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Detrital zircon resolve longevity and evolution of silicic magmatism in extinct volcanic centers: A case study from the East Fjords of Iceland

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ABSTRACT

Breiðuvík and Kækjuskörð are two neighboring extinct eruptive centers in the East Fjords of Iceland. Together, they compose the second-largest volume of silicic rock in the country (after Torfajökull, an active volcanic system in southern Iceland). We use ages and compositions of detrital zircon collected from two rivers, the Stóraá and Krossá-Kækjudalsá, to investigate the origins and longevity of silicic magmatism at Breiðuvík-Kækjuskörð. Zircon populations from the two catchments have identical median U-Pb dates (12.9 Ma), O isotopes (δ^{18}O Vienna standard mean ocean water = 3.1‰ versus 3.3‰), and Hf isotopes (ε_{Hf} = 14.7). We interpret coherence of zircon elemental and isotopic compositions to indicate that a significant volume of relatively uniform silicic material was produced in close temporal and spatial proximity between 11.2 ± 0.7 Ma and 15.0 ± 0.9 Ma (all errors are 1σ), dominated by assimilation–fractional crystallization processes. To test the robustness of this longevity estimate, we applied Monte Carlo modeling to the Breiðuvík-Kækjuskörð detrital zircon results and found the age span to be statistically resolvable at ≥2.8 m.y. While this lifespan is comparable to those of large mafic-silicic volcanic systems that have been described in other settings globally, it is the longest reported estimate for any Icelandic volcano, where typical longevity is thought to be ~0.5–1.5 m.y. The ≥2.8 m.y. lifespan we present for Breiðuvík-Kækjuskörð is a conservative assessment, because the dates used in this study only represent the zircon-saturated period of magmatic activity. This study demonstrates that detrital zircon analysis of volcanigenic sediment provides an efficient and powerful tool that can illuminate histories of zircon-saturated magmatism at targeted volcanic centers and systems. This approach can be particularly valuable in dominantly mafic provinces where silicic material is subordinate (e.g., ocean islands, flood basalt provinces), where glaciation, erosion, or alteration has transformed the landscape, or in areas that are inaccessible (e.g., obscured by glacial ice).

INTRODUCTION

Silicic magmatism is a relatively common feature of volcanic provinces dominated volumetrically by basaltic lavas. The bimodal association of abundant basalt with varying amounts of silicic magmatism is observed in a range of tectonomagmatic settings, including intracontinental hotspot tracks (e.g., Steens–Columbia River–Yellowstone, USA); continental rifts and large igneous provinces (e.g., Paraná-Etendeka, Namibia-Brazil; Africa-Arabian volcanic province, Ethiopia-Yemen; Karoo, southern Africa); and oceanic islands (e.g., Azores) and plateaus (e.g., Kerguelen) (e.g., Christiansen, 1984; Peate et al., 1992; Wallace et al., 2002; Snyder et al., 2004; I.U. Peate et al., 2005; Pankhurst et al., 2011; Coble and Mahood, 2012). Characterizing the silicic magmas and elucidating their genesis can offer insights into processes within large igneous provinces and the formation of juvenile continental crust (e.g., Pankhurst et al., 2011).

Iceland, located at the intersection of a mantle hotspot and the Mid-Atlantic Ridge, offers a unique example of a basaltic province that produces significant volumes of silicic magma. Rhyolite is estimated to compose ~10% of the erupted products of the island's volcanoes (e.g., Walker, 1966; Gunnarsson et al., 1998; Jónasson, 2007). The longevity of the dominantly mafic volcanic centers is poorly constrained because dating of basalts by radiometric methods is notoriously difficult due the general absence of minerals which can be precisely dated using U-Pb systematics. Zircon, a mineral that is very rare in mafic magmas but commonly present in rhyolitic melts, is especially valuable because it can provide both precise and accurate radiometric ages as well as elemental and isotopic tracers that provide petrogenetic

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information (e.g., I.U. Peate et al., 2005; Kemp et al., 2007; Claiborne et al., 2010a; Barboni and Schoene, 2014).

In this paper we evaluate the longevity and evolution of silicic magmatism at two large, closely spaced, dissected volcanic centers in northeastern Iceland using stream-sampled detrital zircon. We compare this life history to that inferred for central volcanoes in Iceland and, more generally, to silicic magmas within basaltic provinces globally. This approach, i.e., dating and chemical analysis of stream-sampled zircon, is an efficient way to evaluate the history of dissected volcanic centers.

GEOLOGIC CONTEXT

Volcanic Longevity and Silicic Magmatism in Iceland

Of the erupted material from Iceland's volcanoes, ~10% is rhyolite (e.g., Walker, 1966; Gunnarsson et al., 1998; Jónasson, 2007). Much of this material is concentrated in large central volcanoes, where the relative abundance of silicic material increases to ~20%–30% of the exposed rocks (Walker, 1963; Gunnarsson et al., 1998). These major systems have been estimated to have a maximum lifespan of ~0.5–1.5 m.y. (e.g., Saemundsson, 1979; Jakobsson, 1979; Thordarson and Larsen, 2007). There is ambiguity in the literature as to whether this estimate of longevity solely reflects active volcanism, or whether it includes the magmatic underpinnings of the system. Furthermore, these estimates are mostly based on K-Ar ages and magnetostratigraphy; zircon dates are notably lacking.

The most extensively investigated volcanic systems in Iceland are those that have recently erupted. Among these active volcanic systems, Torfajökull in southern Iceland (Fig. 1) has the largest areal exposure of silicic rock of any center (active or extinct) in Iceland, and it is the only one that is dominantly silicic (e.g., Gunnarsson et al., 1998). With an eruptive record spanning ~400 k.y., it also has the longest well-documented history of any historically active Icelandic volcano (McGarvie et al., 2006). Kerlingarfjöll (~300 k.y.; Flude et al., 2010), and Öræfajökull (Saemundsson, 1979) may span similar periods; Krafla has a somewhat shorter recognized history of ~100 k.y. (Jónasson, 1994). The relatively young Ljósufjöll, on Snæfellsnes, is the only volcanic system that has a documented lifespan approaching 1 m.y., from ca. 1.1 Ma to after 100 ka (Flude et al., 2008). A recent study of the Austurhorn intrusive complex in southeastern Iceland (Padilla et al., 2016) revealed a duration of ~300 k.y. for the zircon-saturated history of the system, suggesting comparable longevity of Icelandic intrusive and volcanic systems.

Volcanic systems whose silicic products erupted over a substantial timespan (>~100 k.y.) include Torfajökull, Kerlingarfjöll, Thingmuli, and Ljósufjöll (Fig. 1). All of these volcanoes reveal substantial diversity in the compositions of silicic rocks, and distinct compositional series have been identified at Torfajökull (peralkaline versus subalkaline, metaluminous; McGarvie et al., 2006), Kerlingarfjöll (high-Nb versus low-Nb, all subalkaline, metaluminous; Flude et al., 2010), and Thingmuli (high-Fe versus low-Fe, all subalkaline, metaluminous; Charreteur et al., 2013). None of these volcanoes, however, exhibits a monotonic evolution through time from less to more silicic or vice versa (e.g., McGarvie et al., 2006; Flude et al., 2010; Charreteur et al., 2013). At Torfajökull, volcanism was initially peralkaline but shifted to subalkaline and metaluminous after ca. 70 ka. At Kerlingarfjöll, early low-Nb lavas gave way to high-Nb lavas ca. 250 ka. High- and low-Fe magmas erupted at Thingmuli with no discernible correlation between composition and time.

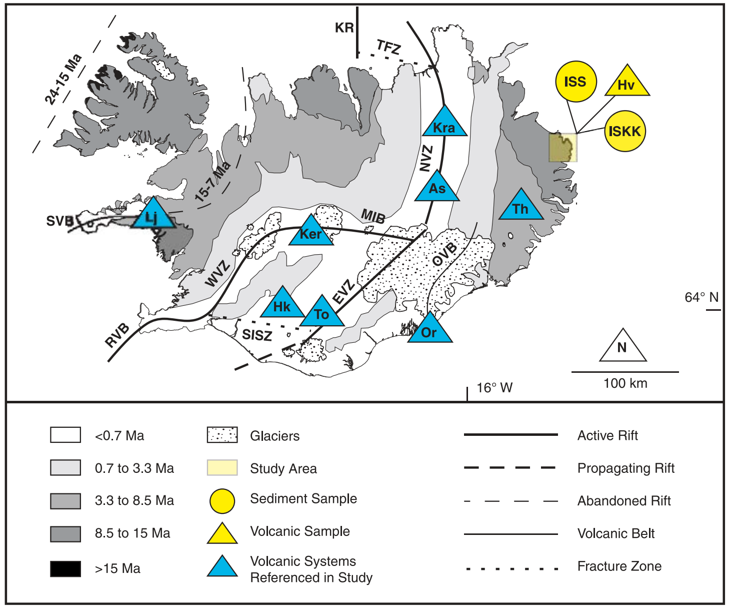


Figure 1. Map of Iceland, including major tectonic features, volcanic systems mentioned in this study, and the general field area and sample locations for this study. Major tectonic features: WVZ—Western Volcanic Zone; EVZ—Eastern Volcanic Zone; NVZ—Northern Volcanic Zone; RVB—Reykjanes Volcanic Belt; KR—Kolbeinsey Ridge; SVB—Snæfellsness Volcanic Belt; OVB—Öræfi Volcanic Belt; SISZ—South Iceland Seismic Zone; MIB—Mid-Iceland Belt; TFZ—Tjörnes Fracture Zone. Volcanic systems: Lj—Ljósufjöll; Ker—Kerlingarfjöll; Hk—Hekla; To—Torfajökull; Or—Öræfajökull; As—Askja; Kra—Krafla; Th—Thingmuli. Field area and samples (general area is the Borgarfjörður eystri); Hv—Hvítserkur, volcanic landform in area; ISS and ISKK—detrital samples. The base map is modified from Thordarson and Hoskuldsson (2002).

Borgarfjörður Eystri: Breiðuvík and Kækjuskörð Silicic Centers

Prior to the ongoing magmatic activity at Torfajökull, the Borgarfjörður eystri region in the northernmost East Fjords was the site of the most voluminous outpourings of silicic magma recognized in Iceland's history (Gustafsson et al., 1989; Johannesson and Saemundsson, 2009; Berg, 2016; Vogler 2014).

Four closely spaced volcanic centers, active ca. 13–12 Ma (Martin et al., 2011), comprise this terrane: Dyrfjoll, Breiðuvík, Kækjuskörð, and Herfell (Fig. 2). The landscape is dominated by pale-colored mountains, reflecting the silicic substrate that constitutes >20% of the region (Berg, 2016; Vogler, 2014; Figs. 3 and 4).

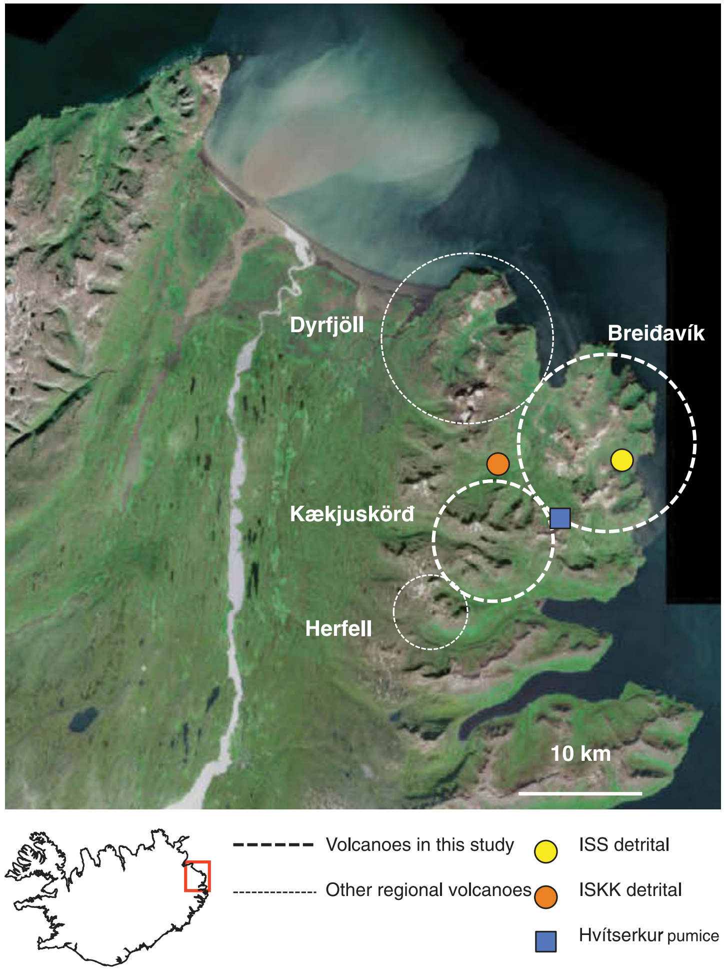


Figure 2. Regional distribution of major volcanic centers in the Borgarfjörður eystri region in the East Fjords of Iceland. Approximate boundaries for discrete centers are from Gustafsson et al. (1989). The aerial photograph of the region was acquired from Landmælingar Íslands.

The concept of a volcanic system as proposed by Walker (e.g., 1958, 1963) for other Icelandic silicic centers is perhaps not strictly applicable in the Borgarfjörður eystri region. Both the size of the silicic region and the abundance of differentiated rocks greatly exceed other localities, except for Torfajökull. Furthermore, the absence of a recognized fissure swarm, which typically characterizes volcanic systems elsewhere (cf. Thordarson and Larsen, 2007), suggests a unique magmatic-tectonic setting for Borgarfjörður eystri. The volcanic systems described by Walker and others farther south in the East Fjords, and elsewhere in Iceland, are thought to have been principally formed in an extensional tectonic environment (Walker, 1958, 1963, 1964, 1966; Gibson and Walker, 1963; Carmichael, 1964). However, the Breiðuvík area may be related to a fracture zone and propagating rift segment of the modern Northern Volcanic Zone (NVZ) (Martin et al., 2011). For these reasons, we use the term volcanic center for each of the volcanic (silicic) sites within the Borgarfjörður eystri region (center < complex < system).

