

Paleomagnetic evidence of large footwall rotations associated with low-angle faults at the Mid-Atlantic Ridge

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ABSTRACT

Exposures of gabbros and mantle-derived peridotites at slow-spreading oceanic ridges have been attributed to extension on long-lived, low-angle detachment faults, similar to those described in continental metamorphic core complexes. In continental settings such detachments have been interpreted as having originated and remained active at shallow dips. Alternatively, currently shallow dipping fault surfaces may have originated at moderate to steep dips and been flattened by subsequent flexure and isostatic uplift. While the latter interpretation would be more consistent with Andersonian faulting theory, it predicts large footwall tilts that have not been observed in continental detachment faults. Here we use the magnetization of oceanic gabbro and peridotite samples exposed near the Fifteen-Twenty Fracture Zone on the Mid-Atlantic Ridge to demonstrate that substantial footwall rotations have occurred. Widespread rotations ranging from 50° to 80° indicate that original fault orientations dipped steeply toward the spreading axis.

Keywords: Ocean Drilling Program, peridotite, gabbro, mid-ocean ridge, paleomagnetism, detachment fault.

INTRODUCTION

Detachment faults play a crucial role in accommodating extension at slow-spreading mid-ocean ridges, where melt extraction processes are partially inhibited and magmatic products may be trapped as gabbroic bodies at depths of 15–20 km (Kelemen et al., 2004; Lizarralde et al., 2004). Low-angle detachments may accommodate as much as tens of kilometers of extension, leading to the exhumation of thick lower crust and mantle rock sections (Cannat et al., 1995; Tucholke and Lin, 1998). Seismic reflection experiments on Early Cretaceous lithosphere of the African plate have demonstrated the existence of ridge-ward-dipping crustal-scale detachments with a convex-upward geometry flattening updip from 30° to <15° (Ranero and Reston, 1999). Little is known, however, about the subsurface dip of active detachments, because the strong seismic attenuation under spreading centers only allows limited imaging of the shallow crust (Canales et al., 2004).

Doubts persist on whether normal faults can slip at shallow dips because low-angle focal mechanisms solutions are rare and Andersonian fault mechanics do not predict slip at normal faults dipping <30°. Slip at low angles, however, can be explained through rotation of the stress field with depth, increase of fluid pressure, and the distribution of weak layers in the lower crust (Wernicke, 1995). Two competing end-member models exist that describe the subsurface geometry of detachment faults at mid-ocean ridges.

One envisages constant dip low-angle detachments cutting through the magmatic zone under the ridge axis (Karson and Winters, 1992). The other suggests steepening detachments rooting under the spreading axis at either the brittle-ductile transition (Tucholke and Lin, 1998) or at the shallow cold lithosphere, possibly related to serpentinization fronts (Escartín et al., 2003).

The magnetic remanence of footwall rocks can provide information on the amount of tilt since the magnetization was acquired and thus place bounds on the original subsurface geometry of faults. The use of the remanence vector as a measure of tectonic tilting assumes that the magnetization of footwall rocks was acquired prior to deformation and that the remanence vector behaves as a passive marker during subsequent brittle deformation. In continental detachments, paleomagnetic studies have revealed little footwall tilting, leading to the inference that slip occurred on shallowly dipping fault surfaces (Livaccari and Geissman, 2001). Interpretation of continental data is, however, complicated by syndeformational magmatism and slow cooling, as well as the fact that ages of the footwall rocks may significantly predate extension. In contrast, the young age, relatively rapid cooling, and simple constructional history at oceanic core complexes should facilitate recognition of footwall tilt.

