Fast rift propagation at a slow-spreading ridge

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ABSTRACT

Bathymetric, magnetic, gravity, and morphologic data from the flank of the slow-spreading Mid-Atlantic Ridge reveal obliquely oriented features that offset magnetic isochrons and morphological patterns within individual ridge segments. These features form angles of ~10°–40° with the isochrons and are inferred to result from rift propagation at rates several times the spreading rate, representing the fastest propagators yet observed at a slow-spreading ridge. These fast propagators appear to have formed as a result of tectonic extension migrating along ridge segments as the segments change from more magmatic to less magmatic periods of spreading.

INTRODUCTION: RIFT PROPAGATION AT MID-OCEAN RIDGES

Rift propagation along mid-ocean ridge spreading axes has been recognized for ~20 years (e.g., Hey, 1977). This process generally involves the lengthening of one spreading segment at the expense of its neighbor as the offset between them migrates along the strike of the ridge with respect to relatively fixed points on the ridge such as transform faults (Fig. 1). This migration creates a wake of pseudofaults that are oblique to the ridge axis and point in the direction of offset migration. By measuring the acute angle θ between the propagating ridge and a pseudofault and knowing the half-spreading rate *v* from magnetic anomalies, the propagation rate *p* may be computed ($v/p = \tan\theta$).

Initial investigations of active propagating rifts (or "propagators") were made at ridges spreading at intermediate rates, such as the Galapagos spreading center (e.g., Hey et al., 1980) and the Juan de Fuca Ridge (e.g., Hey, 1977), where propagation rates are about equal to half-spreading rates. Fast (e.g., Naar and Hey, 1986) and "ultra-fast" (e.g., Cormier and Macdonald, 1994) rift propagation was detected at the fast-spreading East Pacific Rise, where ratios of propagation to half-spreading rate were as high as 10. Many moderate- to fast-propagating rifts at medium- to fast-spreading ridges were observed in Geosat satellite altimetry data from the southern oceans (e.g., Phipps Morgan and Sandwell, 1994). Rift propagation has also been identified at the slow-spreading Mid-Atlantic Ridge (e.g., Brozena and White, 1990; Carbotte et al., 1991; Sloan and Patriat, 1992; Kleinrock et al., 1992, Sempere et al., 1995), where reported propagation to half-spreading rate ratios are usually 0.5 or less. Here we describe the first evidence for fast rift propagation along a slow spreading ridge, the Mid-Atlantic Ridge near 26°N, where ratios in excess of 2 are observed. After describing the geological setting and observations, we investigate possible causes for such fast propagation and their implications.

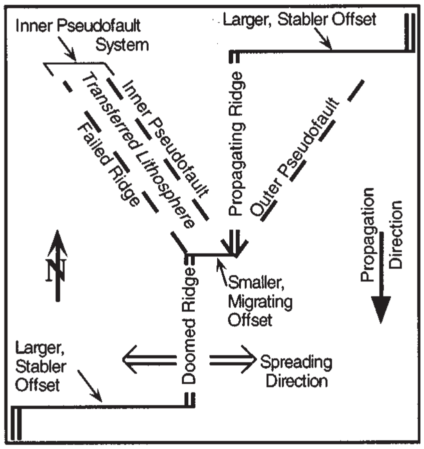

Figure 1. Schematic diagram of tectonic elements of propagating rift/migrating offset located between two larger offsets, showing propagating (lengthening) rift, doomed (shortening) rift, V-shaped pattern formed by outer pseudofault and inner pseudofault system (including failed rift, inner pseudofault, and transferred lithosphere). After Hey et al. (1986).

METHODS

We collected multibeam bathymetry (Hydrosweep), long-range side-scan sonar imagery (HAWAII MR1 system), and gravity, magnetics, and single-channel seismic reflection data along lines spaced 4-9 km apart from an ~200 km by 400 km area on the west flank of the Mid-Atlantic Ridge near 26°N extending from the zero-age ridge crest to crust as old as 29 Ma (Fig. 2). For explanation of data collection and processing and a description of the overall segmentation history see Tucholke et al. (1997).

