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ERUPTIVE HISTORY OF TEPHRA ON UNDIRHLÍÐAR RIDGE, ICELAND

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INTRODUCTION

This study considers the origin of the extensive tephra exposed on the ridge between Undirhlíðar and Vatnsskarð quarries. Schopka et al. (2006) have chronicled the formation of Helgafell, a similar hyaloclastic basaltic ridge a few kilometers from Undirhlíðar, providing an excellent analog and comparison for this study.

The simple subglacial eruption model developed by Jones (1968, 1970) suggests that tephra forms at the end of an eruption sequence in a shallow lake, which may completely drain over the course of the eruption. However, recent work by Pollock et al. (2014) suggests that subglacial eruptions may be more complicated because explosive fragmental material occurs between packages of effusive pillow lavas at Undirhlíðar quarry. Furthermore, Schopka et al. (2006) suggest that Helgafell, which is dominated by fragmental material, formed entirely subglacially under at least 500 m of ice.

This study presents a comprehensive investigation of the tephra cone on Undirhlíðar ridge with the aim of reconstructing its eruptive history. This analysis considers the stratigraphy, degree of palagonitization, glass shape, glass water content and geochemistry. It is hypothesized that the tephra formed during a subaqueous explosive eruption with multiple eruptive events following the formation of the rest of the ridge.

METHODS

Photos and detailed field notes were converted into a comprehensive stratigraphic column of the tephra cone (Fig. 1). Eighteen samples (17 tephra samples and one bomb) were collected on Undirhlíðar Ridge representing the entire stratigraphy of the tephra cone. Thin sections were made of the 15 samples consisting of consolidated materials. Thin sections were analyzed for glass shape in ImageJ. Photos of 10 hand samples were analyzed in ImageJ using color thresholds to select pixels that were exclusively black (glass) or orange (palagonite). ImageJ was then used to calculate percent area covered by both colors to determine palagonite and fresh glass content.

Fresh glass from three samples was doubly polished following the method of Hiatt (2014) and prepared for analysis by Fourier Transform Infrared Spectroscopy (FTIR). Only three samples were included in the FTIR analysis due to difficulty in extracting fresh glass from highly palagonitized tephra. FTIR analysis was conducted at the University of Massachusetts Amherst (UMass) on a Bruker Tensor 27 FTIR with attached Hyperion 3000 microscope. The chemical compositions of this fresh glass from the three samples were also obtained using a Cameca SX50 Electron Microprobe at UMass. Additionally, chemical compositions of glasses in four polished thin section were determined using a Zeiss DSM-50 scanning electron microscope (SEM-EDS) at Amherst College. H20Solve (Moore et al., 1998) was then used to calculate eruption pressure based on H_2O wt.% and geochemistry. Water depth was then calculated from eruption pressure.

RESULTS

Stratigraphy

Tephra deposits are dominated by lapilli- and ash-size grains that are palagonitized to some degree (~20-60%) but locally contain up to ~75% fresh glass (Figs. 1 & 2). Basal units (units 1, 3 and 4) are tuff breccia to volcanic breccia with basaltic and rare gabbroic lithic clasts. They are cross-bedded and rather poorly sorted, although there is some normal grading. Unit 5 consists of vitric lapilli tuff and is cut by a well-constrained dike. The uppermost exposure (unit 6) consists of fine, normally graded beds with few large clasts and glassy bombs. There are some erosive surfaces between beds.

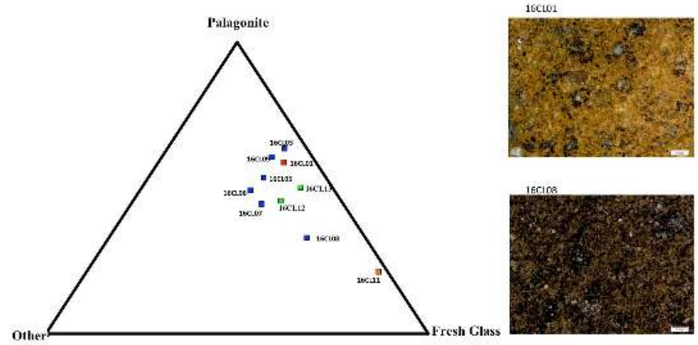
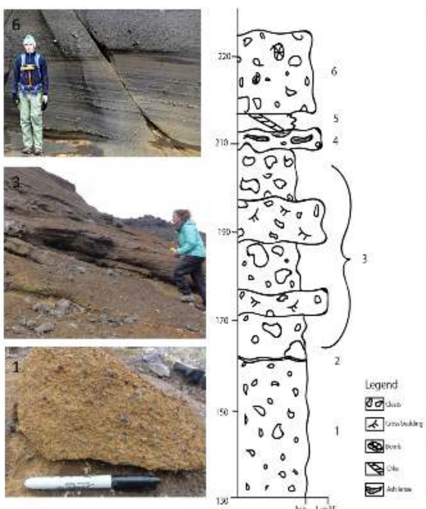