PALEOMAGNETIC DATA FROM FIFTEEN-TWENTY FRACTURE ZONE

Drilling during Ocean Drilling Program (ODP) Leg 209 sampled mantle-derived peridotites

and associated gabbroic intrusions at 6 shallow (<210 m) drill sites near the Fifteen-Twenty Fracture Zone (Kelemen et al., 2004) (Fig. 1). Most sites drilled rocks younger than 1 Ma near the top of the rift valley walls. Sites 1268 and 1270 are well south of the Fifteen-Twenty Fracture Zone, in areas with relatively well developed, ridge-parallel bathymetric fabrics. Sites 1271 and 1272 drilled on a high-relief dome at the inside corner south of the transform. North of the transform, Site 1274 drilled ultramafic rocks on the western flank of the rift valley, and Site 1275 recovered substantial gabbroic material from ~2 m.y. old crust, at the top of a high relief domal corrugated surface interpreted as a detachment fault (Escartín et al., 2003; Fujiwara et al., 2003).

Serpentinized peridotites show a simple demagnetization behavior, with a low-stability drilling overprint and a single high-stability component removed by 580 °C. The broad range of unblocking temperatures is consistent with a remanence carried by relatively coarse grained magnetite produced during low-temperature (<~350 °C) serpentinization (Lawrence et al., 2002; Oufi et al., 2002). Although some gabbroic samples have complex magnetizations (see GSA Data Repository¹), a high-temperature component with a narrow range of unblocking temperatures close to 580 °C was identified in all samples. This component represents an aver-

¹GSA Data Repository item 2007050, paleomagnetic methods and data analysis, is available online at www.geosociety.org/pubs/ft2007.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

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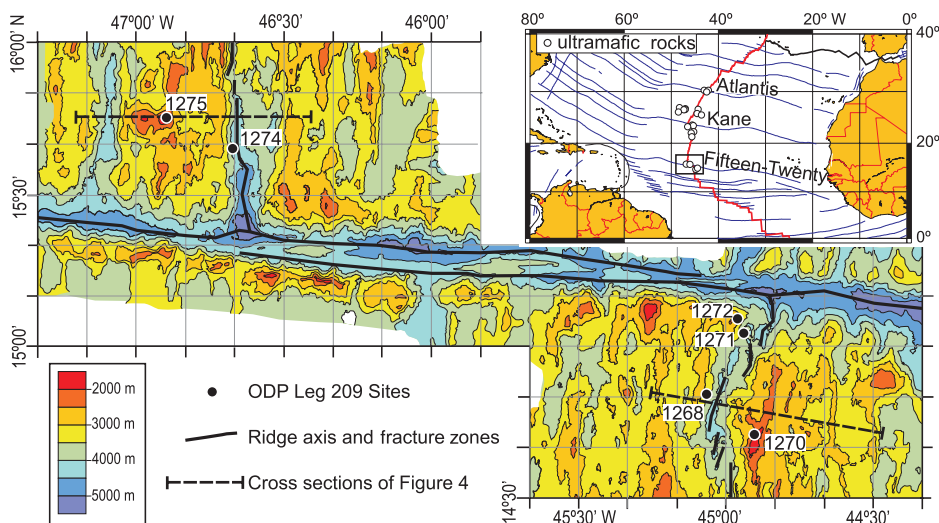


Figure 1. Bathymetry of Fifteen-Twenty Fracture Zone region (Fujiwara et al., 2003) and location of Ocean Drilling Program Leg 209 sites. Inset map shows distribution of known ultramafic outcrops along North Atlantic ridge (Tucholke and Lin, 1998). Dashed lines indicate cross sections in Figure 4.

age ~15% of the total remanence and is attributed to fine-grained magnetite, likely carrying a primary thermoremanence acquired during initial cooling. Thus the remanence of gabbroic samples likely predates that of serpentinized peridotites, though we emphasize that only the timing, rather than the precise origin, of the remanence is critical for evaluating tectonic tilt.

