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Stephen M. Jones, Nicky White, John Maclennan

Geochemistry Geophysics Geosystems G3
AN ELECTRONIC JOURNAL OF THE EARTH SCIENCES
Published by AGU and the Geochemical Society

Article
Volume 3, Number 10
24 October 2002
1059, doi:10.1029/2002GC000361
ISSN: 1525-2027

V-shaped ridges around Iceland: Implications for spatial and temporal patterns of mantle convection

Stephen M. Jones and Nicky White
Bullard Laboratories, Madingley Rise, Madingley Road, Cambridge, CB3 0EZ, UK
(jones@esc.cam.ac.uk; nwhite@exc.cam.ac.uk)

John Maclennan
Bullard Laboratories, Madingley Rise, Madingley Road, Cambridge, CB3 0EZ, UK

Now at Laboratoire de Géosciences Marines, Institut de Physique du Globe de Paris, 75005 Paris, France
(maclenna@ipgp.jussieu.fr)

[1] V-shaped lineations in the bathymetry and in the free-air gravity field surrounding Iceland result from crustal thickness variations caused by temporal variations in melt production rate at the Mid-Atlantic Ridge. We have studied the record of V-shaped ridges in the basins surrounding Iceland by plotting the short-wavelength component of the gravity field in terms of age versus distance from Iceland. The V-shaped ridge gravity signal is obscured by crustal segmentation and by sediment more than 1–2 km thick. The best V-shaped ridge record is found in the unsegmented part of the Irminger Basin, where Oligocene-Recent V-shaped ridges occur with a primary periodicity of 5–6 Myr and a secondary periodicity of 2–3 Myr. V-shaped ridge records from the Iceland Basin and from east of the Kolbeinsey Ridge to the north of Iceland correlate with the record from the Irminger Basin but are less complete. A record of uplift of the Greenland-Iceland-Faroes Ridge based on paleoceanographic data is correlated with the gravity record of V-shaped ridges. There is less decisive evidence for V-shaped ridges in crust of Eocene age. The observation that V-shaped ridges propagate up to 1000 km from Iceland is compatible with a model in which the Iceland Plume head spreads out from the plume stalk below a depth of $\sim$100 km, as suggested by geochemical arguments and studies of mantle rheology. Time-dependent flow in the plume head probably results from time-dependent flow up the plume stalk from deep below Iceland. These pulses may have triggered jumps in location of the spreading axis observed in the Icelandic geological record.

Components: 9806 words, 15 figures.

Keywords: V-shaped ridges; Iceland Mantle Plume; time-dependent convection; Northern Component Water.

Index Terms: 8121 Tectonophysics: Dynamics, convection currents and mantle plumes; 3045 Marine Geology and Geophysics: Seafloor morphology and bottom photography.

Received 10 April 2002; **Revised** 23 June 2002; **Accepted** 2 July 2002; **Published** 24 October 2002.

Jones, S., N. White, and J. Maclennan, V-shaped ridges around Iceland: Implications for spatial and temporal patterns of mantle convection, *Geochem. Geophys. Geosyst.*, *3*(10), 1059, doi:10.1029/2002GC000361, 2002.

1. Introduction

[2] Using a sparse set of bathymetry profiles, *Vogt* [1971] mapped a set of topographic ridges which are symmetrical about the Reykjanes Ridge spreading axis and which converge southward, away from Iceland. These V-shaped ridges are recognized in modern bathymetry data sets, but they are much more clearly imaged by the free-air gravity field, with the crest of each ridge corresponding to a gravity high (Figures 1 and 2). *Vogt* [1971] inferred that the V-shaped ridges reflect variations in the thickness of oceanic crust generated at the Reykjanes Ridge and that these variations are caused by pulses of relatively hot asthenosphere that travel southward away from Iceland in the head of the Iceland Plume. Similar time-transgressive crustal thickness anomalies have been generated by interaction between the Azores mantle plume and the nearby spreading ridge [*Vogt*, 1979; *Cannat et al.*, 1999]. South of Iceland, a wide-angle seismic profile across the youngest V-shape ridge and the adjacent trough has confirmed that the crustal thickness varies by 2 ± 1 km [*Smallwood and White*, 1998]. V-shaped ridges formed since Mid-Miocene time have been linked to episodic uplift of the Greenland-Iceland-Faroes Ridge [*Wright and Miller*, 1996]. Northern Component Water is a cold, dense, isotopically distinct water body that forms in the Norwegian-Greenland Sea to the north of Iceland. The changing height of the Greenland-Iceland-Faroes Ridge can therefore be inferred from the amount of Northern Component Water supplied to the global ocean through time. Thus temporal and spatial variations in the Iceland Plume convective system generate both melting anomalies and fluctuating dynamic support in the region surrounding Iceland.

[3] The principal aim of this study is to present a complete chronology of V-shaped ridge evolution since the start of spreading in the earliest Eocene, addressing crust created at all the spreading centers surrounding Iceland. Recently, *Ito* [2001] has shown how observations of the geometry of the V-shaped ridges can be used to constrain three-dimensional (3-D) numerical convection models of the Iceland Plume. We anticipate that future studies modeling convection will benefit from an improved set of observations. An improved V-shaped ridge chronology will benefit other subjects besides the study of mantle dynamics. Since changes in the global oceanic current system are known to be related to climate change, it is possible that fluctuations in uplift related to the V-shaped ridges have influenced global climate. In addition, *White and Lovell* [1997] suggested that fluctuations in uplift associated with the V-shaped ridges affected the sedimentary record of the continental margins surrounding the North Atlantic.

[4] First, we discuss the present knowledge of 3-D mantle flow beneath Iceland, as a framework within which to understand the description of the V-shaped ridges. In sections 3 and 4, we present a detailed description of the V-shaped ridges visible in the free-air gravity field and review the paleoceanographic evidence for uplift associated with the V-shaped ridges. Finally, we discuss some of the implications of these observations for determining of patterns of mantle flow.

2. V-Shaped Ridges and the Iceland Plume

[5] The first problem is to understand the cause of the melting anomalies that build the V-shaped ridges. Such melting anomalies could be caused by variations in temperature and/or variations in composition. The observed crustal thickness variation of 2 km can be explained by a variation in the average temperature in the melting zone of 30–35°C, assuming a dry peridotite mantle source [*White et al.*, 1995; *Smallwood and White*, 1998]. Alternatively, the plume temperature may remain constant, and melting anomalies may be caused by variations in mantle composition. For example, it is possible to explain V-shaped ridge crustal thickness maxima by melting a source containing a few percent garnet pyroxenite by volume [*Hirschmann and Stolper*, 1996]. Variation in isotopic ratios in basalt samples collected across the region where the youngest V-shaped ridge intersects the Reykjanes Ridge suggest that some variation in source composition does occur [*Taylor et al.*, 1997]. In addition, studies of temporal variations in rare earth

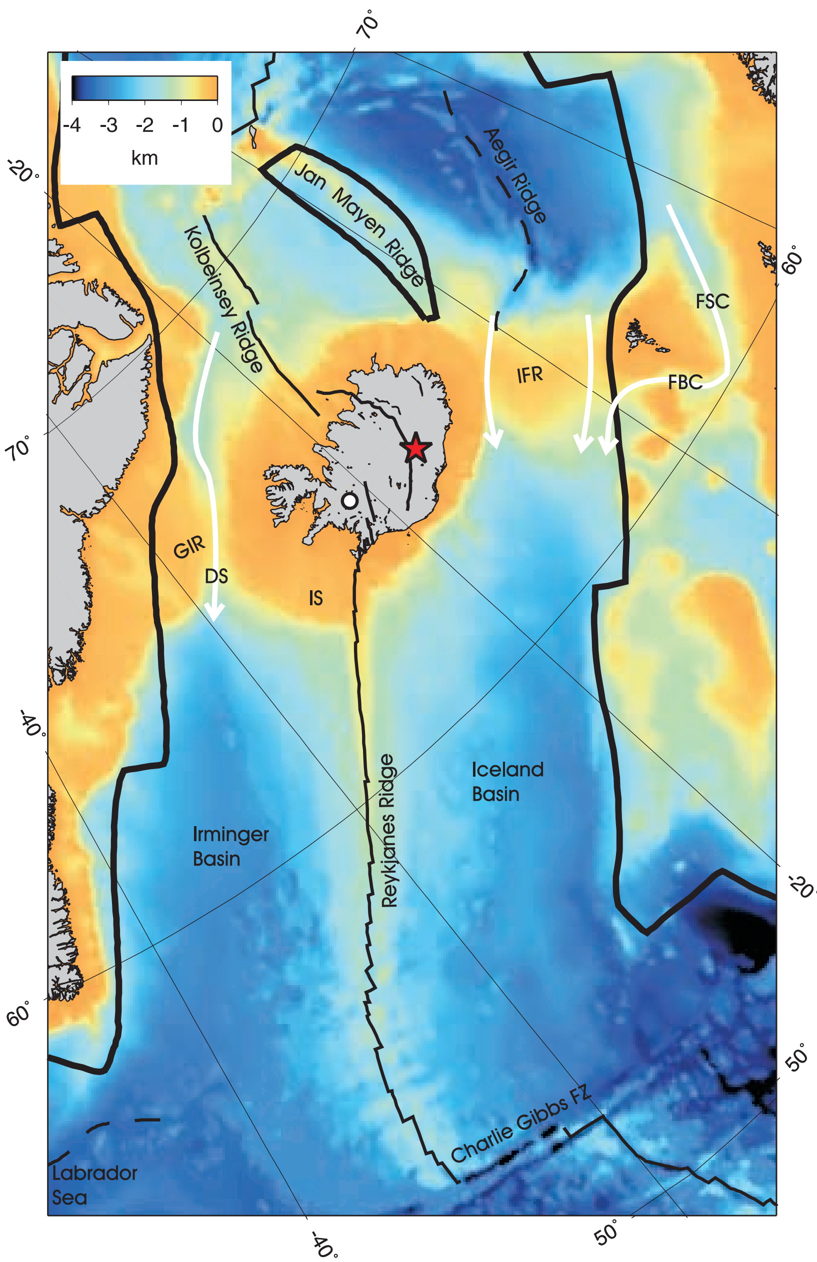

Figure 1. Location map showing physical features discussed in the text superimposed on the ETOPO5 topography field. Heavy black lines mark continent–ocean boundaries. Red star marks the present day center of the Iceland Plume; white circle marks the origin for distance measurements in Figures 7–9. White arrows show pathways for influx of Northern Component Water, generated north of Iceland, into the global ocean system. DS = Denmark Strait; FBC = Faroe Bank Channel; FSC = Faroe Shetland Channel; GIR = Greenland-Iceland Ridge; IFR = Iceland-Faroes Ridge.

element concentrations and in isotopic ratios onshore Iceland indicate variations in source composition through time [*Schilling and Noe-Nygaard*, 1974; *Hanan and Schilling*, 1997]. Paleoceanographic data suggest that times of anomalously high melt production associated with the V-shaped ridges are coeval with increased dynamic support of the Greenland-Iceland-Faroes Ridge [*Wright and Miller*, 1996]. This observation implies that the mantle source which generates enhanced melting is less dense than the background plume mantle. However, a source containing garnet pyroxenite

