Reviewed research article

Geochemistry of igneous rocks in Iceland: a review

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Abstract — *Two important large-scale geochemical trends are observed in Iceland and the adjoining spreading ridges, one along the ridges and active rift zones, and the other between the rift zones and off-rift areas of recent volcanism. Along the ridges, basalt compositions are increasingly enriched in incompatible elements (i.e. elements which preferentially partition into melts) towards Iceland, reflecting enhanced melting of fusible, fertile components of a heterogeneous mantle. These heterogeneities may be garnet pyroxenites that are derived from recycled oceanic lithosphere. Recent basalts erupted outside the rift zones are more enriched in incompatible elements than those of the rift zones. These two trends reflect variations in mantle temperature, compositional structure and flow field as well as the role of tectonics. Mantle melts move rapidly from their deep source regions towards the surface in porous channels or dykes. These melts mix and cool in lower-crustal magma chambers before eruptions. The limited basalt production rate away from the rift zones results in a relatively low crustal thermal gradient, facilitating the production of silicic magmas by fractional crystallization of incoming basalts. However in the hot rift zones, where hydrothermal activity is plentiful, crustal anatexis may result to produce silicic melts. Thorough mixing of crustal melts and solid crustal material with basalts may account for the compositional features of large fissure eruptions such as Laki.*

INTRODUCTION

Icelandic magmatism is unique for several reasons. The presence of an island with a substantial shelf that straddles a spreading ridge is indicative of unusually high mantle melt production rates: typical ridges are submerged in kilometres of ocean. Faults and fissures, caused by rifting, open access for rainwater into the crust's interior. Interaction of these waters with hot crustal rocks leads not only to conspicuous geothermal activity at the surface but also to metamorphism of basalt and gabbro at depth. The large proportion of silicic magmas produced in Iceland relative to other oceanic islands is often linked to anatexis of these metabasalts. Finally, the presence of glaciers results in abundant formation of hyaloclastite that upon subsidence may affect the mechanical strength of the crust and locations of magma chambers beneath the currently active volcanoes. The wide range of resulting magmatic processes can be studied in great detail due to excellent exposures. Iceland has therefore become a focus not only for an international community of mid-ocean ridge specialists but also for those investigating magmatic processes that may operate in any global tectonic setting.

Reviews of the origin of Icelandic basalts and silicic formations have been published recently (Jonasson, 2007; Sigmarsson and Steinthorsson, 2007) and will not be repeated here. However, the aim of this paper is to briefly summarize current understanding of magma formation and its sources as inferred from the compositional variability of post-glacial lavas and tephra. It will start with large-scale variations and arguments pertinent to the existence of a mantle plume beneath Iceland. After that, second order variations revealing the probable role of recycled oceanic lithosphere in the form of pyroxenites will be discussed with relevant implications for the scale of mantle heterogeneity and melt-homogenisation processes. The role of deglaciation on mantle melting is given a particular emphasis. Then, the increasing application of geochemistry to better understanding of volcano behaviour will be addressed. This enterprise concerns both the fingerprinting of magma migration between volcanoes and evaluation of timescales of magma processes, in addition to the contribution of magma-derived volatiles to the atmosphere.

THE ICELAND GEOCHEMICAL ANOMALY

Mid-ocean ridge basalts (MORBs), including those from the Reykjanes Ridge (Figure 1) are olivine tholeiitic basalts. However, along the Reykjanes Ridge their incompatible element concentration increases systematically toward Iceland reaching a maximum in the subaerially-erupted basalts (e.g. Schilling, 1973). Subsequent measurements of isotope ratios in the same samples revealed more radiogenic Sr and Pb isotope compositions in Icelandic basalts compared to MORB (Figure 2). These results were interpreted in terms of mixing between enriched basalts derived from a hot mantle plume under Iceland and MORB generated from depleted upper mantle. The influence of the Iceland mantle plume on the basaltic composition reaches at least 60°N. Prominent V-shaped ridges preserved in the oceanic crust south of Iceland also record the influence of the plume on melt generation as far as 58°N. These ridges reflect periodic southwards propagation of a melting anomaly beneath the Reykjanes Ridge, most likely related to pulsed variations in mantle temperature. (Vogt, 1971; Ito, 2001; White and Lovell, 1997; Jones *et al.*, 2002).

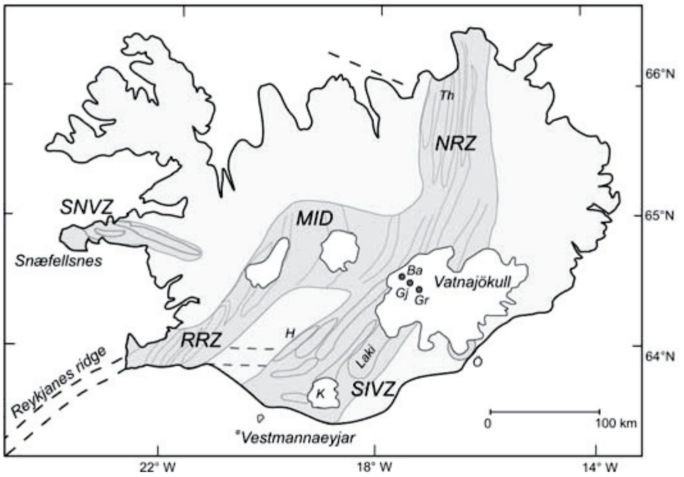


Figure 1. Map of Iceland showing the neovolcanic zones and volcanic systems. The three different rift zones are RRZ, NRZ and MID respectively, for the Reykjanes Rift Zone, the Northern Rift Zone and the Mid-Iceland belt. The SNVZ and SIVZ stand respectively for the Snæfellsnes Volcanic Zone and the South-Iceland Volcanic Zone. The abbreviations Th, H, K and Gr denote, respectively, Þeistareykir, Hekla, Katla and Grímsvötn volcanic systems. The presumed centre of the Iceland plume is close to the Bárðarbunga central volcano (Ba). Gj denotes the 1996 eruption site of Gjálp, and Ö the Öræfajökull volcano. *–Einfaldað kort af Íslandi sem sýnir útlínur gosbeltanna og skammstafanir þeirra eldstöðva og eldstöðvakerfa sem þessi grein fjallar um.*

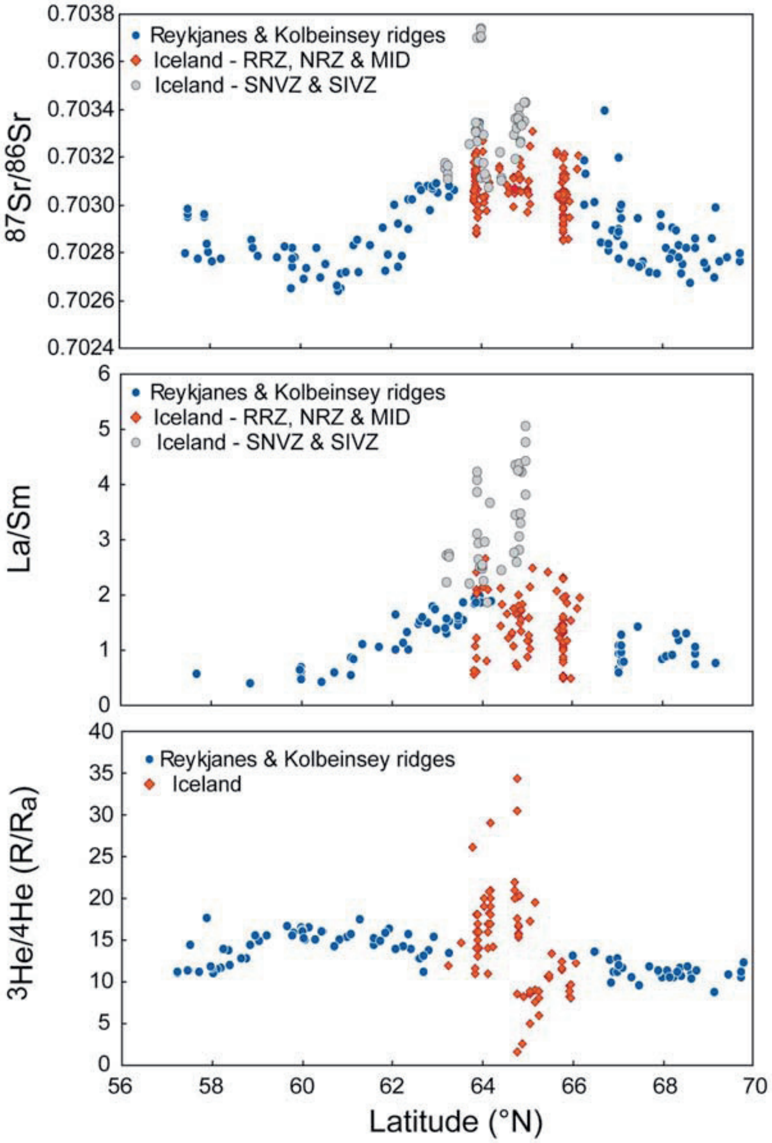


Figure 2. Geographical variations along the Mid-Atlantic Ridge adjacent to Iceland and across Iceland. Iceland has an elevated Sr-isotope ratio that gradually lowers to the south and north. A similar pattern is evident from La/Sm and He-isotope ratios although low ratios are also observed on Iceland. These reflect melting of an unusually depleted mantle-component and the presence of recycled crust in the plume, respectively. Data sources are as follows: Sr: Hart *et al.*, 1973; Mertz *et al.*, 1991; Sigmarsson *et al.*, 1991a,b, 1992a, 2000; Hémond *et al.*, 1993; Taylor *et al.*, 1997; Schilling *et al.*, 1999; Stecher *et al.*, 1999; Chauvel and Hémond 2000; Kempton *et al.*, 2000; Prestvik *et al.*, 2001; Stracke *et al.*, 2003; Thirlwall *et al.*, 2004; and Kokfelt *et al.*, 2006. La/Sm: Schilling, 1973; Schilling *et al.*, 1983; MacDonald *et al.*, 1990), McGarvie *et al.* (1990), Hémond *et al.*, 1993; Devey *et al.*, 1994; Chauvel and Hémond, 2000; Prestvik *et al.*, 2001; Stracke *et al.*, 2003; and Kokfelt *et al.*, 2006. He: Condomines *et al.*, 1983; Kurz *et al.*, 1985; Poreda *et al.*, 1986; Schilling *et al.*, 1999; Breddam *et al.*, 2000; Dixon *et al.*, 2000; Hilton *et al.*, 2000; Dixon, 2003; Macpherson *et al.*, 2005a,b. – *Landfræðilegar breytingar á samsetningu basalts eftir úthafshryggjunum og rekbeltum Íslands. Íslenskt berg hefur hlutfallslega hátt* ^{87}*Sr/*^{86}*Sr sem lækkar til suðurs eftir Reykjaneshrygg og til norðurs eftir Kolbeinseyjarhrygg. Svipað gildir um hlutföll La/Sm og He-samsæta nema hvað lág hlutföll þessarra efna mælast einnig í íslensku bergi. Þennan breytileika má skýra með blöndun möttulbráða úr fyrrverandi úthafsskorpu, sem sokkið hefur ofan í möttulinn og komið aftur upp með möttulstróknum, og misskertum möttli eftir fyrri bráðnunarferli.*

