Direct geological evidence for oceanic detachment faulting: The Mid-Atlantic Ridge, 15°45′N

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ABSTRACT

From a detailed survey and sampling study of corrugated massifs north of the Fifteen-Twenty Fracture Zone on the Mid-Atlantic Ridge, we demonstrate that their surfaces are low-angle detachment fault planes, as proposed but not previously verified. Spreading-direction–parallel striations on the massifs occur at wavelengths from kilometers to centimeters. Oriented drill-core samples from the striated surfaces are dominated by fault rocks with low-angle shear planes and highly deformed greenschist facies assemblages that include talc, chlorite, tremolite, and serpentine. Deformation was very localized and occurred in the brittle regime; no evidence is seen for ductile deformation of the footwall. Synkinematic emplacement of diabase dikes into the fault zone from an immediately subjacent gabbro pluton implies that the detachment must have been active as a low-angle fault surface at very shallow levels directly beneath the ridge axis. Strain localization occurred in response to the weakening of a range of hydrous secondary minerals at a very early stage and was highly efficient.

Keywords: detachment fault, oceanic core complex, mid-ocean ridge, Mid-Atlantic Ridge.

BACKGROUND

Exposure of serpentinized peridotites on the seafloor at slow-spreading ridges implies that incorporation of asthenospheric mantle into the lithosphere must occur at the ridge axis. This observation requires that melt supply is not sufficient to form a continuous magmatic crust (e.g., Cannat, 1993), that the magmatic crust is removed by tectonic means (e.g., Karson, 1990; Tucholke and Lin, 1994), or a combination of both. It has long been suggested that low-angle normal faults may exhume gabbros and peridotites, potentially accommodating a significant component of plate separation in the absence of magmatism (e.g., Dick et al., 1981; Karson and Dick, 1983). Such structures were envisaged to be closely analogous to detachment fault systems in extending continental terranes (e.g., Davis and Lister, 1988).

Candidates for oceanic detachment faults were identified in the late 1990s at several locations along slow-spreading ridges, in the form of flat or gently domed massifs with spreading-direction–parallel striations on their surfaces (e.g., Cann et al., 1997; Tucholke et al., 1998). However, direct evidence as to the precise nature of the striated surfaces has so far been lacking, and little is known about the mode of formation of the massifs, the geometry and extent of faults in depth, or mechanisms of strain localization. The striations or corrugations have been interpreted variously as abrasion marks (Cann et al., 1997), compressional structures (Tucholke et al., 1998), and ridge-perpendicular extensional faults (Karson, 1999). Submersible studies have shown that these striated surfaces are covered by sediment or by basaltic rubble and show only isolated exposures of gabbro and/or serpentinized peridotite, with very little deformed material having been observed (Searle et al., 1999; Tucholke et al., 2001).

We here present geologic and geophysical evidence that demonstrates that these massif structures are formed by detachment faulting. With multibeam bathymetry data and deep-tow backscatter (TOBI) images collected during RRS *James Clark Ross* cruise JR63, and near-bottom digital photos collected during RV *Atlantis* cruise A4-4, we document the nature of the spreading-direction–parallel striations. With 63 oriented cores collected with the BRIDGE wireline rock drill (MacLeod et al., 1998; Allerton et al., 1999), supplemented by 23 dredge hauls, we provide the first systematic sampling of in situ material from a striated surface and the most complete constraint to date on the origin and conditions of deformation of these structures.

MORPHOLOGY OF THE STRIATED SURFACE AT 15°45′N

Bathymetry data reveal several striated surfaces off axis, both north and south, of the Fifteen-Twenty Fracture Zone (Escartín and Cannat, 1999; Casey et al., 2000). They are morphologically similar to other corrugated massifs found in the vicinity of ridge discontinuities along slow- and intermediate-spreading ridges (e.g., Tucholke et al., 1998). However, the structures near the Fifteen-Twenty Fracture Zone cannot be associated directly with any nearby inside corner of a ridge-transform intersection, as commonly observed elsewhere.

