Geophys. J. Int. (2006) **165,** 672–676 doi: 10.1111/j.1365-246X.2006.02941.x

FAST TRACK PAPER

Older crust underlies Iceland

G. R. Foulger

Department of Earth Sciences, University of Durham, Durham, DH1 3LE, *UK. E-mail: g.r.foulger@durham.ac.uk*

Accepted 2006 January 30. Received 2006 January 27; in original form 2004 July 18

SUMMARY

The oldest rocks outcropping in northwest Iceland are ∼16 Myr old and in east Iceland ∼13 Myr. The full plate spreading rate in this region during the Cenozoic has been ∼2 cm a^{-1}, and thus these rocks are expected to be separated by ∼290 km. They are, however, ∼500 km apart. The conclusion is inescapable that an expanse of older crust ∼210 km wide underlies Iceland, submerged beneath younger lavas. This conclusion is independent of any considerations regarding spreading ridge migrations, jumps, the simultaneous existence of multiple active ridges, three-dimensionality, or subsidence of the lava pile. Such complexities bear on the distribution and age of the older crust, but not on its existence or its width. If it is entirely oceanic its maximum age is most likely 26–37 Ma. It is at least 150 km in north–south extent, but may taper and extend beneath south Iceland. Part of it might be continental—a southerly extension of the Jan Mayen microcontinent. This older crust contributes significantly to crustal thickness beneath Iceland and the ∼40 km local thickness measured seismically is thus probably an overestimate of present-day steady-state crustal production at Iceland.

Key words: crust, hotspot, Iceland, microplate, plume.

1 INTRODUCTION

The mid-Atlantic ridge in Iceland comprises several volcanic zones (Fig. 1; Saemundsson 1979). Spreading presently occurs along two parallel zones in south Iceland, the western and eastern volcanic zones (WVZ and EVZ), and along a single zone only, the northern volcanic zone (NVZ), in north Iceland.

The history of spreading in north Iceland is complex. Critical to unravelling the spreading history is radiometric dating of samples, though only the top ∼1 km is accessible to sampling. Two extinct rift zones occur in the west, the Western Fjords Zone, which became extinct at ∼15 Ma, and the Snaefellsnes–Skagi zone, which became extinct at ∼7 Ma. It is commonly stated that spreading in north Iceland always proceeded along a single rift that migrated east, and that the NVZ, therefore, developed at ∼7 Ma. However, this is not correct. Radiometric ages, regional isochrons, unconformities, tectonic relationships, the regional dip of lavas and deformation associated with the Tjörnes Fracture Zone shows that spreading about a proto-NVZ has occurred since at least ∼13 Ma (Saemundsson 1979; Jancin *et al.* 1985, 1995). On the basis of marine magnetic isochrons and the structure of the Icelandic shelf edge Bott (1985) suggests that such spreading started at ∼26 Ma (Fig. 2). Subsequently, the proto-NVZ jumped westwards twice, leaving extinct spreading axes in east Iceland (Fig. 1; Saemundsson 1979). Thus, prior to ∼7 Ma, spreading probably occurred along a parallel pair of volcanic zones in north Iceland, as presently occurs in south Iceland (see Foulger & Anderson 2005; Foulger *et al.* 2005, for detailed reviews). The oldest lavas in eastern Iceland were thus probably erupted from the easternmost ridge and lavas of the same age now outcropping in western Iceland were produced at the ridge in western Iceland.

