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Reykjanes Ridge evolution: Effects of plate kinematics, small-scale upper mantle convection and a regional mantle gradient

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ABSTRACT

The Reykjanes Ridge is a key setting to study plate boundary processes overlaid on a regional mantle melting anomaly. The ridge originated as one arm of a ridge-ridge-ridge triple junction that separated Greenland, Eurasia, and North America. It initially formed a linear axis, spreading orthogonally at slow rates without transform faults or orthogonal crustal segmentation. Stable spreading continued in this configuration for ~18 Myr until Labrador Sea spreading ceased, terminating the triple junction by joining Greenland to North America and causing a rapid ~30° change in opening direction across the ridge. The ridge abruptly became segmented and offset by a series of transform faults that appear to decrease in length and spacing toward Iceland. Without further changes in opening direction, the ridge promptly began to reassemble its original linear configuration systematically and diachronously from north to south, even though this required the ridge to spread obliquely as it became linear again. Prominent V-shaped crustal ridges spread outward from the axis as the ridge became linear. This reconfiguration is presently nearly complete from Iceland to the Bight transform fault, a distance of nearly 1000 km. Both mantle plume and plate boundary processes have been proposed to control the tectonic reconfigurations and crustal accretion characteristics of the Reykjanes Ridge. Here we review the ridge characteristics and tectonic evolution and various models proposed to influence them.

1. Introduction

The Reykjanes Ridge is a slow-spreading (~20 mm/yr full rate) mid-ocean ridge located in the North Atlantic between the Bight Fracture Zone and Iceland (Fig. 1). It originated at about anomaly 24 forming the Greenland-Eurasia plate boundary, which was part of a triple junction that partitioned opening between North America, Greenland and Eurasia (Johnson et al., 1973; Kristoffersen and Talwani, 1977; Laughton, 1971; Vogt et al., 1969; Vogt and Avery, 1974). Since about anomaly 18 it became the North America-Eurasia plate boundary when the Labrador Sea arm of the triple junction failed (Smallwood and White, 2002). Over the course of its evolution it has exhibited a remarkable series of changes in tectonic and crustal structure as well as displaying prominent gradients in depth and crustal thickness between the Bight Fracture Zone and Iceland (Smallwood and White, 2002). The Reykjanes Ridge initially had a linear geometry and spread stably in this configuration for ~18 Myr. When Labrador Sea spreading failed the direction of spreading across the Reykjanes Ridge changed by ~30° and the ridge abruptly became segmented and offset by transform faults in a stair-step geometry (Vogt et al., 1969). It then promptly began to eliminate the just-formed offsets progressively from north to south to re-establish its original linear configuration (Hey et al., 2016; Martinez and Hey, 2017), even though this required it to spread obliquely by ~30°. As it became linear again, prominent southward-pointing V-shaped crustal ridges and troughs developed outward from the axis onto the ridge flanks. Since the Reykjanes Ridge intersects the Iceland "hot spot", its changing tectonic configurations and crustal structure have been interpreted to directly reflect mantle plume flow and temperature variations and it is often viewed as a window into mantle plume dynamics (e.g., Ito, 2001; Ito et al., 1999; Jones et al., 2002; Jones, 2003; Parnell-Turner et al., 2013, 2014, 2017; Vogt, 1971; White et al., 1995; White, 1997). However, the fundamental processes of forming and eliminating ridge segmentation and transform faults, developing migrating segmentation discontinuities (Carbotte et al., 2015; Grindlay et al., 1991; Hey, 1977; Macdonald et al., 1988; Okino et al., 1998; Tucholke et al., 1997; Wang et al., 2015), and developing large systematic changes in crustal thickness and axial depth with changing mantle volatile content (Martinez et al., 2006; Taylor and Martinez, 2003) are exhibited at many normal mid-ocean and back-arc ridges and do not require "mantle plume" effects. These observations support an

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alternative hypothesis: that dynamic plate boundary processes superimposed on a rather passive regional mantle anomaly may explain the evolution of the Reykjanes Ridge.

In this review, we examine the development of the Reykjanes Ridge in the context of general properties of slow-spreading mid-ocean ridges but influenced by a strong regional mantle anomaly that forms prominent gradients in depth and crustal thicknesses along the length of the ridge. We see strong parallels in the development of the Reykjanes Ridge with well documented characteristics of slow-spreading ridges

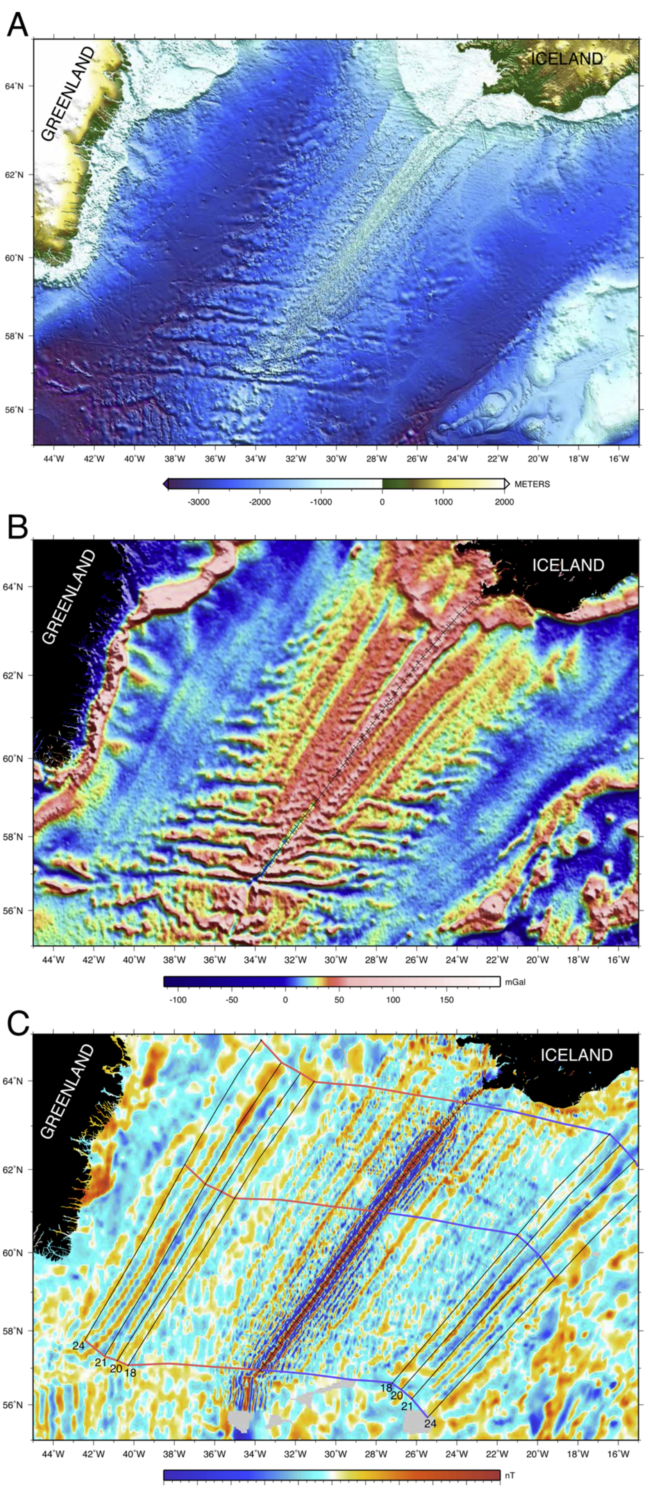

Fig. 1. Maps of the Reykjanes Ridge and flanking North Atlantic basin. A) Topography grid from the compilation of Becker et al. (2009), version SRTM15. B) Satellite-derived free air gravity anomalies (Sandwell et al., 2014) grid version 24.1. C) Compiled magnetics grid (Macnab et al., 1995) with additional ship data from RRS Charles Darwin (CD87) (Searle et al., 1998), R/V Knorr (KN189-4) (Hey et al., 2010) and R/V Langseth (MGL1309) (Martinez and Hey, 2017). Fine crosses show axis location. In C red and blue lines are seafloor spreading flowlines from the rotation poles of Smallwood and White (2002). Black lines are the rotated position of the current Reykjanes Ridge axis at the stage pole chrons numbered at the bottom showing the nearly parallel alignment with the early magnetic isochrons. This geometric alignment indicates that the current linear but obliquely spreading Reykjanes Ridge reassembled the same geometry it had during its early linear but orthogonally-spreading stage following the intervening stair-step segmented phase of spreading that formed the prominent fracture zones evident in the gravity data (B). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

but amplified in magnitude and directed by underlying mantle gradients. Here we focus on sampled horizontal gradients in chemistry, particularly volatile content (Nichols et al., 2002), and possibly temperature (Cochran and Talwani, 1978; Delorey et al., 2007) because these properties affect bulk mantle melting and viscosity and are especially important in controlling small-scale upper mantle convection (Choblet and Parmentier, 2001). Small-scale upper mantle convective instabilities within the “damp” melting regime are generally recognized as a primary cause of crustal segmentation at slow-spreading ridges (Lin and Phipps Morgan, 1992; Lin et al., 1990; Forsyth, 1992; Phipps Morgan and Parmentier, 1995) and the anomalous properties of the regional Iceland hot spot (increased volatile content and mildly elevated temperature) are predicted to enhance such instabilities (Braun et al., 2000). Because the Reykjanes Ridge has experienced both abrupt kinematic changes as well as progressive and systematic changes in plate boundary configuration while overlying a regional mantle melting anomaly that diminishes with distance from Iceland it presents a type-setting to examine mechanical (plate-controlled) and magmatic (mantle) drivers of plate boundary evolution.

We draw on several key properties of mid-ocean ridges to explain its evolution: (1) Large and abrupt changes in plate motion are observed to induce abrupt plate boundary segmentation such that the new segments develop quickly and are typically oriented orthogonal to the new relative plate opening direction (Goodliffe et al., 1997; Hey et al., 1988; Menard and Atwater, 1968; Okino et al., 1998). It is possible that the abrupt reconfigurations are effected by ridge rotation (Menard and Atwater, 1968) or propagation (Hey, 1977; Hey et al., 1988) but that these mechanisms are not always resolved. These reconfigurations appear to be mechanically controlled in the sense that they represent responses of lithospheric plate boundary zones to stresses imposed by kinematic plate motion changes. (2) Where ridge offsets are small, crustal segmentation on slow-spreading ridges appears to often migrate along axis producing broad V-shaped wakes forming crustal thickness variations bounded by non-transform discontinuities (e.g., Gente et al., 1995; Sempéré et al., 1993; Wang et al., 2015). Further, (3) ridge segments can evolve by asymmetric spreading to form new offset segments from a previous long linear axis and offset segments can merge to form new longer unsegmented axes (Sempéré et al., 1993; Schouten and White, 1980; Tucholke et al., 1997). These observed changes in segmentation, even when relative plate motion is steady, suggest a primarily magmatic (mantle) control on the evolution of plate boundaries by lateral and along-axis migration of magmatic centers at slow-spreading ridges (Gente et al., 1995; Sempéré et al., 1993; Tucholke et al., 1997).

At typical slow-spreading ridges unaffected by hot spot anomalies, the changes in segmentation are not generally systematic in that segment discontinuities can migrate in opposite directions and at different rates (e.g., Gente et al., 1995; Wang et al., 2015) suggesting that the most likely causes of these changes are small and irregularly distributed chemical heterogeneities in mantle composition that affect melting. Just as small and spatially irregular mantle chemical heterogeneities may cause segmentation to form, disappear, propagate and otherwise evolve in non-systematic ways at slow-spreading ridges (e.g., Michael et al., 1994; Niu et al., 2001; Tucholke et al., 1997), we surmise that the large and systematic regional horizontal gradients in mantle properties along the ~1000 km length of the Reykjanes Ridge can cause systematic changes in its crustal segmentation. Studies of the evolution of segmentation at slow spreading ridges (e.g., Carbotte et al., 2015) thus establish a framework for a new interpretation of the evolution of the Reykjanes Ridge. Abrupt changes in plate motion, which must occur simultaneously along the entire plate boundary, are likely expressed differently when the plate boundary overlies a large spatial variation in mantle properties that affects melting and rheology. We refer to this horizontal variation in mantle properties as a mantle gradient which may involve both thermal and compositional variations (especially volatile content which strongly affects both the mantle solidus and viscosity). In the North Atlantic surrounding Iceland, the anomalous mantle gradient is reflected most prominently in Reykjanes Ridge axial depth, which varies from nearly 3000 m at the Bight Fracture Zone to sea level at the Reykjanes Peninsula and reaches average elevations of 700–800 m above sea level within Iceland. Prominent geochemical gradients are also noted along the length of the Reykjanes Ridge. In particular water content increases northward along the ridge and peaks beneath Iceland (Nichols et al., 2002). Elevated water contents are also sampled within the volcanic province of west and east Greenland and within the Greenland-Iceland-Faroe Ridge (Jamtveit et al., 2001) indicating that elevated water contents have been a characteristic and long-lived aspect of the North Atlantic mantle melting anomaly. Most models assume that these horizontal gradients are formed by lateral flow from a narrow mantle plume (e.g., Murton et al., 2002; Niu and Hékinian, 2004; Vogt, 1971). However, this need not be the case. The regional anomalous mantle gradient may be formed and emplaced as a broad upwelling (Anderson and Natland, 2014) as imaged in recent tomographic studies (French and Romanowicz, 2015). It may alternatively be formed through plate tectonic processes of subduction and collisional suturing (Schiffer et al., 2014). In either case, entrainment of ambient mantle material during the process of emplacement may create horizontal chemical and thermal gradients within the broad mantle anomaly without need for outward flow from a central narrow plume. Such broad mantle anomalies may lay passively beneath thickened orogenic continental lithosphere long before rifting and seafloor spreading activate dynamic processes of small-scale convection by upwelling the anomalous mantle above its solidus. This new view of the Reykjanes Ridge thus incorporates normal processes of slow-spreading ridges and superimposes them on a passive regional mantle anomaly with strong and systematic horizontal gradients to explain its tectonic and crustal evolution, obviating the need for a dynamic mantle plume.

2. Plate kinematic evolution of the Reykjanes Ridge

Seafloor spreading on the Reykjanes Ridge can be subdivided into three distinct modes based on kinematics and geometry of the axis. (1) Early spreading occurs orthogonally on a single linear axis. (2) An abrupt change in opening direction creates stair-step offsets of the spreading axis so that the new segments are orthogonal to the new opening direction. (3) Without further changes in direction of spreading, the offset ridge segments progressively merge back to reassemble the original single linear axis although this now requires oblique spreading. Below we describe the main features of each of these modes.

2.1. Early unsegmented orthogonal seafloor spreading

During the final stages of continental breakup and immediately following, extensive magmatism developed along the East Greenland and conjugate European margins forming a distinctive seismic stratigraphy referred to as “seaward dipping reflector” sequences (Hinz, 1981; Larsen and Jakobsdóttir, 1988; Whitmarsh and Miles, 1987; Mutter et al., 1982; Mutter, 1985). These are interpreted to be wedge-shaped subaerially erupted volcanic flows formed at volcanic continental margins that dip toward an axis of emplacement that migrates seaward by plate spreading and eventually becomes a submarine seafloor spreading center. The volcanic sequences may overlie continental crust at their landward ends and transition to oceanic crust at the seaward ends (Barton and White, 1997; Geoffroy, 2005; Holbrook et al., 2001; Hopper et al., 2003; Korenaga et al., 2000). Crustal thicknesses are estimated to be up to 18.3 km thick near the continental margins decreasing to 8–10 km during the subsequent seafloor spreading stage (Hopper et al., 2003). This early intense magmatism is a characteristic feature of many “volcanic” passive margins and lasts for a few million years before declining during the subsequent seafloor spreading stage (Hopper et al., 2003). The voluminous volcanism may be explained, at least in part, by the enhancing effects of the rift thermal structure in which rift lithospheric edges create a cold thermal contrast with respect to hotter asthenospheric material that flows into the gap. Foundering of the denser cooled asthenospheric material due to conduction from the thick rift edges leads to enhanced upwelling near the rift center and thus enhanced melting (Boutilier and Keen, 1999; Buck, 1986; Mutter et al., 1988; Zehnder et al., 1990). The initial thermal structure of the rift thus promotes an active circulation of the asthenosphere in excess of that required to simply fill the gap caused by lithospheric thinning. However, a further enhancing mechanism is likely the onset of melting as thinning continental lithosphere advects asthenosphere above the solidus. Although numerical models have not yet reached a consensus on the appropriate conditions to generate the early excess volcanism, it appears that melt-enhancing mantle properties are also needed to produce the early excess volcanism compared to later more typical oceanic spreading (Nielsen and Hopper, 2002, 2004). Generally, elevated mantle temperatures have been considered likely although fertility variations especially volatile content may also be important (Nielsen and Hopper, 2004). Early intense melting likely reduces the concentration of the most fertile elements from the mantle, including volatiles, leading to a decrease in magmatism. A gradient in elevated mantle water content decreasing southward from Iceland has been observed in sampled axial lavas (Nichols et al., 2002) may have existed throughout the history of spreading in this part of the North Atlantic (Jamtveit et al., 2001), as suggested by residual basement depth anomalies that consistently increase toward Iceland within the entire basin flanking the Reykjanes Ridge (Fig. 2) (Louden et al., 2004; White, 1997). Especially elevated mantle water content may have promoted vigorous small-scale active convection during the initial breakup (Jamtveit et al., 2001) contributing to the excess volcanism of that stage as it appears that mantle temperature did not vary greatly (Korenaga et al., 2000). The enhanced small-scale convection induced in the early volcanic phase is expected to decline as excess fertile mantle components, especially volatiles, are depleted. In addition, the cold rift thermal boundary layer is heated by the small-scale convection and thus the early high thermal gradients at the rift edges are eroded with time and spatially separated from the seaward-migrating spreading center. Further, melting itself generates depleted, more viscous and buoyant residual mantle that acts as a negative feedback to early rift-induced convection. In the North Atlantic voluminous magmatism is asymmetrically distributed toward the Greenland margin (Hopper et al., 2003) and may possibly be explained by a rift jump during this phase (Korenaga et al., 2000; Smallwood and White, 2002).

