Bull Volcanol (2010) 72:523–538
DOI 10.1007/s00445-010-0344-0

RESEARCH ARTICLE

Rhyolites at Kerlingarfjöll, Iceland: the evolution and lifespan of silicic central volcanoes

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Received: 1 October 2008 / Accepted: 5 January 2010 / Published online: 6 February 2010

Abstract Kerlingarfjöll central volcano is Iceland's second largest outcrop of Quaternary rhyolite and is part of the Icelandic Western Rift Zone. Geochemical and Ar/Ar age data show that at least 21 different rhyolite eruptions have taken place at Kerlingarfjöll over the last 350 ka. Ar/Ar dating was carried out on samples of obsidian which showed variable reproducibility, illustrating the difficulty in dating young Icelandic volcanics. Nevertheless, reasonable estimates of eruption age have been derived for a number of eruptive units that are consistent with observed stratigraphy, enabling an understanding of the temporal evolution of Kerlingarfjöll. Two rhyolite magma types are present. The first is an older, low-Nb rhyolite that was erupted episodically along a cryptic curved fracture system, to form a discontinuous ring of rhyolite mountains, between 350 and 250 ka. This discontinuous ring is similar to structures observed at other volcanoes in Iceland, suggesting that the development of a curved fracture that acts as a pathway for episodic silicic eruptions is a feature of central volcano development. The second magma is a younger, high-Nb rhyolite that was erupted episodically between 250 and 68 ka in the northern part of Kerlingarfjöll, forming two clusters, both of which have areas of intense hydrothermal activity. Repose periods for rhyolite volcanism are thought to be on the order of tens of thousands of years, and it is possible that Kerlingarfjöll will erupt rhyolite again in the future.

Keywords Iceland · Rhyolite · Central volcano · Ar/Ar dating · Obsidian · Subglacial volcanism

Editorial responsibility D.B. Dingwell

Electronic supplementary material The online version of this article (doi:10.1007/s00445-010-0344-0) contains supplementary material, which is available to authorized users.

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Introduction

Iceland represents an area of thickened oceanic crust formed by the interaction of the Mid-Atlantic Ridge and the Iceland Hot Spot and thus may be the modern-day equivalent of proto-continental crust. Whilst most of Iceland is basaltic, rhyolites and more recently discovered trachytes make up 8–12% of the outcropping rocks (Walker 1966; Saemundsson 1979; Flude et al. 2008), although this estimate does not include unconsolidated silicic pyroclastic rocks removed by erosion (Lacasse and Garbe-Schonberg 2001). Silicic volcanism in Iceland is of particular interest for a number of reasons. In terms of understanding early continental crust formation, it is the presence of large proportions of silicic rocks that distinguishes oceanic from continental crust; thus, studying the formation of silicic material in oceanic crust affords insights into the relevant processes. Iceland is also the main source of silicic tephra

in the northern Atlantic (Lacasse and Garbe-Schonberg 2001), and although less common than basaltic equivalents, silicic eruptions pose a substantial hazard to the local communities and air traffic over the north Atlantic (Miller and Casadevall 2000). Finally, silicic volcanic rocks, being enriched in potassium compared to basalt, give the best opportunity of providing radiometric ages using the K–Ar or Ar/Ar methods. Studies of silicic rocks at Icelandic volcanoes have tended to focus on Iceland's more famous, historically active volcanoes, such as Hekla (e.g. Sigmarsson et al. 1992; Sverrisdottir 2007) or Askja (e.g. Sigurdsson and Sparks 1981; Macdonald et al. 1987) or on the debate concerning the formation of Icelandic rhyolites by fractional crystallisation of basalt or by crustal melting (e.g. Macdonald et al. 1990; Nicholson et al. 1991; Jónasson 1994; Gunnarsson et al. 1998; Jónasson 2007). However, few studies have addressed the timescales of Icelandic volcanism, concentrating on magma residence times of historical eruptions (e.g. Sigmarsson 1996) or dating older (often >1 Ma) rocks (Gale et al. 1966; Moorbath et al. 1968), often with reference to establishing the broad timescale of rift zone activity (Hardarson et al. 1997). The absence of a chronological framework for volcanism in Iceland raises a number of key questions, such as the longevity of Icelandic volcanism, including the repose periods for less active volcanoes (necessary to determine whether a dormant volcano is likely to erupt again), how Icelandic volcanoes evolve over time, whether structural controls on eruption sites are long- or short-lived, whether any geographical or geochemical trends are time-related and whether silicic volcanism is affected by glacial loading and unloading as-is basaltic volcanism (e.g. Hardarson and Fitton 1991; Slater et al. 1998; Maclennan et al. 2002). A question specific to Icelandic volcanism regards the formation of rhyolite ring structures that have been found by ground-penetrating radar at the ice-covered volcanoes Myrdalsjökull, Öraefajökull and Hofsjökull (Björnsson 1988; Björnsson et al. 2000). Do these represent calderas (Björnsson et al. 2000), the volcanic products of a caldera-forming eruption being restricted to the vent area by overlying ice (McGarvie 2009), or did they form incrementally during numerous separate eruptions?

Three recent studies have contributed to addressing these questions using Ar/Ar dating. McGarvie et al. (2006) demonstrated that the rhyolite-dominated central volcano Torfajökull (Iceland's largest outcrop of Quaternary rhyolite) has been active for at least 400 ka and that the magmatic system underwent a significant change during the last glacial period (Weichselian), McGarvie et al. (2007) established that the monogenetic volcanic edifice Prestahnukur was erupted during the last interglacial–glacial transition, and the small-volume, off-rift volcano Ljósufjöll has been shown to be surprisingly long-lived, with silicic volcanic activity spanning over 600 ka (Flude et al. 2008). This paper aims to further contribute to this work and address the above questions by examining the eruptive history (through Ar/Ar dating), petrography, mineralogy and geochemistry of Kerlingarfjöll, a central volcano in the Western Rift Zone. This volcano is of particular interest to address the issues raised above as it has erupted numerous small-volume rhyolites, making it Iceland's second largest outcrop of Quaternary rhyolites. While it has not erupted historically, it exhibits extensive hydrothermal activity (Grönvold 1972).

Geological context

Kerlingarfjöll is a central volcano situated to the SW of the Hofsjökull icecap in central Iceland. It is topographically well defined, rising from glacial outwash plain surroundings (less than 700 m above sea level (a.s.l.)) to between 1,000 and 1,488 m a.s.l. The highest peaks are concentrated in the northern part of the volcano where they form two clusters (termed the Eastern and Western Clusters, both of which exhibit marked hydrothermal activity, Grönvold 1972) and scattered in the south, forming a discontinuous topographic ring (Fig. 1). Rhyolite makes up approximately 20–27% of the complex and forms the bulk volume of the largest peaks (Grönvold 1972). All of the volcanic products at Kerlingarfjöll were erupted subglacially and form steep-sided fragmental deposits of limited lateral extent (Grönvold 1972); thus, stratigraphic correlation and relative dating of the rhyolite eruptive units are challenging. Stevenson (2004) deduced that the eruptive unit South Höttur overlies volcanic products from the Höttur edifice and Grönvold (1972) noted that Loðmundur overlies rhyolite material from an unidentified (probably buried) edifice. Basalt underlies many of the rhyolite tuyas (Grönvold 1972), and Stevenson et al. (2009) noted an upward progression of basalt to dacite to rhyolite in the Western Cluster. Levels of glacial erosion are low, with many units (e.g. Loðmundur and Höttur) retaining a flat lava cap, suggesting that all of the rhyolites were erupted during the last glacial period (Grönvold 1972). The rhyolites represent small-volume eruptions with bulk-rock volumes (calculated from topographic maps by assuming simple geometries) of less than 0.3 km^3. The hydrothermal activity in the north of the volcano is secondary, produced by boiling of groundwater at depth, rather than being of magmatic origin (Grönvold 1972). There are at least 21 different rhyolite eruptive units at Kerlingarfjöll, as identified by Grönvold (1972), Stevenson (2004) and this study, on the basis of field observations and chemostratigraphic fingerprinting.

