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GLACIOVOLCANIC MEGAPILLOWS OF UNDIRHLÍÐAR, REYKJANES PENINSULA, SOUTHWESTERN ICELAND

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INTRODUCTION

Models for the development of subglacial volcanoes (Pedersen and Grosse, 2014, Pollock et al., 2014) leave significant questions regarding magma distribution dynamics in constructing a pillow-dominated glaciovolcanic ridge (tindar). Dikes and lava tubes play important roles in controlling lava distribution at mid-ocean ridge pillow edifices (Soule et al,. 2007); at Undirhlíðar, a quarry on the Reykjanes Peninsula in southwestern Iceland exposing a cross-section of a tindar, dikes have been shown to feed pillow units, and irregularly shaped intrusions (massive columnar jointed basalts, MCJBs) may be related to a shallow plumbing system (Pollock et al., 2014). Fieldwork along the 3 km length of ridge between Undirhlíðar and Vatnsskarð quarries identified oversized pillow-like outcrops of basalt with radial columnar jointing, concentric bands of vesicles and (where present) glassy rims (Fig. 1). While pillow lavas in the quarry average cross-sectional horizontal/vertical dimensions of 0.5/0.2 m, these outcrops average 5.3/3.4 m. They occur in contact with basalt breccia resembling pillow rubble. Although not previously identified at Undirhlíðar, comparable features have been called “megapillows” in Hawaii (Bear and Cas, 2007), Tasmania (Goto and McPhie, 2004), New Zealand (Bartrum, 1930, Walker, 1992), Japan (Yamagishi 1991), and British Columbia (Hungerford et al., 2014). These geologists hypothesize that megapillows represent channels by which lava is fed from the volcanic vent to the advancing pillow front. This raises the question of whether such features are truly mega*pillows* – by definition extrusive and subaqueous – or if they represent intrusive feeder tubes or post-eruption intrusions. We report petrographic and geochemical analyses of nine megapillow outcrops from Undirhlíðar and investigate their role in tindar construction through spatial and compositional relationships among megapillows and other lava units of the ridge.

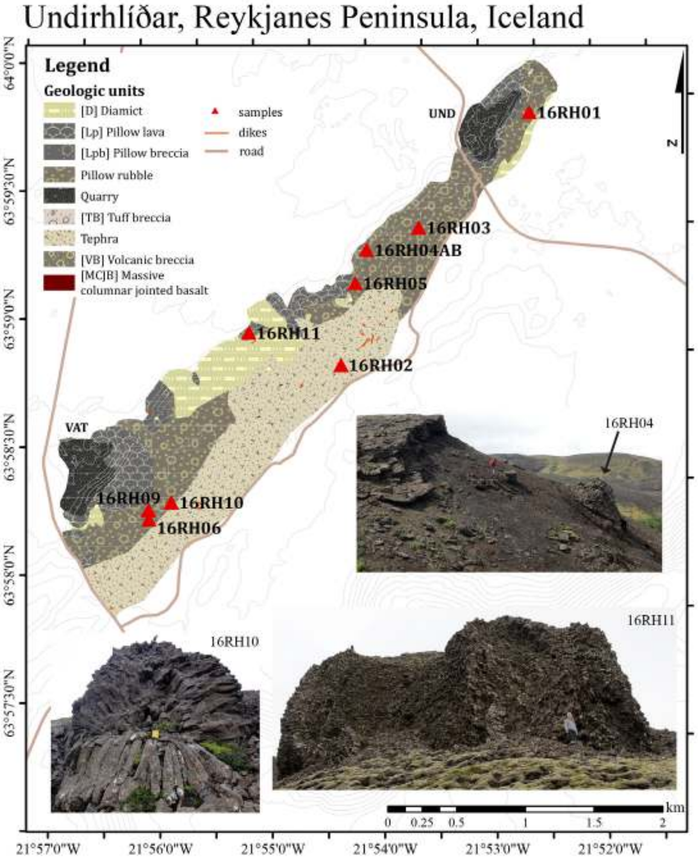

Figure 1. Geologic map of Undirhlíðar showing quarries (UND and VAT), lithologic units, sample locations, and topography, and field photos of some outcrops sampled. Note radial jointing, irregularity of shape, enormity, and situation on slope among pillow rubble. 16RH06 also indicates the locations of samples 16RH07 and 16RH08, taken from the same outcrop.

