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Multibeam investigation of the active North Atlantic plate boundary reorganization tip

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A B S T R A C T

The previous orthogonal ridge/transform staircase geometry south of Iceland is being progressively changed to the present continuous oblique Reykjanes Ridge spreading geometry as North America–Eurasia transform faults are successively eliminated from north to south. This reorganization is commonly interpreted as a thermal phenomenon, caused by warmer Iceland plume mantle progressively interacting with the ridge, although other diachronous seafloor spreading reorganizations are thought to result from tectonic rift propagation. New marine geophysical data covering our reinterpretation of the reorganization tip near 57°N show successive transform eliminations at a propagation velocity of ~110 km/Myr, ten times the spreading half rate, followed by abrupt reorganization slowing at the Modred transform as it was converted to a migrating non-transform offset. Neither the simple thermal model nor the simple propagating rift model appears adequate to explain the complicated plate boundary reorganization process.

1. Introduction

There have been three distinct phases of seafloor spreading along the Mid-Atlantic Ridge (MAR) south of Iceland (e.g. Vogt, 1971; Vogt and Avery, 1974; White, 1997; Smallwood and White, 2002; Jones et al., 2002; Jones, 2003; Merkuryev et al., 2009), as shown by changes in plate boundary configuration in both gravity maps (Fig. 1; Sandwell et al., 2014) and magnetic anomaly maps (Fig. 2; Macnab et al., 1995; Merkuryev et al., 2009; Merkuryev and DeMets, 2014).

Immediately after Greenland – Eurasia breakup ~55 Ma (chron 24), an initial orthogonally-spreading (Smallwood and White, 2002) ridge system without transform faults was established, forming continuous magnetic and gravity lineaments nearly parallel to the continental margins (Figs. 1–2). This pattern changed approximately synchronously ~37 Ma (chron 17; Jones, 2003) into a more typical slow-spreading orthogonal ridge/transform pattern (Fig. 2). This transition to orthogonal spreading probably resulted from the nearly instantaneous response to a change in spreading direction from ~125° to ~100°, caused by the termination of spreading on the Greenland–North America Rift as those plates became coupled together (Vogt, 1971; Vogt and Avery, 1974; Vogt and Johnson, 1975; Jones, 2003), although other mechanisms have been suggested.

Very shortly after that initial reorganization, at least by ~34 Ma (between chrons 15 and 13; Fig. 2), the most recent major reorganization of this plate boundary initiated south of Iceland and continues at present. The orthogonal North America–Eurasia ridge/transform staircase geometry is progressively changing to the present non-segmented oblique spreading geometry on the Reykjanes Ridge as transform faults are successively eliminated (Vogt, 1971; Vogt and Avery, 1974; White, 1997; Smallwood and White, 2002; Jones et al., 2002, 2014; Jones, 2003; Merkuryev et al., 2009).

Various models have been proposed for this latest reorganization. Vogt and Johnson (1975) proposed that channeled subaxial

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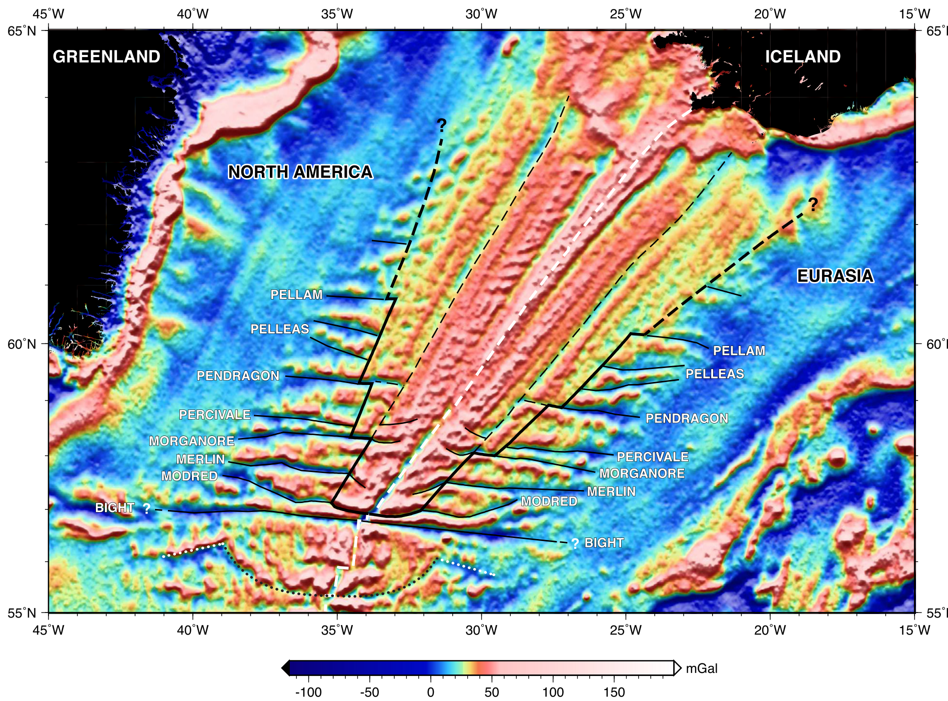

Fig. 1. Satellite gravity (Sandwell et al., 2014) and tectonic boundaries south of Iceland. White dashes approximate Reykjanes Ridge axis. Heavy black step-like V pattern is our interpreted diachronous transform elimination reorganization boundary, drawn through fracture zone (FZ) terminations and separating younger seafloor without FZs from older seafloor formed by previous orthogonal ridge/transform spreading geometry, dashed near Iceland where uncertain. Light dashed boundaries between the Pendragon and Morganore FZs show the younger reorganization wake that we interpret as the extensions of the E scarps nearer Iceland (also light dashes) formed by the Loki propagator that left Iceland 15 Ma (Benediktsdóttir et al., 2012). The old FZs formed by the transforms eliminated by the reorganization are approximately E–W black lines, names from Vogt and Avery (1974). The dashed sections of Pendragon indicate uniquely-formed sections discussed in text. The V-shaped ridges, troughs and scarps (VSRs) are the structures slightly oblique to the Reykjanes Ridge axis enclosed by the reorganization boundary, and at least south of the Pellam FZ their boundaries coincide with the reorganization boundary. Bight is the first transform fault remaining south of Iceland, Modred is now a migrating non-transform offset (NTO). Thin black V-shaped lines extending from reorganization boundaries toward the ridge axis are wakes of migrating NTOs. Black dots show pseudofault wake of an independent propagator that terminated FZ-like structures (white dots) south of Bight. All figures were made using Generic Mapping Tools (GMT; Wessel et al., 2013).