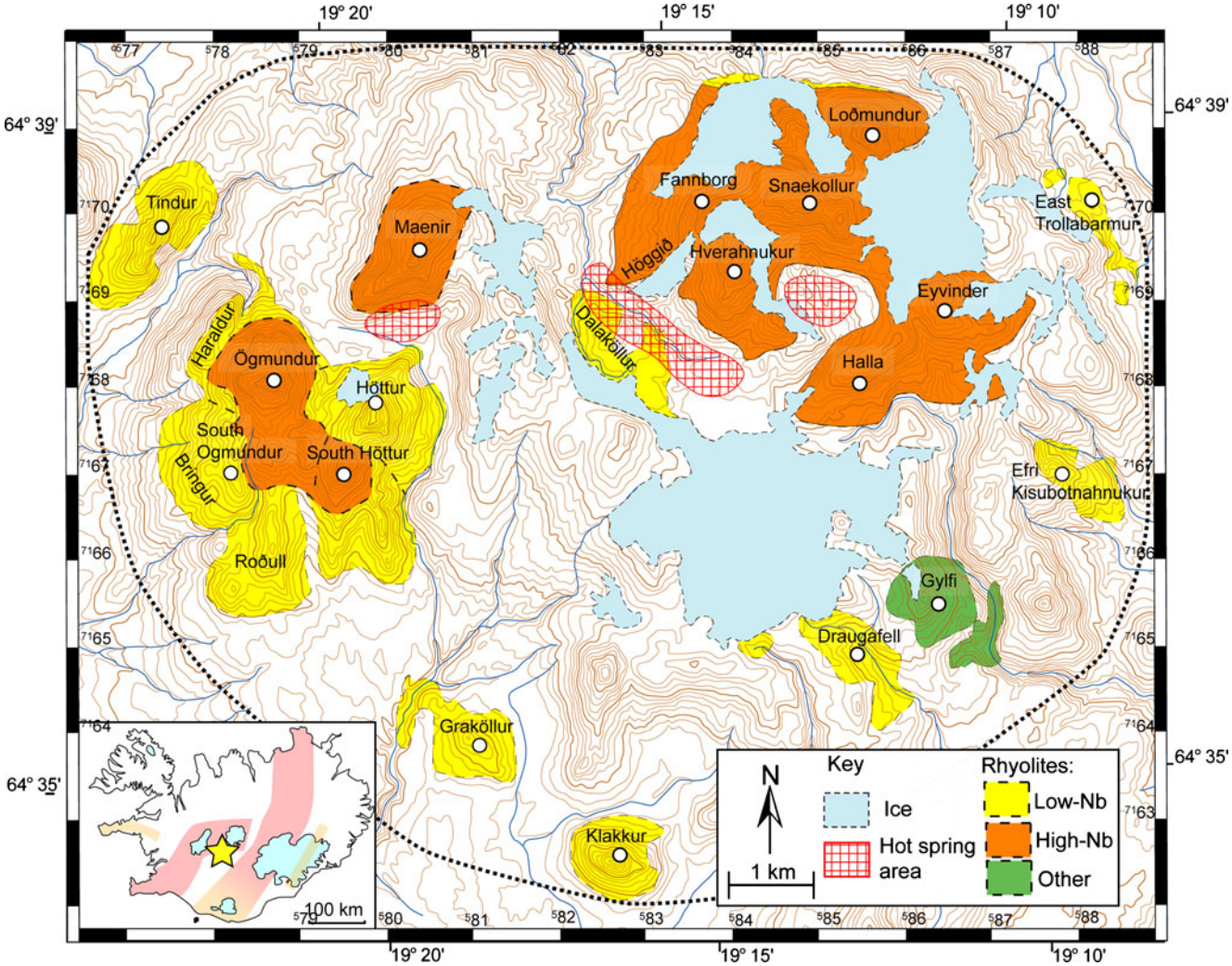

Fig. 1 Map of the rhyolite volcanics at Kerlingarfjöll. Location of Kerlingarfjöll is represented by the *yellow star* on the map of Iceland. *Red areas* on the Iceland map represent rift zones, and *orange areas* represent flank (non-rifting volcanic) zones. Contours and ice after Map Sheet 1814 II (Defence Mapping Agency 1988). Rhyolite locations and geochemical grouping after Grönvold (1972), Stevenson (2004) and this study. Low- and high-Nb rhyolites refer to classifications given in "Geochemistry and mineralogy: results and classification". The approximate extent of the volcanic complex is shown by a *dotted line*

Samples and petrography

We have selected samples from 14 eruptive units for Ar/Ar dating to determine their age and from 19 units for X-ray fluorescence (XRF) major and trace element analysis. Samples from six units were selected for electron microprobe mineral analyses of feldspar phenocrysts.

Wherever possible, fresh obsidian was sampled at Kerlingarfjöll. Most Kerlingarfjöll obsidian is aphyric to slightly porphyritic with phenocrysts (all ≤1 mm) of plagioclase + brown clinopyroxene + magnetite with hematite exsolution ± zircon and occasional orthopyroxene ± green clinopyroxene ± fayalite ± ilmenite. In most cases, the phenocrysts are euhedral and show no indication of being out of equilibrium with the melt. Only a few phenocrysts are subhedral, having been broken or resorbed to some degree, and some glomerocrysts of plagioclase and clinopyroxene are present. Zircon is present in trace amounts in most units and occurs either by itself or as inclusions in plagioclase phenocrysts.

The obsidian at Kerlingarfjöll is quite variable in terms of structure (flow banding) and freshness, so the different obsidian types have been classified into one of five types (type G: fresh, massive glass; type P: pitchstone; type F: flow banded obsidian; type S: spherulitic obsidian; type M: pillow margin facies. Please see full descriptions in the online supplementary material, Section S1).

Methodology

XRF and microprobe analyses were carried out, primarily for classification and to allow geochemical identification of eruptive units, in the Department of Earth Sciences at The Open University. Operational details are provided in the Online supplementary material.

Ar/Ar dating was carried out on splits of obsidian. Full details of sample preparation and analysis are provided in the online supplementary material (Section S2). Samples were irradiated with splits of Alder Creek Sanidine neutron fluence monitor (1.186±0.006 Ma; Turrin et al. 1994; Nomade et al. 2005) at the Oregon State University TRIGA reactor, for between 0.55 and 13 h, using the CLICIT (cadmium lined in core irradiation tube) facility to minimise interaction with thermal neutrons that cause the ^{40}K(n, p)^{40}Ar reaction and production of ^{36}Cl. Ar/Ar analysis was carried out using the MS1 Noble Gas Mass Spectrometer in the Isotope Geochemistry Laboratories at the University of Manchester. Between one and six obsidian splits were analysed from each unit. Each split was analysed by stepped heating in a tantalum-lined resistance furnace, with the gas released from 20-min duration temperature steps of 400°C, 1,200°C and 1,600°C. During analysis of the first batch of samples, masses 35 and 41 were also measured to check for chlorine or hydrocarbon contamination and interference. None was detected, and for subsequent batches masses 35 and 41 were only analysed during routine system blanks. The gas from each temperature step was analysed, but the 400°C step was used as a cleanup step to remove atmospheric gasses absorbed onto the surface of the samples, and the 1,600°C step was used to fully degas the split before the next analysis. Only the 1,200°C step was used to calculate the Ar/Ar age. In many ways, this method resembles the total fusion Ar/Ar method as it does not provide any information about the isotopic composition of the trapped Ar component in the split. This simplified methodology was necessary to release sufficient radiogenic ^{40}Ar (^{40}Ar*: ^{40}Ar that has been corrected for atmospheric argon by assuming that $^{40}Ar^{*}=^{40}Ar_{measured}-295.5\times^{36}Ar$) from the sample with which to calculate an eruption age. Where three or more splits from a unit were analysed, the data were plotted on an isotope correlation diagram to evaluate the data and, if appropriate, obtain an isochron age for the unit.

Geochemistry and mineralogy: results and classification

Major and trace element data are available as an online supplementary data set. The Kerlingarfjöll rhyolites are subalkaline (Fig. 2). They are metaluminous and show an overall decrease in agpaitic index with increasing silica content. The major elements do not form a cohesive trend on variation diagrams (Fig. 2), but most elements (except K_2O) show a general decrease with increasing SiO_2. With the exception of Rb, trace elements seem to show an overall decrease in concentration or no systematic change with increasing silica. Rb is the only trace element to show an overall increase with silica content, and this follows the same pattern as K_2O, with a maximum value (99 ppm) in the middle of the range of silica values. On many element plots (Fig. 2), the data seem to fall into one of two groups. These are most easily distinguished by the elements Nb and Ba, and these elements are used to classify the eruptive units into low-Nb or high-Nb groups. One sample (K31, unit Gylfi) does not fall into either group but has a composition intermediate between the two.

Each low-Nb eruptive unit has quite a wide compositional range (e.g. Höttur has 78–83 ppm Rb), and the composition of individual units tends to overlap (Fig. 2). Conversely, the high-Nb eruptive units tend to have a narrower compositional range (e.g. Ögmundur has 88–90 ppm Rb) with less overlap between units. The two groups show a degree of overlap in many of the major and trace elements. Overall, the high-Nb group is more enriched in Al_2O_3, Na_2O, K_2O, Rb, Nb, Y, Sr, Ba, Zn and Ga and more depleted in SiO_2 than the low-Nb group. This enrichment of Na_2O and K_2O in the high-Nb group means that the groups are also distinguishable by their total alkali content (Na_2O+K_2O). This allows those units that were not sampled in this study but were analysed for major elements by Grönvold (1972; Grákollur, the rhyolites north of and underlying Loðmundur, Dalakollur and Hoggið) to be classified into one of the groups. Geochemical data from Stevenson (2004) on units from the Western Cluster allow the units Haraldur, Bringur, Rođull and ridges south of South Höttur to be classified. The low-Nb group includes Höttur, Tindur, Haraldur, Bringur–South Ögmundur–Roðull, the ridges south of South Höttur, Grákollur, Klakkur, Draugafell, Efri Kisubotnahnukur, East Tröllabarmur and possibly the rhyolites north of and underlying Loðmundur. The high-Nb group includes Ögmundur, South Höttur, Maenir, Dalakollur, Hverahnukur, Fannborg, Snaekollur, Loðmundur, Halla-Eyvindur and Höggið (see Fig. 1).

