Learning Science Through Research
Published by Keck Geology Consortium

Short Contributions
30th Annual Symposium Volume
29th April, 2017
ISBN: 1528-7491

CONSTRAINTS ON MAGMA TRANSPORT AND ERUPTION DYNAMICS AT A GLACIOVOLCANIC PILLOW RIDGE, SOUTHWEST ICELAND

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INTRODUCTION

Glaciovolcanic ridges have been recognized for their ability to serve as analogs for Mars and as records of ice-sheet conditions, but their location under hundreds of meters of ice means that direct observations of glaciovolcanic eruptions are rare. Glaciovolcanic ridges have been exposed by Holocene ice retreat at many locations in western Canada (e.g., Edwards et al., 2009), Antarctica (e.g., Smellie et al., 2008), and Iceland (e.g., Höskuldsson et al., 2006). Studies of these ridges have led to a relatively simple monogenetic model for glaciovolcanic eruptions: an initial period of effusive eruptions at the base of an englacial lake creates pillow lavas; as water depth shallows, the eruption transitions to entirely explosive activity, blanketing the pillow lavas with a layer of fragmental volcanic material (e.g., Jones, 1970; Allen et al., 1982; Hickson, 2000). However, observations of glaciovolcanic pillow exposures in Iceland (Pollock et al., 2014) and British Columbia (Edwards et al., 2009) show packages of pillow lavas separated by fragmental volcanic material. These observations indicate that the general model for monogenetic glaciovolcanic pillow-dominated eruptions needs to be further tested and revised.

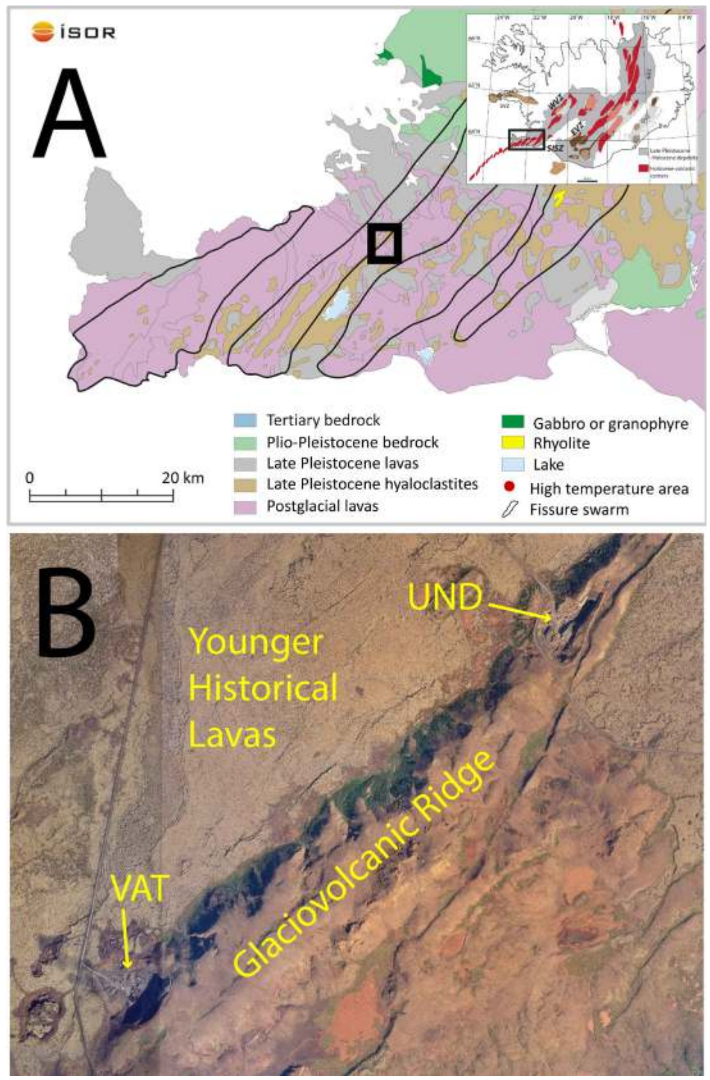

Figure 1. (A) Geologic map of the Reykjanes Peninsula (Saemundsson et al., 2010). Volcanic segments are outlined (after Jakobsson and Gudmundsson, 2008). Box shows location of field site. Inset shows regional setting in Iceland's Western Volcanic Zone (WVZ; after Edwards et al., 2012). (B) Aerial overview of the glaciovolcanic ridge and locations of Undirhlíðar (UND) and Vatnsskarð (VAT) quarries. This study focused on portion of the ridge between the quarries.

