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Explosive subglacial rhyolitic eruptions in Iceland are fuelled by high magmatic $\text{H}_2\text{O}$ and closed-system degassing.

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ABSTRACT

Rhyolitic eruptions beneath Icelandic glaciers can be highly explosive, as demonstrated by Quaternary tephra layers dispersed throughout northern Europe. However, they can also be small and effusive. A subglacial rhyolitic eruption has never been observed, so behavioral controls remain poorly understood and the influence of pre-eruptive volatile contents is unknown. We have therefore used secondary ion mass spectrometry to characterize pre-eruptive volatile contents and degassing paths for five subglacial rhyolitic edifices within the Torfajökull central volcano, formed in contrasting styles of eruption under ice ~400 m thick. This includes the products of the largest known eruption of Icelandic subglacial rhyolite of ~16 km$^3$ at ca. 70 ka. We find pre-eruptive water contents in melt inclusions ($\text{H}_2\text{O}_{\text{MI}}$) of up to 4.8 wt%, which indicates that Icelandic rhyolite can be significantly more volatile rich than previously thought. Our results indicate that explosive subglacial rhyolite eruptions correspond with high $\text{H}_2\text{O}_{\text{MI}}$, closed-system degassing, and rapid magma ascent, whereas their effusive equivalents have lower $\text{H}_2\text{O}_{\text{MI}}$ and show open-system degassing and more sluggish ascent rates.
Volatile controls on eruption style thus appear similar to those for subaerial eruptions, suggesting that ice plays a subsidiary role in controlling the behavior of subglacial rhyolitic eruptions.

**INTRODUCTION**

During subaerial eruptions, volatiles are considered a key factor in determining eruptive style, with (1) a high pre-eruptive H$_2$O and CO$_2$ content and (2) closed-system degassing leading to more-explosive volcanism (Eichelberger et al., 1986; Jaupart, 1998; Martel et al., 1998; Cashman, 2004). During subglacial eruptions, there are additional controlling factors that are poorly understood; e.g., a component of explosivity is thought to be influenced by the degree of magma-water interaction (Tuffen et al., 2001; Guðmundsson, 2005). However, experimental rhyolite-water interactions suggest that vesicles may actually hinder phreatomagmatic explosions (Austin-Erickson et al., 2008).

Unlike for subaerial eruptions, it is therefore unclear whether high volatile contents favor or inhibit explosive eruptions of rhyolite beneath ice.

Subglacial rhyolitic edifices have a wide spectrum of sizes, morphologies, and lithofacies, reflecting varying degrees of explosivity and the added complexities of a subglacial eruption setting (McGarvie, 2009). Eruptive products range from vesicle-poor quench hyaloclastites (Tuffen et al., 2001, 2008) to fine-grained, pumiceous pyroclastic deposits (Tuffen et al., 2002, 2008; Stevenson et al., 2011). Edifices range from small ($<$0.1 km$^3$) mounds and ridges to large ($\sim$1 km$^3$) steep-sided, flat-topped tuyas, representing effusion-dominated and explosion-dominated activity respectively (Tuffen et al., 2007). However, eruption controls are poorly constrained, partly due to a lack of observed eruptions. Speculative models have suggested effusive activity is favored by
either low initial volatile content (McGarvie et al., 2007; Stevenson et al., 2011), gas escape from magma (open-system degassing) (Furnes et al., 1980), the filling of subglacial cavities by erupted products (Tuffen et al., 2007, 2008), or thick overlying ice (Tuffen, 2010).

Iceland’s largest known subglacial rhyolitic eruption, the ~16 km$^3$ ring fracture eruption at Torfajökull (ca. 70 ka), mostly involved explosive tuya-forming activity (McGarvie et al., 2006). The eruption punctured an ~400-m-thick ice sheet at a number of localities (McGarvie et al., 2006), generating widespread tephra layers, probably including the 6-cm-thick layer recently discovered in a marine core from the Norwegian Sea (Brendryen et al., 2010). It is presently unclear whether this was one continuous eruption (McGarvie, 1984) or several closely spaced events (Brendryen et al., 2010).

Better understanding of eruption controls is essential for hazard mitigation and reduction of socio-economic impact, especially given Iceland’s mid-Atlantic location. Explosive Icelandic eruptions can disrupt trans-Atlantic and/or European commercial flights, as demonstrated by the 2010 Eyjafjallajökull and 2011 Grímsvötn eruptions (Petersen et al., 2012).