We examine in detail one of these corrugated surfaces, located 35 km north of the Fifteen-Twenty Fracture Zone and ~27 km west of the ridge axis (~15°45′N, ~46°55′W, Fig. 1). The surface extends 25 km and 15 km along and across axis, respectively. It now dips to 15° away from the axis, but is inferred to have dipped in the opposite direction when active. Assuming a constant spreading rate of 26 km/m.y. (Escartín and Cannat, 1999), this detachment formed ca. 2 Ma and remained active for ~1 m.y. Bathymetry data show a large-scale undulation with an ~10 km wavelength and an amplitude of ~1 km that defines two ribbons of elevated seafloor elongated parallel to the spreading direction (Fig. 1). Su-

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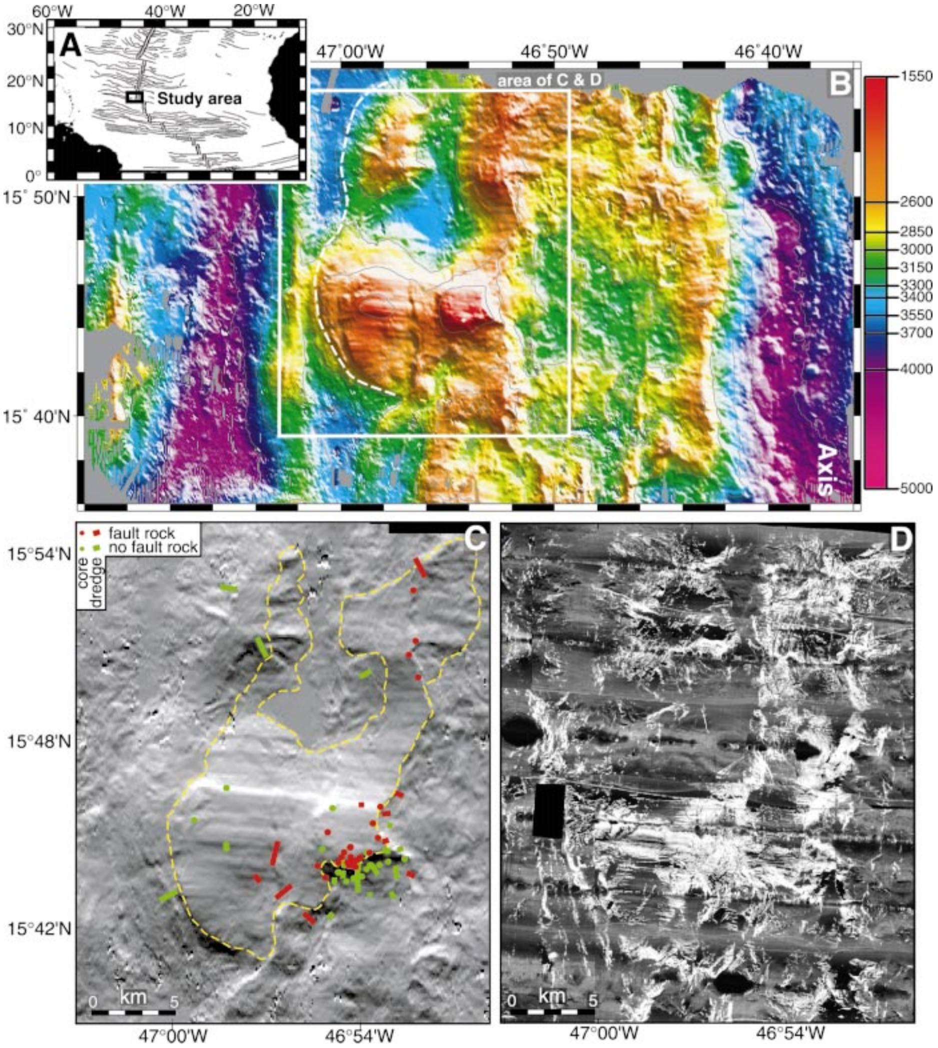

Figure 1. A: Location of Fifteen-Twenty Fracture Zone region on Mid-Atlantic Ridge. B: Color shaded-relief bathymetry of ridge axis (at right) and corrugated surface (inside box) at 15°45′N. Western limit of striations is marked with dashed line. C: Shaded-relief bathymetry, illuminated from north, showing locations of drill and dredge sites (circles and bars, respectively) and presence or absence of high-strain fault rocks. D: Deep-tow backscatter (TOBI) image, with high backscatter regions shown in white. Corrugated surface (marked by yellow dashed line in C) is continuous and has corrugations on scales from few kilometers to few hundred meters.