This study focuses on the volcanic centers Breiðuvík and Kækjuskörð. The surface geology in the field area is composed exclusively of extrusive rocks (e.g., Gustafsson et al., 1989; Vogler, 2014); intrusive bodies are not observed, other than the prevalent north-trending regional basalt dikes and high-level dikes crisscrossing the eroded silicic centers (e.g., cone sheets; cf. Dyrfjöll to the northwest; Burchardt et al., 2011). Breiðuvík, the largest of the silicic centers in the Borgarfjörður eystri region, is exposed over ~30 km^2 and is a downsag caldera ~10 km in diameter with estimated subsidence >600 m (Fig. 3; Vogler, 2014). Within this area, silicic rocks constitute as much as 35% of the bedrock; intermediate rocks compose ~15%, and the remaining 50% is basalt (Vogler, 2014). A majority of the silicic rocks are lavas, but the most prominent unit is the large Hvítserkur ignimbrite, which likely filled the Breiðuvík caldera before extensive glacial erosion. Immediately to the west, the smaller Kækjuskörð center also exposes abundant silicic lavas and smaller ignimbrites. These units are overlain by another large (≥5 km^3) ignimbrite (Gustafsson et al., 1989) that likely originated from the nearby Mount Herfell, southwest of Kækjuskörð.

METHODS

Approach: Stream-Sampled Zircon as an Indicator of Longevity and Evolution of Silicic Volcanoes

Detrital zircon from modern sediments provides information about eroded terranes that may be otherwise difficult or impossible to investigate (e.g., Fedo et al., 2003; Moecher and Samson, 2006; Barth et al., 2013). We posit that strategically selected sediment samples from specific, confined, localities, like the flanks of a volcanic edifice, or within the bounds of a caldera, can provide an overview of the magmatic history of a specific volcanic center. A detrital study of this nature lacks the detail that comes with close observations of field relationships and targeted sampling of specific igneous units (e.g., Berg, 2016; Vogler, 2014; Sharman et al., 2015). However, detrital sampling has the benefit

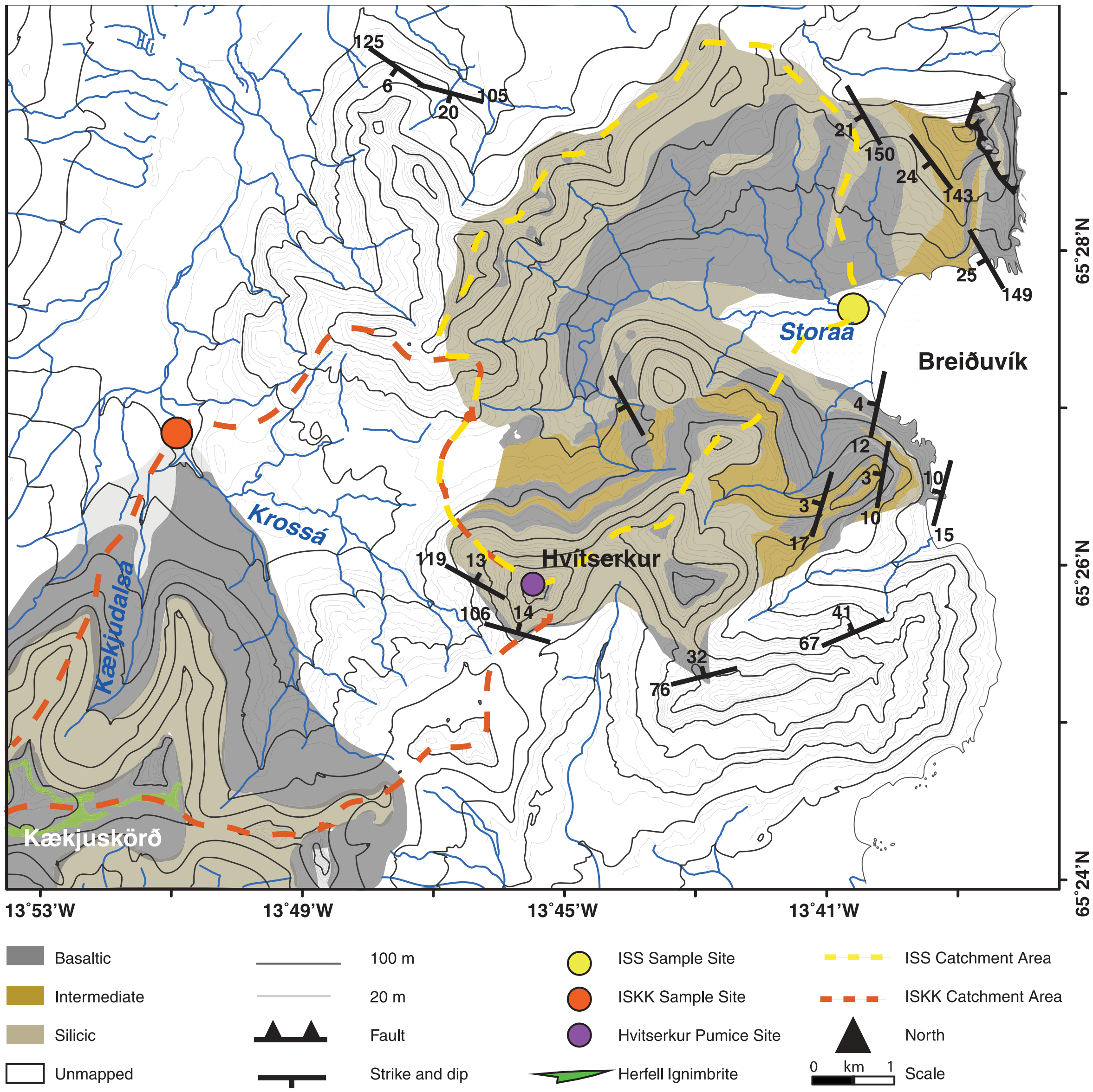


Figure 3. Geologic map of the Breiðuvík-Kækjuskörð field area and sample locations. The geologic map includes rock compositions, local landforms, and important structural features. It was created using the Landmælingar Íslands IS 50V database, Lambert Conformal Conic projection with the ISN 1992 projected coordinate system, and ArcMap10 (modified from Vogler, 2014; Gustafsson et al., 1989). Sample ISS was collected from the Stóraá River at 65°27′45″N, 13°40′32″W. The catchment area for sample ISS is entirely within the recognized extent of the Breiðuvík caldera. Sample ISKK was collected from the confluence of the Krossá and Kækjudalsá Rivers at 65°27′35″N, 13°50′31″W. Its catchment includes prominent peaks from the western edge of the Breiðuvík volcanic center, including Hvítserkur. The ISKK catchment also extends west to include silicic material from the neighboring Kækjuskörð center. A piece of pumice was extracted from a sample of Hvítserkur ignimbrite, collected at 65°25′51″N, 13°45′23″W.

Figure 4. Field area photographs. (A) ISKK sample location indicated with white box. (B) ISS sample location indicated with white box. (C) A close-up view of material collected for sample ISS, from the Stóraá River. (D) Mount Hvítserkur, an ignimbrite peak crosscut by dikes and capped by basalt, is within catchments for both samples ISS and ISKK. An individual piece of pumice was separated from this ignimbrite deposit. The sample location is indicated by the white box.

of minimizing human-introduced biases inherent to sampling in situ rock units (e.g., issues of desirability related to accessibility or alteration and decisions about selecting samples that are unique versus representative). The detrital zircon spectra could be strongly biased toward one or more zircon-rich units in the drainage basin. This overrepresentation is an unavoidable but acceptable risk in a reconnaissance study such as this.

We use trace elements, U-Pb dates, and O and Hf isotopes from detrital zircon sampled in streams that drain large exposures of Breiðuvík and Kækjuskörð to undertake a reconnaissance study of the two volcanic centers. The objectives of this detrital investigation are to: (1) determine if the closely spaced Breiðuvík and Kækjuskörð centers have distinguishable silicic histories; (2) estimate the total lifespan of silicic magmatism at large, extinct, Icelandic volcanoes; (3) investigate the character and evolution of silicic magmas at these volcanoes through time; and (4) evaluate the effectiveness and efficiency of stream sampling and analysis of zircon for resolving the evolution of eroded volcanic centers.

Sampling

Rocks in the Borgarfjörður eystri region have undergone extensive metasomatic alteration by hydrothermal fluids (Vogler, 2014), limiting petrogenetic insight using whole-rock geochemical data. Therefore, we focus our analyses on zircon, a mineral that is generally resistant to hydrothermal alteration (Schmitt and Hulen, 2008; Watts et al., 2011; Bindeman et al., 2012; Milicich et al., 2013; Klemetti et al., 2014).

We collected sand samples (~10 kg each) from two small rivers with drainage basins within the exposures of the Breiðuvík and neighboring Kækjuskörð volcano (Figs. 2 and 3). Sample ISS comes from the Stóraá River, a braided stream with a catchment entirely within the margins of the Breiðuvík caldera. The drainage area upstream of our sampling location encompasses the southern, western, and northwestern sectors of the caldera (>30% of the mapped caldera area). Approximately 50% of the catchment region is composed of silicic material. Sample ISKK was collected at the confluence of the Krossá and Kækjudalsá Rivers. The catchment area includes portions of prominent peaks associated with Breiðuvík (Hvítserkur and Hvítuhnjúkar) and minor exposures of the Herfell ignimbrite, but it is dominated by eruptive units from Kækjuskörð. Sample ISS therefore represents the Breiðuvík area while sample ISKK is more representative of the broader Borgarfjörður eystri region, specifically providing insight into the silicic material exposed at Kækjuskörð.

The catchment areas of the Stóraá and Krossá-Kækjudalsá Rivers drain only Breiðuvík and Kækjuskörð volcanic centers. Glacially derived sediment and modern river sediments in this confined region are locally derived, and assumed to originate only from the two volcanic centers (plus possible contributions from the local Herfell ignimbrite). Therefore, all zircon grains should relate directly to the magmatic history of Borgarfjörður eystri. No younger strata are present to complicate the detrital record. Any contributions from ancient (i.e., pre-Icelandic crustal contributions, e.g., Paquette et al., 2006, 2007; Torsvik et al., 2015) should be detectible by anomalously old zircon ages, high $\delta^{18}O$, or low ε_{Hf} values. Explosive silicic eruptions with extensive tephra distribution are known in Iceland, but we hope that the relative paucity of zircon in a typical Icelandic eruptive unit (e.g., Carley et al., 2011), coupled with aerial fractionation of dense zircon crystals, will minimize zircon contamination of the field area. Any zircon that did not originate in the region of study should be recognized by distinctive ages, ε_{Hf} or $\delta^{18}O$ values.

In addition to river sands, we collected a representative pumice sample from the Hvítserkur ignimbrite within the Breiðuvík caldera. The Hvítserkur ignimbrite is the most prominent eruption product in this area, and we consider this pumice to be a representative whole-rock sample of Breiðuvík magma.

Sample Preparation

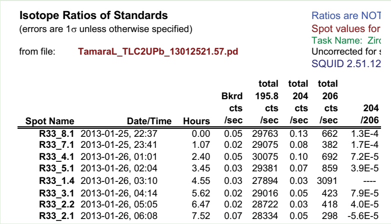
Zircon crystals were separated from river sands (sieved to <500 μm) using density (water and heavy liquid), magnetic, and hand-picking techniques. When hand-picking zircon grains, great care was taken to pick grains indiscriminately, to ensure that the diversity of zircon crystals present in the samples was preserved, without preference given to crystals of a certain size (large or small), shape (euhedral) or condition (e.g., broken, clear or colored). Grains were mounted in epoxy, ground and polished to expose crystal centers, and imaged by cathodoluminescence (CL) using a Tescan Vega 3 LM variable pressure scanning electron microscope at Vanderbilt University (Nashville, Tennessee). These CL images were used to guide ion microprobe and laser ablation analysis spot locations.

A portion (~20 g) of an individual piece of pumice from the Hvítserkur ignimbrite was powdered in an agate mortar and pestle for whole-rock isotope analysis. Another small portion (~20 g) was coarsely crushed using an agate mortar and pestle, and glass was removed by rinsing in concentrated hydrofluoric acid for 30 s at room temperature. Cleaned material was put through the standard density, magnetic, and hand-picking zircon separation steps. Two zircon crystals were found in the Hvítserkur pumice sample. These crystals were mounted, polished, imaged, and analyzed with the detrital zircon grains.

Analytical Methods

U-Pb Geochronology

U-Pb ages were determined for 247 detrital zircon grains (83 from sample ISS and 164 from sample ISKK) using the sensitive high-resolution ion microprobe with reverse geometry (SHRIMP-RG) at Stanford University (Stanford, California). Zircon crystals separated from the Hvítserkur pumice were too



Isotope Ratios of Standards
(errors are 1σ unless otherwise specified)

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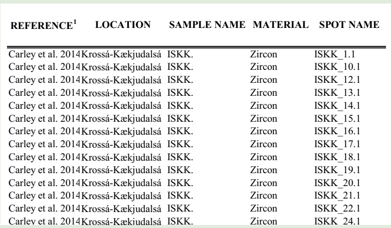
Spot Name	Date/Time	Hours	Bkrd cts /sec	total 195.8 cts /sec	total 204 cts /sec	total 206 cts /sec	204 /206
R33_8.1	2013-01-25, 22:37	0.00	0.05	29763	0.13	662	1.3E-4
R33_7.1	2013-01-25, 23:41	1.07	0.02	29075	0.08	382	1.7E-4
R33_4.1	2013-01-26, 01:01	2.40	0.05	30075	0.10	692	7.2E-5
R33_5.1	2013-01-26, 02:04	3.45	0.03	29381	0.07	859	3.9E-5
R33_1.4	2013-01-26, 03:10	4.55	0.03	27894	0.03	3091	----
R33_3.1	2013-01-26, 04:14	5.62	0.02	29016	0.05	423	7.9E-5
R33_2.2	2013-01-26, 05:05	6.47	0.02	28722	0.03	418	4.0E-5
R33_2.1	2013-01-26, 06:08	7.52	0.07	28334	0.05	298	-5.6E-5

[1]Supplemental Table S1. Zircon U-Pb ages. Please visit http://doi.org/10.1130/GES01467.S1 or the full-text article on www.gsapubs.org to view Table S1.