Feldspar microprobe data are given in the online supplementary material. Feldspars are all oligoclase, with An contents from 14% to 30% (see supplementary material Fig. S3.1). The two geochemical groups are also evident in the feldspar compositions; the low-Nb units contain more calcic oligoclase ($An_{25–30}$) while the high-Nb units contain more sodic oligoclase ($An_{14–22}$).

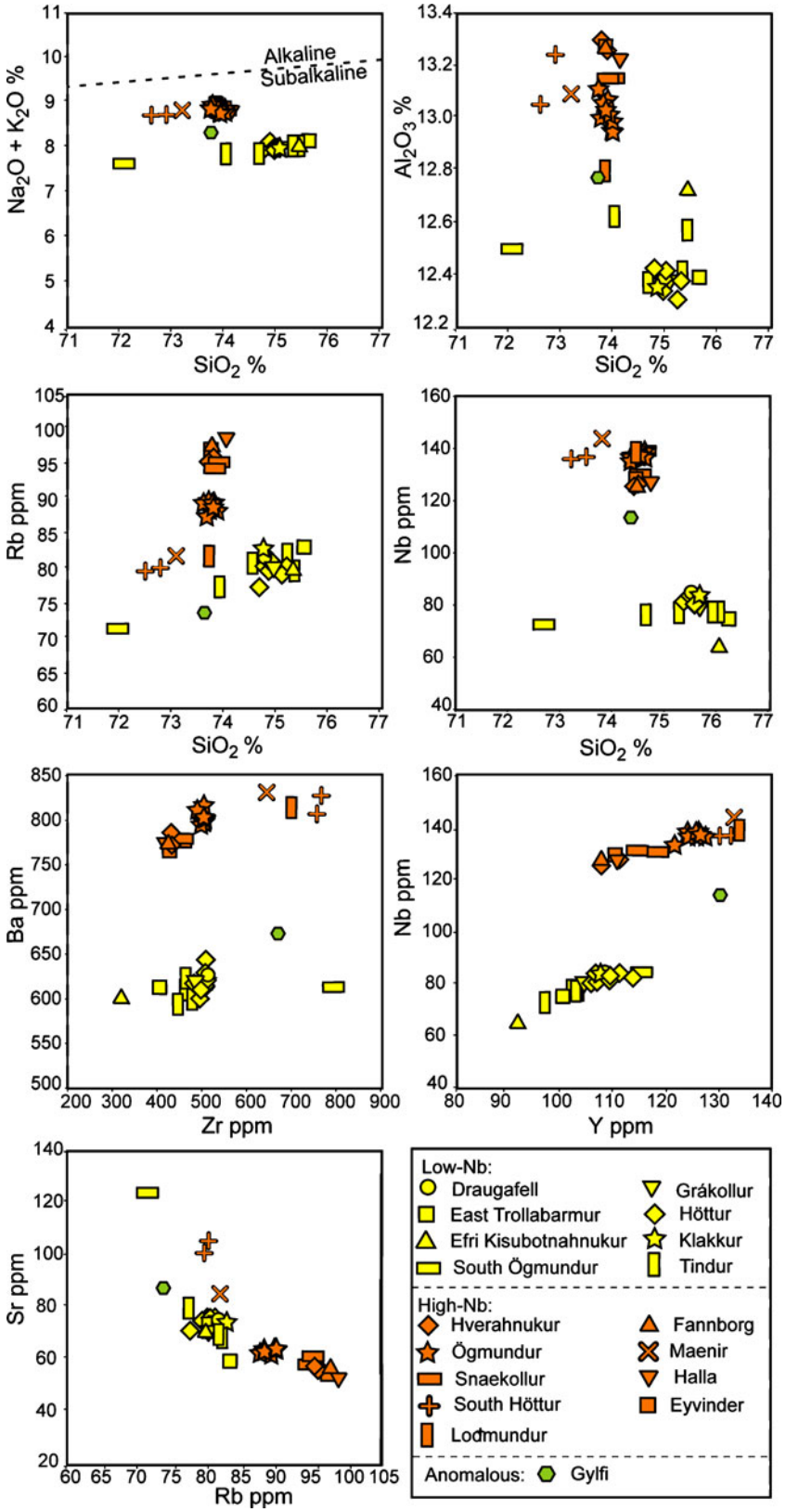

Fig. 2 Selected major and trace element variation diagrams for the Kerlingarfjöll rhyolites. Most of the samples fall into one of two geochemical groups: low Nb and Ba (*yellow symbols*) and high Nb and Ba (*orange symbols*). Alkaline–subalkaline divide after Irvine and Baragar (1971)

Ar/Ar dating results

Samples were analysed from the low-Nb units of Draugafell, Höttur, Tindur, East Tröllabarmur, Efri Kisubotnahnukur and Klakkur and the high-Nb units of Eyvindur, Hverahnukur, Maenir, Ögmundur, South Höttur, Fannborg, Loðmundur and Snaekollur. The results of individual split analyses are listed in Tables S4.1–3 in the online supplementary data. The radiogenic ^{40}Ar yields of the analyses range from 0% (zero age) to 44% and show a general increase with increasing age. The results from each unit (with errors reported at 1σ level) are discussed below where they are related to the obsidian categories defined in "Samples and petrography". The estimated eruption ages for each unit are summarised in Table 1 and, where appropriate, are plotted as isotope correlation diagrams in Fig. 3.

Five glass splits were analysed from Höttur; four of Ker00/43 and one of Ker2 (both obsidian type M). The Höttur obsidians produced a range of ages from 284±34 to 537± 145 ka. The data were plotted on an isotope correlation diagram (Fig. 3) and produced an acceptable isochron with an age of 345±17 ka, a mean square of weighted deviate (MSWD) of 1.06 (p=0.36) and an intercept of 294.1±0.9, indistinguishable from the atmospheric value. We interpret this isochron age as a best estimate for the eruption age for Höttur.

One split was analysed from Draugafell from sample K23, which is obsidian type F. This gave an age of 336± 16 ka. Given the wide spread of apparent ages produced by some of the other units, this cannot be interpreted as an accurate date with confidence and represents only an approximate estimate of the eruption age.

Three splits were analysed from Tindur (splits a, b and c) from sample Ker00/34, which is of obsidian type P. The splits produced ages of (a) 285±25 ka, (b) 246±24 ka and (c) 312±27 ka. These span an age range of over 60 ka. Plotting the data on a three-point isotope correlation diagram (Fig. 3) does not produce a good correlation according to the criteria of Wendt and Carl (1991; MSWD= 1.68, p=0.19), and none of the data points can be identified as being anomalous. The middle age (285 ka) is within 2σ of the other two ages and all of the ages are within 3σ of each other. A weighted average gives a best-estimate eruption age of 279±15 ka, but we accept that this is a conservative error.

Two splits were analysed from Efri Kisubotnahnukur (sample K18) which is of obsidian type M. Splits K18a and b gave ages of 292±17 and 257±10 ka, respectively. These two splits produced an age range of 35 ka and overlap at the 2σ level. Further age measurements are required to refine the age of Efri Kisubotnahnukur, but we suggest it erupted between around 300 and 250 ka ago.

Table 1 The rhyolite units with their eruption age, obsidian type and estimated eruption volume

Unit	Geochemical group	No. of splits	Age (ka)	Note	Obsidian type	Volume (km^3)
Höttur	Low Nb	5	345±17	A	M	0.25
Draugafell	Low Nb	1	~336	D	F	0.12
Tindur	Low Nb	3	279±15	C	P	0.19
Efri Kisubotnahnukur	Low Nb	2	~250–300	D	M	0.15
Klakkur	Low Nb	2	255±5	B	S	0.09
East Trollabarmur	Low Nb	1	~249	D	M	0.02
Eyvindur	High Nb	2	247±7	C	M	0.11
Ögmundur	High Nb	4	219±23	A	G, F	0.27
Loðmundur	High Nb	2	184±10	B	F	0.18
Snaekollur	High Nb	2	~150–190	D	P	0.11
South Höttur	High Nb	3	149±15	B	P	0.04
Maenir	High Nb	2	125±24	B	F	0.29
Hverahnukur	High Nb	3	68±21	A	F, S	0.10
Fannborg	High Nb	2	<100	D	G	0.14

Obsidian Types are described in the online supplementary material: *M* = pillow margin facies, *F* = flow banded, *P* = pitch stone, *S* = spherulitic, *G* = fresh massive glass. *Volumes* are bulk rock and calculated by assuming simple geometric shapes, such as cones, wedges or slabs, for each eruptive unit. *Note*: A = the eruption age is derived from a multipoint isochron. B = the eruption age is derived as a weighted average based on two or more splits that are within 1σ of each other. C = the eruption age is derived as a weighted average of either two splits that are within 2σ of each other or three splits that are within 3σ of each other. D = an eruption age could not be derived, or only one split was analysed, and ages quoted are a rough estimate, to put the timing of eruption in context (age ranges quoted are a rough estimate and suggested errors on single split ages are on the order of ~70 ka).