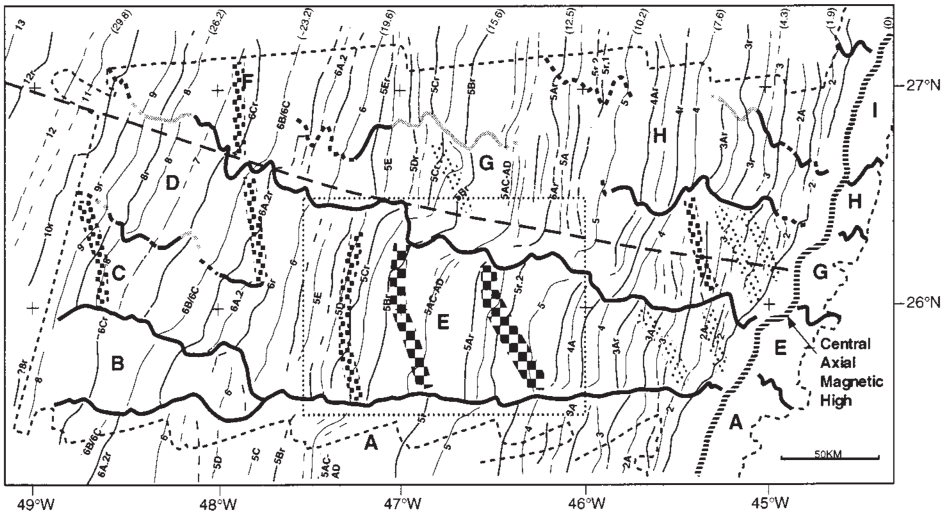

Figure 2. Schematic of magnetic anomalies (numbered lines, with crustal ages in parentheses), and primary segments (A–I) and their boundary traces (heavy lines, gray where left-stepping and dashed where weakly developed). Straight dashed west-northwest–trending line is synthetic spreading flow line. Two well-developed oblique features discussed in text as fast propagator traces are highlighted by north-northwest–trending thick checkered bands; additional north-northwest thick bands show 10 more possible propagators inferred from morphology plus geophysics (heavy random dot pattern—5 examples) and from only magnetics (lighter random dot pattern—5 examples). Dotted box near center shows area of Figure 3. Dashed line near perimeter shows coverage from survey and other data (after Tucholke et al., 1997).

