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Journal of Volcanology and Geothermal Research 141 (2005) 23–44
Journal of volcanology and geothermal research
www.elsevier.com/locate/jvolgeores

A source for Icelandic magmas in remelted Iapetus crust

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Received 23 July 2003; accepted 13 October 2004

Abstract

The geochemistry and large melt volume in the Iceland region, along with the paucity of evidence for high, plume-like temperatures in the mantle source, are consistent with a source in the extensive remelting of subducted Iapetus crust. This may have been trapped in the Laurasian continental mantle lithosphere during continental collision in the Caledonian orogeny at ~420–410 Ma, and recycled locally back into the asthenosphere beneath the mid-Atlantic ridge by lithospheric delamination when the north Atlantic opened. Fractional remelting of abyssal gabbro can explain the major-, trace- and rare-earth-element compositions, and the isotopic characteristics of primitive Icelandic tholeiite. An enriched component already present in the recycled crustal section in the form of enriched mid-ocean-ridge basalt, alkalic olivine basalt and/or related differentiates could contribute to the diversity of Icelandic basalts. Compositions ranging from ferrobasalt to olivine tholeiite are produced by various degrees of partial melting in eclogite, and the crystallization of ferrobasalt as oxide gabbro, i.e., containing the magmatic Fe–Ti oxide minerals, ilmenite and magnetite, may explain the anomalously high density of the Icelandic lower crust. The very high $^{3}He/^{4}He$ ratios observed in some Icelandic basalts may derive from old helium preserved in U+Th-poor residual Caledonian oceanic mantle lithosphere or olivine-rich cumulates in the crustal section. The persistence of anomalous volcanism at the mid-Atlantic ridge in the neighborhood of Iceland suggests that in the presence of lateral ridge migration, the shallow fertility anomaly must be oriented transverse to the mid-Atlantic ridge. The Greenland–Iceland–Faeroe ridge is co-linear with the western frontal thrust of the Caledonian collision zone, which may thus be associated with the fertility source. The fertile material beneath the Iceland region must lie at a steep angle or be thickened by deformation or imbrication to supply the large volumes of basalt required to build the thick crust there. “Hot spot” volcanism and large-igneous-province emplacement often occurs within or near to old suture zones and similar processes may thus explain anomalous magmatism elsewhere that is traditionally attributed to plumes.

Keywords: Iceland; plume; hotspot; plate tectonics; recycled crust

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0377-0273/$ - see front matter
doi:10.1016/j.jvolgeores.2004.10.006

1. Introduction

The Greenland–Iceland–Faeroe ridge comprises a belt of anomalously thick crust that varies from ~250 to 600 km in north–south extent and spans the entire North Atlantic ocean (Fig. 1a). It formed as a result of chronic, locally enhanced magmatism at the mid-Atlantic ridge (MAR). The typical seismic crustal thickness of ~30 km (Foulger et al., 2003) suggests that melt has been extracted at a rate up to three times greater than on the neighboring Kolbeinsey and Reykjanes ridges, where the seismic crust is only ~10 km thick (Foulger et al., 2003). This large-volume melting anomaly is usually explained as the result of a hot mantle plume.

Foulger and Anderson (in press) describe several primary geophysical and tectonic observations from the Iceland region that require special adaptions of the classical plume model, thereby detracting from its credibility. These include the geographical distribution

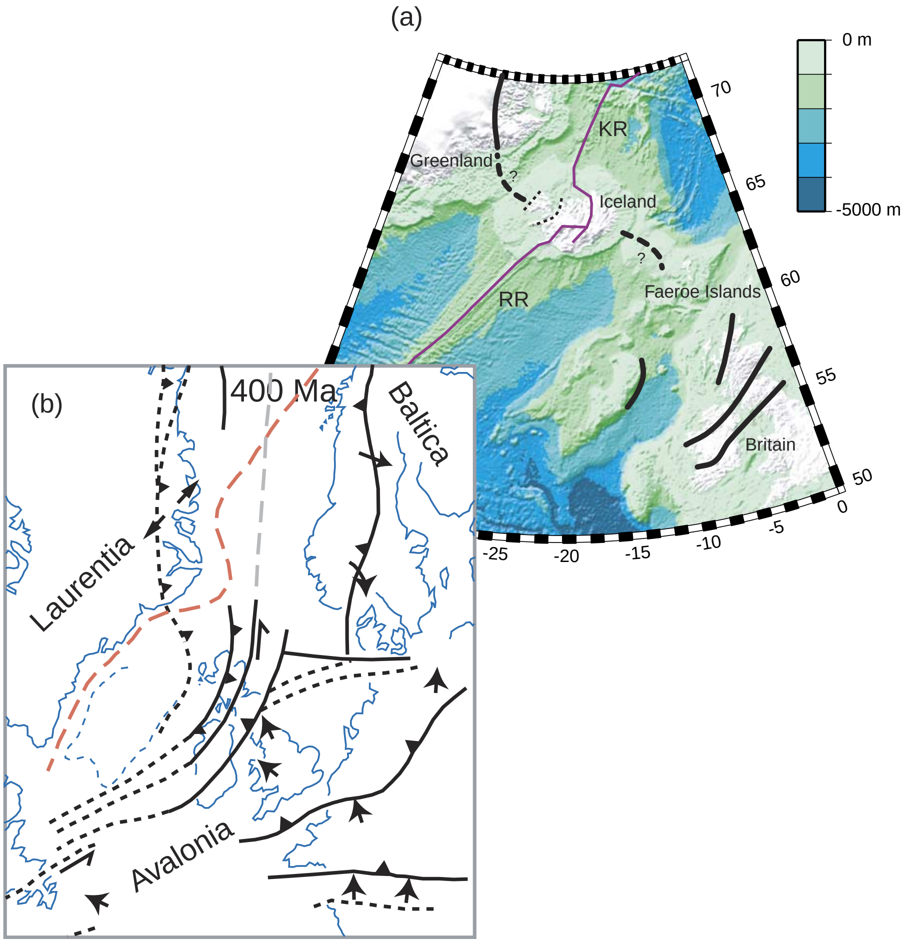

Fig. 1. (a) Bathymetry of the North Atlantic, showing the Greenland–Iceland–Faeroe bathymetric ridge which is underlain by crust with a seismic thickness of ~30 km. Other shallow areas are blocks of stretched continental crust. Thin black line: MAR; thin dashed black lines: extinct ridges; thick lines: faults of the Caledonian collision belt (Soper et al., 1992); thick dashed line: inferred trend of the western Caledonian frontal thrust crossing the Atlantic Ocean (Bott, 1985). RR: Reykjanes Ridge, KR: Kolbeinsey Ridge (adapted from Foulger and Anderson, in press). (b) Closure of the Iapetus Ocean at 420–410 Ma by convergence of Laurentia, Baltica and Avalonia. Arrows: convergence directions; thick lines: faults and orogenic fronts, gray dashed line: inferred line of the Caledonian suture. Black triangles indicate sense of thrust faults and fronts. Slabs are thought to have been subducted beneath Greenland, Baltica and Britain. Bold dashed line: inferred line of opening of MAR at ~54 Ma (from Soper et al., 1992; Skogseid et al., 2005; Roberts, 2003).

of melt, complex tectonics, colinearity with the frontal thrust of the Caledonian collision belt, the paucity of evidence for elevated temperatures and the lack of a seismic anomaly in the lower mantle. They propose alternatively that the enhanced melt production may result from remelting recycled, eclogitised subducted Iapetus oceanic crust. Such crust may have been trapped in the continental mantle lithosphere of the Laurasian supercontinent when it formed through collision of the continents of Laurentia, Baltica and Avalonia at 420–410 Ma. This collision created the Caledonian orogenic belt (Fig. 1b). The Laurasian supercontinent broke up again at ~54 Ma when the North Atlantic began to form. At this time, continental lithosphere fertilised by crust trapped during the earlier continental suturing may have delaminated and been recycled into the asthenosphere that now underlies the North Atlantic. In the future neighborhood of Iceland, the new MAR crossed the western frontal thrust of the Caledonian collision belt approximately orthogonally. This configuration may have resulted in anomalously fertile upper mantle being available at the ridge at this latitude for an exceptionally long time, and much longer than to the north and south, where the proto-MAR formed more nearly longitudinally along the Caledonian suture.