More recent studies on Nd, He, Os and Hf isotope compositions, in addition to those of Sr and Pb, from the Reykjanes Ridge corroborate the earlier results and further confirm the existence of an enriched mantle source beneath Iceland (e.g. Hilton *et al.*, 2000). The peak in He-isotope ratio (R/R_a ($= [^3He/^4He]_{samples}/[^3He/^4He]_{air}$)) in Central Iceland (Figure 2) indicates that the mantle source of the magmas is closer to primordial noble-gas composition under Iceland than under the adjoining submerged ridges (Breddam *et al.*, 2000; Graham, 2002; Moreira *et al.*, 2001). The association of high-$^3He/^4He$ basalts from oceanic islands with large igneous provinces, hot spot tracks, slow shear-velocity anomalies and significant buoyancy flux has been taken as a proof for the existence of a deep-seated mantle reservoir that is only sampled by the strongest mantle plumes (Courtillot *et al.*, 2003). Much effort has been spent on identifying different mantle reservoirs through the isotope composition of the Icelandic basalts, but without a general consensus yet. The plots of $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ against $^{206}Pb/^{204}Pb$ in Figure 3 nevertheless demonstrate that at least three different mantle components are needed to explain the isotope composition of the basalts. Moreover, the mantle-plume hypothesis has been challenged and the anomalous melt production beneath Iceland attributed to the presence of fertile recycled crust in the magma source (Foulger *et al.*, 2005). Systematic and fine-scale studies are required in order to disentangle the effects of mantle temperature and source fertility in the production of the Icelandic melting anomaly.

Neither variations in mantle-plume temperature nor lithospheric thickness alone are able to reproduce the geochemical trends observed on N-S transects of the active rift zones (Figure 2). While the E-W trend of Figure 4 shows enriched compositions in regions of low melt production, that of Figure 2 demonstrates the association of enriched compositions with locations of high melt production along the rift zones and surrounding mid-ocean ridges. For instance, large volume basaltic eruptions from central Iceland, where crustal thickness may be >40 km, tend to be more enriched than those from locations where the rift zones

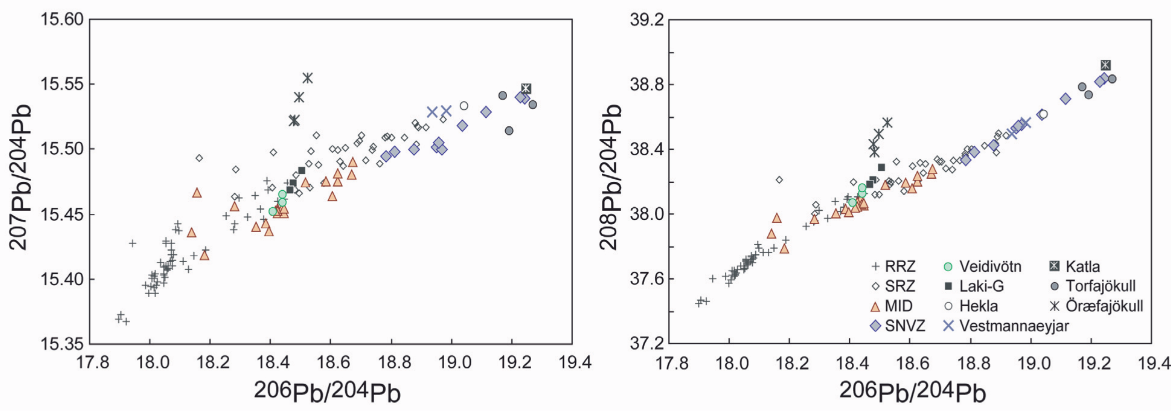


Figure 3. Lead-isotope systematics in post-glacial lavas show that although binary mixing of un-radiogenic and radiogenic mantle components (or melts therefrom) does account for most of the variation, a third component is needed to fully explain the isotope ratios observed. Data compiled from Stecher *et al.*, 1999; Chauvel and Hémond, 2000; Prestvik *et al.*, 2001; Stracke *et al.*, 2003; Thirlwall *et al.*, 2004, and Kokfelt *et al.*, 2006. Laki-G stands for Laki-Grímsvötn volcanic system. Published error bars are smaller than the symbols. – *Fylgni samsætuhlutfalls blýs í bergi frá Nútíma sýnir að þótt skýra megi flest hlutföllin með tveggja þátta blöndun geislavirks og lítt geislavirks möttuls, eða möttulbráða, þarf þriðja þáttinn (meginlandsskorpu?) til að skýra allar mæliniðurstöðurnar.*

approach the coast. The sense of these correlations can be accounted for by the models shown in Figure 5c,d. If the proportion of the upwelling mantle composed of enriched and fusible material such as garnet pyroxenites increases towards central Iceland, it follows that greater volumes of enriched melts will be generated in this region (Figure 5c, Foulger *et al.*, 2005). Alternatively, increased plume flow through the deep part of the melting region under central Iceland may both raise melt production rates and weight the average basalt composition towards that of enriched melts generated deep in the melting region (Figure 5d, Maclennan *et al.*, 2001). The 5–10 fold increase in mantle upwelling rates in the deep parts of the melting region compared to the shallow region is consistent both with the results of numerical convection models of plume flow under Iceland (Ito, 2001) and with interpretation of U-series disequilibrium data from Iceland (Kokfelt *et al.*, 2003). However, the relative importance of upwelling rates and variable presence of garnet pyroxenite in production of the U-series disequilibrium signature is not yet understood (Sigmarsson *et al.*, 1998).

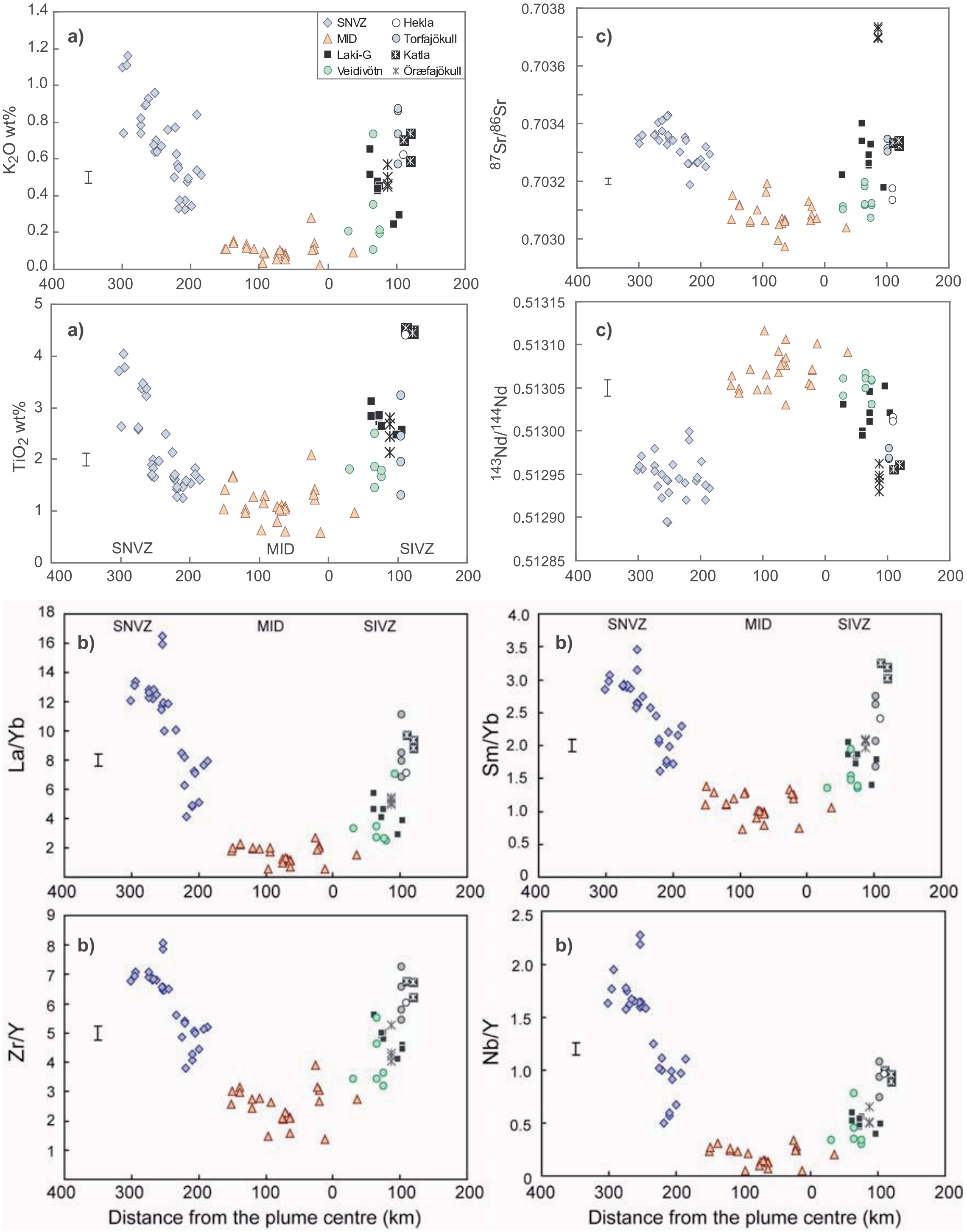
PLUME STRUCTURE, TECTONICS, AND MANTLE-MELT GENERATION

