**Plate boundary processes and small-scale mantle convection beneath the Reykjanes Ridge: Implications for mantle plumes and the nature of hotspots**

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**Abstract**: Because the Reykjanes Ridge intersects the Iceland hotspot, crustal features of the ridge and flanks have been interpreted as directly reflecting rapid mantle plume flow and temperature variations, providing long-standing arguments for a dynamic mantle plume beneath Iceland and the North Atlantic basin. Here we propose an alternate hypothesis: that plate boundary processes and small-scale buoyant mantle convection superimposed on a broad and relatively passive thermochemical mantle anomaly can instead explain these dynamic features.

The Reykjanes Ridge originated as a linear unsegmented axis spreading orthogonally. It became segmented following a change in plate opening direction. Segmented crust was thinner than unsegmented crust. The ridge then systematically and progressively eliminated the just-formed segmentation to reestablish its original geometry, even though it now had to spread obliquely to do this. Prominent ridge-flank V-shaped crustal ridges and troughs formed in this latest spreading stage. These features have been proposed to reflect dynamic mantle plume flow and temperature changes. Less explored has been how plate tectonic processes can instead account for them. The linear inception of a ridge may result from the linear geometry of continental breakup, not a planar vertical sheet of mantle plume flow. The abrupt segmentation of a ridge following a change in plate opening direction has been observed at other spreading centers to be a mechanical adjustment of the plate boundary to a new opening direction and need not involve mantle plume flow or mantle temperature changes. Thinner crust accreted in the segmented stage is a predicted effect of segmentation on plate-driven mantle upwelling and does not require regional or local mantle temperature changes. The elimination of ridge segmentation and offsets resulting in the reassembly of the axis back to its original linear configuration suggests a “memory” of the plate boundary zone due to a deep low-viscosity “wet” melting regime that remained linear following the abrupt change in opening direction and guided the reassembly of the axis. The reassembly mechanism of the segmented axis back to its original configuration was by lateral migration of individual organized spreading segments and their subsequent breakup to smaller segments to achieve a linear but now oblique plate boundary zone, not though a thermally-driven transition to ductile behavior. V-shaped crustal ridges can result from small-scale mantle upwelling instabilities propagating along the long, deep, linear and low-viscosity wet melting regime propelled by a regional gradient in mantle properties away from Iceland, instead of thermal pulses embedded in rapid radial mantle plume flow. This mechanism obviates the need for a high-viscosity dehydration layer to deflect the plume to avoid unrealistically thick crust predicted by the extremely rapid upwelling rates inherent in pulsing plume models. Stratigraphically-recorded uplift and subsidence events are a predicted effect of episodic buoyant mantle upwelling not transient mantle temperature pulses. Varying concentrations of incompatible elements in Reykjanes Ridge axial lavas are a predicted effect of varying the mode of mantle upwelling from a broad triangular passive melting regime to more focused upwelling during the passage of a buoyant small-scale instability, and need not require varying mantle temperatures.

The existence of the Iceland hotspot and associated regional excess melting on the Reykjanes Ridge may be explained by the slow advection of a broad low-viscosity thermochemical anomaly possibly from the deep mantle, as inferred from tomographic images. Or it may result from a mantle anomaly emplaced by ancient subduction and continental suturing events. This mantle anomaly may have existed passively below solidus depths prior to North Atlantic continental rifting. As this low-viscosity fertile mantle rose above the solidus, driven by initial continental rifting and subsequent seafloor spreading, shallow melt-induced small-scale convection would produce the excess hotspot melting, rather than a rapidly rising hot mantle plume jet. Observed elevated volatile content in erupted lavas along the Reykjanes Ridge peaking beneath Iceland indicate that the anomalous mantle has low-viscosity and a lowered solidus temperature, properties that promote vigorous small-scale convection, so that high temperature or highly fertile mantle material (eclogite) are not required to produce excess melting. Thus, dynamic crustal features of the North Atlantic basin can be explained as the direct result of plate kinematics, plate boundary processes and small-scale upper mantle convection (which can evolve rapidly) superimposed on and enhanced by a broad and relatively passive thermochemical mantle anomaly.