METHODS

We have determined the pre- and post-eruptive volatile contents, and reconstructed degassing paths, for five contrasting subglacial rhyolite edifices at Torfajökull (Fig. 1; Table 1) including four edifices from the ca. 70 ka ring fracture event: southeast Rauðfossafjöll and Sökkull Tuya, which were both explosive and burst through the ice to produce tuyas (Tuffen et al., 2002); Dalakvísl, which formed through mixed explosive-effusive activity (Tuffen et al., 2008); and Kökufjall, a small, effusively
formed edifice. The fifth edifice is Bláhnúkur, a small effusively generated edifice (Tuffen et al., 2001), formed during a different eruption during the last glacial period (Owen et al., 2012). Grain-size distributions were acquired to confirm and quantify field observations relating to the degree of magma fragmentation and explosivity of these eruptions.

The volatile content of feldspar- and pyroxene-hosted melt inclusions (MI) and matrix glasses were analyzed using secondary ion mass spectrometry (SIMS). We used the “one-by-one approach” of Johnson et al. (1994) to identify MI that may have gained water. The matrix glass of every sample was analyzed using Fourier transform infrared spectroscopy (FTIR) to determine water speciation and therefore check for post-quenching hydration. Two samples identified as hydrated were discarded. Post-entrapment crystallization can cause volatile enrichment within MI, possibly leading to the formation of a vapor bubble (Steele-MacInnis et al., 2011). Therefore all bubble-bearing MI were discarded. Electron probe microanalysis (EPMA) data from MI and matrix glass suggest that post-entrapment crystallization played a minimal role in most of the remaining MI, as would be expected in rapidly quenched deposits (Lowenstern, 1995) emplaced beneath ice.

Our final data set consists of 62 analyses from 28 different MI within ten samples collected from five Torfajökull edifices. See the GSA Data Repository1 for additional geological background, sample descriptions, analytical and modeling methods, raw data, and data justification, including detail on identification of hydrated samples and post-entrapment modification processes.

RESULTS
Clear trends in volatile content are apparent (Fig. 2), with MI from effusive edifices (Kökufjall and Bláhnúkur) containing significantly less H$_2$O$_{MI}$ (≤1.8 wt%) than those from explosively formed tuyas (southeast Rauðfossafjöll and Sökkull Tuya; ≤3.9 wt%). Dalakvísl (mixed effusive-explosive) spans the full range of water contents, including the highest measured value of 4.8 wt% H$_2$O$_{MI}$ (Fig. 2). Low-H$_2$O$_{MI}$ effusive samples are also C-rich, whereas H$_2$O-rich, explosively-generated samples are Cl-poor (Fig. 2). The H$_2$O$_{MI}$ contents of feldspar- and clinopyroxene-hosted MI are similar. Matrix glasses contain 0.1–1.1 wt% H$_2$O$_{MI}$ (Fig. 2), consistent with quenching at elevated pressures beneath ice hundreds of meters thick (see Tuffen et al. [2010] for detailed explanation of quenching pressure and ice-thickness reconstruction from H$_2$O degassing). Inferred ice thicknesses (mostly ~400 m) from lithofacies and degassing models (McGarvie et al., 2006; Owen et al., 2012) differ little between edifices and show no correlation with behavior (Table 1), so diverging eruption styles are not attributable to different ice thicknesses.

The major-element composition of melt inclusions and matrix glasses from Bláhnúkur and the ring fracture event are broadly similar (70–76 wt% SiO$_2$), so compositional variation cannot explain the different eruptive styles. Some Bláhnúkur MI show SiO$_2$ enrichment and alkali depletion, consistent with post-entrapment feldspar crystallization, and so Bláhnúkur H$_2$O$_{MI}$ contents are maximum values. However, these are among the most H$_2$O-poor MI (≤1.8 wt%), so any volatile enrichment due to crystallization does not mask differences between edifices. SiO$_2$ enrichment is absent from Dalakvísl MI, suggesting that their high H$_2$O$_{MI}$ contents are original.

