Iceland is cool: An origin for the Iceland volcanic province in the remelting of subducted Iapetus slabs at normal mantle temperatures

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Abstract

The time-progressive volcanic track, high temperatures, and lower-mantle seismic anomaly predicted by the plume hypothesis are not observed in the Iceland region. A model that fits the observations better attributes the enhanced magmatism there to the extraction of melt from a region of upper mantle that is at relatively normal temperature but more fertile than average. The source of this fertility is subducted Iapetus oceanic crust trapped in the Caledonian suture where it is crossed by the mid-Atlantic ridge. The extraction of enhanced volumes of melt at this locality on the spreading ridge has built a zone of unusually thick crust that traverses the whole north Atlantic. Trace amounts of partial melt throughout the upper mantle are a consequence of the more fusible petrology and can explain the seismic anomaly beneath Iceland and the north Atlantic without the need to appeal to very high temperatures. The Iceland region has persistently been characterised by complex jigsaw tectonics involving migrating spreading ridges, microplates, oblique spreading and local variations in the spreading direction. This may result from residual structural complexities in the region, inherited from the Caledonian suture, coupled with the influence of the very thick crust that must rift in order to accommodate spreading-ridge extension. The local tectonics can explain a number of significant features observed on land in Iceland. Eastward-widening, fan-shaped extension across a west-east zone traversing central Iceland culminates in northwest Vatnajokull and causes the enhanced volcanism there that is traditionally assumed to indicate the center of a thermal plume. A captured microplate containing oceanic crust up to ~ 30 Myr old underlies central Iceland and comprises a block with crust up to ~ 40 km thick. The general locus of spreading in the Iceland region has not migrated east relative to the Kolbeinsey ridge as is often claimed, but has remained relatively fixed since ~ 26 Ma. Enhanced magmatism and ocean-island basalt geochemistry at "hotspots" in general may be explained as the products of structures and processes imparted to the upper mantle by plate tectonic processes, suggesting that a separate mode of mantle convection, i.e., mantle plumes, is unnecessary.

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1. Introduction

The idea that the Iceland volcanic province results from a thermal plume rising from deep in the lower mantle is almost universally used as an *a-priori* assumption and a framework within which new data are interpreted. However, it cannot account for several first-order observations concerning Iceland, and thus may not be correct (Foulger, 2002; Foulger et al., 2003a). It is reasonable, in any case, to develop alternative hypotheses which are motivated by the data and to explore whether they can survive further scientific testing.

Observations from the Iceland region that appear paradoxical in the plume model are as follows. Since the opening of the north Atlantic at ~ 54 Ma, the locus of melt extraction has been at the mid-Atlantic ridge (MAR) where it crosses the Caledonian suture. In the context of a plume, this is a coincidence. For a mantle plume currently beneath Iceland to have been fixed relative to other Atlantic and Indian ocean hotspots, it must have migrated southeastwards at a rate of ~ 2 cm/a relative to the North American plate, from a location beneath central Greenland at ~ 60 Ma (Lawver and Muller, 1994). No age progression of volcanism is associated with such a trajectory. The Tertiary volcanism that accompanied continental breakup was so widespread that lateral flow for up to 1,000 km is required if the melt emanated from a localized source beneath Greenland (Chalmers et al., 1995). Why material should have flowed to the mid-Atlantic ridge (MAR) at the latitude of Iceland and not to other locations on the ridge is unexplained.

There is no petrological or heat-flow evidence for high, plume-like temperatures in the region. Magmatic temperatures and the absence of picritic glass are consistent with moderate temperatures only (Ribe et al., 1995; Korenaga and Kelemen, 2000; von Herzen, 2001; Breddam, 2002; Stein and Stein, 2003). Constant temperatures during the opening of the ocean are implied (Holbrook et al., 2001), not the increasing temperatures implied for early plume head volcanism evolving to plume stem temperatures. Furthermore, seismic attenuation measurements suggest that the 30-km-thick crust beneath Iceland is colder than at equivalent depths beneath the East Pacific Rise (Menke and Levin, 1994). The idea that crustal thickness can be used as a proxy for high mantle temperature thus appears to be not valid. Seismic tomography finds no evidence for the deep, downward-continuous low-wave-speed anomaly expected for a thermal plume, but both teleseismic tomography and whole-mantle tomography show that the strong low-wave-speed anomaly observed in the shallow mantle beneath Iceland does not extend deeper than the mantle transition zone (Ritsema et al., 1999; Foulger et al., 2000; Foulger et al., 2001).

Overall, the observations from the Iceland volcanic province suggest that the melt anomaly there is an upper-mantle, normal-temperature phenomenon. Its coincidence with the Caledonian suture suggests a causative relationship. The primary observations that require explanation are the local production of up to three times the amount of melt produced on the Reykjanes and Kolbeinsey ridges to the north and south, local tectonic complexity, and some ocean-island-basalt (OIB) type geochemistry in the midst of generally mid-ocean-ridge basalt (MORB) type major element, trace-element and isotope geochemistry. In this paper, we propose that the Iceland melting anomaly results from the remelting of recycled subducted oceanic Caledonian crust at the spreading ridge where it crosses the Caledonian suture. Such a source can account for the exceptionally large volume of melt in the presence of relatively normal mantle temperatures. The local tectonic complexity probably results from heterogeneous stress and structure in the region of the Caledonian suture zone, and its attendant complex geology, coupled with the locally very thick crust.

A source for the excess melt in recycled subducted oceanic crust is consistent with the petrology and geochemistry of Icelandic lavas, and modeling of that is presented in a companion paper (Foulger et al., 2003b). This is consistent with other work which argues for a low-temperature, fertile mantle source for "hotspots" (e.g., Green et al., 2001). The objective of the current paper is to present an alternative explanation for the melt volumes and tectonics of the Iceland volcanic province. Our approach reverses the traditional cause-and-effect chain of reasoning. We consider the magmatic anomaly in the Iceland region of the north Atlantic to be the *result* of lithospheric architecture, breakup, mantle inhomogeneity and unstable tectonics, and not the *cause* of these complexities, via a deep mantle plume or a high-temperature anomaly.

2. Tectonic evolution of the North Atlantic

The north Atlantic has been a region of tectonic complexity throughout the Phanerozoic. Prior to ~ 500 Ma the continents of Laurentia and Baltica were separated by the Iapetus ocean, and these were separated from the continent of Avalonia to the south by Tornquist's Sea (Figure 1a) (e.g., Soper et al., 1992). Between ~ 440 Ma and ~ 400 Ma the last stages of closure consumed these oceans and formed the Caledonian suture, a broad zone of compression with branches in east Greenland, Scandinavia, Britain, Europe and Newfoundland (Figure 1b). The easternmost branch of the Caledonian suture ran down what is now the east coast of Greenland to merge with the complex array of northerly trending left-lateral shear zones that dissect Britain. Subduction beneath this branch of the suture was to the southwest (e.g., Barker and Gayer, 1984).

The colliding cratons were presumably ~ 150-200 km thick (Polet and Anderson, 1995), and at least this length of latest-subducting slab was thus trapped in lithospheric levels of the suture. The last crust to subduct into the mantle beneath the cratons was probably also relatively young and buoyant. Such crust becomes neutrally buoyant at shallow depth (Oxburgh and Parmentier, 1977). The upper few hundred kilometers of the mantle beneath the sutured supercontinent was thereby refertilized by buoyant, trapped slabs.

The cratons separated once again when the MAR formed at ~ 54 Ma. To the north, the new ridge formed along the suture zone, but to the south it formed a new split within the Laurasian continent (Figure 1b). At the boundary between these two contrasting regions, the new MAR crossed the east Greenland – Britain suture branch. It was that crossing which was subsequently the locus of chronic, high melt productivity, and about which the Iceland volcanic province formed, including the Greenland-Iceland-Faeroe ridge and Iceland itself (Figure 2) (e.g., Bott, 1985). Because the suture branch was approximately orthogonal to the new MAR, lateral migration did not transport the MAR away from the suture early on, as occurred to the north and south where the MAR formed parallel to the suture zone. Instead, long-term access to mantle fertilised by subducted Caledonian crust resulted in the steady-state production of igneous crust ~ 30 km thick, three times thicker than along the Kolbeinsey and Reykjanes ridges to the north and south (Foulger et al., 2003a).

Supporting evidence for recycled crust of Caledonian age in the basalts of east Greenland, Iceland and Britain comes from calculated compositions of parental melts, trace- and rare-earth elements (REE) and radiogenic isotope ratios (Chauvel and Hemond, 2000; Korenaga and Kelemen, 2000; Breddam, 2002; Lesher et al., 2003). Subducted slabs include sediments, altered basaltic upper crust, gabbroic lower crust, and depleted lithospheric mantle. Continental debris may be included because of the proximity of the latest-subducting slab to the colliding cratons. The crustal part may include enriched mid-ocean-ridge basalts and alkalic olivine basalt such as occur on and near spreading ridges today. This variety of source material, combined with processes associated with remelting the Icelandic crust (Oskarsson et al., 1982), can account for the petrological and geochemical variability of Icelandic basalts, in addition to their exceptionally large volume (Foulger et al., 2003b).