The oldest rocks outcropping in Iceland occur in the extreme northwest and are ∼16 ± 0.3 Myr old (Moorbath *et al.* 1968; Hardarson *et al.* 1997). In the extreme east, the oldest rocks are ∼12.92 ± 0.14 Myr old (Ross & Mussett 1976). These rocks are separated by up to 500 km measured in the current spreading direction of N105°E (Fig. 1). The full spreading rate at the latitude of Iceland has been ∼2 cm a^{-1} throughout the Cenozoic (Nunns 1983) and at this rate 16 Ma and 13 Ma rocks erupted from a single rift zone would be separated by only ∼290 km of accreted oceanic crust. The additional 210 km of crust must, therefore, have formed earlier and be covered by younger lavas. If it formed symmetrically on both sides of a ridge spreading at a full rate of 2 cm a^{-1} it would have taken ∼10.5 Myr to form. If it formed on one plate only, it would have taken ∼21 Myr to form. Following this reasoning, the maximum age of this older crust is between 26.5 (=16 + 10.5) and 37 (=16 + 21) Myr. It is conceivable that there were complexities associated with local rift jumps prior to the formation of a second active spreading ridge in the north Iceland region. In this case, oceanic crust even older than 37 Ma could be present, but no evidence requires this.

An estimate of the north–south extent of the older crust may be made from the north–south extent of outcropping of the oldest rocks in northwest and east Iceland, which is ∼150 km. Rocks as old as 13 Ma are not known in south Iceland, where the island is narrower