REFERENCE[1]	LOCATION	SAMPLE NAME	MATERIAL	SPOT NAME
Carley et al. 2014	Krossá-Kækjudalsá	ISKK.	Zircon	ISKK_1.1
Carley et al. 2014	Krossá-Kækjudalsá	ISKK.	Zircon	ISKK_10.1
Carley et al. 2014	Krossá-Kækjudalsá	ISKK.	Zircon	ISKK_12.1
Carley et al. 2014	Krossá-Kækjudalsá	ISKK.	Zircon	ISKK_13.1
Carley et al. 2014	Krossá-Kækjudalsá	ISKK.	Zircon	ISKK_14.1
Carley et al. 2014	Krossá-Kækjudalsá	ISKK.	Zircon	ISKK_15.1
Carley et al. 2014	Krossá-Kækjudalsá	ISKK.	Zircon	ISKK_16.1
Carley et al. 2014	Krossá-Kækjudalsá	ISKK.	Zircon	ISKK_17.1
Carley et al. 2014	Krossá-Kækjudalsá	ISKK.	Zircon	ISKK_18.1
Carley et al. 2014	Krossá-Kækjudalsá	ISKK.	Zircon	ISKK_19.1
Carley et al. 2014	Krossá-Kækjudalsá	ISKK.	Zircon	ISKK_20.1
Carley et al. 2014	Krossá-Kækjudalsá	ISKK.	Zircon	ISKK_21.1
Carley et al. 2014	Krossá-Kækjudalsá	ISKK.	Zircon	ISKK_22.1
Carley et al. 2014	Krossá-Kækjudalsá	ISKK.	Zircon	ISKK_24.1

[2]Supplemental Table S2. Zircon trace elements. Please visit http://doi.org/10.1130/GES01467.S2 or the full-text article on www.gsapubs.org to view Table S2.

Sample	Spot position	N	d18O	1 sigma error	Note
130-02-zrn0c	core	2	3.93	0.13	Gurenko et a
130-02-zrn1r	rim	2	3.42	0.13	Gurenko et a
130-02-zrn2r	rim	1	4.44	0.12	Gurenko et a
130-02-zrn2c	core	1	3.7	0.12	Gurenko et a
130-02-zrn2m	mantle	1	3.28	0.13	Gurenko et a
130-02-zrn3m	mantle	2	2.97	0.13	Gurenko et a
130-02-zrn3c	core	1	3.9	0.13	Gurenko et a
130-02-zrn4c	core	2	2.96	0.15	Gurenko et a
130-02-zrn4m	mantle	1	4.44	0.09	Gurenko et a
130-02-zrn4r	rim	1	5.2	0.1	Gurenko et a
130-02-zrn5r	rim	2	4.53	0.12	Gurenko et a
130-02-zrn5m	mantle	1	3.99	0.12	Gurenko et a
130-02-zrn6c	core	2	3.18	0.12	Gurenko et a
130-02-zrn7m	mantle	1	3.51	0.12	Gurenko et a
130-02-zrn7c	core	1	2.99	0.12	Gurenko et a

[3]Supplemental Table S3. Zircon oxygen isotopes. Please visit http://doi.org/10.1130/GES01467.S3 or the full-text article on www.gsapubs.org to view Table S3.

small for isotopic analysis using the SHRIMP-RG. Analyses were performed using an O_2^- primary ion beam accelerated at 10 kV, with an intensity varying from 5.0 to 6.8 nA. The primary ion beam spot had a diameter between 25 and 28 µm and a depth of ~2–3 µm. This high spatial resolution allowed us to target specific zones within zircon grains, guided by CL images. We preferentially targeted the interiors and rims of grains to capture the oldest and youngest zircon age populations. To efficiently do this assessment of age range, the majority of ages in this detrital study were collected using three scans (peak hopping cycles from mass 188 through 254) per analysis. A subset of ages was collected with five or six scans through the acquisition routine. The uncertainty of the calculated ages measured using the short scans is 2–3 times larger than for long scans. Measurement of U-Pb age standards (R33: 419 ± 1 Ma; Black et al., 2004) were done every 5th analysis for 5 scan data, and every 6th or 7th for the 3 scan data. Data reduction for geochronology follows the methods described by Williams (1997) and Ireland and Williams (2003) and uses the Microsoft Excel add-in programs Squid 2.51 and Isoplot3.76 of Ludwig (2009, 2012). The data are not corrected for ^{230}Th disequilibrium because adjustments to ages would be minor (<0.1 m.y.; within analytical uncertainty). Furthermore, in this detrital context, the necessary Th/U value of the parent melt is unconstrained and would only be an estimate. (Further information can be found in Supplemental Table S1[1].)

Elemental Compositions

Elemental compositions were measured on 69 zircon crystals (32 from sample ISS, 35 from sample ISKK, and 2 from the Hvítserkur pumice) using the SHRIMP-RG. The primary beam energy ranged from ~1.5 to 2.5 nA O_2^- and the analytical spots had a diameter of ~15 µm and sputter depth of ~1 µm. Trace element abundances were calculated relative to those on in-house standard MAD (Madagascar Green zircon; Barth and Wooden, 2010). We used methods following those described in Claiborne et al. (2006, 2010b), and Barth and Wooden (2010). Elemental compositions for Borgarfjörður eystri zircon (ISS and ISKK) were presented by Carley et al. (2014) as part of a larger data set. Because these compositions are very relevant to this study, they are also available in Supplemental Table S2[2].

Oxygen Isotopes

Oxygen isotope analyses were collected from 134 zircon crystals (50 from sample ISS, 83 from sample ISKK, and 1 from the Hvítserkur pumice). Oxygen isotope ratios for Breiðuvík area zircon (ISS and ISKK) were previously included as part of a larger data compilation by Carley et al. (2014). Because these data are highly relevant to this study, they are included in Table 1. Additional information (e.g., analytical session, standards) can be found in Supplemental Table S3[3].

Hf Isotopes in Zircon

Hf isotope compositions were measured for 71 detrital zircon crystals (30 for sample ISS and 41 for sample ISKK) using a Thermo-Scientific Neptune multicollector–inductively coupled plasma–mass spectrometer (MC-ICP-MS) interfaced to a GeoLas 193 laser ablation (LA) MC-ICP-MS, fired for 600 shots at 10 Hz and 5 J/cm^2 during a single analytical session at the Memorial University of Newfoundland (St. John's). Zircon crystals separated from the Hvítserkur pumice were too small for Hf isotope analysis by LA-MC-ICP-MS. The laser ablation pits had a diameter of ~50 µm, with a typical depth of ~45 µm. The Hf isotopic composition of zircon crystals is the last measurement to be collected in the analytical sequence because the ~50 µm spot and the depth of the ablation pit typically accounts for most of the analyzable space on Icelandic zircon crystals, and typically little remains after analysis is complete.

The analytical methods closely followed those of Fisher et al. (2011) and Souders et al. (2012), the only modification being the addition of 4 mL/min of nitrogen gas to improve the sensitivity of the MC-ICP-MS. Reference zircons (cycled between Plešovice, R33, MUNZirc Batch 142 and 144, and FC1) were analyzed from an in-house standard mount after every eight Icelandic zircon unknowns. Results are presented as ε_{Hf} values, which were calculated using the present-day CHUR (chondrite uniform reservoir) $^{176}Hf/^{177}Hf$ ratio of 0.282785 (Bouvier et al., 2008). Further information can be found in Supplemental Table S4[4].

Bulk-Rock Hf Isotopes

The bulk-rock Hf isotopic composition of a single piece of pumice from the Hvítserkur ignimbrite was determined at the Radiogenic Isotope and Geochronology Laboratory (RIGL) at Washington State University (WSU, Pullman), using the RIGL-WSU Thermo Finnigan MC-ICP-MS and following methods described in detail by McDowell et al. (2016). Analytical results were corrected for mass fractionation using $^{179}Hf/^{177}Hf = 0.7325$ and normalized using Hf standard JMC-475 ($^{176}Hf/^{177}Hf = 0.282160$). Further information can be found in Supplemental Table S5[5].

RESULTS

U-Pb Geochronology

The 83 dated zircon grains from sample ISS (Breiðuvík only) have a median age of 12.9 Ma, and a weighted mean age of 13.0 ± 0.1 Ma (mean square of weighted deviates, MSWD = 3.4; Fig. 5). The youngest and oldest individual ages measured in this zircon population are 11.2 ± 0.8 Ma and 14.5 ± 0.4 Ma, respectively (individual age errors are 1σ). The 5 youngest ISS zircon crystals have a weighted mean age of 11.8 ± 0.4 Ma (MSWD = 0.28), while the

TABLE 1. AGE AND ISOTOPE RESULTS

Sample*	Age (Ma)	Age error (1σ)	Age method	$\delta^{18}O$	$\delta^{18}O$ error (1 s.e.)	ε_{Hf}	ε_{Hf} error (2 s.e.)
Hvítserkur Ignimbrite. Location: 65°25′51″N, 13°45′23″W							
Pumice	.	.	.	.	.	15.2[2,†]	0.1
1 (6)	.	.	.	3.6	0.3	.	.
Stóraá River. Location: 65°27′45″N, 13°40′32″W							
2.1 (2)	14.1	0.9	long	3.0	0.4	.	.
2.2 (2)	12.6	0.3	short	.	.	.	.
3.1 (2)	12.7	0.1	long	.	.	.	.
3.2 (2)	12.7	0.5	short	.	.	.	.
4 (2)	12.0	0.8	short	3.1	0.4	.	.
5.1 (2)	12.7	0.2	long	3.4	0.4	15.7	1.1
5.2 (2)	12.8	0.3	short	.	.	.	.
7.1 (2)	13.1	0.3	long	3.2	0.5	15.3	0.7
7.2 (2)	12.0	0.3	short	.	.	.	.
8 (2)	14.1	0.3	short	3.3	0.4	.	.
9 (2)	14.0	1.3	short	2.8	0.4	.	.
10.1 (2)	13.2	0.2	long	2.7	0.4	.	.
10.2 (2)	12.7	0.9	short	.	.	.	.
11 (2)	12.8	0.3	short	3.5	0.4	16.2	0.9
12.1 (2)	12.5	0.5	long	3.2	0.4	.	.
12.2 (2)	11.9	0.5	short	.	.	.	.
13 (2)	13.3	0.5	short	3.4	0.4	13.2	0.9
14.1 (2)	12.5	0.9	long	.	.	14.6	0.9
14.2 (2)	12.2	0.9	short	3.3	0.4	.	.
15.1 (2)	13.1	0.1	long	3.1	0.4	14.1	1.4
15.2 (2)	12.7	0.3	short	.	.	.	.
16 (2)	13.1	0.6	short	3.3	0.4	14.1	1.7
17 (2)	11.2	0.8	short	3.5	0.4	.	.
18.1 (2)	12.5	0.3	long	3.3	0.4	.	.
18.2 (2)	14.0	0.4	short	.	.	.	.
19.1 (2)	12.6	0.6	short	.	.	.	.
19.2 (2)	.	.	.	3.4	0.4	.	.
20 (2)	13.1	0.3	short	3.7	0.4	.	.
21 (2)	12.4	0.5	short	3.2	0.4	.	.
22 (2)	12.7	0.3	short	3.5	0.4	.	.
23 (2)	13.2	0.3	short	3.4	0.4	14.5	0.6
24 (2)	12.4	0.5	short	3.5	0.4		
25 (2)	.	.	.	3.5	0.4	.	.
26 (2)	12.7	0.6	short	3.4	0.4	.	.
27.1 (2)	13.0	0.4	long	.	.	.	.
27.2 (2)	14.3	0.5	short	3.0	0.4	.	.
28 (2)	11.9	0.3	short	3.3	0.4	.	.
29 (2)	12.7	0.4	long	3.4	0.4	16.2	1.5
29 (2)	11.6	0.5	short	.	.	.	.
30.1 (2)	12.5	0.2	long	.	.	.	.
30.2 (2)	13.3	0.4	short	2.8	0.4		
31.1 (2)	12.6	1.5	short	.	.	.	.
31.2 (2)	.	.	.	2.9	0.4	14.7	1.3
32.1 (2)	12.3	0.4	long	3.0	0.4	.	.
32.2 (2)	12.3	0.6	short	.	.	.	.

(*continued*)

TABLE 1. AGE AND ISOTOPE RESULTS (*continued*)

Sample*	Age (Ma)	Age error (1σ)	Age method	δ¹⁸O	δ¹⁸O error (1 s.e.)	ε_{Hf}	ε_{Hf} error (2 s.e.)
Stóraá River. Location: 65°27'45"N, 13°40'32"W							
34.1 (2)	12.8	0.3	long	3.1	0.4	.	.
34.2 (2)	13.0	0.3	short	.	.	.	.
35 (2)	12.9	0.4	short	0.7	0.6	.	.
36.1 (2)	12.9	0.9	short	2.3	0.4	.	.
36.2 (2)	.	.	.	.	.	15.4	0.5
37.1 (2)	14.5	0.4	long	3.2	0.4	.	.
37.2 (2)	13.6	0.5	short	.	.	.	.
38.1 (2)	12.7	0.4	long	.	.	.	.
38.2 (2)	13.0	0.4	short	3.3	0.4	.	.
39.1 (2)	13.1	0.1	long	3.0	0.4	15.4	0.7
39.2 (2)	12.7	0.3	short	.	.	.	.
40 (2)	13.1	0.4	short	3.3	0.4	.	.
41 (2)	13.3	0.6	short	3.1	0.4	.	.
43 (2)	12.4	0.6	short	.	.	.	.
45 (2)	13.3	0.3	short	.	.	13.9	1.1
46 (2)	13.4	0.9	short	.	.	.	.
47 (2)	12.9	0.4	short	.	.	.	.
48 (2)	12.4	0.5	short	.	.	.	.
1 (3)	.	.	.	4.5	0.4	.	.
10 (3)	14.1	0.3	short	.	.	14.5	0.7
11 (3)	12.1	0.2	short	3.1	0.4	14.1	0.6
12 (3)	13.5	0.4	short	3.2	0.4	15.3	1.0
13 (3)	14.1	0.4	short	3.1	0.4	14.7	0.7
14 (3)	.	.	.	3.1	0.4	15.3	2.0
15(3)	13.4	0.4	short	.	.	.	.
16 (3)	12.6	0.5	short	.	.	15.5	0.8
18 (3)	13.8	0.6	short	.	.	15.4	0.9
19 (3)	12.0	0.4	short	.	.	14.8	0.9
2 (3)	12.2	0.2	short	2.8	0.4	.	.
20.1 (3)	13.6	0.8	short	.	.	14.1	0.8
20.2 (3)	12.5	0.2	short	.	.	.	.
21.1 (3)	12.8	0.3	short	.	.	14.2	0.9
21.2 (3)	13.7	0.6	short	.	.	.	.
22 (3)	13.5	0.8	short	.	.	.	.
23 (3)	13.8	0.2	short	.	.	15.0	0.7
3 (3)	12.6	0.2	short	3.0	0.4	15.0	0.8
4 (3)	13.1	0.6	short	3.2	0.4	14.7	1.4
6 (3)	13.2	0.8	short	3.0	0.4	.	.
7 (3)	12.9	1.0	short	2.9	0.4	14.0	1.0
8 (3)	12.2	0.4	short	2.7	0.4	14.3	0.6
9 (3)	14.3	0.2	short	3.0	0.4	16.8	1.9
30 (3)	.	.	.	.	.	14.4	0.8
Krossá and Kækjudalsá Rivers. Location: 65°27'35"N, 13°50'31"W							
1.1 (2)	11.8	0.3	long	.	.	.	.
1.2 (2)	12.8	0.5	short	3.2	0.4	.	.
2 (2)	15.0	0.9	short	3.3	0.4	.	.
3.1 (2)	13.7	0.6	long	.	.	.	.
3.2 (2)	13.0	0.5	short	3.3	0.4	.	.
4 (2)	.	.	.	4.2	0.4	.	.