Figure 2. Centimeter-scale striations on seabed photomosaic obtained with Woods Hole Oceanographic Institution deep-towed camera system on RV *Atlantis* cruise A4-4. Striations parallel larger scale corrugations (Fig. 1) and 094° regional spreading direction. Similar seafloor outcrops imaged and sampled using BRIDGE rock drill yielded fault rock.

perimposed on these structures are smaller scale corrugations with wavelengths of ~1–3 km and amplitudes of <200 m. TOBI data reveal yet finer scale striations, with spacings of 100–500 m, that extend to 1 km parallel to the spreading direction. Near-bottom photographs demonstrate that most of the detachment surface is covered by sediment, with rock outcrops in the form of elevated ridges tens of meters wide, hundreds of meters long, and <10 m in relief elongated parallel to the spreading direction. The surfaces of these outcrops are smooth and covered with centimeter-scale striations, also parallel to the spreading direction (Fig. 2).

The corrugated surface is truncated by inward-dipping ridge-parallel normal faults: to the west on a structure associated with several small, outward-dipping faults, and to the east by a single inward-facing fault with >1 km of relief (Fig. 1). The corrugated surface shows rapid transition toward the north and south into ridge-parallel abyssal-hill terrain, with no clear tectonic boundary. The corrugated surface has additionally been dissected by inward- and outward-dipping ridge-parallel faults, one pair of which downfaults the two ribbons of elevated seafloor by ~500 m, leaving four upstanding knolls of striated seafloor (Fig. 1). On the TOBI images, mass wasting throughout the area is suggested by cuspate landslide scarps, associated talus deposits, and highly reflective areas with cuspate debris fans (Fig. 1D). These features are especially evident on the eastern and southern flanks of the southeast knoll.

COMPOSITION OF THE STRIATED SURFACE AND FOOTWALL

Sampling of the corrugated surface during cruise JR63 was concentrated on the southeast knoll, the shallowest part of the detachment (Fig. 1C). Gabbros and serpentinized peridotites had previously been sampled from the south flank and summit of this massif, respectively (Matsumoto et al., 1998; M. Braun, 2001, personal commun.). Drill cores and dredge hauls yielded peridotite, gabbro, and diabase together with their altered and deformed equivalents (Fig. 1C). Basalts are found only as small clasts (<5 cm) within sedimentary breccias on the surface of the massif. Fault rocks are abundant on the top of the striated surface, or near it along its flanks. They are mylonitic, with strong foliations dipping subparallel to the striated surface in oriented cores (Figs. 3A and 3B). Microstructural observations show that deformation was predominantly cataclastic, with syntectonic crystal growth in some samples. The fault rock is formed primarily of talc, chlorite, and tremolite-actinolite, and minor serpentine. Traces of relict spinel and ilmenite suggest that the protoliths included both mafic and ultramafic rocks. These textures and assemblages indicate high-strain deformation under greenschist facies conditions. Occurrences of chilled margins in undeformed diabase in contact with fault rock and the presence of unaltered, deformed diabase clasts incorporated into the fault rock (Figs. 3A and 3B) suggest synkinematic emplacement of dikes into and across the detachment.

Away from the corrugated surface, the rocks are generally much less deformed. Most serpentinized peridotites preserve mesh tex-

