On the recent bimodal magmatic processes and their rates in the Torfajökull–Veidivötn area, Iceland

G.F. Zellmer a,b,⁎, K.H. Rubin a, K. Grönvold c, Z. Jurado-Chichay a

a Department of Geology and Geophysics, SOEST, University of Hawaii at Manoa, 1680 East West Road, Honolulu, HI 96822, USA
b Institute of Earth Sciences, Academia Sinica, 128 Academia Road, Sec. 2, Nankang, Taipei 11529, Taiwan, ROC
c Volcanological Institute, University of Iceland, IS-101, Reykjavík, Iceland

A R T I C L E   I N F O

Article info
Article history:
Received 14 November 2007
Received in revised form 13 February 2008
Accepted 14 February 2008
Available online 4 March 2008
Editor: R.W. Carlson

Keywords:
U-series disequilibrium
petrogenesis
rhyolite volcanism
rift zone
crustal melting

A B S T R A C T

Historical bimodal composition eruptions spanning Torfajökull central volcano and neighbouring Veidivötn fissure swarm in southeastern Iceland provide clues about the nature and timing of basalt and rhyolite petrogenesis and eruption at an active divergent plate boundary. This study focuses on lavas and tephras of the last two regional eruptions in 871 and 1477 AD, using samples that approximate mafic and felsic endmember compositions relative to regional mixing trends in literature data from the area. Whole rock and mineral U-Th-Ra isotopic compositions demonstrate both rapid petrogenetic timescales and limited compositional variation in the basalt and rhyolite magma sources. Rhyolites display the greatest 230Th excesses (≤17%) at only slightly lower (230Th/232Th) activity ratios than co-eruptive Veidivötn basalts. Both magma types display small but significant 230Th–Ra excesses (≥10% and ≤60% in rhyolites and basalts, respectively). U-series isotopic and trace element data are consistent with crustal melting dominated by young (≤60 kyr), K-metasomatized mafic protoliths similar in composition to the Veidivötn tholeiites as source of the 871 and 1477 rhyolites. Young protolith ages are inconsistent with published models that call on old materials as source rocks for Icelandic rhyolites (e.g., old, silicic segregation lenses or isostatically subsided lavas). Zero-age U-Th and few-ka Ra-Th mineral-whole rock isochrons indicate that crystals formed shortly prior to eruption, consistent with petrographic and compositional indicators that they are phenocrysts, and suggest that the rhyolite melts are of Late Holocene age.

© 2008 Elsevier B.V. All rights reserved.

1. Introduction

1.1. Icelandic bimodal volcanism

The combined effects of divergent plate boundary and hot spot volcanism have produced a thick basaltic crust in Iceland, contributing to one of few examples of extensive oceanic rhyolite volcanism. Icelandic volcanism tends to be compositionally bimodal, which raises several fundamental questions about how evolved magmas are created from their mafic source compositions, the duration of the process, and why rhyolitic volcanism is common at some Icelandic volcanoes yet not at others.

Hypotheses for silicic magma petrogenesis in Iceland include near-liquidus (crystal fractionation ± assimilation) and near-solidus (crustal melting) processes, and proposed differentiation processes may vary according to the local tectonic setting. Multiple authors have favored extensive (up to 90%) fractional crystallization of basaltic magmas (Carmichael, 1964; Macdonald et al., 1990; Lacasse et al., 2007), sometimes with concurrent crustal assimilation or contamination (Nicholson et al., 1991) to form the rhyolites. However, while significant quantities of intermediate composition magmas erupt at some sites (especially at Hekla, Sigvaldason, 1974), they are generally rare in Iceland (e.g., Walker, 1966; Saemundsson, 1978). Dramatic shifts in magmatic 18O in the most felsic Icelandic lavas imply meteorically altered crust in their petrogenesis (Muehlenbachs et al., 1974). Hence, many previous authors have suggested that rhyolites are predominantly generated by partial crustal melting of unaltered or hydrothermally altered old crustal basalts (O’Nions and Grönvold, 1973; Sigvaldason, 1974; Hémond et al., 1988; Sigmarsson et al., 1991; Jónasson, 1994; Lacasse et al., 2007; Martin and Sigmarsson, 2007), or their silicic differentiation products (Sigurdsson, 1977; Gunnarsson et al., 1998).

Contemporaneous eruption of basalts and rhyolites has been a prominent manifestation of Icelandic bimodal volcanism during postglacial times. Since the 1975–1984 Krafla fires fissure eruption (e.g., Björnsson et al., 1977), lateral magma flow between central volcanoes and neighbouring fissures swarms has been considered a common attribute of eruptions within “volcanic systems” (e.g., Saemundsson, 1978) along the divergent plate boundary. Examples of rhyolite-producing central volcanoes with associated basaltic fissure eruptions include Askja volcano and Sveagjá fissures (Sigurðsson and Sparks, 1978a,b), Grímsvötn volcano and Laki fissures (cf. Bindeman et al., 2006), and Katla volcano and Eldjá fissures (cf. Lacasse et al., 2007). Basaltic magma injection as a trigger of the 1875
Askja plinian rhyolite eruption was explored by Sparks et al. (1977, 1981). A similar mechanism was later proposed for the rhyolitic eruptions at Torfajökull central volcano and nearby Veidivötn basaltic fissures eruptions, with the twist that basaltic magmas erupted at Veidivötn are thought to be sourced from Bárðarbunga, a second central volcano some 100 km to the north (Blake, 1984; Larsen, 1984; McGarvie, 1984; McGarvie et al., 1990).