Undirhlíðar ridge on the Reykjanes Peninsula in southwest Iceland is one of several NE-SW glaciovolcanic ridges that was formed by subglacial eruptions during the late Weichselian (Fig. 1). The glaciovolcanic ridges are composed of fragmental volcanic material and pillow lava, which have been exploited as a building material. As a result, several active and inactive quarries exist on the peninsula. Two of these quarries, Undirhlíðar and Vatnsskarð, have been the target of a multi-year study to document the three-dimensional structure, stratigraphy, and geochemistry of glaciovolcanic deposits.

The investigations in Undirhlíðar and Vatnsskarð have revealed the overall complexity of glaciovolcanic eruptions, including transitions in explosive-effusive eruption behavior, interconnected shallow magma transport networks, and within-ridge changes in lava composition (Pollock et al., 2014). Pillow lavas dominate, but we also observe dikes, shallow intrusions, and fragmental units, including interbedded tuff, lapilli tuff and tuff-breccia (Fig. 2). Geochemical variations reveal two distinct magmatic groups: an incompatible element-enriched lava (La_N/Sm_N 1.60 +/- 0.03, Nb/Zr .15 +/- .002) that is found only at the base of Undirhlíðar quarry and a less-enriched lava (La_N/Sm_N 1.28 +/- 0.04, Nb/Zr 0.14 +/- 0.02) that is found in Vatnsskarð and in the upper units of Undirhlíðar quarry (Fig. 3A). The less-enriched lava spans a greater range in compositions and includes several mineralogically distinct units that are characterized by large olivine and plagioclase crystals up to 1 cm in diameter. Mineralogical and geochemical variability within both groups can be explained by fractional crystallization in separate, shallow-level melt reservoirs (Fig. 3B).

We have developed a model for the formation of the ridge based on the lithostratigraphic, petrographic, and geochemical relationships in Undirhlíðar quarry (Pollock et al., 2014). The base of the ridge was