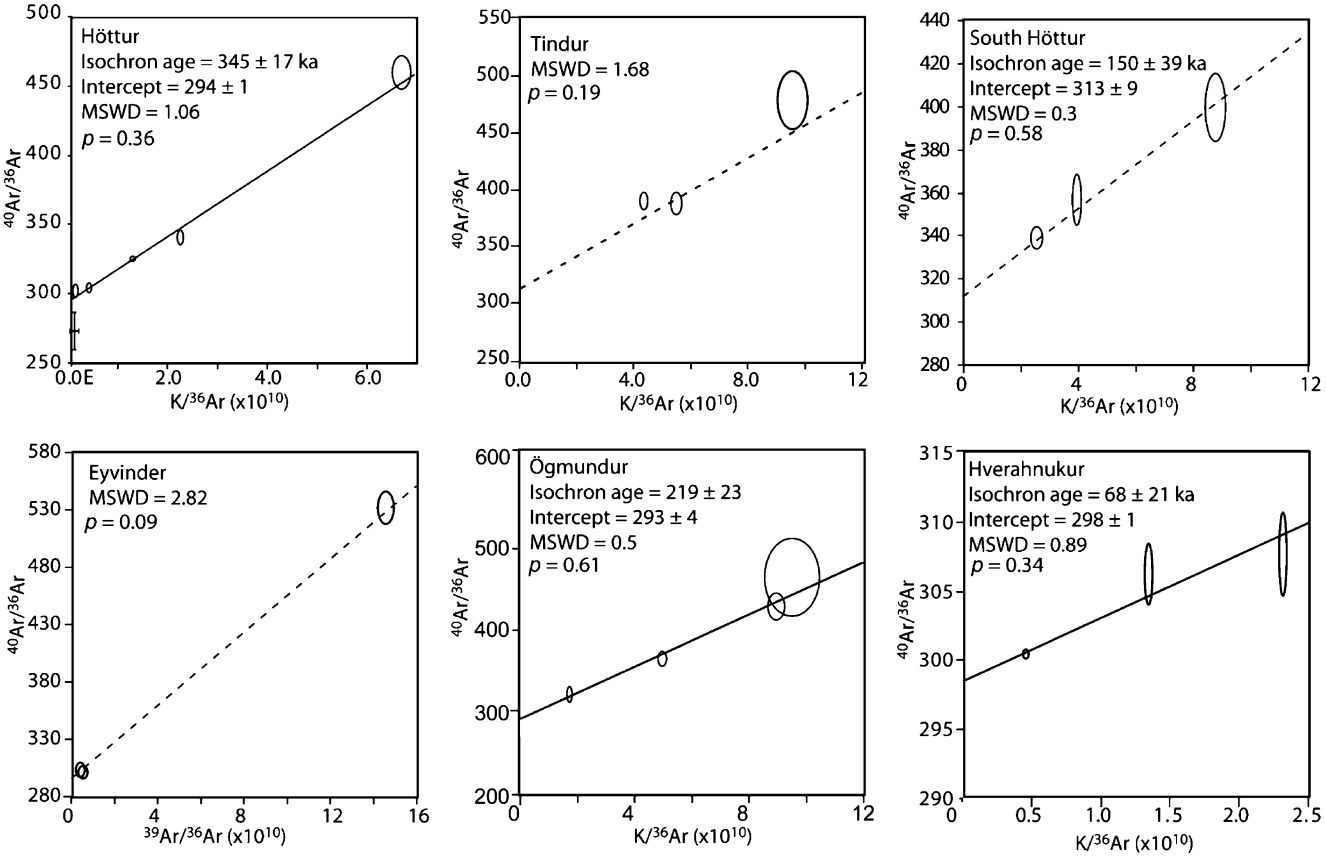

Fig. 3 Ar isotope correlation diagrams for the Kerlingarfjöll rhyolites. *Ellipses* are data points showing errors to one standard deviation. *Dashed lines* represent isochrons that did not produce a satisfactory correlation. Errors stated on ages and intercepts are one standard deviation

Two splits were analysed from Klakkur (K27) which is of obsidian type S and contains up to 3% spherulites. Splits K27a and b gave ages of 253±7 and 259±10 ka, respectively, and are within 1σ of each other. The weighted average is 255±5 ka.

One split was analysed from East Tröllabarmur (K39), which is obsidian type M. This gave an age of 249±14 ka. Given the wide spread of ages produced by some of the other units, this cannot be interpreted as a definitive date but provides an approximate eruption age.

Three splits were analysed from Eyvindur (K33), which is of obsidian type M and contains ~10% areas of tube pumice. Splits a, b and c gave ages of 265±13, 170±29 and 240±9 ka, respectively, showing a wide age variation. Splits a and b both released proportionally more ^{36}Ar (thus, presumably contained more atmospheric argon) than split c. Plotting the data on an isotope correlation diagram produces an isochron age of 235±15, an intercept of ^{40}Ar/^{36}Ar value of 296±1 and an MSWD of 2.82 (p= 0.09). This MSWD is unacceptably large according to the criteria of Wendt and Carl (1991). The high level of ^{36}Ar, in combination with the prevalence of pumiceous areas, suggests that the variation in age is due to alteration and loss of ^{40}Ar* from the system. While care was taken to avoid altered, pumiceous or matrix-rich shards of obsidian during picking, it is possible that some of this material was incorporated. As split b is significantly younger (much more than 2σ, despite the larger error) than splits a and c, this is assumed to have been most affected by ^{40}Ar loss and should not be used to calculate an eruption age. It is possible that splits a and c give old apparent ages due to excess ^{40}Ar, but we do not think this is the case as the intercept of the isotope correlation diagram is indistinguishable from atmospheric argon (Fig. 3). Splits a and c have ages within 2σ of each other, and a best-estimate weighted mean of these splits gives an age of 247±7 ka, although we accept that this is a very conservative error.

Four glass splits were analysed from Ögmundur, from two different samples. Ker00/46a (obsidian Type G) produced an age of 202±22 ka and splits Ker3a, b and c (obsidian type F) produced ages of 198±15, 216±20 and 259±36 ka, respectively. Plotting these data on an isotope correlation diagram (Fig. 3) gives an isochron age of 219± 23 ka with an intercept of 293±4 and an acceptable MSWD of 0.5 (p=0.61). This is interpreted as the eruption age.

Two glass splits were analysed from Loðmundur (K12 a and b, obsidian type F, with large flow bands, up to 1 cm thick) and gave ages of 184±15 and 185±14 ka, respec-

tively. A weighted average of splits a and b is taken to be the eruption age and is 184±10 ka.

Three glass splits were analysed from South Höttur (Ker00/38, obsidian type P), giving ages of (a) 249±24 ka, (b) 176±21 and (c) 226±37, respectively. The ages span a range of 73 ka. Plotting the data on an isotope correlation diagram produces an apparent correlation, with the slope formally equivalent to an age of 150±39 ka (Fig. 3). However, the relatively large errors combined with the use of just three data points have resulted in an unacceptably low MSWD of 0.3, according the criteria of Wendt and Carl (1991), suggesting that experimental errors are overestimated. The $^{40}Ar/^{36}Ar$ intercept is 313±9, indicating that excess ^{40}Ar is present and this is probably the cause of the age variability between splits. Recalculating the split ages to correct for this excess argon, by correcting for a trapped $^{40}Ar/^{36}Ar$ value of 313 rather than the atmospheric value of 295.5 and assuming that the excess ^{40}Ar is evenly distributed throughout the sample, gives ages of 147±24, 146±22 and 161±37 ka for splits a, b and c, respectively. These are all indistinguishable from each other at the 1σ level and a weighted average of the three splits (recalculated to account for excess ^{40}Ar) is taken to be the eruption age and is 149±15 ka.

Two splits were analysed from Maenir (Ker5, obsidian type F) giving ages of (a) 126±31 and (b) 125±38 ka. These ages are indistinguishable from each other and give a weighted average of 125±24 ka, which is taken as the eruption age.

Three splits were analysed from Hverahnukur from two samples (Ker1 and K5) which gave ages of 77±19 ka (Ker1a), 160±12 ka (K5a) and 118±23 ka (K5b), respectively. Sample Ker1 is obsidian types S and K5 is type F. The oldest (160 ka) and youngest (77 ka) of these ages are significantly different from one another, while the middle age (118 ka) is within 2σ of both of the other ages. Plotting the data on an isotope correlation diagram (Fig. 3) produces an isochron age of 68±21 ka with an intercept of 298±1 and an acceptable MSWD of 0.9 (p=0.34). This suggests that a small amount of excess ^{40}Ar is present and may be the main cause of variation in the ages. The isochron age (68±21 ka) is taken to be the eruption age.

Two glass splits were analysed from Snaekollur (K10a and b, obsidian type P) which gave ages of 189±11 and 152±12,ka respectively. These two ages do not overlap at the 1σ level and a definite eruption age cannot be calculated from the available data; however, it is suggested that Snaekollur was erupted between ~150 and ~190 ka.

Two splits were analysed from Fannborg (K9) and gave ages of (a) 83±7 ka and (b) 40±20 ka. Sample K9 is obsidian type G but contains rare, very small (<<1 mm) spherulites. The youngest age is less than half of the oldest age, and the ages are more than 2σ apart, despite the large error on split b. Although these data are not conclusive, it seems clear that Fannborg is one of the youngest eruptive units at Kerlingarfjöll, probably having erupted less than 100 ka and may be as young as 20–40 ka.

