Project Title: Test Between Thermal and Tectonic Hypotheses for North Atlantic Seafloor Spreading Geometry Reorganization

Project Short Title:	Bight Reorganization	**Project Status:**	Submitted
UNOLS Project ID #:	103031	**Version #:**	1
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Science Discipline: Marine Geophysics

Large Program Abbr:

If Other Science Discipline, specify:

Large Program Comments:

Project Status: New Proposal

Agency/Division/Program	Grant/Project Number	Agency Funding Status
NSF/OCE/MGG	1154071	Funded

Agency Description:

Institutional Proposal #:

Proposal Deadline submitted for: 8/15/2011

Project Start Date: 7/01/2012 **End Date:** 6/30/2015

Project Budget: $494,090

Year	Ship(s) Requested (Name Or Size)	Total Days Req.	Start Date	Repeat/Multi-ship/ Clearance Req./Est. Cost	Status
2013	Knorr	37	6/15/2013	N/N/Y/1531530	Submitted

Project Webpage:

Summary of Field Work: Multibeam and geophysical survey of southern end of Reykjanes Ridge and flanks near Bight FZ.

Summary of Facility Requirements: Multibeam, gravimeter, 2 magnetometers, 3.5 & 12 kHz profilers

Summary of Other Requirements or Comments: Dredge/wax core trawl winch and mechanical wire.

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PI Name:	Richard Hey	**Version #:**	1
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Funding Agencies:	NSF/OCE/MGG		

UNOLS Request ID #:	1004735	**Last Modified:**	8/03/2011
Request Type:	Primary	**Date Submitted:**	8/03/2011
Submitted By:	Richard Hey		

Year	Ship/Facility	Optimum Start	Earliest Start	Latest Start
2013	Knorr	6/15/2013	6/01/2013	7/31/2013

Dates To Avoid: early fall through early spring due to frequent storms in North Atlantic

	Science Days	Mob Days	DeMob Days	Transit Days (Est)	Total
Op Days Needed	33	2	2	0	37

Multi-Ship OP? No **Description:**

Repeating Cruise? No **# of Cruises:** 0 **Interval:**

Repeating Description:

Schedule Justification: Require large UNOLS ship for continuous multibeam and geophysical survey of Reykjanes Ridge and ancillary dredging/wax coring.

	Lat/Long	Marsden Grid	Navy Op Area
Beginning			NA01
Ending			NA04

Op Area Summary: Reykjanes Ridge

Op Area Size: 300x300 nautical miles

Op Area Details: Southern end of Reykjanes RIdge and flanks near Bight Fracture Zone

Foreign Clearance Required: Yes

Coastal States: Greenland, Iceland

Foreign Clearance Comments: Iceland, Greenland

Start Port: Reykjavik, Iceland

Intermediate Ports: None

End Port: Reykjavik, Iceland

Port Explanation: to provide useful transits to & from survey area

Chief Scientist: Richard Hey

 # in Science Party: 9 **# of Science Teams:** 1 **# of Marine Techs:** 1

Science Party Explanation: geophysical watchstanders, multibeam technician

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Instrumentation that affects scheduling

Dynamic Positioning
Multibeam
Dredging/Coring/Large Dia. Trawl Wire

Instrumentation Explanation: Ship multibeam system, gravimeter, 2 magnetometers, 12 kHz & 3.5 kHz profilers, dredge/wax core and trawl winch.

Major Ancillary Facilities

Ancillary Facilities Explanation:

Project Description: Introduction

There is a massive ongoing reorganization of North Atlantic seafloor spreading geometry occurring at present along the Mid-Atlantic Ridge (MAR) south of Iceland. The previous orthogonal ridge/transform staircase geometry typical of slow-spreading ridge systems is being progressively changed to the present non-segmented oblique spreading geometry on the Reykjanes Ridge as transform faults are successively eliminated. This fundamental plate boundary reorganization, obvious in gravity maps (Fig.1; Sandwell's website: http://topex.ucsd.edu/marine_grav/jpg_images/grav4.jpg; Sandwell & Smith, 2009) & magnetic anomaly maps (Fig. 2; Vogt et al., 1969; Vogt & Avery, 1974; Macnab et al., 1995; Merkouriev et al., 2008; Maus et al., 2009) initiated south of Iceland ~40 Ma (chron 17) & slowly extended south (Vogt, 1971; White, 1997; Jones et al., 2002). The tip of this reorganization phenomenon presently appears to be at or near the northernmost remaining transform fault south of Iceland, the Bight transform fault near 56.8°N (Fig. 1). This reorganization is presently interpreted as a thermal phenomenon, with a pulse of 50°C warmer mantle expanding away from the Iceland plume causing a progressive change in subaxial mantle rheology from brittle to ductile, so that transform faults can no longer be maintained (White, 1997). This explanation is nearly universally assumed to be true (White, 1997; White & Lovell, 1997; Smallwood & White, 1998,2002; Ito, 2001; Albers & Christensen, 2001; Jones et al., 2002,2010; Jones, 2003; Poore et al., 2006,2009,2011; Parkin & White, 2008; White et al., 2010) & is used to infer important conclusions about deep Earth & lithospheric geodynamics that are also nearly universally assumed to be true.

However, the thermal/ductile hypothesis has never been rigorously tested, although it makes testable predictions about the seafloor structural & magnetic fabric characterizing the reorganization tip & wake, & about the tip location. It is important to do this test because of the far-reaching implications of the thermal model for fields ranging from geodynamics (e.g. Ito, 2001; Jones et al., 2002) to hydrocarbon exploration (e.g. Parkin et al., 2007; Rudge et al., 2008) to global climate change (e.g. Wright & Miller, 1996; Poore et al., 2006,2009,2011), & because there is an alternative mechanism for seafloor spreading reorganizations, rift propagation, which does not include a brittle-ductile transition required by the thermal hypothesis. Given that the Reykjanes Ridge is certainly the most obvious & arguably the type-example of active plate boundary reorganization, it is somewhat surprising that a thermal mechanism has near universal acceptance here whereas most if not all other reorganization examples are thought to result from the tectonic rift propagation mechanism. These other well studied examples of plate boundary reorganization by ridge propagation include the Northeast Pacific "Zed" area, Juan de Fuca, Galapagos, Australia-Antarctic Discordance, South Pacific, Easter & Juan Fernandez microplates, Southeast Indian Ridge, & Mid-Atlantic Ridge (MAR) (e.g. Shih & Molnar, 1975; Hey & Vogt, 1977; Hey, 1977; Atwater, 1981,1989; Delaney et al., 1981; Johnson et al., 1983; Searle & Hey, 1983; Vogt et al., 1983; Wilson et al., 1984; Schilling et al., 1985; Caress et al., 1988; Hey et al., 1986,1988,1989; Macdonald et al., 1988; Wilson, 1988,1991; Atwater & Severinghaus, 1989; Kleinrock & Hey, 1989a,b; Kleinrock et al., 1989,1997; Searle et al., 1989; Cande & Haxby, 1991; Carbotte et al., 1991; Naar & Hey, 1991; Larson et al., 1992; Schouten et al., 1993; Cormier & Macdonald, 1994; Phipps Morgan & Sandwell, 1994; Gente et al., 1995; Wilson & Hey, 1995; Christie et al., 1998; Kruse et al., 2000; Conder et al., 2000; Scheirer et al., 2000; Briais et al., 2002; Marjanovic et al., 2011; Dannowski et al., 2011). Rift propagation is primarily a tectonic mechanism, & makes quite different predictions from those of the thermal model about the reorganization tip & wake structures. In particular, only the propagating rift hypothesis predicts the presence of a zone of lithosphere transferred from one plate to the other. The obvious test between these hypotheses is not presently possible because of the surprisingly large data gap at the tip of this reorganization.

