

Origin of Icelandic basalts: A review of their petrology and geochemistry

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Abstract

The petrology and geochemistry of Icelandic basalts have been studied for more than a century. The results reveal that the Holocene basalts belong to three magma series: two sub-alkaline series (tholeiitic and transitional alkaline) and an alkali one. The alkali and the transitional basalts, which occupy the off-rift volcanic zones, are enriched in incompatible trace elements compared to the tholeiites, and have more radiogenic Sr, Pb and He isotope compositions. Compared to the tholeiites, they are most likely formed by partial melting of a lithologically heterogeneous mantle with higher proportions of melts derived from recycled oceanic crust in the form of garnet pyroxenites compared to the tholeiites. The tholeiitic basalts characterise the mid-Atlantic rift zone that transects the island, and their most enriched compositions and highest primordial (least radiogenic) He isotope signature are observed close to the centre of the presumed mantle plume. High-MgO basalts are found scattered along the rift zone and probably represent partial melting of refractory mantle already depleted of initial water-rich melts. Higher mantle temperature in the centre of the Iceland mantle plume explains the combination of higher magma productivity and diluted signatures of garnet pyroxenites in basalts from Central Iceland. A crustal component, derived from altered basalts, is evident in evolved tholeiites and indeed in most basalts; however, distinguishing between contamination by the present hydrothermally altered crust, and melting of recycled oceanic crust, remains non-trivial. Constraints from radiogenic isotope ratios suggest the presence of three principal mantle components beneath Iceland: a depleted upper mantle source, enriched mantle plume, and recycled oceanic crust.

The study of glass inclusions in primitive phenocrysts is still in its infancy but already shows results unattainable by other methods. Such studies reveal the existence of mantle melts with highly variable compositions, such as calcium-rich melts and a low-¹⁸O mantle component, probably recycled oceanic crust. Future high-resolution seismic studies may help to identify and reveal the relative proportions of different lithologies in the mantle.

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1. Introduction

During the first half of the 20th century, petrology in Iceland revolved largely around three theoretical problems: (a) the paradox that despite being a part of the mid-Atlantic ridge, Iceland appeared to distinguish itself from it petrologically, (b) the relationship between the sub-alkalic and alkalic magma suites, and (c) the origin of the silicic rocks in Iceland, which were thought to be abnormally voluminous compared to other oceanic islands. Arthur Holmes (1918), inspired by Alfred Wegener's theory of continental drift, proposed that Iceland is underlain by sialic crust, left between Greenland and Europe when the Atlantic Ocean opened. He also published the first variation diagram of Icelandic rock compositions that suggested that the basalt belonged neither to the "Atlantic" (alkalic) nor the "Pacific" (calc-alkalic) suite, thus pointing the way to the third suite, the tholeiitic. Holmes pointed out the main characteristics of the "Thulean suite", i.e. high Ti and Fe, and silica saturation.

Peacock (1925, 1926, 1931) embarked on a major project entitled "The Petrology of Iceland" which partly was based on samples he collected in an excursion with G.W. Tyrrell to Iceland in 1924. Based on his analyses he divided Icelandic rocks into two main suites, "an earlier calc-alkali series and a later series of mildly alkalic character." The alkalic basalts evolve, according to him, to trachyte whereas the calc-alkalic series evolves to rhyolite. Tom Barth (1952), in his *Theoretical Petrology*, thinks that Icelandic rocks resemble in some respect continental volcanics, i.e. tholeiitic series, which may be influenced by "patches of sialic continental crust underneath the Thulean basalt plateaux." And Noe-Nygaard (1966) reiterates that the Fe- and Ti-rich characteristics of the Thulean province, first suggested by Holmes (1918), distinguish it from mid-ocean ridge basalts. According to him, Icelandic volcanics reflect their twofold origin, with the Tertiary formation belonging to the Wyville–Thompson ridge, the Quarternary formation to the mid-Atlantic ridge. Two years earlier, Bodvarsson and Walker (1964) had shown how the entire Icelandic rock suite is formed in the rift zones as a result of the more or less continuous spreading of the ocean floor, and that all Tertiary rock types have their counterparts in Quarternary and Holocene volcanic centres, even though the latter may appear to be more varied petrologically.

Regarding the question of the silicic rocks (treated separately in this volume), Holmes' (1918) contention that Iceland is underlain by old sialic crust prevailed until 1965 when, at George Walker's instigation it was conclusively shown by Sr-isotope analyses that the silicic and basaltic rocks are consanguineous (Moorbath and Walker, 1965). Reflecting the continental (on both sides of the Atlantic) age-long feud between proponents of granitization and crystal fractionation, respectively, the evolved rocks in individual volcanic centres were attributed to either remelting of sialic crust (e.g. Walker, 1964; van Bemmelen and Rutten, 1955; Tryggvason, 1965) or crystal fractionation (Einarsson, 1950; Carmichael, 1964).

