in rocks is slowed 3-to-6 fold by the reversing nature of the geomagnetic field, compared with the effect expected in a field that is constantly polarized oppositely to the original remanence. The process is studied analytically and numerically for the known geomagnetic polarity sequence, as well as for simulated sequences having constant-length and Poisson-distributed lengths of polarity intervals. For equal average-interval lengths, the random Poisson reversing process causes more rapid decay than does the periodic reversing process.

Introduction

Many rocks and sediments are relatively unstably magnetized and cannot preserve a geomagnetic polarity message for a very long time. The longevity of the message depends on the decay time-constants of the constituent magnetic grains and also on the geomagnetic polarity sequence that has alternately assisted and hindered the retention of the original polarity. This paper describes the impact that the alternating polarity sequence has had upon the magnetization of grains with relatively short time-constants. Its purpose is to establish the minimum time-constants that are necessary for the reliable preservation of an ancient polarity message to the Present.

The paleomagnetic polarity message carried by ancient rocks undergoes endless assault by the fluctuating ambient magnetic field. Each magnetic grain continually seeks to reach a magnetization which is in harmony with its environment. The rate at which equilibrium is approached is characterized by a relaxation-time , which in Neel's theory is an exponential function of the grain's volume, saturation magnetization, temperature, microscopic coercive force, and the ambient field (c.f. Dunlop and West, 1969, equations 2-6)[3].

Numerous experiments have confirmed generally that a natural aggregate of magnetic particles, such as a rock, will seek equilibrium according to log t, where t is the exposure time to a constant ambient field. Several theories accounting for this behavior are reviewed by Dunlop (1973)[2]. The log t relation accurately describes the accumulation of viscous remanent magnetization (VRM) in igneous rocks, and has been used to infer the magnetic stability of oceanic basalts (Lowrie, 1973; Peirce et al., 1974)[6,7]. Many basalts recovered in the Deep Sea Drilling Project have demonstrated a very high rate of VRM acquisition in the laboratory, suggesting that the lineated marine magnetic anomalies are not due principally to the shallowest basaltic layers.

In a typical laboratory test, the VRM acquired by a demagnetized specimen in a weak laboratory field is observed periodically for about 10^3 hours. Measurements of VRM vs log t are then fitted with a straight line, which is extrapolated to 3×10^9 hours, the length of Brunhes Normal polarity epoch. The predicted Brunhes VRM is compared with the remanence first measured in the specimen to see if the specimen's original remanence can be explained by Brunhes VRM alone.

Rocks inferred to be stable by this laboratory VRM test nevertheless may not have correctly preserved their original polarity message. Instead, they may have lost it long before the Brunhes epoch. Given enough time, VRM will successfully contaminate all polarity records. We will examine the maximum duration of polarity messages that have been subjected to an ambient field described by the geomagnetic polarity timescale, or rather its rectangular alternating-wave representation.

Numerical Method

Begin with an hypothetical collection of grains possessing only a single magnetic time-constant τ. If the original polarity message in these grains were to survive to the Present, then it would also survive in grains with longer relaxation times. Mathematically the problem involves simple exponential decay of magnetism between the normal and reversed equilibrium extremes. We will observe the sign of magnetization as the grains are exposed numerically to the

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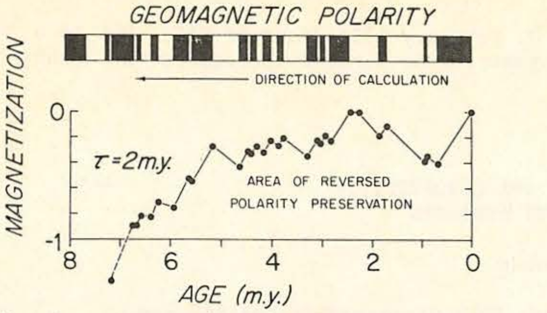

Fig. 1. Computation of greatest age for a reversed polarity message in grains with = 2 m.y. relaxation-time, using equation 2 as explained in the text. Reversed messages beginning below the curve and having m.y. will have decayed toward zero, but not have switched to normal polarity during the past 6.75 m.y. Note how the constraint of equation 2 was applied near 2.3 m.y. to keep the polarity negative when calculating backwards through time. Black is normal and white is reversed in the geomagnetic polarity log above the graph.

geomagnetic field, assumed to be bipolar with constant magnitude.

Given a starting magnetization A ($-1 \leq A \leq +1$), an equilibrium or destination value B (+1 or -1), and a single time-constant τ, the intermediate magnetization C is given by

$$C = (A-B)e^{-t/\tau} + B \qquad (1)$$

where t (a positive number) is the time elapsed. Our convention is that a positive-sign represents Normal polarity, while negative represents Reversed. The sign of B changes at each geomagnetic polarity transition, so that C fluctuates up or down, depending on the field polarity at the given time. The computation of C through time involves an iteration of equation (1) for each succeeding polarity interval. Eventually, magnetization C will switch sign, and the original polarity message will have expired. We wish to learn the maximum duration of that message. This is equivalent to low pass filtering the square-wave representation of the magnetic time-scale. The Appendix describes the general outcome of this process for periodic and Poisson rectangular waves.