The Reykjanes Ridge began forming linear identifiable magnetic isochrons by anomaly 24, (ca. 55 Ma) and continued in this mode until the change in opening direction near anomaly 17 (ca. 37 Ma). During this time the Reykjanes Ridge formed the Greenland-Eurasia plate boundary, one arm of the Greenland-Eurasia-North America ridge-

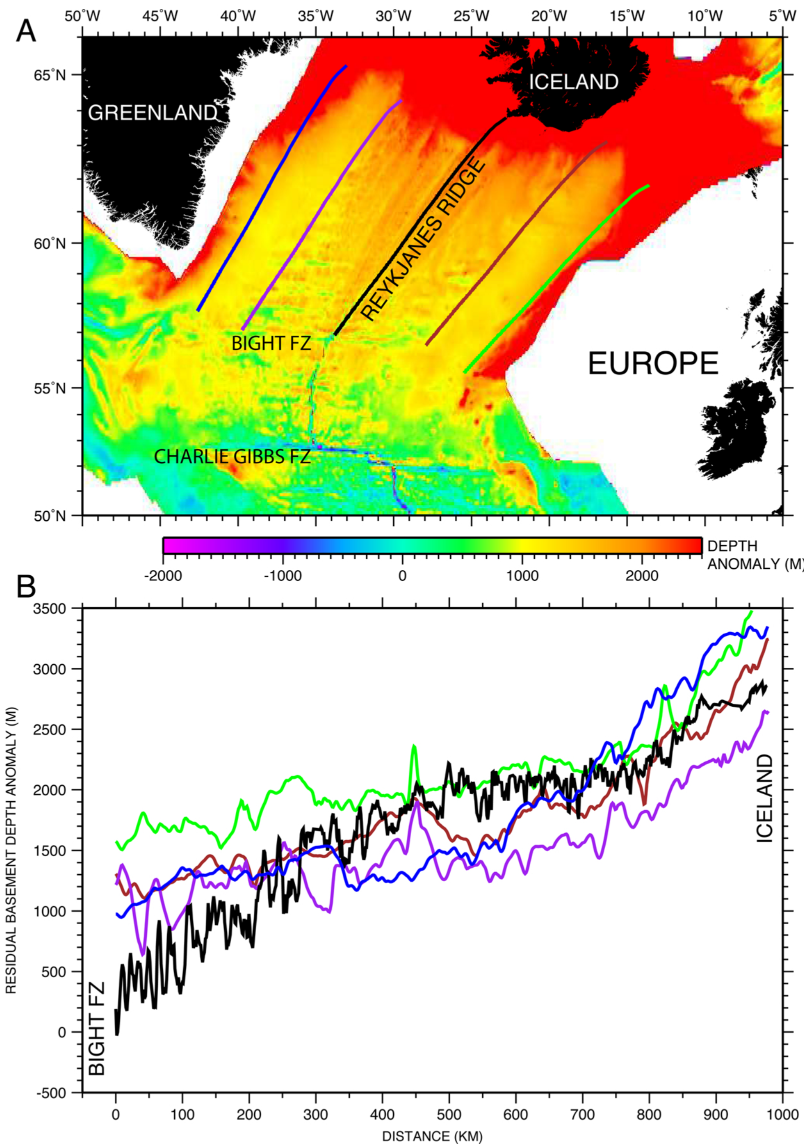

Fig. 2. North Atlantic residual basement depth anomalies. A) grid of residual basement depth anomalies from Louden et al. (2004) depicts the basement depth corrected for sediment loading and thermal subsidence and referenced to a nominal depth of 2600 m for zero-age oceanic crust. Black line is the current Reykjanes Ridge axis. The blue and green lines are the reconstructed position of the axis at anomaly 24 following continental breakup. The purple and brown lines are the linear axis reconstructed to just after anomaly 17 when the ridge was abruptly offset by transform faults. The map shows a large and persistent anomaly in the North Atlantic since continental breakup including the time of transform offset spreading. B) Lower panel shows profiles of the Reykjanes Ridge axial depth +2600 m (black line) and the residual basement depth anomaly sampled at the location of the reconstructed axis (indexed by color) shown in A). The profiles show similar long-wavelength monotonic gradients away from Iceland implying persistent gradients in mantle properties. Although basement depths increase just after forming an offset plate boundary (purple and brown lines) the profiles continue to show a long wavelength shallowing toward Iceland. The greater depths at the southern end of the current Reykjanes Ridge axis (black line) relative to the flank profiles likely reflects dynamic effects associated with formation of the axial valley (e.g., Chen and Morgan, 1990). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

ridge-ridge triple junction in the North Atlantic basin. The initial intense magmatism forming the seaward dipping reflector sequences during breakup and initial spreading had declined (Hopper et al., 2003; Korenaga et al., 2000), but not to normal oceanic crustal thicknesses. Anomalously voluminous volcanism persisted on the Greenland-Iceland-Faroe ridge possibly forming ~25–30 km thick oceanic crust (Smallwood et al., 1999) with unidentifiable isochrons. Alternatively, extensive continental crust has also been recently interpreted to occur beneath the Greenland-Iceland-Faroe Ridge (Foulger et al., 2019) adding to previous inferred occurences beneath Iceland (Foulger, 2006) and the Faroe islands platform (Richardson et al., 1998). In addition to the persistent excessive seaward dipping reflector-type volcanism along the Greenland-Iceland-Faroe Ridge, an anomalous gradient in crustal thickness and basement depth continued to characterize the Reykjanes Ridge axis and flanks (Smallwood et al., 1995; White, 1997). Crustal thicknesses vary from near normal values (~5.5–6.0 km) (Whitmarsh and Calvert, 1986) 20 km south of the Charlie Gibbs FZ to about 10 km near the Greenland-Iceland-Faroe Ridge (Smallwood et al., 1995, 1999). Residual basement depth anomalies flanking the Reykjanes Ridge also indicate similar persistent gradients in crustal thicknesses (Louden et al., 2004) (Fig. 2). Thus, while early magmatism on the Reykjanes Ridge followed the general pattern seen at volcanic margins of decreasing from the large excesses forming the seaward-dipping reflectors near breakup (Boutilier and Keen, 1999), it did not decline to normal values but continued to form anomalous gradients in crustal thickness and depth toward Iceland (Louden et al., 2004; Smallwood et al., 1995, 1999; White, 1997). This persistent basement depth anomaly implies that the underlying mantle also had persistent horizontal gradients in melting properties (increasing toward and peaking beneath Iceland) throughout the evolution of the Reykjanes Ridge.

Early crustal accretion along the Reykjanes Ridge displays no spreading-parallel crustal segmentation (Fig. 1). Although essentially complete sedimentation covers the early basement (Fig. 1A), satellite-derived free-air gravity maps (Fig. 1B) provide an indication of buried basement structure. The gravity anomalies show subtle linear anomalies converging southward with the ridge axis in the early crust. These gravity lineations have been interpreted as resulting from a form of V-shaped crustal ridges (Parnell-Turner et al., 2014; White, 1997), like those of the present phase of spreading, representing loci of enhanced melting that migrated southward along axis forming one limb of the V-shaped ridges on each flank. These early V-shaped ridges are better expressed on the western flank, possibly due to thinner sediments there (Parnell-Turner et al., 2014).

The lack of spreading-parallel segmentation along a nearly 1000 km length of a slow-spreading ridge is unusual. Typically, crustal segmentation is seen in passive margin gravity data to develop soon after breakup even at volcanic margins and to continue into mature seafloor spreading (Behn and Lin, 2000). In cases where both rifted continental margin and early oceanic basement are well-imaged, the seafloor spreading segmentation is often seen not to be inherited from rifted margin structure (Taylor et al., 2009). The oceanic magmatic segmentation develops largely independently of margin tectonic structure, except at large initial offsets of the continental margin, and may evolve through slow along-axis propagation of non-transform discontinuities even where plate spreading is stable (Taylor et al., 2009). After seafloor spreading matures, robust crustal segmentation is a prominent and persistent aspect of slow-spreading ridges, even where offsets of the axis are small or absent (Phipps Morgan and Parmentier, 1995). Thus, the lack of spreading-parallel segmentation along the early Reykjanes Ridge is an important and unusual feature of this system. As discussed below, this may be explained by the nature of segmentation at slow-spreading ridges, which reflects the stability of buoyant mantle upwelling cells that form the crustal thickness variations (Lin et al., 1990; Lin and Phipps Morgan, 1992; Phipps Morgan and Parmentier, 1995). Where these cells are spatially stable, they form crustal segmentation orthogonal to the ridge. If they propagate slowly compared to the spreading rate, they form broad V-shaped crustal wakes as commonly seen at normal slow-spreading ridges (Fig. 3). If they propagate rapidly along axis compared to the spreading rate, they form acute V-shaped crustal ridges on the ridge flanks, as we propose for the flanks of the present Reykjanes Ridge (Fig. 1).

2.2. Segmented orthogonal seafloor spreading

The early linear and orthogonally-spreading Reykjanes Ridge (the Greenland-Eurasia plate boundary) was stably opening in this configuration for about 18 Myr. During this time there is no evidence that any spreading-parallel segmentation (transform faults or non-transform discontinuities) formed, although as noted above, V-shaped crustal ridges have been inferred from satellite-derived gravity data, which may represent a type of migrating crustal segmentation. Near anomaly 17 (ca. 37 Ma) an abrupt ~30° counterclockwise change in opening direction occurred as Labrador Sea spreading ceased, Greenland tectonically became part of North America (Smallwood and White, 2002), and the Reykjanes Ridge became part of the North America-Eurasia plate boundary. The prior triple junction (Johnson et al., 1973; Kristoffersen and Talwani, 1977; Laughton, 1971; Vogt et al., 1969; Vogt and Avery, 1974) ceased to exist and the Bight transform fault initiated, offsetting the Reykjanes Ridge from the southward continuation of the Mid-Atlantic Ridge. Rather than simply spreading obliquely on the prior linear axis, the Reykjanes Ridge itself responded by abruptly forming a series of offset spreading segments oriented orthogonal to the new opening direction. The resulting fracture zones and non-transform discontinuities are best imaged in regional gravity and magnetic data (Fig. 1B, C). These data indicate that segment lengths and transform offsets decrease to the north toward Iceland. They also appear to show subtle northern discontinuities, especially evident in the satellite-derived gravity data north of ~62°N on the western ridge flank (Fig. 1B) migrating in a northward direction, although exactly what these features represent is not entirely clear from the available data. Close to the Iceland platform, segmentation becomes indistinct in these data sets and it is possible that offset ridge segments did not develop north of about 64°N (Fig. 1). In this area, the spreading may have simply become oblique, accommodating the change in direction of opening by developing en echelon axial volcanic ridges within the prior linear plate boundary zone. But why the entire axis did

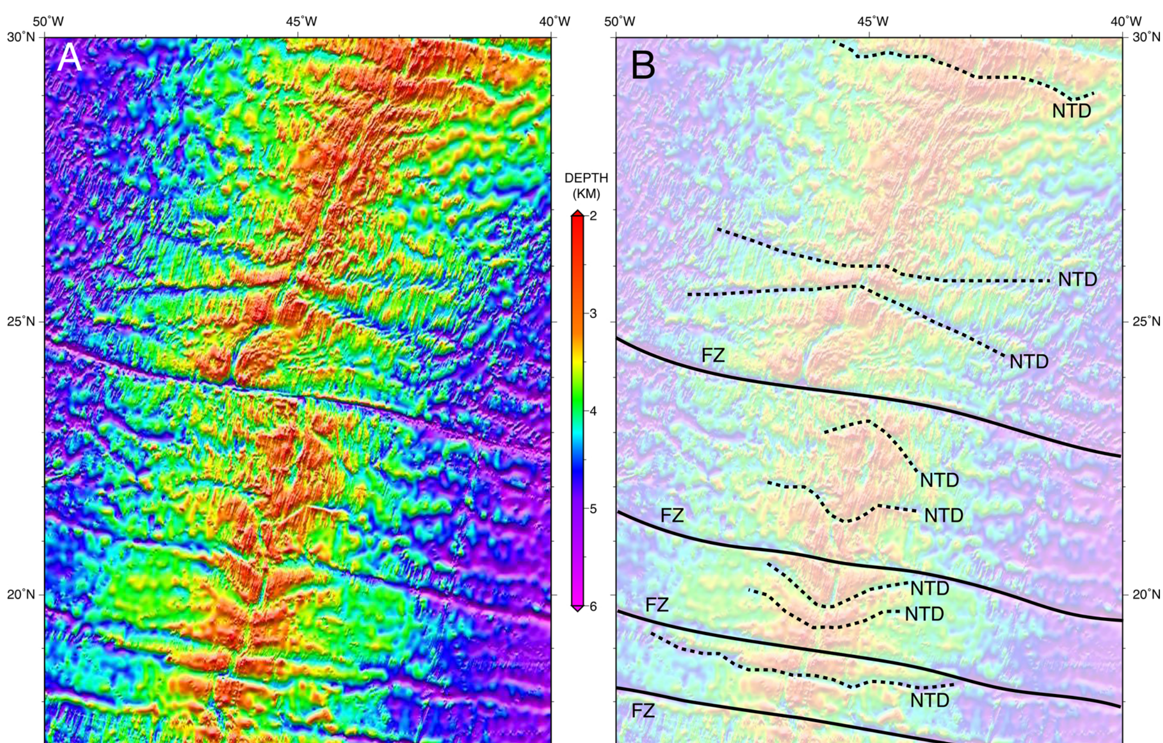

Fig. 3. Propagating non-transform discontinuities on slow-spreading ridges. A) Bathymetry grid of ship and satellite gravity-predicted bathymetry (Sandwell et al., 2014) and B) tectonic interpretation. A typical section of the slow-spreading Mid-Atlantic Ridge shows multiple propagating non-transform discontinuities (NTDs, dashed lines in B) and fracture zones (FZ, solid lines). Where ridge offsets are small the NTDs can propagate often in opposite directions and at different rates even within small regions showing that they are not responding to regional mantle flow. The fracture zones delineate plate opening flowlines and their steadier trends show that NTD propagation is not in response to plate motion changes. Most likely, NTD propagation is in response to small and irregular variations in mantle properties that affect melting behavior and/or viscosity, such as volatile content and/or other fertility variations (depleted or enriched heterogeneities). Along the Reykjanes Ridge strong and monotonic gradients in mantle properties are indicated by systematic residual basement depth anomalies away from Iceland (see Fig. 2). These gradients likely drive rapid monotonic propagation of upwelling instabilities (Fig. 7) to form the ridge flank acute V-shaped ridges and troughs.

not do this is an important question since the offset stair-step ridge segments that did form immediately began to evolve back to the prior linear but now obliquely-spreading configuration. What appears evident in the regional data (Fig. 1) is that with increasing distance from Iceland, the development of new orthogonally-spreading, longer and larger-offset segments was initially favored. This observation suggests that the gradient in mantle melting away from Iceland, reflected in the residual basement depth anomalies (Fig. 2), had a strong effect on the nature of the segmentation. When the direction of plate motion changed the entire plate boundary was simultaneously affected by the new opening stresses but near Iceland the plate boundary appears to have simply remained linear in its original configuration and accommodated the new strains by spreading obliquely. To the south, new segments oriented orthogonal to the new opening direction formed, with increasing lengths and transform offsets with distance from Iceland.

When directions of seafloor spreading change, divergent plate boundaries tend to reconfigure so as to be approximately perpendicular to the new relative plate opening direction (Menard and Atwater, 1968), although possibly less so for slow-spreading ridges (Atwater and Macdonald, 1977). However, there are several mechanisms by which this can be achieved. The geologic mechanisms that led to offset ridge segments oriented perpendicular to the new opening direction at the Reykjanes Ridge are not resolved in the regional data sets (Fig. 1). At least three general mechanisms have been proposed for plate boundary reconfiguration in response to a change in plate opening direction: ridge rotation (Menard and Atwater, 1968), synchronous ridge jumps (Goodliffe et al., 1997) and ridge propagation (Hey, 1977) (Fig. 4). A relevant observation in the gridded magnetic dataset (Fig. 1C) is that the positive band of magnetic anomalies near Chron 18, when the opening direction changed, appears to be wider on the western ridge flank compared to the conjugate anomalies on the eastern flank. If so, it suggests that the reconfiguration mechanism was asymmetric, retaining more material on the western flank than on the eastern flank. Of the mechanisms described above, this is most compatible with a propagating ridge (Hey, 1977) mechanism (Fig. 4B) or a synchronous ridge jump mechanism (Goodliffe et al., 1997) (Fig. 4C) to the east. A breakup of the ridge into rotating segments (Menard and Atwater, 1968) (Fig. 4A), however, appears less likely as this produces overall symmetric crustal accretion, unless additional asymmetric effects occur. The asymmetry of the magnetic anomalies suggests that the new stair-step plate boundary could have been formed by a series of southward propagating ridges from nucleation points along the previous linear axis (Fig. 4B), rather than northward propagation or symmetric northward and southward propagation from these points.