The birth of Surtsey Island (1963) and the theory of plate tectonics coincided with a new spurt in petrologic studies of Icelandic rocks. After years of detailed geological mapping in eastern Iceland, George Walker and his students discovered that the Tertiary lava pile was constructed of central volcanoes and associated dyke or fissure swarms. Silicic rocks and evolved basalts characterized the central volcanoes whereas more primitive basalts were confined to the distal fissure swarm. Together these two structural units form a volcanic system. One of these systems, Thingmuli, was the subject of a detailed petrologic study by Carmichael, one of Walker's students. The simultaneous scientific revolution of plate tectonics and the technological invention of the electron microprobe (EMP) made Carmichael's study a true breakthrough in petrologic understanding. First, his detailed study of systematic major-element compositional variations in a whole magma suite, from primitive basalts to rhyolites, became a classical example of a tholeiitic magma series related to extensional tectonics (Carmichael, 1964). For instance, icelandites are now known to stand for Fe-rich andesites, the intermediate rock name of the tholeiitic series. Second, the variability of the whole-rock compositions was shown to be reflected in the mineral solid-solution compositions, traceable by the EMP (Carmichael, 1967). At Surtsey, the EMP was used to relate the mineral composition to intensive parameters such as temperature and oxygen fugacity yielding coherent results with those derived from state-of-the-art volcanic gas analysis (Sigvaldason and Elisson, 1968; Steinthórsson, 1972). These studies emphasized a more analytical or quantitative approach to petrogenetic research than before, and can be considered to mark the beginning of modern petrologic investigations in Iceland.

In this review, we try to synthesize the different interpretations and speculations on the origin of basaltic rocks in Iceland, and discuss how some ideas have been strengthened by additional results whereas others have been abandoned. Inevitably, the review reflects to some extent the authors' conception of which interpretations and speculations have passed the test of time. A chronological order is followed, discussing the most important, peer-reviewed papers in the

order they were published to track the evolution of the proposed ideas, which at the same time reflects the evolution of analytical techniques in petrology.

2. Holocene basalts

2.1. Major-element composition and tectonics

In the early 1970s, [Jakobsson \(1972\)](#) compiled available basalt analyses and illustrated a systematic compositional variation according to tectonic setting. Basalts of the tholeiitic series are only produced in the active rift-zones of Iceland whereas those of the alkalic series are confined to the two off-rift volcanic zones, in South-Iceland and the Snæfellsnes Peninsula ([Fig. 1](#)). He also proposed a third magma series, the “transitional alkali series” having abnormally high alkali metals, iron and titanium concentrations for silica-saturated basalts. Basalts of this series geographically link the two others both in South-Iceland ([Jakobsson, 1972](#)) and in Snæfellsnes Peninsula ([Sigmarsson et al., 1992a](#)). Furthermore, [Jakobsson \(1979\)](#) observed that each volcanic system generally appeared to be compositionally distinctive.

2.2. Implications of a mantle plume and trace element constraints

In a now-classic paper, [Schilling \(1973\)](#) demonstrated a systematic geographical variation in incompatible elements, including rare-earth elements (REE) and their ratios (e.g. La/Sm) along the Reykjanes Ridge, which he attributed to two different mantle sources, a mantle plume beneath Iceland and a normal oceanic upper mantle ([Fig. 2](#)). These results prompted similar studies along the Icelandic rift-zones ([Brooks and Jakobsson, 1974](#); [Sigvaldason et al., 1974](#); [Sigvaldason and Steinthórsson, 1974](#)) which showed continuation in this trend, with maximum values of large-ion lithophile elements (LILE) reached in Central Iceland. However, depleted olivine tholeiites, similar to mid-ocean ridge basalts (MORB), were also found to be present in Central Iceland and elsewhere in the rift-zones. This pattern,

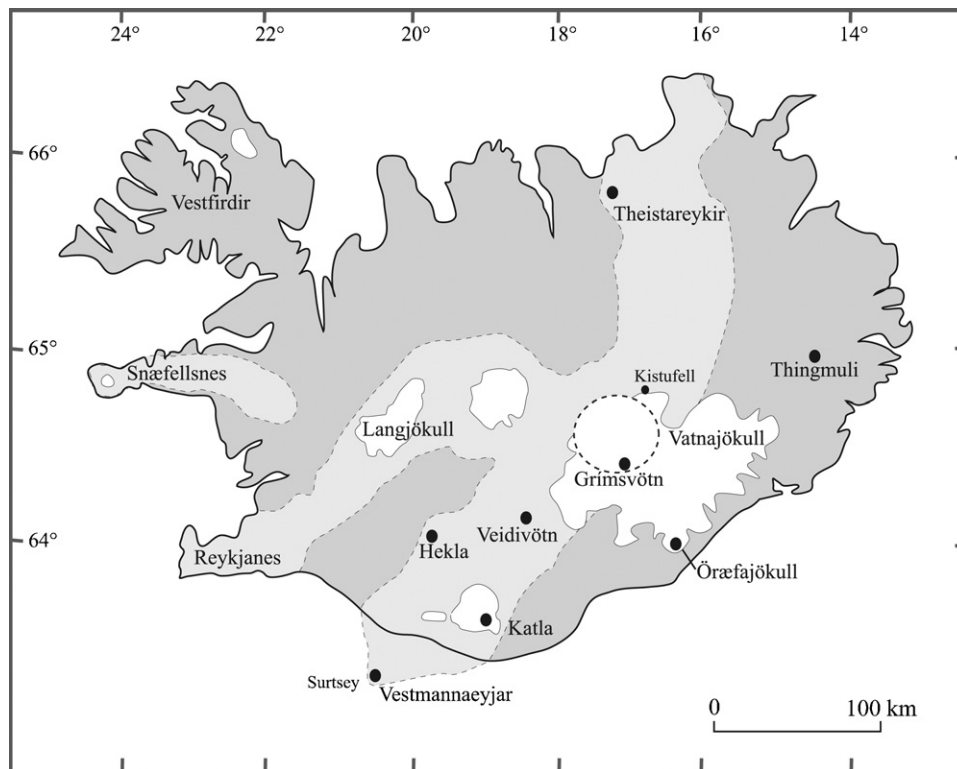


Fig. 1. Map of Iceland showing neovolcanic rift zones and off-rift zones, presumed centre of the mantle plume and localities discussed in the text. The off-rift zones occupy the Snæfellsnes Peninsula and South-Central Iceland.

