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Magma degassing during subglacial eruptions and its use to reconstruct palaeo-ice thicknesses

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A B S T R A C T

The degassing of magmatic volatiles during eruptions beneath ice sheets and glaciers, as recorded by the dissolved volatile content quenched in volcanic rocks, could provide powerful new constraints on former ice thicknesses in volcanic areas. As volcanic rocks are readily dateable using radiometric methods, subglacial volcanoes may therefore provide crucial information on the timing of palaeo-environmental fluctuations in the Quaternary. Volatile degassing is also likely to control the mechanisms of subglacial eruptions and their associated hazards.

In this paper we lay out a number of criteria that must be satisfied for degassing to potentially record palaeo-ice thicknesses, using a variety of new datasets and calculations to highlight existing problems with the technique. These include uncertainties about volatile solubilities, non-equilibrium degassing, sample heterogeneity, hydration, post-quenching movement and whether subglacial pressures deviated significantly from glaciostatic. We propose new strategies for improvement of the technique and discuss how magmatic volatiles may control the style of subglacial eruptions.

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1. Introduction

Volcanoes that have interacted with ice provide a valuable palaeo-environmental record, as the nature of deposits formed (e.g. subglacial–subaerial transitions) may be used to reconstruct approximate ice thicknesses (e.g. Smellie, 2000, 2008; Smellie et al., 2008). Indeed, as volcanic rocks are readily datable through radioactive decay series they may provide a unique opportunity to track the history of how ice sheets have fluctuated during past global climate change (Smellie et al., 2008).

However, many subglacially erupted formations do not provide any clear evidence for approximate ice surface elevations — especially those that erupted entirely beneath the ice (e.g. Skilling, 1994; Tuffen et al., 2001; Dixon et al., 2002; Schopka et al., 2006; McGarvie et al., 2007; Edwards et al., 2009). In these cases the pressure-dependent solubility of magmatic volatiles may potentially be used to estimate palaeo-pressures at the eruption site, which may provide information on both palaeo-ice thicknesses and the local subglacial hydrology.

The degassing of magmatic volatiles during subglacial eruptions (principally H_2O, CO_2, S, F and Cl) may strongly influence eruptive mechanisms and associated hazards, as is the case with subaerial eruptions (Sparks, 2003; Edmonds, 2008). Additionally, volatile degassing controls the emission of climate-affecting gases such as CO_2 and SO_2 into the oceans and atmosphere (Gíslason et al., 2002; Edmonds, 2008). As melting of ice sheets may promote subglacial volcanic activity (Maclennan et al., 2002; Pagli and Sigmundsson, 2008) there is therefore scope for feedback between climate change and patterns of subglacial volcanism (Huybers and Langmuir, 2009).

In this paper we present a critical overview of the use of volatile contents in subglacially erupted glasses to reconstruct palaeo-ice thicknesses. New data is provided that highlights the strong heterogeneities in volatile contents within samples that may seriously hamper use of the technique. We then systematically outline the criteria that must be met by samples in order for quenching pressures to be recorded, before discussing the interpretation of quenching pressures and their relationship to palaeo-ice thicknesses. Finally, the potential effect of volatiles on the mechanisms of eruptions is described, along with key topics for future research.

1.1. Previous studies of degassing: subglacial basaltic eruptions

To date studies of volatile degassing at subglacial volcanoes have concentrated on Icelandic and British Columbian examples (Table 1). Studies involved measurement of the dissolved volatile contents in glassy samples collected from different elevations at subglacially erupted tuyas (that pierced the ice surface and became subaerial) and tindar ridges (that remained entirely subglacial). A schematic diagram of magma degassing and vesiculation during eruptions is given in Fig. 1; see Smellie (2000) for detailed definitions of eruption types.

In the first study to use magmatic volatile contents as a method to estimate the palaeo-ice thickness, Dixon et al. (2002) looked at degassing at Tanzilla Mountain, British Columbia — an entirely englacial volcanic edifice composed of alkali basalt overlying a base of tholeiitic pillow lavas. H_2O, S and Cl data showed that although the tholeiitic base had not significantly degassed the overlying alkali basalt had done so. Pressure–solubility relations for basaltic magma (Dixon and Stolper, 1995) were to estimate the confining pressure consistent with the measured H_2O concentrations; this led to the estimate that 400–900 m of ice lay over the vent during the eruption. This range of figures was roughly consistent with independent estimates of the ice sheet thickness.

Schopka et al. (2006) measured the water contents of samples from the base to the summit of Helgafell, a small-volume, 330 m-high Pleistocene basaltic tindar ridge in western Iceland. Surprisingly, no systematic relationship between water content and elevation was found and the low water contents (0.26–0.37 wt.%) were consistent with lower quenching pressures than expected (equivalent to only 90–180 m of ice). The authors speculated that meltwater drainage may lead to confining pressures considerably less than glaciostatic, so that the magma did not feel the full weight of the overlying ice when it quenched at the vent.

Höskuldsson et al. (2006) found high water contents (0.85–1.04 wt.%) in Pleistocene pillow lavas at Kverkfjoll, Iceland, which were consistent with eruption between 1240 and 1880 m of ice. As Kverkfjoll is located in the centre of Iceland where the ice thickness may have reached 2 km during glacial periods this range of values is realistic. Hoskuldsson et al. also used the vesiculation of some pillow lavas to argue that a sudden decrease in subglacial pressure occurred, due to the release of subglacial meltwater in a jökulhlaup flood.

Edwards et al. (2009) found high magmatic water contents in basaltic pillow lavas at Mt Edziza, British Columbia that make up an englacially erupted ridge. They found significant variations in volatile content with elevation, but there was no simple trend, and so suggested that the level of an ice-confined lake may have fluctuated during the eruption.

1.2. Previous studies of degassing: subglacial intermediate and silicic eruptions

Studies to date of degassing during subglacial silicic eruptions have been restricted to Icelandic examples. McGarvie et al. (2007) measured water contents in rhyolitic lavas at Prestahnúkur, a 600 m-high subglacially erupted edifice dominated by lava flows. Low water contents (0.10–0.14 wt.%) were attributed to low-pressure degassing at the vent followed by substantial downslope flow. Tuffen et al. (2008) found elevated water contents (0.50–0.52 wt.%) in glass from Dalakvísl, Torfajökull consistent with partial degassing during an explosive eruption within an subglacial cavity.

In the only study of intermediate magma to date Stevenson et al. (2009) found high water contents (0.67–1.32 wt.%) in andesitic and dacitic glasses from Kerlingafjöll central volcano. As the highest water content measured required unrealistically thick ice (>3 km), it was attributed to loading by thick ice and pyroclastic deposits. Tuffen and Castro (2009) traced degassing from the feeder dyke to subaerial rhyolitic lavas erupted through thin ice/firn at Hrafntinnuhryggur, Krafla. They found that subaerial lavas were degassed but with substantial small-scale heterogeneity (0.11–0.20 wt.% H_2O) and the inferred quenching pressure from water contents in the feeder dyke was too high to be explained by loading by ice/firn alone.

Denton et al. (2009) studied the post-emplacement hydration of rhyolitic lavas and hyaloclastites from Torfajökull and Krafla and