

# Tertiary volcanism in Iceland

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**Abstract** — *The Tertiary igneous rocks of Greenland, Iceland, the Faeroes and Britain have been the subject of study and debate for more than a hundred years. Iceland is of particular significance because the coincidence of a mantle plume with the Mid-Atlantic Ridge combines the two fundamental forces that promote magmatism, namely the elevated mantle potential temperature induced by the Iceland plume and adiabatic decompression in response to spreading at the ridge. Furthermore, the exposed Iceland crust contains evidence of major ridge-jumps over the last 16 million years and this relocation of the magmatic focus has been a prominent process in the evolution of the island. The control on ridge-jumping is clearly related to the interaction of the mantle plume with the overlying lithospheric plate. This process has had a significant impact on the investigation of magmatic, tectonic and sedimentary processes. The bulk of the Tertiary region is made of subaerial tholeiitic flood basalts separated by minor clastic interbeds, usually of volcanic origin. The relatively monotonous Tertiary lithology is interrupted where central volcanoes occur with their buried palaeotopography, evolved rocks, hydrothermal alteration and stratigraphic complexities. It has become clear that the range of chemical composition of Tertiary basalt is much more limited than that seen among Pleistocene and Holocene basalt, and depleted basalt appears, surprisingly, to be absent from the Tertiary succession. These observations can be explained by processes of crustal accretion operating today in the active rift zones of Iceland. It is a widely held assumption that V-shaped ridges observed in the gravity field around the Reykjanes Ridge imply variation in plume temperature and plume activity. Temporal variations in some isotope ratios in the Tertiary lava flows seem to coincide with the formation of the V-shaped features, and this could be consistent with a pulsating plume model.*

## INTRODUCTION

The striking similarities between the Tertiary igneous rocks of Britain, the Faeroes, Iceland and E Greenland have long been recognised and their formation and relationship has caused geologists to lock horns in debate since the late 1800s. The Iceland Tertiary formations play an important role in the history of the North Atlantic igneous province. Magmatic activity in the province started at about 61 Ma in a geological event which became in effect the genesis of the North Atlantic Ocean and was to change the course of history in the region. Up until this time the break-up of the North Atlantic continents had progressed from sedi-

mentary basins to sea-floor spreading with volcanic activity confined to the actual spreading axes of the new ocean basins. However, between 61 and 56 Ma the North Atlantic region saw a massive outburst of volcanic activity across an area extending ~2000 km from Arctic Canada to Scotland (e.g. Storey *et al.*, 2007). Flood basalts of this age are found in Baffin Island, West Greenland, East Greenland, Northern Ireland, and Scotland. Volcanism on this scale requires a sudden increase in the temperature of the mantle beneath the region, and the most plausible reason for this is the initiation of the mantle plume now situated underneath SE Iceland (Figure 1).

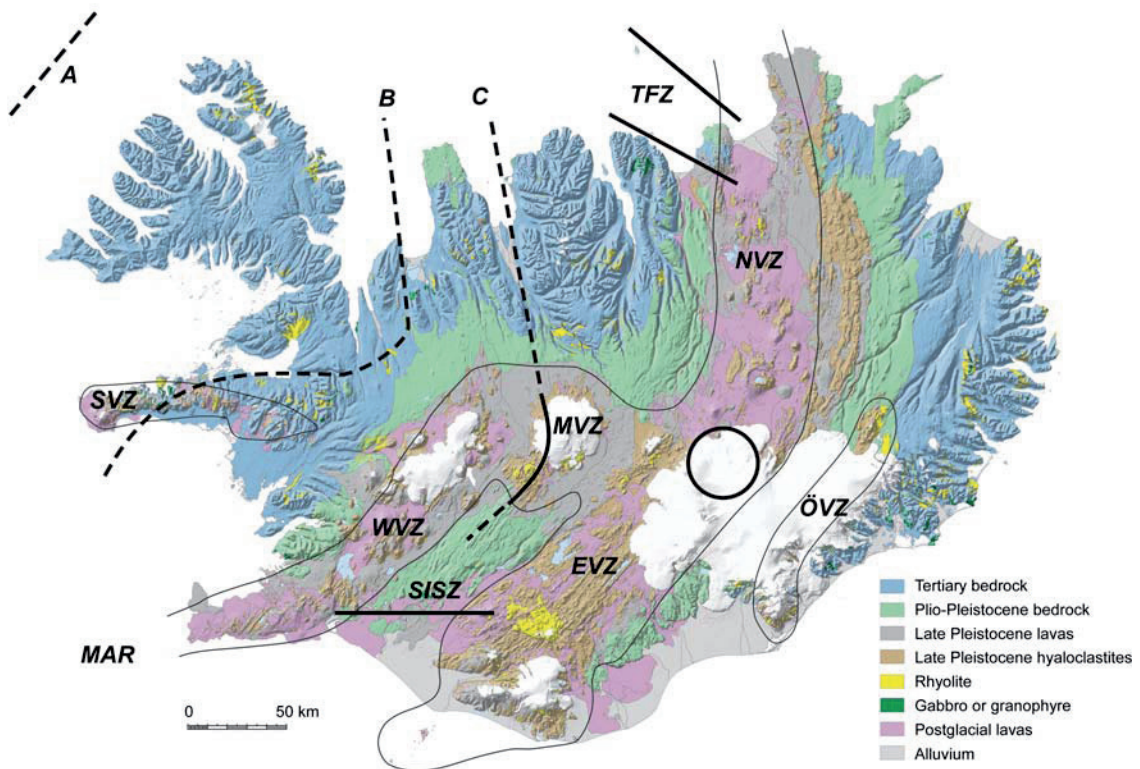


Figure 1. The neovolcanic zones and rift systems in Iceland. **A** = Northwest rift axis; **B** = Snæfellsnes-Húnaflói rift axis; **C** = Skagafjörður rift axis; **MAR** = Mid-Atlantic Ridge; **WVZ** = Western Volcanic Zone; **MVZ** = Mid-Iceland Volcanic Zone; **NVZ** = Northern Volcanic Zone; **EVZ** = Eastern Volcanic Zone; **SISZ** = South Iceland Seismic Zone; **TFZ** = Tjörnes Fracture Zone; **SVZ** = Snæfellsnes Volcanic Zone; **ÖVZ** = Öræfajökull Volcanic Zone. Circle represents the approximate centre of the Iceland plume (modified from Jóhannesson and Sæmundsson, 1999) – *Gos- og rekkbelti Íslands*.

The Iceland plume has been imaged seismically and is seen to have a relatively narrow stem with a radius of  $\sim 150$  km (e.g. Wolfe *et al.*, 1997; Bijwaard and Spakman, 1999; Bjarnason, 2008) and to originate at a depth of  $>660$  km in the mantle (e.g. Shen *et al.*, 1998). At the time of its origin, however, the plume is likely to have developed a large mushroom-like head extending over a radius of  $\sim 1000$  km (e.g. Richards *et al.*, 1989). Past positions of the plume head with respect to the continents can be reconstructed from known plate motions, and it may have been close to West Greenland at  $\sim 62$  Ma (Lawver and Müller, 1994). Although the two plates of the

North Atlantic Ocean are spreading symmetrically, the whole region is drifting slowly to the northwest with respect to the Iceland plume. Plate reconstructions suggest that the plume would have crossed the East Greenland coast at 40 to 35 Ma (Lawver and Müller, 1994) and reached the Mid-Atlantic Ridge at  $\sim 25$  Ma (e.g. Vink, 1984).

Since  $\sim 25$  Ma, the ridge has remained linked to the plume centre. During Anomaly 6 (24–19 Ma ago), the Mid-Atlantic Ridge axis moved on top of the mantle plume and then gradually west of it (e.g. Vink, 1984). However, as the spreading ridge system in Iceland continues to drift NW with respect to the plume

it is periodically recaptured by the plume through the process of rift-relocation or ridge-jumping. This plume-ridge interaction has been a dominant process in the formation and tectonic evolution of Iceland.

Today the Mid-Atlantic Ridge is represented on land by the Western and the Northern Volcanic Zones (WVZ and NVZ respectively, Figure 1). The WVZ and NVZ are offset along a region known as the Mid-Iceland Volcanic Zone (MVZ). The NVZ is connected to the Kolbeinsey Ridge in the north by the Tjörnes Fracture Zone (TFZ). The Eastern Volcanic Zone (EVZ) is currently propagating to the south with the Vestmanna Islands representing the tip of the propagator. The EVZ is connected to the WVZ by the South Iceland Seismic Zone (SISZ). Eventually, a ridge-jump is expected whereupon the focus of extension in S Iceland will transfer from the WVZ to the EVZ (e.g. Sæmundsson, 1980). The EVZ is thus a juvenile rift segment which eventually will connect to the Mid-Atlantic Ridge (e.g. Gudmundsson, 2007). Geodetic GPS studies are consistent with a propagating ridge model for S Iceland with the WVZ whilst the EVZ accommodates 100–55% of plate motion, decreasing from NE to SW (La Femina *et al.*, 2005).

It is believed that the general tectonic trends in Iceland as seen today have remained the same for at least 24 Ma (e.g. Sæmundsson, 1980). Therefore, two rift segments are always active simultaneously in S Iceland, one mature and the other juvenile. The tectonic scenario has resulted in a close relationship between the Iceland plume and the ridge system, where earthquakes are common in the fracture zones which accommodate the offset in the spreading axes caused by the NW motion of the ridge system relative to the plume.

## THE TERTIARY REGIONS

It is conventional to divide the Icelandic bedrock into four main chronological successions that differ from the international time-scale in some respects (e.g. Gradstein *et al.*, 2004). Because of the ongoing debate amongst geologists regarding the terms Tertiary and Quaternary and their definition in the geological time scale, the local Icelandic time-scale is used in this paper:

1. The Holocene and late glacial succession, 0–0.015 Ma.
2. The Upper Pleistocene succession 0.015–0.78 Ma.
3. The Plio-Pleistocene succession, 0.78–3.3 Ma.
4. The Tertiary succession, 3.3–16 Ma.

This division has been widely used in the literature and is based on the distinctive character of volcanic rock successions formed during each period which broadly correlate with climate change through time. The Tertiary and Plio-Pleistocene regions are located on either side of the active volcanic zones (Figure 1) and are characterised by basaltic lava series. These are cut by deep valleys forming the fjord landscapes which are typical for E Iceland and much of N and NW Iceland. The Tertiary and Plio-Pleistocene rocks cover approximately half of the total area of Iceland (103,000 km<sup>2</sup>), or 36,000 km<sup>2</sup> and 15,000 km<sup>2</sup> respectively.