Compositional heterogeneity is the preferred explanation for the large melt volumes in the absence of very high temperatures (Ribe et al., 1995; Korenaga and Kelemen, 2000; von Herzen, 2001; Breddam, 2002; Stein and Stein, 2003). High water contents also decrease the melting point and lengthen the melting column, but this alone increases crustal thickness only slightly (Asimow and Langmuir, 2003). We suggest here that increased fertility of the North Atlantic is the main cause of the anomalously large melt production at Iceland.

3. Present regional setting

Today, the entire ~ 1,000-km broad part of the Atlantic ocean between the Charlie Gibbs and Jan Mayen fracture zones is characterized by regional anomalies in bathymetry and gravity and a temperature anomaly that peaks at +50 to 100˚C (Ribe et al., 1995; Boutilier and Keen, 1999; Korenaga and Kelemen, 2000; Breddam, 2002). Such a temperature anomaly is within the normal range of variation for the mantle, and may result from continental insulation by the Laurasian supercontinent prior to the opening of the north Atlantic (Klein and Langmuir, 1987; Anderson, 1994b). The entire region is underlain by a low seismic wave-speed anomaly that extends from the surface down as far as the mantle transition zone (Ritsema et al., 1999; Foulger et al., 2000; Foulger et al., 2001).

The topographic, geochemical and structural anomalies that culminate at Iceland decrease smoothly, to a first order, down the Reykjanes ridge south of Iceland. Variable rates of magmatism have formed southward-propagating, diachronous V-shaped topographic ridges on its flanks (Vogt, 1971). To the north of Iceland, discontinuities in structure and geochemistry occur across the 120-km long Tjornes fracture zone, and diachronous topographic ridges are present but less clear than on the Reykjanes ridge. Iceland itself is a ~ 350 x 500 km subaerial portion of the aseismic Greenland-Iceland-Faeroe ridge. Most of the currently submarine part of this ridge is thought to have been originally emplaced subaerially, and subsequently cooled and subsided below sea level (Nilsen, 1978).

4. The volumetric melt anomaly

How much excess melt is there in the Iceland region? The seismic crustal thickness beneath the Greenland-Iceland-Faeroe ridge is typically ~ 30 ± 5 km, contrasting sharply with the ~ 10 km crustal thickness that characterizes the north Atlantic oceanic crust elsewhere (Foulger et al., 2003a) (Figure 3a). Tectonic complexities have resulted in local variations in crustal thickness beneath Iceland itself, including somewhat thinner crust beneath western Iceland than eastern Iceland, and a block 40 km thick beneath central Iceland (Figure 3b). These variations are discussed in Section 7.

Seismic crustal thickness is often used as a proxy for the amount of melt formed at mid-ocean ridges, though retention of melt in the uppermost mantle may render it a slight underestimate (Cannat, 1996). In the case of the Icelandic crust, an additional complexity is the mismatch between the density contrast expected between oceanic lower crust and mantle (~ 300 kg/m^3, assuming an olivine gabbro lower crust and peridotite upper mantle) and that indicated by isostasy for average Icelandic lower crust and mantle (~ 90 kg/m^3) (Menke, 1999). On density grounds, it is thus unsafe to assume that Icelandic-type crust is simply scaled-up oceanic crust with the same petrologies.

One possibility is that some of the ~ 23 ± 5 km thick Icelandic lower crust may comprise entrained mantle rocks. The small density contrast with the mantle would encourage such entrainment in upwardly mobile melt, though the absence of any mantle xenoliths in Iceland, and seismic wave-speeds for the lower crust that are typical of gabbro, provide no supporting evidence (Foulger et al., 2003a). Nevertheless, such a model gives a lower bound for the melt thickness. If the entire density-contrast anomaly is explained as the lower crust comprising a mixture of average olivine gabbros and depleted harzburgite, then it follows that only ~ 30% of the lower crust is olivine gabbro, and only ~ 50%, or ~ 15 km of the total crust is melt. If, on the other hand, the anomalously high lower crustal densities result from high-density cumulates, e.g., oxide gabbro, then the entire lower crust represents melt. These considerations suggest lower and upper bounds for the typical melt thickness of ~ 15 and ~ 30 km, or 1.5 – 3 times that on the immediately adjacent Reykjanes and Kolbeinsey ridges.

In the absence of a major temperature anomaly, a more fusible mantle composition is a primary candidate explanation for the melt volume anomaly. Suture zones such as the Caledonian contain subducted slabs, including eclogitized crust. The volumes of melt that may be extracted from subducted oceanic crust, peridotite and crust-peridotite mixtures has been investigated quantitatively by Yaxley (2000), who studied experimentally the melting relations of mixtures of homogeneous fertile peridotite and average oceanic crust. The addition of basalt to peridotite reduces both the solidus and liquidus (Figure 4a). This results both in melting beginning at a lower temperature in the basalt-peridotite mixture, and in higher melt fractions at a given temperature. Figure 4b shows that under the experimental conditions, the addition of a few tens of percent of basalt to peridotite can enhance the melt volume by up to a factor of 4 for temperatures higher than ~ 1,500˚C. In this way, at normal mid-ocean ridge temperatures, significantly more melt is expected for a crust-peridotite mixture than for a peridotite mantle. A few tens of percent of basalt in a peridotite mantle can thus account for the great melt thickness formed at the MAR where it crosses the Caledonian suture. Heat-balance questions are raised by such a model, which predicts that large amounts of heat are extracted from the mantle along with the advected melt (Foulger et al., 2003b).

5. Tectonic Evolution of the Iceland Region

A number of local features in Iceland are commonly quoted as being consistent with a localised plume source for the excess melt beneath central Iceland. These include eastward-migration of the locus of spreading in Iceland, thought to be consistent with an eastward-migrating plume, and a maximum in crustal thickness and volcanic activity beneath central Iceland. The features quoted are, however, required by the complex tectonic history of the region, which is described in this section.

Following the opening of the north Atlantic at ~ 54 Ma, the spreading history of the ocean basin that formed within the Caledonian suture, to the north of the Iceland volcanic province, contrasted with that which formed within the Laurentian continent to the south (Figure 5). The zone where the Iceland volcanic province later formed functioned as a tectonic divide, and was persistently unstable, featuring paired spreading ridges and intervening microplates.

At the time of opening a ~ 100-km long, right-stepping transform fault, the Faeroe transform fault (FTF), formed where the new spreading ridge crossed the edge of the Caledonian suture (Bott, 1985) (Figure 5a). Along much of the new margin, rifting caused thick Archean lithosphere and new oceanic crust to be juxtaposed. Vigorous magmatism, building a volcanic margin with crust up to ~ 25 km thick occurred along a ~ 2,000-km-long portion of the new rift including the margins of Greenland (Boutilier and Keen, 1999). This may have resulted from EDGE convection, which is driven by lateral temperature gradients where thick lithosphere meets hotter mantle (Anderson, 1994a; Anderson, 1995; Boutilier and Keen, 1999; Korenaga and Kelemen, 2000). Increased mantle fertility from Caledonian-age subducted crust in the shallow upper mantle may also have enhanced melt production, and geochemical evidence for such a component is found in the basalts of eastern Greenland (Lesher et al., 2003). Initial vigorous magmatism dwindled to more typical oceanic rates along most of the margin after a few Myr. However, the magmatic rate remained high at the latitude of Iceland, and built the ridge of crust ~ 30 ± 5 km thick that now traverses the entire north Atlantic. Tectonic complexities rafted several continental blocks into the ocean, including the Jan Mayen microcontinent (JMM) and the Faeroe block.

Spreading proceeded relatively simply for the first ~ 10 Myr following opening, but at ~ 44 Ma, a major reorganization occurred north of the FTF. A second spreading center, the Kolbeinsey ridge, developed within the Greenland craton (Figure 5b). Complimentary fan-shaped spreading then occurred along both the original Aegir ridge and the Kolbeinsey ridge during the period 44 - 26 Ma, causing ~ 32˚ of counterclockwise rotation of the intervening, continental JMM (Figure 5c). This resulted in up to ~ 60 km of transtension across the FTF, which corresponds to opening at up to ~ 15% of the local full spreading rate of 1.9 cm/a (DeMets et al., 1994). The onset of this phase of extension coincides with a time when the magmatic production rate increased greatly, and formation of the ~ 250-km-wide Iceland-Faeroe ridge of thickened crust gave way to formation of the Iceland volcanic plateau, which is up to 600 km in north-south extent (Figure 2). This increased magmatism may have been permitted by the transtensional opening across the FTF. Renewed volcanism in east Greenland at this time was associated with the opening of the new rift there, and may have resulted from increased EDGE convection as the microcontinent split off (Korenaga, 2000).