In the present paper we examine whether the geochemistry of Icelandic basalts is consistent with such a model. Schilling (1973) suggested that the anomalous geochemistry along the Reykjanes and Kolbeinsey ridges and in Iceland was due to the deep mantle plume that had been proposed by Morgan (1971) to underlie Iceland. This hypothesis experienced complications. The comparative geographical extents and amplitudes of some of the geochemical anomalies are the reverse of what is expected in relation to similar anomalies around the Azores. That region is also proposed to be underlain by a plume, but the melt anomaly there is much smaller than at Iceland (Schilling et al., 1983). The compositions of Icelandic lavas cannot be explained by the original two source “components” (mantle peridotite and an enriched “plume” component) suggested by Schilling (1973). Different studies advocate different numbers and combinations of a suite of components proposed (e.g., Stracke et al., 2003), including North Atlantic depleted mantle, fertile peridotite, both “enriched” and “depleted” plume components, and an additional component to explain high helium isotope ratios observed in Iceland. The expected radial symmetry about central Iceland of geochemical signatures attributed to a plume (e.g., Condomines et al., 1983; Schilling et al., 1983) is not observed, geochemical discontinuities occur across relatively minor structures such as the 120-km-long Tjornes Fracture Zone in north Iceland, and the temperatures of the most primitive Icelandic melts are similar to those calculated for mid-ocean ridge basalts (e.g., Breddam, 2002).

The calculated compositions of parental melts, concentrations of trace- and rare-earth elements (REE) and the ratios of radiogenic isotopes have been interpreted as indicating a contribution from remelted ocean crust of Caledonian age to the compositions of basalts from Iceland and Britain (Chauvel and Hemond, 2000; Korenaga and Kelemen, 2000; Breddam, 2002; McKenzie et al., 2004). Subducted slabs are not homogenous, but include sediments, altered basaltic upper crust, gabbroic lower crust, and depleted lithospheric mantle. The crustal part includes normal mid-ocean-ridge basalt (N-MORB), enriched MORB (E-MORB), alkalic olivine basalt (AOB) and related differentiates such as occur on spreading ridges and nearby seamounts today. Such a variety of source material, combined with recycling and remelting of the subsiding Icelandic crust itself (Oskarsson et al., 1982) may account for both the petrological and geochemical variability of Icelandic basalts, and their exceptionally large volume.

We do not argue that the geochemistry of Iceland is inconsistent with contemporary plume theory. Variants of plume model have already been developed to accommodate each new observation as it has been made (Foulger and Natland, 2003; Foulger and Anderson, in press). Instead we build on the alternative model suggested by Foulger and Anderson (in press) and show that the geochemistry of both primitive and differentiated Icelandic tholeiites is consistent with extensive melting of a complete section of subducted oceanic crust in the eclogite facies. We conclude that extensive melting of such a source can explain the Iceland melting anomaly in the Iceland region without the requirement for either high temperatures or a deep mantle source, evidence for which is sparse. The derivation of up to 30 km of melt from remelting of ~7-km-thick crust would require that essentially intact subducted slabs dip steeply or are imbricated, or that melt from distributed, refertilised mantle peridotite is extracted.

2. Continental collisions and the fate of subducted slabs

The formation of ocean crust with normal thickness, uniform spreading at ridges and the subduction of old, dense lithosphere to at least the base of the upper mantle are aspects of steady-state plate tectonics that may not characterize the opening and closing stages of oceans. The opening stage is often associated with bursts of magmatism that build seaward-dipping reflectors, thick sequences of flood basalts and large igneous provinces. Lateral temperature gradients, edge-driven convection, and the extraction of melt from exceptionally large depths may be important (Mutter and Zehnder, 1988; King and Anderson, 1995, 1998; Boutilier and Keen, 1999). When continental break-up occurs along old collision belts, as it did in the North Atlantic, magmatism may be further enhanced by mantle made unusually fertile and fusible by eclogitised subducted oceanic crust trapped in the lithosphere.

The final oceanic lithosphere consumed when oceans close may be young, thin, and hot near ridges and beneath back-arc basins, as commonly occurs at the present-day (Meibom and Anderson, 2003). Such lithosphere is buoyant, evidence for which is found in the obduction of ophiolites during the terminal stages of continental collision, and flat subduction of young lithosphere. Both low-angle subduction observed tomographically for young lithosphere, and thermal modelling, suggest that if oceanic lithosphere is younger than ~50 My it may sink no deeper than a few 100 km (Oxburgh and Parmentier, 1977). At a half-spreading rate of 1 cm/year, this might apply to as much as 500 km of plate. Much young subducted lithosphere, including ocean crust, could thus be retained in the shallow mantle, along with mantle wedge material and dehydration fluids. Old, thick, cold lithosphere probably sinks to much greater depths.

Where might this material reside? A length of the final subducting lithosphere equivalent to the thickness of the colliding cratons, or up to ~150–200 km (Polet and Anderson, 1995), might be trapped between them and retained in the continental lithosphere. Buoyant oceanic lithosphere subducted beneath this, perhaps up to several 100 km depth, might be retained in the asthenosphere as flat slabs beneath collision belts. Slabs dip at angles of several tens of degrees and thus may underlie extensive areas that are considerable distances from the surface trace of the suture in a down-dip direction (Fig. 1b).

The formation of the Caledonian suture at ~420–410 Ma involved the unusual collision of three continents. Laurentia and Baltica collided in an east–west direction, closing the Iapetus ocean between them, and northerly drifting Avalonia docked against their southern borders when Tornquist's sea closed (Dewey and Shackleton, 1984; Soper et al., 1992) (Fig. 1b). This supercontinent broke up again at ~54 Ma when the new MAR formed. The northern part of the MAR ran approximately longitudinally along the Caledonian collision zone. In the area where the Iceland volcanic region later formed, however, the MAR crossed the western frontal thrust, which extends from east Greenland to Britain, and formed a new rift within the continental lithosphere of Greenland outside the Caledonian collision belt.

High rates of magmatism for the first few My built volcanic margins with sequences of basalt including seaward-dipping reflectors up to ~25 km thick. This magmatism may have been enhanced by melting of continental mantle lithosphere fertilised by Iapetus slabs. After a few My magmatism waned everywhere except along the line of the frontal thrust, where the Greenland–Iceland–Faeroe ridge continued to form. Availability of unusually fusible material there might have been prolonged if the fertility anomaly were oriented parallel to the spreading direction such that the MAR migrated along it. If the original slab dipped to the south, some Iapetus slab material might also be tapped at the Reykjanes ridge, which could explain the continuation of geochemical anomalies along the MAR south of Iceland. This, along with a moderate temperature anomaly of 50–100 K (Ribe et al., 1995; Clift, 1997; Clift et al., 1998), which might result from continental insulation prior to breakup (Anderson, 2000b), might explain the geochemical and bathymetric anomalies there (Foulger and Anderson, in press).

3. Temperature

There is little evidence from Iceland itself for the anomalously high mantle potential temperatures that might be expected for a plume (see Foulger and Anderson, in press for a detailed discussion; Vinnik et al., in press). Interpretations of seismic anomalies in terms of temperature are ambiguous as the effects of temperature cannot be separated from those of melt and composition. The presence of partial melt in the mantle beneath Iceland is required by some seismological data (e.g., Vinnik et al., in press) reducing the need to appeal to high temperatures to explain the observations. Petrological estimates of temperature have been attempted using olivine-glass thermometry, high-MgO glass thermometry and major-element systematics. These studies, and the absence of picritic glass in Iceland, suggest temperatures little elevated above those beneath normal ridges (Breddam, 2002; Gudfinnsson et al., 2003; Presnall and Gudfinnsson, in press). Bathymetric modeling is most consistent with a regional temperature anomaly of 50–100 K (Ribe et al., 1995; Clift, 1997; Clift et al., 1998). Such a temperature anomaly is consistent with some indications that temperature may be slightly elevated in the Iceland region, e.g., the presence of abundant chromite phenocrysts (G. Fitton, personal communication, 2004). However, the temperature anomalies required for plumes to rise through their own thermal buoyancy are generally calculated to be 200–300 K (e.g., Sleep, 2004). Although the absence of data cannot disprove high temperatures, few data support them. A theory for Icelandic petrogenesis appears to be required that explains the excessive crustal thickness and geochemical similarities to typical MORB with source temperatures at most only mildly elevated above those beneath normal mid-ocean ridges, and similar to those beneath the neighboring Reykjanes and Kolbeinsey ridges where the crust is much thinner.

Picrite magmas interpreted as indicating high source temperatures (Larsen and Pedersen, 2000) are reported from Greenland, Scotland and Baffin Island where they are associated with continental breakup and the opening of the Labrador Sea and the North Atlantic. Higher temperature magmas associated with the rifting of cratons 150–200 km thick might be explained by derivation from greater depth in the mantle than MORB. Evidence for surface uplift prior to breakup is also cited in support of a hot, upwelling plume model. Such observations do not uniquely require a hot plume, however. Vertical motions in the north Atlantic have been variable throughout the Cenozoic, uplift of the margins at the time of breakup did not exhibit a circular pattern (Lundin and Dore, in press) and post-rifting subsidence suggests temperature anomalies no higher than 100 K, which are much lower than those thought to characterize plumes (Clift, 1997; Clift et al., 1998). Lastly, even if high temperatures were associated with continental breakup, this does not require high temperatures beneath Iceland itself at the present-day.