A regional geochemical study of Recent basalts from the off-rift zones of Snæfellsnes and South Iceland shows significant variability in major, trace and isotope composition that correlates with the distance along strike of the volcanic zones (Figure 4). The basalts are more enriched (e.g. higher La/Yb, ^{87}Sr/^{86}Sr) with increasing distance from the centre of the Iceland hot-spot beneath NW Vatnajökull (e.g. Meyer *et al.*, 1986; Sigmarsson *et al.*, 1992a; Furman *et al.* 1995; Carpentier and Sigmarsson, 2005; Kokfelt *et al.*, 2006). Along the Snæfellsnes Volcanic Zone, the ^{3}He/^{4}He increases eastwards from 7R$_a$ to 12R$_a$ reaching 18R$_a$ in basalts at the junction of Snæfellsnes and the rift-zone crossing Iceland. These correlations are currently taken to reflect larger proportions of melts from garnet pyroxenite at the periphery of Iceland (Figure 6). The garnet pyroxenite is thought to be derived from recycled oceanic lithosphere which has been entrained in the convecting lherzolite upper mantle. Such pyroxenite heterogeneities are expected to be geochemically enriched and fusible in comparison to the depleted and refractory upper mantle lherzolites.

Two important trends in basalt composition are observed with distance from the putative hot-spot centre. With increasing N-S distance along the active rift zones from central Iceland the basalts become increasingly depleted e.g. with lower La/Sm (Figure 2). However, along the E-W axis from the hot-spot centre to the tip of the Snæfellsnes peninsula, or to the Vestmannaeyjar, the basalts are increasingly enriched with distance from central Iceland (Figure 4). These geochemical trends reflect variation in mantle properties and tectonic style, particularly the transition from the rift zones, where much of the plate spreading takes place, to the flank zones, where little extension occurs.

Before the geochemical observations can be interpreted in terms of large-scale processes, it is necessary to highlight the importance of small-scale compositional heterogeneity in the Icelandic mantle. The presence of isotopic variation within individual volcanic systems, lava flows and melt inclusions from single specimens indicates that the Icelandic mantle is compositionally heterogeneous on a length scale of 50 km or less (Hémond *et al.*, 1993; Stracke *et al.*, 2003; Maclennan, 2008). The amplitude of this compositional heterogeneity is important, with >50% of the range of Pb-isotopic composition of all Atlantic MORB samples present in melt inclusions from a single lava flow (Maclennan, 2008). If the enriched material within the mantle is also readily fusible it follows that the isotopic composition of basalt does not reflect the average composition of upwelling mantle in a straightforward way because small degrees of melting will preferentially sample the enriched heterogeneities (Ito and Mahoney, 2005).

Important constraints on mantle melting come from geophysical and geological estimates of the rates of mantle-melt production. Along the rift zones, a number of seismological studies suggest an increase in crustal thickness from ∼20 km near the coast to >40 km in central Iceland, implying a doubling of the melt production rates near the focus of the hot-spot


a)
K$_2$O wt%
SNVZ
MID
Laki-G
Veidivötn
Hekla
Torfajökull
Katla
Öræfajökull
c)
^{87}Sr/^{86}Sr
a)
TiO$_2$ wt%
SNVZ
MID
SIVZ
c)
^{143}Nd/^{144}Nd
b)
La/Yb
SNVZ
MID
SIVZ
b)
Sm/Yb
SNVZ
MID
SIVZ
b)
Zr/Y
b)
Nb/Y
Distance from the plume centre (km)
Distance from the plume centre (km)
400
300
200
100
0
100
200

(e.g. Darbyshire *et al*., 2000). The lack of significant crustal thickening associated with the off-rift volcanism of the Snæfellsnes Peninsula would then indicate that mantle melt production rates are lower in such settings than within the rift zones.

Four mechanisms for generating the observed relationships between basalt composition and melt production rates along the transects of Figures 2 and 4 are displayed on Figure 5. The trends displayed in the profiles from Snæfellsnes, through central Iceland, to the Vestmannaeyjar (Figure 4) may be accounted for either by changes in mantle potential temperature (Figure 5a) or lithospheric thickness (Figure 5b). Variation in mantle potential temperature with distance from the plume centre leads to variation in the extent of melting. Small degrees of mantle melting, such as those expected under Snæfellsnes, encourage sampling of fusible, enriched mantle heterogeneities and the eruption of enriched alkali basalts (e.g. Fitton *et al*., 2003). Conversely, basalts from Central Iceland have relatively depleted compositions, in accordance with the notion that higher potential temperatures in the mantle cause higher degree of melting and increased relative contribution from lherzolite melting (Figure 5; Carpentier and Sigmarsson, 2005; Kokfelt et al, 2006; Sigmarsson and Steinthorsson, 2007). The differing tectonic settings encountered on the profile of Figure 4 may also control the extent of melting. The centre of profile (MID) crosses the rift-zones in central Iceland. However, the ends of this profile, near the coast, sample regions with limited lithospheric extension, either in the Snæfellsnes flank zone or in the tip of the propagating SIVZ at the Vestmannaeyjar. When extension rates are low, the litho-

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Figure 4. Geochemical parameters vs. distance from the assumed plume centre (close to Bárðarbunga central volcano). (a) K_2O and TiO_2 wt%, (b) selected trace-element ratios, (c) Sr and Nd isotope ratios. Higher potassium and titanium concentrations in basalts farthest away from the plume centre reflect the more alkaline character of these basalts. Residual garnet appears to control the trace-element pattern in (b) especially beneath the periphery of Iceland. This garnet signature could either result from deeper melting and/or indicate a garnet-rich mantle mineralogy. The more radiogenic Sr-isotope (Pb and He also; see text) composition in the alkali-rich basalts suggests that they result from the melting of garnet pyroxenite (possibly a recycled crust). The diluted incompatible-element concentrations (e.g. K and Ti), declining garnet signature and less radiogenic $^{87}Sr/^{86}Sr$ towards the plume centre are best explained by increasing mantle melting in which lherzolite-derived melts dominate those from pyroxenites. The elevated melt production beneath Iceland is therefore only in part attributable to fertile and recycled oceanic crust in the magma source but rather to high potential temperatures in the mantle plume. Results from MacDonald *et al*., 1990; Sigmarsson *et al*., 1992a,b, 2000; Hémond *et al*., 1993; Stecher *et al*., 1999; Chauvel and Hémond, 2000; Prestvik *et al*., 2001; Thirlwall *et al*., 2004; Kokfelt *et al*., 2006; and Carpentier and Sigmarsson, 2008. – *Jarðefnafræðilegir þættir sem fall af fjarlægð frá ætlaðri miðju heita reitsisns (Bárðarbunga). (a) styrkur* K_2O *og* TiO_2 *í þyngdarprósentum, (b) valin snefilefnahlutföll, (c) samsætuhlutföll Sr og Nd. Hærri kalí og títan styrkur í basalti fjærst miðju heita reitsins endurspeglar alkalísk einkenni þess. Snefilefnahlutföllin eru best skýrð með tilvist granats í afgangsmöttulbergi eftir bráðnun og basaltmyndun. Þáttur granatsins er talinn mestur vestast á Snæfellsnesinu og syðst í Suðurlandsgosbeltinu sem afleiðing dýpri möttulbráðnunar og/eða tilvistar óvenju granatríks möttulbergs. Hærri Sr (sem og Pb og lægri He) samsætuhlutföll í alkalí-ríkara basaltinu bendir til að þau myndist við uppbræðslu granatpýroxeníts sem hugsanlega er gömul úthafsskorpa sem sokkið hefur niður í möttulinn og komið aftur upp með möttulstróknum undir Íslandi. Útþynntur styrkur utangarðsefna (s.s. K og Ti), lægri snefilefnahlutföll (minna granat í móðurberginu) og lægri* $^{87}Sr/^{86}Sr$ *en hærri* $^{143}Nd/^{144}Nd$ *í basalti nær miðju möttulstróksins eru best skýrð með aukinni möttulbráðnun þar sem lherzólítbráð yfirgnæfir bráð pyroxenítsins í nýmynduðu basaltinu. Mikil möttulbræðsla undir Íslandi verður því aðeins að hluta skýrð með hringrás úthafsskorpu um möttulinn og bræðslu hennar, og því er mjög líklegt að hátt möttulhitastig undir Íslandi sé ráðandi þáttur við myndun basaltsins.*