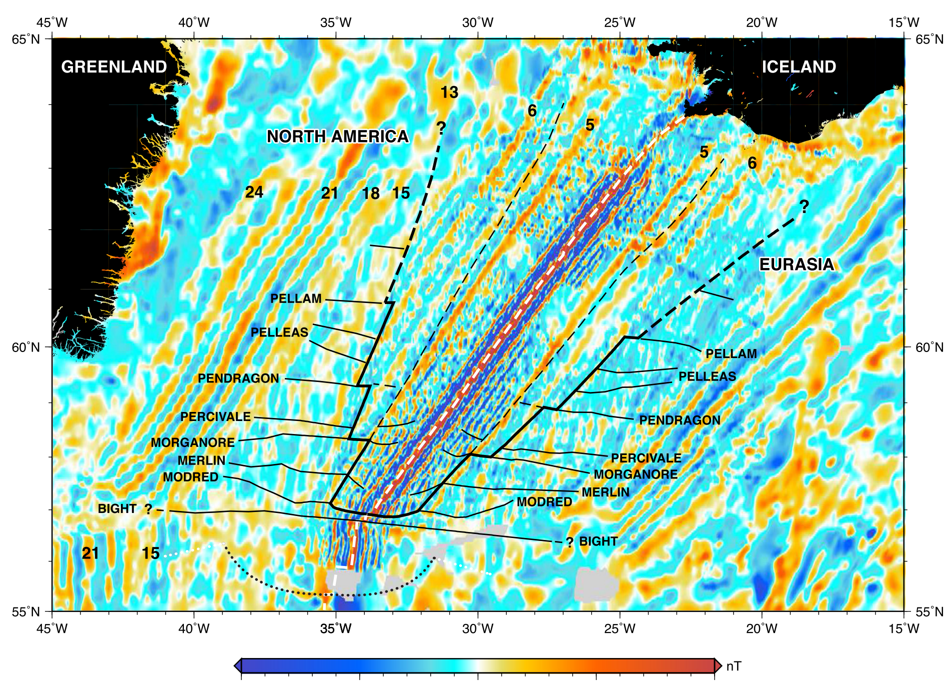

Fig. 2. Compiled magnetics data available through Geological Survey of Canada (Macnab et al., 1995) merged with RRS Charles Darwin (CD87) data (Searle et al., 1998; courtesy of Roger Searle), 2007 R/V Knorr cruise data (Hey et al., 2010) and our 2013 R/V Marcus G. Langseth towed Geometrics G-882 magnetometer data. Major chrons numbered, tectonic boundaries from Fig. 1.

asthenospheric flow (Vogt, 1971) from the Iceland hotspot follows the overall trend of the plate boundary, heating and weakening the lithosphere, progressively eliminating transform faults and rotating each ridge segment into co-linear position by Zed-type differential asymmetric spreading (Menard and Atwater, 1968). An alternative interpretation (White, 1997; Jones, 2003) agrees that the reorganization is a thermal phenomenon, but with the transform elimination boundary thought to represent a critical isotherm in the head of the Iceland plume. Above this isotherm transform faults can no longer be maintained. Alternatively, rift propagation is the accepted seafloor spreading reorganization mechanism in most other areas, with the exception of instantaneous reorganizations. Although this tectonic mechanism was briefly suggested for the Reykjanes Ridge reorganization (Johansen et al., 1984; Merkuryev et al., 1994), it was not generally accepted for several reasons, including the lack of clearly defined propagating ridge tectonic elements, and to first order there was symmetric seafloor spreading (Vine, 1966), whereas rift propagation must produce asymmetric accretion.

To determine exactly how this ongoing reorganization is occurring we conducted a marine geophysical survey surrounding our hypothesized active reorganization tip, including the northernmost transform fault remaining south of Iceland, the Bight transform (Fig. 1; Sandwell et al., 2014; Applegate and Shor, 1994), and the three most recent transform eliminations north of Bight. With the exception of a single SeaMARC II/Hydrosweep swath that revealed Bight to be a 15–17 km long transform fault (Applegate and Shor, 1994), this area had been mostly unsurveyed.

The reorganization boundaries in Figs. 1 and 2 are strongly constrained by our new data between the Morganore fracture zone (FZ) and the reorganization tip (Figs. 3–5). Unfortunately the only high-resolution data along any part of the reorganization boundaries are our new data at the tip. North of this the boundaries have been drawn in several ways. We agree with interpretations that include reorganization boundaries with offsets at various FZs (e.g. Vogt and Johnson, 1975; Merkuryev et al., 2009; Poore et al., 2009; Parnell-Turner et al., 2014), consistent with the interpretation that this reorganization had trouble getting past some transform faults (Vogt and Johnson, 1975). We appear to be in closest agreement with the Poore et al. (2009) and Parnell-Turner et al. (2014) boundaries. Our reorganization boundaries were based on the transform eliminations, and thus were constrained to go through our interpretations of the terminations of the ∼E–W FZ structures as shown by satellite gravity data (Fig. 1; Sandwell et al., 2014). These eliminations take some time and thus space, so the exact locations of the FZ terminations are open to interpretation. We think our interpretations (Figs. 1–2) are reasonable, and think it significant that narrow straight lines drawn between these points, with step-like offsets at the Pellam, Pendragon, and Morganore FZs (all FZ names are from Vogt and Avery, 1974), appear to be the boundaries enclosing all of the oblique gravity structures corresponding to the diachronous V-shaped ridges, troughs and scarps (VSRs) flanking the Reykjanes Ridge (Vogt, 1971). Fig. 2 shows that these simple straight-line reorganization boundaries interpreted from the gravity data provide a good overall fit to the regional magnetic anomaly pattern, separating younger oblique from older orthogonal patterns, and that the reorganization boundaries are the same ages at conjugate positions, as required. If these boundaries were known exactly the reorganization history would be precisely defined, but to the extent they remain interpretive different reorganization models remain possible. For example, if the boundaries were U-shaped they would indicate progressive reorganization slowing and would be consistent with radial plume flow models (Vogt, 1971).

