The 1362 AD Öræfajökull eruption, Iceland: Petrology and geochemistry of large-volume homogeneous rhyolite

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Abstract

The ice-covered Öræfajökull stratovolcano is composed mostly of subglacial pillow lava and hyaloclastite tuff, ranging from basalt to rhyolite. A large devastating plinian eruption in 1362 AD produced 10 km³ (2 km³ DRE) rhyolitic ash and pumice from a vent within the summit caldera, with fallout mainly towards ESE. The ejected rhyolite magma with 0.5–1% crystals of oligoclase, fayalite, hedenbergite, ilmenite and magnetite was remarkably homogenous throughout the eruption.

A 1.8 m thick tephra section on the SE flank of the volcano has 14 recognizable units. The tephra is dominated by fine-grained vesicular glass with bubble wall thickness of 1–5 μm. The high and even vesiculation of the glass indicates fast magma ascent and explains the extreme mechanical fragmentation within the eruptive column. The grain-size distribution indicates time-variable intensity of the plinian eruption with three evenly spaced phases of maximum fragmentation. An initial vent-clearing explosion produced phreatomagmatic debris with up to 35% lithic fragments. The low abundance (<3%) of lithic fragments during the subsequent eruption indicates that the conduit and vent remained stable. The tephra fallout deposit is characterized by upwards increasing pumice dimensions and occasional bomb-like pumice blocks, indicating less mechanical fragmentation during contraction and lowering of the plinian column.

A conservative estimate of 20–40 km³ for the total volume of the magma reservoir is based on the erupted volume of highly differentiated and homogeneous rhyolite. The 365-year period between 1362 and a minor benmoreitic eruption in 1727, and the absence of currently detectable magma reservoirs in the crust below Öræfajökull show that differentiated crustal magma chambers feeding large plinian eruptions can be established and disappear on a 100–500 year timescale.

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1. Introduction

The ice-covered Öræfajökull stratovolcano rests unconformably on a glacially dissected and isostatically uplifted Tertiary basalt pile at the southern termination of the Eastern Volcanic Flank Zone in SE Iceland (Prestvik, 1985) (Fig. 1). The NE–SW-trending 120-km-long off-rift volcanic zone, about 50 km east of the Eastern Rift
Zone is characterized by alkaline to tholeiitic transitional volcanism. The Öræfajökull edifice, reaching an altitude of 2119 m a.s.l., is dominated by subglacially erupted hyaloclastite units with pillow lava and tuff ranging from basalts to rhyolites (Prestvik, 1980, 1985).

The most recent Öræfajökull eruptions occurred in 1362 with a large plinian eruption and 1727 AD with a small benmoreitic eruption. The devastating 1362 eruption was among the largest plinian eruption in historical time in Iceland. The eruption probably lasted for only 1 or 2 days and produced at least 10 km$^3$ rhyolitic tephra, corresponding to 2 km$^3$ dense rock equivalent (DRE) (Thorarinsson, 1958). The tephra fall was mainly to the east–southeast (Fig. 2), and the initial phase of the eruption was phreatomagmatic. The widespread deposit forms one of the volcanic marker horizons in sedimentary successions in the North Atlantic (Pilcher et al., 2005).

The present study of mineralogy, petrology, geochemistry and grain-size distribution of the rhyolitic tephra in a single section is based on the study of Thorarinsson (1958). The investigated profile is, to the authors’ knowledge, the most extensive and complete section through the 1362 Öræfajökull tephra deposit.

We will try to partly reconstruct the magma chamber conditions and eruption dynamics of the 1362 event based on the mineralogy, petrology, geochemistry and grain-size distribution of the rhyolitic tephra. The large volume of remarkably homogeneous rhyolite erupted has important implications for the pre-eruption magma reservoir. The geochemical similarities with the Skærgaard and Bushveld granophyres will also be discussed.

2. General geology of the Öræfajökull volcanic system

The Late Tertiary volcanic basement southeast of Vatnajökull was deeply dissected by glacial erosion through a time span of 3 Ma (Helgason and Duncan, 2001). Parts of this isostatically uplifted volcanic sequence were formed by subglacial eruptions during the same interval (Prestvik, 1985). The currently active Öræfajökull volcano is built unconformably on this...
Elevated basement and forms the southwestern end of the NE-trending Eastern Volcanic Flank Zone (EVFZ). Most of the volcano is younger than 0.7 Ma (Brunhes, normally magnetized) but reversely magnetized rocks occur in lower parts of the edifice. The non-rifting EVFZ is parallel to, but 50 km southeast of the Eastern and Northern Rift Zones. The Icelandic volcanic flank zones have transitional alkalic to tholeiitic volcanism (Prestvik et al., 2001).

The crater rim surrounds an elliptical summit caldera with an area of 14 km² and unknown depth. The post-glacial activity in the summit area seems to have been almost exclusively explosive and tephrochronological studies in the neighborhood of the volcano show that this activity was rather limited and did not add much to the height and volume of the volcano (Thorarinsson, 1958).