Icelandic volcanoes tend to be either tholeiitic or alkalic, depending on their occurrence within or outside of the primary active rift zones (e.g., Jakobsson, 1979). Postglacial eruptions from Torfajökull have included low and high-K basalts, and high-K rhyolites. The last two

1.2. U-series disequilibria

U-series isotopic studies constrain the timing and conditions of petrogenesis, making them useful for tests of proposed rhyolite generating processes. U-series nuclides are sensitive to the time since chemical fractionation, so they can be used to make inferences about magma ages upon eruption and to distinguish between recently modified and long-lived chemically closed magma sources. Further, the partitioning behavior of U-series isotopes is strongly dependent on the types and proportions of minerals present, and the dynamics of melting and differentiation processes. Early studies demonstrated the utility of U-series isotopes in Icelandic petrogenetic processes (Condomines et al., 1981) and suggested that U-series variations in Icelandic basalts resulted largely from recent assimilation of partial melts of old hydrothermally altered crust (Hémond et al., 1988). It was later suggested that mixing of melts derived from undepleted off-axis mantle and depleted rift zone mantle was important in off-rift settings (e.g., the Snaefellsnes peninsula, Sigmarsson et al., 1992b). Combined Ra-Th and oxygen isotope data have been used to infer that when involved, bulk-digestion of hydrated basaltic crust can be rapid (~8 ka), such as prior to the 1783–1784 Laki basaltic fissure eruption (Bindeman et al., 2006). There have been few prior U-series disequilibria studies of siliceous Icelandic magmas, limited to small data sets from Askja, Krafla and Hekla used with other data types to argue for a role of crustal melting of hydrothermally altered basalts (Nicholson et al., 1991; Sigmarsson et al., 1991; 1992a).

Finally, the Icelandic plume plays a role in divergent plate boundary volcanism by producing a systematic excess $^{230}$Th drop and correlated variations in Pb–Nd–Sr–O isotopes and trace element ratios towards the hot spot center as a result of faster mantle upwelling rates and greater degrees of melting of a more heterogeneeous mantle source (Kokfelt et al., 2003, 2006). The same scenario has been invoked to explain general isotope variations in Hawaii (Sims et al., 1999) as well as temporal fluctuations at Kilauea, where changing melting conditions over the past 200 yrs have been detected by sampling variably wide regions of the upwelling Hawaiian hotspot source (Pietruszka et al., 2001).

2. Geological background

The geology of the active volcanic rift zone in South Central Iceland, which includes both Torfajökull and Veidivötn, is summarized here on basis of previous studies (Jakobsson, 1979; Blake, 1984; Larsen, 1984; Macdonald et al., 1990; Gunnarsson et al., 1998; Sigmarsson et al., 2000). Torfajökull central volcano is situated on the northern edge of the practically non-rifting Southern Flank Zone, southwest of...
the Veidivötn fissure swarm. A simplified geological map of the region (Fig. 1) shows that the fissure swarm occupies roughly 85 × 10 km², forming the southern part of the actively rifting Eastern Rift Zone. It has erupted tholeiitic basalts of a relatively narrow compositional range with a 600–800 year recurrence interval during the historical and post-glacial eras. In the extreme southwest of the Eastern Rift Zone, the Veidivötn fissure swarm intersects Torfajökull central volcano, a dominantly rhyolitic plateau rising ~600 m above the surrounding basaltic terrain and representing both the largest volume of exposed silicic extrusives and the most productive geothermal system in Iceland. The bulk of the plateau is composed of last glacial lavas and tephras. An old ring structure has been identified within these deposits, suggested by Saemundsson (1972) to mark the locus of a caldera complex (Fig. 1). Postglacial silicic lavas with alkaline affinities have erupted both within and outside this ring structure, and are associated with northeast–southwest trending faults and fissures. Mafic magmas have also erupted along these fissures, predominantly as transitional alkali basalts in the southwest and as tholeiites in the Veidivötn fissure swarm to the northeast. Direct observations, ash deposition patterns, and geochronological evidence indicate that the last three eruptions of tholeiitic basalts from Veidivötn and rhyolites from Torfajökull occurred simultaneously (Larsen, 1984). Abundant evidence of pre- and syn-eruptive mafic and felsic magma mixing occurs at the intersection of the Veidivötn fissures and the Torfajökull ring structure, suggesting that some postglacial Torfajökull rhyolite eruptions have been triggered by influx of mafic melts. The difference between basalt compositions erupted within and to the northeast of the Torfajökull ring structure is one reason why various authors have suggested that the Veidivötn magmas are associated with the volcanic system of the compositionally similar Bárðarbunga central volcano, situated about 100 km to the northeast.

This study addresses potential petrogenetic relationships between basaltic and silicic magmas erupted in the Torfajökull region, with a focus on the last two historical eruptions. On basis of geochemical and geographical patterns, deposits from the 871 AD and 1477 eruptions, which with exception of the 871 AD Hrafninnhuiraun flow (HRN in Fig. 1) occurred in what Macdonald et al. (1990) refer to as northeast Torfajökull, are distinguished here from recent, undated eruptions of what will be referred to as “west Torfajökull”, outside and west of the ring structure (i.e. LAF, LFD, LFL, MKD; cf. Fig. 1 caption for a key to locality abbreviations), including associated fissures of transitional alkali basaltic and intermediate magmas.