(*continued*)

TABLE 1. AGE AND ISOTOPE RESULTS (*continued*)

Sample*	Age (Ma)	Age error (1σ)	Age method	$\delta^{18}O$	$\delta^{18}O$ error (1 s.e.)	ε_{Hf}	ε_{Hf} error (2 s.e.)
Krossá and Kækjudalsá Rivers. Location: 65°27'35"N, 13°50'31"W							
5.1 (2)	11.5	0.3	long	.	.	.	.
5.2 (2)	14.0	0.7	short	3.0	0.4	.	.
6 (2)	12.5	0.7	short	3.2	0.4	.	.
7 (2)	10.9	1.8	short	3.2	0.4	.	.
8.1 (2)	12.5	0.1	long	.	.	.	.
8.2 (2)	13.1	0.3	short	1.3	0.6	.	.
9 (2)	12.4	0.6	short	2.4	0.4	.	.
10 (2)	13.4	0.3	short	3.2	0.4	.	.
11.1 (2)	.	.	.	3.2	0.5	.	.
11.2 (2)	.	.	.	.	.	.	.
12 (2)	12.9	0.6	short	3.2	0.4	.	.
13.1 (2)	12.9	0.1	long	.	.	16.2	1.3
13.2 (2)	12.3	0.2	short	.	.	.	.
13.3 (2)	.	.	.	3.1	0.4	.	.
14.1 (2)	13.1	0.3	long	.	.	.	.
14.2 (2)	13.2	0.3	short	3.1	0.4	.	.
15.1 (2)	13.2	0.5	long	.	.	.	.
15.2 (2)	12.8	0.6	short	2.9	0.4	.	.
16 (2)	14.9	0.4	short	1.3	0.4	.	.
17 (2)	13.5	0.3	short	2.7	0.4	.	.
18.1 (2)	12.0	0.2	long	.	.	.	.
18.2 (2)	12.2	0.4	short	2.7	0.4	.	.
19 (2)	12.1	0.3	short	2.6	0.4	.	.
20.1 (2)	12.8	0.2	long	.	.	.	.
20.2 (2)	13.0	0.3	short	2.7	0.4	.	.
21.1 (2)	13.1	0.1	long	.	.	.	.
21.2 (2)	13.2	0.3	short	2.6	0.4	.	.
22 (2)	11.8	1.5	short	2.6	0.4	.	.
23 (2)	13.3	0.3	short	2.7	0.4	.	.
24.1 (2)	13.0	0.2	long	.	.	14.7	1.8
24.2 (2)	12.4	0.3	short	2.7	0.5	.	.
25.1 (2)	12.7	0.4	long			16.3	1.6
25.2 (2)	12.7	1.0	short	2.3	0.4	.	.
26 (2)	12.6	1.0	short	2.3	0.4	.	.
53 (2)	13.0	0.5	short	.	.	.	.
54.1 (2)	13.1	0.3	long	.	.	.	.
54.2 (2)	12.8	0.5	short	.	.	.	.
56.1 (2)	13.7	0.3	short	.	.	.	.
56.2 (2)	.	.	.	.	.	.	.
57 (2)	13.4	0.4	short	.	.	.	.
58 (2)	13.0	0.7	short	.	.	.	.
59 (2)	13.2	0.9	short	.	.	.	.
60 (2)	13.0	0.4	short	.	.	.	.
61.1 (2)	12.8	0.4	long	.	.	.	.
61.2 (2)	12.0	0.7	short	.	.	.	.
62 (2)	13.3	1.1	short	.	.	.	.
63 (2)	11.8	0.5	short	.	.	.	.
64 (2)	12.3	0.5	short	.	.	.	.
65.1 (2)	13.4	0.8	long	.	.	.	.

(*continued*)

TABLE 1. AGE AND ISOTOPE RESULTS (*continued*)

Sample*	Age (Ma)	Age error (1σ)	Age method	$\delta^{18}O$	$\delta^{18}O$ error (1 s.e.)	ε_{Hf}	ε_{Hf} error (2 s.e.)
Krossá and Kækjudalsá Rivers. Location: 65°27'35"N, 13°50'31"W							
65 (2)	13.3	0.3	short	.	.	.	.
66 (2)	13.1	0.3	short	.	.	.	.
67.1 (2)	12.6	0.3	long	.	.	.	.
67.2 (2)	12.0	0.8	short	.	.	.	.
68 (2)	12.5	1.1	short	.	.	.	.
69 (2)	13.5	0.3	short	.	.	.	.
70.1 (2)	12.9	0.2	long	.	.	.	.
70.2 (2)	13.7	0.7	short	.	.	.	.
71 (2)	11.4	0.8	short	.	.	.	.
72 (2)	11.8	0.5	short	.	.	.	.
73 (2)	12.6	0.3	short	.	.	.	.
74 (2)	13.5	0.6	short	.	.	.	.
75 (2)	13.0	0.3	short	.	.	.	.
76 (2)	11.2	0.7	short	.	.	.	.
77 (2)	12.5	0.4	short	.	.	.	.
78 (2)	12.6	1.5	short	.	.	15.2	1.5
80 (2)	12.1	1.1	short	.	.	.	.
81 (2)	12.0	0.4	short	.	.	.	.
82 (2)	14.3	1.0	short	.	.	.	.
83 (2)	12.2	0.9	short	.	.	.	.
84 (2)	12.6	0.5	short	.	.	.	.
10 (6)	.	.	.	3.4	0.3	.	.
11 (6)	.	.	.	3.0	0.3	.	.
12 (6)	.	.	.	3.3	0.3	.	.
13 (6)	.	.	.	3.0	0.4	.	.
14 (6)	.	.	.	3.1	0.3	.	.
15 (6)	.	.	.	3.6	0.3	.	.
16 (6)	.	.	.	3.1	0.3	.	.
17 (6)	.	.	.	3.0	0.3	.	.
18 (6)	.	.	.	2.9	0.3	.	.
19 (6)	.	.	.	3.0	0.3	.	.
2 (6)	.	.	.	3.3	0.3	.	.
3 (6)	.	.	.	2.7	0.3	.	.
4 (6)	.	.	.	3.3	0.3	.	.
5 (6)	.	.	.	3.4	0.3	.	.
6 (6)	.	.	.	3.3	0.3	.	.
7 (6)	.	.	.	3.0	0.3	.	.
8 (6)	.	.	.	3.1	0.3	.	.
9 (6)	.	.	.	2.8	0.3	.	.
1 (4)	12.9	0.2	short	3.4	0.2	14.6	1.3
10 (4)	13.4	1.1	short	3.7	0.2	15.4	1.5
11 (4)	12.2	0.2	short	3.6	0.2	14.7	0.7
12 (4)	14.3	0.7	short	3.2	0.2	.	.
15 (4)	12.6	0.7	short	3.9	0.2	14.6	0.8
13 (4)	12.4	0.4	short	3.7	0.2	15.2	0.7
14 (4)	13.0	0.5	short	3.7	0.2	14.5	0.7
16 (4)	12.9	0.3	short	3.9	0.2	14.5	0.8
17 (4)	12.3	0.6	short	3.5	0.2	14.6	0.8
18 (4)	13.0	0.7	short	3.7	0.2	14.3	1.2

(*continued*)

TABLE 1. AGE AND ISOTOPE RESULTS (*continued*)

Sample*	Age (Ma)	Age error (1σ)	Age method	$\delta^{18}O$	$\delta^{18}O$ error (1 s.e.)	ε_{Hf}	ε_{Hf} error (2 s.e.)
Krossá and Kækjudalsá Rivers. Location: 65°27′35″N, 13°50′31″W							
19 (4)	12.7	0.2	short	3.7	0.2	14.7	1.1
2 (4)	11.4	0.8	short	3.7	0.2	15.1	0.8
20 (4)	13.2	0.7	short	4.0	0.2	.	.
21 (4)	13.4	1.2	short	3.7	0.2	.	.
22.1 (4)	12.4	0.4	short	.	.	.	.
22.2 (4)	.	.	.	3.9	0.2	14.2	1.1
23 (4)	13.8	1.5	short	3.8	0.2	14.1	0.9
24 (4)	13.4	1.1	short	3.9	0.2	.	.
25 (4)	13.2	0.3	short	3.1	0.2	15.5	1.4
26 (4)	13.2	0.1	short	3.6	0.2	15.1	0.8
27 (4)	13.4	1.0	short	3.6	0.1	14.7	0.9
28 (4)	13.6	0.4	short	3.5	0.2	14.7	0.8
29 (4)	12.6	0.4	short	3.6	0.2	14.1	0.7
3 (4)	12.9	0.7	short	3.2	0.2	15.4	1.2
30 (4)	13.7	0.2	short	3.7	0.2	14.0	0.9
31 (4)	13.9	0.2	short	3.5	0.1	14.6	0.9
32.1 (4)	13.3	0.5	short	.	.	.	.
32.2 (4)	.	.	.	3.6	0.2	14.8	0.7
33 (4)	12.2	0.7	short	3.4	0.2	14.9	0.8
34 (4)	13.5	0.5	short	3.7	0.2	.	.
35 (4)	13.0	0.2	short	3.4	0.2	.	.
36 (4)	13.7	0.2	short	3.6	0.2	.	.
37 (4)	12.6	0.5	short	3.6	0.2	14.7	1.1
38 (4)	13.2	0.5	short	3.5	0.2	.	.
39 (4)	13.0	0.9	short	3.5	0.2	14.5	0.8
4 (4)	.	.	.	3.5	0.2	13.1	0.8
5 (4)	12.8	0.3	short	3.6	0.2	14.9	0.9
6 (4)	12.4	0.8	short	3.7	0.2	14.1	0.8
7 (4)	14.2	1.7	short	3.6	0.2	14.0	0.8
8 (4)	13.3	1.5	short	3.5	0.2	.	.
9 (4)	12.7	0.4	short	3.7	0.2	13.4	0.7

Note: s.e.—standard error. Periods in otherwise blank spaces indicate "not measured". long—ages measured using five or six scans through acquisition routine; short—ages measured using three scans (more details can be found in Analytical Methods: U-Pb Geochronology).

*Sample names are as follows: Grain. Specified spot. (mount); so, the name "1.2 (4)" translates to grain 1, spot 2, mount 4. Spots are only indicated where necessary for indicating multiple spots on individual grains; otherwise only grain and mount are reported.

†ε_{Hf} value reported for Hvitserkur pumice is for a whole-rock isotope analysis. All other data reported in this table are for analyses conducted on zircon.

oldest 5 ISS crystals had a weighted mean of 14.3 ± 0.3 Ma (MSWD = 0.17). The calculated errors for weighted means do not account for MSWD values; the MSWD values are interpreted to reflect scatter in the age of the zircon population and not analytical error.

The 164 dated zircon crystals from sample ISKK (primarily Kækjuskörð drainage, partially Breiðuvík) have a median age of 12.9 Ma and a weighted mean age of 12.9 Ma ± 0.1 (MSWD = 3.1). The youngest and oldest individual zircon crystals are 11.2 ± 0.7 Ma and 15.0 Ma ± 0.9, respectively, while the weighted means of the youngest and oldest 5 grains are 11.3 ± 0.7 Ma (MSWD = 0.04) and 14.7 ± 0.6 Ma (0.23), respectively.

Elemental Compositions

Elemental compositions of detrital zircon grains from Breiðuvík-Kækjuskörð are highly variable, but define a coherent population. The most obvious characteristics generally reflect those of magmatic zircon. They are highly enriched in heavy rare earth elements and Y relative to light rare earth elements; have relatively large positive Ce anomalies and relatively moderate negative Eu anomalies (Fig. 6); and they have very high Hf, U, and Th concentrations (e.g., Hoskin and Schaltegger, 2003; Claiborne et al., 2006, 2010b; Grimes et al., 2007, 2015; Carley et al., 2014; Fig. 7; Table S2 [see footnote 2]).

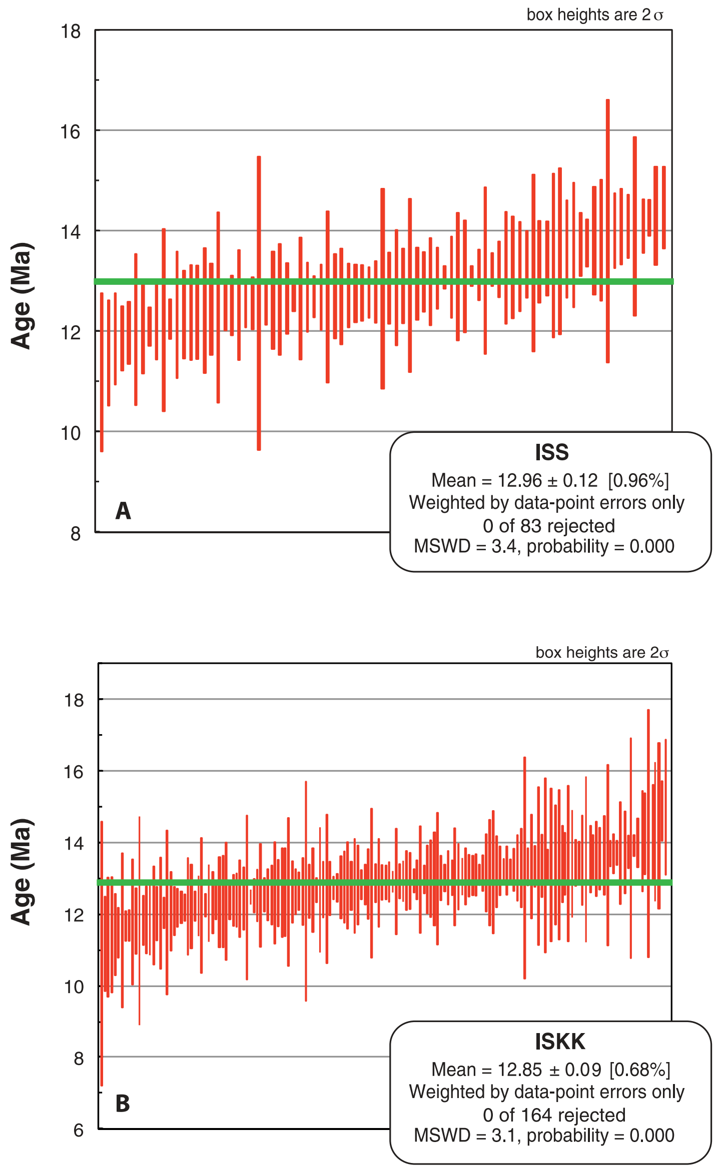


Figure 5. Zircon ages are presented on weighted mean plots (MSWD—mean square of weighted deviates). Weighted means for each sample are represented by green lines (ISS: 12.96 Ma; ISKK: 12.85 Ma). (A) Results for ISS (n = 83). (B) Results for ISKK (n = 164).

