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Propagating rift model for the V-shaped ridges south of Iceland

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[1] We present new marine geophysical data which constrain the seafloor spreading history of the Reykjanes Ridge near Iceland and the origin of its flanking V-shaped topographic and gravity ridges. Contrary to the geometry assumed in pulsing plume models, the V-shaped ridges are not symmetric about the Reykjanes Ridge axis, and seafloor spreading has not been symmetric about a stable axis. Thus, existing models must at least be modified to include an additional asymmetry-producing mechanism; the best understood and documented such mechanism is rift propagation. One possibility is that plume pulses drive the propagators. However, rift propagation also produces V-shaped wakes with crustal thickness variations, suggesting the possibility that a pulsing Iceland plume might not be necessary to explain the Reykjanes V-shaped ridges, scarps, and troughs.

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1. Introduction

[2] The diachronous topographic and gravity V-shaped ridges, scarps and troughs flanking the Mid-Atlantic (Reykjanes) Ridge south of Iceland (Figure 1), commonly called V-shaped ridges (VSRs), are generally considered strong evidence for a pulsing mantle plume [*Vogt*, 1971]. They clearly show that something in the plume-ridge system has varied, and as the Reykjanes Ridge was thought to be symmetrically spreading in a stable geometry [*Vine*, 1966, 1968; *Talwani et al.*, 1971;

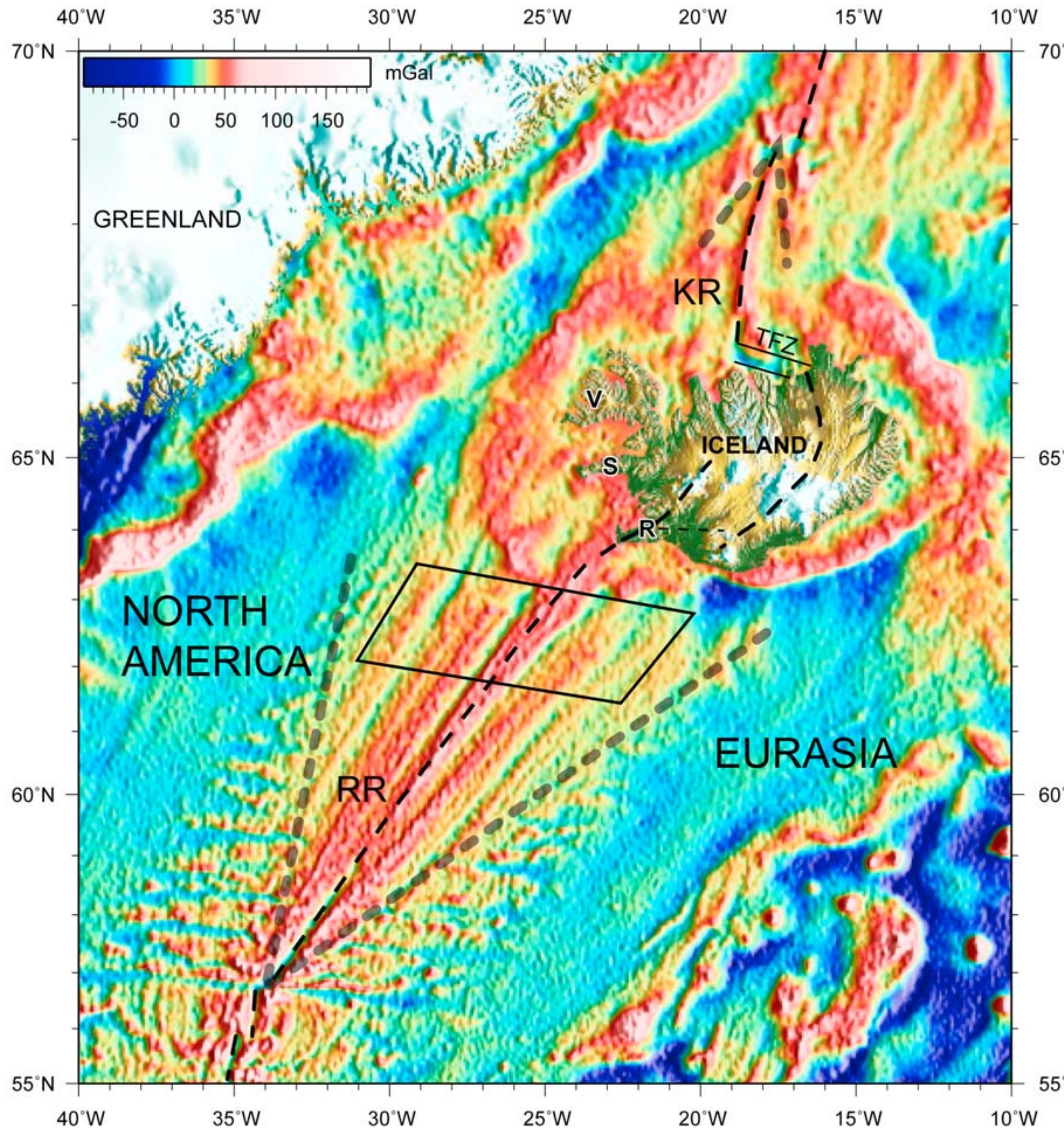

Figure 1. Satellite gravity and tectonic boundaries near Iceland [*Sandwell and Smith*, 2009] with gridded land topography superimposed. Heavy black dashes show Reykjanes Ridge (RR), Kolbeinsey Ridge (KR), and their extensions through Iceland. The VSRs we reinterpret here are the ridges and troughs slightly oblique to the Reykjanes Ridge axis enclosed by the southward pointing gray dashed V. Box shows location of profiles 16–25. TFZ, Tjornes Fracture Zone; V, Vestfirdir; S, Snæfellsnes; R, Reykjanes Peninsula.

Herron and Talwani, 1972], it was thought the plume must have had variable flux. *Vogt* [1971] proposed the varying flux is either channeled under the ridge axis ("pipe" flow) or spreads radially away from the plume center, progressively reaching farther along the axis to form diachronous VSRs, necessarily symmetric about the axis when measured along seafloor spreading flow lines. Vogt's elegant hypothesis has since been extended and modeled by many others, and is the generally accepted explanation for the VSRs, with various models of pulses of asthenosphere or temperature hypothesized to create the VSRs as zones of thicker crust than the troughs [*Vogt*, 1971, 1974; *Vogt and Johnson*, 1972; *White et al.*, 1995; *White*, 1997; *White and Lovell*, 1997; *Smallwood and White*, 1998, 2002; *Ito*, 2001; *Albers and Christensen*, 2001; *Jones et al.*, 2002; *Jones*, 2003; *Poore et al.*, 2006, 2009].

[3] Although the "pulsing plume" paradigm is generally accepted, there is an alternative tectonic mechanism, propagating rifts, that produces a somewhat different V geometry than Vogt-type models, and can also produce crustal thickness variations without plume pulses, or even plumes. The test between these alternative models requires a detailed understanding of the seafloor spreading history of the Reykjanes Ridge. Here we present results from a recent marine geophysical expedition that show that seafloor spreading has not occurred symmetrically about a stable Reykjanes Ridge axis, and that the VSR pattern is not symmetric about the axis. The data are consistent with a sequence of new Reykjanes Ridge axes propagating south away from Iceland, usually but not always transferring lithosphere from Eurasia to North America, with their diachronous wakes forming the VSR boundaries. Thus existing models for the origin of the VSRs are at best incomplete, and rift propagation was probably involved in their formation. One obvious possibility is that plume pulses drive these propagators, but we also present an alternative model in which the VSR crustal thickness variations are produced by rift propagation and failure processes rather than by waxing or waning magmatism.

2. Rift Propagation Away From the Iceland Hot Spot

[4] Figure 1 shows the satellite gravity pattern near Iceland [*Sandwell and Smith*, 2009]. Obvious V patterns with tips near 69°N and 57°N suggest large-scale oceanic rift propagation away from Iceland. Certainly the northward pointing V, flanking the Kolbeinsey Ridge north of Iceland, has been convincingly interpreted as a propagating rift, clearly defined by the aeromagnetic anomaly pattern [*Vogt et al.*, 1980; *Appelgate*, 1997]. South of Iceland the seafloor spreading geometry appears to have changed twice, from oblique and unsegmented near the continental margins, to a more typical slow spreading orthogonal ridge/transform geometry that produced en echelon fracture zones (FZ), to the present linear oblique ridge axis inside the southward pointing V [*Vogt and Avery*, 1974]. These progressive transitions are commonly interpreted as effects of long-term variations in mantle temperature, with periods of ~30–50°C warmer mantle flowing away from the hot spot producing the unsegmented ridges, and periods of relatively cooler mantle producing the segmented ridges [e.g., *White et al.*, 1995; *White*, 1997; *Smallwood and White*, 2002; *Jones et al.*, 2002]. However, *Johansen et al.* [1984] suggested that rift propagation could be responsible for the progressive elimination of the en echelon transform faults.

[5] The time transgressive abrupt change in ridge geometry across the southern V resembles patterns that propagating rifts produce, with V-shaped pseudofaults [*Hey*, 1977] separating new lithosphere created on the propagating rift from older lithosphere formed on the ridge system being replaced. An example is seen in the northeast Pacific, where rift propagation changed an existing segmented Pacific-Farallon ridge-transform system to a remarkably long and straight ridge axis at anomaly 6 time [*Shih and Molnar*, 1975; *Atwater*, 1989; *Atwater and Severinghaus*, 1989]. This hypothesized southward propagation of an oblique Reykjanes Ridge into the region of orthogonal spreading, which presumably continues today near 57°N, began about 40 Ma, when plate motions changed and the seafloor spreading geometry was reorganized throughout the North Atlantic [*Vogt and Avery*, 1974; *Johansen et al.*, 1984; *Jones*, 2003]. Propagation elsewhere has also occurred in response to changes in plate motion [e.g., *Hey and Wilson*, 1982; *Wilson et al.*, 1984; *Caress et al.*, 1988; *Atwater*, 1989; *Briais et al.*, 2002].

[6] On Iceland itself, propagation of both the Northern and Eastern Volcanic Zones away from the hot spot, thought to be under Vatnajökull (the large glacier in Southeast Iceland (Figure 1)), is generally accepted to be occurring at present [*Sæmundsson*, 1979; *Schilling et al.*, 1982; *Hardarson et al.*, 1997, 2008; *Einarsson*, 2008]. Earlier rift propagation onto the southwest Iceland shelf has also been proposed [*Kristjánsson and Jónsson*, 1998]. This is consistent with the common observation of rift propagation away from other hot spots, including Galapagos [e.g., *Hey and Vogt*, 1977; *Wilson and Hey*, 1995], Juan de Fuca [e.g., *Delaney et al.*, 1981; *Johnson et al.*, 1983], Easter [e.g., *Schilling et al.*, 1985; *Naar and Hey*, 1991], and Amsterdam–St. Paul [e.g., *Vogt et al.*, 1983; *Conder et al.*, 2000].

