Widespread tephra dispersal and ignimbrite emplacement from a subglacial volcano (Torfajökull, Iceland)

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ABSTRACT

The tephra dispersal mechanisms of rhyolitic glaciovolcanic eruptions are little known, but can be investigated through the correlation of eruptive products across multiple depositional settings. Using geochemistry and geochronology, we correlate a regionally important Pleistocene tephra horizon—the rhyolitic component of North Atlantic Ash Zone II (II-RHY-1)—and the Thórsmörk Ignimbrite with rhyolitic tuyas at Torfajökull volcano, Iceland. The eruption breached an ice mass >400 m thick, leading to the widespread dispersal of II-RHY-1 across the North Atlantic and the Greenland ice sheet. Locally, pyroclastic density currents traveled across the ice surface, depositing the variably welded Thórsmörk Ignimbrite beyond the ice margin and ~30 km from source. The widely dispersed products of this eruption represent a valuable isochronous tie line between terrestrial, marine, and ice-core palaeoenvironmental records. Using the tephra horizon, estimates of ice thickness and extent derived from the eruption deposits can be directly linked to the regional climate archive, which records the eruption at the onset of Greenland Stadial 15.2.

INTRODUCTION

The stratigraphic correlation of volcanic products, particularly tephra, is a powerful means of studying the past eruptive behavior of volcanoes and linking together disparate palaeoenvironmental records (Lowe, 2011). The more depositional settings in which an eruption is identified, the more information can be pooled together to understand the eruption and the prevailing environmental conditions. However, it can be challenging to find correlative volcanic products across multiple realms, especially terrestrial settings that are subjected to periodic glaciation (Larsen and Eiríksson, 2008). In this paper, we use correlation methods to (1) assess the tephra dispersal mechanisms of rhyolitic glaciovolcanic eruptions, and (2) precisely integrate glaciovolcanic–glacial–marine depositional data with the regional climate record.

Rhyolitic glaciovolcanism is an abundant feature of the active volcanic zones of Iceland (McGarvie, 2009) and is also reported in the Cascades volcanic arc, northwestern USA (Leschinsky and Fink, 2000), and the Hallett Volcanic Province, Antarctica (Smellie et al., 2011). Current knowledge of the behavior of rhyolitic glaciovolcanic eruptions is drawn from proximal deposits only (e.g., Stevenson et al., 2011; Owen et al., 2013a). Without any established correlations between glaciovolcanic rhyolites and distal tephra, it is not known whether these eruptions have produced widespread tephra deposits (Tuffen et al., 2002, 2007; McGarvie, 2009).

Glaciovolcanic edifices, such as tuyas, are valuable palaeoenvironmental indicators that record the presence of ice at the time of their eruption, and can preserve evidence of the coeval ice thickness and basal thermal regime (Jones, 1968; Smellie and Skilling, 1994; Smellie et al., 2011). Integration of this information with climate records has been restricted by the large uncertainties in eruption ages (e.g., ⁴⁰Ar/³⁹Ar ages, with typical uncertainties of thousands of years) relative to the time scales of climate variability (e.g., the decadal to centennial scale climate shifts during the last glacial period; Svensson et al., 2008).

Alternatively, a direct link to the regional palaeoclimate archive could be established through the identification of tephra from the same eruptions within ice cores and marine sediments. The distal tephra in this study is II-RHY-1, the rhyolitic component of North Atlantic Ash Zone II, which is dated to the last glacial period at 55,380 ± 2367 yr b2k (before A.D. 2000; ²⁰⁷⁰Ar) (Greenland Ice Core Chronology 2005 [GICC05]; Svensson et al., 2008). II-RHY-1 is an important part of the tephrostratigraphy of the North Atlantic region due to its widespread distribution and occurrence at a time of abrupt climatic change: the onset of Greenland Stadial (GS) 15.2 (Bramlette and Bradley, 1941; Zielinski et al., 1997; Austin et al., 2004; Austin and Abbott, 2010). Atmospheric transport of the tephra resulted in distal fallout onto the Greenland ice sheet and sea ice (Ruddiman and Glover, 1972; Ram and Gayley, 1991), leading to sea-ice rafting of the tephra as far as 2300 km to the south and southwest of Iceland (Ruddiman and Glover, 1972; Wastegård et al., 2006). The volume of airfall tephra, ice-rafted tephra, and redeposited tephra in the marine stratigraphy is substantial, but poorly constrained (Ruddiman and Glover, 1972; Lackschewitz and Wallrabe-Adams, 1997; Brendyren et al., 2011; Voelker and Haflidason, 2015).