2. Thermal model for Reykjanes Ridge reorganization

The generally accepted model (White, 1997; Jones, 2003) proposes that this ongoing transform-eliminating reorganization results from a thermally induced change in lithospheric behavior from the previous brittle rheology, producing the orthogonal ridge/transform fault pattern, to a ductile rheology producing the oblique unsegmented ridge pattern. The change from brittle to ductile behavior occurs as a critical plume head isotherm (∼50°–80 °C warmer than normal; Jones, 2003) progressively interacts with the ridge segments, reorganizing the geometry from orthogonal to oblique. White (1997) concluded that the Reykjanes Ridge patterns show that there is a delicate thermal balance between the spreading rate and crustal cooling rate that determines whether there is a ductile or brittle response to the lithospheric extension, and that the normal slow-spreading pattern of orthogonal spreading, transform faults, and axial valleys (e.g. Macdonald, 1982) is easily perturbed to the much different highly oblique pattern without transform faults, fracture zones or an axial valley. Seismic, geochemical and modeling results have been interpreted as consistent with this model, (White, 1997; Smallwood and White, 2002; Jones, 2003). Although this is the only area where this is the generally accepted reorganization mechanism, some studies have concluded that Iceland is the most vigorous plume (Poore et al., 2009; Parnell-Turner et al., 2014; Jones et al., 2014), and the Reykjanes Ridge is a unique mid-ocean ridge, arguably the most hotspot-influenced ridge.

White (1997) and Jones (2003) thought that the limit of the transform fault eliminations was coincident with the transition from axial ridge to axial valley, supporting a thermal model, as both of these phenomena were thought to coincide with the onset of ductile behavior at the reorganization tip, near 58°N. However, modern data show there is actually ∼200 km between the transition from axial high to axial valley (58.8°N, Keeton et al., 1997) and the most recent transform fault elimination near 57°N (Fig. 1; Sandwell et al., 2014), weakening this argument.

3. Too-simple tectonic model for Reykjanes Ridge reorganization

Many seafloor spreading reorganizations are accomplished by rift propagation, often away from hotspots, in which a new rift breaks through existing lithosphere and replaces a preexisting ridge that has a different, less-favorable geometry. This model predicts that the transform faults were eliminated by propagating rifts, and thus that the fracture zone terminations should coincide with either pseudofaults or failed rifts (Hey and Wilson, 1982). On the plate the propagator breaks through these would be relatively narrow and simple outer pseudofaults, whereas on the other plate they would be wider and more complex inner pseudofaults that include the failed rifts and lithosphere transferred by the rift propagation (Hey et al., 1986; Kleinrock and Hey, 1989; Kleinrock et al., 1989). The V-shaped pseudofault reorganization wakes show the propagation velocities, and are straight (great circles) when both propagation and spreading rates are constant.

Although progressive seafloor spreading reorganizations commonly occur this way (e.g. Juan de Fuca, Hey and Wilson, 1982; Northeast Pacific, Atwater, 1989; Galapagos, Wilson and Hey, 1995; Southern MAR, Southeast Indian Ridge, Pacific–Antarctic Ridge and Chile Rise, Phipps Morgan and Sandwell, 1994), there are significant differences between those other reorganizations (which occur at faster spreading rates) and the Reykjanes Ridge reorganization. In typical rift propagation a more orthogonally-spreading ridge propagates through preexisting lithosphere to replace a more obliquely-spreading axis, often following a change in plate motion. Here it is the obliquely-spreading ridge replacing the orthogonal one, and there is no indication that plate motion has changed significantly during the past 35 Ma. The other major difference is that along the Reykjanes Ridge the propagators and ridge jumps proposed have generally been small-offset, usually 7 km or less, within the ∼15 km wide plate boundary zone,

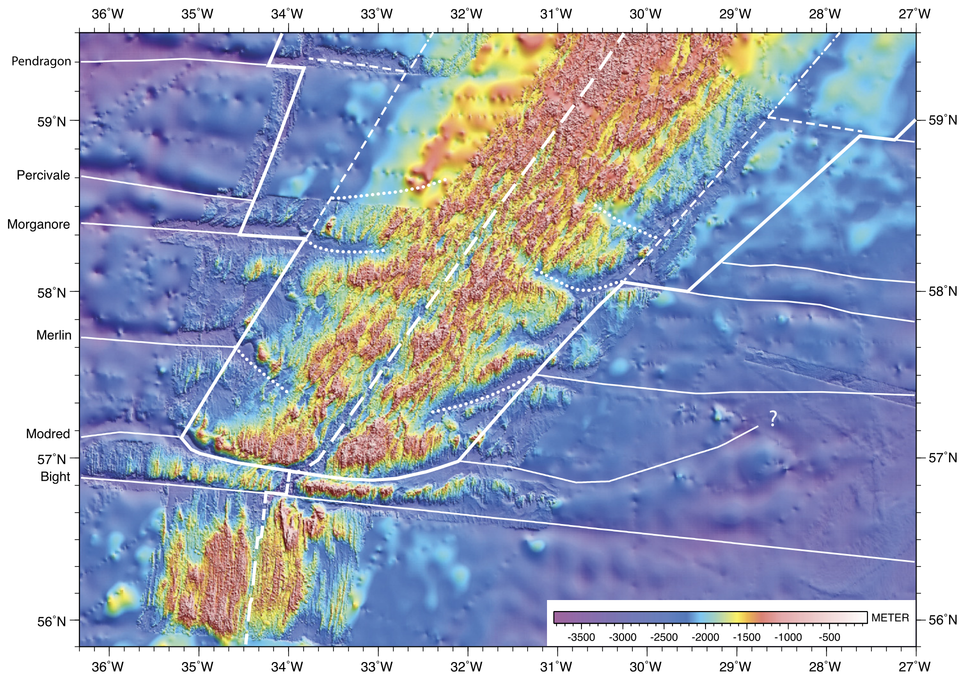

Fig. 3. New hull-mounted Simrad EM122 1° × 1° 12 kHz multibeam echo sounder bathymetry collected on R/V Marcus G. Langseth in 2013, combined with British Simrad EM12 multibeam data (Keeton et al., 1997) along and east of the axis north of ∼58.5°N (the Percivale FZ), surrounded by predicted bathymetry from Smith and Sandwell (1997). Heavy white step-like transform-eliminating reorganization boundaries based on FZ terminations as in Fig. 1, dashed where they extend from the youngest Pendragon FZ terminations to the Morganore FZ terminations, dashed-dot lines north of Pendragon are E scarps from Fig. 1. FZs (thin white lines) and NTO wakes (dotted white lines) as in Fig. 1. Thick white dashed lines are simplified spreading axes. Note en-echelon trough along oversimplified reorganization boundary on North America near 34°W between Percivale FZ termination and Pendragon FZ discontinuity, consistent with failed rift graben interpretation.

generally assumed to be characterized by non-rigid plate behavior (e.g. Macdonald, 1982), in contrast to classic propagators that break through rigid plates well outside the plate boundary zone.

