Strain decoupling across the decollement of the Barbados accretionary prism

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ABSTRACT

The interrelation between deformation styles and behavior of fluids in accretionary prisms is under debate, particularly the possibility that overpressuring within the basal decollement may enable mechanical decoupling of the prism from the subducting material. Anisotropy of magnetic susceptibility (AMS) data from sediments spanning the basal decollement of the Barbados accretionary prism show a striking progression across this structure that strongly supports the hypothesis that it is markedly overpressured. In the accretionary prism, above the decollement, the minimum AMS axes are subhorizontal and oriented nearly east-west, whereas the maximum AMS axes are oriented nearly north-south and shallowly inclined. At the top of the decollement, the minimum AMS axes orientations abruptly change to nearly vertical; this orientation is maintained throughout the decollement and in the underthrust sediments below. The AMS orientations in the prism sediments above the decollement are consistent with lateral shortening due to regional tectonic stress, as the minimum axes generally parallel the convergence vector of the subducting South American plate and the maximum axes are trench-parallel. Because the orientations of the AMS axes in deformed sediments usually parallel the orientations of the principal strains, the AMS results indicate that the incremental strain state in the Barbados prism is one dominated by subhorizontal shortening. In contrast, the AMS axes within and below the decollement are consistent with a strain state dominated by vertical shortening (compaction). This abrupt change in AMS orientations at the top of the decollement at Site 948 is a direct manifestation of mechanical decoupling of the off-scraped prism sediments from the underthrust sediments. The decoupling horizon occurs at the top of the decollement zone, coinciding with the location of flowing, high-pressure fluids.

INTRODUCTION

Recent multidisciplinary studies have focused on the expulsion and migration of fluid and the relation of these processes to the decollement and other faults in active accretionary prisms (see review by Moore and Vrolijk, 1992). Much of this work is based upon porosity profiles derived from physical properties of sediment, but the relative contributions of compaction and tectonic strains to porosity reduction cannot be extracted from these data (Karig, 1990). A limited number of triaxial consolidation experiments (Moran and Christian, 1990) imply high lateral (tectonic) in-situ stresses in the Barbados prism, suggesting that porosity reduction by tectonic strains may be significant. Measurements of preferred orientations of minerals are needed to distinguish between the components of porosity collapse resulting from compaction and those from tectonic strains. Such data will also provide more spatially detailed information on the orientations of differential stresses in accretionary prisms (Karig and Morgan, 1994), leading to an improved understanding of the mechanics of prism deformation.

Strain measurements in accretionary-prism sediments are rare because the markers commonly utilized in strain analyses are generally absent (e.g., Karig and Lundberg, 1990). Strain geometries recorded by the preferred orientations of minerals are more readily obtained in accretionary-prism sediments by optical methods (e.g., Agar et al., 1989), X-ray texture goniometry (e.g., Morgan and Karig, 1993), or magnetic anisotropy. The last method is particularly suited to the study of fabrics and strains in weakly deformed sediments (Borradaile, 1991). Our results show that magnetic fabrics are good proxies for incremental strain orientations in the Barbados prism; determination of these fabrics leads to important inferences regarding the states of stress and fluid pressure across the decollement.

STRUCTURES AND SEDIMENTS IN THE BARBADOS PRISM

Leg 156 of the Ocean Drilling Program (ODP) revisited the area of the Barbados accretionary prism drilled by Deep Sea Drilling Project–ODP Legs 78A and 110 with the aim of documenting the relation between structures and fluid pressure. Site 948 was cored from 420 to 590 m below sea floor (m bsf), with good recovery (>95%) throughout the drilled interval. The site can be divided into three structural units: the accretionary prism (420–490 m bsf), the decollement zone (490–530 m bsf), and the underthrust sediments (530–590 m bsf) (Fig. 1). The two relevant lithologic units defined

