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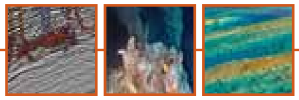

# Active Long-Lived Faults Emerging Along Slow-Spreading Mid-Ocean Ridges

BY DEBORAH K. SMITH, JAVIER ESCARTÍN, HANS SCHOUTEN, AND JOHNSON R. CANN

## OCEANIC DETACHMENT FAULTS AND CORE COMPLEX FORMATION

In the classic mid-ocean ridge model, new seafloor is generated through a combination of magmatic diking feeding lava flows at the spreading axis, and the formation of short-offset, high-angle normal faults that dip toward the axis. These processes lead to the formation of a layered magmatic crust and linear, ridge-parallel abyssal hills on both ridge flanks. This model of ocean crust generation applies well to fast-spreading mid-ocean ridges (i.e., > 80 mm $yr^{-1}$), but it is not always valid at slower-spreading ridges. Instead, at slow-spreading ridges such as the Mid-Atlantic Ridge (MAR), which is opening at about 25 mm $yr^{-1}$, the formation of long-lived faults (called detachments) on one flank of the ridge axis is an important process in seafloor formation (Cann et al., 1997; Karson, 1999; MacLeod et al., 2009; Schroeder et al., 2007; Smith et al., 2008; Tucholke et al., 1998). In fact, active detachment faults have been identified along nearly half of the MAR axis between 12° and 35°N (Escartín et al., 2008).

Continued extension on a single fault leads to significant flexural rotation of the fault block (Garcés and Gee, 2007; MacLeod et al., 2011; Morris et al., 2009; Schouten et al., 2010). If extension continues for more than about 5 km, continued rotation means that the exhumed fault surface becomes near horizontal from its initial dip of about 60° beneath the axis, and the seafloor domes as a result of regional isostatic compensation (e.g., Buck,

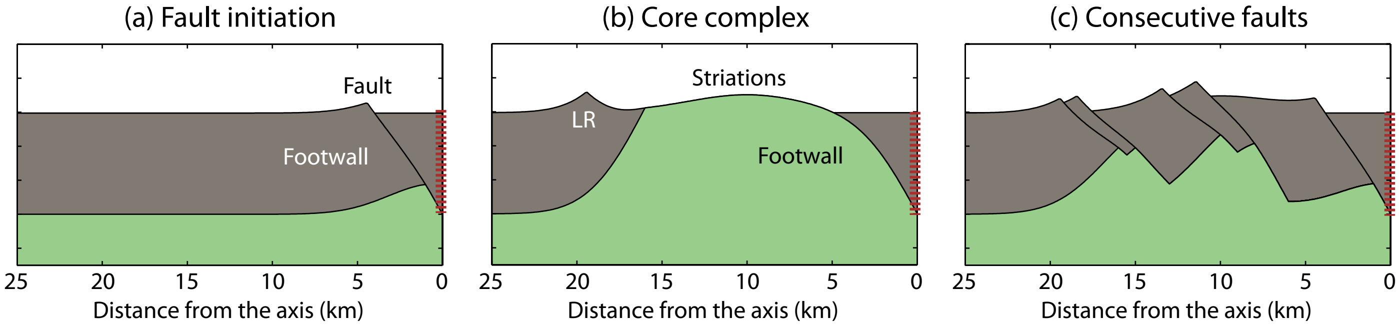

Figure 1. Cartoon showing two styles of faulting at a slow-spreading ridge. Faults are shown as subsurface black lines, and the footwall is marked. A normal fault forms, dipping at 60° beneath the axis. (a) In this panel, fault offset is 1 km, and the fault block has rotated outward away from the ridge axis by 18° to form an outward-facing scarp. (b) Continued faulting and extension brings lower crustal rocks to the seafloor and forms a "core complex." In this panel, the fault offset is 16 km, and outward rotation of the top of the fault has increased to 36° to create a narrow linear ridge (LR) that marks the breakaway where the fault initially formed. The exposed footwall may be striated. (c) In this panel, no long-lived faults have formed. Instead, consecutive short-lived faults cut the lithosphere on the ridge flank to form classic abyssal hill topography. Red dashed line = spreading axis. Brown shading = crust that predates faulting. Green shading = material below the crust that is brought to the surface during core-complex formation.