The small Reykjanes Ridge jumps modeled magnetically (Hey et al., 2010; Benediktsdóttir et al., 2012) occur in patterns consistent with rift propagation. They predict lithospheric transfer that explains the observed pattern of progressively developed asymmetric accretion, with more seafloor added to North America than Eurasia, most obvious near Iceland (Fig. 2). Furthermore, many of the modeled failed rifts correspond to gravity troughs and many of the modeled pseudofaults correspond to VSR scarps. For example Vogt's (1971) VSR "E scarps" (Fig. 1) correspond to the predicted pseudofault wakes of Benediktsdóttir et al.'s (2012) proposed "Loki propagator", interpreted from the systematically younger ridge jumps from north to south away from Iceland (see their Fig. 9). Those observations are consistent with small-scale rift propagation, although there are no obvious zones of transferred lithosphere with the characteristic structural patterns observed elsewhere, possibly because the jumps are so small. Briais and Rabinowicz (2002) and Rabinowicz and Briais (2002) proposed a similar model in which migration of 2nd-order ridge offsets could produce the VSRs. Such migration is usually thought to result from propagation of second-order ridge segments separated by non-transform offsets (NTOs) (e.g. Macdonald et al., 1988; Carbotte et al., 1991; Grindlay et al., 1991; Cormier and Macdonald, 1994).

In typical large-scale propagating rift areas the reorganizations are usually accomplished by simple propagation without the involvement of significant NTO migration. This scale of propagation appears to be common along the southern Reykjanes Ridge, as indicated by northeast- and southwest-pointing broad V-shaped (or U-shaped) trough wakes with azimuths much different from the major southwest-pointing VSRs (Figs. 1–4), indicating much slower propagation velocities.

4. New results

Our 33-day marine geophysical survey was conducted in August–September 2013 on the R/V Marcus G. Langseth. The new EM122 multibeam data (Fig. 3), together with shipboard and satellite-derived free-air gravity data (Fig. 4), show a monotonic sequence of FZ terminations from north to south of the Pendragon, Morganore, Merlin and Modred FZs. This survey, combined with previous data (Keeton et al., 1997; Searle et al., 1998; E. Kjartansson, pers. comm., 2007; Höskuldsson et al., 2007; Hey et al., 2010), completes the multibeam mapping of the oblique Reykjanes Ridge axis and shows definitively that transform faults no longer exist between the Bight transform and Iceland. Just north of the Bight transform, the Modred transform has evolved to a NTO (Fig. 5), and then there is a continuous oblique ridge axis without transform offsets connecting with the Reykjanes Peninsula rifting on Iceland (Fig. 1). South of the Bight transform there are numerous MAR transform faults and orthogonal seafloor spreading (Sandwell et al., 2014). This is the pattern expected if the transform-eliminating reorganization tip is presently at the Modred NTO near 57°N, just north of the Bight transform, rather than in the areas farther northeast proposed in several alternative interpretations (e.g. White, 1997; Smallwood and White, 2002; Jones, 2003; Parnell-Turner et al., 2014).

The EM122 backscatter data (Fig. 5) show that the oblique Reykjanes Ridge axis (high backscatter) north of Modred curves to overlap with the tip of the still orthogonally-spreading axis between the Modred NTO and the Bight transform. There is no transform fault at the Modred offset at present, but rather an ∼10 km long NTO between curving overlapping ridge segments, as seen at overlapping spreading centers elsewhere (e.g. Macdonald et al., 1984, 1988). The pattern of curved faults extending away from the overlap zone shows there has been a long-term history of the curvature of the axes toward each other. The backscatter data show a more oblique pattern north of Bight than the fine-scale

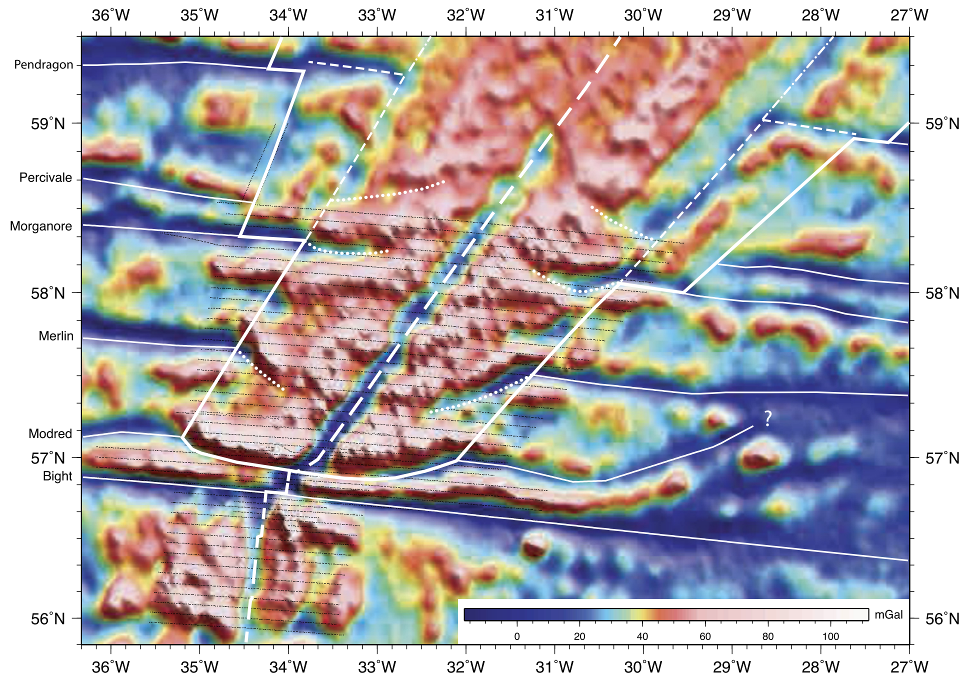

Fig. 4. R/V Langseth free-air gravity data from a Bell BGM-3 gravimeter (ship tracks shown by fine dotted black lines, dots indicate positions of gravity measurements used) merged with satellite-derived gravity (Sandwell et al., 2014) outside mosaic survey area. Tectonic boundaries as in Fig. 3.

bathymetry, suggesting the Bight–Modred ridge segment may be reorienting at present. There is no clear evidence for pseudofaults, failed rifts, or zones of transferred lithosphere predicted by the propagating rift model or for Zed-type ridge rotations by differential asymmetric spreading (Menard and Atwater, 1968) predicted by the Vogt and Johnson (1975) thermal model.