Rare earth element concentrations vary by a factor of 10–100 (La 0.1–10 × chondrite, Lu 10^3-10^4 × chondrite), but patterns are very similar between the two samples (Fig. 6). Likewise, U and Th are high and quite variable (~20–1000 ppm and 10–1100 ppm, respectively; Fig. 7), with U concentrations covarying with Th (Th/U = 0.25–1.5) and Nb (~4–400 ppm).

The concentrations of Hf in Breiðuvík-Kækjuskörð zircon crystals range from 7000 to 14,000 ppm, and correlate negatively with Ti (Fig. 8), which has concentrations of 4–36 ppm. Hf and Ti concentrations define two populations: ~60% of the analyses have Hf >10,000 ppm and Ti <10 ppm, while the rest have Hf <10,000 ppm and Ti >10 ppm. The wide range of Ti suggests crystallization at variable temperatures (Watson and Harrison, 2005; Ferry and Watson, 2007). The median (7.5 ppm) and mean (10.8 ppm) of Ti are relatively high by global standards but somewhat lower than average for Iceland (Fu et al., 2008; Carley, 2014).

Oxygen Isotopes

The ISS zircon population (n = 50) has $\delta^{18}O$ values that range from 0.7‰ ± 0.6‰ to 3.7‰ ± 0.4‰ (errors are 1σ), with a median value of 3.1‰ and a weighted mean of 3.1‰ ± 0.1‰ (MSWD = 0.77; Fig. 9). The 5 ISS analyses

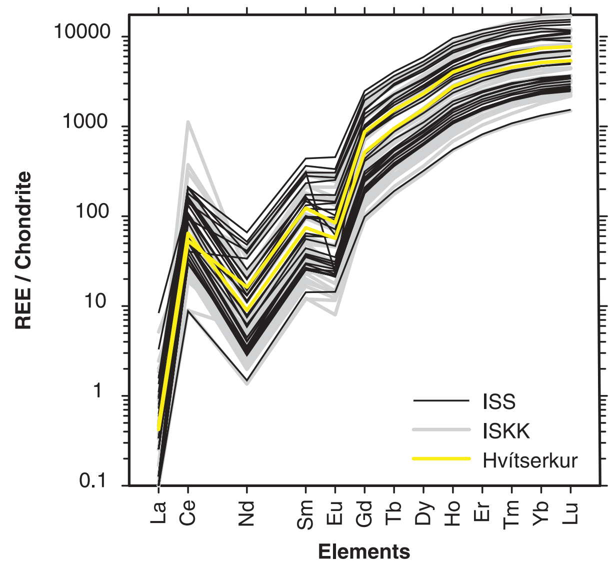
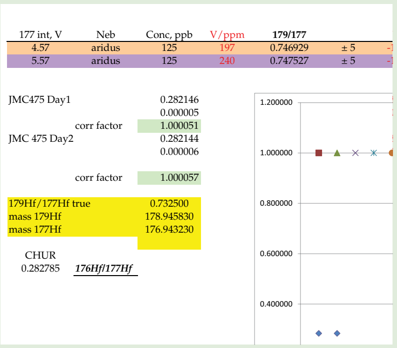


Figure 6. Zircon rare earth elements (REE)/chondrite. Results for ISS (n = 31), ISKK (n = 32), and IEHv (Hvítserkur pumice; n = 2) REEs normalized to chondrite values from McDonough and Sun (1995).

File	Sample ID	$^{176}Hf/^{177}Hf$	2SE	$^{176}Lu/^{177}Hf$	2SE	$^{176}Yb/^{177}Hf$
13je11a37	b144	0.282143	0.000041	0.013512	0.000031	0.270461
13je11a69	b144	0.282098	0.000044	0.014613	0.000059	0.293779
13je11a81	b144	0.282155	0.000033	0.010586	0.000029	0.209506
13je11b03	b144	0.282101	0.000029	0.011802	0.000056	0.236892
13je11b38	b144	0.282135	0.000029	0.010157	0.000003	0.202037
13je12a03	b144	0.282128	0.000023	0.010073	0.000009	0.197426
13je12a28	b144	0.282090	0.000042	0.014684	0.000061	0.288586
13je12B03	b144	0.282069	0.000039	0.014819	0.000036	0.295544
13je12b35	b144	0.282132	0.000037	0.014961	0.000035	0.290697
13je12c10	b144	0.282063	0.000053	0.013181	0.000009	0.251617
13je12c16	b144	0.282127	0.000038	0.012884	0.000002	0.250565
	mean	*0.282113*				
	2SD	*0.000061*				

[4]Supplemental Table S4. Zircon hafnium isotopes. Please visit http://doi.org/10.1130/GES01467.S4 or the full-text article on www.gsapubs.org to view Table S4.



177 int, V	Neb	Conc, ppb	V/ppm	179/177	
4.57	aridus	125	197	0.746929	± 5
5.57	aridus	125	240	0.747527	± 5

JMC475 Day1		0.282146
		0.000005
	corr factor	1.000051
JMC 475 Day2		0.282144
		0.000006
	corr factor	1.000057
179Hf/177Hf true		0.732500
mass 179Hf		178.945830
mass 177Hf		176.943230
CHUR		
0.282785	*176Hf/177Hf*	

[5]Supplemental Table S5. Bulk rock hafnium isotopes. Please visit http://doi.org/10.1130/GES01467.S5 or the full-text article on www.gsapubs.org to view Table S5.

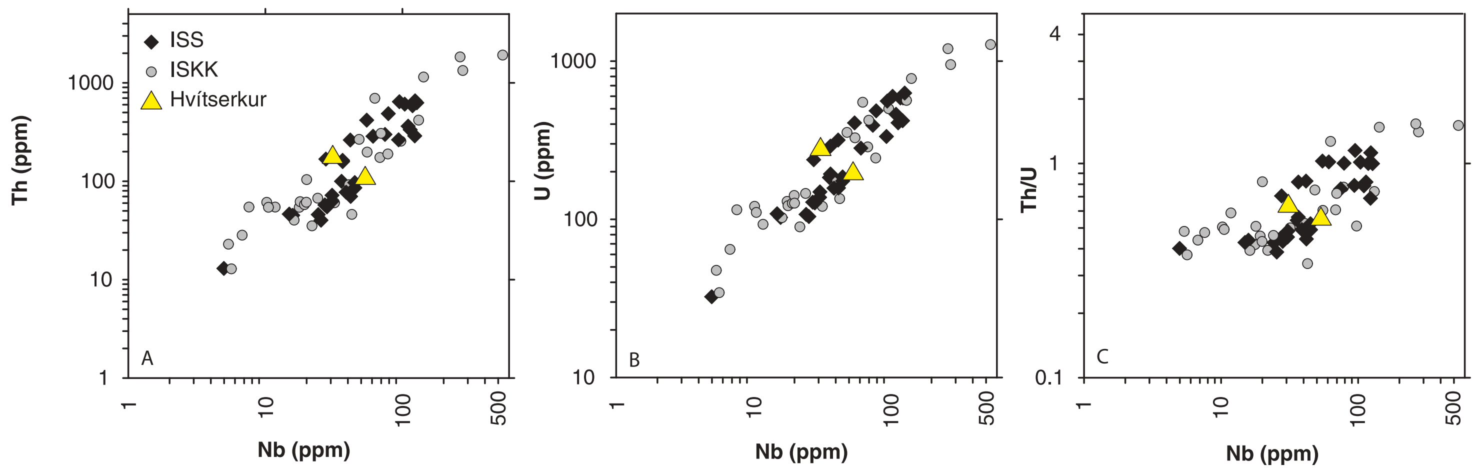


Figure 7. Zircon trace element results for ISS (n = 31), ISKK (n = 32), and IEHv1c (Hvítserkur pumice) (n = 2) for elements U, Th, and Nb.

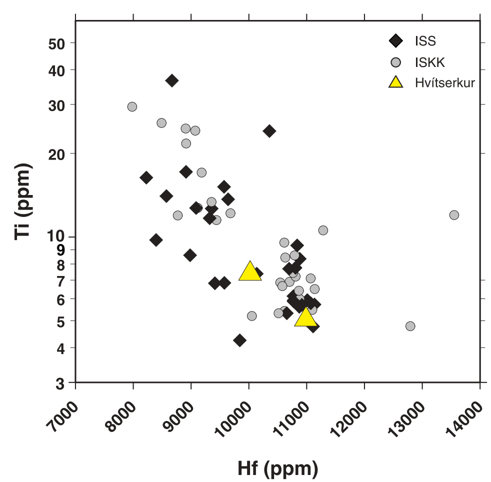


Figure 8. Zircon Ti versus Hf results for ISS (n = 31), ISKK (n = 32), and Hvítserkur (n = 2).

with the lowest $\delta^{18}O$ values have a weighted mean of 2.4‰ ± 0.02‰ (MSWD = 2.8); the 5 highest analyses have a weighted mean of 3.5‰ ± 0.4‰ (MSWD = 0.03). The $\delta^{18}O$ of ISKK zircon (n = 83) ranges from 1.3‰ ± 0.6‰ to 4.2 ± 0.4‰, with a median value of 3.3‰ and a weighted mean of 3.5‰ ± 0.1‰ (MSWD = 2.1). The weighted mean for the 5 lowest values is 2.1‰ ± 0.8‰ (MSWD = 2.4); for the 5 highest values, the weighted mean is 3.9‰ ± 0.2‰ (MSWD = 0.15).

These oxygen values are consistent with the range of 1.1‰–4.7‰ reported by Berg (2016) for Borgarfjörður Eystri; they are significantly lower than whole-rock analyses of devitrified ignimbrite from the Borgarfjörður eystri region (Martin and Sigmarsson, 2010; Berg, 2016). The heavier oxygen signatures in the bulk rock samples are probably a consequence of post-eruptive, low-temperature, metasomatic alteration of the devitrified ignimbrite. The discrepancy in $\delta^{18}O$ demonstrates the inherent complications in O isotope analyses of altered whole-rock samples, and emphasizes the robustness of zircon in recording the primary magmatic conditions (Valley, 2003).

Hf Isotopes (Zircon and Bulk Rock)

The range of ε_{Hf} for the ISS zircon population (n = 31) is +13.2 ± 0.5 to +16.8 ± 1.0 (1 σ standard error). The 31 analyses have a median ε_{Hf} of 14.7 and weighted mean of 14.8 ± 0.3 (MSWD = 2.8; Fig. 10). The 5 analyses with the lowest ε_{Hf} have a weighted mean of 13.9 ± 0.4 (MSWD = 0.68), and 16.2 ± 0.5 (MSWD = 0.47) for the 5 highest analyses.

The 42 Hf analyses done on sample ISKK zircon grains have a minimum ε_{Hf} value of 14.7 ± 1.1, a maximum of 16.3 ± 1.6, and a median of 14.7. The zircon grains analyzed have a weighted mean of 14.6 ± 0.2 ε_{Hf} (MSWD = 1.9). The 5 analyses with the lowest ε_{Hf} have a weighted mean of 13.6 ± 0.4 (MSWD = 0.9) and 15.8 ± 0.5 (MSWD = 0.39) for the 5 highest analyses.

A high-precision solution analysis of the Hvítserkur pumice yielded a bulk-rock ε_{Hf} value of 15.1 ± 0.1 (1σ).

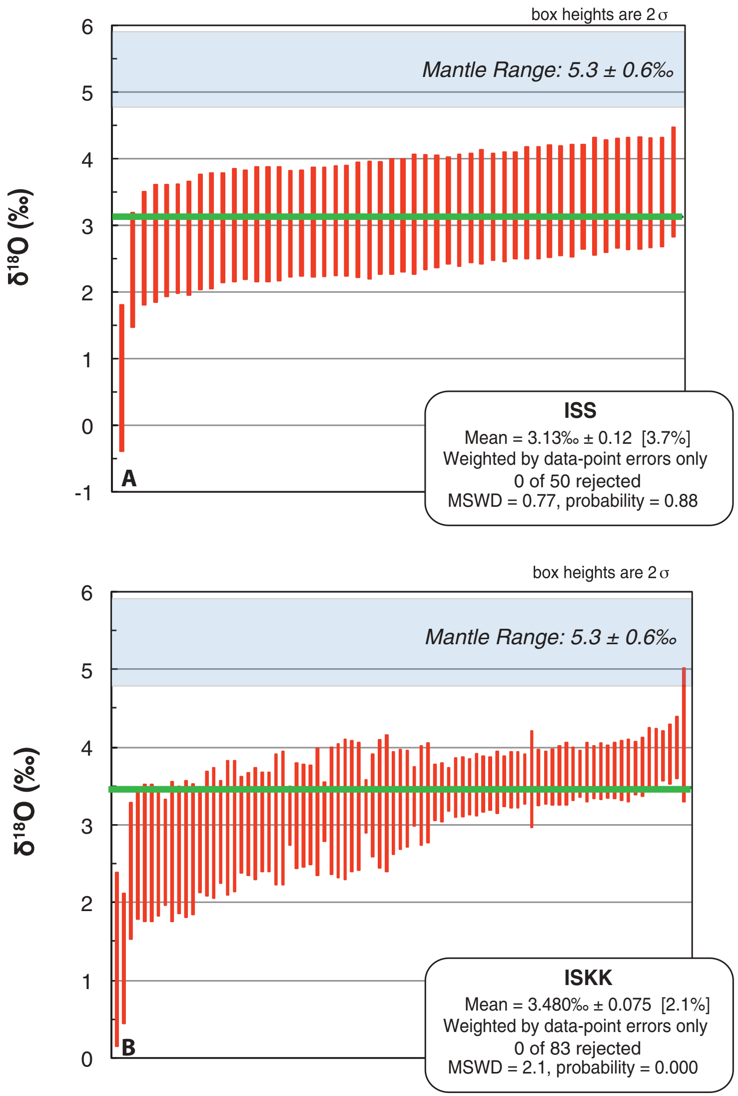


Figure 9. Zircon oxygen isotope results (MSWD—mean square of weighted deviates). (A) ISS (n = 50). (B) ISKK (n = 83). Weighted means are represented by a green line on each plot (ISS: 3.13 $\delta^{18}O$; ISKK 3.48 $\delta^{18}O$). The estimated ranges of $\delta^{18}O$ for zircon equilibrated with mantle-derived magmas are indicated by the gray bars (5.3‰ ± 0.6‰; Valley, 2003; cf. mid-ocean ridge zircon, 5.3‰ ± 0.8‰ and 5.2‰ ± 0.5‰, reported by Cavosie et al., 2009, and Grimes et al., 2011, respectively).