3. Methods

Samples were collected using eruption deposit maps of Larsen (1984), with the aim to avoid mixed-magma samples. Information about sampling locations, mineral separation techniques, sample preparation for geochemical analyses, and analytical methodologies (including analyses of standards) are given in the supplementary data in the Appendix.

Whole rocks were analyzed for major and trace element abundances by XRF, and for additional trace elements by ICP-MS at the University of Hawaii. Electron microprobe analyses of mineral compositions were conducted at the Instituto de Geofísica, UNAM, in Mexico City.

U-series and radiogenic isotope analysis methods in the SOEST Isotope Lab are summarized in the appendix, with full discussion in (Pietruszka et al., 2001; Rubin, 2001; Rubin et al., 2005). High abundance sensitivity ion-counting thermal ionization mass spectrometry of all U-series nuclides used a Sector54-warp.

4. Results

4.1. Petrographic observations

The products of both historical eruptions are petrographically very similar at the thin section scale. Most phenocrysts are euhedral or subhedral, without significant zoning under the microscope or in microprobe transects (see Fig. 2 electron backscatter images). Veidivötn basalts typically contain Ca-rich plagioclase and pyroxene phenocrysts plus olivine microlites set in a fine-grained groundmass dominated by feldspar, pyroxene and accessory magnetite. Torfajökull rhyolites have plagioclase and pyroxene phenocrysts plus magnetite microlites set in a glassy to fine crystalline groundmass dominated by feldspar microlites. Titaniferous amphibole microphenocrysts and apatite microlites occur as accessory phases in the 871 AD rhyolites.

4.2. Comparative mineral chemistry

Veidivötn basalts from 871 AD have Mg-rich olivines (Fo74–86). Clinopyroxenes and plagioclases display wider compositional ranges: En42–54Fs6–15Wo36–47 and An52–92 (Fig. S1a in the Appendix).

![Fig. 2. Selected EM images of the most recent Veidivötn basalts and associated Torfajökull rhyolites, with 200 μm scale bars. Insets are from the same sample and to the same scale as the respective main images.](Image)
Torfajökull 871 AD rhyolites have more iron-rich clinopyroxenes (En30–39Fs20–32Wo36–44); feldspar compositions range from andesine (An45) to anorthoclase (Or29) in two populations distinguished on a ternary feldspar diagram. Geothermometry (Fuhrman and Lindsley, 1988) suggests that the two populations formed in overlapping temperature ranges, with a slight extension (≈50 °C) toward lower temperatures for the much less abundant potassic population (cf. Fig. S1a in the Appendix). Minerals of the 1477 eruption have very similar compositions at slightly smaller overall range, perhaps reflecting the lower number of analyses (cf. Fig. S1b in the Appendix). Basalts have Mg-rich olivines (Fo73–82) and clinopyroxenes (En45–53Fs9–15Wo36–42), and calcic plagioclase feldspars (An86–87). A small population of clinopyroxenes is richer in iron, compositionally similar to those found in co-eruptive rhyolites (En36–40Fs20–25Wo36–42). Rhyolitic feldspar compositions mimic those of the preceding eruption, ranging from andesine (An38) to anorthoclase (Or29), although the two crystal populations are less distinct than in the 871 eruptions (cf. Fig. S1b in the Appendix).

It is noteworthy that most individual crystals within the rhyolites are unzoned and chemically homogeneous, despite the overall ranges in crystal chemistry. Similarly, most crystals from the basalts are unzoned to slightly normally zoned. Crystals of both magma types display little if any signs of host melt disequilibria, in contrast to previous studies describing extensive crystal-melt disequilibria in the Torfajökull–Veidivötn area (Blake, 1984; Mørk, 1984). This difference is due to the focus of this study on endmember lava compositions.

4.3. Whole-rock major and trace element data

Whole rock major and trace element XRF data and trace and rare earth element (REE) ICPMS data appear in Tables 1 and 2 in the Appendix, respectively. Veidivötn basalts analyzed here show a small compositional range of about 2 wt.% SiO$_2$, mirrored by relatively small variations in other elements and oxides except for Al$_2$O$_3$ and Sr (Fig. 3 and Fig. S2 in the Appendix). Previously published data on mixed magmas and on fissure eruption basalts from west Torfajökull have intermediate compositions (McGarvie, 1985; Jakobsson, 1979; McGarvie, 1984; Gunnarsson, 1987; Hansen and Grönvold, 2000). Relatively low MgO, Ni and Cr of end-member basalts indicate that none of the samples studied here are primary mantle melts. Torfajökull rhyolites display a larger compositional range: increasing SiO$_2$ is accompanied by increases in K$_2$O and Nb, decreases in Na$_2$O, Sr, Zr, Hf and REE, and slight decreases in TiO$_2$ and P$_2$O$_5$.