We use this magnetite component to estimate the amount of tilt since the remanence was acquired. A key assumption in the use of paleomagnetic data to document tectonic tilt is that the remanence was acquired over sufficient time ($\sim 10^3$ – 10^4 yr) to average secular variation so that the initial remanence coincides with the time-averaged geocentric axial dipole (GAD) direction at the site. The intimate interfingering of gabbroic material into host peridotite, high-temperature contacts (e.g., large crystals at the contact), and high-temperature ductile fabrics cutting some gabbros suggest that wall-rock temperatures were >600 °C during gabbro emplacement (Kelemen et al., 2004). The small-scale (<1 m) heterogeneity, both in terms of modal proportions and grain size, of gabbroic rocks also suggests that most sites have sampled multiple intrusions. Multiple generations of serpentine (and magnetite) formation in ultramafic samples also imply significant temporal averaging in peridotite magnetization.

The mean inclinations from gabbroic rocks at all sites sampled during Leg 209 deviate substantially from the expected GAD inclination at the sites (Fig. 2), and therefore require significant tilting since the remanence was acquired. The deepest penetration and most

substantial recovery of gabbroic material were from Holes 1275B and 1275D (109 and 209 m below seafloor, respectively). Several intervals of consistent shallow negative inclinations, likely separated by faults, are present at Site 1275 with mean inclinations as shallow as -6.5° (95% bounds of -2.2° – -10.7°) (McFadden and Reid, 1982). Near the base of Hole 1275D, diabase samples yield positive inclinations close to the expected normal polarity GAD inclination (29°) at the site. The steeper, normal polarity inclinations of the diabase indicate that some dike intrusions postdate significant tilting of the reverse polarity gabbroic host rock.

Results from Site 1268 also document a history of substantial footwall rotation. Both gabbros and peridotites yield positive mean inclinations, as expected from the location of the site within the Central Anomaly (0–0.78 Ma) (Fujiwara et al., 2003). The mean inclination of gabbroic samples is 12.4° (95% bounds $18.8^\circ/6.0^\circ$), substantially shallower than the expected dipole inclination at the site (28°). Values statistically indistinguishable from the GAD inclination were obtained from the host peridotites (34.9° ; 95% bounds $46.6^\circ/23.2^\circ$) as well as talc-altered rocks (32.8° ; 95% bounds $39.3^\circ/26.3^\circ$). Textural relationships indicate that talc replaces serpentine in the Site 1268 peridotites, an observation that has been attributed to silica metasomatism, where the silica is derived from gabbros and peridotites undergoing high-temperature (>350 °C) hydrothermal alteration (Bach et al., 2004). We suggest that the shallow gabbro inclinations represent an early thermal remanence that has undergone significant rotation, with

