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Geodynamics of rift–plume interaction in Iceland as constrained by new $^{40}Ar/^{39}Ar$ and in situ U–Pb zircon ages

E. Martin [a,b,*], J.L. Paquette [a], V. Bosse [a], G. Ruffet [c], M. Tiepolo [d], O. Sigmarsson [a,e]

[a] Laboratoire Magmas et Volcans, OPGC, Université Blaise Pascal, CNRS, 5 rue Kessler, 63038 Clermont Ferrand, France
[b] Institut des Sciences de la Terre de Paris, UMR-CNRS 7193, UPMC (Univ. Paris 6), 75005 Paris, France
[c] Géosciences Rennes (UPR-CNRS 4661), Université de Rennes, France
[d] C.N.R., Istituto di Geoscienze e Georisorse, Unità di Pavia, via Ferrata 1, I-27100, Pavia, Italy
[e] Institute of Earth Sciences, University of Iceland, 101 Reykjavik, Iceland

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ABSTRACT

The interaction between a rift zone and a mantle plume leads to exceptional situations in Iceland where the island is 1.5 wider than expected, given the North-Atlantic spreading rate. In order to give a better idea of the timeframe of this evolution, we present 32 new $^{40}Ar/^{39}Ar$ and in-situ U–Pb dating on zircon from 16 volcanic systems located from the west to east coasts of Iceland. The North Iceland Rift Zone (NIRZ) was initiated at least 12 Ma ago. Furthermore, during these last 12 Ma, the NIRZ half spreading rate was between 0.7 and 1.2 cm/yr and it propagated to the south at a rate of 1.0–1.2 cm/yr. The excess width of Iceland can thus not be explained by faster spreading rate in the past. Here we discuss a model that explains the ~200 km 'excess' of crust, taking into account the eastward relocation of the rift zone and corresponding older crustal capture over the course of Iceland's geological history. The most recent rift relocation is dated at approximately 6 Ma at Snæfellsnes Peninsula in the west, whereas the oldest volcanic systems (15–13 Ma) from the extreme north east of Iceland were most likely generated at the Kolbeinsey ridge north of Iceland rather than in the NIRZ itself.

The need for rift relocations and crustal capture to explain the width of Iceland strongly suggests that during rift–plume interaction the mantle plume plays an active role. It forces the active rift zone to be frequently relocated by rift jumps above its center leaving inactive rift zones as older synclines in the geological record. This result in an eastward position of the rift zone in Iceland relative to the North Atlantic ridge, and it can be predicted that in a few tens of millions of years the Mid-Atlantic ridge and the Icelandic plume may become decoupled.

1. Introduction

Interactions between a mantle plume and a mid-oceanic ridge generate a complex tectonic situation with intriguing consequences such as enhanced magma productivity (e.g. Vogt, 1971; Schiling 1973, 1985; Sæmundsson, 1979; Gudmundsson, 2000). One central question in such geodynamic context is whether mantle plumes play a passive or active role during such interaction. The best known and most studied plume–ridge interaction is the Icelandic plateau, for which four categories of geodynamic evolution models have been suggested. The first category suggests that the magmatism is concentrated at the plate boundary, which suggests symmetrical repartition of volcanic formation from a unique rift zone (e.g. Menke and Sparks, 1995; Pálmason, 1973, 1986; Pálmason, 1981). This model fails in explaining the asymmetric age repartition of the volcanic systems, the asymmetric dip of lava flows towards the nowadays active rift zone and some volcanic formation unconformities. The second category of models consists of wide and diffuse plate boundary (e.g. Walker 1974; Bourgeois et al., 2005). This could explain the asymmetric age and structure repartition in Iceland; however it does not explain why and how magmatism and volcanic activity moves in this wide and diffuse rift-zone in course of the Iceland geological history. In the third class of model the presence of the mantle plume beneath Iceland is not considered (e.g. Foulger and Anderson, 2005). This model is not coherent with current understanding of the link between magma productivity, tectonics and magma sources (e.g. Sigmarsson and Steinthorsson, 2007, and references therein). The fourth type of model, contrary to the last one, considers the relative motion of the rift-zone and the mantle plume center, which leads to rift relocation by rift jumps (e.g. Garcia, et al., 2003; Hardarson, et al., 1997; Hardarson, et al., 2008; Jancin, et al., 1985; Jóhannesson, 1980; Oskarsson, et al., 1985; Sæmundsson, 1979; Vink, 1984). In this model the mantle plume moves eastward relative to the mid-oceanic ridge, which is relocated progressively above the plume center by

* Corresponding author at: Institut des Sciences de la Terre de Paris, UMR-CNRS 7193, UPMC, 75005 Paris, France.
E-mail address: erwan.martin@upmc.fr (E. Martin).