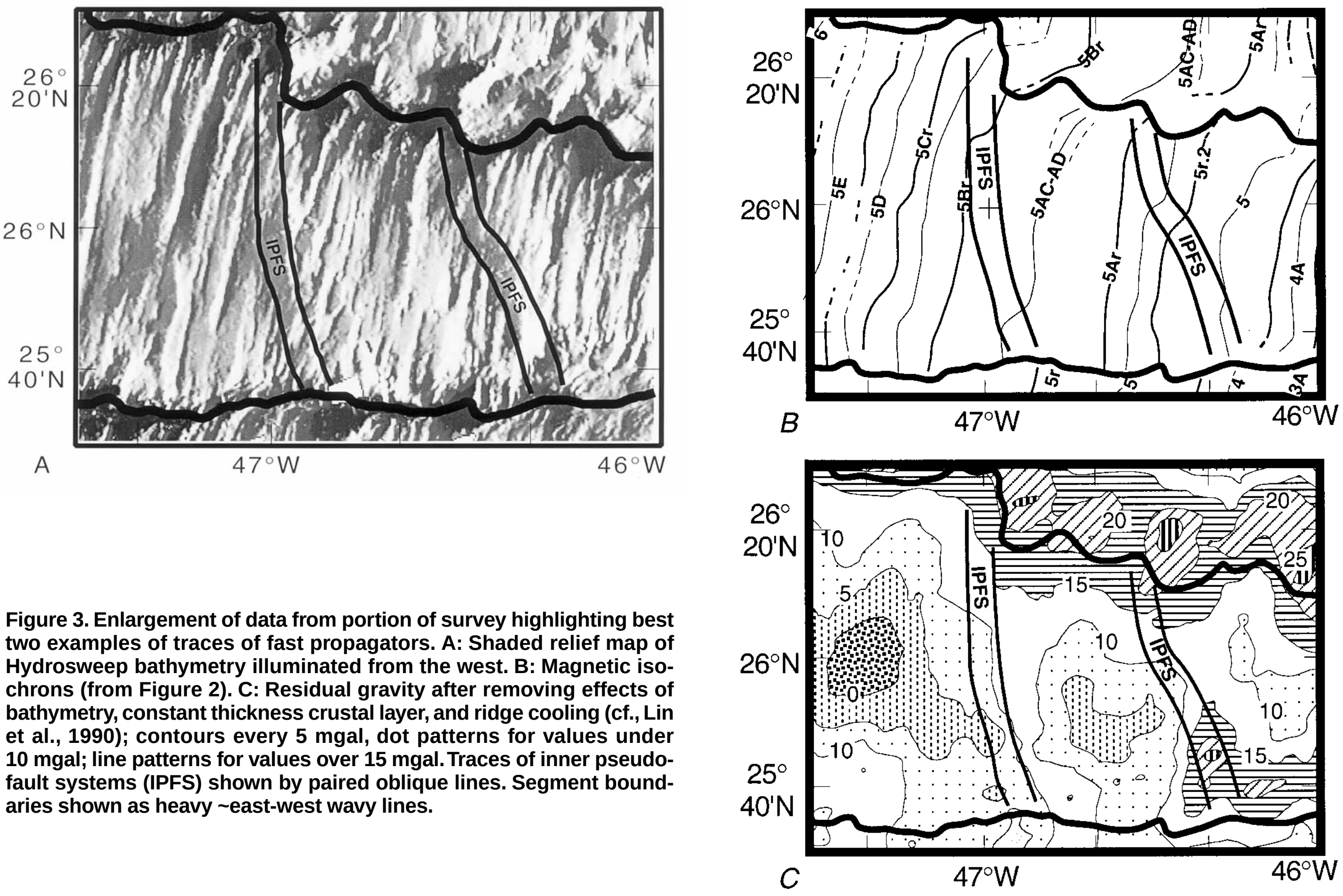

Figure 3. Enlargement of data from portion of survey highlighting best two examples of traces of fast propagators. A: Shaded relief map of Hydrosweep bathymetry illuminated from the west. B: Magnetic isochrons (from Figure 2). C: Residual gravity after removing effects of bathymetry, constant thickness crustal layer, and ridge cooling (cf., Lin et al., 1990); contours every 5 mgal, dot patterns for values under 10 mgal; line patterns for values over 15 mgal. Traces of inner pseudofault systems (IPFS) shown by paired oblique lines. Segment boundaries shown as heavy ~east-west wavy lines.

OVERALL CRUSTAL SEGMENTATION

Between the Kane and Atlantis fracture zones, 18 right-stepping nontransform offsets ("second order" discontinuities, applying the offset order terminology of Macdonald et al., 1980) offset the Mid-Atlantic Ridge (e.g., Sempere et al., 1990; Smith and Cann, 1992). The eastern margin of our survey (Fig. 2) covers five of these offsets and the four intervening "second order" spreading segments (applying the segment order terminology of Macdonald et al., 1988) between 25°30'N and 27°10'N. Based on bathymetry, morphology, magnetics, and gravity, Tucholke et al. (1997) found that the overall pattern of segmentation in this area has been mostly stable but was modified ~24–20 Ma during a major change in spreading direction when several segments were initiated or eliminated. The second-order ridge segments have lengths of ~40–70 km and lifespans of at least ~10–20 m.y., and they are offset 0–60 km (typically ~20–30 km) by second-order offsets that have migrated along the Mid-Atlantic Ridge axis at rates ~0–5 km/m.y. Thus, angle θ between the traces of discontinuity migration (pseudofaults) and features presumably parallel to the ridge at the time (i.e., crustal isochrons such as magnetic anomaly stripes and abyssal hill lineaments) generally exceed 80°.