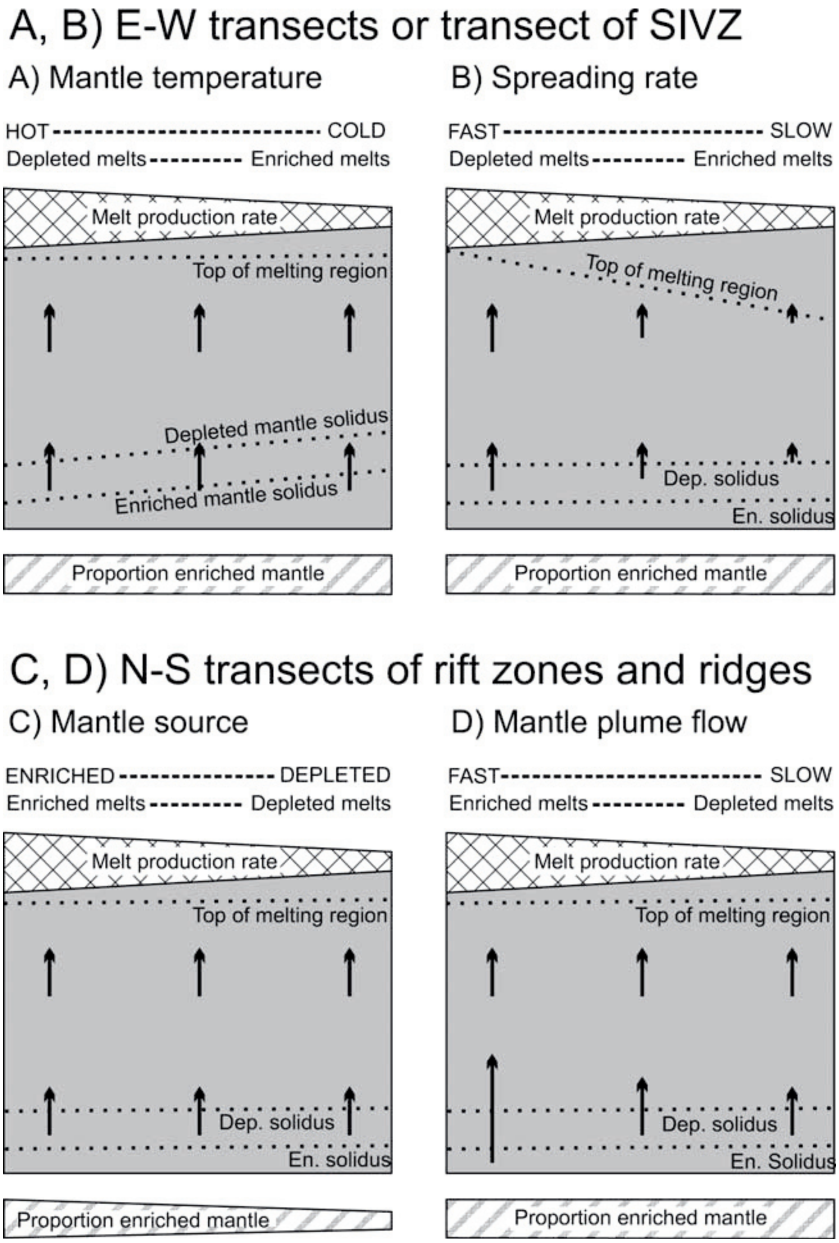

A, B) E-W transects or transect of SIVZ
A) Mantle temperature
HOT ---- COLD
Depleted melts ---- Enriched melts
Melt production rate
Top of melting region
Depleted mantle solidus
Enriched mantle solidus
Proportion enriched mantle
B) Spreading rate
FAST ---- SLOW
Depleted melts ---- Enriched melts
Melt production rate
Top of melting region
Dep. solidus
En. solidus
Proportion enriched mantle
C, D) N-S transects of rift zones and ridges
C) Mantle source
ENRICHED ---- DEPLETED
Enriched melts ---- Depleted melts
Melt production rate
Top of melting region
Dep. solidus
En. solidus
Proportion enriched mantle
D) Mantle plume flow
FAST ---- SLOW
Enriched melts ---- Depleted melts
Melt production rate
Top of melting region
Dep. solidus
En. Solidus
Proportion enriched mantle

Figure 5. Schematic diagrams of processes responsible for controlling regional variations in basalt composition in Iceland. All show vertical slices through the mantle melting region, with depth increasing downwards and distance from the centre of Iceland increasing from left to right. The average composition of the melts generated, in terms of enriched/depleted, is indicated as a function of position above each plot. The vertical thickness of the hatched area indicates the melt production rate, which correlates with the crustal thickness in mature rift zones. The depth to the top of the melting region, the solidus of a depleted lherzolite source and that of an enriched garnet pyroxenite source are marked with dotted lines. The approximate depth of the lherzolite solidus may be ∼100 km under Iceland, with that of the pyroxenite a few tens of kilometres deeper. The lengths of the vertical arrows indicate the rates of mantle upwelling. This upwelling is responsible for the adiabatic decompression melting. The thickness of the bar at the base of each plot indicates the proportion of enriched material present in the upwelling mantle. While the mantle is compositionally heterogeneous on a length scale of <50 km, the thickness of this bar reflects long-wavelength variations in the mantle composition (>100 km). In (A) and (B) the degree of enrichment correlates inversely with the melt production rate, while in (C) and (D) the melt production correlates directly with enrichment of the basalt compositions. (A) High mantle potential temperature under central Iceland, low under edges. Note the shoaling of the solidi with decreasing temperature. The shortened melting column under the edges of Iceland leads to preferential melting of enriched material. (B) Varying spreading rates, suitable for studying variations along a propagating rift (SIVZ) or for transitions from rift zones to flanks zones (e.g. mid-Iceland to Snæfellsnes). The thicker lithosphere at lower extension rates leads to a deeper cap to the melting region and shortened melting column under the coasts. (C) Variation in the proportion of enriched, fusible material in the upwelling mantle. (D) Variation in plume upwelling rates. The large arrow, deep in the melting region under central Iceland reflects rapid upwelling driven by plume-buoyancy. Shallower in the melting region the upwelling is driven by plate separation alone. See Maclennan *et al.* (2001) for further details. *–Einfaldar skýringarmyndir á ferlum sem taldir eru skýra breytileika í samsetningu íslenska basaltsins. Myndirnar sýna lóðrétt snið í gegnum bræðslusvæði möttulsins, dýpi eykst niður á við og fjarlægð frá miðju Íslands til hægri eftir hverri mynd. Þykkt krossstrikaða svæðisins endurspeglar magn möttulbráðar sem tengd er skorpuþykkt þróaðra rekbelta. Punktalínur sýna efri mörk bræðslusvæðisins, bræðslumörk eða solidus skerts lherzólíts og granatpýroxeníts. Dýpi niður á bræðslumark lherzolíts undir Íslandi er metið u.þ.b. 100 km. Bræðslumark pýroxeníts er fáeinum tugum km grynnra. Lengd lóðréttu örvanna gefur til kynna rishraða möttulsins með tilheyrandi þrýstilétti og hlutbræðslu. Þykkt skástrikaða svæðisins táknar hlut frjós möttulefnis (pýroxeníts) í rísandi möttli. Öfug fylgni er á milli frjós möttulefnis og möttulbráðnunar, myndir (A) og (B), en bein fylgni milli frjósemi möttulefnis og styrk utangarðsefna í basalti sem gýs á yfirborði, myndir (C) og (D). (A) Möttulhitastig er hæst undir miðju landsins en lækkar til jaðranna. Bræðsluferill möttulefnisins grynnkar með lækkandi möttulhita og hlutfall pýroxeníts í heildarbráðinni hækkar. (B) Þykkt steinhvolfsins (lithosphere) er háð rekhraða. Aukin þykkt lækkar heildarbráðnun og hækkar hlut pýroxenítbráðar. (C) Breytileg hlutföll frjós möttulefnis (pýroxeníts). (D) Breytilegur rishraði möttulstróks. Hratt ris (löng ör) er undir miðju landinu en á minna dýpi hefur rekhraði áhrif á rishraða möttulefnisins. Líkanið er nánar útlistað í grein Maclennan o. fl. (2001).*

sphere thickens as conductive cooling from the surface dominates over heating by upwards advection of mantle. Low extension rates force the top of the melting region to greater depths and decrease the extent of melting. Therefore, the transition from rift-zone to off-rift-zone volcanism is expected to correspond to a change from more depleted basalts to more enriched ones, as observed in Figure 4.

Disentangling of the effects of plume temperature, composition, and flow and tectonics on the basalt compositions will require both collection of detailed geochemical datasets and the development of quantitative models of melting of compositionally heterogeneous mantle.