The region continued to be characterized by relatively simple spreading about the Reykjanes ridge to the south. In the neighborhood of the Iceland volcanic province, however, spreading proceeded about a pair of parallel centers that progressively migrated south through the repeated extinction of old rifts and the opening of new. At ~ 26 Ma the Aegir ridge became extinct, spreading became confined to the Kolbeinsey ridge, and a second parallel spreading center formed to the immediate south (Figure 5c). The eastern center developed into the currently active Northern Volcanic Zone (NVZ) (c.f., Figures 5c and 6a). Continuity of the lava succession in eastern Iceland, and the absence of an eastward extension of the Tjornes fracture zone beyond the NVZ shows that the eastern center has been long-lived and has remained approximately fixed with respect to the Kolbeinsey ridge since at least 15 Ma and probably since ~ 26 Ma (Saemundsson, 1979; Jancin et al., 1985).

As a consequence of the fixed spatial relationship of the eastern spreading center with the Kolbeinsey ridge, the western center was progressively transported west relative to the Kolbeinsey ridge. This center experienced at least two rift extinctions, accompanied by the opening of new rifts further east with better colinearity with the Kolbeinsey ridge. At ~ 15 Ma the western rift became extinct and a new rift opened ~ 80 km further east (Figure 6a), and at ~ 7 Ma this new rift in turn became largely extinct and the presently active Western Volcanic Zone (WVZ) formed (Figure 6c). Extension across a pair of parallel spreading centers has occurred in south Iceland since ~ 2 Ma when the Eastern Volcanic Zone (EVZ) formed (Saemundsson, 1979) (Figure 6d).

The continually evolving, parallel-pair spreading center configuration has resulted in a jigsaw of ephemeral microplates. These include the JMM (Figure 5), and two microplates in Iceland. One lay between the northern pair of parallel spreading centers (the Trollaskagi microplate) and one between the southern pair (the Hreppar microplate) (Figures 6 and 7). The palinspastic reconstruction (Figure 6) shows that oceanic crust up to ~ 30 Myr old has been trapped beneath central and southeast Iceland as a consequence of the complex history of spreading. Recent ancient ages determined for zircons from basalts in southeast Iceland suggest the presence of continental crust beneath that area, suggesting that the JMM may have continued further south than shown in Figure 5c (Amundsen et al., 2002). In this case, a sliver of continental crust might have been captured between the parallel pair of spreading centers that formed at ~ 26 Ma, and currently underlie central and southeastern Iceland. The presence of such a sliver may have been influential in the formation of the parallel spreading-center pair.

The palinspastic reconstruction of the evolution of Iceland shown in Figure 6 the simplest possible interpretation of the data available. It is based on the ages of surface lavas, and those that flowed subaerialy may have flowed some tens of km from their eruption site. No attempt has been made to correct for this error source, which would tend to result in an overestimate of the width and age of the trapped, old oceanic crustal block beneath central Iceland. The maximum estimate of ~ 550 km (compared with the 285 km corresponding to 15 Myr of extension at the 1.9 cm/a local average spreading rate) might thus be too large. It is clear, nevertheless, from the locations of Tertiary spreading centers, that the ~ 15 Ma isochrons are much more widely separated on land in Iceland than is expected for a time-averaged spreading rate of 1.9 cm/a, such that the conclusion that older, captured crust underlies Iceland is inescapable.

6. Local variations in spreading direction

The tectonic disequilibrium in the Iceland region throughout its history has been accompanied by local, minor variations in the direction of plate motion associated with the propagating spreading axes and the intervening microplates. Four sets of observations suggest that the local spreading direction rotates clockwise from north to south (Figure 7):

1. The trend of dikes in the NVZ is ~ 10˚N suggesting a local spreading direction in north Iceland of ~ 100˚, close to the global plate direction of ~ 105˚ (DeMets et al., 1994). In south Iceland, dikes in the EVZ and WVZ trend at ~ 45˚ and ~ 35˚ respectively, suggesting clockwise rotation of the spreading direction by 25-35˚.

2. GPS measurements show that the direction of motion at the east coast rotates clockwise by ~ 45˚ from northeast to southeast Iceland (Hofton and Foulger, 1996; Voelksen, 2000).

3. The tension axes of focal mechanisms of large strike-slip earthquakes in the fracture zones in north and south Iceland are orientated ~ 60˚ more southerly in south Iceland than in north Iceland (Bjarnason and Einarsson, 1991; Einarsson, 1991).

4. Plio-Pleistocene and Tertiary dikes in north and south Iceland trend typically at 0 - 10˚ and 40 - 50˚ respectively, suggesting that a ~ 30-50˚ difference in local direction of motion has persisted since at least ~ 15 Ma (Saemundsson, 1979).

Long-term, large-scale motion between the North American and Eurasian plates is coherent, and the variations in direction of motion are apparently local to the Iceland region only. Such small, local variations in the direction of crustal motion are possible in the context of large-scale coherent plate motion since rapid post-tectonic stress redistribution is enabled by the relatively low viscosity that characterizes the Icelandic lithosphere (Foulger et al., 1992; Hofton and Foulger, 1996).

A more southerly direction of motion in south Iceland predicts transtension across a zone trending west-east through central Iceland. Such transtension encourages normal faulting, diking and volcanism. Iceland is traversed from west to east by a zone of volcanism and normal-faulting earthquakes (Figure 7). From west to east, this zone includes the Snaefellsnes Volcanic Zone (SVZ), a re-activated rift with a low level of volcanism, and the Borgarfjordur area immediately east of this, where normal-faulting earthquakes have occurred, some with easterly orientated fault planes (Einarsson et al., 1977). Volcanic production increases eastward in the Middle Volcanic Zone (MVZ), and culminates at a cluster of major volcanoes traversing the Vatnajokull icecap that includes Bardarbunga, Grimsvotn and the recently active Gjalp volcano (Gudmundsson et al., 1997). These volcanoes and the MVZ form the highest topography in Iceland and the area of greatest melt productivity (Foulger et al., 2003a). Volcanism dwindles beneath east Vatnajokull, and extinct volcanoes in the southeast coastal zone (Saemundsson, 1979; Jóhannesson and Saemundsson, 1998) show that major magmatism and thus local dilation is a long-term characteristic of this region but does not extend far into the Eurasian plate.

Both the observed local variation in the direction of crustal motion, and the nature of this east-west zone is consistent with transtension increasing from west to east, to culminate beneath the MVZ and northwestern Vatnajokull. The transtensional zone is the modern expression of a complex of colinear microplate boundary elements that has developed since ~ 26 Ma and may include reactivated older spreading centers, transform faults and fracture zones (c.f., Figures 6 and 7). It is orientated at ~ 95˚, which is ~ 10˚ more northerly than the plate direction. This suggests that up to a few km of north-south opening have occurred at its easternmost end beneath northwest Vatnajokull since the development of the EVZ at ~ 2 Ma. The orientations of Plio-Pleistocene and Tertiary dikes indicate that total microplate rotations in Iceland have been small, probably < ~ 10˚. Major seismic activity in south Iceland and volcanic activity at the southern end of the EVZ (Saemundsson, 1979; Einarsson, 1991) suggest that a new, easterly orientated transtensional shear zone is currently developing along the southern edge of the southern (Hreppar) microplate.

7. Discussion

Debate about the Icelandic volcanic province often focuses on the concept of a very localized melt source beneath central Iceland, specifically northwest Vatnajokull, and lateral flow from there at shallow depth, perhaps even as far as the Charlie Gibbs fracture zone. However, this does not account well for many observations, and the large-scale anomaly that extends throughout most of the north Atlantic may well result from dispersed structure and processes rather than radial flow from a highly localised source.

Crustal thickness beneath the entire north Atlantic ocean is ~ 10 km, somewhat thicker than the ~ 7-km global average (Mutter and Mutter, 1993) (Figure 3a). This is consistent with a modest, regional temperature high of 50 – 100˚C that may result from earlier continental insulation by the Laurasian supercontinent (Anderson, 1994b). The whole area is influenced by the Caledonian suture, which extends from northern Scandinavia and Greenland to Newfoundland and central France (Figure 1). Several subduction zones, some of which experienced reversals in polarity, were involved (Dewey and Shackleton, 1984), and thin, buoyant, late-stage subducted plate is likely to have fertilized the upper mantle throughout the region. The thermal relaxation time of oceanic lithosphere is 10 - 20 Myr, and thus in the 440 Myr since subduction the slabs would have achieved complete thermal re-equilibration with the surrounding mantle (Stein and Stein, 1996).The development of varying degrees of partial melt in the more fusible subduced oceanic crust, coupled with the modest temperature anomaly, can account for the ~ 1,000-km-broad upper-mantle seismic wave-speed anomaly (Foulger et al., 2000; Foulger et al., 2001). Up to ~ 0.3% partial melt in the upper ~ 300 km of the mantle, and up to ~ 0.1% beneath this, down to the transition zone, could account for the seismic wave-speed anomalies observed. Extension of the depth range of the melting column is an expected consequence of the increased volatile content and fertility associated with subducted material, and can explain the greater depth range of the seismic anomaly beneath the north Atlantic than beneath the MAR in general (Montagner and Ritsema, 2001).