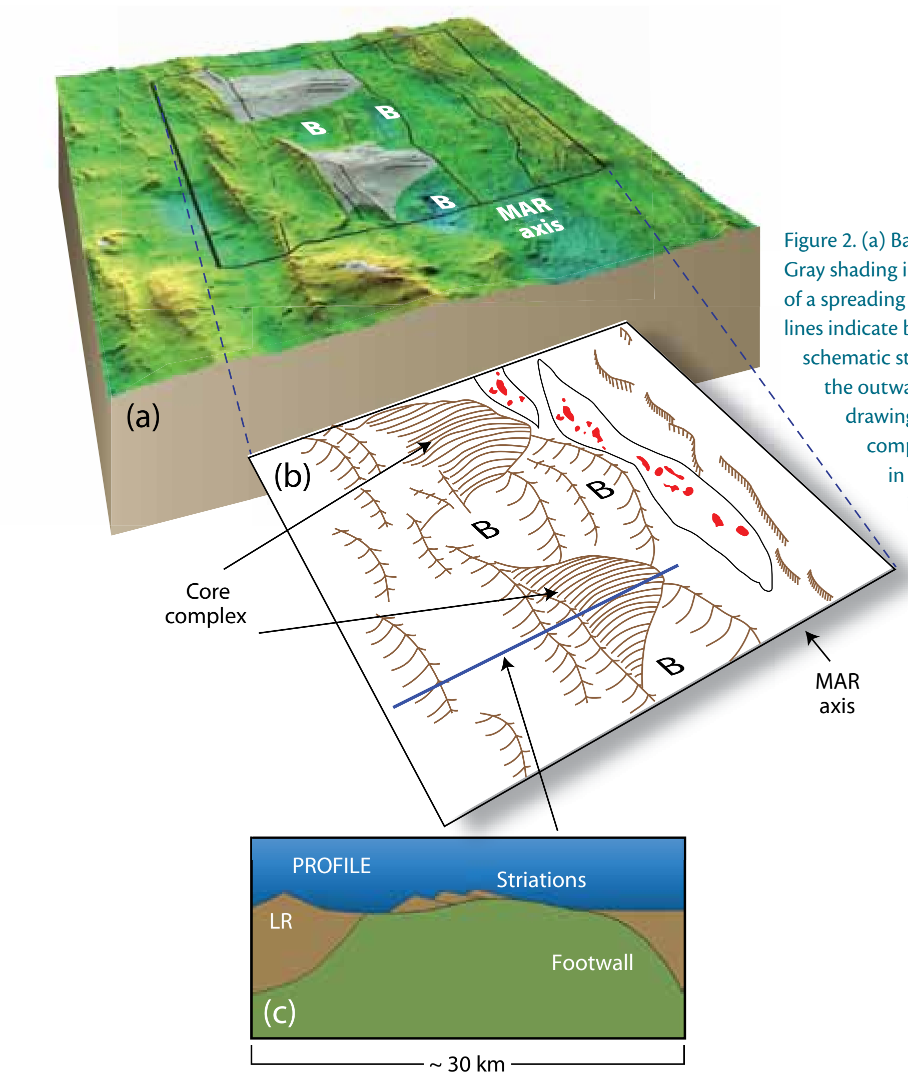

Figure 2. (a) Bathymetry from the 13°N region of the Mid-Atlantic Ridge. Gray shading indicates two core complexes that have formed in the middle of a spreading segment. The box is the region interpreted in (b). Black lines indicate borders of the MAR axis, the tops of rotated faults, and schematic striations on core complexes. Basins that have formed during the outward rotation of the tops of the faults are marked B. (b) Line drawing of the bathymetry in the box in (a) showing striated core complexes and the tops of rotated faults. B's indicate basins as in (a). At the spreading axis, axial volcanic ridges are outlined in black. Red areas indicate that volcanism occurs along the axis. The blue line locates the profile shown below. (c) Schematic profile across the southern core complex similar to the profiles shown in Figure 1. Striations on the exposed footwall are labeled. LR = linear ridge created by the outward rotation of the top of a fault. Faulted sections of brown-shaded material on the top of the core complex surface are rafted blocks of the median valley floor.