Discussion of Ar/Ar data and implications for dating volcanic glass

This is the first time that a comprehensive dating study has been carried out at a rhyolite-dominated Icelandic rift zone central volcano, and the lack of similar studies reflects the difficulties inherent in dating these rocks. In Table 1, each eruption age has been assigned a note to briefly describe how the age was derived and aid in evaluating the quality of the data (see Table 1 caption). Figure 4 shows how the ages of individual splits compare with the derived eruption age to highlight the variation in precision of the data between eruptive units. A minority of units (Klakkur, Loðmundur, Maenir) show good reproducibility, but these are based on only two splits, and subsequent analyses may produce a greater spread of ages. The possible causes of this variation in ages will be evaluated below.

Excess ^{40}Ar Excess ^{40}Ar ($^{40}Ar_E$) was found in the eruptive units South Höttur and Hverahnukur, producing a spread in the ages of individual splits. This suggests that $^{40}Ar_E$ could be the cause of age variation in other units. However, isotope correlation diagrams suggest that $^{40}Ar_E$ is not present in Höttur (Fig. 3) and that the spread of ages produced by Tindur is due to disturbance of the Ar isotope system (by processes such as alteration), rather than $^{40}Ar_E$. It is impossible to evaluate the effect, if any, of excess ^{40}Ar on units where only one or two splits have been analysed. However, we suggest that those units showing apparently good reproducibility have not been affected by $^{40}Ar_E$ as a greater spread in ages would be expected; none of the splits in Hverahnukur are within 1σ of each other, and two splits in South Höttur are only just within 1σ of each other, despite large (>10%) errors. If $^{40}Ar_E$ is present, the ages will be an upper estimate only and could be much younger, depending on the proportion of $^{40}Ar_E$ in the obsidian.

Alteration Obsidian is metastable and is therefore prone to alteration which may affect the Ar/Ar system. Devitrification involves in situ recrystallisation of the glass, and the effects of this on the retention of Ar are unknown. Hydration can affect the siting and retention of both Ar and K (Cerling et al. 1985; Kaneoka 1972; Lanford et al. 1979) and thus can disturb the Ar/Ar system by affecting both the parent and daughter isotopes, potentially resulting in older or younger apparent ages. However, the loss on ignition (LOI) values of the analysed obsidians is relatively

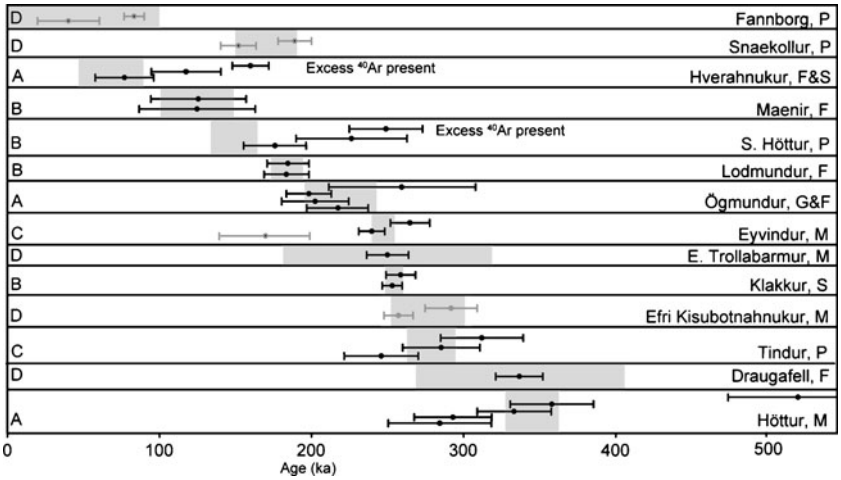

Fig. 4 Representation of variability in Ar/Ar ages of the individual splits (*error bars*), compared to the calculated eruption age (*shaded area*). *Error bars* represent individual splits. *Grey error bars* represent data from splits not used to calculate the overall eruption age. *Letters* on the *right* correspond to obsidian types ("Samples and petrography"), and *letters* on the *left* refer to how the eruption age was derived (Table 1, "Ar/Ar dating results")

low (generally <0.7%, see online supplementary data), suggesting that they have not been greatly affected by hydration. There does not seem to be a correlation between age reproducibility and LOI values; for instance, an eruption age could not be calculated for Efri Kisubotnahnukur, which has a lower LOI (0.28%) than Klakkur (0.37%) which apparently gave reproducible results. If alteration of the glass was the main cause of spread in the data, we would expect to see a correlation between reproducibility of ages and the type of obsidian analysed. All analyses of type M obsidian (Höttur, Efri Kisubotnahnukur, Eyvindur) produced a noticeable spread in data. The prevalence of cracks, hydration rims and fine-grained matrix makes this type of obsidian vulnerable to alteration. Although care was taken to select shards of the freshest glass possible for analysis, small amounts of hydrated or matrix material may have been incorporated, and shards of apparently fresh glass may have contained microcracks not visible under a microscope. Type M obsidian does not seem to give precise Ar/Ar ages. All analyses of type P obsidian (Snaekollur, South Höttur, Tindur) also produced a spread of data, but that of South Höttur was attributed to $^{40}Ar_E$. Conversely, the isotope correlation diagram for Tindur indicates that the Ar system has been disturbed, as would be expected if the variation was due to post-eruptive loss of Ar or K. Type P obsidian does not seem to consistently give good Ar/Ar ages. Obsidian type F was analysed as part of four eruptive units (Ögmundur, Loðmundur, Maenir and Hverahnukur). Hverahnukur exhibited a range of ages, but this was attributed to $^{40}Ar_E$. Three out of the four data points for Ögmundur are within 1σ of each other, and the outlying point (Ker3c) has a large error, due to a comparatively large error on the ^{36}Ar measurement (see online supplementary material, ~16% compared to ≤6% for other splits from Ögmundur). Type F obsidians are by nature variable, and while care was taken to select glass shards from the freshest parts of the sample, some devitrified material may have been incorporated into split Ker3c to account for its anomalous age. The other two units that were analysed with type F obsidian, Loðmundur and Maenir, gave precise results, but only two splits from each unit were analysed, and we recognise that further analyses may produce a spread of data. So far, type F obsidian appears to give reasonably good Ar/Ar results. Type G obsidian was analysed as part of Ögmundur where it produced an age indistinguishable from other splits and for Fannborg which gave two inconsistent results. This suggests that fresh, homogenous obsidian may produce unreliable Ar/Ar ages; however, it is feasible that the obsidian splits from Fannborg incorporated the very small and rare spherulites described in "Ar/Ar dating results". Type S obsidian was analysed as part of Hverahnukur, which contains excess ^{40}Ar, and for Klakkur, where two splits produced indistinguishable ages. This suggests that spherulite formation does not alter the Ar isotope system of the surrounding glass and that as long as spherulites are avoided the glass is equivalent to type F.

Evidently, the state of alteration of obsidian is not the only factor controlling the quality of Ar/Ar data, but it is clear that type M obsidians are particularly problematic; type F and S obsidians can give reproducible ages, and the quality of the data from types P and G is variable.

^{36}Ar content Many of the samples released a relatively large proportion of gas measured at mass 36 (up to ~5×10^{-9} cm^3 STP g^{-1}, KER2a, see online supplementary material). This is assumed to be ^{36}Ar, rather than hydrocarbon or chlorine contamination because background levels of masses 35 and 41 were measured for the first few samples analysed and gave no indication of contamination. Furthermore, cadmium shielding during irradiation minimises the production of ^{36}Cl. The proportion of $^{40}Ar^*$ to total ^{40}Ar (corrected for neutron interferences) is particularly low (<3%) in the samples with notably high ^{36}Ar

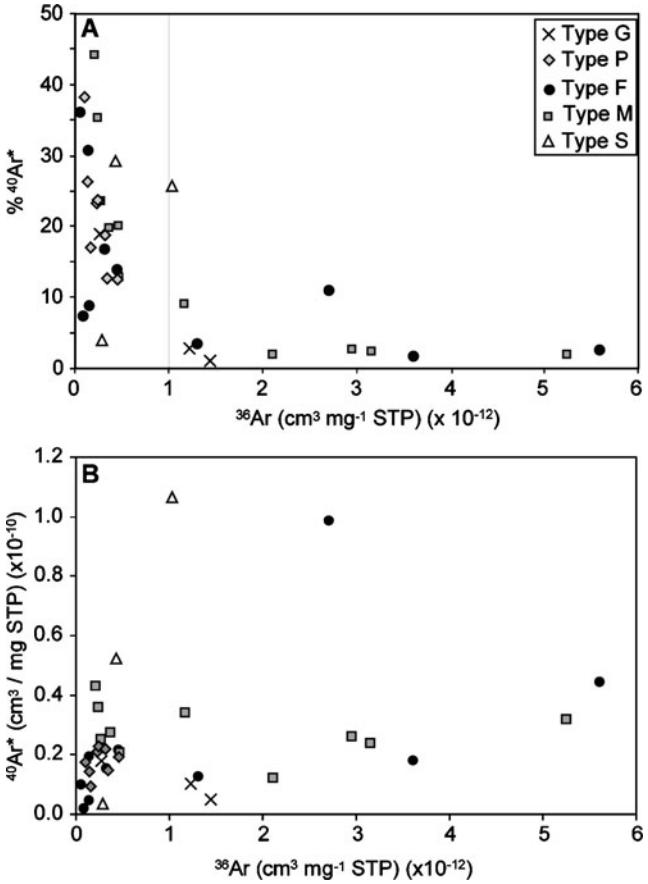

Fig. 5 **a**, **b** Volume of ^{36}Ar plotted against the proportion of ^{40}Ar* to total ^{40}Ar (%^{40}Ar*) and the volume of ^{40}Ar* released from each sample. *Symbols* refer to the different petrographic types of obsidian. Samples that released a large amount of ^{36}Ar gave low %^{40}Ar* yields but normal volumes of ^{40}Ar*, suggesting that the gas measured at mass 36 is atmospheric ^{36}Ar and that using this to correct for atmospheric ^{40}Ar is appropriate