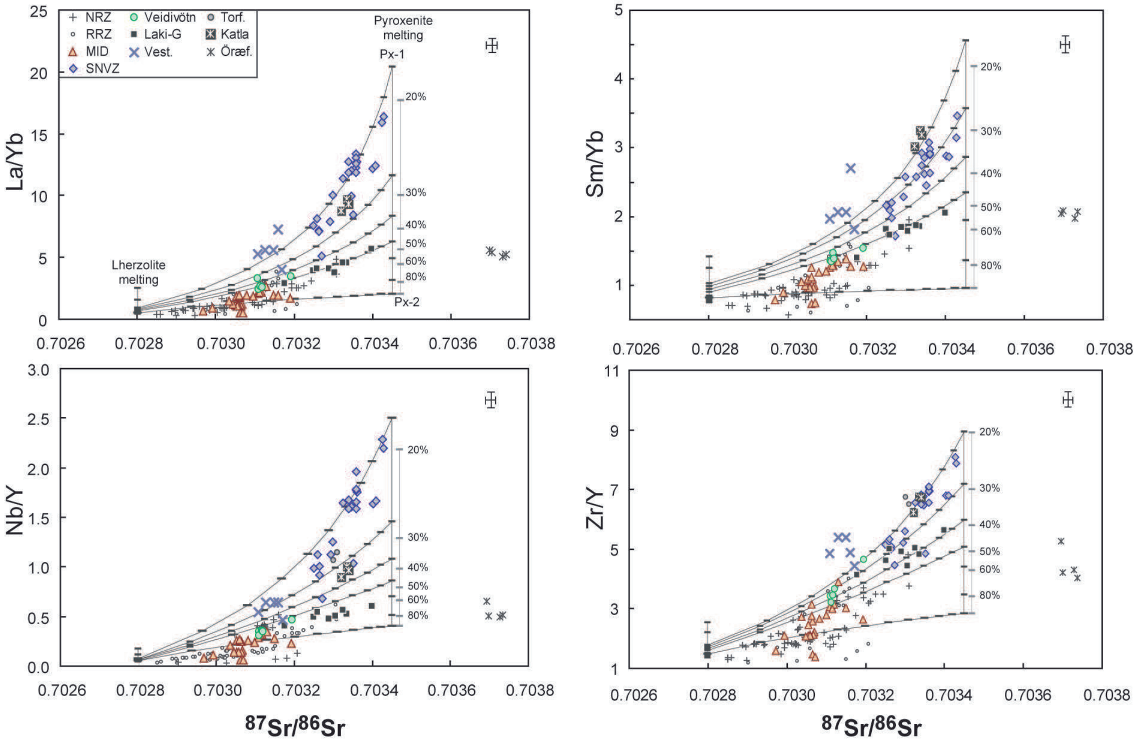


Figure 6. La/Yb, Sm/Yb, Nb/Y and Zr/Y vs. ^{87}Sr/^{86}Sr. Melting trajectories of garnet pyroxenites (Px-1, Px-2) and spinel lherzolite (with mineralogy and chemical compositions detailed in Carpentier and Sigmarsson, 2008) are shown. Partial melting (%) are indicated for Px-1 and Px-2 along the melting trajectories. Lherzolite melting trajectory only shows 1% to 50% partial melting. Two different sets of partition coefficients used for pyroxenites melting result in very similar melting trajectories. For clarity, only mixing model between Px-1 melts and lherzolite melts are presented. The mixing curves were calculated between melts produced by 20, 30, 40, 50, and 100% partial melting of pyroxenite and melts produced respectively by 5, 6, 8, 10 and 20% partial melting of spinel lherzolite. Mixing curves are marked with 10% mixing increments. All the compiled basalt compositions can be explained by this model except those having the lowest trace element ratios. These most likely originate from depleted mantle during upwelling that most likely has lost its most fertile components in earlier melting event(s). – *Hlutföll La/Yb, Sm/Yb, Nb/Y og Zr/Y á móti* ^{87}*Sr/*^{86}*Sr. Sýndar eru lóðréttar bræðslukúrfur tvenns konar granatpýroxeníts (Px-1 og Px-2) og spínel-lherzólíts. Bræðsluhlutföll í % eru sýnd fyrir Px-1 og Px-2 eftir bræðslukúrfunum, en aðeins bræðsluhlutföll frá 1% til 50% eru sýnd fyrir bræðslu lherzólítsins. Tvær útgáfur af dreifistuðlum snefilefnanna á milli steinda og bráðar gáfu mjög líkar niðurstöður. Til einföldunar eru hér aðeins sýnd blöndunarlíkön fyrir mismunandi bráðir Px-1 (20, 30, 40, 50 og 100%) og spínel-lherzólíts (5, 6, 8, 10, og 20% hlutbráðir). Skýra má samsetningu langflestra gerða íslensks basalts með þessu blöndunarlíkani, aðeins basalt með lægstu snefilefnahlutföllin verður ekki skýrt á þennan máta. Samsetning þess fellur best að bræðslu á skertu möttulefni, sem tapað hefur lágbræðsluþættinum vegna ris möttulstróksins og samfarandi þrýstiléttis. Samsetning basalts frá Öræfajökli krefst sértækrar skýringar og er talið líklegast að meginlandsskorpa hafi átt þar hlut að máli. Skekkjumörk mælinga (2σ) eru sýnd efst til hægri.*

DEGLACIATION, MANTLE MELTING AND MELT TRANSPORT

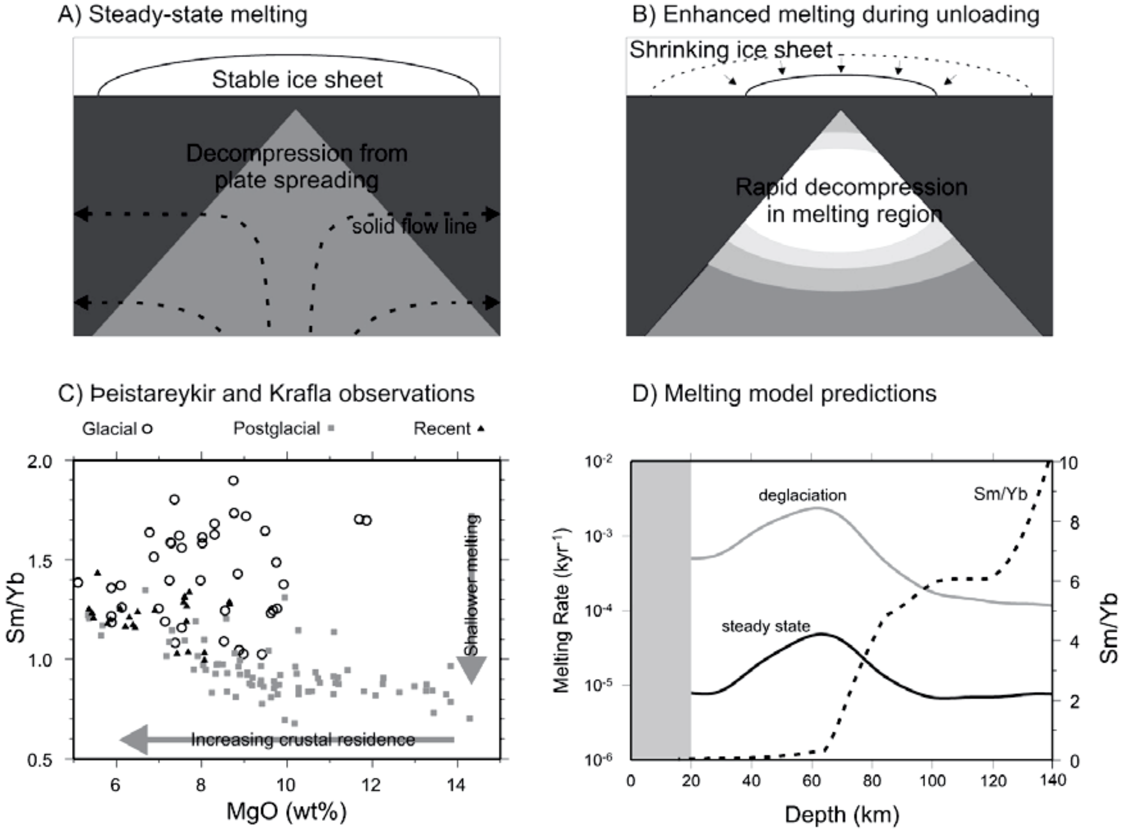
Models of mantle melting under spreading ridges assume adiabatic decompression, followed by rapid transport of melt to the surface for eruption. Uniquely amongst the spreading ridges, Iceland has been glaciated. The effect of glacial unloading on melting behaviour provides an excellent opportunity not only to test decompression melting models but also to constrain melt extraction timescales from the mantle. Whereas the last ice age started to wane at ∼18 ka, rapid deglaciation and isostatic rebound of Iceland took place at ∼12 ka (Norðdahl and Pétursson, 2005).

Deglaciation exposed tuyas and hyaloclastite ridges which had formed in subglacial eruptions. The maximum elevation of these subglacial eruptions above the surrounding plains indicates that the ice may have been over 1 km thick in places. The earliest postglacial volcanic activity in the rift zones is dominated by the eruption of large lava shields. Tephrochronological studies have found that average eruption rates in the first 2–5 kyr after deglaciation were 8–50 times higher than those during the last 3–4 kyr (Jakobsson *et al.*, 1978; Vilmundardóttir and Larsen, 1986; Sæmundsson, 1991; Sigvaldason *et al.*, 1992; Sinton *et al.*, 2005).

Early models of the postglacial volcanic burst focussed on changes in the stress state in the crust during glacial unloading (Gudmundsson, 1986; Sigvaldason *et al.*, 1992). These stress changes allow enhanced tapping of crustal magma chambers. The presence of picritic eruptions exclusively in the early postglacial period indicates that the crustal magmatic storage system was perturbed during this time. However, physical models of processes in magma chambers are not yet sufficiently advanced for making quantitative links between changes in eruption volume and chemistry as a result of deglaciation. An alternative cause of variation in early postglacial magmatic processes was proposed by Hardarson and Fitton (1991) who studied geochemical variations in the Snæfellsjökull volcano. They suggested that glacial unloading perturbed mantle melting and resulted in enhanced melting during deglaciation.

Detailed calculations of the effect of glacial unloading on mantle decompression and melting were performed by Jull and McKenzie (1996). These authors modelled decompressional melting of a homogeneous mantle source and showed not only that deglaciation can increase melting rates by a factor of 30 or more but also that decompression rates are predicted to increase preferentially in the shallow part of the melting region. This feature of the depth-distribution of decompression allows a straightforward geochemical prediction to be made from the models because the incompatible trace element composition of melt is coupled to its depth of generation, as demonstrated by the variations in predicted Sm/Yb shown in Figure 7D. The models predict that the Sm/Yb of aggregated fractional melt produced during unloading should be a factor of two lower than that of melt generated during steady-state activity. Comparison of the model predictions with observations from Krafla and Theistareykir indicates that deglaciation has indeed influenced mantle melting under the rift zones (Maclennan *et al.*, 2002). The observations in Figure 7C show that early postglacial eruptions tend to be more MgO rich than those from glacial or more recent times, indicating that the burst in volcanic activity did not result from draining of crustal magma chambers that had stored melt during the glaciation. Geochemical variations broadly consistent with the mantle melting model of Jull and McKenzie (1996) have also been observed on the Reykjanes Peninsula (Jakobsson *et al.*, 1978; Gee *et al.*, 1998) and the Western Rift Zone (Sinton *et al.*, 2005).

The correspondence between the model predictions and the observed eruption rate and geochemical variations in the rift zones not only provides a verification of simple adiabatic decompression melting models but also constrains the upwards melt transport velocities in the mantle: The lag time between glacial unloading, which causes mantle melting, and the burst in volcanic activity reflects the melt transport time from the mantle to the surface. In regions where good tephrochronological controls are available, the peak in eruption rates was attained <1 kyr after the final deglaciation and rebound (Maclennan *et al.*, 2002; Sinton *et al.*, 2005). This time lag is reproduced by melt transport models where the vertical melt velocity



is >50 m yr^{-1}. Such velocities cannot be supported by a uniform distribution of porous flow in the mantle and require focussing of the flow into higher-porosity melt channels, such as those proposed by Kelemen *et al*. (1997).

MIXING AND CRYSTALLISATION OF BASALTS IN SHALLOW MAGMA CHAMBERS

Polybaric partial melting of heterogeneous mantle generates a wide range of melt compositions beneath individual volcanic systems. These melts are transported rapidly towards the surface in porous channels, where some mixing may occur. However, variable melt compositions are supplied from the mantle to magma chambers under Iceland. This variability has been documented by studies of the composition of olivine-hosted melt inclusions in primitive basalts and picrites from the rift zones (Gurenko and Chaussidon, 1995; Maclennan *et al*., 2003a; Maclennan, 2008). Trace element variation is also present in whole-rock samples from an individual primitive basalt flow from Theistareykir (Maclennan *et al*., 2003b). Concurrent mixing and crystallisation in lower crustal magma chambers leads to the production of evolved basalts with relatively uniform isotopic and trace element composition.