Systematic mapping on a regional scale has been carried out in many Tertiary areas but is far from complete. The work of G. P. L. Walker in E Iceland presented a new perspective on Icelandic geology and he introduced several new methods and concepts in his stratigraphic research (see Watkins and Walker, 1977). The section in E Iceland involves an 8.5-km-thick lava succession which represents a 10 Ma time interval from about 13.4 Ma. The contribution of Carmichael (e.g. 1967) to Icelandic petrology, petrography and classification of igneous rocks was significant and a guideline for many subsequent workers. In recent years several composite Tertiary sections, each containing hundreds of lava flows, have been sampled for palaeomagnetic remanence direction measurements (see Kristjánsson and Jonsson, 2007) and geochemical studies. Many have been dated by K-Ar or Ar-Ar radiometric methods (e.g. Watkins and Walker, 1977; McDougall *et al.*, 1976, 1977, 1984; Sæmundsson *et al.*, 1980; Kristjánsson *et al.*, 1980, 1992, 2004; Jancin *et al.*, 1985; Hardarson *et al.*, 1997).

## THE AGE AND ORIGIN OF ICELAND

Iceland is part of a much larger geological entity located at the junction of two large submarine ridges, the Mid-Atlantic Ridge and the Greenland-Iceland-Faeroes Ridge. Iceland, and its insular shelf, cover about 350,000 km<sup>2</sup> and rises more than 3000 m above the surrounding deep-ocean floor. About 103,000 km<sup>2</sup> of the area is above sea level, the rest surrounding the island as a 50–200 km wide insular shelf sloping gently to depths of around 400 m before dropping steeply to the deep-ocean floor.

The oldest subaerial rocks are found at the NW and E extremes of the island. In the NW peninsula they date back to more than 15 Ma (Moorbath *et al.*, 1968; McDougall *et al.*, 1984; Harðarson *et al.*, 1997; Pringle *et al.*, 1997) and to about 14 Ma in E Iceland (e.g. McDougall *et al.*, 1976; Watkins and Walker, 1977). The oldest rocks in N Iceland have been dated at about 12 Ma (Sæmundsson *et al.*, 1980; Jancin *et al.*, 1985). Zircons with much older ages of 126–242 Ma reported from E Iceland are believed to be derived from splinters of continental crust buried under the island (Paquette *et al.*, 2007).

An ancestral Iceland may have formed a land mass over the mantle plume off the east coast of Greenland. The Greenland-Iceland-Faeroes Ridge represents a hot-spot trail which may have been partly above sea level because of the thermal anomaly caused by the plume. This is supported by palaeobotanical evidence which suggests that proto-Iceland was connected to the continents via a continuous land bridge, or a chain of islands, from the early Cenozoic and into the middle Miocene (Grimsson *et al.*, 2007). However, Iceland, as we know it today, was probably formed during Anomaly 6 when the present day tectonic framework and the plume-ridge interaction were initiated resulting in excessive volcanism creating a large island.

## STRATIGRAPHY AND CENTRAL VOLCANOES

The bulk of the Tertiary areas is made up of subaerial tholeiitic flood basalts separated by minor clastic interbeds, usually of volcanic origin. Basaltic volcan-

ism has mainly been confined to two types of volcanoes: crater rows and lava shields. Crater rows vary in length, from being only a short fissure with a single or a few craters up to being 80 km, comprising hundreds of eruptive vents. In the eroded Tertiary pile the craters have often been weathered away but their feeder dykes are still visible. The thickness of individual lava flows in the pile is most often 5–15 m but can reach more than 50 m. Some of the largest and thickest flows are feldspar-porphyrific which often form series of lavas that are prominent in the Tertiary landscapes and traceable for long distances because of their thickness and resistance against erosion (e.g. Watkins and Walker, 1977).

Lava shields are generally thought to be monogenetic (Walker, 1971; Jakobsson *et al.*, 1978; Rossi and Gudmundsson, 1996) and most often emitted from a single circular crater. Rifting is rarely recognised. The lava flows are of olivine tholeiite or picrite composition and occur mainly at the margins or outside the fissure swarms associated with the central volcanoes. During Holocene the shields have been more productive than the crater rows erupting larger volumes of lava. Lava shields are also fairly common in the Plio-Pleistocene formations. In the Tertiary lava pile, on the other hand, shields are rather rare and seem to have been much less productive than the crater rows. It has been noted that many of the postglacial lava shields of Iceland are of early Holocene or late glacial age which has been related to glacial isostasy (Sigvaldason and Steinthorsson, 1974; Jakobsson *et al.*, 1978; Gudmundsson, 1986; MacLennan *et al.*, 2002; Hjartarson, 2003). This may explain the different lava shield activity during Tertiary and Holocene.

The relatively monotonous Tertiary lithology is interrupted where central volcanoes occur with their buried palaeotopography, evolved rocks, hydrothermal alteration and stratigraphic complexities. The bulk of acidic rocks are intrusions and lavas but 30–40% consist of pyroclastic deposits. In crater regions agglomerate layers are common, lahars are often found and airborne tephra has frequently been carried long distances downwind from the source forming prominent marker horizons in the Tertiary vol-

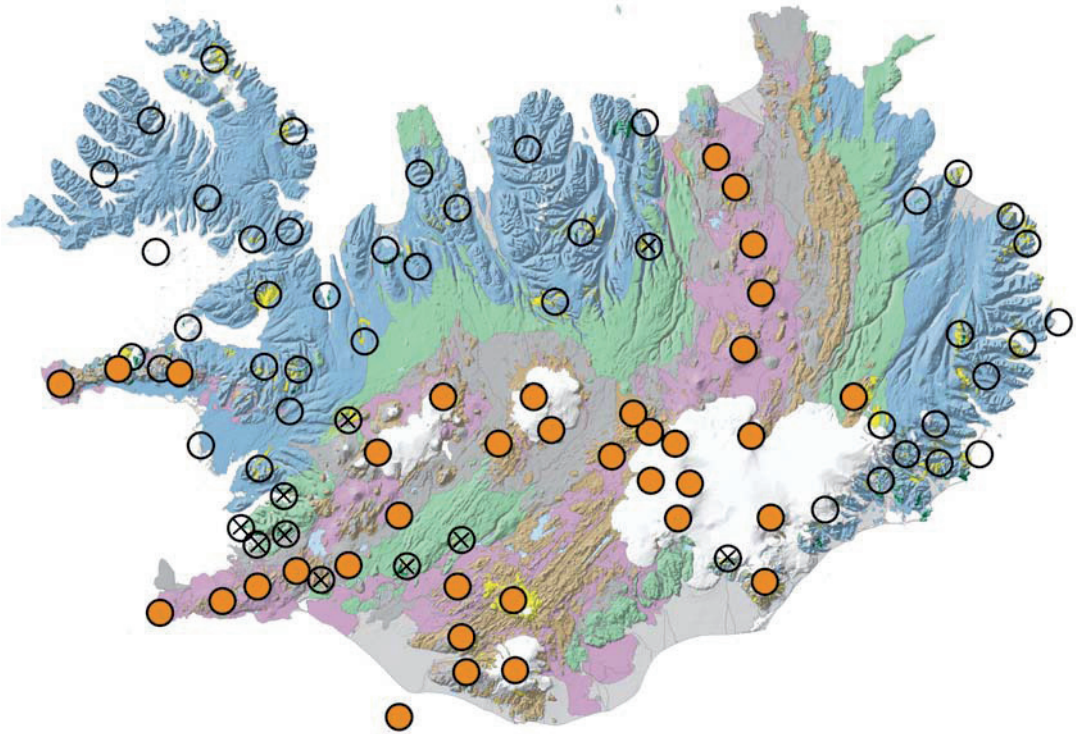


Figure 2. Central volcanoes in Iceland. Tertiary volcanoes; open circles, Plio-Pleistocene; crossed circles and active volcanoes; brown circles (based on Jóhannesson and Sæmundsson, 2003a,b) – *Virkar og útdauðar megineldstöðvar á Íslandi*.

canic pile. Large ignimbrite layers have also proven to be excellent markers (Walker, 1963; Sæmundsson and Noll, 1974; Franzson, 1978, 2006). More than 40 central volcanoes are known in the Tertiary formation (Figure 2) and several individual volcanic systems have been studied in detail (e.g. Walker, 1963; Carmichael, 1967; Sigurdsson, 1970; Hald *et al.*, 1971; Sæmundsson and Noll, 1974; Jóhannesson, 1975; Franzson, 1978; Jonasson *et al.*, 1992; Geirsson, 1993; Hjartarson, 2003; see Jóhannesson and Sæmundsson, 1998a,b). The lifespan of individual volcanic systems has been found to vary from 300 ka to over 1 million years (e.g. Sæmundsson, 1980, 1986). Several central volcanoes probably exist on the shelf E and W of Iceland as well as on the Iceland-Faeroes

Ridge. These have been inferred from geophysical surveys and, in some cases, confirmed by dredging (see Kristjánsson and Helgason, 1988).

Central volcanoes can be divided into rift zone and off-rift central volcanoes, the off-rift complexes often forming high and prominent stratovolcanoes while in the rift zone they are lower, except when erupting under glaciers, and frequently form calderas. Only rift zone central volcanoes are known in the Tertiary regions (Figure 2). The deeply eroded extinct volcanoes are represented by acid and intermediate rocks and local cone sheet swarms, whereas the parts of the volcanic system that are outside the central volcanoes are represented by a tholeiitic lava pile and swarms of regional dykes and normal faults. The sheet swarms

are usually circular or elliptical in shape, several km in radius and can often be related to intrusive rock bodies that form the uppermost parts of fossil magma chambers. The regional dykes occur in well defined swarms that are several km wide and sometimes tens of km in length. They usually cut the lava flows in the strata pile at nearly right angles. The thickness of the regional dykes ranges from a few cm to over 20 m, averaging around 5 m and their proportion rarely exceeds 10% in surface exposures (Sæmundsson, 1986).

Sediments up to 200 m thick may occasionally be found in the Tertiary stratigraphy accounting for 5–10% of the whole (Jakobsson, 1980; Sæmundsson, 1980). This is far less than seen in younger areas that were subject to subglacial volcanism. Thin layers of reddish silty or tuffaceous sediments are the most common type of interbeds in the Tertiary pile. They are thought to be mostly of aeolian origin especially of wind-blown ash that has experienced chemical weathering towards laterite indicating humid warm temperate climate. Prominent sedimentary horizons, for example in NW Iceland, can be traced tens of kilometres from fjord to fjord (Jóhannesson and Sæmundsson, 1998a,b), and seem to have formed during transitions when a new volcanic system began to develop marginal to an older one which was fading out. These sediments are of terrestrial origin, fluvial or lacustrine, often with thin ash layers and sometimes with lignite seams and plant impressions. The paleobotanical records in these sediments reflect the climatic oscillations in the N Atlantic region and indicate a slow cooling during late Miocene and Pliocene. Diamictite layers of glacial origin are found in the Tertiary of SE Iceland indicating localised glaciers in the area as early as 5–4 M.y. ago (e.g. Geirsdóttir *et al.*, 2007).