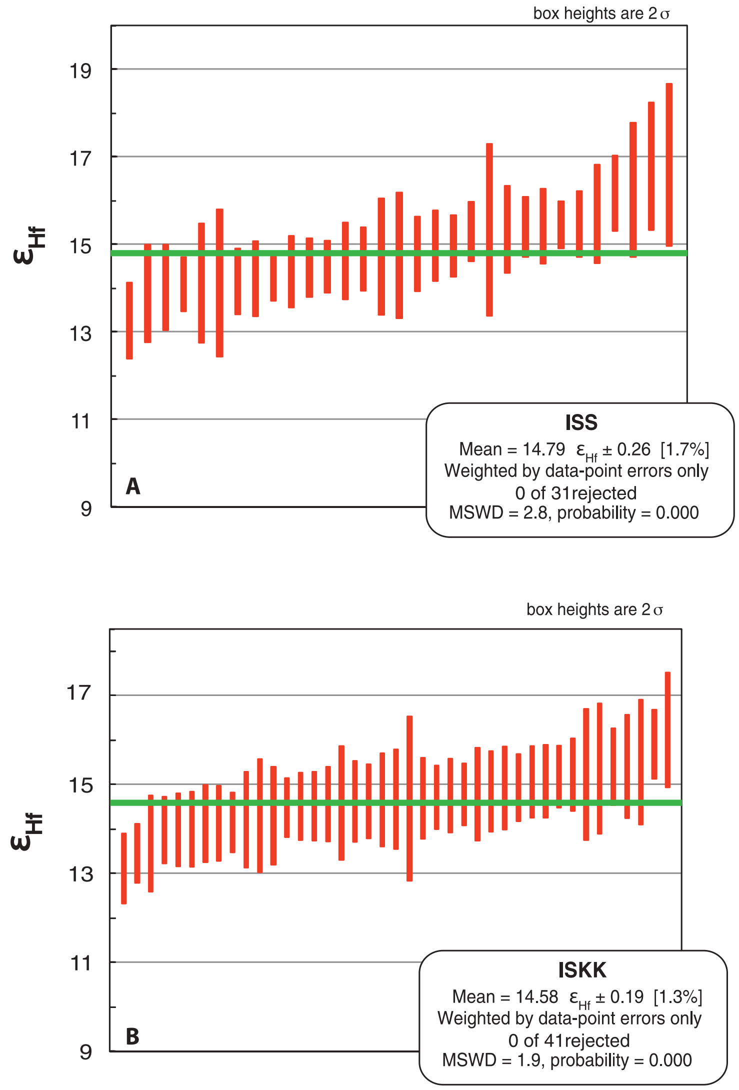


Figure 10. Zircon Hf isotopes (MSWD—mean square of weighted deviates). (A) ISS (n = 31). (B) ISKK (n = 41). Weighted means represented by a green line on each plot (ISS 14.79 ± 0.26 ε_{Hf}; ISKK 14.58 ± 0.19 ε_{Hf}).

DISCUSSION

Comparison of Breiðuvík and Kækjuskörð

Similarities in zircon populations from samples ISS (Breiðuvík) and ISKK (mostly Kækjuskörð, contributions from Breiðuvík) suggest that zircon from these two closely spaced volcanic centers shared similar magmatic histories in terms of source rock, magmatic processes, and timing of magmatic activity and zircon crystallization. Both samples are zircon rich compared to other Icelandic volcanic and detrital samples (e.g., Carley et al., 2011, 2014; Carley, 2014). For ISS and ISKK, the weighted means of age (13.0 ± 0.1 Ma versus 12.9 ± 0.1 Ma) and Hf isotopes (14.8 ± 0.3 ε_{Hf} versus 14.6 ± 0.2 ε_{Hf}; Fig. 11) are within error of one another, and they are also very similar in weighted mean of $\delta^{18}O$ (3.1‰ ± 0.1‰ versus 3.5‰ ± 0.1‰).

Similarities between ages, O isotopes, and Hf isotopes in zircon populations from samples ISS and ISKK were quantified using Kolmogorov-Smirnov (K-S) testing (Fletcher et al., 2007). In a K-S test, populations are considered to be subsamples from the same distribution as long as the probability values (P) are >0.05. In the case of Breiduvik-Kækjuskörð, the K-S tests yielded high probabilities of similarity between samples ISS and ISKK for age (P = 1.00), O isotopes (P = 0.31) and Hf isotopes (P = 0.95). Other statistical tests (e.g., cross-correlation coefficient, similarity coefficient, and likeness coefficient; Saylor and Sundell, 2016) lead essentially to the same conclusion. Although K-S testing reveals striking similarities between zircon populations from these two drainages, there is no discernible correlation between Hf or O and age (Fig. 12).

Despite the fact that the detrital zircon samples represent mixed populations of volcanic phenocrysts, which potentially include antecrysts and xenocrysts, they define a coherent range of ε_{Hf} and $\delta^{18}O$ compositions, notable when compared to those for other Icelandic systems (Fig. 13). However, the statistical overlap in ages and isotopic compositions between ISS and ISKK suggests that zircon from these two volcanic centers were sourced from a system or systems that generated silicic magmas from the same or similar source rocks, influenced by similar modification processes in the crust, during the same prolonged period (discussed in the Geochemical Character, Petrogenesis, and Evolution of Silicic Magmas at Breiðuvík-Kækjuskörð section). Furthermore, the weighted means for ε_{Hf} for ISS (14.8 ± 0.3) and ISKK zircon (14.6 ± 0.2) are within 2σ error of the bulk-rock ε_{Hf} of Hvítserkur pumice (15.1 ± 0.1), which supports the interpretation that detrital zircon crystals provide a robust representation of the system that produced these volcanoes.

Lifespan of Silicic Magmatism at Breiðuvík and Kækjuskörð

Published ages for the Borgarfjörður eystri region range from 13.5 to 12.1 Ma (Berg, 2016; Martin et al., 2011; cf. Paquette et al., 2006, 2007). The difference between these ages is within the 0.5–1.5 m.y. age range that is typically

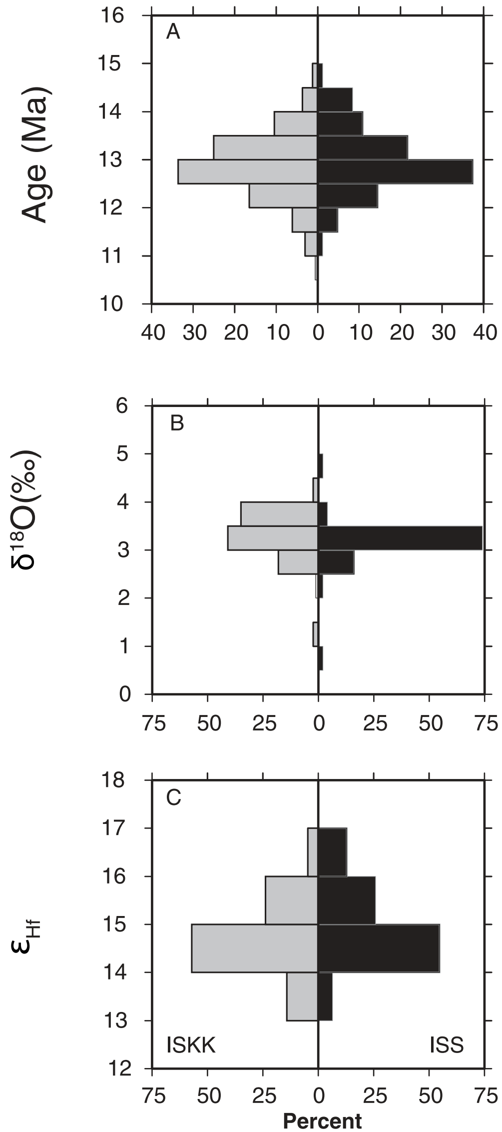


Figure 11. Comparison of ISS and ISKK ages and isotopes. Histograms are presented side by side to demonstrate the similarities between zircon from samples ISS and ISKK in ages (n = 83 for ISS, n = 164 for ISKK), O isotopes (n = 50 for ISS, n = 83 for ISKK), and Hf isotopes (n = 31 for ISS, n = 41 for ISKK). Bin width for each set of histograms is scaled to approximate a typical analytical error (U-Pb = 0.5 m.y., 1σ; $\delta^{18}O$ = 0.5‰, 1σ; ε_{Hf} = 1, 2σ). Errors associated with each individual analysis can be found in Figures 5, 9, 10, and 12 (ages, O, Hf, and ages versus isotopes, respectively).

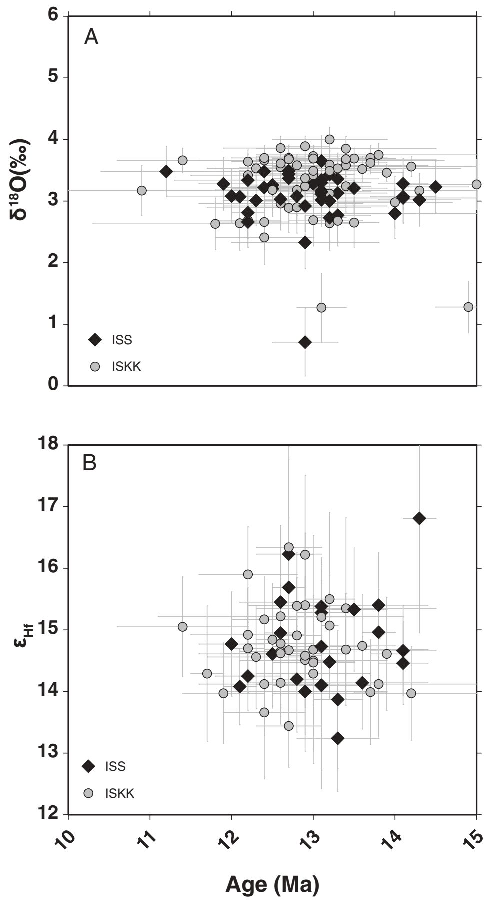


Figure 12. Zircon O and Hf isotopes compared to time. (A) Oxygen ($\delta^{18}O$) results for sample ISS (n = 44) and ISKK (n = 59). (B) Hafnium (ε_{Hf}) results for sample ISS (n = 26) and sample ISKK (n = 39). Error bars are 1σ for age and $\delta^{18}O$ and 2σ for ε_{Hf}. Individual data points and their errors are available in Table 1.

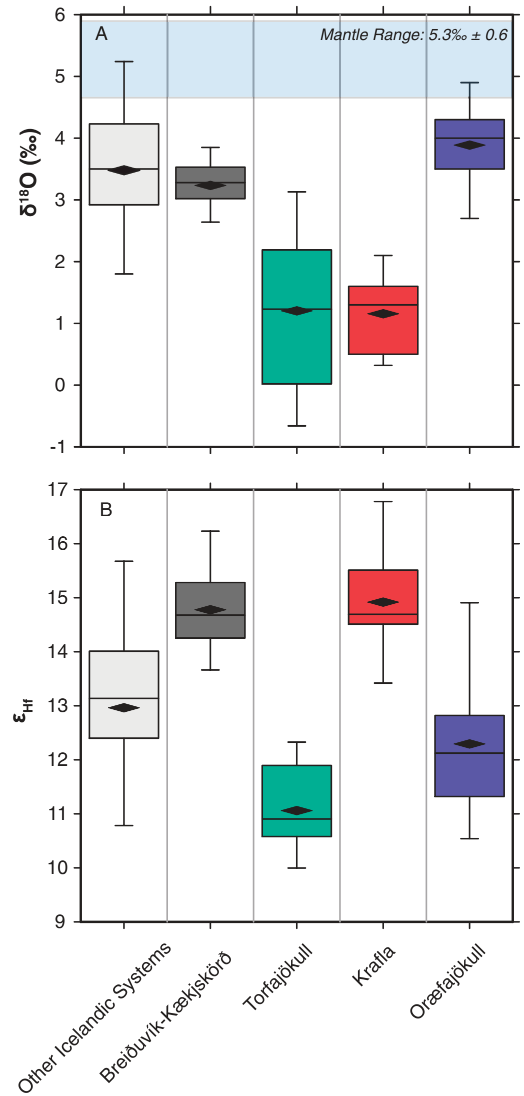


Figure 13. Isotopic compositions of Breiðuvík-Kækjuskörð compared to other Icelandic systems. (A) The $\delta^{18}O$ of ISS and ISKK zircon are compared to Torfajökull (n = 65), Krafla (n = 25), Öræfajökull (n = 16), and other Icelandic zircon (n = 699; Bindeman, 2008; Carley et al., 2014; Gurenko et al., 2015). The range of $\delta^{18}O$ for mantle zircon (Valley et al., 1998; Valley, 2003) is included for reference. (B) ISS and ISKK ε_{Hf} compared to modern systems: Torfajökull (n = 25), Krafla (n = 10), Öræfajökull (n = 13), and other Icelandic zircon (n = 211; Supplemental Table S3 [see footnote 3]; Carley, 2014). In A and B, the boxes represent the middle 50% (25th to 75th percentile) of data for each population. The line bisecting each box represents the median, and the black diamonds represent mean values. Error bars reflect the 2σ standard deviation after excluding outliers. The Iceland category does not include analyses from Breiðuvík-Kækjuskörð, Torfajökull, Krafla, or Öræfajökull.

associated with the lifespan of a volcanic system in Iceland. However, this detrital study reveals U-Pb zircon ages from Breiðuvík-Kækjuskörð that range from ca. 15.0 to 11.2 Ma, suggesting a substantially longer period of magmatism during which zircon crystallized (Figs. 5, 11, 12, 14, and 15; Tables 1 and 2).

