Publisher: GSA
Journal: GEOL: Geology
Article ID: G33647

Explosive subglacial rhyolitic eruptions in Iceland are fuelled by high magmatic H_2O and closed-system degassing

Jacqueline Owen[1], Hugh Tuffen[1], and David W. McGarvie[2]

[1]*Lancaster Environment Centre, Lancaster University, Lancaster LA1 4YQ, UK*

[2]*Department of Environment, Earth and Ecosystems, The Open University, Milton Keynes MK7 6AA, UK*

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 (H_2O_{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 H_2O_{MI}, closed-system degassing, and rapid magma ascent, whereas their effusive equivalents have lower H_2O_{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_2O 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 (~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 Repository[1] 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_2O_{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_2O_{MI} (Fig. 2). Low-H_2O_{MI} effusive samples are also C-rich, whereas H_2O-rich, explosively-generated samples are Cl-poor (Fig. 2). The H_2O_{MI} contents of feldspar- and clinopyroxene-hosted MI are similar.

Matrix glasses contain 0.1–1.1 wt% H_2O_{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_2O 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_2O_{MI} contents are maximum values. However, these are among the most H_2O-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_2O_{MI} contents are original.

DISCUSSION

Behavioral Control of Pre-Eruptive Water Content

The pre-eruptive water content (H_2O_{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_2O_{MI}, being lower at Kökufjall (≤0.3 wt% H_2O_{MI}, effusive) than at Dalakvísl, southeast Rauðfossafjöll, or Sökkull Tuya (>2.9 wt% H_2O_{MI}, explosive). Perhaps surprisingly, our highest measured H_2O_{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_2O_{MI} and the explosivity of eruptions. H_2O 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_2O-rich/Cl-poor and H_2O-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_2O-Cl trends (Fig. 2) have been modeled using H_2O-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_2O-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_2O_{MI} 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_2O_{MI} and show evidence for slow ascent rates and open-system degassing, whereas explosively erupted samples have high H_2O_{MI} 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 (≤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

Owen was funded by Natural Environment Research Council (NERC) studentship NE/G523439/1; Tuffen by NERC grants NE/G000654/1 and NE/E013740/1, and a Royal Society University Research Fellowship. McGarvie was supported by The Open University Staff Tutor Research and Scholarship Fund. We thank the Environment Agency of Iceland for allowing fieldwork and sampling from

Fjallabak nature reserve and the Icelandic Museum of Natural History for sample export permission. Richard Hinton and Chiara Petrone assisted with SIMS and EPMA analyses, respectively. Reviews by two anonymous reviewers greatly improved the manuscript.

REFERENCES CITED

Austin-Erickson, A., Büttner, R., Dellino, P., Ort, M.H., and Zimanowski, B., 2008, Phreatomagmatic explosions of rhyolitic magma: Experimental and field evidence: Journal of Geophysical Research, v. 113, B11201, doi:10.1029/2008JB005731.

Brendryen, J., Haflidason, H., and Sejrup, H.P., 2010, Norwegian Sea tephrostratigraphy of marine isotope stages 4 and 5: Prospects and problems for tephrochronology in the North Atlantic region: Quaternary Science Reviews, v. 29, p. 847–864, doi:10.1016/j.quascirev.2009.12.004.

Cashman, K.V., 2004, Volatile controls on magma ascent and eruption, *in* Sparks, R.S.J., and Hawkesworth, C.J., eds., The State of the Planet: Frontiers and Challenges in Geophysics, Volume 150: Washington, D.C., American Geophysical Union, p. 109–124.

Eichelberger, J.C., Carrigan, C.R., Westrich, H.R., and Price, R.H., 1986, Non-explosive silicic volcanism: Nature, v. 323, p. 598–602, doi:10.1038/323598a0.

Furnes, H., Fridleifsson, I.B., and Atkins, F.B., 1980, Subglacial volcanics—On the formation of acid hyaloclastites: Journal of Volcanology and Geothermal Research, v. 8, p. 95–110, doi:10.1016/0377-0273(80)90009-8.

Guðmundsson, M.T., 2005, 6. Subglacial volcanic activity in Iceland, *in* Caseldine, C., Russell, A., Harðardóttir, J., and Knudsen, Ó, eds., Developments in Quaternary Sciences, Volume 5: New York, Elsevier, p. 127–151.

Guðmundsson, M.T., Sigmundsson, F., Björnsson, H., and Högnadóttir, T., 2004, The 1996 eruption at Gjálp, Vatnajökull ice cap, Iceland: efficiency of heat transfer, ice deformation and subglacial water pressure: Bulletin of Volcanology, v. 66, p. 46–65, doi:10.1007/s00445-003-0295-9.

Humphreys, M.C.S., Edmonds, M., Christopher, T., and Hards, V., 2009, Chlorine variations in the magma of Soufrière Hills Volcano, Montserrat: Insights from Cl in hornblende and melt inclusions: Geochimica et Cosmochimica Acta, v. 73, p. 5693–5708, doi:10.1016/j.gca.2009.06.014.