1988) to form a "core complex massif" (Figure 1). Core complex massifs expose lower crustal and upper mantle rocks at the seafloor (e.g., Dick et al., 1981; Cann et al., 1997; Blackman et al., 1998; Tucholke et al., 1998; Escartín and Cannat, 1999; Karson, 1999; Cannat et al., 2006; Ildefonse et al., 2007). The surfaces capping core complexes often show distinctive striations that run parallel to the spreading direction (Figure 2). The detachment fault associated with an active core complex dips beneath the seafloor < 5 km from the spreading axis and roots beneath the axis (e.g., deMartin et al., 2007).

Rather than forming only at the ends of spreading segments near fracture zones and other ridge-axis discontinuities, as had been thought, several core complexes have been identified in the middle of spreading segments (Figure 2). Adjacent mid-segment core complexes may have resulted from movement along a single detachment fault (e.g., Smith et al., 2006, 2008; MacLeod et al., 2009; Reston and Ranero, 2011). Detachment faulting and the formation of core complexes may continue in a region for many millions of years, producing large fields of core complexes off axis (e.g., Okino et al., 2004; Cannat et al., 2006; Smith et al., 2006, 2008; Schroeder et al., 2007; Reston and Ranero, 2011).

The controls on the formation of oceanic detachment faults and core complexes remain poorly understood, but must differ significantly from those controlling extension when seafloor spreading occurs in the "classic" manner. It has been argued that detachment faults and associated core complexes begin as high-angle (dipping about 60°) faults beneath the spreading axis, just as classic shorter-offset faults do (e.g., Tucholke et al., 1998; Morris et al., 2009; Schouten et al., 2010; MacLeod et al., 2011). But why does one fault continue to extend for millions of years, rolling over to form a core complex, while another stops after extending for a relatively short time? Models examining the relationship between magma supply to the ridge axis and detachment fault formation have been put forward, many of which suggest that detachment faults form when magma supply is low (e.g., Buck et al., 2005; Escartín et al., 2008; Tucholke et al., 2008; MacLeod et al., 2009; Olive et al., 2010; Schouten et al., 2010). This low magma supply model is still a matter of debate, however, because observations suggest that melt extraction from the mantle beneath the axis may be high during the evolution of detachment faulting (e.g., Dick et al., 2000; Grimes et al., 2008).

> “THE ULTIMATE GOAL OF ALL OF THESE STUDIES WILL BE TO IDENTIFY THE MAGMATIC AND RHEOLOGICAL CONDITIONS THAT ARE REQUIRED FOR THE INITIATION AND SUSTAINED EVOLUTION OF THESE LARGE-OFFSET NORMAL FAULTS.”

Detachment faults and core complexes are especially important because they expose at the seafloor deep-seated rocks formed beneath mid-ocean ridges, permitting investigation of oceanic lithosphere structure. They sustain both long-lived, high-temperature hydrothermal circulation and low-temperature, hydrogen-rich, serpentinite-related systems with associated mineral deposits and ecosystems. And, detachment faults and core complexes contribute substantially to the formation of major expanses of the seafloor. For example, if close to 50% of the northern MAR spreading axis (12°–35°N) is experiencing detachment faulting (Escartín et al., 2008), then up to 25% of new seafloor there may be composed of core complexes. In addition, ocean detachment faults provide important comparisons for those who study the formation of continental core complexes (e.g., John and Cheadle, 2010).