DISCUSSION
Behavioral Control of Pre-Eruptive Water Content

The pre-eruptive water content (H$_2$OM$_{MI}$) of the large-volume, predominantly explosive ca. 70 ka event is considerably higher than that of Bláhnúkur (smaller, effusive). However, the ca. 70 ka magma displays a range of H$_2$OM$_{MI}$, being lower at Kókufjall (≤0.3 wt% H$_2$OM$_{MI}$, effusive) than at Dalakvísl, southeast Rauðfossafjöll, or Sökkull Tuya (>2.9 wt% H$_2$OM$_{MI}$, explosive). Perhaps surprisingly, our highest measured H$_2$OM$_{MI}$ came from the small-volume Dalakvísl edifice (<0.2 km$^3$) rather than the larger-volume (~1 km$^3$) tuyas. However, Dalakvísl has the finest-grained and most-vesicular ash of any of our sampling locations, suggestive of efficient magma fragmentation (Stevenson et al., 2011) in a powerful but perhaps brief explosive phase.

We have therefore found a strong positive correlation between H$_2$OM$_{MI}$ and the explosivity of eruptions. H$_2$O is considered to be the most influential volatile species in terms of determining eruptive behavior during subaerial eruptions (Cashman, 2004); it may be equally important when eruptions occur beneath ice.

The differentiation between H$_2$O-rich/Cl-poor and H$_2$O-poor/Cl-rich MI suggests that different edifices are recording different source magmas (whether separate magma bodies, a volatile-stratified chamber, or temporal gaps for melt evolution) rather than progressive degassing of a single homogenous supply.

Degassing Paths and Open- Versus Closed-System Degassing

Measured H$_2$O-Cl trends (Fig. 2) have been modeled using H$_2$O-Cl degassing systematics for rhyolitic melts (Villemant and Boudon, 1998; Villemant et al., 2008; Humphreys et al., 2009). Each edifice shows a single, distinct H$_2$O-Cl trend, with the exception of Dalakvísl, which displays two different trends perhaps related to its bimodal
eruptive behavior. Data scatter prevents discrimination between open- and closed-system
degassing from degassing paths alone, but the chlorine distribution ratios \( D_{Cl} \) required
to fit effusive sample data (≥50) greatly exceed those for explosive sample data (≤30).
Microlite crystallization can drive an increase in \( D_{Cl} \) (Webster and De Vivo, 2002;
Villemant et al., 2008), and effusive samples are significantly more microlite-rich than
their explosive counterparts (Figs. 1E and 1F). Microlite crystallization occurs during
magma ascent and degassing (Lipman et al., 1985; Sparks et al., 2000) and is favored by
slow magma rise, which also favors open-system degassing (Jaupart, 1998). In contrast,
less microlite crystallization typically occurs during closed-system degassing (Martel et
al., 1998; Villemant et al., 2003, 2008). We therefore propose that our effusive samples
experienced slow ascent rates and open-system degassing, whereas our explosive samples
experienced fast ascent rates and closed-system degassing.

‘Wet’ Icelandic Rhyolite

Our data indicate far higher \( H_2O_{MI} \) than anticipated, as Icelandic rhyolite is often
quoted as being “dry” in the absence of melt inclusion analysis (Sigurdsson, 1977;
MacDonald et al., 1990; Jónasson, 2007). The only measurement to date of \( H_2O_{MI} \) in
Icelandic rhyolite (Öraefajökull, 2 wt%; Sharma et al., 2008) is significantly lower than
our measurements, as are matrix-glass \( H_2O \) data from rhyolite tapped into by an
exploratory well at ~2 km depth (Krafla, 1.77 wt%; Elders et al., 2011[Q1: The in-text
citation "Elders et al., 2011" is not in the reference list. Please correct the citation,
add the reference to the list, or delete the citation. Q1]). In addition, primitive
Icelandic basalts are considered to be dry (<1 wt% \( H_2O \); Nichols et al., 2002). Although it
is unclear whether the high \( H_2O_{MI} \) originates from partial melting of hydrated basalts at
depth (Martin and Sigmarsson, 2007) or by another mechanism such as partial fusion of hydrothermally altered silicic material at shallower depths (Macdonald et al., 1987), our unexpectedly high H$_{2}$OMI values clearly highlight how Icelandic central volcanoes, even those covered by thick ice, can generate large-volume, highly explosive rhyolitic eruptions.