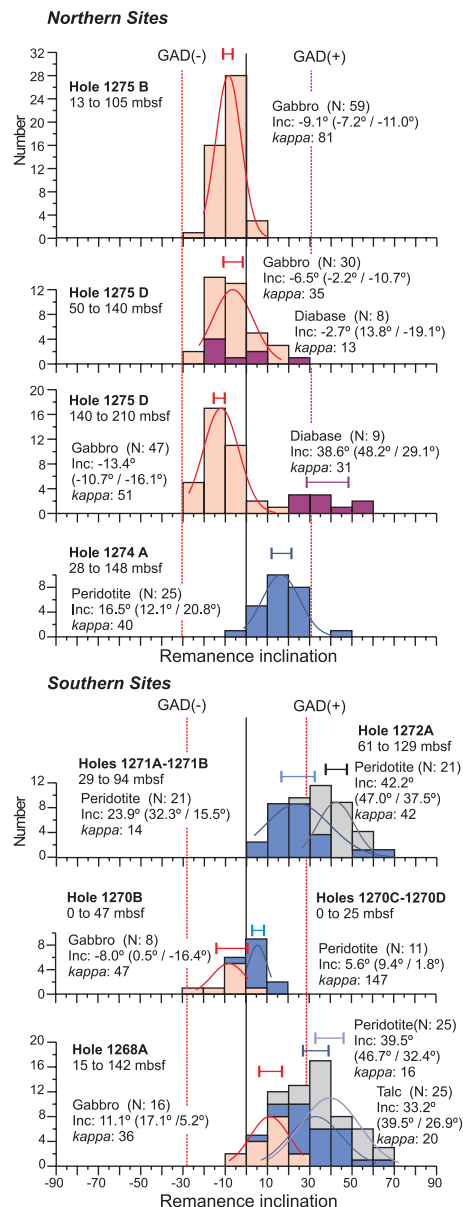


Figure 2. Summary of paleomagnetic inclination data. Dotted vertical lines represent inclination of normal (+) and reversed (-) polarity geocentric axial dipole (GAD) at sites (mbsf—m below seafloor). Gabbroic rocks from all sites yield mean inclination values shallower than expected, suggesting that tectonic rotations have taken place after cooling to below their Curie temperature. Ultramafic rocks yield varied results, indicating that magnetization of peridotites may predate (Sites 1270, 1274) or postdate (Sites 1268, 1271) tectonic rotations (see text for details).

later serpentinization and talc alteration leading to remanence acquisition that postdates most of the footwall rotation.

Both gabbroic samples from Hole 1270B and serpentinized peridotite samples from Holes 1270C and 1270D (200 m to the east) have sub-horizontal inclinations, making polarity deter-

mination uncertain. We used the orientation of the pervasive foliation relative to the remanence in both gabbros and peridotites to infer the polarity of the magnetization. Assuming that both gabbros and peridotites have a common foliation attitude, we conclude that gabbros are reversely magnetized and peridotites have normal polarity (Kelemen et al., 2004). Site 1270 is near the edge of the broad positive magnetization region flanking the present-day spreading axis (Fujiwara et al., 2003), presumably including crust generated during the Jaramillo (chron C1r.1n), Brunhes (chron C1n), and the intervening reversed polarity interval, and is therefore broadly consistent with the presence of dual polarities at this site.

Serpentinized peridotites from Sites 1271 and 1272 yield average inclinations similar to the expected GAD inclination (Fig. 2). It is possible that the magnetization is a late (possibly viscous) remanence that does not preserve any tectonic information.

ESTIMATES OF FOOTWALL ROTATION

Although the azimuth of drill core samples is not known, footwall rotations can be determined if the orientation of the rotation axis and sense of rotation are independently determined (Fig. 3). In the near-ridge extensional context, rotations about ridge-parallel subhorizontal axes are, in principle, the most plausible. A more accurate determination of rotation axis can be obtained from observations of corrugations on low-angle fault surfaces. Corrugations form parallel to the slip direction and allow constraining rotation axes at right angles to the corrugations on the fault plane. At Site 1275 corrugations show a fairly uniform E-W trend (Escartin et al., 2003) over tens of kilometers on a domed detachment surface. At Site 1270, corrugations are oriented 280° on a low-angle kilometer-scale fault surface. Corrugated fault surfaces were not identified at Sites 1268 and 1274, and we used the strike of faults to determine the azimuth of rotation axes. We have thus inferred a rotation axis 010° for sites south of the fracture zone, and 000° for the northern sites. Sites 1271 and 1272, at the southern inside corner high, were excluded from further analysis because at this location deformation cannot be represented with a simple two-dimensional model and the rotational behavior is much less predictable.

The widespread occurrence of shallow paleomagnetic inclinations implies that tectonic rotations ranging from 50° to 80° have affected most sites sampled during Leg 209 (Fig. 3). These large rotations provide compelling evidence that currently shallow dipping fault surfaces were originally steeper ($>60^\circ$) when active (Fig. 4). We note that the substantial rotations about nearly N-S axes are accompanied by comparable shifts in the remanent declination. Fully