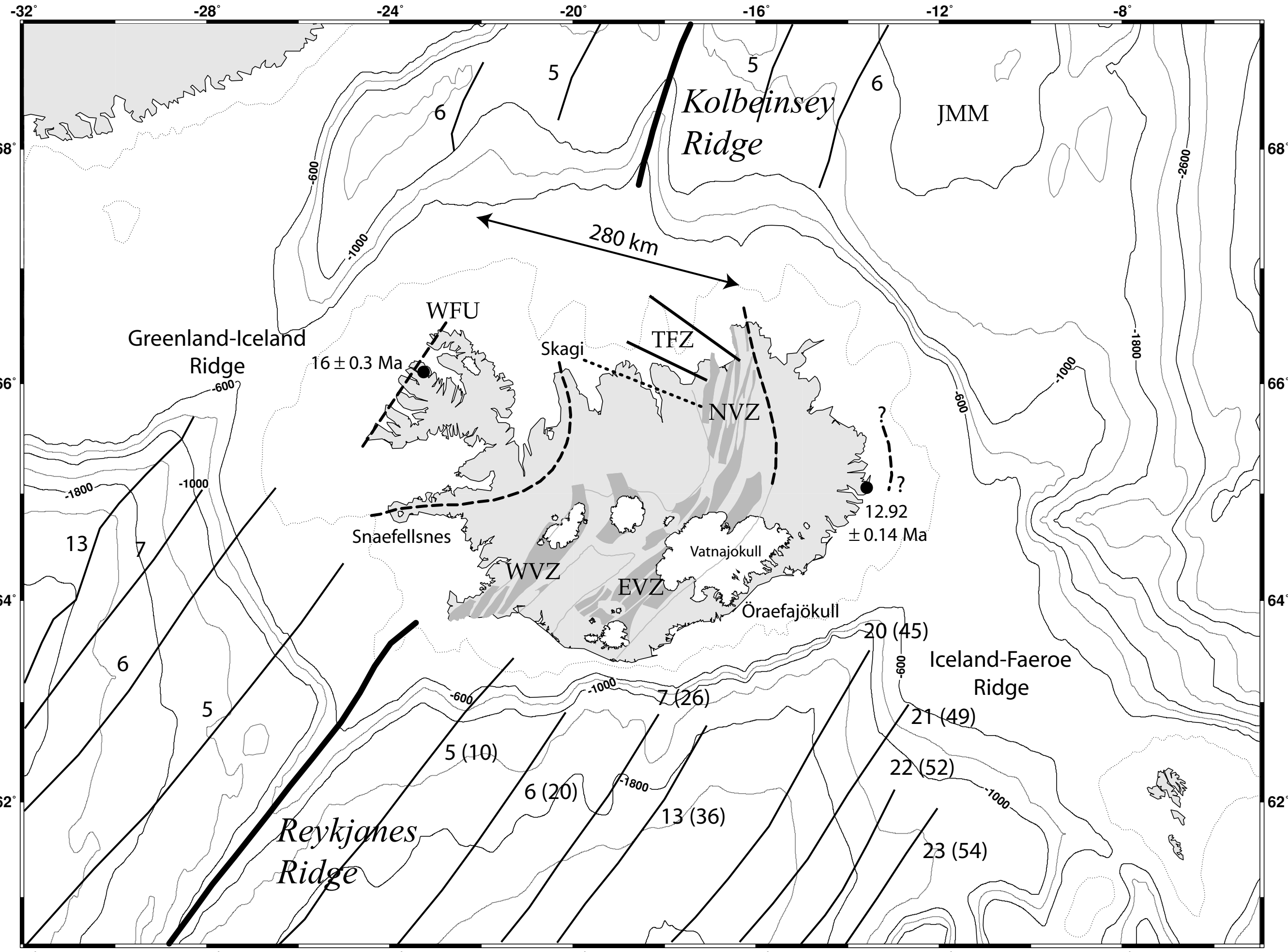

Figure 1. Map of the Iceland region showing bathymetric contours and tectonic features. Oceanic magnetic anomalies (Nunns 1983) are labelled with anomaly number. Approximate ages in Ma are shown in parentheses after the anomaly number on the eastern flank of the Reykjanes ridge. Thick black lines: axes of Reykjanes and Kolbeinsey ridges, thin lines on land: outlines of neovolcanic zones, grey: spreading segments, white: glaciers. WVZ, EVZ, NVZ: Western, Eastern, Northern Volcanic Zones, TFZ: Tjörnes Fracture Zone. Individual faults are shown by lines, dotted where uncertain. Dashed lines: extinct rift zones (two in west Iceland and two in east Iceland), WFU: Western Fjords Unconformity. Lavas northwest of this unconformity formed at an extinct rift that lies offshore. Black dots: locations of rocks dated at 16 ± 0.3 Ma and 12.92 ± 0.14 Ma (Moorbath *et al.* 1968; Ross & Mussett 1976; Hardarson *et al.* 1997). Line with arrowheads: the width of oceanic crust predicted to separate the 16 and 13 Ma isochrons, given a ∼2 cm a^{-1} full spreading rate. This is much less than the distance between the outcrops, measured in the spreading direction. JMM: Jan Mayen microcontinent.

in the spreading direction and the most easterly and westerly regions are covered by young lavas and sediment. However, an estimate of the maximum age of crust there may be made from the width of the island. For example, the distance from the WVZ to the volcano Öraefajökull, measured in the present-day spreading direction, is ∼200 km (Fig. 1). Part of this crust must have been created at the EVZ, which formed at ∼2 Ma. Assuming that subsequent to 2 Ma half the spreading occurred along the EVZ and half along the WVZ, then ∼20 km of crust would have formed at each. Of this, the 20 km that formed along the EVZ, plus the 10 km that formed on the eastern flank of the WVZ, will currently contribute to the crust between the WVZ and Öraefajökull. It then follows that, at this latitude, $200 - 30 = 170$ km formed prior to 2 Ma. If this crust formed on the eastern flank of the WVZ and/or its predecessors in western Iceland (i.e. on one plate) it would have taken ∼17 Myr to form. This suggests that crust at least as old as $17 + 2 = 19$ Ma underlies the Öraefajökull area. This crust is older than the oldest exposed rocks in Iceland, but younger than the minimum age of 26 Ma deduced above for submerged crust beneath north Iceland. The EW width of the older, submerged crust thus probably reduces to the south.

2 DISTRIBUTION AND NATURE OF THE OLDER CRUST

There are two end-member possibilities for the spatial distribution of the older crust:

(a) It forms a coherent oceanic microplate, analogous to the Easter microplate, underlying central Iceland. This possibility is suggested by the plate boundary reconstruction of Bott (1985) (Fig. 2). On the basis of ocean-floor magnetic isochrons and structural arguments, Bott (1985) suggested that at ∼26 Ma, crustal accretion in the region changed from spreading along a single ridge

