Coring-related deformation of Leg 208 sediments from Walvis Ridge: Implications for paleomagnetic data

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Abstract

Both shipboard and shore-based magnetic studies of Ocean Drilling Program (ODP) Leg 208 sediments produced poor-quality directional data. A noisy inclination signal and a pervasive declination bias demonstrate that the sediments had been remagnetized and/or deformed. In an attempt to characterize any deformation, we carried out anisotropy of magnetic susceptibility (AMS) experiments on a suite of samples from Sites 1262 and 1267. Results show that the cores have suffered at least two kinds of deformation, one producing a tilting of the foliation (by up to 40° from horizontal in some intervals), and the other producing a lineated fabric. The former is firmly linked to lithology – higher carbonate content results in a higher degree of tilting – while the latter may be more closely tied to depth, suggesting the two fabrics result from different processes. The remanence directions show no obvious correlation to either fabric, suggesting that some third mechanism may have remagnetized the sediments, possibly an isothermal remanence acquired during the drilling process. In this study, the severity of the deformation may be linked to the high carbonate content of the cores, but pinpointing precise causes for both the AMS fabric and the directional anomalies remains elusive. It is clear, however, that the deformation is complex, pervasive and has significant implications for the interpretation paleomagnetic data from Leg 208.

Keywords: Ocean drilling program Leg 208; Anisotropy of magnetic susceptibility; Coring-related deformation; Paleomagnetism

1. Introduction

ODP Leg 208 sampled predominantly carbonate-rich sediments from Walvis Ridge in the South Atlantic. Shipboard magnetostratigraphic results from pass-through measurements on half-cores provided disappointing results for many sites. The sediments suffered from a frequently noisy inclination signal and an overprint or deformation that resulted in a severe and pervasive, high-coercivity declination bias (Zachos et al., 2004; Bowles, 2006). A large (~50–80% of the natural remanent magnetization) vertical drilling overprint was typically removed by 15 mT alternating field (AF) or 200°C thermal demagnetization. Working half discrete sample inclinations generally agreed with the pass-through magnetometer data from the intact archive half core sections, although in some cases discrete samples provided less ambiguous results (Bowles, 2006).

The magnetostratigraphy was difficult or impossible to interpret at most sites in sediments above the Paleocene–Eocene (P–E) boundary, where inclination data are quite scattered. Below this boundary, gradual increases in clay content and magnetic susceptibility are accompanied by increases in remanent intensity;
although significant variation exists, intensities are on the order of $10^{-3}$ A m$^{-1}$ above the boundary and $10^{-2}$ A m$^{-1}$ below. These increases are further accompanied by a suppression of scatter in the inclination data, and most reversal boundaries could be identified in the inclination record. Many of the discrete sample data cluster around the expected geocentric axial dipole value of 53°–56°. However, some inclinations appear excessively steep and may be related to an incompletely removed vertical drilling overprint. The declination bias was present throughout the entire section in the pass-through data. The bias toward 0° (core coordinates) in the archive halves was sometimes mirrored by a more subtle bias toward 180° in discrete samples from the working half (Bowles, 2006). In spite of the more subtle declination bias of the discrete samples, they in no way produced a more reliable declination record than the pass-through data. The fact that discrete samples (taken from the center of the core) also gave poor-quality directional results suggests that the mechanism(s) corrupting the record (deformation and/or remagnetization) is not restricted to the core edges; this has important implications for many paleomagnetic studies.