A model that attributes the local volumetric melt anomaly of the Iceland region to remelting of Caledonian trapped and shallowly subducted slab accounts well for several observations. In the absence of a large temperature anomaly, increased fertility or focusing is required. The presence of recycled subducted crust is a widely accepted model that can explain both ocean island basalt geochemistry (e.g., Hofmann and White, 1980) and the great melt volumes at large igneous provinces that cannot be explained by a peridotic petrology at realistic temperatures (e.g., Cordery et al., 1997). Deep recycling is the conventional interpretation but no lower-mantle seismic anomaly is detected beneath Iceland , and youthful slabs equilibrate at shallow depth, even if very old slabs penetrate deeply. Recycled crustal components of Caledonian age are detected in lavas of the Iceland volcanic province (Korenaga and Kelemen, 2000; Lesher et al., 2003), and the Caledonian orogenic belt encompassed almost the entire north Atlantic igneous province. The melt anomaly, as measured by crustal thickness, is sharply bounded by the Icelandic shelf edge (Figures 2, 3a and 7), and this, along with the correlation between geochemistry and transform zones in the region, suggests shallow, local control of melt extraction rather than deep, broad-scale control.

The possibility that the anomalous melt volume may be derived simply from a relatively shallow fertility anomaly raises some interesting questions:

a) The question of heat: Whereas peridotic systems have been studied exhaustively (e.g., Asimow et al., 2001) details of how eclogite or eclogite-peridotite mixtures melt under conditions of passive adiabatic upwelling is less well understood. What is known is that basalt- or eclogite-rich assemblages can be completely molten at temperatures below the peridotite solidus, and that they will start to melt at greater depths. For a given amount of melt, the thermal requirements of each are about the same except that less specific heat is required to melt the eclogite assemblage. Detailed thermal information that is not yet available is required before heat-balance calculations can be made that indicate whether the full melt thickness at the Iceland volcanic province can be provided by normal, passive, ridge-like upwelling of eclogite-rich mantle alone.

b) The question of homogenization: The degree to which subducted slabs homogenize with the surrounding host mantle is unknown. The results of Yaxley (2000), on which we draw in this paper, correspond to homogenized basalt-peridotite mixtures, not intact slabs. A progressively warming crustal slab embedded in the upper mantle could blend with surrounding mantle by the resorption of eclogitic melt into sub-solidus peridotite before it reached the surface. Such a process has been shown experimentally to occur, and would suppress the extraction of early siliceous melts since these are highly reactive with peridotite (Yaxley and Green, 1998). Solid-state convection at upper mantle Rayleigh numbers is unlikely to be chaotic or turbulent and is therefore not an efficient homogenizer (Meibom and Anderson, 2003).

   Partial melting of efficiently homogenized subducted, eclogitized crust and peridotite may be viewed as one end-member scenario, and the remelting of largely intact eclogite slabs may be viewed as another end member. Extensive melting of such slabs, and ponding and homogenization of the melt can explain the detailed petrology and geochemistry of Icelandic lavas, as discussed in a companion paper (Foulger et al., 2003b).

The unstable jigsaw tectonics that has persistently characterized the Iceland volcanic province can explain several major features. The development of a parallel pair of spreading ridges at ~ 26 Ma captured an intervening block which, if entirely oceanic, contains crust up to ~ 30 Myr old (c.f. Figures 5c and 6a). This block has remained beneath central Iceland to the present day (Figures 6a – e), during which time it has continually been loaded with additional surface lavas and perhaps also thickened by intrusions. It correlates well with the locus of exceptionally thick (> 30 km) crust beneath central Iceland (Figure 3b). This feature, usually interpreted as the center of a plume beneath Iceland, may thus instead, represent a thickened, subsided, captured microplate. This explanation fits the observations better than a plume since the latter predicts a laterally extensive band of equally thick crust extending to the northeast and southwest, parallel to the predicted plume trajectory, which is not observed (Foulger et al., 2003a).

Eastward migration of spreading in Iceland is often cited as evidence in support of an eastward-migrating plume. The palinspastic reconstruction (Figure 6) shows, however that this has not occurred. The regular progression of basalts extending from the NVZ to the east coast, shows that spreading has proceeded about the eastern center since at least ~ 15 Ma (Saemundsson, 1979; Bott, 1985; Jancin et al., 1985) and marine observations suggest that this situation has probably been relatively stable since ~ 26 Ma (Bott, 1985). Spreading about a parallel pair of ridges is unstable and, given the fixed location of the eastern rift relative to the Kolbeinsey ridge, the western rift has been required to re-equilibrate by repeated relocations to the east or else be rafted away with the north American plate. These relocations do not represent an eastward migration of the general locus of melt extraction in the region, which has remained fixed relative to the Kolbeinsey ridge. Indeed, southerly ridge migration is a more prominent characteristic of the Iceland region than easterly migration. The diachronous, V-shaped ridges flanking the Reykjanes ridge have a similar periodicity to rift reorganizations in Iceland and are probably related. The broad distribution of spreading qualifies the Iceland region as a diffuse plate boundary (Zatman et al., 2001).

It is unknown whether the western spreading center relocated further east in single episodes ("jumps") or by gradual propagation of new rift branches from the south, behavior similar to propagating centers on the East Pacific rise. In view of the relative shortness of the new ridges (of the order of the length of one or two spreading centers) and the great thickness of the crust, this may be an ill-posed distinction. However, the net effect seems to have been similar to what occurs on the East Pacific rise, which is to shorten transform offsets, increase the linearity of the active ridge, and raft abandoned ridges away with the plate.

The tectonic history can also explain the observation that the crust beneath western Iceland is thinner than beneath eastern Iceland (Figure 3b). This observation is enigmatic in the context of the southeastward-migrating plume model, since that model predicts thicker crust beneath northwestern Iceland, in the wake of the plume, than beneath eastern Iceland, where the plume has yet to arrive (Foulger et al., 2003a). The tectonic history of Iceland suggests that the eastern spreading center has persistently been dominant compared with the western center, which has experienced at least two rift extinctions and migrations. This suggests that magmatism at the western center has been less than at the eastern center, which would result in thinner crust being formed in the west, and less surface volcanism, which is observed.

The palinspastic reconstruction suggests that the west-east volcanic zone crossing central Iceland is a transtensional zone extending in a fan-shaped manner widening to the east, with opening peaking in the MVZ and the volcano cluster of northwestern Vatnajokull. Up to a few km of north-south opening have occurred at its easternmost end beneath northwest Vatnajokull since the development of the EVZ at ~ 2 Ma. Volcanism will be enhanced where extension is greatest, and this model thus explains the high volcanic rates beneath the MVZ and northwest Vatnajokull without the requirement for an independent, special, local magma delivery system such as a plume.

The unusual jigsaw tectonics of the Iceland region may result from several factors. Structure in the mantle itself, inherited from the Caledonian suture, may have guided the formation of plate boundary and transverse tectonic elements. The region comprises the boundary zone between ocean basins to the north and south that have persistently exhibited contrasting spreading styles. At least two continental microplates, the JMM and the Faeroe microplate, have affected spreading locally, and recent evidence suggests that a third sliver of continental crust may underlie Iceland (Amundsen et al., 2002). The geochemistry of Icelandic lavas suggests that this may be small in volume, but it may nevertheless have been a factor in controlling the surface tectonics of the region. In addition, the great crustal thickness itself has probably influenced surface tectonics. Melt forming in the mantle must be transported upward through at least 30 km of crust before reaching the surface, rather than the 7 km typical of mid-ocean ridges, a factor that in itself is likely to give rise to a broader region of surface volcanism. Similar propagating ridge and jigsaw tectonics occur at Afar (Kidane et al., 2001).

The coupled complex jigsaw tectonics and high magmatic rate may provide mutual positive feedback. Where spreading is shared between parallel rifts, the spreading rate across each is reduced to the level of an ultra-slow-spreading ridge. Such low spreading rates and high eruption rates will maximize the downward advection of volatiles by progressive subsidence of surface lavas (Palmason, 1980). Transtension across easterly orientated zones bounding the ephemeral microplates allows additional leakage of melt and has contributed locally to the building of central volcano edifices that rise up to an additional kilometer higher than the ~ 1 km general elevation of the present-day subaerial basalt shield.

The model proposed here offers an alternative to the plume model, which attributes Iceland to an *ad hoc*, narrow, cylindrical column of hot mantle rising from the deep mantle (Morgan, 1971). It can account for most geological and geophysical observations from the Iceland volcanic province. It requires further testing, but in its present speculative state it nevertheless requires fewer forced explanations and fewer contradictions than a plume model. It reverses the traditional view of cause and effect and represents a profoundly different view of mantle dynamics. Melt extraction is controlled by lithospheric extension and mantle compositional variations related to plate tectonic structures and processes, rather than by hot upwellings from great depth, driven by a second, mode of convection independent of plate tectonics. Many of the key characteristics of the Iceland volcanic province, e.g., large melt volume, ocean-island basalt geochemistry and the lack of evidence for high temperatures and heat flow, are similar to those at other “hotspots” and large igneous provinces. Similar models may thus provide candidate alternative hypotheses for the genesis of other volcanic provinces.