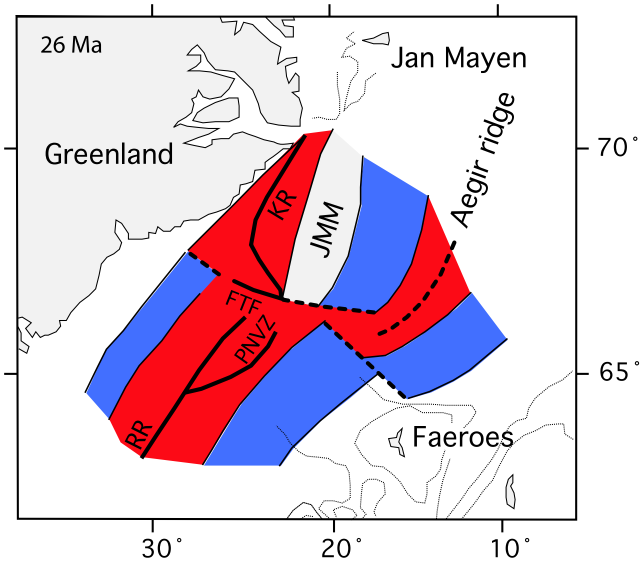

Figure 2. Plate boundary configuration in the Iceland region at 26 Ma, in Mercator projection (from Bott 1985). Light grey: continental crust, blue: oceanic crust aged 54–44 Ma, red: oceanic crust aged 44–26 Ma. Heavy solid lines: active plate boundaries, heavy dashed lines: extinct plate boundaries and transform faults, thin lines: bathymetric contours, KR, RR: Kolbeinsey and Reykjanes ridges, PNVZ: proto-northern volcanic zone, JMM: Jan Mayen microcontinent and FTF: Faeroe transform fault. The Aegir ridge became extinct and the PNVZ formed at ~26 Ma.

to spreading about a parallel pair of ridges. This change may have corresponded to the birth of the proto-NVZ east of a pre-existing spreading ridge. A block of oceanic crust that had formed on the eastern flank of the pre-existing ridge would thus have been 'captured' between the two ridges and subsequently submerged beneath younger subaerial lavas. The original western ridge is now extinct and spreading occurs only along the contemporary NVZ. This model implies that a captured oceanic microplate with crust at least as old as 37 Ma presently lies west of the NVZ and submerged beneath younger lavas (Fig. 1). The observation that variations in age along short lines perpendicular to extinct or active rift zones in west and east Iceland show reasonable agreement between age and distance from the rift zone, given the expected spreading rates, tends to favour this scenario (Saemundsson 1979).

(b) The older crust is widely distributed throughout Iceland. This could be the case if new spreading zones formed within the older crust when ridge jumps occurred. Such jumps occurred in both western and eastern Iceland (e.g. Saemundsson 1979; Helgason 1984; Jancin *et al.* 1985; Foulger 2002, Fig. 1). The older crustal block might then have been repeatedly split.

Scenarios intermediate between (a) and (b) are also possible. The older crust may underlie only the extreme west and east of Iceland. Much of the older crust may form a coherent block beneath central Iceland, with some split off by ridge jumps and now underlying western and/or eastern Iceland.

Some of the older, captured crust might be continental, for example, if the Jan Mayen microcontinent, most of which lies beneath the ocean northeast of Iceland, extended farther south than suggested by Bott (1985; see also Foulger & Anderson 2005 for a comprehensive review of kinematic reconstructions for the Iceland region) (Figs 1 and 2). It is unlikely that a block of continental crust 210 km wide underlies Iceland, because the Jan Mayen microcontinent itself is only 100–150 km wide. Furthermore, such a large mass of continental crust would have a major and widespread influence on the petrology of Icelandic basalts, for example, raising $^{87}Sr/^{86}Sr$ isotope ratios, which is not observed. Nevertheless, evidence for at least some continental crust is provided by elevated $^{87}Sr/^{86}Sr$ and Pb isotope ratios in basalts from Öraefajokull (Prestvik *et al.* 2001).