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successive jumps. Nowadays, the mantle plume center is presumed to be located beneath the NW part of the Vatnajökull icecap (e.g. Eysteinsson and Gunnarsson, 1995; Wolfe, et al., 1997; Figs. 1 and 2). The consequence of such successive rift zone relocations above the mantle plume center is that the rift zone in Iceland is moving eastward in relation to the Mid-Atlantic ridge. This model readily explains the eastward location of the Icelandic rift-zone relatively to the Mid-Atlantic ridge (Fig. 1).

Considering the plume–ridge interaction in the North Atlantic (e.g. Mjelde et al., 2008, and references therein), one of its geodynamic consequences is the surprising width of Iceland that remains a major enigma (Bott, 1985; Helgason, 1985; Hjartarson, 2009; Pálmason, 1981; Walker, 1975, 1976). Given the age of the oldest rocks and the spreading rate of the rift zone, only ~300 km of the ~500 km wide crust could have been generated over the course of Iceland's geological history.

In this study we present a combination of new $^{40}Ar/^{39}Ar$ and U–Pb zircon ages focused on Plio-Pleistocene and Tertiary volcanoes from the Snaefellsnes peninsula to the eastern fjords. These new age constraints allow us to suggest a synthetic model of the geodynamic evolution of Iceland. Our model, which combines oceanic spreading and rift relocations (or jumps), provides a comprehensive explanation of the 'enigmatic' present-day width of Iceland.

2. Geological setting and sampling strategy

As in any rifting context, volcanic rocks in Iceland are principally generated in the rift zone before drifting away at a speed imposed by the spreading rate of the rifting system itself. As a consequence, the youngest volcanic formations in Iceland are obviously in the rift zone, while the oldest are the most distant from the rift zone, in the north-east and north-west fjords (Fig. 2). It should be noted that some off-rift magmatism is present in the Snæfellsnes volcanic zone (SNVZ), southernmost part of the South-Iceland volcanic zone (SIVZ) and in the Öræfajökull volcanic belt (OVB; e.g. Sæmundsson, 1979). The oldest rocks dated in the north west of Iceland are around 15–16 Ma old and those on the eastern coast about 12–13 Ma old (e.g. Moorbath et al., 1968). In order to cover most of Iceland's geological formations from Tertiary to recent ages, rock samples were collected from the east to the west coast of Iceland (Fig. 2).

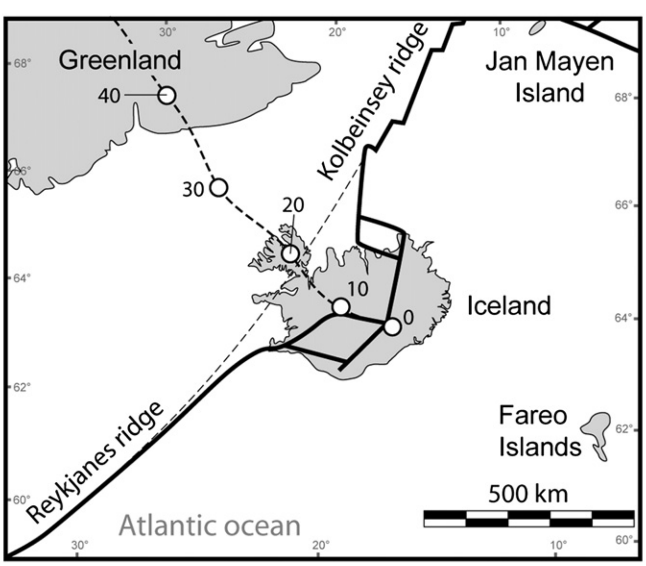

Fig. 1. Map of the North Atlantic Ocean, showing the location of Iceland as well as the location of the mantle plume center over the course of time (ages in Ma; Lawver and Muller, 1994). Note the rift-zone location compared to the Mid-Atlantic ridge (dashed line illustrating the hypothetical ridge if there were no interaction with the mantle plume).