We propose a month-long marine geophysical expedition to collect the multibeam, magnetics & gravity data that would provide a definitive test between the fundamentally different thermal & tectonic hypotheses for exactly how the Iceland plume (or whatever form of mantle convection or heterogeneity creates Iceland) caused the reorganization of the MAR south of Iceland. The data will be collected along best-estimate flowline profiles & will be sufficiently closely spaced for three-dimensional analysis. An important result of this test will be that modelers will either be confident that their thermal Reykjanes Ridge reorganization models are providing accurate information about Earth's behavior, or that they can confidently begin to model the correct mechanism instead. An additional benefit of this project will be the first accurate map of the Bight transform fault/fracture zone complex, known to be an important pathway for westward flow of North Atlantic mid-water circulation across the Reykjanes Ridge boundary (Bower et al., 2002), an important control on global climate change (Siedler et al., 2001).

North Atlantic Tectonic Evolution

There have been three distinct phases of North America - Eurasia seafloor spreading south of Iceland (Figs. 1,2; Vogt et al., 1969; Vogt, 1971; Vogt & Avery, 1974; White, 1997; Smallwood & White, 2002; Jones et al., 2002; Jones, 2003; Merkouriev et al., 2009). An initial orthogonally-spreading ridge system without transform faults was established immediately after Greenland - Eurasia breakup ~55 Ma, forming seafloor without fracture zones. This pattern abruptly changed ~42 Ma into a more typical slow-spreading orthogonal ridge/transform staircase pattern caused either by a change in seafloor spreading direction (Vogt, 1971; Vogt & Avery, 1974), or a decrease in the North Atlantic mantle temperature (White, 1997; Smallwood & White, 2002). Very shortly after, beginning at ~anomaly 17 time, ~40 Ma (Vogt, 1971; Vogt & Avery, 1974; White, 1997; Jones et al., 2002), the most recent fundamental reorganization of this plate boundary initiated south of Iceland. The orthogonal ridge/transform geometry that had just been formed began to be progressively eliminated by the southward-growing oblique Reykjanes Ridge. The tip of this reorganization phenomenon appears to have very recently reached at least to within 20 km of the Bight transform fault, commonly called the Bight fracture zone (FZ) near 56.8°N (Fig. 1). Whether this reorganization is continuing at present or is stopped at the Bight FZ is unknown. This is at the southern tip of the large-scale southwest pointing V shown in Figs. 1&2. This V as drawn is clearly oversimplified, but on a first-order scale separates seafloor formed on the oblique unsegmented Reykjanes Ridge system from older seafloor formed on the more typical orthogonally segmented slow-spreading ridge/transform system, such as those segments still active south of the Bight FZ. Whatever the mechanism involved, this was a major reorganization event in the plate tectonic history of the North Atlantic. Determining exactly how this ongoing major reorganization occurred is the object of this project.

Vogt & Johnson (1975) thought that the earlier transition <u>to</u> orthogonal spreading could readily be explained as the response of the spreading process to a change in spreading direction using the concept of Menard & Atwater (1968). This change in direction of Greenland-Eurasia seafloor spreading from ~125° to 100° was presumably caused by the termination of spreading on the Ran Ridge between Greenland & North America which happened about the same time. They noted that the ongoing transition from the orthogonal staircase geometry to oblique spreading was more problematic, but perhaps was caused by pipelike asthenosphere flow from the Iceland hotspot, either causing a more hexagonal tension regime in the lithosphere or by weakening the sub-axial lithosphere in such a way that new spreading would favor a reorientation to oblique spreading. Fig. 3 (from Vogt & Johnson, 1975) shows a conceptual model for how this evolution would occur if channelled pipelike asthenospheric flow from the Iceland hotspot following the overall oblique trend of the plate boundary heats, erodes, remelts & weakens the axial lithosphere overlying its path. Each progressively farther southwest ridge segment in turn would gradually feel the warmer asthenosphere & begin to gradually rotate into position with the soon to be colinear segment to the northeast, an example of "Zed-pattern" rotation by differential asymmetric spreading (Menard & Atwater, 1968). We describe this geometry in some detail because Fig. 3, although published 36 years ago, is the only figure we've found that actually shows how this ridge reorientation is supposed to have occurred in any existing model.

Vogt & Johnson's (1975) longitudinal flow model was based on Vogt's (1971) channelled "pipe flow" model, which was once the preferred explanation for how the plume interacts with the ridge axis, although it is now thought that his alternative radial plume flow model (Vogt, 1971) is correct. This is because recent geodynamic models strongly argue against channeled flow under the Reykjanes Ridge axis (Ito, 2001; Jones, 2002), as a consequence of melt extraction & dehydration (Hirth & Kohlstedt, 1996) producing a strong compositional lithosphere uniformly above the solidus depth. In these recent models there is no basal lithospheric relief (channel) associated with the ridge axis (or with transform faults); thus the Iceland mantle plume must be affecting the Reykjanes Ridge through radial rather than channelled flow, & Vogt & Johnson's (1975) asthenosphere flow model for the transition to oblique spreading must be modified somewhat.

White (1997) proposed the now accepted conceptual thermal mechanism, in which radial flow of warmer plume asthenosphere expanding away from Iceland progressively changes the lithospheric rheology from brittle to ductile. This evolution is described in words but not with a figure, but this progressive thermally-induced rheological change in behavior is similar to the thermally-induced lithospheric weakening model of Vogt & Johnson (1975) in two important ways. In both models the causative mechanism is lithospheric thermal weakening, & propagating rifts are not involved in either model, so presumably the detailed plan form evolution would be essentially as predicted by Fig. 3. Certainly no subsequent authors have thought that any revision to Vogt & Johnson's (1975) Fig. 3 schematic evolution was necessary, & ridge rotation, along with ridge propagation, are the two basic alternative seafloor spreading reorientation mechanisms known (Fig. 4, from Kearey & Vine, 2003). (A third possible mechanism would be an instantaneous "ridge jump" or "synchronous" reorientation as proposed for the Woodlark Basin (Goodliffe et al., 1997), but this mechanism does not apply here because a clear diachronous pattern is evident along the Reykjanes Ridge flanks).