The Jan Mayen microcontinent may have tapered to the south and not been sharply truncated on its southern boundary as suggested by the reconstruction of Bott (1985), and a thin sliver may have been captured beneath Iceland. In this case, the old Faeroe Transform Fault (Fig. 2) might currently underlie central Iceland, extending from Snaefellsnes across Iceland to Vatnajokull (Fig. 1), rather than underlying the present north coast of Iceland as suggested by Bott (1985). Iceland would then have formed over an old transform fault. The presence of a thin sliver of continental crust beneath south Iceland could in theory be tested by reconstructing the north Atlantic margins at the time of break-up at ~54 Ma. However, a sliver a few tens of kilometres in width might not be detectable given the uncertainty in the locations of the continent–ocean margins.

The requirement for older, submerged crust beneath the younger lavas is in full agreement with the crustal accretion model of Palmason (1973, 1980). This model shows how the volcanic pile subsides beneath the weight of new erupted lavas as crustal accretion proceeds. Lavas may flow for long distances from the rift where they were erupted, and this model shows that lavas observed at the surface are expected to be younger than those beneath. For example, at ~100 km distance from a rift, the surface lavas might be 5 Myr old but those at ~10 km depth might be up to 10 Ma. Nevertheless, the Palmason model cannot explain the 500-km horizontal separation of 13–16 Ma lavas in east and west Iceland without the need for submerged crust older than 16 Ma. In 16 Myr, at a full spreading rate of 2 cm a^{-1}, a swathe of crust only 320 km wide could have formed. Lavas erupted at 16 Ma that flowed for long distances laterally must have flowed over still older crust.

In a simple, theoretical, steady-state, single-rift case, lavas could have flowed great distances to the west and east and all the older crust could lie distally under the extreme west and east of Iceland. However, such a simple, 2-D case does not apply to Iceland, which is known to have experienced multiple rift jumps, extinctions and spreading along pairs of parallel rifts. The older crust is, therefore, almost certainly more widespread beneath Iceland.

An alternative model frequently suggested to dispense with the need for older crust is that spreading occurred along a single, eastward-jumping ridge only, and that the oldest lavas in east Iceland simply flowed further from the active zone than those in the west. The disparity in flow distances would have to be large, however, that is, up to 210 km. (This could be tested by comparing the geochemistry of lavas of equal age in west and east Iceland, or by estimating the distances of flows from their sources from their thicknesses and dips.) This model also provides no explanation regarding why north Iceland is wider than south Iceland. It must be emphasized however that, while such a model would have implications for the spatial distribution of older crust beneath Iceland, neither it nor any variant can remove the requirement for a ~210-km-wide expanse of crust submerged beneath Iceland that is older than any exposed at the surface. This requirement is uniquely constrained by the width of Iceland in the spreading direction. It could only be removed if the full spreading rate in Iceland were locally ~3.4 cm a^{-1}, almost double the ~2 cm a^{-1} measured for the immediately adjacent Reykjanes and Kolbeinsey ridges, a kinematically untenable scenario.