A declination bias similar to that observed in Leg 208 cores has been reported in many other studies of ODP cores (e.g., Shipboard Scientific Party, 1995; Fuller et al., 1998; Herr et al., 1998; Aubourg and Oufi, 1999; Shipboard Scientific Party, 1998; Shipboard Scientific Party, 2000). Most authors attribute the bias to a hard, inward directed, radial component that is not removed by AF or thermal demagnetization, and the results from Leg 208 are consistent with this. The source of this radial overprint has been alternately attributed to grain reorientation (from vibration during travel up the drill string) in the presence of a magnetic field generated by the core barrel (Shipboard Scientific Party, 1988; Fuller et al., 1998; Shipboard Scientific Party, 2000); a “conical fabric” resulting from soft-sediment deformation along the edges of the core liner (Aubourg and Oufi, 1999; Herr et al., 1998; Acton et al., 2002); some combination of a radial magnetic field component in the coring assembly and sediment deformation during the coring process itself (Shipboard Scientific Party, 1998; Shipboard Scientific Party, 2000). Almost all of the above-referenced studies are based on a nanofossil ooze or other carbonate-rich sediment, and Fuller et al. (2006) summarize and document many of the difficulties paleomagnetists encounter in working with ODP carbonate sediments. A radial component overprint is not limited to sediments; a declination clustering around 0° has also been observed in gabbroic cores from ODP Site 735 (Shipboard Scientific Party, 1999), and a hard, radial-in overprint has been detected in basalt from ODP Site 1256 (Shipboard Scientific Party, 2003b), a tuff from Site 1223 (Shipboard Scientific Party, 2003a), and in drill cores from the Columbia River Basalt in Washington State, USA (Audunsson and Levi, 1989).

If sediment deformation plays a role in the poor quality of the remanence directions, then measurements of the anisotropy of magnetic susceptibility (AMS) should show evidence for a deformed sedimentary fabric. The goal of the present study is to document the type and degree of deformation that may be present in Leg 208 cores. AMS was therefore measured on discrete samples from Leg 208 Sites 1262 and 1267, and the results are interpreted here in terms of a sedimentary fabric that has its origin—in part—in deformation. The anisotropy ellipsoid is described by a second-order tensor, the eigenvectors ($V_1$, $V_2$, $V_3$) of which represent the directions of the ellipsoid axes, and the eigenvalues of which represent the length of the axes ($\tau_1 > \tau_2 > \tau_3$). In a normal, undeformed sedimentary fabric, the AMS ellipsoid is oblate ($\tau_1 \approx \tau_2 > \tau_3$), and the $V_3$ (minimum) axis is vertical.

Throughout this paper, we refer to directions in core coordinates (i.e., unoriented with respect to true north). In the right-handed ODP orientation convention, $+X$ points into the split face of the working half core and is defined as north; $+Y$ is east and points toward the double line on the core liner; $+Z$ points downcore.

Other authors have interpreted AMS results in terms of coring-related deformation. Aubourg and Oufi (1999) found a slight deflection (by a few degrees toward the $-X$ direction) of the minimum ($V_3$) axis from the vertical, along with a clustering of $V_1$ along the $Y$ axis in core coordinates in carbonate cores from Leg 161. Kanamatsu and Matsuo (2003; using data from Kanamatsu, 1996) found a similar, but much more variable, deflection of $V_3$ toward $-X$, ranging from 0° to nearly 90° in fine-grained siliciclastic sediments from Hole 898A. Both studies attribute this to a conical fabric developed by the down-dragging of soft sediments along the core liner. This interpretation was supported by AMS results from Herr et al. (1998) who found $V_3$ deflections toward the $Y$ and $-Y$ directions from samples taken from the $-Y$ and $+Y$ sides of the core (respectively), adjacent to the core liner in carbonate cores from Leg 157. All of these results are consistent with a foliation dipping down in all directions away from the center of the core.

2. Methods

Discrete samples were taken from the working half of the cores of Sites 1262 and 1267 in standard 8 cm$^3$
cubes. These two sites share very similar lithologies, but Site 1267 is more expanded, so similar lithological units occur at shallower depths (below seafloor) at Site 1262 relative to Site 1267. Most of the samples from Site 1262 were closely spaced (up to 10 cm), targeting specific reversal boundaries. Hole 1267A was coarsely sampled (one sample per core section) throughout, with some denser, targeted sampling near reversal boundaries. Samples were stepwise AF demagnetized as described in Bowles (2006).

We measured AMS on selected samples from all of the major lithologic units. Samples were measured on a Kappabridge KLY2 using a 15-position measurement scheme (Jelinek, 1976). Anisotropy of anhysteretic remanent magnetization (AARM) was also measured on a small subset of samples from Site 1262 (8 samples between ~99.5 and 124 m composite depth) in order to compare the fabric generated by the remanence-bearing minerals only with the AMS fabric (which has contributions from the paramagnetic grains). Owing to the difficulty of orienting the cubes in the small, horizontal coil, ARMs were applied in only six directions (+x, +y, +z, −x, −y, −z), using an 80 mT AC field with a 0.05 mT bias.