Although there had been very brief suggestions that propagating rifts might have been involved (Johansen et al., 1984; Mercuriev et al., 1994), this was never accepted as the reorganization mechanism in this area. The reason the propagating rift alternative was ignored was that the younger seafloor record (Fig. 1) of the part of the Reykjanes Ridge flanked by V-shaped ridges (Vogt, 1971) seemed to prove that there had been no rift propagation (Johansen et al., 1984), while a great deal of data & modeling were interpreted as being consistent with a purely thermal origin of these structures. Thus the thermal model has always been assumed to be true. However, results from our prior work (Hey et al., 2010) show the strong probability of rift propagation farther north associated with the V-shaped ridges on the younger Reykjanes Ridge lithosphere, suggesting it is a possible explanation for this earlier reorganization as well.

Results from prior NSF support of Hey, Martinez and Höskuldsson

Award: OCE-0452132 - Investigation of Reykjanes Ridge Evolution Near Iceland
Amount: $373,394 *Dates:* 9/15/06- 8/31/11

Rift propagation had appeared to be impossible in this area because it had long been thought that the V-shaped ridges, troughs & scarps (VSRs) flanking the Reykjanes Ridge between 57°N & Iceland (Fig. 1) were symmetric about the axis (Vogt, 1971), & that seafloor spreading had been symmetric (Vine, 1966,1968). This was the conventional plate tectonic wisdom that led directly to the pulsing plume model (Vogt, 1971), & if it were true rift propagation, which must produce asymmetry, could not have occurred. However, our expedition collected marine geophysical data along seafloor spreading flowlines that showed that the VSRs are not symmetric about the spreading axis but instead have an asymmetric geometry consistent with rift propagation (Hey et al., 2010). Thus all previous models for VSR formation, including pulsing plume models involving series of rapidly expanding pulses of asthenospheric mantle or temperature which diachronously modulate magma production as they intersect the ridge axis, are at best incomplete, because none include or predict the asymmetry we documented, & so at the very least must be modified to include an additional asymmetry-producing mechanism. The best understood & most common of these mechanisms is rift propagation. Interestingly, the well-known & well-documented properties of propagating rifts (PRs) by themselves, without a pulsing plume or even a steady-state plume, can produce asymmetric & diachronous V-shaped crustal thickness variations (West, 1999; Kruse et al., 2000; Marjanović et al., 2011), which are also the essential features of the VSRs on the Reykjanes Ridge. It appears possible that PRs could interact with a pulsing or steady-state plume (or mantle heterogeneity, as non-plume models for Iceland have been proposed, e.g. Anderson, 2000; Foulger & Anderson, 2005), to produce many phenomena previously attributed to a pulsing plume & steady-state ridge, including VSRs. We emphasize that we have not disproved the pulsing plume hypothesis, & as we (Hey et al., 2010) noted "one obvious possibility is that plume pulses drive these propagators". However, diachronous VSRs with crustal thickness variations can be formed in more than one way, their asymmetric geometry here is consistent with rift propagation, not with previous pulsing plume models, & thus they can no longer be considered convincing proof of a pulsing Iceland plume.

In addition, a significant new result (Benediktsdóttir, 2011) is that excellent magnetic anomaly fits require some rift propagation toward Iceland, in addition to the propagation away from Iceland we previously identified. These new northward propagators predicted by her magnetic modelling explain some previously puzzling systematic gravity patterns. These newly identified propagators toward Iceland can't be driven by plume pulses even if the ones propagating away from Iceland are.

Broader Impacts on Education and Human Resources included that two of the students involved in the expedition & initial publications are minority students, & six are women. Three students participated in our cruise through the NSF-funded Marine Advanced Technology Education (MATE) program, which provides opportunities for practical at-sea internship experience to students. There was considerable media interest, & a middle school science teacher participated on the expedition & maintained a popular website. Our initial results have been reported at national & international meetings (Hey et al., 2007,2008,2009; Benediktsdóttir et al., 2008; Höskuldsson et al. 2009,2010a,b) & our initial paper was published in G-cubed (Hey et al., 2010). One M.S. thesis has been completed (Benediktsdóttir, 2011), two additional papers will be submitted as soon as this proposal is in (Benediktsdóttir et al., 2011a,b), & others are in various stages of preparation.

Our previous results show that rift propagation very likely contributed to VSR formation, suggesting this could also be a viable hypothesis for the large-scale diachronous North Atlantic reorganization wake bounding the VSRs, i.e. the causative reorganization mechanism could be tectonic instead of thermal as generally assumed. Unlike the fast small-offset propagating ridges inferred to have formed the VSRs, the larger offset & slower propagation at the Bight reorganization tip should provide a clearer opportunity to examine the mechanism of ridge reorientation on the Reykjanes Ridge. Whatever the cause, the tip of this reorganization is a very interesting place, & this tip presently appears to be near the Bight transform (Fig. 1).

The Bight transform fault

The Bight transform intersects the Reykjanes Ridge crest at 56°47'N, 34°06'W & separates the orthogonally spreading MAR axis to the south from the oblique spreading to the north (Applegate & Shor, 1994). The appropriately named Bight FZ, formed by the Bight transform fault, occurs at a large-scale magnetic bight in the NE Atlantic (Fig. 2; Vogt et al., 1969; Vogt & Avery, 1974; Klitgord & Schouten, 1986; Srivastava & Tapscott, 1986; Vogt, 1986a). The magnetic anomalies to the north trend NE-SW, parallel to the oblique Reykjanes Ridge axis, while those to the south trend N-S, parallel to the MAR axis farther south. From the time that seafloor spreading was initiated north of the Bight FZ between Greenland & Eurasia, ~55 Ma, this magnetic bight marked the location of the North America-Eurasia-Greenland triple junction. There is a nearly continuous (although complicated) connection seen in the gravity signal (Fig.1) between the North America-Greenland failed rift (Ran Ridge) & the Bight FZ. Thus the Bight transform, only 15-17 km long (Fig. 5, from Applegate & Shor, 1994), has been an important North Atlantic plate boundary for ~55 Ma.

The Bight FZ also has a strong influence on North Atlantic mid-water circulation. The MAR represents a significant barrier to inter-basin exchange between the Iceland & Irminger Basins, & currents flow preferentially through transform/FZ valleys to cross the ridge axis. Float data tracking Iceland-Scotland Overflow Water showed that five of the seven deep floats that crossed the ridge axis westbound into the Irminger Basin did so through the Bight FZ (Bower et al., 2002). A more accurate mapping of the depths & structural continuity of this tectonic feature & any associated structural deeps crossing the axis will thus be of value to physical oceanographers because it will improve detailed numerical simulations of North Atlantic circulation & thus the understanding of the transport of heat & fresh water across the MAR barrier, an important control on global climate change (Siedler et al., 2001). Given that the current Bight transform is known to be an important structurally (tectonically) controlled pathway for present-day north Atlantic circulation, it is likely that the previous elimination of transforms in this area had important oceanographic & climactic influences. Thus, a better understanding of the mechanism & evolution of transforms along this key flow pathway in the north Atlantic would be of value in paleo-oceanographic & paleo-climatic models. Our proposed study may also offer an alternative *tectonic* explanation to the correlations proposed by Poore et al. between the VSRs & changes in north Atlantic sedimentation & climate currently based on assumed plume thermal pulses.

