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Anisotropy of magnetic susceptibility as a tool for recognizing core deformation: reevaluation of the paleomagnetic record of Pleistocene sediments from drill hole OL-92, Owens Lake, California

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Abstract

At Owens Lake, California, paleomagnetic data document the Matuyama/Brunhes polarity boundary near the bottom of a 323-m core (OL-92) and display numerous directional fluctuations throughout the Brunhes chron. Many of the intervals of high directional dispersion were previously interpreted to record magnetic excursions. For the upper ~120 m, these interpretations were tested using the anisotropy of magnetic susceptibility (AMS), which typically defines a subhorizontal planar fabric for sediments deposited in quiet water. AMS data from intervals of deformed core, determined from detailed analysis of sedimentary structures, were compared to a reference AMS fabric derived from undisturbed sediment. This comparison shows that changes in the AMS fabric provide a means of screening core samples for deformation and the associated paleomagnetic record for the adverse effects of distortion. For that portion of core OL-92 studied here (about the upper 120 m), the combined analyses of sedimentary structures and AMS data demonstrate that most of the paleomagnetic features, previously interpreted as geomagnetic excursions, are likely the result of core deformation. © 2000 Published by Elsevier Science B.V. All rights reserved.

Keywords: magnetic susceptibility; anisotropy; paleomagnetism; sediments; deformation

1. Introduction

In recent years, numerous paleomagnetic studies of sediment cores have attempted to examine the fine details of geomagnetic field behavior. Such studies provide constraints for modeling the geodynamo as well as geochronologic control for the cores. The validity of these paleomagnetic interpretations, of course, depends on the fidelity of the paleofield records. Unrecognized sediment deformation, either natural or induced, is a potential source of erroneous paleomagnetic interpretation [1]. This problem is exacerbated in studies using sediment cores because the coring process may cause deformation and such defor-

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mation is commonly difficult to recognize in the small section provided by a core. A rapid method of screening paleomagnetic data for the effects of deformation is needed. Anisotropy of magnetic susceptibility (AMS) provides a measure of sedimentary fabric [2], which results from a combination of depositional and postdepositional factors. More than 20 years ago, Marino and Ellwood [3] showed that such magnetic fabrics, defined by AMS, could be used to assess the reliability of paleomagnetic data derived from sediments. The AMS method is straightforward; anomalous magnetic fabrics may indicate sediment deformation and thus paleomagnetic directions associated with such fabrics cannot be trusted. At the time of Marino and Ellwood's study, however, instruments capable of accurate AMS measurements were not widely available and the measurements were time consuming (their study used only 12 samples). Consequently, few studies have employed this method to screen paleomagnetic results. Sensitive instruments capable of rapid, accurate measurement of AMS are now widely available and, as we show here, the AMS method provides a convenient, powerful tool for screening large amounts of paleomagnetic data derived from sediment cores. In this study, we compare AMS from undeformed core, from core in which sedimentary structures are clearly deformed by drilling, and from core for which detailed descriptions are lacking.

Core OL-92 from Owens Lake, California, was obtained using rotary-core drilling into 323 m of lacustrine sediments, estimated to represent the past 800 000 years [4]. The visual identification of zones of deformed core [5] provides an opportunity to test the usefulness of AMS as a tool for recognizing sediment deformation.

Because deposition in Owens Lake was rapid and was probably nearly continuous, the core potentially contains a detailed record of geomagnetic field behavior for the late Quaternary. Glen and Coe [6] presented paleomagnetic results that documented the Matuyama/Brunhes (M/B) polarity boundary near the core bottom. In addition, they interpreted a detailed field behavior record during the M/B transition as well as numerous magnetic excursions during the Brunhes chron. Although these paleomagnetic results were considered tentative, pending efforts to assess the validity of the record, many of the features were interpreted to correlate with magnetic excursions reported in the literature (Fig. 1). These correlations were then used to corroborate the depth/age model for the OL-92 core that was based on mass accumulation rates [7]. If the paleomagnetic record from core OL-92 is shown to record excursions, then this record will provide important age control of the sedimentary section as well as a remarkable archive of geomagnetic field behavior throughout the Brunhes chron.

