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# Insights into the dynamics of mafic magmatic-hydromagmatic eruptions from volatile degassing behaviour: The Hverfjall Fires, Iceland

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ABSTRACT

The style and intensity of hydromagmatic activity is governed by a complex interplay between the relative volumes of magma and water that interact, their relative viscosities, the depth of subsurface explosions, the substrate properties, and the vent geometry. Fundamental questions remain, however, regarding the role of magmatic vesiculation in determining the dynamics of magma-water interaction (MWI). Petrological reconstructions of magmatic degassing histories are commonly employed to interpret the pre- and syn-eruptive conditions during 'dry' magmatic eruptions, but the application of similar techniques to hydromagmatic activity has not yet been fully explored. In this study, we integrate glass volatile measurements (S, Cl, $H_2O$ and $CO_2$) with field observations and microtextural measurements to examine the relationship between degassing and eruptive style during the Hverfjall Fires fissure eruption, Iceland. Here, coeval fissure vents produced both 'dry' magmatic (Jarðbaðshólar scoria cone complex) and variably wet hydromagmatic (Hverfjall tuff ring) activity, generating physically distinct pyroclastic deposits with contrasting volatile signatures. Matrix glass volatile concentrations in hydromagmatic ash (883 ± 172 [1σ] ppm S; 0.45 ± 0.03 [1σ] wt% $H_2O$; ≤20 ppm $CO_2$) are consistently elevated relative to magmatic ash and scoria lapilli (418 ± 93 [1σ] ppm S; 0.12 ± 0.48 [1σ] wt% $H_2O$; $CO_2$ below detection) and overlap with the range for co-erupted phenocryst-hosted melt inclusions (1522 ± 127 [1σ] ppm S; 165 ± 27 [1σ] ppm Cl). Measurements of hydromagmatic glasses indicate that the magma has degassed between 17 and 70% of its initial sulfur prior to premature quenching at variably elevated confining pressures. By comparing volatile saturation pressures for both magmatic and hydromagmatic glasses, and how these vary through the eruptive stratigraphy, we place constraints on the conditions of MWI. Crucially, our data demonstrate that the magma was already vesiculating when it encountered groundwater at depths of 100–200 m, and that the external water supply was sufficient to maintain MWI throughout the eruption with no significant vertical or lateral migration of the fragmentation surface. We propose that development of an in-vent water-sediment slurry provides a mechanism through which the elevated confining pressures of ~1.6–2.6 MPa (or up to 6 MPa accounting for uncertainty in $CO_2$ below analytical detection) could be maintained and buffered throughout the eruption, whilst enabling vertical mixing and ejection of fragmented juvenile and lithic material from a range of depths. Importantly, these results demonstrate that the volatile contents of hydromagmatic deposits provide valuable records of (1) the environment of MWI (e.g., groundwater versus surface water, vertical migration of the fragmentation level) and (2) the state of the magma at the time of fragmentation and quenching. We further suggest that the volatile content of tephra glasses provides a reliable alternative (or additional) indicator of a hydromagmatic origin, particularly for reduced Ocean Island Basalts where late-stage volatile saturation and degassing (S, $H_2O$) occurs over a pressure range relevant to typical MWI environments.



## 1. Introduction

Hydromagmatic eruptions are generated by the explosive interaction of magma with external water. In contrast to 'dry' basaltic eruptions that are driven purely by the rapid exsolution and expansion of magmatic volatiles (Mangan & Cashman, 1996; Mangan et al., 2014; Parfitt, 1998), the energy released during magma-water interaction (MWI) is further influenced by the efficiency of heat exchange with water and/or steam. Energetic water vaporisation/expansion during MWI causes extensive melt fragmentation, which is enhanced by the brittle response of silicate melt to rapid quenching (e.g., Büttner et al., 2002; Cashman & Scheu, 2015; Colgate & Sigurgeirsson, 1973; Kokelaar, 1986; Liu et al., 2015; Liu et al., 2017; Lorenz, 1975; Peckover et al., 1973; Sheridan & Wohletz, 1983; Van Otterloo et al., 2015; Wohletz, 1986; Zimanowski et al., 1991; Zimanowski et al.,