The most widespread Tertiary sedimentary horizons are related to unconformities that seem to represent rift relocations. An extensive unconformity with laterite-lignite horizon in NW Iceland marks the extinction of the NW Iceland rift at about 15 Ma (Harðarson *et al.*, 1997). In E Iceland a major sedimentary horizon of this kind has been mapped (see Jóhannesson and Sæmundsson, 1998ab). The lava flows below the unconformity may have originated from the Snæfellsnes-Húnaflói rift zone (SH rift zone),

whereas flows above originate from the current NVZ. A similar horizon, found in the Fnjóskadalur valley in N Iceland, marks the unconformity at the western boundary between these formations. The well known Tjörnes sedimentary layers (2.5–4 Ma) in N Iceland probably represent a continuation of this unconformity (Eiriksson *et al.*, 1990; Simonarson and Eiriksson, 2008). Another major sedimentary horizon, the Hreðavatn horizon, in the Borgarfjörður area in W Iceland, marks the extinction of the SH rift and the initiation of the presently active WVZ (Jóhannesson, 1980; Grimsson, 2007).

On a regional scale the Tertiary plateau lavas dip gently towards the active or extinct rift zones from which they were formed (e.g. Sæmundsson, 1967, 1974; Jóhannesson, 1980). In E Iceland the dip increases from around 2° at the highest levels (around 1000 m.a.s.l.) to about 7–10° at sea level. Walker (1960) suggested that the lava flows had reached an upper limit of around 1.5 km above sea level, at which dyke frequency was zero and lavas essentially horizontal but this horizon has now been removed by erosion. The upward decrease in dip is accompanied by thickening of individual lava groups down the direction of dip, which suggests that the regional dip was imparted to the pile during its growth (Walker, 1960; Gibson and Piper, 1972). The dipping of the lava pile is the result of continuous loading and subsidence of the rift zone crust which decreases towards the rift zone margins (Palmason, 1973, 1986).

## RIFT RELOCATIONS

For the last 50 Ma the North Atlantic plate system has been drifting WNW relative to the Iceland plume (e.g. Vink, 1984, DeMets *et al.*, 1990; Arnadóttir *et al.*, 2008). As the Mid-Atlantic Ridge axis moved on top of the mantle plume and then gradually west of it during Anomaly 6, the rift axis has attempted to maintain its position on top of the plume by repeated relocations of the rift system to the east leaving behind extinct axial rift zones in the western part of the island. Such extinct rift zones have been identified as synclinal structures in the basalt pile (e.g. Sæmundsson, 1967; Jóhannesson, 1980; Vink, 1984; Oskarsson *et al.*, 1985) and unconformities with sedimen-

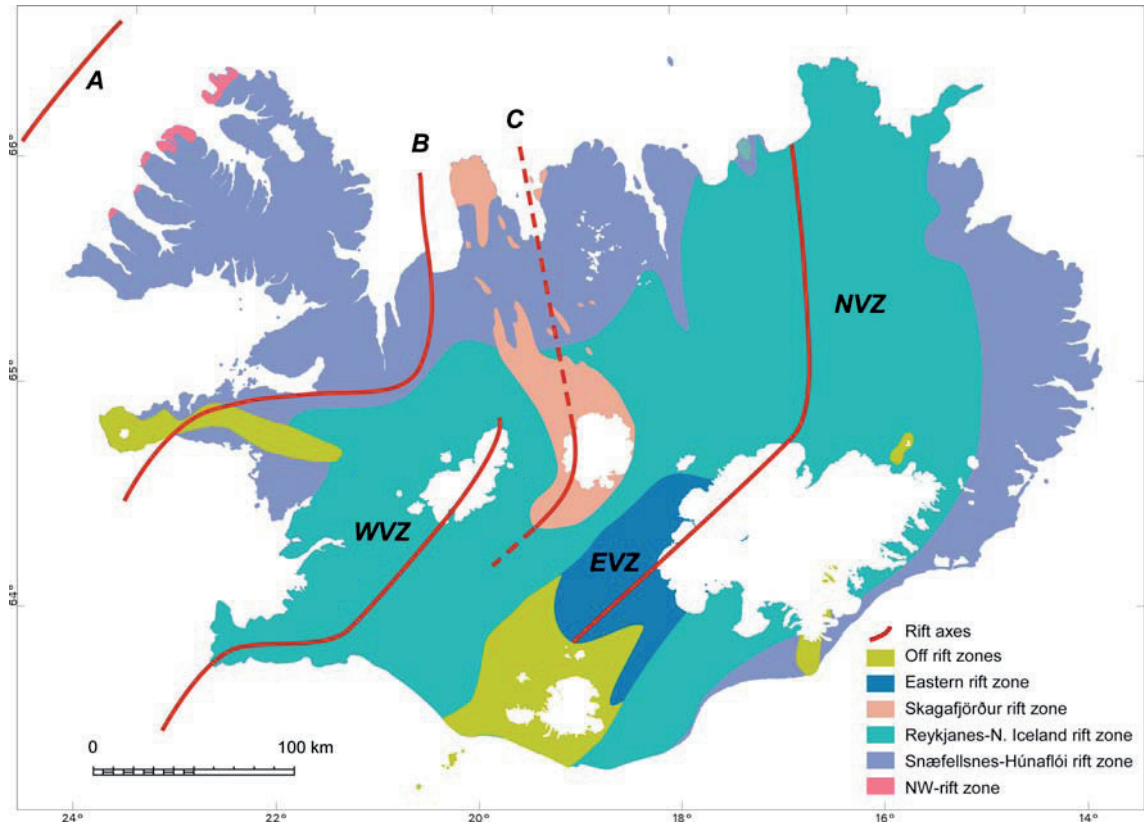


Figure 3. The Iceland crust has been formed in different rift zones (and off-rift zones). The oldest rocks in NW Iceland originate in the NW-rift zone (A), the lower Tertiary regions in West, North and East Iceland originate in the Snæfellsnes-Húnaflói rift zone (B) The Holocene and Plio-Pleistocene along with the upper Tertiary regions mostly originate in the active rift zones of today. The contribution of the Skagafjörður rift zone (C) and the off-rift zones is also indicated – *Myndin sýnir hvernig jarðskorpa Íslands hefur myndast í hinum mismunandi rekbeltum.*

Table 1. Rift zones and rift relocations in Iceland – *Aldur rekbelta og rekbeltaflutninga.*

Rift zone	Time of initiation <i>Ma</i>	Ref.
Northwest Iceland rift zone	24	Hardarson <i>et al.</i> (1997)
Snæfellsnes – Húnaflói rift zone	15	Hardarson <i>et al.</i> (1997)
Western-Northern rift zone	6 – 7	Sæmundsson (1980)
Eastern rift zone	2 – 3	Sæmundsson (1980)
Skagafjörður rift zone	1.6 – 1.7	Hjartarson (2003)

tary horizons may also relate to large scale rift relocations (Sæmundsson, 1974). Relocation of the magmatic focus through rift-jumping is a prominent process in the evolution of Iceland and the exposed Iceland crust contains evidence of several rift jumps over the last 16 Ma (Sæmundsson, 1967, 1980, 1986; Jóhannesson, 1980; Palmason, 1981; Harðarson *et al.*, 1997; Hjartarson, 2003). It has been proposed that a complete rift cycle in Iceland lasts for at least 12 Ma from initial propagation to extinction (Harðarson *et al.*, 1997).

The control on rift-jumping is probably related to the interaction of the mantle plume with the overlying, migrating, lithospheric plate. Relocation of active magmatism towards the plume may simply be a response to this migration. What remains unclear, however, is whether relocation is triggered by episodic increase of magmatic productivity from the plume centre (Vogt, 1971, 1983; Schilling, 1973; Schilling *et al.*, 1982) or if the thermal structure generated by plume-ridge interaction militates against continued magmatism remote from the plume centre. The first implies that deep seated processes inherent within the mantle plume trigger ridge relocations (Schilling, 1973; Schilling *et al.*, 1982), whereas the second points to shallow processes, where ridge relocations are simply the result of the gradual migration of the spreading axis away from the plume centre (e.g. Harðarson *et al.*, 1997).

Well documented rift relocations in the geological record of Iceland are shown in Table 1. The NW rift zone (Figures 1 and 3) is thought to have formed some 24 million years ago west of the NW Peninsula (Harðarson *et al.*, 1997). It was active for 8–10 million years (until about 15 Ma), but then the focus of spreading shifted to the east forming the SH rift which was active for another 8–10 million years (Harðarson *et al.*, 1997). However, about 6 million years ago active spreading was relocated to its present location (Figure 1) forming the WVZ and the NVZ (Sæmundsson, 1974, 1980; Jóhannesson, 1980; Kristjánsson and Jonsson, 1998). The SH rift, however, remained active until about 7–5 Ma (Jóhannesson, 1980; Pringle *et al.*, 1997). The most recent rift relocation in N Iceland occurred when the Skagafjörður

rift (Figure 3) became active at 1.7 – 1.6 Ma and a temporary rift axis (failed rift) was generated (Hjartarson 2003). Plio-Pleistocene rocks found at Skagi and Skagfjörður point to this rift zone which may also relate to the fissure swarm which extends north from the active Hofsjökull central volcano in the MVZ. In S Iceland the picture is more complicated as the EVZ (Figure 1) seems to be an evolving spreading axis initiated about 2–3 Ma (e.g. Sæmundsson, 1980). Subsequently spreading has taken place in both the WVZ and the EVZ but is fading in the WVZ and increasing in the EVZ (e.g. Jonsson *et al.*, 1997; La Femina *et al.*, 2005). The EVZ is propagating southwards into crust that at depth may be 20 million years old, and may with time replace spreading in the WVZ (Sæmundsson, 1980; Einarsson, 1991; Foulger, 2006; Gudmundsson, 2007). The rift relocation scenario described above is the one most often referred to but some variations have also been published (e.g. Jancin *et al.*, 1985; Foulger, 2006; Garcia *et al.*, 2008).