Use of a paleomagnetic record such as that from OL-92 for age control requires: (1) that the observed directions of remanent magnetization are accurate enough to discern interesting features of the ancient geomagnetic field (reversals, excursions, or waveforms due to secular variation), and (2) that features of interest can be unambiguously correlated with corresponding features from well-established, dated paleomagnetic records. Many factors can affect the quality of sedimentary magnetic records, including sediment grain size [8,9], depositional environment (e.g., [10]), authigenic growth and/or destruction of magnetic minerals (e.g., [11]), and natural and coring-induced deformation [1]. Perhaps the best way to evaluate the quality of sedimentary paleomagnetic records is to compare multiple records from a given sedimentary sequence. Unfortunately, this approach is often prohibitively time consuming and expensive.

In the absence of multiple records, great care must be taken to evaluate factors such as magnetic mineralogy and possible deformation. Two types of evidence cast doubt on the paleomagnetic record from core OL-92. First, the mineralogy of magnetic minerals in the Owens Lake sediments is complex. Reynolds et al. [12] observed that, whereas some parts of the section contain abundant fresh detrital titanomagnetite, much of the magnetite in other parts of the section has been destroyed by sulfidization. In addition, greigite, a highly magnetic authigenic monosulfide mineral, is present in many samples of Owens Lake sediment (S. Lund, personal communication, 1994; and [12]). Second, careful analysis of sedimentary