The II-RHY-1 tephra has been identified in a terrestrial setting as the Thórsmörk Ignimbrite, a variably welded ignimbrite in southern Iceland (Sigurdsson, 1982; Lacasse et al., 1996; Tomlinson et al., 2010; Guíllou et al., 2019). It has been suggested that Tindfjallajökull volcano was the source of the ignimbrite (Jørgensen, 1980); however, recent observations on the physical volcanology of this deposit by Moles et al.
(2018) suggest that this is not the case. Furthermore, Grönvold et al. (1995) noted a geochemical similarity between II-RHY-1 and rhyolites at Torfajökull volcano, particularly the “Ring Fracture Rhyolites”. These suggested sources, as well as nearby volcanoes Eyjafjallajökull and Katla, are considered here.

METHODS

Potential correlations between samples from distal, medial, and proximal settings were investigated using both geochemistry and geochronology. II-RHY-1 tephra shards were extracted from four North Atlantic marine sediment cores (Table DR1 and Fig. DR1 in the GSA Data Repository1). The occurrence and stratigraphic position of II-RHY-1 in the cores were determined by Abbott et al. (2018). Ash and glassy fiamme samples were collected from the Thórsmörk Ignimbrite (Fig. 1A; Table DR2). Proximal rhyolite lavas were sampled at Tindfjallajökull (four samples; Table DR3) and Torfajökull (16 samples; Table DR4). The selected Torfajökull lavas include those known to have erupted during the last glacial period (i.e., Ring Fracture Rhyolites, Bláhúnukur, and “unnamed ridge”; McGarvie, 1984; McGarvie et al., 2006; Clay et al., 2015; Table DR5). These deposits contain a significant proportion of fragmental material (e.g., hyaloclastite, ash), though samples were sourced from fresh lavas to minimize alteration effects.

The geochemistry of the samples was determined using electron probe microanalysis (EPMA; major elements) and laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS; trace elements). A glassy fiamma from the Thórsmörk Ignimbrite, glass shards from II-RHY-1, and five lava samples from the Torfajökull Ring Fracture Rhyolites were selected for groundmass 40Ar/39Ar dating. Full methods are supplied in the Data Repository.

RESULTS AND INTERPRETATION

The geochemical data confirm that II-RHY-1 and the Thórsmörk Ignimbrite have highly similar compositions, overlapping on all bivariate plots (Figs. 1B–1C; Figs. DR3–DR5), though both deposits have variable trace element compositions (e.g., the trend to more evolved compositions seen in Fig. 1C). A glassy fiamma from the Thórsmörk Ignimbrite yielded an 40Ar/39Ar plateau age of 51.3 ± 4.2 ka (2σ), supporting the observation of Guíllou et al. (2019) that the age of the ignimbrite (55.6 ± 4.8 ka [2σ] in their study) is concurrent with the ice core chronology (GICC05) age of II-RHY-1 (Fig. 1D. Fig. DR6). Thus, our new geochemical and geochronological data strengthen the previously recognized correlation between II-RHY-1 and the Thórsmörk Ignimbrite.

Tephra from II-RHY-1 and the Thórsmörk Ignimbrite have compositions that overlap with the Ring Fracture Rhyolites of Torfajökull volcano on all geochemical plots (Figs. 1B–1C; Figs. DR3–DR5), indicating a strong geochemical similarity between these groups. In contrast, known compositions from Tindfjallajökull, Katla, and Eyjafjallajökull volcanoes, and from other Torfajökull rhyolites, are dissimilar to those of these tephra (Fig. 1B; Fig. DR3).

Groundmass 40Ar/39Ar inverse isochron ages of the Ring Fracture Rhyolites overlap with the ages of II-RHY-1 and the Thórsmörk Ignimbrite (Fig. 1D; Table DR8; Fig. DR6). Inverse isochrons are the preferred method of age calculation for these samples due to their non-atmospheric initial 40Ar/39Ar contents (Table DR8). Dating of groundmass arguably achieves a more representative eruption age than dating of feldspar crystals, which yield older apparent ages for the Ring Fracture Rhyolites (Guíllou et al. [2019] feldspar 40Ar/39Ar age: 77 ± 6 ka [2σ]; see discussion in the Data Repository, section 7). None of the other Torfajökull rhyolites dated in previous studies (McGarvie et al., 2006; Clay et al., 2015) have similar ages to the tephras. Thus, our new geochemical and geochronological evidence strongly suggests that II-RHY-1, the Thórsmörk Ignimbrite, and the Torfajökull Ring Fracture Rhyolites are the products of the same eruptive event (full results data set in Tables DR9–DR16).