**Introduction**: The North Atlantic basin records a remarkable set of diverse crustal features and tectonic events superimposed on a regional mantle anomaly. Crustal thicknesses peak at about 40 km beneath Iceland [*Darbyshire et al.,* 2000], thick crust of the Greenland-Iceland-Faroe Ridge extends across the basin, and crustal thicknesses gradually decrease from about 11 km on the northern Reykjanes Ridge [*Weir et al.,* 2001] to more typical ~6.5 km thick crust of slow-spreading ridges south of the Charlie Gibbs Fracture Zone [*Whitmarsh and Calvert,* 1986]. The margins of the basin record the continental rifting events and breakup that initiated seafloor spreading on a long linear ridge and the subsequent spreading history of the ridge records the response of tectonic events on crustal accretion. An abrupt change in opening direction of ~ 30° is associated with a regional tectonic reconfiguration of the entire basin. Transform faults and offset ridge segments abruptly formed oriented orthogonally to the new spreading direction and were subsequently diachronously eliminated by ridge segments migrating laterally, fragmenting and merging to re-form the original linear geometry. As a result, the new linear plate boundary zone is presently oriented about 30° oblique to the opening direction although individual axial volcanic ridges within this zone are arrayed en echelon and retain their nearly orthogonal orientation to the spreading direction. Prominent V-shaped crustal ridges and troughs formed as the plate boundary zone became linear and oblique, created as discrete melting anomalies rapidly migrated southward along the axis and the resulting variations in crustal thickness were passively spread onto the ridge flanks. As Iceland is often viewed as the volcanic center of a classic (hot, narrow and rapidly rising) mantle plume (Morgan, 1971) and the Reykjanes Ridge intersects this feature, almost all of the crustal structures of the ridge and its flanks have been interpreted in terms of dynamic variations in mantle plume flow and temperature. Here instead we propose a new hypothesis: that plate boundary processes, plate kinematic changes, and small-scale mantle convection can explain the dynamic features of the basin previously ascribed to mantle plume behavior, and that these processes are superimposed on a broad and relatively passive mantle anomaly extending beneath the North Atlantic basin [*Cochran and Talwani,* 1978]. Because these plate tectonic explanations have been less-studied and explored in the context of the Reykjanes Ridge than prevalent “pulsing” plume models, we often refer to better studied cases to illustrate analog tectonic and geodynamic processes that have not been applied to the Reykjanes Ridge.