3. Results

Directions and lengths of the AMS eigenvectors are given in Supplementary Table 1. The degree of anisotropy (as measured by $\tau_1/\tau_3$) is a weak function of depth, but appears to be primarily controlled by lithology with values typically <1.03 in the carbonate units and values up to 1.06 in the more clay-rich units (Fig. 1). The shape of the ellipsoid is predominantly oblate ($\tau_1 \approx \tau_2 > \tau_3$), typical of sedimentary fabrics. However, a few sections show statistically distinct $V_1$ and $V_2$ ($\tau_1 > \tau_2 > \tau_3$) based on the Hext (1963) $F$-test for statistical anisotropy. This triaxial fabric implies the development of a weak lineation, in addition to the foliation.

The most striking features of the AMS data are the orientations of the principal axes in core coordinates (Fig. 1). $V_3$ – vertical in a normal, undeformed sedimentary fabric – is severely deflected toward the $−X$ direction in the sections with high carbonate (low clay) content. This deflection is consistent with a tilting of the foliation down and toward $+X$ in core coordinates. Furthermore, the development of the triaxial fabric mentioned above manifests itself in a clustering of $V_1$ axes in a direction typically close to $0^\circ$ (+X) in most (though not all) cases (Figs. 1a, c and f and 2). While both a lineation and a deflection of the $V_3$ axes could result from sediments aligned by sea-floor bottom currents, in that case one would expect the AMS axes to be well grouped in geographic coordinates. In the present case, however, the $V_3$ axes are significantly better grouped in core coordinates; the Fisherian precision parameter ($\kappa$, Fisher, 1953) decreases (scatter increases) when data are rotated into geographic coordinates. For example, in Fig. 1b, $\tau$ decreases from 89.9 to 39.9 when data are rotated into geographic coordinates; for Fig. 1c $\tau$ decreases from 23.2 to 15.1. While similar data from $V_1$ and $V_2$ are more ambiguous ($\tau$ is typically <5 to begin with and may increase or decrease slightly when rotated), it seems unlikely that the fabric results from currents rather than coring- or post-coring-related deformation.

This fabric is consistent from hole to hole within Site 1262; Fig. 2 shows the interval from ~95 to 125 m composite depth (mcd) for all three holes, and all three have the same ~40° deflection from the vertical in $V_3$ and a statistically triaxial fabric with $V_1$ in the northwest quadrant. The same severe deflection of $V_3$ is present in the few measured samples from the same stratigraphic level at site 1267 (~194–228 mcd), though the fabric remains statistically oblate (Fig. 3a).

AARM results also show a deflection of $V_3$ from the vertical, similar in direction and magnitude to that of the AMS (Fig. 4; Supplementary Table 2). The degree of anisotropy ($\tau_1/\tau_3$) ranges between 1.03 and 1.08—significantly greater than for the AMS data. The $V_3$ axes are not as well grouped as in the AMS, and the AARM ellipsoids are not statistically anisotropic, based on the Hext (1963) $F$-test for anisotropy at the 95% confidence level. We suggest these differences result from small uncertainties in sample orientation in the coil, combined with the inability of the six-position measurement scheme to fully describe the anisotropy ellipsoid in samples that are weakly anisotropic. The fact that the AARM ellipses are not randomly oriented, but rather share a common orientation with the AMS data suggests that the data have some significance. The remanence-bearing grains thus appear to be involved in whatever deformation is causing the $V_3$ deflection, although the remanence directions show no simple correlation to either the AMS or AARM fabrics.

