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Megamullions and mullion structure defining oceanic metamorphic core complexes on the Mid-Atlantic Ridge

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Abstract. In a study of geological and geophysical data from the Mid-Atlantic Ridge, we have identified 17 large, domed edifices (megamullions) that have surfaces corrugated by distinctive mullion structure and that are developed within inside-corner tectonic settings at ends of spreading segments. The edifices have elevated residual gravity anomalies, and limited sampling has recovered gabbros and serpentinites, suggesting that they expose extensive cross sections of the oceanic crust and upper mantle. Oceanic megamullions are comparable to continental metamorphic core complexes in scale and structure, and they may originate by similar processes. The megamullions are interpreted to be rotated footwall blocks of low-angle detachment faults, and they provide the best evidence to date for the common development and longevity (~1–2 m.y.) of such faults in ocean crust. Prolonged slip on a detachment fault probably occurs when a spreading segment experiences a lengthy phase of relatively amagmatic extension. During these periods it is easier to maintain slip on an existing fault at the segment end than it is to break a new fault in the strong rift-valley lithosphere; slip on the detachment fault probably is facilitated by fault weakening related to deep lithospheric changes in deformation mechanism and mantle serpentinization. At the segment center, minor, episodic magmatism may continue to weaken the axial lithosphere and thus sustain inward jumping of faults. A detachment fault will be terminated when magmatism becomes robust enough to reach the segment end, weaken the axial lithosphere, and promote inward fault jumps there. This mechanism may be generally important in controlling the longevity of normal faults at segment ends and thus in accounting for variable and intermittent development of inside-corner highs.

1. Introduction

Geological research in continental extensional environments has demonstrated the widespread occurrence of detachment faults characterized by low-angle normal slip, a subregional to regional scale of development, and displacements of tens of kilometers or more [*Davis and Coney*, 1979; *Crittenden et al.*, 1980; *Armstrong*, 1982; *Davis and Lister*, 1988]. Footwalls of these faults commonly expose metamorphic rocks that were ductilely deformed deep in the crust (~12–16 km) and then more brittlely deformed during exhumation [e.g., *Hodges et al.*, 1987]; tectonically juxtaposed hanging wall rocks are largely unmetamorphosed. The footwall "metamorphic core complexes" often have domed forms that are up to several tens of kilometers in diameter, and such features have been referred to as "gigantic fault mullions" [*Wright et al.*, 1974; *Stewart*, 1983].

Slow spreading mid-ocean ridges constitute an analogous extensional environment where magma supply is limited and probably episodic; thus brittle deformation is key to forming topography, controlling crustal structure, and exposing once deep-seated rocks [*Harper*, 1985; *Macdonald*, 1986; *Karson*, 1990]. From studies of multibeam bathymetry on the Mid-Atlantic Ridge (MAR) [*Tucholke et al.*, 1996; *Cann et al.*, 1997], it recently has been recognized that this analogy may extend to the formation of oceanic metamorphic core complexes through slip on areally extensive and long-lived normal faults. In this paper we report the structure of a large, newly identified set of these features, here termed megamullions, on the MAR in the North Atlantic Ocean, and we propose a mechanism for their origin and evolution.

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2. Geological Background

Theoretical models [e.g., *Sparks et al.*, 1993] and observational geophysics [*Kuo and Forsyth*, 1988; *Lin et al.*, 1990; *Tolstoy et al.*, 1993] indicate that the least magmatic portions of slow spreading ridge segments are at segment ends where the ocean crust tends to be thin, the lithosphere is thick, and brittle deformation and fault throw are maximized [*Shaw and Lin*, 1993; *Escartín et al.*, 1997a]. Crustal morphology, gravity, and seafloor sampling also show that there is a consistent, strong asymmetry between inside-corner (IC) and outside-corner (OC) tectonic settings across the rift axis near segment ends [*Tucholke and Lin*, 1994]. Compared to OC crust, ICs are shallower and have more elevated residual mantle Bouguer anomaly (RMBA) that suggests thinner crust, and they also have more widely spaced and larger-throw normal faults and fewer volcanic features (seamounts, hummocky flows). IC crust along plate flow lines away from the ridge axis exhibits a series of structural massifs or "IC highs," and many of these are associated with strongly elevated RMBA (typically 20–25 mGal). Dredging on the MAR confirms that such IC highs consistently expose lower crustal gabbros and/or serpentinized upper mantle peridotites and that they therefore have thin or missing crust [*Tucholke and Lin*, 1994; *Cannat et al.*, 1995].

The marked IC-OC asymmetry has been interpreted to develop by displacement on low-angle normal faults similar to detachment faults in continental environments [*Dick et al.*, 1981; *Karson*, 1990; *Tucholke and Lin*, 1994], with the fault footwalls forming inside corners and the hanging walls being transported to outside corners. However, the structure and slip magnitude of these faults remain poorly documented. The megamullions described here occur in IC tectonic settings, and their structure provides compelling new evidence that they originated by slip on extensive and long-lived low-angle detachment faults.

3. Characteristics of Megamullions

We identified 17 megamullions that range in age from 0 to 28 Ma within the limits of detailed off-axis surveys on the MAR (Figure 1 and Table 1). The features are recognized from two diagnostic geomorphological characteristics in multibeam swath bathymetry (Plate 1): (1) a broad, dome-like shape that often is elongated parallel to plate flow lines and (2) occurrence on the megamullion surface of pronounced synforms and antiforms (mullion structure) whose axes also parallel flowlines. Each megamullion is interpreted to be an exhumed footwall block whose surface coincides with the trace of a long-lived detachment fault. Megamullions appear at inside corners of both transform and nontransform offsets (Table 1); thus their occurrence is independent of offset length at adjacent ridge-axis discontinuities.