4. Geochemistry

Most Icelandic basalts are tholeiites similar to N-MORB, but differ from them in their isotopic ratios, trace-element concentrations, and major-oxide abundances (Meyer et al., 1985; Hanan and Schilling, 1997; Kempton et al., 2000). Most compositions are higher in fractionation-corrected parental Na_2O (Na_8) (Fig. 2a) and TiO_2 than those from the adjacent ridges. Partial melting of an homogeneous mantle to produce thick crust (Fig. 2b) would predict less Na_2O and TiO_2 because of the greater degree of partial melting and larger depth range of melting required (Langmuir et al., 1992). Nevertheless, even above the thickest (~40 km) crust in central Iceland (Foulger et al., 2003), primitive lavas found at Kistufell volcano (Breddam, 2002) have Na_8 similar to basalt glasses from the East Pacific Rise (EPR), where the crust is only 7 km thick. Below, we use the primitive Kistufell basalts as type examples of primitive Icelandic tholeiite in comparisons with oceanic crust.

As pointed out by Chauvel and Hemond (2000) and Breddam (2002), primitive Icelandic tholeiite is similar to gabbroic ocean crust. We extend this comparison using large data sets from Hess Deep in the eastern Pacific, and Atlantis Bank on the Southwest Indian ridge. At the latter, a very long section of gabbroic oceanic crust was cored at ODP Hole 735B. At both locations almost all gabbros are adcumulates with little trapped melt (Natland et al., 1991; Natland and Dick, 1996, 2001, 2002). They span all stages of differentiation including, with decreasing temperature, troctolite, olivine gabbro, gabbronorite, oxide gabbro

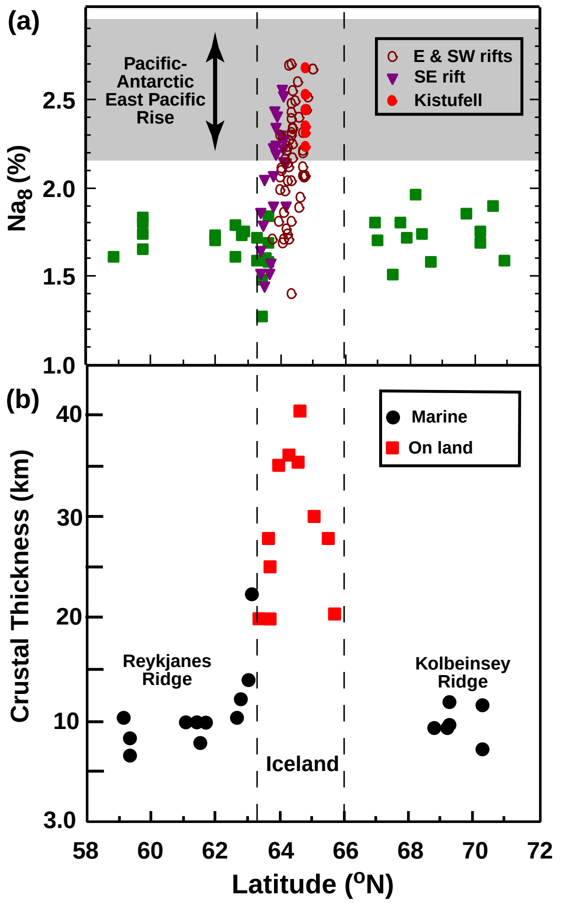

Fig. 2. (a) Parental soda (Na_8) in basalt glass vs. latitude. Data from Kolbeinsey and Reykjanes ridges from Lamont petrological database (PetDB). Icelandic compositions from Meyer et al. (1985) and Breddam (2002). Range for Pacific–Antarctic EPR is from Castillo et al. (1998). (b) Crustal thickness vs. latitude, from a compilation of seismic experiments in Iceland and the North Atlantic (adapted from Foulger and Anderson, in press).

(i.e., containing the magmatic Fe–Ti oxide minerals, ilmenite and magnetite), and minor residual granitic material. The oxide gabbros from Hole 735B contain up to 11% TiO_2 and 30% cumulus magmatic oxides. About 20% of the section is gabbro with 1–30% of ilmenite and magnetite. At pressures >1.5–3.0 GPa these would be rutile-rich eclogite (e.g., Yoder and Tilley, 1962).

The gabbroic facies at Hole 735B experienced differentiation by deformation (Bowen, 1920) during which the diverse lithologies were intimately juxtaposed in complex fashion while melt was present. Crystallization temperatures ranged from ~1200 to ~700 °C (Natland et al., 1991). A similarly wide range of remelting temperatures would be expected for granitic to troctolitic rocks transformed to the eclogite facies. Experimental studies on natural eclogites indicate a crystallization/melting interval of ~400 K at pressures of >2 GPa. Most experiments, however, have been done on bimineralic, garnet–clinopyroxene eclogite rather than iron-rich ferroeclogite with significant proportions of rutile±amphibole or granitic material in the eclogite facies.

Trace-element concentrations in gabbroic cumulates are controlled by the compositions of precipitated minerals rather than the liquids. Concentrations in individual rocks may be variable, but the ratios of elements and their average concentrations in the complete crustal section are determined mainly by partitioning into clinopyroxene and plagioclase, and crystal separation from the residual liquid fraction. The bulk gabbro assemblages at Hess Deep and Hole 735B thus have low concentrations of, e.g., Y, Zr, and TiO_2, and proportions set primarily by clinopyroxene, compared with their parental liquids (Table 1).

We calculate an average bulk composition for 1508 m of gabbro from Hole 735B using all analyses for which major oxides, REE and many trace elements have been obtained (Natland and Dick, 2002), and weighting the analyses by the density-corrected mass proportion of each lithology in the hole (Dick and Natland, 2000). The section probably represents about 60% of the gabbroic layer, including its central, most typical, portion. Complete remelting of all lithologies within it would probably leave only about 10% of the most refractory crustal materials behind (which were not cored at Hole 735B) (Natland and Dick, 2002). This composition (Table 1) would provide a liquid that is magnesian but non-picritic, with lower concentrations of Y, Zr, and TiO_2 than typical primitive N-MORB. In all these respects such a liquid is similar to primitive Kistufell tholeiite (Table 1).

The REE pattern of this average Hole 735B gabbro is also similar to those of Kistufell basalts, being flat and with only a small Eu anomaly (Fig. 3). The low overall REE concentrations calculated are a consequence of low partitioning into cumulus olivine, plagioclase and augite, strong partitioning into the melt, and expulsion of that melt from intercumulus porosity structure during compaction and adcumulus growth. Average Hole 735B gabbro is, however, slightly depleted in light REE compared with Kistufell tholeiites. Icelandic tholeiites are also lower in Zr compared with REE than N-MORB is, one of the attributes of the so-called "depleted plume component" (Kempton et al., 2000). However, this attribute is also matched by most troctolitic and olivine-gabbro cumulates at Hole 735B (Fig. 4).

Average Hole 735B gabbro has lower Zr/Y and Nb than either Kistufell tholeiite or typical N-MORB (Fig. 5). The lower Zr/Y again is a consequence of the rocks being cumulates in which concentrations of these elements are controlled mainly by clinopyroxene. Both the higher Nb and light REE in Kistufell tholeiite and N-MORB may be explained by liquid derived from melting abyssal gabbro with the addition of, or mixing with, a small fraction of an enriched (E-MORB or AOB) component or silicic material such as trondhjemite or rhyolite. All of these are already present in recycled ocean crust by analogy with rocks from the EPR and nearby seamounts (Natland, 1989; Niu et al., 2002). The high Nb in basalt glasses from the EPR reveals E-MORB influence among many N-MORB glasses (Fig. 5) and we expect a comparable geochemical range to be retained during remelting of subducted oceanic crust. Most recently, McKenzie et al. (2004) have presented evidence from correlations between isotope ratios and elemental concentrations for subducted OIB of Caledonian age beneath Theistareykir, north Iceland. The enriched component may be distributed as lavas, dikes, veins, cumulates and reaction zones in ocean crust and adjacent abyssal peridotite. It need not reside in a physically separate reservoir, nor come from the deep mantle. Light REE flattening and Nb enrichment in Kistufell tholeiite can be explained by addition of 4.8% of seamount-type AOB to average Hole 735B gabbro (Table 1; Figs. 3–5). This is slightly less than the 6.2% of E-MORB with >0.5% K_2O dredged on the EPR and nearby seamounts between Siqueiros and Clipperton Fracture Zones, according to the Lamont Petrology Database. It can also be explained by mixing with a similarly small amount of rhyolite, which is present at many central volcanoes in Iceland.