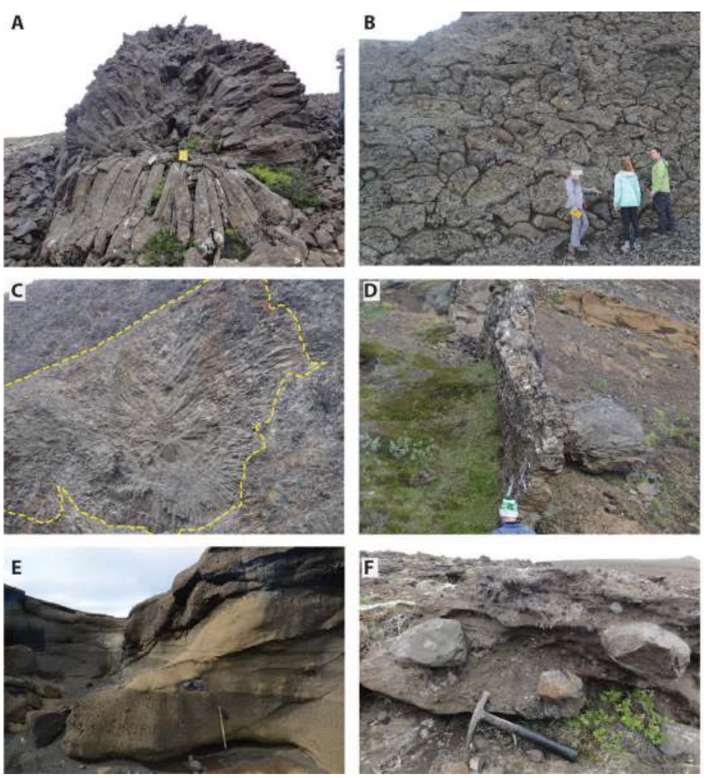

Figure 2. Outcrop-scale photos of lithologic units observed along the ridge. (A) 'mega-pillow' standing in relief along the ridge, (B) pillow lavas exposed on a quarry wall, (C) massive columnar-jointed basalt (MCJB) or intrusion outlined in yellow (field of view is ~15 m), (D) dike (~0.5 m wide) standing in relief on the ridge flank, (E) tephra showing sedimentary structures, grain size variations, and bombs, (F) glacial diamict with very poorly sorted gravel, cobbles, and large boulders.

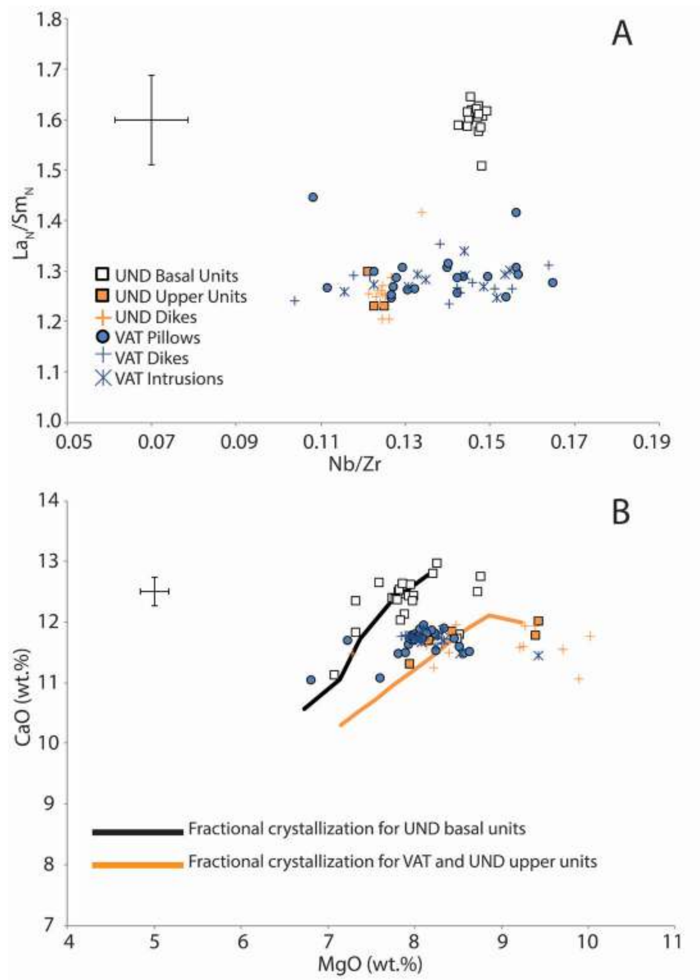

Figure 3. (A) Trace element compositions of Undirhlíðar (UND) and Vatnsskarð (VAT) samples. La and Sm are normalized to chondrite (Sun and McDonough, 1989). (B) Major element variations of Undirhlíðar (UND) and Vatnsskarð (VAT) samples in weight percent. Lines represent crystallization trends calculated using rhyolite-MELTS (v.1.2.0; Ghiorso and Gaulda, 2015; Gaulda et al., 2012) for hydrous (0.4 wt.% H2O) parent magmas at 2 kb pressure and the QFM buffer. Error bars on both graphs represent 2-theta standard deviation.

built during an initial effusive phase, which erupted olivine-free, incompatible element-enriched lava from a shallow melt reservoir. The eruptive activity paused for an unknown period of time and was followed by an explosive eruptive phase, which generated local lenses of tuff-breccia and lapilli tuff. A second effusive phase produced dikes that intruded the initial effusive deposits and erupted pillow lavas that drape over the western edge of the existing ridge. This effusive phase taps a separate melt reservoir, erupting a less-enriched lava bearing large olivine phenocrysts. Finally, there was a third effusion on the east side of the quarry, which intruded the fragmental units and erupted a capping layer of pillow lavas. The lavas from this final eruption are also derived from the second melt reservoir but do not contain large olivine phenocrysts.