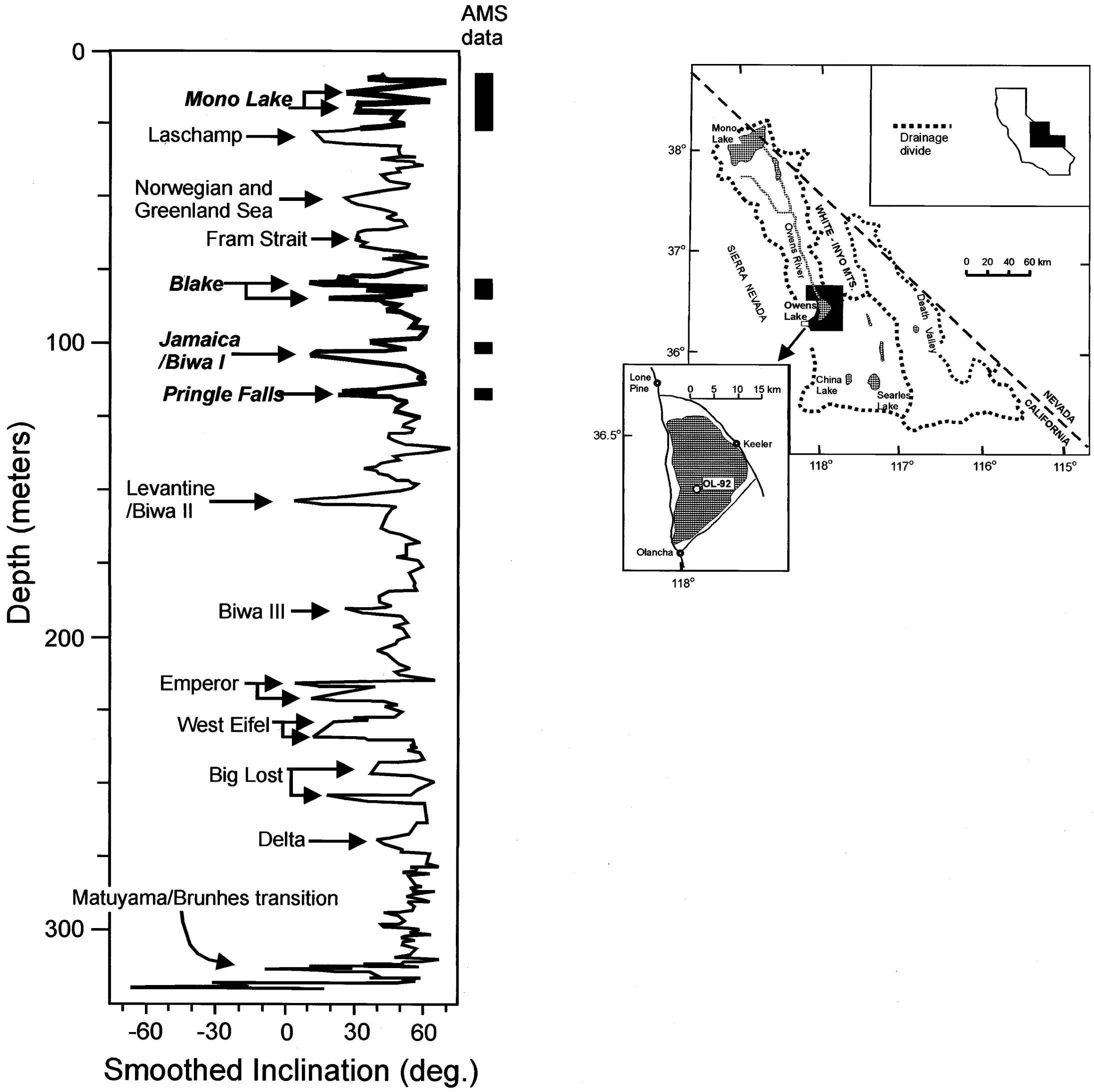

Fig. 1. Smoothed paleomagnetic inclination record and interpreted excursions for core OL-92, from Owens Lake, California (modified from figure 6 of Glen and Coe [6]). Black bars indicate four zones from which AMS data were collected. These zones span the Mono Lake, Blake, Jamaica/Biwa I, and Pringle Falls excursions (indicated by heavier curves). The inset shows the location of drill hole OL-92.

structures in the upper part of core OL-92 revealed numerous zones of coring-induced deformation (Fig. 2).

Visual observations of core deformation combined with AMS data demonstrate that AMS provides a powerful means of identifying zones of probable core deformation. The presence of deformation in zones of high paleomagnetic dispersion shows that the previously interpreted geomagnetic excursion history for core OL-92 [6] is invalid.

2. Methods

One hundred twenty-two of the paleomagnetic samples used by Glen and Coe [6] were obtained for AMS analysis. The sample set covers four