Additional similarities between average Hole 735B gabbro and Kistufell basalts include positive Sr and negative Pb anomalies, low-^{18}O (Breddam, 2002), and elevated $^{87}Sr/^{86}Sr$, which results from seawater alteration. This is associated with elevated Rb in altered gabbros (Hart et al., 1999). By radioactive decay of Rb over several 100 My, the average $^{87}Sr/^{86}Sr$ of trapped Iapetus ocean crust would increase somewhat from the original values in abyssal gabbro. Other isotopic ratios suggest an age for Icelandic basalt sources of several hundred My, consistent with ocean crust that was young when the Caledonian suture formed (Korenaga and Kelemen, 2000; McKenzie et al., 2004).

Great abundances of differentiated ferrobasalts are observed in Iceland, particularly at central volcanoes (Carmichael and McDonald, 1961; Walker, 1963), and the diverse rock compositions there have been attributed to remelting of the thick Icelandic crust (Oskarsson et al., 1982). Ferrobasaltic liquid cannot be produced by partial melting of mantle peridotite, as liquids so produced must be in equilibrium with magnesian olivine and pyroxenes. Primitive olivine tholeiite, however, occurs mainly in small volumes along the rift zones of Iceland, always away from central volcanoes (Breddam, 2002; Stracke et al., 2003). The ferrobasalts of both the rifts and central volcanoes could, however, be derived from partial melting of an eclogitic mantle source beneath Iceland, in which case a great deal of differentiated basalt could pass from the mantle into the crust. Thus, significant quantities of oxide gabbro, carrying several percent or more of the dense magmatic oxide minerals, ilmenite and magnetite, might have crystallized in the Icelandic lower crust. Isostasy indicates that average Icelandic lower crust has an unusually high density only ~90 kg/m^3 lower than that of the underlying mantle (Menke, 1999), despite having a crust-like average compressional-wave velocity of ~7.2 km/s (e.g., Darbyshire et al., 1998; Foulger et al., 2003). This may be compared with the density contrast of ~300 kg/m^3 expected if the lower crust were olivine gabbro and the mantle peridotite. Abyssal oxide gabbros have so much ilmenite and magnetite, they have very high densities of up to 3200 kg/m^3, but crust-like seismic velocities (Itturino et al., 1991). Eclogite melting could thus also provide a candidate explanation for

Table 1
Average compositions of lithologies discussed in the text

Sample	1 735B troctolite	2 735B olivine gabbro	3 735B differ gabbro	4 735B oxide gabbro	5 735B Felsic	6 735B Trond	7 735B strip average	8 Hess Troctolite	9 Hess Olivine Gabbro	10 Hess differ. gabbro
SiO_2	47.11	50.56	50.98	46.35	58.98	69.54	50.74	46.60	50.24	51.11
TiO_2	0.25	0.38	0.62	4.23	0.54	0.24	1.34	0.33	0.33	0.68
Al_2O_3	15.29	17.17	16.62	13.21	16.81	16.67	16.08	19.16	19.18	15.24
Fe_2O_3	0.81	1.24	1.92	3.86	0.43	0.31	0.00	0.00	0.00	0.00
FeO	6.89	4.25	6.40	12.16	4.16	1.10	8.34	6.26	5.22	8.49
FeOT	7.62	5.37	8.13	15.63	4.55	1.38	8.34	6.26	5.22	8.49
Fe_2O_3T	8.46	5.96	9.03	17.37	5.05	1.53	9.27	6.95	5.80	9.43
MnO	0.14	0.12	0.15	0.24	0.09	0.02	0.16	0.10	0.11	0.15
MgO	15.88	9.42	7.77	6.44	4.61	0.37	8.84	14.20	8.75	8.23
CaO	10.72	13.03	11.51	9.44	7.66	2.07	11.11	12.27	13.66	12.06
Na_2O	1.91	2.76	3.32	3.30	5.51	6.92	3.19	1.00	2.46	2.34
K_2O	0.06	0.05	0.11	0.11	0.24	0.65	0.11	0.12	0.13	0.02
P_2O_5	0.01	0.02	0.06	0.15	0.07	0.01	0.09	0.03	0.02	0.06
Total	99.07	99.00	99.46	99.49	99.10	97.90	100.00	100.07	100.10	98.38
MgNo	0.812	0.784	0.664	0.460	0.677	0.357	0.687	0.824	0.776	0.667
# in ave	27	175	52	69	34	3	17	3	21	8
Weighted %	0.85	79.56	8.84	10.59	0.11	0.05				
Trace elements										
Ba		4.85	6.44	8.55	20.52		9.5	7.24		
Rb	1		1	1	1	1	0.562	1		1
Sr	130	162	172	151	152	144	158	74	118	93
Y	7	12	20	37	59	46	27	10	11	22
Zr	11	24	51	168	297	107	78	18	14	43
Nb	0.5	0.4	0.5	3.7	5.6	4.7	1.7	0.6		1.1
Th		0.2	0.3	0.3	1.2	2	0.2			
Pb	0.5	0.8	1.2	1.5	1.9	2.5	0.6			
Zn	47.3	37.1	51.7	107.1	31.2	10	54.2	38.3	36.6	62

Ni	284.4	107.7	74.6	56.9	42.7	31.2	138.1	390	150	103
Cr	551	250	105	94	61	41		516	388	267
Co	65.7	36.8	41.3	60.5	19.8	7.1	42.2	37.5	36	45.1
V	91	142	186	535	85	32	197	182		2387
Hf					8.7		2.1		12.1	
Sc	24.4	36.8	37.1	42.7	20.4	5		11.5	30.4	
Ta		0.1		0.3	0.5	0.7				
U	0.02	0.02	0.12	0.07	0.38	0.54	0.035			
Rare earth elements										
La	0.63	1.04	1.99	3.84	15.38	24.2	4.79	0.68	0.56	1.54
Ce	2.15	3.16	6.22	12.76	42.77	58.84	14.89	2.12	1.86	4.72
Pr	0.49	0.59	1.39	2.26	6.91	7.78				0.92
Nd	2.06	3.12	5.54	11.77	25.13	29.72	10.22	1.77	1.81	4.51
Sm	0.7	1.1	2.08	3.91	6.68	6.48	3.09	0.61	0.7	1.96
Eu	0.38	0.58	1.08	1.58	1.92	1.48	1.14	0.33	0.41	0.76
Gd	1.28	1.64	3.01	4.87	8.01	6.16		0.97	1.11	2.77
Tb	0.17	0.3	0.54	1	1.4	1.2	0.73		0.2	0.48
Dy	1.59	1.99	3.62	5.69	9.95	7.38				3.37
Ho	0.34	0.43	0.78	1.31	2.26	1.65			0.27	0.67
Er	0.99	1.22	2.24	3.66	6.95	5.21				2.26
Tm	0.15	0.19	0.35	0.63	1.12	0.87			0.13	
Yb	0.72	1.14	2.07	3.7	7.17	6.59	2.77	0.71	0.86	
Lu	0.11	0.17	0.32	0.56	1.09	1.06	0.4	0.11	0.14	0.3

Data pertaining to lithologies discussed in the text. Major elements are given in wt.%, trace elements in parts per million. FeOT=all iron as FeO, and Fe_2O_3T=all iron as Fe_2O_3, are not included in the totals of major oxides. MgNo=atomic Mg/(Mg+Fe^{2+}), where Fe^{2+}/(Fe^{2+}+Fe^{3+})=0.90, the average for all lithologies at Hole 735B. Columns 1–6: average gabbros, computed for all samples for which REE measurements were made, using chemical definitions of Natland and Dick (2002) and their Appendix B; Column 7: average of 17 strip samples of the upper 500 m of the hole (Hart et al., 1999); Columns 8–12 similar averages for Hess Deep; Column 13; weighted average gabbro from Hess Deep; Column 14: weighted average for Hole 735B for major oxides and selected trace elements using all chemical analyses, from Dick and Natland (2000); Column 15: average of all Hole 735B samples analyzed for REE, using weighted percentages given below each average of columns 1–6; Column 16: weighted average olivine gabbro plus troctolite from Columns 1 and 2; Column 17: weighted average of differentiated gabbro, oxide gabbro, felsic veins and trondhjemite, from columns 3–6; Column 18: average of two Ne-normative alkalic olivine basalts from seamounts near the EPR; Column 19: average olivine tholeiite glass from Kistufell (Breddam, 2002); Column 20: same as column 19 except for whole rock; Column 21: 95.2% of column 16 plus 4.8% of column 18.