The structure of the observed detachment fault systems, from older to younger crust, consists of (1) an isochron-parallel ridge that defines the "breakaway" zone where the fault initially nucleated, (2) a relatively narrow zone of depressed crust, (3) a dome comprising the megamullion itself, and (4) a valley-and-ridge structure, usually isochron-parallel, at the termination of the fault (Plate 1 and Figure 2). From breakaway to termination, observed fault surfaces extend 16 to 35 km in the dip direction. At ambient spreading half rates of ~8–24 km/m.y. [*Schulz et al.*, 1988; *Gente et al.*, 1995; *Sempéré et al.*, 1995; *Tucholke et al.*, 1997], the faults accommodated slip for periods of ~1.0–2.6 m.y. (Table 1). Along strike, the faults extend a maximum of 14–42 km, but only 50–80% of this length exhibits mullion structure observable in multibeam bathymetry.

The breakaway zone of a detachment fault usually is marked by a linear ridge (abyssal hill), the young side of which is interpreted to be the remnant fault plane (Plate 1 and Figure 2). In some cases the fault did not initiate instantaneously over its full along-isochron length, but it eventually grew along strike by merging with later formed normal faults nearer the segment center. The zone of younger, depressed crust is several hundred meters deeper than the breakaway ridge (Figure 2). This zone rarely exhibits well-defined mullion structure, but it often has small, isochron-parallel ridges tens to 100 m high (Plate 1). These appear to be formed by high-angle normal faults that dissect the detachment surface (Figure 2), and they also may contain stranded remnants (klippen) of the basaltic hanging wall.

The domed megamullions typically are elevated 1.2–2.0 km above younger and older crust (Plate 1, Figure 2, and Table 1), and their surfaces show the best development of slip-parallel mullion structure. The entire mullioned surface can be cut by high-angle, isochron-parallel normal faults (e.g., Plate 1c). On the young side of a megamullion dome the detachment fault surface usually dips gently to contact a younger ridge that defines the termination of the fault (Plate 1 and Figure 2).

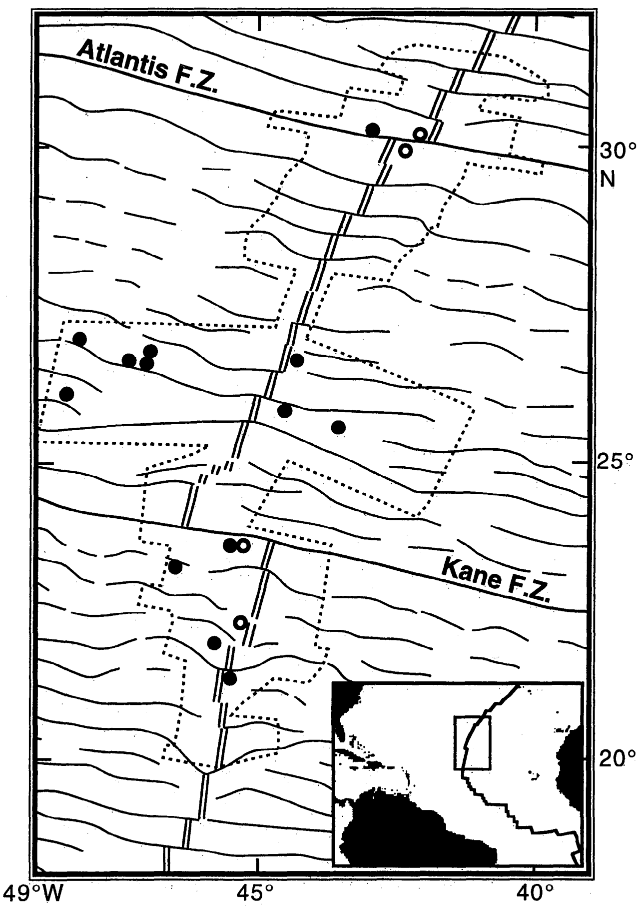


Figure 1. Locations of megamullions (dots) identified in this study. Open dots are megamullions that have been sampled [*Auzende et al.*, 1994; *Cannat et al.*, 1995; *Cann et al.*, 1997]; serpentinized peridotites with or without gabbros and basalts were recovered. The megamullions were identified by analysis of multibeam bathymetry within the limits shown by the dotted lines [*Pockalny et al.*, 1988; *Purdy et al.*, 1990; *Rommevaux et al.*, 1994; *Gente et al.*, 1995; *Sempéré et al.*, 1995; *Fujimoto et al.*, 1996; *Tucholke et al.*, 1997; B. Tucholke et al., unpublished data, 1996] (many of these data are available on the World Wide Web at http://imager.ldeo.columbia.edu/ridgembs/n_mar/html/n_mar.html). The base map shows the MAR axis (double lines), traces of nontransform discontinuities (light lines), and Atlantis and Kane fracture zones as interpreted from the marine gravity field derived from satellite altimetry [*Smith and Sandwell*, 1995].

The synforms and antiforms composing most observed mullion structure have amplitudes of a few tens of meters (the lower limit of detection in conventional multibeam bathymetric data) to ~100 m, but the largest have amplitudes up to 600–700 m. We expect that mullion structure, grooves, and striations smaller than can be resolved by multibeam bathymetry are present, as observed for example in near-bottom side-scan sonar data over two megamullions near Atlantis Fracture