8. Conclusions

1. The plume hypothesis cannot account for several primary observations at the Iceland volcanic province, including the lack of evidence for either a time-progressive volcanic track, high temperatures or a seismic anomaly in the lower mantle.

2. The actual observations in Iceland and the north Atlantic region imply that the Iceland melt extraction anomaly is related to local compositional fertility caused by subducted Caledonian crust in the upper mantle where the MAR crosses a branch of the Caledonian suture. This has resulted in a high local rate of magmatism along a 350-km section of the MAR which has built a ridge of crust 1.5 – 3 times thicker than the regional that traverses the whole north Atlantic. Trace amounts of partial melt in the upper mantle down to the transition zone can explain the seismic anomaly there without high temperatures.

3. The Iceland region has persistently exhibited complex leaky jigsaw tectonics involving a southward-migrating parallel pair of spreading ridges and intervening microplates. Small amounts of transtensional opening along the easterly orientated microplate borders have permitted volcanism in addition to that occurring along the spreading ridges.

4. The tectonic disequilibrium in the Iceland region is associated with local variations in the spreading direction. Eastward-increasing, fan-shaped transtension occurs about a west-east zone traversing central Iceland from the Snaefellsnes peninsula to Vatnajokull. The culmination of extension at the eastern end of this zone can explain the enhanced volcanism in the MVZ and northwest Vatnajokull, traditionally assumed to represent the location of a mantle plume.

5. A captured microplate that is probably mostly or completely of oceanic affinity now underlies central Iceland. It contains oceanic crust up to ~ 30 Myr old, and has been continually loaded with surface lavas up to the present day. It currently forms part of a block with crust up to ~ 40 km thick beneath central Iceland.

6. The locus of spreading in the Iceland region has not migrated east as is often claimed. Instead, a pair of parallel spreading centers has existed since at least 15 Ma and probably since 26 Ma. The easternmost center has remained approximately fixed with respect to the Kolbeinsey ridge. This factor has required the westernmost center to repeatedly jump east to maintain approximate linearity with the Kolbeinsey ridge.

7. The leaky jigsaw tectonics of the Iceland region may reflect structure in the mantle inherited from the Caledonian suture. It may also be related to the high magmatism and thick crust, and the two may provide positive feedback.

8. The model described here provides an alternative to the plume model that is more consistent with a broad suite of observations from the Iceland region. Similar interpretations may be viable for other "hotspots" and volcanic provinces.

9. The opening and closing phases of continental separation and collision that are critical to the Iceland volcanic province are different from the behaviors of mature ridges and zones subducting old crust.

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Figure 1 Closure of the Iapetus ocean at (a) 440 Ma, and (b) 400 Ma, by convergence of Laurentia, Baltica and Avalonia. Arrows: convergence directions; thick lines: faults and orogenic fronts. Black triangles indicate sense of thrust faults. Slabs were subducted beneath Greenland, Baltica and Britain (after Soper et al., 1992). Dashed red line indicates position of MAR that formed at ~ 54 Ma.

Figure 2 Present-day bathymetry of the north Atlantic, showing the Greenland-Iceland-Faeroe bathymetric ridge that which is underlain by crust ~ 30 km thick. Other shallow areas are blocks of stretched continental crust. Thin black line: MAR; thin dashed black lines: extinct ridges; thick lines: faults of the Caledonian suture (Soper et al., 1992); thick dashed line: inferred trend of suture crossing the Atlantic Ocean (Bott, 1987), IVP: Iceland volcanic plateau, CGFZ: Charlie Gibbs fracture zone.

Figure 3 a) Crustal thickness vs. latitude, from a compilation of seismic experiments in Iceland and the north Atlantic (Whitmarsh, 1975; Bunch and Kennett, 1980; Goldflam et al., 1980; Ritzert and Jacoby, 1985; Whitmarsh and Calvert, 1986; Larsen and Jakobsdottir, 1988; Mutter and Zehnder, 1988; Smallwood et al., 1995; Weigel et al., 1995; Kodaira et al., 1997; Kodaira et al., 1998; Navin et al., 1998; Smallwood and White, 1998; Du and Foulger, 1999; Du and Foulger, 2001; Holbrook et al., 2001; Weir et al., 2001; Du et al., 2002; Foulger et al., 2003a), b) Contour map showing the thickness of the crust, defined as the depth to the V_s = 4.2 km/s horizon, from receiver functions (from Foulger et al., 2003a). Grey dots show positions of stations where crustal thicknesses were determined.

Figure 4 a) Solidus and liquidus for fertile peridotite containing varying percentages of average altered oceanic crust. opx: orthopyroxene, ol: olivine (adapted from Yaxley, 2000), b) Relationship between melt fraction F and temperature for fertile peridotite and a mixture of 30% average altered oceanic crust and 70% fertile peridotite. The peridotite line is the parameterisation of McKenzie and Bickle (1988) for normal fertile peridotite, and the crust-peridotite line is an approximate estimate for the bulk composition corresponding to the liquidus minimum of (a). The higher average dF/dT and lower solidus temperature for the mixture results in enhanced melt productivity at a given temperature (derived from data in Yaxley, 2000).

Figure 5 Tectonic evolution of the Iceland region at 54, 44 and 26 Ma, in Mercator projection (from Bott, 1985). Gray: continental crust, heavy solid lines: active plate boundaries, heavy dashed lines: extinct plate boundaries, thin lines: bathymetric contours, FTF: Faeroe transform fault, KR, PRR, RR: Kolbeinsey, proto-Reykjanes, Reykjanes ridges, NVZ: Northern volcanic zone, JMM: Jan Mayen microcontinent, N: Norway, P: pole of rotation of JMM 44 – 26 Ma, numbers: sea floor age in Ma.

Figure 6 Tectonic evolution of Iceland at 15, 10, 7, 2 and 0 Ma. Black lines indicate the boundaries of modeled blocks. The oldest rocks exposed in Iceland are 17 Myr old. Blue: unmodeled oceanic areas, yellow: areas that are part of present-day Iceland but are now covered with later lavas, green: rock currently exposed at the surface, solid, dashed and dotted red lines: active, imminent and extinct plate boundaries, blue lines: inferred position of the 15 Ma isochron, red and black numbers: ages of rock in Myr, red: ages of rocks currently covered with younger lavas, black: ages of surface rocks. Where ages are shown in both black and red, older rock underlies younger surface rock. The extent of rock in a given age range offshore is inferred assuming a spreading rate of 1.9 cm/a about the KR and the RR. On land, the possible age range of rocks in a given block is deduced assuming spreading is equally distributed between parallel spreading center pairs, where these exist. The ages of rocks onland are taken from the literature (Saemundsson, 1979; McDougall et al., 1984; Hardarson et al., 1997; Duncan and Helgason, 1998; Udagawa et al., 1999; Helgason and Duncan, 2001). The positions of the extinct NWF (Northwest Fjords) and SSZ (Snaefellsnes-Skagi zone) rifts are taken from Saemundsson (1979). Other extinct rifts are required by space considerations, given the ages of surface rocks.

Figure 7 Bathymetry of the Greenland-Iceland-Faeroe ridge, along with present-day tectonics of Iceland, in general stereographic projection. SVZ, WVZ, EVZ, MVZ, NVZ: Snaefellsnes, Western, Eastern, Middle and Northern Volcanic Zones, NWF: Northwest Fjords area. TM, HM: the northern (Trollaskagi) and southern (Hreppar) microplates, B: Borgarfjordur area. Thick lines in north: faults of the Tjornes Fracture Zone (TFZ), short, thin lines in south: faults of the South Iceland Seismic Zone, dark grey zones: fissure/dike swarms of presently active spreading spreading segments, white: icecaps, black outlines: active central volcanoes/calderas, black elongate ellipses: Plio-Pleistocene and Tertiary dike swarms (Saemundsson, 1979), arrows: motion relative to points in the NVZ measured using GPS 1987 - 1992 (Hofton and Foulger, 1996). Representative focal mechanisms of earthquakes are shown in lower hemisphere stereographic projections with black compressional quadrants (Bjarnason and

Einarsson, 1991; Einarsson, 1991). The long-lived composite transtensional zone that traverses central Iceland today comprises the SVZ, the Borgarfjordur area of normal-faulting earthquakes in west Iceland, the MVZ and the confluence of this with the NVZ and EVZ in northwest Vatnajokull. Bard: Bardarbunga, Grim: Grimsvotn, star: Gjalp. Volcanism and the size and number of major central volcanoes, increase to the east. Volcanism dwindles beneath eastern Vatnajokull and is extinct at the southeast coast of Iceland (Jóhannesson and Saemundsson, 1998).