**Background: Pulsing plume models**

Long-standing models for Iceland, the Reykjanes Ridge and the North Atlantic basin invoke the presence of a mantle plume, a rapidly upwelling narrow jet of hot mantle material originating from near the core-mantle boundary [*Morgan,* 1971], to explain the anomalous crustal thickness at Iceland and regionally within the North Atlantic basin [*White,* 1997]. This model has several variants to account for specific features of Iceland, the spreading ridge, basin, and margins. A general feature of these models, however, is a rapidly rising narrow jet of hot mantle material that spreads laterally beneath the lithosphere. In plume models, the Reykjanes Ridge provides a key indicator of plume behavior since, as a seafloor spreading center, its crustal accretion over time is presumed to record changes in plume flow and temperature. This underlying assumption has guided the interpretation of many studies of the North Atlantic basin. The ridge is flanked by acute V-shaped crustal ridges and troughs that have been interpreted as formed by rapid mantle plume flow with embedded temperature variations upwelling beneath Iceland and then radially expanding beneath the North Atlantic basin, or channeled beneath the Reykjanes Ridge axis [*Vogt,* 1971]. The roughly symmetric V-shaped ridges are inferred as formed by the temperature pulses migrating along the ridge axis and locally inducing increased melting resulting in increased crustal thicknesses at the ridge axis. As crust passively spreads away from the axis, the axially produced crustal thickness variations would generate V-shaped patterns of crustal thickness on the ridge flanks. Since the spreading rate on the ridge is well-known from magnetic isochrons, the angle that the flanking crustal ridges make with the axis is a direct measure of the along-axis flow of mantle plume material and the embedded thermal anomalies: *v = u / tan θ*, where *v* is the along-axis propagation rate of plume flow and thermal anomalies, *u* is the half spreading rate and *θ* is the angle between the crustal ridge and the spreading axis. We refer to these type of models generally as “pulsing plume” models as first proposed conceptually by *Vogt* [1971] and geodynamically modelled by *Ito et al.* [1999] and *Ito* [2001]. Using the geometry of the V-shaped ridges, estimates of the along-axis flow rate (*v)* have ranged from 200 [*Vogt,* 1971] to over 1000 mm/yr [*Wright and Miller,* 1996] (i.e., from about 20 to over 100 times the half spreading rate). Most geodynamic models currently predict radial spreading of the plume [e.g., *Ito,* 2001] and assume a narrow (~150 km radius [*Wolfe et al.,* 1997]) plume stem so that the upwelling rates within the plume stem are predicted to be even faster than horizontal flow rates in the plume head due to radial spreading (increasing toward the plume stem as 1/r of the plume stem radius). Thus, in pulsing plume models hot mantle material within the plume stem is predicted to be upwelling at rates of several 100 to several 1,000 mm/yr as a geometric requirement of their interpretation of the process forming the V-shaped ridges. *Ito et al.* [1999] and *Ito* [2001] recognized that such rapid upwelling rates of hot mantle material would generate unreasonably large crustal thickness (hundreds of km) by decompression melting on crossing the solidus. Since the plume is assumed to be ridge-centered there is essentially no thermal lithosphere to prevent the rapidly upwelling mantle from crossing the solidus and melting extensively. Plume melting would occur entirely within the upwelling plume stem and highly depleted residual mantle would flow horizontally and not generate V-shaped ridges [*Ito,* 2001]. To avoid these problems, these authors [*Ito,* 2001; *Ito et al.,* 1999] proposed that mantle material above the solidus becomes dehydrated by melt extraction and increases in viscosity by several orders of magnitude such as to deflect the plume laterally below the solidus. In this model, it is only plate-driven spreading that allows a small fraction of mantle plume material to flow above the solidus and melt in a passively-driven ridge melting regime. An unstated corollary of this model is that if spreading were to cease, all plume melting would also cease as plume material would be entirely deflected horizontally below its solidus by the high-viscosity dehydration layer. The model makes no allowance for low-degree melting in a deep “wet” melting regime or other mechanism of mantle plume melting, instead emphasizing the importance of the high-viscosity dehydration layer and passive plate-driven advection above the solidus for the formation of V-shaped ridges [*Ito,* 2001; *Ito et al.,* 1999]. A further unstated corollary of this model is that it should also preclude plume melting at intraplate settings such as Hawaii, where a dehydration layer should also exist and additionally be embedded within a 90 Ma thermal lithosphere, producing an even greater rheological barrier to deflect the plume, with no plate spreading to advect any part of it above the solidus.

Thus, ridge-centered pulsing plume models present a dilemma for plume models in general. They require a rheological boundary to deflect the rapidly upwelling hot plume material in the stem and prevent unreasonably large crustal thickness being produced by decompression melting, yet the rheological boundary would preclude melting at any plume not centered on a ridge as mantle dehydration should be a general property of all oceanic lithosphere that has had a crustal layer produced by mantle melting [*Hirth and Kohlstedt,* 1996; *Phipps Morgan,* 1997].

**Changes in segmentation and crustal thickness on the Reykjanes Ridge**

The pulsing plume model has become central to several other models related to Iceland, the Reykjanes Ridge, its flanks, and the evolution of North Atlantic basin in general. Beyond the V-shaped ridges themselves, large-scale tectonic reconfigurations of the North Atlantic basin have been interpreted to be controlled by regional mantle plume flow and temperature variations. It is argued by several workers that the formation and later elimination of transform faults and segmentation on the Reykjanes Ridge is a consequence of mantle plume temperature [*Abelson and Agnon,* 2001; *Abelson et al.,* 2008; *Jones,* 2003; *Merkur’ev et al.,* 2009; *White,* 1997]. These models assume that transform faults cannot form during periods of hot mantle plume flow beneath the basin because it induces a transition to ductile behavior in the lithosphere. As supporting evidence, some models cite reduced crustal thicknesses during the segmented stages of spreading as indicators of lower mantle temperatures and therefore depressed melting relative to the unsegmented stages of spreading.