Table 1. Characteristics of Megamullions in the Central North Atlantic Ocean

Latitude °N	Longitude °W	Age Offset, m.y.	BA Age, Ma	Duration, m.y.	Maximum Dimensions, km: Dip	Maximum Dimensions, km: Strike	Approximate Area, km^2	Relief ΔH, m: Maximum	Relief ΔH, m: Average	RMBA Δg, mGal	Mullion Structure: Amplitude, m	Mullion Structure: λ, km	Structural Development
30°17′	43°00′	~4.0	9.1	1.2	25	16/23	380/530	2000	2210	~7	30–300	0.3–4.6	excellent
*30°12′	42°07′	5.9	1.8	1.1	17	30/42	360/640	1550	1870	20	70–420	1.1–7.0	excellent
*29°55′	42°30′	5.1	4.6	2.6	22	12/24	250/470	1450	1750	~16	tens	0.1s–1.0	excellent
26°58′	48°17′	~0	28.0	1.6	20	12/22	240/440	1900	1070	11	45–50	1.1–2.0	excellent
26°45′	47°00′	<0.1	20.3	1.2	30	13/17	360/480	1600	910	15	120–700	3.0–5.6	excellent
26°36′	47°03′	~1.5	20.2	1.0	23	11/20	250/460	1700	930	12	600–620	7.0–8.0	excellent
26°37′	44°20′	~0.2	2.3	1.6	20	18/18	320/320	1150	700	27	tens to 400	0.5–6.0	excellent
26°34′	47°20′	~1.0	21.5	1.1	35	15/19	530/670	1150	490	10	180–235	3.0–4.6	fair
26°07′	48°30′	~1.5	26.5	1.3	21	18/28	360/560	1800	1030	14	60–490	1.1–4.7	excellent
25°50′	44°33′	1.0	4.1	1.5	20	12/19	240/340	1300	690	15	105–230	1.7–3.0	fair
25°34′	43°35′	1.7	11.9	1.6	16	12/18	180/290	1400	790	8	130	3.0	good
23°37′	45°33′	10.5	5.6	2.2	20	13/26	250/470	1650	790	~7	tens	hundreds	good
*23°30′	45°20′	10.5	3.3	1.2	24	35/40	700/800	1600	860	18	85–420	2.0–5.9	excellent
23°16′	46°31′	~0.3	12.4	1.6	17	11/18	180/300	1150	520	~15	tens to 250	0.5–3.0	very good
*22°18′	45°15′	~0.2	2.2	2.2	22	12/16	250/350	2150	1050	~25	420	3.4	excellent
22°01′	45°48′	3.3	6.4	1.0	16	9/35	140/350	1350	1440	~20	tens	0.5–0.7	excellent
21°18′	45°39′	~3.5	1.5	1.5	18	9/14	150/240	1400	420	NA	tens to 120	1.0–3.0	excellent

Age offset is at adjacent discontinuity at time of breakaway. BA age is estimated age at which initial breakaway occurred (timescale of *Cande and Kent* [1995]). Duration gives approximate period of fault slip deduced from crustal ages at fault breakaway and termination. Dimension in dip direction is from breakaway to termination; in strike direction the first value is only for zone exhibiting mullion structure, and the second value is maximum likely distance over which the detachment fault may have been active, extending to the center of the adjacent ridge-axis discontinuity. Approximate areas are based on these dimensions and reflect maximum area of mullion structure and maximum area which may have been affected by the fault, respectively. Maximum relief is measured from crest of megamullion to maximum depth in preceding depression or succeeding valley at fault termination; average relief is height above average seafloor depth for the associated crustal age, derived from a North Atlantic empirical crustal age/depth curve [*Tucholke and Vogt*, 1979]. Δg is difference between maximum RMBA over megamullion and average RMBA of "normal" crust in the preceding or succeeding magmatic episode of spreading; NA, not available. Under mullion structure, amplitudes and wavelengths of synforms and antiforms are approximations measured along fault strike (along isochrons) in bathymetric contour maps, and they are least certain for smaller features. Structural development ranks the quality of development megamullions and mullion structure compared to the ideal development described in text.

*Serpentinzed peridotites and gabbros sampled from the megamullion [*Auzende et al.*, 1994; *Cannat et al.*, 1995; *Cann et al.*, 1997].

Zone (30°12′N and 29°55′N, Table 1) [*Cann et al.*, 1997]. It is because of their generally small amplitude that these synforms and antiforms were not previously recognized. The undulations are very difficult to detect in conventional bathymetric contour maps, and only shaded-relief images with low-angle lighting emphasize their structure (Plate 1). Furthermore, most multibeam bathymetric surveys of slow spreading ocean crust have been run along track lines that parallel plate flowlines and the mullion structure; thus consistent beam point errors in these data can create track-parallel depth artifacts that are difficult to distinguish from real seafloor features. The observation that mullion structure is restricted only to a zone between a defined breakaway and fault termination is key to its identification in flow line–parallel multibeam bathymetric data. In the along-isochron direction, wavelengths of the synforms and antiforms are hundreds of meters for the smaller features, and up to 6–8 km for the largest. Available data (Table 1) show that the wavelength to amplitude ratio ranges between 10:1 and 30:1 and suggest that the ratio is scale-invariant.

Megamullions have elevated RMBA (Figure 2 and Table 1) and thus apparently thin ocean crust. Of the 17 megamullions identified here, four have been sampled (Figure 1 and Table 1), and in each case, serpentinized peridotites, with or without gabbros and basalts, were recovered. The presence of outcropping mantle is consistent with significant thinning of ocean crust and exhumation of the mantle by long-lived detachment faults. Structural features of the ultramafic rocks are described at only one of the four sampled localities [*Auzende et al.*, 1994], but those observations, together with descriptions of serpentinites dredged elsewhere on slow spreading ridges [e.g., *Jaroslow et al.*, 1996], indicate that the rocks typically contain abundant petrofabrics developed by progressive plastic to brittle deformation and retrograde metamorphism. Thus the deformation history of the footwall rocks is interpreted to be similar to that of continental metamorphic core complexes.

Actual dips of the oceanic detachment faults at their initial breakaway and during subsequent megamullion development are not well determined. Observed dips at fossil, off-axis terminations average 23 ± 8°, but these probably are minimum values because of block rotation during transport from the rift valley to the MAR flank. Two of the observed megamullions have detachment faults that are currently active or were recently active within the rift valley walls (22°18′N and 21°18′N, Table 1); their dips are about 35°–37°. With a dip of 35°, a detachment fault would cut through "normal," 5–6 km thick crust and begin to expose mantle within ~7–9 km in the dip direction. However, because crustal thickness tends to be reduced at the ends of spreading segments [*Tolstoy et al.*, 1993; *Cannat*, 1996], the mantle is likely to be exposed on the surface of the footwall within a only few kilometers in the dip direction.