The model demonstrates the dynamic processes by which glaciovolcanic ridges are constructed and has raised several additional questions:

(1) To what extent can pillow lava characteristics help us understand the formation of pillow lavas? Pillow lavas are the only lasting record of a preexisting englacial lake, so understanding the details of their vesicle distribution and jointing patterns may provide new insights into the hydrology of the enclosing ice. Vesicles have been used as indicators of paleo-pressures during subaqueous eruptions (Jones, 1969), in some cases recording sudden drainage events (Höskuldsson et al., 2006).

(2) How do eruption morphologies change with emplacement pressure and magmatic conditions? Jones (1969, 1970) proposed that basal pillow lavas are formed at water depths greater than 500 m and that upper fragmental material are the product of explosive eruptions at shallow water depths (~100-200 m). However, geochemical variations in subglacial pillow ridges, including Undirhlíðar, suggest that eruption morphology may also be related to magmatic conditions, rather than simply emplacement pressure (Moore & Calk, 1991; Moore et al., 1995; Jakobsson and Johnson, 2012; Pollock et al., 2014).

(3) How is lava distributed along and across the ridge structure? In the quarries, we observe irregularly shaped intrusions that may be related to the shallow plumbing system. Lava tubes and dikes may play important roles in controlling the distribution of lava within the growing pillow edifice, as they do on mid-ocean ridges (e.g., Soule et al., 2007).

To address the questions raised by our previous work, this project focused on the ~3 km-long area between Undirhlíðar and Vatnsskarð (Fig. 1). Our group comprised eight student researchers: six students selected through the Keck Geology Consortium and two students who assisted with field and lab work. On 21 June 2017, we flew from our home cities to Iceland. We explored our field site for the first two days, visiting characteristic localities in Undirhlíðar quarry and hiking the length of the ridge. In consultation with the project directors, students identified research questions and developed strategies for data collection and analysis. The remaining two weeks of field work were focused on detailed mapping, sampling, and data collection, including observations of pillow lava characteristics, taking high-resolution photos, and recording GPS information.

We returned to The College of Wooster to process our field data and prepare samples for petrographic and geochemical analysis. The lab work varied by project; students processed GPS data, analyzed high-resolution photos, prepared whole-rock powders for analysis by XRF and ICP-MS, polished glass chips for analysis by FTIR and EPMA, and cut billets for thin sections. The students made significant progress on their research by the end of the summer experience (17 July 2017) and were able to submit three abstracts to the 2016 Annual GSA Meeting.

Students pursued their research during the following academic year and participated in weekly meetings with directors. In late September, our group reunited in Denver, CO, to present our three posters (Heineman et al., 2016; Thompson et al., 2016; Wallace et al., 2016). Some participants also visited each other to conduct analytical work, including SEM-EDS analyses at Oberlin College and FTIR and EPMA analyses at UMass Amherst.

STUDENT PROJECTS

The research group collaborated to produce a new geologic map of the ridge (Fig. 4). The bulk of the ridge comprises coherent pillow lavas and pillow