Yet in other oceanic basins the formation of transform faults has been shown to be a purely mechanical effect of an abrupt change in plate opening direction. Probably the best-studied example occurs in the Parece Vela basin of the Philippine Sea Plate where an abrupt change in opening direction led to the synchronous formation of a set of closely-spaced transform faults from a previous spreading system without transform faults along more than 1000 km of divergent plate boundary [*Okino et al.,* 1998]. Other well-documented examples of changes in ridge segmentation following abrupt changes in opening direction occur in the Northeast Pacific [*Caress et al.,* 1988; *Hey et al.,* 1988] and the Woodlark basin [*Goodliffe et al.,* 1997]. The lack of hotspot activity in these areas and the essentially synchronous nature of the change in segmentation spanning hundreds to thousands of km along the plate boundary argue against a mantle thermal effect. Because plates are rigid changes in motion must be accommodated along their entire plate boundary zones synchronously. In contrast, it is difficult to explain how thermal changes could regionally affect enormous volumes of mantle to cause synchronous changes in plate boundary configuration over length scales on the order of 1000 km.

Furthermore, the observed change in crustal thickness associated with the change in ridge segmentation on the Reykjanes Ridge [*White,* 1997] is a predictable effect of segmentation itself on mantle advection, requiring no change in mantle temperature [*Phipps Morgan and Forsyth,* 1988]. The basic physical principles involved were demonstrated in a numerical model by *Phipps Morgan and Forsyth* [1988]. A long, linear (2-D) ridge generates a maximum plate-driven vertical advection for a given spreading rate. If the ridge becomes multiply segmented and offset, then mantle can flow into the area of the melting regime horizontally from across the segment ends and this flow accommodates some of the volume that would otherwise have been taken up by vertical advection. This effect decreases the total vertical mantle advection produced by a segmented ridge compared to a linear unsegmented ridge for the same spreading rate. In purely plate-driven models of passive mantle flow [*Phipps Morgan and Forsyth,* 1988], the effect of horizontal mantle advection across segment ends is the principal cause for crustal thinning approaching a transform fault. This effect may extend over an along axis length of 40 km or more from the segment end, as observed seismically and modeled from Bouguer gravity anomalies [*Whitmarsh and Calvert,* 1986]. For the Reykjanes Ridge, where during the segmented stage of spreading, the ridge lengths were on the order of 50 km long and offset by about 30 km transform faults the segmentation effect on mantle advection extends over the entire spreading segments. Thus, upon becoming segmented, the vertical mantle advection on the Reykjanes Ridge decreased by about 30% causing a corresponding decrease in crustal thickness with no mantle temperature change.

A further demonstration that high mantle temperatures or high melt productivity does not eliminate transform faults by inducing ductile behavior is provided by the existence of the Tjornes transform fault immediately adjacent to northern Iceland itself and within the broad shallow volcanic platform surrounding the island. The Tjornes transform fault is a long-lived (7-9 My) major fault zone connecting the Northern Rift Zone on Iceland with the Kolbeinsey Ridge [*Gudmundsson et al.,* 1993; *Rognvaldsson et al.,* 1998]. It is very seismically active sustaining major earthquakes up to magnitude 7, demonstrating brittle behavior and the ability to accumulate large seismic stresses. This major tectonic feature of Iceland has persisted across several inferred plume pulses and during the inferred plume advance that, in pulsing plume models, eliminated the transform faults along the Reykjanes Ridge [*Jones,* 2003; *White,* 1997]. The proposal that high mantle plume temperatures can eliminate transform faults by inducing ductile behavior in the lithosphere is also conceptually belied by the inference of a strong rheological layer capable of deflecting the flow from the plume center itself without becoming thermally eroded [*Ito,* 2001]. Presumably, the rheological layer extends throughout the oceanic lithosphere and the Reykjanes Ridge transform faults are embedded within this highly viscous layer, as it is modeled to be flat at its base and extend to solidus depths [*Ito,* 2001]. How then can the Iceland plume thermally weaken transform faults to ductile behavior up to 1000 km away from the plume center when they are embedded within the same the rheological boundary that is not thermally weakened even directly above the plume stem?