Jaupart, C., 1998, Gas loss from magmas through conduit walls during eruption, *in* Gilbert, J.S., and Sparks, R.S.J., eds., The Physics of Explosive Volcanic Eruptions: Geological Society of London Special Publication 145, p. 73–90.

Johnson, M.C., Anderson, A.T., and Rutherford, M.J., 1994, Pre-eruptive volatile contents of magmas: Volatiles in Magmas, v. 30, p. 281–330.

Jónasson, K., 2007, Silicic volcanism in Iceland: Composition and distribution within the active volcanic zones: Journal of Geodynamics, v. 43, p. 101–117, doi:10.1016/j.jog.2006.09.004.

Lipman, P.W., Banks, N.G., and Rhodes, J.M., 1985, Degassing-induced crystallization of basaltic magma and effects on lava rheology: Nature, v. 317, p. 604–607, doi:10.1038/317604a0.

Lowenstern, J.B., 1995, Applications of silicate-melt inclusions to the study of magmatic volatiles, *in* Thompson, J.F.H., ed., Magmas, Fluids and Ore Deposits: Mineralogical Association of Canada Short-Course Volume 23, p. 71–99.

Macdonald, R., Sparks, R.S.J., Sigurdsson, H., Mattey, D.P., McGarvie, D.W., and Smith, R.L., 1987, The 1875 Eruption of Askja Volcano, Iceland—Combined Fractional Crystallization and Selective Contamination in the Generation of Rhyolitic Magma: Mineralogical Magazine, v. 51, p. 183–202, doi:10.1180/minmag.1987.051.360.01.

MacDonald, R., McGarvie, D.W., Pinkerton, H., Smith, R.L., and Palavz, A., 1990, Petrogenetic evolution of the Torfajökull Volcanic Complex, Iceland I. Relationship between the magma types: Journal of Petrology, v. 31, p. 429–459, doi:10.1093/petrology/31.2.429.

Martel, C., Pichavant, M., Bourdier, J.L., Traineau, H., Holtz, F., and Scaillet, B., 1998, Magma storage conditions and control of eruption regime in silicic volcanoes: Experimental evidence from Mt. Pelée: Earth and Planetary Science Letters, v. 156, p. 89–99, doi:10.1016/S0012-821X(98)00003-X.

Martin, E., and Sigmarsson, O., 2007, Crustal thermal state and origin of silicic magma in Iceland: The case of Torfajökull, Ljósufjöll and Snæfellsjökull volcanoes: Contributions to Mineralogy and Petrology, v. 153, p. 593–605, doi:10.1007/s00410-006-0165-5.

McGarvie, D.W., 1984, Torfajökull: A volcano dominated by magma mixing: Geology, v. 12, p. 685–688, doi:10.1130/0091-7613(1984)12<685:TAVDBM>2.0.CO;2.

McGarvie, D.W., 2009, Rhyolitic volcano-ice interactions in Iceland: Journal of Volcanology and Geothermal Research, v. 185, p. 367–389, doi:10.1016/j.jvolgeores.2008.11.019.

McGarvie, D.W., Burgess, R., Tindle, A.G., Tuffen, H., and Stevenson, J.A., 2006, Pleistocene rhyolitic volcanism at Torfajökull, Iceland: Eruption ages, glaciovolcanism, and geochemical evolution: Jökull, v. 56, p. 57–75.

McGarvie, D.W., Stevenson, J.A., Burgess, R., Tuffen, H., and Tindle, A.G., 2007, Volcano-ice interactions at Prestahnúkur, Iceland: rhyolite eruption during the last interglacial-glacial transition: Annals of Glaciology, v. 45, p. 38–47, doi:10.3189/172756407782282453.

Nichols, A.R.L., Carroll, M.R., and Hoskuldsson, A., 2002, Is the Iceland hot spot also wet? Evidence from the water contents of undegassed submarine and subglacial pillow basalts: Earth and Planetary Science Letters, v. 202, p. 77–87, doi:10.1016/S0012-821X(02)00758-6.

Owen, J., Tuffen, H., and McGarvie, D.W., 2012, Using dissolved H_2O in rhyolitic glasses to estimate palaeo-ice thickness during a subglacial eruption at Bláhnúkur (Torfajökull, Iceland): Bulletin of Volcanology, v. 74, p. 1355–1378, doi:10.1007/s00445-012-0601-5.

Petersen, G.N., Bjornsson, H., and Arason, P., 2012, The impact of the atmosphere on the Eyjafjallajökull 2010 eruption plume: Journal of Geophysical Research, v. 117, D00U07, doi:10.1029/2011JD016762.

Sharma, K., Self, S., Blake, S., Thordarson, T., and Larsen, G., 2008, The AD 1362 Öræfajökull eruption, S.E. Iceland: Physical volcanology and volatile release:

Journal of Volcanology and Geothermal Research, v. 178, p. 719–739, doi:10.1016/j.jvolgeores.2008.08.003.