Table 1 (*continued*)

Sample	11 Hess Oxide Gabbro	12 Hess Tonalite	13 Hess weighted average	14 Dick and Natland (2000) 735b Average	15 735B Ave all REE	16 735B Troct+ Oliv. Gab.	17 735B DOOG+	18 EPR AOB	19 Kistufell average glass	20 Kistufell aver oliv. Tholeiite	21 All REE+ 4.8% AOB
SiO_2	50.45	67.30	50.45	50.60	50.11	50.46	48.65	49.18	48.34	48.48	50.07
TiO_2	1.71	0.70	0.56	0.87	0.81	0.38	2.59	2.44	0.99	0.95	0.89
Al_2O_3	11.64	15.52	18.05	16.10	16.68	17.13	14.82	17.7	15.87	15.84	16.73
Fe_2O_3	0.00	0.00	0.00	1.37	1.58	1.23	2.98	0	0.00	0.00	1.5
FeO	12.92	3.56	6.53	6.19	5.30	4.27	9.55	8.86	9.18	9.22	5.47
FeOT	12.92	3.56	7.25	7.42	6.72	5.38	12.22	8.86	9.18	9.22	6.82
Fe_2O_3T	14.35	3.96	9.05	8.25	7.46	5.98	13.58	9.84	10.20	10.24	7.57
MnO	0.22	0.05	0.14	0.14	0.14	0.12	0.22	0.19	0.16	0.16	0.14
MgO	9.10	0.97	9.31	9.21	9.01	9.48	7.08	6.17	9.71	10.66	8.87
CaO	11.37	6.46	12.74	12.50	12.49	12.99	10.42	9.07	13.80	12.52	12.33
Na_2O	2.16	4.56	2.52	2.80	2.87	2.75	3.36	3.94	1.78	1.73	2.92
K_2O	0.03	0.19	0.03	0.05	0.07	0.05	0.14	1.34	0.07	0.07	0.13
P_2O_5	0.24	0.46	0.04	0.05	0.04	0.02	0.15	0.59	0.05	0.09	0.07
Total	99.84	99.77	100.11	99.88	99.05	98.88	99.77	99.66	99.95	99.71	99.72
MgNo	0.593	0.360	0.741	0.720	0.705	0.758	0.596	0.590	0.686	0.705	0.699
# in ave	6	1			360	158	202	2	10	16	
Weighted %											
Trace elements											
Ba	23.93	33.7						354.9		14.77	
Rb	1						1.06	26		1	
Sr	82	119	114	163	161	161.50	161	526		123	178.9
Y	47	129	15	13	15.4	11.93	29.6	24		17	15.9
Zr	173	469	23	30	41.8	23.83	116.2	255		44	52.1
Nb	4.4	17			0.78	0.41	2.33	44.7		2.9	2.9
Th							0.37	2.9		0.1	
Pb					0.92	0.80	1.44	2.04		0.2	0.97
Zn	74.5	0.3		43	45.9	37.20	81.9	99.4		69.6	48.4

Ni	93.5	9	154	106	100.8	109.40	65.1	95.8		250.7	100.6
Cr	181			295	223	252.90	99.1	120		431	218
Co	51.5				39.9	37.10	51.8	33.5		50.8	39.6
V	455	49		240	187	141.30	376	176		237	186
Hf								5.5		1.3	
Sc					37.3	36.60	40.2	21.1		38.6	36.5
Ta								2.5		0.2	
U					0.02	0.02	0.19	0.98		0.03	0.098
Rare earth elements											
La	4.76	13.7			1.45	1.030	3.18	30.34		2.5	2.84
Ce	14.58	41.73			4.5	3.150	10.1	65.11		6.7	7.41
Pr	3.18				0.86	0.590	2	8.38		1.01	1.22
Nd	11.93	38.85			4.29	3.110	9.16	32.2		5.38	5.62
Sm	4.32	12.47			1.51	1.090	3.22	6.68		1.83	1.76
Eu	1.21	3.22			0.75	0.580	1.47	2.19		0.75	0.82
Gd	5.83	15.36			2.13	1.630	4.17	6.35		2.51	2.33
Tb	1.15				0.42	0.300	0.91	0.9		0.43	0.44
Dy	6.69	17.22			2.55	1.980	4.91	5.11		2.83	2.68
Ho	1.6				0.58	0.430	1.2	1		0.64	0.6
Er	4.14	10.79			1.6	1.220	3.17	2.7		1.68	1.64
Tm					0.28	0.190	0.64	0.36		0.26	0.28
Yb	3.02	9.96			1.52	1.130	3.12	2.35		1.71	1.56
Lu	0.61	1.69			0.25	0.170	0.59	0.35		0.28	0.26
	127.11	107.29									

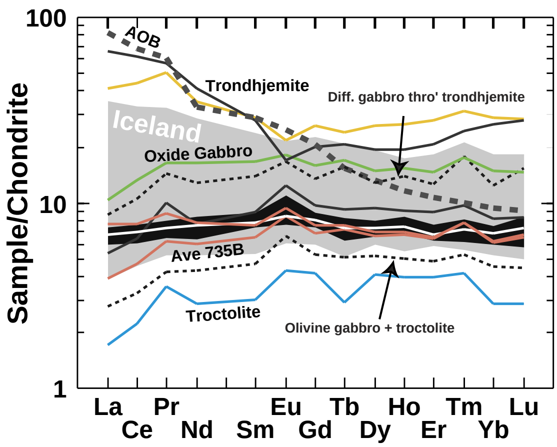

Fig. 3. Chondrite-normalized REE patterns for average Hole 735B gabbro lithologies (solid black lines) compared with the range (black) and average (solid white line) of basalts from Kistufell (Breddam, 2002) and the range of basalts from Iceland rifts (Maclennan et al., 2002) (gray field). Bold gray dashed line: average of two Ne-normative AOB from seamounts near the EPR (Table 1), two dashed white lines: weighted average of all samples analyzed for REE from Hole 735B (lower), and the same composition plus 4.8% AOB (upper). The latter closely matches average Kistufell olivine tholeiite. In general, the flat to enriched REE patterns of Icelandic basalts can be produced by mixing melt derived from abyssal gabbro and either an enriched material such as AOB, or silicic material, such as trondhjemite. Data are given in Table 1.

the anomalously high density of the Icelandic lower crust.

Extensive remelting of eclogitic ocean crust, transformed from a typically diverse suite of abyssal gabbros and basalts, can thus account for both primitive and differentiated Icelandic tholeiites. During transformation to eclogite in subduction zones, trace-element concentrations and ratios in abyssal gabbros plausibly are preserved and survive later remelting. Radiogenic isotopes that evolved following subduction add to those in E-MORB, dikes and reaction zones already present in the subducted crust, as well as altered ocean crust. Recycled abyssal gabbro can explain the high Y/Zr, low Zr/La, low concentrations of REE and high-field-strength incompatible elements such as Zr, Y, Ti, Hf and Ta, positive Sr and negative Pb anomalies, flat REE patterns, MORB-like general characteristics, non-picritic MgO and Mg# of most primitive Icelandic basalts (Chauvel and Hemond, 2000), and the great melt volumes produced at relatively moderate temperatures. More enriched and differentiated Icelandic basalts may result from small-degree partial melting of eclogite, that taps the iron-rich oxide-gabbro in the eclogite, and incorporation of AOB and related rock, which must also reside in both subducted crust and adjacent abyssal peridotite. Some characteristics of primitive Icelandic basalts previously attributed to alteration and sub-arc melt extraction from ocean crust (Breddam, 2002), e.g., Y,

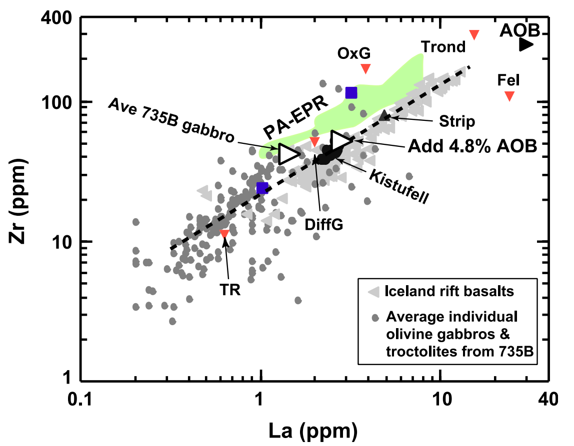

Fig. 4. Zr vs. La showing how reduced Zr/La in Icelandic tholeiites can result from extensive melting of abyssal gabbro. Red symbols: from lower left to upper right, they are, from Table 1, columns 1 and 3–6—average 735B troctolite (TR), 735B differentiated gabbro (DiffG), 735B oxide gabbro (OxG), 735B felsic (Fel), and 735B Trondhjemite (Trond). Blue symbols: averages of olivine gabbro and troctolite (lower left—Table 1, column 2) and differentiated gabbro through trondhjemite (upper right, i.e., the weighted average of all the samples used for the four red symbols to the upper right). Basalt compositions plot to upper right, whereas gabbro cumulate compositions plot to lower left. Extreme differentiates are at the extreme upper right. The weighted average Hole 735B gabbro (lower left bold open triangle) combines primitive gabbro cumulates with differentiated seams and veins of oxide gabbro and trondhjemite, and resembles primitive Icelandic tholeiite. Strip: average of 17 strip samples of the upper 500 m of Hole 735B (Table 1; Hart et al., 1999), is similar to moderately differentiated Icelandic tholeiite. A model composition (upper right bold open triangle) combining average Hole 735B gabbro plus 4.8% AOB (Niu et al., 2002) resembles primitive Kistufell tholeiite. Icelandic basalts are shifted to lower Zr at given La than MORB from the Pacific–Antarctic EPR (green field). The Iceland trend could be produced either by crystallization differentiation of primitive Icelandic tholeiite inheriting low Zr/La from a gabbroic melt source, or direct partial melting of such a source, mixed with a small amount of AOB. Mixing with small amounts of either enriched (e.g., AOB) or silicic material (e.g., rhyolite, trondhjmeite) does not shift Zr/La (data from Table 1; Breddam, 2002; Maclennan et al., 2002).