## SEISMICITY AND ACTIVE DETACHMENT FAULTS

Between 1999 and 2003, six autonomous hydrophones were moored in the North Atlantic from 15°–35°N (North MAR study area marked on Figure 3a) to record the seismicity of the slow-spreading MAR (Smith et al., 2002). The improved detection capability and earthquake location accuracy of the hydrophone array, compared to land-based teleseismic networks, provided new insights into the overall spatial and temporal patterns in ridge-axis tectonic and magmatic processes. In particular, the seismicity data from the hydrophones indicated that regions along the axis with persistent hydrophone seismicity were most likely correlated with regions of active detachment faulting and core complex formation (Figure 3b; e.g., Escartín et al., 2008; Smith et al., 2008).

Figure 4 shows the multibeam bathymetry collected at 13°N and 16°N with the location of hydrophone-recorded earthquakes plotted. Seismicity occurring within the axial valley is probably associated with the high-angle portion of the detachment faults deep beneath the axis, such as observed at the TAG detachment fault at 26° along the MAR (deMartin et al., 2007). There is also seismicity within the core complexes themselves, suggesting deformation associated with flexing and bending of the detachment footwall both across and along the axis.

## THE WAY FORWARD

Hydrophones are currently being deployed for two years in the equatorial Atlantic (Figure 3a). This region is especially interesting because of its tectonic

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history associated with the opening of the Atlantic Ocean. A strongly segmented MAR, with limited magma supply, is offset on some of the longest transform faults in the ocean (e.g., the > 900 km Romanche Transform Fault). Using the data collected by the equatorial hydrophone array, it will be possible to identify regions of high hydroacoustic seismicity at the ridge axis and, thus, probable regions of active detachment faulting. It is expected that detachment faults will be common along the equatorial Atlantic MAR because of the thicker and colder-than-normal oceanic lithosphere as well as an inferred mantle thermal minimum in the region resulting in overall low melt production (e.g., Bonatti et al., 2001). Of interest will be whether the patterns in seismicity change along the axis, and whether the patterns are different north and south of the very long-offset Romanche Transform Fault, which likely separates geochemically distinct regions of the Atlantic.

Along with continued acoustic monitoring of the mid-ocean ridges, a next step is the collection of near-bottom geophysical and geological data. These data, combined with results from numerical models, will provide the most complete view of the mechanisms that operate and interact throughout an oceanic detachment fault system and, in particular, of the links between the distribution and nature of deformation,