[7] Here we propose that in addition to this other rift propagation away from Iceland, the same fundamental process is also occurring on a different scale, with very fast small-offset propagators creating the series of much more acutely angled VSRs

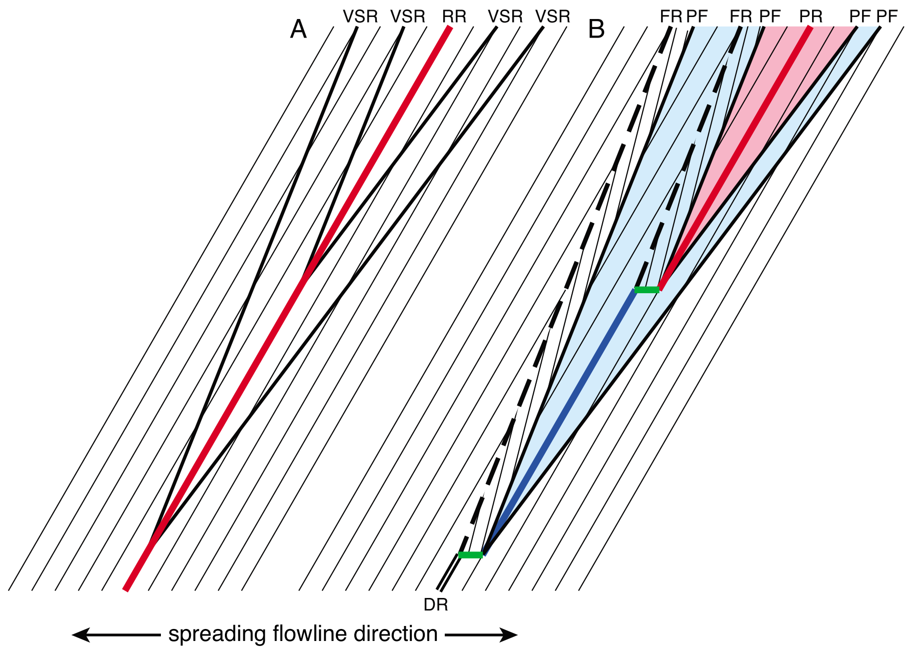

Figure 2. Alternative models for V-shaped seafloor structures, modified for oblique spreading. (a) Vogt-type variable mantle flux models [*Vogt*, 1971] produce V-shaped ridges (VSRs) and isochrons (light lines parallel to Reykjanes Ridge, RR), symmetric about the axis (red) when measured along flow lines (horizontal). (b) Propagating rift model (with ridge offsets exaggerated for clarity) produces asymmetric accretion and asymmetric V-shaped wakes. Red shaded area shows lithosphere bounded by pseudofaults (PF) created on the most recent (red) propagating rift (PR), which also produces a zone of transferred lithosphere (with rotated isochrons) and a failed rift (dashed) [*Hey*, 1977; *Hey et al.*, 1986, 1989]. Blue shaded area shows lithosphere created on previous (blue) PR axis, which is also replacing an earlier propagator (parallel black lines, DR). Note asymmetric location of youngest PR axis relative to oldest scarps and isochrons.

enclosed by the large-scale southward pointing V (Figure 1). Numerous other V-shaped patterns seen in the *Sandwell and Smith* [2009] satellite-derived gravity data are known to be propagating rift wakes [e.g., *Vogt et al.*, 1983; *Wilson et al.*, 1984; *Naar and Hey*, 1991; *Phipps Morgan and Sandwell*, 1994; *Wilson and Hey*, 1995; *Christie et al.*, 1998; *Kruse et al.*, 2000], so our hypothesis is both plausible and supported by our new data, but has not been proposed previously because presumed symmetry of seafloor spreading and of the VSRs flanking the Reykjanes Ridge precluded it.

3. Symmetric Versus Asymmetric Geometries

[8] Figure 2 shows the alternative symmetric [*Vogt*, 1971] and asymmetric [*Hey*, 1977; *Hey et al.*, 1980, 1989] models for V-shaped seafloor structures. Vogt-type models entail series of rapidly expanding pulses of asthenosphere or temperature which diachronously modulate magma production along the existing ridge axis. Nothing in these pulsing plume models produces asymmetry, at least not in any existing models. The Reykjanes Ridge is spreading obliquely, which must produce some apparent VSR asymmetry on profiles perpendicular to the axis [*Johansen et al.*, 1984], e.g., the classic *Talwani et al.* [1971] data collected before plate tectonics defined spreading flow lines, but the Vs should be symmetric on profiles measured along flow lines (Figure 2a). VSR symmetry is also predicted by the alternative *Hardarson et al.* [1997, 2008] hypothesis discussed later.

[9] In contrast, rift propagation must produce asymmetric patterns. A propagating ridge is offset laterally from the ridge it replaces; it breaks through existing lithosphere and transfers some from one plate to the other. This produces both asymmetric seafloor spreading and asymmetric V-shaped wakes (Figure 2b). One limb of each wake is a narrow outer pseudofault, separating lithosphere created on the propagating and failing ridges, whereas the other is a wider sequence of inner pseudofault/ transferred lithosphere/failed rift. If the pseudofaults and failed rifts form scarps, as seen for

example in the Galapagos area [*Searle and Hey*, 1983; *Hey et al.*, 1986; *Kleinrock and Hey*, 1989; *Kleinrock et al.*, 1989; *Wilson and Hey*, 1995], a sequence of propagators would produce nested scarps that would be different distances from the new ridge axis on each plate (except for the youngest pseudofaults), although pseudofault scarps form symmetrically at the same time at their respective propagator tips (Figure 2b). The angles subtended by the Reykjanes VSRs in our survey area are ~10° and the spreading half rate is ~10 km/Myr, so the propagation rates would have been cotan(~5°) times faster, i.e., ~100 km/Myr, the zones of transferred lithosphere would show very little rotation (~10°), and they would be as narrow as the propagating rift/failing rift offsets, which must be small (<~10 km), with correspondingly small ridge jumps, or they would have been discovered previously. At these high latitudes skewness is low and magnetic rotation is less obvious.

[10] The determination of symmetry or asymmetry in VSR geometry and seafloor spreading thus provides a test between the propagating rift and Vogt-type geometries.

4. Data Collection

[11] An advantage of our data acquisition and modeling approach was that our ship tracks followed North America–Eurasia seafloor spreading flow lines (~100°, rather than orthogonal to the ~037° Reykjanes Ridge trend). This places the data in the proper geometry at the outset, with ridge flank features correctly positioned with respect to their origin on the ridge axis. Our data were collected on R/V *Knorr* in June–July 2007, prior to but in good agreement with new high-resolution flow lines [*Merkouriev and DeMets*, 2008], except near the outer edges of our profiles (Figure 3). All published estimates of recent North America–Eurasia rotations are tightly clustered, consistent with the orientation of the Charlie-Gibbs FZ and the ~100° present spreading direction [*DeMets et al.*, 1994]. Some of the short-wavelength excursions in the very detailed (21 stage rotations in the past 20 Ma) Merkouriev and DeMets flow line shown below our southernmost profile 25 (Figure 3) could result from errors in picking short reversal boundaries, the kind of errors unrecognized rift propagation would cause. The maximum azimuthal discrepancy between our tracks and a simplified Merkouriev and DeMets rotation history using 7 stage poles during the past 20 Ma (provided by C. DeMets (personal communication, 2009)) is ~5°, and usually much smaller.

5. VSR Asymmetry: E Scarps

[12] The major conjugate V structures that *Vogt* [1971] identified as the outward facing E scarps (ridge R3 of *Jones et al.* [2002]or ridge 2d of *Poore et al.* [2009]) south of 62°N continue through our new Seabeam data (Figure 3a). All topographic structures are more obvious on the North America plate west of the ridge axis, because to the east all but the biggest are buried by thick sediments pouring off Iceland during glacier outburst floods (jökulhlaups) following subglacial eruptions. The gravity signal is less affected by the sediments, and shows clearly that equivalent structures must occur on the Eurasia plate as well (Figure 3b). The E scarps are everywhere farther from the Reykjanes Ridge axis on North America than Eurasia.

[13] The exact location of the spreading axis is somewhat ambiguous. In detail, the neovolcanic axis shows the characteristic Reykjanes Ridge pattern of overlapping en echelon axial volcanic ridges. These youngest eruptive centers follow the overall oblique Reykjanes Ridge axis but individually are oriented subnormal to the present spreading direction, and have complicated evolutions on a finer scale than discussed here [e.g., *Parson et al.*, 1993; *Murton and Parson*, 1993; *Searle et al.*, 1998; *Peirce and Sinha*, 2008]. Although on any given profile the en echelon structures produce some uncertainty in the exact location of the seafloor spreading axis, it is presumably near the center of the youngest rifting and volcanism. The axes in Figures 3–7 assume that a more essential linear oblique plate boundary (Figure 1) follows below the middle of the shallowest en echelon volcanic ridge pattern. Slight (1–2 km) eastward shifts away from the exact center of rifting on a few profiles produced a more linear axial interpretation and better fits to the Brunhes anomaly in our magnetic modeling and thus our axis is somewhat time-averaged. This axis is tightly constrained on profiles 12–18 where the heavily sedimented Iceland shelf is being rifted apart (Figures 3 and 4), and this is where the asymmetry is greatest. This VSR asymmetry is most clearly demonstrated by the bathymetry and gravity profiles in Figure 5. The well-defined E scarps on profiles 17–18 are ~20 km farther from the axis on North America than on Eurasia.