4. Interpretation of Megamullions

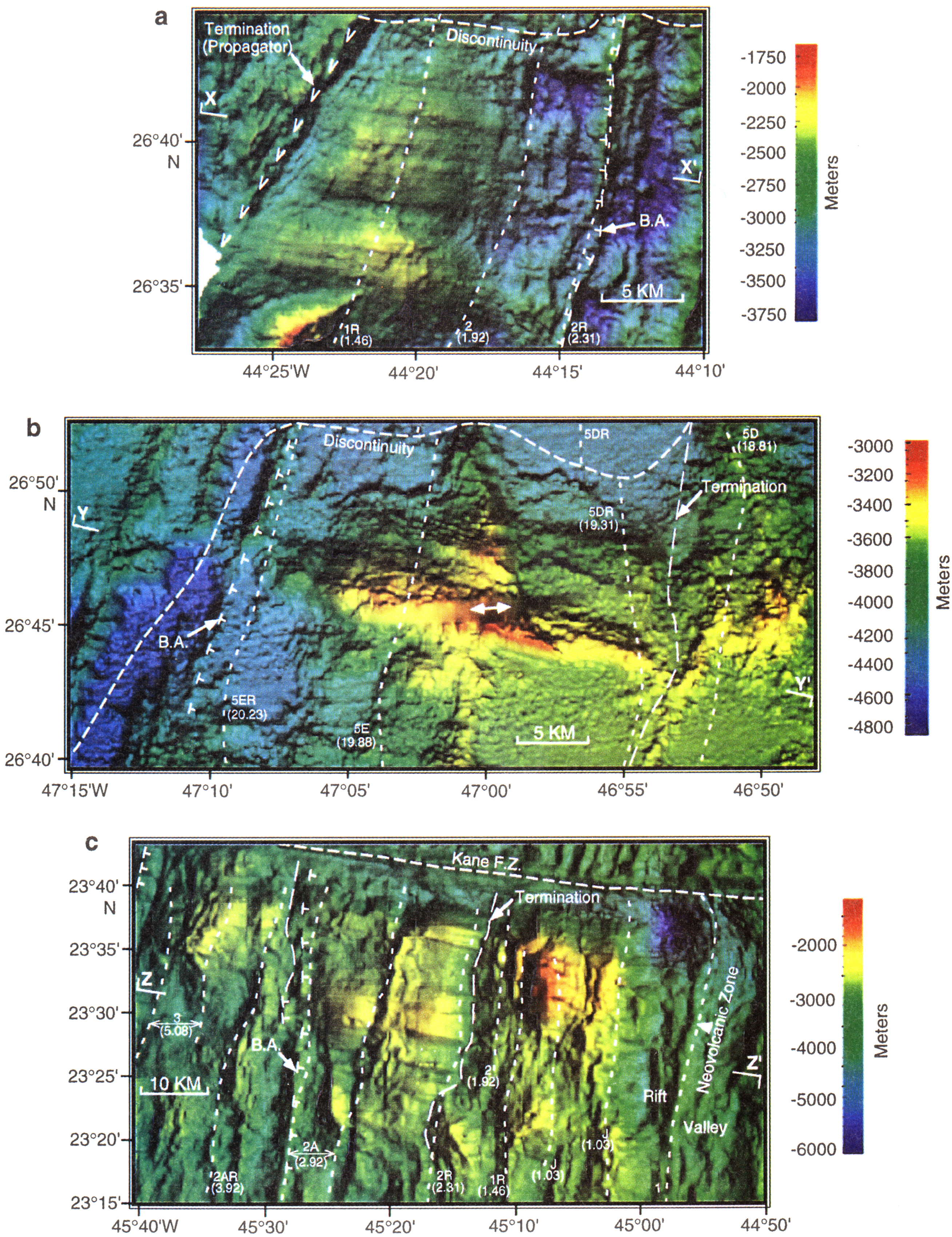
The initiation, prolonged slip, and ultimate demise of detachment faults that create the megamullions may be closely linked to changes in magmatism at the ridge axis. Along plate flow lines following segment centers on the flank of the Mid-Atlantic Ridge, RMBA values vary up to 20 mGal or more with a period of about 2–3 m.y. [*Pariso et al.*, 1995; *Tucholke et al.*, 1997], suggesting temporal variations in crustal thickness of 1–3 km. These variations have been interpreted as alternations between phases of magmatic extension wherein a significant part of the extension is accommodated by solidification of void-filling melts, and phases of relatively amagmatic extension wherein extension is taken up primarily by brittle strain on faults [*Tucholke and Lin*, 1994; *Pariso et al.*, 1995; *Tucholke et al.*, 1997]. Elevated RMBA over megamullions observed at segment ends correlates along isochrons with elevated RMBA over the remaining length of a spreading segment, suggesting that detachment faulting is most robust during phases of relatively amagmatic extension.

The breakaway of a detachment fault normally falls within a zone where the RMBA is increasing toward the spreading axis and crust therefore is thinning (Figures 2a and 2b); this is interpreted to be the early part of an amagmatic phase of seafloor spreading. However, the breakaway also can fall within a zone of already elevated gravity and thin crust (Figure 2c). In either case, the fault is likely to have cut completely through the crust and into the upper mantle. This depth of brittle faulting is consistent with observations at the present MAR axis. Both teleseismic and microearthquake studies indicate brittle rupture at depths up to 10–12 km below the seafloor, or about twice the depth of normal-thickness crust, near the ends of spreading segments [*Bergman and Solomon*, 1990; *Kong et al.*, 1992; *Wolfe et al.*, 1995].

Considering the above observations, we interpret the general structure and lithology of the footwall between the breakaway zone and the termination of a detachment fault as illustrated in Figure 2. Seafloor from the breakaway zone into the adjacent depression may include a cross section both of relatively thin crust and uppermost mantle, as suggested by elevated RMBA. The exposed fault surface in this zone initially nucleated through the brittle lithosphere, and it is characterized by brittle deformation (e.g., irregular topography and high-angle normal faults cutting the detachment fault) and by poorly developed mullion structure. The succeeding fault surface, marked by well-developed mullion structure, is interpreted as exposing a section of the upper mantle exhumed from near and below the brittle/plastic transition. The attitude of a detachment fault at depth is unknown; it may steepen, thus exhuming a subvertical cross section of the crust and mantle [*Tucholke and Lin*, 1994], or it may flatten [*Karson*, 1990] and exhume a subhorizontal section. Direct studies of outcropping lithologies and paleomagnetic vectors of the footwall rocks are needed to determine original fault dip and subsequent rotation of the footwall as it is unroofed.