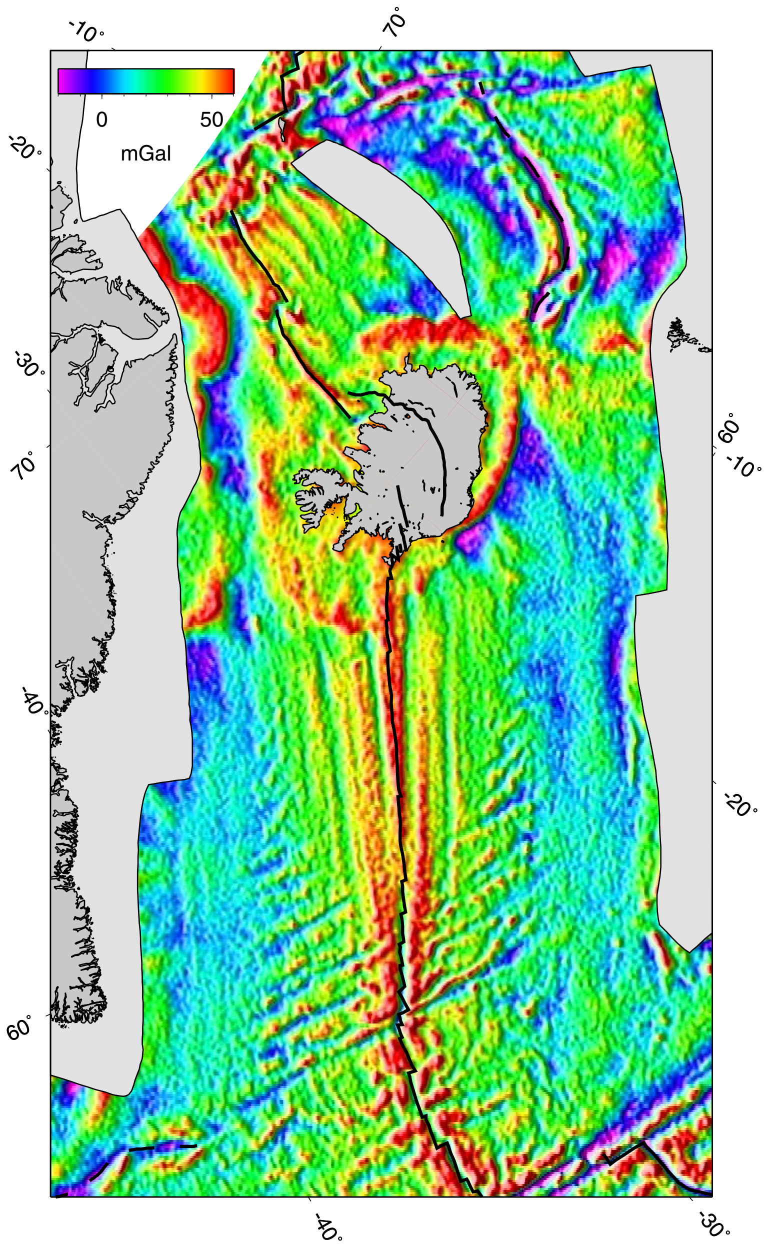

Figure 2. Free-air gravity field around Iceland from satellite altimetry, illuminated from the north-west [*Sandwell and Smith*, 1997].

would be more dense than a peridotite source. Therefore an increase in temperature would also be required to explain the coincidence between crustal thickness maxima and peaks in dynamic support. For ease of presentation, in the remainder of this paper we consider that temperature fluctuations alone caused the V-shaped ridges. A detailed discussion of the geochemical evidence is beyond the scope of this study; we simply note that the relative contributions of temperature and composition to the V-shaped ridge melting anomalies are not yet clear.

[6] The next problem is to understand the general pattern of convective flow beneath Iceland. The geometry of the V-shaped ridges requires that melting anomalies propagate away from Iceland, but two end-member flow patterns might explain

this geometry. In one end-member situation, flow beneath the spreading ridge is entirely horizontal. In the other end-member situation, flow is entirely vertical, but asthenospheric temperature anomalies are inclined to the vertical, generating melting anomalies that migrate laterally. Scenarios involving entirely horizontal flow can be rejected on several grounds. Horizontal-only flow beneath a spreading ridge is not possible for solid mantle since plate separation drives an upwelling flow. *Vogt* [1976] proposed that pulses of excess magma flow large distances horizontally beneath the spreading axis to form the V-shaped ridges. However, gravity, bathymetry, and seismic studies of the Mid-Atlantic Ridge suggest that any horizontal flow of magma is likely confined within segments of length 30–80 km [*Lin et al.*, 1990]. Such segments are considerably shorter than the length scale of the V-shaped ridges, so we henceforth consider that horizontal migration of magma is unimportant in generating the V-shaped ridges. *Bell and Buck* [1992] suggested that anomalously thick, hot crust north of 59°N undergoes rapid ductile flow, leading to a smooth ridge axis with the morphology of a fast spreading ridge. However, this type of horizontal crustal flow is probably insignificant on timescales and length scales appropriate to the V-shaped ridges [*McKenzie et al.*, 2000].

[7] Assuming that a component of vertical upwelling must occur beneath a spreading ridge, there are still two kinematic models that might explain the geometry of the V-shaped ridges. The first case is illustrated in Figure 3a and is characterized by a combination of both horizontal and vertical flow (model A). Hot mantle rises in a plume conduit beneath Iceland and spreads out laterally to form a head hundreds of kilometers wide. V-shaped ridges are formed as temperature anomalies spread outward in the plume head in response to plume-driven flow, while simultaneously moving upward through the melting zone in response to plate spreading. The plume head could be radially symmetric [*White and Lovell*, 1997; *Ito*, 2001] or channeled preferentially beneath the spreading center [*Albers and Christensen*, 2001]. *Ito* [2001] presented a dynamic model very similar to model A; although in Ito's model, temperature fluctuations within the melting zone result from variations in plume flux (achieved by varying the width of the plume conduit) rather than advection of hotter blobs round the plume system. In the second case (model B), only vertical upwelling occurs beneath the Reykjanes Ridge (Figure 3b). This scenario might occur if the plume has a low flux that is sequestered into oceanic lithosphere in the region of Iceland itself. Alternatively, it might occur if the plume is a vertical sheet [e.g., *Houseman*, 1990] oriented at a high angle to the Reykjanes Ridge, so that any lateral flow in the plume head spreads beneath the Greenland-Iceland-Faroes Ridge. In model B, excess asthenospheric temperature beneath the Reykjanes Ridge reflects a broad thermal halo in the upper mantle that surrounds the plume conduit. V-shaped ridges are generated when inclined sheets of anomalously hot mantle embedded within this thermal halo rise vertically beneath the spreading axis. Model B is similar to the model suggested by *Cannat et al.* [1999] to explain a V-shaped crustal thickness anomaly near the Azores.

[8] It is difficult to distinguish between the two models illustrated in Figure 3 using observations. Tomographic models have imaged a plume conduit of radius 100–200 km situated beneath SE Iceland, although the depth to which the conduit extends remains controversial [e.g., *Bijwaard and Spakman*, 1999; *Ritsema et al.*, 1999; *Allen et al.*, 1999]. Tomographic images also indicate unusually low velocities throughout the upper mantle beneath the region between Europe and Greenland [*Bijwaard and Spakman*, 1999; *Ritsema et al.*, 1999]. Although the latter observation appears to favor model B, it is premature to use tomographic images to decide between the two models. Spatial resolution of current tomographic models is generally limited to hundreds of kilometers in the upper mantle, partly because most of the seismic energy passes through the upper mantle at a steep angle. Furthermore, conversion of velocity anomalies into temperature anomalies is uncertain at temperatures close to the solidus and in the presence of partial melt. The effects of anelasticity and anisotropy conspire to make the problem even more difficult [e.g., *Allen et al.*, 1999]. In the remainder of this paper we assume that the pattern of convection beneath Iceland resembles model A. Our rationale

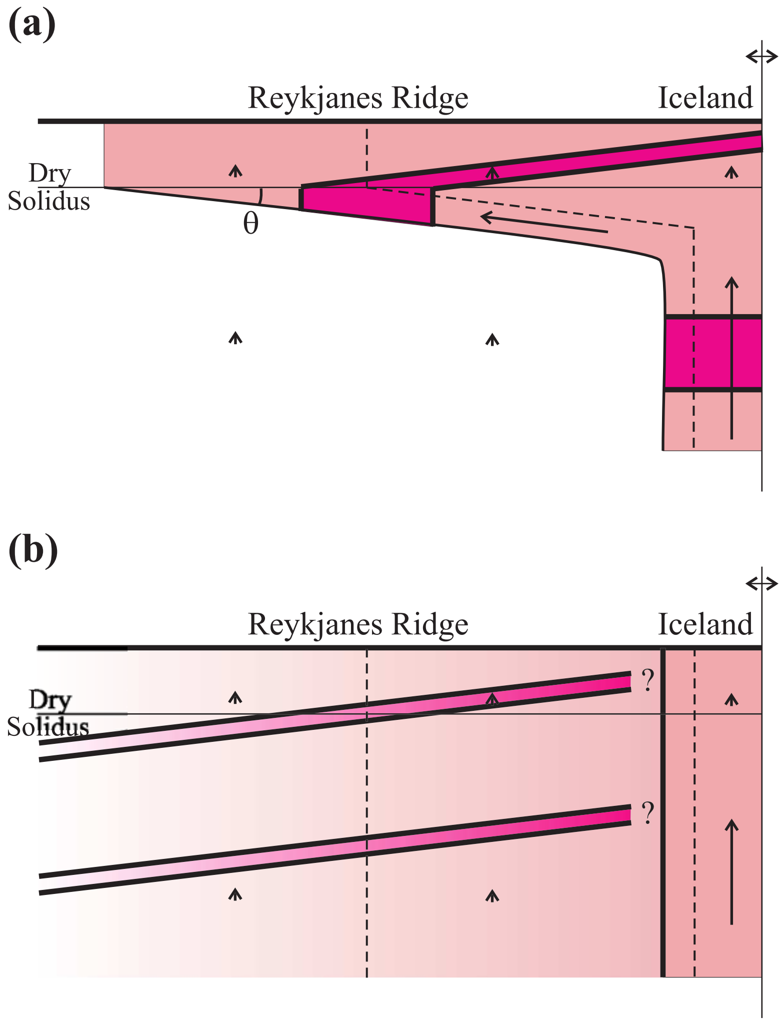

Figure 3. Schematic vertical sections through the upper mantle in the plane of the spreading axis, showing two geometries of temperature anomalies that could kinematically explain the V-shaped ridges. Dashed lines are flow stream lines and arrow lengths give an indication of relative flow speeds. Colors provide an indication of temperature; white represents normal temperatures and pinker shades represent anomalously high temperatures. Model (a) is characterised by both horizontal and vertical flow. Mantle viscosity increases significantly above the dry solidus occurs as dehydration occurs [*Ito et al.*, 1999]. Below the dry solidus a combination of horizontal flow in the plume head and vertical flow in response to plate separation occurs. Above the dry solidus only vertical flow occurs. Model (b) is characterised by vertical-only flow at all depths. See section 2 for further explanation.

is that 3-D numerical convection studies that assume this flow pattern are able to explain features such as the gravity, topographic and crustal thickness variations around Iceland [*Ito et al.*, 1999]. However, we note that model A has yet to be verified, or model B rejected, by direct geophysical or geochemical observations.