The Öræfajökull stratovolcano is composed mostly of subglacially erupted pillow lava and hyaloclastite breccia and tuff covering a compositional range from basalt, via hawaiite, mugearite, benmoreite and trachyte to rhyolite (Prestvik, 1979, 1980, 1985; Prestvik et al., 2001). The rock suite is largely bimodal, with predominantly basaltic and rhyolitic compositions (Prestvik, 1980). Based on major element modeling Prestvik (1985) concluded that the intermediate lavas and some rhyolites were derived by fractional crystallization, but that most rhyolites were formed by partial melting of older crustal rocks. However, Prestvik et al. (2001) argued that the consistent O–Sr–Nd–Pb isotopic composition of the entire compositional spectrum from basalt to rhyolite is strong evidence that the intermediate and rhyolitic melts were produced by fractional crystallization of basaltic parental magmas.

3. The 1362 Öræfajökull eruption

Thorarinsson (1958) provides an extensive overview of the 1362 eruption, based on written accounts and studies of numerous tephra sections. The following short
review is based on Thorarinsson’s account. The main eruption in June 1362 was purely explosive and rhyolitic, with the vent(s) located within the caldera. The regular and uniform tephra fall distribution (Fig. 2) indicates that the plinian phase was short-lived, probably 1–2 days.

The estimated total volume of the tephra layer from the 1362 eruption on land and sea is 10 km³, corresponding to 2 km³ DRE. The total area within the 0.1 cm isopach is estimated to nearly 300,000 km², and the tephra has been recognized in peat bogs in Scandinavia (Pilcher et al., 2005) and as a large particle pike in ice cores at Summit, Greenland (Palais et al., 1991).

The eruption caused several glacial lahars (jökulhlaups) on the west–southwest and to the southeast side of the volcano (Thorarinsson, 1958). These floods destroyed some farms, but most of the devastation was caused by tephra fall from the eruption (Thorarinsson, 1958). Before the eruption, the Öræfí district was one of the most productive agricultural areas in Iceland, and at least 30 farms were destroyed and abandoned for decades after the eruption. Rural settlements as far as 70 km east of Öræfajökull were damaged by the tephra fall, and many were abandoned for several years. Another explosive eruption of benmoreitic composition (T. Prestvik, personal

![Stratigraphy of the tephra deposit from the 1362 eruption at Öræfajökull, measured at Bleikafjall about 4 km east of the crater.](image-url)
communication) occurred in late August 1727. Its volume was small compared with the 1362 eruption and probably did not exceed 0.2 km$^3$ of tephra (Thorarinsson, 1958).

4. Description of the tephra layer

Three separate tephra sections of the 1362 Öræfajökull eruption were observed and measured initially. The thickest and most complete section at Bleikafjall (Figs. 2 and 3) about 4 km SSE of the summit crater was selected for further detailed study. The sections show no signs of cross-stratification, bedforms, ripples or other indication of surge or pyroclastic flow, or erosional disturbances in relation to glacial or fluvial activity. This suggests that the layers were deposited continuously during a single eruption. The lack of signs of depositional breaks between the layers and the occurrence of accretionary lapilli, as well as irregular and angular pumice, all indicate that the deposits represent a fallout sequence.

The 181 cm thick section at Bleikafjall can be divided into 14 separate units based on grain-size distribution and abundance of pumice and lithic fragments (Fig. 3). The units range in thickness from 3 to 24 cm. The tephra varies from translucent to white and gray. A colour change to light brown, caused by the lithic fragments, is found in the lower units 13 and 14 (Fig. 4). The slight colour changes through the rest of the sequence can possibly be related to variable oxidation of the ash layer.

5. Analytical methods

The grain-size distribution of the 1362 tephra was determined by two methods. The coarse fraction was sieved by hand, measuring the intermediate diameter of each particle. The fraction $<1$ mm was analyzed by laser diffraction on a Malvern Mastersizer 2000 with a Hydro 2000 MU. Each sample was measured 3 times for 15 s at a pump speed of 2500 RPM. The interval from 0.25 to 1.0 mm was analyzed by both methods in order to check and calibrate the results.

Major and trace elements were analyzed by X-ray fluorescence spectrometry (XRF) using glass beads and
Table 1
Whole-rock analyses of tephra from the 1362 eruption at Öræfajökull

<table>
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<th>2</th>
<th>3</th>
<th>4</th>
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<th>14</th>
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<td>69.5</td>
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<td>0.28</td>
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Rb  77  76  77  76  75  75  74  76  77  74  76  77  78  76  69  1
Sr  75  72  68  72  79  70  70  68  78  72  73  67  81  110  3
Ba  592  577  575  571  571  587  581  587  594  562  592  579  590  554  10
Y   110  110  110  109  110  110  110  110  109  110  109  109  110  110  10
Zr  755  756  757  764  782  766  769  761  768  767  765  762  755  697  7
V   5  8  4  5  4  4  3  6  3  6  4  6  13  61  2
Nb  76  76  76  75  76  76  77  74  75  76  76  75  72  1
Th  11  10  11  11  9  10  12  12  12  12  13  12  11  12  11  1
Sc  3  4  1  2  3  3  2  2  2  2  2  4  1  2  6  1
Zn  155  153  153  155  157  154  154  154  155  154  155  155  157  156  1
Ga  28  28  28  28  28  28  28  28  28  28  28  28  28  28  29  27  1