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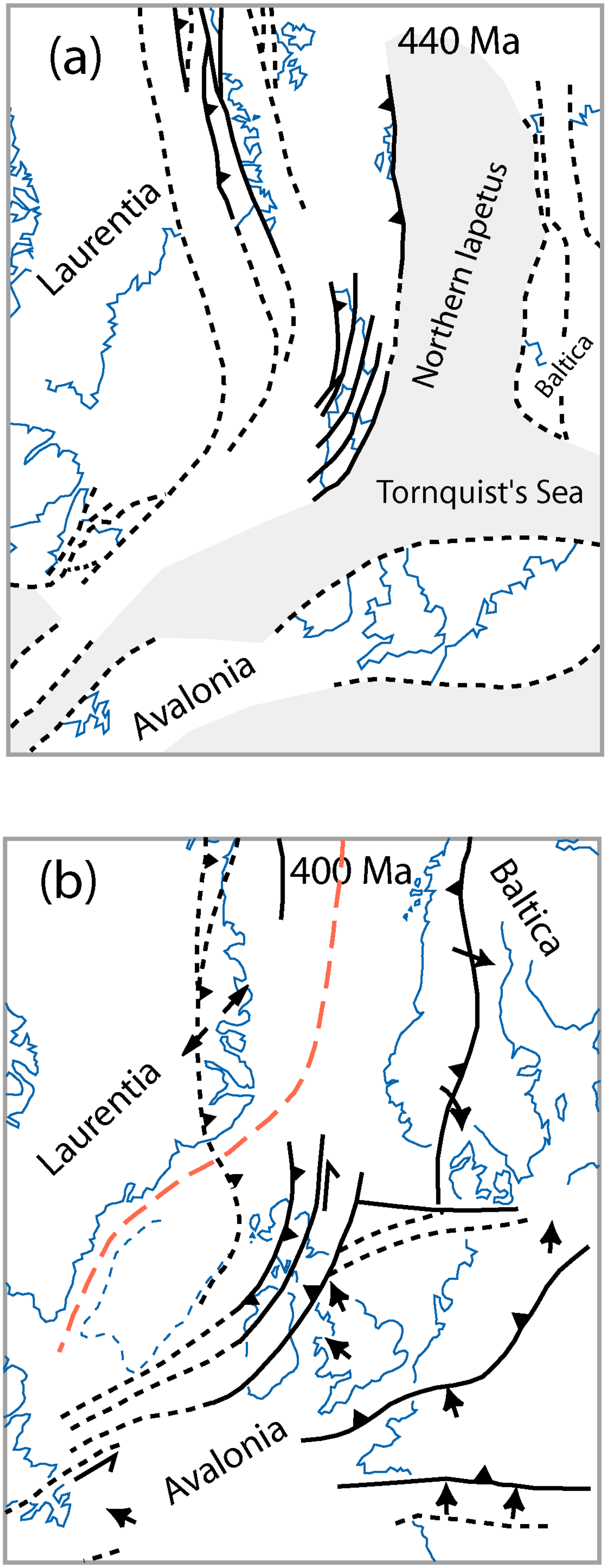
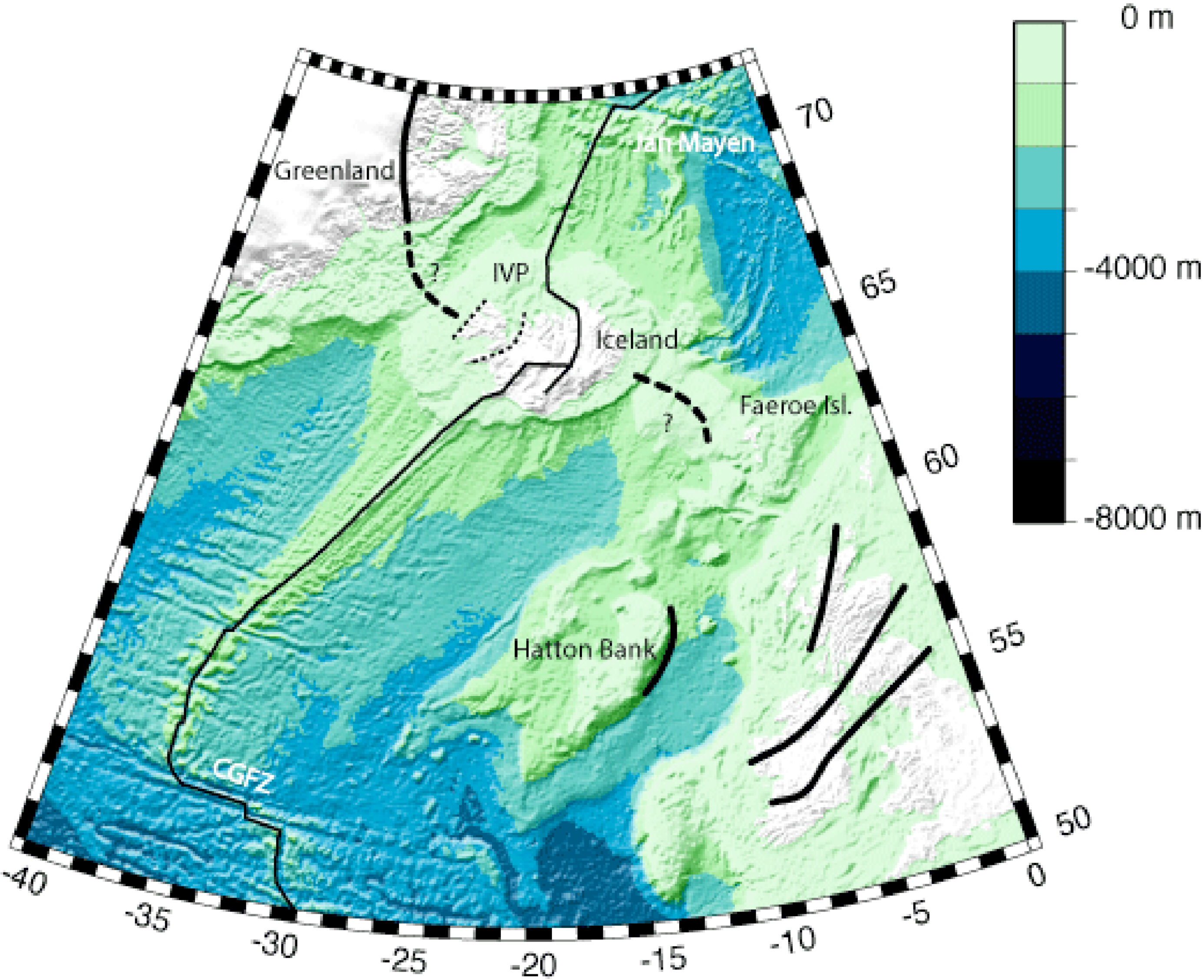

(a)
440 Ma
Laurentia
Northern Iapetus
Baltica
Tornquist's Sea
Avalonia
(b)
400 Ma
Baltica
Laurentia
Avalonia

Figure 1



0 m
-4000 m
-8000 m
70
65
60
55
50
-40
-35
-30
-25
-20
-15
-10
-5
0
Greenland
Jan Mayen
IVP
?
Iceland
Faeroe Isl.
?
Hatton Bank
CGFZ