Chondrite-normalized REE abundances in the 871AD and 1477 eruptions (Fig. 4) show LREE enrichment over HREE and negative Eu anomalies, both most pronounced in the rhyolites. These trends, which mimic those in Macdonald et al. (1990), are consistent with feldspar fractionation of a LREE-enriched source. Basalts and rhyolites have very similar middle to heavy REE patterns, pointing to compositional similarities of their respective source regions. Older postglacial eruptions of west Torfajökull likewise display overall similar REE patterns to the most recent Torfajökull eruptions studied.
Mineral separates from selected samples have indistinguishable ($^{230}$Th/$^{232}$Th) activity ratios from their respective host rocks and define zero-age U–Th isochrons for the 871 AD rhyolite and the 1477 basalt (Fig. 5b). Whole-rock (WR) and mineral separate data are plotted on Ba-normalized Ra–Th equiline diagrams in Fig. 6. Assuming the minerals in each rock formed contemporaneously and rapidly compared to the $^{226}$Ra half-life, and that Ba is a proxy stable isotope for $^{226}$Ra, the slope of these mineral isochrons yields the time of formation of the mineral assemblage (e.g., Volpe and Hammond, 1991). This method generates ages of 1.4±0.3 and 2.0±0.2/0.1 ka (2σ) for the 1477 basalt and rhyolite respectively (in years before eruption), and 3.2±0.4 ka (2σ) for the 871 rhyolite. Correcting ($^{226}$Ra/$^{230}$Th) in each of these whole rocks for decay over this time period gives parental magma ($^{226}$Ra/$^{230}$Th) of 2.03, 1.33 and 1.18 for the 1477 basalt, 1477 rhyolite, and 871 rhyolite, respectively. There are multiple potential complicating factors with this simple age assessment, such as time delay between melt formation and the onset of crystalization, non-instantaneous (perhaps even sequential) formation of phenocrysts during crustal residence, and imperfections to the use as Ba as a proxy to Ra in mineral melt partitioning. In the discussion section, we will examine each of these in turn.

Our new Sr isotope data slightly extend the $^{87}$Sr/$^{86}$Sr ranges of Veidivötn basalts and Torfajökull rhyolites to 0.70307–0.70328 and 0.70322–0.70342, respectively (Fig. 3 in the Appendix). By comparison, published $^{87}$Sr/$^{86}$Sr data on mafic west Torfajökull samples range from 0.70328 to 0.70348. An early study pointed to distinctly higher $^{87}$Sr/$^{86}$Sr in rhyolites than in basalts of this area (O’Nions and Grönvold, 1973), but subsequently published $^{87}$Sr/$^{86}$Sr data collectively display a less clear-cut distinction at Torfajökull, with a total $^{87}$Sr/$^{86}$Sr variation amounting to 10 times the analytical uncertainty (Stecher et al., 1999). Although our Veidivötn values are slightly elevated compared to those in the literature, nothing about the analyses themselves make them suspect; likewise, contamination by rhyolitic melts, which occurs in Veidivötn basalts at the southern end of the fissure (Mark, 1984), is inconsistent with near-end-member incompatible element compositions of our samples. Thus the data

**4.4. Isotope data**

Sr- and U-series isotope data are given in Table 1. All samples show excess $^{230}$Th when plotted on a U–Th equiline diagram (Fig. 5). The tholeiites lie within the field of postglacial main rift basalts of Kokfelt et al. (2003) at 12–14% $^{230}$Th excess, while the rhyolites with 14–17% $^{230}$Th excess are displaced to slightly lower ($^{238}$U/$^{232}$Th) and ($^{239}$Th/$^{232}$Th) activity ratios (Fig. 5a). All whole-rock samples display small but significant $^{226}$Ra excesses of 33–45% for the basalts, placing them in the overall Iceland range of Kokfelt et al. (2003), and 3–10% for the rhyolites (cf. Table 1; note ($^{226}$Ra/$^{230}$Th) are ratios on the date of eruption). These are the first published $^{226}$Ra data for Icelandic rhyolites.