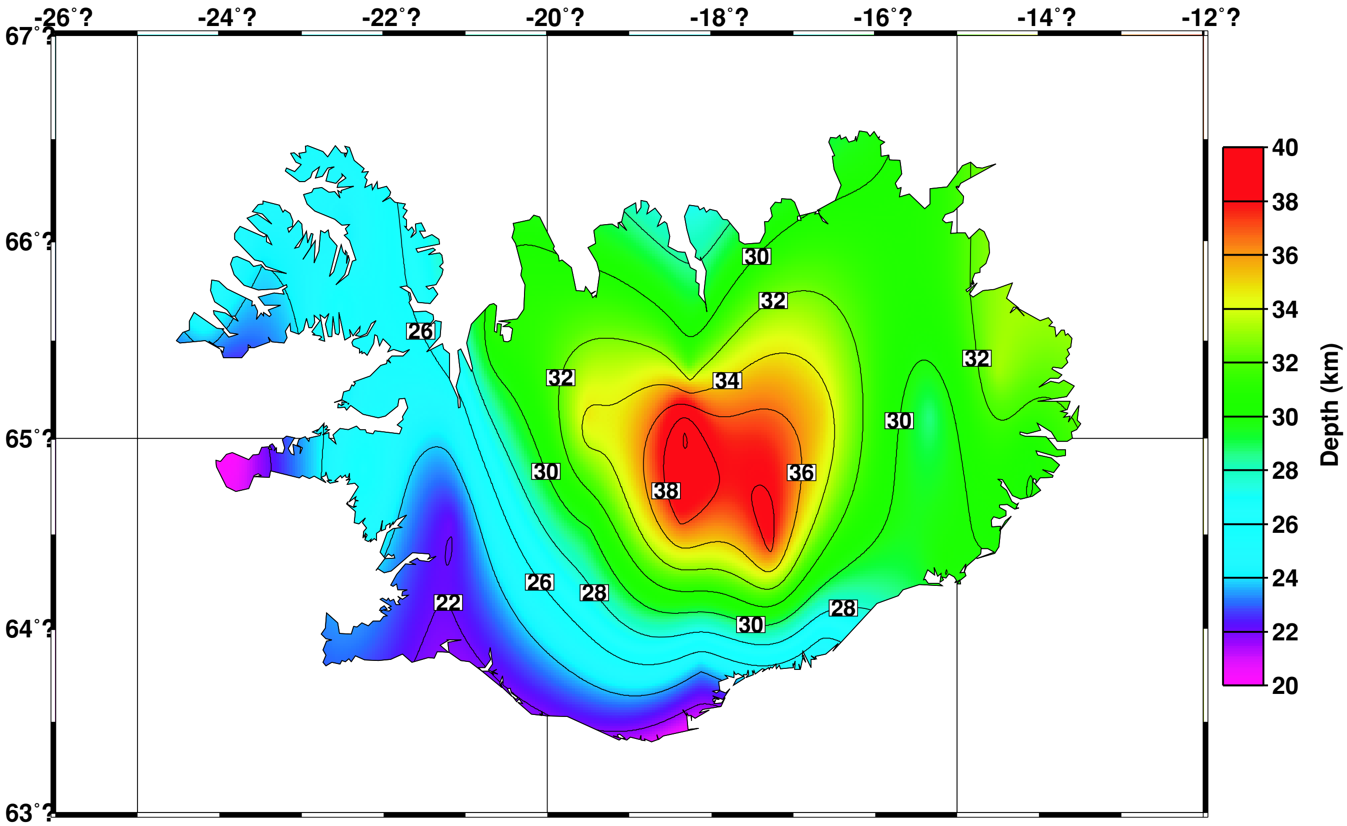

Figure 3. Seismic crustal thickness (defined as the depth to the $Vs = 4.2$ km s^{-1} horizon) from receiver functions (from Foulger *et al.* 2003). The region beneath which the crust is thicker than ~30 km also coincides with an extensive low-velocity layer in the lower crust there. In peripheral areas not well covered by receiver functions, and where low-velocity layers are absent, this model agrees broadly with the results of explosion seismology (e.g. Darbyshire *et al.* 2000).

3 IMPLICATIONS FOR CRUSTAL THICKNESS

A captured block of older crust would contribute significantly to crustal thickness beneath Iceland. If the older crust is oceanic and has a similar thickness to that currently being produced on the Reykjanes ridge (~10 km) and a lateral extent of ~210 × 150 km (31 500 km^2), then it has a volume of ~3.15 × 10^5 km^3. Continuation of the captured crust beneath south Iceland would increase this estimate, and a smaller thickness would reduce it. Recent estimates of ~4 km for the thickness of crust formed at the Aegir ridge at ~26 Ma (N. Kusznir, personal communication, 2004) would reduce the volume estimate to ~1.26 × 10^5 km^3.