While the severe tilting of the foliation disappears in the deepest parts of the holes (accompanied by increased clay content), the lineation appears to become better defined (Figs. 1f and 3b). This suggests that the tilting of the foliation and the lineation are produced by two different mechanisms. Curiously, this lineation in Hole 1267A (Fig. 3b) is clearly oriented along the $Y$ axis, while the lineation from the same stratigraphic unit in Hole 1262B is oriented along the $X$ axis (Fig. 1f).
4. Discussion

The fact that the eigenvectors of the AMS ellipsoids are well grouped in core coordinates (unoriented with respect to north) means that the fabric must be developed during or after the coring process. Thus, we can interpret the results as representing at least two kinds of syn- or post-coring deformation: (1) a significant tilting of the foliation or bedding plane down and toward +X (north) in core coordinates; (2) a lineation or preferred orientation of $V_1$ roughly oriented between the +X and −Y directions (north–northwest) at Site 1262, but along the Y axis in...
Fig. 2. AMS results from discrete samples at Site 1262, above the P/E boundary. Symbols and conventions as in Fig. 1.

The observed $\sim 40^\circ$ deflection of $V_3$ seems to be inconsistent with suggestions that the tilting results from soft-sediment deformation along the edges of the core liner (Aubourg and Oufi, 1999; Herr et al., 1998; Acton et al., 2002). While Herr et al. (1998) see significant tilting of $K_3$ (of a magnitude similar to the present study) adjacent to the core liner, Aubourg and Oufi (1999) report only a few degrees of tilting from samples taken from the center of the core, as ours are. Severely bowed structures (concave downcore) can be seen in the upper few tens of meters at Sites 1262 and 1267, with a maximum dip of $\sim 40^\circ$–$50^\circ$ adjacent to the core liner. In the center of the cores, however, the dip is significantly less, and at greater depths the cores show little evidence for this kind of deformation, except very close to the core.
liner. Although our samples may be slightly bigger (and thus sample slightly closer to the core liner) than those of Aubourg and Oufi (1999), it is hard to imagine a \( \sim 40^\circ \) average tilting of the bedding plane throughout the sample at depths \( >100 \) m (e.g., Figs. 1c and d and 2).

We suggest that tilting of the foliation in the Leg 208 sediments cannot be explained by deformation along the core liner alone, although this almost certainly contributes. Although core splitting was discounted by Aubourg and Oufi (1999) as a source of the anomalous fabric, we suggest that this may contribute to the severity of the tilting seen in the center of the Leg 208 cores. Leg 208 cores were split from bottom to top, which would produce shearing consistent with a tilting of the foliation down and toward \(+X\) in the working half core.

The second aspect of the Leg 208 AMS fabric that requires explanation is the development of a triaxial fabric and the grouping of the \( V_1 \) axes. Because the grouping is not consistent (N–S at Site 1262 and E–W in parts of Hole 1267A), it is unlikely the result of a single process. Gravenor et al. (1984) suggested that a lineation may develop from realignment of clay particles along the cube edges as it is pushed into the core, resulting in a deflection of \( V_1 \) into the push direction \(+X/\)north in the present study. This could be consistent with the grouping of \( V_1 \) axes in the north–northwest at Site 1262, although it is difficult to understand what might result in the consistent deflection to the northwest, away from north (Fig. 2).

In contrast to the rough orientation along the \( X \) axis of the \( V_1 \) axes at Site 1262, the deeper, more indurated samples from 1267A (>\( \sim 240 \) mcd) show a grouping along the \( Y \) axis, similar to that seen by Aubourg and Oufi (1999). Copons et al. (1997) suggested that sampling might result in a compression parallel to the push direction and a corresponding extension perpendicular to the push direction. This might result in \( V_1 \) grouping along the \( Y \) axis in our coordinate system. Copons et al. (1997) also suggest that once the core is split, the core liner relaxes into a slightly oblate shape, resulting in tension (and corresponding alignment of \( V_1 \) ) in the \( Y \) direction. Tensional cracks in the \( X–Z \) plane can indeed be seen in many Leg 208 carbonate cores, but are less frequent in the deeper, clay-rich sections such as those in which we find the \( Y \) oriented \( V_1 \). It seems unlikely that either of these processes would dominate in the more indurated sediments and not in the softer sediments. We therefore discount both of these explanations to explain the lineation in any of the Leg 208 samples.