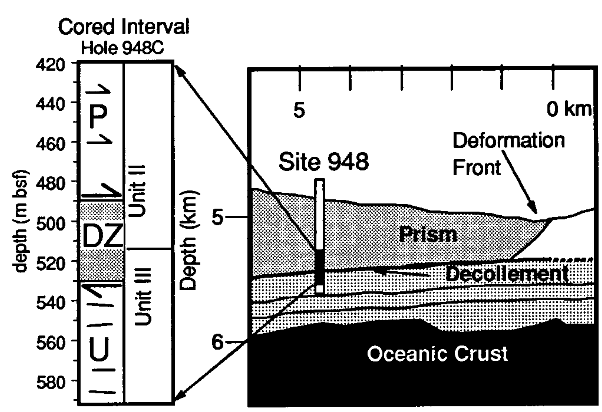

Figure 1. Diagram of Barbados accretionary prism, illustrating major tectonic features and location of ODP Site 948. Enlargement at left shows cored interval of Hole 948C (420–590 m bsf). This interval is subdivided into three structural domains: P is accretionary prism (420–490 m bsf), DZ is decollement zone (490–530 m bsf), and U is underthrust sediment (>530 m bsf). Half arrows indicate thrust faults.

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for Site 948 are unit II (420–514 m bsf), a bioturbated claystone with volcanic ash, and unit III (514–590 m bsf), a claystone with interbeds of silty clay and nannofossil oozes (Shipley et al., 1995). Within the accretionary prism, intervals of scaly fabric are the characteristic macroscopic structures (Shipley et al., 1995). Bedding orientations range from nearly horizontal to dips of 60°. The top of the decollement zone is marked by an abrupt increase in the intensity and thickness of the scaly fabric intervals, together with a zone of brecciated sediment, and rhodochrosite and phillipsite veins. Indications of focused fluid flow and of high fluid pressures, in the form of geochemical anomalies and abnormally high porosities recorded by core logs (logging-while-drilling), respectively, are near the top of the decollement zone (Shipley et al., 1995; Moore et al., 1995). The lower part of the decollement is characterized by stratal disruption and minor folding. The change in deformation style within the decollement zone is a reflection of the change in lithology at the lithostratigraphic boundary between unit II and unit III. The underthrust sediments are well-bedded, with shallow bedding dips (<30°).

MAGNETISM AND MAGNETIC FABRICS IN SEDIMENTS

Magnetism in Sediments

Anisotropy of magnetic susceptibility (AMS) measurements were made on 427 samples (6 cm^3 volume) from Site 948 by using a KLY-2 Kappabridge at the University of Minnesota's Institute for Rock Magnetism. All minerals in marine sediments contribute to the low-field magnetic susceptibility measured for AMS, so the sources of magnetic susceptibility must be evaluated to determine the significance of the measured fabrics. The measured low-field susceptibility (χ_{LF}) can be subdivided into components carried by ferrimagnetic (e.g., magnetite), paramagnetic (clays and Fe-Mg-Mn minerals), and diamagnetic (quartz, calcite) minerals. Measurements of high-field susceptibility (χ_{HF}) made above the saturation magnetization of the ferrimagnetic minerals determine the magnetic susceptibilities of the paramagnetic and diamagnetic minerals. The ratio (χ_{HF})/(χ_{LF}) is inversely proportional to the relative contribution of the ferrimagnetic phases to the low-field susceptibility used for AMS.

Comparison of high-field susceptibility (χ_{HF}) and low-field susceptibility (χ_{LF}) shows that lithology controls the carriers of the AMS. The χ_{HF}/χ_{LF} ratio for lithostratigraphic unit II is less than 0.10, indicating that ferrimagnetic minerals are the dominant contributors to the AMS in unit II. Curie temperatures of 540 to 560 °C and lack of a Verwey transition in most of the samples (Özdemir et al., 1993) indicate that low-Ti magnetite and titanomaghemite (hereafter, "magnetite and maghemite") are the primary ferrimagnetic minerals in the unit II sediments. The AMS measurements in these sediments thus record preferred orientations of magnetite and maghemite.