Major elements in wt.%, trace elements in ppm.
pressed powder pellets, respectively, at the Universities of Tromsø (1998, whole-rock tephra samples) and Freiburg (2006, whole-rock pumice fragments from selected samples). The estimated analytical precision is listed in Tables 1 and 2 (1σ). The total compositional ranges of the tephra samples (1–12), recording minor crystal fractionation in the eruption column (0.8–3.8 wt.% crystal content), correspond to about 4σ. The compositional variation of the pumice samples with 0.5–1 wt.% crystal content, however, corresponds to about 2σ. The minor deviations between the whole-rock tephra and pumice fragment compositions in absolute terms are caused by interlaboratory bias between the Tromsø and Freiburg XRF-laboratories.

Polished sections of pumice fragments from 6 selected samples were analyzed by wavelength-dispersive electron microprobe at the Institut für Mineralogie, Petrologie und Geochemie, Albert-Ludwigs-Universität Freiburg. Operating conditions were 15 kV, with a beam current of 8 nA. In order to minimize sodium loss, sodium was counted first for 8 s, then the other elements for 20 s. The analytical accuracy is considerably lower than that of the tephra XRD analyses, partly related to Na-migration under the electron beam. In spite of our efforts to reduce these effects, it seems clear that the analyses suffer from considerable Na-deficiency. Based on the analysis of glass standards, we estimate this deficiency to be 10–20%.

Mineral grains and lithic fragments were separated from the glass by panning under water, followed by heavy liquid separation and handpicking. The mineral separates were mounted in epoxy and polished, prior to mineral analysis by wavelength-dispersive electron microprobe at the Nordic Volcanological Institute, University of Iceland (rebuilt and upgraded 7-channel ARL-SEMQ instrument). The detectors for Si, Al, Fe and Ca have fixed positions and the three remaining detectors are mobile, motor-driven spectrometers. Natural and synthetic standards were used for calibration, and the data were corrected for background using a mean atomic number procedure. Operating conditions were 20 nA and 15 kV, except for feldspar, which was analyzed with a beam current of 10 nA in order to minimize sodium loss. Based on repeated analyses of standards and samples, the analytical error (1σ) appears to exceed the extremely limited compositional variations of each of the minerals plagioclase, clinopyroxene and olivine (Table 3).

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<td>1.58</td>
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The analyses cover 1–4 analytical spots on 8–15 grains of each mineral in each of the 14 tephra units.

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Pl (1σ)</th>
<th>CPX (1σ)</th>
<th>Ol (1σ)</th>
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<td>47.7 (1.0)</td>
<td>29.8 (0.6)</td>
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<td>TiO₂ (wt.%)</td>
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<td>0.48 (0.11)</td>
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<tr>
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<tr>
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<tr>
<td>MnO (wt.%)</td>
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<td>2.79 (0.20)</td>
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<tr>
<td>MgO (wt.%)</td>
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<td>–</td>
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<td>Cr₂O₃ (wt.%)</td>
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<td>Sum</td>
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<td>99.48</td>
<td>98.88</td>
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The analyses cover 1–4 analytical spots on 8–15 grains of each mineral in each of the 14 tephra units.

Pl=An₁₄Ab₈₁Or₅ oligoclase.
Average of 150 EMP analyses.
CPX=Wo₄₄.₃En₂₂.₂Fs₅₂.₇ hedenbergite.
Average of 140 EMP analyses.
Ol=F₆₈.₇–F₉₃.₃ fayalite.
Average of 135 EMP analyses.
(−) Below detection.

Table 3
Mineral compositions of the 1362 Öræfajökull tephra from units 1 to 14

Major elements in wt.%, trace elements in ppm. XRF analyses carried out at Geochemisches Institut, Albert Ludwigs University.
6. Grain-size distribution and proportion of crystals and lithic fragments

The fallout is extremely fine-grained vesicular glass with bubble wall thicknesses of 1–5 μm. Needle-like glass fragments in the pumice indicate exsolution of magmatic gases and vesiculation of the melt during fast magma ascent. The grain-size fraction less than 0.25 mm makes up 53–84 wt.% of the samples, and the grain-size spectra have 3 distinct peaks with maximum fragmentation (Figs. 5 and 6).

The total amount of phenocrysts in the pumice samples is 0.5 to 1 wt.%, based on the measured proportions in larger pumice fragments in this section. This is considered to be representative of the crystal content of the magma. The mineral proportion in the bulk fallout tephra is between 0.5 and 3.8 wt.% and negatively correlated with the proportion of the finest grain size fractions of the tephra. The variation in mineral content between pumice and tephra is related to gravitational separation in the fallout column. Oligoclase, fayalite and hedenbergite constitute 50–80, 10–25, and 10–25 wt.% of the phenocryst populations, respectively.