Figure 2. Ternary diagram showing composition of tephra where "other" represents lithic fragments and unidentified materials. Tephra deposits are dominated by lapilli- and ash-size grains that are palagonitized to some degree (~20-60%) but locally contain up to ~75% fresh glass, based on ImageJ analysis of hand samples. Colors correspond to units in Figure 1. Images illustrate highly palagonitized (16CL01) and relatively fresh (16CL08) hand sample images.



Unit	Description
6	Similar matrix to unit 3, consolidated, homogeneous clasts, some glassy bombs, layers of ash interbedded with lapilli tuff
5	Vitric lapilli tuff, smooth surface, cut by well constrained dike
4	Lapilli tuff/tuff breccia with lenses of ash, possibly isolated body
3	Tuff breccia with interbedded lapilli tuff, heterogeneous clasts up to 1m, dipping beds, cross bedding, some normal bedding, palagonitization irregular, erosional cave features with cemented rims Note: beds within unit not to scale
2	Thin fine grained grey ash layer
1	Palagonitized fine grained tuff breccia, heterogeneous clasts up to 10cm

Figure 1. (Left) Field images of units 6, 3, and 1, from top to bottom. (Center) Comprehensive stratigraphic column of a cross section of the South side of the tephra cone. (Right) Descriptions of stratigraphic units. Color of unit numbers correlates with Figure 2.

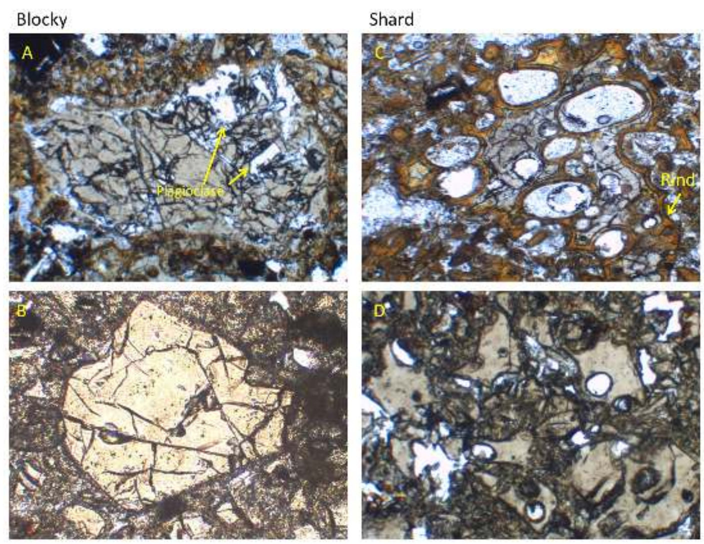


Figure 3. A and B are examples of blocky chips. C and D are examples of shard chips. Note plagioclase crystals in glass in slide A and rind palagonitization on image C.

PETROGRAPHY

Samples contain 29-76% fresh glass and 21-63% palagonite (Fig 2). Lower units (units 1 and 3) tend to be more palagonitized.

Samples contain both shard-like and blocky glass (Fig. 3). Shard-like glass is heavily vescilulated and is characterized by curved edges whereas blocky glass is not vesicular and is characterized by straight edges (Fig.3). Heavily palagonitized samples from lower units (units 1 and 3) contain higher proportions of blocky glass (greater than 50%) whereas less palagonitized samples from uppermost unit (unit 6) contain higher proportions of shard-like glass.