The mechanism of segmentation may have been influenced by the relative motion of the plates and spreading center with respect to the deeper and presumably more stable mantle. As many of the parameters associated with absolute plate motions are still areas of active investigation and significant uncertainty, we present a conceptual model for this possible effect. Although various models of plate motion relative to the deeper mantle have been proposed (e.g., Crespi et al., 2007; Doglioni, 1990; Doglioni et al., 2005; Scoppola et al., 2006) they generally predict a westward component of motion. Here we adopt the Gripp and Gordon (2002) solution for North America-Eurasia with respect to their "hot spot" reference frame as a conservative estimate, as we are primarily examining possible effects of a relative motion of the plate boundary with respect to the deeper mantle. If westward plate boundary motions were also occurring generally throughout the history of North Atlantic opening and at rates similar to today, this would imply a greater westward velocity of the plate boundary than the plate-driven mantle upwelling rate beneath the ridge (Fig. 5). Different effects of plate motion with respect to the mantle have been proposed. Motion of an age-dependent lithospheric thermal boundary layer relative to the asthenosphere has been suggested to cause asymmetric melt production favoring the leading plate as asthenosphere broadly

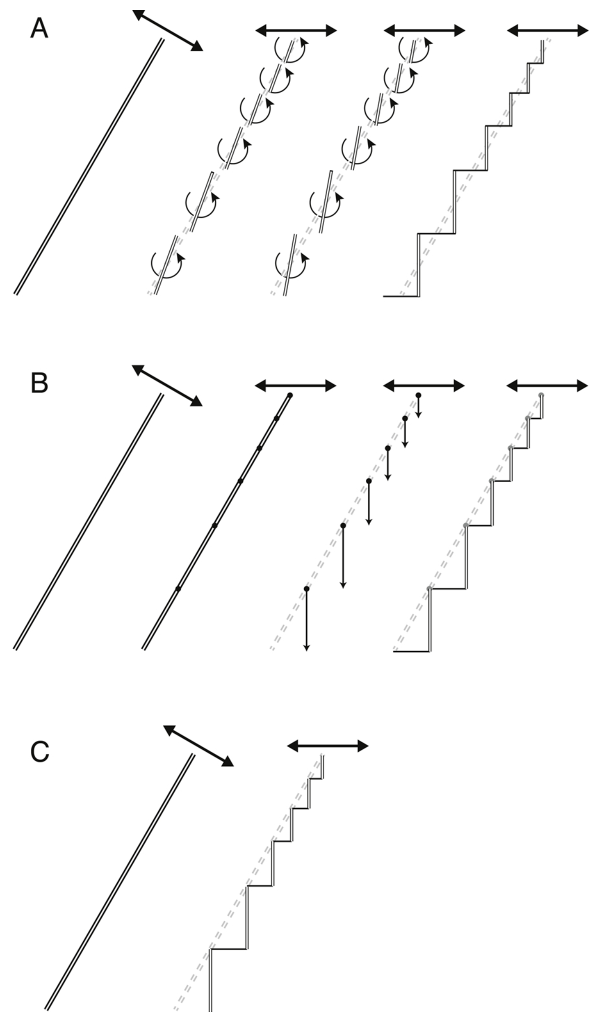

Fig. 4. Plate boundary reconfiguration mechanisms. Various mechanisms have been proposed by which plate boundaries reconfigure following changes in plate motion. Each panel depicts subsequent times from left to right. Double line is the spreading axis, dashed grey double line shows the extinct axis position as an indicator of symmetry or asymmetry. A) Ridge rotation (Menard and Atwater, 1968) in which the plate boundary breaks into segments that progressively rotate into the new spreading-orthogonal configuration. This mechanism produces conjugate fanning patterns in tectonic fabric and magnetic lineations for each segment. It is symmetric with respect to the previous axis unless additional asymmetry producing mechanisms occur. B) Ridge propagation (Hey et al., 1988) in which new ridge segments nucleate (dots) and propagate (arrowed line segments) orthogonal to the new opening direction. As the segments begin to overlap they cease propagation and form transform faults. This mechanism produces an asymmetric shift of the axis if propagation of each new segment is in the same direction. C) Synchronous ridge jumps (Goodliffe et al., 1997) form a new plate boundary oriented orthogonal to the new opening direction. This mechanism can be asymmetric or symmetric depending on whether the new axes are offset or not from the previous axis.

upwells beneath a thinning thermal lithosphere toward the axis and then advects downward beneath a thermally thickening trailing plate (e.g., Carbotte et al., 2004; Conder et al., 2002; Chalot-Prat et al., 2017). However, this effect is eliminated close to the ridge if mantle above the dry solidus is sufficiently viscous due to dehydration (Hirth and Kohlstedt, 1996; Phipps Morgan, 1997; Yale and Phipps Morgan, 1998) to prevent the asthenosphere sensing the relief of the thermal boundary layer. Near the axis buoyant, melt depleted, dehydrated and therefore viscous mantle above the dry solidus becomes the mechanical layer separating a strong "compositional" lithosphere from a weak ductile asthenosphere (Fig. 5B). The motion of the ridge axis relative to

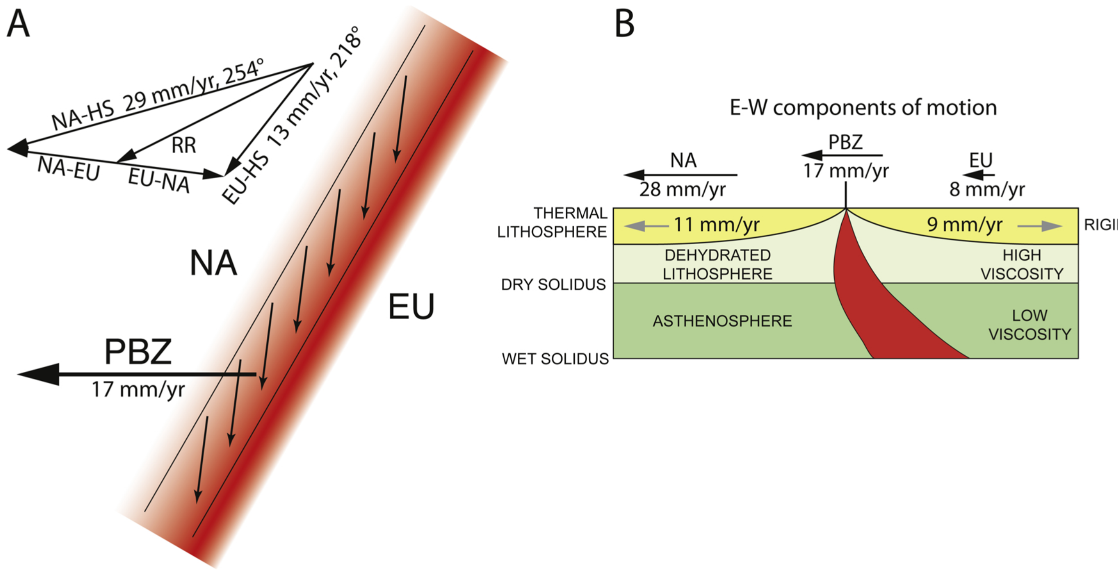

Fig. 5. Plate boundary motion with respect to deeper mantle. (A) A mechanism for producing the observed asymmetric crustal accretion between the North American (NA) and Eurasian (EU) plates may be through propagation of axial volcanic ridges (AVRs, southward pointing fine arrows), which form centers of volcanism within the plate boundary zone (PBZ, delimited by fine lines). In a "hot spot" (HS) reference frame the North American and Eurasian plates near the Reykjanes Ridge both have westward components of motion (see inset vector triangle for plate motions in hot spot reference frame following Gripp and Gordon, 2002). For a slightly asymmetric spreading this implies a southwestward motion of the Reykjanes Ridge (RR) plate boundary zone with respect to the mantle. If the westward component of motion of the plate boundary is about 17 mm/yr, it results in about a 10% asymmetry in crustal accretion, consistent with asymmetric isochron separations on the ridge flanks (Hey et al., 2010). The maximum upwelling rate for a two-dimensional passive (plate-driven) solution of mantle flow, which produces most of the crust, is $2U/\pi$ (Phipps Morgan, 1987), where U is the half spreading rate, yielding about 6.4 mm/yr. Deeper buoyant upwelling lags further east as advection above the dry solidus is expected to be approximately symmetric (Conder et al., 2002). B) Cross-section depicting E–W component of plate motions and eastward lag of the damp melting regime. The primary region of melt production within the mantle above the dry solidus is approximatley smmetric but the deeper damp melting interval lags asymmetrically toward the east with respect to the plate boundary zone. This process assumes that dehydrated mantle above a horizontal dry solidus is sufficiently viscous that the underlying asthenosphere does not upwell due to the sloping boundary of the thermal lithosphere (yellow area), which would predict an opposite sense in the asymmetry of melt production (Carbotte et al., 2004). This asymmetry in mantle magma production could favor the southward propagation of AVRs (A) such that they continually nucleate and propagate toward the area of greater magma production leading to an overall crustal accretion asymmetry by transferring material within the plate boundary zone to the North American plate. Near-bottom observations showing elevated magnetization intensities at the southern end of an AVR (Searle et al., 1994) are consistent with this mechanism. Gray arrows schematically depict the relative plate motion away from the plate boundary zone resulting in greater crustal accretion on the North American plate. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

the deeper mantle should then lead to a skew or asymmetry in the melting regime beneath the ridge, whereby the melting regime lags to the east relative to the westward moving plate boundary. Numerical modeling suggests that this skew should primarily affect the low-viscosity mantle beneath the dry solidus as increased mantle viscosity above the dry solidus results in symmetric corner flow advection of mantle (Conder et al., 2002). This sense of asymmetry should have persisted before and after the plate motion change since these changes were relatively small compared to the westward component of plate motion (Fig. 5). Because of this skew in the spreading mantle upwelling pattern, when the change in plate motion occurred, the new spreading segments may have more easily developed toward the eastern side of the former plate boundary, more directly over the eastward-lagging melting regime. This could have happened by the nucleation of a series of propagating ridges on the linear axis which then rapidly propagated southward (Fig. 4B). As the series of new orthogonally spreading ridges began to overlap one another, propagation would cease and transform faults develop. The new stair-step plate boundary would thus form consistently to the east of the previous linear axis and better align the new axis with the skewed melting regime (Fig. 5) and explain the asymmetric width of positive anomalies near Chron 18, forming a wider band of transferred lithosphere on the western flank. This mechanism may also explain smaller scale asymmetric accretion within the plate boundary zone (Hey et al., 2010) by axial volcanic ridge (AVR) propagation (Fig. 5).

Southward propagation of a series of new ridge segments from the linear axis is also consistent with general rift propagation models that predict propagation in a downward direction along topographic gradients (Phipps Morgan and Parmentier, 1985). This manner of plate boundary reorganization has been documented in the northeastern Pacific (Hey et al., 1988), Galapagos Spreading Center (Hey and Vogt, 1977; Wilson and Hey, 1995) and SE Indian Ridge (Vogt et al., 1983; Conder et al., 2000). Given the ambiguity of the low-resolution regional data (Fig. 1) a resolution to this issue awaits acquisition of detailed data sets to resolve the geologic mechanism of plate boundary reorganization.

The westward motion of the plate boundary with respect to the deeper mantle may also explain proposed systematic eastward ridge jumps on Iceland (Hardarson et al., 1997). Since the buoyant upwelling instabilities are fundamentally tied to plate divergence they move with the plate boundary, but lag to the east, as noted above. Beneath Iceland the stronger upwelling instabilities there due to higher mantle water content (Nichols et al., 2002) are probably rooted more deeply (due to a deeper wet solidus) than along the Reykjanes Ridge to the south. Thus, they may lag somewhat more to the east than the shallower melting regime of the Reykjanes Ridge. When an episodic upwelling instability forms and rises beneath Iceland it may thus be centered to the east of the westward moving plate boundary (Gripp and Gordon, 2002) and trigger a rift relocation to the east of the previous plate boundary (Hardarson et al., 1997) that is better aligned with the source of melt.

2.3. Unsegmented oblique seafloor spreading

One of the most remarkable aspects of the kinematic evolution of the Reykjanes Ridge is its ongoing transition back to a linear axis (Hey et al., 2016; Martinez and Hey, 2017). Not only is this transition eliminating the recently-formed orthogonal spreading and transform fault segmentation, but the new linear configuration is geometrically the same as had the ridge offsets and transforms never formed and the prior linear axis had simply begun spreading obliquely without changing position (Martinez and Hey, 2017). This geometric coincidence is shown by the close correspondence of the present linear Reykjanes Ridge axis reconstructed to its position prior to anomaly 17 following the rotation poles of Smallwood and White (2002) (Fig. 1C). The reconstructed axis closely parallels linear anomalies 18–24 formed when the early ridge was linear.

The transition back to this linear configuration was diachronous and systematic, occurring first in the north and progressing southward, but in a punctuated manner with step-like transitions (Hey et al., 2016). No significant changes in spreading direction occurred during this transition, as shown by the linear geometry of the Bight Fracture Zone following anomaly 17 (Fig. 1) and other prominent North Atlantic fracture zones such as Charlie Gibbs that also remained linear. A detailed survey of the southern end of the Reykjanes Ridge and flanks shows that the reconfiguration there was accomplished by the asymmetric lateral migration of individual segments such as to shorten transform offsets followed by a rapid transition to an oblique geometry once the offsets became shorter than about the width of the plate boundary zone (~10–15 km) (Martinez and Hey, 2017). As the stair-step segmentation was eliminated so was the pattern of crustal accretion determined by this plate boundary geometry. As the axis became linear and obliquely spreading, prominent V-shaped crustal ridges developed as loci of enhanced melting rapidly propagated southward along the axis. This pattern of axially-migrating magmatic centers is similar to what occurs at slow spreading ridges when ridge offsets are small (Fig. 3) except that the migrations on the Reykjanes Ridge were rapid and consistently southward. The removal of transform offsets is complete north the Bight transform fault (Hey et al., 2016; Martinez and Hey, 2017), with the next northern offset shortened to less than the width of the plate boundary zone and breached by an axial volcanic ridge, terminating the transform fault by converting it to a non-transform discontinuity and forming a continuous plate boundary zone from there to Iceland (Martinez and Hey, 2017). Presently, there are no transform faults along the North Atlantic plate boundary between the Bight transform fault and Iceland, although complex bands of seismically active transcurrent faulting occur near or within Iceland itself, especially along the Tjörnes transform zone, adjacent to northern Iceland and along the South Iceland Seismic Zone (Bergerat et al., 2000; Bergerat and Angelier, 2008; Einarsson, 1991; Homberg et al., 2010; Rognvaldsson et al., 1998; Stefansson et al., 2008; Tryggvason et al., 2002).

The first ridge segment south of the Bight transform fault, however, retains typical characteristics of a slow-spreading ridge, with abyssal hills oriented orthogonally to the spreading direction and a prominent circular bull's eye mantle Bouguer gravity low (>25 mGal), unlike the elongate anomalies of the Reykjanes Ridge (Martinez and Hey, 2017) that display small along-axis variations (typically < 5 mGal) (Searle et al., 1998). As this orthogonal segment is located south of the former Bight triple junction it was always part of the North America-Eurasia plate boundary and not tectonically part of the early Reykjanes Ridge, which formed the Greenland-Eurasia plate boundary prior to about anomaly 17. This difference in the plate tectonic origin and evolution of these adjacent segments that are now part of the same plate boundary may have important influences on their future development. The observations suggest that the transition to oblique spreading and the development of ridge-flank V-shaped ridges may end at the Bight transform fault and not progress farther to the south due to their different origin and evolution, including their history of segmentation and plate boundary geometry.

3. Geology of the Reykjanes Ridge axis

The axial zone of the Reykjanes Ridge has now been fully mapped by multibeam systems and interferometric sonars from the Bight transform fault to Iceland, most surveys also including gravity and magnetics data (Appelgate and Shor, 1994; Benediktsdóttir et al., 2012; Hey et al., 2010; Hey et al., 2016; Höskuldsson et al., 2007; Keeton et al., 1997; Lee and Searle, 2000; Martinez and Hey, 2017; Murton and Parson, 1993; Pałgan et al., 2017; Parson et al., 1993; Searle et al., 1998). Surrounding North Atlantic basin areas are much less resolved primarily in 1–2 arc minute grids of compiled ship bathymetry (Amante, 2009), satellite-derived predicted bathymetry (Smith and Sandwell, 1997) and free-air gravity (Sandwell et al., 2014) grids as well as 5-km grids of compiled ship magnetic anomaly data (Macnab et al., 1995). These and other local studies provide a diverse range of observations on the geology of the active plate boundary zone and general features of its evolution in time. The summary below focuses on recent findings of the plate boundary zone geology and active processes.

3.1. Geology of the Reykjanes Ridge plate boundary zone

Macdonald (1982) describes the plate boundary zone of mid-ocean ridges as the area of active crustal emplacement and tectonic deformation before the lithosphere becomes part of an internally rigid plate. At the Reykjanes Ridge the plate boundary zone is characterized by high acoustic backscatter and high amplitude magnetic field and magnetization anomalies (Lee and Searle, 2000; Searle et al., 1998) and by axial volcanic ridges (AVRs) that are oriented approximately perpendicular to the opening direction and arrayed in an en echelon right-stepping pattern (Magde and Smith, 1995; Pałgan et al., 2017; Searle et al., 1998). The plate boundary zone has a remarkably uniform width along the Reykjanes Ridge, forming a 10–15 km wide zone despite the axis varying from a topographic high to a valley (Searle et al., 1998). At the Reykjanes Ridge, the plate boundary zone is identified by a contrast in volcano-tectonic fabric with the zone itself characterized by AVRs and subparallel faults and fissures oriented approximately perpendicular to the opening direction (Murton and Parson, 1993; Pałgan et al., 2017) whereas the edges of the plate boundary zone are marked by the development of larger displacement faults aligned with the overall oblique trend of the axis. The interplay of these two trends gives the flanking seafloor a complex fabric with remnants of the AVR spreading-orthogonal fabric superimposed by the oblique plate boundary zone fabric (Martinez and Hey, 2017). AVRs are found along the entire length of the Reykjanes Ridge plate boundary zone. These volcanic structures are generally 10–30 km long, a few km wide and up to a few hundred meters high. Their approximately orthogonal orientation to the opening direction results in their right-stepping en-echelon configuration to accommodate the overall oblique trend of the plate boundary zone (Searle et al., 1998).