The χ_{HF}/χ_{LF} ratio for lithostratigraphic unit III is greater than 0.90, indicating that paramagnetic and diamagnetic minerals are the largest contributors to AMS in unit III. Clay minerals have both high susceptibilities and high single-mineral anisotropies, whereas diamagnetic minerals and phases have low susceptibilities (Borradaile et al., 1987) and weak preferred orientations in uncemented sediments, so the diamagnetic material in the sediments can be treated as an isotropic dilutant to the measured AMS. The AMS results from unit III thus reflect the preferred orientations of clay minerals.

Magnetic Fabrics

Anisotropy of magnetic susceptibility depicts the orientation and degree of alignment (intensity) of the preferred orientations of minerals as an ellipsoid. The orientations of the principal susceptibility axes ($\chi_{max} > \chi_{int} > \chi_{min}$) are commonly coaxial with the axes of the strain ellipsoid; in particular, the orientation of χ_{min} is almost

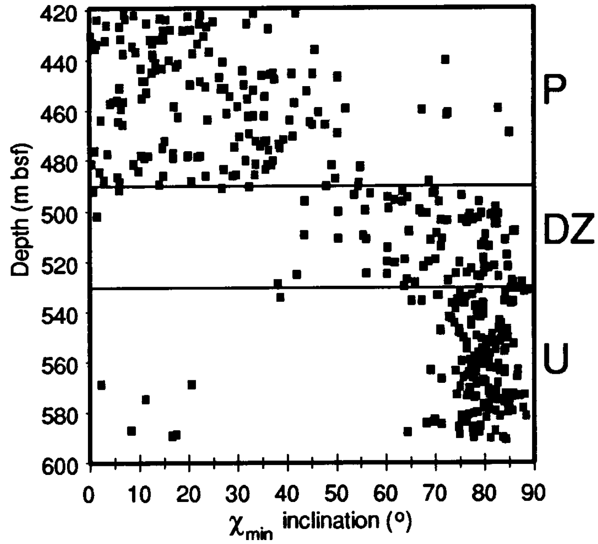

Figure 2. Inclination of minimum AMS axes vs. depth for Site 948 sediments. Structural domains as in Figure 1.

always parallel to the orientation of the axis of the maximum shortening strain (Borradaile, 1991). Unlithified sediments in accretionary prisms can easily respond to applied stresses by development of mineral preferred-orientation fabrics, and so the pole to planar fabric elements (in this case χ_{min}) serves as a proxy for the orientation of the maximum shortening strain (Byrne et al., 1993; Owens, 1993; Karig and Morgan, 1994).

Low-field AMS Results

The AMS results from Site 948 can be described in terms of two end-member orientations: one with shallowly inclined χ_{min} and χ_{max} axes and the other with subvertical χ_{min} and subhorizontal χ_{max} axes. These fabrics are defined by the orientation of χ_{min} (rather than χ_{max}) because χ_{min} is the most reliable proxy for strain orientation. The shallow χ_{min} orientations are in the accretionary prism, from 420 m bsf to about 490 m bsf (Fig. 2). The steep χ_{min} orientations occur in the decollement zone and in the underthrust sediments, from 490 to 590 m bsf (Fig. 2).

The shallow χ_{min} orientations define planar fabrics with steep (>60°) dips in the accretionary prism. The orientations of bedding and scaly fabric planes in this part of the accretionary prism, with few exceptions, have shallow (<60°) dips (Shipley et al., 1995). The AMS results from the accretionary prism are thus interesting in that they do not seem to correspond to the orientations of any observed macrostructures. To better understand these fabric orientations, it is desirable to compare the AMS orientations with the orientations of the tectonic elements of the Barbados accretionary prism. Although the cores were collected by rotary drilling, shipboard paleomagnetic results from a subset of the samples were of high enough quality to allow for the reorientation of 68 of the samples by rotating the measured characteristic remanence direction to present-day north (Shipley et al., 1995). Reorientation of the AMS axes in the prism domain (420–490 m bsf) offers a clearer picture of their significance. The reoriented χ_{min} axes are mostly subhorizontal and oriented east-west, matching the convergence direction of N78°E (Deng and Sykes, 1995); the reoriented χ_{max} axes are subhorizontal and oriented north-south (Fig. 3A). The trend of the trench in this area is nearly due north, which is closely matched by the orientation of the χ_{max} axes in the prism. Thus, magnetite and maghemite grains in the Barbados accretionary prism have been aligned in orientations governed by present-day tectonics, recording convergence-parallel shortening strains.