The thermal & tectonic models require different explanations for why the initial Bight reorganization V subtends a much broader angle than the subsequent VSRs, showing that whatever caused it the initial reorganization progressed at a slower velocity than the subsequent events. Ridge propagation is fundamentally a lithospheric tectonic mechanism & so predicts initial slow propagation as transforms are first eliminated, with faster subsequent propagation events. The Bight propagator is the slowest because it faces large resistive stresses breaking through the ~1.5-1.7 Ma Eurasia lithosphere at this 15-17 km Reykjanes Ridge offset. Subsequent propagators are bounded by smaller offsets & propagate much faster (forming the VSRs as their wakes), but can't continue at the same velocity past the Bight reorganization tip because as soon as they do, they become the reorganization tip & face the same resistive stresses, resulting in the same slow rate the ancestral reorganization tips had while attempting to break through thick North Atlantic lithosphere.

Why the initial reorganization pulse is the slowest is unexplained by the thermal model. In models of an expanding mantle plume "pancake" subsequent plume pulses shouldn't have greater velocities than the earlier pulses as they would have to displace the earlier plume material outward even faster. Radial plume models involve sub-lithospheric flow of mantle material (e.g. White, 1997; Ito, 2001; Jones et al., 2002) & therefore should not be sensitive to lithospheric structures such as transform faults, so any interaction with these features is excluded as an explanation for the slow initial reorganization. Based on the regional gravity & bathymetric pattern, with shallower than normal depths extending south of the Bight FZ to the Charlie-Gibbs FZ (Fig. 6), it looks like the southern limit of Iceland plume influence is well south of the Bight FZ, yet that's the limit of the plate boundary reorganization & VSRs.

The thermal model (Figs. 3&4A) & tectonic model (Figs. 4B, 7&8) also predict distinctively different seafloor structural & magnetic patterns that should permit the elucidation of how this important plate boundary reorganization actually happened. The difference between these models is significant because only the thermal model requires transient convective circulation of the mantle & a delicate balance between brittle & ductile plate behavior. We propose to determine the geologic mechanism & detailed timing of the elimination of transform faults in this area to test between these fundamentally different hypotheses & allow future modeling efforts to confidently model the correct phenomenon.

The thermal model for Reykjanes Ridge reorganization

The accepted model (White, 1997) proposes that this ongoing reorganization results from a thermally induced change in lithospheric behavior from a 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 50°C warmer mantle expanding away from the Iceland plume progressively interacts with the ridge segments, reorganizing the geometry from orthogonal to oblique. Seismic, petrologic & modeling results are all interpreted as consistent with this thermal hypothesis, in which there is a delicate balance between the spreading rate & the crustal cooling rate (White, 1997; White & Lovell, 1997; Smallwood & White, 1998,2002; Ito, 2001; Jones et al., 2002,2010; Jones, 2003; Parkin et al., 2007; Parkin & White, 2008; Rudge et al., 2008; Poore et al., 2006,2009,2011).

According to this model, on normal slow-spreading ridges the rate of cooling exceeds the rate of heat input from igneous injections so faulting can extend down to the stronger mantle near the axis, while on fast-spreading ridges the higher rate of igneous injection means that conductive cooling cannot cool the mantle sufficiently to produce brittle behavior before the new lithosphere has moved away from the axis. On the Reykjanes Ridge the increased crustal thickness means that even at the slow spreading rates the mantle beneath the spreading axis remains sufficiently hot to behave ductilely for three reasons. First, the increased crustal thickness means that there is an increase in the frequency of melt injection. Second, the mantle temperature itself is somewhat hotter, perhaps 50°C, than it is away from mantle plumes, & so has further to cool before it becomes brittle. Third, & probably most importantly, the increased crustal thickness provides a thicker insulating layer which means that it takes longer for the underlying mantle to cool. Bell & Buck (1992), using similar arguments, suggest that the lower crust beneath the Reykjanes Ridge remains sufficiently hot to flow ductilely. Chen & Morgan (1990) similarly show that an increase in crustal thickness & in mantle temperature can account for the absence of a median valley on the Reykjanes Ridge (White, 1997). Increased melt flux may also suppress faulting (Ito & Behn, 2008) & therefore lower hydrothermal activity as observed on the Reykjanes Ridge (Baker & German, 2004) & thereby also suppress crustal cooling.

White (1997) concluded that "It is clear from the history of seafloor spreading in the North Atlantic that on slow- spreading ridges the normal pattern of crustal generation with axial valleys, fracture zones & orthogonal spreading is easily perturbed to a pattern without an axial valley & without fracture zones. There is a delicate thermal balance which controls the temperature of the lithosphere at the spreading axis, & which determines whether there is a ductile or brittle response to the lithospheric extension at the axis. A mantle temperature increase of as little as 50°C beneath the spreading axis causes a change from a brittle, fracture-zone dominated regime to a ductile spreading regime capable of supporting highly oblique spreading & without fracture zones or an axial valley".

Although no evolution figures were drawn in White (1997), or in any of the subsequent papers based on this idea that we're aware of (if reviewers know of any we'd appreciate the reference) to illustrate how this happens, this qualitative description is very similar to the evolution shown in Fig. 3 (Vogt & Johnson, 1975). There is no need for rift propagation in this model, so presumably it envisages a pattern of progressive continuous rotation of each orthogonal ridge segment in turn as the radially-expanding warmer isotherm reaches each subsequent segment & the plate behavior changes from brittle to ductile. This would produce ridge rotation by differential asymmetric spreading, faster to the NW & SE of each segment, & slower to the NE & SW, with no transferred lithosphere (Fig. 3).

As Vogt & Johnson (1975) noted, this is the same mechanism proposed by Menard & Atwater (1968) to explain the "Zed" pattern asymmetry observed in the NE Pacific (Fig. 4A). It was also proposed by Carlson (1981) to explain the ridge reorientation in the Juan de Fuca area. Although this reorganization mechanism was once universally accepted, & is still included in textbooks (e.g. Fig. 6.19 of Kearey & Vine, 2003), Menard & Atwater later changed their minds & agreed that the Zed area reorientations were actually accomplished by rift propagation (Caress et al., 1988; Hey et al., 1988; Atwater, 1989), rift propagation is almost universally accepted as the reorientation mechanism in the Juan de Fuca area (Hey, 1977; Hey & Wilson, 1982; Delaney et al., 1983; Wilson et al., 1984; Nishimura et al., 1984; Wilson, 1988; Johnson et al., 1989), & even textbooks (e.g. Kearey & Vine, 2003, Fig. 6.20; Cox & Hart, 1986) now agree that rift propagation is the common cause of ridge geometry reorganization.