The grain-size distribution shows that the eruption proceeded in three successive stages. Whereas the initial phreatomagmatic stage produced debris with 12–35% lithic fragments in the grain-size fraction 1–0.25 mm (samples 13 and 14), the lithic fragment content is below 3% in the rest of the section. The lithic fragment population is dominated by basalt and rhyolite, but minor amounts of hyaloclastite tuff, andesitic and trachytic lavas, chalcedony, and shale are also present. In distal facies of the fallout tephra, the initial phase is recognized as a pale brownish basal layer with about 3% lithic fragments below the otherwise white glassy ash (Thorarinsson, 1958).

7. Geochemistry

7.1. Tephra composition

The major and trace element analyses for the bulk tephra samples show remarkably similar compositions,
except for the stratigraphically lowest samples, 13 and 14 (Table 1). The compositions of samples 13 and 14 are related to high contents of lithic fragments, and the bulk tephra chemistry of these samples will not be considered in the following discussion. The total range of major and trace element abundances of samples 1–12 is very limited and comparable to the estimated 4σ-range of the XRF analyses (Table 1, Fig. 7). Weak, but significant, correlations between various elements and the total mineral content recorded for each sample are consistent with the observed phenocryst assemblage of oligoclase, fayalite and hedenbergite in proportions 4:1:1 (weight proportions). Most of the major elements and some of the trace elements are shown as functions of the total crystal content of the tephra in Fig. 7. The elements enriched in the minerals relative to the melt (e.g. Al, Na, Ca, Fe, Ti, Mn, Sr, and Ba) are positively correlated with the crystal content, whereas other elements (e.g. Si, K, Rb, Cl, S and H, expressed as LOI (loss on ignition)) show weak negative correlations with the mineral content. This observation indicates that the glass composition throughout this tephra section is even more homogeneous than the whole-rock tephra samples with total crystal contents of 0.8–3.8% (i.e. samples 1–12).

Our best estimate for the glass compositions are derived from the intersection of least squares regression lines (element concentration as function of the total crystal content) with the zero percent mineral axes. Because the analytical uncertainty is considerably lower for the XRF analyses than for the EMP analyses, this estimate is probably a more reliable value for the melt composition than the direct melt analyses. The relative changes between the linear regression values for 0% and 3.75% crystals are greatest for the volatile content, expressed by the LOI value. LOI is 23% higher in the 100% melt composition, indicating that fractional crystallization enriches the melt in H and S. Water is clearly the dominant volatile component, because the total variation in S and Cl is only 150–200 ppm and minor variations in the oxidation state of Fe cannot affect the LOI variation to a significant extent. The relatively large increase in water content expressed as LOI from the tephra with more than 2.5% crystals to tephra with less than 1% crystals may, however, largely be related to the accompanying glass fragmentation increase and attributed to depositional processes in the fallout from the eruption column.

The composition of the 1362 AD rhyolite is similar to other rhyolites from Öræfajökull (Prestvik, 1985). The Al₂O₃ (13.1 wt.%) and K₂O (3.28%) contents are lower and higher, respectively, compared to Icelandic rift zone rhyolites at a corresponding SiO₂ content of 69.4% (e.g. Oskarsson et al., 1982; Nicholson et al., 1991). Furthermore, the contents of P₂O₅ (0.03%) and Na₂O (5.37%) are higher, and that of CaO (1.14%) is lower, than in corresponding rift zone rhyolites (0.01%, 3.9% and 2.7%, respectively, at the 69.4% SiO₂ level for the Krafla compositional trends of Nicholson et al., 1991).

7.2. Pumice composition

Additional whole-rock analyses of pumice fragments from six selected tephra layers were performed in order to further investigate the potential effects of gravitational fractionation of crystals and glass in the eruption column (Table 2). The compositional variation of the pumice, corresponding to about 2σ (Table 2), is slightly smaller than the compositional range of the tephra samples 1–12. The minor interlaboratory deviations between the Tromsø and Freiburg XRF-laboratories are larger than any detectable systematic variation between the pumice samples with a crystal content of 0.5–1 wt.% and the tephra samples (1–12) with 0.8–3.8 wt.%
crystals. The pumice composition therefore confirms the extremely homogeneous nature of the magma.

7.3. Glass composition

The glass samples have identical compositions within the estimated analytical uncertainty and they are compositionally similar to the whole-rock tephra (Table 4). However, the minor crystal content of the tephra results in slightly higher Si and K and lower Ti, Al, Fe, Ca and Na of the glass (Table 1). Due to the estimated Na-deficiency of 10–20% in our analyses, we compare the data assuming a 15% Na-deficiency. The pumice glass from the sampled tephra section and the linear regression estimate of melt compositions from the tephra analyses are compositionally identical within analytical uncertainty to glass shards from tephra horizons from the 1362 AD eruption sampled in the Óræfa district, Svinafell (10 km west of the summit), Lofoten (northern Norway) and northern Ireland (Sigurdson, 1982; Palais and Sigurðsson, 1989; Pilcher et al., 1995; Larsen et al., 1999; Pilcher, 2005). A comparison of these analyses on a volatile-free basis (normalized to 100%) is presented in Table 5. The lack of variation exceeding the EMP-analytical uncertainty indicates that almost the entire erupted magma volume had a uniform composition. The analyses of assumed Óræfajökull 1362 tephra in ice cores from the central Greenland ice cap (Palais et al., 1991), however, differ markedly from the compositions presented in Table 5. The unusually high silica content of 76.9 wt.% and the large analytical uncertainty quoted for these analyses indicate that this discrepancy may be due to analytical errors.