The extent of rift jumps occurring during rift relocations has been somewhat unclear (e.g. Einarsson 1991; Helgason, 1984). The ongoing rift relocation in S Iceland results in a 100 km displacement and the displacement that took place during the rift relocation at 6–7 Ma, when the SH rift zone was replaced by the North Iceland rift zone, was around 130 km (given a half spreading rate of 9.1 mm/yr). Since that time the distance between the extinct and active rift axes has increased to 190 km because of continued crustal spreading.

## BUILD UP RATES

Combined palaeomagnetic work and radiometric dating has shown that the buildup rate in the Tertiary areas varies between 0.4 km/Ma in W Iceland (Table 2) to 2 km/Ma in N Iceland (see Kristjánsson and Jonsson, 2007). However, local variations are also seen, as buildup may be expected to be slower at higher altitudes and faster near volcanic centres. It has also been suggested that variation in production rates is affected by rift-relocations, the rate being highest just after the rift has shifted to a new location (Pringle *et al.*, 1999). The average time interval between Tertiary lava flows has been estimated at 10 ka in areas away from central

Table 2. Buildup rates of the Iceland lava pile (partly from Kristjansson and Jonsson, 2007). – *Upphleðsluhraði íslenska jarðlagastaflans.*

Area	Ages (Ma)	Thickness (km)	Rate (km/Ma)	References
NW Rift	15–16	0.3	0.3	Pringle <i>et al.</i> (1999)
E-Iceland	3.3–13.4	8.5	0.8	Watkins and Walker (1977)
NW-Iceland (West)	11.5–14	4.1	1.8	McDougall <i>et al.</i> (1984)
NW-Iceland (Central)	12–13.6	2.6	1.6	Kristjansson and Johannesson (1996)
NW-Iceland (East)	8–12	3.2	0.7	McDougall <i>et al.</i> (1984)
W-Iceland	2–7	3.5	0.7	Watkins <i>et al.</i> (1977)
W-Iceland	5–11.5	2.5	0.4	Kristjansson and Johannesson (1999)
Tröllaskagi	9.5–11	2.5	1	Sæmundsson <i>et al.</i> (1980)
N-Iceland, lower				
Tröllaskagi	9–9.5	2.5	3.9	Sæmundsson <i>et al.</i> (1980)
N-Iceland upper				
N-Iceland	5–9	2.9	0.7	Kristjansson <i>et al.</i> (2004)
N-Iceland (West)	7.3–8.2	1.0	1.1	Kristjansson <i>et al.</i> (1992)
SW-Iceland	2–4.5	2.1	1.0	Kristjansson <i>et al.</i> (1980)

volcanoes (Kristjansson and Jonsson, 2007).

Near the axis of a gentle anticline in the Borgarfjörður region, midway between the extinct SH rift zone and the presently active WVZ (Figure 1), an unconformity is overlain by thick sedimentary units (e.g. Jóhannesson, 1980; Grimsson, 2007). Lava flows below the unconformity originate from the SH rift zone, whereas flows above originate from the current WVZ, the oldest dating back to 6–7 Ma (McDougall *et al.*, 1977; Jóhannesson, 1980). The oldest rocks from the core of the anticline have been dated at about 13 Ma (Moorbath *et al.*, 1968) and the youngest lava flows at 5–7 Ma (Moorbath *et al.*, 1968; Aronson and Sæmundsson, 1975; Jóhannesson, 1980; Pringle *et al.*, 1997). The rocks immediately above the unconformity in NW Iceland represent the oldest exposed lava flows from the SH rift zone and these are around 15 Ma old (Hardarson *et al.*, 1997). The initiation of the SH rift has not been dated but apparently activity had slowed down by 9 Ma and the rift had died out by 7–5 Ma (Jóhannesson, 1980; Kristjansson and Jonsson, 1998, Pringle *et al.*, 1997). The final stages of the NW Iceland rift zone, which became extinct by

15 Ma, have been identified and show that about 8 million years separate these two rift extinction events (Hardarson *et al.*, 1997). However, this does not reveal the duration of a full rift zone cycle from initial propagation to extinction.

## CRUSTAL ACCRETION PROCESSES

Proposed models of crustal structure and accretion of the Tertiary areas generally assume that they were formed within rift zones and subsequently drifted to the present position through sea-floor spreading (e.g. Walker, 1965; Gibson and Piper, 1972; Sæmundsson, 1980; Palmason, 1986). Structural relationships indicate that the lava pile grew in an axial rift zone as lenticular units from elongated volcanic systems which included dyke swarms intersecting the central volcanoes. These units are thickest in the vicinity of the central volcanoes.

Crustal accretion in Iceland today occurs predominantly along the active rifts of the WVZ and EVZ in the south, and the NVZ in the north (Figure 1). The volcanic productivity is anomalously high relative to normal segments of the ridge, and the thin and

weak lithosphere cannot support the mass of the volcanics, which therefore subside rapidly. The kinematics of crustal accretion has been modeled by a number of authors but, for Iceland, the quantitative model of Palmason (1973, 1986) has been successful in explaining the structure, petrology and geochemistry of the lava pile (e.g. Oskarsson *et al.*, 1985, Steinthorsson *et al.*, 1985; Hardarson and Fitton, 1997).

In the Palmason model the mass of lava erupted in the rift axis causes rapid subsidence and burial as spreading proceeds, such that flows erupted closest to the axis form the deepest parts of the lava pile (Figure 4). Only flows erupted or emplaced more than ~15 km from the axis will remain in the top 2 km of the crust and therefore be available for future sampling. The total relief in the deep valleys of NW and E Iceland never exposes lava flows deeper than 2 km in the lava pile at any given location. The Tertiary lava pile in E Iceland away from central volcanoes represents an eruption rate equivalent to one lava flow approximately every 10 ka in each measured profile (Watkins and Walker, 1977; see Kristjánsson and Jon-

sson, 2007). This is a significantly lower eruption rate than that experienced at any location in the axial rift zone and is consistent with the observable part of the Tertiary pile consisting mostly of the distal parts of lava flows large enough to have escaped the rift axis or rocks that were emplaced close to the flanks (Hardarson and Fitton, 1997).

The Palmason model is further supported by geochemical arguments. It has been shown that the bulk of Tertiary and Plio-Pleistocene basalt lavas are remarkably uniform in composition regarding isotope and trace element ratios, much more so than basalt erupted in the neovolcanic zones (e.g. Hardarson and Fitton, 1994, 1997). The apparent lack of depleted lava flows in the Tertiary lava pile is also consistent with the model for crustal accretion in Iceland. The most depleted samples found in the neovolcanic zones invariably seem to be small-volume olivine basalt or picrite flows, which are only generated through the highest degrees of partial melting, probably following removal of the more easily fusible parts of a heterogeneous source (e.g. Hardarson and Fitton, 1997).

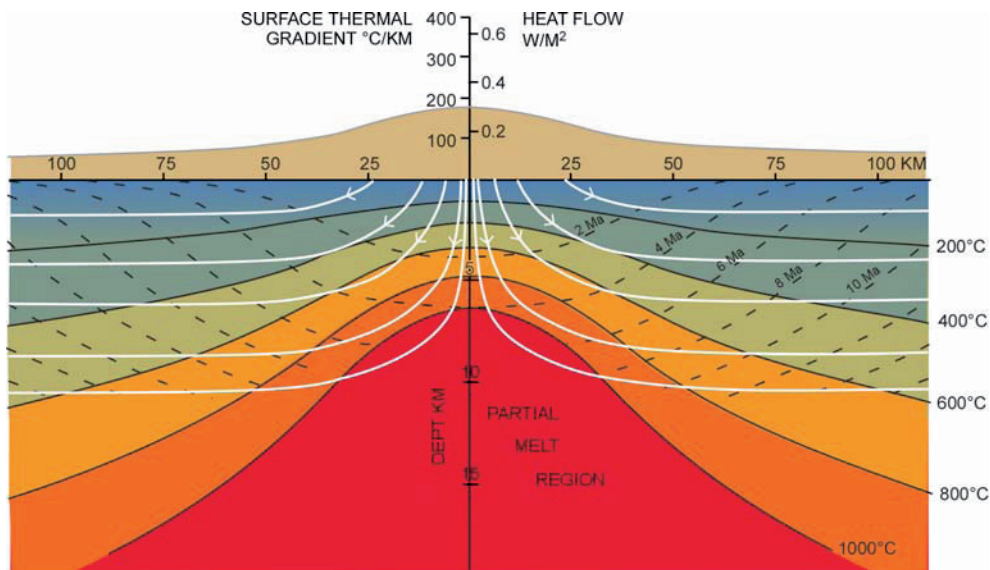


Figure 4. The Palmason (1986) model of crustal accretion in Iceland. The diagram represents a section through the crust across the axial zone, showing isotherms (solid lines), isochrons (broken lines) and material trajectories (white lines with arrows) – *Líkan Guðmundar Pálmasonar sýnir uppbyggingu og myndun jarðskorpunnar.*

Such flows are apparently confined to the actively-spreading sections of the axial zone and are not likely to escape from the axial zone. According to the Palmason model, these flows will ultimately be preserved only in the deeper parts of the crust never to be seen again. Thus, the Tertiary basalt record is heavily biased against small-volume rift axis flows.

Large flows, on the other hand, which originate within the axial zone and spread far, or rocks that are emplaced at the rift flanks, become preserved in the accessible part of the future lava pile. These originate from magma reservoirs that can effectively homogenise the input primary magmas and thereby represent the average of the available mantle components at any given time (Hardarson and Fitton, 1997). It has been shown that such rocks found in the neovolcanic zones today are indeed relatively homogeneous in composition and are comparable in composition to the Tertiary and Plio-Pleistocene lava pile (Hardarson and Fitton, 1997).

### EXCESS SPREADING?

North Atlantic spreading rates are well known from calculations based on magnetic anomalies parallel to the Mid-Atlantic Ridge and on radiometric dates. The average sea-floor spreading north and south of Iceland is about 1.8 cm/yr and has been estimated to be the same on land (e.g. DeMets *et al.*, 1990). These observations, however, lead to some discrepancies, first noted by Walker (1975). The oldest rocks, around 14–16 Ma, are found at the tip of peninsulas in E and NW Iceland, separated by 480 km. If this age is multiplied by the spreading rate the outcome is 15 Ma x 18.3 mm/yr = 275 km. This predicted width is about 40% less than the actual width of the country.