contents ($>1\times10^{-12}$ cm^3 mg^{-1}; Fig. 5). This ^{36}Ar is assumed to be atmospheric and is used to correct for atmospheric ^{40}Ar so small inaccuracies in the measured ^{36}Ar content can have a large effect on the calculated age. Large proportions of atmospheric argon swamp the radiogenic component, and the relatively large errors and spread of some of the data may be due to these high levels of ^{36}Ar. However, there is no obvious correlation between the reproducibility of the data and the ^{36}Ar content; some units that gave reproducible split ages (e.g. Klakkur) or produced good isochrons (e.g. Hverahnukur) contain a mixture of low and high ^{36}Ar yields, while some units that produced a spread of ages (e.g. Tindur) also produced low ^{36}Ar yields. Figure 5 plots the ^{36}Ar and ^{40}Ar* content according to the different petrographic types and shows that there is no correlation between ^{36}Ar content and type of obsidian. Previous K–Ar studies on Icelandic volcanics have also noted high levels of atmospheric argon (Gale et al. 1966; Udagawa et al. 1999), suggesting that this problem is widespread in Iceland. The source of these high levels of atmospheric argon is unknown but it may have been incorporated during eruption through interaction with glacial ice, repeated fracture healing (Tuffen et al. 2003) of flowing lava, or in the magma chamber by interaction with hydrothermal fluids or assimilation of altered crustal material.

It is possible that some of the lavas have trapped an argon component with an unusually low ^{40}Ar/^{36}Ar ratio (<296—possibly an isotopically fractionated atmospheric component) or that the gas measured at mass 36 is actually an unidentified organic specie that has not been effectively removed by getter purification and was not identified by measuring masses 35 and 41. If either of these scenarios are the case, the ages presented here, especially those with corresponding high ^{36}Ar levels, will be younger than the true eruption age, due to over-correction of atmospheric ^{40}Ar. However, there is no correlation between high levels of ^{36}Ar and low absolute concentrations of ^{40}Ar* (Fig. 5). This suggests that the low ^{40}Ar* yields (as a proportion of total ^{40}Ar) are due to high levels of atmospheric argon; if the gas measured at mass 36 was not atmospheric ^{36}Ar, we would expect lower absolute ^{40}Ar* values in the samples with high ^{36}Ar contents, which is not seen (Fig. 5).

Evidently, Ar/Ar dating of Icelandic volcanics is not straightforward, and we accept that many of the ages presented here should be considered critically. Nevertheless, the youth of these Ar ages is in-keeping with the presence of hydrothermal activity at Kerlingarfjöll; they are in agreement with the limited stratigraphic relationships that have been deduced (South Höttur is younger than Höttur), and the apparent relationships between time, geochemistry and eruption location, as discussed below, would be difficult to generate by chance using inaccurate data, thus supporting the validity of the age estimates obtained.

Eruptive history of Kerlingarfjöll

Rhyolite eruptions at Kerlingarfjöll have spanned a time period of around 300,000 years from ~68 to ~345 ka. The order of eruption is shown in Table 1. The most recent rhyolite eruption was either Fannborg or Hverahnukur, both of which are probably less than 100 ka. Plotting the age data onto the oxygen isotope curve (a proxy for global temperature and analogous to ice volume, Petit et al. 1999) shows when eruptions took place in relation to ice ages (Fig. 6). This reveals that rhyolite activity spans the last four glacial periods. The ages are not precise enough to assign an eruption to a glacial or interglacial stage, but some eruptions (e.g. Ögmundur) may have taken place in northern-hemisphere interglacial periods (see Fig. 6).

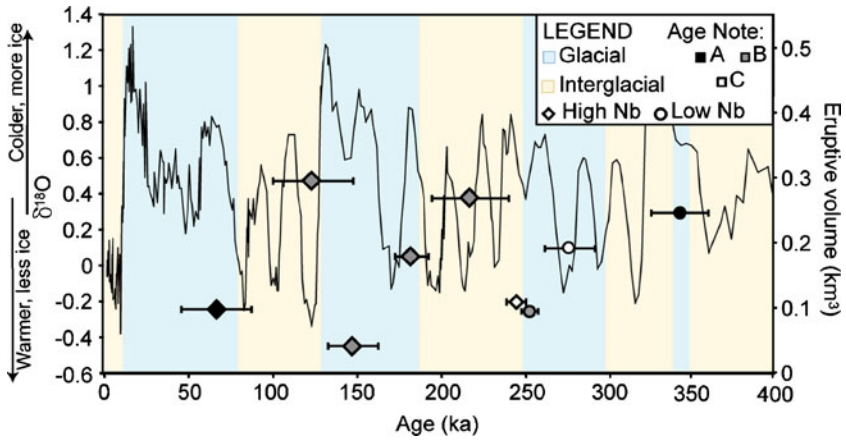

Fig. 6 The ages and eruptive volume of the Kerlingarfjöll rhyolites superimposed onto the oxygen isotope curve from the Vostok Ice Core (Petit et al. 1999). It is reasonable to use O isotope data from Antarctica as a proxy for global ice volume as a one-to-one coupling of climate data has been shown between Antarctic and Greenland ice cores (EPICA Community Members 2006). *Shading of symbols* corresponds to the eruption age notes in Table 1 to allow for easier evaluation of the data. Units that did not produce a satisfactory eruption age have not been plotted. European glacial/interglacial periods are according to Lowe and Walker (1997)

Accurate repose intervals between eruptions cannot be calculated as not all of the eruptive units have been dated. However, maximum repose periods can be estimated by comparing the time between relatively well-constrained eruption ages. This gives a range of estimated repose periods (values incorporating the errors in the eruption ages) between 4–20 ka (Klakkur to Eyvindur) and 12–102 ka (Maenir and Hverahnukur). This variation in likely repose period suggests that eruptions were episodic rather than regular with repose periods often on the order of tens of thousands of years.

When the ages of the eruptive units are compared to their geochemistry, it is clear that the two geochemical groups identified in "Geochemistry and mineralogy: results and classification" are temporally distinct, the low-Nb rhyolites erupting before the high-Nb rhyolites (Fig. 7). This difference in timing of eruption between the two geochemical groups suggests that the rough-estimate ages (age note D) are valid approximations, as the low-Nb units (Draugafell, Efri Kisubotnahnukur and East Tröllabarmur) are all older than the high-Nb rhyolites. The change in chemistry from low- to high-Nb rhyolites took place around 250 ka. No eruption hiatus is evident between the two groups, and they may have coincided for a short period.

Eruption volumes are plotted against time in Fig. 6. The volume of individual eruptions is variable (from 0.02 to 0.29 km^3), and there is no apparent systematic change in eruption volume over time.

In Fig. 8, the eruption ages are plotted onto a map of Kerlingarfjöll. The younger high-Nb rhyolites are restricted to the northern part of the volcano, as part of the Eastern and Western Clusters, while the older low-Nb rhyolites form the discontinuous rhyolite ring described in "Geological context". There does not seem to be any systematic variation in eruption site over time for the low-Nb rhyolites. Taken as a group, the high-Nb rhyolites appear to become spatially restricted over time, with the most recent eruptions having occurred close to the current hydrothermally active area in the Eastern Cluster. However, when viewed as two separate clusters, there is no conclusive pattern, except perhaps a westward migration of activity in the eastern cluster.

To summarise, episodic rhyolite volcanism at Kerlingarfjöll began at least around 345 ka. Low-Nb rhyolites were erupted first, forming a discontinuous ring. Around 250 ka, rhyolite volcanism became concentrated in the northern part of the volcano, and the high-Nb rhyolites were erupted. Over time, the areal extent of rhyolite volcanism became restricted, with the most recent eruptions focussing around the sites of current hydrothermal activity.

Comparison of high- and low-Nb rhyolites

Two distinct groups of rhyolite have been identified at Kerlingarfjöll: an early low-Nb rhyolite and a later high-Nb rhyolite, and the question remains whether they represent two individual magma batches or whether one is parental to the other.