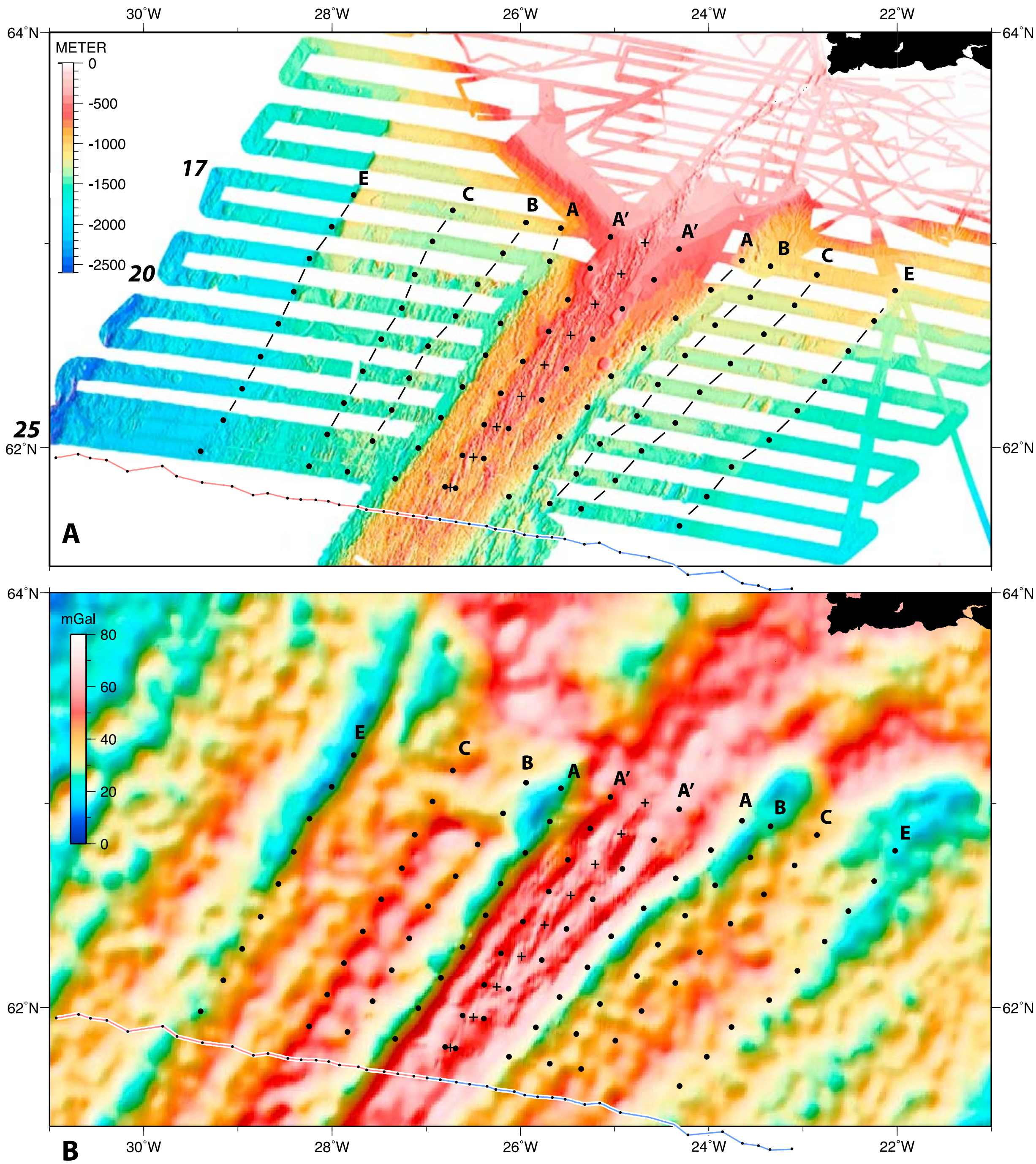

Figure 3. VSR asymmetry shown by (a) compiled multibeam bathymetry data and (b) satellite-derived gravity [*Sandwell and Smith*, 2009] combined with new axial mosaic shipboard gravity, illuminated from the southeast. The dots are the ridge jump boundaries (pseudofault wakes) used in our magnetic anomaly models (Figure 7) to fit the observed seafloor spreading asymmetry and make the conjugate scarps the same ages. Only the A and E scarps follow *Vogt*'s [1971] original terminology. Crosses show simplified seafloor spreading axis; new Seabeam track lines (numbered) are generally good approximations to the revised North America–Eurasia spreading flow lines [*Merkouriev and DeMets*, 2008] shown below our southernmost profile 25, except on the outer parts of our profiles past the E scarps. The E scarps could be interpreted differently south of profile 20, where the main gravity anomaly high shifts closer to the axis.

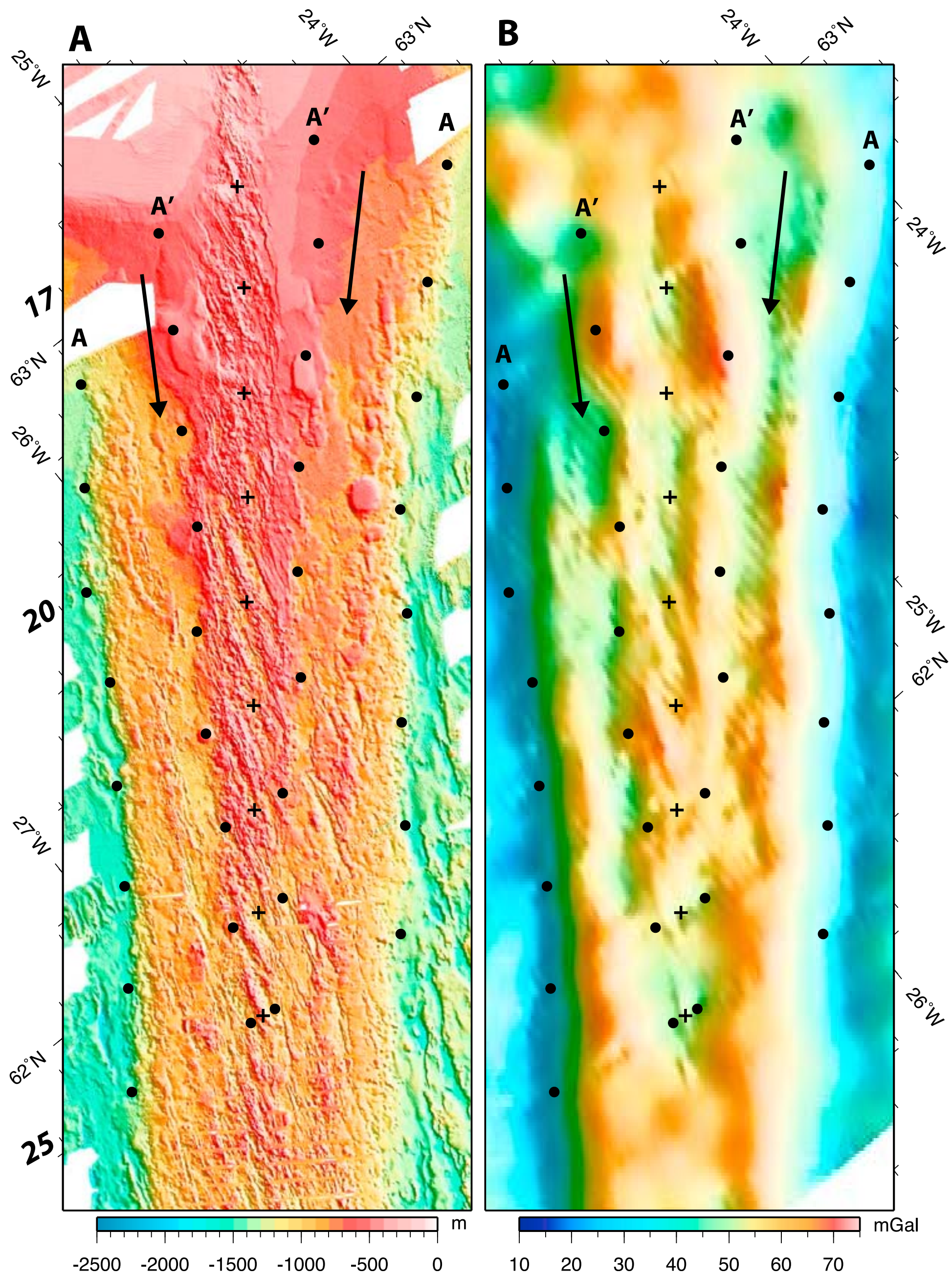

Figure 4. Detailed axial mosaic showing evidence for the A′ propagator. (a) Compiled multibeam bathymetry data and (b) new shipboard gravity combined with satellite gravity [*Sandwell and Smith*, 2009], illuminated from the right. Dots show pseudofault (ridge jump) locations from our models, and crosses show simplified oblique seafloor spreading axis on each profile. Bathymetric troughs with subdued structures correlate with gravity troughs (arrows) extending north away from what we interpret to be the A′ propagating rift tip near 61.7°N. The propagating axis is closer to the North America A scarp than the more centrally located ridge axis being replaced, providing an explanation for the A scarp asymmetry. The corresponding trough is slightly wider on Eurasia than North America because Eurasia contains the failed rift and transferred lithosphere produced at the small left-stepping ridge offset.

[14] This asymmetry is much greater than can be explained by possible axial mislocation even if the axis were at the extreme western edge of the recent rifting (and that axis location would imply enormous A scarp asymmetry (Figures 3–5)). In addition, VSR asymmetry can be demonstrated completely independently of the exact position of the present axis. The two youngest major gravity troughs flanking the spreading axis occur at the bases of Vogt's two biggest scarps, the A and E

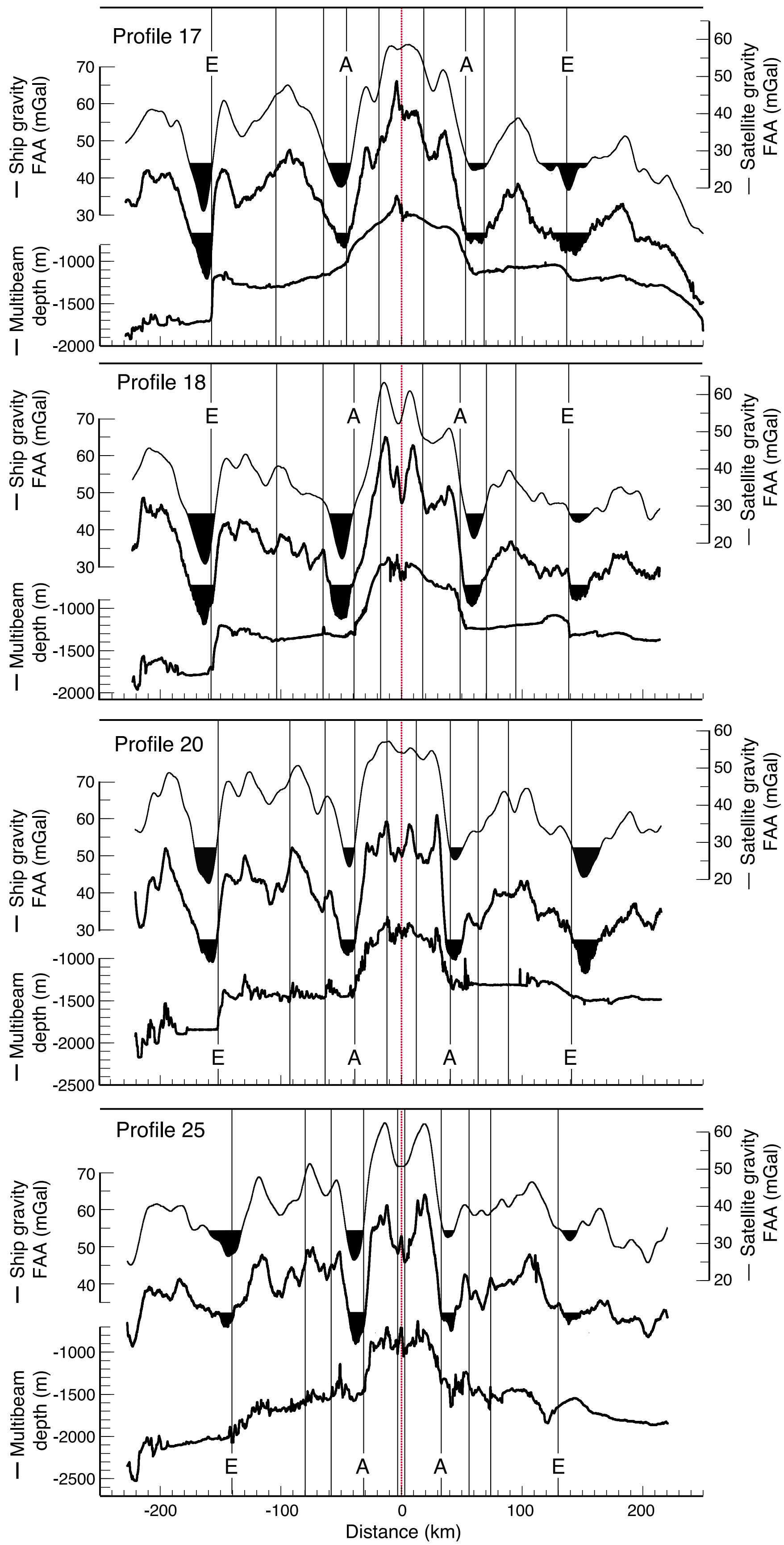
Profile 17
Profile 18
Profile 20
Profile 25
E
A
Ship gravity FAA (mGal)
Multibeam depth (m)
Satellite gravity FAA (mGal)
Distance (km)
-200
-100
0
100
200

Figure 5

scarps. The separation between these troughs along flow line profiles is always greater on North America than Eurasia. For example, on profile 17 they are separated by ~110 km on North America, but by only ~80 km on Eurasia (Figure 5). The conjugate features must have formed contemporaneously at a ridge axis, yet today there is ~30 km more lithosphere on North America than Eurasia between the A and E troughs and scarps. The sediment asymmetry can explain the observed gravity amplitude asymmetry, but not the width asymmetry.

