Characterization of soft-sediment deformation: Detection of cryptoslumps using magnetic methods

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ABSTRACT

Many workers have explored anisotropy of magnetic susceptibility (AMS) of sediments as an indicator of deformation. Several studies have used deflection of the eigenvector associated with the minimum in susceptibility, V_3, as a criterion for deformation. We examine the AMS record of a well-exposed slump and find that although demonstrable deformation can occur without deflecting the V_3 directions, an oblate AMS fabric is transformed into a triaxial fabric during initial deformation. Transformation of the fabric from oblate to triaxial appears to be highly correlated with an increase in natural remanent magnetization scatter, whereas deflection of the V_3 axes is not. We suggest that subtle soft-sediment deformation can be detected by using AMS fabric.

Keywords: Ardath Shale, soft-sediment deformation, anisotropy of magnetic susceptibility, paleomagnetism.

INTRODUCTION

The magnetic fabric of geological materials, in particular of sediments, has been a focus of interest for decades (e.g., Ising, 1942; Granar, 1958; Rees, 1965). Given that it is extremely sensitive to strain, magnetic fabric has recently been used to detect subtle deformation of sediments and to distinguish geomagnetic features from deformational artifacts (e.g., Rosenbaum et al., 2000). Cronin et al. (2001) suggested that the anisotropy of magnetic susceptibility (AMS) could be used to detect slumps not otherwise obvious from the geologic field evidence (so-called cryptoslumps).

A range of laboratory experiments has been done on the depositional controls of magnetic fabric and its relationship to natural remanent magnetization (NRM; summarized in Tauxe, 1998.) In quiet-water conditions, there is a tendency for elongate particles to lie subparallel to the bedding plane. Because the magnetic susceptibility is usually at a maximum parallel to the long axis of particles, $\mathbf{V}_1$ will tend to be within the bedding plane. (Because many articles on AMS confuse eigenvalues and eigenvectors, referring to both as, e.g., $k_{\min}$, we use the terminology of Tauxe [1998], whereby the eigenvectors are denoted by $\mathbf{V}$ and the eigenvalues as τ, τ_1 being the largest and τ_3 the smallest.) There is no preferred direction within the bedding plane, however, so $\mathbf{V}_2$ and $\mathbf{V}_1$ will be indistinguishable, as will the associated eigenvalues τ_2 and τ_1. Hence the magnetic fabric will be oblate with a vertical $\mathbf{V}_3$ direction.

In moderate water currents, especially on inclined bedding planes, particles may be slightly imbricated, resulting in slightly off-vertical $\mathbf{V}_3$ directions. Here we expect the fabric to be characterized by an oblate AMS ellipsoid, but the $\mathbf{V}_3$ direction will be antiparallel to the direction of paleocurrent. When deposition occurs under high current flow, with particles entrained, the $\mathbf{V}_1$ distribution is streaked, $\mathbf{V}_1$ is perpendicular to the flow direction (Jeffrey, 1922), and the fabric is characterized by prolate or triaxial ellipsoids.

What happens to the magnetic fabric during postdepositional deformation is more complex. Initial theoretical work on the relationship between magnetic fabrics and actual grain fabrics with respect to strain was done by Owens (1974), Hrouda and Hruskova (1990), and Housen et al. (1993). Most studies concerning strain in relation to AMS fabric have dealt with tectonic scales (e.g., Kanamatsu et al., 2001; Pares et al., 1999) and at least weakly metamorphosed rocks. However, as suggested by Rosenbaum et al. (2000) and Cronin et al. (2001), it appears that even minor amounts of soft-sediment deformation can have a profound effect on the paleomagnetic record. Such deformation, however, can be extremely difficult to detect on the basis of visual observations alone, hence the term cryptoslump. In this paper we pursue the idea that soft-sediment deformation can be detected through the use of AMS by investigating both cryptoslumped sediments from a marine environment along with the sediments from within and above the slump to try to confirm observations of Cronin et al. (2001). Our cryptoslump can be traced to a slumping event along the outcrop. Without the excellent exposure along the outcrop, however, its slumped nature would not be easily detected. Our goal is to develop a robust test for deformation based on the AMS characteristics of the slumped versus undeformed sediments.