Mineralogically, feldspar compositions between the two groups are distinct with low-Nb rhyolites containing more calcic feldspars than the high-Nb rhyolites (see online supplementary material). The two groups show different geochemical behaviour; the low-Nb rhyolites exhibit a spread of data within an eruptive unit, and many units are chemically similar, while high-Nb rhyolites have a more restricted compositional range within each eruptive unit, and many units are chemically distinct. Figure 7 shows

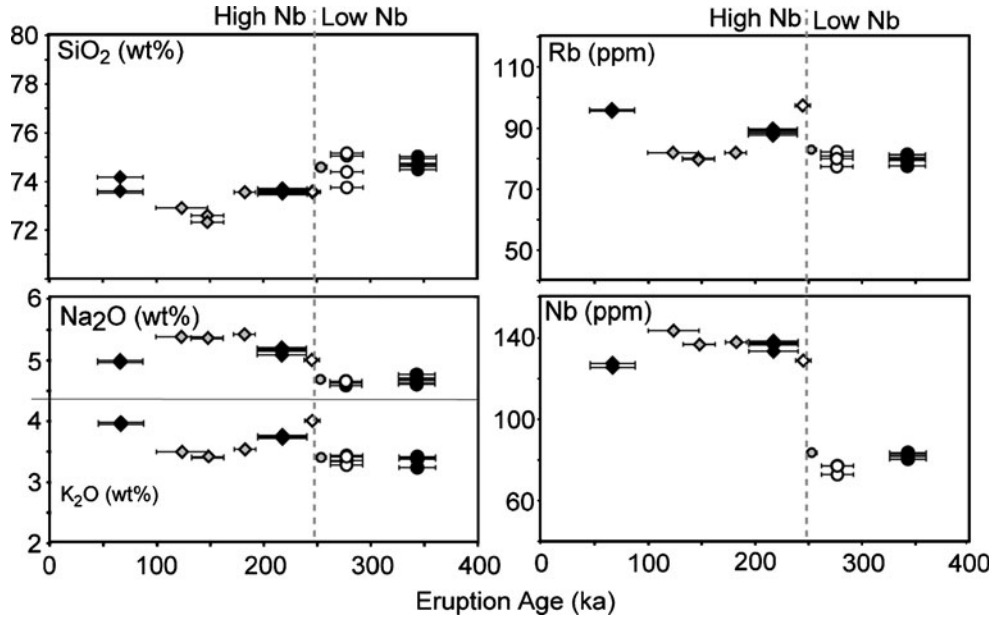

Fig. 7 Eruption age vs. chemical composition of the rhyolites. The low- and high-Nb rhyolites are distinct, having erupted at different times and showing different geochemical behaviour over time. *Symbols* as in Fig. 6

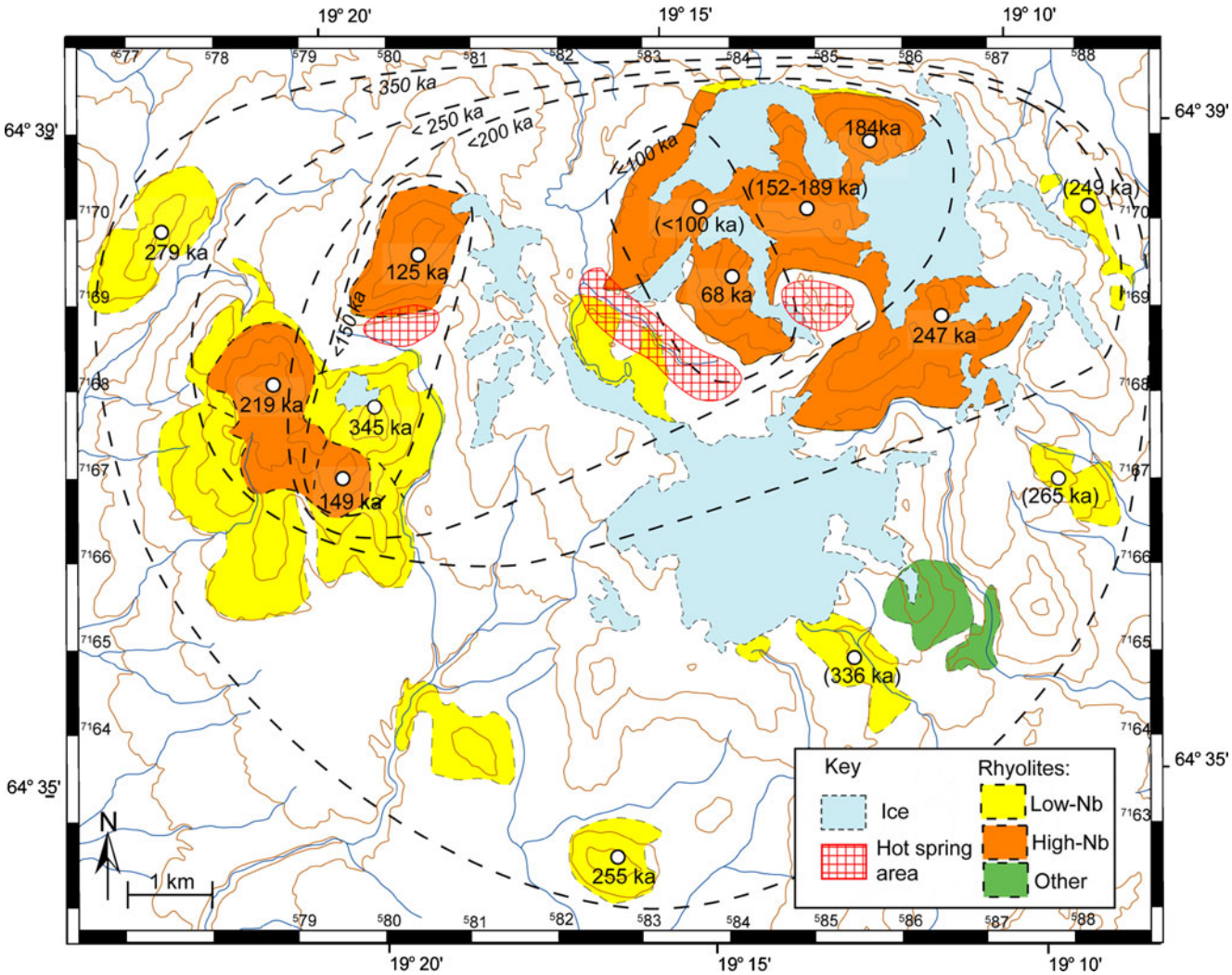

Fig. 8 Map of the Kerlingarfjöll rhyolites with eruption ages. *Dashed lines* are contours of maximum eruption age, to qualitatively illustrate how rhyolite volcanism may have become more spatially restricted over time, coinciding with the areas of hydrothermal activity

geochemical behaviour of the rhyolites over time. Rb and SiO_2 levels in the low-Nb group show minimal interunit variation, but in the high-Nb group both Rb and SiO_2 decrease and then increase again over time. The alkalis behave similarly in the low-Nb group, but anti-sympathetically in the high-Nb group, K_2O decreasing as Na_2O increases and vice versa. Factors controlling the site of eruption differ between the two groups, low-Nb eruptions were restricted to the periphery of the volcano, and high-Nb rhyolites concentrated in the north. Finally, the high-Nb rhyolites are depleted in SiO_2 and slightly enriched in Rb compared to the low-Nb rhyolites (Fig. 7). Rb is an incompatible element so it would be expected to increase with increasing SiO_2 content during fractional crystallisation or melting. This is contrary to what we observe, and it seems unlikely that either rhyolite group could be produced by fractionation of the other. We speculate that the rhyolites represent two distinct batches of magma but acknowledge that further work is required to confirm this.

Implications for volcanic evolution

The small volume and episodic timing of eruptions indicate that the ring structure at Kerlingarfjöll was formed incrementally and is not the product of a caldera-forming eruption. The ring structure is made up of low-Nb rhyolite which exhibits minimal variation in geochemical composition between eruptive units (Fig. 2) that are often geochemically indistinguishable. This suggests that the low-Nb rhyolites originated from a common magma reservoir; thus, the eruption site is likely to be controlled by a structural weakness rather than the location of the rhyolite magma at depth, implying the presence of a (cryptic) curved fracture system at Kerlingarfjöll that acted as a pathway for small-volume eruptions. If such a scenario is common to Icelandic rift zone central volcanoes, it should be evident in the exhumed Austurhorn central volcano in southeast Iceland. The Austurhorn intrusion comprises a gabbro inner, surrounded by numerous granites that were intruded along the gabbro margin (Furman et al. 1992). This mirrors the ring distribution of the low-Nb rhyolites which post-date the main phase of basaltic volcanism (Stevenson et al. 2009). It is possible that such a ring fracture is an integral part of Icelandic central volcano development with the emplacement and cooling of a basaltic magma body beneath a central volcano resulting in a structural weakness around the edge of the basaltic magma chamber that is exploited by silicic magma during emplacement and eruption.

The ring fracture became inactive around 250 ka with the inception of the high-Nb rhyolites which were erupted in the northern part of the volcano. If the distribution of ages is interpreted as spatial restriction over time, this may be the result of the inward solidification of a body of magma; the most recent eruptions representing the last dregs of eruptible magma with latent heat driving hydrothermal activity. Alternatively, the areas of hydrothermal activity may be the direct result of the most recent volcanism, and earlier eruptives may have been associated with similar hydrothermal areas which have since been buried. As such, any future eruptions of high-Nb rhyolite are expected to occur in the vicinity of the hydrothermal areas. This second rhyolitic magma body probably formed above the initial basalt magma body or after the basalt had solidified, as the rhyolites show no evidence of magma mixing or mingling with a more basic magma.