Individual Reykjanes Ridge AVRs are morphologically similar to the AVRs that characterize the plate boundary zones of slow spreading ridges generally (Searle et al., 2010; Smith and Cann, 1990). The AVRs are composed of numerous small volcanic cones and lava flows that overlap and coalesce to form the individual ridges (Magde and Smith, 1995). At more orthogonally opening slow spreading ridges the AVRs are typically aligned end-to-end or with small non-systematic offsets and little overlap. Often a single AVR will transect the length of the ridge segment (Searle et al., 2010). The Reykjanes Ridge AVRs overlap significantly (by about 1/3 to 1/2 of their lengths) (Magde and Smith, 1995; Searle et al., 1998). Interestingly, the AVRs along the entire length of the Reykjanes Ridge, to first order, do not vary in mode of formation or morphology, with emplacement of small point-source volcanoes and hummocky to lobate lavas dominating (Magde and Smith, 1995) despite the northward increase in overall crustal thickness (~7–11 km) (Bunch and Kennett, 1980; Smallwood et al., 1995; White, 1997). The main variations in the AVRs along the Reykjanes Ridge axis are in the morphology of the individual volcanoes composing them, with a higher abundance, greater height, and greater number of smooth vs. hummocky morphologies near 61°N (Magde and Smith, 1995) where a V-shaped ridge intersects the axis (Searle et al., 1998). In contrast, at fast-spreading ridges the mode of volcanism is fundamentally different, typically dominated by effusive sheet flows or hummocky lobate flows emanating from fissures with few point source volcanoes within the neovolcanic zone (Fornari et al., 1987; Sinton et al., 2002).

The common characterization of the axial high part of the Reykjanes Ridge as similar to fast-spreading ridges is thus only true in the very broad sense of both forming axial highs. Fast-spreading ridges have more peaked and narrower axial highs (< 10 km) with an axial summit caldera only 1–2 km wide along the summit (Macdonald et al., 1984). Ridge flank morphology is much smoother as well (Goff, 1991). Perhaps the greatest contrasts between the axial high Reykjanes Ridge and fast spreading ridges are the common presence of magma lens reflectors and high-temperature hydrothermal venting at axial high fast spreading ridges (Baker et al., 2016; Scheirer and Macdonald, 1993) compared to their limited apparent occurrence on the Reykjanes Ridge (German et al., 1994; Keeton et al., 1997; Sinha et al., 1997, 1998).

3.2. Asymmetric spreading on the Reykjanes Ridge

Magnetic surveys oriented along spreading flowlines across the Reykjanes Ridge within the oblique spreading phase have resolved small but systematic asymmetries in spreading with a few tens of km greater accretion overall on the North American plate than on the Eurasian plate (Benediktsdóttir et al., 2012; Hey et al., 2010). Although the along-axis pattern of displacement of magnetic isochrons identifies a systematically propagating process accreting material preferentially to one plate (Hey et al., 2010), the mechanism producing this asymmetry is not a classic propagating rift mechanism (Hey et al., 1980) where one distinct spreading axis replaces another. This is shown by the lack of features on the Reykjanes Ridge generally associated with rift propagation, such as failed rifts and transferred lithosphere (Hey et al., 1989). Detailed examination of the magnetic profiles indicates that the asymmetry was generated through the accumulated transfer of lithosphere by small individual propagation events each with offsets generally less than 10 km and not always transferring lithosphere to the North American plate (Benediktsdóttir et al., 2012). These individual small-offset propagation events are therefore likely occurring entirely within the 10–15 km wide plate boundary zone.

Although the detailed geologic mechanism for this type of propagation was not described, one possibility is that it is accomplished by propagation of the AVRs themselves (Fig. 5A). Given the systematic right-stepping en echelon geometry of the AVRs, if they were to individually propagate southward they would asymmetrically transfer material within the plate boundary zone to the North American plate. Such a mechanism would not produce recognizable large-scale failed rifts, transferred lithosphere, or pseudofaults as the process is taking place within the plate boundary zone where deformation and volcanism is distributed and later further dismembered at the oblique boundary faults (Fig. 5A) (Murton and Parson, 1993; Parson et al., 1993; Searle et al., 1994).

The tendency for southward propagation of AVRs may be controlled by the SW migration of the plate boundary zone in the mantle “hot spot” reference frame (Gripp and Gordon, 2002). As discussed above, such a migration suggests an eastward lag or asymmetry between the surficial plate boundary and its deeper melting regime (see Fig. 5B). Since the plate boundary and its melting regime are oblique with respect to the AVRs, which are oriented more northerly and perpendicular to the opening direction, the southern ends of the AVRs tend to more closely approach the center of the underlying melting regime than their northern ends (Fig. 5A). This geometry suggests that the AVR southern ends may have a greater melt supply than the northern ends. Such a configuration may promote volcanic growth of the AVRs toward their southern ends and tectonic dismemberment of their northern ends, and thus favor an overall southward propagation. The cyclic nucleation and propagation of new AVRs in this pattern would transfer small amounts of material from one plate to the other. This mechanism is consistent with magnetization variations along an individual AVR near 58°N, resolved in closely-spaced magnetic tracks, which displays increased amplitudes at its southern end (Searle et al., 1994), as seen at true propagating ridge tips (Christie and Sinton, 1981; Wilson and Hey, 1995). The skew in the melting regime toward the eastern side of the plate boundary zone also may explain the generally larger bounding faults, more robust rift mountains and the sharper magnetic polarity transition width on the eastern side (Searle et al., 1994).

Evolutionary models for AVRs describe a cyclic process of volcanic growth and maturation followed by tectonic dismemberment (Parson et al., 1993; Peirce and Sinha, 2008; Searle et al., 1994) although other detailed studies suggest more complex evolutions at individual AVRs (Pałgan et al., 2017). These models primarily consider the temporal evolution of these features without a systematic spatial migration. Given a spatial lag between the ridge axis and the deeper melting regime suggested by plate motion models (Gripp and Gordon, 2002), a preferred southward propagation of AVRs, as described above (Fig. 5A), may exist. If so, the cyclic temporal evolution of AVRs at the Reykjanes Ridge may also involve a spatial evolution whereby southward propagating AVRs are volcanically younger at their southern ends and more tectonically dismembered at their northern ends. Successive nucleation of fissures at the western end of the plate boundary zone and their southward propagation may also lead to a cyclic evolutionary sequence of AVRs that additionally involves a systematic tectonic transfer of material from the Eurasian to the North American plate.

One observation not accounted for in this model are the occasional short intervals of transfer of material from the North American to the Eurasian plate, inferred from magnetic anomaly modeling (Benediktsdóttir et al., 2012). These are described as northward propagation events and are rare compared to the general pattern favoring westward accretion of material. They may be related to the southward propagation of pulses of enhanced melting that form the V-shaped ridges. It is possible that as these pulses migrate across a set of AVRs the locus of enhanced melt production is temporarily reversed to the north, promoting northward propagation of the AVRs. Given their right-stepping en echelon configuration, northward propagation would transfer material to the Eurasian plate. More detailed near-bottom observations are needed across sets of AVRs to test these conceptual models.

4. Discussion

Although most models for the evolution of the Reykjanes Ridge assume that its changing crustal and tectonic configurations directly reflect the dynamics of an underlying mantle plume, here we evaluate its evolution in terms of general characteristics of slow spreading ridges but superimposed on a regional mantle anomaly with systematic horizontal gradients in melting properties. We hypothesize that this mantle gradient was not formed by outward flow from a narrow plume stem but instead formed either as a broad upwelling from deeper in the mantle (Anderson and Natland, 2014) or though ancient subduction and suturing events (Schiffer et al., 2014). However it formed, its horizontal gradient in melting properties beneath the Reykjanes Ridge (most likely caused by variations in the concentration of H_2O and other volatiles) has significant effects in modulating the intensity of small-scale upper mantle convective instabilities and spatially directing their propagation.

4.1. General characteristics of slow-spreading ridges

A key feature of slow-spreading ridges is the significant role that active buoyant mantle upwelling is hypothesized to play in their crustal accretion, segmentation, and kinematic evolution (Bonatti et al., 2003; Choblet and Parmentier, 2001; Crane, 1985; Kuo and Forsyth, 1988; Lin et al., 1990; Parmentier and Phipps Morgan, 1990; Phipps Morgan and Parmentier, 1995; Schouten et al., 1985; Tolstoy et al., 1993; Whitehead et al., 1984). Within the melting regimes of slow-spreading ridges the formation of depleted residual mantle and to a lesser degree retained melt and the thermal structure resulting from plate-driven mantle advection can cause buoyant diapiric upwelling of mantle material (Scott and Stevenson, 1989; Sotin and Parmentier, 1989) at a rate faster than that driven purely by plate separation (Reid and Jackson, 1981). Although early studies attributed diapiric upwelling primarily to melt buoyancy itself (Crane, 1985; Schouten et al., 1985; Whitehead et al., 1984), studies of melt migration suggest that there is little retained melt within the melting regime mantle matrix (Ahern and Turcotte, 1979; McKenzie, 1985) and therefore most buoyancy results from mantle depletion due to the loss of dense phases and increase in the MgO/FeO ratio in the residue (O'Hara, 1975; Oxburg and Parmentier, 1977) and the advected thermal structure caused by plate spreading (Scott and Stevenson, 1989). Central observations consistent with diapiric mantle upwelling are the fundamentally different segmentation and crustal thickness variations that characterize slow- vs. fast-spreading ridges. At slow-spreading ridges crustal thickness variations from segment center to segment ends are significantly greater than at fast spreading ridges (Detrick et al., 1995; Kuo and Forsyth, 1988; Tolstoy et al., 1993) and segmentation itself is more prevalent, forming even when there is little or no offset of the axis (Phipps Morgan and Parmentier, 1995). This is thought to occur because buoyant upwelling instabilities are a Rayleigh-Taylor type phenomenon, initiated by plate-driven mantle upwelling and melting on crossing the solidus, but evolving to discrete spaced diapirs or convective cells even if the axis is long, linear and without offsets (Choblet and Parmentier, 2001; Lin et al., 1990; Phipps Morgan and Parmentier, 1995). When ridge offsets are small (or zero) the buoyant instabilities can migrate along the strike of the axis forming V-shaped wakes consisting of thicker crust segment centers bounded by zones of thinner crust forming non-transform discontinuities (Dannowski et al., 2018; Phipps Morgan and Parmentier, 1995; Schouten and White, 1980; Sempéré et al., 1995; Tucholke et al., 1997; Wang et al., 2015). This contrasts with observations at fast-spreading ridges where typically no large crustal thickness changes occur along-axis unless there are significant offsets of the axis. At fast-spreading ridges there are two general models for their less segmented structure: (1) rapid plate-driven mantle advection may prevent the development of discrete three-dimensional buoyant instabilities, resulting in two-dimensional upwelling patterns (Lin et al., 1990; Lin and Phipps Morgan, 1992; Parmentier and Phipps Morgan, 1990), and (2) mantle upwelling may in fact be three-dimensional but redistribution of melt in shallow continuous melt lenses or along-axis ductile crustal flow may counter or prevent large crustal thickness variations (Lin and Phipps Morgan, 1992; Phipps Morgan and Parmentier, 1995). Geochemical evidence that different mantle upwelling configurations (Fig. 6) lead to differences in melt chemistry (Langmuir et al., 1992; Niu and Batiza, 1994; Plank and Langmuir, 1992), however, appears to favor two-dimensional plate-driven advection at fast-spreading ridges and three-dimensional diapiric advection at slow-spreading ridges.

Rheological layering within the mantle melting regime produced by the extraction of water (Hirth and Kohlstedt, 1996; Phipps Morgan, 1997) may also affect the mantle advection pattern beneath slow-spreading ridges (Bonatti et al., 2003; Braun et al., 2000; Choblet and Parmentier, 2001). In these models (Fig. 6), the deeper part of the melting regime between the wet and dry solidi may retain appreciable water and thereby maintain a sufficiently reduced viscosity to enable buoyant mantle upwelling (Braun et al., 2000; Choblet and Parmentier, 2001). Above the dry solidus water extraction from the mantle is more efficient (Hirth and Kohlstedt, 1996) and the damp melting interval transitions to a higher viscosity part of the melting regime where plate-driven (passive) mantle advection predominates. By limiting the height of the buoyant upwelling interval to between the wet and dry solidi, these new geodynamic models (Braun et al., 2000; Choblet and Parmentier, 2001) appear to resolve the discrepancy present in previous numerical models (Barnouin-Jha et al., 1997; Magde and Sparks, 1997; Parmentier and Phipps Morgan, 1990) that predicted longer wavelength buoyant upwelling than could explain the observed shorter wavelength segmentation at slow spreading ridges.

In addition to these predicted spatial effects, geophysical and geochemical observations resolve significant temporal crustal thickness variations (~1.5–2 km) on time scales of ~2–4 Myr along flowlines from individual slow-spreading segments, interpreted as episodic behavior of the buoyant mantle instabilities (Bonatti et al., 2003; Pariso et al., 1995; Tucholke et al., 1997). These observations suggest that episodic buoyant upwelling instabilities contribute a modulating effect of about a third or less to the total crustal thickness produced by passive plate-driven upwelling, which we assume is a continuous background process as long as spreading continues.

Geochemical effects are also predicted due to the form of mantle advection. Mantle flowlines in buoyant (active) advection are focused (Fig. 6B) so that the buoyantly upwelling mantle experiences similar degrees of melting whereas in passive (plate-driven) mantle advection flowlines widen with depth to form broad triangular melting regimes (Fig. 6A) wherein the deep wide base of the triangle undergoes low degrees of melting but contributes appreciably greater quantities of incompatible elements to the pooled melt for the same mantle properties (composition and temperature) (Langmuir et al., 1992; Plank and Langmuir, 1992). Although often interpreted as indicators of mantle temperature (Klein and Langmuir, 1987), variations in the concentration of incompatible elements may instead reflect changes in the pattern of mantle flow though the melting regime (active vs. passive) (Langmuir et al., 1992; Plank and Langmuir, 1992) even when the mantle itself is uniform in composition and temperature (Fig. 6). The non-steady state behavior of buoyant mantle upwelling, predicted in geodynamic models (Scott and Stevenson, 1989) and observed through sampling (Bonatti et al., 2003) and gravity variations (Pariso et al., 1995; Tucholke et al., 1997) may thus impart both crustal thickness and geochemical variations even along individual ridge segments. Thus, along the Reykjanes Ridge axis and flanks, observed anti-correlated variations in incompatible element concentrations and crustal thickness (Jones et al., 2014) need not indicate underlying mantle temperature variations, but rather the episodic passage of buoyant (active) upwelling instabilities in an otherwise plate-driven (passive) advective melting regime (Fig. 6). These shorter wavelength temporal and spatial variations induced by the changing geometry of mantle upwelling would be superimposed on the longer wavelength regional mantle anomaly gradient toward Iceland (Fig. 2).