Table 5 also demonstrates that the average glass composition has slightly higher Si and K and lower Al, Na, Ca, Fe, Ti, Mn and Mg than the average tephra composition. Least squares mass balance fractionation....

<table>
<thead>
<tr>
<th>Sample</th>
<th>Average</th>
<th>1σ</th>
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| SiO2   | 71.4    | 70.8
| TiO2   | 0.23    | 0.25
| Al2O3  | 13.4    | 13.8
| FeO    | 3.29    | 3.49
| MnO    | 0.11    | 0.09
| MgO    | 0.01    | 0.02
| CaO    | 0.99    | 1.10
| Na2O   | 4.71    | 4.70
| K2O    | 3.40    | 3.31
| Sum    | 97.75   | 97.74

Major elements in wt.%.  

Fig. 7. Total mineral content (wt.%) versus major and trace elements in tephra samples 1–12. The analyses are normalized to 100% (including loss on ignition, LOI), and the thin lines are linear regression curves with associated equations. Estimated average 2σ error bars are shown for each of the elements or oxides. The linear regression equations are used to derive an estimate of the crystal-free melt composition (Table 5 and text).
modeling relating the compositions and proportions of the minerals to various bulk tephra and glass compositions gives solutions that are consistent with the observed proportions of oligoclase, fayalite and hedenbergite (with or without minute quantities of ilmenite). However, the solutions generally overestimate the total mineral content (3–9%), relative to the observed maximum mineral content of 3.8% in sample 11.

7.4. Mineral morphology and chemistry

The mineral assemblage of the 1362 tephra is composed primarily of euhedral to subhedral oligoclase and euhedral fayalite and hedenbergite. There is no sign of crystal resorption by the melt, and the crystal diameters are generally less than 1 mm for plagioclase and about 0.5 mm for olivine and clinopyroxene. Ilmenite and titanomagnetite occur as inclusions in clinopyroxene and olivine. The small and mostly euhedral silicate phenocrysts are remarkably homogenous with no detectable zonation, indicating that the minerals are in or close to compositional equilibrium with the erupted rhyolite melt. The entire compositional variation is within the analytical precision (Table 3).

The mineral compositions are shown in Fig. 8. The oligoclase crystals have composition An14Ab81Or5.5. The hedenbergites occur as long prismatic crystals, and contain inclusions of ilmenite, titanomagnetite and glass. The hedenbergite composition is Wo44.7En2.6Fs52.7. The fayalite phenocrysts (Fa99.7Fo0.3) contain inclusions of ilmenite, titanomagnetite, pyroxene and glass. Some of the fayalite crystals show indications of rapid crystallization with elongated glass inclusions parallel to the c-axis.

The included oxides have occasionally characteristic octahedral shapes. Black metallic hexagonal plate-shaped crystals of hematite are observed in all layers, except layers 13 and 14, indicating oxidation of the melt during the eruption.

8. Discussion

The investigated tephra section, located 7–8 km from the main crater, documents the uniform mineralogical and chemical composition of the erupted magma and the overall intensity of the main plinian eruption. Although this section cannot provide complete information about the entire magma volume, additional analyses of glass shards from the...
associated tephra horizon covering a 3000 km wide area including Iceland, central Greenland, northern Norway and Ireland indicate that the entire erupted magma was uniform rhyolite with a melt compositional range comparable to or lower than the analytical uncertainty of the EMP analyses used. The whole-rock tephra analyses presented by Thorarinsson (1958) and Prestvik (1985) are probably also identical to our analyses within analytical errors.

The field relations, including accretionary lapilli and angular pumice fragments, demonstrate that the investigated sections of 1362 AD Öræfajökull tephra represent in-situ airfall deposits. The high proportion of lithics in the lowermost tephra unit indicates that the eruption started with a major conduit- and vent-opening explosion event, followed by a relatively constant jet through an open conduit. The lithic fragment content is a sensitive indicator of the competence and stability of the conduit wall rocks. The undisturbed nature of the airfall tephra sections at relatively high-altitude locations near the summit crater of Öræfajökull indicates that the volcano did not have a very thick ice cover before the eruption. Historical accounts, confirm a thin summit glacier prior to the eruption (e.g. Thorarinsson, 1958). Accretionary lapilli found in the fine-grained tephra layers are generally assumed to be diagnostic of combined ashfall and rain. High air humidity may also be related to a steam-rich eruption column caused by melting of the ice cover.

The negative correlation between fragmentation level and crystal content may be related to differential settling velocity in the fallout zone to the eruption column. During periods of high wind speed and/or turbulence the coarser ash and pumice fragments as well as the denser mineral fragments will settle preferentially nearer the source than the finer ash. These stratigraphic variations in grain size may reflect intensity variations in the eruption column.