GEOLOGIC SETTING

The Ardath Shale Formation of the La Jolla Group is part of a sequence of Eocene (49–46 Ma) rocks. The La Jolla Group was deposited within an ancient submarine channel and fan system that opened westward to the Pacific Ocean; it has since been uplifted to its present position (Kennedy, 1975; Chanpong, 1975). The Ardath Shale crops out along the base of an ~100-m-high sea cliff (Fig. 1) north of the pier at the Scripps Institution of Oceanography (La Jolla, California). Contained in the cliff are a number of cut-and-fill channel sequences that were likely sediment-transport conduits much like the Scripps Canyon head today. On the basis of data presented by May and Warme (1991), the paleocurrent direction is inferred to have been ~230°. Lohmar et al. (1979) used foraminifera to estimate a paleodepth of 200–600 m. This places the sedimentary environment of the Ardath Shale in the outer shelf or upper slope.

The Ardath Shale at the Scripps locality is mostly covered by modern beach sand, but extends 5 m above the beach in places. The lowest part of the exposed unit has well-defined horizontal laminations with no observed deformation. Above this, there is a 1-m-thick zone of soft-sediment deformation inferred to have been caused by slump-

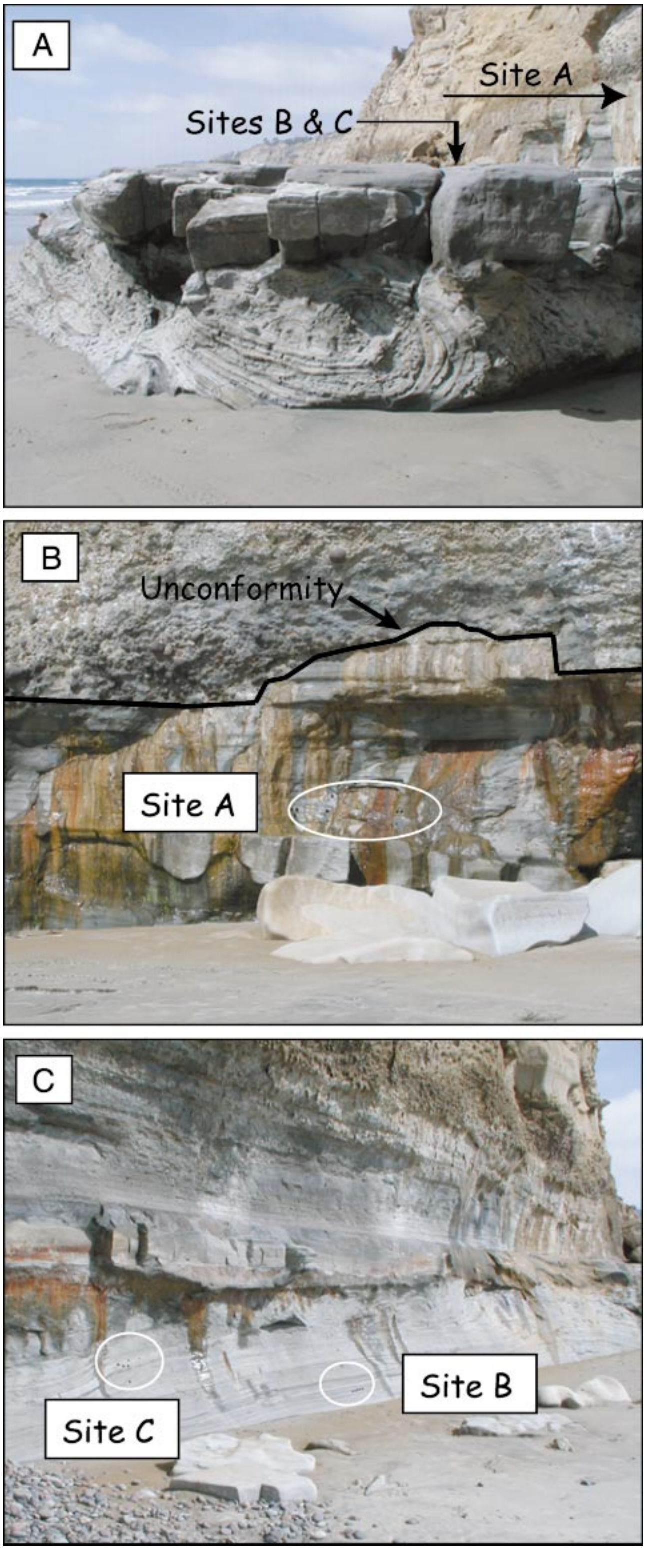

Figure 1. Photographs of slumped outcrop of Ardath Shale north of Scripps Pier at 32°52′05.6″N, 117°15′13.2″W. A: Prominent slump; view to north. B: Context of site A above slump; view to east. C: Context of sites B and C, within and below slump, respectively; view to east.

ing. There are overturned and recumbent folds as much as 1 m across (Fig. 1A). The overlying part of the Ardath Shale extends for another 2 m and is well laminated and apparently undisturbed. The top of the Ardath here is an erosional unconformity with an overlying conglomerate (Fig. 1B).