Thus if the thermal model here is correct, the mode of reorganization in the North Atlantic is fundamentally different than that in most other areas, so it is important to test between it & the alternative tectonic model for this reorganization.

The tectonic model for Reykjanes Ridge reorganization

A propagating rift replaces a preexisting ridge with a different less-favorable geometry, often because of a change in plate motion, by breaking through existing lithosphere & transferring lithosphere from one plate to the other. A testable difference between this & the thermal model is that only this tectonic mechanism produces a wake including pseudofaults, a failed rift, & a zone of transferred lithosphere, which is often called an overlap zone or sheared zone because overlapping propagating & failing ridges with distributed shearing & bookshelf faulting between them occur in many areas (Figs. 7C,8; Hey et al., 1986,1989,1992,1995; Searle et al., 1989; Kleinrock & Hey, 1989; Naar & Hey, 1991; Wetzel et al., 1993; Korenaga & Hey, 1996; Scheirer et al., 2000; Conder et al., 2000). Transferred lithosphere can result from this kind of continuous rift propagation (Figs. 7B,C), or by discontinuous rift propagation (Fig. 7A), where chunks of lithosphere are torn nearly instantaneously off of one plate & added to the other. In either case there would be a failed rift that would not be expected in the thermal model. Thus the propagating rift model offers two basic endmember geometry possibilities for the reorganization V pattern, both significantly different from the thermal model zed geometry.

At the type-example Galapagos 95.5°W propagator (Fig. 8), the pseudofault pattern shows continuous propagation (Figs. 7B,C), & continuous lithospheric transfer (Figs. 7B,C), with gradually curving structures (Fig. 7C) resulting from distributed shear within a broad overlap zone as the propagating ridge accelerates from zero to full spreading rate, & the failing ridge decelerates to zero (Hey et al., 1986,1989; McKenzie, 1986; Kleinrock & Hey, 1989a,b). However, the Galapagos failed rift pattern of discrete en echelon grabens is that predicted by discontinuous rift failure (Fig. 7A; Hey et al., 1986; Kleinrock et al., 1989). This curious difference between continuous rift propagation but discontinuous rift failure has not been convincingly explained, & it would be interesting to see whether the same pattern is found along the slow spreading but magmatically robust Reykjanes Ridge.

Applegate & Shor (1994) collected a single Sea MARC II sidescan sonar swath in this area (Fig. 5), & concluded the Bight transform is a right-stepping 15-17 km offset along a single linear fault oriented 092°, nearly parallel to the local plate motion azimuth of 093° predicted by the MORVEL model (DeMets et al., 2010). This is consistent with the Sandwell & Smith (2009) satellite-derived gravity data (Fig. 1) & predicted topography (Fig. 6). This implies an equivalent 15-17 km wide transferred lithosphere zone bounded by a failed rift, similar in width to the Galapagos 95.5° PR (22-23 km).

The similar ratio of spreading rate to propagation rate at this hypothesized Bight PR to that at Galapagos 95.5°W means similar structural rotation is expected. The total angle subtended by the large-scale reorganization V wake is ~44° (Fig.1), so the average propagation rate predicted is ~22 km/Myr, & the structural & magnetic rotation predicted in the transferred lithosphere zone is ~39° (the relevant equations in various forms are in Searle & Hey, 1983; Hey et al., 1986; McKenzie, 1986; & most accurately according to our present understanding in Kleinrock, 1989). Thus the seafloor fabric in the zone of transferred lithosphere could closely resemble the Galapagos pattern (Fig. 8). However, it could also be more complicated as shown at the 21.5°N MAR (TAMMAR) propagator (Dannowski et al., 2011), where the transferred lithosphere fabric is dominated by the inward curvature of the overlapping propagating & failing rifts, as in Wilson's (1991) model. The clearly defined pseudofault/failed rift pattern is still compelling evidence for TAMMAR propagation (Dannowski et al., 2011), & would be at Bight as well even if the transferred lithosphere pattern is different from Fig. 8. The seafloor being transferred & rotated by the hypothetical Bight PR was created by orthogonal spreading ahead of the reorganization tip & should have had ridge-parallel fabric, so the rotation should be more obvious than if en echelon AVR fabric were being rotated.

The significant asymmetry of this big reorganization V (Figs. 1,2) shows that average lithospheric accretion was greater on North America than on Eurasia, i.e. most failed rifts would be on North America as expected at present at the right-stepping Bight transform. The predicted recent failed rift azimuth is 350°, but the detailed transferred lithosphere pattern depends on the detailed pattern of transform offsets that were eliminated (note that the predicted failed rift trend diverges from the inner pseudofault trend because of the right-stepping transform offsets eliminated).

This area is far from Iceland & has relatively thin sediment cover so it will be possible to map the structures with Seabeam. A sediment core (MD99-2254) at the exact latitude of Bight FZ, but 3° east, found sedimentation rates ranging from 6-19 cm/Kyr (Solignac et al., 2004), & typical sedimentation rates in the North Atlantic are a few cm/Kyr, or a few tens of m/Myr (e.g. Andrews et al.,1996). Vogt (1986b) concluded the average pelagic sedimentation rate in the Reykjanes Ridge area was variable, but averaged 37 m/Myr, consistent with rates from nearby DSDP sites 609 & 611 (Ruddiman et al., 1987). Thus the typical 75-200 m high seafloor abyssal hill structures & 200-500 m axial volcanic ridge relief in this area (Applegate & Shor, 1994) won't be buried for many million years. GLORIA data (Searle & Laughton, 1981) show abyssal hill fabric extending at least 100 km off-axis (~10 Ma) near 60°N, so Seabeam should reveal whether or not rotated fabric occurs in our predicted transferred lithosphere zone northwest of the Bight FZ.

The Bight data gap

Whatever is happening at the tip of this reorganization phenomenon, considering the obvious importance of this reorganization in the evolution of the North Atlantic, there is a surprisingly large data gap in this area. The structural patterns (Figs. 1,6,9,10) strongly suggest to us that the reorganization phenomenon very recently reached the Bight transform fault near 56.8°N (or a smaller discontinuity near 56.9°N), because all transforms between there & Iceland have been eliminated. In contrast, in the influential White (1997) model, because the reorganization is assumed to be a thermal brittle/ductile transition phenomenon, the end of transform faulting is predicted to coincide with the axial ridge/axial valley transition, which clearly occurs between 58.5° & 59°N (Fig. 1), probably explaining why the extensive British axial mosaic data (Keeton et al., 1998; Searle et al., 1998) ends at ~58°N instead of extending to the Bight transform fault (Fig. 9). However, it is clear that behind the Bight transform there is a continuous oblique plate boundary with no transform offsets (Fig. 1; (http://topex.ucsd.edu/marine_grav/jpg_images/grav4.jpg), exactly the pattern expected at a transform-eliminating reorganization tip, so in contrast to the White (1997) model we interpret the reorganization tip to be over 200 km farther along axis, in the Bight data gap. We encourage reviewers to look at the Sandwell & Smith (2009) map & see what you think. The non-coincidence of the end of the transform regime (56.8°N) & the axial ridge/valley transition (58.5-59°N) is problematic for the thermal model, as both phenomena are predicted to coincide with the onset of ductile behavior at the reorganization tip. In contrast, the tectonic model predicts the transform faults should end at the propagating rift tip, which is almost always an axial valley ahead of an axial ridge that takes some time to develop behind the initial tectonic rifting, as observed here &, e.g., at Galapagos 95°W (Fig. 8).