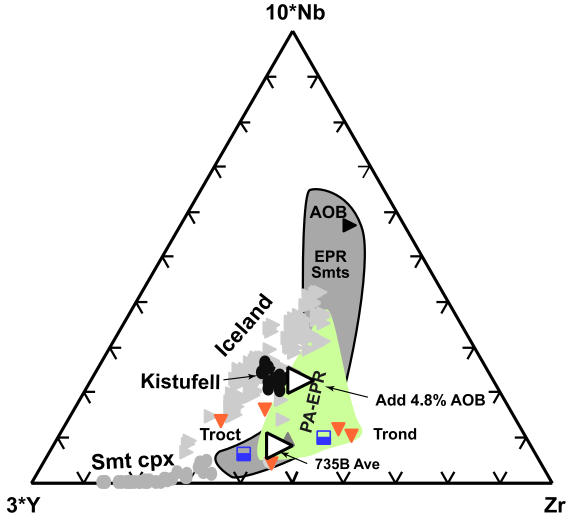

Fig. 5. Ternary diagram comparing proportions of Zr, 10*Nb, and 3*Y. The latter two are expanded for clarity. Symbols and labels are as in Fig. 4. Data fields for the Pacific–Antarctic EPR (green field) and eastern Pacific seamounts (dark grey field) (Niu et al., 2002) are shown for comparison. Also shown are estimated compositions of clinopyroxene (gray dots) calculated to be in equilibrium with seamount liquids, using partition coefficients of Hart and Dunn (1993). Cumulates rich in clinopyroxene that crystallized from N-MORB to AOB thus should have higher Y/Zr than the liquids themselves. Nb enrichment at given Y/Zr is explained by mixing with AOB. Icelandic basalts thus plot toward higher Y at given Nb and Zr than basalts from the Pacific–Antarctic–EPR, consistent with derivation by melting from abyssal–gabbro precursors, and they have similar proportional enrichment in Nb as many N-MORB from the Pacific–Antarctic–EPR. This figure distinguishes two mixing trends, between: (1) primitive tholeiite derived from melting gabbro, and trondhjemite (high Zr, low Nb), and (2) primitive tholeiite and AOB (high Zr, high Nb). Basalts from both Iceland and the Pacific–Antarctic–EPR demonstrate at least the latter, and perhaps both types of mixing in some samples. Some Icelandic tholeiites with higher Y/Zr than those from Kistufell closely resemble Hole 735B troctolite, and thus may have been derived from a less differentiated, average gabbroic precursor.

Nb, Zr, and TiO_2 proportions, positive Sr, and negative Pb anomalies, mimic the same features in abyssal gabbro cumulates. These features thus do not uniquely require that the recycled oceanic crust was subducted beneath arc volcanoes.

5. Helium isotope ratios

The highest non-cosmogenic $^3He/^4He$ isotope ratios at a currently active "hot spot", up to ~42 Ra, (where Ra is the atmospric $^3He/^4He$ ratio) are found in Iceland (Hilton et al., 1999; Breddam, 2001). (Recently, ratios of up to 49.5±1.5 Ra have been reported from basalts in Baffin Island; Stuart et al., 2003.) Such observations are widely assumed to be an unambiguous indicator of a lower mantle component in surface rocks, partly because it is assumed that they result from high [^3He] content, and partly because other regions assumed to be underlain by plumes, such as Yellowstone and Hawaii, also have high ratios. However, this interpretation is non-unique. Other models for derivation of high $^3He/^4He$ from the shallow mantle have been proposed (Anderson, 1998a,b; Foulger and Pearson, 2001; Meibom et al., 2003).

The presumption that high $^3He/^4He$ is derived from the lower mantle assumes that it is essentially undegassed. A high absolute concentration of [^3He] would have prevented $^3He/^4He$ ratios from reducing with time in response to the production of ^4He from the decay of U+Th over the lifetime of the Earth. The value of $^3He/^4He$ in the lower mantle is thus predicted to have remained at a few 10s of Ra, and to provide a source for the high $^3He/^4He$ observed at Iceland and elsewhere. This theory has the following problems:

(1) Mass balance calculations show that the concentration of ^3He predicted in the lower mantle is comparable with that in chondritic meteorites (Kellogg and Wasserburg, 1990). This is at odds with high-temperature models of planetary accretion. The Earth is thought to have accreted at high temperature because of the energy of accretion, segregation of the core, and impact with a Mars-sized body that caused the Moon to form. Extensive degassing must have occurred at these times. This is supported by the observation that the Earth is strongly depleted in cosmochemically volatile species such as Na, K, Cl, and Rb, which are less volatile than He. It is thus unlikely that a large part of the Earth has remained undegassed (Anderson, 1989).

(2) If high-$^3He/^4He$ arises from a component with a high absolute He concentration then the helium concentrations in OIB, where such high ratios are commonly observed, are expected to be much higher than in MORB. However, the helium abundances in OIB are 2–3 orders of magnitude lower

than in MORB. It is generally assumed that this results from preferential degassing of OIB as a result of their shallow depth of eruption. This can be tested using the relative concentrations of heavier noble gases. The heavy noble gasses have a greater tendency to degas on eruption than helium, so He/Ne and He/Ar in OIB should be higher the more degassed a magma is. It is found, on the contrary, that these ratios are higher in MORB than in OIB, suggesting that MORB is more degassed than OIB, not less (Anderson, 1998b; Anderson, 2000a; Moreira and Sarda, 2000; Ozima and Igarashi, 2000). OIB therefore do not arise from a source higher in [He] than MORB and their high $^3He/^4He$ ratios cannot be explained in this way (Anderson, 1998a,b).

High-$^3He/^4He$ can also result from a deficit of ^4He as a result of storage of old helium in a low time-integrated U+Th host rock or mineral (Anderson, 1998a,b). The controlling parameters are then U+Th/^3He and time.

Possible low-U+Th host materials are the residuum left after basalt melt is extracted from mantle peridotite (Anderson, 1998a,b) and ultramafic cumulates (Natland, 2003). Either contains only traces of U+Th and thus helium stored in such rocks for hundreds of millions or even billions of years would preserve its older, higher $^3He/^4He$ ratio with little change. Olivine-rich cumulates of various ages are present in both sub-cratonic and oceanic lithosphere, and both are therefore likely hosts for volatiles released during remelting in the mantle beneath Iceland. Olivine crystals in cumulates contain encapsulated gas bubbles with He, but they contain essentially no U+Th because melt is excluded by the mechanism of inclusion incorporation during crystal growth (Natland, 2003). The minerals will aggregate as cumulates where intercumulus melts are expelled during compaction and subsequent adcumulus growth. Cumulates thus are time capsules that preserve largely unchanged initial $^3He/^4He$ ratios.

The volatiles in olivine-rich cumulates probably would dominate materials scavenged from them during later partial remelting, and thus high $^3He/^4He$ would not necessarily correlate with other indices of isotopic enrichment in Icelandic tholeiites, a continuing conundrum of Icelandic isotope geochemistry (Stracke et al., 2003). Indeed, depending on how volatiles entrained in this way concentrate in ascending magmas or temporary storage areas in their progress toward eruption, there is no reason why even the absolute concentration of ^3He should be low in any given lava.

Our model suggests that delamination of Laurasian continental mantle lithosphere has emplaced residual oceanic lithsophere of Caledonian age beneath Iceland. Any of the ultramafic materials plausibly could contribute moderate-to-high $^3He/^4He$ to Icelandic tholeiite depending on the age and distribution of the sources. Quantitative calculations of the $^3He/^4He$ values in such rocks are difficult because details of degassing, metasomatism and radiogenic ingrowth cannot be accurately determined, but the values observed are permitted by plausible assumptions. The strength of the helium argument for an Icelandic deep mantle plume has previously been the presumed necessity to tap an ancient, long-isolated, undegassed reservoir that is clearly not the same as the modern MORB reservoir. We suggest here that the helium resides instead in the mantle near the surface of the Earth.

6. Physical models for melting subducted crust

The extent to which subducted crust trapped at shallow levels in the mantle re-homogenizes with its peridotite host is not known. The retention of essentially pristine blocks of crust of the order of kilometers in thickness, and complete homogenization with mantle peridotite, represent end-member scenarios. We have focused on the former possibility, and shown that the geochemistry of lavas from Iceland is consistent with large-scale remelting of eclogitized, subducted Caledonian crust, with contributions from adjacent peridotite. The necessary kilometer-scale lengths of pristine blocks could have been preserved in Caledonian continental mantle lithosphere.