8.1. Magma chemistry, equilibrium conditions and volatile content

The extreme compositional homogeneity of the glass and phenocrysts of the 1362 AD tephra is remarkable for a rhyolitic eruption unit of 2 km³ DRE. The homogeneity of melt and minerals and the uniform and low crystal content of the tephra throughout the eruption indicate a well-equilibrated magma reservoir. It is possible that the erupted tephra was extracted only from the upper portions of a much larger and compositionally zoned reservoir.

There are almost no other documented examples of rhyolites or granites with crystallization assemblages very similar to the Öræfajökull 1362 AD tephra. Whereas other rhyolites from the Öræfajökull complex have similar bulk composition and phenocryst mineralogy (Prestvik, 1985), they do not have plagioclase, olivine and clinopyroxene with as high proportions of the albite, fayalite and hedenbergite end members as the 1362 AD tephra.

The other examples of crystallization assemblages that most closely match the 1362 tephra seem to be the granophyres of the late-stage differentiates of the Skaergaard and Bushveld complexes (e.g. Wager and Brown, 1968). The most differentiated cumulus mineral assemblages observed in both Skaergaard and Bushveld are An₃₀, Fo₀ and W₀₄₂–₄₃En₀–₁Fs₅₇. Both of these assemblages include magnetite and the Skaergaard assemblage also includes ilmenite and apatite. The similarity with the 1362 tephra is close, although the 1362-tephra plagioclase is considerably more albitic than the granophyre plagioclase. The assumed parental magma compositions of the Skaergaard intrusion and the Öræfajökull volcanic system (e.g. Prestvik, 1985; Nielsen, 2004, Trønnes et al., unpublished analyses) are similar high Fe–Ti–tholeiitic basalts. The higher (Na+K)/Ca and (Na+K)/Al ratios in the Öræfajökull tholeiites (0.39 and 0.27, respectively) compared to the Skaergaard parental magma estimate (0.29 and 0.21, respectively) may explain the higher proportions of albite and orthoclase in the most differentiated plagioclase of the Öræfajökull tephra. The Skaergaard granophyre compositions are also broadly similar to...
the 1362 tephra, but with considerably lower (Na+K)/Ca and (Na+K)/Al ratios (Wager and Brown, 1968).

The almost pure fayalite and hedenbergite mineral compositions of the 1362 magma make it difficult to model the $P$–$T$ conditions of the mineral–melt equilibria with common thermodynamics-based software. The mineral–melt assemblage does indicate, however, that the water and oxygen fugacities of the magma were relatively low. The simultaneous incipient crystallization of oligoclase (Ab$_{81}$Or$_{5}$), fayalite, hedenbergite and Fe–Ti-oxides reflects a melt composition with high Fe, Ti, Na and K, relative to Mg, Ca and Al.

The lack of hydrothermal activity in the Öræfajökull area may indicate that the magma evolution and differentiation occurred in deep crustal reservoirs. The crust under Vatnajökull is 30–40 km thick (Kaban et al., 2002) and a deep-seated magma chamber system is possible. Multiple magma reservoirs have been inferred elsewhere in Iceland, e.g. in relation to the 1984 Krafla eruption (Tryggvason, 1986). Hildreth (1981) suggested that large eruptions of non-basaltic magma tap thermally and compositionally zoned magma reservoirs. Normally, as the eruptions proceed, successively deeper magma chamber levels may be tapped, until eventually more mafic scoria accumulates on top of the earlier erupted silicic pumice. Many of the largest plinian eruptions from Icelandic volcanoes have resulted in tephra deposits grading upwards from silicic pumice to intermediate and mafic scoria. In particular, the large Holocene eruptions from Icelandic volcanoes have resulted in tephra deposits resulting in rapid subsidence of the partially altered and hydrothermally altered wall rocks.

Beard and Lofgren (1989, 1991) determined the compositional characteristics of silicic melts in equilibrium with metasabasaltic lithologies at 0.1–0.3 GPa at $H_{2}O$-saturated and $H_{2}O$-undersaturated (dehydration melting) conditions. The combined SiO$_{2}$, FeO$_{total}$ and Al$_2$O$_3$ contents of the Öræfajökull rhyolites indicate a relatively dry magma. The Al$_2$O$_3$ content of the melts is positively correlated with $P_{H_{2}O}$, increasing with increasing $H_{2}O$ content. The low Al$_2$O$_3$ content (13.1 wt.% of the rhyolitic tephra is below the dehydration melting field (Thy et al., 1990; Beard and Lofgren, 1991).

Compared to most rhyolites and basalts in a mid-ocean ridge setting, Icelandic rhyolites and basalts generally have elevated K$_2$O content. This is even more pronounced in the flank zone rhyolites (Thy et al., 1990). The high K$_2$O content of 3.3 wt.% in the 1362 AD tephra is a typical example of the latter type. Experimental data show that the K$_2$O content of silicic melt formed by dehydration melting of a metasabasaltic source is a function of the K$_2$O content of the starting material. Water-saturated melting, stabilizing residual amphibole, yields K$_2$O-poor melts (e.g. Beard and Lofgren, 1989; Thy et al., 1990; Beard and Lofgren, 1991). The high K$_2$O content of the Öræfajökull 1362 AD silicic tephra is consistent with a large proportion of fractional crystallization of a relatively dry melt as opposed to melting of a water-rich metasabaltic source containing residual amphibole. The Cl, Ba and Zr contents are higher in the Öræfajökull 1362 AD tephra (Table 1) than in average Icelandic rift-zone rhyolites, although some rift-zone rhyolites are within the same compositional range (Jonasson, 1994).