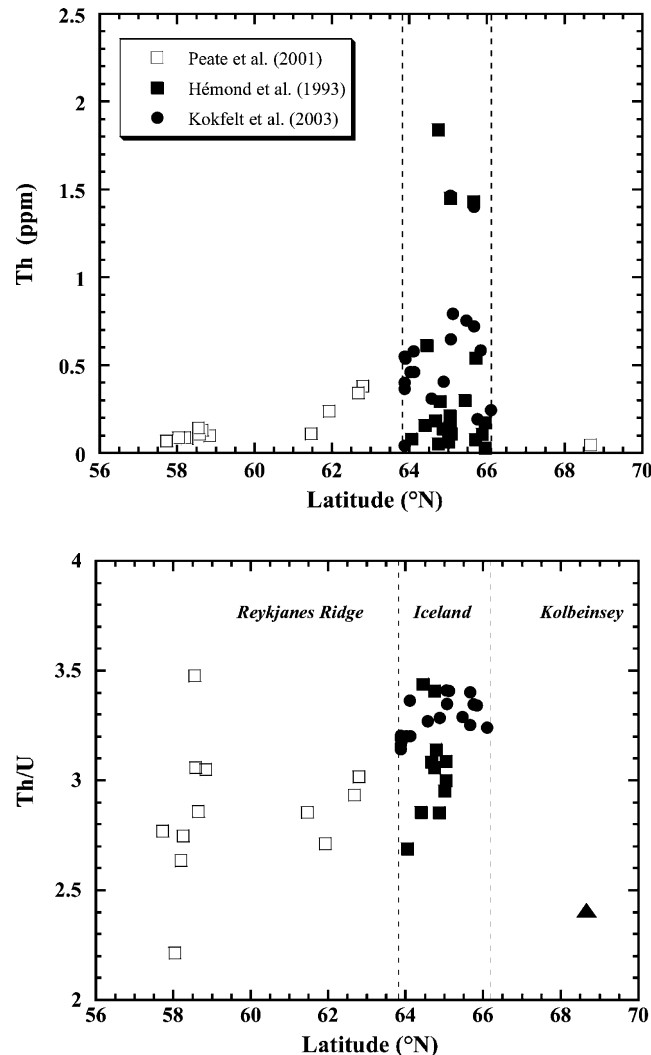


Fig. 2. Variations in Th concentration and Th/U measured by isotope dilution in basalts from Reykjanes Ridge (Peate et al., 2001), along the rift-zone through Iceland and Kolbeinsey Island (Hémond et al., 1993; Kokfelt et al., 2003). Thorium is an incompatible LILE with an analogue behaviour to K in basalts. High concentrations in LILE in Central Iceland have been taken to indicate the presence of a hot spot there whereas the low concentrations are consistent with remelting of a depleted mantle plume material. The highest Th values are from more differentiated basalts. The variability of Th/U is greater in Reykjanes Ridge basalts than those from Iceland, which at face value may indicate the presence of the mantle plume in their source region (see text for further discussion). However, no replicate analyses are available for the extreme Th/U south of Iceland and, therefore, the consistency of the results cannot be evaluated. The value for Kolbeinsey is inferred from Sims and Hart (2006).

therefore, was thought to contradict Schilling's model and rather to reflect variable melting degrees of a single mantle source. It was emphasized (Sigvaldason et al., 1974) that both low- and high-K basalts are produced on the same fissure swarm. This debate was global, since trace element abundances and their ratios in basalts are both affected by the source composition and the extent of mantle melting. A better tracer of the magma source, inert to processes of melting and crystallization, was therefore needed.

2.3. Magma sources and isotope ratios

As mentioned in the Introduction, the relatively low and similar $^{87}\text{Sr}/^{86}\text{Sr}$ -ratios of Icelandic basalts and rhyolites (Moorbath and Walker, 1965) clearly demonstrated the absence of a continental crust beneath the country. The full power of this tracer was illustrated in the first systematic study of the geographical variations of $^{87}\text{Sr}/^{86}\text{Sr}$ in basalts

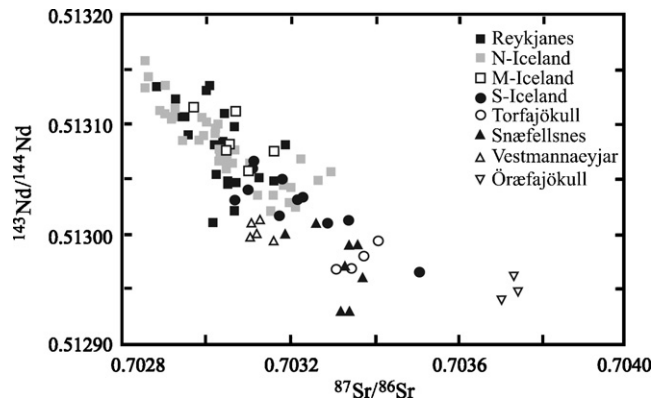


Fig. 3. Covariation of Nd and Sr isotope ratios in Icelandic basalts showing a significant spread that requires at least three mantle components in the source region. This spread can be explained by mixing of melts from a MORB source with high $^{143}\text{Nd}/^{144}\text{Nd}$ and low $^{87}\text{Sr}/^{86}\text{Sr}$, and two enriched component with low $^{143}\text{Nd}/^{144}\text{Nd}$ but variably high $^{87}\text{Sr}/^{86}\text{Sr}$. Results from Thirlwall et al. (2004) and references therein, and Carpentier and Sigmarsson (in preparation). New results from Kokfelt et al. (2006) confirm the displayed variations.