OBLIQUE FEATURES WITHIN SEGMENTS

In bathymetric and magnetic data from the survey area, we identify a new class of tectonic features, heretofore not described in slow-spreading crust, that cut obliquely across the standard bathymetric and magnetic lineaments at relatively low angles to the isochrons. At least 2, and perhaps up to 12 such oblique features, all of which have a general northwesterly trend, can be identified in morphology, gravity, or magnetic data. In this paper we primarily discuss the two best examples of these oblique features. They occur near long 46.3°W and 47.0°W within crust formed at second-order Segment E (Fig. 2) and contain elongate, partially sediment-filled basins up to ~30 km long and ~5 km wide that disrupt the regular abyssal hill morphology (Fig. 3A). The pattern of abyssal hills on either side of these features is distinct, and it is difficult to confidently correlate structures across these features. Single-channel seismic-reflection profiles show that the basins are filled with ~100–150 m (locally up to 350 m) of sediment, and they show partially buried scarps in the ocean crust.

The oblique features are associated with distinct kinks in the trace of magnetic anomalies (Fig. 3B). In the 46.3°W and 47.0°W examples, pairs of kinks produce right-stepping net offsets of ~7 km in magnetic isochrons.

Residual gravity anomalies (Fig. 3C) show the 46.3°W and 47.0°W features to occur at transitions from relatively low residual anomalies in the west to elevated anomalies in the east, suggesting a possible causal relationship discussed further below.

Each oblique feature is contained entirely within a single crustal segment and extends much of the way from the trace of the northern nontransform (second order) discontinuity to the trace of the southern one. Thus, the process that produced these features affected much of a single whole segment, but not its neighbors.

FAST PROPAGATORS IN SLOW-SPREADING CRUST

The combination of oblique morphologic disruption coincident with offset of magnetic anomalies is strongly suggestive of a propagating rift system (e.g., Hey et al., 1986), and we propose this explanation for the features described. Assuming the propagating rift model, the right-stepping isochron offsets and the overall northwest-trending geometry of the 46.3°W and 47.0°W features require that the rifts propagated south, and that the observed features thus represent inner pseudofault systems, each of which consists of an inner pseudofault, transferred lithosphere, and a failed rift (Fig. 1). At these best-developed examples, the angle θ between inner pseudofault complexes and crustal isochrons ranges from 20° to 40°, constraining propagation rate to half-spreading rate (*p/v*) ratios as 1.2 to 2.7. For the 14 km/m.y. half-spreading rate here, this indicates propagation rates of 17-40 km/m.y.

The size (~7 km or ~0.5 m.y.) of these fast-migrating dextral offsets is ~20% that of the dextral offsets of the slowly migrating second-order nontransform discontinuities bounding Segment E to the north and south (Fig. 2). In this case, the second-order offsets are akin to the lower order offsets in Figure 1 and the fast propagators are thus third-order offsets that effected a reorganization of second-order Segment E.