The two geochemical groups of rhyolite are chemically, temporally and spatially distinct, suggesting that they represent two distinct magma batches whose emplacement and eruption were affected by different structural controls. The suggested magmatic and volcanic evolution of Kerlingarfjöll is summarised in Fig. 9. Each batch of rhyolite magma was erupted over a period in the order of hundreds of thousands of years, a surprisingly long time span for such a small-volume system. Rhyolite magmas cannot persist for so long at near-liquidus conditions, and it seems much more likely that the rhyolites were derived from a silicic mush zone, similar to that suggested by Jónasson (2007) and Flude et al. (2008).

While it is difficult to precisely constrain the climate at the time of eruption due to the errors on the eruption ages, some units (most noticeably Ögmundur) appear to have erupted during interglacial or warm periods, indicating that Kerlingarfjöll was probably ice-covered for much of the time during interglacials. Given that Kerlingarfjöll currently hosts numerous small permanent ice fields and is less than 15 km from the Hofsjökull ice cap, this is not surprising.

The question of whether rhyolite volcanism at Kerlingarfjöll should be considered active is debatable. Given the potentially long repose periods, not enough time has passed since the last eruptions (Hverahnukur of Fannborg) to conclude that Kerlingarfjöll is extinct. However, the possible restriction in eruption location over time, tentatively interpreted as the inward solidification of a body of magma, combined with the secondary hydrothermal activity suggests that Kerlingarfjöll may be nearing the end of its rhyolitic lifetime. Nevertheless, the last eruption of the low-Nb rhyolites was small volume and was contemporaneous with or closely followed by the first of the high-Nb rhyolites. This was an abrupt change in both magma source and control on eruption location and a similar event, i.e. the inception of a new batch of rhyolite, cannot be ruled out. From a hazard perspective, the small volume and apparent lack of explosive or caldera-forming eruptions are reassuring.

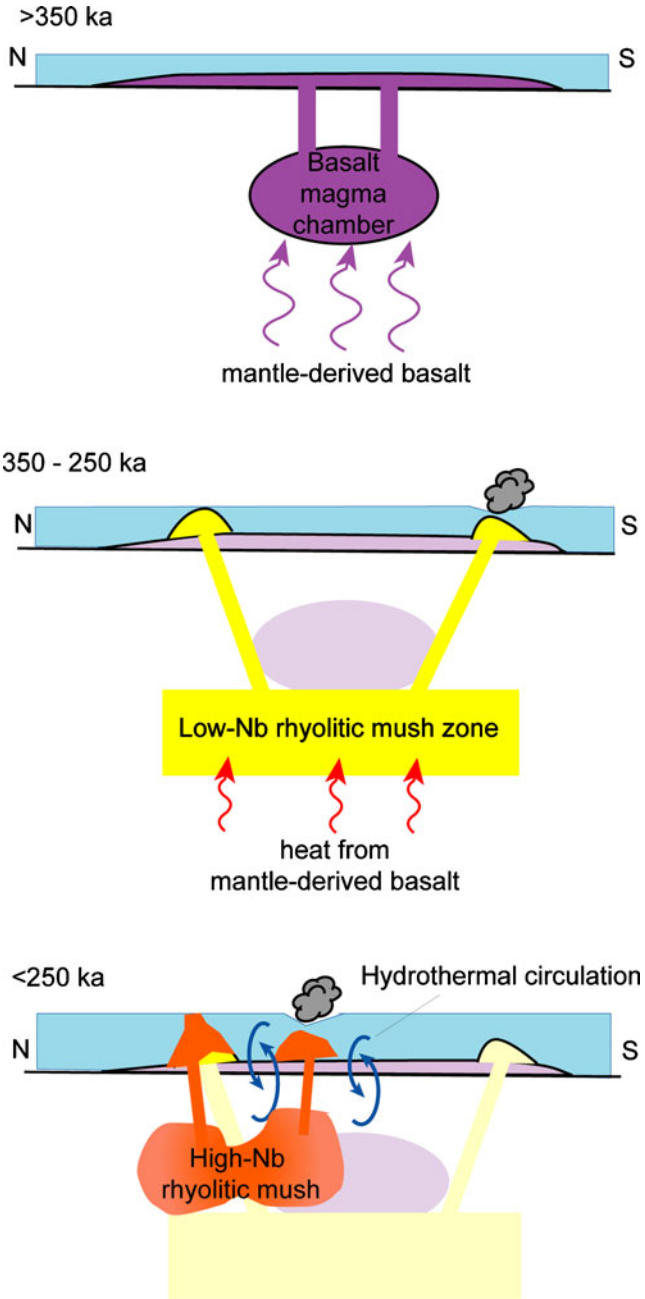

Fig. 9 Schematic diagram representing the volcanic evolution of Kerlingarfjöll over time. *Blue block* represents overlying ice. Basaltic magma pools to form a magma chamber and feed early basaltic eruptions. Rhyolitic magma mush that forms beneath the basaltic magma chamber is emplaced and erupted along a ring fracture at the periphery of the magma chamber. Finally, a new batch of rhyolitic magma mush is emplaced and feeds eruptions in the northern part of the volcano and drives secondary hydrothermal circulation. The low-Nb rhyolites are thought to originate beneath the basaltic magma chamber based on the apparent correspondence of eruption sites with the structure of the Austurhorn intrusion (Furman et al. 1992). The site of origin or possible storage of the high-Nb rhyolites is unclear, but erupted rhyolites are not thought to have interacted with basalt magma and thus are physically separated from the basalt or were emplaced after the basalt had solidified

Wider implications

If Kerlingarfjöll is representative of Icelandic rift zone central volcanoes, it appears that rhyolite activity in Iceland is prolonged and episodic rather than rapid and short-lived. This suggests that many rhyolite systems considered to be dormant may erupt again. The ring distribution of rhyolites is similar to those observed at ice-covered volcanoes, and it has been suggested that these represent calderas (Björnsson 1988; Björnsson et al. 2000). Our results indicate that the ring structure rhyolites at Kerlingarfjöll are formed incrementally over tens to hundreds of thousands of years and are not the product of a caldera-forming eruption. Their distribution is similar to that of post-caldera rhyolites worldwide (e.g. Nemrut Dagi, Turkey, Ozdemir et al. 2006; Jemez volcanic field, New Mexico, Spell and Harrison 1993), i.e. small-volume eruptions occurring at the caldera rim and on the caldera floor. However, such rhyolites tend to form after large silicic caldera-forming eruptions, of which there is no evidence at Kerlingarfjöll. We suggest that other rhyolitic ring structures in Iceland may have formed incrementally and reflect a crustal weakness inherent to central volcano development, causing rhyolite emplacement and eruption along a cryptic curved fracture system, coupled to the interaction of silicic and cooling basic magma beneath the volcano.

The fact that all of the rhyolites are subglacial but have not necessarily been restricted to glacial periods indicates that the area has spent most of its history ice-covered and has only been relatively ice free (as now) during the most sustained warm periods. Bourgeois et al. (2000) concluded that, during the last glaciation, Kerlingarfjöll was beneath an ice divide, with minimal ice flow or glacial erosion. The fact that rhyolites at Kerlingarfjöll erupted during the last four glacial periods show minimal glacial erosion suggests that the model of ice flow of Bourgeois et al. controlled by geothermal processes has been relevant, at least in central Iceland, for the last ~400 ka.

Conclusions

We present the first systematic combined dating and geochemical study of a rhyolite-dominated Icelandic rift zone central volcano. Kerlingarfjöll central volcano has erupted a sequence of basalt to dacite to low-Nb rhyolite to high-Nb rhyolite. The rhyolitic phase of activity started over 300 ka ago, persisted until at least ~68 ka and is possibly still active. The rhyolite volcanism is small volume and episodic, consisting of two separate phases of rhyolite

activity: an older low-Nb rhyolite that was erupted between ~350 and ~250 ka along a cryptic ring fracture around the periphery of the volcano and a younger high-Nb rhyolite that was concentrated in the northern part of the volcano. Repose periods are long, on the order of thousands to tens of thousands of years. Hydrothermal areas at Kerlingarfjöll appear to be associated with the more recent high-Nb rhyolite eruptions, and any future eruption of high-Nb rhyolite is expected to be associated with similar hydrothermal activity. Kerlingarfjöll should not yet be considered extinct. The presence of discontinuous rings of rhyolite (which are not thought to represent calderas) at other volcanoes suggests that the development of a curved fracture system, which acts as a pathway for small-volume episodic eruptions, is a feature of central volcano development. The Kerlingarfjöll area has spent most of the last 400 ka covered in a substantial thickness of ice with minimal glacial erosion taking place. Finally, Ar/Ar dating of Icelandic obsidian is possible, but with difficulty. There is minimal correlation between the quality of the Ar/Ar data and the textures or type of obsidian, and analysis of multiple splits of a sample is necessary to rule out the presence of excess ^{40}Ar and the effects of hydration and devitrification.

Acknowledgements S. Flude was funded by NERC studentship NER/S/A/2001/06307. John Stevenson is thanked for help preparing XRF samples and for the loan of a camping stove at Kerlingarfjöll when SF's blew up. Stuart Gilfillan, Adam Morris, Helen Rowland and Emily Hobson are thanked for assistance in the field. Dave Blagburn and Bev Clementson are thanked for keeping the MS1 running smoothly and ensuring a ready supply of tantalum crucibles. Sarah Sherlock, Mike Henderson and Ben Edwards are thanked for constructive comments.

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