Fig. 9 shows the large gap in existing multibeam coverage, with our proposed survey polygon outlined. The mosaic area from 58°-59°N (Keeton et al., 1998) is Hydrosweep data from a 1990 Ewing cruise, & is well north of our predicted reorganization tip & transferred lithosphere zone, & is focused on the ridge axis, which is not our primary goal, although we will collect mosaic data that includes the part of the axis closest to the 56.8°N Bight tip. This would provide complete multibeam mapping of the oblique Reykjanes Ridge axis that begins at Iceland & ends at the Bight FZ, contrary to the thermal model, & allow comparative volcanic/tectonic studies of the entire ridge axis. A small amount of additional data reported by Keeton et al., which we also hope to obtain before our expedition, do not presently appear to be available through either NGDC or BRIDGE. Only a few multibeam swaths & a single SeaMarc II swath (Applegate & Shor, 1994) go through any part of our main survey area. The deep trough trending ~E-W near 56°47'N is probably part of the Bight transform (Applegate & Shor, 1994). Our predicted transferred lithosphere zone is NW of this structure, where no SeaMarc II & almost no multibeam data exists (Fig. 9).

Merkouriev & DeMets (2008, 2009) published the extensive Russian magnetic anomaly & single beam bathymetry data north of the Bight FZ. According to them, the survey tracks of systematic surveying were spaced at 5–7 km in the axial zone, & 15–20 km on the flanks of the ridge, & up to 50 km in the adjacent basins. The surveying accuracy was 0.5 km. The only bathymetric figure published with these data is from Merkouriev & Demets (2009). None of this Russian bathymetric data is multibeam (Merkouriev, pers. comm., 2010), & so is insufficient for our proposed test.

Fig. 2 shows that this area also has a significant data gap in the compiled aeromagnetic & ship magnetics data, partially filled by the Russian data. Searle et al. (1998) & Lee & Searle (2000) found several areas of high-amplitude crustal magnetization along the Reykjanes Ridge, including near the other 2 active PR tips hypothesized by Hey et al. (2010), consistent with results in other areas (e.g. Hey & Vogt, 1977; Hey et al. 1980), but a major data gap still exists at this third & most important of the hypothesized PR tips.

The extensive British rock sampling program (Taylor et al., 1995; Murton et al., 2002) began at ~57.5°N, well north of our proposed survey area, so there is also a significant sampling data gap at the reorganization tip. In case of equipment malfunction we will be prepared to wax core & dredge in this area to help fill this gap, & John Sinton at UH has indicated he would be more than happy to analyze any samples we collect (see attached letter of interest).

Additional test: reorganization wake linearity

Radial thermal anomaly expansion models (& to a much lesser extent channeled "pipe flow" models) predict that the flow must slow with distance from the plume (Vogt, 1971), & thus that the reorganization wakes must increasingly curve at a higher angle toward the axis. For example, Ito's (2001) radial flow model for the VSRs predicts 16° of curvature at 600 km from the plume. In contrast, tectonic pseudofault wakes are linear (great circles) if the ratio of propagation rate to spreading rate is constant. Interestingly, although the initial reorganization was far slower, comparable to the spreading rate, at a regional scale those boundaries also appear straight (Figs. 1,2) & not curved as radial spreading would predict. Thus reorganization wake linearity is another possible test between tectonic & radial thermal models. We propose to transit to & from the Bight survey area along the (better defined because of less sediment) North American limb of the reorganization wake to determine the linearity or curvature of this structure. Because the ~1000 km scale of this feature is big enough that flat-map distortions are important, this test is ideally conducted & demonstrated on a sphere, which will be possible using a "Magic Planet" projector that Dr. Jeffrey Gillis-Davis at HIGP has acquired.

Existing data (Figs. 1,2) suggest to us that, if the PR model is correct, sometimes this initial Reykjanes propagation was continuous, in areas where there appear to be continuous oblique pseudofault V wakes (& continuous oblique VSRs), & sometimes discontinuous, where fracture zones cut across this wake, marking periods when propagation temporarily stopped & thus fracture zones formed at the temporarily active ridge-transform offsets. Similar temporary transform-like offsets associated with propagation pauses are seen at a much smaller scale farther north along the axis (Benediktsdóttir, 2011).

Cruise Logistics

We suspect that once our survey has determined what mechanism is reorganizing the plate boundary geometry & defined the critical structures, geochemists & seismologists will be interested in detailed studies of these areas (as they were in the alternative 58.5-59°N tip area inferred from the thermal model), but we think the necessary first step is to produce high-resolution maps of these structures. This plan will allow us to survey at high speed & cover a broad enough area to guarantee that all of the critical structures & best sampling sites will be determined. All tracks except the transit tracks will be run in the survey area shown in detail in Figs. 9 & 10 along the predicted seafloor spreading flowlines. Estimates of the local azimuth of seafloor spreading here range from 092-098° (DeMets et al., 1990,1994,2010; Applegate & Shor, 1994; Merkuriev & DeMets, 2008; DeMets, pers. comm., 2010). The Fig. 10 flowlines shown, which seem to match the FZ trends the best, were calculated from the NUVEL best-fitting pole for North America - Eurasia (63.2°N, 134.5°E) & have a local azimuth of 096°. As the Reykjanes Ridge is spreading highly obliquely (~30°) to the ridge trend, only flowline profiles properly relate features on the flanks to the location of their origin on axis. Ridge-perpendicular or other non-flowline profiles that are later projected onto the spreading direction actually transect features originally formed at different axial locations & have led to miscorrelation of features between ridge flanks (Johansen et al., 1984; Hey et al., 2010).