How much melting of an eclogitic source is required? Experiments on eclogite and in simple four- or five-component systems (without TiO_2) show that initial small-degree melts are similar to andesite (Yoder and Tilley, 1962; Yasuda et al., 1994). As the degree of batch melting increases, melt compositions progressively approach the composition of the sample being melted. At 10–30% partial melting, liquids are ferrobasaltic with low SiO_2, and at 80% they are olivine tholeiite similar to those of Iceland (Ito and Kennedy, 1974). The effect of higher pressure is to reduce SiO_2 in the basaltic partial melts and the proportion of normative hypersthene in liquids (Ito and Kennedy, 1974). These differences are the same as those observed between the average bulk composition of abyssal gabbro and that of primitive Icelandic tholeiite. Even at the extremes of eclogite partial melting, however, when contributions from adjacent peridotite might be most significant, the geochemical signature of abyssal gabbro still predominates. Strict comparison of Icelandic tholeiite to natural gabbro compositions, and the experiments of Ito and Kennedy (1974), suggest that 60–80% melting of the original bulk gabbroic assemblage is required.

How might such high degrees of melting be attained? A subducted eclogite slab will thermally re-equilibrate after residing in the mantle for ~10 thermal relaxation times (e.g., Stein and Stein, 1997). The thermal relaxation time of subducted lithosphere is 10–20 My, and thus 420–410 My is ample for Caledonian-aged slabs to have attained nearly the same temperature as the surrounding mantle. Thus, eclogite upwelling beneath the MAR in the Iceland region will be much closer to its solidus than peridotite, or it may even be partially molten. Seismic data require melt to be present in the low-velocity layer beneath Iceland which lies at depths of 80–140 km (Vinnik et al., in press). Contrary to early indications of a narrow melting interval of about 80–90 K for eclogite (Yoder and Tilley, 1962), subsequent experimental data establish a melting interval of nearly 400 K at 2–3 MPa (Ito and Kennedy, 1974; Yasuda et al., 1994; Pertermann and Hirschmann, 2003). The melting interval is similar to that of abyssal gabbro at 1 atm (Koepke et al., 2004), and 200–250 K below that of volatile-free lherzolite (Hirschmann, 2000; Presnall and Gudfinnsson, in press) at all pressures. Initial partial melts at 2–3 MPa are approximately andesitic in composition; more extensive melts range from ferrobasaltic to olivine tholeiite as extent of partial melting proceeds. No melting experiments have been conducted on the eclogitic equivalent of a very oxide-rich ferrogabbro (rutile-rich eclogite) or on high-pressure metasediments in the eclogite facies. We conclude that a melt equivalent to a moderately differentiated abyssal tholeiite can readily be generated from an average eclogitic abyssal gabbro, and partial melting beyond a few tens of percent will not greatly affect the generally basaltic composition.

Differentiated oxide-rich, amphibole-bearing or granitic lithologies present in the ocean crust may add significantly to the melting interval and would diversify the geochemistry. Nevertheless, the large degrees of melt suggested by the geochemistry could be attained by heating eclogite to approximately the same temperature as is required to produce 20% of partial melt in peridotite (Yaxley, 2000). The difference between 20% partial melting, producing a liquid approximately equivalent to ferrobasalt, and 80% partial melting, producing olivine tholeiite (Ito and Kennedy, 1974), may only correspond to a few tens of K temperature difference at a given pressure.

How could such large degrees of melt be retained prior to eruption? Melt extraction from partially molten rock can begin at degrees of melting of less than 1% (e.g., McKenzie, 1984). Progressively extracted melt increments derived from eclogite would thus have to pond and re-homogenize in some reservoir, probably below the base of the crust, prior to eruption. A similar process of fractional melting, aggregation, and homogenization is also required beneath normal spreading ridges since MORB is thought to be formed by up to ~20% partial melting of peridotite integrated over a melt column. Incremental melt extraction, however, may not operate efficiently over a large melting domain, thus the extent to which ideal fractional melting can operate is uncertain (Natland, 1989).

Another possibility, raised by the experiments of Yaxley and Green (1998), is that the subducted slab homogenizes with surrounding peridotite and that most or all remelting takes place in a particularly fertile peridotite assemblage. The homogenization could occur by progressive incorporation of early, small melt increments leaked from an inclined mass of eclogite into overlying peridotite. The hybrid can then be considered as peridotite with a shift in bulk composition toward basalt, or what Anderson (1989) has termed “piclogite”. The thermal and mass-balance aspects of this case are useful to consider. At temperatures normal for extraction of MORB along other parts of the MAR, peridotote homogenized with a few tens of percent of subducted crust can satisfy the volumetric requirements for Iceland (Yaxley, 2000; Foulger and Anderson, in press). The basaltic products of partial melting would be similar to those derived from normal peridotite but larger in volume.

Whether passive, isentropic upwelling of eclogite, an eclogite/peridotite mixture, or a wet piclogite/ peridotite assemblage would release sufficient energy to provide the latent heat of melting required to produce the thickness of crust at Iceland is not known. This cannot be calculated yet because the entropy values for the relevant minerals throughout the relevant temperature and pressure ranges are insufficiently well known (P. Asimow and D. Presnall, personal communications, 2003). Addressing this question is an important future research task. Nor are we certain exactly how much melt must be explained. Although the seismic crust (i.e., the layer with compressional-wave-speed Vp<~7.2 km/s) is three times thicker beneath Iceland than beneath the Reykjanes ridge, the near-mantle densities of the lower Icelandic crust might also permit a component of entrained mantle peridotite (Foulger and Anderson, in press). The amount of melt that needs to be explained might thus be significantly less than ~30 km.

7. The geometry of subducted slabs

In the extreme case where all of the typical 30-km seismic crust thickness at Iceland represents melt, at least this amount of crust might be required from the uppermost mantle. Remelting of a single average 7-km thickness of ocean crust is thus insufficient. Thickening of slab material, whether by increased slab dip or imbrication, is also required. In the simplest case, where a single, intact dipping slab is trapped, continental collision will have steepened it to a high angle (Fig. 6). Archaean cratons may be ~150–200 km thick, and a slab caught at a steep orientation may produce much more than a single thickness of crust. The trapped slab may also be contorted, deformed, faulted and perhaps broken into segments and imbricated, in a style similar to that of the sinistral Caledonian strike slip faults in northern Britain (Soper et al., 1992) (Fig. 1). Such imbrication could also

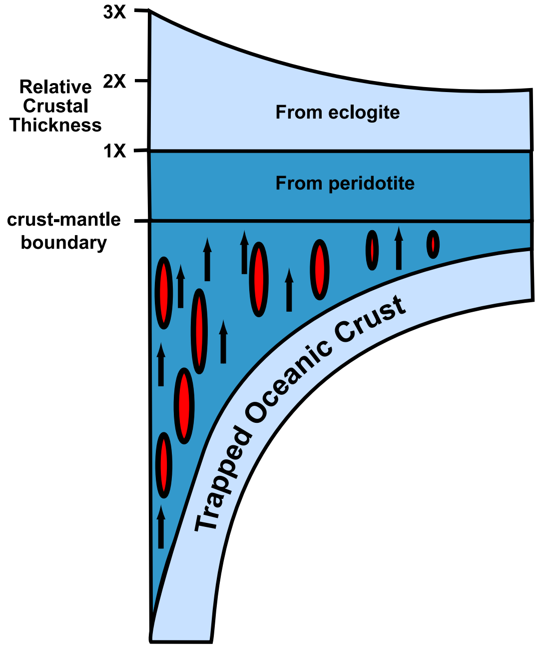

Fig. 6. Schematic diagram illustrating simply how anomalously large amounts of melt may be obtained from remelting a subducted crustal slab of normal thickness. The slab is emplaced at a high angle in the mantle. In this particular example, two thicknesses of melt might be derived from remelting eclogite in trapped oceanic crust, and one thickness is derived from melting mantle peridotite, yielding triple the amount of melt normally observed at MORs. White ellipses signify rising melt.

increase the total thickness of underlying subducted crust at a given place, thereby increasing the potential amount of basalt locally (Carswell et al., 1999). The sense of the frontal thrust in Greenland suggests that the subducted slab material over which the Greenland–Iceland–Faeroe ridge formed may have dipped to the southwest. North–south asymmetry of the causative fertility anomaly may thus be responsible for the north–south tectonic and geochemical asymmetry observed in the Iceland region (Foulger and Anderson, in press).