The usual pattern of normal faulting in the MAR rift valley is that of a major axis-bounding fault near the base of the rift valley wall; this fault is active until it is replaced by a new fault closer to the rift axis, typically at ~0.1 m.y. intervals. These inward jumps are thought to occur because it is easier to break a new fault in the thin axial lithosphere than it is to overcome crustal deformation and friction on the older fault, which must penetrate progressively thickening lithosphere as it cools off axis [*Forsyth*, 1992; *Shaw and Lin*, 1996]. How then, does a detachment fault associated with a megamullion manage to accommodate continuing slip for a period of 1–2 m.y.? We suggest that long-lived slip is explained both by the occurrence of long phases of relatively amagmatic seafloor spreading and by weakness of the fault zone. During an amagmatic phase of spreading, axial lithosphere cools rapidly, probably within 10^4–10^5 years [*Lin and Parmentier*, 1989], so it will not be significantly weaker than nearby off-axis lithosphere that contains the valley-bounding fault. Hence continued slip may occur on the existing fault in preference to formation of a new, inboard fault until a new magmatic phase weakens the axial lithosphere. The dominant 1–1.6 m.y. lifetimes of detachment faults (Table 1) are consistent with the length of a normal amagmatic phase within a full 2–3 m.y. amagmatic/magmatic cycle.

Plate 1. (opposite) Shaded-relief images of multibeam bathymetry which represent a spectrum of morphologic variation in megamullions of the central North Atlantic; see Table 1 for characteristics. Cross-sections X-X′, Y-Y′, and Z-Z′ noted in Plates 1a, 1b, and 1c, are shown in Figure 2. (a) Megamullion at the IC of a small, right-stepping nontransform discontinuity just east of the MAR axis at 26°40′N (illumination from NW). The breakaway (BA) zone of the detachment fault, the fault termination (here a propagating rift) and crustal isochrons (dotted lines with labeled magnetic anomalies and ages (Ma) in parentheses) are noted. The megamullion includes two large, gently domed antiforms (amplitude ~400 m and along-isochron wavelength ~6 km); note the very linear, low-relief (tens of meters) mullion structure that corrugates the detachment fault surface in the ~E-W fault-slip direction, particularly on the domes at left. Small-throw (tens of meters), high-angle normal faults parallel to isochrons cut through the detachment fault, notably near the breakaway. Survey orientation was approximately NW-SE, so the low-relief mullion structure clearly is not an artifact of beam point noise. (b) Megamullion at the IC of a small, left-stepping nontransform discontinuity, centered at 26°45′N (illumination from south); labeling as in Plate 1a. The WNW elongated, centrally located antiform has an amplitude of 700 m and an along-isochron wavelength of about 5 km; a much smaller amplitude WNW trending mullion structure is visible to the north. Beam point artifacts create subtle relief in the approximately WSW survey orientation, but these artifacts are readily distinguishable from the WNW oriented mullion structure. The double-ended arrow shows a data gap with interpolated depths between multibeam survey swaths. (c) Shaded-relief image centered on megamullion near 23°30′N (illumination from east) in an IC tectonic setting south of the large-offset Kane transform fault. Note the prominent approximately E-W oriented synforms and antiforms composing the mullion structure on the megamullion surface and the large west facing, high-angle normal faults that cut the megamullion surface in the area of anomaly 2A. Many of the survey tracks parallel the mullion structure, but the synforms and antiforms are clearly developed only between the indicated breakaway and termination, so they are not beam point artifacts. The breakaway and termination of an older, less well developed megamullion (23°37′N, Table 1) are marked at upper left. The present IC high (red) has lower crustal gabbros exposed on its north and east margins, but detachment faults there have not been long-lived, and significant mullion structure has not developed.