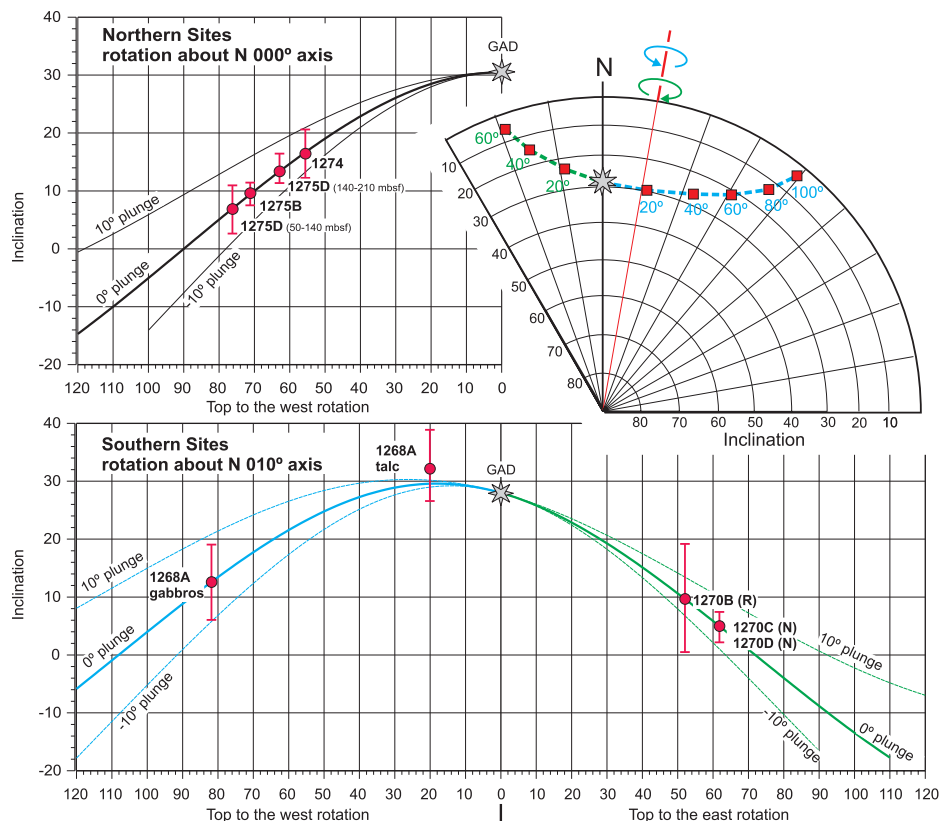


Figure 3. Model of effect of rotations on inclination data. Lines represent rotation of expected field vector (geocentric axial dipole, GAD) about given axis. Confidence bounds represent rotations about axes plunging $\pm 10^\circ$. Model assumes that footwall uplift is accompanied by rotation of ridge flanks in sense top away from ridge. Equal-area projection represents rotation of reference vector 000/28 about 010° horizontal axis. Talc-altered peridotites from Hole 1268A (mbsf—m below seafloor) are plotted at a rotation value that yields maximum inclination. Results from Sites 1271 and 1272 are not plotted due to large uncertainty in rotation axis orientation and because inclinations are similar to expected GAD value.

oriented cores would thus provide a means to independently evaluate the large postulated rotations. We suggest that the large rotations documented here may in part reflect the fact that the temperature of the brittle-ductile transition in oceanic crust is near or above the Curie point of magnetite (Hirth et al., 1998), allowing a more complete record of brittle deformation to be captured than in continental settings.

Our data are most easily reconciled with flexural-isostatic flattening of a long-lived steep active fault zone (Buck, 1988; Tucholke and Lin, 1998; Wernicke and Axen, 1988). Our results indicate substantial (50° – 80°) rotation for Sites 1270 and 1268, on comparable age crust (~ 1 m.y.) (Fujiwara et al., 2003) on either side of the spreading axis (Fig. 3). These results suggest that initially steeply dipping conjugate faults, possibly rooted at the brittle-ductile transition, might be active simultaneously (Fig. 4). Although shallow-dipping detachments and pronounced morphological asymmetry have been noted elsewhere (Cannat et al., 1997; Karson and Winters, 1992), such

asymmetry does not appear to be required to expose gabbros and mantle-derived peridotites. Also, as evidenced by the numerous gabbroic intrusions, the process does not take place amagmatically, and part of the extension may be balanced by magmatic accretion (Allerton et al., 2000). It may be exceptional that footwall rotation of as much as 80° is accommodated by a single fault. More likely, isostatic readjustment of the unroofed plate will lead to progressive flattening of the fault surface until it becomes inactive and a new steep fault eventually forms closer to the active zone.