The northernmost and southernmost portions of the 46.3°W and 47.0°W pseudofault systems are less well-defined than the central portions (Fig. 3). The trace of kinks in the magnetic stripes indicate a continuity of each pseudofault system across virtually the entire length of Segment E. Complex structural patterns interrupting the oblique traces, however, may suggest that the pseudofaults terminate or become subparallel to isochrons. Unfortunately, the gravity (Fig. 3C) and crustal magnetization data (Tucholke et al., 1997) are inconclusive. Continuous pseudofaults would suggest a fairly steady propagation across the entire length of Segment E. Conversely, pseudofaults that terminate or merge into isochrons would suggest that the fast propagating rifts began as very short segments (less than ~10–20 km) created by ~5 km eastward ridge jumps of the northernmost portion of Segment E (or, indistinguishably, by extremely rapid southward propagation from the nontransform offset between Segments E and G at rates >75 km/m.y.) and that the propagation events culminated with similar jumps or extremely rapid propagation rates. In either case, the nearly full-segment length of the event suggests a second-order–segment-scale cause for the propagation.

POTENTIAL CAUSES

Several mechanisms have been proposed to cause rift propagation, including concentration of gravity sliding stresses, greater propagation likelihood for longer cracks, changes in direction of sea-floor spreading, and motion of the ridge in an absolute (hot-spot) reference frame.

Phipps Morgan and Parmentier (1985) and Phipps Morgan and Sandwell (1994) showed that rifts at medium- and fast-spreading ridges tend to propagate down the along-ridge-axis topographic gradient, away from high points along the ridge; they attribute this to increased crack-tip stresses caused by differential gravitational sliding stresses. Higher areas have farther to slide, so gravitational sliding stress is greater there than at lower areas, producing concentrated stress at the crack tip. Near the 46.3°W and 47.0°W pseudofaults, the most elevated crust from Segment E is along its southern margin, and depth increases toward the north. Thus, if the current topographic pattern reflects that at the time of rift propagation, the propagators were propagating uphill, contrary to the gravity-sliding hypothesis. Given the ~7 km isochron offsets, it is likely that the propagation was occurring within the median valley walls (typically ~20 km wide; e.g., Sempere et al., 1993). By analogy with the highs present at the along-axis midpoint of typical Mid-Atlantic Ridge median valleys, the apparent initiation of propagators at segment ends suggests initial propagation upslope. Thus, the gravity-sliding model is insufficient here.

The regional along-ridge topographic trend is deeper to the south all the way from near the Azores to the equatorial fracture zones. This might suggest a southward focusing of the gravitational sliding stress compatible with the observed southward propagation direction (Figs. 1 and 2). It is unlikely, though, that such a broad-scale trend could drive motion of the small fast propagators without similarly driving southward migration of second-order discontinuities; numerous second-order offsets (e.g., Müller and Roest, 1992) in the area are known to migrate north, including the 26 m.y. history of the southern-bounding offset of Segment E (Tucholke and Schouten, 1988).

Another popular hypothesis explaining along-axis migration of some small-offset propagators relate crack length with crack propagation driving force (e.g., Macdonald et al., 1991): a longer ridge section should lengthen at the expense of adjacent shorter sections. Our observations, however, suggest initiation of propagation near the northern discontinuity where a very short crack propagated at the expense of a longer one.

It has also been proposed that rift propagation may be due to relative motion between the spreading plate boundary and the underlying, fixed asthenosphere (Schouten et al., 1987; Tucholke and Schouten, 1988). This argument has largely been discounted because of more recent observations of discontinuities that have migrated in opposite directions along nearby portions of a plate boundary (e.g., Müller and Roest, 1992). In this area, northward migration of the Segment E/Segment A discontinuity is counter to the southward growth of the fast propagators, so a causal relation of plate boundary motion with respect to the mantle and rift propagation is unlikely here.

Changes in the direction of sea-floor spreading have coincided with rift propagation (e.g., Wilson et al., 1984; Hey et al., 1988). Despite evidence for some plate-motion change, no clear evidence exists for fast propagators associated with specific spreading-direction changes.