To assess the implications of the spread of dates obtained in our data set, we first evaluate whether the wide range of measured ages reflects error-based scatter. The MSWD value for $^{206}Pb/^{238}U$ ages is 3.4 for ISS (83 analyses) and 3.1 for ISKK (164 analyses). These high MSWD values preclude the possibility of a single age population of zircon (Mahon, 1996). Thus, we infer that the range of

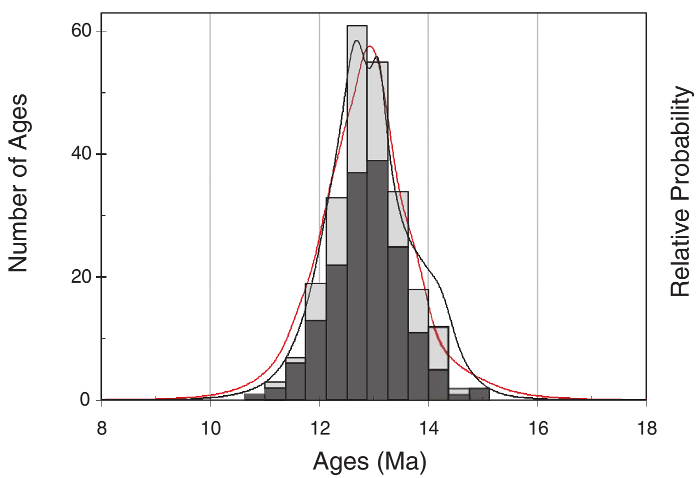


Figure 14. Distribution of zircon ages. Sample ISS zircon ages (n = 83) are presented with the dark gray histogram and the red probability density curve. Sample ISKK zircon ages (n = 164) are presented with the light gray histogram and black probability density curve. Both populations show a prominent peak ca. 13 Ma.

zircon ages within each sample reflects a prolonged magmatic history during which zircon growth occurred. The continuous spread in ages (Figs. 5 and 15) could reflect (1) nearly continuous zircon growth within an evolving magmatic system; or (2) multiple episodes of punctuated, short-lived zircon growth (e.g., Bindeman and Melnik, 2016) that are shorter than the analytical precision of individual analyses. The analytical limitations of the current data set prevent us from confidently ruling out either alternative.

To quantify the longevity of the zircon-saturated history of this magmatic system (whether punctuated or continuous), we first combine ages for samples ISS and ISKK to achieve a greater n value, and thus a more statistically robust data set. This tactic is justified by isotopic similarities in age and other isotopes (Fig. 11; Table 2). Similar to the individual samples, the combined zircon population has a weighted mean age of 12.9 ± 0.1 Ma (MSWD = 3.2, n = 247) and a probability density curve that closely resembles a normal distribution (Fig. 15).

The longevity suggested by this combined zircon population may be >3 m.y., or more conservatively ≥2.8 m.y., depending on the approach used to evaluate the observed spread of ages. The absolute difference between the minimum (11.2 ± 0.7 Ma) and maximum (15.0 ± 0.9 Ma) ages for individual zircon crystals yields a lifespan of 3.8 ± 1.1 m.y. Limiting consideration to measured ages with analytical precision <0.5 m.y., the difference between the high-precision minimum (11.5 ± 0.3 Ma) and maximum (14.9 ± 0.4 Ma) is 3.4 ± 0.5 m.y. The difference between weighted mean ages for the 5 oldest and 5 youngest ages in our combined data set supports an age span of 3.4 ± 0.9 m.y. The time captured by two standard deviations (1.4 m.y.) about the

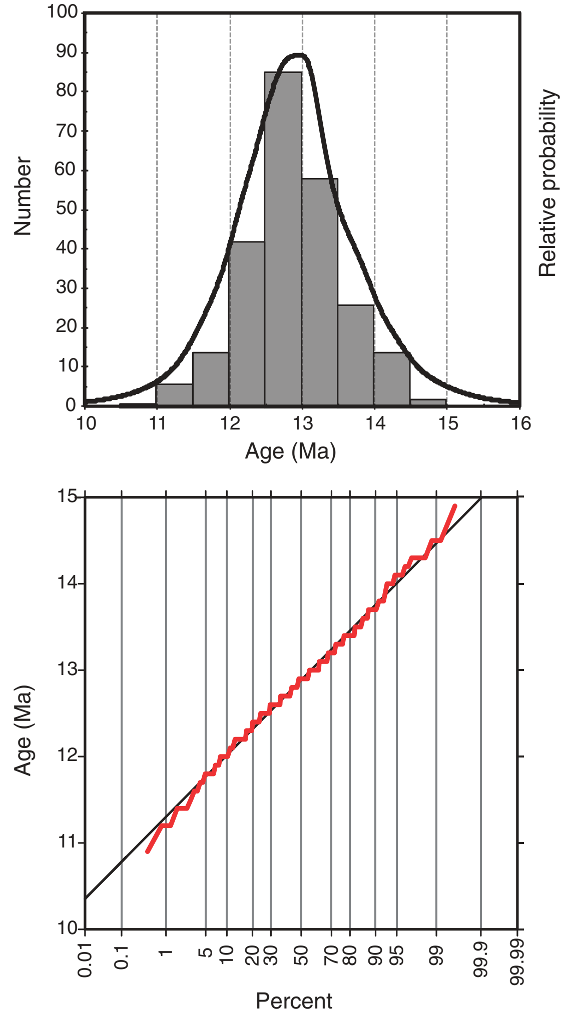


Figure 15. Combined ISS and ISKK zircon ages. (A) A histogram of ages for the combined ISS and ISKK zircon sample population (n = 243), with bin width set to 0.5 m.y. (average error, 1σ); (B) The diagonal black line indicates where data points would plot if the ages of ISS and ISKK zircon displayed a perfect normal distribution. The red line shows the distribution of true measured ages for samples ISS and ISKK, indicating that normal distribution is a fair way to characterize this population (an important consideration in establishing parameters for Monte Carlo modeling).

mean (12.9 Ma) of the combined ISS and ISKK data set is ≥2.8 m.y., the most conservative assessment of magmatic longevity in this study.

Whether the detrital zircon ages from eroding volcanic terranes at Breiðuvík-Kækjuskörð represent a record of continuous or punctuated zircon saturation,

TABLE 2. MONTE CARLO MODELING

Window of time (centered on the mean)	Number of times sampling exercise repeated (NN)	Probability of not finding an age exceeding the defined window of time	Statement of outcome: "If we were to repeat the exercise of collecting and analyzing n zircons NN times, there is a…"
Sample size (n) = 83 (ISS sample size)			
10 m.y.	100	1.00	100% chance that we would not find a zircon with a measured age outside the mean ±5 m.y.
	100	1.00	
5.6 m.y. (4σ) (4 standard deviations)	100	0.70	75% chance that we would not find a zircon with a measured age outside the mean ±2.8 m.y.
	100	0.70	
	1000	0.75	
4.2 m.y. (3σ)	100	0.34	30% chance that we would not find a zircon with a measured age greater than the mean ±2.1 m.y. (3σ); 70% chance that we would find zircons with a measured age exceeding a 4.2 m.y. window about the mean.
	100	0.33	
	100	0.30	
	100	0.27	
	100	0.31	
	1000	0.29	
3 m.y.	100	0.04	2% chance that we would not find a zircon with a measured age greater than the mean ±1.5 m.y.; 98% chance that we would find zircons with an age exceeding the 3 m.y. window about the mean age.
	100	0.02	
	100	0.20	
Sample size (n) = 247 (ISS + ISKK sample size)			
10 m.y.	100	1.00	100% chance that we would not find a zircon with a measured age outside the mean ±5 m.y.
	100	0.98	
	100	0.99	
5.6 m.y. (4σ)	100	0.48	42% chance that we would not find a zircon with a measured age outside the mean ±2.8 m.y.
	100	0.41	
	1000	0.41	
4.2 m.y. (3σ)	100	0.01	3% chance that we would not find a zircon with a measured age greater than the mean ± 2.1 m.y. (3σ); 97% chance that we would find zircons with a measured age exceeding the 4.2 m.y. window about the mean.
	100	0.05	
	100	0.00	
	1000	0.03	

Note: Sample ISS represents the Breiðuvík area; sample ISKK represents the Borgarfjörður eystri region, Iceland.

the ≥2.8 m.y. history convincingly documents greater longevity than has been previously recognized in Iceland. The previously proposed maximum lifetime of an Icelandic volcanic system (≥1.5 m.y.) has essentially been doubled (e.g., Saemundsson, 1979; Jakobsson, 1979; Thordarson and Larsen, 2007).

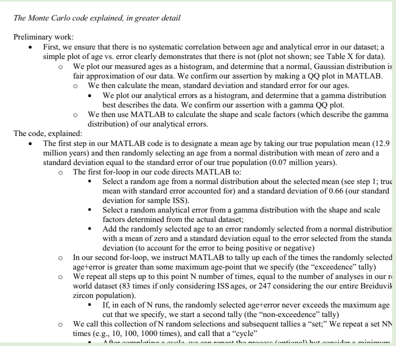
To evaluate the confidence that we can place in this estimated duration of silicic magmatic activity at Breiðuvík-Kækjuskörð, we performed Monte Carlo modeling in MATLAB (https://www.mathworks.com/). In our modeling, we theoretically replicate our detrital zircon sampling and dating by randomly selecting ages and errors from within their respective distributions (in this case, normal distribution for ages, gamma distribution for errors). We tested sample sizes of 83 and 247 based on the number of ages we measured for the individual sample ISS and for the combined ISS and ISKK samples, respectively. These simulations were repeated many times (i.e., 100× , 1000×). Modeling results are summarized in Table 2, and details of our procedures are described in Supplemental Item S1[6].

Using Monte Carlo modeling to emulate our sampling and dating of sample ISS (n = 83), we determine that if we were to repeat this study with a similar sample size there is a 97% likelihood that we would find a zircon that exceeds a 3 m.y. time span about the mean age (13.0 Ma). In revisiting the sampling of all dated Breiðuvík-Kækjuskörð zircon (ISS + ISKK, n = 247), we find that there is a 98% likelihood that we would find a zircon that exceeds a 3 m.y. time span about the mean age (13.0 Ma). Therefore, the Monte Carlo model supports the assessment that the age span captured by zircon at Breiðuvík-Kækjuskörð is ≥2.8 m.y.

Our results suggest that Breiðuvík-Kækjuskörð detrital zircon grains document a longer magmatic history than has been reported for any other Icelandic volcanic system. Zircon-saturated silicic activity likely spanned an interval of ≥2.8 m.y., from ca. 14.5 to 11.5 Ma. While crystallization was active throughout this prolonged interval of time, the majority of zircon growth likely occurred during a shorter window of time that better aligns with previous estimates of Icelandic volcano longevity: an interval of 1.4 m.y. (2σ standard deviations) centered around the mean age of 13 Ma.

Does the Lifespan of Silicic Magmatism Equate with the Lifespan of the Volcanic Center?

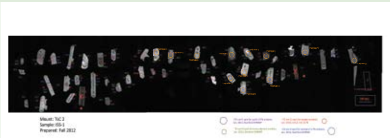
We contend that our data provide a useful estimate of longevity of the silicic portion of the Breiðuvík-Kækjuskörð system, but this does not necessarily imply that we have defined the lifetime of the system as a whole. Two possi-


The Monte Carlo code explained, in greater detail

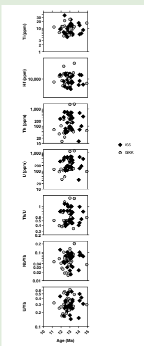
Preliminary work:
- First, we ensure that there is no systematic correlation between age and analytical error in our dataset; a simple plot of age vs. error clearly demonstrates that there is not (plot not shown; see Table X for data).
  - We plot our measured ages as a histogram, and determine that a normal, Gaussian distribution is fair approximation of our data. We confirm our assertion by making a QQ plot in MATLAB.
  - We then calculate the mean, standard deviation and standard error for our ages.
    - We plot our analytical errors as a histogram, and determine that a gamma distribution best describes the data. We confirm our assertion with a gamma QQ plot.
  - We then use MATLAB to calculate the shape and scale factors (which describe the gamma distribution) of our analytical errors.

The code, explained:
- The first step in our MATLAB code is to designate a mean age by taking our true population mean (12.9 million years) and then randomly selecting an age from a normal distribution with mean of zero and a standard deviation equal to the standard error of our true population (0.07 million years).
  - The first for-loop in our code directs MATLAB to:
    - Select a random age from a normal distribution about the selected mean (see step 1; true mean with standard error accounted for) and a standard deviation of 0.66 (our standard deviation for sample ISS).
    - Select a random analytical error from a gamma distribution with the shape and scale factors determined from the actual dataset;
    - Add the randomly selected age to an error randomly selected from a normal distribution with a mean of zero and a standard deviation equal to the error selected from the standa deviation (to account for the error to being positive or negative)
  - In our second for-loop, we instruct MATLAB to tally up each of the times the randomly selected age+error is greater than some maximum age-point that we specify (the "exceedence" tally)
  - We repeat all steps up to this point N number of times, equal to the number of analyses in our r world dataset (83 times if only considering ISS ages, or 247 considering the our entire Breiduvik zircon population).
    - If, in each of N runs, the randomly selected age+error never exceeds the maximum age cut that we specify, we start a second tally (the "non-exceedence" tally)
  - We call this collection of N random selections and subsequent tallies a "set;" We repeat a set NN times (e.g., 10, 100, 1000 times), and call that a "cycle"

[6]Supplemental Item S1. Monte Carlo MATLAB. Please visit http://doi.org/10.1130/GES01467.S6 or the full-text article on www.gsapubs.org to view Item S1.



[7]Supplemental Item S2. Zircon CL images. Please visit http://doi.org/10.1130/GES01467.S7 or the full-text article on www.gsapubs.org to view the Item S2.



[8]Supplemental Item S3. Zircon compositions versus time. Please visit http://doi.org/10.1130/GES01467.S8 or the full-text article on www.gsapubs.org to view Item S3.