In contrast to the prism, reoriented samples from the decollement have χ_{max} orientations that are subhorizontal and either north-south or east-west; their χ_{min} axes are steep and oriented southeast-northwest (Fig. 3B). Measurements of scaly fabric dips in the decollement range between 10° and 30° (Shipley et al., 1995), which also agrees with the orientations of these AMS fabrics.

The change from shallow to steep χ_{min} orientations occurs near the top of the decollement (Fig. 2). By analogy with the AMS results from the prism above, these magnetite and maghemite orientations indicate a change from horizontal shortening to vertical shortening at the top of the decollement zone. The change in AMS (strain?) orientations coincides (stratigraphically) with several indicators of flowing, high-pressure fluids. The primary indicator of fluid flow (a large porewater Cl^- anomaly) occurs at 493 m bsf (Shipley et al., 1995). Zones of brecciated sediment suggestive of high fluid pressures occur from 490 to 496 m bsf. Core physical properties and logging-while-drilling results also indicate the presence of high fluid pressures in two narrow intervals (505 and 514 m bsf) in the upper part of the decollement (Moore et al., 1995). The abrupt change in AMS orientations from horizontal-compression geometries to vertical-compaction geometries near the top of the decollement is thus most likely a manifestation of mechanical decoupling of the off-scraped prism sediments from the underthrust sediments across an interval of overpressured and hence weakened sediments.

Changes in the degree of preferred orientation (fabric intensity) are manifested by changes in the degree of anisotropy ($P = \chi_{max}/\chi_{min}$). The degree of anisotropy measured by AMS is a function of both the minerals present (different minerals have variable single-crystal anisotropies) and their degree of alignment. Therefore, the fabric intensities measured by AMS for lithological unit II and lithological unit III are not directly comparable. Trends in fabric intensity are, however, directly comparable within each lithological unit. The degree of anisotropy for lithological unit II decreases from $P =$ 1.05–1.07 in the accretionary prism to values of $P < 1.02$ within the decollement (Fig. 4). The degree of preferred orientation thus generally decreases toward and reaches a minimum in, the decollement zone. The abrupt change in AMS orientation together with the decrease in degree of anisotropy at the top of the decollement are best explained by mechanical decoupling, rather than by high shear strains, as increasing shear strain would produce both a rotation of χ_{min} and a large increase in the degree of anisotropy. For lithological unit III, relatively high degrees of anisotropy occur in the underthrust sediments just below the decollement (530–540 m bsf), and relatively uniform anisotropies occur below 540 m bsf (Fig. 4).

High-field AMS Results

Comparison between magnetic fabrics and the scaly clay fabrics can be made by measurement of magnetic anisotropy using high fields, which in these sediments is controlled by clay minerals. Ten representative samples were selected, from which oriented 1 cm^3 subsamples were cut. A vibrating sample magnetometer was used to measure χ_{HF} in nine orientations, from which anisotropy of (high-field) magnetic susceptibility results were calculated according to McCabe et al. (1985). The clay fabrics measured by high-field anisotropy have much higher degrees of anisotropy (Fig. 5A). Note that the sample from the well-developed scaly fabric zone near the top of the decollement (star in Fig. 5A) displays a relatively low degree of anisotropy.