Efficient mixing can lead to the development of uniform isotopic compositions for moderately evolved basalts from individual volcanic systems, particularly in the SIVZ and flank zones (e.g. Sigmars-

Figure 7. Influence of glacial unloading on melt generation and composition. A) When the ice-sheet does not vary in size the decompression and melting of mantle is driven by plate spreading. B) During deglaciation, decompression in the melting region is dominated by unloading of the ice. C) Theistareykir and Krafla whole-rock data from Maclennan *et al.* (2002). Postglacial samples are those erupted between the deglaciation of the area and 7 ka. Recent samples are erupted between 7 ka and the present day. The length of the arrow labelled "shallower melting" corresponds to the relative variation in Sm/Yb predicted for aggregated fractional melts between glacial and early postglacial times by the models of Maclennan *et al.* (2002). D) Solid lines show the variation in melting rate with depth for steady-state melting and during the time of glacial unloading. Full details of the melting model are given in Maclennan *et al.* (2002, 2003a) and references therein. Note that during unloading the melting rates are increased throughout the melting region, but that the greatest relative increase occurs in the shallower parts of the region. The composition of instantaneous fractional melts is shown as a dashed line. These fractional melt compositions were calculated assuming a uniform lherzolite starting composition, with the spinel to garnet transition occurring between 80 and 100 km depth. The fraction of melt generated is <0.05 at depths of >80 km and rises to 0.27 at 20 km depth, close to the base of the crust. Partition coefficients were allowed to vary during melting in the response to the expected variation in modal mineralogy during decompression and melting. The Sm/Yb ratios of the instantaneous fractional melts were calculated under the assumption that Sm/Yb of the mantle source was $\sim$1, close to primitive mantle. If a depleted mantle source was used then these values should be multiplied by a factor of 0.68. *–Áhrif bráðnunar jökla á uppbræðslu í möttli og kvikusamsetningu. A) Uppbræðsla möttulsefnis er háð rekhraða og möttulhitastigi. B) Bráðnun ísaldarjökulsins veldur þrýstilétti og möttulbráðnun sem stjórnast af stærðarbreytingu jökulhörfunarinnar. C) Niðurstöður efnagreininga á basalti frá Þeistareykjum og Kröflu. Sýni merkt "postglacial" eru af basalthraunum sem runnu frá lokum ísaldar þar til fyrir 7.000 árum. Sýni merkt "Recent" eru yngri en 7.000 ára. Samkvæmt bræðslulíkani Maclennan o. fl. (2002) vex hlutfall leginnar kviku í jarðskorpunni í kjölfar þrýstilækkunar vegna jökulhörfunar, og hlutfall Sm/Yb hækkar. D) Samfelldar línur tákna breytilegan bræðsluhraða með dýpi við sístæða bræðslu á tímabili jöklabráðnunar. Hörfun jökla hefur mest áhrif á grunnstæða uppbræðslu möttulsins. Brotna línan táknar reiknaða samsetningu upphafsbráðarinnar að því gefnu að möttulefnið sé eingöngu úr lherzólíti og að bræðslan byrji á mörkum granat-spínel hamskiptanna á 80–100 km dýpi. Neðan 80 km bráðnar 5% lherzólíts og eykst hlutbráðnunin í 27% á 20 km dýpi nálægt mörkum skorpu og möttuls, dreifistuðlar breytast og endurspegla ætlaða steindasamsetningu möttulbergsins og breytingu þess með dýpi, þrýstilétti og hlutbráðnun. Jafnframt er gert ráð fyrir að Sm/Yb hlutfall möttulsins sé nálægt frumstæðum möttli eða 1. Ef samsetning venjulegs, skerts möttuls væri notað í útreikningum ber að að margfalda Sm/Yb gildin með stuðlinum 0,68.*

son *et al.*, 1992a, 2000; Furman *et al.*, 1995). The constant isotope ratios can be used as fingerprints for a given volcano as successfully applied to the 1996 Gjálp eruption that occurred midway between two large central volcanoes (Figure 8). Mixing is able to produce large volumes of compositionally uniform melt, such as the large lava field formed during the 1783–1784 Laki eruption (Sigmarsson *et al.*, 1991a). However, this magma underwent considerable crustal contamination and incorporated xenocrysts during ascent to the surface (Bindeman *et al.*, 2006).

FORMATION OF SILICIC MAGMA AND TIME SCALES OF MAGMA DIFFERENTATION

Studies of U-series disequilibria in silicic rocks from Iceland have proven to be valuable in distinguishing between two possibilities for their origin extensive fractional crystallization of basaltic magma, or partial melting of hydrothermally altered crust. Several characteristics of silicic magmas are better explained by the latter process, as summarized by Jónasson (2007), with strongest arguments coming from

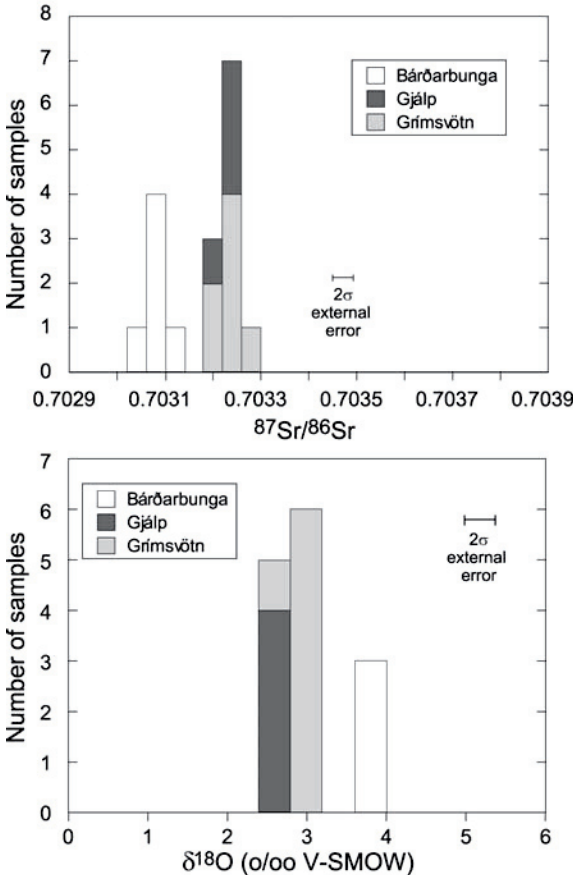


Figure 8. Histogram of Sr- and O- isotope ratios in historical volcanics of Bárðarbunga and Grímsvötn volcanic systems. Isotope ratios can be powerful tracers of magma origin and migration. A clear example is given by the products of the 1996 Gjálp eruption, which took place midway between Bárðarbunga and Grímsvötn central volcanoes. The products have the same Sr and O isotope ratios as the basalts from the latter volcano and, therefore, the magma erupted at Gjálp most likely originated at Grímsvötn. – *Súlurit með samsætuhlutföllum Sr og O í gosefnum frá eldstöðvakerfum Bárðarbungu og Grímsvatna á sögulegum tíma. Samsætuhlutföll geta gefið sterkar vísbendingar um uppruna kviku og tilfærslu hennar í skorpunni. Gott dæmi eru gosefni Gjálpargossins 1996, sem átti sér stað mitt á milli megineldstöðva Bárðarbungu og Grímsvatna. Gosefnin hafa sömu samsætuhlutföll og basalt Grímsvatna og því verður að teljast að kvikan sem gaus í Gjálp sé þaðan upprunnin.*

the U-series disequilibria. Lower (^{230}Th/^{232}Th) are observed in silicic rocks compared to intermediate or basaltic lavas from the same volcano (Figure 9) and since fractional crystallization cannot alter isotope ratios of heavy elements, this process cannot produce the silicic magmas, in general. The lower Th-isotope ratio is readily explained by a two-stage melting scenario: partial mantle melting produces basalts with Th-excess over U, these basalts will reach radioactive equilibrium between U and Th with time and form the Icelandic crust with lower Th-isotope ratio than the original basalt. Partial crustal melting will subsequently generate silicic magmas with lower Th-isotope ratio (see Figure 9 and Sigmarsson *et al.*, 1991b). This model is corroborated by variations in stable isotope ratios such as O, B, Fe and Li (e.g. Hattori and Muehlenbachs, 1982; Nicholson *et al.*, 1991; Rose-Koga and Sigmarsson, 2008; Schuessler *et al.*, 2008).

It is not surprising that the large proportions of silicic rocks in Iceland, compared to other oceanic islands, are formed by crustal reprocessing. The rift-zones open up the crust with faults and fissures causing high permeability and easy access for rain water. Interaction of these waters with hot rock leads to geothermal activity and consequent alteration and high-T metamorphism of the basaltic crust. High geothermal gradients characterise the active rift zones of Iceland, where melt supply rates from the mantle are high. Therefore, the combined action of the plume, which causes Iceland to be subaerial, and the rifting at Mid-Atlantic Ridge, results in the ab-