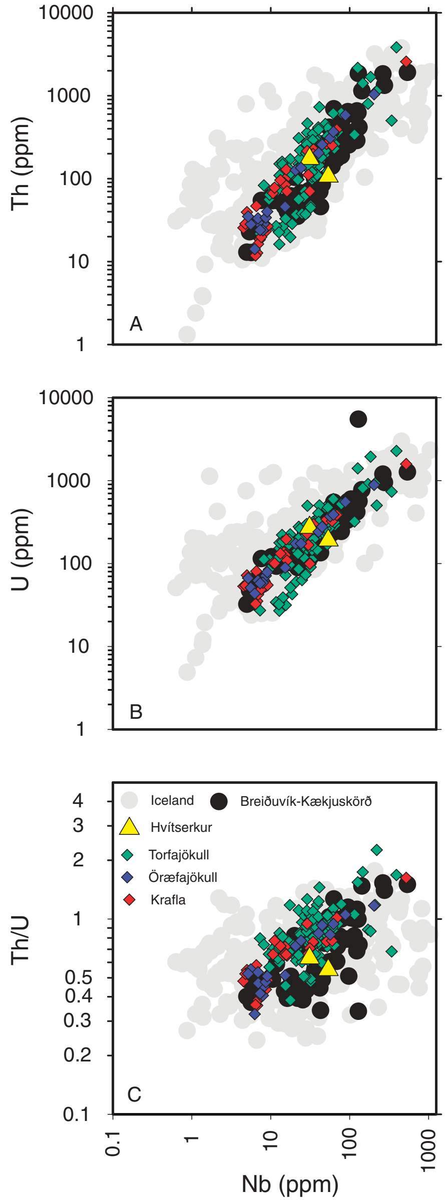


Figure 16. Zircon elemental compositions in an Icelandic context. U, Th, and Nb in Breiðuvík-Kækjuskörð zircon (ISS + ISKK, n = 63) and the Hvítserkur ignimbrite (n = 2) are compared to zircon from modern silicic systems: Torfajökull (n = 104), Krafla (n = 30), and Öræfajökull (n = 23). Zircon from other systems across Iceland are also considered (n = 583; see Carley et al., 2014; Supplemental Item S2; see footnote 7).

ble complications are evident: (1) basaltic magmatism may have been more protracted than silicic magmatism, initiating earlier and/or terminating later, but left no recognizable zircon record; or (2) the eruptive portion of the Breiðuvík-Kækjuskörð history may have been shorter than suggested by the zircon record if a prolonged period of silicic intrusion preceded the first eruptions.

We consider the first possibility (prolonged basaltic magmatism) to be likely. In Iceland and other basalt-dominated provinces where volcanic systems also produce silicic magma, dominantly or entirely mafic eruptions tend to give way late in a center's history to mixed or dominantly silicic eruptions (see following discussion, "Breiðuvík-Kækjuskörð in a Global Context"). This is consistent with the inference that silicic magmatism in these settings is either a consequence of mafic magma undergoing extreme fractionation, or mafic magma prompting anatexis of basalt-heated crust.

The second possibility (zircon captures a long intrusive but short eruptive history) is also plausible. It is common for antecrystic zircon to crystallize early in plutonic portions of systems, before entrainment in later eruptive events (e.g., Charlier et al., 2005; Claiborne et al., 2010a; Schmitt et al., 2011). However, we doubt that this could account for a substantial portion of the ≥2.8 m.y. history of zircon ages observed at Breiðuvík-Kækjuskörð. Documented examples of erupted antecrysts are rarely more than a few hundred thousand years older than the eruption in which they reached the surface. Furthermore, the zircons in this study do not have characteristics that suggest growth and storage in a plutonic environment and subsequent entrainment. They are typically small and acicular (<~150 µm long) with simple zoning, and few or none show evidence of resorption (Supplemental Item S2[7]).

Geochemical Character, Petrogenesis, and Evolution of Silicic Magmas at Breiðuvík-Kækjuskörð

Breiðuvík-Kækjuskörð zircon compositions are variable but within the established elemental and isotopic range of Icelandic zircon (Figs. 13, 16, and 17; Carley et al., 2014). Similarities reveal that Breiðuvík-Kækjuskörð magmas broadly share petrogenetic origins with those generated throughout Iceland's history. Elemental and isotopic compositions of Breiðuvík-Kækjuskörð zircon show no discernible change through time (Fig. 12; Supplemental Item S3[8]), suggesting negligible changes in petrogenesis of silicic magmas over the long history of the centers, in terms of either sources or magma evolution.

The wide range in zircon trace element concentrations, including an abundance of relatively low Ti, high Hf analyses that cluster near the most evolved end of the Iceland range, suggests considerable fractionation of the zircon-saturated host magmas (Fig. 16; cf. Carley et al., 2014; Grimes et al., 2015; Claiborne et al., 2006, 2010b). Time independence of compositions, however, suggests repeating cycles of fractionation rather than a continuing monotonic process (see Supplemental Item 3 [footnote 8]).

Narrow ranges of ε_{Hf} and $\delta^{18}O$ indicate little variability in source materials that contributed to the Breiðuvík-Kækjuskörð magmas. At ~+15, ε_{Hf} for

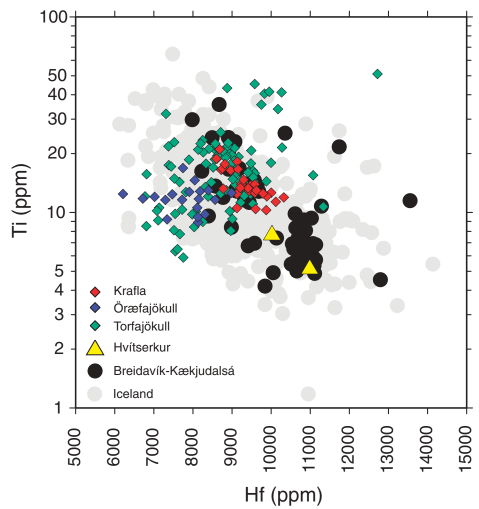


Figure 17. Zircon elemental compositions in an Icelandic context. Ti and Hf in Breiðuvík-Kækjuskörð zircon (ISS + ISKK, n = 63) and the Hvítserkur ignimbrite (n = 2) are compared to zircon from modern silicic systems: Torfajökull (n = 104), Krafla (n = 30), and Öræfajökull (n = 23). Zircons from other systems across Iceland are also considered (n = 583; see Carley et al., 2014; Supplemental Item S2; see footnote 7).

Breiðuvík-Kækjuskörð zircon is above average among Icelandic volcanic zircon (Fig. 13; Carley, 2014). This ε_{Hf} is, however, typical of rift zone basalts and matches closely values for basalts of similar age from this region (Eastern Iceland rift zone; Kitagawa et al., 2008; Peate et al., 2010). These high ε_{Hf} values indicate that the Breiðuvík-Kækjuskörð magmas were derived from a depleted mantle source that was more similar to the sources of mid-oceanic ridge basalt and Iceland rift basalts than to the relatively enriched mantle proposed for Icelandic off-rift-axis basalts and rhyolites. The tight clustering of $\delta^{18}O$ values near the Icelandic zircon median of +3.2‰ (Carley et al., 2014) suggests that either the source material was mildly, yet uniformly, hydrothermally altered crust, or that parental magmas were uniformly contaminated by more highly altered crustal material (cf. Carley et al., 2014; Padilla et al., 2016).

The compositional similarities of zircon from both Breiðuvík and Kækjuskörð volcanic centers, and their identical age distributions, strongly suggest a common magmatic and volcanic origin. It is likely that Breiðuvík and Kækjuskörð together are part of a single volcanic complex (center < complex < system).

Silicic Magmas in the Breiðuvík-Kækjuskörð Complex Compared to those in Active Icelandic Volcanic Systems

Zircon compositions from three active systems, Krafla, Öræfajökull, and Torfajökull, are compared to the extinct Breiðuvík-Kækjuskörð complex (Figs. 1, 13, 16, and 17). Krafla is an active volcanic system situated on the actively rifting Northern Volcanic Zone (Fig. 1). Öræfajökull had the most voluminous explosive eruption of notably homogeneous silicic magma in Iceland's recorded history, in A.D. 1362 (Thorarinsson, 1958; Larsen et al., 1999; Selbekk and Tronnes, 2007; Sharma et al., 2008). Its explosivity and homogeneity prompt a comparison with Breiðuvík-Kækjuskörð. Torfajökull is included in the comparison as the only system in Iceland that has erupted as much or more silicic material than the Borgarfjörður eystri region, which includes Breiðuvík and Kækjuskörð (Gustafsson et al., 1989; Johannesson and Saemundsson, 2009; Berg, 2016; Vogler, 2014).

The $\delta^{18}O$ values of Breiðuvík-Kækjuskörð zircons are within a narrow range (~3.5‰–4‰) relative to those from Krafla (~0.5‰–2‰), Öræfajökull (~2.5‰–5‰), and Torfajökull (~0.5‰–3‰; Fig. 13). This coherency indicates little variability in the contributions of altered crustal source materials to the Breiðuvík-Kækjuskörð magmas throughout the long (likely ≥2.8 m.y.) history of the complex relative to the three modern systems. The lighter oxygen signature at both Krafla and Torfajökull (Fig. 13) suggests a greater influence of altered crustal material at these active rift zone volcanoes than at Breiðuvík-Kækjuskörð.

The ε_{Hf} of Breiðuvík-Kækjuskörð zircon grains (ε_{Hf} ~13.5–16.5) are among the highest Hf isotope values yet discovered for Icelandic zircon (Fig. 13), similar only to zircon from Krafla (ε_{Hf} ~13.5–17). These two zircon populations, which share a connection with the Northern Volcanic Zone, are markedly more radiogenic than those of Torfajökull (ε_{Hf} ~10–12) and Öræfajökull (ε_{Hf} ~10.5–15; Figs. 1 and 13). Torfajökull is situated on the propagating Eastern Volcanic Zone and Öræfajökull is on the off-rift Öræfi Volcanic Belt (Fig. 1).

Elemental compositions reveal that the crystallization conditions of zircon at Breiðuvík-Kækjuskörð, while not unusual for Icelandic systems, differ in detail from those at the active systems in this comparison. For similar Nb concentrations, Breiðuvík-Kækjuskörð zircons tend to have lower values of Th/U than those from Torfajökull, Krafla, or Öræfajökull (Fig. 16). Breiðuvík-Kækjuskörð zircon compositions also differ from the three active systems in extending to markedly higher Hf (suggestive of more highly fractionated magmas) and lower Ti (indicating lower crystallization temperatures) (Figs. 16 and 17; Carley et al., 2011, 2014).

Breiðuvík-Kækjuskörð in a Global Context

The estimated lifespan of silicic magmatism at Breiðuvík-Kækjuskörð is consistent with eruptive durations reported for silicic magmas in systems dominated by basalt elsewhere on Earth. Well-constrained estimates for individual systems range from ~1 to 3 m.y. (Steens–Columbia River–Yellowstone, USA, large rhyolite caldera systems; e.g., Christiansen 1984; Coble and Mahood 2012, 2016; Benson and Mahood, 2016; Karoo rhyolites; e.g., Riley et al., 2004; and Yemen rhyolites; I.U. Peate et al., 2005). Silicic volcanic rocks in these systems are commonly interbedded with basalt, but increase in abundance toward the upper part of the volcanic sections (e.g., Pankhurst et al., 2011). Basalt-rhyolite sequences in Iceland follow a similar pattern, with silicic volcanism appearing, and often dominating, the late eruptive sequence at systems such as Krafla (Jónasson, 1994), Hekla (Sigmarsson et al., 1992; Sverrisdottir, 2007), Kerlingarfjöll (Flude et al., 2010), and Thingmuli (Charreteur et al., 2013). Despite this similar temporal relationship between basalt and rhyolite in mafic-dominant provinces, this study of Breiðuvík-Kækjuskörð is the first to suggest a longevity for Icelandic magma systems that is comparable to those that are typical globally.

CONCLUSIONS

A focused detrital zircon study, as presented here for Breiðuvík-Kækjuskörð, is a powerful approach for illuminating a comprehensive history of silicic magmatism at an individual volcanic center or in a focused eruptive region. This is particularly true when the nuanced details provided by individual eruptive units and their relationships are not critical to the regional-scale history. This detrital approach combats sampling bias (e.g., limiting numbers of samples for analytical practicalities, preferentially selecting samples that are easily accessible) that might otherwise obscure important chapters of a system's history and general geochemical characteristics. Furthermore, this sampling technique is essentially nondestructive to the natural landscape, and it is effective and efficient for understanding the magmatic underpinnings of the geology of a drainage basin (particularly when measured results are further corroborated by modeling, such as with the Monte Carlo approach to assessing age heterogeneity exercised in this study). A focused detrital accessory mineral approach to investigating silicic systems has widespread applicability. It can be applied globally in locations where rocks have undergone pervasive alteration, where accessibility is a barrier (particularly for systems that are remote, rugged, or obscured by glacial ice), or where silicic histories are overwhelmed in dominantly basaltic terranes (e.g., ocean islands, flood basalt provinces).

Constraining the longevity of Icelandic volcanoes has important implications for better understanding rhyolitic centers that are active, and potentially hazardous. Before now, the approximate lifetime of Icelandic volcanic systems was estimated to be 0.5–1.5 m.y. (Saemundsson, 1979), based on K-Ar dating and correlation with the paleomagnetic time scale. Zircon geochronology adds precise, robust age data to Iceland's geologic record that was not achievable by earlier methods. Extinct silicic complexes such as Breiðuvík-Kækjuskörð provide a lifecycle perspective that is unachievable with volcanic systems that are still active today. With a zircon record that captures ≥2.8 m.y. of silicic activity, we demonstrate that Breiðuvík-Kækjuskörð underwent magmatic activity longer than has ever been previously reported for an Icelandic volcano. It also establishes that Icelandic volcanoes are capable of achieving magmatic longevity comparable to other long-lived silicic systems in otherwise mafic settings, such as Karoo (Pankhurst et al., 2011) and Yemen (I.U. Peate et al., 2005).

If Breiðuvík-Kækjuskörð is representative of silicic systems in Iceland, it is important that we recalibrate our assessment of magmatic lifespans in Iceland. If Breiðuvík is unique in Iceland, it begs the question, why is Breiðuvík-Kækjuskörð different from typical silicic systems in Iceland, and does its unique nature (including its longevity) explain the great concentration of silicic magma found in the region?

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