Orientations of the clay fabrics differ somewhat from the magnetite and maghemite fabrics measured by AMS. Minimum χ_{HF} axes are steeply inclined in the accretionary prism, closely matching the orientations of macroscopic bedding and/or scaly fabrics (Fig. 5B). At the top of the decollement, minimum χ_{HF} axes are shallowly inclined and are consistent with a subhorizontal compression strain. Within the decollement and underthrust sediments, the minimum χ_{HF} axes are again steeply inclined, and the orientations of the samples within the decollement match the orientations of the scaly fabrics (Fig. 5B). The abrupt change in clay fabric geometry at the top of the decollement zone is, like the AMS fabrics, most likely due to strain decoupling by high-pressure fluids.

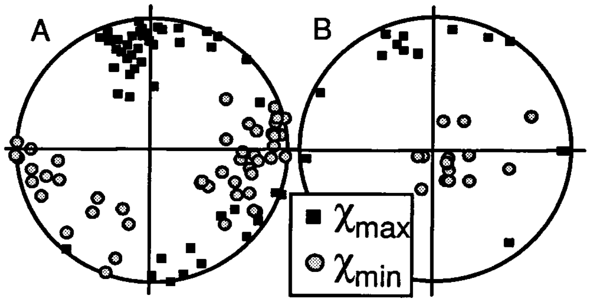

Figure 3. Equal-area, lower-hemisphere projections of reoriented AMS maximum and minimum axes for (A) accretionary prism (420–490 m bsf) and (B) decollement zone (490–527 m bsf).

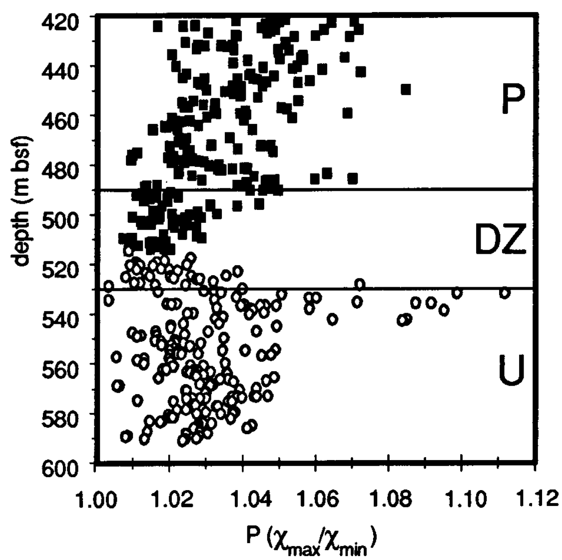

Figure 4. Degree of anisotropy vs. depth for Site 948. Solid squares indicate results from lithological unit II; circles indicate results from lithological unit III.

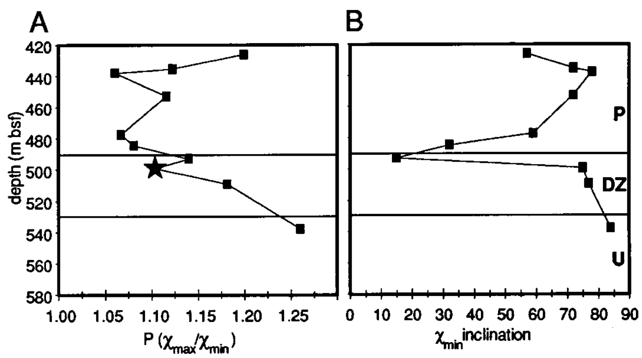

Figure 5. A: Degree of anisotropy vs. depth (as in Fig. 4) for anisotropy of high-field-susceptibility results from Site 948. Star indicates sample from scaly fabric interval near top of decollement. B: Inclination of minimum high-field-susceptibility axes for Site 948 (as in Fig. 2).

FABRIC INTENSITY IN THE DECOLLEMENT

The low degree of preferred orientation indicated by the AMS and high-field anisotropy results from the top of the decollement is paradoxical, in that intense, macroscopic scaly fabrics also occur in the upper part of the decollement zone. There are several possible explanations of why the lowest degree of preferred orientation occurs where deformation appears to be most highly concentrated.