In order to discover the maximum possible age for a presently expiring reversed-polarity message, the inverse of (1), namely

$$A = (C-B)e^{+t/\tau} + B \qquad (2)$$

is iterated backwards through time into preceding polarity intervals, constrained by A (past) ≤ 0, with starting conditions B (present) = + 1 and C (present) = 0. Time t, the length of the current polarity interval, is still a positive number, even though we are now moving into the past rather than into the future. Whenever A (past) attempts to exceed zero, it is held fixed at zero until a preceding reversed polarity interval is reached that draws A toward negative values again. The interation terminates when $A < (-B)$. This will occur within a Normal-polarity interval, whose younger end is the oldest the Reversed message could be.

The calculations are slightly different for Normal polarity messages. The initial condition is A = 0 at the most recent (Brunhes/Matuyama) polarity transition. The operating constraint is A (past) ≥ 0, with starting values of B = -1 and C = 0. The computation into prior times terminates in a Reversed zone, when $A > B$. The message must post-date the younger end of that interval.

Results

Numerical experiments were conducted to study the effect of the geomagnetic polarity time-scale[1,4,5,8] on grains with various relaxation-times τ. As an example, Figure 1 shows a computation for $\tau = 2$ m.y. In order for an original reversed polarity message to have survived to the Present, its age could not have exceeded 6.75 m.y. Were it not for frequent geomagnetic reversals (i.e., frequent rejuvenating periods of reversed polarity), the message here could have expired in as little as 1.4 m.y. after acquisition. The fluctuating geomagnetic polarity helped to extend the duration of

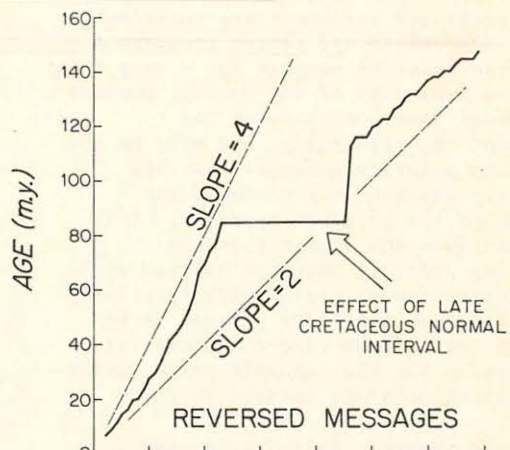

Fig. 2. Relation of relaxation-time to maximum age of Reversed polarity messages, using the composite paleomagnetic-time-scales of Heirtzler et al. (1968, 1971); Larson and Pitman (1972); Cox (1969); Talwani et al. (1971) and Larson and Pitman (1972) and assuming a bipolar geomagnetic field of constant magnitude. The calculations were made at 1 m.y. intervals of . The preservation of a reversed polarity message is seen here to depend on grains with relaxation-times exceeding 1/4 to 1/2 the age of the message. Note the large effect of the anomalous Late Cretaceous Quiet Interval, which was normally polarized.

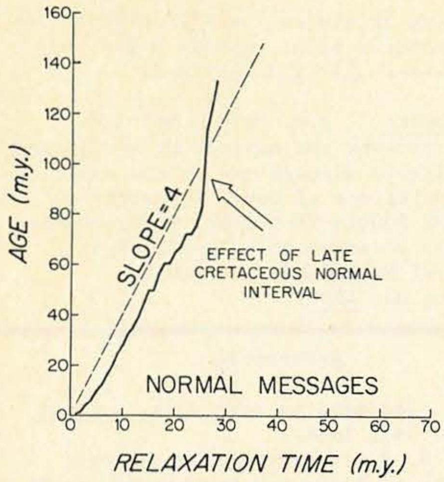

Fig. 3. Relation of relaxation-time to maximum age of Normal polarity messages. The curve follows that of Figure 2 closely for messages younger than the Late Cretaceous Normal Interval.

the message nearly five-fold. Unknown intervals of Reversed polarity obviously would extend that duration further, whereas unknown Normal intervals would shorten it. It is interesting to note that the message is more stable during times when the field reverses more frequently, which is the result expected from the analogy with low-pass filtering.

The duration of Reversed polarity messages for $\tau \leq 70$ m.y. is shown in Figure 2. For rocks younger than 84.6 m.y., the result follows nearly a straight line of slope 3.5, implying that time-constants there should exceed 1/3.5 the rock's age in order for the reversed polarity message to survive to the Present.