[15] This extra lithosphere, characterized by strong positive linear gravity anomalies (Figures 3 and 5) suggesting a nested sequence of smaller-scale VSRs [*Jones et al.*, 2002; *Poore et al.*, 2009], explains why the E scarps are 20 km farther from the ridge axis on North America than Eurasia (not 30 km farther because the A scarps are also asymmetric). If these scarps were symmetric, as assumed in all existing models, the propagating rift explanation could not work (without incredible coincidences), so our hypothesis passes this falsification test (Figure 2b). The asymmetry decreases abruptly to ~12 km extra North America lithosphere near profile 20, where the scarp pattern becomes more complicated in both gravity and bathymetry data, then continues to decrease slightly toward the south (Figures 3 and 5).

[16] VSR asymmetry has been noted before. *Johansen et al.* [1984] pointed out that the *Talwani et al.* [1971] data were not collected along flow lines, so structures identified as symmetric on these profiles were necessarily formed at different times on the two plates. When they reanalyzed this original data that led *Vogt* [1971] to his hypothesis, they found the same asymmetry we do. They concluded that if the VSRs are caused by asthenosphere flow, the processes at the axis must be more complicated than implied by *Vogt*'s [1971] models. *Jones et al.* [2002] also noted asymmetry in VSR morphology as defined by satellite gravity, and suggested this asymmetry may reflect complexities in tectonic processes at the spreading axis or in transport of magma from the mantle to the crust. We show that rift propagation provides a cohesive explanation for this important observation, as well as for the existence of asymmetric seafloor spreading in this area.

6. Seafloor Spreading Asymmetry

[17] Rift propagation must produce asymmetric accretion of lithosphere to the plates (Figure 2b), and this is certainly contrary to the conventional wisdom that seafloor spreading on the Reykjanes Ridge has been symmetric [*Vine*, 1966, 1968; *Talwani et al.*, 1971; *Herron and Talwani*, 1972]. However, our new data clearly show that asymmetry exists in our survey area, and similar asymmetry has been noted in other data farther south [e.g., *Sæmundsson*, 1979; *Müller et al.*, 1998; *DeMets and Wilson*, 2008]. Most notably, asymmetry can be seen in Figure 6 of *Vine* [1968], an iconic color image of the classic Project Magnet aeromagnetic stripes [*Heirtzler et al.*, 1966] correlated with the magnetic reversal time scale, where the older anomalies on North America are slightly but systematically farther from the axis than those on Eurasia. Vine's interpretation of symmetry consistent with seafloor spreading in those data was of course correct on the scientific revolution scale, and a critical step in the plate tectonic revolution, but we argue the small-scale asymmetry is essential to understanding the origin of the VSRs.

[18] Figure 6 shows our new magnetic anomaly data. Our identifications of the distinctive major positive magnetic anomalies 5 (~10 Ma) and 6 (~20 Ma) agree with all previous work [e.g., *Vine*, 1966, 1968; *Talwani et al.*, 1971; *Herron and Talwani*, 1972; *Smallwood and White*, 2002; *Jones et al.*, 2002; *Jones*, 2003; *Merkouriev and DeMets*, 2008; *DeMets and Wilson*, 2008]. These anomalies are always farther from the Reykjanes Ridge axis on North America than Eurasia, demonstrating asymmetric seafloor accretion. Anomaly 6, at or near the edges of our profiles (Figures 6 and 7), is ~26 km farther from the axis on North America than Eurasia on profile 17, ~23 km farther from the axis on profile 20, and ~18 km farther on profile 25.

Figure 5. Satellite (top curve in each profile) and shipboard (middle curve in each profile) free-air gravity anomalies and bathymetry (bottom curve in each profile) for selected profiles derived from the Figure 3 data. Note the asymmetry of both the E scarps (farther from the axis (red) on North America) and the A scarps (farther from the axis on Eurasia), although on each profile equivalent scarps are equal ages because of the proposed ridge jumps (vertical lines). The gravity troughs (shaded) at the bases of the A and E scarps are always wider apart on North America than Eurasia, demonstrating VSR asymmetry independent of the exact location of the present ridge axis. Perhaps this axis should be even more asymmetrically located relative to the A scarps on profiles 17 and 18. On profile 25 the E scarps are complicated, and the major pseudofaults should perhaps be closer to the axis, but asymmetry would still exist.

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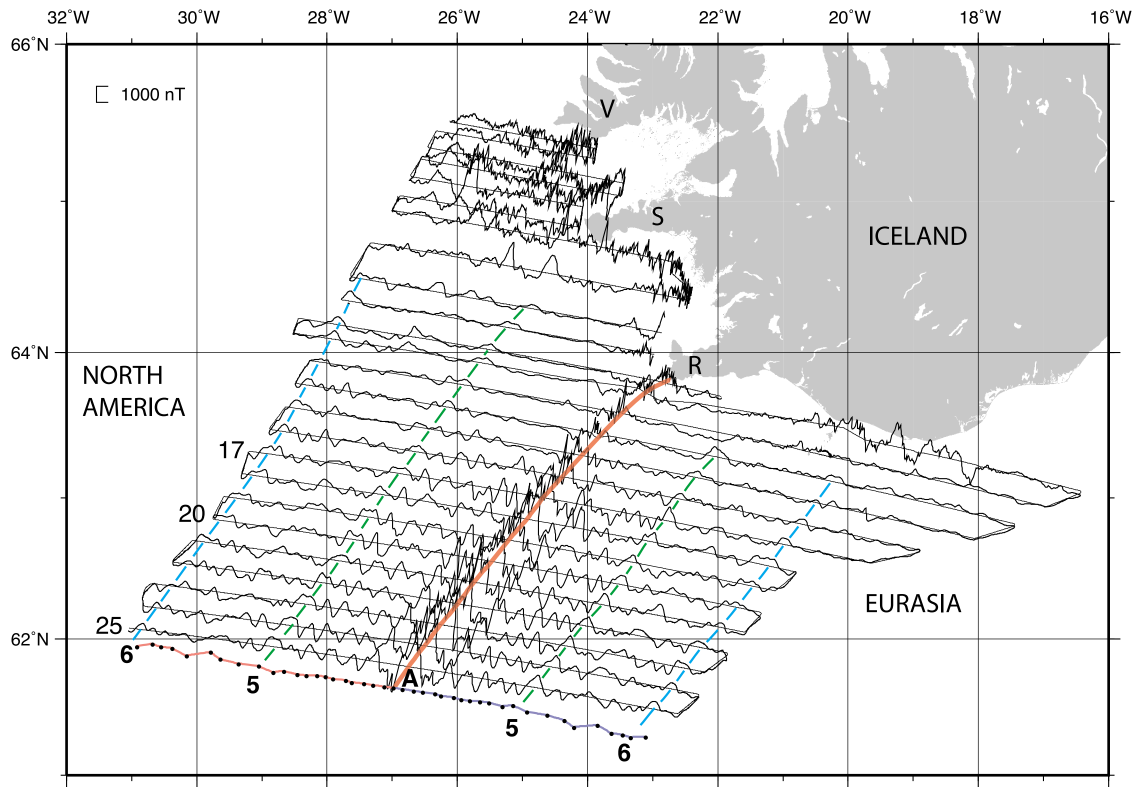

Figure 6. New marine magnetic anomaly data projected onto 010°, essentially perpendicular to track, which demonstrate asymmetric seafloor spreading. Anomalies 5 (green dashes) and 6 (blue dashes) are identified and are always farther from the ridge axis (A, red line) on North America than Eurasia, with asymmetry increasing to the north. The outermost dots in the *Merkouriev and DeMets* [2008] flow line included below the data show the predicted positions of the beginning of anomaly 6 (19.72 Ma) if spreading had been symmetric, further demonstrating asymmetry. The spacing between anomalies 5 and 6 is also consistently (~10 km) greater on North America than Eurasia, demonstrating seafloor spreading asymmetry independent of the exact location of the present ridge axis. V, Vestfirdir; S, Snæfellsnes; R, Reykjanes Peninsula.

Farther north on the Iceland shelf this asymmetry increases to a maximum where the Reykjanes Ridge axis changes trend [*Höskuldsson et al.*, 2007] to join the Reykjanes Peninsula. There is also consistently greater (~10 km) spacing between anomalies 5 and 6 on North America than on Eurasia (Figures 6 and 7), consistent with the bathymetry and gravity data (Figures 3 and 5) in demonstrating asymmetric spreading completely independent of the exact present axial location.

[19] Unfortunately the magnetic anomaly resolution here is too low to demonstrate whether the seafloor spreading asymmetry arises continuously, perhaps by some form of regional asymmetric spreading, or discontinuously, by ridge jumps produced by propagators. However, even the type example of regional asymmetric spreading, the Australia-Antarctic Discordance [*Weissel and Hayes*, 1971], is now understood to result from rift propagation [*Vogt et al.*, 1983; *Phipps Morgan and Sandwell*, 1994; *Christie et al.*, 1998], as is the classic example of "zed pattern" asymmetry originally thought to result from continuous ridge rotation [*Menard and Atwater*, 1968] in the northeast Pacific [*Caress et al.*, 1988; *Hey et al.*, 1988]. With the possible exception of complicated back-arc basins [*Deschamps and Fujiwara*, 2003], all other major asymmetric areas with sufficiently high resolution data, such as Juan de Fuca [*Shih and Molnar*, 1975; *Wilson et al.*, 1984], Galapagos [*Hey and Vogt*, 1977; *Hey et al.*, 1980; *Wilson and Hey*, 1995], and the Easter Microplate [*Naar and Hey*, 1991] have been shown to result at least primarily from rift propagation, so the same hypothesis for this area is certainly plausible. In contrast, even if some sort of continuous asymmetric spreading did exist it would not produce V patterns, so an additional anomalous mechanism such as plume pulses would be required. Rift propagation produces both asymmetric spreading and V-shaped wakes, and is thus a more efficient explanation.

[20] Additionally, we collected very high density data as part of our axial mosaic survey, including complete Seabeam coverage out past Vogt's A scarps (Figures 3a and 4a), which demonstrate A scarp asymmetry and suggest that it results from rift propagation.