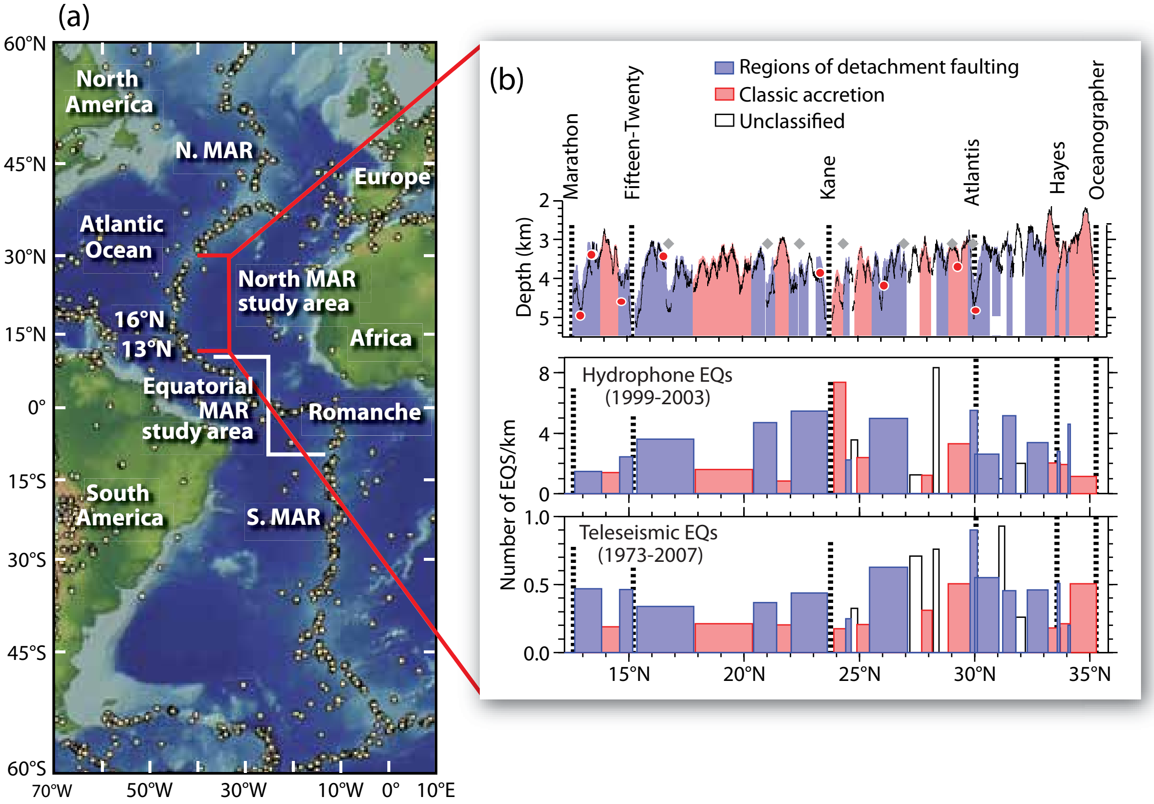

Figure 3. (a) Map of the Atlantic Ocean. Yellow dots show locations of teleseismic earthquakes from the National Earthquake Information Center (NEIC) catalog with M > 4.5 between 1976 and 2009. Within the North MAR study area, high rates of hydroacoustically recorded seismicity were correlated to active detachment faults as shown in (b) (Smith et al., 2006, 2008; Escartín et al., 2008). A new study area in the equatorial Atlantic will yield information on ridge-axis detachment faulting in this region of large-offset transform faults. The Romanche Transform Fault is marked. Figure 4 shows the details of the 13°N and 16°N areas. (b) Histogram showing a bathymetric profile along the ridge axis in the top panel, number of hydrophone-recorded earthquakes (EQs) per kilometer of ridge in the middle panel, and number of teleseismically recorded earthquakes per kilometer of ridge in the bottom panel. Dashed lines indicate the locations of transform faults. Rose shading shows regions of the ridge axis that spread by classic magmatic accretion, and blue shading shows regions of the axis that spread by detachment faulting on one flank. Note the correlation of high rates of seismicity with active detachment faulting. Red circles = known hydrothermal fields. Gray diamonds = known hydrothermal plumes. There also is an association of hydrothermal activity and active detachments. *Histogram modified from Escartín et al. (2008)*

