Overprinting of natural magnetic remanence in lake sediments by a subsequent high-intensity field

Robert S. Coe* & Joseph C. Liddicoat†

* Earth Sciences Department, University of California, Santa Cruz, California 95064, USA
† Environmental Sciences, Barnard College, Columbia University, 3009 Broadway, New York, New York 10027-6598, USA

There has been considerable debate recently on how well sedimentary rocks record transitional field directions during a polarity reversal1–5. This has not been an easy question to answer because the input geomagnetic signal for a given sedimentary record is not known independently, and because the process by which remanent magnetization is acquired by sediments is difficult to duplicate in the laboratory. The geomagnetic excursion recorded by sediments outcropping around the shores of Mono Lake, California6–8, offers an unusually good opportunity to examine this question. We report here a study of the Mono Lake Excursion (MLE) at a new locality on the southeast shore where, although the records satisfy usually applied standards of palaeomagnetic quality, it is clear from comparison with records from other localities that the field directions during a time of low field intensity have not been faithfully preserved. The distinctive directions of natural remanence in the discrepant part of the record show that the southeast shore sediments were overprinted by the ensuing higher-intensity field acting on the still unconsolidated sediment, apparently by realigning some magnetic grains that had previously been locked in.

Mono Basin (Fig. 1) has proved to be an almost ideal natural laboratory in which to study the fidelity of sedimentary magnetization. Well-exposed sections outcrop in several places around the lake and contain numerous tephra marker horizons that enable unambiguous identification of stratigraphic position. The lake sediments are mainly fine-grained silt composed of glacial flour derived from granitic and metamorphic rocks of the Sierra Nevada, with smaller amounts of volcanic material and clastic carbonate9. Bedding is regular and only rarely disturbed, the deposition rate based on 14C dates10 is high (25 to 40 cm kyr−1), and a stable component of natural remanent magnetization (NRM) that decays univectorially to the origin is obtained easily by either alternating field (AF) or thermal demagnetization techniques2,11. Finally, previous studies8 of the MLE in seven sections at three localities around the lake have obtained highly reproducible recordings using AF demagnetization (Fig. 1) that can serve as a standard signal against which to compare other recordings of the excursion. Indeed, a longer record10 at one of these localities, Wilson Creek (Fig. 1), that includes the MLE has been used successfully as a reference for temporal correlation of lake sediments in the western United States11.

The MLE is precisely located by a distinctive tephra layer (Wilson Creek Ash Bed 15, referred to as Ash 15), which divides it into two parts of roughly equal duration. Interpolation between 14C-dated horizons (assuming for the sedimentation rate) suggests the MLE began 29,000 14C-yr ago and lasted 2,000 yr (refs 7, 8, 10). (Note that various studies12,13 indicate that 14C ages for this time are several thousand years too young.) The magnetic signature is distinctive (Fig. 1): a sharp swing in direction to the west and up at lower NRM intensity is followed by a swing to the east and steeply down at higher NRM intensity. The NRM and partially demagnetized NRM vary similarly with depth in all seven sections, consistent with our earlier relative palaeointensity experiments based on NRM/ARM ratios at 20 mT demagnetization level (see Table 3 and Fig. 9a in ref. 7). These results indicate that the field was as much as four times weaker during the first, older directional swing of the excursion than during the second, younger swing.

At a new locality (Fig. 1) in wave-cut bluffs on the southeastern shore of Mono Lake, however, the signature of the MLE obtained by AF demagnetization of samples from three parallel sections separated by 10–600 m is significantly different (Fig. 2a) from that found on the northwestern and eastern side of the lake. In the first part of the excursion, below the Ash 15 marker, the swing to negative inclination and westerly declination is absent. But the following swing to steeply downward directions in the second part of the excursion signature is reasonably well represented, bearing in mind that the large differences in declination in Fig. 2a stem from much smaller differences in overall direction due to the high inclinations (87–60°).

What could be the explanation of the discrepancy in magnetic signatures? The palaeomagnetic directional records strongly suggest that the sediments deposited at the southeastern shore during the first part of the MLE bear a partial imprint of the succeeding part of the excursion. The evidence for this is contained in the 30 cm of section just below Ash 15 (Fig. 2a), which are magnetized with unusual directions that are much more easterly and substantially steeper (average 50°E, 70° down) than either the axial or today's inclined dipole field. Thus, conventional viscous overprinting—the continual drift of remanent magnetization towards equilibrium with the ambient field—is ruled out. What field, then, could have produced an overprint with this distinctive direction? The obvious candidate is the steep easterly field of the second, higher-intensity part of the excursion. A number of alternative hypotheses for the first directional swing in the three southeastern shore records do not stand up to scrutiny. There is no evidence for local disturbances such as slumping or for a hiatus in any of them. It is not probable that we missed the earlier swing by failing to sample low enough in the section, because a several hundred percent jump in sedimentation rate would be required to push the missing swing below our lowest samples. Moreover, with either of the above hypotheses we would still be left without an explanation for the unusually steep and easterly directions that we find in place of the swing. Finally, to suppose instead that the magnetic signature of the southeast shore is the more accurate representation of the geomagnetic excursion is unrealistic for several reasons. The agreement of the records carrying the usual MLE signature (Fig. 1) is extraordinary by palaeomagnetic standards, distinctly better than the still moderately good agreement of the three records from the southeastern shore (Fig. 2a). Although reproducibility of results between sections is not sufficient to prove accuracy, it is a necessary criterion and is far and away the most commonly employed test for reliability of palaeomagnetic recording. An even more telling argument, in our opinion, is the lack of a plausible explanation other than magnetization during a geomagnetic field excursion for the
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FIG. 1. Localities and corresponding palaeomagnetic records from previous studies (filled circles of the Mono Lake Excursion (MLE)3,13. These highly reproducible records define the standard signature against which we compare other recordings of the MLE. The location of this highly reproducible standard records of the first swing. The recent suggestion by Quidelleur and Valet (personal communication, 1993) that spuriously shallow inclinations may result from the greater relative influence of gravity when the magnetic field is weak cannot apply in this case because the directions swing through the horizontal plane to 30° negative inclination. In contrast, assuming that the standard records from the other localities do represent the actual geomagnetic field, the discrepant directions found at the southeastern shore below Ash 15 can be explained quite naturally: they are the result of overprinting by the stronger, steep and easterly field that followed during the second part of the excursion.