7. A Scarp Asymmetry

[21] The A scarps show the opposite sense of asymmetry as the E scarps, appearing consistently closer to the present seafloor spreading axis on North America than Eurasia (Figures 3a and 4a). On profiles 17 and 18, the A scarp is more than 10 km farther from the axis on Eurasia than North America. The asymmetry decreases toward the south but these scarps are still ~5 km farther from the axis on Eurasia than North America on profile 20, and ~3 km farther on profile 25. We consider these to be conservative estimates: if we had assumed the present axis runs through the exact center of the AVR pattern, the A scarp asymmetry would be slightly greater (and the E scarp asymmetry slightly less). The A scarp asymmetry could be eliminated if the axis were farther east (e.g., at the extreme eastern edge of the newest rifting on profiles 17 and 18), instead of near the center as we assume (Figures 4 and 5), but in that case the E scarp asymmetry would become correspondingly greater, e.g., ~30 km farther from the axis on North America than Eurasia on profiles 17 and 18 (Figures 3 and 5). No axis can make both the A scarps and the E scarps symmetric, so the existence of VSR asymmetry is incontrovertible.

[22] The A scarp asymmetry can only result from rift propagation if there is a propagator (A′) younger than our proposed A scarp propagator. If there were, we would expect to see an organized ridge axis located asymmetrically between the A scarps, with a V-shaped wake, and perhaps a high-amplitude magnetic anomaly zone at the propagator tip [*Hey and Vogt*, 1977]. This is exactly the pattern we observe (Figures 4, 6, and 7). Existing pulsing plume models do not predict or include asymmetry, and thus would need to invoke an additional asymmetric spreading mechanism to match the data. In contrast, rift propagation requires these kinds of asymmetries.

8. Propagating Rift Interpretation

[23] Rather than the more stochastic axial shifts that have been suggested farther south along the Mid-Atlantic Ridge (MAR) within a broad nonrigid plate boundary zone [e.g., *Ballard and van Andel*, 1977; *Macdonald*, 1982], the A′ propagator appears to show a very organized replacement of one ridge axis by another only a few kilometers away, and explains how the conjugate A scarps can be the same age on each profile although they are different distances from the new axis (Figures 3–5 and 7). The new axis appears to have a V-shaped ridge and trough wake defined by both gravity and bathymetry. The outward facing scarps bounding the elevated propagating axis separate the typical AVR pattern from topographically low areas of suppressed structures extending north in a V-shaped pattern coinciding with a V-shaped gravity low (Figures 3–5). The inward facing scarps separate this V-shaped trough from older seafloor with shallower topography and more clearly defined tectonomagmatic structures. We interpret this as the wake of an A′ propagator which created the trough and may have altered the normal monotonic destruction of axial volcanic ridges with age proposed farther south along the Reykjanes Ridge [*Parson et al.*, 1993; *Murton and Parson*, 1993; *Searle et al.*, 1998]. According to our interpretation, the trough is narrower on North America because the small (1–4 km) propagating rift/failed rift offset is left-stepping to an axis farther south centered between the A scarps (Figure 4), and thus the transferred lithosphere and failed rift are on Eurasia. This V-shaped pattern was previously noted by *Searle et al.* [1998], who proposed it resulted from a pulse of extra asthenosphere moving down the existing axis. However, that mechanism would not produce the evident A scarp asymmetry, so rift propagation is a more comprehensive explanation. The tip of this propagator appears to be at ~61.7°N or 61.5°N, depending on whether the pseudofaults correlate with the outward or inward facing scarps.

[24] Although this tip correlates with the highest-amplitude axial magnetic anomaly in the area, this could be a coincidence and not the kind of propagating rift tip effect of high magnetization caused by highly fractionated ferrobasalts commonly seen elsewhere [*Hey and Vogt*, 1977; *Hey et al.*, 1980, 1989; *Christie and Sinton*, 1981; *Sinton et al.*, 1983; *Vogt et al.*, 1983; *Wilson and Hey*, 1995]. The Reykjanes Ridge is obviously anomalous in many ways so these propagators (and failed rifts) might also have anomalous geochemical patterns, and any signal might be small and difficult to discern. Certainly if there were a large effect it would have been discovered previously [*Taylor et al.*, 1995; *Murton et al.*, 2002].

[25] If the VSRs are propagator wakes, the pseudofaults could conceivably correlate with either the inward facing scarps at the outer edges of the topographic and gravity troughs, or with the outward facing scarps at the inner edges of the troughs (Figure 4). If the inward facing scarps are the pseudofaults, they would in some ways be similar to the structures at the Galapagos 95.5°W propagator, where there is a topographically low area at the propagating rift tip bounded by inward facing pseudofault scarps. This tip depression eventually evolves to a V-shaped trough, bounded on the other side by the gradually developing constructional axial ridge [*Hey et al.*, 1986, 1992; *Kleinrock and Hey*, 1989]. In this case the troughs bounding the A′ propagator could be tip depression wakes. This would in important ways be similar to the innovative model of *Hardarson et al.* [1997, 2008], in which the troughs defining the VSRs are considered the anomalous features, formed as the big ridge jumps on Iceland [e.g., *Sæmundsson*, 1979; *Hardarson et al.*, 1997, 2008] disrupted the normal enhanced supply of asthenosphere from the plume to the ridge. However, propagating rifts would form the troughs differently, by the rifting of preexisting cold lithosphere which produces enhanced viscous head loss [*Sleep and Biehler*, 1970] and probable crustal thinning during the acceleration from no spreading to the full spreading rate on the developing propagating ridge axis [*Hey et al.*, 1980, 1986, 1989, 1992; *Searle and Hey*, 1983; *Phipps Morgan and Parmentier*, 1985; *Kleinrock and Hey*, 1989; *West et al.*, 1999; *Kruse et al.*, 2000]. Whether these effects could produce the 1–2 km crustal thickness variations associated with the Reykjanes VSRs [*White et al.*, 1995; *Smallwood and White*, 1998] is unknown, but *Kruse et al.* [2000] concluded that the pseudofault gravity lows associated with Easter and Juan Fernandez microplate rift propagation could result from ~0.3–1 km thinner than normal crust, so the order of magnitude appears to be reasonable.

[26] Although this could be a plausible hypothesis for the A′ pattern, which could conceivably produce VSR troughs with crust thinner than normal for this area and resulting relative gravity lows without the need for a pulsing plume, there is an apparent problem with this interpretation for the A and especially E propagators. In these cases, if the inward facing scarps are the pseudofaults, the large outward facing A and E scarps would not be any kind of tectonic boundary. Instead they would have to result from sudden increases of asthenosphere supplied to the propagating ridge axis long after the propagating rift tip passed and created the troughs. For example, there appears to be an ~20–30 km wide bathymetric trough, mostly filled by sediments, on the North America plate just west of the E scarp (Figures 3 and 5). If the outer boundary of this E scarp trough is the pseudofault, this would require an ~2–3 Ma time lag between initial rifting and the formation of the E scarp at the constructional axis. In the Galapagos area, the time lag is ~200,000 years, and the resulting constructional ridge forms much more gradually than the abrupt A and E scarps [*Hey et al.*, 1986, 1989, 1992; *Kleinrock and Hey*, 1989].

[27] It seems more likely that the steep outward facing A and E scarps mark the pseudofault wakes, formed at the tips of new, magmatically more robust propagating ridges. This would in some ways be similar to East Pacific Rise (EPR) propagator morphology at superfast (>~140 km/Myr) spreading rates [*Klaus et al.*, 1991; *Cormier and Macdonald*, 1994; *Hey et al.*, 1995; *Martinez et al.*, 1997], although those have much gentler outward facing pseudofault slopes without a scarp-like appearance. *Cormier and Macdonald* [1994] found ridge propagation rates ~14 times greater than the spreading half rate on the EPR near 18°–19°S, comparable to the aspect ratios of our proposed Reykjanes propagators. The Reykjanes Ridge near Iceland has axial high morphology more similar to superfast spreading ridges than to slow spreading ridges [e.g., *Macdonald*, 1982; *Searle et al.*, 1998]. It also lacks transform faults for >900 km, so it behaviorally resembles the superfast EPR as well [*Sandwell*, 1986; *Naar and Hey*, 1989; *Sandwell and Smith*, 2009]. If this outward facing pseudofault interpretation is correct, the sudden influx of asthenosphere would happen essentially simultaneously with the ridge propagation. This could happen because a plume pulse was providing the driving mechanism for the propagator, or perhaps because the propagator created a more favorable conduit for the asthenosphere supplied by a possibly steady state plume, perhaps by breaching a transform dam in South Iceland [*Sleep*, 2002] or by eliminating small discontinuities hindering subaxial flow (J. Phipps Morgan, personal communication, 2007). However, in this case the troughs between the VSRs could not be propagator tip depression wakes because they would be outside the pseudofaults (Figure 2b). Additionally, although propagator tips are always deeper than the magmatically more robust ridge axis behind them [e.g., *Hey et al.*, 1980; *Phipps Morgan and Parmentier*, 1985], there are not large propagator tip depressions at superfast spreading rates.