METHODS

A geologic map of the exposed lithofacies comprising ~3 km of the ridge was constructed using data collected with Trimble Juno GPS units and compiled in ArcGIS (ESRI) with sample locations, topographic contours and nearby roads, shown in the ISN 1993 Lambert Conic Conformal projection. Fourteen thin sections were created out of twelve rock samples from nine outcrops, representing the crystalline interior of each megapillow and features (when present) such as glassy margins, vesicle bands and regions of alteration. Thin sections were analyzed using standard polarizing light microscopy on a Leica DM750P microscope and photographed on a Leica ICC50 HD camera. Selected samples were analyzed using energy dispersive spectrometry (EDS) under a TESCAN Vega3 scanning electron microscope with an Oxford X-Max^{N} 80 detector.

Twelve whole-rock geochemical analyses of megapillow samples were acquired. Powders were prepared from fresh crystalline megapillow interiors and crushed in alumina ceramic grinding containers. Loss on ignition (LOI) was determined by heating the samples at 950 °C for 1 h following the methods of Boyd and Mertzman (1987). Fused glass beads and pressed pellets were prepared and major and minor elements were measured at The College of Wooster by X-ray fluorescence (XRF) spectrometry, all following the methods of Pollock et al. (2014). Low-abundance trace elements were measured by inductively coupled plasma mass spectroscopy (ICP-MS; VG PlasmaQuad 3) at Washington State University. Geochemical analyses of pillow unit, dike, and MCJB samples and MCJB thin sections acquired by Pollock et al. (2014) were used for comparison with new data.

RESULTS

Petrography

All samples analyzed in thin section are vesicular plagioclase-phyric olivine basalts with plagioclase-rich groundmass that fall into two groups: **(1)** porphyritic with mostly plagioclase laths, some (<10%) augite and rare (<2%) olivine phenocrysts in a microcrystalline matrix, and **(2)** coarser-grained porphyritic with large (up to ~1 mm) plagioclase laths and more (~10-20%) augite and olivine phenocrysts, frequently subophitic (Fig. 2). Among the phenocrysts in both groups were "crystal clots", spherulitic glomerocrysts of plagioclase laths with olivine or augite at the center. Samples in both groups contain up to 5% round opaque oxides. Group **(1)** is found mostly towards the northeast end of the ridge, and group **(2)** to the southwest (Fig. 1).

(1) The samples of the first group, 16RH01, 16RH02A/B, 16RH03, and 16RH04A/B, show bimodal crystal size distribution of up to 15% phenocrysts of ~0.5+ mm, mainly plagioclase or augite and rarely olivine, in a devitrifying microcrystalline plagioclase and augite matrix. Some plagioclase show visible zoning in cross-polarized light. Vesicles are mostly ~0.5-2.0 mm in diameter and comprise ~15-30% of the samples. 16RH02A and 16RH04A contain chrome spinel inclusions.

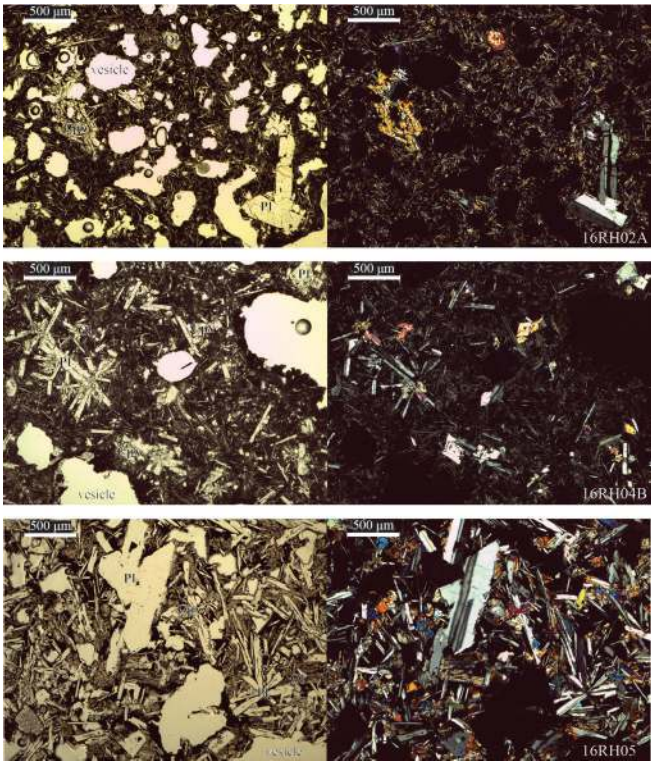

Figure 2. Thin section photos in plane-polarized (left) and cross-polarized (right) light of samples 16RH02A, 16RH04B, and 16RH05. Note finer- and coarser-grained samples and crystal textures of groundmass and phenocrysts, including glomerocrysts, plagioclase laths, phenocryst zoning and devitrification. Magnification: 40x