Hjartarson (2006) has calculated the drift of 25 reliably dated central volcanoes of Tertiary and Plio-Pleistocene age. All of them seem to have drifted farther than can be explained by the crustal spreading rate in the North Atlantic. The mean distance from their suggested place of origin is on average 70% greater than expected which could imply excess spreading in Iceland. The spreading also seems to have been symmetrical at the axis with fairly similar rates towards east and west through time. The sug-

gested excess spreading rate, however, does not appear in GPS-measurements monitoring the continuous crustal spreading in Iceland (e.g. Sigmundsson, 2006). Therefore, it must be discontinuous and although it seems regular on a long-time scale it does not show up in the short-time GPS-data sets available. Another problem is, that if the active rift zones in Iceland were indeed spreading at a rate faster than in adjacent parts of the North Atlantic then there should be evidence of deformation around Iceland, and such evidence is lacking.

Efforts have been made to solve the problem by assuming that ancient oceanic crust or a hidden piece of continental crust is located somewhere below the surface between the rift axes (e.g. Foulger and Anderson, 2005; Foulger, 2006). This could explain the apparent extra width of Iceland. However, this does not explain how far many central volcanoes have reached from their suspected place of origin. Whatever the underlying cause it is obvious that there are discrepancies between rates and dates in Iceland.

### GEOCHEMISTRY

The first modern description of the general petrology of Iceland was that of Martin A. Peacock (1925, 1931). His interest was sparked by the rock collection of Sir George S. Mackenzie, and the basis of his work was a visit to Iceland in 1924 in the company of G. W. Tyrrell. Peacock (1925) divided the Iceland rocks into pre-glacial (Miocene), inter-glacial (Plio-Pleistocene) and post-glacial (Recent) formations. He (Peacock, 1925, 1931) distinguished between two principal rock series, which according to him were an early calc-alkalic series with rhyolitic differentiates, and an inter- and post-glacial series of mildly alkalic character with trachytic differentiates. Peacock's chronological division was on the same lines as Holmes (1918), who had divided the Icelandic rocks into three groups, post-glacial, Quaternary (basalt in part ice striated) and Tertiary basalt.

Subsequent research has shown that the Tertiary rocks in Iceland belong to the tholeiitic series, ranging from picrite through to rhyolite, but picrites are relatively rare (Jakobsson, 1980). The abundance of evolved rocks in Iceland has long been recognised

and several estimates have been made of their relative abundance. For example, Walker (1966) found that approximately 10% of the Tertiary volcanic succession in E Iceland is made of silicic rocks. Jakobsson *et al.* (2008) found the abundance of silicic rocks in Recent and Upper Pleistocene formations to be 11%. The silicic rocks are exclusively seen in central volcanoes and intrusives, some of which do not appear to be connected to central complexes.

Most of what we know about the geochemical composition of Iceland at present comes from studies on the neovolcanic zones, that is on basaltic rocks less than about 0.8 million years old. Studies on the Tertiary rocks of Iceland have mostly been confined to the central complexes and intrusive rocks which are of limited use for petrogenetic studies because they are composed largely of evolved rocks and have often suffered from the effects of hydrothermal alteration. However, Wood (1978, 1979) and Wood *et al.* (1979) published a large data set for major and trace elements, including REEs, on basalt from a well-known palaeomagnetic stratigraphic traverse in E Iceland (e.g. Watkins and Walker, 1977). Further data on the E Iceland section comes from the Iceland Research Drilling Project (IRDP) which was undertaken in the late seventies and the results were published in the *Journal of Geophysical Research* (vol. 87, no. B8, 1982). Bailey and Noe-Nygaard (1976) published a number of major and selected trace element analyses from a profile in NW Iceland and Schilling *et al.* (1982, 1983) published rare earth element results of basalt broadly distributed throughout Iceland including the E, NW and W Tertiary areas. Schilling *et al.* (1982, 1983) suggested that blobs rather than a continuous plume may be rising under the region.

Published radiogenic isotope data from the Tertiary lava pile are mainly for Sr, Nd and Pb (e.g. Welke *et al.*, 1968; O'Nions and Pankhurst, 1973; Sun and Jahn, 1975; O'Nions *et al.*, 1976, 1977; Wood *et al.*, 1979; Hanan and Schilling, 1997; Hardarson *et al.*, 1997; Hanan *et al.*, 2000). Helium isotope ratios have been measured in rocks from NW Iceland and they show among the highest  $^3\text{He}/^4\text{He}$  values yet reported for mantle plumes. Isotope data from these rocks may provide one of the best estimates of the He-Sr

Nd-Pb-isotope systematics of the mantle component common to many plumes (Hilton *et al.*, 1999; Ellam and Stuart, 2004). Several studies have revealed that oxygen isotopes show exceptionally low  $\delta^{18}\text{O}$  in the more evolved basalt in the rift zones of Iceland and that these values could not be of mantle origin only. It appears that the Icelandic crust is progressively depleted in  $\delta^{18}\text{O}$  with depth as a result of oxygen isotopic exchange with, or assimilation of low- $\delta^{18}\text{O}$  hydrothermally altered basalt. As with He-isotopes, few studies have been carried out on oxygen isotope ratios in Icelandic Tertiary rocks. However, the results on mineral separates indicate that the Tertiary rocks are affected in the same way as in the rift zones but they have also been subject to secondary alteration which raises the  $\delta^{18}\text{O}$  values in whole-rock samples (Hartori and Muehlenbachs, 1982; Jonasson *et al.*, 1992; Hardarson, 1993; Gautason, 2000).

It was mentioned earlier that while the Tertiary lava flows do show some impressive and systematic compositional variations, these are small compared to the diversity of recent magmatism in the neovolcanic zone. The only known exception to this general rule is basalt from the far NW of Iceland beneath an unconformity that marks the end of magmatic activity in the NW Iceland rift (Hardarson *et al.*, 1997). In addition, depleted basalt has not been found in the Tertiary lava pile. This was noted by Schilling *et al.* (1982), who interpreted it as evidence for a recent influx of N-MORB-source mantle into the melt zone beneath Iceland and suggested that the plume is currently entering a declining phase. However, Hardarson and Fitton (1997) suggested that this could simply be an artifact of crust-forming processes consistent with the Palmason (1986) crustal accretion model.

One explanation for the extreme elemental and isotopic variability of neovolcanic basalt might be that these have fortuitously sampled different mantle sources to the bulk of Tertiary activity. However, it is also possible that only rift zone magmas sample the mantle at a small enough scale to reveal the full range of mantle heterogeneity beneath Iceland. By contrast, the bulk of Tertiary lava flows were either erupted on the rift flanks or represent rift-zone flows large enough to escape the rift zones and thus be preserved within

the Icelandic crust that is available in outcrop in agreement with Palmason's (1986) model. Thus, the composition of the Tertiary lavas may represent an average of the available mantle reservoirs at any given time, whereas, the neovolcanic basalt records more of the compositional range. Depleted basalts erupted in the neovolcanic zones are compositionally distinct from N-MORB and their absence from the Tertiary succession could therefore be a product of preservation rather than the result of waning plume activity (Fitton *et al.*, 1997; Hardarson and Fitton, 1997).

In a classic paper O'Nions and Pankhurst (1973) reported a secular decrease in the  $^{87}\text{Sr}/^{86}\text{Sr}$  of Icelandic basalt from around 0.70345 at 15 Ma to about 0.70315 for late- and postglacial basalt (O'Nions *et al.*, 1976). This could indicate variable degrees of disequilibrium partial melting of a grossly homogeneous mantle source, partial melting of a heterogeneous mantle source, or mixing of two or more mantle sources, with the plume activity decreasing since 15 Ma. Another explanation is that this variation and the apparent secular decline in LREE enrichment from Tertiary to Recent times resulted from pulsating mantle plume activity (fading output of the primitive plume portion), or increasing plume temperature, which may also be responsible for rift jumping (Schilling *et al.*, 1982, 1983; White *et al.*, 1995). Pb isotopes also show a secular variation, with the highest  $^{206}\text{Pb}/^{204}\text{Pb}$  found in 7–8 Ma basalt, coinciding with the formation of one of the V-shaped ridges (Figure 5) south of Iceland (Hanan and Schilling, 1997; Hanan *et al.*, 2000). This may suggest a link between a pulsing plume and crustal accretion on the Reykjanes Ridge. However, the range in Sr and Nd isotopic ratios from the extinct rift axis in NW Iceland is comparable to the range seen in the presently active rift zone which indicates that similar sources have been available through the geological history of the island (Hardarson *et al.*, 1997). To complicate things though, the bulk of the NW rift lava flows show Pb isotope ratios that plot within the field of Atlantic MORB, but such basalt has not yet been found elsewhere in Iceland (Hardarson *et al.*, 1997). It is quite clear from the above that the Iceland Tertiary holds many geochemical secrets still to be revealed.

## V-SHAPED RIDGES

Prominent diachronous V-shaped features in the gravity field along the Reykjanes Ridge south of Iceland (Figure 5) are generally interpreted as the effects of pulses, at 5 to 10 Ma intervals, of hotter (and therefore more readily melted) mantle moving down the ridge away from the plume (Vogt, 1971, 1983; Schilling *et al.*, 1982; White *et al.*, 1995; White and Lovell, 1997; Ito, 2001; Jones *et al.*, 2002). The troughs (blue in Figure 5) between successive V-shaped ridges (in red) may, however, result from relocation of the spreading centre caused by the Mid-Atlantic Ridge drifting slowly to the northwest with respect to the plume centre (Hardarson *et al.*, 1997). The plume periodically recaptures the spreading centre by initiating a new segment of ridge to the southeast of the old one which is therefore left stranded and dies. A reduction in plume flux down the dying rift axis during these periods of relocation may explain the V-shaped features without the need for a pulsing plume. The only occurrence of depleted basalt in the Icelandic Tertiary lava pile is in flows formed within the NW Iceland rift (Figure 1). These flows are composed of depleted basalt resembling that generated from ambient upper mantle (true N-MORB), in contrast to depleted basalt from the neovolcanic zone, and were erupted from a dying rift axis immediately before spreading relocated to the southeast (Hardarson *et al.*, 1997). This apparent influx of depleted ambient upper mantle also coincided with the time (15 Ma) when a trough between two of the V-shaped ridges began to propagate from Iceland. This can be seen in Figure 5, which shows that the outer of the two prominent blue V-shaped troughs extrapolates to the extinct NW Iceland rift (Figures 1 and 3). The inner of the two troughs similarly extrapolates to the extinct SH rift implying a causal link between spreading-centre relocation and the V-shaped features, and giving cause to question the generally accepted pulsing-plume hypothesis. A reduction in plume flux down the dying rift axis during periods of relocation may therefore explain the V-shaped features without the need for a pulsing plume.