Despite numerous detailed seismic studies, or perhaps because of them, the thickness and nature of the crust beneath Iceland is still enigmatic. The thickness of the layer with crust-like seismic wave speeds varies from ~15 km beneath the shelf off the southwest coast (Weir *et al.* 2001) to ~40 km beneath central Iceland (Foulger *et al.* 2003, Fig. 3; see this paper also for a detailed review of the Icelandic crust). This layer may be all crust but it is also possible that beneath ~15 km depth it is mantle or a crust–mantle mixture (see Björnsson *et al.* 2005, for a review).

The layer is exceptionally thick—30–40 km (average 35 km)—beneath an area ~20 000 km^2 in size in central Iceland. The volume in excess of 30 km deep is thus ~20 000 × 5 = 10^5 km^3 and could thus all be accounted for by older, captured crust. This suggests that, if the low-wave-speed layer is crust, then current production at the ridge by ongoing processes is only ~30 km thickness, and not ~40 km as is sometimes assumed in models of magma genesis at Iceland. Such a conclusion is consistent with seismic crustal thickness estimates of ~30 km for the adjacent Iceland-Faeroe and Iceland-Greenland ridges (Bott & Gunnarsson 1980; Richardson *et al.* 1998; Smallwood *et al.* 1999; Holbrook *et al.* 2001). Regardless of whether the layer in general is crust, mantle or a mixture, the presence of a submerged microplate could account for the observation of an extensive low-velocity zone below ~10 km depth beneath central Iceland (Du & Foulger 2001; Foulger *et al.* 2003) since submerged oceanic or continental crust would contain relatively low-velocity components. Knowledge of the true magmatic production rate at Iceland is critical to the current debate regarding the cause of this melting anomaly (Foulger & Natland 2003).

4 CLOSING REMARKS

Understanding the tectonic evolution of Iceland and the magmatic production rate are vital components of understanding why it exists. The fact that the landmass is shrouded in young lavas is a hindrance to discovering answers but cannot conceal the fact that significant questions remain unanswered. These include the nature and composition of the lower crust, whether some continental crust underlies the island, the distribution of crust older than 16 Ma, the history of rift migrations and microplate evolution, the tectonic evolution of the complex region west of the NVZ, the nature of the Snaefellsnes–Vatnajokull transverse volcanic zone and why Iceland is narrower in the south than in the north. The challenge to earth scientists is to design experiments that have the power to cast light on these problems.

ACKNOWLEDGMENTS

This research was supported by Natural Environment Research Council (NERC) grant GR3/10727 and a Sir James Knott Foundation fellowship held by GRF. The ideas were matured by discussions with Mark Jancin and Warren Hamilton and this paper was precipitated by a debate with Godfrey Fitton. It was improved in response to reviews by Peter Vogt, Axel Björnsson and an anonymous reviewer.

REFERENCES

Björnsson, A., Eysteinsson, H. & Beblo, M., 2005. Crustal formation and magma genesis beneath Iceland: magnetotelluric constraints, in *Plates, Plumes, and Paradigms*, pp. 665–686, eds Foulger, G.R., Natland, J.H., Presnall, D.C. & Anderson, D.L., Geological Society of America.

Bott, M.H.P., 1985. Plate tectonic evolution of the Icelandic transverse ridge and adjacent regions, *J. geophys. Res.,* **90,** 9953–9960.

Bott, M.H.P. & Gunnarsson, K., 1980. Crustal structure of the Iceland-Faeroe ridge, *J. Geophys.,* **47,** 221–227.

Darbyshire, F.A., White, R.S. & Priestley, K.F., 2000. Structure of the crust and uppermost mantle of Iceland from a combined seismic and gravity study, *Earth planet. Sci. Lett.,* **181,** 409–428.

Du, Z.J. & Foulger, G.R., 2001. Variation in the crustal structure across central Iceland, *Geophys. J. Int.,* **145,** 246–264.

Foulger, G.R., 2002. Plumes, or plate tectonic processes?, *Astron. Geophys.,* **43,** 6.19–6.23.

Foulger, G.R. & Natland, J.H., 2003. Is 'hotspot' volcanism a consequence of plate tectonics? *Science,* **300,** 921–922.