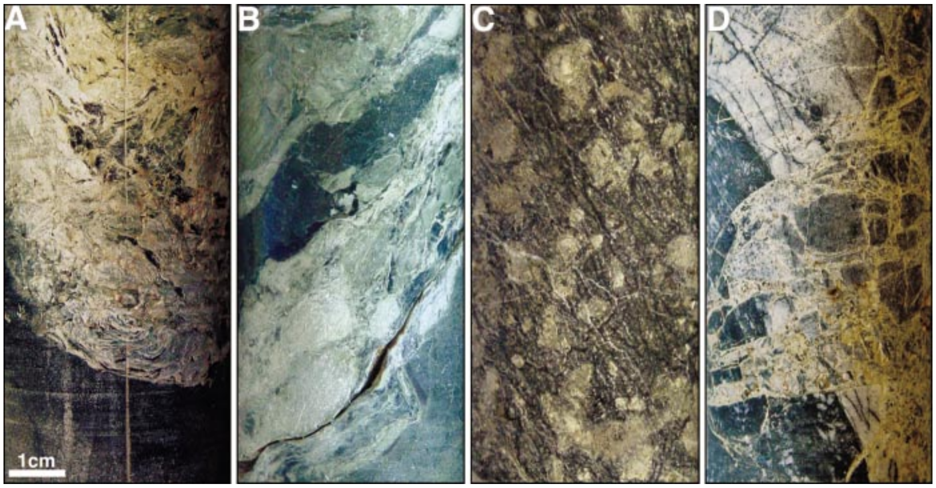

Figure 3. Selected core samples from BRIDGE rock drill. A: Undeformed diabase dike (dark) with chilled margin intruding highly deformed chlorite-actinolite fault rock (core BR90). B: Diabase (dark) incorporated into talc-bearing foliated cataclasite (BR40). C: Undeformed mesh-textured (lizardite bearing) serpentinized peridotite (BR61). D: Fault breccia with clasts of diabase and secondary quartz-plagioclase assemblage (BR82). Cores BR90, BR40, and BR61 were taken from striated surface; core BR82 is from ~250 m beneath it; all are from southeast knoll except BR61 (southwest knoll).

tures, containing relict undeformed olivine and bastite after pyroxene in addition to late-stage serpentine veins (Fig. 3C). Gabbros and diabase grade from undeformed, through locally brittlely deformed, into highly brecciated rocks (Fig. 3D). All the macroscopic and microstructural observations demonstrate that brittle deformation is dominant; no evidence for any high-temperature crystal plastic deformation is preserved. The undeformed rocks also show lower degrees of alteration, even when in close proximity to the fault rocks.

The dredged and drilled gabbros all come from the pluton sampled by Matsumoto et al. (1998). Gabbro samples were taken from landslide or fault scarps on the southern and eastern slopes of the southeast knoll, on outcrops that are structurally beneath the detachment. Diabase and fault rocks are found primarily at or near the detachment surface, whereas peridotites are found both flanking the gabbro and close to the detachment. The spatial distribution of lithologies indicates the presence of a discrete gabbro body >2 km (probably ≥ 5 km) in diameter intruding peridotites, with an irregularly shaped roof just beneath but in close proximity to the detachment. The diabase is spatially related to the gabbro and almost certainly issued from it, seemingly in the form of a swarm of dikes.

DISCUSSION

Our geologic and geophysical observations verify the hypothesis that corrugated surfaces found along slow-spreading mid-ocean ridges are exposed detachment faults (Cann et al., 1997; Tucholke et al., 1998). Coincidental bathymetry, high-resolution sonar data, and near-bottom photographs demonstrate that bathymetry corrugations, high-backscatter lineations, and outcrop striations, spanning wavelengths from >1 km down to centimeters, are all parallel to the spreading direction and are therefore structurally related. Kilometer-scale corrugations may relate to the linkage of precursory structures as the detachment fault formed. Elongated outcrops with striations (Fig. 2) correspond to the high-backscatter lineations (Fig. 1D). The sizes and geometries of individual rock outcrops are similar to those described from continental detachment surfaces (e.g., John, 1987), and smaller-scale striations are analogous to slickenlines found along exposed fault surfaces.

Recovered samples from the top of the 15°45′N surface demonstrate that the striated pavement is associated with high-strain cataclastic mylonites with foliation subparallel to the surface. Fault rocks are restricted to the uppermost flanks of the knoll (Fig. 4), forming a fault zone $\sim$100 m thick or less. The presence of relatively undeformed and unaltered rocks immediately beneath the surface indicates that deformation is highly localized on the detachment fault and does not penetrate far into the footwall.