[9] A final problem concerns the origin of the temperature pulses within the plume head that generate the melting anomalies. Two classes of model have been proposed. In the first class, temperature variations in the plume head result from temperature variations in the plume stem. In this model, plume pulses rise from the thermal boundary layer at which the plume originates, implying that plume pulsing is an intrinsic aspect of mantle circulation. Alternatively, *White et al.* [1995] and *Hardarson et al.* [1997] have suggested that V-shaped ridges may be caused by jumps in the location of the spreading axis observed in the Icelandic geological record. In this case, flow

within the plume stem could be steady, but interaction with the base of the plate disrupts the flow into the plume head. We discuss this problem further after presenting the observations.

3. Observations: Gravity Record of V-Shaped Ridges

3.1. Imaging the V-Shaped Ridges

[10] The most prominent component of the free-air gravity field displayed in Figure 2 is the long-wavelength gravity high centered on the active mid-ocean ridge, which results mainly from convective support by the Iceland plume [*Anderson et al.*, 1973; *Jones et al.*, 2002]. When this long-wavelength gravity anomaly is removed, short wavelength features that are related to the thickness and structure of the crust can be seen more clearly (Figure 4). Two sets of gravity lineations are visible in crust formed at the Reykjanes Ridge, south of Iceland: V-shaped ridges, oriented at a small angle to the spreading ridge; and fracture zones, which trend roughly W-E. Oceanic crust segmented by fracture zones is typical of slow-spreading ridges such as the Mid-Atlantic Ridge away from the influence of mantle plumes. Unsegmented crust, which exhibits V-shaped ridges in some places, is thought to be formed above unusually hot asthenosphere [*Phipps Morgan et al.*, 1987; *White*, 1997].

[11] Following *Vogt* [1971], V-shaped ridge chronologies are constructed by plotting features of interest in terms of age versus distance from a reference point on the spreading axis. This age-distance projection allows the symmetry of V-shaped ridges from either side of the spreading center to be assessed and allows V-shaped ridges from north of Iceland to be compared with those to the south. In addition, the age-distance projection facilitates comparison between observations and dynamic convection models. The basins surrounding Iceland contain some of the clearest magnetic anomalies in the Atlantic, principally because hot asthenosphere associated with the Iceland Plume has inhibited formation of fracture zones (Figure 5). We have picked magnetic anomalies in these basins and matched them with the geomagnetic polarity timescale of *Cande and Kent* [1995]. This age information was then gridded to produce an age map for the basins surrounding Iceland in which V-shaped ridges can be identified (Figure 6).

[12] The next problem in producing a V-shaped ridge chronology is measurement of distance from a reference point at the time of formation of any piece of oceanic crust. A reference point of 64.8°N, 21°W on Iceland was used when calculating distances for all the age-distance plots presented in this study. This point was chosen at the intersection of onshore projections of the Reykjanes and Kolbeinsey Ridges with a plate motion flow line passing through the present center of the Iceland Plume (Figure 1). Points of known age within the ocean basins were restored to their position at the spreading center using the relevant rotation poles [*Smallwood and White*, 2002]. The distance between the newly positioned point and the reference point was then calculated assuming a spherical Earth. This method of measuring distance accounts for the fact that the spreading direction along the Reykjanes Ridge altered by ~30° between chrons 18 and 17 (Late Eocene), as illustrated by the plate spreading flow line marked on Figure 5.

[13] The most subjective element of previously published V-shaped ridge chronologies is picking the V-shaped ridges. It is difficult to decide which features to pick when the V-shaped ridge gravity signal is of low amplitude or when the ridges bifurcate. We therefore avoid picking at this stage and transform the whole gravity field into the age–distance space. Figure 7 shows the result of performing this transformation on the short-wavelength gravity field from the Irminger and Iceland Basins and the basin to the east of the Kolbeinsey Ridge. Figure 8 provides a detailed interpretation of V-shaped ridges in the Irminger and Iceland Basins. Figure 9 shows the result of stacking V-shaped ridge records for the Irminger and Iceland Basins. The stacked plot allows the symmetry of the V-shaped ridges to be assessed. Features which are not symmetrical about the Reykjanes Ridge are unlikely to be the result of melting anomalies at the spreading center. Figure 10 shows representative one-dimensional (1-D) V-shaped ridge

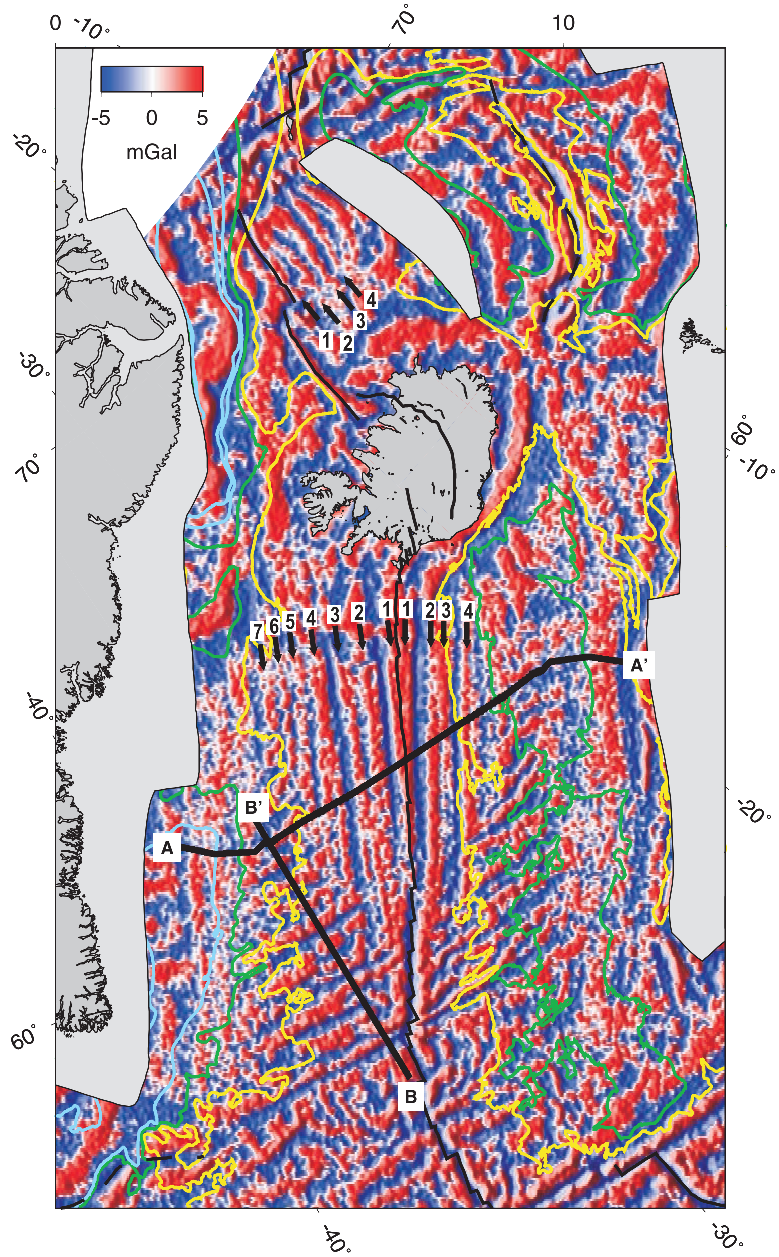

Figure 4. Short-wavelength component of satellite gravity field, related to variations in the thickness and structure of oceanic crust. The long-wavelength gravity field was calculated using a Gaussian filter of radius 100 km and subtracted from the original field to give the short-wavelength field. Numbered arrows refer to the scheme used to describe V-shaped ridges in the text and other figures. Coloured lines indicate sediment thickness after *Srivastava et al.* [1988]; yellow = 500 m; green = 1 km; blue = 1.5 km, 2 km and 2.5 km. Lines A–A′ and B–B′ mark locations of profiles in Figure 11.

records generated by stacking the clearest parts of the two-dimensional (2-D) records covering the Irminger and Iceland Basins. These 1-D records illustrate relative amplitudes and along-strike variation of the V-shaped gravity ridges, which are probably related directly to variations in the melt anomalies at the spreading axis. The 1-D records can also be correlated easily with the paleoceanographic observations in section 4.

3.2. Description of V-Shaped Ridges

[14] The clearest V-shaped ridges are those in the region of unsegmented crust adjacent to the Rey-

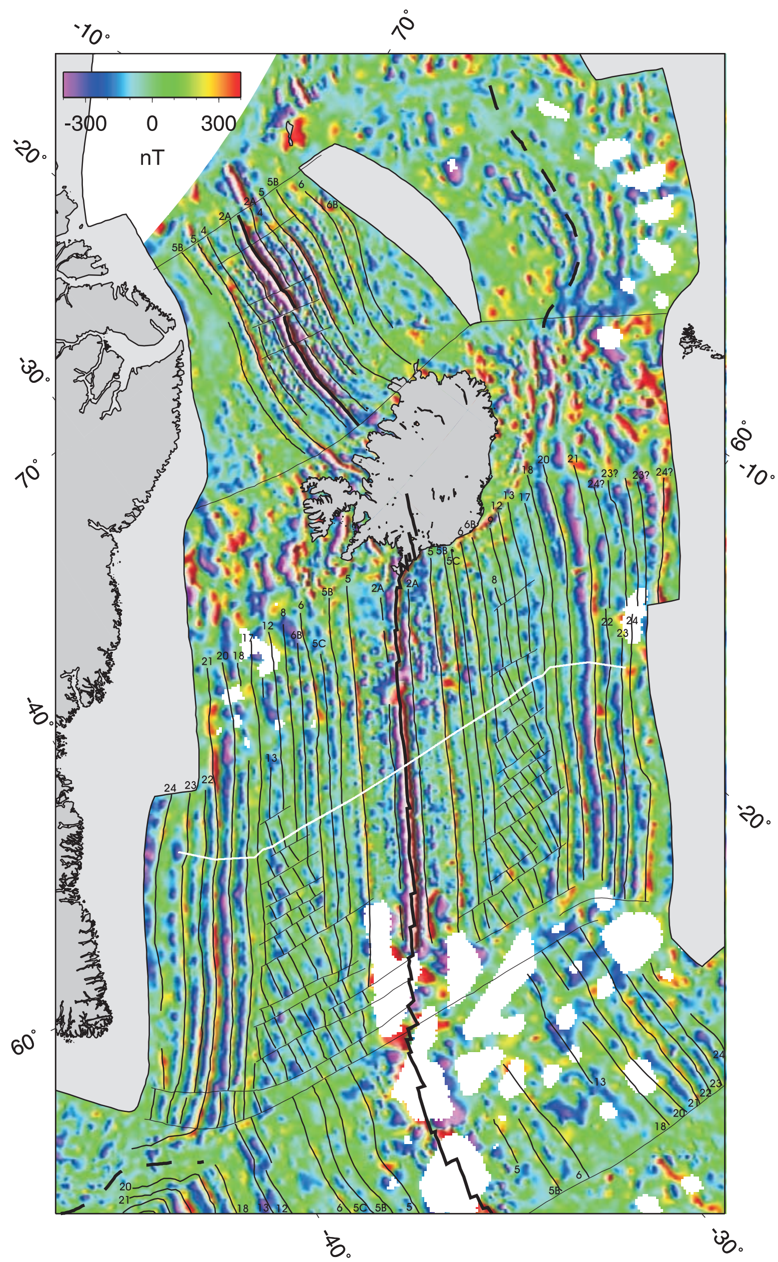

Figure 5. Magnetic anomaly compilation of *Macnab et al.* [1995]. White regions contain no data. Black lines mark magnetic anomalies picked and used in this study. White line marks plate-spreading flowline calculated from the poles of *Smallwood and White* [2002].