along the Reykjanes Ridge (Hart et al., 1973), revealing more radiogenic Sr in basalts on Iceland. This was further confirmed by more radiogenic Pb inland, illustrating that mantle plume mixing along the Reykjanes Ridge was most probable (Sun et al., 1975; Sun and Jahn, 1975). Moreover, a correlation was apparent in the basalts between Sr isotope ratios, LREE/HREE, and Nd isotope ratios (O’Nions et al., 1976, 1977), which confirmed the existence of more than one mantle source beneath Iceland (Fig. 3). However, at the same time, studies of oxygen isotopes revealed exceptionally low- $\delta^{18}\text{O}$ (down to 1.8‰) in the more evolved basalts from a given fissure swarm (Muehlenbachs et al., 1974), so low that they could clearly not be of mantle origin only. Compared to MORB with “normal” $\delta^{18}\text{O}$ (5.5–6‰), the low- $\delta^{18}\text{O}$ basalts had to record magma interaction with the hydrosphere, either directly or via geothermal alteration.

2.4. Crustal contamination

A part of the LILE-variation in the basalts and the low oxygen isotope ratios could thus, according to Óskarsson et al. (1982), be better explained by contamination of primitive olivine tholeiites by the hydrothermally altered basalt crust. With reference to Palmason’s (1973) kinematic model of crustal accretion, these authors also attributed the origin of silicic rocks in Iceland to partial melting of metabasalts in the amphibolite facies, leaving restites that upon further melting could generate undersaturated alkali basalts (Steinthórsson et al., 1985). Óskarsson et al. (1982, 1985) thus advocated a simple model involving just one mantle melt (olivine tholeiite) together with large and variable crustal influence to explain the origin of all rock types in Iceland. This model appeared to explain lower $^3\text{He}/^4\text{He}$ in evolved – and thus LILE-enriched – tholeiites (Condomines et al., 1983) and the correlation between Sr, Th and O isotope ratios in basalts along the rift-zones, given the assumption of high $^{87}\text{Sr}/^{86}\text{Sr}$ in the siliceous crustal melts and lower but restricted values for the mantle (Hémond et al., 1988). It should be noted, however, that these studies were mostly based on a rather dispersed sampling of lavas having variable ages, and that different interpretations were reached in studies based on finer sampling scale, both in time and space.

2.5. Mantle heterogeneity

Detailed geochemical studies of individual volcanic systems started with the study of Zindler et al. (1979) of basalts from three fissure swarms in the Reykjanes Peninsula (Jakobsson et al., 1978). They observed significant variations in $^{143}\text{Nd}/^{144}\text{Nd}$ that correlated negatively with chondrite normalized $[\text{La}/\text{Sm}]_{\text{N}}$, illustrating small-scale mantle heterogeneity beneath the Reykjanes Peninsula. Variable $[\text{La}/\text{Sm}]_{\text{N}}$ was also observed by Meyer et al. (1985) in basalts from further north along the Reykjanes-Langjökull rift-zone as well as in several volcanic systems from the South-Iceland volcanic zone. In combination with published isotope results from the same volcanic systems, these variations were explained in terms of increasing melting of a heterogeneous mantle source towards Central Iceland. This appeared particularly appropriate for the geographical variations along the South-Iceland volcanic zone, with

alkali basalts in the Vestmannaeyjar volcanic system in the south, transitional alkali basalts at Katla and Hekla further north in the non-rifting volcanic zone, and tholeiites in the Veidivötn and Grímsvötn volcanic systems in the rift zone. Moreover, the compositional variation correlates to a first degree with the increasing volume of Holocene basalts inland (Jakobsson, 1979), as could be expected for an immature propagating rift segment. Meyer and co-workers speculated that the rift propagation might have been caused by a blob of the mantle plume that had spread out laterally. Alternative to this mantle plume/blob concept of Schilling et al. (1982) was the suggestion of a lithologically veined mantle originally proposed by Wood (1979, 1981). These two concepts differ profoundly in that the former relates the variable basalt compositions to a depleted upper mantle and undepleted mantle plume, whereas the latter concept favours two-stage melting of a single mantle modified by in situ melt migrations and sufficient time to produce evolved isotope ratios. However, all these studies ignored the stable isotope constraint of $\delta^{18}\text{O}$ that clearly requires interaction with the hydrosphere. In the mid-1980s, the studies of Icelandic basalts had thus diverged in two mutually exclusive directions: (1) single mantle-melt and dominating crustal control on basalt compositions, or (2) negligible crustal contamination but diverse mantle-melts from a heterogeneous asthenospheric mantle.

