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1 Explosive subglacial rhyolitic eruptions in Iceland are
2 fuelled by high magmatic H₂O and closed-system
3 degassing

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8 **ABSTRACT**

9 Rhyolitic eruptions beneath Icelandic glaciers can be highly explosive, as
10 demonstrated by Quaternary tephra layers dispersed throughout northern Europe.
11 However, they can also be small and effusive. A subglacial rhyolitic eruption has never
12 been observed, so behavioral controls remain poorly understood and the influence of pre-
13 eruptive volatile contents is unknown. We have therefore used secondary ion mass
14 spectrometry to characterize pre-eruptive volatile contents and degassing paths for five
15 subglacial rhyolitic edifices within the Torfajökull central volcano, formed in contrasting
16 styles of eruption under ice ~400 m thick. This includes the products of the largest known
17 eruption of Icelandic subglacial rhyolite of ~16 km³ at ca. 70 ka. We find pre-eruptive
18 water contents in melt inclusions (H₂O_{MI}) of up to 4.8 wt%, which indicates that
19 Icelandic rhyolite can be significantly more volatile rich than previously thought. Our
20 results indicate that explosive subglacial rhyolite eruptions correspond with high H₂O_{MI},
21 closed-system degassing, and rapid magma ascent, whereas their effusive equivalents
22 have lower H₂O_{MI} and show open-system degassing and more sluggish ascent rates.

23 Volatile controls on eruption style thus appear similar to those for subaerial eruptions,
24 suggesting that ice plays a subsidiary role in controlling the behavior of subglacial
25 rhyolitic eruptions.

26 INTRODUCTION

27 During subaerial eruptions, volatiles are considered a key factor in determining
28 eruptive style, with (1) a high pre-eruptive H₂O and CO₂ content and (2) closed-system
29 degassing leading to more-explosive volcanism (Eichelberger et al., 1986; Jaupart, 1998;
30 Martel et al., 1998; Cashman, 2004). During subglacial eruptions, there are additional
31 controlling factors that are poorly understood; e.g., a component of explosivity is thought
32 to be influenced by the degree of magma-water interaction (Tuffen et al., 2001;
33 Guðmundsson, 2005). However, experimental rhyolite-water interactions suggest that
34 vesicles may actually hinder phreatomagmatic explosions (Austin-Erickson et al., 2008).
35 Unlike for subaerial eruptions, it is therefore unclear whether high volatile contents favor
36 or inhibit explosive eruptions of rhyolite beneath ice.

37 Subglacial rhyolitic edifices have a wide spectrum of sizes, morphologies, and
38 lithofacies, reflecting varying degrees of explosivity and the added complexities of a
39 subglacial eruption setting (McGarvie, 2009). Eruptive products range from vesicle-poor
40 quench hyaloclastites (Tuffen et al., 2001, 2008) to fine-grained, pumiceous pyroclastic
41 deposits (Tuffen et al., 2002, 2008; Stevenson et al., 2011). Edifices range from small
42 (<0.1 km³) mounds and ridges to large (~1 km³) steep-sided, flat-topped tuyas,
43 representing effusion-dominated and explosion-dominated activity respectively (Tuffen
44 et al., 2007). However, eruption controls are poorly constrained, partly due to a lack of
45 observed eruptions. Speculative models have suggested effusive activity is favored by

46 either low initial volatile content (McGarvie et al., 2007; Stevenson et al., 2011), gas
47 escape from magma (open-system degassing) (Furnes et al., 1980), the filling of
48 subglacial cavities by erupted products (Tuffen et al., 2007, 2008), or thick overlying ice
49 (Tuffen, 2010).

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

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

62 **METHODS**

63 We have determined the pre- and post-eruptive volatile contents, and
64 reconstructed degassing paths, for five contrasting subglacial rhyolite edifices at
65 Torfajökull (Fig. 1; Table 1) including four edifices from the ca. 70 ka ring fracture
66 event: southeast Rauðfossafjöll and Sökkull Tuya, which were both explosive and burst
67 through the ice to produce tuyas (Tuffen et al., 2002); Dalakvísl, which formed through
68 mixed explosive-effusive activity (Tuffen et al., 2008); and Kökufjall, a small, effusively

69 formed edifice. The fifth edifice is Bláhnúkur, a small effusively generated edifice
70 (Tuffen et al., 2001), formed during a different eruption during the last glacial period
71 (Owen et al., 2012). Grain-size distributions were acquired to confirm and quantify field
72 observations relating to the degree of magma fragmentation and explosivity of these
73 eruptions.

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

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

91 **RESULTS**

92 Clear trends in volatile content are apparent (Fig. 2), with MI from effusive
93 edifices (Kökufjall and Bláhnúkur) containing significantly less H_2O_{MI} (≤ 1.8 wt%) than
94 those from explosively formed tuyas (southeast Rauðfossafjöll and Sökkull Tuya; ≤ 3.9
95 wt%). Dalakvísl (mixed effusive-explosive) spans the full range of water contents,
96 including the highest measured value of 4.8 wt% H_2O_{MI} (Fig. 2). Low- H_2O_{MI} effusive
97 samples are also C-rich, whereas H_2O -rich, explosively-generated samples are Cl-poor
98 (Fig. 2). The H_2O_{MI} contents of feldspar- and clinopyroxene-hosted MI are similar.