Deformation along the fault plane occurred in the brittle regime, at relatively low temperatures, and in the presence of fluids. The mineral assemblages found in the fault rocks imply alteration of mafic and ultramafic rocks under low greenschist facies conditions and a substantial fluid flux both prior to and during deformation. Strain localization along the fault plane was highly effective and long lived, almost certainly as a result of the presence of very weak minerals, including serpentine (e.g., Reinen et al., 1994; Escartín et al., 1997) and talc (Edmond and Paterson, 1972), and other layer silicates (chlorite, tremolite). Lowered effective confining pressures in the presence of fluids along the fault almost certainly contributed significantly to weakening of the fault zone.

The subsurface geometry of detachment faults is not well defined in either continental or oceanic environments. Their angle of initiation is debated (e.g., Davis and Lister, 1988; Axen and Bartley, 1997) owing to the theoretical mechanical difficulty of nucleating and allowing slip on faults at $<45°$ (Anderson, 1942). It has therefore been suggested that detachments initiate and slip at high angles, becoming inactive as they rotate by flexure to low angles, such that fault-plane dips increase with depth (e.g., Buck, 1988; Wernicke and Axen, 1988; Lavier et al., 1999). These models have been adopted for oceanic as well as continental detachments (e.g., Tucholke et al., 1998; Lavier et al., 1999). Detachments are assumed to root at or near the brittle-ductile transition, supported by the observation of broad zones of ductilely deformed rocks in continental detachments (e.g., John, 1987) and in gabbros exposed at Atlantis Bank (Southwest Indian Ridge; Dick et al., 1991; MacLeod et al., 1998).

However, unlike in continental detachments and the Atlantis Bank structure, there is no evidence for ductile deformation in the immediate vicinity of the Fifteen-Twenty Frac-

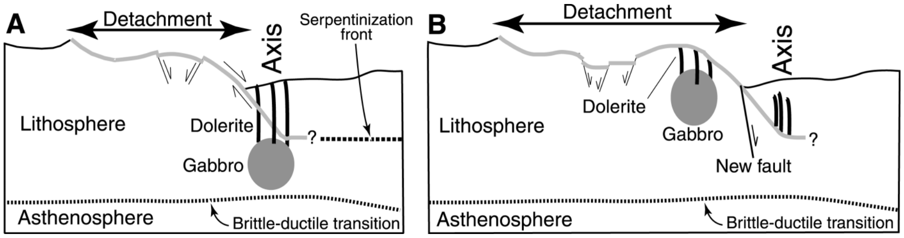

Figure 4. Proposed evolution and geometry of detachment (marked by gray line). A: Emplacement of discrete gabbro intrusion beneath ridge axis below but in proximity to active detachment, feeding swarm of synkinematic to postkinematic diabase dikes. Detachment soles out in brittle lithosphere, well above brittle-ductile transition. Serpentinization front may provide rheological boundary where detachment roots. B: Continued displacement exposes dikes and uplifts gabbro in footwall; detachment is eventually terminated by high-angle fault.

ture Zone detachment, nor of any progressive thinning and decrease of the temperature of deformation within the fault zone. If any precursory higher-temperature deformation ever occurred on this fault zone, it must have been extremely localized. Presuming that the gabbro and diabase were intruded within the axial valley, the geologic relationships presented here require that the Fifteen-Twenty Fracture Zone detachment was active within the brittle lithosphere, well above the brittle-ductile transition, directly beneath the ridge axis (Fig. 4). We propose that the detachment soled out along an alteration front horizon at relatively shallow depth within the brittle lithosphere, a rheological boundary distinct from the brittle-ductile transition (Fig. 4). The detachment probably slipped at a low angle rather than steepening rapidly to a high angle in the axial valley, as in previous models (e.g., Tucholke et al., 1998). Limited evidence in support of a low-angle geometry has come from gravity (Blackman et al., 1998) and seismic reflection studies (Ranero and Reston, 1999). The abrupt decrease of strength of peridotites at small degrees of serpentinization ($<$15%, Escartín et al., 2001) may provide a profound rheological contrast between a serpentine-free, stronger, lower lithosphere and a weaker, slightly serpentinized upper lithosphere. Penetration of fluids along permeable pathways in the upper lithosphere is likely to induce marked weakening upon formation of serpentine and a range of other secondary minerals (e.g., talc, chlorite), localizing strain very efficiently onto large, discrete shear zones within the shallow lithosphere. Oceanic detachment faults need not be initiated at the brittle-ductile transition.

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