The Late Cretaceous Normal Interval (84.6-111.5 m.y. B.P. in the timescales here) causes a dramatic departure from this line. Figure 2 shows that reversed messages older than 84.6 m.y. will not survive in grains with $\tau < 45$ m.y. The computations of equation 2 terminate within the Quiet Interval, for $23 \leq \tau \leq 45$ m.y. For $\tau > 45$ m.y., the grains's age should not exceed 2 .

The curve for Normal-polarity messages (Figure 3) closely follows that of reversed messages (Figure 2) back to the Late Cretaceous Normal Interval. At that point, the two diverge abruptly, because that interval is so detrimental to Reversed messages.

Once a polarity message is acquired, it will survive only for a period of 0.7 τ after the ambient field switches to opposite polarity, unless an additional field reversal occurs before that time has elapsed. Numerical results show that the reversing magnetic field acts as a cushion, extending the life-span of messages to periods of 2-to-4 τ, or 3-to-6 times longer than would be expected in a constant field of opposite polarity.

This benefit is easily overcome by small increases in ambient temperature, however. In small applied fields, the relaxation time is roughly proportional to exp (positive constant/absolute temperature).[3] For original time-constants of 1-100 m.y., halving and quartering of the relaxation time can be achieved by raising the ambient temperature from 273°K (0°C), for example, to nominal values of only 276.5° and 280°, respectively. More dramatically, raising from 273°K to a room temperature of 300°K would lower the time-constant by more than two orders of magnitude. Thus, in comparison to temperature, the VRM cushion provided by the reversing paleofield is small.

In summary, the reversing geomagnetic field has provided a persistent buffer to the erasure of polarity messages by viscous remanent magnetization. It has extended the longevity of messages some 3-to-6 times longer than could be expected if the field were non-reversing. This interesting and beneficial effect is equivalent to that of a life-long temperature reduction of 5°K in ancient rocks.

APPENDIX

FIRST ZERO-CROSSING OF A LOW PASS FILTERED RECTANGULAR WAVE

This appendix describes the expected first zero-crossing time for low-pass filtered periodic and Poisson rectangular waves. It is the mathematical analogue of the viscous demagnetization process that is addressed in the main text of this paper. When a rectangular wave alternating between +1 and -1 passes through a first-order leaky integrator, i.e. the most simple kind of low-pass filter, the output at the end of each input polarity interval is given recursively by

$$C_i=[C_{i-1}-(-1)^i]e^{-t_i/\tau}+(-1)^i \tag{A1}$$

The i-th polarity interval has length t_i; the output at the end of the i-th polarity stage is C_i; and τ is the characteristic exponential time-constant for the filter. Odd-numbered values of i refer to negative polarity intervals.

For the simulation of a viscously-decaying magnetic polarity message, as described in the text, we set $C_o = 1$ to represent the initial magnetic message just prior to the first polarity reversal from +1 to -1. The recursion (A1) is then evaluated forwards in time for i = 1, 2,... until the sign of C_i changes, at which point the original polarity message will have been lost.

For constant length polarity intervals, using $t_i = 1$ and $C_o = 1$, the output at the N-th stage is

$$C_N = 2\left(\frac{\alpha^{N+1} + (-1)^N}{\alpha + 1}\right) - (-1)^N \qquad \text{(A2)}$$

where $\alpha = e^{-t/\tau}$

The first zero-crossing occurs within an odd-numbered interval, obtained by solving (A2) analytically for N when $C_N = 0$:.

$$N = \underset{\text{Integer}}{\overset{\text{Nearest}}{\text{odd}}}\left(\frac{\ell n\left(\frac{1-\alpha}{2}\right)}{\ell n\alpha}\right) + 1 \qquad \text{(A3)}$$

For Poisson distributed t_i, expression (A2) can be integrated with the probability density function:

$$PDF\ (t) = \lambda e^{-\lambda t} \qquad \text{(A4)}$$

For average polarity intervals of $\lambda^{-1}=1$, the first zero crossing time is (ignoring the nearest-odd-integer function in (A2):

$$T = \int_{T>0}^{\infty} - \tau \ell n\left(\frac{1 - e^{-t/\tau}}{2}\right) e^{-t}\, dt \qquad \text{(A5)}$$

Recognizing that $\ell n(1 - X) = X + X^2/2 + X^3/3 + \ldots$ for $(0 \leq X \leq 1)$, the integrand can be expressed as an infinite series, integrated term-by-term and to reduced yield:

$$T = -\tau\ \ell n\ (0.5) \qquad \sum_{m=1}^{\tau} \left({}^1/_m \right) \qquad \text{(A6)}$$

Values of N/τ and T/τ for $T_i=1$ (periodic process) and $\lambda^{-1}=1$ (Poisson process) are compared in the Appendix Table for various $\tau = 1\ldots, 1000$. The Poisson process terminates more rapidly than does the periodic process. This behavior was verified using numerical simulations, also summarized in the Table. Evidently, at least in part, the Poisson process is faster because the t_i are unbounded; hence a zero-crossing is always finitely probable at each odd-numbered step, whereas N for the periodic process if rigidly fixed.

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