What kind of process could produce the observed overprinting? Not simple time averaging of the MLE signal; this process could smooth away the first directional swing (if we assume that there had been an unusually high remanence lock-in zone during deposition of the southeastern-shore sediments) but cannot account for the lack of smoothing of the second directional swing relative to the standard signal above Ash 15 (Fig. 2a). Rather, some previously locked magnetic grains below Ash 15 must have been realigned, the stronger field during the second part of the MLE supplying the extra torque needed to overcome the frictional restraining forces on some of the magnetic grains in the still wet and unconsolidated sediments. This is the same mechanism proposed very recently by Lovlie16, who simulated it by inducing remanence in suspensions of magnetite grains in slowly curing epoxy resin. The essential difference from the simpler time-averaging processes commonly discussed with regard to post-depositional remanent magnetization is that the lock-in depth of a magnetic grain below the water–sediment interface is not constant; instead, because the mechanical constraints restricting grain realignment increase continuously during consolidation, lock-in depth increases with field strength. With the process suggested here, the later strong-field swing to steep inclinations would be preserved because the ensuing field was weaker.

Why the sediments exposed along the southeastern shore were susceptible to this kind of overprinting, and the sediments from the other localities around the lake are not, is a good question that we cannot answer yet. Because the sediments are more finely laminated and were deposited at a 60% higher rate at the southeastern shore, we thought originally that they would carry an even higher-resolution record of the MLE. A summary of relevant information is as follows. X-ray diffraction and Curie-point determinations on magnetic concentrates of sediment sampled at Wilson Creek indicate only one magnetic mineral, titanium-poor magnetite (Fig. 2a in ref. 7; ref. 15). Thermal demagnetisation of samples from all sections removes 95-99% of the NRM by 575 °C, consistent with the identification of magnetite. Agreement between stable remanence directions from thermal and alternating field demagnetisation is extremely good right through the excursion, as shown for paired specimens from the same samples (taken by hand) from the southeastern shore (Fig. 2b) and Mill Creek (not shown). Thus Mono Lake sediments do not suffer from the same problem that was reported for Lake Tecopa sediments16, in which paired samples through the Brunes–Matuyama transition were found to give very different results under AF and thermal demagnetisation. Anisotropy of magnetic susceptibility measurements of remaining undemagnetized samples above Ash 15 at the southeastern shore and Mill Creek localities reveal typical results for undisturbed sedimentary fabrics, with minimum axes within 5–10° of the normal to bedding, 10% foliation and 1° lineation. We conclude that a more thorough magnetic and sedimentological characterisation is needed to shed light on the essential differences in properties between the southeastern shore section and the other sections. This will require resampling the critical sections to obtain suitable material for study.

Records of the MLE have been reported from four other localities in western North America, and at only one of them is the earlier directional swing well recorded (Gulf of California17). At the other three it is missing or is only vaguely expressed (Summer Lake in Oregon11,18 and Carson Sink and Pyramid Lake in Nevada19). These earlier records did not drive us to the conclusion that the low-field part of the MLE was overprinted.
FIG. 2  a, Comparison of the three new recordings (filled symbols, SES, A, B, C) of the Mono Lake Excursion obtained from sediments at the southeastern shore against the standard MLE signal (open circles) from Mill Creek locality (see map in Fig. 1). Note that the first directional swing, below Ash 15, is missing in the southeastern shore records. A common-depth scale (shown vertical) is achieved by stretching the MLE record by 60%, so that the interval between Ash 15 and overlying Ash 14 is the same as at the southeastern shore (0.7 m). b, Comparison of AF (filled circles) and thermal (open circles) demagnetization results for adjacent pairs of specimens from the southeastern shore sampled through the Mono Lake Excursion. The intensity values are after 20 mT and 200 °C demagnetization steps.

by the succeeding stronger fields because the directions exhibited below the marker ash are much more scattered and are not strikingly different from those of the recent field; hence they do not rule out ordinary viscous remagnetization. However, the same overprinting mechanism, but operating to a somewhat lesser extent than at the southeastern shore, can account very nicely for the absence of the expected directional swing in these records. Thus, it is reasonable to suppose as well that some sedimentary records of geomagnetic reversals may have suffered similar overprinting of their low-field portions by the higher fields at the end of polarity transitions, and also by relatively high-field episodes that may occur within transitions. By themselves, the three MLE records from the southeastern shore of Mono Lake appear quite acceptable, in that they meet or exceed the standards usually applied for consistency within hand samples and between sections, undisturbed sedimentary fabric, simplicity of magnetic mineralogy and quality and consistency of AF and thermal demagnetization results. Our next goal is to identify the critical properties that make the southeastern-shore sediments susceptible to such overprinting, which in turn should

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