**Uplift and subsidence and North Atlantic basin stratigraphy**

Other proposed effects of the pulsing plume model are isostatic uplift and subsidence events across the North Atlantic basin specifically affecting the shallow Greenland-Iceland-Faroe ridge such as to control deep water flow across this boundary and associated sedimentary sequences [*Poore et al.,* 2011; *Poore et al.,* 2009; *Poore et al.,* 2006; *Wright and Miller,* 1996]. The isostatic changes are proposed to be caused by the temperature pulses embedded within the radiating mantle plume flow. These authors only consider thermal plume-related explanations for these observations. Another general cause of uplift and subsidence unrelated to mantle plume activity is small-scale mantle convection produced locally. This effect has been proposed to influence a broad range of phenomena, from rift-shoulder uplift [*Buck,* 1986] to regional sedimentary sequences in basins [*Petersen et al.,* 2010]. As we argue later, vigorous and pronounced small-scale buoyant mantle convection is predicted by the elevated water contents along the Reykjanes Ridge, peaking beneath Iceland [*Nichols et al.,* 2002], which lead to a pronounced lowering of the mantle solidus temperature by hundreds of degrees [*Katz et al.,* 2003] and a lowering of mantle viscosity by at least two orders of magnitude [*Hirth and Kohlstedt,* 1996]. Especially strong episodic convective cells, promoted by an enhanced volatile content [*Nichols et al.,* 2002] lowering of the mantle solidus and viscosity, could lead to uplift and subsidence events affecting the regional sediment stratigraphy and correlating with the V-shaped ridges, which we also propose are generated by this mechanism [*Martinez and Hey,* 2017]. Thus, the locally-produced upper mantle small-scale convective instabilities can explain the uplift and subsidence events affecting the Greenland-Iceland-Faroe ridge and North Atlantic basin stratigraphy as well as explain the formation of crustal V-shaped ridges.

**A new model: Plate boundary processes, small-scale buoyant mantle advection and changing plate kinematics superimposed on a broad and passive mantle anomaly.**

Our proposal for a non-mantle plume model for the dynamic features of the Reykjanes Ridge is based on the observed ability of processes that have been documented at normal mid-ocean ridges to account for rapid plate boundary evolution and changes in crustal thickness. Yet clearly something else is going on as otherwise the Reykjanes Ridge would be a normal mid-ocean ridge. A significant anomalous feature of the North Atlantic basin is a large regional basement depth anomaly peaking beneath Iceland and extending at least to the Jan Mayen Fracture Zone to the north and the Charlie Gibbs Fracture Zone to the south. Anomalous depths and associated gravity anomalies have been recognized extending beyond these areas and attributed to an upper mantle anomaly, with possibly moderately elevated temperatures (~75°C) [*Cochran and Talwani,* 1978]. Combining these two elements we propose that the anomalous features of the North Atlantic basin can be explained by kinematic changes, plate boundary processes and small-scale buoyant mantle convection superimposed on a regional upper mantle anomaly that itself is relatively passive (that is, slowly evolving relative to the kinematic, plate boundary and small-scale convection). In this model, small-scale buoyant mantle advection is a primary cause of excess melting enhanced by elevated mantle volatile concentrations increasing toward and peaking beneath Iceland and possibly moderately elevated temperatures. The compositional gradients create even more pronounced gradients in mantle properties (solidus temperature and viscosity) that drive convective instabilities rapidly along the ridge axis in a wave-like manner, without actual along-axis flow of mantle material. The wave-like propagation of convective instabilities along a long and linear ridge axis removes the need for extreme upwelling rates beneath a mantle plume stem, obviating the need for a highly viscous dehydration layer to defect the rapidly rising plume and avoid unrealistic and unobserved crustal thicknesses beneath Iceland. Below we develop each part of this new model focusing on geologic and geophysical observations that support it, as geodynamic experiments have only begun to explore its physical mechanisms.