**Table 1**

<table>
<thead>
<tr>
<th>Sample #</th>
<th>Unit</th>
<th>T2</th>
<th>T2-px</th>
<th>T2-plag</th>
<th>T2-mt</th>
<th>T3</th>
<th>T3-mt</th>
<th>T3</th>
<th>T6</th>
<th>T7</th>
<th>T7-px</th>
<th>T7-plag</th>
<th>T7-mt</th>
<th>T7</th>
<th>871 AD</th>
<th>871 AD</th>
<th>871 AD</th>
<th>871 AD</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rock type</td>
<td></td>
<td>Basalt</td>
<td>Basalt</td>
<td>Basalt</td>
<td>Basalt</td>
<td>Rhyolite</td>
<td>Rhyolite</td>
<td>Basalt</td>
<td>Basalt</td>
<td>Rhyolite</td>
<td>Rhyolite</td>
<td>Basalt</td>
<td>Basalt</td>
<td>Rhyolite</td>
<td>Rhyolite</td>
<td>Rhyolite</td>
<td>Rhyolite</td>
<td></td>
</tr>
<tr>
<td>Eruption year</td>
<td>1477</td>
<td>1477</td>
<td>1477</td>
<td>1477</td>
<td>1477</td>
<td>1477</td>
<td>1477</td>
<td>1477</td>
<td>1477</td>
<td>1477</td>
<td>1477</td>
<td>1477</td>
<td>1477</td>
<td>1477</td>
<td>1477</td>
<td>1477</td>
<td>1477</td>
<td></td>
</tr>
<tr>
<td>$^{87}$Sr/$^{86}$Sr</td>
<td>0.703291</td>
<td>0.703154</td>
<td>0.703409</td>
<td>0.703409</td>
<td>0.703236</td>
<td>0.703433</td>
<td>0.703236</td>
<td>0.703433</td>
<td>0.703236</td>
<td>0.703433</td>
<td>0.703236</td>
<td>0.703433</td>
<td>0.703236</td>
<td>0.703433</td>
<td>0.703236</td>
<td>0.703433</td>
<td>0.703236</td>
<td>0.703433</td>
</tr>
<tr>
<td>$^{238}$U/$^{232}$Th</td>
<td>0.000015</td>
<td>0.000015</td>
<td>0.000015</td>
<td>0.000015</td>
<td>0.000015</td>
<td>0.000015</td>
<td>0.000015</td>
<td>0.000015</td>
<td>0.000015</td>
<td>0.000015</td>
<td>0.000015</td>
<td>0.000015</td>
<td>0.000015</td>
<td>0.000015</td>
<td>0.000015</td>
<td>0.000015</td>
<td>0.000015</td>
<td>0.000015</td>
</tr>
<tr>
<td>$^{230}$Th ppm</td>
<td>0.3902</td>
<td>0.01272</td>
<td>0.003702</td>
<td>0.097</td>
<td>15.89</td>
<td>7.677</td>
<td>0.5940</td>
<td>7.677</td>
<td>0.5940</td>
<td>7.677</td>
<td>0.5940</td>
<td>7.677</td>
<td>0.5940</td>
<td>7.677</td>
<td>0.5940</td>
<td>7.677</td>
<td>0.5940</td>
<td>7.677</td>
</tr>
<tr>
<td>$^{232}$U ppm</td>
<td>0.1216</td>
<td>0.00424</td>
<td>0.00376</td>
<td>0.0304</td>
<td>4.715</td>
<td>2.262</td>
<td>0.1823</td>
<td>5.270</td>
<td>1.059</td>
<td>0.1379</td>
<td>2.148</td>
<td>0.1379</td>
<td>2.148</td>
<td>0.1379</td>
<td>2.148</td>
<td>0.1379</td>
<td>2.148</td>
<td></td>
</tr>
<tr>
<td>$^{238}$U/$^{232}$Th</td>
<td>0.945</td>
<td>1.012</td>
<td>3.083</td>
<td>0.611</td>
<td>1.108</td>
<td>0.770</td>
<td>1.335</td>
<td>0.823</td>
<td>1.059</td>
<td>0.1379</td>
<td>2.148</td>
<td>0.1379</td>
<td>2.148</td>
<td>0.1379</td>
<td>2.148</td>
<td>0.1379</td>
<td>2.148</td>
<td></td>
</tr>
<tr>
<td>$^{226}$Ra ppm</td>
<td>0.000015</td>
<td>0.000015</td>
<td>0.000015</td>
<td>0.000015</td>
<td>0.000015</td>
<td>0.000015</td>
<td>0.000015</td>
<td>0.000015</td>
<td>0.000015</td>
<td>0.000015</td>
<td>0.000015</td>
<td>0.000015</td>
<td>0.000015</td>
<td>0.000015</td>
<td>0.000015</td>
<td>0.000015</td>
<td>0.000015</td>
<td>0.000015</td>
</tr>
<tr>
<td>$^{226}$Ra ppm</td>
<td>0.01272</td>
<td>0.00424</td>
<td>0.00376</td>
<td>0.0304</td>
<td>4.715</td>
<td>2.262</td>
<td>0.1823</td>
<td>5.270</td>
<td>1.059</td>
<td>0.1379</td>
<td>2.148</td>
<td>0.1379</td>
<td>2.148</td>
<td>0.1379</td>
<td>2.148</td>
<td>0.1379</td>
<td>2.148</td>
<td></td>
</tr>
</tbody>
</table>

Parentheses denote activity ratios, which were calculated from atomic abundance analyses using $\lambda_{238}U=1.551\times10^{-10}$ yr$^{-1}$, $\lambda_{230}Th=9.195\times10^{-6}$ yr$^{-1}$ and $\lambda_{226}Ra=4.332\times10^{-4}$ yr$^{-1}$.
It is important to first evaluate petrogenetic processes in the magmas of interest before interpreting the U-series results in terms of magmatic processes and timescales. While the intermediate volcanics in northeast Torfajökull are hybrid magmas resulting from pre-eruptive mixing of Torfajökull rhyolites and Veidivötn basalts (Blake, 1984; McGarvie, 1984; McGarvie et al., 1990), the new whole-rock data presented here do not fall on the geochemical mixing trends (cf. Fig. 3 and Fig. S2 in the Appendix), implying that they provide insights into the primary petrogenetic processes operating in the region. The small MgO range (6.74 to 7.08) in the end member Veidivötn basalts provides almost no information about the mineral assemblage that governed their magmatic evolution. However, low MgO, Cr and Ni contents indicate significant olivine removal. Al₂O₃ and Sr compatibility (cf. Fig. 3), and small negative Eu anomalies (0.91 < Eu/Eu* < 0.94; cf. Fig. 4) suggest that plagioclase feldspar was also part of the fractionating assemblage. Within the Torfajökull rhyolites, Al₂O₃ and Sr compatibility and strongly negative Eu anomalies indicate plagioclase dominated fractionation. Apparently, significant potassic feldspar and biotite fractionation from rhyolitic melts did not occur since K₂O and Nb behave incompletely. TiO₂, P₂O₅, and – at higher SiO₂ – Zr compatibility implicate titanomagnetite, apatite, and zircon fractionation, respectively, in some of the rhyolites.