kjanes Ridge, with a maximum amplitude of ~30 mGal (Figure 11). These young V-shaped ridges in the gravity field correspond to topographic ridges at the seabed that were originally mapped using bathymetric profiles [*Vogt*, 1971; *Johansen et al.*, 1984]. V-shaped ridges are not visible in segmented oceanic crust, and V-shaped ridges which are clearly defined in the northern parts of the Iceland and Irminger basins appear to be truncated at the diachronous part of the boundary between segmented and unsegmented crust. Sections through the gravity field show that the amplitude of the V-shaped ridge anomalies is half to one quarter of the amplitude of the fracture zone anomalies (Figure 11). These observations suggest that V-shaped crustal thickness anomalies may exist within the segmented crust, but their gravity signal is swamped by that of the fracture zones. However, an attempt to remove

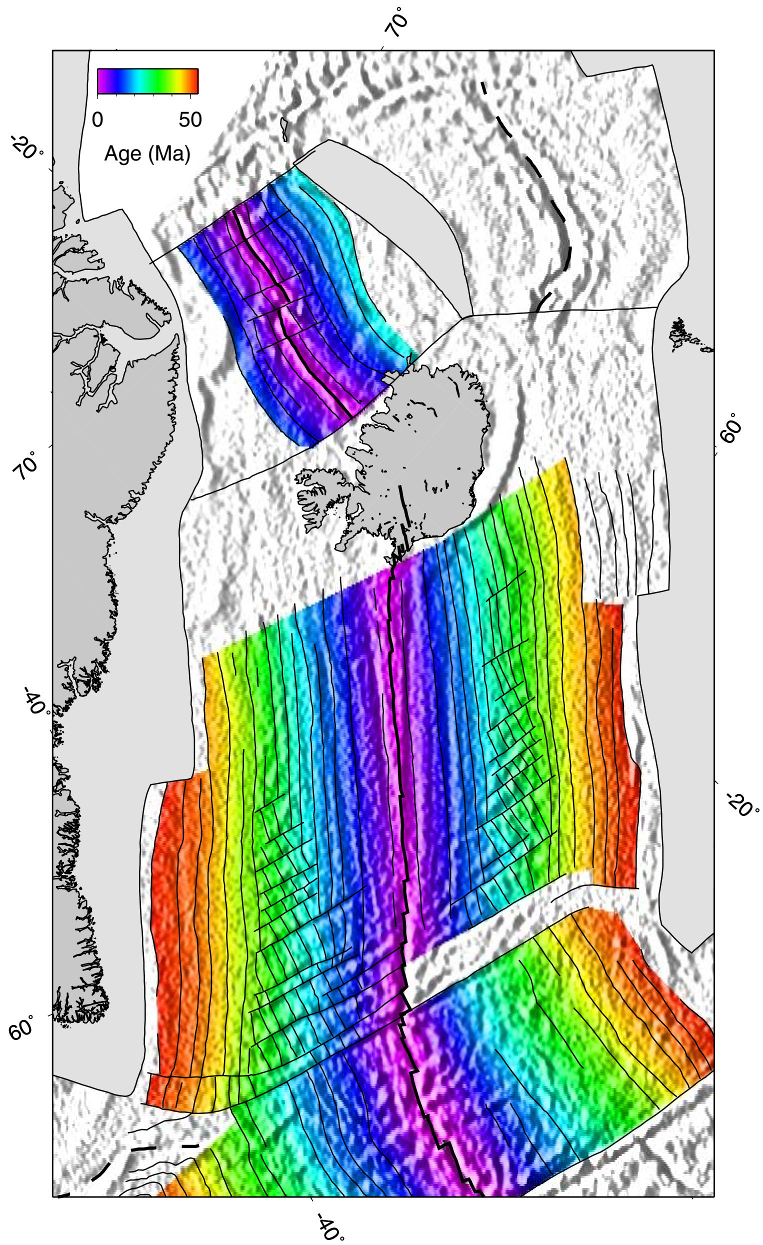

Figure 6. Age map from gridding the magnetic anomaly data picked from Figure 5. Gridding was done with continuous curvature splines [*Smith and Wessel*, 1990], and picks within each fracture zone-bounded segment were gridded separately and then combined to produce sharp discontinuities at the fracture zones. Grey-scale shading indicates the relief of the short-wavelength gravity field (Figure 4). Note good correlation between fracture zones picked from the magnetic dataset and the gravitational signature of fracture zones.

the fracture zone gravity signal by directional filtering in the Fourier domain did not reveal any clear V-shaped ridges gravity anomalies within the region of segmented crust [*Jones*, 2000].

[15] The clearest and most complete V-shaped ridge record is seen in the Irminger Basin, where sediment cover is negligible. Seven ridges can be identified, labeled R1–R7 on Figures 4 and 7. One of the most striking features of the Irminger Basin V-shaped ridges is their regular 5–6 Myr periodicity. Although V-shaped ridges occur regularly through time, they vary in amplitude, suggesting that successive pulses in the plume head

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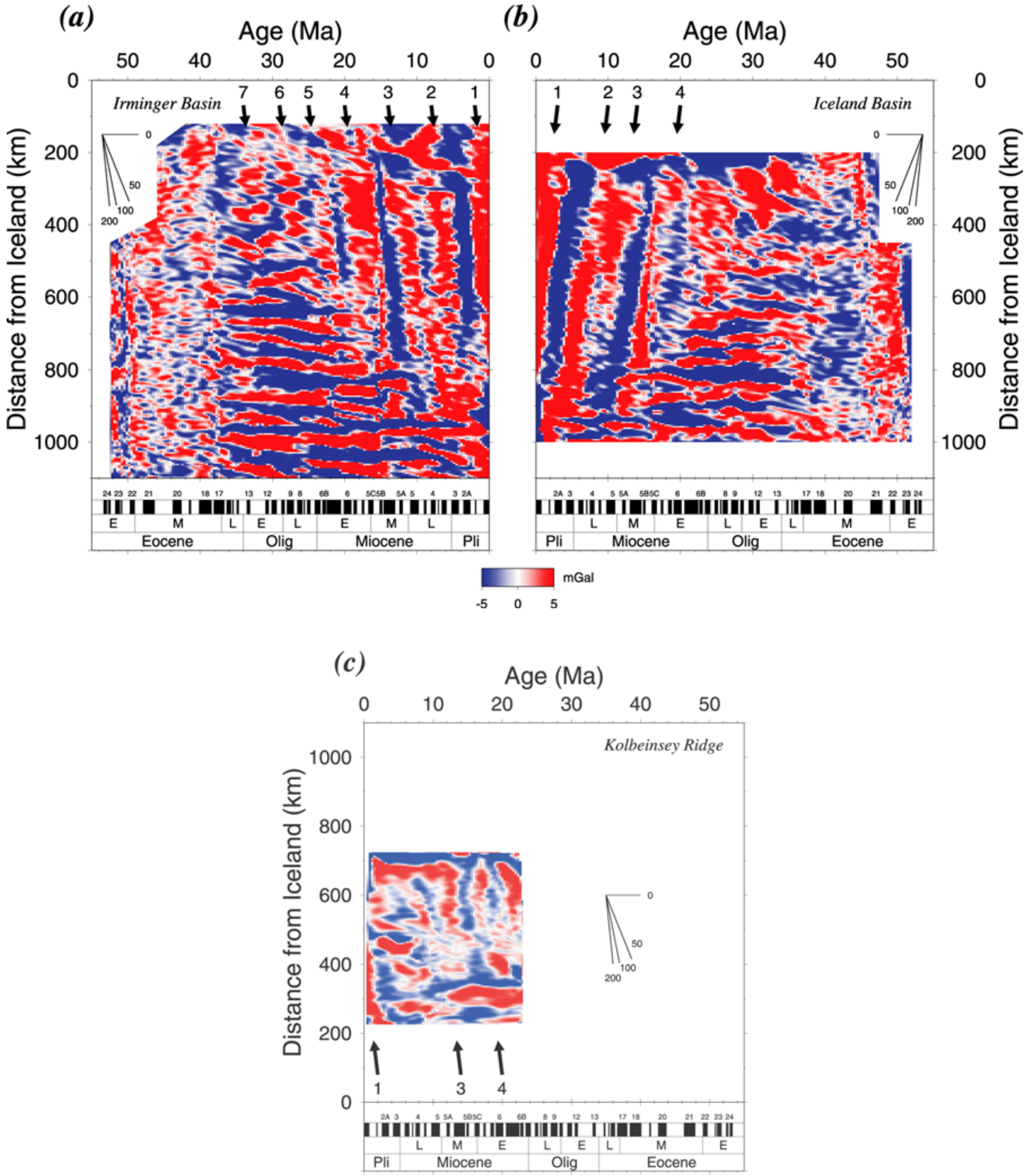

Figure 7. Age-distance plots of the short wavelength component of the gravity field over (a) the Irminger Basin, (b) the Iceland basin, and (c) the basin between the Kolbeisney Ridge and the Jan Mayen continental fragment. Numbered arrows above each plot refer to the scheme used to describe V-shaped ridges in the text and other figures. Numbered lines below name of each basin indicate propagation speeds in km Myr^{-1} for features lying at various angles. Black bars below each plot mark normally magnetised chrons from the geomagnetic timescale of *Cande and Kent* [1995] and adjacent numbers mark the chrons identified around Iceland in this study.