Our data suggest that mechanisms of extension at slow-spreading mid-ocean ridges differ from rifted continental crust. The change in extensional geometry from listric to convex-upward faults may reflect the change in the distribution of weak layers once seafloor spreading initiates (Whitmarsh et al., 2001). Subvertical weak zones developed under spreading centers, possibly resulting from rising melts, may have controlled the steep attitude of detachment roots.

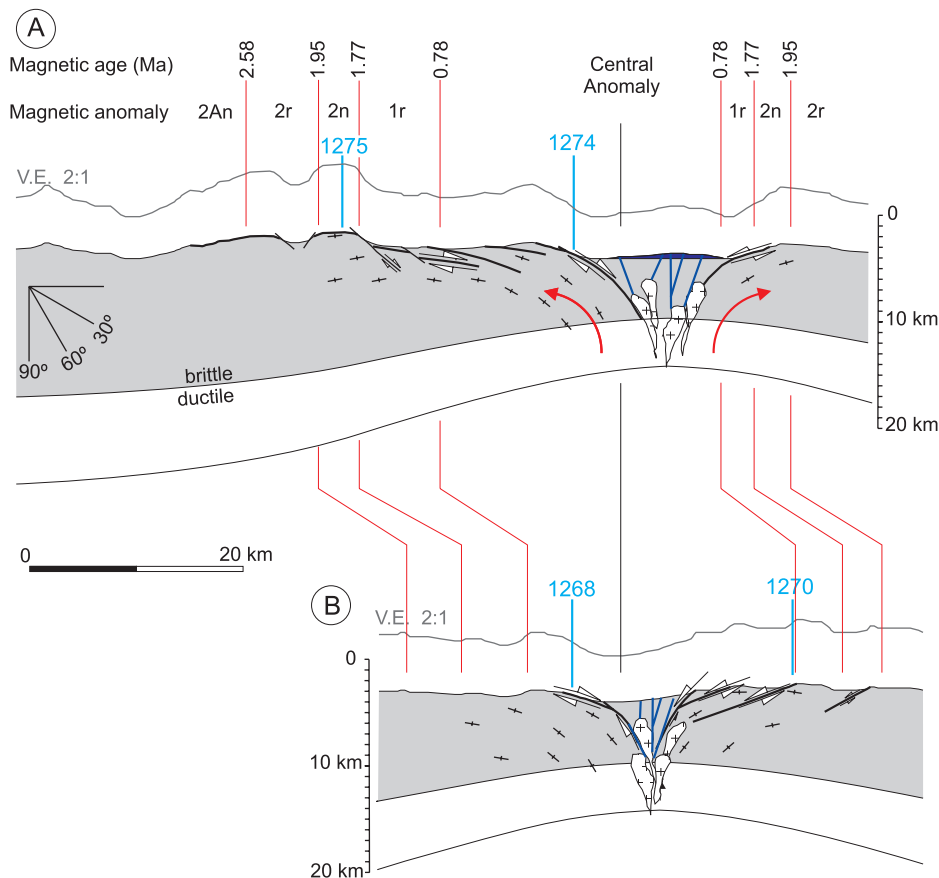


Figure 4. Schematic cross sections north and south of Fifteen-Twenty Fracture Zone (see Fig. 1 for location). Increasing dip of faults toward ridge as inferred from paleomagnetic inclination data (see text for details). Slip along steepening faults on both sides of rift valley causes foot-wall rotation and flattening of fault planes. Magnetic anomalies after Fujiwara et al. (2003).

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