a
Termination (Propagator)
Discontinuity
X
X'
B.A.
5 KM
1R (1.46)
2 (1.92)
2R (2.31)
26°40' N
26°35'
44°25'W
44°20'
44°15'
44°10'
-1750
-2000
-2250
-2500
-2750
-3000
-3250
-3500
-3750
Meters
b
Discontinuity
5DR
5D (18.81)
Termination
5DR (19.31)
Y
Y'
B.A.
5ER (20.23)
5E (19.88)
5 KM
26°50' N
26°45'
26°40'
47°15'W
47°10'
47°05'
47°00'
46°55'
46°50'
-3000
-3200
-3400
-3600
-3800
-4000
-4200
-4400
-4600
-4800
Meters
c
Kane F.Z.
Termination
Z
Z'
3 (5.08)
B.A.
10 KM
2 (1.92)
Neovolcanic Zone
Rift
Valley
J (1.03)
2AR (3.92)
2A (2.92)
2R (2.31)
1R (1.46)
J (1.03)
1
23°40' N
23°35'
23°30'
23°25'
23°20'
23°15'
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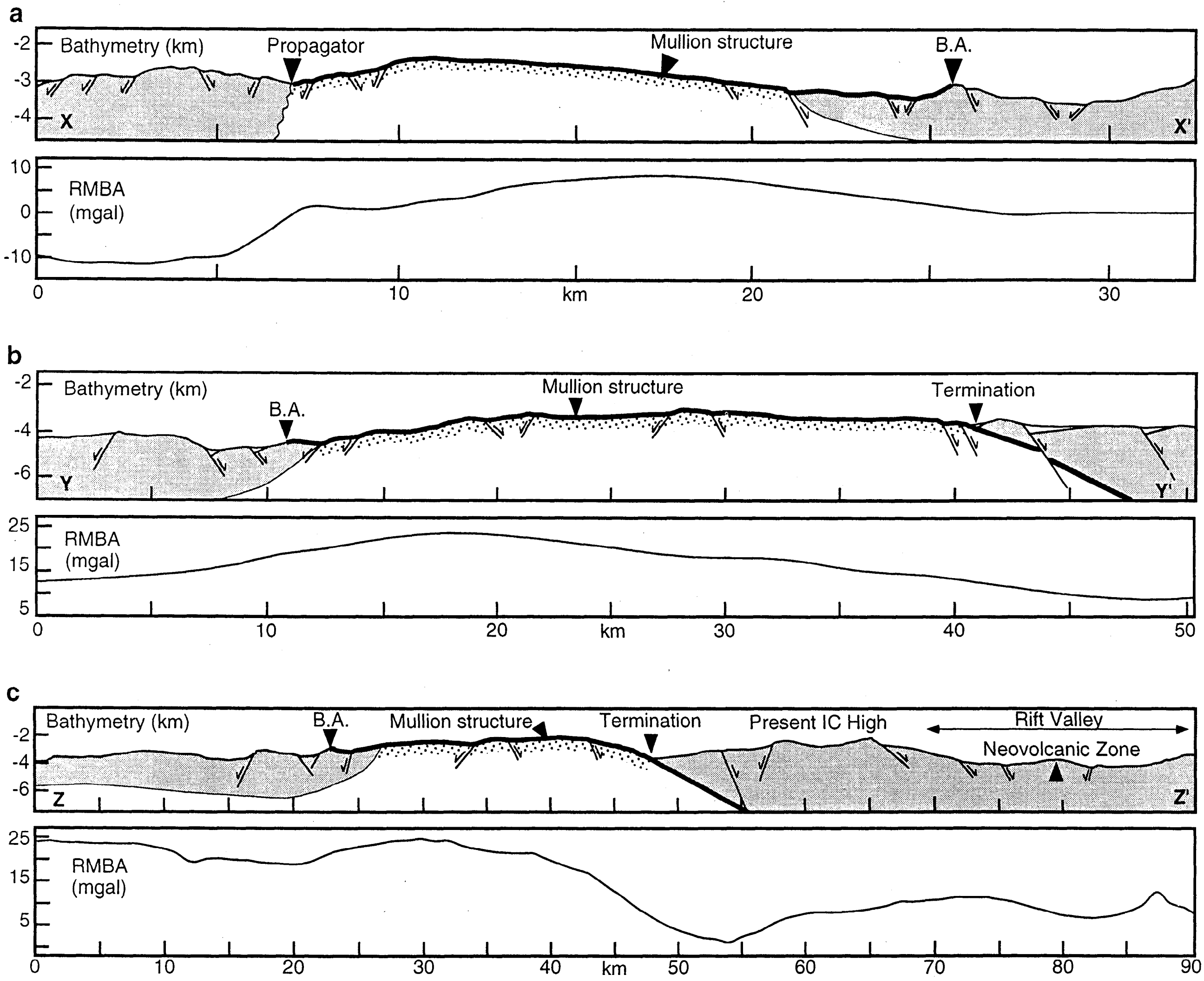

Figure 2. Dip profiles of bathymetry and RMBA over the three megamullions in Plate 1. The bathymetric profiles have no vertical exaggeration and include qualitative interpretations of subseafloor structure based on patterns of seafloor morphology and RMBA. The interpreted detachment fault is marked by a heavy solid line. Shaded and unshaded areas are approximations of crust and mantle distribution, respectively, and the dot pattern shows observed extent of well-developed mullion structure.

Detachment faults also may be exceptionally weak because of a transition from dislocation creep to diffusion creep in shear zones near the brittle-plastic transition in the mantle [*Jaroslow et al.*, 1996] and because of the presence of serpentinites along the fault [*Cann et al.*, 1997; *Escartín et al.*, 1997b]. Serpentinization of mantle peridotites occurs at temperatures below ~400°–500°C in the presence of water [e.g., *Macdonald and Fyfe*, 1985] and appears preferentially in shear zones [*Coulton et al.*, 1995] which may be common pathways for delivery of seawater to the mantle. Oceanic serpentinites (i.e., lizardite and chrysotile) have substantially lower fracture strength and frictional strength than unaltered peridotite and gabbro [*Raleigh and Paterson*, 1965; *Reinen et al.*, 1994; *Escartín et al.*, 1997b], and they also have a nearly nondilatant style of brittle deformation that may confine fluids to further weaken the fault [*Escartín et al.*, 1997b]. Such weak faults also have low optimum dip angles [*Forsyth*, 1992; *Escartín et al.*, 1997a], which may help to explain the apparently shallow dip of oceanic detachment faults.

We interpret the eventual termination of slip on a detachment fault to be caused by significant magmatism in the rift valley inboard of the fault. This could be a minor episode of magmatism within an amagmatic phase of seafloor spreading, or it could mark the initiation of a new magmatic phase. Associated lithospheric heating and consequent thinning may lower the integrated brittle strength of the axial lithosphere below the frictional strength of the detachment fault, thus reestablishing a pattern of inward jumping normal faults. In this case, the ridge at the termination of a detachment fault may represent an abandoned fragment of the original hanging wall (Figure 2c). If heating significantly affects the footwall, new high-angle normal faults may intersect the footwall at depth (Figure 2b) or even where it is exposed, and the footwall may be onlapped by young basalt flows. In some instances it also appears that fault termination was accomplished by rift propagation. In Plate 1a, for example, southward rift propagation from the neighboring spreading segment progressively terminated the detachment fault between ~1.0 and 0.7 Ma; the sharply reduced RMBA over crust just younger than the megamullion (Figure 2a) indicates that the propagation was caused by renewed magmatism and formation of thicker crust.

In Figure 3 we schematically interpret the evolution of a detachment fault and formation of a megamullion near the end of a spreading segment. The initial fault probably has steep dip (Figure 3a); it breaks through thin rift valley crust and into the upper mantle near the beginning of, or during, an amagmatic phase of seafloor spreading, allowing seawater to penetrate and serpentinize mantle peridotites. Isostatic rebound of the footwall uplifts the ridge at the breakaway zone and progressively reduces the dip of the fault (Figure 3b). With continued slip, the footwall rebounds and probably rotates in a "rolling hinge" [*Buck*, 1988; *Hamilton*, 1988; *Wernicke and Axen*, 1988]. Thus the exposed fault becomes nearly level over the surface of the megamullion and even reverses dip in the depression near the breakaway zone (Figure 3c). Klippen of the basaltic hanging wall may be scattered across the detachment surface. Subvertical simple shear and flexural failure in the bending footwall may promote high-angle normal and possible reverse faulting [*Manning and Bartley*, 1994]; such high-angle faults are observed to dissect the detachment fault parallel to isochrons (Plate 1 and Figure 2). At the segment center, minor magmatism probably weakens rift-valley crust during stages in Figures 3a–3c and causes normal, inward fault jumps, but these do not propagate to the segment end where the megamullion is developing. Extension on these successive, short-lived faults may transpose into slip on the detachment as suggested in Figure 3e, or the faults may be separated from the detachment by a transfer zone. Megamullion formation is terminated when magmatism heats and weakens the axial lithosphere at the segment end, thus promoting inward fault jumps and causing the detachment fault to be abandoned (Figures 3d and 3e).