Although the exact locations of the terminations of the ∼E–W FZs are somewhat interpretive, narrow straight-line reorganization boundaries can be drawn through reasonable places (Figs. 3–4). Our new multibeam mosaic between ∼58.5°N and ∼56°N covers the elimination of the Morganore, Merlin and Modred transforms on both plates, and the Percivale transform elimination on North America. It includes the Bight transform/FZ system and the first orthogonally-spreading ridge segment south of the Bight transform. The young reorganization boundaries extending to the reorganization tip are thus strongly constrained. In addition, a brief survey of the Pendragon FZ termination on North America during our transit helps constrain the older reorganization history. On Eurasia, the Pendragon elimination is partly constrained by RRS Charles Darwin Simrad multibeam data (Fig. 3; Keeton et al., 1997; Searle et al., 1998), and by gravity data (Fig. 4; Sandwell et al., 2014).

The terminations of the Pendragon, Morganore, Merlin and Modred FZs are essentially co-linear (Figs. 3–4). The spreading half rate (∼11 km/Myr, Merkuryev and DeMets, 2014) and ∼11° angle subtended by these reorganization boundaries suggest that the transform-elimination reorganization propagated through our mosaic survey area at a constant velocity of ∼110 km/Myr until it intersected the Modred transform, where propagation abruptly slowed and the transform offset was converted into the very slowly southward-migrating NTO that exists today at the reorganization tip (Fig. 5).

Notably, these latest transform-elimination boundaries occur along essentially linear extensions of the VSR E scarps (dashed lines between Pendragon and the Iceland shelf in Fig. 1; dashed-dot lines north of Pendragon in Figs. 3–4) discovered by Vogt (1971). The E scarps and other VSRs were originally thought to be symmetric plume pulse wakes (Vogt, 1971; White, 1997), but later were shown to be asymmetric (Jones et al., 2002; Hey et al., 2010) and have been interpreted as ridge jump boundary pseudofaults by Hey et al. (2010) and Benediktsdóttir et al. (2012) based on detailed magnetic modeling between 62°N and Iceland. The direct linkage of the FZ terminations near the reorganization tip with the E scarps suggests that the Pendragon, Morganore, Merlin and Modred transform eliminations and the E-scarp VSR formation involved the same process, whatever that may be.

The transform-elimination process led to distinctive non-flowline broad V-shaped gravity and bathymetry troughs continuing southwest (at least initially) from the Morganore, Merlin and Modred FZ terminations, and from what appears to be an unnamed FZ between Morganore and Merlin, that become lower-amplitude approaching the axis (dotted lines in Figs. 3–4). These have considerably different azimuths from the ∼E–W flowline FZ troughs, and from the VSR troughs closer to Iceland that subtend much more acute angles (Fig. 1). We interpret these as wakes of slowly migrating NTOs that evolved from the transform/FZ troughs. They are analogous to V-shaped pseudofault troughs characteristic of propagator wakes documented where the ridge jumps are bigger and the magnetic anomalies are easier to understand (e.g. Wilson and Hey, 1995; Kruse et al., 2000; Marjanovic et al., 2011). Here they develop when the ridge offsets are of the same order as the width of the plate boundary zone, so distinct rift propagation structures such as failed rifts and transferred lithosphere are generally not clearly defined (although a small asymmetry characteristic of rift propagation is discernable). Such structures are not explained by current thermal models, and incompletely explained by the simple propagating rift model, which predicts that a distinct failed rift or pseudofault graben should exist at each FZ termination. There is an en-echelon trough near 34°W that extends ∼80 km from a Pendragon FZ discontinuity to the Percivale FZ termination, seen in two overlapping multibeam swaths collected on our transit to and from the mosaic area (Fig. 3), that could be a failed rift. This trough appears to be structural, with two ∼40 km long fault-bounded grabens trending ∼N–S connected by a short (∼10 km) E–W FZ-type offset near 59°N. Similar offset graben structures characterize the Galapagos 95.5°W failed rifts