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1997). High vesicularities and bubble number densities within some hydromagmatic pyroclasts demonstrate that significant vesiculation can take place prior to MWI (Mastin et al., 2004; Murtagh et al., 2011; Liu et al., 2015; Liu et al., 2017; Rausch et al., 2015), with the shape and size distributions of fragmented particles determined by the bubble population at the time of quenching and brittle fragmentation. Magma ascent histories and degassing budgets can be reconstructed from the volatile concentrations preserved within pristine melt inclusions and the matrix glass of erupted pyroclasts (e.g., Edmonds, 2008; Hartley et al., 2014; Johnson et al., 2010; Métrich & Wallace, 2008; Métrich et al., 1991; Métrich et al., 2010; Self et al., 2008; Þórðarson & Self, 2003; Þórðarson et al., 1996; Wallace, 2003; Wallace & Edmonds, 2011; Wallace et al., 2015). Yet, similar geochemical approaches to explore the dynamics of MWI remain comparatively under-utilised.

Mixed eruptions including both magmatic and hydromagmatic phases (either at a single vent or at different vents along an active fissure) are common in Iceland due to the abundance of external water sources within volcanic environments. Icelandic tephra erupted during hydromagmatic and magmatic activity have distinct residual volatile compositions, with matrix glass sulfur concentrations ($S_{MG}$) consistently elevated within hydromagmatic pyroclasts (Óladóttir et al., 2008; Schipper et al., 2015; Sigmarsson et al., 2013; Þórðarson et al., 1996; Þórðarson et al., 2001; Þórðarson et al., 2003). The Laki fissure eruption of 1783–84 provides an illustrative example of a mixed eruption: hydromagmatic tephra comprises ~20% of the total tephra volume, with the remainder produced by 'dry' Strombolian activity. Laki hydromagmatic glasses contain variable but elevated $S_{MG}$ (490–1260 ppm; average 933 ± 212 ppm), whilst Strombolian glasses contain uniformly low $S_{MG}$ concentrations (418–640 ppm; average 490 ± 82 ppm; Þórðarson et al., 1996). These residual sulfur concentrations correspond to contrasting degassing efficiencies of 25–70% and 62–75% for hydromagmatic and magmatic activity, respectively, relative to the initial sulfur content of 1677 ± 225 ppm preserved in olivine-hosted melt inclusions ($S_{MI}$; Métrich et al., 1991; Þórðarson et al., 1996).

The progressive exsolution of sulfur with decreasing magma overpressure is well-recorded in exposed subglacial volcanic edifices (tuyas) in Iceland (Moore & Calk, 1991) and elsewhere (e.g., British Columbia; Dixon et al., 2002; Edwards et al., 2009; Hungerford et al., 2014), which exhibit decreasing $S_{MG}$ with increasing elevation. Glassy hyaloclastite samples erupted at water depths >400 m (equivalent to 4 MPa hydrostatic pressure) contain $S_{MG}$ ≥ 500 ppm, whilst the glassy margins of all subaerial lava flow units capping tuyas are degassed to $S_{MG}$ ≤ 200 ppm (Moore & Calk, 1991). Similarly, glassy pillow basalt rims erupted under variable water depths off the Reykjanes Ridge (SE Iceland) indicate that sulfur is largely retained in the melt until ~200 m water depth (~2 MPa hydrostatic pressure) after which sulfur degassing takes place rapidly (Moore and Schilling, 1973). The elevated $S_{MG}$ values observed in hydromagmatic tephra are therefore consistent with higher quench pressures, whereby rapid cooling of magma during MWI arrests degassing and thus preserves the residual melt volatile concentration at the depth of interaction (Mastin et al., 2004; Þórðarson et al., 1996).

Hawaiian basalts exhibit a similar dichotomy in volatile content between magmatic and hydromagmatic tephras, but with the transition displaced to slightly lower S contents than the more iron-rich Icelandic basalts (Mastin et al., 2004; Moore, 1965; Moore & Fabbi, 1971; Schipper et al., 2010). Tephra from the Keanakāko'i eruption of Kīlauea (where magma interacted with a surface lake; Mastin, 1997) have $S_{MG}$ between 250 and 600 ppm, which are again elevated relative to those of equivalent 'dry' Kīlauean lava fountain deposits (<100–300 ppm; e.g., Mastin et al., 2004; Sides et al., 2014; Swanson & Fabbi, 1973; Moussallam et al., 2016; Helz et al., 2017). Similarly, eruptive products from the submarine (<1400 ppm S) and subaerial (100–200 ppm S) rift zones of Mauna Loa exhibit similarly contrasting volatile contents, with glassy submarine pillow rims also preserving decreasing S and Cl concentrations with reduced water depths (Davis et al., 2003).