Igneous hornblende is stable in silicic melts at $H_{2}O$ contents above 4–5 wt.%, and temperatures less than about 950 °C at all crustal pressures (Burnham, 1979; Naney, 1983; Merzbacher and Eggler, 1984; Rutherford and Devine, 1988). Such $H_{2}O$ contents require a minimum total pressure of 0.1 GPa, with $P_{total} \geq P_{H_{2}O}$ (Burnham, 1979). The lack of amphibole in the Öræfajökull silicic rocks, as well as in most other Icelandic rhyolites (e.g. Grönvold, 1972; Jonasson, 1994), indicates that the $H_{2}O$ contents of the melts prior to eruption were less than 3–4 wt.%. The main exception to the general lack of amphibole in Icelandic rhyolites is found in the Torfajökull central volcano, which is the largest silicic centre in Iceland (e.g. Gunnarsson et al., 1998). The Torfajökull volcanic system is also the largest and most powerful high-temperature geothermal area in Iceland, with extensive and pervasive hydrothermal alteration. The appearance of amphibole in the silicic melts may therefore be related to supply of hydrothermal solutions to the melt either directly from groundwater or via anatectic contributions from hydrothermally altered wall rocks.

8.2. Rhyolite petrogenesis in volcanic rift zones and flank zones

The Icelandic rift zones are continuously covered by new lava flows and hyaloclastite deposits, while older units subside under the surface load. The volcanic productivity of the Icelandic rift zones is anomalously high relative to the half-spreading rate of 10 km/Ma, resulting in rapid subsidence of the partially altered and hydrated volcanic pile. Pálsson (1973) and Oskarsson
et al. (1982) developed models for crustal accretion and petrogenesis in Iceland.

Major and trace element compositional variation and a strong decrease in $^{18}$O/$^{16}$O ratios from basalts to rhyolites indicate that anatexis of the hydrothermally altered pile of subsiding basalts contributes significantly to the generation of silicic melts in the rift-zone central volcanoes (e.g. O’Nions and Grönvold, 1973; Sigvaldason, 1974; Muehlenbachs et al., 1974; Oskarsson et al., 1982; Hemond et al., 1988; Nicholson et al., 1991; Jonasson, 1994; Gunnarsson et al., 1998). Melting of magma chamber wall rocks is promoted by fractional crystallization of the mafic to intermediate magmas. The presence of live $^{10}$Be (2.1–2.9 $\times$ $10^6$ atoms/g) in fresh obsidian samples from central volcanoes of the Icelandic rift zones demonstrates further that the time period from hydrothermal alteration to crustal melting is short and that $^{10}$Be is partitioned efficiently from the hydrothermal fluid via the alteration assemblage to the partial melt (Grönvold et al., 2000).

The existing geochemical data for a range of basaltic, intermediate and silicic rocks of the Öræfajökull system demonstrates a different scenario (Prestvik et al., 2001). The O–Sr–Nd–Pb isotopic data show no systematic and significant difference between the basaltic, intermediate and rhyolitic units. O–isotopic data for other flank zone volcanic systems, e.g. the Snæfell, Vestmannaeyjar, Snæfellsjökull and Ljósufjöll, demonstrate a similar uniformity between evolved rocks and basalts (Sigmarsson et al., 1992; Hards et al., 2000). The analogous phase relations of the 1362 AD tephra and the Bushveld and Skaergaard granophyres may support the contention that the production of intermediate and silicic melts in Öræfajökull is mostly a result of fractional crystallization.

The indication that the volcanic flank zone magmas formed and evolved under lower water activity than the rift zone magmas is consistent with the lack of extensive geothermal activity in the flank zone central volcanoes. This limits the hydration of the crust and may lead to more extensive fractional crystallization accompanied by latent heat dissipation without bringing the wall rocks to their solidus temperatures. The limited amounts of crustal anatexis in the silicic melt generation may be understood in light of the thicker, cooler and stronger non-rifting crust and lithosphere. The more limited volcanic loading combined with cooler and stronger crust prevents significant subsidence of hydrated basalts.

8.3. Magma chamber volume and residence time

An erupted volume of 2 km$^3$ DRE rhyolitic tephra indicates a large magma reservoir prior to eruption. A rhyolitic melt fraction formed by fractional crystallization from basaltic via intermediate melt compositions constitutes 15–30% of the parental basaltic magma batch. The alternative model where rhyolitic melt is formed by crustal anatexis above and peripheral to a fractionating mafic magma reservoir would require similar volume relations (e.g. Oskarsson et al., 1982; Jonasson, 1994; Gunnarsson et al., 1998). The extraction of magma from crustal reservoirs is generally far from complete, with a commonly quoted extraction efficiency of 0.1–10% (e.g. Bower and Woods, 1998 and reference therein). Assuming that a magma chamber can erupt maximum 10% of its total volume, the Öræfajökull 1362 chamber was at least 20 km$^3$. A basaltic intrusion into such a large magma chamber would not necessarily result in eruption of basaltic lava fragments, but might result in a volume change and a heat flow perturbation in the magma chamber capable of triggering an eruption.