These are simplistic speculations, and it is unlikely that a near-pristine slab is emplaced beneath Iceland in a simple geometry similar to that of its original subduction. Laurasia migrated north by ~60° subsequent to the closure of the Caledonian suture, and Iapetus slabs subducted into the asthensophere were probably left behind. The most likely source of the proposed recycled crust is thus continental mantle lithosphere that delaminated and was re-introduced into the asthenosphere beneath the North Atlantic during and following continental breakup at ~54 Ma (see Foulger and Anderson, in press for more detailed discussion). Catastrophic delamination has been suggested as a process that may recycle continental mantle lithosphere into the asthenosphere and trigger eruption of flood basalts (Tanton and Hager, 2000). Any slab material transported back into the asthenosphere along with delaminated continental mantle lithosphere would have been contorted and deformed and today would bear little resemblance to its original form. Nevertheless, such deformation may well have concentrated much more than a single thickness of crust vertically beneath Iceland. The long-term enhanced volcanism of the Iceland region suggests that this delamination created a zone of mantle fertility oriented parallel to the plate motion direction. This is also the local direction predicted by an Antarctica-fixed reference frame for migration of the north America plate and the MAR relative to deeper mantle (Foulger and Anderson, in press). Another possibility is that erosion of the subcontinental lithosphere and recycling back into the asthenosphere is a continuous process that accompanies the westward migration of Greenland and the MAR behind it.

The study presented in this paper relates to Icelandic basalts only. The whole North Atlantic Tertiary Igneous province is estimated to comprise $5–10\times10^6$ km^3 of basaltic magma (Saunders et al., 1997). There is considerable uncertainty in this estimate as the composition of the lower crust is enigmatic (Foulger et al., 2003; Foulger and Anderson, in press). It is unknown how much might be consistent with an origin in Iapetus crust as most of it is beyond the reach of drilling or sampling, or has not been dredged. Basalts older than ~15 My in the extreme northwest of Iceland are more MORB-like than most Icelandic basalts, which might suggest significant changes in source composition at about the time the ~500-km-wide Icelandic plateau began to form. The North Atlantic Igneous Province outside Iceland might thus involve different source components from the bulk of Iceland itself. However, various features of the NAIP, including the large volume and the existence of enriched ferrobasalts, resemble Icelandic features and thus recycled eclogite may be important throughout.

8. Discussion

Our suggestion that the Iceland melt anomaly is derived from shallow structures in the mantle and processes consequential to plate tectonics is consistent with seismic tomography. This shows that seismic anomalies beneath the Iceland region are by far the strongest in the upper 250 km, with a weak tail that extends down no deeper than the transition zone (Ritsema et al., 1999; Foulger et al., 2000, 2001; Du et al., submitted for publication). Such structure is consistent with melt extraction processes being confined to the shallow upper mantle, with an unextractable (<<1%) degree of partial melt throughout the upper mantle beneath. The seismic structure is much more extensive than the island of Iceland itself (Ritsema et al., 1999). Our suggested model is consistent with the north–south tectonic and compositional asymmetry of the Iceland region, which is expected if rifting occurs above a mantle heterogeneity that is characterized by north–south asymmetry inherited from a dipping subducted slab. In such an environment, the abrupt changes in geochemistry observed across relatively small structures such as the Tjornes Fracture Zone in north Iceland are expected.

Continental breakup and rifting frequently occur along pre-existing suture zones, where they may be accompanied by high rates of magmatism. The model proposed here for Iceland may thus also apply to other "hot spots" that originated at volcanic margins in suture zones and continued to generate large melt volumes near ridges, e.g., the Tristan da Cuhna "hot spot" (Smith, 1993; Lundin and Dore, in press). Where ridge migration proceeds in a direction approximately parallel to a zone of fertility, enhanced magmatism is predicted to persist at a fixed location on the ridge. Where the direction of migration is oblique to the mantle fertility zone, the locus of enhanced melt production is predicted to migrate along the ridge, such as appears to occur at the Tristan da Cunha "hot spot" (Fairhead and Wilson, in press; Vogt and Jung, in press). Many continental flood basalts, e.g., the Deccan Traps and the Siberian Traps, also erupted in or near suture zones (Smith, 1993). At some of these, thermal anomalies and major precursory uplift have been shown to have been absent (e.g., Czamanske, 1998; Ito and Clift, 1998). Enhanced mantle fertility may also be able to explain these large melt anomalies in the absence of high temperatures.

In addition to being trapped within the continental lithosphere in collision zones, slab material may also be plated onto its lower surface, preserved there for long periods and only involved again in mantle convection after breakup occurs. The compositional variation of North Atlantic mantle revealed by regional variations in basalt geochemistry suggests that bulk lithological heterogeneities in the mantle can be maintained for long periods. Sharp changes occur in the compositions of basalts between Iceland and the Reykjanes and Kolbeinsey ridges, suggesting that the sources of the latter are mainly peridotitic, not eclogitic. If the source of Icelandic basalts is indeed eclogitic slab material, then the peridotite sources of basalts from the adjacent ridges may include even older refractory subcratonic mantle and depleted Paleozoic abyssal peridotite, in contrast to the comparatively fertile MORB mantle source that supplies many other ridges. The nearest such mantle is, as Schilling (1973) proposed, south of the Charlie–Gibbs Fracture Zone (Kempton et al., 2000). Still further south, the Azores platform features basalts with still different, more typically alkalic, compositions, found in the Azores Islands themselves. Clearly, the mantle that supplies the North Atlantic cannot be an homogeneous entity that produces variable basalts simply as a result of differences in mantle temperature, as is assumed in many models (Langmuir and Bender, 1984; Klein and Langmuir, 1987; McKenzie and Bickle, 1988).

The ideas proposed in this and our companion paper (Foulger and Anderson, in press) are embryonic and have not benefited from the three decades of sophisticated geochemical and geophysical investigation and modeling that underpins the plume hypothesis. We offer them as a prototype alternative for further testing. Predictions of our model include that “hot spots” tend to be located in regions of tectonic and structural change and complexity that are under extension, and that large melt volumes are produced where such regions lie in or near to old suture zones. Where the mantle beneath is refractory, small melt volumes only are produced. The spatial distribution of melt is predicted to correlate with surface tectonic features. Geochemical signatures are predicted to be consistent with recycled oceanic lithosphere and/or continental mantle lithosphere, and large melt volumes are predicted have geochemistry consistent with remelted eclogite from subducted oceanic crust. Melt extraction processes will tend to be shallow, and associated seismic anomalies will not extend into the deep mantle. Globally, “hot spots” will correlate only weakly with high mantle potential temperature anomalies.

9. Conclusions

(1) The geochemistry, melt volume and paucity of evidence for elevated temperatures in the source of basalts in the Iceland region are consistent with derivation from extensive melting of subducted Iapetus ocean crust trapped in the Laurasian continental mantle lithosphere at the time of Caledonian suturing. The crust involved was probably the latest to be subducted prior to closure of the Iapetus Ocean, may have been relatively hot, and reached neutral buoyancy in the shallow upper mantle. It was recycled into the convecting mantle beneath the north Atlantic by lithospheric delamination.

(2) Fractional remelting of abyssal gabbro as eclogite, along with a component of E-MORB, can explain the major-, trace- and rare-earth-element compositions, and the isotopic characteristics of primitive Icelandic tholeiite. Basalts ranging from ferrobasalt to olivine tholeiite result from various degrees of partial melting of eclogite. The occurrence of substantial oxide gabbro crystallized from ferrobasalt in the lower crust of Iceland may explain the anomalously high densities there.

(3) High $^{3}He/^{4}He$ ratios may result from the preservation of old helium either in U+Th-poor residual mantle of Caledonian or Archaean age still in the melt region, or in olivine-rich cumulates from which late-stage, U+Th-bearing melt was excluded during crystal growth and expelled during compaction.

(4) The subducted Iapetus oceanic crust recycled beneath Iceland must have been thickened by emplacement at a high angle, imbrication or other deformation, in order to be able to supply the large volumes of melt required to build the thick crust of Iceland.

(5) High rates of melt extraction have persisted for ~ 54 My at the MAR in the Iceland region. If the MAR is migrating laterally with respect to deeper mantle, the zone of fertility being tapped must be orientated parallel to the plate motion direction. The Greenland–Iceland–Faeroe ridge is approximately colinear with the western frontal thrust of the Caledonian collision zone, beneath which the crust currently being recycled may have been stored.

(6) Continental breakup and flood-basalt eruption often occurs near or within old sutures and collision zones. Similar processes may thus explain “hot spots” and large igneous provinces elsewhere that are traditionally attributed to plumes.

Acknowledgments

We thank Seth Stein, Jerry Winterer, Warren Hamilton, Dean Presnall and Peter Vogt for helpful input, and Wes Hildreth and Peter Wyllie for thoughtful reviews of early drafts of the manuscript. Careful reviews by J. Godfrey Fitton and Lotte M. Larsen, who do not necessarily ascribe to the ideas described herein, improved the paper. The work was supported by NERC grant GR3/10727 and a Sir James Knott Foundation Fellowship held by GRF.

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