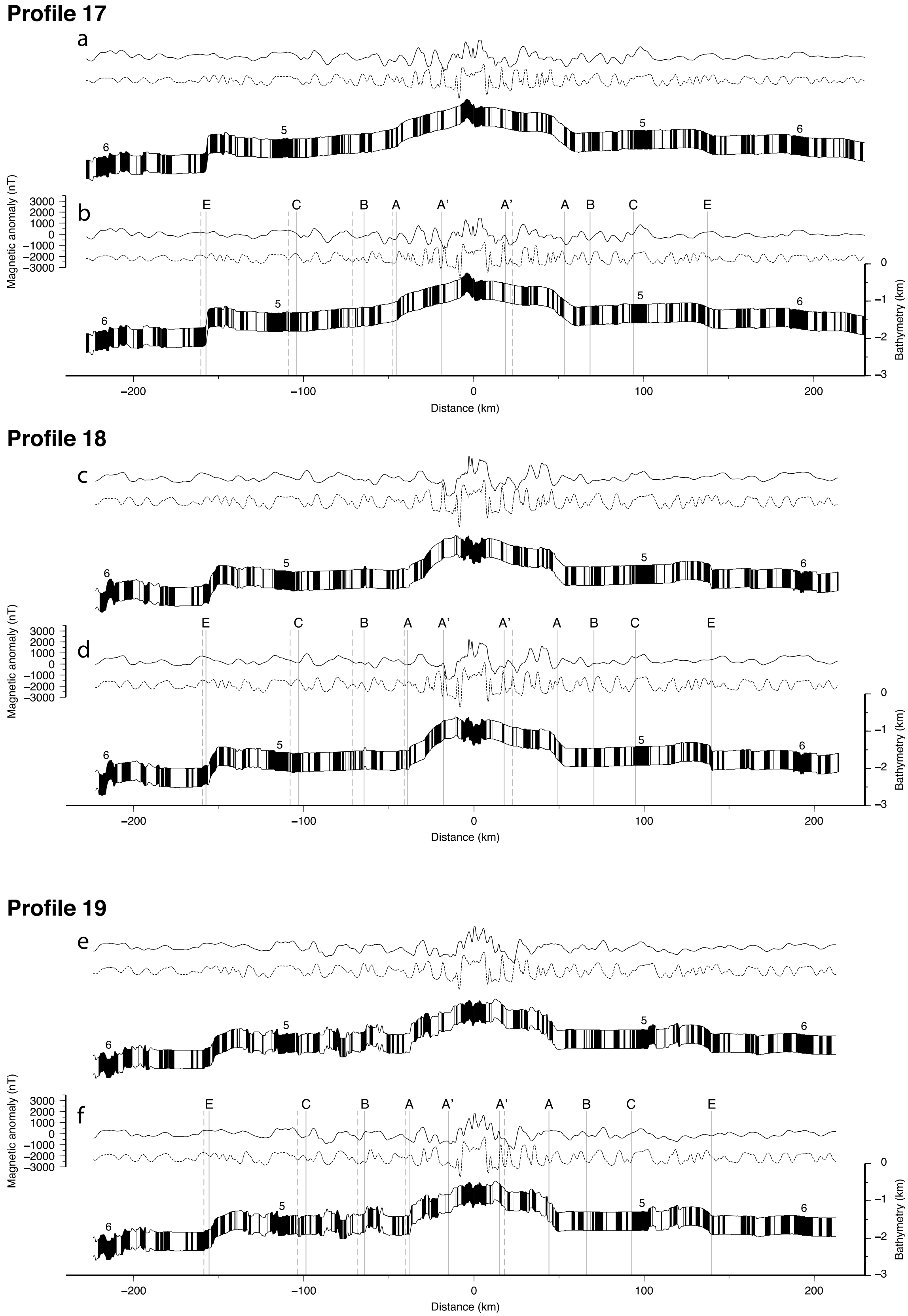
Profile 17
a
b
Profile 18
c
d
Profile 19
e
f
E
C
B
A
A'
5
6
Magnetic anomaly (nT)
3000
2000
1000
0
−1000
−2000
−3000
Bathymetry (km)
0
−1
−2
−3
−200
−100
0
100
200
Distance (km)

Figure 7

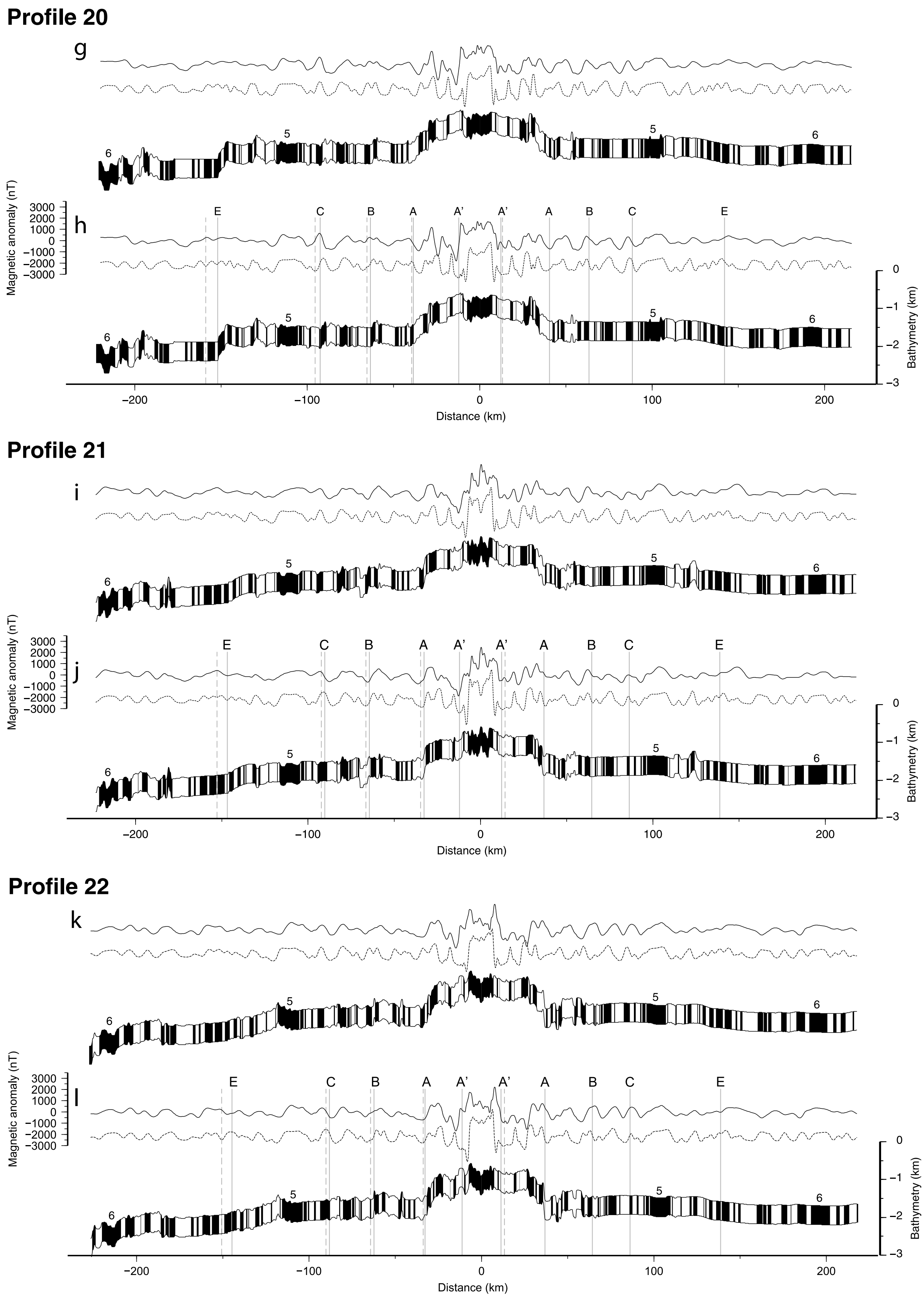

Figure 7. (continued)

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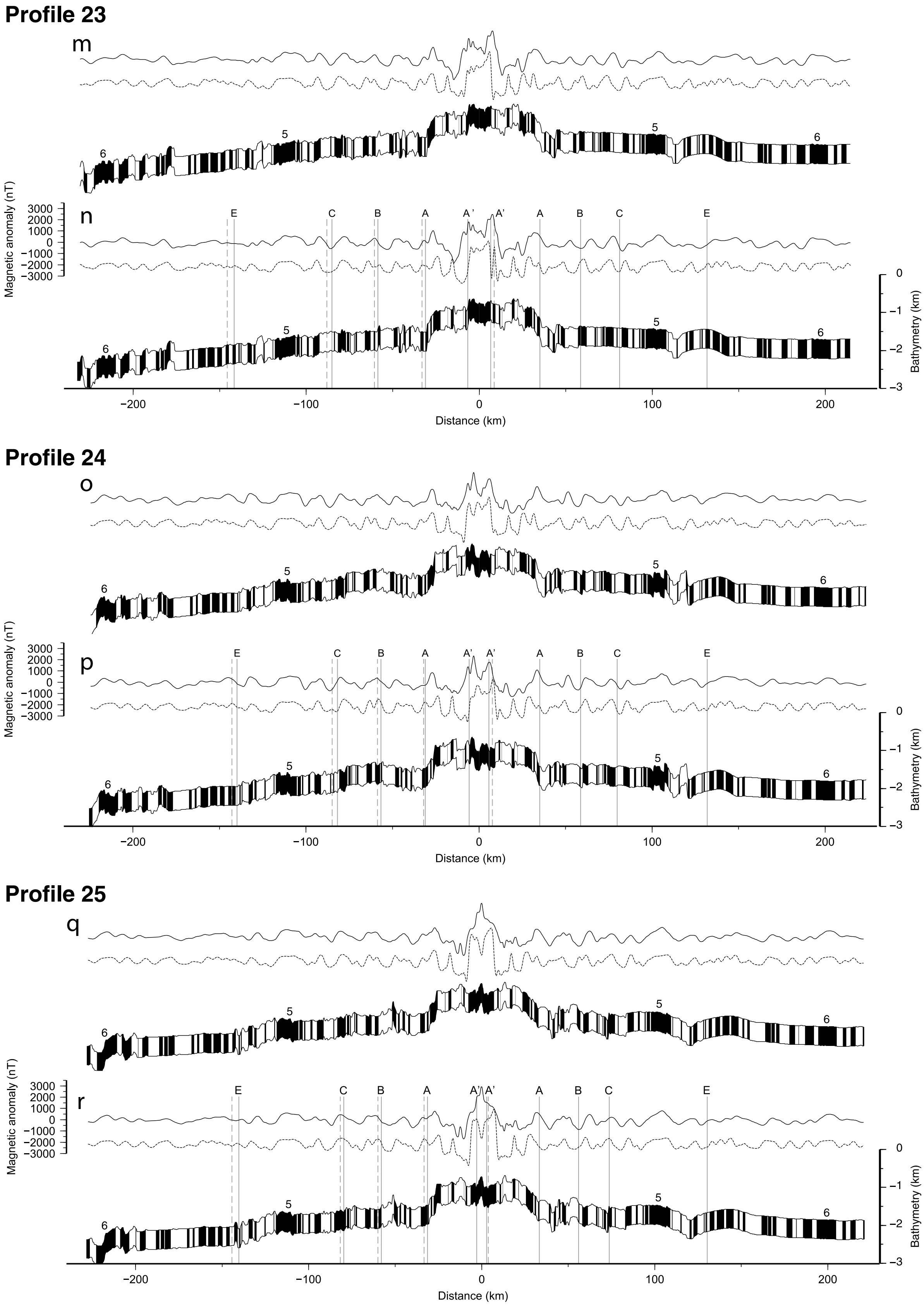

Figure 7. (continued)

[28] The troughs could perhaps instead be failed rift depressions, with thinner crust than normal for this area. In the Galapagos area there are clearly defined failed rift grabens thought to result from the transitional spreading period during the required deceleration from the full rate to zero on the failing rift [*Hey et al.*, 1986, 1989, 1992; *Kleinrock et al.*, 1989; *Wilson and Hey*, 1995]. Deep failed rift grabens are also formed in the superfast spreading 28°–29°S dueling propagator area between the Easter and Juan Fernandez microplates [*Hey et al.*, 1995; *Korenaga and Hey*, 1996; *Martinez et al.*, 1997]. Normally, the failed rift grabens occur on only one side of the new axis (Figure 2b). However, there could be an additional complexity at a small offset propagator; that is, if the rift failure signature were wider than the propagating ridge/failed ridge offset, part would end up outside the pseudofaults on both plates. Both the intermediate spreading Galapagos failed rift grabens and the superfast dueling propagator failed rift grabens are typically ~10 km wide, wider than the Reykjanes Ridge jumps we model. The Galapagos 95.5°W failing rift lavas are predominantly highly magnesian [*Christie and Sinton*, 1981; *Hey et al.*, 1989, 1992], as are the Reykjanes V-shaped trough samples [*Taylor et al.*, 1995].