The proposed survey polygon shown (Figs. 1,2,6,9,10) is somewhat schematic because we expect to refine it based on what we discover during the survey, e.g. if our survey suggests that ductile ridge behavior now appears to be occurring between the Bight & Charlie Gibbs FZs we would preferentially map farther to the south, or we may decide that the extreme SE corner of this survey area is less important to cover than spending extra time surveying some distance along the reorganization wakes on one or both sides to cover additional original stair-step segments. The tectonic model predicts that all conjugate parts of the wakes should be asymmetric (transferred lithosphere & a failed rift on one side, a simpler lithospheric juxtaposition on the other outer pseudofault side, but the sense of these asymmetries may alternate depending on how the original Reykjanes Ridge was segmented & how the Bight PR replaced these segments. The size of the survey area shown is based on a 6 km track spacing. Seabeam 3012-P1 on R/V Knorr, a convenient ship we have used before near Iceland, is a 120° beam system which collects multibeam bathymetry & backscatter in a swath 3.4 X water depth. Existing data near the area, & the single multibeam transit track through the area, show that although the ridge axes are ~2.5 km deep axial valleys, numerous near-axis structures are as shallow as 1 km (Fig. 9; Applegate & Shor, 1994; Searle et al., 1998; Keeton et al., 1998). We think that a complete mosaic is important for a definitive test of whether or not transferred lithosphere zones exist, & if they show structures predicted by continuous or discontinuous propagation, or whether zed patterns exist instead. Thus additional survey tracks between those shown will be necessary to fill in the shallowest areas. The total length of the 41 flowline tracklines shown is 4822 nm. Adding in the dogleg connections adds 130 nm for a total track length of 4952 nm. At a conservative survey speed of 10 kts this would take 495 hours or 21 days, & we propose to use another 6 days for fill-in between these initial tracklines, so the track spacing would be 3 km in the shallowest areas.

One way transit directly to Reykjavik would be 2 days; however by using one additional day each way we could collect 2 swaths along the western limb of the big reorganization V-wake shown in Fig. 1 from the Bight reorganization tip to an apparent intersection with the Greenland shelf, as well as 2 long flowline profiles from Greenland to Reykjavik which would help constrain the Greenland-Eurasia spreading history. For water depths of ~2.5 km suggested by the pattern of off-axis depths near the Iceland shelf (Hey et al., 2010), each transit swath would be ~8.5 km, so we would collect an ~17 km total swath along this boundary, about the predicted width of the predicted transferred lithosphere zone in our mosaic area, to test the radial flow model by determining the linearity of the reorganization wake, to extend our tip survey results, & to test for changes in reorganization behavior. For example, some zones could show continuous rotation, whereas others might show discontinuous patterns, as suggested by the fracture zones at or across the oversimplified boundary shown in Fig.1.

This survey will reveal the details of exactly what is happening at the tip of this reorganization phenomenon & provide the data for a definitive test between our tectonic model & the thermal model. Probably the least interesting result possible would be a detailed understanding of exactly how a thermal plume pulse reorganizes plate boundary geometry if there is no rift propagation, which would still be a significant result, so this project is guaranteed of success no matter what we find. Conjugate margins along these transform elimination events will be examined, providing multiple tests with varying transform offsets of these models. For example, the propagating ridge model predicts that one boundary should correspond to a simple "outer pseudofault" whereas the conjugate is a complex "inner pseudofault" incorporating transferred lithosphere & a failed rift (Figs. 4B,7,8). The thermal plume models predict no such structural asymmetries (Figs. 3, 4A). The survey will also determine the detailed timing of the elimination of the transforms through magnetic modeling of flowline profiles & full 3-D inversions for seafloor magnetization (e.g., Miller & Hey, 1986; Martinez et al., 1991). The gravity data would be used to investigate dynamic effects at the tip of this phenomenon (e.g. Phipps Morgan & Parmentier, 1986) as well as infer crustal thickness variations (Phipps Morgan & Blackman, 1993). Gravity will also help resolve basement variations near the outer edges of the survey box & transit along the older parts of the reorganization V limb where sedimentation may limit direct imaging of basement structure.

Thus we propose a 33 day multibeam, magnetics & gravity survey, using Reykjavik as our port. If a multibeam ship with a 3-component magnetometer is available we would happily use it, because rotation of magnetic vectors using this technique has documented PR shear zone rotations elsewhere (Korenaga & Hey, 1996). However, our proposed towed magnetometer data density should be high enough to carry out full 3-D magnetic field mapping & magnetization inversions, so a 3-component magnetometer is not required.

Summary

The Bight FZ area near 56.8°N appears to be the tip of whatever phenomenon is reorganizing the plate boundary geometry in the North Atlantic, whether caused by propagation of thermal warming or tectonic rifting. This area offers the possibility of a definitive test between these basic competing models for this major reorganization, i.e. the presence or absence of a zone of transferred lithosphere.

In the Bight FZ area our continuous PR model predicts that an ~15 km wide zone of lithosphere is being rotated ~40° counterclockwise. The discontinuous propagation model predicts that ~15 km chunks of Eurasia are transferred with essentially no rotation, producing a 30 km wide zone on North America symmetric about a failed rift axis. The thermal model predicts no lithospheric transfer or failed rift, but continuous ridge rotation & zed patterns. The presence or absence of a transferred lithosphere zone, predicted only by our PR model, should thus be a definitive test between models. The thermal model is generally accepted as the causative mechanism for this reorganization, with no necessity for an additional tectonic mechanism, in contrast to many other areas of the world where tectonic rift propagation is generally accepted, with no necessity for an additional change from brittle to ductile behavior. This project thus offers the potential for significant changes in our geodynamic understanding of the Iceland plume & how it produces its obviously large effect on North Atlantic evolution. Our tectonic model for this reorganization does not dispute that there is an important melting anomaly, possibly a plume, associated with Iceland & the Reykjanes Ridge. Rather it is an alternative proposal for how the large-scale plate boundary reorganization occurred, in which plate boundary processes superimposed on the Iceland melting anomaly need not necessarily involve deep-seated mantle plume pulses.

There is global significance in understanding the origin & dynamics of the Iceland-Reykjanes Ridge system, the type-example of hotspot-ridge interaction. Observations from & numerical models of this system have had considerable impact in many studies of global importance, including the origin of large igneous provinces, mantle convection & thermal evolution. These studies are used to estimate fundamental parameters such as the strength of active upwelling & melting rate beneath Iceland, which have been used in a wide variety of fields (e.g. White, 1997; White & Lovell, 1997; Smallwood & White, 1998,2002; Ito, 2001; Albers & Christensen, 2001; Jones et al., 2002; Korenaga et al., 2002; Jones, 2003; Sallares et al., 2005; Poore et al., 2006,2009, 2011; Parkin et al., 2007; Rudge et al., 2008; Hartley et al., 2011). A better understanding of the dynamics of the Reykjanes Ridge reorganization will be important for many geodynamic problems with wide-ranging implications.