Well-developed, domed megamullions represent only a small fraction of IC highs in the slow spreading crust of the North Atlantic. Why are they not more common? As surmised earlier, for long-lived detachment faults to form it appears necessary (1) that the fault be weak and (2) that a long phase of relatively amagmatic extension must occur. Because observed deep seismicity at the ridge axis [*Toomey et al.*, 1988; *Bergman and Solomon*, 1990; *Kong et al.*, 1992; *Wolfe et al.*, 1995] suggests a high incidence of fault pathways for water to reach and serpentinize the mantle and because abundant serpentinites have been recovered from the seafloor [e.g., *Cannat et al.*, 1992, 1995; *Tucholke and Lin*, 1994], it seems likely that the first condition is widely met in slow spreading crust. Thus we propose that the critical control is the recurrence time of magmatic extension at the segment end. Even minor magmatic episodes occurring within an overall amagmatic phase may weaken the rift-valley lithosphere sufficiently to create a new, inboard fault and thus halt slip on the existing detachment fault. We suggest that the common IC highs adjacent to transform and nontransform discontinuities are juvenile megamullions produced by this "short-circuiting." The extent to which normal IC highs expose lower oceanic crust or upper mantle will be determined by the duration of their associated faults. Only long-lived phases of amagmatic extension are likely to produce long-lived detachment faults.

The prominent mullion structure observed on the surfaces of megamullions appears to be a persistent feature of long-lived detachment faults, but its specific causes are uncertain. Three kinds of mechanisms have been suggested to explain these corrugations on continental normal faults [see, e.g., *Fletcher et al.*, 1995]: (1) heterogeneous vertical stress, (2) footwall warping caused by horizontal compression normal to the extension direction, and (3) fault traces that follow preexisting structural weaknesses. Heterogeneous vertical stress can be created by factors such as lateral thermal variations within the spreading segment, buoyancy forces related to serpentinization at depth, or simply footwall unloading by the detachment fault. These are long-wavelength phenomena that could explain the domed shapes of the megamullions, but they cannot account for the finer-scale synforms and antiforms composing the mullion structure.

Compression of the footwall is a more viable alternative for origin of the mullion structure. Several studies in continental areas indicate that extension-parallel synforms and antiforms are progressively deformed during footwall exhumation [e.g., *Yin and Dunn*, 1992; *Mancktelow and Pavlis*, 1994; *Fletcher et al.*, 1995], which suggests that extension-normal, horizontal compression is important. Possible causes of the compression include regional tectonic configuration [*Mancktelow and Pavlis*, 1994], lateral stresses associated with crustal thinning [*Fletcher et al.*, 1995], and footwall volume expansion during unloading [*Spencer*, 1982]. With respect to tectonic configuration, at mid-ocean ridges we expect horizontal, isochron-parallel extension rather than compression because of contraction of the cooling lithosphere [*Collette*, 1974; *Turcotte*, 1974]. However, plate motion changes can put a ridge axis discontinuity and adjacent IC crust into compression [e.g., *Menard and Atwater*, 1968; *Tucholke and Schouten*, 1988]. Determining whether this is a viable explanation for observed mullion structure will require analysis of megamullion development in the context of detailed plate motion history. Of the other possible explanations for compression, volume expansion of the exhumed footwall is of particular interest because oceanic megamullions appear commonly to expose serpentinites, and serpentinization can increase the volume of peridotites by ~30–60% [*Coleman*, 1971]. If the mantle is serpentinized significantly beyond the immediate shear zone of a detachment fault, compression produced by volume expansion could be important to syntectonic deformation of the fault plane in the oceanic lithosphere.

It is also possible that mullion structure represents original configuration of the fault plane, which developed by following preexisting discontinuities in the lithosphere. For example, the structure could originate in the shallow crust by linking of initially offset faults, or it could develop at depth in heterogeneous lithology [*Lee and Bruhn*, 1992] or by following structure in folded mylonites [*John*, 1987]. It is conceptually possible to distinguish the effects of syntectonic footwall warping caused by horizontal compression from the geometric effects of preexisting structure. Syntectonic warping should create sympathetic deformation of the remnant hanging wall, while control by preexisting structure, at least in the shallow lithosphere, might be deduced from the fine-scale structure of the breakaway zone. Unfortunately, these features are near the resolution limits of existing multibeam bathymetric data. Thus determining the origin of mullion structure ultimately will require near-bottom, high-resolution geomorphic studies of the breakaway zone, the fault surface, and the remnant hanging wall, as well as macroscopic and microscopic studies of rock deformation across the megamullions.

5. Conclusions

Oceanic megamullions are analogous to metamorphic core complexes that are developed in continental environments.