DISCUSSION

The Source of II-RHY-1 and the Thórsmörk Ignimbrite

Our new work resolves the long-standing ambiguity regarding the origin of II-RHY-1 and the Thórsmörk Ignimbrite by recognizing Torfajökull, not Tindfjallajökull, as the source

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1GSA Data Repository item 2019213, additional sample information and locations, sample preparation and analysis methods, full results dataset, additional geochemistry plots, 40Ar/39Ar geochronology plots, and tables of new and published 40Ar/39Ar ages, is available online at http://www.geosociety.org/datarepository/2019/, or on request from editing@geosociety.org.
Figure 2. Model of rhyolite tuya formation modified from Tuffen et al. (2002) to show tephra dispersal and ignimbrite emplacement. During explosive phase (A), breaching of ice leads to development of subaerial eruption plume and propagation of pyroclastic density currents (PDCs) across ice surface. Proximal deposits are confined by ice to form steep-sided tuya, while tephra is deposited on ice surface and beyond (B). In example of Ring Fracture Rhyolites eruption studied here, variably welded ignimbrite (Thórsmörk Ignimbrite) is preserved ~30 km from source, and major tephra horizon (II-RHY-1) is reported as far as 2300 km from source.

Figure 2A: Explosive phase
- Tephra dispersal
- PDC propagation
- Subaerial ice-bound lava
- Supraglacial tephra deposit

Figure 2B: Effusive phase and final state
- Tephra deposit beyond ice margin
- Ignimbrite: welding

Tephras in fossil ice contain abundant volcanic glass and are high in sulfur (Lee et al., 2007). Volcanic ice has a characteristic blue–green color due to light scattering by air bubbles and glass shards. Tephra deposits from explosive eruptions are often deeply trenched by meltwater. Volcanic ash and glass shards may be entrained in the meltwater, forming a syn-eruptive tephra deposit.

Tephras in fossil ice also provide a record of volcanic eruptions at subglacial volcanoes. For example, the Etna Plinian eruption of 1669 AD produced a tephra layer that is preserved in ice across Sicily and central Italy. The tephra layer is characterized by glass shards and pyroclastic debris that were transported by the eruption columns and pyroclastic density currents (PDCs). The tephra layer is typically 1–2 m thick and contains abundant glass shards and pyroclastic debris. The tephra layer also contains a variety of volcanic glass types, including felsic and mafic compositions.

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Linking Glaciolavonism-Derived Paleoenvironmental Information with Other Records

Tephra II-RHY-1 is a widespread isochronous horizon that marks the eruption of the Ring Fracture Rhyolites directly within an array of small subglacial volcanoes of Torfajökull volcano, southern Iceland, as documented in this paper. The PDCs were still hot after traveling over ice or tephra-covered ice. A significant volume of tephra was likely deposited on the ice surface proximal to the eruption, and is now lost from the terrestrial record (Tuffen et al., 2002; Stevenson et al., 2011). The preserved ignimbrite (estimated volume: 1.5–2 km$^3$ dense-rock equivalent; Þorarinsson, 1969) is interpreted to have been deposited in a largely or wholly ice-free environment (i.e., outside the ice margin), and its outcrop thus defines the minimum extent of this environment at the time of the eruption.

CONCLUSIONS
Our data identify the Ring Fracture Rhyolites of Torfajökull volcano, southern Iceland, as the source of the Thórsmörk Ignimbrite and the distal tephra II-RHY-1. This correlation demonstrates that explosive rhyolitic eruptions at subglacial volcanoes can result in widespread tephra dispersal. Additionally, our work shows that pyroclastic density currents can propagate across and beyond an ice mass for ~30 km to emplace a variably welded ignimbrite. Rhyolitic glaciolavonic eruptions preserve a record of ice cover at the vent and can also deposit an isochronous tephra horizon in a variety of depositional settings. Tephra from these eruptions can thus be used to precisely date glaciolavonicism-derived paleoenvironmental information relative to the regional climate archive.

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