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

Jonathan D. Moles[1], Dave McGarvie[2], John A. Stevenson[3], Sarah C. Sherlock[1], Peter M. Abbott[4,5,6], Frances E. Jenner[1], and Alison M. Halton[1]
[1]Faculty of Science, Technology, Engineering and Mathematics, The Open University, Walton Hall, Milton Keynes MK7 6AA, UK
[2]Lancaster Environment Centre, Lancaster University, Lancaster LA1 4YQ, UK
[3]British Geological Survey, The Lyell Centre, Research Avenue South, Edinburgh EH14 4AP, UK
[4]Department of Geography, College of Science, Swansea University, Singleton Park, Swansea SA2 8PP, UK
[5]Institute of Geological Sciences, University of Bern, Baltzerstrasse 1, 3012 Bern, Switzerland
[6]School of Earth and Ocean Sciences, Cardiff University, Main Building, Park Place, Cardiff CF10 3AT, UK

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 paleoenvironmental 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 paleoenvironmental 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 glaciovolcanism-derived paleoenvironmental data with the regional climate record.

Rhyolite 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 (Lescinsky 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 tephras, 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 paleoenvironmental 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., $^{40}Ar/^{39}Ar$ 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 paleoclimate 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; 2σ) (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; Brendryen 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; Guillou 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.

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(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 Repository[1]). 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, Bláhnúkur, 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 $^{40}Ar/^{39}Ar$ 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 $^{40}Ar/^{39}Ar$ plateau age of 51.3 ± 4.2 ka (2σ), supporting the observation of Guillou 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.

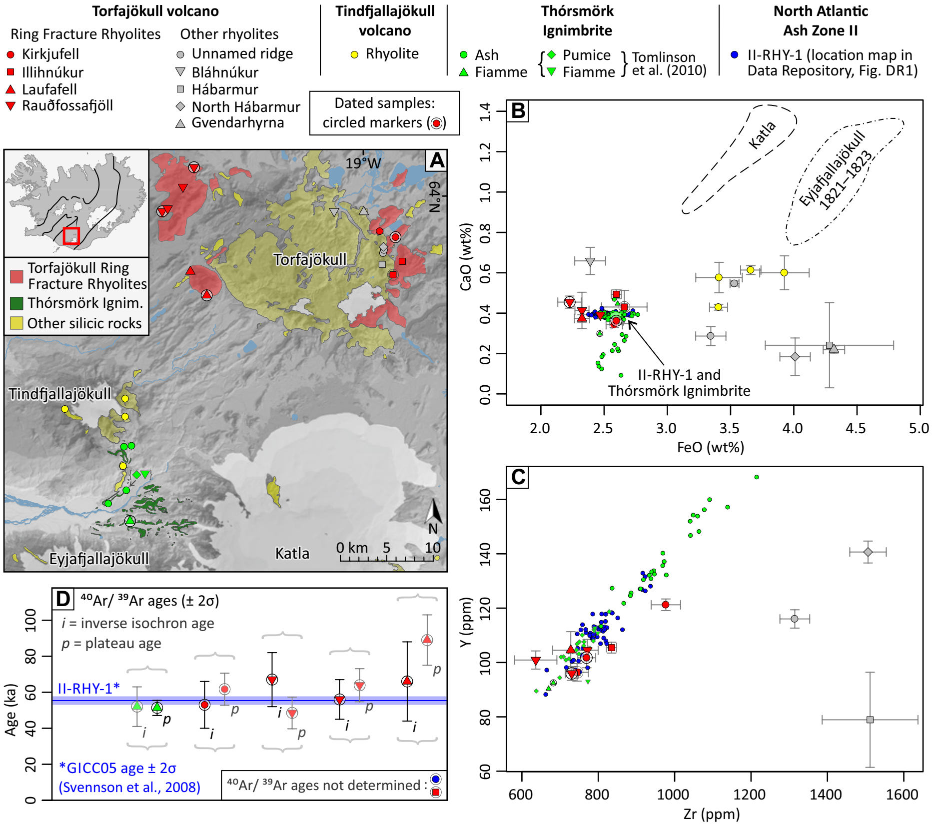

Figure 1. A: Location map of Thórsmörk Ignimbrite and nearby volcanoes in southern Iceland. Geological mapping from Jørgensen (1980), Jóhannesson and Sæmundsson (1989), Sæmundsson and Friðleifsson (2001), and Moles et al. (2018). B: Selected major elements plot of tephra II-RHY-1, Thórsmörk Ignimbrite, and rhyolites from potential source volcanoes. Katla composition from Lacasse et al. (2007); Eyjafjallajökull (A.D. 1821–1823 eruption) from Larsen et al. (1999). Lavas are plotted as mean and standard deviation of multiple analyses. Individual shard data are plotted for tephras. C: Selected trace elements plot of II-RHY-1, Thórsmörk Ignimbrite, and rhyolites from Torfajökull volcano. D: $^{40}Ar/^{39}Ar$ ages and comparison with Greenland Ice Core Chronology 2005 (GICC05) age of II-RHY-1. Inverse isochron and plateau ages are shown for each sample, with recommended ages in black (see discussion in the Data Repository, section 7 [see footnote 1]).

Tephras 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 tephras (Fig. 1B; Fig. DR3).