Figure 2

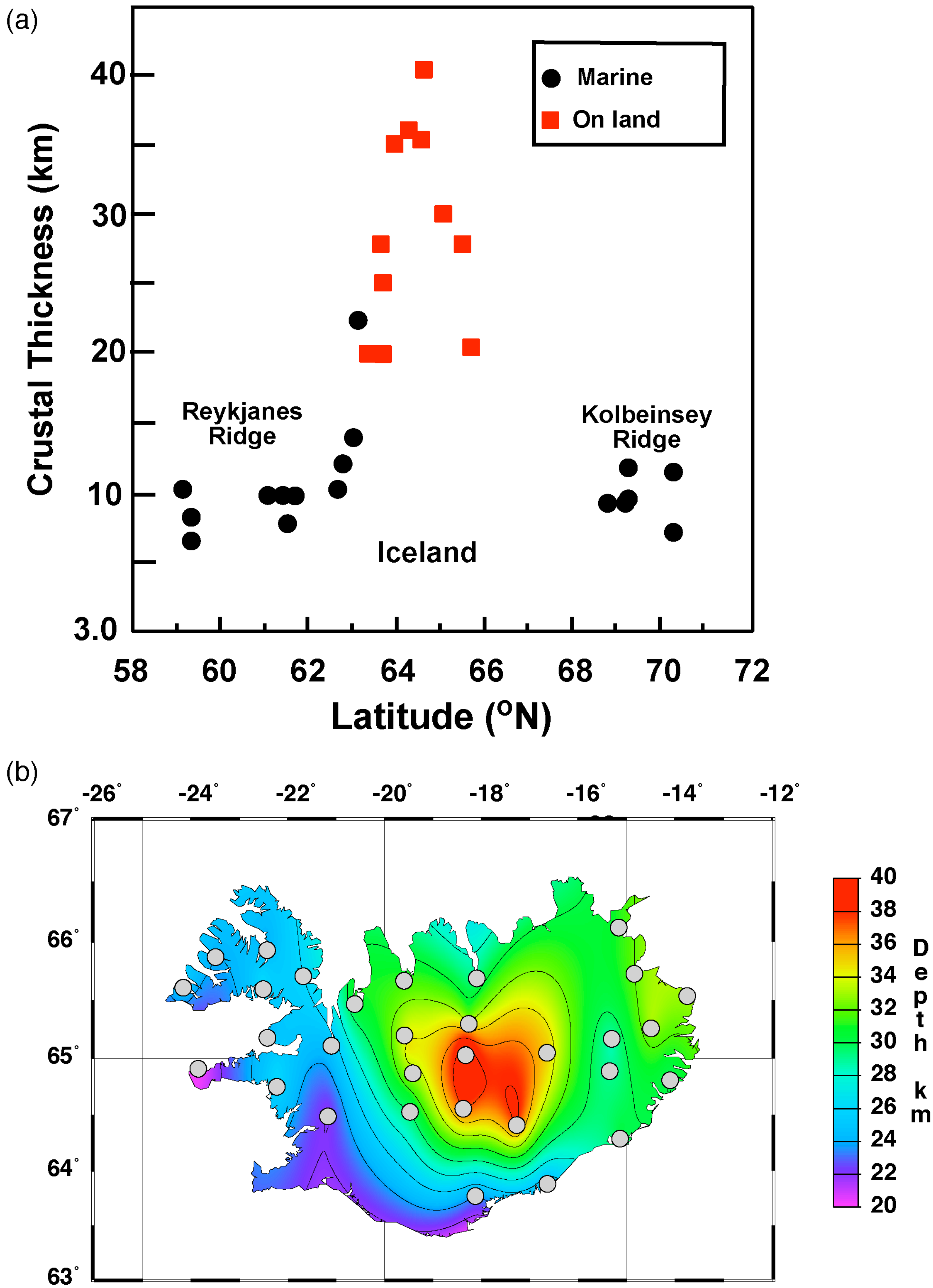

(a)
Crustal Thickness (km)
Latitude (°N)
Marine
On land
Reykjanes Ridge
Kolbeinsey Ridge
Iceland
3.0
10
20
30
40
58
60
62
64
66
68
70
72
(b)
-26°
-24°
-22°
-20°
-18°
-16°
-14°
-12°
67°
66°
65°
64°
63°
Depth km
40
38
36
34
32
30
28
26
24
22
20

Figure 3

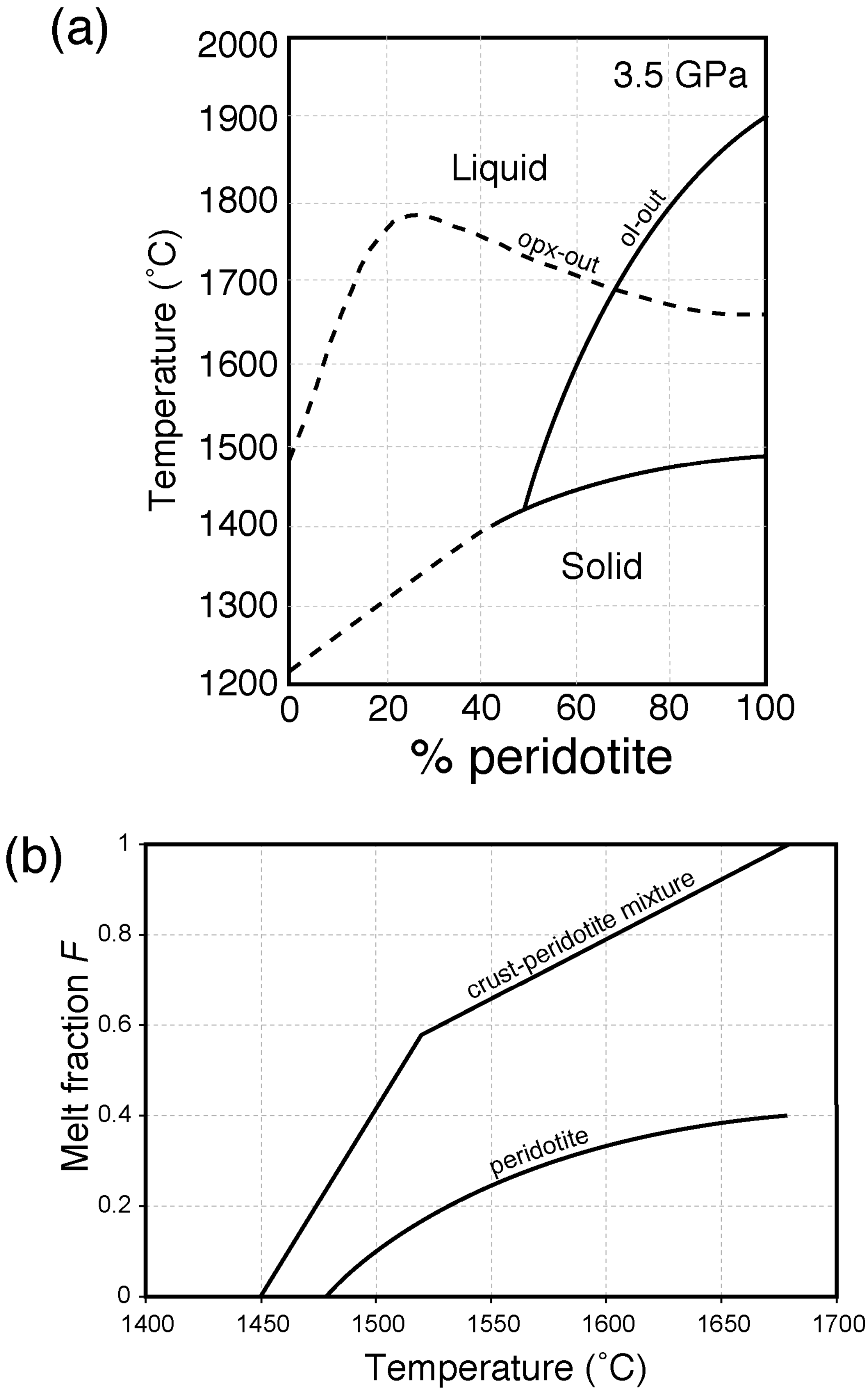

(a)
3.5 GPa
Liquid
ol-out
opx-out
Solid
Temperature (˚C)
2000
1900
1800
1700
1600
1500
1400
1300
1200
0
20
40
60
80
100
% peridotite
(b)
crust-peridotite mixture
peridotite
Melt fraction F
1
0.8
0.6
0.4
0.2
0
1400
1450
1500
1550
1600
1650
1700
Temperature (˚C)

Figure 4

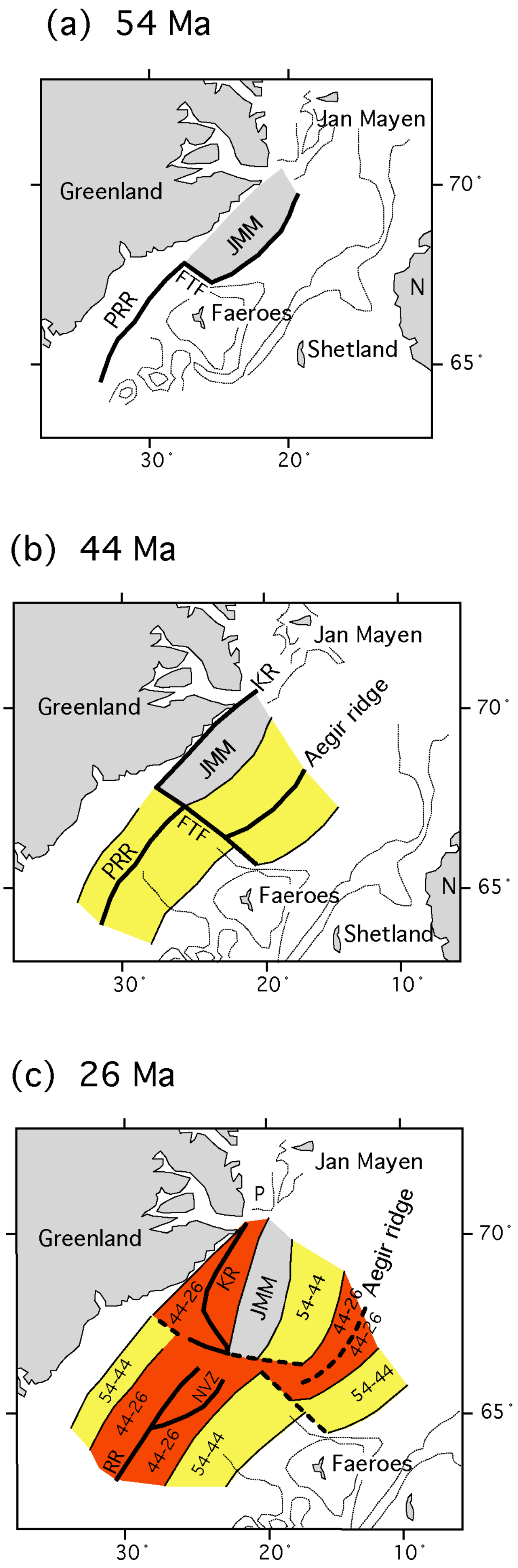

(a) 54 Ma
Jan Mayen
Greenland
JMM
FTF
PRR
Faeroes
N
Shetland
70°
65°
30°
20°
(b) 44 Ma
Jan Mayen
KR
Greenland
Aegir ridge
JMM
FTF
PRR
Faeroes
N
Shetland
70°
65°
30°
20°
10°
(c) 26 Ma
Jan Mayen
P
Greenland
Aegir ridge
KR
JMM
44-26
54-44
NVZ
RR
Faeroes
70°
65°
30°
20°
10°