**Asymmetric Crustal Accretion**

Recent marine geophysical surveys [*Benediktsdóttir et al.,* 2012; *Hey et al.,* 2010] have shown a small but systematic asymmetry in crustal accretion on the unsegmented oblique axis of the Reykjanes Ridge. Systematic and progressive shifts are recognized in isochrons position from profile to profile in the GPS-navigated flowline magnetic data. These data identify discrete propagation events on the recent unsegmented part of the Reykjanes Ridge, some of which propagate toward Iceland, but the majority propagate southward [*Benediktsdóttir et al.,* 2012]. The best understood mechanism for generating crustal asymmetries of this type is rift propagation [*Hey,* 1977], where an offset ridge axes lengthen along its strike and replaces an adjacent axis where both axes form part of the plate boundary between the same two plates. The tectonic boundary separating the crust formed on the propagating axis and that formed on the dying axis is termed a pseudofault, and forms a V-shaped geometry where the tangent of the angle that the pseudofault makes with the ridge axis is the ratio of the half spreading rate and the propagation rate. Propagating rifts are well-understood tectonic phenomena whereby lithospheric material is transferred from one plate to another resulting in asymmetric crustal accretion. However, the rift propagation events on the Reykjanes Ridge form a distinct class of plate boundary evolution. Although clearly identified by systematic shifts in magnetic isochrons, the Reykjanes Ridge propagating rifts do not involve a discrete axis lengthening and replacing another discrete axis. All the ridge propagation events identified are within the ~10-15 km width of the oblique Reykjanes Ridge plate boundary zone [*Benediktsdóttir et al.,* 2012]. Since divergent plate boundary zones are characterized by distributed tectonic and volcanic activity [*Macdonald,* 1982] accommodating extension diffusely before the plates become essentially rigid on the flanks there is no discrete axes replacing another discrete axis in the case of the Reykjanes Ridge propagation events. The center of accretion systematically shifts along the plate boundary zone, but there is only one plate boundary zone. Thus many of the characteristics of propagating rifts are not developed in this setting, including identifiable transferred lithosphere [*Kleinrock and Hey,* 1989a], a tectonically rifted propagator tip and progressively developing magmatism along the propagating axis [*Kleinrock and Hey,* 1989b] and characteristic geochemical anomalies (Fe-Ti basalts) [*Christie and Sinton,* 1981]. Because of the short offsets implied by the magnetics data, it is likely that the propagation “events” share the same melting regime as well as plate boundary zone and are shallow crustal phenomena. The question of what exactly is “propagating” in these events is not clear from present data, but we offer a tentative explanation below.

The plate boundary zone of the Reykjanes Ridge is characterized by small volcanic constructions a few km wide and up to a few tens of km long and several hundred m high termed axial volcanic ridges (AVRs) [*Martinez and Hey,* 2017; *Parson et al.,* 1993; *Peirce and Sinha,* 2008; *Searle et al.,* 1998]. On the Reykjanes Ridge axis, the AVRs are oriented approximately orthogonally to the plate opening direction and are therefore arrayed in a right-stepping en echelon configuration to accommodate the oblique geometry of the plate boundary zone with respect to the plate opening direction. In this configuration if individual or small groups of AVRs locally propagated southward they would effectively move the center of volcanism (represented by the ensemble of AVRs) to the east of the plate boundary zone and transfer crust to the west. This process would have to take place locally and not along the entire plate boundary zone, at least not at the same rate, as that effect would mimic continuous asymmetric spreading and not be detected as propagation events in the magnetic profiles. What driving mechanism could favor the local propagation of individual or small groups of AVR’s rather than a continuous propagation of all the AVRs? One potential driving mechanism is the fact that the Reykjanes Ridge axis is moving southwestward with respect to the deeper mantle [*Gripp and Gordon,* 1990]. Assuming that there is some lag between the plate boundary location at the surface and the locus of deeper mantle advection driven by viscous coupling to the plate separation, then the upwelling zone would tend to lag to the east of the plate boundary zone. This effect would tend to favor melt generation and volcanism slightly to the eastern side of the plate boundary zone, so that AVRs would tend to propagate southward and thus relocate to the east above the zone of greatest melt production. This effect by itself, however, would tend to favor a continuous propagation of all the AVRs. A secondary effect that could favor local propagation of AVRs is the migration of small-scale buoyant instabilities along axis, as we describe in more detail later. The passage of a buoyant instability and its associated enhanced melting could promote the local propagation of AVRs to maintain their position over this favorable volcanic locus. These two effects may explain local propagation of AVRs and the correlation of magnetically identified propagation events with the V-shaped ridges and troughs [*Hey et al.,* 2010]. Thus, the propagation events on the Reykjanes Ridge that are identified magnetically [*Benediktsdóttir et al.,* 2012] are not likely the direct causes of the V-shaped ridges and troughs, as the implied offsets are too small to generate crustal thinning and the other characteristic features of true ridge propagation as descried above. Rather, it is the axially migrating buoyant upwelling instabilities that directly generate the crustal thickness variations that form the V-shaped ridges and troughs, and promote the local propagation of AVRs within the plate boundary zone to generate the magnetically identified propagation events.