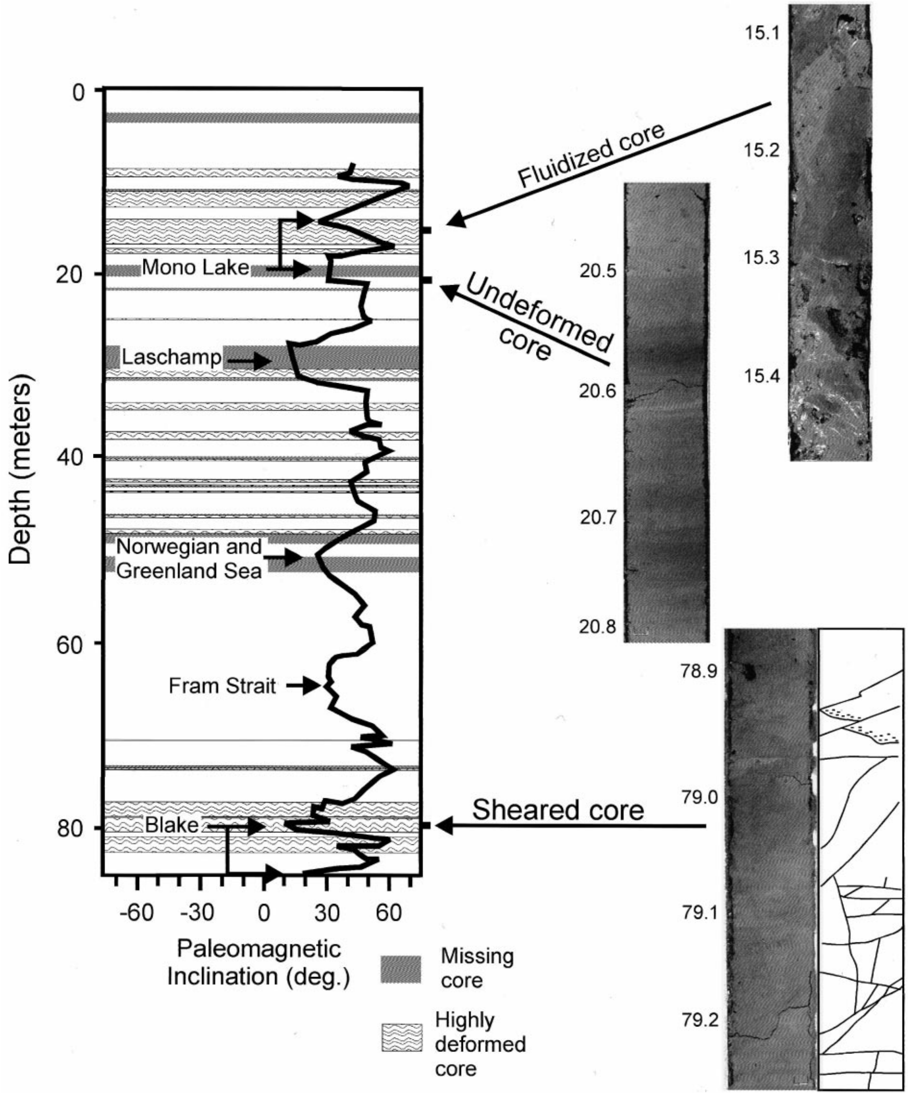

Fig. 2. Smoothed paleomagnetic inclination record for the upper 82 m of core OL-92. Previously interpreted excursions are shown in relation to zones in which severe core deformation is visually apparent [5]. The three photographs document two types of deformed core (sediment that has been fluidized and sediment that has been disrupted by numerous shear planes), as well as an interval of undeformed core. The drawing to the right of the photograph of sheared core is a map of some of the shear planes evident on the cut core face. The stippled horizon in the upper part of this drawing represents the base of a deformed silty layer.

depth intervals, 119.7–115.5 m, 103.6–99.6 m, 85.2–78.1 m, and 27.7–12.5 m. As interpreted by Glen and Coe [6], these depth intervals span the Pringle Falls, Jamaica/Biwa I, Blake, and Mono Lake excursions, respectively (Fig. 1). Twenty-three specimens from the uppermost interval (27.7–20.4 m) are from undeformed core stratigraphically below an interpreted excursion. Most of the samples defining the interpreted Blake and Mono Lake excursions were taken from highly deformed material (Fig. 2) [5]. Sedimentary structures and possible core deformation below 83 m have not been described in detail. Although the paleomagnetic specimens had been placed in plastic boxes, the samples had desiccated during the several years following the paleomagnetic investigation of Glen and Coe [6]. Because all samples underwent similar drying, comparison of AMS results among groups of samples are valid, although drying may have had some effect on individual AMS results.

AMS is defined by differences in length and orientations of the principal axes of the magnetic susceptibility ellipsoid depicted in Fig. 3 [13]. The AMS of typical detrital magnetic grains is controlled by grain shape, with higher susceptibility corresponding to larger grain dimensions [14]. The AMS of sediment results from the preferred alignment of the longer and shorter axes of these magnetic grains. For sediment deposited in quiet water, the longer grain axes tend to be randomly distributed in the horizontal plane thereby producing a sedimentary foliation. In such sediments, AMS defines a planar fabric with the maximum (K1) and intermediate (K2) axes of the ellipsoid nearly equal in magnitude and subhorizontal, and the minimum axis (K3) subvertical. AMS was measured using a KLY-3 Kappa Bridge (use of product name does not imply endorsement by the USA government).

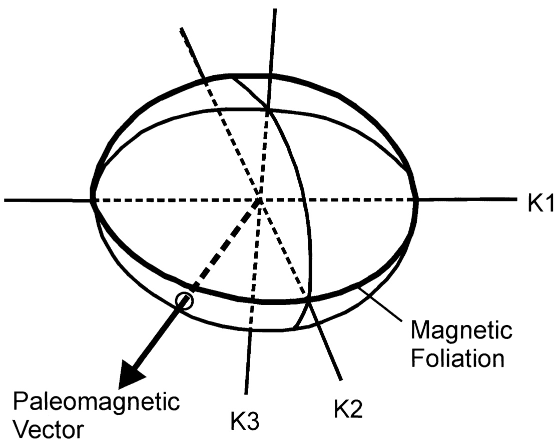

Fig. 3. Magnetic susceptibility (MS) ellipsoid. Anisotropy of magnetic susceptibility is defined by the orientations and magnitudes of the maximum (K1), intermediate (K2), and minimum (K3) axes. A sedimentary fabric is commonly defined by an oblate ellipsoid (K1 ≈ K2) with K3 subvertical. There is no fixed relation between the paleomagnetic vector and the MS ellipsoid.

3. Rationale

Although recognition of deformation is important to many studies of sediment cores, such information is commonly incomplete because careful core description is labor intensive and deformation is difficult to recognize in the absence of distinct bedding or other well-defined sedimentary structures. Severe core deformation, like that in the fluidized intervals of OL-92 (Fig. 2), not only distorts the sediment, but incorporates foreign material (e.g., drilling mud) and mixes material from different stratigraphic horizons [5]. Recognition of such severe deformation is essential to all studies of cored sediments. Some investigations, such as detailed paleomagnetic studies, may be adversely affected by even minor amounts of unrecognized deformation.