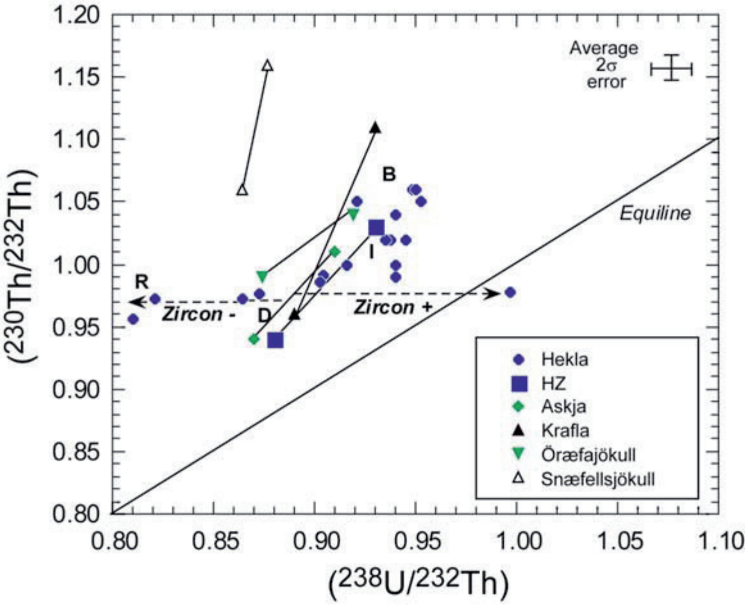


Figure 9. U-Th equiline diagram showing radioactive disequilibria between the parent nuclide ^{238}U and its product ^{230}Th that have proved valuable in resolving the debate on the origin of silicic magma in Iceland. Samples in radioactive equilibrium would plot on the equiline but Icelandic volcanic rocks show ^{230}Th enrichment over ^{238}U as do most lavas from oceanic islands and mid-ocean ridges. Plotted are silicic-basaltic magma pairs from five volcanoes, three of which were produced contemporaneously in a single eruption. Also are shown representative basalts (B), icelandite (I), dacite (D) and rhyolite (R) from Hekla volcano. In all cases, the silicic magma has lower Th-isotope ratio inconsistent with fractional crystallization mechanism for their formation. The origin of the silicic magmas is best explained by partial melting of hydrothermally altered crust. Further evolution from dacites to rhyolites is often accompanied by fractionation of zircon-bearing assemblages (zircon -) causing much lower U/Th ratio in the most evolved rhyolites. Accumulation of zircon crystals (zircon +) explains the dacite with ^{238}U-excess (to the right of the equiline). – *Jafnvægislínurit U og Th sem sýnir geislavirkt ójafnvægi á milli* ^{238}*U sem klofnar og myndar skammlífu dóttursamsætuna* ^{230}*Th. Bergsýni sem væru í geislavirku jafnvægi féllu á “Equiline” línuna ((þ.e. (*^{230}*Th/*^{238}*U) = 1) en flest gosberg Íslands sem og úthafshryggja og úthafseyja hafa hærri geislavirkni* ^{230}*Th en sem nemur* ^{238}*U (þ.e. (*^{230}*Th/*^{238}*U) > 1). Á myndinni eru sýndar mæliniðurstöður á súrum og basískum pörum (tengd með beinni línu) frá fimm eldstöðvum þar af þrjú pör sem mynduðust í sama gosinu. Jafnframt eru sýndar dæmigerðar niðurstöður fyrir basalt (B), íslandít (I), dasít (D) og rhýólít (R) frá Heklu. Í öllum tilvikum hefur súra bergið lægra Th samsætuhlutfall [(*^{230}*Th/*^{232}*Th)] sem útilokar að hlutkristöllun frá basalti sem líklegt myndunarferli súra bergsins. Aftur á móti er hlutbræðsla ummyndaðrar basaltskorpu talin besta skýringin og í fullu samræmi við geislavirkt ójafnvægi U-Th. Slík hlutbráð hefur samsetningu dasíts sem myndar rhýólít við kólnun og kristöllun þar sem steindin zirkon fellur út og skilst frá (zircon -) og veldur mun lægra U/Th hlutfalli í afleiddu kvikunni (rhýólíti). Samsöfnun zirkonkristalla (zircon +) skýrir samsetningu dasíts með hærri geislavirkni* ^{238}*U en* ^{230}*Th.*

normally high proportion of silicic magmas in Iceland. However, the geothermal gradient is significantly lower at the periphery of the island far from the rift-zones. There, basalt production is limited and mantle melts readily cool and crystallize to a large degree, causing the formation of silicic magma without much crustal interaction (Martin and Sigmarsson, 2007 and references therein).

RATE OF MAGMA DIFFERENTATION

The U-series are exceptionally good tracers of the origin of silicic rocks in Iceland due to the short half-life of ^{230}Th. In addition, the rapid decay of ^{230}Th and other U-series nuclides provides information about the timescales of magmatic processes (Condomines *et al.*, 2003). Silicic rocks elsewhere are in most cases in U-Th radioactive equilibrium which has been interpreted to reflect a magma differentiation time in excess of several 100 kyr (e.g. Reagan *et al.*, 2000). This equilibrium is in contrast with Icelandic dacites and rhyolites which show significant Th-excesses over U, in addition to Ra-excesses over Th (Sigmarsson *et al.*, 1992b). This Ra-Th disequilibrium constrains the differentiation of the dacites to less than 8000 years, implying that either the rate of magma differentiation is faster at Icelandic volcanoes or underestimated elsewhere.

Shorter magmatic timescales can be derived from trace-element and stable-isotope diffusion in xenocrysts out of equilibrium with the melt. Such studies are still rare in Iceland, but were employed on Laki products showing that the age of the Laki magma at the time of its eruption was most likely between 100 and 1000 years (Figure 10; Bindeman *et al.*, 2006). Further studies of mineral-melt disequilibria will probably improve constraints on the timescales of magmatic processes. Crystal-size distributions can also potentially reveal residence time of magma such as the 10–20 years for plagioclase crystals in the 1973 Eldfell eruption (Higgins and Roberge, 2007). This residence time corresponds well with the 10 years differentiation time in a magma chamber estimated from ^{210}Pb-^{226}Ra disequilibria in basalts from Surtsey and the 1973 mugearite-hawaiite lavas in Vestmannaeyjar archipelago (Figure 11; Sigmarsson, 1996). The scenario envisaged is injection of basaltic melt beneath

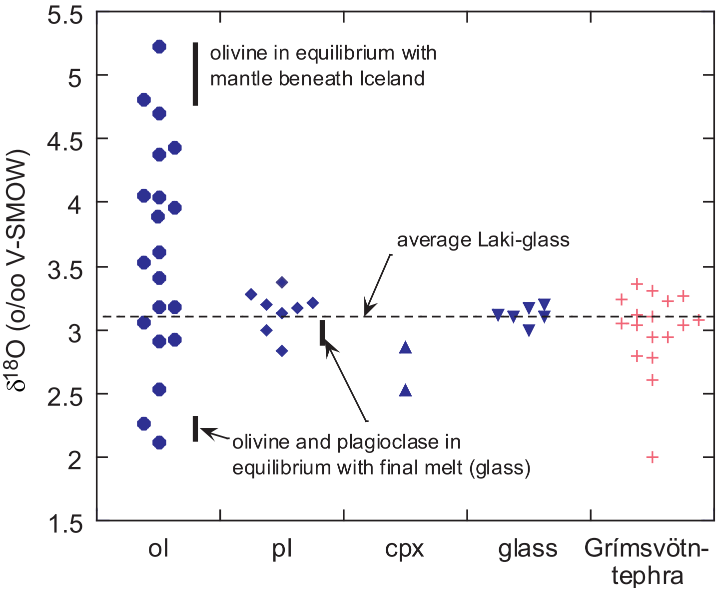


Figure 10. Oxygen isotope composition in minerals and glasses from the Laki 1783–84 eruption in addition to tephra from several Grímsvötn eruptions. Both Laki and Grímsvötn glasses have δ^{18}O amongst the lowest measured in basalts and reflect crustal contamination. The crystals show significant isotope disequilibria with the glass that has not been erased by diffusion due to their short residence time in Laki magma. Models of oxygen diffusivity in olivines imply magma residence time of 100–1000 years before the Laki eruption, consistent with ^{210}Pb-^{226}Ra-^{230}Th disequilibrium results (see Bindeman *et al.*, 2006). – *Súrefnissamsætuhlutföll í steindum og gjóskugleri frá Skaftáreldum ásamt gjósku Grímsvatna. Gler í gosefnum Laka, Lakagíga og Grímsvatna hafa einhver allægstu* δ^{18}*O gildi sem mælst hafa í basalti um alla veröld og eru þessi lágu gildi talin stafa af skorpumengun rísandi möttulkviku. Steindirnar, sérstaklega olivín (ol) sýna mikið samsætuójafnvægi við lokabráð sem storknaði sem gjóskugler (lóðrétt strik sýna jafnvægisgildi). Þetta ójafnvægi bendir til að flestar steindirnar séu framandsteindir sem féllu í kvikuna eða sem kvikan reif með sér á leið sinni til yfirborðs. Líkanreikningur á flökti súrefnis um kristallana, sem að lokum myndi jafna út mismunandi samsætugildi innan og utan kristallsins, bendir til að kvikan hafi dvalið 100–1000 ár neðra fyrir Skaftáreldagosið. Þessi aldur samsvarar niðurstöðum geislavirks ójafnvægis á milli* ^{210}*Pb,* ^{226}*Ra og* ^{230}*Th.*

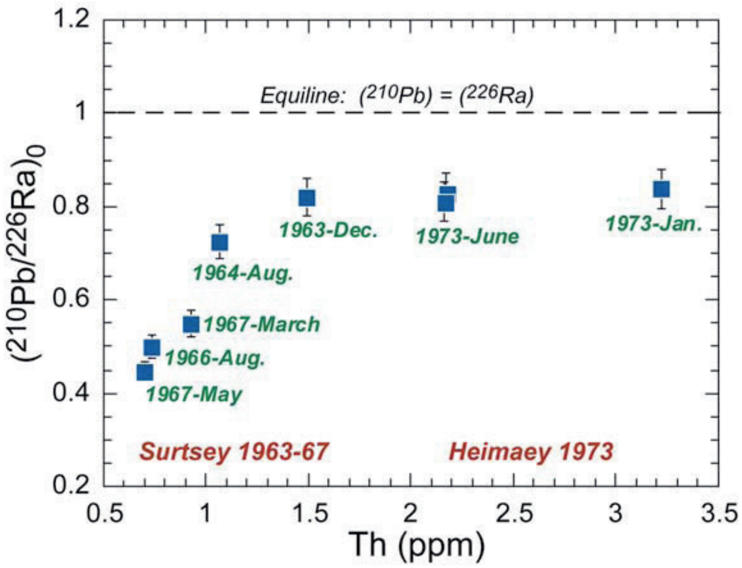


Figure 11. ^{210}Pb-^{226}Ra disequilibria (corrected for post-eruptive decay) vs. Th concentrations in lavas from the 1973 Heimaey and 1963–67 Surtsey eruptions in the Vestmannaeyjar archipelago. The constant $(^{210}Pb/^{226}Ra)_0$ in basalt from the first eruption phase at Surtsey and the early mugearite and late hawaiite from Heimaey shows that fractional crystallization does not alter this ratio and that lower values in later basalts from Surtsey are best explained by magma mixing of fast-rising mantle melts with significant ^{210}Pb- deficit (see Sigmarsson, 1996). – *Geislavirkt ójafnvægi ^{210}Pb og ^{226}Ra (gosgildi) sem fall af styrk utangarðsefnisins Th í 20. aldar gosefnum Vestmannaeyja. Einsleitt hlutfall (^{210}Pb–^{226}Ra) í basalti Surtlu og mugearíti og hawaíiti sem gusu snemma og síðla í 1973 gosi Eldfells, sýna að hlutkristöllun breytir ekki þessi hlutfalli. Lægri gildi annarra gosefna Surtsey eru best skýrð með kvikublöndun líkra möttulbráða sem risið hafa hratt frá myndunarstað sínum þar sem geislavirkni ^{210}Pb er mjög lág miðað við ^{226}Ra*

Heimaey during the 1963–67 Surtsey eruption, followed by rapid cooling and fractional crystallization forming evolved hawaiite and mugearite at the top of a magma chamber. During the decade separating these two youngest eruptions in the Vestmannaeyjar volcanic system, volatiles gradually accumulated, leading to the 1973 eruption.