(2) The second group, containing samples 16RH05, 16RH06, 16RH07, 16RH08A/B, 16RH09, 16RH10 and 16RH11, is coarser-grained and highly crystalline with very little glass. These samples are dominated both in phenocrysts and groundmass by plagioclase laths which show spherulitic and trachytic textures. Olivine and augite phenocrysts are euhedral, up to ~0.5 mm in diameter and contain opaque oxides and parts of other crystals.

Geochemistry

Twelve whole-rock geochemical analyses of megapillow samples were acquired and compared with analyses of pillow lava units on the ridge and MCJBs of Vatnsskard, and those of pillow units and dikes of Undirhlíðar reported by Pollock et al. (2014) (Fig. 3).

Megapillows are generally lower in MgO (6.4-8.4 wt. %) and higher in Al_2O_3 (7.2-17.4 wt. %) and Na_2O (2.2-6.4 wt. %) than other lava units of the ridge and quarries. The samples higher in Al_2O_3, i.e. 16RH10, represent the coarser-grained, more crystalline basalts of petrographic group **(2)**. Samples 16RH01, 16RH03, and 16RH04B make up the high end of MgO, representing a more primitive magma composition, and are found near Undirhlíðar, further northeast than the other outcrops.

Rare earth element abundance patterns for most megapillows (Fig. 4) are similar to one another, overlap with the upper pillow units from Undirhlíðar (Lp3) and show strong Eu anomalies (average Eu/Eu* = 1.1) as compared to pillow units. 16RH02 and 16RH11 are significantly enriched as compared to other megapillows and to the units at Undirhlíðar, 16RH11 even more so in the lighter elements. Both show relatively low wt. % MgO and come from units that lie near one another and the tephra cone on opposite sides of the ridge axis (Fig. 1).

Of nine megapillow samples for which La_N/Sm_N was calculated, seven fall within the range of La_N/Sm_N = 1.22-1.35. Sample 16RH11 shows an elevated La_N/Sm_N ratio of 1.63, within the range of Lp1-2; 1bRHo2 (La_n/Sm_n=1.45) does not match nay measured pillow unit.