Thus, active (buoyant, three-dimensional, diapiric, episodic) mantle upwelling distinguishes slow-spreading ridges from intermediate- and fast-spreading ridges where passive (plate-driven, two-dimensional, sheet-like, steady-state) mantle upwelling appears to predominate (Lin and Phipps Morgan, 1992; Parmentier and Phipps Morgan, 1990; Phipps Morgan and Parmentier, 1995). This difference in the form of mantle advection affects not only the pattern and rates of mantle flow and thereby melt generation rates and crustal thickness along ridge segments (Kuo and Forsyth, 1988; Lin and Phipps Morgan, 1992; Lin et al., 1990; Tolstoy et al., 1993) but also the chemistry of the melts (Langmuir et al., 1992; Plank and Langmuir, 1992). At the slow-spreading Reykjanes Ridge (~40–20 mm/yr full spreading rate over the history of the ridge) buoyant mantle advection should not only exist but should be amplified by the lowered solidus temperature and mantle viscosity (Choblet and Parmentier, 2001) due to elevated water content and its increasing concentration toward Iceland (Nichols et al., 2002) and moderately elevated temperatures (~75°C) indicated by both regional gravity anomalies (Cochran and Talwani, 1978) and seismic

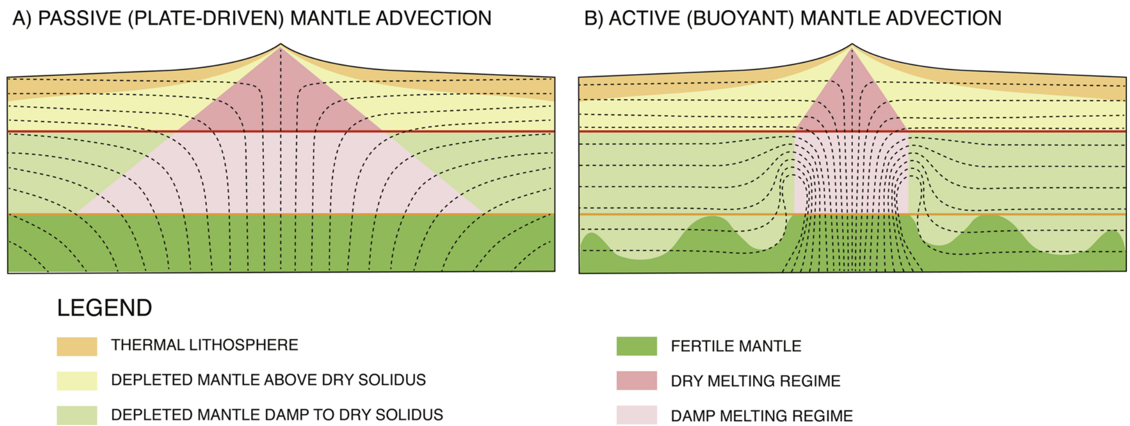

Fig. 6. Schematic vertical cross-sections depicting mantle flowlines (dashed lines) beneath a ridge for A) passive (plate-driven) mantle advection (after Reid and Jackson, 1981) and B) active (buoyant) mantle advection (after Bonatti et al., 2003). Red horizontal line indicates the dry solidus and the orange line the damp solidus. A) Plate driven mantle advection produces broad triangular melting regimes wherein the deeper portions contribute large quantities of incompatible elements to the pooled melt. B) Within the damp melting interval (between dry and damp solidi) mantle viscosities are low and buoyant upwelling can occur (Braun et al., 2000; Choblet and Parmentier, 2001). The more focused flowlines and greater upwelling rates of active mantle advection relative to passive flow produce greater extents of melting, lower incompatible element concentrations, and thicker crust for the same mantle composition and temperature (e.g., Plank and Langmuir, 1992). Because of the greater upwelling rates of active upwelling, depleted mantle locally accumulates displacing fertile mantle leading to the variation in the boundary depth between depleted and fertile mantle (mantle prior to melting and melt extraction). The accumulation of depleted mantle creates a negative feedback to the active upwelling itself, leading to episodic behavior (Bonatti et al., 2003; Scott and Stevenson, 1989). This episodic behavior may be envisioned as an alternation between the two end-member forms of mantle convection shown above (A and B). At the Reykjanes Ridge the episodic axial propagation of buoyant upwelling instabilities (B) within an otherwise plate driven advective flow regime (A) leads to the crustal thickness and chemical variations associated with the V-shaped ridges as mantle advection varies between these end-member regimes. The spacing of the V-shaped ridges indicate episodes of buoyant upwelling and propagation of the instabilities along axis at intervals of 3–6 Myr (Jones et al., 2002). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

shear wave velocity anomalies (Delorey et al., 2007). Spatial (horizontal) mantle chemical gradients may cause buoyant instabilities to migrate as indicated at normal slow-spreading ridges by the frequent occurrence of V-shaped traces formed by crustal segmentation centers and bounding non-transform discontinuities (Fig. 3). These crustal thickness variations are seen to propagate along axis and often in opposite directions even within local areas (Dannowski et al., 2018; Gente et al., 1995; Phipps Morgan and Parmentier, 1995; Wang et al., 2015) showing that they do not reflect regional mantle flow (Fig. 3). Most likely, the propagations are driven by small and random mantle chemical heterogeneities that affect bulk mantle melting as observed at segments with good geochemical constraints (Michael et al., 1994; Niu et al., 2001). In contrast to these small and irregular variations, the existence of strong and systematic regional mantle gradients in properties that affect melting along the Reykjanes Ridge is supported by observed axial and ridge flank variations in basement depth, crustal thickness and residual basement depth anomalies (basement depth corrected for the effects of subsidence with age and sediment load) (Louden et al., 2004; Fig. 2), as well as by direct measurement of water content in axial lavas (Nichols et al., 2002). It appears likely that some combination of a moderate temperature anomaly (~75°C (Cochran and Talwani, 1978; Delorey et al., 2007)) and systematic variation in volatile content (Nichols et al., 2002) are responsible for these horizontal spatial gradients in mantle melting. Thus, although sampling along the Reykjanes Ridge and flanks has revealed multiple systematic chemical variations in major and trace elements and isotopes (Fitton et al., 1997; Jones et al., 2014; Murton et al., 2002; Schilling, 1973) we focus on volatile content (primarily H_2O, e.g., Nichols et al., 2002) and possibly temperature (Cochran and Talwani, 1978; Delorey et al., 2007) because these properties strongly affect mantle melting and viscosity and are key to the development of buoyant mantle upwelling (Braun et al., 2000; Choblet and Parmentier, 2001). Water, in particular, has long been proposed as an alternative to elevated mantle temperature to enhance mantle melting at "hot spots" (e.g., Asimow et al., 2004; Bonatti, 1990). Although we cannot separate out individual contributions of water content, other chemical fertility variations, and temperature on overall crustal production, the residual basement depth anomaly reflects the combined effects of these potential factors and shows a clear and consistent trend both on and off axis between the Bight Fracture Zone and Iceland (Fig. 2). Thus, the systematically varying geochemical trends along with the systematic variations in depth, crustal thickness, and residual basement depth anomalies indicate a spatial (horizontal) *mantle gradient* in melting and rheologic properties, extending at least between the Bight FZ and Iceland. We discuss this anomalous mantle gradient primarily with respect to its effects on the Reykjanes Ridge south of Iceland and refer to it as a thermo-chemical mantle anomaly without further specifying its properties other than to note that it has an apparent step-like increase beneath Iceland and grades to background values by the Charlie Gibbs fracture zone in terms of major effects on crustal thickness and seafloor depth. Important effects of this mantle gradient are not only that it modulates overall melting along the Reykjanes Ridge, but that it should also promote buoyant mantle upwelling instabilities and may cause them to propagate along axis (Fig. 7) similar to the way that small and irregular mantle heterogeneities cause crustal segmentation and non-transform discontinuities to migrate along typical slow-spreading ridges (Fig. 3). Thus, we surmise that each episode of buoyant upwelling begins beneath Iceland where the mantle anomaly peaks and propagates southward along-axis to the Bight transform fault, where this long-established tectonic discontinuity (including the predecessor triple junction) prevents further propagation. Propagation to the north of Iceland is inhibited by a major long-lived transform-like tectonic offset across the northern Greenland-Iceland-Faroe-Ridge that initially offset the Aegir Ridge from the early extension of the Reykjanes Ridge plate boundary through Iceland and later offset the Kolbeinsey Ridge from the plate boundary through Iceland (Nunns, 1983). Today the Tjörnes transform fault system north of Iceland forms the active part of this boundary (Rognvaldsson et al., 1998; Stefansson et al., 2008). The limits placed by these lithospheric tectonic boundaries on the axial propagation of small-scale convective instabilities indicates that they are fundamentally shallow mantle phenomena tied to the melting regimes of divergent plate boundaries. It should be noted that the

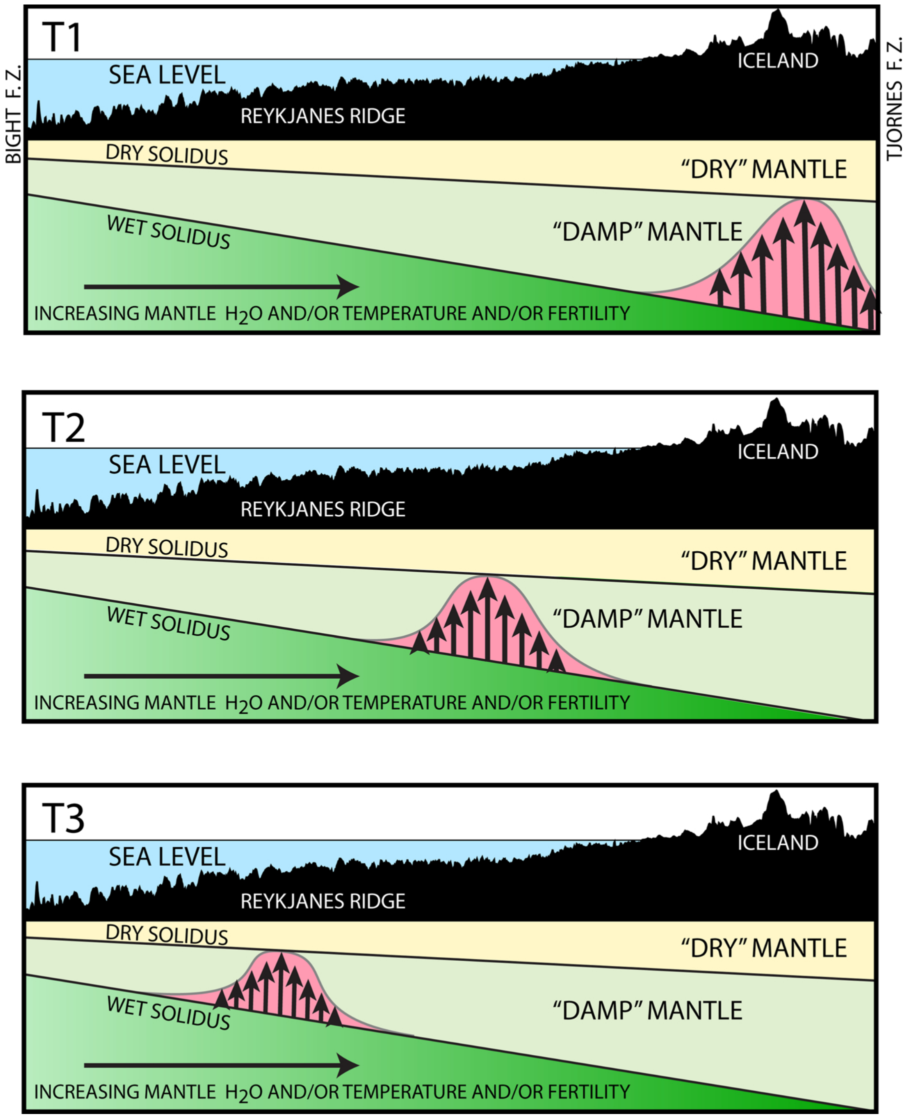

Fig. 7. Conceptual model of propagating buoyant upwelling instabilities beneath Iceland and along the Reykjanes Ridge. Black areas show bathymetry and topography along the plate boundary overlaid on schematic depictions of the mantle. Panels show sequential times (T1–T3) during which an upwelling instability (pink area with upward pointing arrows) forms beneath Iceland and propagates southward along the Reykjanes Ridge "damp" melting regime where elevated water contents maintain low mantle viscosity and promote melting. Gradients in mantle water content and perhaps temperature increasing toward Iceland imply deepening dry and wet solidi toward Iceland. This spatial mantle gradient both modulates overall mantle melting and causes the upwelling instabilities to initiate beneath Iceland and propagate systematically southward to form the V-shaped crustal ridges observed on the flanks. The upwelling instabilities (pink areas) depict the episodic formation and propagation of 3-D buoyant vertical advection cells (Fig. 6B) with upwelling rates in excess of that produced by background 2-D plate-driven "passive" advection (Fig. 6A). Thus, although the instabilities rapidly propagate along-axis in a wave-like manner there is no large-scale along-axis mantle flow. The propagating instabilities are delimited by the long-lived tectonic discontinuities at the Bight and Tjörnes transform faults showing that they are upper mantle phenomena tied to the melting regimes of the divergent plate boundary. Figure modified from Martinez and Hey (2017). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

propagation of buoyant upwelling mantle instabilities does not imply actual along-axis flow of mantle material, rather it is the upwelling instability itself that migrates in a wave-like manner along axis (Martinez and Hey, 2017). The propagation of the upwelling instabilities, probably even during the continental rift phase, may be what favored initial formation of a linear axis and what drove the reassembly of the linear axis following an abrupt kinematically-driven breakup of the axis.

Our model for the Reykjanes Ridge thus incorporates normal plate tectonic processes operating at slow-spreading ridges, including small-scale upper mantle convection, superimposed on a relatively passive regional upper mantle thermo-chemical anomaly to explain its evolution and properties. It provides an alternative to "mantle plume" hypotheses that require large, dynamic and rapid changes in regional mantle flow and temperature to explain these same phenomena. We discuss these implications and a speculative origin for the regional thermo-chemical mantle anomaly in a final section.

4.2. Melting regime control on plate boundary configurations

The large-scale systematic changes in tectonic configuration of the Reykjanes Ridge are perhaps its most prominent and distinctive characteristic. We propose that these changes were controlled by plate kinematics and the effects of a regional mantle anomaly with horizontal gradients. This control is seen at normal slow-spreading ridges in the along-axis migration of centers of melting leading to V-shaped crustal thickness patterns and non-transform discontinuities (Fig. 3) as well as in the lateral migration of ridge axes by asymmetric seafloor spreading to form and eliminate transform faults (Gente et al., 1995; Schouten and White, 1980; Tucholke et al., 1997). At normal ridges these processes often appear to be random, likely controlled by irregular distributions of mantle chemical heterogeneities that affect melting properties as they are entrained into the ridge melting regime by mantle flow induced by plate spreading. We hypothesize that where there are strong and persistent regional gradients in mantle melting properties, the effects on the plate boundary may be systematic and dominate over kinematic (mechanical) lithospheric effects. This is because of the importance of buoyant upwelling at slow spreading ridges. Factors that control mantle melting, such as regional gradients in composition, likely affect the dynamics of these buoyant instabilities.

The evolution of the Reykjanes Ridge took place over a regional mantle anomaly that extended over the length of the ridge and likely significant parts of the pre-rift continent. During the rift phase, as continental lithosphere thinned, the anomalous mantle would have been advected above its solidus and begun to melt, forming small-scale convective instabilities. Such instabilities have been proposed during the rift phase of the Red Sea for example (Bonatti, 1985), but along the rifting Greenland-Eurasia margin, the underlying mantle gradients would have caused the convective instabilities to propagate along the axis of the rift away from the area that later becomes Iceland. These small-scale convective instabilities may have led to the voluminous melt produced as seaward dipping reflectors near breakup and early seafloor spreading, but not as two-dimensional cells as commonly portrayed (Mutter et al., 1988) and modeled (Boutilier and Keen, 1999), but as three-dimensional instabilities migrating along the rift. Propagation of such migrating instabilities would have locally produced voluminous volcanism followed by periods of much less volcanism leading to the distinctive and discrete sequences of seaward dipping reflectors. The propagation itself could have helped to create a linear melting regime even during the rift phase so that at continental breakup the initial seafloor spreading axis was linear. Large excesses in mantle volatiles would have been diminished by the early voluminous volcanism leading to a decrease in magma production. However, the propagation of convective instabilities along the deep melting regime would have continued into the seafloor spreading stage forming V-shaped crustal ridges on the ridge flanks from the linear spreading axis (Parnell-Turner et al., 2014). Seafloor spreading continued stably in this mode until the change in opening direction near anomaly 17.

The abrupt ~30° counterclockwise rotation in plate opening direction led to the fragmentation of the lithosphere to form new spreading segments oriented orthogonal to the new stress regime. As discussed above, the geological mechanisms of the fragmentation are not resolved in current data, but longer segments with longer offsets appear to have been formed with distance from Iceland. Despite long-held theories that ridge segments prefer to orient themselves perpendicular to local opening stresses (Menard and Atwater, 1968), the offset Reykjanes Ridge segments only did this initially near the time of plate motion change and then promptly began to evolve diachronously back to its prior linear configuration even though this required oblique spreading. This evolution indicates a stronger controlling mechanism acting on the plate boundary that predominated over the tendency to form orthogonal spreading centers perpendicular to the relative opening direction.

In our model, the controlling mechanisms for the reestablishment of a linear axis and elimination of transform faults are the original linear geometry of the deep "damp" melting regime and the upwelling instabilities that propagate along it due to a regional mantle gradient. The Reykjanes Ridge appears to have always maintained a deep linear melting regime that did not change configuration significantly even when the axis was segmented and offset. The plate boundary lithospheric offsets of a few tens of km were not sufficient to significantly offset the trend of the deep (>60 km) damp melting regime as shown in numerical models where the spreading axis is only offset by similar amounts (e.g, Kuo and Forsyth, 1988). Rather, it appears that it was the continuity of this linear deep damp melting regime that caused the axis to reconfigure back to its previous geometry. The abrupt change in opening direction near anomaly 17 resulted in a mechanical breakup and rotation of the lithosphere so that new segments were oriented perpendicular to the new opening direction, but this lithospheric kinematic change was decoupled by the much lower viscosity of the underlying asthenosphere and did not rotate the deep damp linear melting regime of the previous axis. The new lithospheric tectonic spreading segments were offset from the deeper damp melting regime which continued in its linear configuration and guided the reassembly of the axis to conform again with this geometry. The propagation of buoyant instabilities likely also continued during the offset ridge stage, but as crustal accretion was largely determined by the offset configuration of the shallower dry melting regime, V-shaped crustal ridges could not form. As the ridge progressively became linear again from north to south, flanking crustal V-shaped ridges were correspondingly formed by the propagating instabilities that continued in the deep damp melting regime.

In contrast to this distinctive and unified behavior of the Reykjanes Ridge, ridge segments south of the Bight transform fault (and the earlier triple junction) were always segmented and offset in a stair-step pattern and orthogonally-spreading. Although the anomalous mantle associated with the Iceland hotspot is generally inferred to continue southward to the Charlie Gibbs fracture zone, the ridges north and south of the Bight transform fault had different tectonic origins and configurations and therefore different plan view shapes to their melting regimes. Thus, they may continue to have different configurations and evolutions into the future. Modeling of magnetic anomalies, however, indicates that the offset of the segment south of the Bight transform fault with the Reykjanes Ridge is diminishing with time (Benediktsdóttir et al., 2016). The continuation of the mantle gradient from Iceland to south of the Bight transform fault may therefore cause the propagating upwelling instabilities to extend beyond the Bight transform fault if ridge offsets become small enough. Merging of the deep melting regimes to a uniform linear geometry could then cause elimination of the Bight transform fault and segments further to the south to also become part of the linear and obliquely-spreading Reykjanes Ridge and eventually also develop flanking V-shaped ridges.