**Formation and elimination of segmentation on the Reykjanes Ridge**

* The synchronous segmentation of the ridge and subsequent diachronous removal of segmentation involved plate boundary processes causing asymmetric seafloor spreading and ridge segment migration, not changing mantle temperatures.
* The large-scale plate boundary reconfigurations of the Reykjanes Ridge that removed segmentation progressed in a series of rapid steps separated by pauses, indicating a plate boundary control related to removal of segmentation offsets, not progressive mantle thermal effects.

**Reassembly of the ridge axis and “memory” of the melting regime**

* The removal of segmentation is shown by geometric plate reconstructions to reassemble the original linear and unsegmented configuration, even though now the opening direction has changed by ~30° so that oblique spreading is required.
* This suggests a strong organizing mechanism that favors even significant oblique spreading in order for the ridge to re-occupy its original locus. Mantle plume models suggest a simple thermal transition to ductile crustal or lithospheric behavior as hot plume material regionally returns that would not explain why the original location of the ridge or highly oblique spreading are favored.
* Instead of thermally-induced changes in regional lithospheric rheology, we suggest that the vertical rheological layering between a more viscous upper “dry” melting regime and a deeper low-viscosity “wet” melting regime can explain the controlling mechanism of ridge reassembly: Originally both were aligned and linear from the inception of seafloor spreading. When the abrupt change in opening direction occurred, the lithosphere and upper part of the viscous dry melting regime abruptly formed new spreading segments aligned orthogonal to the new opening direction. The mechanism for this was probably through the development of a series of rapidly propagating rifts oriented orthogonally to the new direction, as typically observed elsewhere. However, the low-viscosity deeper wet melting regime was decoupled from the abrupt change and persisted in its original configuration. This persistent linear and deep locus of upwelling may have favored migration of the lithospheric plate boundary zone back to its original configuration to once again align the upper and lower parts of the melting regime.

**Formation of V-shaped ridges by axially propagating small-scale buoyant instabilities**

* Buoyant convective instabilities are considered a typical process operating at slow-spreading ridges, where the natural buoyancy produced by partial melting, melt depletion of the residual mantle and upwelling of deeper hotter mantle can cause the low viscosity material within the melting regime to rise faster than the rate it would flow by purely plate-driven advection [*Scott and Stevenson,* 1989]. This mechanism explains the crustal segmentation of slow spreading ridges which can form prominent (~2 km) crustal thickness variations from segment center to segment ends even where there are no offsets of the axis. Such segmentation cannot form at fast spreading ridges, where plate-driven upwelling dominates mantle flow and melting, unless there are significant offsets of the ridge axis [*Phipps Morgan and Forsyth,* 1988].
* At normal slow-spreading mid-ocean ridges, segment boundaries (non-transform discontinuities, NTDs) are observed to migrate when offsets are small or zero [*Wang et al.,* 2015]. Typically, there is no preferred migration direction indicating that they are not responding to a regional mantle flow. The migration of NTDs is therefore most likely driven by small heterogeneities or local gradients in mantle properties that induce the underlying buoyant instabilities to migrate.
* Propagating small-scale buoyant instabilities have been proposed to explain the rapid formation and propagation of seamount chains flanking the southern East Pacific Rise, refuting previous models involving passive mantle flow due to lithospheric cracking or stretching [*Forsyth et al.,* 2006; *Harmon et al.,* 2006; *Weeraratne et al.,* 2007].
* V-shaped ridges can be explained as a result of propagating buoyant mantle upwelling, driven by large gradients in mantle properties away from the Iceland hotspot. Strong regional gradients in mantle properties south of Iceland are supported by the observed persistent basement depth anomalies away from Iceland [*White,* 1997].