varied in temperature (Figure 10). The troughs between ridges R1 and R2 and R3 and R4 are the highest amplitude V-shaped ridge features in the Iceland and Irminger Basins. In contrast, ridges R2 and R3 are separated by a trough of much smaller amplitude. The V-shaped ridges vary in morphology along their length. In particular, ridges R3 and R4 bifurcate at 650 km and

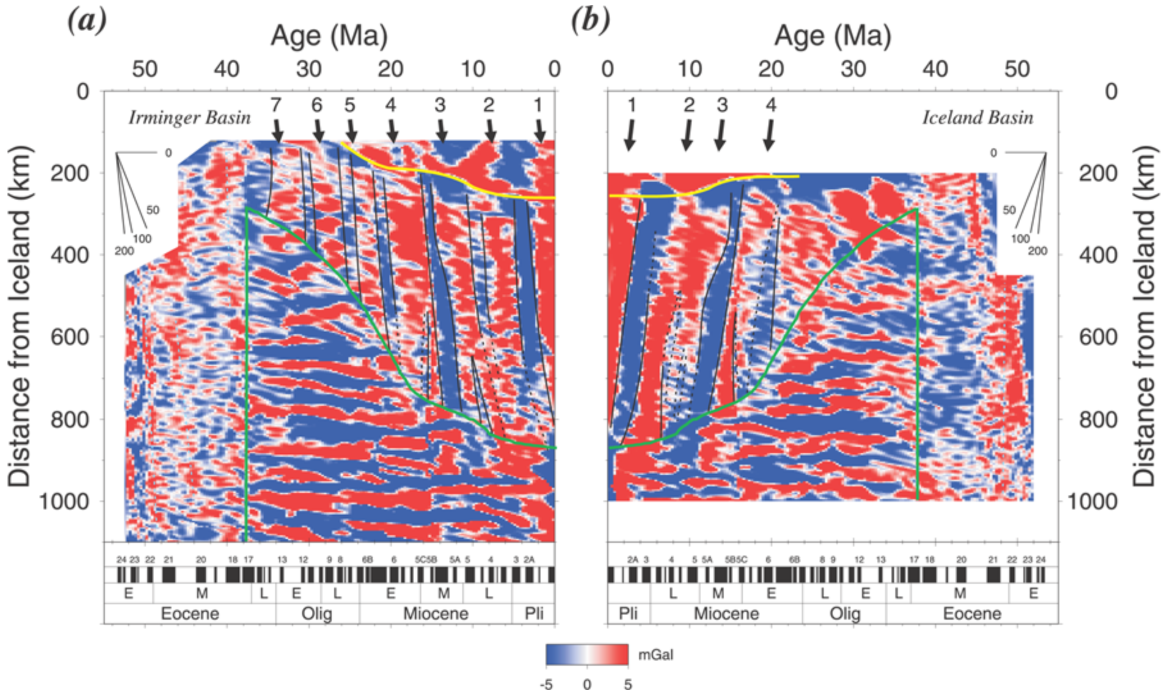

Figure 8. As Figure 7a and b, with interpretation superimposed. Black = V-shaped ridges. Green = boundary between segmented and unsegmented crust. Yellow = edge of Iceland Shelf. Light blue = indistinct gravity lineations of uncertain origin.

500 km from Iceland, respectively, in both the Iceland and Irminger Basins. The 1-D record (Figure 10) is too close to Iceland to image double peaks in ridges R3 and R4, but it does suggest that ridge R2 has a double peak. These bifurcations and associated double peaks may represent a second order plume-head pulsing on a timescale of 2–3 Myr. Conjugate V-shaped ridges vary in morphology between the Iceland and Irminger Basins. For example, in the Irminger Basin ridges R2 and R3 are distinct relatively close to Iceland but appear to merge further away from Iceland (Figure 8). However, in the Iceland Basin, these ridges can be distinguished far from Iceland but merge relatively close to Iceland. This mismatch may reflect complexities in tectonic processes at the spreading axis. Alternatively, it may reflect complexities in transport of magma from the mantle melting zone to the crust.

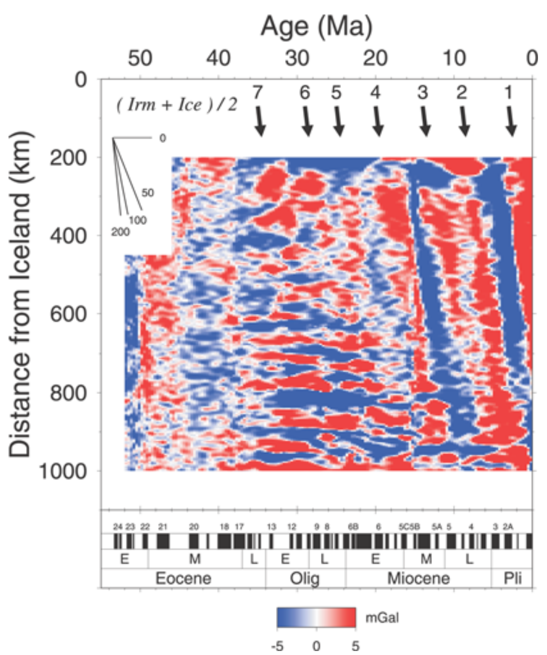

Figure 9. (a) Stacked age-distance plot for gravity record of V-shaped ridges in the Irminger and Iceland Basins. Stratigraphic data as for Figure 7.

[16] The V-shaped ridge gravity signal results mainly from the density contrast between water and topographic ridges in oceanic basement. When these topographic ridges are mantled by sediment, the density contrast is reduced leading to attenuation of the gravity signal. Evidence for attenuation of the V-shaped ridge gravity signal by sediment cover can be found in the northern parts of the Iceland and Irminger Basins in Oligocene-aged crust, between magnetic chrons 6–13 (Fig-

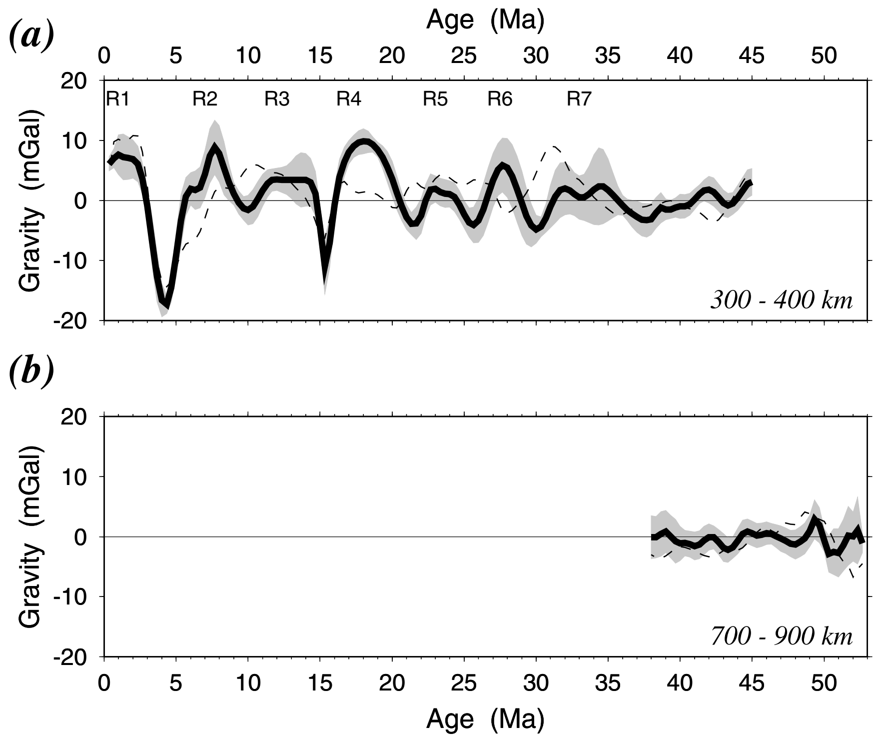

Figure 10. (a) Heavy black line marks the mean gravity profile across the Irminger Basin between 300–400 km from Iceland. Grey envelope marks the region of ±1 standard deviation. Thin black line is the mean profile across the Iceland Basin at the same distance. (b) Same for a distance of 700–900 km from Iceland.

ure 5). V-shaped ridges R5–R7 are reasonably clear in this part of the Irminger Basin, where the sediment cover is of negligible thickness. However, the conjugate V-shaped ridges in the Iceland Basin, which lie beneath > 1 km of sediment, are less distinct.

[17] V-shaped ridges are also visible to the north of Iceland, in the oceanic crust between the Kolbeinsey Ridge and the Jan Mayen continental fragment. These V-shaped ridges appear to converge on the Kolbeinsey Ridge to the north, away from Iceland. Northward convergence is anticipated, since plate models in the hot spot reference frame suggest that the Iceland Plume center has remained in the vicinity of the Greenland–Iceland–Faroes Ridge since 30 Ma [*Lawver and Müller*, 1994]. The V-shaped ridges which formed on the eastern side of the Kolbeinsey Ridge are not mirrored on the western side. This lack of symmetry is probably due to the fact that the V-shaped ridge gravity signal has been attenuated by the gravity signal caused by up to 4 km of overlying sediments shed from Greenland (Figure 4). The record of V-shaped ridges formed at the Kolbeinsey Ridge covers a relatively small area and is best interpreted in comparison with the records from the Iceland and Irminger Basins. Ridges R1 and 2 cannot be seen clearly, probably because of the gravitational effects of the various fracture zones that segment crust younger than magnetic chron 4 (Figure 5). Ridges R3 and R4 can be identified with confidence and correspond closely in age–distance space with the ridges south of Iceland.