2.6. Hybrid models

With this knowledge at hand, several studies were undertaken in which detailed sampling of individual volcanic systems was combined with geochemical investigation involving simultaneously major- and trace-elements, and stable and radiogenic isotope ratios (O, Sr, Nd and Th) (e.g. Furman et al., 1991; Nicholson et al., 1991; Sigmarsson et al., 1991, 1992a,b; Hémond et al., 1993). Based on several criteria, these studies assumed that direct mantle melts should have $\delta^{18}\text{O}$ in the range 5.0–6.0‰, and that those basalts having higher or lower values were recording low-temperature alteration or crustal contamination, respectively. Applying this criterion to new results and the existing compositional database for Recent basalts, it became clear that only alkali basalts, olivine-tholeiites, and picrites could give unambiguous information about the mantle reservoirs and melting processes. Alkali basalts from the Snæfellsnes volcanic zone could reflect melting of an isotopically and chemically enriched component of the Icelandic mantle whereas more depleted parts of the mantle gave rise to the picrites and olivine tholeiites. Alkali basalts from Vestmannaeyjar (Fig. 1), at the tip of the propagating rift in South-Iceland, were best explained by smaller-degree melting of a similar mantle source as that beneath the Reykjanes Peninsula.

2.7. Lherzolite melting models

The picrites and olivine-tholeiites from the Reykjanes Peninsula, as well as those from Theistareykir in North-Iceland, attracted much attention in the last decade of the past century. Following physical melting models of McKenzie and co-workers (McKenzie, 1984; McKenzie and Bickle, 1988; Watson and McKenzie, 1991), in which different mantle temperatures and decompression melting were given more attention, the potential influence of the thermal regime induced by the mantle plume was considered. McKenzie and O'Nions (1991) inferred from REE spectra that melting probably begins at the depth of the spinel/garnet transition in a lherzolitic mantle. Elliot et al. (1991) suggested that picrites and olivine-tholeiites from the Reykjanes Peninsula and Theistareykir were best explained by the mixing of instantaneous melts formed by different degrees of melting at variable depth, not much different from the proposition of Zindler et al. (1979), whereas mixing of mantle melts and crustal contamination was favoured by Gee et al. (1998a). Faulty (Hanan and Schilling, 1997) Pb-isotope analyses led Elliot and co-workers, and also Thirlwall (1995), to propose a highly depleted mantle domain within the plume beneath Iceland. The existence of such a depleted plume-component is still advocated by several workers (Kerr et al., 1995; Fitton et al., 1997; Kempton et al., 2000; Eiler et al., 2000) whereas others consider it to be a misconception (Hanan et al., 2000). This debate appears to be mainly semantic in nature—whether the refractory mantle giving rise, through decompression melting, to the most primitive basalts was formed during an earlier melting event, or as an integral result of the evolution of the continuously melting mantle plume.

In particular, the depleted nature of the basalts from Theistareykir has attracted many workers and led to the publication of numerous papers (e.g. O'Nions et al., 1976; Elliot et al., 1991; Hémond et al., 1993; Eiler et al., 2000; Sigurdsson et al., 2000; Skovgaard et al., 2001; Slater et al., 2001; MacLennan et al., 2003a,b; Stracke et al., 2003a,b; Thirlwall et al., 2004). In essence, these studies have not yet reached a consensus about the origin of these primitive basalts but they illustrate either fine-scale mantle heterogeneity or crustal contamination of the depleted mantle melts.

2.8. Subducted crust beneath Iceland?

Oxygen isotopes measured in crystal separates from the primitive Theistareykir basalts reveal not only mantle-like $\delta^{18}\text{O}$ values but very low values as well ($\delta^{18}\text{O}$ lower than 4‰: Eiler et al., 2000; Skovgaard et al., 2001; MacLennan et al., 2003a). Hitherto, such low- $\delta^{18}\text{O}$ have in Iceland been taken as a certain indication of crustal contamination. However, although these results strongly suggest crustal involvement in the basalt genesis, they do not distinguish between interaction with the present crust and partial melting of an older recycled oceanic crust in the mantle source. Skovgaard et al. (2001) compared O isotopes with those of Os in samples from lava flows already studied by others, and showed that their results were best explained by the mixing of melts from recycled oceanic lithosphere. A recycled component in the mantle beneath Theistareykir now also appeals to Stracke et al. (2003a,b) and MacLennan et al. (2003a). However, it is not certain that these studies represent analytical results from the same statistical population. Whereas major- and trace-element concentrations are obtained on whole-rocks and melt inclusions, and radiogenic isotopes are measured on whole-rocks, the O-isotopes reveal variations in the minerals only. The occurrence of disaggregated nodules in some of the lava flows (MacLennan et al., 2003a) suggests that at least some of the minerals could have crystallized from different melts, or magma batches, having diverse histories. Such a situation calls for the utmost care in ascribing chemical parameters derived from different objects to the same population. Indeed, disagreement between different laboratories on high-precision Pb and Hf isotope measurements (Hanan et al., 2000 versus Fitton et al., 2003; Baker et al., 2004, 2005 versus Albarède et al., 2005) on samples from the same lava flow may, in part at least, be due to sample heterogeneity. This is especially true for isotopes of elements that are incorporated in crystals, such as O (silicates, oxides), Pb and Os (sulphides).

Nevertheless, melting of a subducted oceanic crust could be considered as an alternative source for the enriched Icelandic basalts as has been suggested for other oceanic islands (Hofmann and White, 1982). This was done by Chauvel and Hémond (2000) and Kokfelt et al. (2006) who took an extreme point of view by proposing that all basalts in Iceland are derived from the partial melting of recycled oceanic crust. Although this interpretation neglects the constraints provided by rare gases such as He-isotopes, the importance of lithological heterogeneity in the Iceland mantle in generating different basalts must be considered.