SAMPLING AND ANALYSIS

We sampled three sites within and surrounding a major slump in the Ardath Shale. The geologic context of the three sites is shown in Figure 1. Site A (Fig. 1B) is located 1 m above the slump in well-laminated and visually undeformed shale. Site B (Fig. 1C) is located 50 cm below the base of the slumped interval, and site C is located in the bottom 10 cm of the slump. The sampling site for site C is a less deformed region of the slump with bedding visibly deformed, but still within 10° of the bedding above and below the slump. Cores were drilled with a gasoline-powered drill and cut into nominal 1 inch (2.5 cm) specimens.

AMS Measurements

AMS measurements[1] were done at the Scripps Paleomagnetic Laboratory on a Kappabridge KLY-2 by using the 15 measurement scheme of Jelinek (1978). We calculated the best-fit tensor for each specimen by using Hext statistics (Hext, 1963; see also Tauxe, 1998). The directions of the eigenvectors for all specimens are shown in Figure 2A–2C. To assess the statistical distribution of these data, we used a variation of the bootstrap described by Constable and Tauxe (1990) and Tauxe (1998). The bootstrap eigenvectors for the data sets are shown in Figure 2D–2F, and the bootstrap eigenvalues are shown as histograms in Figure 2G–2I. The 95% confidence bounds for the minimum τ_3, intermediate τ_2, and maximum τ_1 eigenvalues are plotted above the each histogram.

In general, the eigenvectors associated with the minimum in magnetic susceptibility $\mathbf{V}_3$ are subvertical in all three sites. The intermediate and maximum susceptibility eigenvectors ($\mathbf{V}_2$ and $\mathbf{V}_1$, respectively) girdle the horizontal. The subtle differences in ellipsoid shape hold the key to our interpretation as to origin of the fabric.

The average eigenvector $\mathbf{V}_3$ for site A (Fig. 2A) is near vertical, but the distribution of the mean eigenvectors (Fig. 2D) shows that it is deflected an average of 12.7° toward 242.7°, in good agreement with the local paleocurrent indicators mentioned previously. The AMS (magnitude) ellipsoid is oblate, as indicated by the overlap of the 95% confidence bounds of τ_1 and τ_2 in Figure 2G.

The specimen (Fig. 2B) and the bootstrap eigenvectors (Fig. 2E) for site B both show that $\mathbf{V}_2$ and $\mathbf{V}_1$ are in two distinct groups. The histogram confidence intervals of eigenvalues (Fig. 2H) show that the intermediate and maximum axes are statistically distinct; therefore the ellipsoid is classified as a weak triaxial fabric. We conclude that this sediment has been deformed by the slumping of overlying sediments that occurred while they were still soft. Cronin et al. (2001) termed this kind of deformation ‘‘cryptoslumping.’’

The $\mathbf{V}_3$ directions from site C (Fig. 2C) are well grouped about the vertical. The $\mathbf{V}_1$ and $\mathbf{V}_2$ directions are also tightly grouped in the horizontal direction; $\mathbf{V}_1$ is oriented roughly perpendicular to the direction of inferred compression (east-west from the vergence of the slumps). The eigenvalues are distinctly triaxial (Fig. 2I).

Remanence Measurements

Measurements of the NRM of the specimens were made by using a three-axis CTF cryogenic magnetometer, located in a magnetically

[1]GSA Data Respository item 2003018, explanation of bootstrap method and raw AMS data, is available from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, editing@geosociety.org or at www.geosociety.org/pubs/ft2003.htm.