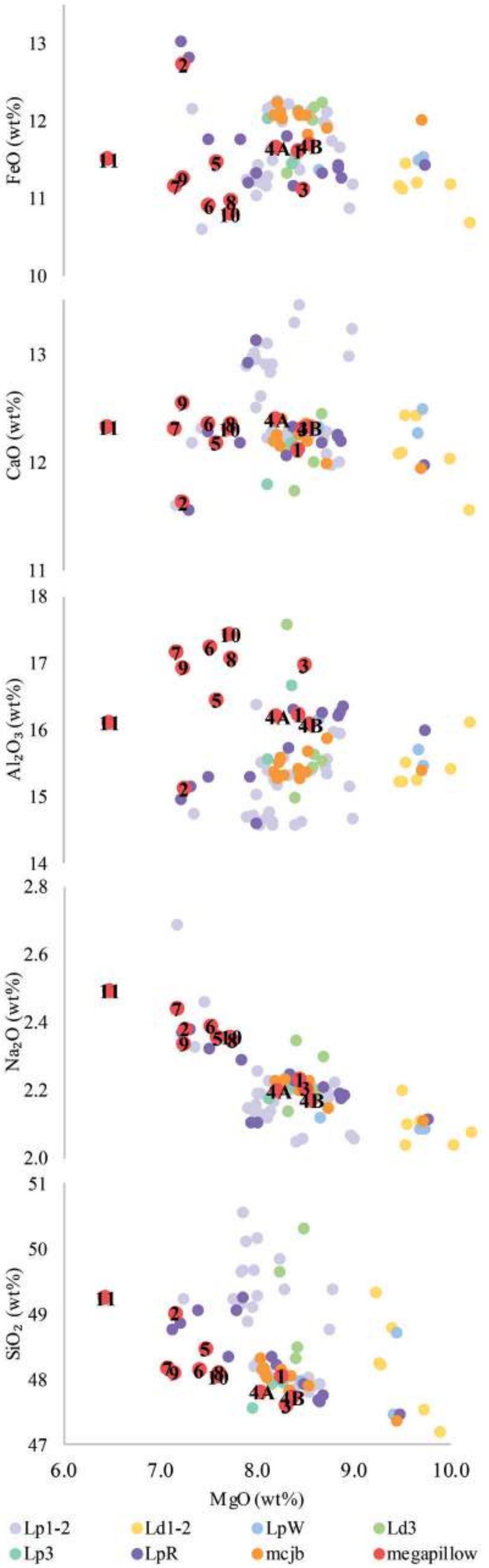

Figure 3. Major element plots of wt. % MgO (x) vs. wt. % major oxides FeO, CaO,Al_2O_3, Na_2O, SiO_2, (y) for megapillows (red), MCJBs (orange), Undirhlíðar pillow units Lp1-2 (light purple), Lp3 (turquoise) and LpW (light blue), dikes Ld1-2 (yellow) and Ld3 (light green), and ridge pillow units, LpR (purple).

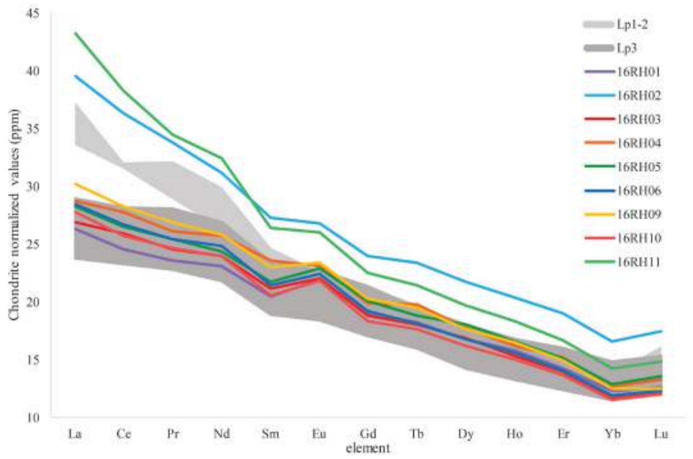

Figure 4. Chondrite-normalized (Sun & McDonough, 1989) rare earth element diagrams showing element abundances (ppm) in megapillows and ranges of pillow lava units from two distinct magma batches, Lp1-2 (light gray) and Lp3 (dark gray), in Undirhlíðar (Pollock et al., 2014).

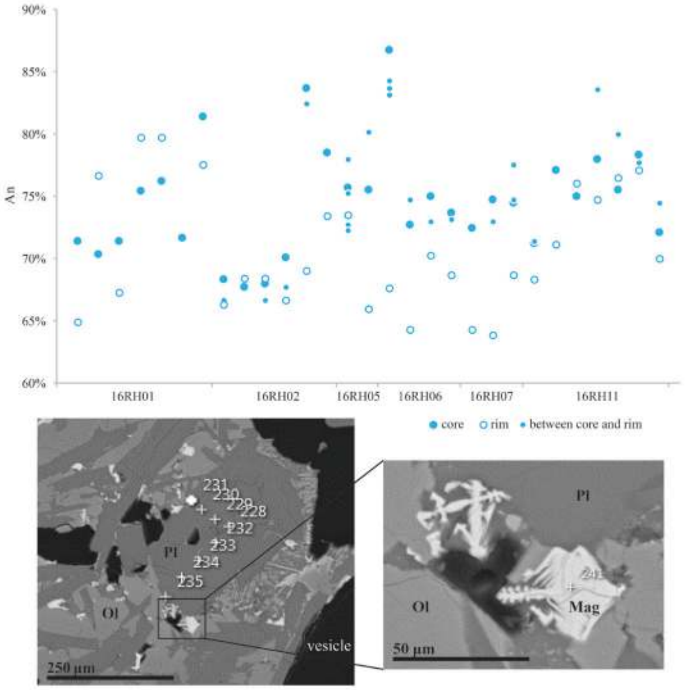

Figure 5. Above: Plot of measured An values from core to rim of 29 plagioclase phenocrysts from six samples. Filled circle indicates a value measured at the core, open circle at the rim, smaller filled dot between core and rim. Below: Electron images of sample 16RH05 show locations of acquired spectra, bright Fe-rich edges of olivine phenocrysts, and dendritic interstitial Fe-Ti oxides.