2.9. Potential effects of the Pleistocene deglaciation

Comparison of trace-element ratios in Holocene and Pleistocene basalts from Vestmannaeyjar and Snæfellsnes, the two alkali-basalt regions in Iceland, suggested accelerated mantle melting due to pressure release caused by the deglaciation around 11 ky ago (Hardarson and Fitton, 1991). The effect of rapid deglaciation on mantle-melting rates has also been discussed for Theistareykir (Slater et al., 1998), and melt-production rates up to a factor of 30 times higher than today have been proposed (e.g. Jull and McKenzie, 1996; MacLennan et al., 2002 and references therein). Similar observations are, however, explained for the Reykjanes Peninsula by crustal contamination (Gee et al., 1998b). These models, which assume instantaneous melt escape from a lithologically and compositionally homogeneous mantle, are still in their infancy, but they do illustrate a probable and interesting link between the exogenic and endogenic processes.

3. Pleistocene basalts

To date, surprisingly few petrological and geochemical studies have been undertaken on the Pleistocene formation in Iceland. This formation is characterized by the intercalation of hyaloclastites (palagonitized volcanic glasses) and lava flows that represent the alternation of glacial and interglacial periods, respectively. Subglacial eruptions gave rise to table mountains (tuyas) and hyaloclastite ridges rather than shield volcanoes and crater rows, respectively. Unfortunately, owing to incomplete geological mapping the temporal and spatial distribution of the different rock formations is often unclear. In an EMP study of Pleistocene glasses from South-Iceland and Snæfellsnes, Thy (1982) showed that compositionally they differ little from Holocene lavas and probably record variations induced by polybaric crystallization. A more recent study of a single monogenetic table mountain, Kistufell, located close to the centre of the Iceland mantle plume (Fig. 1), suggests that its high-MgO basalts may represent melting of a recycled oceanic gabbro (Breddam, 2002). However, the association of low $\delta^{18}\text{O}$ and high He-isotope ratios in Kistufell, which strongly suggest a relatively undegassed mantle reservoir, may be better explained by the interaction of a primitive mantle melt with hydrothermally modified crustal gabbros containing little helium.

At the base of many table mountains, pillow lavas with glassy rims are exposed and these rims have retained enough of their original magmatic gases to allow reliable analysis of rare-gas isotopes (e.g. Kurz et al., 1985; Breddam et al., 2000; Moreira et al., 2001; Dixon, 2003). Whereas MORB has uniform $^3\text{He}/^4\text{He}$ of 8 ± 1 times the atmospheric ratio (Ra), subglacial pillow glasses have values as high as 26 (R/Ra). Moreover, ratios higher than 20 coincide with a gravity low in Central Iceland and may delineate the conduit of the mantle plume (Breddam et al., 2000 and references therein). These high He-isotope ratios can be considered primordial since they are associated with solar-like neon isotope ratios (Moreira et al., 2001). They thus strongly indicate the presence of an undegassed mantle reservoir that is being sampled by the Iceland mantle plume and is recorded in the Pleistocene basaltic glasses. Moreover, Breddam et al. (2000) showed that the He-isotope ratios are decoupled from those of Pb and $[\text{La}/\text{Sm}]_{\text{N}}$, whereas they correlate with highly incompatible element ratios, such as Nb/Th. This can be explained if the very first mantle melts form at the wet solidus at depths below 100 km, and migrate fast towards the surface relative to the low-degree-melts-depleted mantle which melts due to decompression at the dry solidus (Breddam et al., 2000). Such a scenario concurs with (a) rheological models indicating lateral spread of the mantle plume at greater depths than the dry solidus (Ito et al., 1999), (b) relatively high $^3\text{He}/^4\text{He}$ away from the plume centre, for instance in the alkaline basalts of the Vestmannaeyjar archipelago (Kurz et al., 1985), as well as (c) indications for radium-rich fluid inducing flux-melting beneath the island Surtsey (Sigmarsson, unpublished results). Moreover, the dehydration melting model also accounts for the bell-shaped along-axis variations of potassium over Iceland, and implies considerable source heterogeneity within the mantle plume itself (Ito et al., 1999; Thirlwall et al., 2004).

Such channelled flow of plume material has often been visualized beneath the Reykjanes Peninsula and Ridge, forming the well-known V-shaped ridges on either side of the Reykjanes Ridge (e.g. Vogt, 1971; Ito, 2001). Again, relatively high He isotopes agree with such plume flow and the radiogenic-isotope ratios as well (Hilton et al., 2000). Elsewhere at the periphery of the volcanic zones in Iceland, crystals separated from Holocene lava flows display He-isotope composition with significantly lower R/Ra. For instance at Theistareykir in the north, values similar to those of MORB are observed (Breddam et al., 2000), whereas crystals from lavas in both the westernmost part of Snæfellsnes and Öraefajökull in the SE have R/Ra lower than MORB (Sigmarsson et al., 1992a). These latter basalts, having the lowest $^3\text{He}/^4\text{He}$, are best explained by the melting of a mantle source having a recycled oceanic crust component (see below). Finally, the variable and high He isotopes provide a first-order argument against the veined-mantle melting model since high R/Ra cannot be generated by radioactive decay through time.