Groundmass $^{40}Ar/^{39}Ar$ 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 $^{40}Ar/^{36}Ar$ 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 (Guillou et al. [2019] feldspar $^{40}Ar/^{36}Ar$ 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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[1] GSA Data Repository item 2019213, additional sample information and locations, sample preparation and analysis methods, full results dataset, additional geochemistry plots, $^{40}Ar/^{39}Ar$ geochronology plots, and tables of new and published $^{40}Ar/^{39}Ar$ ages, is available online at http://www.geosociety.org/datarepository/2019/, or on request from editing@geosociety.org.

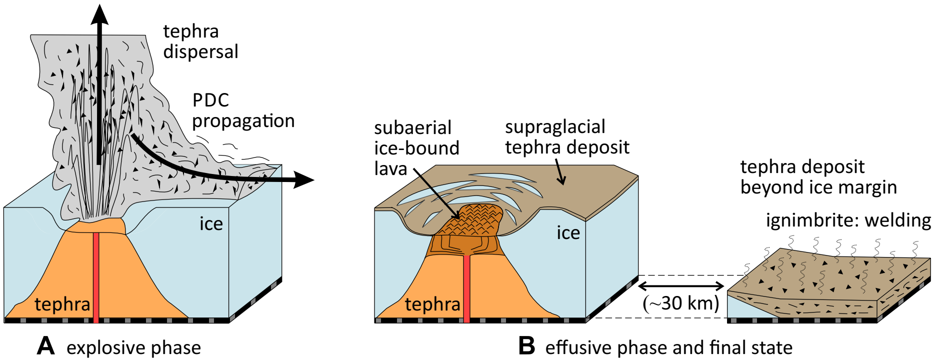

Figure 2. Model of rhyolite tuya formation modified from Tuffen et al. (2002) to show tephra dispersal and ignimbrite emplacement. During explosive phase (A), breaching of ice leads to development of subaerial eruption plume and propagation of pyroclastic density currents (PDCs) across ice surface. Proximal 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.

volcano. This is supported by the observation that ignimbrite deposits on the flanks of Tindfjallajökull lack proximal facies; in fact, lithic clasts decrease in size and abundance toward the volcano (Moles et al., 2018). Additionally, there was no significant change in local sediment deposition regimes at Tindfjallajökull, as would be expected following a major eruption (Moles et al., 2018).

The identified proximal products of the eruption—the Ring Fracture Rhyolites of Torfajökull volcano—are considered to be the largest rhyolitic eruption deposit in Iceland, with a preserved volume of ~18 km^3 (dense-rock equivalent; McGarvie, 2009). A ring of tuyas was emplaced during the eruption, confined by an ice mass >400 m thick (Tuffen et al., 2002; McGarvie et al., 2006). Explosive activity formed steep-sided tephra piles before the effusive emplacement of intrusions and lava caps (Tuffen et al., 2002, 2008; Owen et al., 2013b).

Tephra Dispersal during Rhyolitic Glaciovolcanic Eruptions

Our new correlation provides the first documented link between rhyolite tuyas and distal tephra deposits, indicating that a subglacial rhyolitic eruption breached the ice to produce a subaerial eruption plume (Fig. 2). This confirms that widespread and voluminous tephra dispersal can be an important feature, and hazard, of rhyolite glaciovolcanism (as hypothesized by Tuffen et al. [2002] and Stevenson et al. [2011]). Although magma fragmentation during the eruption was initially enhanced by meltwater (Tuffen et al., 2008, 2002), investigations of these and other rhyolite tuyas show that the influence of meltwater rapidly declines with time and explosivity is principally driven by magmatic volatiles (Owen et al., 2013a; Stevenson et al., 2011). The development of volatile-driven subaerial eruption plumes after the ice is breached suggests that rhyolite glaciovolcanism can disperse tephra in the same style as rhyolite volcanism in ice-free settings.

The correlation of rhyolite tuyas with an ignimbrite demonstrates another previously undocumented phenomenon and hazard: pyroclastic density currents (PDCs) can occur during rhyolite tuya-forming eruptions and can travel tens of kilometers across an ice mass (Fig. 2). Welded ignimbrite deposits are present ~30 km from Torfajökull (Jørgensen, 1980), indicating that 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; Thórarinsson, 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.

Linking Glaciovolcanism-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 high-resolution proxy records, such as ice-core δ^{18}O profiles, which document the climate and the associated environmental conditions (Ruddiman and Glover, 1972; Grönvold et al., 1995; Zielinski et al., 1997; Austin et al., 2004; Abbott et al., 2018). Reconstructions of coeval ice conditions in south Iceland (i.e., ice >400 m thick at Torfajökull; absent in Thórsmörk) can now be directly linked to this vast archive of paleoenvironmental information and can act as boundary conditions for models of the Icelandic ice sheet during the last glacial period. Based on the North Greenland Ice Core Project (NGRIP) ice core record, II-RHY-1 was deposited 40 ± 5 yr after the start of GS 15.2 (Svensson et al., 2008; Rasmussen et al., 2014). The use of tephra to integrate glaciovolcanism-derived data with the regional climate record provides a significant advance in precision compared to absolute dating alone (e.g., Clay et al., 2015), and can be applied to any glaciovolcanic eruption that produced an identifiable distal tephra horizon.

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 glaciovolcanic 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 glaciovolcanism-derived paleoenvironmental information relative to the regional climate archive.

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