Comparison of the average inclinations and dispersions of K3 axes among groups of samples provides a simple, yet powerful screen for core deformation. Ideally, results from suspect intervals can be compared to those from similar sediment that is demonstrably undeformed. Deformation that disrupts the AMS fabric will: (1) increase the dispersion of K3 axes, and (2) deflect K3 axes, *on average*, toward shallower inclinations. Not all deformation will produce significant shallowing of the K3 axis. Therefore, steep K3 axes do not guarantee undisturbed sediment. K3 axes that are significantly shallower than those derived from undisturbed sediment, however, provide a strong reason to question the integrity of samples.

Paleomagnetic results are evaluated by comparing characteristic directions of remanent magnetization and K3 axes from intervals of high paleomagnetic dispersion (excursions?) to those from intervals of low dispersion. It is important to note that at the *sample level*, deformation will not produce a simple relation between paleomagnetic directions and the orientations of K3 axes. Even if samples are affected only by rigid body rotation, in which the angles between the paleomagnetic vectors and the K3 axes are preserved, the results will be complex (Fig. 4). Although rotations about some axes produce rather simple relations, the net effect of rotations about many axes is

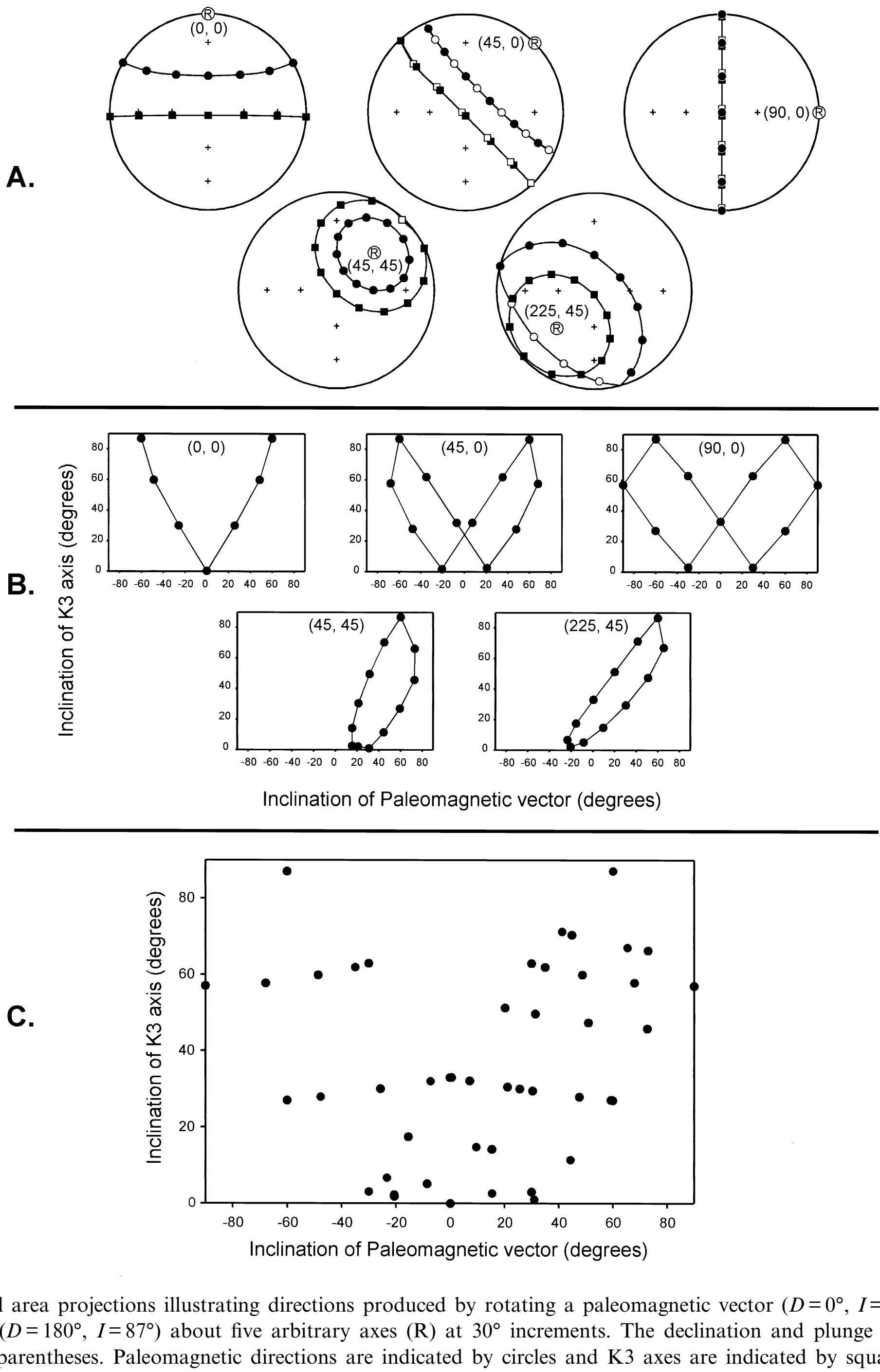

Fig. 4. (A) Equal area projections illustrating directions produced by rotating a paleomagnetic vector ($D = 0°$, $I = 60°$) and a sub-vertical K3 axis ($D = 180°$, $I = 87°$) about five arbitrary axes (R) at 30° increments. The declination and plunge of rotation axes are indicated in parentheses. Paleomagnetic directions are indicated by circles and K3 axes are indicated by squares. Filled symbols are on the lower hemisphere, open symbols are on the upper hemisphere. (B) Plots of inclinations of K3 axes vs. inclinations of paleomagnetic directions for the rotations indicated in panel A. Note that the relation between variations of the two inclinations is very different for different axes. (C) Plot of inclinations of K3 axes vs. inclinations of paleomagnetic vectors. The plotted points are those shown on the five plots in panel B. Note that there is no clear relation between the two inclinations.