Both Aubourg and Oufi (1999) and Herr et al. (1998) suggest a link between the AMS fabric, a declination bias and a conical fabric, stating that the coring-induced drag would result in a radial component to the magnetization. While true, the orientation of the radial component should change with polarity, as noted by Acton et al. (2002); a positive inclination should produce a radial-in horizontal component, while a negative inclination should be radial-out. This appears to be true in the two cores documented by Acton et al. (2002), who show that this kind of declination bias may be corrected for the deformation. It also appears to be true for some of the cores from both Herr et al. (1998) and Aubourg and Oufi (1999), while in other cores, the declination bias is consistent with a radial-in component only (Schmincke et al., 1995; Comas et al., 1996).

There is no evidence in the Leg 208 data that the declination bias changes with polarity; in all of the pass-through data, the declination bias is consistent with a magnetization that would be radial in. While the discrete sample data are more ambiguous in this respect, Fig. 5c and 5d shows the cumulative distribution function (cdf) of measured declinations for Sites 1262 and 1267 (blue lines). In order to determine if there is indeed a declination bias in the discrete sample data, we must compare this distribution with an expected distribution. Given a large number of randomly oriented cores, the declinations should be randomly distributed between 0 and \( 360^\circ \), and the cdf should be a straight line (Fig. 5a, dashed gray line).

In our case, however, we have only a few cores, whose orientations are not random. The expected distribution of measured declinations (assuming no deformation) was calculated in the following manner. For each core, we assumed an orientation as given by the Tensor tool, which estimates orientation during coring by measuring the angle between the double liner on the core barrel and magnetic north. We then draw a set of declinations from a Fisher distribution with a precision parameter \( (\kappa) \) of 25 and an inclination of \( 54^\circ \). These declinations are then transformed with the core orientation data to produce declinations in ODP core coordinates. The numbers of normal and reverse polarity samples were set to equal the numbers of positive and negative inclinations in the measured data for each core. The resulting simulated directions are shown by the top stereo plot insets (Fig. 5a and b), and the dashed gray lines show the cdfs of the simulated declinations. When compared to the actual data, it can be seen that the cdfs of the actual data (heavy black lines) rise more steeply through the middle of the distribution, suggesting a bias toward \( 180^\circ \), which is consistent with a radial-in magnetization only.

We can further test whether the tilting observed in the AMS data is likely linked to the declination bias. The bottom left insets in Fig. 5 show the simulated directions...
described above after applying a 40° tilt, down toward +X (north), as suggested by the AMS data. If the tilting were linked to the directional anomalies, one would expect the distribution of the simulated, tilted declinations (thin black lines) to correspond more closely to the observed declinations (heavy black lines) than did the untitled simulated declinations (dashed gray lines). While this appears true at Site 1267, the distribution at Site 1262 clearly moves even farther away from the observed declinations. We therefore conclude that the severe tilting shown in the AMS data is not the source of the declination bias in the Leg 208 cores.

The declination bias observed in the Leg 208 cores (0° in the archive half and 180° in the working half) must therefore have another origin. This radial-in only magnetization is more consistent with an incompletely removed isothermal remanence (IRM) acquired during the coring process.

5. Conclusions

As has been noted by others, no single deformation and/or remagnetization source can be easily isolated to explain all the data. Deformation required to produce the AMS fabrics appears to be complex and to have multiple origins. The severe tilting of the foliation in certain intervals appears to be linked to high carbonate content. Furthermore, the declination bias observed in Leg 208 cores (0° in the archive half and 180° in the working half) has no obvious link to the AMS fabric, and is more likely produced by an IRM acquired during or after coring, rather than by coring-related deformation.

It is clear that with the present drilling and core treatment techniques, a significant amount of information (paleomagnetic direction, intensity, and magnetic fabric) is destroyed in these relatively soft, weakly
magnetized sediments. Great care must be taken in attributing geological significance to any of the magnetization or magnetic fabric data from Leg 208. If one were only working on a single APC core, it could be possible to misinterpret the magnetic fabric and/or directions in terms of some real geologic process. In the present case, it appears that the inclination is at least partially preserved in the more clay-rich sediments, allowing polarity determinations, but little else.

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Appendix A. Supplementary data

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References