4.3. Alternative thermal models for the origin and elimination of transform faults

Other explanations for the development (and later elimination) of segmentation offsets on the Reykjanes Ridge have invoked regional mantle temperature changes in response to mantle plume flow or changing proximity to the plume center (Abelson and Agnon, 2001; Abelson et al., 2008; Jones, 2003; White, 1997). These models propose similar processes hypothesizing that when hotter mantle plume material underlies the spreading center the lithosphere behaves in a ductile manner and transform fault and fracture zones cannot form and when this plume influence is somehow suppressed or removed, cooler lithosphere allows for transform faults and fracture zones to develop. None of these models describe geologic mechanisms for the formation or removal of transform faults. They also do not account for the persistence of the regional residual basement depth anomaly (Louden et al., 2004; Fig. 2) throughout the time of both spreading on a linear axis and offset axes, which should disappear if mantle plume heating ceased and mantle reverted to a normal thermal structure. The consistent gradients, all shallowing toward Iceland, during the entire opening of the North Atlantic rather imply a continuous presence of a mantle anomaly, although not necessarily due to temperature. As discussed below, the primary change in the regional crustal characteristics associated with the offset segmented stage of spreading is an apparent crustal thinning, which can be explained by the effect of plate boundary offsets on mantle upwelling (Magde and Sparks, 1997; Phipps Morgan and Forsyth, 1988) without requiring mantle temperature changes.

Other observations also argue against mantle temperature changes as a cause for the formation and elimination of transform faults. Rather than simply eliminating transform faults, a general thermal weakening of the lithosphere would likely lead to the disappearance of narrow plate boundary zones altogether and to diffuse extension as occurs in some backarc basins due to the weakening effects of a continuous water flux from the subducting slab (Martinez et al., 2018). Yet along the Reykjanes Ridge, it is the hottest part of the system—the divergent plate boundary itself, that retains its focused form of crustal accretion forming well-defined magnetic anomalies (Merkouriev and DeMets, 2014; Fig. 1B) throughout the process of formation and elimination of transform faults. Even the current phase of oblique spreading on a linear axis produces clearly identifiable isochrons on magnetic profiles (Benediktsdóttir et al., 2012; Hey et al., 2010) as well as in magnetic anomaly and seafloor magnetization maps (Lee and Searle, 2000; Martinez and Hey, 2017). Thus, a plume-influenced thermal weakening of the Reykjanes Ridge lithosphere does not explain the organized asymmetric-spreading mechanism of removal of the transform faults observed in the southern segments (Martinez and Hey, 2017), the systematic reconfiguration of the axis to its prior geometry and the continued organized accretion of crust throughout these transitions within narrow divergent plate boundary zones to form well-defined magnetic anomalies. Plume models also require an extremely rapid retreat followed by advance of enormous volumes of mantle material with highly contrasting temperatures beneath this area of the North Atlantic basin to effect the proposed changes in lithospheric rheology and plate boundary reconfigurations.

Other ideas invoking along-axis ductile crustal flow were proposed to explain an interpreted lack of segmentation on the current Reykjanes Ridge (Bell and Buck, 1992). As noted above, these models and ideas do not properly take into consideration the nature of the ridge flank V-shaped crustal ridges and troughs–as a type of magmatic crustal segmentation. Various studies have identified the intersection of a V-shaped ridge with the ridge axis as a locus of enhanced magmatism and crustal thickness (Hey et al., 2010; Jones et al., 2014; Lee and Searle, 2000; Murton et al., 2002; Parnell-Turner et al., 2013; Searle et al., 1998). Due to the acute angle of intersection, the crustal thickness variations formed by these features have low topographic gradients along the Reykjanes Ridge axis but they are similar in overall amplitude (~2 km) (White et al., 1995) to crustal thickness variations between segment centers and non-transform discontinuities at normal slow-spreading ridges (Tucholke et al., 1997; Wang et al., 2015). The Reykjanes V-shaped ridges and troughs are thus a form of magmatic crustal segmentation ~2 km in amplitude that are clearly formed on axis and persist indefinitely on the ridge flanks comparable to crustal segmentation at non-transform discontinuities at normal slow-spreading ridges. If ductile crustal flow along the Reykjanes Ridge axis actually removed magmatic crustal segmentation then ridge flank V-shaped ridges could not form, which is clearly not the case (Fig. 1).

Thus, the very existence of V-shaped crustal ridges and troughs (apparently to the inception of spreading (Parnell-Turner et al., 2014)) argues against ductile crustal flow in general as the cause for the lack of transform faults on the current Reykjanes Ridge. These models are also challenged by existence of the Tjörnes transform fault directly adjacent to northern Iceland, near the center of the proposed mantle plume in these models. The Tjörnes transform fault system offsets the plate boundary passing through Iceland from the Kolbeinsey Ridge, the continuation of the plate boundary north of Iceland. The Tjörnes transform fault sustains abundant and strong (to M 7) strike-slip seismic activity (Rognvaldsson et al., 1998; Stefansson et al., 2008) with maximum earthquake depths in the range of 10–16 km (Rognvaldsson et al., 1998), similar to that of major long-lived North Atlantic transform faults (Bergman and Solomon, 1988) located south of the Charlie Gibbs Fracture Zone and beyond the presumed Iceland plume influence as indicate in basement depth anomalies (Louden et al., 2004). These earthquake studies together with seismic shear wave studies (Menke and Sparks, 1995; Menke et al., 1996) indicate thick but strong and brittle crust even beneath Iceland itself. Taken together, these characteristics document strong, thick and brittle crustal and lithospheric mechanical behavior rather than weak ductile flow. The plate boundaries immediately north of the Greenland-Iceland-Faroe Ridge (first the Aegir Ridge and later the Kolbeinsey Ridge) have always been offset from the plate boundary through what is now Iceland and the Reykjanes Ridge by a major transcurrent feature (Nunns, 1983). Thus, the present Tjörnes transform fault and the earlier long existence of transform fault systems along the northern edge of the Greenland-Iceland-Faroe Ridge and proximal to the proposed plume center argue against a thermal weakening of the crust and lithosphere to a ductile state as the explanation for the elimination of transform faults along the present Reykjanes Ridge up to 1000 km farther away from the putative plume center under Iceland.

Other global examples where plume effects are not suspected also argue against mantle thermal processes in the formation or elimination of transform faults. For example, in the western Pacific the Parece Vela basin underwent a rapid change in opening direction from E-W to NE-SW near anomaly 6A. As a result, an over 800-km-long ridge, which was previously segmented by only a few non-transform discontinuities and short-offset propagating ridges, abruptly became segmented by closely-spaced transform faults oriented in the new opening direction (Okino et al., 1998). Similarly, the Woodlark Basin in the SW Pacific underwent an abrupt change in opening direction from ~N-S to ~NNW-SSE and the entire 500-km-long spreading axis synchronously re-oriented to be orthogonal to the new opening direction (Goodliffe et al., 1997). In both these cases the abrupt nature of the change in plate motion and synchronous segmentation and reconfiguration of entire axes over hundreds of km indicates a mechanical response of the lithosphere rather than mantle thermal effects on lithospheric rheology. Likewise, the abrupt onset of segmentation along ~900 km of the Reykjanes Ridge indicates predominantly a mechanical response of the lithosphere to a kinematic change. However, the North Atlantic mantle anomaly likely did have a modulating effect on the style of reconfiguration. Shorter and smaller-offset segments formed northward toward Iceland suggesting a modulation of the mechanism of segmentation by the gradient in the melting away from Iceland. These modulating effects do not indicate abrupt temporal changes in underlying mantle temperature as in plume models, rather they reflect the long-lived gradients in mantle properties toward Iceland and their steady-state effects on lithospheric rheology and mechanics.

4.4. Crustal thickness changes with modes of spreading on the Reykjanes Ridge

Changes in crustal thickness are inferred to be associated with the three modes of spreading and segmentation of the Reykjanes Ridge (White, 1997). Crustal thicknesses are only locally constrained by seismic determinations in a few places but based on these measurements are generally estimated to be >8 km (reaching 10–11 km) in "unsegmented" or "smooth" crust without fracture zones and are roughly estimated to be ~7 km in "segmented" or "rough" crust with fracture zones (Abelson et al., 2008; Jones, 2003; White, 1997). From these few spot measurements it is inferred that during the spreading modes when the axis was linear and without fracture zones the accreted crust was typically ~2 km or ~30% thicker and the mantle 50°C warmer than during the spreading mode with stair-step ridge axis offsets and fracture zones (White, 1997).

Because of this apparently systematic variation in crustal thickness, several studies infer that mantle temperature changes related to plume activity or proximity were also involved (Abelson et al., 2008; Jones, 2003; White, 1997). As noted above, these models also suggest that higher mantle temperatures led to a rheological change in the lithosphere such that transform faults could not form when the lithosphere was hotter and presumably ductile and point to the thicker crust formed during these stages as supporting evidence. The changes in crustal thickness are inferred to directly reflect mantle temperature changes of ~50°C (White, 1997) based on two-dimensional models of passive mantle upwelling and melting (e.g., McKenzie and Bickle, 1988). These models imply highly variable mantle plume activity wherein plume material across the entire North Atlantic Basin between the Bight Fracture Zone and the Greenland-Iceland-Faroe Ridge abruptly cools, contracts, interacts less with the axis, or is otherwise "suppressed" during the segmented spreading stage and then rapidly advances and/or is thermally expressed (Abelson et al., 2008; Howell et al., 2014; Jones, 2003; White, 1997).

The above models, however, do not take into account important three-dimensional (3-D) effects of offsets of the divergent plate boundary on mantle advection (Magde and Sparks, 1997; Phipps Morgan and Forsyth, 1988). When a ridge axis is long and linear, the first-order passive plate-driven mantle advection pattern is well-characterized by two-dimensional (2-D) analytical solutions (e.g., Reid and Jackson, 1981). These form two-limbed corner flow patterns. The region where mantle flowlines have a vertical component of flow outlines the triangular melting regimes above the solidus characteristic of 2-D passive plate spreading (e.g., Langmuir et al., 1992). These 2-D flow solutions generate a maximum melting rate for a given plate spreading rate following simple decompression melting relations (e.g., McKenzie and Bickle, 1988). When a ridge axis has offset segments, however, mantle flow can have horizontal flow components in the third dimension across the ends of the segments toward the segment centers (Phipps Morgan and Forsyth, 1988). This horizontal flow of mantle diminishes the vertical flow near the segment ends. Since horizontally flowing mantle does not undergo decompression it generates no melt. As shown by independent numerical models (Magde and Sparks, 1997; Phipps Morgan and Forsyth, 1988) a segmented spreading center will generate thinner crust than an unsegmented ridge for the same mantle temperature and spreading rate. Shorter ridge segments and larger transform offsets enhance this effect (Magde and Sparks, 1997). Incorporating the effects of a thickening lithospheric thermal boundary layer on the mantle advection pattern (Blackman and Forsyth, 1992) modifies the flow pattern beneath a segmented ridge, more tightly focusing vertical advection near the ridge axis and generally increasing upwelling rates but continues to predict lower vertical advection rates near transform offsets compared to the segment centers. The departures of thermal boundary layer models relative to thin and flat lithospheric models are greatest for shallower levels, with advection patterns more similar to the Phipps Morgan and Forsyth (1988) model at deeper levels.

Following the Phipps Morgan and Forsyth (1988) model, a calculation of the total vertical advection above a 60 km depth solidus for nominal parameters for the Reykjanes Ridge offset spreading stage (52 km long ridges offset by 30 km long transform faults) yields about 30% less overall vertical advection volume per unit time than for a linear two-dimensional ridge (Fig. 8). The decrease in vertical advection volume per unit time directly translates into diminished overall crustal thickness. Since temperature is not involved in this simple model of plate-driven flow of uniform viscosity mantle (Phipps Morgan and Forsyth, 1988), the thinner crust predicted is directly a result of the effect of plate boundary offsets on the pattern of mantle advection and not any cooling "transform fault" effect, which would only further enhance the effect of offsets, as shown in more complex numerical modeling experiments with variable viscosities and thermal structures (Magde and Sparks, 1997).

Observationally, this effect is noted along the Chile Ridge where spreading rate is constant, but segmentation varies strongly. Both depth and mantle Bouguer gravity anomalies are observed to increase over shorter segments with larger offsets (Martinez et al., 2002). It is also well known from seismic and gravity observations that crust thins toward transform faults and fracture zones over significant distances (~40 km) where transform offsets are large (e.g., Whitmarsh and Calvert, 1986). At the relatively short segments (typically <70 km long) formed during the Reykjanes Ridge offset spreading stage the diminished upwelling due to plate boundary offsets can therefore affect the entire segment.

Together the geodynamic and observational studies indicate that systematic changes in crustal thickness between transform-offset and linear stages of spreading on the Reykjanes Ridge can be accounted for by the effects of plate boundary offsets themselves on mantle upwelling and melting without need to invoke changes in mantle temperature.

4.5. Mantle plume upwelling vs. small-scale convection: vertical basement motions, V-shaped crustal ridges and mantle melting

Vertical motions of the shallow (typically <500 m depth) Greenland-Iceland-Faroe Ridge are thought to control the flow of deep cold water masses from the Arctic and have been inferred based on sedimentation patterns and variations in thermally controlled isotope ratios in the adjacent basins (Poore et al., 2011; Poore et al., 2006; Poore et al., 2009; White and Lovell, 1997; Wright and Miller, 1996). These models propose that the vertical motions are caused by time-varying mantle thermal anomalies embedded in mantle plume material that upwells beneath Iceland and radiates outward horizontally beneath

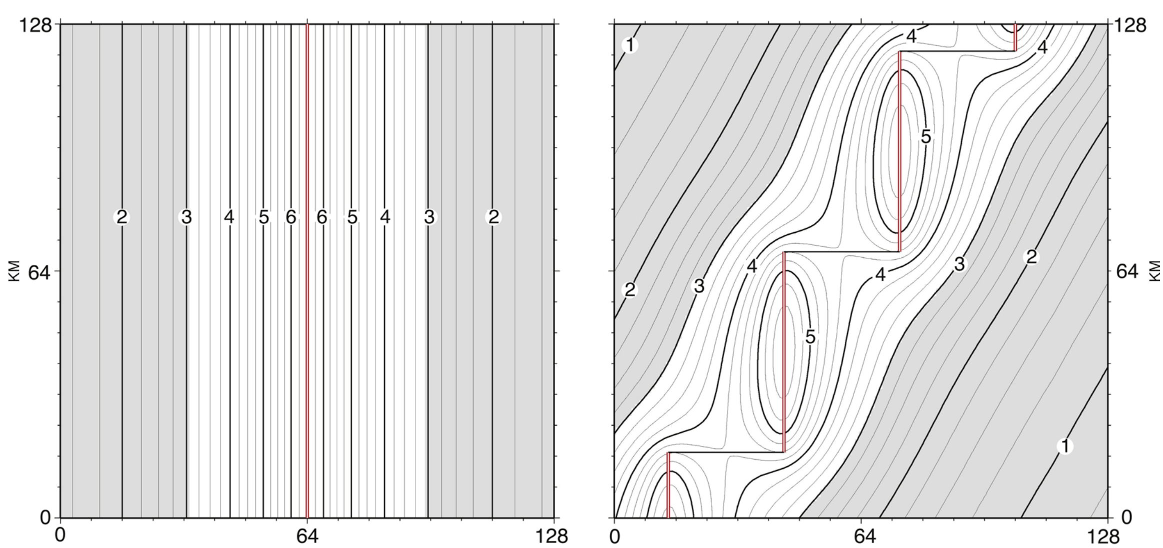

Fig. 8. Map views of the plate-driven passive mantle upwelling patterns generated by a linear ridge (left panel) and a ridge offset by transform faults (right panel) following the numerical method of Phipps Morgan and Forsyth (1988) for a uniform viscosity mantle and flat infinitely thin plates. The divergent plate boundary is indicated by fine red double lines. Transform faults are shown as fine single black lines. The linear ridge produces a maximum volumetric mantle upwelling rate for a given spreading rate. At a segmented and offset ridge, horizontal flow of mantle material across the segment ends leads to diminished upwelling near the offsets. We sum the vertical upwelling component between 60 and 6 km depth and within the 3 km^3/Myr contour (white areas) for each case. Relative to a linear ridge, the total volumetric upwelling rate in this area is diminished in an offset ridge for the same spreading rate and total length of ridge. For nominal parameters for the Reykjanes Ridge (52 km length segments offset by 30 km long transform faults, spreading at a full rate of 20 mm/yr) the total volumetric upwelling rate is diminished by about 30% relative to a linear axis. This translates into an equivalent thinning of the overall crustal thickness with no mantle temperature changes, purely as a result of the effect of the segmented and offset axis compared to a linear divergent boundary on mantle advection. More complex mantle rheologic models (Blackman and Forsyth, 1992; Magde and Sparks, 1997) show the same general effect although advection patterns and magnitudes vary. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

the North Atlantic Basin locally creating isostatic thermal uplift/subsidence events. The horizontally radiating embedded thermal anomalies are also proposed to give rise to the V-shaped ridges flanking the Reykjanes Ridge. All of these models determine the radial rate of flow of the thermal anomalies in the mantle plume head from the geometry of the V-shaped ridges. As the V-shaped ridges form acute angles with the Reykjanes Ridge axis, the predicted horizontal flow rates are large, at least 10 times the spreading half rate, with even faster vertical rates implied in the plume stem since, for a constant upwelling rate, horizontal flow slows due to radial spreading. For example, from the geometry of the V-shaped ridges Wright and Miller (1996) calculate horizontal mantle plume flow rates of 160 to over 1000 mm/yr while Poore et al. (2009) calculate mantle upwelling rates within the plume stem of 270 mm/yr. Other mantle plume models, based on geochemical modeling, have also been proposed with similar very rapid upwelling rates. For example, Brown and Lesher (2014) calculate upwelling rates up to 14 times the rate of plate separation in addition to elevated mantle temperatures (85–210°C).