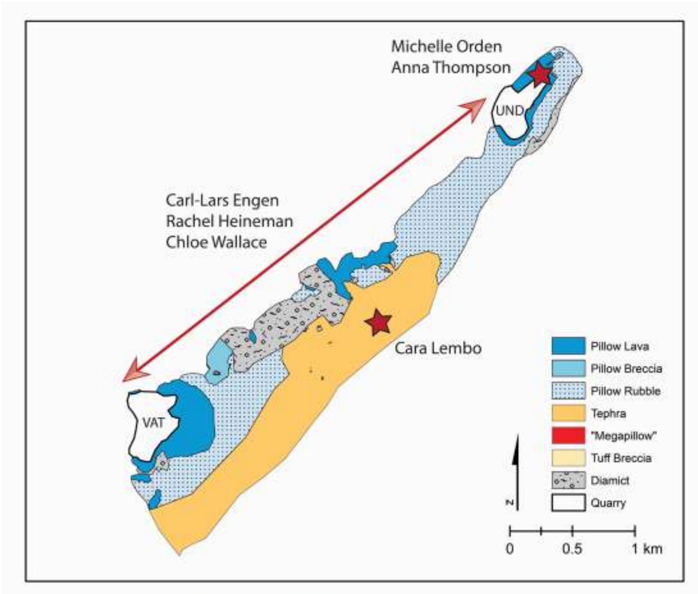

Figure 4. Geologic map of the study area. Much of the ridge consists of coherent or fragmented pillow lava units (blue). An extensive tephra deposit (yellow) is newly identified on the southeast flank of the ridge. Undirhlíðar (UND) and Vatnsskarð (VAT) quarries are labeled. Locations of student projects are indicated by their names. Anna Thompson and Michelle Orden worked on a pillow lava unit in the northwest corner of Undirhlíðar quarry. Cara Lembo worked on the tephra deposit. Rachel Heineman and Chloe Wallace worked on several outcrops along the length of the ridge. Carl-Lars Engen focused on Undirhlíðar quarry and a transect along the top of the ridge.

lava rubble, consisting of loose, broken pillow lava fragments. Erosional gullies on the northwest flank of the ridge expose units of pillow breccia interpreted to be volcanic in origin, containing vesiculated and glassy pillow fragments interbedded with variably palagonitzed hyaloclastite. Some of the exposures on the northwestern side of the ridge are obscured by a younger deposit of glacial diamict (Fig. 2F). The diamict is matrix supported with subangular to rounded gravel to boulder-sized clasts. The matrix consists of yellow, predominantly sand-sized grains of blocky glass. We identified a laterally extensive tephra deposit on the southeast flank of the ridge that extends from the center of the ridge to the southern tip. The tephra deposits reveal a complex stratigraphy, with multiple units of tuff, lapilli tuff, and tuff-breccia (Fig. 2E). The units show sedimentary structures, like cross-bedding and graded bedding, and variable degrees of palagonitization. Standing in relief within the tephra and pillow rubble are dikes (Fig. 2D), tabular approximately meter-wide intrusions with chilled margins, and 'megapillows' (Fig. 2C), outcrops

Figure 5. The Iceland Glaciovolcanism team: (left to right) Ben Edwards, Anna Thompson, Chloe Wallace, Cara Lembo, Rachel Heineman, Michelle Orden, Carl-Lars Engen, Ben Kumpf, and Meagen Pollock (not pictured, Will Kochtitzky).

of massive lava with pillow-like characteristics, such as radial jointing, concentric vesicle bands, and glassy rims, when present.

Anna Thompson (Carleton College) focused on the formation of vesicles in pillow lavas. She developed a classification system for vesicle patterns, quantified vesicle characteristics by analyzing high-resolution images, and estimated physical lava properties using geochemical and petrographic analyses. She used her findings to constrain a theoretical model that tracks the movement of bubbles in a cooling pillow lava. She found that the vesicle distribution pattern depends on cooling rate, location relative to the length of the pillow tube, and emplacement pressure. She suggests that concentric vesicle rings can be formed by rapid cooling or multiple magma pulses.

Michelle Orden (Dickinson College) investigated the formation of fractures in pillow lavas with the goal of understanding details about the emplacement environment. Based on detailed field observations and photo analysis, she developed seven fracture categories, described common natural fracture patterns, and discovered correlations between fractures and pillow size. She calculated that a temperature change of 46^{o}C was required to form a fracture in a cooling basaltic pillow and created a 2-D thermal model to simulate fracture development during cooling. She suggests that cooling can explain the initiation and propagation of some fractures, but not all, and proposes improvements for an advanced cooling model.