99 Matrix glasses contain 0.1–1.1 wt% H_2O_{MI} (Fig. 2), consistent with quenching at
100 elevated pressures beneath ice hundreds of meters thick (see Tuffen et al. [2010] for
101 detailed explanation of quenching pressure and ice-thickness reconstruction from H_2O
102 degassing). Inferred ice thicknesses (mostly ~ 400 m) from lithofacies and degassing
103 models (McGarvie et al., 2006; Owen et al., 2012) differ little between edifices and show
104 no correlation with behavior (Table 1), so diverging eruption styles are not attributable to
105 different ice thicknesses.

106 The major-element composition of melt inclusions and matrix glasses from
107 Bláhnúkur and the ring fracture event are broadly similar (70–76 wt% SiO_2), so
108 compositional variation cannot explain the different eruptive styles. Some Bláhnúkur MI
109 show SiO_2 enrichment and alkali depletion, consistent with post-entrapment feldspar
110 crystallization, and so Bláhnúkur H_2O_{MI} contents are maximum values. However, these
111 are among the most H_2O -poor MI (≤ 1.8 wt%), so any volatile enrichment due to
112 crystallization does not mask differences between edifices. SiO_2 enrichment is absent
113 from Dalakvísl MI, suggesting that their high H_2O_{MI} contents are original.

114 **DISCUSSION**

115 **Behavioral Control of Pre-Eruptive Water Content**

116 The pre-eruptive water content (H_2O_{MI}) of the large-volume, predominantly
117 explosive ca.70 ka event is considerably higher than that of Bláhnúkur (smaller,
118 effusive). However, the ca.70 ka magma displays a range of H_2O_{MI} , being lower at
119 Kökufjall (≤ 0.3 wt% H_2O_{MI} , effusive) than at Dalakvísl, southeast Rauðfossafjöll, or
120 Sökkull Tuya (> 2.9 wt% H_2O_{MI} , explosive). Perhaps surprisingly, our highest measured
121 H_2O_{MI} came from the small-volume Dalakvísl edifice (< 0.2 km³) rather than the larger-
122 volume (~ 1 km³) tuyas. However, Dalakvísl has the finest-grained and most-vesicular ash
123 of any of our sampling locations, suggestive of efficient magma fragmentation
124 (Stevenson et al., 2011) in a powerful but perhaps brief explosive phase.

125 We have therefore found a strong positive correlation between H_2O_{MI} and the
126 explosivity of eruptions. H_2O is considered to be the most influential volatile species in
127 terms of determining eruptive behavior during subaerial eruptions (Cashman, 2004); it
128 may be equally important when eruptions occur beneath ice.

129 The differentiation between H_2O -rich/ Cl -poor and H_2O -poor/ Cl -rich MI suggests
130 that different edifices are recording **different** source magmas (**whether separate** magma
131 bodies, a volatile-stratified chamber, or temporal gaps for melt evolution) rather than
132 progressive degassing of a single homogenous supply.

133 **Degassing Paths and Open- Versus Closed-System Degassing**

134 Measured H_2O - Cl trends (Fig. 2) have been modeled using H_2O - Cl degassing
135 systematics for rhyolitic melts (Villemant and Boudon, 1998; Villemant et al., 2008;
136 Humphreys et al., 2009). Each edifice shows a single, distinct H_2O - Cl trend, with the
137 exception of Dalakvísl, which displays two different trends perhaps related to its bimodal

138 eruptive behavior. Data scatter prevents discrimination between open- and closed-system
139 degassing from degassing paths alone, but the chlorine distribution **ratios** (D_{Cl}) required
140 to fit effusive sample data (≥ 50) greatly exceed those for explosive sample data (≤ 30).
141 Microlite crystallization can drive an increase in D_{Cl} (Webster and De Vivo, 2002;
142 Villemant et al., 2008), and effusive samples are significantly more microlite-rich than
143 their explosive counterparts (Figs. 1E and 1F). Microlite crystallization occurs during
144 magma ascent and degassing (Lipman et al., 1985; Sparks et al., 2000) and is favored by
145 slow magma rise, which also favors open-system degassing (Jaupart, 1998). In contrast,
146 less microlite crystallization typically occurs during closed-system degassing (Martel et
147 al., 1998; Villemant et al., 2003, 2008). We therefore propose that our effusive samples
148 experienced slow ascent rates and open-system degassing, whereas our explosive samples
149 experienced fast ascent rates and closed-system degassing.