complicated. Any deformation that affects a core at the sub-sample level, either by plastic flow or through movement along shear planes, need not preserve internal angular relations and the results will be even more complex. For *groups of samples*, however, a relation between high dispersion of paleomagnetic directions and increased dispersion and lower average inclination of K3 axes provides strong evidence that anomalous paleomagnetic directions are the result of deformation rather than a record of paleofield behavior.

4. Results and discussion

The interval of undeformed core, 27.7–20.4 m, was used to establish a reference AMS fabric for undisturbed sediment (Fig. 2). The fluidized interval, 19.0–12.5 m, provides a similar reference for core affected by extreme deformation. For the undeformed core, the standard deviation of K3 inclinations (STD_{K3}, used here as a measure of dispersion) is less than 6.5°, and inclinations of K3 axes (INC_{K3}) average 84° (Fig. 5 and Table 1). In this interval, INC_{K3} is greater than 80° for more than 90% of the samples and only one sample yielded an INC_{K3} less than 70°. As expected, INC_{K3} from the fluidized interval are much more scattered with STD_{K3} of almost 26°. The average INC_{K3} in this interval is 66.5°; fewer than 55% of the K3 axes are steeper than 80° and 38% are inclined at less than 70°.

AMS results from the other three depth intervals span the range between these end members. Core in the interval 85.2–78.1 m, which is highly disrupted by shear fractures, yields an average INC_{K3} and STD_{K3} close to those from the fluidized core. In this interval, only about a quarter of the samples yield INC_{K3} greater than 80° and more than 30% yield INC_{K3} less than 70°. For the interval 119.7–115.5 m, INC_{K3} averages 76°, STD_{K3} is about 14°, and INC_{K3} is greater than