Foulger, G.R. & Anderson, D.L., 2005. A cool model for the Iceland hot spot, *J. Volc. geotherm. Res.,* **141,** 1–22.

Foulger, G.R., Du, Z. & Julian, B.R., 2003. Icelandic-type crust, *Geophys. J. Int.,* **155,** 567–590.

Foulger, G.R., Natland, J.H. & Anderson, D.L., 2005. A source for Icelandic magmas in remelted Iapetus crust, *J. Volc. geotherm. Res.,* **141,** 23–44.

Hardarson, B.S., Fitton, J.G., Ellam, R.M. & Pringle, M.S., 1997. Rift relocation—a geochemical and geochronological investigation of a palaeo-rift in northwest Iceland, *Earth planet. Sci. Lett.,* **153,** 181–196.

Helgason, J., 1984. Frequent shifts of the volcanic zone in Iceland, *Geology,* **12,** 212–216.

Holbrook, W.S. *et al.*, 2001. Mantle thermal structure and active upwelling during continental breakup in the north Atlantic, *Earth planet. Sci. Lett.,* **190,** 251–266.

Jancin, M., Young, K.D., Voight, B., Aronson, J.L. & Saemundsson, K., 1985. Stratigraphy and K/Ar ages across the west flank of the northeast Iceland axial rift zone, in relation to the 7 Ma volcano-tectonic reorganization of Iceland, *J. geophys. Res.,* **90,** 9961–9985.

Jancin, M., Young, K.D., Voight, B. & Orkan, N.I., 1995. Dikes, minor faults and mineral veins associated with a transform-fault in North Iceland - Discussion, *J. Str. Geol.,* **17,** 1627–1631.

Moorbath, S., Sigurdsson, H. & Goodwin, R., 1968. K-Ar ages of the oldest exposed rocks in Iceland, *Earth planet. Sci. Lett.,* **4,** 197–205.

Nunns, A.G., 1983. Plate tectonic evolution of the Greenland-Scotland ridge and surrounding regions, in *Structure and Development of the Greenland-Scotland Ridge*, pp. 1–30, eds Bott, M.H.P., Saxov, S., Talwani, M. & Thiede, J., Plenum Press, New York and London.

Palmason, G., 1973. Kinematics and heat flow in a volcanic rift zone, with application to Iceland, *Geophys. J. R. astr. Soc.,* **33,** 451–481.

Palmason, G., 1980. A continuum model of crustal generation in Iceland; kinematic aspects, *J. Geophys.,* **47,** 7–18.

Prestvik, T., Goldberg, S., Karlsson, H. & Gronvold, K., 2001. Anomalous strontium and lead isotope signatures in the off-rift Oraefajokull central volcano in south-east Iceland. Evidence for enriched endmember(s) of the Iceland mantle plume?, *Earth planet. Sci. Lett.,* **190,** 211–220.

Richardson, K.R., Smallwood, J.R., White, R.S., Snyder, D.B. & Maguire, P.K.H., 1998. Crustal structure beneath the Faroe Islands and the Faroe-Iceland Ridge, *Tectonophysics,* **300,** 159–180.

Ross, J.G. & Mussett, A.E., 1976. ^{40}Ar/^{39}Ar dates for spreading rates in eastern Iceland, *Nature,* **259,** 36–38.

Saemundsson, K., 1979. Outline of the geology of Iceland, *Jokull,* **29,** 7–28.

Smallwood, J.R., Staples, R.K., Richardson, K.R. & White, R.S., 1999. Crust generated above the Iceland mantle plume: from continental rift to oceanic spreading center, *J. geophys. Res.,* **104,** 22 885–22 902.

Weir, N.R.W., White, R.S., Brandsdottir, B., Einarsson, P., Shimamura, H. & Shiobara, H., 2001. Crustal structure of the northern Reykjanes ridge and Reykjanes peninsula, southwest Iceland, *J. geophys. Res.,* **106,** 6347–6368.