Water Content Analysis

Polished glass analyzed on the FTIR from three samples contains 0.052 wt.%, 0.079 wt.%, and 0.138 wt.% H_2O. This water content is significantly lower than the water content of pillows on the ridge at similar elevations (Fig. 4). The H_2O contents

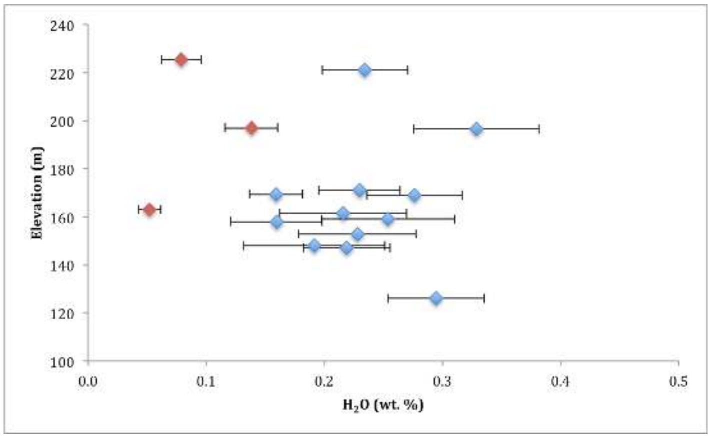


Figure 4. H_2O (wt.%) Vs. Elevation (m). Tephra samples are shown in orange while ridge pillow samples from similar elevation are shown in blue. Pillow water contents from Wallace (this volume). The tephra has significantly lower water content than the pillows.

correspond to eruption depths under 0.55 m, 1.28 m and 41.27 m of water, respectively. The sample with the highest water content is a bomb sampled from the uppermost tephra unit. The other samples are from units 3 and 6.

Geochemistry

The chemical compositions of tephra samples overlap with compositions of lava from the entire ridge, but on average have lower MgO contents (6.80 – 7.24 wt.%; Fig. 5) and Mg numbers (Mg# 48.0 – 49.6). Upper tephra units (16CL11, 16CL12, 16CL16) have lower wt% CaO and MgO values and are higher in wt.% Al_2O_3 and K_2O than lower tephra units (16CL08, 16CL03, 16CL01, 16CL06; Fig. 5).

DISCUSSION

The data support the hypothesis that multiple eruptive pulses formed the tephra cone during a subaqueous explosive eruption following the ridge formation. The data further suggest that the cone was erupted into a shallow lake and that the cone built up in the lake throughout the eruption.

Field evidence is consistent with the interpretation that the cone-building eruption was likely subaqueous with several eruptive pulses. Series of graded beds in unit 6 and interbedded tuff breccia and lapilli tuff in unit 3 are evidence of multiple eruptive pulses. Cross

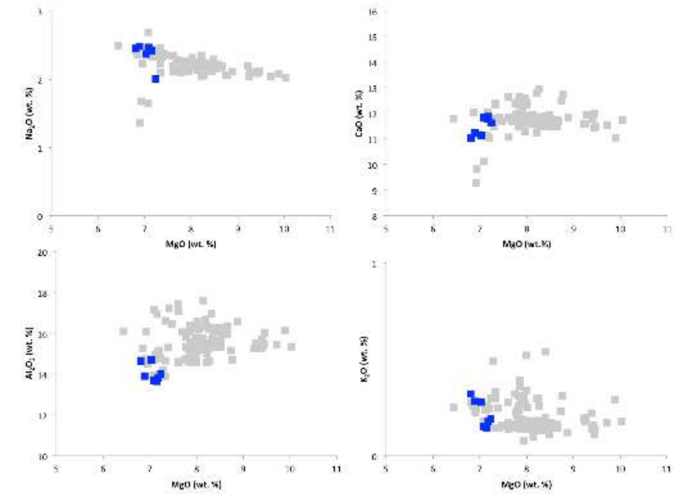


Figure 5. Na_2O, CaO, Al_2O_3 and K_2O vs. MgO (in wt.%). Samples from the present study are shown in blue. Samples from the Undirhlíðar ridge, including pillows and intrusions, are shown in grey. Tephra samples are constrained to the lower MgO portion of the ridge suite.

bedding in units 3 and 6 indicates influence of water in deposition. Cross bedding in the uppermost unit, along with the lack of accretionary lapilli and the presence of few bombs, suggests that there was no subaerial eruptive phase.