VOLATILES

The role of volatiles and a separate gas phase in starting eruptions has long been established. However, estimates of their mass emissions during Icelandic eruptions and thus volcanic contribution to the atmosphere are still surprisingly rare. The so-called petrological method, where the difference in volatile concentrations measured in non-degassed melt inclusions found in phenocrysts and that of degassed groundmass glasses yields the volatile mass emitted to the atmosphere (e.g. Sigurdsson, 1982; Devine *et al.*, 1984; Thordarson *et al.*, 1996), has become an important tool in discussing past emissions of volatiles. This approach relies upon proper identification of phenocrysts versus xenocrysts, since the latter will lead to an erroneous conclusion. The method can be improved by taking into account the increased volatile concentrations caused by fractional crystallization and when applied to the last Hekla eruption (Figure 12) it yields an estimated mass transfer of 0.1 Mt HCl, 0.2 Mt HF and 4 Mt SO_2 for the 2000 eruption (Moune *et al.*, 2007).

Assessment of volatile degassing from the composition of volcanic glasses from tephra layers permits discussion of environmental factors such as the presence or absence of glaciers or ice-caps covering active volcanoes, for example Mýrdalsjökull capping the Katla central volcano. Phreatomagmatic tephra erupted during the last 8400 years yields sulphur concentrations higher than magmatic tephra due to rapid cooling when the magma encounters glacial meltwater. This observation indicates that this glacier

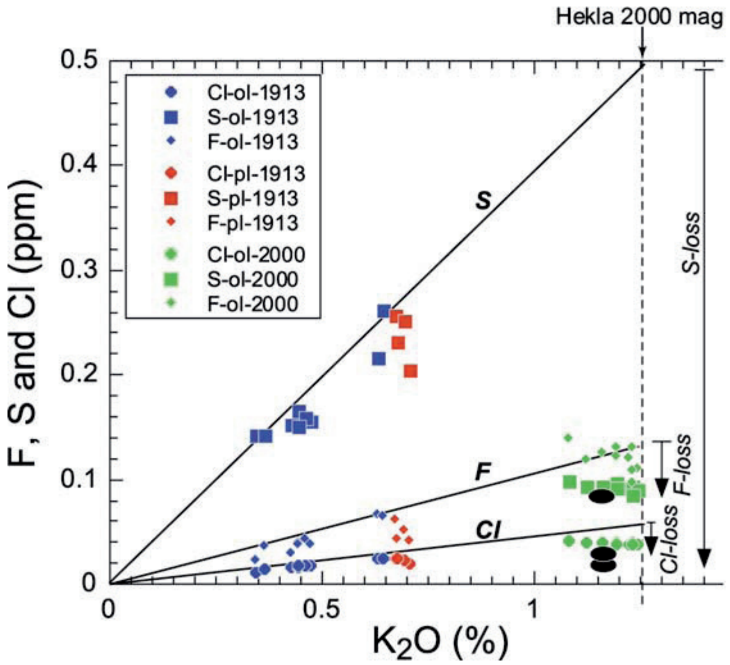


Figure 12. Volatile evolution beneath Hekla. The halogens and sulphur were measured in melt inclusions from olivines of variable MgO content and plagioclases in the 1913 basalt close to Hekla, and in olivines from the 2000 Hekla basaltic icelandite and its interstitial groundmass glasses (black filled oval symbol). The low S concentrations in olivines erupted in 2000AD is explained by their crystallization out of a partially degassed magma. Regression line calculated through the analyses of olivine melt inclusions from the basalts intercept the origin as expected if fractional crystallization causes variations in the concentration. The extrapolated intercept with the K_2O concentration measured in the 2000 basaltic icelandite yields the expected concentration of volatiles before degassing. The difference between these expected values and degassed groundmass values gives improved estimates of volatile mass transfer from Hekla to the atmosphere (see text and Moune *et al.*, 2007 for further details). – *Þróun rokgjarnra efna undir Heklu. Styrkur halógena og brennisteins var mældur í glerinnlyksum í ólivínsteind af breytilegri samsetningu og plagíóklas í basalti frá Lambafitjargosinu 1913 og í ólivín úr basísku íslandíti sem myndaðist í Heklugosinu 2000, ásamt grunnmassa þess síðarnefnda (svartar sporöskjur). Lágur brennisteinsstyrkur í innlyksum ólivíns frá 2000 gosinu skýrist með kristöllun út úr kviku sem var að hluta til afgösuð. Bestu línur voru reiknaðar í gegnum mæliniðurstöður úr innlyksum ólivína úr basaltinu og skera þær núllpunkt, en slíkt gera sýni, af breytilegri samsetningu, sem myndast hafa vegna hlutkristöllunar frá sömu móðurkviku. Framlenging þessarra lína að K_2O-gildi mældu í basaltíska íslandítinu frá 2000 gosinu, sýnir áætlaðan styrk rokgjarnra efna fyrir afgösun kvikunnar úr síðasta Heklugosi. Munurinn á mill þessa metna styrks og þess sem mældur var í afgösuðum grunnmassanum leiðir til bætts mats á magni eldfjallagass sem Hekla gefur frá sér út í andrúmsloftið.*

survived the thermal maxima during the Holocene (Oladóttir *et al.*, 2007). In-situ analysis of such tephra sequences also yields time-series that record the temporal evolution of magma plumbing systems beneath active volcanoes, which can be shown to control the eruption frequency (Oladottir *et al.*, 2008). Studies of such time-series hold the promise of exciting new results and much improved understanding of volcanoes behaviour and evolution, which are of value for hazard and risk assessments.

CONCLUSIONS

1. The mantle source of Icelandic magma is enriched in incompatible elements and fusible material compared to that of the adjacent spreading ridges to the south and the north.
2. Variations in melt production rate along the spreading ridges and rift zones, as reflected by crustal thickness variations at the spreading centre, are controlled by variations in man-

tle potential temperature, plume upwelling rate and source fusibility. The relative importance of these three variables is not yet established.

3. The extent of mantle melting is greater under the rift zones than off-rift volcanic zones. These variations may be partly controlled by deepening of the top of the melting region as a result of cooling of the plate with age. A decrease in mantle potential temperature with distance from the centre of Iceland may also limit the extent of melting under the off-rift zones.
4. Basaltic melts are transported rapidly from their mantle source regions towards the crust in channels. The melt supplied by these channels to the crust is compositionally heterogeneous on small length scales. Concurrent mixing and crystallisation in deep-seated magma reservoirs effectively homogenises melt before it is fed towards the surface in dykes.
5. Large basaltic lava flows contain minerals that are compositionally heterogeneous and are therefore not in chemical equilibrium. Part of this disequilibrium is caused by addition of minerals from solid parts of the crust into magma batches. Magma mixing after crystallisation from diverse melt compositions may also lead to disequilibrium.
6. Silicic magmas from the periphery of Iceland are in general produced by fractional crystallization whereas those from the interior are partial melts of hydrothermally altered basaltic crust
7. The residence time of magma in crustal chambers is very short, and may be as little as a decade.
8. Icelandic volcanoes contribute significantly to the mass-loading of volatiles into the atmosphere.

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ÁGRIP

Tvær mikilvægar breytingar á samsetningu gosbergs má rekja eftir úthafshryggjum norðan og sunnan Íslands, eftir rekbeltunum og hliðargosbeltunum. Styrkur utangarðsefna (þ.e. þeirra efna sem illa ganga inn í kristalbyggingu helstu steinda) í basalti eykst eftir hryggjunum í átt að Íslandi, með aukinni hlutbræðslu frjós og auðbræðanlegs bergs í samsettum möttli. Líklegast er þetta auðbræðanlega berg samsett af granatpýroxeníti sem áður var úthafsskorpa á yfirborði jarðar. Nútíma basalt frá gosbeltunum hefur hærri styrk slíkra utangarðsefna en það sem myndast í rekbeltunum. Helstu skýringar á breytileika í efnasamsetningu er að finna í mismunandi hitastigi möttuls, bergfræðilegri uppbyggingu, flæði möttulefnis sem og hugsanlegum áhrifum tektóníkur á kvikumyndun. Möttulkvikur rísa hratt til yfirborðs, líklegast í þröngum göngum, og blandast og kólna í djúpstæðum kvikuþróm fyrir eldgos. Hlutfallslega minni basaltkvikuframleiðsla innan hliðargosbeltanna veldur lægri hitastigli, þar sem köld skorpa kælir basaltkviku sem í henni stöðvast og stuðlar að hlutkristöllun sem gefur af sér súrt berg. Í rekbeltunum er mun hærri kvikuframleiðsla og súrt berg myndast við hlutbráðnun skorpunnar. Ítarleg blöndun bráðins skorpubergs og basalts skýrir samsetningu og breytileika kviku sem kemur upp í stórum sprungugosum s.s. Skaftáreldum og Eldgjá.

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