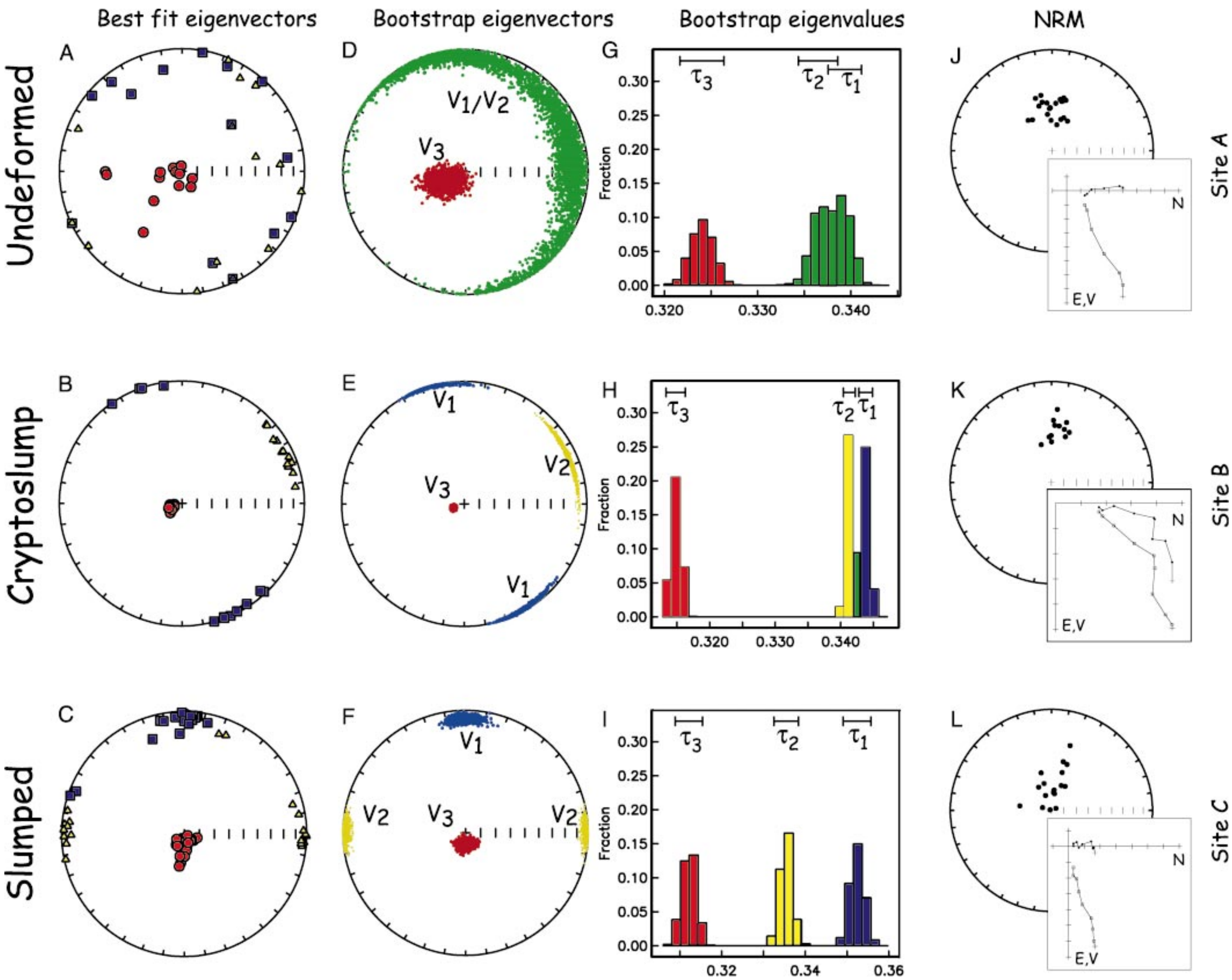

Figure 2. Anisotropy of magnetic susceptibility (AMS) and paleomagnetic data for three sites being studied. A–C: AMS eigenvector orientations. Squares are eigenvectors V_1 associated with maximum eigenvalues (τ_1). Triangles are eigenvectors V_2 associated with intermediate eigenvalues (τ_2), and circles are eigenvectors V_3 associated with minimum eigenvalues (τ_3). These are lower-hemisphere, equal-area projections for (A) site A (undeformed), (B) site B (cryptoslump), and (C) site C (slumped) specimens. D–F: Bootstrapped AMS eigenvector distributions (see text). G–I: Histograms of bootstrapped eigenvalues and 95% confidence bounds. Note that scales for histograms are different for each plot. J–L: Lower-hemisphere, equal-area projections of natural remanent magnetization (NRM) directions and representative vector–end-point diagrams for three sites.

shielded room. Alternating field (AF) demagnetizations were accomplished with an SI-4. NRM directions and representative vector–end-point diagrams for demagnetizations are shown in Figure 2J–2L. These samples were magnetically soft; measurements beyond 40 mT were highly scattered and are not shown. A typical Mr/Ms ratio for the Ardath Shale is 0.074.