The first thing to consider is that the AMS fabrics measure magnetite and maghemite orientations, not the orientations of the clay minerals that compose the scaly fabrics. The low degree of AMS anisotropy may be due to neocrystallization of the titanomaghemite from the primary titanomagnetite derived from volcanic ash layers throughout the sediment. This possibility is suggested by shipboard paleomagnetic results indicating that the prism sediments at Sites 671 and 948 are likely remagnetized (Hounslow, 1990; Shipley et al., 1995). In this case, AMS records an incremental, rather than a finite strain. This explains the overall low degree of preferred orientation in the accretionary prism and decollement, but does not explain the trend toward lowest degrees of preferred orientation in the decollement.

The low degree of anisotropy of clay-mineral fabrics measured by high-field susceptibility in samples with scaly fabrics from the top of the decollement zone is less easily explained in terms of concentrated deformation. Fabric results from the Nankai accretionary prism obtained by x-ray texture goniometry (Morgan and Karig, 1993) also indicate anomalously low degrees of clay-mineral alignment in the decollement zone there. Scanning electron microscope observations also found little penetrative alignment of clay minerals in the scaly fabric zones of the Barbados decollement (Agar et al., 1989). The clay minerals that define the characteristic polished, anastomosing shear zones that are the hallmark of scaly fabrics (and which must accomplish much of the shear strain) are apparently a volumetrically minor component of these sediments. The dominant volumetric component of these scaly sediments consists of the relatively undeformed phacoids that are surrounded by the anastomosing scaly fabrics. From these two accretionary prisms, at least, it appears that weakly aligned mineral fabrics are common features of decollement zones. Weak decollement fabrics are consistent with several views of deformation style and relations between deformation and fluid flow.

First, sediments in the Barbados prism and (especially) the decollement have high porosities and are underconsolidated (Taylor and Leonard, 1990). Maintenance of such high porosities requires that the sediments resist both burial and tectonic compaction, which in uncemented sediments requires high pore-fluid pressures. Several lines of evidence, including physical properties (Taylor and Leonard, 1990), logging data (Moore et al., 1995), and seismic reflection properties (Shipley et al., 1994) point to high fluid pressures in the Barbados prism and decollement. High-pressure fluids thus retard the formation of either compaction or tectonic strains in these sediments.

Second, the low taper angle of the Barbados prism indicates a weak decollement (Dahlen et al., 1984), and domination by brittle, rather than ductile, styles of deformation (Karig and Morgan, 1994). Studies of permeability and fault-zone fabrics (Brown et al., 1994) also emphasize the importance of brittle fractures as fluid conduits in clay-rich sediments. Failure of prism sediments by predominantly brittle modes will also serve to minimize the development of large ductile strains.

CONCLUSIONS

Data on anisotropy of magnetic susceptibility in the Barbados accretionary prism document changes in the preferred orientation of magnetite and maghemite that indicate efficient strain decoupling at the top of the basal decollement. This decoupling is accomplished through the action of high-pressure fluids. The low-field AMS results record incremental strains with a subhorizontal, east-west–shortening geometry in the accretionary prism and vertical compaction geometries in the decollement zone and in the underthrust sediments. Clay-mineral fabrics, measured by high-field AMS, reflect finite strain geometries in the prism that are also consistent with strain decoupling near the top of the decollement. Finite vertical (compaction) strains are recorded in the upper part of the accretionary prism; subhorizontal, east-west–shortening strains are recorded at the top of the decollement; and vertical-compaction strain is recorded again in the decollement and in the underthrust sediments. The differences in magnetite-maghemite and clay-mineral preferred orientations are manifestations of the differences between incremental and finite-strain geometries in the Barbados accretionary prism. Finite strains in the accretionary prism are predominantly sedimentary compaction strains and are not totally overprinted by tectonic strains except near the top of the decollement zone. The incremental strains recorded by neocrystallized magnetite and maghemite reflect the recent tectonic strains developed during east-west shortening of the accretionary prism.

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