[29] According to our interpretation, the E propagator has already caught and either merged with or replaced the older propagator it was following, and subsequently was superceded by the younger C or B propagator near 57°N, where the active propagator is continuing to change the previous orthogonal ridge/transform staircase geometry to a linear oblique ridge axis. The active A propagator is continuing south near 59°N, where the axial ridge changes to an axial valley, and the active A′ propagator tip is near 61.7°N. Two of these tips correlate with high-amplitude magnetic anomalies, and the 3rd is in a data gap [*Searle et al.*, 1998; *Lee and Searle*, 2000]. The large outward facing conjugate VSR scarps such as Vogt's A and E scarps are pseudofaults formed symmetrically at their corresponding propagating rift tips. They are different distances from the present axis (except for the A′ pseudofaults) because of the axial relocations and lithosphere transferred by subsequent propagators (Figure 2b). We can at least show that this interpretation is allowed by the magnetic anomalies, although the anomaly resolution is too low to be definitive (Figure 7).

9. Magnetic Anomaly Modeling

[30] Because the Reykjanes Ridge is spreading obliquely, the magnetized blocks were first calculated using the spreading rate, ridge jump and asymmetry parameters in Table 1, and then projected perpendicular to the ridge prior to calculating the magnetic models. Thus the standard assumption of 2-D magnetized bodies extending parallel to the ridge holds. The magnetic models were then projected back to the track lines and compared to the data. Magnetic anomalies over slow spreading ridges generally lack fine-scale character and resolution [e.g., *Tisseau and Patriat*, 1981; *Macdonald*, 1982; *Mendel et al.*, 2005] which makes it hard to compare an unfiltered or uncontaminated model to real data because the models resolve higher frequencies than the data. We thus used the method of *Tisseau and Patriat* [1981] to suppress the highest frequencies in the models. This method involves making the magnetized blocks narrower prior to the calculation of the magnetic models by using a "contamination coefficient" [*Mendel et al.*, 2005], 0.7 in our models (Figure 7). This technique provides more realistic fits to slow spreading magnetic anomalies [*Tisseau and Patriat*, 1981; *Mendel et al.*, 2005].

[31] These models use a recent astronomically calibrated time scale [*Lourens et al.*, 2004] which implies one significant decrease in North America–Eurasia spreading rate at 7 ± 1 Ma [*Merkouriev and DeMets*, 2008]. Following *DeMets and Wilson* [2008], we have used 6.5 Ma for this change. Al-

Figure 7. Magnetic anomaly models for off-shelf profiles 17–25 with asymmetry produced by (a, c, e, g, i, k, m, o, and q) continuous asymmetric spreading constrained to match the anomaly 6 asymmetry, faster on North America, and (b, d, f, h, j, l, n, p, and r) five ridge jumps, all but the most recent transferring lithosphere from Eurasia to North America. Solid lines are data, dashed lines are models, and magnetic source structure calculated from reversal time scale [*Lourens et al.*, 2004] follows seafloor bathymetry. In ridge jump models, lettered vertical solid lines identify the modeled jump boundaries (pseudofaults) and are the same ages on both plates, although all but the A′ pseudofaults are different distances from the axis. Dashed vertical lines are corresponding failed rifts. Anomalies 5 and 6 are labeled; note the asymmetric accretion, and in profiles 17–19 note that the continuous asymmetric spreading models make the A scarps considerably different ages on the two plates, demonstrating that discontinuous asymmetry must exist. Additional complexities near anomaly 6 are suggested by the bathymetry data but not modeled. Profile 18 is not fit well, possibly because of off-axis volcanism.

Table 1. Spreading Rate, Ridge Jump, and Magnetization Parameters Used for Models in Figure 7

			Jumps		Magnetization	
Track	Period (Ma)	Spreading Rate (mm/yr)	Time of Jump (Ma)	Distance (km)	Period (Ma)	Magnetization (A/m)
17	0–6.5	18.7	2.0	−4	0–0.78	10
	6.5–23	22.5	5.3	2	0.78–15	6
			7.0	7	15–23	4
			9.9	5		
			14.2	3		
18	0–6.5	18.7	1.9	−5	0–0.78	15
	6.5–23	22.5	4.7	2	0.78–15	8
			7.1	7	15–23	6
			9.9	5		
			14.3	2		
19	0–6.5	18.7	1.6	−3	0–0.78	15
	6.5–23	22.6	4.4	2	0.78–15	8
			6.9	4	15–23	6
			9.6	5		
			14.2	3		
20	0–6.5	18.8	1.3	−1	0–0.78	20
	6.5–23	22.6	4.2	1	0.78–15	8
			6.7	2	15–23	6
			9.1	3		
			14.1	7		
21	0–6.5	18.8	1.3	−2	0–0.78	25
	6.5–23	22.7	3.7	2	0.78–15	8
			6.8	2	15–23	6
			8.9	2		
			13.7	6		
22	0–6.5	18.8	1.2	−2	0–0.78	25
	6.5–23	22.7	3.7	1	0.78–15	8
			6.7	2	15–23	6
			8.8	2		
			13.6	6		
23	0–6.5	18.9	0.7	−2	0–0.78	30
	6.5–23	22.8	3.5	2	0.78–15	8
			6.2	2	15–23	6
			8.4	3		
			13.1	4		
24	0–6.5	18.9	0.6	−2	0–0.78	30
	6.5–23	22.9	3.5	1	0.78–15	8
			6.1	2	15–23	6
			8.2	3		
			13.0	3		
25	0–6.5	19.0	0.3	−1	0–0.78	40
	6.5–23	23.0	3.4	2	0.78–15	8
			6.0	2	15–23	6
			7.8	2		
			12.9	4		

ternative modeling using the *Cande and Kent* [1995] time scale produced a better fit to some profiles, especially profile 18, but a worse fit to others, especially profile 19. Here we are only demonstrating that ridge jumps are capable of producing the observed asymmetry, so these initial models include as few assumptions and free parameters as possible; for example, we did not use outward displacement [*Merkouriev and DeMets*, 2008; *DeMets and Wilson*, 2008], which probably explains some of our misfits near the axis, or nonvertical polarity boundaries, and all asymmetry results from 5 ridge jumps on each profile. More detailed analysis will be published elsewhere (Á. Benediktsdóttir et al., manuscript in preparation, 2010).

[32] Figure 7 shows that reasonable fits to the off-shelf magnetic anomalies (except profile 18) can be obtained with jump boundaries (pseudofaults) coinciding with outward facing VSR scarps. These models generally fit the data as well as or slightly better than continuous asymmetric spreading models, and have the important advantage of making all

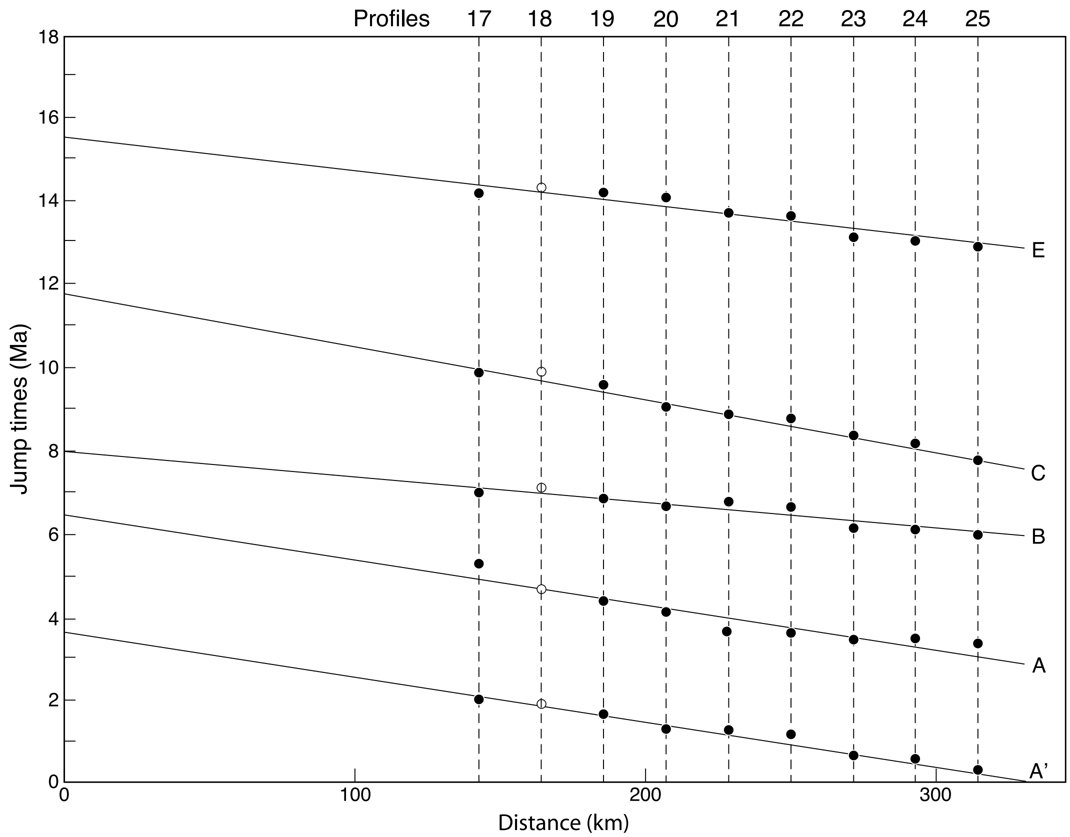

Figure 8. Ridge jump times versus distance along axis for off-shelf profiles with decent anomaly fits (all but profile 18, open circles). Distances measured from an arbitrary point at 64°N, 22.88°W, just offshore the Reykjanes Peninsula on a linear extrapolation of the Reykjanes Ridge axis shown in Figure 3. Corresponding rift propagation rates range from ~80 km/Myr for the C propagator to ~160 km/Myr for the B propagator. This is probably an oversimplified interpretation, and if, for example, there were a "D" propagator, the E propagator jump times would change slightly.

obviously conjugate scarps the same ages. Continuous asymmetry (or no asymmetry) models cannot do this because the sense of asymmetry is different for the A and E scarps. The continuous asymmetry models, constrained to match the total observed anomaly 6 asymmetry, tend to produce areas of good fits separated by areas of poor fits (Figure 7). This suggests the kind of discontinuous asymmetry produced elsewhere by ridge jumps [*Sclater et al.*, 1971]. For these slow spreading rates and small jumps, 7 km or less (Table 1), the models are nonunique, and even the number of jumps is difficult to determine. If each VSR is a propagator wake there might have been as many as 9 in the past 20 Ma (Figure 3), and a jump is a variable in our modeling, so the more we include the better the fit we can get. Our analysis suggests that at least four jumps are necessary to produce decent anomaly fits and make the conjugate scarps the same ages, but including a 5th jump coinciding with Vogt's "B" ridge produces slightly better fits to the magnetic anomaly data, and makes the jump time patterns significantly smoother (Figure 8). Propagators may coalesce as they come south, which we suggest has happened recently at the 57°N propagator, so more jumps may have occurred closer to Iceland than farther away. For example, *Vogt* [1971] noted our B scarp between his A and B structures, but did not name it because it did not extend all the way to the southern part of his data. (Vogt's B structure thus corresponds to our C scarp, but we have kept his terminology for the major A and E scarps).