TABLE 1. SUMMARY OF FISHER (1953) STATISTICS FOR NATURAL REMANENT MAGNETIZATION DIRECTIONS SHOWN IN FIGURE 2

Site	$\bar{D}$	$\bar{I}$	N	R	κ	α_{95}
Site A	0.0	54.9	22	21.54	45.3	4.7
Site B	6.0	46.4	12	11.81	57.5	5.8
Site C	1.9	70.3	18	17.22	21.8	7.6

Note: $\bar{D}$ is mean declination; $\bar{I}$ is mean inclination; N is number of specimens; R is length of resultant vector; κ is the Fisher (1953) precision parameter; and α_{95} is the estimate of the circle of 95% confidence.

The average NRM directions are summarized in Table 1. The average direction from the undeformed site (site A) is close to the expected direction for the Eocene at this locality (351.6° and 54.3°; Diehl et al., 1983). The site mean for the cryptoslump (site B) is significantly shallower than the undeformed site. That from the slump is on average steeper, but is much more scattered, with a κ of 21.8 as opposed to 45.3 for the undeformed site. Without further information, it would be tempting to interpret the data from the cryptoslump as genuine field behavior.

DISCUSSION AND CONCLUSIONS

AMS fabric is sensitive to strain even in small amounts on both regional and local scales. Such strain does not have to be visible for effects to be detectable in the AMS and NRM measurements. Several authors have devised tests for sediment deformation based on AMS fabric. Shor et al. (1984) used a strict test that discards all samples with $f > 15°$, where f is the angular deviation of $\mathbf{V}_3$ from the pole to bedding defined in Crimes and Oldershaw (1967). Rosenbaum et al. (2000) developed a similar test that also relies on the $\mathbf{V}_3$ vector. They expect ''good'' samples to have a standard deviation of $\mathbf{V}_3$ inclination ($\sigma_{\mathbf{V}_3}$) of $<6.5°$ and an inclination average of $\mathbf{V}_3$ ($I_{\mathbf{V}_3}$) of $<6°$ from the vertical. Rosenbaum et al. (2000) found that for undisturbed sections, $\sigma_{\mathbf{V}_3}$ was $<6.5°$ and the $I_{\mathbf{V}_3}$ was 84°. For our undisturbed site (site A), we calculated $\sigma_{\mathbf{V}_3}$ to be 18.3° and $I_{\mathbf{V}_3}$ to be 72.0°. For their deformed cores, Rosenbaum et al. (2000) calculated $\sigma_{\mathbf{V}_3}$ to be 26° and $I_{\mathbf{V}_3}$ to be 66.5°, whereas we found $\sigma_{\mathbf{V}_3}$ to be 5.0° and $I_{\mathbf{V}_3}$ to be 80.9° (site C). In short, we see a relationship that is opposite to that seen by Rosenbaum et al. (2000), whereby the disturbed intervals are actually more tightly grouped and more vertical than the undisturbed interval.

Although the method outlined in Rosenbaum et al. (2000) may be able to distinguish fluidized zones, it is perhaps not the best approach for several reasons. First, the mean inclination from a set having a near-vertical direction will always be biased too low (e.g., see Briden and Ward, 1966; Kono, 1980; McFadden and Reid, 1982). Second, eigenvectors are not independent, so the average minimum eigenvector should be estimated by using Hext (1963) statistics, not Fisher (1953) statistics. Furthermore, as discussed previously, there are many reasons why $\mathbf{V}_3$ could be deflected from the vertical other than postdepositional deformation. Finally, sediments can be severely deformed without deflecting $\mathbf{V}_3$ (see Fig. 2B–2C). The tests of Rosenbaum et al. (2000) and Shor et al. (1984) would not detect the deformation in sites B and C where $\mathbf{V}_3$ is near vertical. We propose that the eigenvalue test illustrated in Figure 2G–2I is much more sensitive to deformation than $\mathbf{V}_3$ deflection.

AMS fabric provides a way to distinguish between synsedimentary structures and subsequent deformation in situations where field observations are ambiguous. Many continental-slope regions show seismic signatures that have been interpreted as either retrogressive slope failure (Gardner et al., 1999) or as depositional features associated with hyperpycnal flows (N. Driscoll, 2000, personal commun.). The presence of a deformed sedimentary fabric would be strong evidence that a structure has undergone slumping.

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