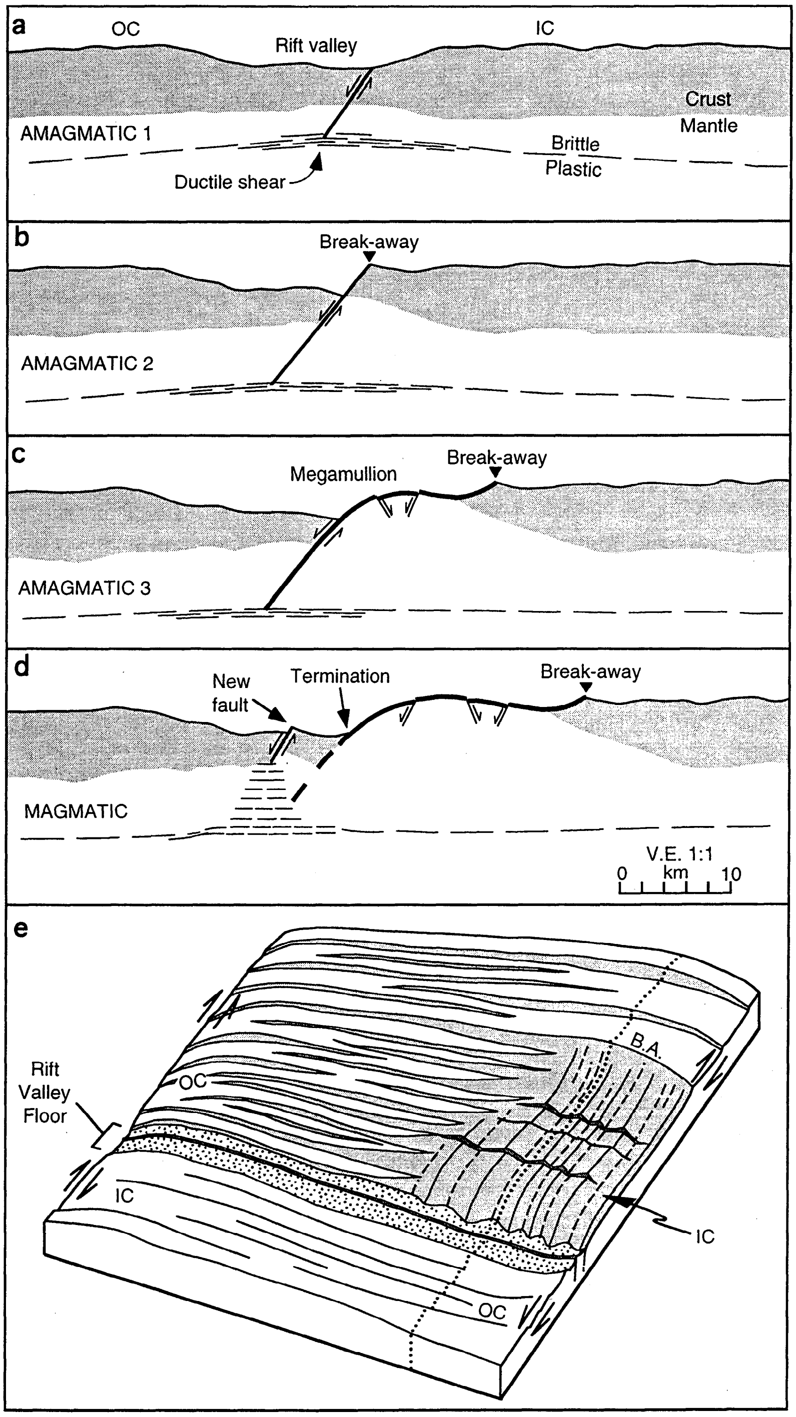

Figure 3. Schematic development of a megamullion, shown in sequential, ~1:1 sections across a rift valley from outside corner (OC) to inside corner (IC) near the end of a spreading segment (see location in Figure 3e). (a) Near the beginning of a long (1–2 m.y.) amagmatic phase of seafloor spreading, a steeply dipping fault cuts through the brittle lithosphere and soles in a zone of ductile shear beneath the brittle-plastic transition. (b) With time, the fault reaches greater depths, following the deepening brittle-plastic transition. (c) Continued slip exposes lower crust and upper mantle in the footwall, eventually forming a domed megamullion on the inside corner by rollover of the footwall block. (d) A magmatic phase of seafloor spreading terminates slip on the detachment fault and growth of the megamullion, as indicated here by formation of a new fault in the weakened rift valley lithosphere. Brief, episodic pulses of magmatism may short circuit this sequence of development (e.g., between stages in Figures 3b and 3c) to create normal inside-corner highs. (e) Perspective sketch of a spreading segment with megamullion development at stage in Figure 3d; dotted line shows orientation of cross section (Figure 3d). The segment is bounded by two left-stepping discontinuities. Fault surfaces are shaded and mullion structure on the detachment surface is shown schematically by solid and dashed lines. High-angle normal faults cutting the detachment surface probably are caused by bending stresses during footwall rollover; in some cases they may propagate from earlier faults at segment center.

Both sets of features develop through slip on long-lived, apparently low-angle normal faults, and they commonly have similar sizes of ~10–40 km, similar domed shapes, and similar development of mullion structure [e.g., *John*, 1987; *Davis and Lister*, 1988; *Tucholke et al.*, 1997]. Furthermore, they both appear to expose deep, plastically deformed rocks that experienced increasingly brittle deformation and retrograde metamorphism as they were exhumed [*Hodges et al.*, 1987; *Jaroslow et al.*, 1996].

On a global scale, oceanic megamullions are likely to be most important on intermediate to slow spreading ridges. With decreasing seafloor spreading rates the magma budget of a mid-ocean ridge is reduced [*Macdonald et al.*, 1993], and magma bodies become rare and transient features [*Sinton and Detrick*, 1992]. If the duration of uninterrupted amagmatic episodes correspondingly increases, we expect that the longevity of detachment faults and thus the frequency of megamullion formation will also increase. The reverse is expected for magma-rich, faster spreading ridges such as the East Pacific Rise, where we consider it unlikely that megamullions will develop except perhaps in unusual instances where cold, off-axis lithosphere becomes rifted (e.g., Hess Deep, on the flank of the East Pacific Rise).

Oceanic megamullions may prove to be particularly important because the longevity of their detachment faults suggest that they expose deep cross sections of the ocean crust and uppermost mantle that are accessible to direct study. Obtaining complete, coherent sections of the crust and upper mantle is a long-standing but thus far unfulfilled goal of the Earth science community [*Joint Oceanographic Institutions Inc.*, 1990]. A combination of on-bottom geological mapping and sampling of megamullions, together with deep-ocean drilling, may finally offer the opportunity to realize that goal.

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