[33] We can always fit the anomalies better on one plate than the other. Our data were collected along small circles about a pole near the center of estimates published before our expedition, but these are excellent approximations to the new *Merkouriev and DeMets* [2008] flow lines from the axis past the C scarps (Figures 3 and 6), so this is where we are most confident in our interpretations and generally fit the anomalies on both plates well. Flow line azimuthal discrepancies become significant outside the E scarps, and the ages of crust mapped at the

outer edges of our profiles could be different on the two plates by almost 200,000 years, perhaps explaining our difficulty in simultaneously matching the older anomaly patterns on both plates (Figure 7). The thick and asymmetric sediment cover produces errors in bathymetry used for the top of the magnetic layer (assumed in our modeling to follow the seafloor) and can explain some of the anomaly misfit, but the most likely explanation is that some profiles have more than 5 jumps.

[34] These models have jump boundaries that become systematically younger to the south, consistent with *Vogt*'s [1971] important observation that the VSRs are diachronous (Figure 8 and Table 1). The propagation rates we derive for the A′, A, C and E propagators are ~110 km/Myr ± 30 km/Myr, with A fastest and C slowest, but the B propagator is significantly faster (~160 km/Myr) (Figure 8). According to these probably oversimplified models, the E scarp propagator was offshore southern Vestfirdir, as shown by its wake in the gravity pattern (Figure 1) ~17 Ma, the A scarp propagator left the area of the Snæfellsnes-Húnaflói fossil spreading axis (S in Figure 1) identified on land [*Sæmundsson*, 1979; *Hardarson et al.*, 1997, 2008] ~7–8 Ma, and the A′ propagator left the Reykjanes Peninsula rift axis between 3 and 4 Ma. If the plume center (or mantle heterogeneity) is moving eastward with respect to the ridge axis, as proposed to explain the large ridge jumps on Iceland [e.g., *Burke et al.*, 1973; *Sæmundsson*, 1979; *Hardarson et al.*, 1997, 2008; *White*, 1997], then most of the propagation events (except A′) on the Reykjanes Ridge would also have relocated the ridge axis closer to the plume.

10. Discussion

[35] We show that there may be an alternative explanation for the VSRs south of Iceland that have generally been interpreted as strong evidence for a pulsing plume. This does not disprove the pulsing plume hypothesis, although existing models must at least be modified by adding an additional mechanism to produce the observed VSR asymmetry, the most likely being rift propagation. One obvious possibility is that plume pulses provide the driving force for the propagating rifts, as proposed farther south along the MAR [*Brozena and White*, 1990]. The large steep outward facing bathymetric scarps produced by the A and E propagators (Figures 3 and 4) are significantly different from pseudofault scarps observed in other areas, and suggest abrupt increases in magma supply [*Vogt*, 1971, 1974; *Vogt and Johnson*, 1972; *White et al.*, 1995; *White*, 1997; *White and Lovell*, 1997; *Ito*, 2001; *Albers and Christensen*, 2001; *Smallwood and White*, 1998, 2002; *Jones et al.*, 2002; *Jones*, 2003; *Poore et al.*, 2006, 2009] associated with these propagators. If the propagators are driven by plume pulses existing models would need only slight modification. Pulses of plume temperature or material would still produce the VSR crustal thickness variations, but instead of supplying an existing Reykjanes Ridge axis, they would be producing gravity spreading stresses [*Phipps Morgan and Parmentier*, 1985] and new propagating ridge axes that reorganize the plate boundary geometry.

[36] However, if rift propagation is at least part of the correct explanation for the VSRs, the question naturally arises whether any additional mechanism such as a pulsing plume is also required. It appears possible that propagating rifts could interact with a steady state plume or mantle heterogeneity to produce many phenomena attributed to a pulsing plume and steady state ridge, including VSRs with crustal thickness variations. The large A and E scarps could conceivably result from abrupt increases in magma supply caused by propagators that greatly improve the plume-ridge plumbing system, and the troughs between the VSRs could conceivably form by propagating rift tectonics. Perhaps the "normal" situation in this anomalous area is a highly elevated ridge axis and unusually thick crust [*Hardarson et al.*, 1997, 2008], so that if there were no rift propagation the Reykjanes Ridge would have formed one giant V-shaped plateau. The troughs that alter the plateau to a series of VSRs might have formed as some combination of propagating rift/failed rift cold wall viscous effect during times of transitional near-zero spreading rates, producing local crustal thinning along the propagator wakes. This could explain why the troughs are so narrow, abrupt, and relatively uniform compared with the ridges (Figures 1, 3, and 5). Other mechanisms than pulsing plumes can drive propagators, e.g., gravity spreading stresses caused by elevated hot spot topography [*Phipps Morgan and Parmentier*, 1985], which would exist whether or not the plume is pulsing. In addition, nonplume models for Iceland have been proposed [e.g., *Anderson*, 2000; *Foulger and Anderson*, 2005], in which the melting anomaly results from an unusually fertile area of shallow upper mantle, perhaps resulting from an ancient recycled subducted slab, rather than a deep mantle plume. If the V-shaped troughs result from crustal thinning produced by rift propagation, rather than from a pulsing plume, there could be significant

implications for mantle geodynamics, and we hope our work will stimulate more theoretical effort to test these ideas.

[37] The observation that the VSRs are bounded by the broad southward pointing V with a tip near 57°N that separates young oblique structures from older orthogonal structures (Figure 1) is consistent with a propagating rift model. The angle subtended by the broad initial V (Figure 1) indicates much slower propagation (similar to the spreading half rate) than the subsequent acute VSR angles (at ~10× spreading half rate). Rift propagation explains this pattern naturally because the first propagator must do more work mechanically breaking cold lithosphere and eliminating the numerous ridge segments and transform faults that existed previously. Once broken, subsequent nested propagators break through younger lithosphere more easily and faster so the younger ones can catch up to the first one, as at the Easter Microplate [e.g., *Naar and Hey*, 1991]. Figure 1 indicates that this has happened at least 5 times. Later propagators suddenly slow as they catch the initial propagator, and replace or merge with it, because when that happens they become the trail-breaking propagator and encounter the same resistive stresses in the colder segmented lithosphere that slowed the previous propagator.

[38] Our model suggests explanations for some other apparent problems with existing pulsing plume models; for example, the VSR pattern south of Iceland appears to be considerably different than to the north (Figure 1). Rift propagation is a lithospheric phenomenon, and thus can explain this asymmetry as a result of the Tjornes FZ [*Sæmundsson*, 1974, 1979] inhibiting propagation (the age contrast and lithospheric thickness across the bounding transform fault is too great to allow easy propagation), whereas it is difficult to see why deep radially symmetric plume pulses should produce the observed north–south VSR asymmetry (or the north–south asymmetry in crustal thickness [*Hooft et al.*, 2006]). A similar point was made by *Sleep* [2002], who noted that plume material may be dammed by lithospheric relief associated with transform faults, with asynchronous breaching north and south of Iceland, whereas plume pulses should produce synchronous plume surges. Additionally, the narrow transform zone offsets of the propagators suggests a shallow driving mechanism (N. Sleep, personal communication, 2009).

[39] There are additional patterns in the Kolbeinsey Ridge area easily explained by rift propagation and not by pulsing plumes. The Spar Offset near 69°N (Figure 1) has been moved both north and south by dueling rift propagation [*Appelgate*, 1997]. Dueling rift propagation has been observed in many other places [e.g., *Johnson et al.*, 1983; *Macdonald et al.*, 1988; *Hey et al.*, 1995; *Korenaga and Hey*, 1996], but it is difficult to see why an outward flowing plume pulse would temporarily retreat back toward Iceland and then propagate away again. Furthermore, north of 69°N a sequence of lineated gravity ridges that might be analogous to the VSRs occurs only on the east flank of the Kolbeinsey Ridge axis (Figure 1). This is the pattern that would be produced by a sequence of propagators always breaking through North America and transferring lithosphere to Eurasia (a similarly consistent pattern is observed at the Easter Microplate [*Searle et al.*, 1989; *Naar and Hey*, 1991]). It is not the pattern expected from radial plume pulses interacting with an existing axis, which should produce structures symmetric about that axis.

[40] *Vogt* [1971] pointed out that conservation of mass requires radial flow velocities to decrease as the inverse of distance from the plume, so the curvature of the VSRs provides a test between channeled flow and radial flow (although as he noted even channeled flow should produce some curvature as material is used up forming new lithosphere). The evident VSR linearity (Figure 1) was originally used to argue for channeled flow [*Vogt*, 1971, 1974; *White et al.*, 1995], although *Ito* [2001] argued that channeled flow would require such low viscosities that much thicker crust would be expected under Iceland than observed. Radial models of pressure pulses that produce solitary waves [e.g., *Ito*, 2001] can have different flow rates than material flow models, and predict different VSR curvature, e.g., 16° of VSR curvature within 600 km of the plume in *Ito*'s [2001] radial flow model. The amount of curvature seen along the VSRs (Figure 1) can be debated, but they are certainly highly linear in our survey area, except near the tip of the A′ propagator. Thus, VSR linearity could be a problem for radial pulsing plume models. In contrast, propagating rift models predict linear wakes if the ratio of propagation rate/spreading rate is constant, and can match any curving pattern by varying that ratio.

[41] The propagating rift and pulsing plume models also predict different structures bounding the troughs between the VSRs, tectonic scarps in our model and constructional slopes in mantle flow models. *White et al.* [1995] argued that radial propagation of a 30°C warmer isotherm would create essentially instantaneous magma increases

along the axis that could produce the observed abrupt outward facing scarps. However, it is not clear that the tail end of a warm plume pulse would also produce an abrupt scarp down toward the axis at the proximal edge of each VSR. It seems that the inward facing V-shaped trough boundaries would be more gradual than the outward facing ones, unless they are tectonic scarps produced by rift propagation. Seismic reflection profiles [*Talwani et al.*, 1971; *Vogt and Johnson*, 1972] indicate similar inward and outward facing scarps bounding these troughs.

[42] One possible explanation for why so many more ridge propagation events are seen south of Iceland than on Iceland is that there have been equivalent numerous rift relocation events on Iceland, but evidence for many of them has been buried by eruptions from subsequent more successful plate boundaries [*Helgason*, 1984].

11. Conclusions

[43] We agree with many others that rift propagation is occurring away from the Iceland hot spot. We suggest that the same basic process is also acting at a different scale to either produce or help produce the V-shaped ridges, troughs, and scarps flanking the Reykjanes Ridge. Rift propagation involves tectonic rifting and magmatic deficits at the propagating and failing rift tips that can produce crustal thinning relative to steady state axes even without plume pulses. We show that a self-consistent kinematic model is possible that creates the observed asymmetric spreading and asymmetric V-shaped wakes by ridge jumps with jump boundaries coinciding with pseudofault scarps separating the VSRs and troughs. These propagators explain how the conjugate VSR scarps can be the same ages although obviously different distances from the axis. No other existing hypothesis produces both asymmetric accretion and V-shaped structures. This suggests that whatever else they may be, the VSRs are also propagating rift wakes, and that whatever the reason for the oblique Reykjanes Ridge geometry, the mechanism that maintains it is periodic adjustment by rift propagation.

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