Figure 5

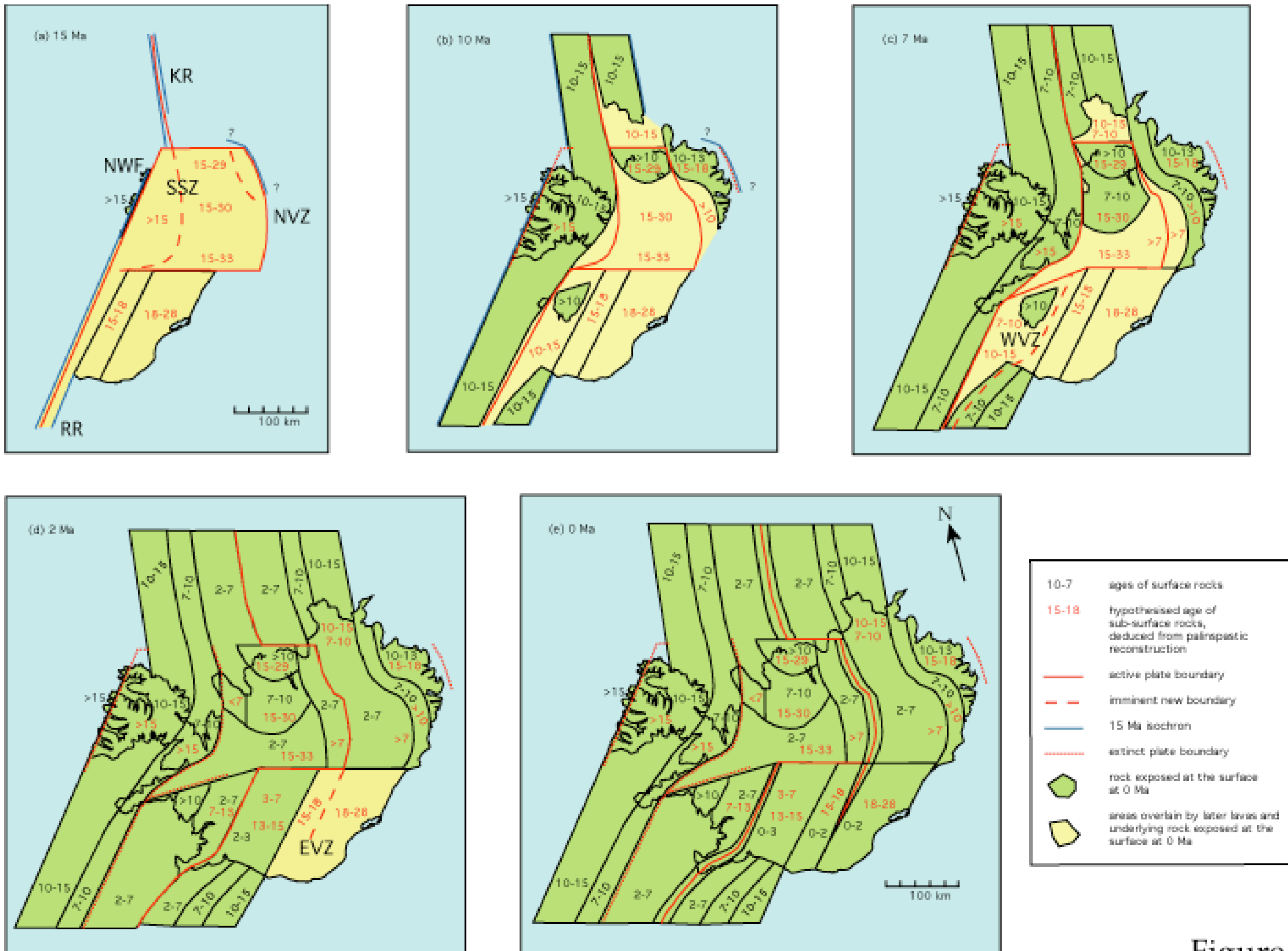

(a) 15 Ma
KR
NWF
SSZ
NVZ
RR
100 km
(b) 10 Ma
(c) 7 Ma
WVZ
(d) 2 Ma
EVZ
(e) 0 Ma
N
10-7 ages of surface rocks
15-18 hypothesised age of sub-surface rocks, deduced from palinspastic reconstruction
active plate boundary
imminent new boundary
15 Ma isochron
extinct plate boundary
rock exposed at the surface at 0 Ma
areas overlain by later lavas and underlying rock exposed at the surface at 0 Ma

Figure 6

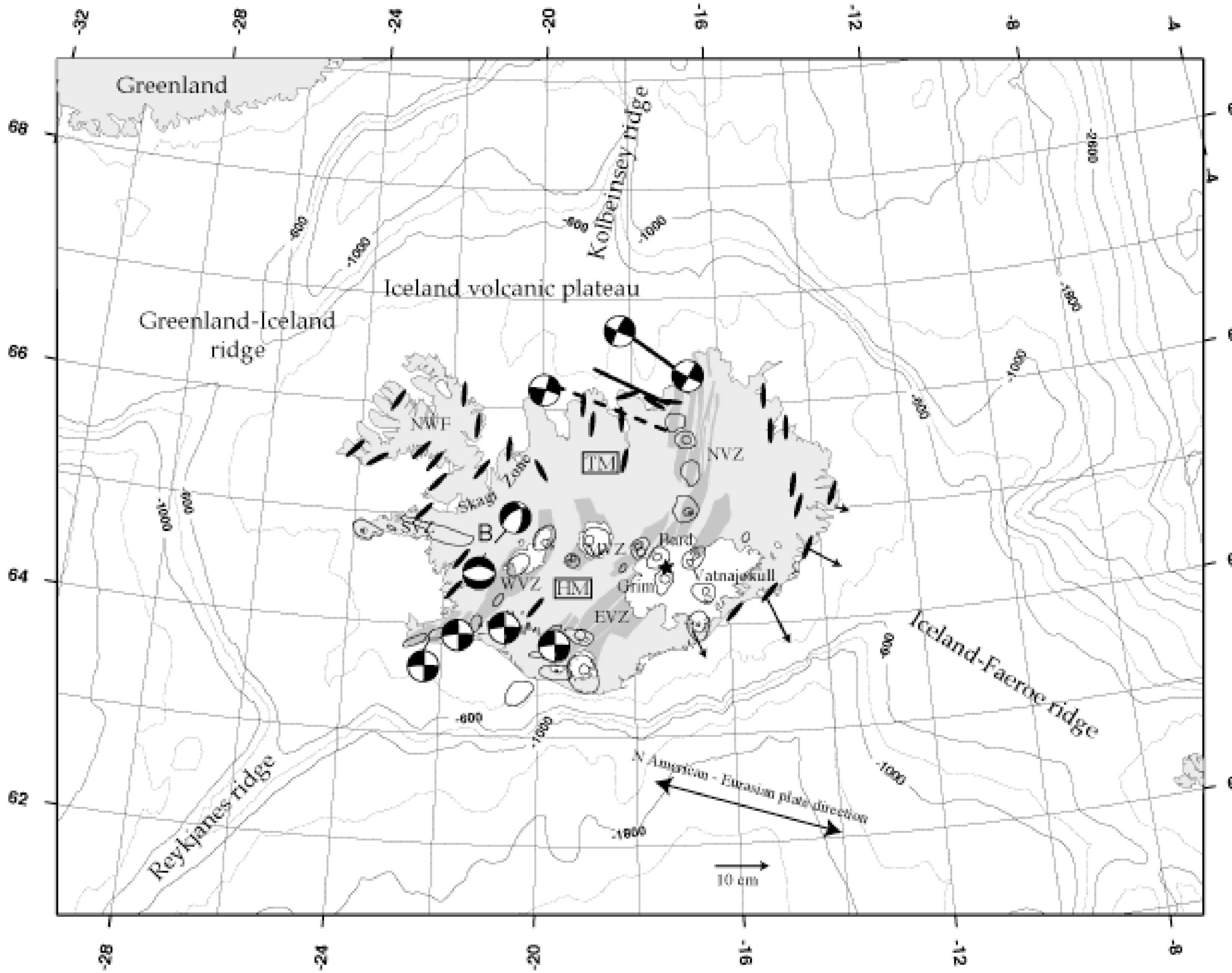

Greenland
Kolbeinsey ridge
Iceland volcanic plateau
Greenland-Iceland ridge
NWF
Skagi
Zone
B
TM
HM
NVZ
WVZ
EVZ
Bard
Grim
Vatnajokull
Iceland-Faeroe ridge
Reykjanes ridge
N American - Eurasian plate direction
10 cm
-2600
-1800
-1000
-600
-32
-28
-24
-20
-16
-12
-8
-4
62
64
66
68

Figure 7