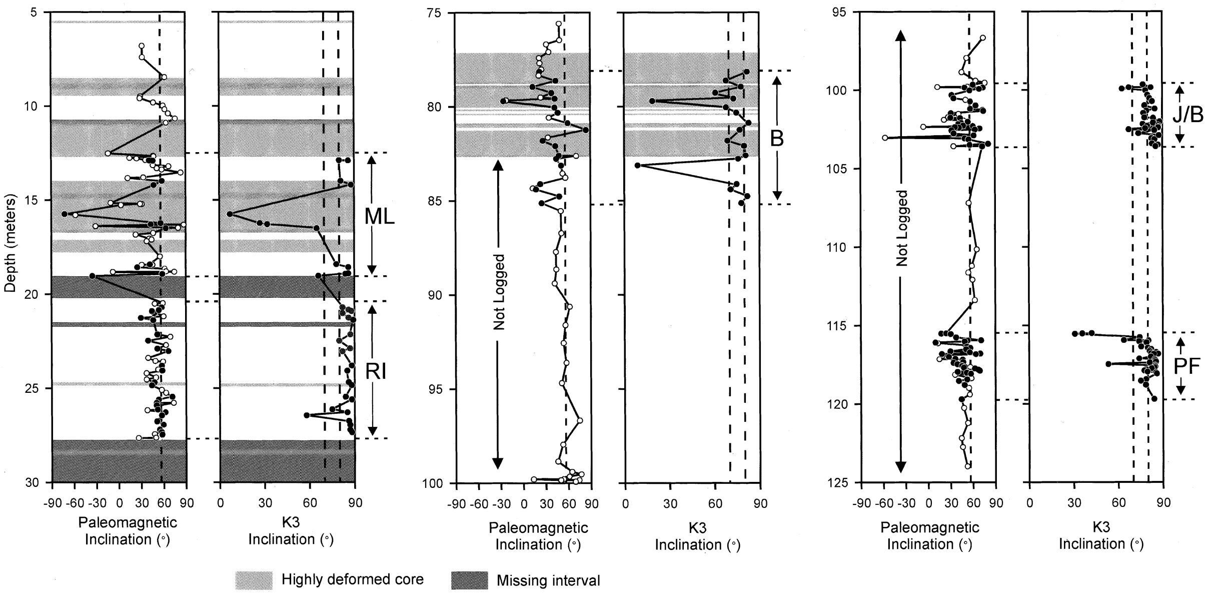

Fig. 5. Unsmoothed paleomagnetic inclinations [15] and inclinations of K3 axes vs. depth. Paleomagnetic directions from the previously interpreted Mono Lake (ML), Blake (B), Jamaica/Biwa I (J/B), and Pringle Falls (PF) excursions are characterized by high dispersion relative to the undisturbed reference interval (RI). Within the interpreted excursions, K3 axes are more highly dispersed and yield shallower average inclinations than in the reference interval. (Note: Dashed line on plots of paleomagnetic inclinations indicate geocentric axial dipole field. Dashed vertical reference lines on the plots of K3 inclinations are at 70° and 80°.) Many of the samples in the Mono Lake and Blake intervals were taken from core now recognized to be highly deformed. Open symbols indicate that AMS data do not exist. AMS data were tabulated by Rosenbaum et al. [16].

80° for 58% of the samples and less than 70° for 14% of the samples. These values are intermediate between the end members and probably indicate significant but less pervasive deformation than that in the fluidized or highly sheared intervals. Little deformation is indicated by AMS results from the 103.6–99.6-m interval. K3 axes in this interval are as well grouped as those from the undeformed reference interval and on average only slightly less steep.

Interpretation of paleomagnetic records from Pleistocene sediments, like that from OL-92, often focuses on identification of magnetic excursions. Excursions are periods of rapid, high-amplitude changes in direction of the geomagnetic field, and their records, therefore, are zones characterized by high dispersion of remanent directions. If such zones are accurate records of magnetic field behavior, there should be no correspondence between these zones and intervals of core disruption. Detailed core descriptions, completed to a depth of 82.6 m, indicate severe deformation and disruption of core OL-92 within the intervals of the interpreted Mono Lake [17,5] and Blake excursions [5]. In addition, examination of sedimentary features in the upper 82 m of core casts doubt on the validity of three other interpreted geomagnetic excursions. Two of these intervals (interpreted as the Laschamps, and Norwegian and Greenland Sea excursions) are spatially associated with documented sediment disruption along with large amounts of missing core (Fig. 2), whereas the third interval (interpreted as the Fram Strait excursion) contains faults and closely spaced laminations of coarse sand [5].

Comparison of paleomagnetic dispersion with the measures of core disruption provided by the AMS data constitutes a simple, yet powerful test. Even in the absence of other evidence of core deformation, the high correspondence between paleomagnetic dispersion and the average INC_{K3} and STD_{K3} is ample reason to reject the previously interpreted Mono Lake, Blake, and Pringle Falls excursions (Fig. 6 and Table 1). Although the AMS data provide little reason to question the interval previously interpreted as the Jamaica/Biwa I excursion, it should be noted that the samples used for AMS measurements do not fully

Table 1
Average values and standard deviations for inclinations of paleomagnetic vectors and K3 axes