Broader Impacts: Education and Human Resources

Resolving the origin of this large-scale plate boundary reorganization has important implications beyond testing a long-held fundamental assumption of Iceland mantle plume geodynamics. Thermal plume pulses have been interpreted as leading to regional uplift/subsidence events that modulate ocean currents & affect climate & sedimentation patterns throughout the North Atlantic. The proposed study will examine alternative tectonic explanations related to the mechanism & timing of the sequential elimination of transform faults in this area & thus has implications for inferred links among these phenomena. An additional benefit of this project will be the first accurate map of the Bight transform fault/fracture zone complex, known to be an important pathway for westward flow of North Atlantic mid-water circulation across the Reykjanes Ridge boundary, an important control on global climate change. The proposed work will involve significant international collaboration with Icelandic scientists, & will support a graduate student who will work on the survey data as a primary part of his/her thesis. As in our previous cruise we plan to mentor several undergraduate students at sea through the NSF-funded Marine Advanced Technology Education (MATE) Internship program & thus further NSF education & human resource development goals. Results will be integrated into classroom teaching by the P.I.s, & thus disseminated to a fairly wide audience including many underrepresented minority groups in Hawaii, enhancing scientific infrastructure. We think that improved understanding of this obviously important plate boundary reorganization will form an invaluable tool for further research & teaching, & we will make these data sets available on a project website. We think a movie of Reykjanes Ridge evolution projected onto a sphere could ultimately be a valuable teaching aid & museum display, & we will work with Jeff Gillis-Davis to make this available at the Bishop Museum in Honolulu & elsewhere. The University of Hawai`i has a plan for the appropriate training & oversight in the responsible & ethical conduct of research & teaching which we will use: http://www.ors.hawaii.edu/_library/documents/pdf-files/UH_RCR_Institutional_Plan_12-16-09.pdf. All data will be provided to the NSF R2R program & NGDC, satisfying all formal obligations as described in the Data Management Plan in Supplementary Documents.

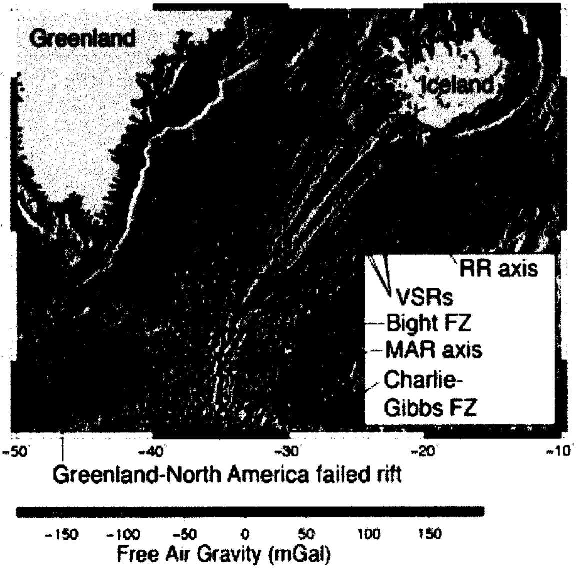

Fig. 1. Satellite gravity near Iceland (Sandwell & Smith, 2009), with oversimplified "big V" reorganization wake separating young oblique seafloor structures parallel to the present Reykjanes Ridge (RR) axis from older orthogonally-segmented ridge-transform fabric, & proposed survey polygon at its tip. The RR axis has become an axial valley in our proposed survey area. The Bight FZ is the E-W trending structure near 57°N extending west toward the failed Greenland-North America rift. The V-shaped ridges & troughs (VSRs) are enclosed by the reorganization V.

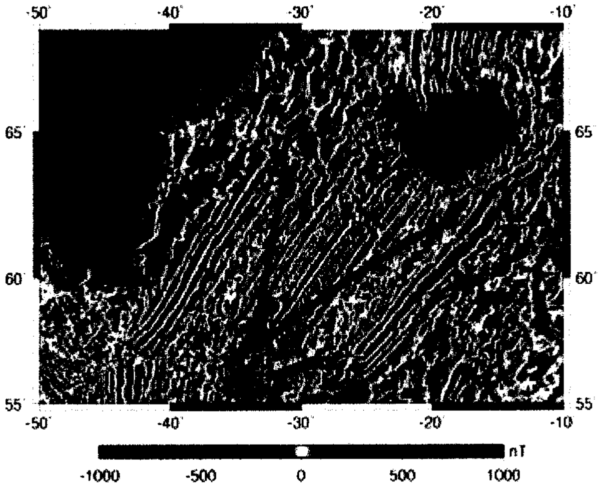

Fig. 2. Compiled magnetic data available through Geological Survey of Canada (Macnab, et al., 1995). The proposed survey will be along seafloor spreading flowlines parallel to the top and bottom of the survey polygon at the tip of the broad reorganization V at the Bight transform fault. Data gaps are shown in gray, partially filled by too sparse Russian data (Merkur'ev et al., 2009).

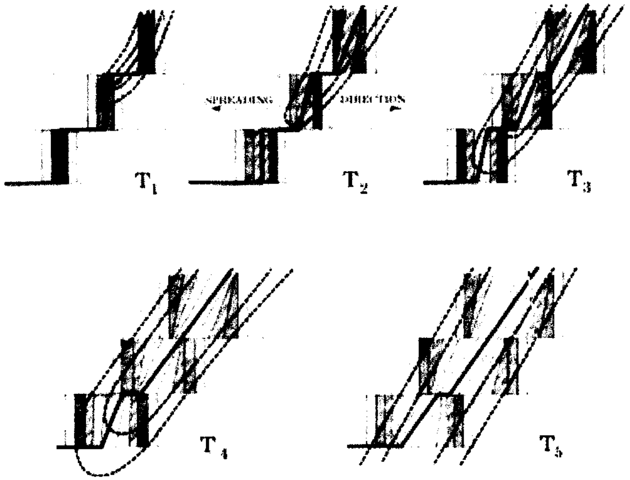

Fig. 3. Vogt & Johnson (1975) reorganization model, in which Iceland asthenosphere flow (dashed contours) thermally weakens axial lithosphere & progressively rotates each segment by differential asymmetric spreading, creating a sequence of "zed pattern" reorganizations (Fig. 4A, Menard & Atwater, 1968). This is also the type of reorganization described qualitatively in the White (1997) thermal model.

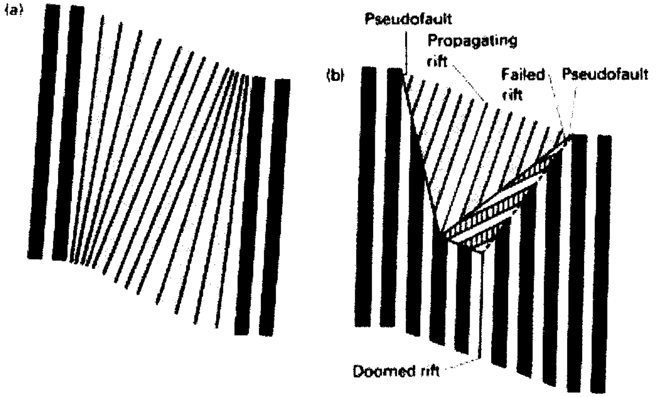

Fig. 4A) Ridge rotation mechanism of plate boundary reorganization (after Menard & Atwater, 1968) vs. B) reorganization by rift propagation. Only the propagating rift mechanism creates a failed rift & zone of transferred lithosphere (oblique isochrons between failed rift & inner pseudofault), & thus there is a definitive test between this & the Fig. 4A ridge rotation mechanism. From Kearey & Vine (2003).