The new data also provide insights into the potential petrogenetic relationship between Torfajökull rhyolites and mafic rocks erupted in the area. Torfajökull rhyolites were previously suggested to have been generated by extensive fractional crystallization of transitional alkali basalts through icelandites (Macdonald et al., 1990). However, the similarity of Al₂O₃ content in basalts and rhyolites casts doubt on this scenario (Fig. 3a). Plagioclase feldspar appears to be one of the major fractionating phases in both the basalts and the rhyolites, so one would expect the rhyolites to have significantly lower Al₂O₃ contents than the basalts if fractional crystallization was indeed dominant during their petrogenesis. This is confirmed using MELTS fractional crystallization modelling (Ghiors and Sack, 1995; Smith and Asimow, 2005). Note that on Fig. 3a, variations in P, [H₂O], and fO₂ change the minimum Al₂O₃ content prior to significant SiO₂ enrichment, but do not change the general shape of the liquid line of decent (cf. Zellmer et al., 2005, who followed a similar line of evidence for arc magma differentiation).

Alternatively, melting experiments (Beard and Lofgren, 1989; Thy et al., 1990) suggest that Icelandic rhyolite major element geochemistry derives from partial melting of greenstones and amphibolite-facies metabasalts (cf. Gunnarsson et al., 1998). Off-axis settings in Iceland normally erupt transitional or alkali basalts, and at Torfajökull this carries through to felsic magmas, which are high-K rhyolites. In addition, rocks from west Torfajökull display relatively high Zr concentrations that remain approximately constant at SiO₂ values greater than about 56 wt.%, suggesting early fractionation of zircon. This is supported by increasing Yb/Lu ratios with progressive differentiation (Figs. 3d and 4), which are known to be strongly increased by zircon fractionation (Henderson, 1985; Fujimaki, 1986). Old west Torfajökull rhyolites, which display the highest Yb/Lu ratios of the area, hence appear to be petrogenetically related to the transitional basalts sampled in that area.

However, the most recently erupted rhyolites do not display a zircon fractionation signature. Instead, they have much lower Yb/Lu ratios, making the transitional alkali basalts unsuitable as source rocks (cf. Figs. 3d and 4). While the data suggest zircon fractionation may be operating in the highest silica rhyolites, Yb/Lu ratios may be buffered by contemporaneous fractionation of apatite (cf. Fig. S2c in the Appendix), which has a weaker but opposite effect on HREE ratios (Henderson, 1985; Fujimaki, 1986). The Yb–Lu–Zr data therefore indicate that the youngest Torfajökull rhyolites are related to partial melting of a Zr poor source, such as has produced the historical Veidivötn tholeiites.
Rubin, 1997), and K/Rb ratios within Veidivötn tholeiites reach values comparable to mafic rocks from west Torfajökull (Fig. S2d in the Appendix). MELTS batch melting of a tholeiitic source with slight enrichment of alkalai can generate silica-rich melts with high Al2O3 and K2O content, although further crystal fractionation including apatite will be required to generate the rhyolites (cf. Fig. 3 and Fig. S2 in the Appendix).

Data on 87Sr/86Sr ratios in tholeiites, transitional alkali basalts and rhyolites from Torfajökull and Veidivötn are rare (Fig. S3 in the Appendix). No systematic trends are apparent, although the transitional alkali rocks display generally higher 87Sr/86Sr ratios than the tholeiites, and are isotopically comparable to the rhyolites. However, fluid mobility of Sr is also well documented, and hydrothermal alteration of intruded low 87Sr/86Sr tholeiites within an area dominated by high 87Sr/86Sr alkali basaltic crust may measurably increase 87Sr/86Sr of the protoliths. It may therefore be argued that the Sr isotopic differences between tholeiites and rhyolites (Fig. S3 in the Appendix) do not preclude a petrogenetic link between these compositions, although a slight admixture of alkali basalt into the tholeiitic protolith might also explain the small Sr isotopic shift. There is insufficient data to test mixing scenarios in detail. Future work would benefit from detailed studies of fluid immobile elements and their isotopes, e.g. neodymium and hafnium.

Finally, it is interesting to note that tholeiitic enclaves occur in the recent Torfajökull rhyolites but not in postglacial ones older than 7 ka, which contain transitional or alkali basaltic enclaves (McGarvie et al., 1990). This change in the composition of mafic enclaves is wholly in line with our suggestion that the magmatic feeding system of Torfajökull Central Volcano shifted from dominantly alkali basaltic to dominantly tholeiitic compositions, consistent with the proposed progressive south-westwards propagation of the Eastern Rift Zone through time (e.g., Hey et al., 1998). Tholeiitic magma influx beneath Torfajökull is also consistent with extremely low shear wave velocities of the crust in the surrounding region (Allen et al., 2002) that point to solidified or partially solidified high-temperature intrusives at depth beneath Torfajökull.

5.3. Whole-rock age constraints on the protoliths of the most recent rhyolites

It has been argued previously that Torfajökull rhyolitic magmas were derived from “relatively recently” intruded mafic to intermediate protoliths on basis of Sr, Nd and Pb isotopic similarity between rhyolites and transitional basalts there (Stecher et al., 1999). However, significantly better constraints on the age of the basaltic protoliths to the 871 and 1477 Torfajökull rhyolites are provided by the U-series chemistry of these rocks. On the broadest geographic scales, U/Th ratios of postglacial tholeiitic protoliths might also explain the small Sr isotopic shift. There is insufficient data to test mixing scenarios in detail. Future work would benefit from detailed studies of fluid immobile elements and their isotopes, e.g. neodymium and hafnium.