Depth interval (m)	N/N[a]	Average paleomagnetic inclination (°)[a]	Standard deviation of paleomagnetic inclination (°)[a]	Average inclination of K3 (°)	Standard deviation of inclination of K3 (°)	$N > 85°$	$N > 80°$	$80° > N > 70°$	$N < 70°$	Interpreted excursion (Glen and Coe [6])
19.0–12.5	48/13	35.1/33.2	33.8/39.0	66.5	25.9	4	7	1	5	Mono Lake
27.7–20.4	47/23	52.2/52.7	9.8/8.7	84	6.4	16	21	1	1	none
85.2–78.1	28/19	35.1/36.6	23.7/21.8	69	24.3	0	5	8	6	Blake
103.6–99.6	42/31	46.2/52.8	23.9/14.4	81	6.1	10	19	9	3	Jamaica/Biwa 1
119.7–115.5	45/36	44.2/45.4	15.7/14.9	76	13.7	12	21	10	5	Pringle Falls

Second number indicates AMS samples.
[a]The first number indicates all paleomagnetic samples in the interval. The second number indicates AMS samples.

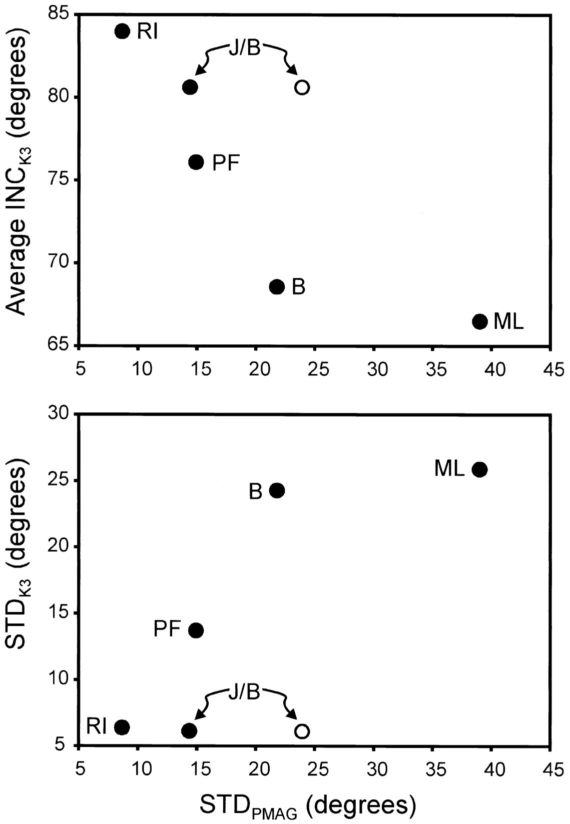

Fig. 6. Average K3 inclination (INC_{K3}) and standard deviation of K3 inclinations (STD_{K3}) vs. standard deviation of paleomagnetic inclination (STD_{PMAG}) for the depth intervals indicated in Fig. 5 and Table 1. Low average INC_{K3} and high STD_{K3} are indicative of deformation; the high correspondence between these parameters and STD_{PMAG} indicates that intervals of high paleomagnetic dispersion (previously interpreted to record the Mono Lake (ML), Blake (B), and Pringle Falls (PF) excursions) are due to deformation rather than geomagnetic field behavior. The solid symbols are based on AMS samples. All paleomagnetic samples in the interval spanning the previously interpreted Jamaica/Biwa excursion (J/B) were used to calculate STD_{PMAG} indicated by the open symbols.

sample the paleomagnetic dispersion used to define this feature (Fig. 6 and Table 1).

5. Conclusions

Although a comprehensive study of AMS requires complex analysis of the orientations and shapes of susceptibility ellipsoids (see for example, [18,19]), a very simple analysis of the orientations of K3 axes provides an effective means of screening sediment cores for deformation. In addition, these studies are useful for assessing the effects of such deformation on associated paleomagnetic data. Comparison of AMS data for undeformed and highly deformed intervals of core OL-92 demonstrates that, as expected, deformation reduces the average inclination of K3 axes and increases their dispersion.

Detailed descriptions of sedimentary structures in the upper 83 m of the core show that dispersed paleomagnetic directions, previously interpreted to record the Mono Lake and Blake excursions, are instead the result of severe core deformation. The AMS results corroborate this interpretation and cast doubt upon the validity of the interpreted Pringle Falls excursion. Observations of core deformation and (or) coarse sediment cast further doubt on the validity of other interpreted excursions in the upper 80 m of the core (Laschamps, Norwegian and Greenland Sea, and Fram Strait).

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