Shallow crustal magma chambers are geophysically indicated beneath the Icelandic volcanoes Krafla, Askja, Grimsvötn and Katla and are all in the rift zone (e.g. Gudmundsson et al., 1994; Brandsdottir et al., 1997; Gudmundsson and Milsom, 1997; Sturkell and Sig mundsson, 2000). The largest of these seems to be the Krafla chamber with an estimated volume of 12–54 km$^3$ (Brandsdottir et al., 1997).

Whereas petrogenetic and crustal deformation models of volcanoes often favour large magma chambers, some seismic attenuation studies have failed to detect such reservoirs. Under the active and frequently erupting Hekla volcano (6 eruptions since 1947), for instance, there is no seismic indication of any significant magma volume above 14 km depth (Soosalu and Einarsson, 2004). This is puzzling in view of the apparent need for a crystal fractionation chamber and the results from crustal deformation modeling, indicating a magma source located at 5–9 km depth (e.g. Kjartansson and Grönvold, 1983; Sigmundsson et al., 1992; Linde et al., 1993; Trygvason, 1994).

Seismic attenuation zones are also absent beneath the neighboring Torfajökull central volcano, which has erupted 3 times during the past 2000 years. The current seismicity pattern within the 12–18 km wide Torfajökull caldera indicate a cooling, but mostly solidified, magma body 4 km in diameter located at about 8 km depth (Soosalu and Einarsson, 2004). Therefore, magma chambers may be relatively short-lived features. This inference is supported by magma chamber fractionation times of about 10 years calculated from U-series disequilibria in samples from the Vestmannaeyjar volcanic systems (Sigmarsson, 1996). In general, recent U–Th-disequilibria studies of zero-age volcanic rocks indicate
that melt generation, porous flow, segregation, fractionation and eruption are surprisingly efficient and rapid processes (e.g. Turner et al., 1986; McKenzie, 2000).

There is no geophysical indication of any major upper crustal (<10–15 km depth) magma reservoir beneath Öræfajökull today, even if such reservoirs were present prior to the 1362 and 1727 eruptions. A time span of 300 years or less may well be sufficient for the generation and shallow injection (and/or eruption) of rhyolitic melt beneath Öræfajökull. The volcanic risk assessment for south Iceland should take such a scenario into account. A plinian eruption, equivalent to the 1362 event, would potentially have severe consequences for Iceland, especially during periods of prevailing easterly winds.

9. Conclusions

The investigated 1.8 m thick pyroclastic section from the Öræfajökull eruption of 1362 represents a tephra-fall deposit from a plinian or phreatoplinian eruption. The total erupted magma volume is estimated to 2 km³ DRE and the plinian phase lasted probably 1–2 days. The high proportion of ash with grain size less than 250 μm (mostly 60–80 wt.%) and the predominance of thin-walled glass shards demonstrate a high degree of fragmentation driven by extensive gas release in the conduit. The grain-size variation through the investigated section indicates that the eruption had 3 intensity peaks of fragmentation.

The initial vent-clearing phase of the eruption is documented by large proportions of lithic fragments in the lowermost section (10–35 wt.% lithic fragments in the lowermost 10–15 cm of the section). The low amount of lithics in the rest of the section (<3 wt.%) indicates that the eruption continued from a single and stable vent. The vent location was probably within the 3–4 km wide summit caldera, which is covered by a glacier.

Remarkably homogenous melt and phenocryst compositions throughout the entire tephra section reflect a magma chamber where about 99 wt.% rhyolitic melt attained complete equilibrium with about 1 wt.% of oligoclase, hedenbergite and fayalite. The large eruption volume and the complete lack of other erupted magma compositions place important constraints on the total volume of the magma reservoir. Assuming a maximum fraction of erupted material of 10%, the total volume of the magma reservoir was at least 20 km³. For a compositionally zoned magma chamber, with the homogeneous rhyolite confined to the uppermost part, this must be a very conservative estimate.

The currently largest shallow magma reservoir in Iceland inferred from geophysical data is the basaltic Krafla magma chamber (12–54 km³), but the reservoir associated with the 1783 AD Laki eruption of 15 km³ evolved basalt (Sigmarsdóttir et al., 1991; Thordarson and Self, 1993) might have been 1–2 orders of magnitude larger.

The short timescales of magma generation, differentiation and magma chamber residence derived from U–Th-series disequilibrium studies (10–100 years) imply that the generation and evolution of a rhyolitic magma volume equivalent to the Öræfajökull 1362 reservoir can be accomplished within a few hundred years. This has important implications for the volcanic risk assessments of potentially very hazardous Icelandic rhyolite volcanoes like Öræfajökull.

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