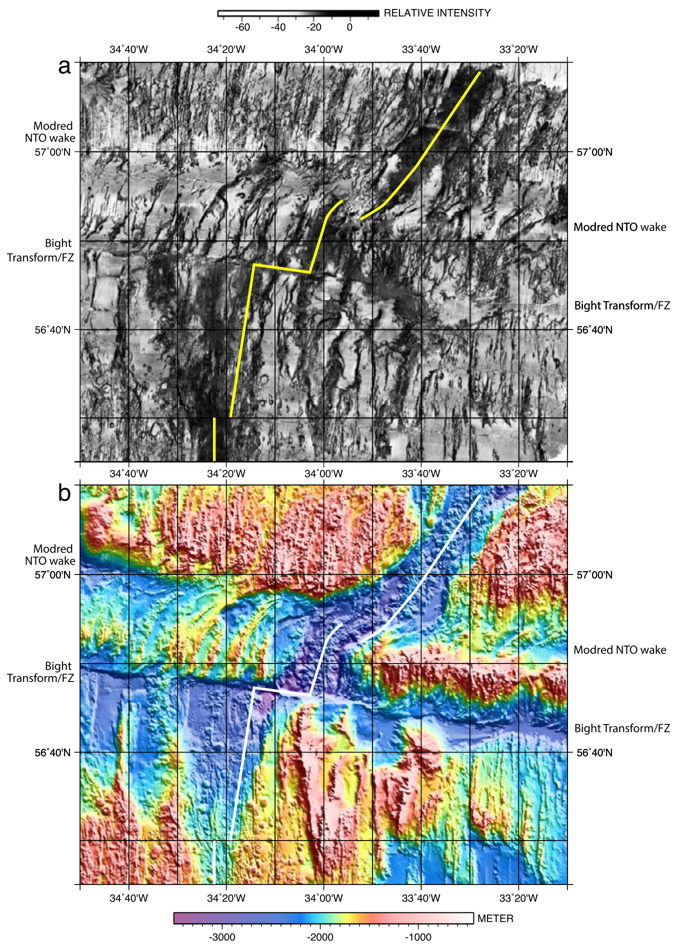

Fig. 5. (a) R/V Langseth EM122 acoustic backscatter mosaic over reorganization tip, derived from the sonar beam amplitudes. There are ∼12 flowline-parallel swaths, ∼7–8 km wide, with track-parallel artifacts where they join. High relative intensities are dark, generally correlating with areas of relatively unsedimented young volcanism. Yellow lines show approximate center of most recent axial volcanism. The complicated pattern of young volcanism south of Bight results from very recent ridge jumps toward the east, shortening the transform (Á. Benediktsdóttir et al., manuscript in preparation, 2015). The Modred NTO near 56°53′N, 33°55′W, separates the oblique Reykjanes Ridge from the non-oblique ridge segment between Modred and Bight. It has an overlapping spreading geometry at present (and for the past several Ma, during which the offset migrated slowly south). The linear Bight transform fault offsets orthogonally-spreading ridge segments near 56°47′N, 34°10′W. It trends ∼099°, slightly greater than predicted by the latest plate motion models (e.g. Merkuryev and DeMets, 2014). (b) R/V Langseth EM122 multibeam bathymetry over same area, showing axial graben pattern, Bight transform fault stability and Modred NTO migration wake.

(Hey et al., 1986; Kleinrock et al., 1989) and are predicted by the propagating rift model to occur as part of an inner pseudofault zone at FZ terminations (Hey and Wilson, 1982). We are unable to think of an alternative explanation for this graben pattern, but the magnetic anomalies are too complicated for confident interpretation.

The southward-pointing troughs at the FZ terminations have different azimuths than the overall reorganization wake (Figs. 3–4), implying different propagation velocities. This suggests that these transform fault offsets evolved into southward-migrating NTOs that migrated more slowly than the large-scale reorganization, lagging well behind the reorganization tip. This is a much different pattern than in large-scale propagating rift systems at faster spreading rates, where the transform offsets migrate with the reorganization tips (e.g. Hey and Wilson, 1982; Caress et al., 1988; Wilson and Hey, 1995).

There appears to have been significant NTO migration here in both directions along axis (Figs. 1–4), which although common elsewhere on the MAR (e.g. Carbotte et al., 1991; Michael et al., 1994; Weiland et al., 1995; Gente et al., 1995; Briais and Rabinowicz, 2002) has generally not been observed in large-scale propagating rift reorganizations (although those authors generally interpret the NTO migration they documented to result from small-scale rift propagation). The pattern here resembles the Macdonald et al. (1984) overlapping spreading center propagation model that results in a progressive reconfiguration of an existing plate boundary rather than an entirely new plate boundary. This process is similar to that described by Michael et al. (1994) and Weiland et al. (1995) farther south along the MAR, and attributed by them to second-order ridge segment propagation within a first-order ridge segment. On the Reykjanes Ridge the reorganization process is more systematic and progressive across first order ridge segment boundaries, eliminating transform faults.

5. Tectonic evolution

We used our interpreted FZ termination geometry (Figs. 3–4) and the North America–Eurasia spreading rates predicted from the Merkuryev and DeMets (2014) plate motion model to calculate the ages of the recent transform eliminations we mapped. After a complicated history discussed below, Pendragon was finally eliminated ∼11 Ma (∼C5n.2o, using the Hilgen et al., 2012 timescale). The reorganization then extended southwest into and through our survey mosaic area (Figs. 3–4) at a constant recent along-ridge reorganization propagation velocity of ∼110 km/Myr, ten times the spreading half rate, reaching and eliminating the Morganore transform ∼10 Ma (∼C5n.1y), the Merlin transform ∼9 Ma (∼C4Ao), and changing the Modred transform to a very slowly migrating NTO ∼8.5 Ma (∼C4Ay). The Merkuryev and DeMets (2014) models with and without outward reversal boundary displacement are somewhat different, and exact FZ termination points are uncertain, suggesting age uncertainties of ∼1 Ma in our estimates.

A propagation velocity an order of magnitude faster than the spreading half rate is a much higher ratio than in most propagating rift areas, but is about the same ratio documented by Cormier and Macdonald (1994) for small-offset propagators along the superfast-spreading Pacific–Nazca Ridge. In the thermal model, these transform eliminations would have been accomplished by a critical plume isotherm interacting with the axis at this rapid constant along-axis velocity before abruptly slowing at Modred.

Since the reorganization slowing at Modred at ∼8.5 Ma, the reorganization wakes show that the axial offset has only been moved south ∼20 km, implying very slow recent migration of this NTO. The reorganization slowing at Modred cannot be the U-shaped reorganization tip predicted by radial plume expansion because that kind of predicted curvature must show continuous $1/r$ slowing away from the hotspot (Vogt, 1971), not the observed abrupt change to a much slower reorganization velocity (Figs. 3, 4).

The gravity and magnetics data (Figs. 1, 2) suggest that between pauses at FZs the reorganization boundaries generally coincide with the time-transgressive VSR boundaries (Poore et al., 2009; Parnell-Turner et al., 2014). The reorganization boundaries appear to be coincident with VSRs between Pellam and Pendragon, and then following a pause, between Pendragon and Morganore. From Morganore south the reorganization boundaries are defined by the FZ terminations (Figs. 3–4).

The reorganization boundaries in Figs. 1 and 2 are consistent with the following diachronous reorganization history. Beginning ∼34 Ma, the orthogonally-spreading North America–Eurasia ridge/transform staircase system began to be eliminated. From ∼30 Ma to ∼22 Ma the average reorganization velocity was ∼50 km/Myr, based on the angles subtended by the boundaries.