**A new model: Plate boundary dynamics superimposed on a broad and passive thermochemical mantle anomaly**

* Excess melting at hotspots can be explained by the effects of small-scale buoyant mantle upwelling instabilities acting on fertile and low viscosity (elevated volatile content) mantle that may have accumulated from prior subduction events or may have been slowly advected from deep in the mantle. Beneath Iceland and the Reykjanes Ridge excess hot-spot melting need not result from rapid upwelling of hot mantle plume material but rather results directly from near-surface vigorous buoyant mantle upwelling instabilities promoted by elevated volatile contents [*Nichols et al.,* 2002] that strongly reduce mantle solidus temperatures (by hundreds of degrees) [*Katz et al.,* 2003] and viscosities (by two or more orders of magnitude) [*Hirth and Kohlstedt,* 1996]. Time variable (episodic) behavior is inherent in this type of instability [*Scott and Stevenson,* 1989] but may also be induced and enhanced by plate boundary processes and mantle gradients. On the Reykjanes Ridge buoyant upwelling instabilities [*Martinez and Hey,* 2017] may initiate and be largest beneath Iceland where measured mantle volatile contents are greatest [*Nichols et al.,* 2002]. The linear melting regime of the Reykjanes Ridge then provides a favorable low viscosity conduit already at mantle solidus temperatures for the propagation of these instabilities. As the instabilities propagate along axis they locally produce increased crustal thicknesses that are spread onto the ridge flanks to form the diachronous V-shaped crustal ridges. Since the horizontally propagating upwelling instability is a wave-like phenomenon it does not involve significant horizontal mantle flow, only the instability propagates at high rates along axis locally producing increased upwelling and melting. In pulsing plume models, extremely high rates (up to meters/yr) of mantle plume upwelling and horizontal flow are geometrically required to explain the acute geometry of the V-shaped ridges [*Wright and Miller,* 1996], so these models also require a highly viscous dehydration layer to deflect the plume and prevent excessive mantle melting and hundreds of km of predicted crustal thickness beneath Iceland [*Ito,* 2001; *Ito et al.,* 1999].
* Small-scale buoyant convective instabilities may be self-sustaining when supplied by broad and relatively passive low-viscosity mantle anomalies at or near solidus temperatures [*Tackley and Stevenson,* 1993]. This concept offers a resolution to many of the difficulties with plume models. They do not require high rates of mantle plume flow or high temperatures. Elevated volatile content [*Bonatti,* 1990] and moderately elevated temperatures (75°C) [*Cochran and Talwani,* 1978] may be sufficient to sustain long durations of excess melting. As the convective cells are sourced in the low viscosity asthenosphere they may be decoupled from plate motion and remain stable in location relative to lithospheric plates. This stability need not result from a source at the core-mantle boundary or in the lower mantle. In ridge-centered settings divergent plate motion removes excess depleted mantle generated by the convective cells that tends to suppress further upwelling, leading to episodic behavior. In intraplate settings, the buoyant and increased-viscosity depleted mantle adheres to the lithosphere and is removed from the location of the small-scale convective cell by plate motion, forming the swells that often characterize hotspot tracks. If the broad mantle anomalies originate in the lower mantle and gradually ascend to shallow levels (as can be inferred from their size and shape in recent tomographic images [*French and Romanowicz,* 2015]) they may explain the unusual geochemical characteristics of hotspots. Broad mantle anomalies may also result from prior subduction and continental suturing events [*Foulger et al.,* 2005]. Such mantle would be hydrous from slab water content and could gradually warm due to continental insulation. If deep- or shallow-sourced anomalous mantle underlies a continental rift it could lead to heightened melting as extension thins the lithosphere and brings the anomalous mantle above the solidus and promotes small-scale convection [*Mutter et al.,* 1988]. At the Reykjanes Ridge flanks, unusually pronounced buoyant convective flow is indicated by vertically aligned strong seismic anisotropy in the upper mantle [*Gaherty,* 2001].
* In the final paragraph of his paper laying out the original concept of a pulsing mantle plume beneath Iceland and the Reykjanes Ridge, *Vogt* [1971] states “While the interpretation of V-shaped ridges as indicators of mantle flow seems promising, we do not claim that it is fact. Other propagating effects such as fractures and fluid instabilities should be explored”. In this paper we have taken early steps in this new direction.

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