4. Tertiary basalts

Despite their large volume, Tertiary basalts in Iceland have been subject to only a very few investigations (e.g. O'Nions and Pankhurst, 1973; Wood, 1978; Schilling et al., 1982; Hanan and Schilling, 1997; Hardarson et al., 1997). On average, the Tertiary basalts show more restricted compositional variation than their Holocene counterparts, which can be attributed to the accretion mechanism at the active rift-zones (Hardarson et al., 1997). Significant secular variations may exist in Sr-isotope compositions (O'Nions and Pankhurst, 1973) and the Pb-isotopes show the strongest radiogenic signal in 7–8 Ma old basalts which coincides with the formation of the V-ridges south of Iceland (Hanan and Schilling, 1997). This may suggest a link between the mantle plume activity and crustal accretion on the Reykjanes Ridge. In-depth interpretation of the Pb-isotopes reveals a possible contribution from a continental lithosphere during basalt genesis and that this contribution has decreased with time (Hanan and Schilling, 1997). It is noteworthy that the highest He-isotope ratios (Hilton et al., 1999) have been found in the Tertiary basalt of Vestfirðir (the NW Peninsula; Fig. 1), and further studies of the older basalt formations in Iceland may well give rise to many unexpected results.

5. Current understanding and further speculations

The Pb-isotope studies of Hanan and Schilling (1997) and Thirlwall et al. (2004) clearly show that at least three mantle components are needed to explain the variability recorded in Icelandic basalts. These components are probably (1) a depleted upper mantle source similar to that of MORB, (2) a mantle plume with high- ^3He lower mantle source, and (3) recycled oceanic crust randomly dispersed in the mantle. In addition, the Tertiary basalts most likely record contribution from continental lithosphere that was left as a splinter beneath the eastern fjord of Iceland after the breakup of Greenland and Europe (Pacquette et al., 2006). This component appears to contribute much less to the basalt generation during Holocene, although the anomalous magmas produced at Öraefajökull may reflect its presence

beneath eastern Iceland. The recycled oceanic crust is likely to be of variable composition, forming eclogite or garnet-pyroxenite at depth that upon adiabatic decompression will undergo partial melting before the enclosing lherzolite (e.g. Hirschmann and Stolper, 1996). Such melting would yield either ne-normative alkali basalts (e.g. Sigmarsson et al., 1998; Hirschmann et al., 2003) or qz-normative basalts (e.g. Pertermann and Hirschmann, 2003) depending on the composition of the pyroxenite. Upon mixing with large melt fractions from lherzolite, the initial mantle melts become diluted in incompatible elements before erupting at the surface. The composition of basalts at surface would therefore depend on several factors such as: (1) the nature of the mantle sources, (2) age and composition of the recycled crust, (3) proportion of garnet pyroxenite in the melting mantle and the relative proportions of melts derived from lherzolite and pyroxenite in the final mixture, and (4) temperature and pressure conditions during melting. Finally, interaction with hydrothermally altered crust will further blur the composition of the true mantle melt.

The variation in basalt composition ranging from alkali basalts through transitional alkali basalts to tholeiites along the off-rift volcanic zones of Snæfellsnes and South-Iceland can be explained by the presence of pyroxenites in the Iceland mantle source. The mantle temperature is expected to be lowest beneath the periphery of the island, farthest

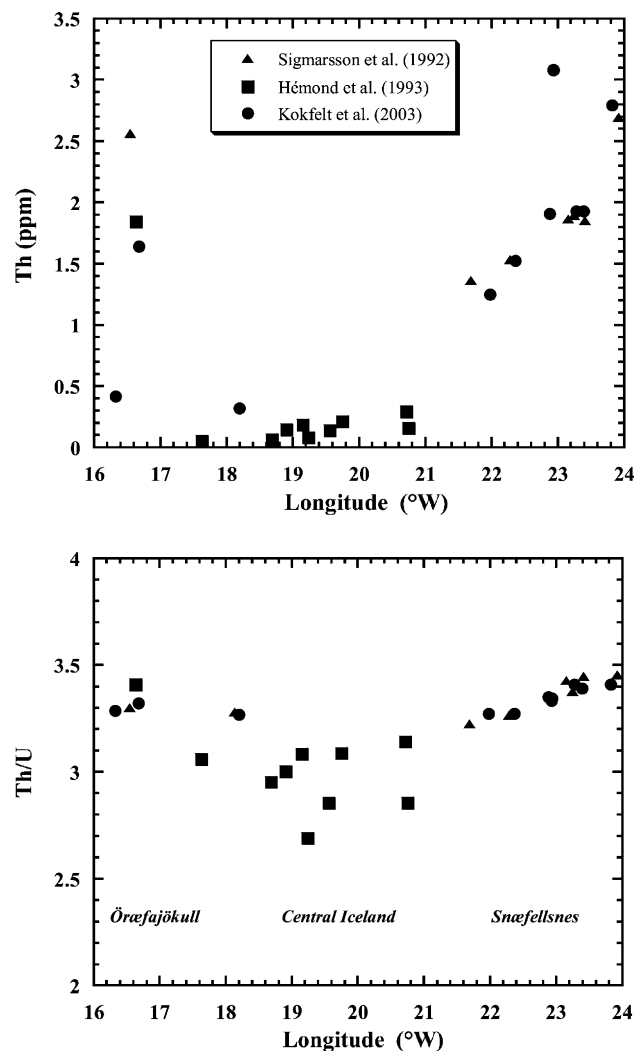


Fig. 4. High-precision analyses of Th concentration and Th/U in Holocene basalts across Iceland. Only basalts from the Snæfellsnes off-rift zone, the mid-Iceland belt and Öraefajökull are used to illustrate the high Th and Th/U values at the periphery of the island where the rift-zone influence is minimal or absent. These variations are positively correlated with the isotope ratios of Sr and therefore a source feature (Carpentier and Sigmarsson, in preparation). Increased dilution of melts from garnet pyroxenite towards the centre of Iceland, where higher mantle temperature is expected, readily accounts for the lower Th/U there (see text for further discussion).