150 **‘Wet’ Icelandic Rhyolite**

151 Our data **indicate** far higher H_2O_{MI} than anticipated, as Icelandic rhyolite is often
152 quoted as being “dry” in the absence of melt inclusion analysis (Sigurdsson, 1977;
153 MacDonald et al., 1990; Jónasson, 2007). The only measurement to date of H_2O_{MI} in
154 Icelandic rhyolite (Öraefajökull, 2 wt%; Sharma et al., 2008) is significantly lower **than**
155 **our measurements**, as **are matrix-glass** H_2O data from rhyolite tapped into by an
156 exploratory well at ~2 km depth (Krafla, 1.77 wt%; Elders et al., 2011[[**Q1: The in-text**
157 **citation "Elders et al., 2011" is not in the reference list. Please correct the citation,**
158 **add the reference to the list, or delete the citation. Q1]]]). In addition, primitive
159 Icelandic basalts are considered to be dry (< 1 wt% H_2O ; Nichols et al., 2002). Although it
160 is unclear whether the high H_2O_{MI} originates from partial melting of hydrated basalts at**

161 depth (Martin and Sigmarsson, 2007) or by another mechanism such as partial fusion of
162 hydrothermally altered silicic material at shallower depths (Macdonald et al., 1987), our
163 unexpectedly high H_2O_{MI} values clearly highlight how Icelandic central volcanoes, even
164 those covered by thick ice, can generate large-volume, highly explosive rhyolitic
165 eruptions.

166 **CONCLUSION**

167 We have determined the pre-eruptive volatile content and degassing paths of
168 subglacial rhyolitic magmas from five different edifices at Torfajökull, Iceland.
169 Effusively erupted magmas have low H_2O_{MI} and show evidence for slow ascent rates and
170 open-system degassing, whereas explosively erupted samples have high H_2O_{MI} associated
171 with faster magma ascent and closed-system degassing. Volatile controls on eruption
172 style during subglacial eruptions therefore appear similar to those for subaerial eruptions,
173 suggesting that ice and meltwater played only a minor role in influencing the explosivity
174 of these eruptions.

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

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323 **FIGURE CAPTIONS**

324 Figure 1. **A:** Simplified **map** of Iceland (**T**—Torfajökull). **B: Simplified geology of**
325 Torfajökull. Sökkull Tuya and Kökufjall are informal names, as official Icelandic names
326 do not exist. Modified from Owen et al. (2012). **C:** Bláhnúkur (effusive, $<0.1 \text{ km}^3$; Tuffen
327 et al., 2001); a thin veneer of lava lobe-bearing quench hyaloclastite covers the
328 preexisting topography. **D:** Southeast Rauðfossafjöll (explosive, $\sim 1 \text{ km}^3$; Tuffen et al.,
329 2002); a flat subaerial lava cap overlies a pedestal of pyroclastic deposits largely
330 obscured by scree. **E,F:** Thin-section images, taken in polarized light, showing melt-
331 inclusion-bearing clinopyroxene phenocrysts, from Bláhnúkur (E) showing microlite-rich
332 matrix glass typical of effusive samples, and from southeast Rauðfossafjöll (F) showing
333 microlite-poor matrix glass typical of explosive samples. **[[In the figure, part B, the two**
334 **lightest shades of gray (older rhyolite and basalt/intermediate) are difficult to**
335 **distinguish]]**

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337 Figure 2. Secondary ion mass spectrometry measurements of H_2O content plotted against
338 Cl content. Different symbols represent host material; different **colors** represent sampling
339 **locations**. For each location, we assigned an initial H_2O and Cl content (as labeled) and

340 used this to model open-system (pale line) and closed-system (dark line) degassing.
 341 Numbers overlying each degassing path show the chlorine distribution ratio (D_{Cl}) used to
 342 create the best fit to our data; superscripts C and O represent closed- and open-system
 343 degassing, respectively. Absolute error is ~10% for H₂O and <20% for Cl (Hinton[[This
 344 needs (at least) a first initial]], 2012, personal commun.)

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 346 ¹GSA Data Repository item 2012xxx, additional geological background, sample
 347 descriptions, analytical and modeling methods, raw data, and data justification, including
 348 detail on identification of hydrated samples and post-entrapment modification processes,
 349 is available online at www.geosociety.org/pubs/ft2012.htm, or on request from
 350 editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO
 351 80301, USA.

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TABLE 1. EDIFICE DESCRIPTIONS

Edifice	Part of ring fracture unit?	Volume (km ³)	Eruptive environment	Inferred ice thickness (m)*	Inferred eruptive style	Existing model for style
Kökufjall	Yes	< 0.1	Subglacial	120 ^a	Effusive	
Bláhnúkur	No	< 0.1 ^b	Subglacial ^b	400 ^c	Effusive ^b	Open-system degassing? ^d Low initial water content? ^e High confining pressure? ^f
Dalakvísl	Yes	<0.2 ^g	Subglacial ^{f,g}	330 ^a	Mixed: effusive-explosive ^g	Increasing confining pressure due to cavity filling? ^{f,g} Depressurization due to a jökulhlaup? ^a
SE Rauðfossafjöll	Yes	~1 ^h	Emergent ^h	290 ⁱ	Explosive ^h	Low confining pressure? ⁱ High initial water content? ^j
Sökkull Tuya	Yes	~1	Emergent	290 ^j	Explosive	

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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)
¹Lithofacies support an entirely subglacial setting, although perlitized 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—xxxxx[[Please include citation for k]].

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