The reorganization wakes are asymmetric, farther from the axis on North America than Eurasia, so some asymmetry-producing mechanism was involved. At ∼22 Ma (∼C6Bo) the reorganization appears to have temporarily stopped at the Pellam transform fault, where oblique ridge-parallel magnetic anomalies are truncated by the FZ (Figs. 1–2). This propagation pause lasted ∼2 Ma, during which time the Pellam FZ continued to form at the temporarily non-propagating ridge-ridge transform. Continuous reorganization resumed ∼20 Ma (∼C6no), moving southwest at a constant velocity of ∼60 km/Myr past the Pellam FZ. It then eliminated two more transforms (Pelleas north and south strands, Vogt and Avery, 1974) before reaching the Pendragon transform ∼18 Ma (∼C5Ey) where there was another long reorganization pause, lasting at least until ∼15 Ma (∼C5ADo).

The next stage in the evolution is less clear. There is evidence that at ∼15 Ma the reorganization extended past Pendragon at ∼60 km/Myr, eliminating the Percivale transform ∼13.5 Ma (∼C5ACy), and reaching the Morganore transform where the reorganization paused again ∼13 Ma (∼C5AAy). This evidence includes oblique ridge-parallel magnetic anomalies and VSR-parallel structures seen in gravity south of Pendragon, between the solid (older) and dashed (younger) reorganization boundaries in Figs. 1 and 2. It also includes the narrow en echelon offset structural trough near 34°W, most likely a failed rift graben, that connects an ∼15 Ma structural discontinuity along the Pendragon FZ to the Percivale FZ termination (Fig. 3). If Percivale had been eliminated independently from the major reorganization all of these observations would lack explanations.

However, there was still some kind of Pendragon feature extending east of the structural discontinuity after 15 Ma, when the reorganization appears to have extended southwest past Pendragon, so this interpretation requires that the youngest sections of Pendragon, formed between ∼15–11 Ma (dashed FZ sections in Figs. 1–4), were created differently than the older (solid) sections that formed during the ∼18–15 Ma pause at the Pendragon transform. This would explain why at ∼15 Ma the Pendragon depth, position and azimuth change slightly, seen most clearly on North America near 59°20′N, 33°50′W (Fig. 3). One possibility is that after the reorganization continued south past it, Pendragon was reestablished as some sort of 2nd or 3rd order offset with a slightly different geometry, possibly a very slowly migrating NTO, even slower than the present Modred NTO migration, or even a zero-offset fracture zone (Schouten and White, 1980), consistent with the lack of significant magnetic anomaly offsets along this section (Fig. 2).

Whatever the details of the earlier history, Pendragon was finally eliminated ∼11 Ma, Morganore ∼10 Ma, Merlin ∼9 Ma, and Modred was changed to a NTO ∼8.5 Ma, as discussed previously.

6. Discussion

The Pendragon, Morganore, Merlin and Modred transform-elimination ages are consistent with the times when the Loki propagator identified near Iceland would have intersected these transforms if it continued propagating southwest away from Iceland at a constant velocity of ∼110–120 km/Myr following initial more rapid propagation as it left Iceland ∼15 Ma (Benediktsdóttir et al., 2012). In this interpretation, the E scarps (dashed boundaries in Figs. 1 and 2 between Pendragon and Iceland) that are linear extensions of these transform eliminations would be pseudofault wakes, whatever else they might be (in the thermal interpretation the E-scarp VSRs would have formed from plume pulses and their asymmetry would require an additional mechanism such as rift propagation, suggesting possible hybrid models, e.g. Hey et al., 2010). The asymmetry of the reorganization boundaries, V-shaped structural troughs extending from the fracture zone eliminations, possible failed rift-type grabens connecting the Pendragon FZ discontinuity and the Percivale FZ termination, and numerous NTO migrations, also suggest that rift propagation was involved in this reorganization.

However, it appears that this propagation must be significantly different than in other areas, and appears to be occurring on several different scales, including regional scale (with "pseudofaults" expressed as VSR boundaries), and local scale (with "pseudofaults" expressed as migrating NTO wakes). This suggests possible different driving mechanisms, with the large-scale propagation driven by the regional bathymetric gradient away from Iceland (e.g. Phipps Morgan and Parmentier, 1985) and the small-scale propagation driven by local extension of magmatically robust spreading segments (e.g. Macdonald et al., 1988; Michael et al., 1994; Weiland et al., 1995; Gente et al., 1995; Briais and Rabinowicz, 2002; Rabinowicz and Briais, 2002). Additionally, here the axial shifts are smaller, the plate boundary zone is wider, and the numerous transform faults offer more resistance than in faster-spreading areas.

Perhaps the reorganization stopped or slowed at the Pellam, Pendragon, Morganore, and Modred offsets because the thicker lithosphere produced greater resistive stresses or "transform damming" (Vogt and Johnson, 1975) across those transforms. Why the reorganization slowed at Modred instead of pausing is unknown, although Modred had an earlier NTO history (Figs. 1–4) and probably a relatively small offset. Another possibility is that better data over the older apparent reorganization pauses would show similar behavior. The offsets on each of the transforms where the reorganization paused were ∼40–45 km (Fig. 2), yet the Pelleas transforms apparently had similar offsets that appear not to have halted the propagation. Each reorganization pause lasted until the transform offset became ∼20–25 km (Fig. 2) and the reorganization was able to extend past it. Note that this is about the minimum offset of northern MAR transform faults, with shorter offsets forming NTOs (e.g. Searle and Laughton, 1977). Interestingly, the Bight transform offset has recently been shortened by ∼20 km by ridge propagations and possibly some discrete jumps transferring lithosphere to North America (Á. Benediktsdóttir et al., manuscript in preparation, 2015), suggesting the previously eliminated transforms could have been shortened the same way. In the South Atlantic, Grindlay et al. (1991) and Carbotte et al. (1991) showed that the Moore transform fault near 26.5°S was shortened by asymmetric spreading or small unresolved ridge jumps until that offset became ∼15 km at ∼3 Ma, at which point ridge propagation across it changed the transform to a NTO, similar to our hypothesized transform eliminations. The Moore FZ/NTO wake geometry (Fig. 3 of Grindlay et al., 1991) is very similar to the Modred FZ/NTO wake geometry and we interpret the evolution the same way.