[18] The gravity field does not provide definitive evidence for the existence of V-shaped ridges in Eocene age crust, older than magnetic chron 17. Some faint gravity lineations oriented roughly parallel to the magnetic stripes can be discerned within the zone of unsegmented oceanic crust in the oldest parts of the Irminger Basin, but no such features can be seen in the conjugate unsegmented crust of the Iceland Basin (Figure 8). If the faint gravity lineations seen in the Irminger

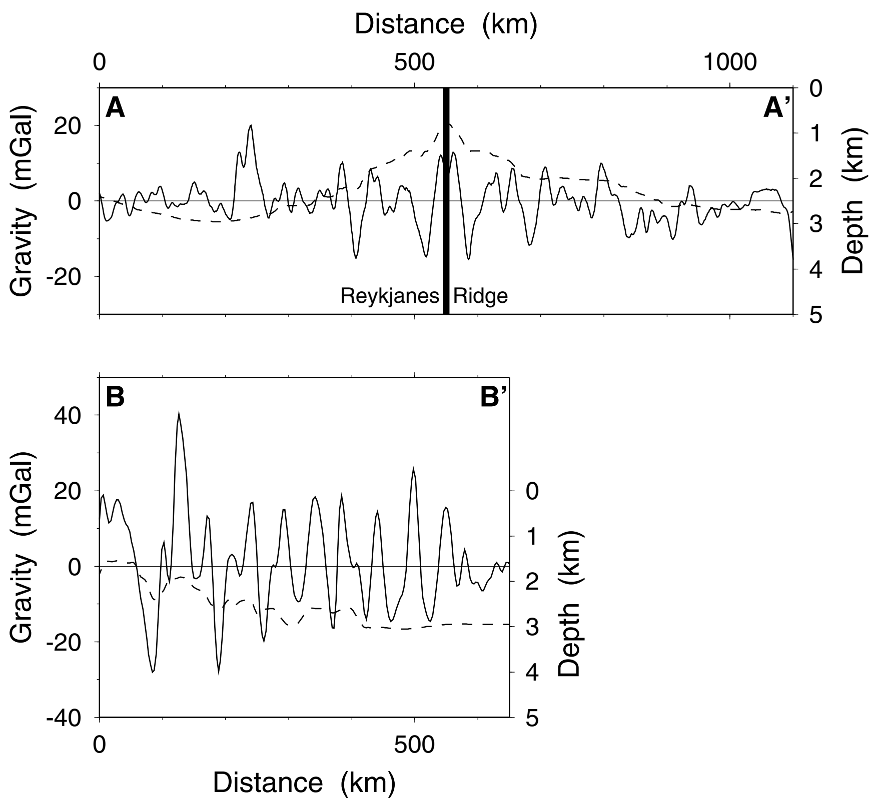

Figure 11. Free-air gravity profiles (solid lines) to illustrate the wavelength and amplitude of the anomalies associated with V-shaped ridges and fracture zones. Topographic profiles from ETOPO5 are shown as dashed lines. Vertical line marks spreading centre. Locations of profiles marked on Figure 4.

Basin were true V-shaped ridges, then conjugate lineations should be more clearly visible in the Iceland Basin where the sediment cover is thinner. Thus the faint lineations in the Eocene of the Irminger Basin may result from heterogeneities within the sediment pile. However, the fact that sediment cover is generally thick over Eocene-aged crust means that we cannot be certain that melting anomalies did not affect the Reykjanes Ridge at this time using the gravity field. Detailed studies using seismic data are required to determine whether Eocene-aged V-shaped ridges exist.

[19] The slope of each V-shaped ridge on the age–distance plot gives the speed of propagation along the spreading axis of the melting anomaly that formed the V-shaped ridge. At distances less than 700 km from Iceland, all the V-shaped ridges have propagation speeds of 200–250 mm yr^{-1}. Beyond 700–800 km from Iceland, there is some evidence that the V-shaped ridges curve and lie at a greater angle to the spreading axis, implying propagation speeds of 100–150 mm yr^{-1}. This curvature is best seen at the younger edges of ridges R2 and R4 in the Iceland Basin and the older edge of ridge R3 in the Irminger Basin (Figure 8).

4. Observations: Paleoceanography

[20] In this section, we review the work of *Wright and Miller* [1996], who described a link between production of Northern Component Water, uplift of the Greenland–Iceland–Faroes Ridge and activity of the Iceland Plume, evidenced by the V-shaped ridges. The main source of Northern Component Water (and its present-day equivalent, North Atlantic Deep Water) is a cold, dense water mass that forms in the Norwegian Sea and Arctic Ocean. This deep water body enters the North Atlantic by flowing southward over the Greenland–Iceland–Faroes Ridge to either side of Ice-

land (Figure 1). Benthic foraminiferal $\delta^{13}C$ records provide one of the best proxies to reconstruct global deepwater circulation patterns because certain benthic foraminifera accurately record $\delta^{13}C$ variations in the dissolved inorganic carbon reservoir. In the modern ocean, there are considerable differences in dissolved inorganic carbon $\delta^{13}C$, reflecting basin-to-basin fractionation caused by deepwater circulation patterns. This fractionation occurs because the $\delta^{13}C$ value and nutrient content of deep/bottom waters is a function of the time the water mass has been isolated from the surface. *Wright and Miller* [1996] used a comparison between $\delta^{13}C$ values in the Pacific, North Atlantic, and Southern Oceans to infer the flux of Northern Component Water into the northern North Atlantic (Figure 12a).

[21] *Wright and Miller* [1996] went on to correlate their record of Northern Component Water flux with a V-shaped ridge record based on a bathymetric profile across the Reykjanes Ridge near 62.5°N (Figure 12b). They calculated depth anomalies by subtracting a half-space cooling model from the topographic profile. Positive depth anomalies represent unusually thick crust and correlate with positive free-air gravity anomalies. The V-shaped ridges imaged on the anomalous depth profile correspond to gravity ridges R1–R4. Ridge R2 exhibits a double peak similar to the twin peaks noted in the gravity signature of ridges R2–R4. The V-shaped ridges are diachronous features, and the result of comparing the record of deepwater flux with a V-shaped ridge record depends on the location of that V-shaped ridge record. *Wright and Miller* [1996] shifted their V-shaped ridge record so that peaks correspond to the times that melting anomalies were situated at Iceland. Figure 12b shows a good negative correlation between times of low Northern Component Water flux and topographic record of V-shaped ridges R2–R4. This negative correlation is just as expected, since times of low Northern Component Water flux should be correlated with times of maximum dynamic support of the Greenland–Iceland–Faroes Ridge, correlated in turn with anomalously high mantle temperature. Note that both of the peaks in ridge R2 are correlated with a drop in Northern Component Water Flux, reinforcing our earlier inference that second order pulsing on a timescale of 2–3 Myr is superimposed on the principal timescale of 5–6 Myr. Figure 12c illustrates an equally good correlation between the record of Northern Component Water flux and the gravity record of V-shaped ridges.

5. Discussion

5.1. Constraints on the 3-D Pattern of Mantle Flow

[22] Well-established models of intraplate mantle plumes indicate that outward flow in the plume head occurs mainly in the horizontal direction [*Courtney and White*, 1986; *Watson and McKenzie*, 1991]. These models are also characterized by mushroom-shaped heads, as the far edges of the plume head cool and begin to sink. However, such models are not applicable to the Iceland Plume because of the complicating effect of the spreading axis. A component of upward flow beneath a spreading axis is a geometrical requirement of plate spreading. The geochemistry of mid-ocean ridge basalt samples provides further evidence that upward flow is occurring. Basalt samples from the length of the Reykjanes Ridge contain trace elements that are incompatible in the mantle [*Schilling*, 1973; *Taylor et al.*, 1997]. The implication is that unmelted mantle is entering the melting region beneath the entire spreading axis. Figure 3a shows that this situation occurs when upwelling driven by plate spreading is taken into account.

[23] A lower bound for the upwelling rate beneath the Reykjanes Ridge can be found by assuming that upwelling occurs passively in response to plate spreading, while active plume-driven upwelling is unimportant. Plate-driven mantle flow is thought similar to a corner flow solution for a viscous incompressible fluid [*Spiegelman and McKenzie*, 1987]. In this model, mantle wells up inside a triangular region whose width is controlled by the wedge angle α and half spreading rate U_0 (Figure 13). *Jull* [1997] cast the corner flow model in Cartesian coordinates and showed that the vertical

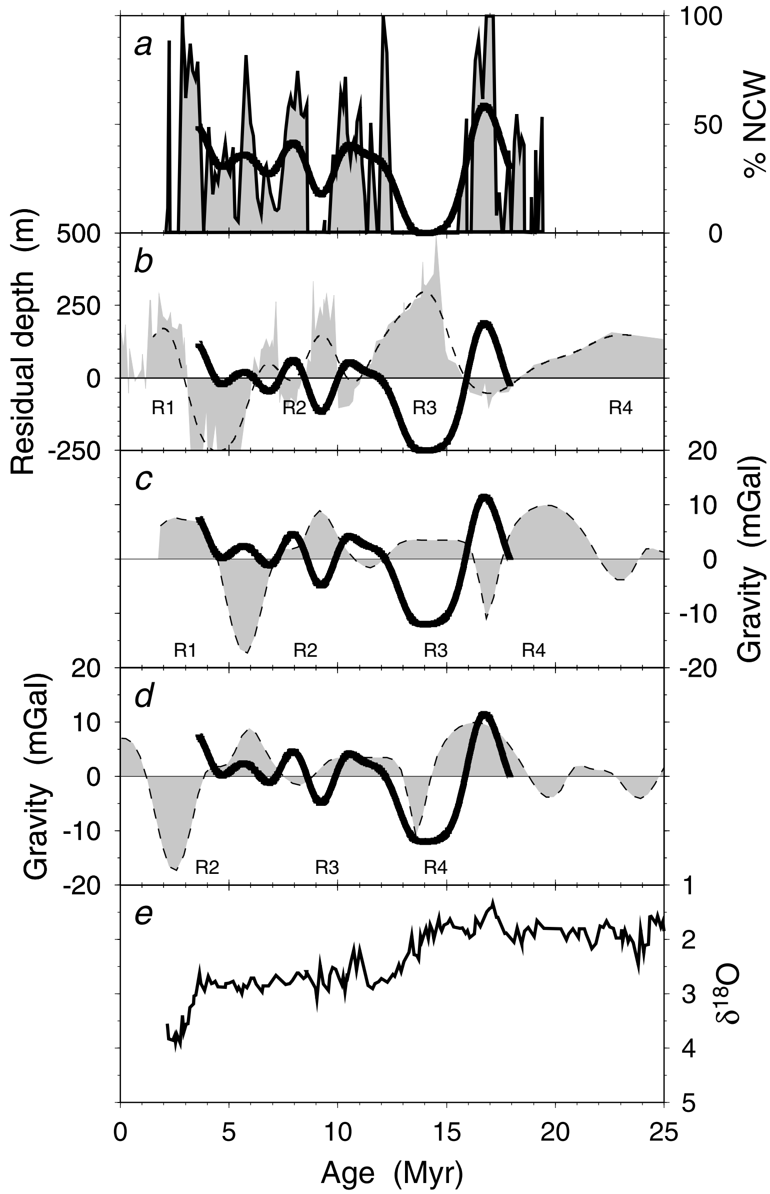

Figure 12. (a) Record of Northern Component Water flux estimated by recording benthic foraminiferal δ^{13}C changes in the Southern Ocean relative to changes in the North Atlantic and Pacific records, from *Wright and Miller* [1996]. Thick black line shows this record filtered at a wavelength of 3 Myr; this filtered record is also superimposed on plots (b), (c) and (d). (b) V-shaped ridge record of *Wright and Miller* [1996] (grey shading), based on anomalous topography observed on a seismic transect perpendicular to the Reykjanes Ridge, shifted in time so that peaks correspond to times that melting anomalies were situated beneath Iceland. Dashed line shows this record filtered at a wavelength of 3 Myr. (c) V-shaped ridge record from short-wavelength gravity field of the Irminger Basin (Figure 10) (grey shading, dashed line), with a time shift of +1.5 Myr so that peaks correspond to times that melting anomalies were situated beneath Iceland. This time shift is calculated by noting that the gravity record is from crust formed 300 km from Iceland, and that the V-shaped ridges propagate at around 200 km Myr. (d) Same as plot (c) but with a time shift of −1.75 Myr, equivalent to the anticipated record of uplift 650 km from Iceland. (e) Benthic foraminiferal δ^{18}O curve of *Wright and Miller* [1996]. The middle Miocene δ^{18}O increase and development of northern hemisphere glaciation during the Pliocene correspond to ridges R1 and R3 respectively, and to changes in flux of Northern Component Water. This match may suggest a link between V-shaped ridges and climate change.