It is also clear that key geochemical source indicators, like Zr, Nb, Y and Sr-, Nd- and Pb isotope ratios, oscillate with time during the period immedi-

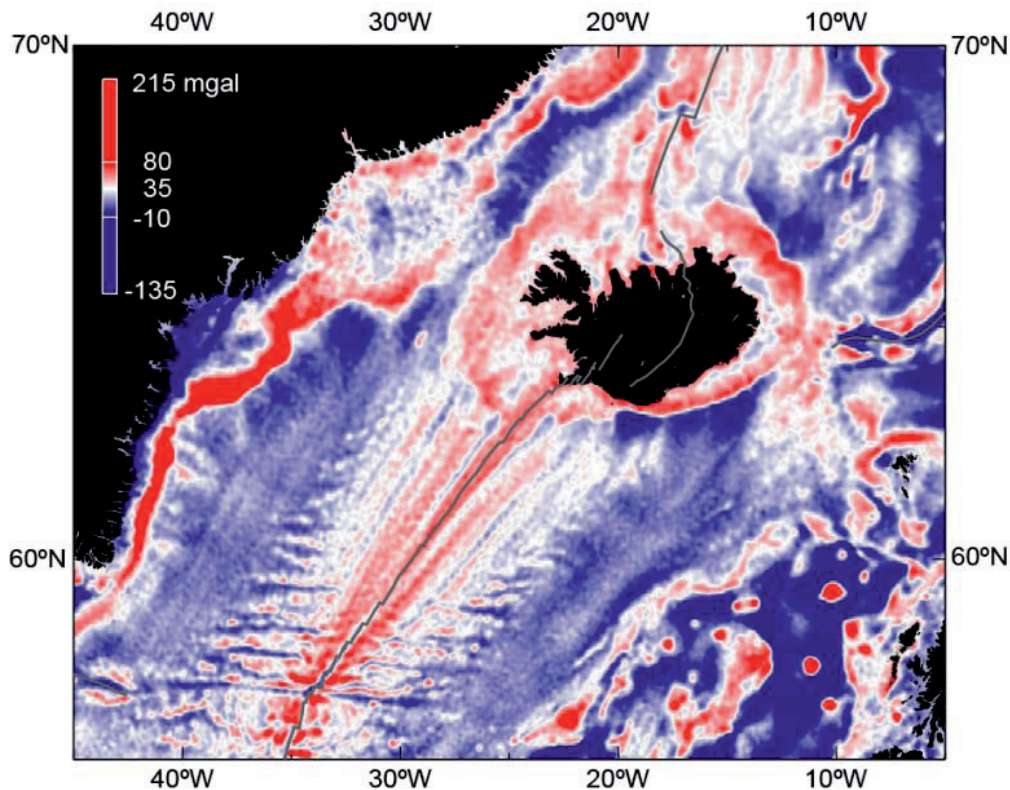


Figure 5. Free-air gravity field around Iceland from satellite altimetry (Sandwell and Smith, 1997). The V-shaped features centred on the Reykjanes Ridge southwest of Iceland are interpreted as variations in the thickness of the ocean crust (thicker in red, thinner in blue). They imply pulses of hotter-than-normal mantle propagating away from Iceland and are taken as strong evidence for pulsing of the Iceland plume. Alternatively, they may be due to interruptions in the flow of plume mantle down the Reykjanes Ridge at times of rift relocation. The active rift zones in Iceland are shown in gray. V-shaped ridges extrapolate to the extinct NW-rift and the Snæfellsnes-Húnaflói rift (Figures 1 and 3) – *Túlkun þyngdarmælinga sýnir legu V-laga hryggja þar sem rauður litur táknar þykka jarðskorpu og blár þunna skorpu. Hryggina má túlka sem afleiðingu misvirks möttulstróks eða rekbeltaflutninga. Lega V-laga hryggja fellur að kulnuðum rekhryggum úti fyrir Vestfjörðum og Snæfellsnesi.*

ately before the ridge jump (e.g. Hanan and Schilling, 1997; Harðarson *et al.*, 1997). This observation implies that there are significant variations in the melt regime and/or source composition during this critical period. The substantial N-MORB component seen in lava flows from the NW Iceland rift, suggests that depleted upper mantle can only influence the composition of Icelandic basalt in a dying rift that is too far

from the plume centre to be dominated by plume mantle. However, whether or not the Iceland plume is a pulsing phenomenon remains unresolved for the time being.

#### Acknowledgements

We are grateful to L. Kristjánsson and K. Sæmundsson for constructive reviews. B. Jónsdóttir for prepar-

ing the figures except figure 5 which was kindly provided by J. MacLennan. Comments by H. Franzson and I. S. Macdonald are much appreciated.

## ÁGRIP

Jarðsaga Íslands er nátengd atburðum, sem áttu sér stað fyrir um 60 milljón árum, þegar íslenski möttulstrókurinn kom undan meginlandsskorpu Grænlands og Norður-Atlantshafið tók að myndast. Frá þeim tíma hefur samspil Íslands og möttulstróksins skipað veigamikinn sess í jarðsögu svæðisins. Ísland, eins og við þekkjum það í dag, tók að myndast fyrir um 20 milljón árum, þegar plötuskil Evrasíu- og Ameríkuflékanna rak yfir möttulstrókin. Ekki er ólíklegt að einhvers konar landbrú hafi verið til staðar milli meginlanda Ameríku og Evrópu um hríð eftir að Norður-Atlantshaf tók að opnast. Flekakerfið í heild sinni rekur hægt til norðvesturs miðað við möttulstrókin og eftir að plötuskilin rak vestur yfir möttulstrókin hafa rekbelti landsins færst til austurs í rekbeltaflutningum (myndir 1 og 3). Slíkir atburðir hafa átt sér stað nokkrum sinnum í jarðsögu landsins og hafa þeir skilið eftir ýmis ummerki í jarðlagastaflanum. Samhverfir V-laga hryggir og þyngdarfrávik er finna má á Reykjaneshrygg suður af Íslandi (mynd 5) benda til að þykkun úthafsskorpunnar á þessum slóðum orsakist af heitu möttulefni, sem streymir frá möttulstróknum í púlsum með nokkurra milljóna ára millibili. Þetta mætti skýra á þann hátt að íslenski möttulstrókurinn sé misvirkur en þó er hugsanlegt að hryggirnir myndist vegna óreglu í möttulflæði samfara rekbeltaflutningum.

Sú hefð hefur skapast á Íslandi að skipta jarðsögu landsins í fjögur tímabil. Jarðlög er tilheyra blágrýtismynduninni (Tertíer) eru 3,3–16 milljón ára, grágrýtismyndun (Plíó-Pleistosen) er 0,8–3,3 milljón ára, móbergsmyndunin (efra Pleistósen) er 0,015–0,8 milljón ára en jarðlög síðjökultíma-nútíma (Holocene-late glacial) eru yngri en 15 þúsund ára (1. mynd). Blágrýtis- og grágrýtis myndanirnar eru um það bil helmingur af flatarmáli landsins. Blágrýtisstaflinn er tiltölulega einsleitur, víðast byggður upp af 5–15 m þykkum hraunlögum, sem hlaðast hvert ofan á annað, en á milli þeirra sitja þunn lög (rauð millilög) af gosösku. Stundum má þó sjá þykk set-

lög, sem oft hafa myndast vegna rofs þegar eldvirkni í tilteknum eldstöðvakerfum lauk eða þegar rekbeltin fluttu sig um set en einnig hafa setlagabunkar myndast í vatni og í sjó, þeirra frægastur eru Tjörneslögin. Í blágrýtismynduninni bregður frá fábreytileikanum þar sem kulnaðar megineldstöðvar skjóta upp kollinum. Í þeim finnst þróað berg (líparít), sem iðulega er ummyndað vegna jarðhita og jarðlagastaflinn kringum þær er oft óreglulegur og brotinn. Ekki færri en 40 megineldstöðvar eru þekktar í blágrýtisstaflanum og er talið að þær hafi verið virkar í 0,3 til liðlega 1 milljón ár.

Upphleðsuhraði jarðlagastaflans er æði misjafn en að jafnaði hefur eitt hraun runnið á hverjum 10 þúsund árum utan megineldstöðvanna en upphleðsluhraðinn er mun meiri í nágrenni þeirra. Jarðefnafræði blágrýtissvæðanna er töluvert einsleitari en í bergi hinna virku rekbelta. Hugsanleg skýring felst í því hvernig jarðskorpa landsins byggist upp og þróast (4. mynd). Einsleitni samsetningar hraunanna er brotin upp á svæðum fornra rekhryggja og á þeim tímaskeiðum þegar rekbelti færðu sig um set.

## REFERENCES

- Árnadóttir, Th., Geirsson H. and W. Jiang 2008. Crustal deformation in Iceland: Plate spreading and earthquakes. *Jökull* 58, this issue.
- Aronson, J. and K. Sæmundsson 1975. Relatively old basalts from structurally high areas in central Iceland. *Earth Planet. Sci. Lett.* 28, 83–97.
- Bailey, J. C. and A. Noe-Nygaard 1976. Chemistry of Miocene plume tholeiites from northwest Iceland. *Lithos* 9, 185–201.
- Bijwaard, H. and W. Spakman 1999. Tomographic evidence for a narrow whole mantle plume below Iceland. *Earth Planet. Sci. Lett.* 166, 121–126.
- Bjarnason, I. Th. 2008. An Iceland hotspot saga. *Jökull* 58, this issue.
- Carmichael, I. S. E. 1967. The mineralogy of Thingmuli, a Tertiary volcano in eastern Iceland. *Am. Min.* 52, 1815–1841.
- DeMets, C., R. G. Gordon, D. F. Argus and S. Stein 1990. Current plate motions. *Geophys. J. Int.* 101, 425–478.
- Einarsson, P. 1991. Earthquakes and present-day tectonics in Iceland. *Tectonophysics* 189, 261–279.
- Eiriksson, J., A. I. Gudmundsson, L. Kristjansson and K. Gunnarsson 1990. Paleomagnetism of Pliocene-Pleistocene sediments and lava flows on Tjörnes and Flatey, North Iceland. *Boreas* 19, 39–55.
- Ellam, R. M. and F. M. Stuart 2004. Coherent He-Nd-Sr isotope trends in high 3He/4He basalts: implications for a common