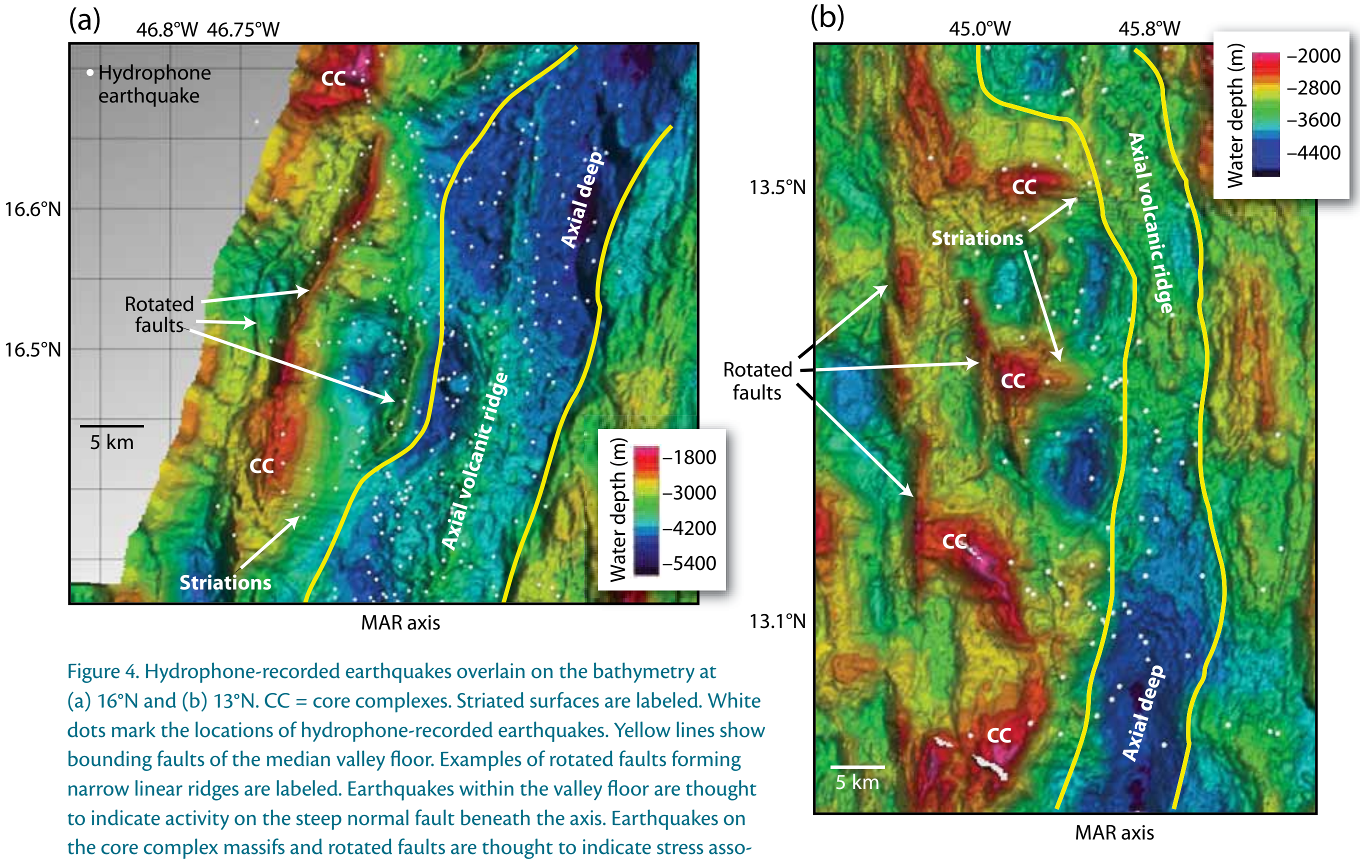

Figure 4. Hydrophone-recorded earthquakes overlain on the bathymetry at (a) 16°N and (b) 13°N. CC = core complexes. Striated surfaces are labeled. White dots mark the locations of hydrophone-recorded earthquakes. Yellow lines show bounding faults of the median valley floor. Examples of rotated faults forming narrow linear ridges are labeled. Earthquakes within the valley floor are thought to indicate activity on the steep normal fault beneath the axis. Earthquakes on the core complex massifs and rotated faults are thought to indicate stress associated with the flexing of faults both along and across the axis.

lithospheric alteration, and magmatic activity at the axis (e.g., Escartín and Canales, 2011).

Sampling of rocks is also an important piece of the puzzle because the composition of basalts from the ridge axis can be used to estimate the magmatic budget at a ridge segment and, hence, to test current models relating magma supply and detachment fault formation (e.g., Buck et al., 2005; Tucholke et al., 2008; MacLeod et al., 2009; Olive et al., 2010; Schouten et al., 2010). To evaluate the models, it will be essential to study a number of different detachment faults and associated volcanic systems at the ridge axis, representing a spectrum of magmatic activity.

The ultimate goal of all of these studies will be to identify the magmatic and rheological conditions that are required for the initiation and sustained evolution of these large-offset normal faults. Knowledge of these conditions will help us to understand how the oceanic lithosphere is constructed in settings where detachment faulting occurs.

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