We anticipate that the reorganization will eventually eliminate the Modred offset. Whether it will also eliminate the Bight transform, as suggested by the recent Bight shortening, is uncertain. The Bight FZ extends west into a significant plate tectonic boundary, the large-scale magnetic bight in the North Atlantic (Vogt, 1971; Vogt and Avery, 1974). The pre-37 Ma (C17) magnetic anomalies to the north trend NE–SW, parallel to the Greenland continental margin, while those to the south trend N–S, parallel to the MAR axis farther south (Fig. 2). From the time that seafloor spreading was initiated north of the Bight transform between Greenland and Eurasia, ∼55 Ma (C24), until seafloor spreading ceased between Greenland and North America ∼37 Ma (C17), this magnetic bight marked the trace of the North America–Eurasia–Greenland triple junction. There would be an essentially continuous connection in the gravity signal between the North America–Greenland failed rift (the gravity trough near 57°N, 45°W) and the Bight FZ if the Bight steps ∼20 km south at the question mark near its western end in Fig. 1 (Sandwell et al., 2014). This suggests the Bight transform has been an important North Atlantic plate boundary for at least 37 Ma, and thus that there is a reason why a plate boundary here is favored, probably related to the initial North Atlantic rifting pattern and evolution of this transform from the triple junction (Vogt, 1971; Vogt and Avery, 1974). In this case we would expect the reorganization to stop at the Bight transform.

White and Lovell (1997) and Jones et al. (2014) have proposed that the VSR pattern extends well south of the Bight transform. However, our multibeam mosaic data show transform-orthogonal abyssal hill structures south of the Bight with no indication of oblique VSRs extending into this area (Fig. 3). We think that the structures south of the Bight interpreted by White and Lovell (1997) to indicate dramatic VSR curvature and $1/r$ radial flow slowing at a reorganization tip near 55°N (black dots in Fig. 1) are instead pseudofaults from an independent propagator, not part of the oblique Reykjanes reorganization, similar to several other independent propagators identified farther south along the MAR (e.g. Carbotte et al., 1991; Grindlay et al., 1991; Gente et al., 1995; Dannowski et al., 2011). That propagator, with another possibly following behind, appears to have been slowly propagating south for ∼20 Ma after eliminating a northward-migrating NTO near 56°N (white dots in Fig. 1). Some of the eliminated transforms north of the Bight, e.g. Pelleas and Modred, show similar non-flowline complexities, indicating that they were not always stable transform faults but instead that some form of slow rift propagation had caused slow migration of those offsets at various times (Figs. 1–2).

The transform eliminations and VSR formations appear to result from the same process. A comprehensive reorganization model must explain not only how the non-flowline troughs are produced as the transforms are eliminated, the asymmetric seafloor accretion pattern, and the greater crustal thicknesses (Smallwood et al., 1995) and lower incompatible trace element concentrations (Jones et al., 2014) of the V-shaped ridges than the V-shaped troughs, but also how all of the reorganization process could propagate at a very constant velocity, with occasional pauses, for 1000 km from Iceland. None of the current models explains all of the observations. The observation that the reorganization has been stopped or greatly slowed by transform offsets appears to be incompatible with models in which deep plume flow under a thick viscous dehydration layer (invoked to prevent otherwise unrealistic crustal thicknesses predicted by the inferred fast plume upwelling; Ito, 2001) causes the reorganization (Jones et al., 2002), because such deep plume flow presumably would not be affected by lithospheric transform offsets. The broad V-shaped troughs extending away from the recent FZ terminations (Figs. 3–4) are more compatible with propagating rift than thermal models, and suggest that NTO formation and migration are an important part of the reorganization process. The propagating rift model does not provide an obvious explanation for the incompatible trace element pattern (Jones et al., 2014). Neither the propagating rift model nor the thermal model provides an obvious explanation for the Reykjanes Ridge obliquity. Martinez et al. (2015) show that the present Reykjanes Ridge axis, reconstructed by the Smallwood and White (2002) Greenland–Eurasia finite rotations, is nearly exactly congruent with the magnetic anomalies formed just after Greenland–Eurasia breakup, strongly suggesting that the reorganization is reestablishing the original continental margin-parallel seafloor spreading geometry, and have proposed a speculative model involving buoyant mantle upwelling propagating under the spreading axis that may ultimately prove successful.

7. Conclusions

There is a regional diachronous reorganization of the North Atlantic seafloor spreading geometry occurring at present. The previous orthogonal North America–Eurasia ridge/transform staircase geometry is being progressively changed to the non-segmented oblique spreading geometry on the Reykjanes Ridge as transform faults are successively eliminated. New marine geophysical data over the reorganization tip boundaries reveal the recent reorganization history and indicate that neither the simple thermal model nor the simple propagating rift model explains all of the observations. The V-shaped structures extending away from the FZ terminations are not predicted by simple thermal models. Similar structures are predicted by propagating rift models but characteristic structures observed in other propagating rift reorganization areas are not clearly expressed here.

Our new data show rapid sequential eliminations of the Pendragon, Morganore and Merlin transform faults followed by abrupt reorganization slowing at Modred as that transform was converted to a slowly-migrating NTO. The youngest FZ terminations occur along linear extensions of the VSR E scarps discovered by Vogt (1971) and interpreted by Benediktsdóttir et al. (2012) as pseudofault wakes of the Loki propagator that left Iceland ∼15 Ma. The transform eliminations are thus linked to the propagation of both ridge axes and VSRs.

The data suggest the following reorganization history. Beginning ∼34 Ma an obliquely-spreading Reykjanes Ridge axis began extending southwest from Iceland at ∼50 km/Myr. At ∼22 Ma the reorganization temporarily stopped at the Pellam transform fault for ∼2 Ma. Continuous reorganization resumed ∼20 Ma at a velocity of ∼60 km/Myr, extending past Pellam to Pendragon and eliminating the Pelleas north and south transforms (or NTOs). There was then a long reorganization pause at the Pendragon transform beginning ∼18 Ma. In our preferred model continued reorganization at ∼60 km/Myr eliminated Pendragon ∼15 Ma and then Percivale ∼13.5 Ma, but then paused at the Morganore transform ∼13 Ma, with the youngest sections of Pendragon formed as a very slowly migrating NTO or zero-offset FZ. Subsequent reorganization caused by the Loki propagator then eliminated Pendragon ∼11 Ma, Morganore ∼10 Ma, and Merlin ∼9 Ma at an approximately constant along-ridge velocity of ∼110 Myr, before slowing at Modred ∼8.5 Ma. The Modred NTO is the present location of the reorganization tip. No transform faults exist between there and Iceland.

Between pauses at FZs the diachronous reorganization boundaries appear to be straight instead of curved in the way that radially expanding plume-ridge interaction would predict. We see no structural evidence that the VSRs extend south past the Bight transform.

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