In this study, we interrogate volatile data from magmatic and hydromagmatic pyroclasts erupted contemporaneously during the Hverfjall Fires, Iceland, to (a) reconstruct the degassing history of magma erupted under different eruptive styles, (b) determine the magma vesicularity at the time of MWI and quenching, (c) calculate the fragmentation pressure/depth of MWI, and (d) explore how changing conditions of magma ascent and fragmentation may relate to transitions in eruptive behaviour. From these data, we consider sulfur degassing in ocean island basalts (OIB) more generally, and evaluate the use of volatiles as geochemical indicators of hydromagmatic processes.

## 2. Geological setting

The Hverfjall Fires (~2500 ka) was a major rifting episode within the Krafla Volcanic System, located in Iceland's Northern Volcanic Zone (Fig. 1; Liu et al., 2017; Mattsson & Höskuldsson, 2011; Sæmundsson, 1991; Þórarinsson, 1979). Effusive activity occurred intermittently along a NNE-SSW aligned fissure, which extended both north and south of the central Krafla caldera within a graben (Sæmundsson, 1991). Most activity was concentrated at the southernmost tip of the fissure, in Mývatn, where coeval 'dry' magmatic and hydromagmatic explosive activity formed part of the Jarðbaðshólar scoria cone complex and Hverfjall tuff ring (and surrounding deposits), respectively. Hydromagmatic activity at the Hverfjall vent was initiated and maintained throughout the eruption by the interaction of magma with groundwater aquifers, with the spatial distribution of magma-water interaction (MWI) determined by the pre-existing hydrological flow regime in the region (Liu et al., 2017).

The hydromagmatic deposits from Hverfjall comprise fine-grained ash fall and massive to finely-stratified base surge units, in addition to the complex proximal stratigraphy within the tuff ring edifice itself (Mattsson & Höskuldsson, 2011; Sæmundsson, 1991). In total, hydromagmatic activity generated approximately 0.15 ± 0.02 $km^3$ of pyroclastic material, of which 0.08 ± 0.01 $km^3$ comprise an extensive fine-grained unconsolidated fall deposit formed during the initial stage of the eruption (Liu et al., 2017). Later eruptive phases were dominated by base surges with runout distances of 3–5 km. Proximal surge exposures show a clear evolution from poorly-sorted matrix-supported massive lapilli-tuff basal units (e.g., $H_{8.9}$ A; Fig. 1c, Table 1) through to well-sorted clast-supported accretionary lapilli-rich intermediate and upper units intercalated with thinly-laminated fine ash (e.g., $H_{8.9}$ F), suggesting a transition from water-saturated to drier emplacement conditions. Large angular blocks and bombs of dense basaltic lavas indicate considerable disruption of the basement substrate by subsurface explosions, although lithic clasts comprise only a minor proportion of medial to distal ash fall deposits (<10%; Liu et al., 2017). The presence of lithic material throughout stratigraphic sections indicates continuous country rock excavation (e.g., Lorenz, 1986; Lorenz, 2003) and/or recycling and ejection of earlier disrupted material (Grættinger et al., 2014; Lefebvre et al., 2012; Lefebvre et al., 2016; Valentine et al., 2015; Valentine et al., 2017). However, the homogeneous lithology of basement rocks and the potential for progressive upward mixing prior to ejection means that the lithic assemblage provides little constraint on the absolute depth of disruption (e.g., Agustín-Flores et al., 2014; Valentine et al., 2017).

'Dry' magmatic activity occurred from a vent within the Jarðbaðshólar cone complex (located ~3 km north of Hverfjall along the fissure strike), during which predominantly Strombolian activity produced a coarse, scoriaceous deposit (with a more limited dispersal distance of ~1.5 km) and subsequent lava flows (Liu et al., 2017; Mattsson & Höskuldsson, 2011). Interbedded magmatic and hydromagmatic deposits indicate that the Hverfjall and Jarðbaðshólar vents were active simultaneously (Mattsson & Höskuldsson, 2011). However, clear differences in the total grain size distribution (TGSD)

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