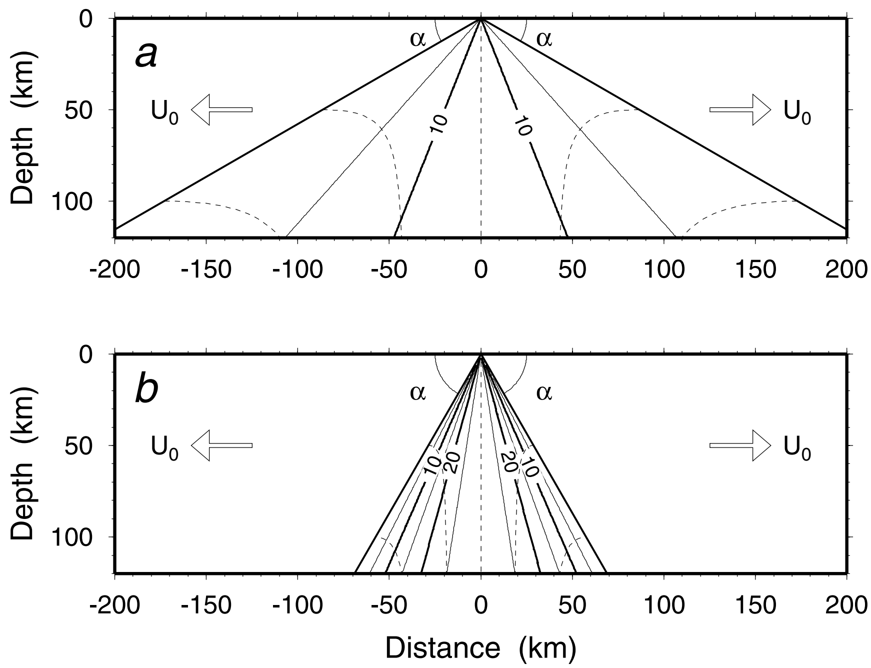

Figure 13. Corner flow solutions showing contours of vertical component of velocity (solid lines; contour interval is 5 mm yr^{-1}) and mantle matrix streamlines (dashed lines) calculated from Equations (1) and (2). (a) Wedge angle α = 30°, plate half spreading rate U_0 = 10 mm yr^{-1}. (b) α = 60°, U_0 = 10 mm yr^{-1}.

and horizontal components of solid mantle velocity v are

$$v_z = A - B\frac{z^2}{x^2 + z^2} \tag{1}$$

$$v_x = B\left[\arctan\left(\frac{x}{z}\right) - \frac{xz}{x^2 + z^2}\right], \tag{2}$$

where $B = 2U_0/[\pi - 2\alpha - \sin(2\alpha)]$ and $A = B \sin^2 \alpha$. In order to find the speed of mantle upwelling from these equations, it is necessary to estimate the wedge angle for the Reykjanes Ridge. *Spiegelman and McKenzie* [1987] presented a method for estimating the wedge angle by combining the characteristic length scale of the corner flow and a half-space cooling model for oceanic lithosphere. It suggests that $\alpha \sim 50°$ is appropriate for slow-spreading ridges such as the Reykjanes Ridge, although dependence on model parameters means that this value is not tightly constrained. Corner flow solutions for $\alpha \sim 30°$ and $\alpha \sim 60°$ are probably reasonable bounds on the pattern of flow beneath the Reykjanes Ridge. Thus, from equation (1), the upwelling velocity beneath the Reykjanes Ridge is 20 ± 10 mm yr^{-1} (Figure 13).

[24] *Gaherty* [2001] suggested that the Iceland Plume induces plume-driven upwelling beneath the Reykjanes Ridge. This inference was based on observations of anomalous seismic polarisation anisotropy which he ascribed to preferential orientation of mineral axes induced by plume-driven flow. However, other geochemical and geophysical evidence suggests that plume-driven upwelling is less important within the melting zone. Crustal thickness has been determined from many wide-angle seismic experiments over Iceland and the surrounding oceans [*White*, 1997]. In some of these locations, rare earth element concentrations of basalt samples are known and have been modelled to find the melt fraction versus depth distributions using the method of *McKenzie and O'Nions* [1991]. The thickness of oceanic crust can be estimated by integrating these melt fractionversus depth distributions. *White et al.* [1995] found that crustal thickness estimates determined from both seismic and geochemical data sets are in agreement. Since a central assumption of the rare earth element modeling method is that upwelling is plate-driven, the match in crustal thickness estimates suggests that there is no need to invoke

plume-driven upwelling beneath the Reykjanes Ridge. The only place in the North Atlantic where plume-driven upwelling is indicated by a mismatch between seismic and geochemical crustal thickness estimates is SE Iceland, thought to lie directly above the plume center [*Maclennan et al.*, 2001]. *Barnouin-Jha et al.* [1997] model another class of buoyant mantle flow beneath spreading centers induced by a combination of Fe-depletion, melt retention, and thermal expansion. However, these flows occur on the spatial scale of individual ridge segments of tens of kilometers, much smaller than the length scale of the V-shaped ridges. Thus the lower bound of 20 ± 10 mm yr^{-1} determined from assuming plate-driven mantle flow is probably a good estimate of the upwelling rate beneath the Reykjanes Ridge.

[25] Dividing the observed V-shaped ridge propagation rate of around 200 mm yr^{-1} by the upwelling rate estimated above gives $\tan\theta = 0.1 \pm 0.05$, where θ is the angle of the base of the plume head to the horizontal (Figure 3a). V-shaped ridges are observed to propagate up to 1000 km from Iceland, so the plume head must diverge from the plume conduit below a depth of 100 ± 50 km. *Maclennan et al.* [2001] investigated the relative roles of plume-driven and plate-driven upwelling beneath Iceland, directly above the plume center. They developed a model that can simultaneously account for rare earth element concentrations and crustal thicknesses imaged on wide-angle seismic profiles. Their results suggest that active, plume-driven upwelling occurs below 100–150 km and upwelling occurs above these depths occurs passively in response to plate spreading. *Ito et al.* [1999] provide an explanation of why plume-driven upwelling does not continue right up to the base of the crust. Rheological experiments suggest that mantle viscosity increases by 2–3 orders of magnitude when water is extracted in the initial stages of partial melting. This viscosity increase associated with dehydration prevents significant active upwelling above the dry solidus, which occurs at a depth of ~100 km. Hence dehyration leads to what we here term a rheological plate, whose base is a horizontal plane at a depth of ~100 km. The plume head spreads radially beneath the flat base of the rheological plate, while passive flow occurs within the rheological plate (Figure 3a). Thus estimates of the depth of the top of the region of active upwelling beneath Iceland based on the geometry of the V-shaped ridges are compatible with both geochemical and seismic observations and also with numerical modeling.

[26] *Vogt* [1971] originally predicted that the curvature of the V-shaped ridges should constrain whether flow in the plume head is radially symmetrical or channeled preferentially beneath the spreading axis. He suggested that V-shaped ridge propagation rates should decrease in inverse proportion to distance from the plume centre in a radially symmetrical case, whereas propagation rates should remain constant with distance in a channeled case. Recent 3-D numerical convection studies have recreated both channeled and radially symmetrical plume head scenarios. *Albers and Christensen* [2001] present a model with a strongly temperature-dependent viscosity that predicts preferential channeling of flow beneath the Reykjanes Ridge. However, *Ito et al.* [1999, 2001] have modeled a radial flow when the rheological effect of mantle dehydration in the early stages of melting is considered, since the base of the rheological plate is roughly horizontal, as discussed above. Both radial and channeled plume models are able to predict the small degree of curvature observed in the V-shaped ridges south of Iceland. Thus it is unlikely that the detailed shape of the V-shaped ridges alone can be used to determine whether plume flow is radially symmetric or channeled beneath the spreading axis.

5.2. Plume Pulsing: Time-Dependent Convection Versus Tectonic Forcing

[27] *Ito* [2001] has demonstrated that it is possible to explain the V-shaped ridges by flux variations that are advected up the plume stalk and spread outwards within the plume head. Temperature variations could be advected round the convection cell in a similar manner. However, an alternative proposition is that temperature pulses in the head of the Iceland Plume that generated the V-shaped ridges were caused by jumps in the location of the spreading axis at the Greenland–Iceland–Faroes Ridge [*White et al.*, 1995; *Hardarson et al.* 1997].

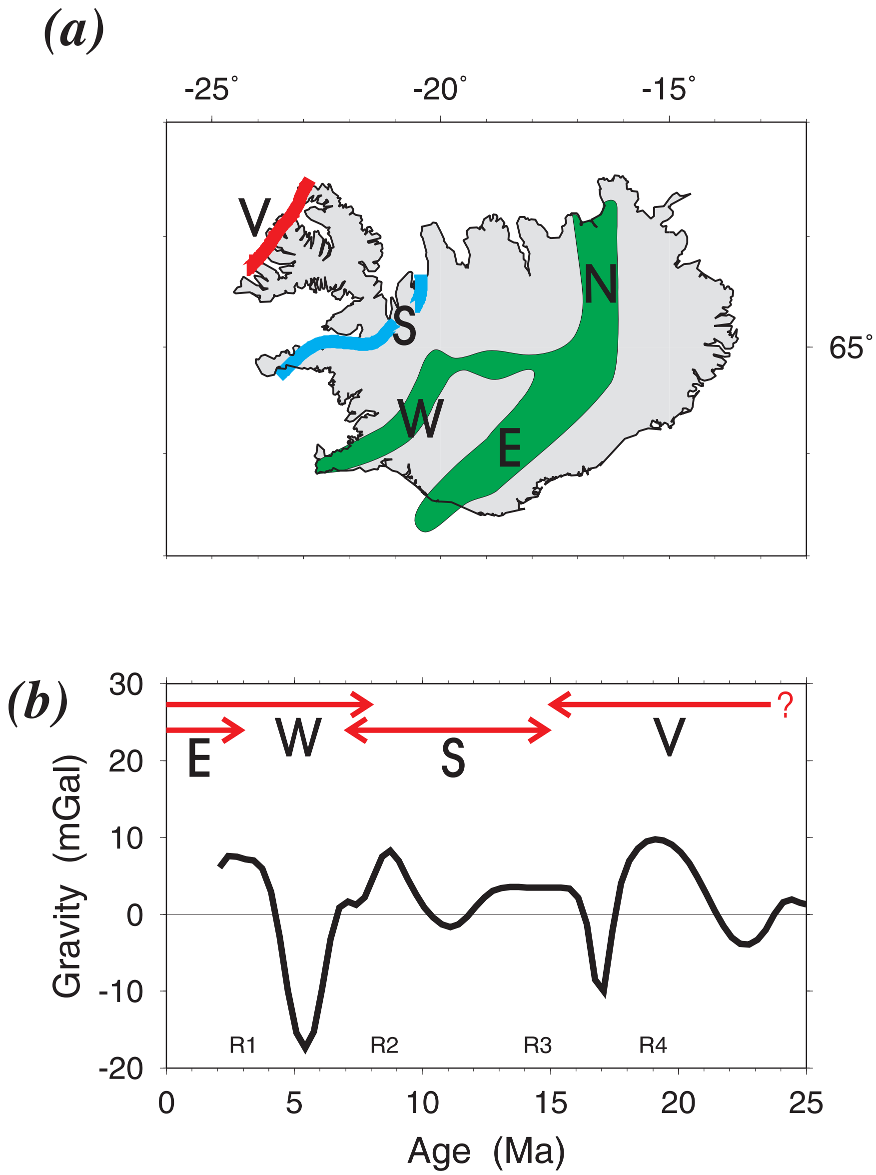

Figure 14. Relationship between gravity record of V-shaped ridges and spreading axis jumps onshore Iceland. (a) Location of active and extinct spreading axes on Iceland. E = Eastern Volcanic Zone; N = Northern Volcanic Zone; S = Snaefellsnes paleo-rift axis; V = Vestfirdir paleo-rift axis; W = Western Volcanic Zone. (b) Black line is the V-shaped ridge record from the short-wavelength gravity field of the Irminger Basin (Figure 10), with a time shift of +1.5 Myr so that peaks correspond to times that melting anomalies were situated beneath Iceland. Red arrows mark times each spreading axis has been active, after *Hardarson et al.* [1997].