5.4. Insights from pre-eruptive crystallization timescales of basalts and rhyolites

Euhedral to subhedral morphologies in the crystal assemblage of the most recent Veidivötn and Torfajökull co-eruptive products (Fig. 2), combined with well-defined fields for plagioclase and pyroxene mineral chemistry data (Fig. S1 in the Appendix), suggest that crystal inheritance is limited. Only a small number of rhyolitic feldspars display slightly lower Na contents and higher equilibration temperatures. These may be antecrysts from a previous crystallization episode. A few pyroxenes of the 1477 eruption are also compositionally different from the main population, and again a xenocrystic or antecrystic origin of these cannot be precluded. However, the bulk of the crystal assemblage of the most recently erupted Veidivötn basalts and Torfajökull rhyolites appears young. This notion is supported by U-series mineral separate analyses of the 871 AD rhyolite and the 1477 basalt, which yield ~ zero age Th–U internal isochrons (Fig. 5b).

Ra–Th data provide tighter time constraints, with pre-eruptive crystallization ages of 1.4 (±0.3) and 2.0 (±0.2–0.1) ka (2σ) for the 1477 basalt and rhyolite respectively, and 3.2 (±0.4) ka (2σ) for the 871 rhyolite (Fig. 6). The results for the 1477 eruption imply that the rhyolite started crystallizing about 700 years earlier than the basalt, i.e. that this particular rhyolite spent ~50% more time evolving before eruption than did the coeruptive basalt. The contrast in rhyolite isochron ages suggest that the 871 rhyolite spent roughly 50% more time between crystallization and eruption than did 1477 rhyolite. It is possible to look for sequential crystallization in two of the three samples with mineral WR data because multiple minerals were analyzed (i.e., T2 and T7). However, no individual mineral appears to fall off of the best fit linear regressions on the isochron diagrams, suggesting that crystallization was simultaneous for those phases (within error). Further, the overall mineral assemblage in these rocks is characterised by small and euhedral crystals and thus appears to be cotectic, implying that individual crystal populations are not significantly different from each other in their age. If crystallization occurred over a protracted time compared to the 226Ra half-life, it would have occurred at roughly the same rate for all of the minerals present.
that a predicted ratio such as \( \frac{D_{\text{Ba}}}{D_{\text{Ra}}} \) would be the same for multiple minerals in a single melt, so Ba normalized mineral-melt data (i.e., Fig. 6) would not be colinear in young lavas even if the minerals formed at the same time. Cooper et al. (2001) observed such non-linearity in a crystal rich Kilauea basalt and, using strain rate parameterization to estimate \( D_{\text{Ba}} \) for plagioclase, suggest a crystallization age of 1 kyr before eruption versus 3.4 kyr if they had assumed \( D_{\text{Ra}} = D_{\text{Ba}} \). The difficulty with applying such an estimate here is that minerals are observed to be strongly colinear on a Ba-normalized diagram such as Fig. 6, such that two point isochrons (i.e., magnetite-melt, plagioclase-melt, clinopyroxene-melt) yield the same result as a multi-point isochron assuming \( D_{\text{Ra}} = D_{\text{Ba}} \). Evaluating each mineral-melt pair separately and using \( D_{\text{Ra}}/D_{\text{Ba}} \) estimated from experimental parameterizations produces disparate ages for the multiple pairs in a single rock, which seems an unlikely result. Further, Blundy and Wood (2003) indicate that fleetingly small values of \( D_{\text{Ra}} \) and \( D_{\text{Ba}} \) in magnetite imply that these elements will not be fractionated from each other by this phase. Because magnetite-melt pairs yield the same ages as other mineral-melt pairs in T2 and T7 assuming \( D_{\text{Ra}} = D_{\text{Ba}} \), this is another reason to suspect that mineral strain parameterized \( D_{\text{Ra}}/D_{\text{Ba}} \) are not applicable. As in all studies that use natural mineral separates, it is always possibly that microinclusions have affected the Th–U–Ra–Ba systematics measured in some of our phases, although it seems rather unlikely that they would have participated in just the right proportion to change mineral specific \( D_{\text{Ra}}/D_{\text{Ba}} \) to a ratio of 1.

Another way to assess time in this system is to assume an isochronal relationship between coeval magmas, such as might occur if a basalt reservoir deep in the crust released pulses of magma at different times that generated basaltic eruptions and rhyolite melting/eruptions from the same closed system melt source. Such basalt–rhyolite pseudo-isochrons for the 1477 and 871 AD eruptions yield \( -5.8 \) kyr and \( -4.7 \) kyr of pre-eruptive magma aging, respectively, both of which are significantly longer than the internal isochron estimates. Such a scenario implies considerable magma aging without crystallization (or loss of early crystallizing phases). This added time interval would also imply parental magma \( \begin{array}{c} ^{226}\text{Ra} \end{array} /\begin{array}{c} ^{230}\text{Th} \end{array} \) of roughly 5 and 8 for the 1477 and 871 basaltas. Such values are unrealistically high relative to melt model predictions for typical source mineralogy and upwelling conditions for dry mantle melting to produce basaltic melts (Spiegelman and Elliott, 1993). Furthermore, the basalt-rhyolite pseudo-isochron relationship assumes the same Ba/Th for the rhyolite and basalts before low pressure differentiation, which is difficult to envision given the large differences between the erupted lavas and the minerals likely to be involved. For these reasons the pseudo-isochrons likely yield extreme overestimates of magma residence times in the crust, implying that magmas did not reside significantly longer in the crust than the internal mineral isochron age estimates.