Chloe Wallace (The College of Wooster) studied paleo-ice thickness along the ridge. She measured volatile contents of glassy pillow rinds from 12 locations along the ridge. She used the volatile contents, along with glass compositions and liquidus temperatures, in an equilibrium solubility model to calculate the emplacement pressures. She found that the lower-elevation pillow lavas were erupted under hydrostatic conditions, then there was a low-pressure (drainage) event followed by another period of pillow lava formation during which the ice thickness reset and hydrostatic conditions resumed.

Rachel Heineman (Oberlin College) studied the 'megapillows.' She identified two megapillow groups based on the textures, mineral compositions, and geochemistry of nine unique megapillow outcrops. Compared to typical pillow lavas, Rachel found evidence for significant plagioclase accumulation in the megapillows, which may have increased lava viscosity, allowing the megapillows to grow larger in diameter. She also identified megapillows in the central part of the ridge with a magma composition that was previously observed only in Undirhlíðar quarry. She suggests that megapillows may form at the advancing eruptive front and feed pillow lavas from their bases.

Cara Lembo (Amherst College) investigated the extensive tephra deposit exposed on the southeast flank of the ridge. She examined the stratigraphy, petrography, and geochemistry of the tephra and compared her findings to Helgafell, an adjacent glaciovolcanic ridge of similar age but dominated by fragmental deposits (Schopka et al., 2006). She concludes that the tephra was erupted in a shallow lake toward the end of the the ridge construction process and that the formation of Helgafell is not entirely analogous.

Carl-Lars Engen (Beloit College) used dynamic digital mapping technology to synthesize ridge-scale observations and develop a model for the sequence of events that built the ridge. He used Esri's Story Maps to design geologic tours of Undirhlíðar quarry and the ridge, creating a comprehensive overview that is accessible to a broad audience.

SCIENTIFIC ACCOMPLISHMENTS

Our research produced a geologic map for the ridge that is at a higher-resolution than the previous map and defines several new units, including pillow rubble and a laterally-extensive tephra cone. In the center of the ridge, we observed a magma composition that was known previously only to exist at the base of Undirhlíðar quarry, suggesting that the first eruptive phase extended along-axis for ~1 km. Our detailed investigation of pillow lavas allowed us to quantify vesicle and fracture characteristics at a level of resolution that is unprecedented in the literature. Our findings suggests that these characteristics cannot be produced by simple cooling models.

Prior to this project, we had no constraints on emplacement pressures. We determined that the base of ridge was built under hydrostatic conditions until an elevation of ~170 m, at which point there was a low pressure (drainage) event, followed by a return to hydrostatic conditions. At the end of the ridge construction process, there was a low pressure explosive eruption that blanketed the southeast flank of the ridge with tephra. Our research supports the two-eruption model of Pollock et al. (2014) and enhances our understanding of ice dynamics during the eruption events.

The results of this project have been widely disseminated. We created online tours of Undirhlíðar quarry and the ridge so that broad audiences, like students and geo-tourists, can learn about glaciovolcanic eruptions and their products. We also presented our findings at the 2016 GSA meeting (Heineman et al., 2016; Thompson et al., 2016; Wallace et al., 2016).

ACKNOWLEDGEMENTS

Our project was supported by the Keck Geology Consortium, ExxonMobil Corporation, and The National Science Foundation (NSF-REU1358987 to Keck, NSF-EAR0958928 to MP, NSF-EAR1220176 to MP, NSF-EAR1039461 to BE, and NSF-EAR1220403 to BE). Additional support was provided by the Dickinson College Research and Development Committee, The College of Wooster Geology

Department, and the Henry J. Copeland Fund. Thanks to the individual institutions for supporting student conference travel. We appreciate the assistance of Dr. Sheila Seaman (UMass Amherst) with FTIR and EPMA analyses. Thanks to Steina Hauksdóttir for assistance with field logistics, Russell Robertson and Will Kochtitzky for help with mapping, and Ben Kumpf for field and lab assistance. We extend a heartfelt thank you to all of the faculty advisers who helped make this project a success.

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