- reservoir, mantle heterogeneity and convection. *Earth Planet. Sci. Lett.* 228, 3–4, 511–523.
- Fitton, J. G., A. D. Saunders, M. J. Norry, B. S. Hardarson and R. N. Taylor 1997. Thermal and chemical structure of the Iceland plume. *Earth Planet. Sci. Lett.* 153, 197–208.
- Foulger, G. R. 2006. Older crust underlies Iceland. *Geophys. J. Int.* 165, 672–676.
- Foulger, G. R. and D. L. Anderson 2005. A cool model for the Iceland hotspot. *J. Volcanol. Geotherm. Res.* 141, 1–22.
- Franzson, H. 1978. *Structure and petrochemistry of the Hafnarfjall-Skardsheiði central volcano and the surrounding basalt succession, W-Iceland*. Unpubl. Ph.D. thesis, Univ. Edinburgh.
- Franzson, H. 2006. An ignimbrite cone-sheet feeder in Hafnarfjall-Skardsheiði central volcano W-Iceland. *IAVCEI. A George P.L. Walker symposium on Advances in Volcanology*, Reykholt, abstracts.
- García, S., J. Angelier, F. Bergerat, C. Homberg and O. Dauteuil 2008. Influence of rift jump and excess loading on the structural evolution of northern Iceland, *Tectonics* 27, TC1006, doi:10.1029/2006TC002029.
- Gautason, B. 2000. *Geochemical aspects of crustal accretion in Iceland*. Unpubl. Ph.D. thesis, Univ. Alberta.
- Geirsdóttir, A., G. H. Miller and J. T. Andrews 2007. Glaciation, erosion, and landscape evolution of Iceland. *J. Geodynamics* 43, 170–186.
- Gibson, I. L. and J. D. A. Piper 1972. Structure of the Icelandic basalt plateau and the process of drift. *Phil. Trans. R. Soc. Lond. A.*, 271, 141–150.
- Gradstein, F. M., J. G. Ogg and A. G. Smith 2004. *Geologic Time Scale 2004*. Cambridge University Press, England, 589 pp.
- Grímsson, F. 2007. Late Miocene sediments of Lake Hredavatn. *Náttúrufræðingurinn* 75, 21–33.
- Grimsson, F., T. Denk and L. A. Simonarson 2007. Middle Miocene floras of Iceland – the early colonization of an island? *Review of Palaeobotany and Palynology* 144, 181–219.
- Gudmundsson, A. 1986. Mechanical aspects of postglacial volcanism and tectonics of the Reykjanes Peninsula, Southwest Iceland. *J. Geophys. Res.* 91, 12,711–12,721.
- Gudmundsson, A. 2007. Infrastructure and evolution of ocean-ridge discontinuities in Iceland. *J. Geodynamics* 43, 6–29.
- Hald, N., A. N. Nygaard and A. K. Pedersen 1971. The Krokksfjörður central volcano in north-west Iceland. *Acta Nat. Islandica II*, 10, 29 pp.
- Hanan, B. B. and J.-G. Schilling 1997. The dynamic evolution of the Iceland mantle plume; the lead isotope perspective. *Earth Planet. Sci. Lett.*, 151, 43–60.
- Hanan, B. B., J. B. Toft, R. K. Kingsley and J.-G. Schilling 2000. Depleted Iceland mantle plume geochemical signature: artifact of multicomponent mixing? *Geochem. Geophys. Geosyst.* 1(4), doi:10.1029/1999GC000009.
- Hardarson, B. S. 1993. *Alkalic rocks in Iceland with special reference to the Snaefellsjökull volcanic system*. Unpubl. Ph.D. thesis, Univ. Edinburgh.
- Hardarson, B. S. and J. G. Fitton 1994. Geochemical variation in the Tertiary basalts of Iceland. *Mineral. Mag.* 58A, 372–373.
- Hardarson, B. S. and J. G. Fitton 1997. Mechanisms of crustal accretion in Iceland. *Geology* 25, 1043–1046.
- Hardarson, B. S., J. G. Fitton, R. M. Ellam and M. S. Pringle 1997. Rift relocation-A geochemical and geochronological investigation of a palaeo-rift in northwest Iceland. *Earth Planet. Sci. Lett.* 153, 181–196.
- Hardarson, B. S., M. S. Pringle, L. Kristjánsson, A. Gudmundsson and H. Johannesson 1999. Stratigraphy and paleomagnetism of a 2.8 km lava succession in central N-Iceland. *IUGG99. The 22nd General Assembly of the International Union of Geodesy and Geophysics*. Univ. Birmingham, Abstracts, vol. B:326.
- Hattori, K. and K. Muehlenbachs 1982. Oxygen isotope ratios of the Icelandic crust. *J. Geophys. Res.* 87, 6559–6565.
- Helgason, J. 1984. Frequent shifts of the volcanic zone in Iceland. *Geology* 12, 212–216.
- Hilton D. R., K. Grönvold, C. G. Macpherson and P. G. Castillo 1999. Extreme  $^3\text{He}/^4\text{He}$  ratios in NW Iceland: constraining the common component in mantle plumes. *Earth Planet. Sci. Lett.* 173, 53–60.
- Hjartarson, Á. 2003. *The Skagafjörður Unconformity, North Iceland and its Geological History*. Unpubl. Ph.D.-thesis, Univ. Copenhagen.
- Hjartarson, A. 2006. *The excess drift in Iceland. A George P.L. Walker symposium on Advances in Volcanology, Reykholt*. Abstracts.
- Holmes, A. 1918. The basaltic rocks of the Arctic region. *Min. Mag.* 18, 180–223.
- Ito, G. 2001. Reykjanes “V”-shaped ridges originating from a pulsing and dehydrating mantle plume. *Nature* 411, 681–684.
- Jakobsson, S. P. 1980. Outline of the petrology of Iceland. *Jökull* 29, 57–73.
- Jakobsson, S. P., J. Jonsson and F. Shido 1978. Petrology of the western Reykjanes peninsula, Iceland. *J. Petrol.* 19, 669–705.
- Jakobsson, S. P., K. Jonasson and I. A. Sigurdsson 2008. The three igneous rock series of Iceland. *Jökull* 58, this issue.
- Jancin, M., K. D. Young, B. Voight, J. L. Aronson and K. Sæmundsson 1985. Stratigraphy and K/Ar ages across the west flank of the northeast Iceland axial rift zone, in relation to the 7 Ma volcano-tectonic reorganization of Iceland. *J. Geophys. Res.* 90, 9,961–9,985.
- Jóhannesson, H. 1975. *Structure and petrochemistry of the Reykjadalur central volcano and the surrounding areas, Midwest Iceland*. Unpubl. Ph.D. thesis, Univ. Durham.
- Jóhannesson, H. 1980. Evolution of rift zones in western Iceland (in Icelandic with an English summary). *Náttúrufræðingurinn* 50, 13–31.
- Jóhannesson, H. and K. Sæmundsson 1998a. *Geological map of Iceland 1:500 000. Bedrock Geology*. Icelandic Institute of Natural History, Reykjavík. (2nd ed.).
- Jóhannesson, H. and K. Sæmundsson 1998b. *Geological map of Iceland 1:500 000. Tectonics*. Icelandic Institute of Natural History, Reykjavík.

- Johannesson, H. and K. Sæmundsson 1999. *Geological map of Iceland*, 1:1 000 000. Icelandic Institute of Natural History, Reykjavík.
- Jóhannesson, H. and K. Sæmundsson 2003a. *Extinct central volcanoes of Iceland. Geological map*, Iceland GeoSurvey, Reykjavík.
- Jóhannesson, H. and K. Sæmundsson 2003b. Active central volcanoes of Iceland. Geological map, Iceland GeoSurvey, Reykjavík.
- Jonasson, K., P. M. Holm and A. K. Pedersen 1992. Petrogenesis of silicic rocks from the Krokksfjörður central volcano, NW Iceland. *J. Petrol.* 33, 1345–1369.
- Jones, S. M., N. White and J. Maclennan 2002. V-shaped ridges around Iceland: Implications for spatial and temporal patterns of mantle convection. *Geochem. Geophys. Geosyst.* 3(10), 1059, doi:10.1029/2002GC000361.
- Jonsson, S., P. Einarsson and F. Sigmundsson 1997. Extension across a divergent plate boundary, the Eastern Volcanic Rift Zone, south Iceland, 1967–1994, observed with GPS and electronic distance measurements. *J. Geophys. Res.* 102, 11913–11929.
- Kristjánsson, L. and J. Helgason 1988. Some properties of basalt lava sequences and volcanic centres in a plate-boundary environment. In: Morton, A. C. and L. M. Parson eds. *Early Tertiary Volcanism and the Opening of the NE Atlantic*. Geol. Soc. London, Spec. Publ. 39, 147–155.
- Kristjánsson, L. and H. Jóhannesson 1996. Stratigraphy and paleomagnetism of the lava pile south of Ísafjarðardjúp, NW-Iceland. *Jökull* 44, 3–16.
- Kristjánsson L. and G. Jonsson 1998. Aeromagnetic results and the presence of an extinct rift zone in W-Iceland. *J. Geodynamics* 25, 99–108.
- Kristjánsson, L. and H. Jóhannesson 1999. Secular variation and reversals in a composite 2.5 km thick lava section in central Western Iceland. *Earth, Planets and Space* 51, 261–276.
- Kristjánsson, L. and G. Jonsson 2007. Paleomagnetism and magnetic anomalies in Iceland. *J. Geodynamics* 43, 30–54.
- Kristjánsson, L., I. B. Fridleifsson and N. D. Watkins 1980. Stratigraphy and paleomagnetism of the Esja, Eyrafjall and Akrafjall mountains, SW-Iceland. *J. Geophys.* 47, 31–42, 1980.
- Kristjánsson, L., H. Jóhannesson and I. McDougall 1992. Stratigraphy, age and paleomagnetism of Langidalur, Northern Iceland. *Jökull* 42, 31–44.
- Kristjánsson, L., A. Gudmundsson and B. S. Hardarson 2004. Stratigraphy and paleomagnetism of a 2.9 km composite lava section in Eyjafjörður, Northern Iceland: a reconnaissance study. *Int. J. Earth Sci.* 93, 582–595.
- La Femina, P.C., T. H. Dixon, R. Malservisi, T. Arnadóttir, E. Sturkell, F. Sigmundsson and P. Einarsson 2005. Strain partitioning and accumulation in a propagating ridge system: Geodetic GPS measurements in south Iceland. *J. Geophys. Res.* 110, B11405.
- Lawver, L. A. and R. D. Müller 1994. Iceland hotspot track. *Geology* 22, 311–314.
- Maclennan, J., M. Jull, D. McKenzie, L. Slater and K. Grönvold 2002. The link between volcanism and deglaciation in Iceland. *Geochem. Geophys. Geosyst.* 3(11), 1062, doi:10.1029/2001GC000282.
- McDougall, I., L. Kristjánsson and K. Sæmundsson 1984. Magnetostratigraphy and geochronology of northwest Iceland. *J. Geophys. Res.* 89, 7,029–7,060.
- McDougall, I., N. D. Watkins, G. P. L. Walker and L. Kristjánsson 1976. Potassium-argon and paleomagnetic analysis of Icelandic lava flows: limits on the age of Anomaly 5. *J. Geophys. Res.* 81, 1505–1512.
- McDougall, I., K. Sæmundsson, H. Jóhannesson, N. D. Watkins and L. Kristjánsson 1977. Extension of the geomagnetic polarity time scale to 6.5. m.y. K-Ar dating, geological and paleomagnetic study of a 3500 m lava succession in western Iceland. *Geol. Soc. Am. Bull.* 88, 1–15.
- Moorbath, S., H. Sigurdsson and R. Goodwin 1968. K-Ar ages of the oldest exposed rocks in Iceland. *Earth Planet. Sci. Lett.* 4, 197–205.
- O’Nions, R. K. and R. J. Pankhurst 1973. Secular variation in the Sr-isotope composition of Icelandic volcanic rocks. *Earth Planet. Sci. Lett.* 21, 13–21.
- O’Nions, R. K., P. J. Pankhurst and K. Grönvold 1976. Nature and development of basalt magma sources beneath Iceland and the Reykjanes Ridge. *J. Petrol.* 17, 315–338.
- O’Nions, R. K., P. J. Hamilton and N. M. Evensen 1977. Variations in  $^{143}\text{Nd}/^{144}\text{Nd}$  and  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios in oceanic basalts. *Earth Planet. Sci. Lett.* 34, 13–22.
- Oskarsson, N., S. Steinthorsson and G. E. Sigvaldason 1985. Iceland geochemical anomaly; origin, volcanotectonics, chemical fractionation and isotope evolution of the crust. *J. Geophys. Res.* 90, 10011–10025.
- Palmason, G. 1973. Kinematics and heat flow in a volcanic rift zone, with application to Iceland. *Geophys. J. R. Astron. Soc.* 33, 451–481.
- Palmason, G. 1981. Crustal rifting and related thermo-mechanical processes in the lithosphere beneath Iceland. *Geol. Rundsch.* 70, 244–260.
- Palmason, G. 1986. Model of crustal formation in Iceland and application to submarine mid-ocean ridges. In: Vogt P. R. and B. E. Tucholke eds. *The Geology of North America*, vol. M., *The Western North Atlantic Region*, 87–98, Geol. Soc. Am., Boulder, Colorado.
- Paquette, J. L., O. Sigmarrsson and M. Tiepolo 2007. Mesozoic zircons in Miocene ignimbrite from E-Iceland: a splinter of a continental crust? *EGU, Geoph. Res. Abs.* 9, 03723.
- Peacock, M. A. 1925. The geology of Iceland. *Trans. Geol. Soc. Glasgow* 17, 185–203.
- Peacock, M. A. 1931. Classification of igneous rock series. *J. Geol.* 39, 54–67.
- Pringle, M. S., B. S. Hardarson and L. Kristjánsson 1999. Variation in crustal accretion modeled as function of Iceland rift cycle, not pulsating plume. *Eos Trans. AGU* 80, F646.
- Pringle, M.S., B. S. Hardarson, L. Kristjánsson and H. Jóhannesson 1997. Decrease in crustal production rate from established and dying rift: examples from western Iceland, *Eos Trans. AGU* 78, 656.