Glass volatile contents support the conclusion that the tephra cone erupted in a shallow lake and built up throughout the eruption. Water contents of tephra samples indicate a very shallow eruption environment (water depth <1.5 m). Though there are only two H_2O measurements of tephra due to the difficulty in obtaining polished glass, the lower sample has higher wt.% H_2O than the upper one, supporting the idea that the ridge built up through the lake during the eruption.

Variations in glass shard texture also support the hypothesis that the eruption was subaqueous and that the cone was built in a shallow lake. Heiken (1974) concludes that volcanic ash forms by two basic fragmentation mechanisms: magmatic gas expansion as magma approaches the surface (magmatic eruptions, low pressure) and quenching due to contact with water (phreatomagmatic eruptions, high pressure). In subaerial low-pressure eruptions, gas is released from the magma during the eruption and quenched glass is vesiculated. Thus the morphology of ash particles is directly related to vesicle shape and density. This type of glass is referred to as “shard-like” in the current study. In contrast, in subaqueous high-pressure eruptions quenching occurs before the gas is released. Thus glass shape is unrelated to vesicles (Heiken, 1974). This type of glass is referred to as “blocky” in the current study.

Both shard-like and blocky glass occur in all tephra analyzed here. However, lower units contain higher proportions of blocky glass chips while upper units contain higher proportions of shard-like glass chips. These differences could occur if the cone built up through the lake. According to this scenario, upper units erupted at extremely shallow water depths, whereas lower units erupted under higher water pressure, resulting in proportionally more shard-like glass in upper units than in lower units.

The proportion of shard-like versus blocky glass may also explain observed differences in palagonitization between units (Fig. 2). Palagonite is an alteration product of glass formed with water and is postulated to begin forming during the eruption and continue after consolidation. It has been suggested that palagonite is in part controlled by temperature, porosity, and fluid composition (Stroncik and Schmincke, 2002). In all samples, shard-like glass chips are on average smaller than blocky glass chips, likely due to the fragility of highly vesiculated glass. Smaller shard-like chips could pack tighter than blocky glass, yielding lower porosity. Lower porosity leads to less fluid flow, so upper units with lower porosity are less palagonitized.

Geochemical evidence suggests that the eruption was likely monogenetic with multiple eruptive pulses. Tephra samples have a narrow range of compositions that overlap with the lower MgO samples from the rest of the ridge. The narrow compositional range suggests that the tephra is erupted from the same magma batch and is more evolved than the pillow-forming ridge lavas. Since the tephra-forming eruption was more evolved, it may have been saturated with more gas and occurred at lower temperature with greater crystallinity, leading to a more explosive eruption style. Upper tephra units have slightly lower CaO and MgO contents and higher Al_2O_3 and K_2O contents than lower tephra units (Fig. 5). These differences suggest that a heterogeneous magma batch may have fed the tephra cone, thus supporting the idea that the tephra erupted in multiple pulses.

Field relationships and emplacement pressures support the timing of the tephra-forming eruption near the end of the ridge construction process. Although the large, well-constrained dike in unit 5 signifies continuing magmatic activity following tephra cone deposition, water contents of the tephra and bomb are significantly lower than pillow lava water contents from similar elevations (Fig. 4), suggesting that pillows formed first under significant pressure while the tephra cone formed later in a shallow eruptive environment. Field observations of the contact between pillows and tephra support this sequence of events; erosional windows through overlaying tephra expose pillows in some areas. Glacial diamict is present on the north side of the ridge, providing evidence of significant erosion after formation.

Overall, this study supports the simple subglacial eruption model developed by Jones (1968, 1970) in which tephra is deposited at the end of the eruption, forming a cone that builds up through a shallow lake. This is contrary to the formation of Helgafell proposed by Schopka et al. (2006), who reported an entirely subglacial eruption under at least 500 m of ice. The present study suggests that Undirhlíđar erupted in a dynamic, shallow-water eruptive environment. Even though the overall stratigraphy (Fig. 1) mirrors Helgafell stratigraphy (Schopka et al., 2006), water contents of tephra analyzed in the present study are significantly lower than those analyzed by Schopka et al. (2006). Water contents remain constant throughout the Hegafell stratigraphy (Schopka et al., 2006), whereas water contents were found to vary with elevation at Undirhlíđar, suggesting that Undirhlíđar formed in a dynamic eruptive environment. Undirhlíđar tephra is significantly more palagonitized than Helgafell tephra. This could be because Undirhlíđar may have spent more time in water than Helgafell, resulting in more extensive palagonitization. Thus, the proximity and stratigraphic similarity may be cause for comparison between Helgafell and Undirhlíđar, but it is clear that they formed in very different environments and are therefore not entirely analogous.