A significant clue to the origin of the fast propagators may be found in the residual gravity data. As noted above, the two best-developed propagators (46.3°W and 47.0°W) correlate with changes from lower to higher residual gravity anomalies (Fig. 3C). This implies that some combination of crustal thinning and/or mantle cooling occurred coevally with the initiation and migration of the fast propagators. These gravity variations are part of a set of broader spatial patterns in the residual gravity anomaly that have been interpreted as being associated with episodicity in the amount of magma supplied to the ridge (Lin et al., 1993; Tucholke et al., 1997). We infer periods of higher magma supply (corresponding to the gravity lows) to be times when plate separation was more dominated by magmatic intrusion, in contrast to periods of lower magma supply (corresponding to the gravity highs) when more of the separation was taken up by faulting (Lin et al., 1993; Tucholke et al., 1997). Thus, the fast propagators seem to have developed during transitions from more magmatic to less magmatic periods of spreading. This may reflect a causal relationship. Because such transistions require an increase in the fraction of total plate separation accommodated by tectonic extension and are associated with a reduction in melt and associated thermal cooling that may strengthen the lithosphere, it may be difficult for an entire segment to respond instantaneously. Fast propagators may represent the progressive, though rapid, along-axis tearing of the lithosphere facilitating the transition to relatively amagmatic periods. If so, the southward propagation direction may reflect a southward migration of the transition to a lower magmatic regime that presumably started at the northern edge of the segment.

CRUSTAL GEOMETRY

In light of current models (e.g., Tucholke and Lin, 1994) of asymmetric ridge-parallel faulting with master detachment faults near inside corners (between rifts and active offsets) and smaller antithetic faults near outside corners (between rifts and the inactive traces of offsets), we expect the southward-bound fast propagators growing 5–7 km east of the previous spreading axis to initially break into inside corner crust in the median valley wall on the northeast side of the doomed ridge. Although the finest details of the rifting process are beyond the resolution of the data available, this propagation into the footwall block of the detachment presumably effects an eastward stepping of the master fault in this northern section of the segment. As rifting progresses southward within the eastern median valley wall, it then propagates into segment center crust which may lack a dominant master fault (Tucholke and Lin, 1994). In such an area this additional denudation may facilitate exposure of lower crust and mantle rocks near segment centers (e.g., Cannat et al., 1992), overcoming the general prediction of Tucholke and Lin (1994) that segment centers should expose only upper crust. Finally, rifting propagates into outside corner crust of the east wall as it completes replacement of the doomed segment. During this last stage, it is rifting the hanging wall; at depth the new rifting may sole into the previous decollement, hence transferring a klippe of outside comer crust to the plate on the west. The final inside/outside corner configuration mimics the initial one (i.e., inside corner at the north and outside corner at the south on the east flank of the ridge), though the rift is now displaced several km to the east.

The small offset (5–7 km), intra–median-valley nature of the fast propagators may also help limit their along-axis extent to individual segments. Although rifting within the relatively thin lithosphere of the young median valley may be feasible, rifting of the thicker lithosphere across the larger segment-end discontinuities (typically 20–30 km) is presumably more difficult.

In addition to the 46.3°W and 47.0°W fast propagators, Figure 2 shows the locations and simplified geometry of an additional ten possible propagator traces. Although not as well developed as the two examples discussed above, and sometimes only identifiable in magnetics data, each of these features has the same type of northwest-trending oblique character suggesting an inner pseudofault complex associated with a southward propagating rift.

CONCLUSIONS

From analysis of new geophysical and morphological data from the Mid-Atlantic Ridge, we observe obliquely offset magnetic isochrons and associated bathymetric anomalies that represent the traces of fast propagating rifts at a slow-spreading ridge. The offsets between the propagating and shortening rifts is typically <10 km, and the propagation rates exceed half-spreading rates by a factor of ~2–4. The propagators transect individual rift segments rapidly, but do not extend into neighboring segments. Hypotheses relating the propagation to plate-motion changes, crack length, and along-axis topographic gradients fail to account for these features. Instead, residual gravity anomalies indicate that this propagation is due to along-axis migration of increased tectonic extension as more magmatic periods of sea-floor spreading give way to less magmatic periods.

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