- Richards, M. A., R. A. Duncan and V. E. Courtillot 1989. Flood basalts and hot-spot tracks: plume heads and tails. *Science* 246, 103–107.
- Rossi, M. J. and A. Gudmundsson 1996. The morphology and formation of flow-lobe tumuli on Icelandic shield volcanoes. *J. Volcanol. Geotherm. Res.* 72, 291–308.
- Sæmundsson, K. 1967. An outline of the structure of SW-Iceland. In: S. Björnsson ed. *Iceland and Mid-Ocean Ridges*, Soc. Sci. Islandica, Rit 38, Reykjavík, Iceland.
- Sæmundsson, K. 1974. Evolution of the Axial Rifting Zone in Northern Iceland and the Tjörnes Fracture Zone. *Geol. Soc. Am. Bull.* 84, 495–504.
- Sæmundsson, K. 1980. Outline of the geology of Iceland. *Jökull* 29, 7–28.
- Sæmundsson, K. 1986. Subaerial volcanism in the western North Atlantic. In: Vogt P. R. and B. E. Tucholke eds. *The Geology of North America*, vol. M., *The Western North Atlantic Region*, 69–86, Geol. Soc. Am., Boulder, Colorado.
- Sæmundsson K. and H. Noll 1974. K/Ar ages of rocks from Húsafell, western Iceland, and the development of the Húsafell central volcano. *Jökull* 24, 40–58.
- Sæmundsson, K., L. Kristjánsson, I. McDougall and N. D. Watkins 1980. K-Ar dating, geological and paleomagnetic study of a 5 km lava succession in northern Iceland. *J. Geophys. Res.* 85, 3628–3646.
- Sandwell, D. T. and W. H. F. Smith 1997. Marine gravity anomaly from Geosat and ERS-1 satellite altimetry. *J. Geophys. Res.* 102, 10,039–10,054.
- Schilling, J.-G. 1973. Iceland mantle plume: Geochemical study of the Reykjanes Ridge. *Nature* 242, 565–571.
- Schilling, J.-G., P. S. Meyer and R. H. Kingsley 1982. Evolution of the Iceland hotspot. *Nature* 296, 313–320.
- Schilling, J.-G., P. S. Meyer and R. H. Kingsley 1983. Rare element geochemistry of Iceland basalts: spatial and temporal variations. In: Bott M. H. P., S. Saxov, M. Talwani and J. Thiede eds. *Structure and development of the Greenland-Scotland Ridge. New Methods and Concepts*, Plenum, New York.
- Shen, Y., S. C. Solomon, I. Th. Bjarnason and C. J. Wolfe 1998. Seismic evidence for a lower-mantle origin of the Iceland plume. *Nature* 395, 62–65.
- Sigmundsson, F. 2006. *Iceland Geodynamics. Crustal Deformations and Divergent Plate tectonics*. Praxis Publishing, Chicester, UK.
- Sigurdsson, H. 1970. *The petrology of the Setberg volcanic region and of the intermediate and acid rocks of Iceland*. Unpubl. Ph.D. thesis, Univ. Durham, Durham, England.
- Sigvaldason, G. E. and S. Steinthorsson 1974. Chemistry of tholeiitic basalts from Iceland and their relation to the Kverfjöll hot spot. In: Kristjánsson L. ed. *Geodynamics of Iceland and the North Atlantic Area*. D. Reidel Publ. Company, Holland, 154–164.
- Simónarson, L. A. and J. Eiríksson 2008. Tjörnes - Pliocene and Pleistocene sediments and faunas. *Jökull* 58, this issue.
- Steinthorsson, S., N. Oskarsson and G. E. Sigvaldason 1985. Origin of alkali basalts in Iceland: a plate tectonic model. *J. Geophys. Res.* 90, 10,027–10,042.
- Storey, M., R. A. Duncan and C. Tegner 2007. Timing and duration of volcanism in the North Atlantic Igneous Province: Implications for geodynamics and links to the Iceland hotspot. *Chemical Geol.* 241, 264–281.
- Sun, S.-S. and B. Jahn 1975. Lead and strontium isotopes in post-glacial basalts from Iceland. *Nature* 255, 527–530.
- Vink, G. E. 1984. A hotspot model for Iceland and the Vøring Plateau. *J. Geophys. Res.* 89, 9,949–9,959.
- Vogt, P. R. 1971. Asthenosphere motion recorded by the ocean floor south of Iceland. *Earth Planet. Sci. Lett.* 13, 153–160.
- Vogt, P. R. 1983. The Iceland mantle plume: status of the hypothesis after a decade of new work. In: Bott M. H. P., S. Saxov, M. Talwani and J. Thiede eds. *Structure and Development of the Greenland-Scotland Ridge, New Methods and Concepts*, Plenum, New York.
- Walker, G. P. L. 1960. Zeolite zones and dike distribution in relation to the structure of basalts of eastern Iceland. *J. Geol.* 68, 515–528.
- Walker, G. P. L. 1963. The Breiddalur central volcano, eastern Iceland. *Quart. J. Geol. Soc. Lond.* 119, 29–63.
- Walker G. P. L. 1965. Some aspects of Quaternary volcanism in Iceland. *Trans. Leicester. Phil. Soc.* 59, 25–40.
- Walker G. P. L. 1966. Acid volcanic rocks in Iceland. *Bull. Volc.* 29, 375–406.
- Walker G. P. L. 1971. Compound and simple lava flows and flood basalts. *Bull. Volc.* 35, 579–590.
- Walker, G. P. L. 1975. Excess spreading axes and spreading rate in Iceland. *Nature* 255, 468–470.
- Watkins, N. D. and G. P. L. Walker 1977. Magnetostratigraphy of Eastern Iceland. *Am. J. Sci.* 277, 513–584.
- Watkins, N. D., I. McDougall and L. Kristjánsson 1977. Upper Miocene and Pliocene geomagnetic secular variation in the Borgarfjörður area of western Iceland. *Geophys. J. R. Astr. Soc.* 49, 609–632.
- Welke, H., S. Moorbath, G. L. Cumming and H. Sigurdsson 1968. Lead isotope studies on igneous rocks from Iceland. *Earth Planet. Sci. Lett.* 4, 221–231.
- White N. and B. Lovell 1997. Measuring the pulse of a plume with sedimentary record. *Nature* 387, 888–891.
- White R. S., J. W. Brown and J. R. Smallwood 1995. The temperature of the Iceland plume and origin of outward-propagating V-shaped ridges. *J. Geol. Soc. London* 152, 1039–1045.
- Wolfe, C. J., I. Th. Bjarnason, J. C. VanDecar and S. Solomon 1997. Seismic structure of the Iceland mantle plume. *Nature* 385, 245–247.
- Wood D. A. 1978. Major and trace element variations in the Tertiary lavas of eastern Iceland and their significance with respect to the Iceland geochemical anomaly. *J. Petrol.* 19, 394–436.
- Wood D. A. 1979. Dynamic partial melting: its application to the petrogenesis of basalts erupted in Iceland, the Faroe Islands, the Isle of Skye (Scotland) and the Troodos Massif (Cyprus). *Geochim. Cosmochim. Acta* 43, 1031–1046.
- Wood D. A., J. L. Joron, M. Treuil, M. Norry and J. Tarney 1979. Elemental and Sr isotope variations in basic lavas from Iceland and the surrounding ocean floor. *Contrib. Mineral. Petrol.* 70, 319–339.