In summary, the U–Th and Ra–Th data presented here indicate that melting and preeruptive crystallization of the most recent volcanic deposits of the Torfajökull–Véidivötn area occurred within a few thousand years prior to eruption, within the Late Holocene. This is consistent with the occurrence of tholeiitic enclaves in Torfajökull rhyolites from the early Late Holocene onwards (McGarvie et al., 1990). Interestingly, pre-eruptive crustal magma residence times exceed the eruption recurrence interval for this system by factors of 2 (basalts) to about 4 (rhyolites), indicating that multiple batches of magma had been accumulating and evolving within the crust several thousand years prior to these eruptions.

5.5. Petrogenesis of silicic lavas from Torfajökull revisited

Gunnarsson et al. (1998) suggested two principal mechanisms involving melting of previously solidified magmas for the petrogenesis of silicic extrusives in Iceland: (1) melting of small, highly differentiated segregation lenses formed in the upper part of prior gabbroic intrusions, followed by subsequent extraction, ascent and pre-eruptive melt accumulation (cf. their Fig. 18); and (2) partial
melting of old, hydrothermally altered extrusives and intrusives, which were brought into the melting region through isostatic subsidence beneath large, long-lived central volcanoes (see their Fig. 19). Such processes require large magma reservoirs. However, seismic studies have not been successful in imaging such chambers (e.g., Allen et al., 2002). Further, large magma reservoirs would be thermally buffered, and rapid petrogenetic processes as those evidenced by this study would not be anticipated to operate in such environments.

The U-series data presented here points to a very different petrogenetic scenario for the most recently erupted Torfajökull rhyolites (as depicted in Fig. 7), based on the similarity of \(^{230}\text{Th}/^{232}\text{Th}\) of coreruptive basalts and rhyolites in both eruptions, and widespread Ra-Th disequilibria in both whole-rocks and minerals. Within the last \(\pm 37\) kyr, we propose that tholeiitic magmas of composition similar to those of the Veidivötn basalts began to intrude beneath Torfajökull central volcano, where they formed protoliths that were subsequently metasomatized through high-temperature hydrothermal activity. During the Late Holocene, further influx of hot, mafic magma lead to repeated small degree \((F \approx 0.2, \text{ cf. Fig. 3 and Fig. S2 in the Appendix})\) partial melting of a large volume of these tholeiitic protoliths. The evolved partial melts accumulated in upper crustal magma reservoirs and began to crystallize (and further differentiate). By 2.5 ka prior to eruption, at least two such reservoirs of rhyolitic composition had formed. Subsequent intersection of the rhyolites by new basaltic melt in 871 AD and 1477 resulted in magma mixing and bimodal eruption from fissures of the Torfajökull–Veidivötn area. Given that at least 10 rhyolite eruptions have occurred at Torfajökull during the Late Holocene, of which at least 5 happened during the last 4 kyr (Macdonald et al., 1990), it is likely that the upper crust beneath Torfajökull was and potentially still is host to small rhyolitic reservoirs formed during the prolonged postglacial history of intrusion and extrusion at the volcano. The thermal state of the crust in this area is therefore elevated, and the next intrusion of mafic magma is not unlikely to trigger further partial melting at depth and/or mobilization of an existing rhyolite melt body, potentially resulting in future co-eruptive volcanic events at Torfajökull central volcano and the Veidivötn fissure swarm.

6. Conclusions

1. Postglacial rhyolites erupted from Torfajökull central volcano are the products of differentiation from recent small degree \((F \approx 0.2)\)
partial melts of previously intruded and metasomatized mafic protoliths.

2. Significant $^{230}$Th excesses of the most recent rhyolites, and similarity of rhyolitic ($^{230}$Th/$^{232}$Th) activity ratios to those of co-eruptive Veidivötn basalts, constrain the age of the protoliths of the most recently erupted rhyolites to ≤37 (+25/-20) kyr. Previous melting models invoking melt extraction from old silicic segregation lenses or rocks with long isostatic subsidence histories are not consistent with the new data.

3. Ra–Th mineral isochrons yield pre-eruptive crystallization ages of up to 3.2 ka, suggesting that the crystall load carried within the rhyolites is also young and that rhyolite melts were generated in the Late Holocene. Crystals display simple growth histories consistent with their being magmatic phenocrysts formed during rhyolite cooling prior to eruption. Crystal-melt disequilibria do not occur in our sample set, and appear to be restricted to the mixed magma samples considered by previous studies.

4. In contrast to old rhyolites from west Torfajökull, which were sourced from the transitional alkali basalts that are abundant in the Southern Flank Zone, the data suggests that the protoliths of the two most recently erupted rhyolites in the area are dominated by tholeiites similar in composition to the co-eruptive Veidivötn tholeiites. Transition from alkalic to tholeiitic source protoliths is mirrored by the same transition observed in the composition of mafic enclaves within postglacial mixed eruption products.火山 activity of Torfajökull appears to be sustained by heat provided to the core of this central volcano through frequent influx of mafic magma of progressively more tholeiitic composition, consistent with the progressive south-westward propagation of the Eastern Rift Zone with time.

Acknowledgements