**CONCLUSION**

We have determined the pre-eruptive volatile content and degassing paths of subglacial rhyolitic magmas from five different edifices at Torfajökull, Iceland. Effusively erupted magmas have low H$_{2}$OMI and show evidence for slow ascent rates and open-system degassing, whereas explosively erupted samples have high H$_{2}$OMI associated with faster magma ascent and closed-system degassing. Volatile controls on eruption style during subglacial eruptions therefore appear similar to those for subaerial eruptions, suggesting that ice and meltwater played only a minor role in influencing the explosivity of these eruptions.

Our data show that Icelandic rhyolite can be significantly more water rich ($\leq$4.8 wt\%) than previously thought, highlighting the potential for highly explosive rhyolitic eruptions from Icelandic central volcanoes, regardless of whether they are covered by ice.

**ACKNOWLEDGMENTS**

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FIGURE CAPTIONS

Figure 1. A: Simplified map of Iceland (T—Torfajökull). B: Simplified geology of Torfajökull. Sökkull Tuya and Kökufjall are informal names, as official Icelandic names do not exist. Modified from Owen et al. (2012). C: Bláhnúkur (effusive, <0.1 km³; Tuffen et al., 2001); a thin veneer of lava lobe-bearing quench hyaloclastite covers the preexisting topography. D: Southeast Rauðfossafjöll (explosive, ~1 km³; Tuffen et al., 2002); a flat subaerial lava cap overlies a pedestal of pyroclastic deposits largely obscured by scree. E,F: Thin-section images, taken in polarized light, showing melt-inclusion-bearing clinopyroxene phenocrysts, from Bláhnúkur (E) showing microlite-rich matrix glass typical of effusive samples, and from southeast Rauðfossafjöll (F) showing microlite-poor matrix glass typical of explosive samples. [[In the figure, part B, the two lightest shades of gray (older rhyolite and basalt/intermediate) are difficult to distinguish]]

Figure 2. Secondary ion mass spectrometry measurements of H₂O content plotted against Cl content. Different symbols represent host material; different colors represent sampling locations. For each location, we assigned an initial H₂O and Cl content (as labeled) and
used this to model open-system (pale line) and closed-system (dark line) degassing.

Numbers overlying each degassing path show the chlorine distribution ratio (DCl) used to create the best fit to our data; superscripts C and O represent closed- and open-system degassing, respectively. Absolute error is ~10% for H2O and <20% for Cl (Hinton, 2012, personal commun.)

1GSA Data Repository item 2012xxx, additional geological background, sample descriptions, analytical and modeling methods, raw data, and data justification, including detail on identification of hydrated samples and post-entrapment modification processes, is available online at www.geosociety.org/pubs/ft2012.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

<table>
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<th>Edifice</th>
<th>Part of ring fracture unit?</th>
<th>Volume (km³)</th>
<th>Eruptive environment</th>
<th>Inferred ice thickness (m)*</th>
<th>Inferred eruptive style</th>
<th>Existing model for style</th>
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<td>Effusive</td>
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<td>No</td>
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<td>400c</td>
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<td>Low initial water content?</td>
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<td>Yes</td>
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<td>Subglaciala</td>
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<td>Mixed: effusive-explosivea</td>
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<td>SE Rauðfossafjöll</td>
<td>Yes</td>
<td>~1h</td>
<td>Emergent</td>
<td>290j</td>
<td>Explosivej</td>
<td>Low confining pressure?</td>
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<tr>
<td>Sökkull Tuya</td>
<td>Yes</td>
<td>~1</td>
<td>Emergent</td>
<td>290j</td>
<td>Explosivej</td>
<td>High initial water content?</td>
</tr>
</tbody>
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*These thicknesses do not take into account ice cauldron depths which could be up to 150 m (Guðmundsson et al., 2004).

Lithofacies support an entirely subglacial setting, although perlite lava at the summit could indicate the initiation of a subaerial lava cap (Tuffen et al., 2008).

- a—our unpublished results; b—Tuffen et al., 2001; c—Owen et al., 2012; d—Furnes et al., 1980; e—Stevenson et al., 2011; f—Tuffen et al., 2007; g—Tuffen et al., 2008; h—Tuffen et al., 2002; i—McGarvie et al., 2006; j—McGarvie et al., 2007; k—xxxx [[Please include citation for k]].