Sigurdsson, H., 1977, Generation of Icelandic rhyolites by melting of plagiogranites in the oceanic layer: Nature, v. 269, p. 25–28, doi:10.1038/269025a0.

Sparks, R.S.J., Murphy, M.D., Lejeune, A.M., Watts, R.B., Barclay, J., and Young, S.R., 2000, Control on the emplacement of the andesite lava dome of the Soufriere Hills volcano, Montserrat by degassing-induced crystallization: Terra Nova, v. 12, p. 14–20, doi:10.1046/j.1365-3121.2000.00267.x.

Steele-MacInnis, M., Esposito, R., and Bodnar, R.J., The effect of post-entrapment crystallization on the H_2O and CO_2 concentrations of rhyolitic (silica-rich) melt inclusions, and implications for magma degassing paths, *in* Bakker, R.J., Baumgartner, M., and Doppler, G., eds., Proceedings, European Current Research on Fluid Inclusions (ECROFI-XXI), Montanuniversität Leoben, Austria, 2011: Wien, Austria, Geologische Bundesanstalt, p. 188–189.

Stevenson, J.A., Gilbert, J.S., McGarvie, D.W., and Smellie, J.L., 2011, Explosive rhyolite tuya formation: Classic examples from Kerlingarfjöll, Iceland: Quaternary Science Reviews, v. 30, p. 192–209, doi:10.1016/j.quascirev.2010.10.011.

Tuffen, H., 2010, How will melting of ice affect volcanic hazards in the 21st century?: Philosophical Transactions of the Royal Society A, v. 368, p. 2535–2558, doi:10.1098/rsta.2010.0063.

Tuffen, H., Gilbert, J., and McGarvie, D., 2001, Products of an effusive subglacial rhyolite eruption: Bláhnúkur, Torfajökull, Iceland: Bulletin of Volcanology, v. 63, p. 179–190, doi:10.1007/s004450100134.

Tuffen, H., McGarvie, D.W., Gilbert, J.S., and Pinkerton, H., 2002, Physical volcanology of a subglacial-to-emergent rhyolitic tuya at Rauðufossafjöll, Torfajökull, Iceland, *in* Smellie, J.L., and Chapman, M.G., eds., Volcano-Ice interaction on Earth and Mars: Geological Society of London Special Publication 202, p. 213–236.

Tuffen, H., McGarvie, D.W., and Gilbert, J.S., 2007, Will subglacial rhyolite eruptions be explosive or intrusive? Some insights from analytical models: Annals of Glaciology, v. 45, p. 87–94, doi:10.3189/172756407782282534.

Tuffen, H., McGarvie, D.W., Pinkerton, H., Gilbert, J.S., and Brooker, R.A., 2008, An explosive-intrusive subglacial rhyolite eruption at Dalakvísl, Torfajökull, Iceland: Bulletin of Volcanology, v. 70, p. 841–860, doi:10.1007/s00445-007-0174-x.

Tuffen, H., Owen, J., and Denton, J., 2010, Magma degassing during subglacial eruptions and its use to reconstruct palaeo-ice thicknesses: Earth-Science Reviews, v. 99, p. 1–18, doi:10.1016/j.earscirev.2010.01.001.

Villemant, B., and Boudon, G., 1998, Transition from dome-forming to plinian eruptive styles controlled by H_2O and Cl degassing: Nature, v. 392, p. 65–69, doi:10.1038/32144.

Villemant, B., Boudon, G., Nougrigat, S., Poteaux, S., and Michel, A., 2003, Water and halogens in volcanic clasts: tracers of degassing processes during Plinian and dome-building eruptions, *in* Oppenheimer, C., Pyle, D.M., and Barclay, J., eds., Volcanic Degassing: Geological Society of London Special Publication 213, p. 63–79.

Villemant, B., Mouatt, J., and Michel, A., 2008, Andesitic magma degassing investigated through H_2O vapour-melt partitioning of halogens at Soufrière Hills Volcano, Montserrat (Lesser Antilles): Earth and Planetary Science Letters, v. 269, p. 212–229, doi:10.1016/j.epsl.2008.02.014.

Webster, J.D., and De Vivo, B., 2002, Experimental and modeled solubilities of chlorine in aluminosilicate melts, consequences of magma evolution, and implications for exsolution of hydrous chloride melt at Mt. Somma-Vesuvius: The American Mineralogist, v. 87, p. 1046–1061.

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 km^3; Tuffen et al., 2001); a thin veneer of lava lobe-bearing quench hyaloclastite covers the preexisting topography. D: Southeast Rauðfossafjöll (explosive, ~1 km^3; 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 H_2O content plotted against Cl content. Different symbols represent host material; different colors represent sampling locations. For each location, we assigned an initial H_2O 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 (D_{Cl}) 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 H_2O and <20% for Cl (Hinton**[[This needs (at least) a first initial]]**, 2012, personal commun.)

[1]GSA 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 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[†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?[f] High initial water content?[j]
Sökkull Tuya	Yes	~1	Emergent	290[k]	Explosive	

*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 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]]**.