Figure 14 shows the correlation between the gravity record of V-shaped ridges and *Hardarson et al.*'s [1997] dates for spreading axis jumps. Spreading axis jumps correlate with times of anomalously high melting beneath Iceland.

[28] Crustal flow is unlikely to explain V-shaped ridges that extend up to 1000 km from Iceland (section 2). Viscosity of mantle within the rheological plate is too high for significant lateral flow to occur *Ito et al.* [1999]. Thus if jumps in location of the spreading axis are to explain the V-shaped ridges, they must affect flow in the plume head beneath the rheological plate; that is, they must be able to generate topography at the base of the rheological plate beneath Iceland. As

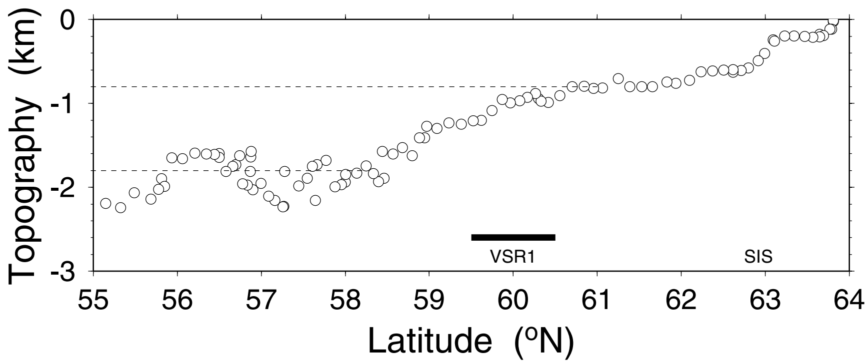

Figure 15. Bathymetric profile along Reykjanes Ridge taken from ETOPO5. Dashed lines indicate the step in bathymetry where V-shaped ridge R1 intersects the Reykjanes Ridge. VSR1 = intersection of V-shaped ridge R1 and Reykjanes Ridge; SIS = southern edge of Iceland Shelf.

discussed in section 5.1, it is likely that the base of the rheological plate corresponds to the dry solidus, which probably lies at a constant depth of ~100 km, independent of lithospheric age. Thus a lateral jump in the spreading axis is not expected to generate a vertical step in the base of the rheological plate. It therefore seems unlikely that jumps in the location of the spreading axis can disrupt flow from the plume stem into the plume head.

[29] It is possible that the temperature variations that caused the V-shaped ridges were also responsible for the spreading axis jumps. Like other plate boundaries, spreading axes tend to retain the same configuration once initiated. However, the spreading axis may sometimes jump to a new location where the plate is substantially weaker. In the North Atlantic, the hottest, weakest lithosphere occurs directly above the stalk of the Iceland Plume, which is currently situated beneath the Vatnajökull icecap in SE Iceland. Hot spot reference frame models show that the plume center has been moving eastward with respect to the plate boundary between Europe and Greenland throughout the Cenozoic [*Lawver and Müller*, 1994], thus accounting for the easterly jumps in the spreading axis observed on Iceland. Temperature pulses that generated the V-shaped ridge melting anomalies are expected to cause periodic additional weakening of the oceanic plate. They may thus trigger the spreading axis to jump from an established location to a new location almost directly above the plume center.

[30] To summarize, we suggest that V-shaped ridges are generated by time-dependent flow that rises up the Iceland Plume conduit from deep within the mantle. These temperature pulses have triggered spreading axis jumps on Iceland. However, further work is required to confirm this view. In particular, 3-D numerical models should be developed to investigate the cause and effect relationships between spreading axis jumps and the temperature pulses that caused the V-shaped ridges. Better knowledge of the ages of the spreading axis jumps would be helpful. Finally, a good understanding of the positioning of the ridge axes with respect to the plume center is also required.

5.3. V-Shaped Ridges, Uplift, and Paleoceanography

[31] V-shaped ridges are correlated with variations in dynamic support of the North Atlantic surrounding Iceland. Here we investigate the magnitude of fluctuations in dynamic support and reconsider the detailed relationship between fluctuations in dynamic support and V-shaped ridge melting anomalies. Variation in dynamic support can be estimated from the variation in bathymetry of the Reykjanes Ridge crest across the region where it intersects V-shaped ridge R1. Figure 15 shows a bathymetric step of 500 m at this location. One component of this change in elevation is related to a change in crustal thickness of 2 ± 1 km [*Smallwood and White*, 1998]. Assuming Airy isostasy, a change in crustal thickness of ΔD results in a water-loaded topographic step of ΔD $(\rho_a - \rho_c)$/

($\rho_a - \rho_w$), where ρ_a = 3180 kg m^{-3} is the density of the asthenosphere, ρ_c = 2800 kg m^{-3} is the crustal density and ρ_w = 1000 kg m^{-3} is the density of water. Thus variation in crustal thickness of 2 ± 1 km between a V-shaped ridge and an adjacent trough should cause a topographic variation of 200–550 m. Given a bathymetric step of 500 m at the Reykjanes Ridge, the dynamic component of support of V-shaped ridge R1 is thus 150 ± 150 m. This estimate is probably a lower bound for the fluctuation in dynamic support at Iceland itself since temperature anomalies are likely to be greater closer to the plume center.

[32] Can fluctuations in dynamic support of a few hundred meters account for the observed variation in Northern Component Water flux? Through the Neogene, the greatest proportion of Northern Component Water has flowed south–eastward through the Faroe-Shetland Channel and then north–westward through the Faroe Bank Channel to enter the north–eastern corner of the Iceland Basin. The Faroe Bank Channel is 20 km wide and 750 m deep at its shallowest point. Northern Component Water flows into the Atlantic through the Denmark Strait and over the Iceland–Faroes Ridge, which lie at depths of 500–600 m. The narrow, shallow geometries of the three spillways across the Greenland–Iceland–Faroes Ridge make the flux of Northern Component Water into the global ocean sensitive to small variations in the ridge depth.

[33] Correlation between deepwater circulation and both the gravity and bathymetric records of plume activity indicates that shut-down of Northern Component Water flux is coeval with uplift of Iceland itself (Figure 12). This observation is not intuitive since the spillways through which Northern Component Water flows across the Greenland–Iceland–Faroes Ridge lie hundreds of kilometers from Iceland. The main spillway is the Faroe Bank Channel, which lies 650 km from the center of the Iceland Plume at present. This channel has probably remained at roughly the same distance from the plume center since the Miocene, as Europe has moved slowly relative to the hot spots during this time period [*Müller et al.*, 1993]. However, the V-shaped ridge gravity record at a distance of 650 km from the plume centre shows a poor correlation with the record of deepwater flux (Figure 12d). A possible explanation for this discrepancy lies in the fact that V-shaped ridge formation and Northern Component Water flux are not controlled by the same process. Northern Component Water flux is controlled by dynamic support, which is in turn controlled by the temperature structure of the plume head and the overlying plate. V-shaped ridges record melting anomalies, controlled by the thermal structure of the region above the dry solidus. Figure 3a shows that the melting anomaly, generated above ~100 km, is expected to lag the leading edge of the thermal anomaly in the plume head.

6. Conclusions

[34] We have studied the gravity record of V-shaped ridges in the basins surrounding Iceland by plotting the short-wavelength component of the gravity field in terms of age versus distance from Iceland. During Oligocene-Recent time, V-shaped ridges occur with a primary periodicity of 5–6 Myr and a secondary periodicity of 2–3 Myr. A record of uplift of the Greenland–Iceland–Faroes Ridge based on paleoceanographic data is correlated with the gravity record of V-shaped ridges.

[35] We highlight the fact that many questions remain about the V-shaped ridges and the geometry of the mantle circulation that caused them. The relative importance of temperature and compositional variability in generating the melting anomalies that built the V-shaped ridges has yet to be studied. The gravity, topographic, and crustal thickness variations around Iceland can be explained using a model in which plume mantle rises within a narrow conduit beneath Iceland and spread out laterally beneath the lithosphere to form a head hundreds of kilometers wide. However, this model has yet to be verified by direct geophysical or geochemical observations. If this model for the convective system beneath Iceland is accepted then the melting anomalies that built the V-shaped ridges are probably generated by time-dependent flow that rises up the Iceland Plume conduit from deep in the mantle. These temperature pulses may have triggered spreading axis jumps on Iceland.

However, 3-D numerical models need to be developed to investigate cause and effect relationships between spreading axis jumps and the temperature pulses that caused the V-shaped ridges to confirm this hypothesis. It is difficult to determine whether V-shaped ridges exist in crust of Eocene age using gravity data because of the relatively thick sediment cover over Eocene crust. Seismic data should be used to investigate this question and hence to determine whether time-dependent flow in the Iceland Plume altered between the Eocene and the Oligocene.

[36] The link between the V-shaped ridges, fluctuations in dynamic support and global deepwater circulation is convincing. More work should done to compare paleoceanographic records with V-shaped ridge records in order to assess the extent to which time-dependent convection in the Iceland Plume has influenced global climate. In addition, the effect of fluctuations in dynamic support on the sedimentary record of the continental margins surrounding the North Atlantic should be investigated.

Acknowledgments

[37] SMJ and JCM were supported by NERC studentships. We thank J. Gaherty, D. Graham, and G. Ito for constructive comments which have improved the manuscript. We also thank B. Lovell and D. Lyness. Department of Earth Science contribution ES.7125.

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