away from the plume centre. In that case, ne-normative pyroxenite melts would be least diluted by lherzolite melts farthest away from Central Iceland (Fig. 4). The increasing alkaline character of basalts towards the periphery is indeed what is observed along the South-Iceland and Snæfellsnes Volcanic Zones (Jakobsson, 1972; Sigmarsson et al., 1992a). Moreover, Stecher et al. (1999), Chauvel and Hémond (2000) and Kokfelt et al. (2006) showed that the most radiogenic Pb-isotope ratios are found in alkali basalts from Snæfellsnes which concurs with the idea that these basalts represent the clearest signal of melts from pyroxenitic lithology. The high- ^3He signature in Vestmannaeyjar compared with He in alkali basalts from Snæfellsnes and Öraefajökull basalts suggests that the initial and relatively water-rich plume melts are more readily diverted south along the propagating rift rather than east and west across the rift-zones.

Although individual volcanic systems produce basalts of relatively uniform isotope compositions, different volcanic systems possess distinctive isotope signatures (Sigmarsson et al., 1992a,b, 2000; Furman et al., 1995). The scale of heterogeneity in the mantle therefore appears to correspond to that sampled by individual volcanic systems. Alternatively, mantle melts having variable compositions derived from heterogeneous source regions are accumulated and thoroughly mixed in deep-seated reservoirs yielding basalts with homogeneous isotope ratios at the surface. High-resolution seismic studies and melt inclusions in early-formed crystals may enable us to distinguish between these two possibilities.

6. Inclusions

The last one-and-half decades have seen increasing interest in melt and fluid inclusions in minerals of Icelandic volcanics. Melt inclusions in early crystals can provide a window to processes at depth, the traces of which are to a large extent obliterated by later petrological events. These include the composition of instantaneous melt fractions at different depths (Steinthórsson and Sigurdsson, in preparation), depth of formation of the minerals and various processes influencing the melt composition (Gurenko et al., 1991, 1992; Gurenko and Sobolev, 2006; Hansteen, 1991), evidence of heterogeneity in the upper mantle (Sigurdsson et al., 2000; Gurenko and Chaussidon, 2002), and trace-element and isotope chemistry of liquids at depth (Gurenko and Chaussidon, 1995, 2002; Slater et al., 2001). Results to date indicate that Cr-spinels from rift- and off-rift primitive basalts in Iceland, respectively, form two distinct compositional groups. The inclusions in these minerals and in primitive olivines show a large compositional range both in terms of major elements, trace elements, and oxygen isotopes. The olivines contain both enriched and depleted melts whereas the inclusions in Cr-spinel are exclusively depleted (Gurenko and Chaussidon, 1995; Sigurdsson et al., 2000; Steinthórsson and Sigurdsson, in preparation). Holocene melts from both the western rift zone and the Snæfellsnes off-rift volcanic zone are saturated with CO_2 at 2–4 kbar pressure and relatively low in water (Hansteen, 1991; Gurenko and Chaussidon, 2002), whereas in upper Tertiary basalts water predominates, with no evidence of CO_2 (I.A. Sigurdsson, S. Jakobsson, in preparation). Inclusions in olivines show a range in oxygen isotopes ($\delta^{18}\text{O}$: 4.0–6.2‰) and an even wider range in the olivines themselves (Gurenko and Chaussidon, 2002). These results clearly show that each basalt is composed of a mixture of different mantle melts, derived from different depths and from a lithologically heterogeneous source with $\delta^{18}\text{O}$ as low as 4‰ and high Ca-melts. Such low- $\delta^{18}\text{O}$ composition strongly suggests the presence of a recycled oceanic crust in the mantle, whereas the high-calcium melts remain enigmatic. Further results from glass inclusions in primitive phenocrysts will without doubt improve our understanding of mantle melting and basalt genesis beneath Iceland.

7. Conclusion

Review of the evolution of ideas concerning the origin of Icelandic basalts and inferences from their compositional variability about the mantle sources beneath Iceland suggest that:

- (1) At least three mantle components are needed to explain the radiogenic isotope ratios of the basalts. Mixtures of melts derived from a depleted upper mantle, the enriched mantle plume, and recycled oceanic crust can account for all the isotope constraints.
- (2) Variable proportions of melts from recycled crust in the form of garnet pyroxenite are likely to be controlled by temperature variations between the hotter mantle plume relative to the ambient mantle. Signature of garnet pyroxenites appears to be strongest in the alkali basalts, decreasing inland towards Central Iceland.

- (3) Compositions of melt inclusions in the most primitive phenocrysts reveal large variability of mantle melts that range from the products of high-degree melting of a depleted mantle source to calcium-rich melts and low- ^{18}O melts that strongly suggest the presence of recycled crust in the Iceland mantle.
- (4) Lithological heterogeneity is likely to be widespread in the mantle representing abundant pyroxenites interspersed with ilmenite. The physical and chemical characteristics of such pyroxenites are different from those of the enclosing ilmenites. Therefore, their identification and their nature present a challenge not only to future petrological and geochemical studies but also to different geophysical studies of the mantle.

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