From the east fjords are both mafic and silicic rock formations were sampled (Table 1). The mafic rocks consist of basalt in Vopnafjördur (Bur) and gabbro in the intrusive complexes of Vesturhorn (Ves) and Austurhorn (Hval). The silicic samples are granophyre from Vesturhorn and Austurhorn intrusions and a lava dome from Hellisheidi (Hell) at Fagridalur volcanic system, rhyolite from the composite dyke in Streitishvarf (Streit) and Höfn (Hofn) in Borgarfjordur, rhyolitic lavas in Berufjördur (Beruf), Sandfell laccolith (San) and Reydarfjördur (Rey) central volcano, rhyolitic ignimbrites in Húsavík (Hus) and Hvítserkur (Hvs) and a rhyolitic dome in Refsstadir (Ref) central volcano. All samples from western Iceland are silicic in composition and consist of granophyre from the intrusion at Fródárheidi (Fro), and Axlarhyrna (Axl), rhyolitic domes in Baula (Bau) and Búdarháls (Bh), rhyolitic dykes in Thjórsárdalur (Tdh) and Setberg (Setb) and a dacite in Drápuhlídarfjall (Drap; Table 1). The reader is referred to Martin and Sigmarsson (2010) for a detailed petrographic description and geochemical composition of these samples.

3. Analytical method

3.1. $^{40}Ar/^{39}Ar$ dating

Twenty samples were analyzed with an $^{40}Ar/^{39}Ar$ laser probe (CO_2 Synrad®). The analyses were performed on single groundmass-rock fragments.

Groundmass fragments were carefully hand-picked under a binocular microscope from crushed rocks (0.3–1 mm fraction) and separated from phenocrysts. The samples were wrapped in Aluminum foil to form packets (11 mm × 11 mm × 0.5 mm). These packets were stacked in piles, within which packets of flux monitors were inserted every 8 to 10 samples. Two sets of samples were irradiated in the McMaster reactor (Hamilton, Canada) in the 5C location, the first one (Axl1, Bau1, Bh1a, Drap2, Fro1, Setb1–3, Thd2–3) for 13.3 h and the second one (Beruf1, Bur2a–3, Hell1, Hofn1, Hval4, Rey3, San1, Streit1a, Ves2) for 14.7 h. In both cases, the irradiation standard was the Taylor Creek Rhyolite sanidine, TCR-2 (28.34 Ma according to Renne et al., 1998). The sample arrangement allowed us to monitor the flux gradient with a precision of $\pm 0.2\%$.

The step-heating experimental procedure has been described in detail elsewhere (Ruffet et al., 1991; 1995). Blanks are performed routinely each first or third run, and are subtracted from the subsequent sample gas fractions. Analyses are performed on the Map215® mass spectrometer at the Géosciences Rennes laboratory.

To define a plateau age, a minimum of three consecutive steps are required, corresponding to a minimum of 70% of the total $^{39}Ar_K$ released, and the individual fraction ages should agree to within 1σ or 2σ with the integrated age of the plateau segment. Nevertheless, pseudo-plateau ages can be calculated with less than 70% of the $^{39}Ar_K$ released. The $^{40}Ar/^{39}Ar$ ages in Table 1 and in Fig. 3 are displayed at the 2σ level.

3.2. U–Pb dating

Zircon crystals were concentrated using conventional separation techniques. After crushing, milling and sieving, the rock powder was passed over a Wilfley table. Zircon crystals were further enriched using heavy liquids and finally a magnetic separator. The final purification was done by hand under a binocular microscope by selecting zircon grains that were euhedral, translucent light-pink colored to colorless.

Analyses of U–Pb were performed on crack-free single zircon crystals mounted in epoxy resin and polished using 0.25 μm diamond paste. In order to identify the inner structures, each zircon grain was imaged using a scanning electron microscope equipped with a