CONCLUSIONS

Formation of the tephra cone on Undirhlíđar Ridge appears to support the simple subglacial eruption model outlined by Jones (1968, 1970): 1) eruption of pillow lavas at great water depths, 2) formation of tephra by explosive eruptions at shallow water depths, and 3) possible subaerial effusion if the eruption continues. Water content suggests that the tephra cone formed at significantly lower pressures than the rest of the pillow ridge. Increasing proportions of shard glass up stratigraphy suggest a decrease in pressure throughout the eruption as the cone built up through the lake. There is abundant stratigraphic and geochemical evidence of multiple pulses throughout the eruption.

Schopka et al. (2006) concluded that pressure remained constant throughout the eruption and proposed a water depth of at least 500 m. In contrast, the results presented here suggest a significant drop in pressure over the course of the Undirhlíđar eruption. These conclusions are consistent with much of the prior work on subglacial eruptions (e.g., Werner and Schmincke, 1999) and the simple subglacial eruption model.

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REFERENCES

Fisher, P.R.V., and Schmincke, P.H.-U., 1984, Submarine Volcaniclastic Rocks, *in* Pyroclastic Rocks, Springer Berlin Heidelberg, p. 265–296, doi: 10.1007/978-3-642-74864-6_10.

Fiske, R.S., 1963, Subaqueous Pyroclastic Flows in the Ohanapecosh Formation, Washington: Geological Society of America Bulletin, v. 74, p. 391–406, doi: 10.1130/0016-7606(1963)74[391:SPFITO]2.0.CO;2.

Heiken, G., 1974, An atlas of volcanic ash:, https://ntrs.nasa.gov/search.jsp?R=19740017769 (accessed October 2016).

Hiatt, Alexander R., 2014, Estimated Hydrostatic/Cryoststic Pressure During Emplacement of Pillow Lavas at Undirhlíðar Quarry, Reykjanes Peninsula, Southwest Iceland [Undergraduate thesis]: Wooster, The College of Wooster, 46 p.

Jones, J.G., 1970, Intraglacial Volcanoes of the Laugarvatn Region, Southwest Iceland, II: The Journal of Geology, v. 78, p. 127–140, doi: 10.1086/627496.

Jones, J.G., 1968, Intraglacial volcanoes of the Laugarvatn region, south-west Iceland--I: Quarterly Journal of the Geological Society, v. 124, p. 197–211, doi: 10.1144/gsjgs.124.1.0197.

Moore, G.M., Vennemann, T., and Carmichael, I.S.E., 1998, An empirical model for the solubility of H2O in magmas to 3 kb: American Mineralogist, v. 83, p. 36–42.

Pollock, M., Edwards, B., Hauksdóttir, S., Alcorn, R., and Bowman, L., 2014, Geochemical and lithostratigraphic constraints on the formation of pillow-dominated tindars from Undirhlíðar quarry, Reykjanes Peninsula, southwest Iceland: Lithos, v. 200–201, p. 317–333, doi: 10.1016/j.lithos.2014.04.023.

Schopka, H.H., Gudmundsson, M.T., and Tuffen, H., 2006, The formation of Helgafell, southwest Iceland, a monogenetic subglacial hyaloclastite ridge; sedimentology, hydrology and volcano-ice interaction: Journal of Volcanology and Geothermal Research, v. 152, p. 359–377, doi: 10.1016/j.jvolgeores.2005.11.010.

Stroncik, N.A., and Schmincke, H.-U., 2002, Palagonite – a review: International Journal of Earth Sciences, v. 91, p. 680–697, doi: 10.1007/s00531-001-0238-7.

Werner, R., and Schmincke, H.-U., 1999, Englacial vs lacustrine origin of volcanic table mountains: evidence from iceland: Bulletin of Volcanology, v. 60, p. 335–354, doi: 10.1007/s004450050237.