These extremely rapid upwelling rates of hot mantle imply extraordinary melting rates by mantle decompression. For comparison, two-dimensional passive plate spreading predicts that the maximum mantle upwelling rate directly beneath a ridge axis is $2U/\pi$ where U is the plate spreading half-rate (Phipps Morgan, 1987; Phipps Morgan and Forsyth, 1988). For the Reykjanes Ridge axis and the plate boundary through Iceland, U = ~10 mm/yr so that the maximum plate-driven mantle upwelling rate should be ~6.4 mm/yr. For a normal mid-ocean ridge, plate-driven mantle upwelling with this maximum rate would produce a crustal thickness of ~6–7 km (Chen, 1992; White et al., 1992), even though most of the mantle flows at less than the maximum rate directly beneath the axis and rises through a smaller melting column (due to the triangular shape of the passive melting regime). In passive plate spreading the residual (melt-depleted) mantle material is removed by plate spreading at the same rate that it is created resulting in an equilibrium steady state system wherein melting and the production of crust is balanced by the removal of the residual mantle column at the spreading rate (Langmuir et al., 1992). Yet plume models propose mantle upwelling rates of 270 mm/yr, or significantly greater, across a plume diameter of up to 300 km (Poore et al., 2009; Brown and Lesher, 2014). By simple proportion, this rate of mantle upwelling should produce at least 42 times greater crustal thickness (>250 km) than a normal mid-ocean ridge (~6–7 km), or much more since elevated mantle temperatures are also required by plume models. Similar conclusions have been reached by three-dimensional geodynamic numerical modeling experiments (Ito, 2001).

In addition to these predicted extraordinary and unobserved crustal thicknesses, much larger volumes of depleted mantle must be also created by mantle plume melting. Since depleted mantle is buoyant (Oxburg and Parmentier, 1977) and at least two orders of magnitude more viscous than the mantle before melting (Hirth and Kohlstedt, 1996) depleted mantle would adhere to the overlying lithosphere and accumulate above and surrounding the rising plume stem material. In plume models for Iceland, the rate of accumulation of depleted, buoyant and viscous mantle material is much greater than the rate of plate spreading so that the deepening and widening growth of this depleted layer rapidly suppresses further mantle plume upwelling, which must be deflected to the perimeter of the rapidly growing welt of depleted plume material. Such a radiating growth of a depleted mantle layer would also suppress melt production on the adjacent spreading centers. These unavoidable physical consequences of mantle plume melting were previously recognized by Ito (2001) leading to his model of a viscous dehydration layer specifically hypothesized to prevent the extreme melting and crustal thicknesses inherent in plume models for Iceland.

Therefore, geodynamic mantle plume models for the Reykjanes Ridge and Iceland generally propose that upwelling plume stem material is mostly deflected laterally before crossing the solidus or excessive melting will be generated (Ito, 2001; Ito et al., 1999). Ito (2001) and Ito et al. (1999) proposed that this could result from a highly viscous mantle dehydration layer produced by the extraction of water as mantle melts (e.g., Hirth and Kohlstedt, 1996). The viscous rheological layer blocks plume upwelling above the solidus so that only the plate-driven “seafloor spreading” component of extension allows melting of plume material above the solidus beneath Iceland and the Reykjanes Ridge. Excess melting is then a result of excess mantle temperature not excess upwelling rate relative to passive plate spreading directly contradicting models such as proposed by Brown and Lesher (2014) and Maclennan et al. (2001) which require significant active upwelling and melting to satisfly geochemical constraints. Thus, geochemical and geodynamic models appear to have contradictory aspects in which melt production and chemistry are difficult to reconcile in a unified physical model. A possible resolution lies in the nature of mantle advection beneath slow-spreading ridges in which dynamic upper mantle small-scale convection alternates episodically with passive plate spreading. The different mantle flow paths implied by these contrasting modes of mantle advection (Fig. 6) predict differences in chemistry and melt production even within chemically and thermally uniform mantle (Plank and Langmuir, 1992).

Although the hypothesis of a viscosity increase in the mantle due to the removal of water is well supported by mineral physics experiments on olivine aggregates (Hirth and Kohlstedt, 1996; Mei and Kohlstedt, 2000a, 2000b), the application of this concept to the deflection of a mantle plume creates several additional dilemmas. For example, it predicts that if plate spreading were to cease across Iceland, so would all plume-related volcanism, as all plume flow would be laterally deflected below the solidus by the dehydration layer (Ito, 2001). This concept further implies that intraplate hot spots such as Hawaii should not exist if generated by mantle plumes, since the oceanic lithosphere there should already contain a highly viscous dehydration layer (formed when residual mantle was originally created by melting at a seafloor spreading center) additionally embedded within an even stronger and thicker ~90 Myr thermal boundary layer. Since there is no divergent plate boundary beneath Hawaii to advect plume mantle above the solidus, no melting should occur. The observation of a long history of voluminous volcanism at Hawaii and many other intraplate volcanic settings shows that melt can be generated beneath and penetrate both a dehydration layer and a ~90 Myr thermal boundary layer and strongly argues against the concept that a dehydration layer by itself (and even in combination with a thick thermal boundary layer) could deflect and prevent melting of a mantle plume centered beneath the essentially zero-age thermal lithosphere under Iceland.

Such issues may be resolved by the hypothesis of upper mantle small-scale convection (e.g., Tackley and Stevenson, 1993). Rather than deep mantle plumes sourcing the melt, intraplate magmatism likely forms in an upper mantle damp melting interval (beneath the dry solidus) due to small-scale convection promoted and sustained by volatile-rich passive mantle thermo-chemical anomalies. At locations such as Hawaii, small-scale convection is maintained by the fast-moving Pacific plate that advects away the depleted, buoyant and more viscous residual mantle that adheres to the lithosphere (e.g., Phipps Morgan et al., 1995), which would otherwise locally accumulate and suppress continued small-scale convection. The low viscosity of the volatile-rich mantle heterogeneities within the asthenosphere further decouples them from the overlying fast-moving lithosphere so that they may only slowly migrate relative to the fast-moving plates. This hypothesis may explain why fast-moving plates such as the Pacific have many more seamount chains than slow spreading plates such as in the Atlantic where seamount chains and other melting anomalies tend to be associated with divergent plate boundaries.

Further arguments for plume models beneath Iceland have been made to explain observations of sedimentary sequences and variations in temperature-controlled oxygen isotope ratios. These observations have been interpreted as reflecting ocean circulation modulated by time-varying uplift/subsidence along the Greenland-Iceland-Faroe Ridge (Poore et al., 2011; Poore et al., 2006; Poore et al., 2009; White and Lovell, 1997; Wright and Miller, 1996). In these models the uplift/subsidence events are created isostatically from thermal variations in the underlying mantle radiating outward from a mantle plume. These vertical motions may be explained more directly, however, as a result of time-dependent dynamic uplift caused by small-scale upper mantle convection itself (Petersen et al., 2010). Such locally-induced basement uplift/subsidence events can have magnitudes of several hundred meters and lateral extents of several hundred km, depending on the period and amplitude of the anomalies (Petersen et al., 2010). Along the Reykjanes Ridge and especially beneath Iceland (and the earlier Greenland-Iceland-Faroe Ridge), we suggest that small-scale convection is unusually robust due to moderately elevated regional mantle temperatures (Cochran and Talwani, 1978; Delorey et al., 2007) and strongly elevated mantle water content peaking beneath Iceland (Nichols et al., 2002), properties that promote small-scale convection. Vertical motions induced by episodic small-scale convection (Petersen et al., 2010) could thus explain both depth variations along the Greenland-Iceland-Faroe Ridge and the propagating melting anomalies forming the Reykjanes Ridge V-shaped ridges (Martinez and Hey, 2017) with the same plate-tectonic mechanism. After each cell formed episodically where the divergent plate boundary intersects the Greenland-Iceland-Faroe Ridge it would have then propagated along the deep low viscosity linear “wet” melting regime of the Reykjanes Ridge to form the V-shaped crustal ridges (Martinez and Hey, 2017). As small-scale convection does not involve significant lateral flow of mantle material (it is only the upwelling instability that propagates laterally), this mechanism accounts for both V-shaped ridges and vertical motions without appealing to extraordinary mantle plume flow rates, large and rapid mantle plume temperature variations, and ad hoc mantle rheological structures required to prevent extreme mantle melting.

4.6. Nature of the North Atlantic mantle melting anomaly

The nature of the North Atlantic mantle anomaly has long been a topic of debate surrounding broader issues concerning hot spots, mantle plumes and mantle melting anomalies. This topic is quite extensive and outside the scope of this review of the Reykjanes Ridge; general aspects are discussed elsewhere (e.g., Anderson and Natland, 2005; Courtillot et al., 2003; Duncan and Richards, 1991; Foulger, 2011). Here we focus on characteristics of the North Atlantic mantle anomaly that may have affected or provide insight into the development of the Reykjanes Ridge and immediately surrounding areas. Prevalent models for the mantle anomaly beneath the Reykjanes Ridge derive from the original mantle plume hypothesis (Morgan, 1971) wherein a narrow, rapidly rising jet of mantle material was proposed to originate at the core-mantle boundary and to buoyantly upwell due to elevated temperature. On crossing the solidus, the plume would generate extensive melt due to its high temperature and rapid upwelling rate. Vogt (1971) applied the plume model to the Reykjanes Ridge to explain flanking crustal V-shaped ridges. These basement ridges had originally been mapped in seismic reflection profiles without, however, identifying a V-shaped pattern (Talwani et al., 1971) but have now been confirmed in satellite-derived gravity maps (e.g., Fig. 1B). Vogt (1971) proposed that the V-shaped ridges resulted from thermal anomalies embedded within mantle plume flow rapidly propagating away from beneath Iceland. The initial question Vogt (1971) posed was whether the flow was radial, within a circular expanding plume head beneath the lithosphere, or channeled inside the contours of a sub axial thermal boundary layer. In Vogt’s analysis a discriminating criterion is the geometry of the V-shaped crustal ridges themselves. In radial flow with a steady plume stem flux, a slowing of the along-axis component of flow is geometrically implied which should produce a curvature and broadening angle of the V-shaped ridges with distance from Iceland. For a channeled flow a steadier along-axis flow rate can be maintained producing little or no curvature of the V-shaped ridges. Given the limited available data at the time and other issues, such as how the incorporation of plume material into the spreading lithospheric plates could affect flow rates, the issue of radial vs channeled flow remained then unresolved.

Some subsequent studies have favored along-axis mantle plume flow based on geochemical gradients away from Iceland (Niu and Hékinian, 2004; Murton et al., 2002). Unlike most other models of plume-driven flow, Niu and Hékinian (2004) suggest that faster spreading to the south along the Reykjanes Ridge drives southward along-axis mantle flow in order to volumetrically accommodate the greater spreading rates to the south. They suggest that along axis flow and progressive melting out of enriched heterogeneities from an Iceland plume can explain along-axis geochemical gradients. However, the slightly faster spreading rate at the southern Reykjanes Ridge over the length of the ridge (~10%) cannot account for the flow rate implied by the geometry of the V-shaped ridges (~10 × the half spreading rate). Such along-axis mantle flow models also do not take into account the increasing viscosity of mantle as melting progresses within the ridge melting regime. Water is highly incompatible on mantle melting and would be among the first components removed by melting above the dry solidus, strongly increasing the residual mantle viscosity (Hirth and Kohlstedt, 1996; Phipps Morgan, 1997). Therefore, slightly greater spreading rates to the south along the Reykjanes Ridge are much more easily accommodated by slightly faster mantle upwelling from the low-viscosity asthenospheric mantle beneath the ridge rather than proposed along-axis flow of strongly increasing viscosity mantle as it progressively melts along a ~1000 km length ridge (Niu and Hékinian, 2004). The strong increase in mantle viscosity on melting argues generally against models of along-axis flow of plume (or any) mantle material within the melting regime, supporting the idea that the mantle geochemical gradients away from Iceland are already developed in the underlying regional mantle anomaly and are simply upwelled into the melting regime by plate spreading to form the geochemical variations observed in the erupted lavas. The existence of geochemical gradients along the Reykjanes Ridge also argues against mantle plume flow beneath the solidus depth as such flow should produce no change in mantle plume composition with distance from the plume stem.

Most geodynamic models generally accepted the premise that the crustal V-shaped ridges directly reflect mantle plume flow, even though Vogt himself cautioned: “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” (Vogt, 1971, p.160). Nevertheless, most conceptual and numerical models have used the V-shaped ridges as primary constraints on modeling mantle plume flow. Most such models now favor radial flow of mantle material. The reason for this derives from the recognition, discussed above, that the extremely rapid mantle plume upwelling rates calculated from the geometry of the V-shaped ridges would generate unreasonably large volumes of melt if allowed to cross the solidus (Ito, 2001). This then led to the need for a high viscosity dehydration layer, but the existence of such a layer would prevent the formation of a sub-axial low viscosity lithospheric groove that would allow channeled plume flow, so this analysis concludes that plume flow must be radial and beneath the solidus.

A variety of geophysical observations directly argue against the existence of a highly viscous dehydration layer capable of deflecting a mantle plume beneath Iceland. For example, Gaherty (2001) found strongly vertically polarized seismic anisotropy in the mantle to a depth of ~100 km surrounding the Reykjanes Ridge (especially in the region younger than 5 Ma), interpreted as resulting from buoyant upwelling, requiring low mantle viscosity. In another seismic study, Delorey et al. (2007) also found strongly vertically polarized upper mantle off-axis at depths <150 km but within 200 km of the ridge (i.e., within the area of the V-shaped ridges) but horizontally polarized uppermost mantle (< 50 km depth) farther from the axis (within transform dominated crust). They interpret the anisotropy within 200 km of the ridge as either reflecting vertical or along-axis flow of mantle, both precluded by the high viscosity dehydration models that predict only horizontal plate-driven flow off axis. They also found a broad region of anomalously low shear wave velocities in the upper mantle. Indications of vertically polarized seismic anisotropy mantle in the depth interval of <150 km are consistent with buoyant upwelling within a deep "damp" melting regime but are not consistent with a high viscosity mantle layer that permits only plate-driven mantle flow, which should produce entirely horizontal anisotropy in the spreading direction. Delorey et al. (2007) and Cochran and Talwani (1978) also analyzed regional gravity data and calculated at most a moderate 75°C thermal anomaly broadly distributed in the North Atlantic upper mantle, which in itself would lower not increase mantle viscosity. These seismic and gravity studies imply a weak upper mantle where buoyant upwelling can shape vertically polarized strain-induced anisotropy.

Further, because Iceland forms a subaerial part of the mid-ocean ridge, detailed examination of the underlying mantle viscosity can be made from geodetic studies of post-glacial rebound and tectonic deformation. These studies, examining the response to the Weichselian and Little Ice Age, span large temporal and spatial scales, (Sigmundsson, 1991; Sigmundsson and Einarsson, 1992) and constrain viscosities to be quite low (1×10^{18} to 5×10^{19} Pa s) in the mantle beneath Iceland. Similar low upper mantle viscosities were determined from tectonic strain measurements associated with historic rifting events on Iceland (Foulger et al., 1992; Hofton and Foulger, 1996; Pollitz and Sacks, 1996). Ito et al. (1999) suggested that temporal scaling effects could account for the much lower viscosities (mostly $<10^{19}$ Pa s) determined in the geodetic studies in contrast to the very high viscosities required in the viscous dehydration layer model (up to 2.5×10^{22} Pa s in the plume stem and increasing by a factor of 100 depending on degree of melting) (Ito, 2001). However, consistently low viscosities determined from the very different temporal and spatial scales associated with the post-glacial rebound and tectonic deformation studies argue against scaling effects reconciling these large differences. In addition, the high mantle water contents determined from lava samples beneath Iceland and the Reykjanes Ridge (Nichols et al., 2002) are consistent with other regional studies indicating strong weakening effects of water on mantle rheology (Dixon et al., 2004). In fact, subsequent numerical geodynamic studies examining proposed effects of mantle plumes, including beneath Iceland, either do not incorporate a viscous dehydration layer at all (Mittelstaedt et al., 2008, 2011) or obtain better results when the viscosity of such a layer is minimized (Howell et al., 2014). Together, the strong vertical seismic anisotropy, low shear wave velocity anomalies, regional gravity anomalies, measured elevated water contents, geodetic tectonic strain and glacial rebound studies consistently imply low viscosity within the upper mantle beneath the Reykjanes Ridge and Iceland and argue against a high-viscosity dehydration layer capable of deflecting a presumed mantle plume (e.g., Ito, 2001).

The above difficulties with the plume model for the Reykjanes Ridge and Iceland led Martinez and Hey (2017) to examine alternatives. They note that at normal slow-spreading ridges, when axial offsets are small individual melting centers can propagate along-axis forming broad V-shaped crustal patterns delimited by non-transform discontinuities (Fig. 3). These propagation episodes can be in opposite directions even within small regions, showing that they are not responding to a regional mantle flow. Propagating segments occur even when plate spreading direction is stable as shown by major bounding fracture zones and transform faults that remain straight (Dannowski et al., 2018; Michael et al., 1994; Wang et al., 2015). Martinez and Hey (2017) inferred that the propagation episodes are driven by small and random variations in mantle properties that affect melting, as supported geochemically where such data exist (e.g., Michael et al., 1994; Niu et al., 2001). At the Reykjanes Ridge the mantle melting anomaly is large, systematic, and long-lived, causing a >3000 m change in axial depth from the Bight transform fault to the Reykjanes peninsula, with similar gradients in residual basement depth (Louden et al., 2004; White, 1997) traceable on the ridge flanks to the inception of spreading (Fig. 2). Thus, Martinez and Hey (2017) proposed that the anomalous mantle gradient (the horizontal variation in mantle melting properties away from Iceland) could itself rapidly propel small-scale upwelling instabilities along the deep low-viscosity (wet) melting regime of the Reykjanes Ridge without along-axis mantle flow, explaining its features and evolution within a unified model consistent with normal characteristics of slow-spreading ridges.

The propagation mechanism may operate because small-scale convection itself is locally self-limiting and is a three-dimensional Rayleigh-Taylor-type phenomenon. Thus, even on a two-dimensional linear axis, convective two-dimensional rolls along the entire length of the ridge are not favored (e.g., Choblet and Parmentier, 2001). By locally upwelling at a greater rate than in passive plate spreading, depleted residual mantle locally accumulates. This residual mantle is more viscous, buoyant, and less fertile than the original mantle and thus suppresses further convection locally. This property is thought to lead to the episodic behavior of small-scale convection at normal slow spreading ridges (e.g., Scott and Stevenson, 1989). However, along a long linear damp melting regime small-scale convection can simply continue in an adjacent along-axis position. By propagating, the convective cell moves away from the accumulated depleted material and into low-viscosity fertile material. Eventually, plate spreading removes the accumulated depleted mantle material and another cycle of buoyant upwelling and propagation can commence. Propagation episodes may occur at intervals of 2–3 to 5–6 Myr based on the spacing of the V-shaped ridges (Jones et al., 2002). Along the Reykjanes Ridge each buoyant upwelling cycle begins beneath Iceland where the mantle anomaly (water content) is greatest (Nichols et al., 2002) and propagates southward along the axis, giving rise to the consistently southward-pointing V-shaped crustal ridges.

Despite extensive observational data supporting the existence of buoyant three-dimensional upwelling at slow-spreading ridges (e.g., Detrick et al., 1995; Dunn et al., 2005; Niu and Batiza, 1994; Phipps Morgan and Parmentier, 1995; Tolstoy et al., 1993), the main counter argument derived from numerical experiments (Magde and Sparks, 1997; Parmentier and Phipps Morgan, 1990) that seemed to indicate that the wavelengths of the upwelling anomalies would be too long (>150 km) to explain the generally shorter (<70 km) crustal segmentation observed at slow-spreading ridges. As discussed above, this discrepancy seems to be resolved in later numerical models that incorporate effects of a layered melting regime viscosity structure. The division of the melting regime into dry and damp melting intervals (Fig. 6) decreases the height of the buoyant upwelling cells and therefore their wavelengths (Braun et al., 2000; Choblet and Parmentier, 2001). In addition, within the deep damp melting interval, melt-induced effects may further promote a change in creep mechanism from dislocation creep to grain boundary sliding that can lower mantle viscosity to $\sim 10^{18}$ Pa s or lower, further decreasing the wavelength of the convective instabilities (Choblet and Parmentier, 2001). Such a layered mantle with a deep and thick "damp" interval and thinner shallow "dry" interval may also reconcile the low viscosities measured by geodetic (Sigmundsson, 1991; Sigmundsson and Einarsson, 1992) and deformation studies (Foulger et al., 1992; Hofton and Foulger, 1996; Pollitz and Sacks, 1996) with the expected increase in viscosity due to the extraction of water from the mantle on melting (Hirth and Kohlstedt, 1996).

Observations from slow spreading ridges and the inferred mineral physics and geodynamic processes involved imply that small-scale convection should be even more enhanced by the properties of the mantle anomaly beneath the Reykjanes Ridge relative to normal mantle (elevated water content and slightly elevated temperature). However, the nature and origin of the regional North Atlantic mantle anomaly was not itself specifically addressed by Martinez and Hey (2017). Two alternatives to a dynamic mantle plume are discussed below.

4.7. Broad and slowly upwelling deep mantle anomalies

Global seismic tomographic studies have identified large (~1000 km wide) anomalies in the mantle beneath several "hot spot" areas, including Iceland (French and Romanowicz, 2015). The anomalies extend from the core mantle boundary to within 1000 km of the suface where some become deflected laterally. If the interpretation of these images is correct, they may depict broad thermo-chemical mantle upwellings (French and Romanowicz, 2015) wherein the temperature may only be elevated sufficiently that deep mantle becomes buoyant and slowly upwells to the shallow mantle as part of a regional mantle flow counterbalancing slab foundering (Anderson and Natland, 2014). Thus, if these interpretations are correct, mantle anomalies such as beneath Iceland and the North Atlantic basin may originate as deep mantle upwellings (from the core-mantle boundary) but not as narrow "plumes", but rather as broad and therefore likely slowly upwelling convective bodies more in the mode described by Anderson and Natland (2014). The upwelled mantle thermo-chemical anomaly may stably lay beneath thick orogenic continental lithosphere below solidus depths, producing little vertical motion and no melt. Such anomalies may also be resupplied by continuing slow and broad upwelling from deep in the mantle (not as a narrow plume) as imaged by French and Romanowicz (2015). Thus, such anomalies may contain chemical features often associated with mantle plumes, but not emplaced as plumes. Such anomalies may also contain significant volatile content lowering their mantle viscosity and solidus (e.g., Bonatti, 1990). In the process of upwelling, they may have entrained ambient mantle material along their margins so that by the time they are emplaced beneath the lithosphere they are already zoned with respect to chemistry and temperature forming regional horizontal mantle gradients in properties. Additionally, sub-solidus solid state convection may also help entrain ambient mantle material into the anomaly to produce zoned thermo-chemical gradients away from the center of the anomaly. Such processes would explain the horizontal geochemical gradients often seen in "hot spot" melting anomalies without need for outward expanding flow from a narrow plume stem. On continental rifting, this mantle material upwells above its solidus and, enhanced by the thermal structure of the rift, produces voluminous melt by vigorous small-scale convection (Boutilier and Keen, 1999; Mutter et al., 1988) and thermally-induced and dynamic vertical motions (Buck, 1986; Petersen et al., 2010). Most likely, beneath the rifting North Atlantic margins this small-scale convection was not two-dimensional, as often depicted, but formed three-dimensional convective cells because of its inherent tendency to form Rayleigh-Taylor-like instabilities (Bonatti, 1985). Due to the anomalous regional mantle thermo-chemical gradient, the three-dimensional convective cells began to rapidly propagate along the developing rift and initial seafloor spreading axis. The especially robust instabilities during this early phase may have formed the seaward-dipping reflector sequences as waves of excess magmatism moving along the margin separated in time. The accumulation of depleted mantle beneath the rift acts as a negative feedback to the continuation of excessive melting until removed by plate spreading. Continued propagation of a less intense series of convective instabilities formed the observed V-shaped ridges in the earliest oceanic crust (Parnell-Turner et al., 2014; White, 1997). The propagation of convective instabilities even during the continental rift phase may be what led to a linear initial spreading axis at the inception of the Reykjanes Ridge. Propagation of the instabilities also explains the absence of spreading-parallel magmatic crustal segmentation that typically characterizes early oceanic crust at passive margins (Behn and Lin, 2000; Taylor et al., 2009) forming instead V-shaped ridges from the inception of seafloor spreading (Parnell-Turner et al., 2014; White, 1997). As the rift widened the intensity of small-scale convection decreased with the separation of the spreading center from the enhancing effect of the rift thermal structure and also because of the likely decrease in volatile content in the mantle by its removal through enhanced melting. However, magmatism did not decrease to normal oceanic values. Intense small-scale convection persisted along the corridor that became the Greenland-Iceland-Faroe Ridge, continuing the seaward-dipping reflector-type volcanism there (Foulger et al., 2019). Stronger convective cells continued to form in this area likely because mantle water concentrations are especially high in this region. Relative to the lowest Reykjanes Ridge samples, calculated mantle water concentrations are 3.8–5.6 times greater beneath Iceland (Nichols et al., 2002). Along the Reykjanes Ridge, melting and crustal thicknesses increased toward Iceland following the gradient in mantle water content (Nichols et al., 2002). Similar effects are seen at backarc spreading centers (Martinez and Taylor, 2002, 2003; Taylor and Martinez, 2003) where crust can thicken from ~5.5 to 9 km due to systematically increasing mantle water content as spreading axes approach the arc volcanic front (Kelley et al., 2006), despite the proximity of a cold subducting slab and increasingly depleted mantle towards the mantle wedge corner (Martinez et al., 2006). Elevated mantle water content as the primary cause of excess melting at other "hot spots" has also been proposed (Bonatti, 1990; Asimow et al., 2004).

4.8. Ancient hydrous mantle wedge material preserved by an orogenic suture

A second alternative formation for the regional North Atlantic mantle anomaly is through prior subduction (Foulger and Anderson, 2005; Foulger et al., 2005). These models suggest that slivers of eclogite or pyroxenite may be embedded in the orogenic continental lithosphere and on rifting contribute to the excess melting. In the North Atlantic, these models are supported by observed remnants of ancient subduction associated with the Caledonian orogeny within the rifted lithosphere (Schiffer et al., 2014). One difficulty with these models is explaining how material incorporated into continental lithosphere could still be contributing to melting, since the separation of the orogenic continental lithosphere would have rapidly advected ambient mantle beneath the divergent plate boundary. A potential resolution is that it is not fertile crustal fragments embedded within orogenic lithosphere that leads to the long-lived melting anomaly but that extensive volumes of hydrous subduction mantle wedge itself are preserved. Recent studies indicate that large quantities of volatiles may be introduced into the mantle by subduction (Cai et al., 2018). Paleo-reconstructions (Roberts, 2003) indicate that the original suturing events of the Caledonian orogeny occurred far south of the current position of the North Atlantic Basin, suggesting that it is not likely that ancient mantle wedge material would have survived as the suture migrated thousands of km northward to the location of the North Atlantic rift and current spreading center. However, hydrous mantle wedge material is buoyant relative to ambient mantle (Gerya and Yuen, 2003; Rey and Muller, 2010). Given complex thick orogenic lithospheric roots potentially containing multiple shallow slab remnants formed in sutures (e.g., Tapponnier et al., 2001) it may be possible to preserve abundant hydrous mantle wedge material surrounded by this complex lithospheric structure (Petersen and Schiffer, 2016). On rifting of the surrounding Caledonian orogenic suture lithosphere, this hydrous, weak and buoyant mantle wedge material, generated by the subduction of the entire ancient Iapetus ocean basin, may have been dispersed within the North Atlantic ambient mantle (Schiffer et al., 2014, 2018) to form the regional mantle anomaly grading into ambient mantle with the observed elevated gradients in water content (Nichols et al., 2002), enabling robust mantle melting through small-scale convection and its rapid axial propagation (Martinez and Hey, 2017). Although melting in the damp interval has low productivity in typical MORB-source mantle with low water contents and assuming passive plate spreading, melt production is proportional to water content (Stolper and Newman, 1994) so that in mantle with elevated water content where a deeper solidus and lower viscosities also enhance small-scale (active) convection, melt production can be significantly augmented without large thermal anomalies (e.g., Asimow et al., 2004). It is also possible that a long residence

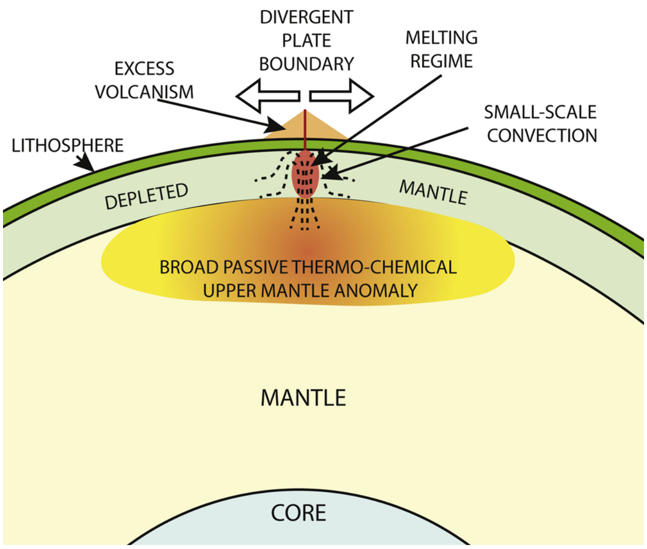

Fig. 9. The dynamic behavior of the Reykjanes Ridge may be explained by plate kinematic, plate boundary processes and shallow small-scale mantle convection acting within a regional thermo-chemical upper mantle anomaly that itself is relatively passive. The divergent plate boundary maintains mantle within the melting regime at its solidus temperature through a continuous background component of passive upwelling and removes depleted mantle through spreading. Within this setting, buoyant three-dimensional upwelling instabilities are generally thought to form at slow spreading ridges. At the Reykjanes Ridge the underlying mantle is anomalous, in particular, water contents increase along the ridge and peak beneath Iceland. Because water affects both the mantle solidus temperature and viscosity it promotes the development of small-scale convective instabilities, and on a linear ridge, may cause them to migrate along-axis (perpendicular to the plane of this two-dimensional cartoon). The regional mantle anomaly may have originated through broad advection of deep mantle material that then passively laid beneath thick continental orogenic lithosphere until rifting advected it above its solidus, triggering melting and robust small-scale convection. Alternatively, the regional mantle anomaly may have originated through plate tectonic processes (subduction and continental suturing) that later enabled anomalous melting when continental rifting and seafloor spreading advected this material above its solidus.

beneath thickened orogenic continental lithosphere allowed for a modest warming of the hydrous mantle wedge material due to a thermal blanketing effect and heating from the radionuclide enriched thick continental crust, further enhancing its magmatic productivity.

4.9. Dynamic plate boundary processes and a passive regional mantle anomaly

The above analyses support a new model for the Reykjanes Ridge and the regional mantle anomaly peaking beneath Iceland (Fig. 9). Whereas previous models viewed the Reykjanes Ridge as a passive recorder of a dynamic mantle plume, our review of the regional data and general processes at slow-spreading ridges inverts this paradigm. It is the mantle anomaly that is relatively passive while the dynamic behavior of the ridge can be explained by plate kinematic effects and plate boundary processes active generally at slow spreading ridges but amplified and directed by gradients in properties that affect melting and mantle viscosity within the regional mantle anomaly. Most prominent is mantle water content since it has a strong effect on both the mantle solidus and viscosity. Other volatiles, such as CO_2, may also be important but are more difficult to measure quantitatively and so fewer data exist on these variables. A key feature of mantle volatile content is that it promotes buoyant mantle upwelling, an inherently dynamic process thought to be generally important at all slow spreading ridges. Because the Reykjanes Ridge originated within and transects a strong regional mantle anomaly centered beneath Iceland that grades to background values with distance, it allows for a detailed examination of mantle effects on melting, crustal accretion, plate boundary evolution, and lithospheric mechanics within the evolution of a single seafloor spreading center.

5. Summary

The evolution of the Reykjanes Ridge may be explained by plate kinematic effects and plate boundary processes that operate generally at slow-spreading ridges but that in the North Atlantic are superimposed on a regional mantle thermo-chemical anomaly. The regional mantle anomaly has strong and systematic horizontal gradients in properties along the Reykjanes Ridge that affect mantle viscosity and melting but the anomaly itself is relatively passive. A general feature of slow-spreading ridges is the important role that upper mantle convective instabilities play in their crustal segmentation and evolution. Where ridge offsets are small these instabilities are often seen to propagate irregularly, forming broad V-shaped non-transform discontinuity wakes, presumably driven by small and irregular mantle thermo-chemical heterogeneities. These buoyant convective instabilities are thought to form within an axial low-viscosity deep "damp" melting regime beneath the dry solidus. Above the dry solidus mantle viscosities rapidly increase due to efficient water extraction and passive (plate-driven) advection predominates. In the North Atlantic, residual basement depth anomalies indicate that the regional mantle anomaly has strong, consistent and long-lived gradients in properties (water and possibly other volatile content and possibly a moderate temperature increase) towards Iceland. The mantle anomaly and gradients likely existed prior to continental rifting. On rifting and lithospheric thinning, anomalous mantle was advected above its solidus and began to melt extensively causing robust convective upwelling instabilities to form and propagate. Propagation of the robust upwelling instabilities beneath the continental rift axis may have led to the seaward dipping reflector-type volcanism and linear form of the initial seafloor spreading center. The continued propagation of weaker instabilities during the spreading phase formed the V-shaped crustal ridges on the Reykjanes Ridge flanks. Spreading continued stably in this mode for ~18 Myr. When Labrador Sea spreading ceased and Greenland was joined to North America, an abrupt ~30°change in opening direction occurred across the Reykjanes Ridge. This caused the near-axis lithosphere to break into new spreading segments orthogonal to the new opening direction and offset by transform faults. Promptly after forming, however, the spreading segments began to evolve back to their original linear configuration diachronously from north to south even though the new linear axis had to open obliquely to accommodate this. As the ridge became linear again, V-shaped flanking crustal ridges reformed, suggesting that the deep "damp" melting regime had remained linear during the stair-step segmented spreading stage and provided the controlling mechanism for the reassembly of the axis back to its original linear configuration. Thus, the Reykjanes Ridge presents a key setting to study mantle and kinematic controls on magmatic and tectonic ridge segmentation and evolution as well as the nature of the melting regime at slow spreading ridges and lithospheric mechanics. Less clear is the nature of the regional mantle thermo-chemical anomaly surrounding Iceland and the North Atlantic Basin. Both an origin as a deep and broad upwelling mantle instability and as remnant mantle wedge material formed during ancient subduction and suture events and dispersed following continental rifting seem plausible. In either case, it appears that the dynamic behavior of the Reykjanes Ridge is explained by plate kinematics and upper mantle convective instabilities within the ridge melting regime propelled by gradients in mantle properties; the regional thermo-chemical mantle anomaly itself is a relatively passive feature. This model is likely applicable to other regions as well and provides a new perspective on the nature of "hot spots".

Declaration of competing interest

None.

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Data availability

Original and processed data acquired on the R/V Knorr and R/V Marcus G Langseth cruises are available at: http://www.rvdata.us/catalog/KN189-04, http://www.rvdata.us/catalog/MGL1309, http://www.marine-geo.org/tools/entry/MGL1309, http://dlacruisedata.whoi.edu/KN/KN189L04/

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