Mineral Compositions

Elemental compositions of selected phenocrysts and oxides in thin sections of six samples were used to estimate major cations and determine An/Ab for plagioclase to examine zoning within crystals. Plagioclase compositions among the selected samples range from An64 to An87 with an average of An73. Core and rim analyses of individual crystals showed varied zoning patterns (Fig. 5); phenocrysts in samples 16RH06 and 16RH07 were all normally zoned, with higher-An cores than rims, while other samples contained a variety of patterns including reverse (ex. 16RH02) or oscillatory (ex. 16RH05) zoning.

Olivine phenocrysts showed visibly bright, Fe-rich rims in electron images (Fig. 5). Interstitial, dendritic oxides of ~50-100 µm are shown by elemental composition to be titanium-rich magnetites.

DISCUSSION

Megapillows are petrographically consistent with the pillow units of Undirhlíðar described by Pollock et al. (2014), distinguishable in group **(2)** by high crystallinity. The petrographic groups are also geographically and geochemically distinct: group **(1)** occurs at the northeastern end of the ridge, closer to Undirhlíðar quarry, and with the exception of 16RH02, these outcrops show consistently more evloved compositions than group **(2)**, which occurs to the southwest near Vatnsskarð with generally higher w t% Al_2O_3.

The most conspicuous question of megapillows is that of their size. Pillow dimensions are primarily controlled by magma composition, effective viscosity and supply rate (Walker ,1992; Bear and Cas, 2007). Megapillows, like other Undirhlíðar lavas are tholeiitic basalts (Pollock et al., 2014), but their effective viscosity relative to pillows of similar composition can be affected by crystallinity (Walker, 1992). Elevated wt % Al_2O_3 and a strong Eu anomaly in whole-rock analyses sets megapillows apart from other lavas of the ridge and suggests significant plagioclase phenocryst accumulation (Crawford et al., 1987). Within megapillows, the highly crystalline samples of petrographic group **(2)** show higher wt % Al_2O_3 (with the exception of 16RH11) than group **(1)**. The presence of a large volume of crystal cargo, somewhat buoyant under pressure in dense magma, would increase the effective viscosity of that magma body, inducing slower, stickier propagation dynamics and enabling the formation of larger pillows. However, effusion rate may also be a significant factor.

16RH02 and 16RH11, found near the tephra cone, stand out among megapillows as magnesium-poor, incompatible element-enriched, and weakest of the Eu anomalies, and within their petrographic groups as exceptions in major element composition. 16RH11, exposed in a gully, is the lowest-elevation megapillow sampled, 100 m below 16RH02. Its La_N/Sm_N ratio of 1.63 lies at the upper end of a range previously only measured in the basal pillow units of Undirhlíðar (Pollock et al. 2014). 16RH02 ($La_N/Sm_N = 1.45$) is well below this range. The rest of the megapillows fall near or within the less-enriched range of upper Undirhlíðar and Vatnsskarð pillow units ($La_N/Sm_N = 1.28\pm0.4$) that Pollock et al. (2014) interpret to represent a later magma batch distinct from the first. The occurrence of megapillows in multiple lithostratigraphic units and of a high-La_N/Sm_N lava unit in locations 2 km apart is consistent with multiple eruptive events in the construction of the ridge and implies a direct geochemical relationship between megapillows and the lava unit in which they are found. However, further data is needed to analyze the possibility of multiple magma sources in megapillows.

Irregular zoning of plagioclase phenocrysts in 16RH01, 16RH02 and 16RH11 records a complicated history, whether of megapillows themselves, i.e. pulses of magma filtering through stable, crystal-rich conduits, or of the phenocrysts' journey through the crust. In 16RH02, near the tephra cone, there is a distinct group of plagioclase crystals with relatively low %An of 65-70, while its neighbor 16RH11 mostly contains phenocrysts of 75-80 %An. This is inconsistent with 16RH02's more primitive composition (high MgO, depleted) relative to 16RH11. The megapillow near Vatnsskarð represented by samples 16RH06 (margin) and 16RH07 (interior) shows generally normal plagioclase zoning, suggesting phenocryst growth during crystallization of a magma body cooling in place. Fe-rich olivine rims and interstitial Fe-Ti oxides developed later on from the last Fe-rich drops of a mostly frozen magma.

By definition, a mega*pillow* is the product of extrusive, subaqueous eruption, rather than an intrusive conduit (such as a lava tube) or post-eruption intrusion. The Undirhlíðar megapillows' glassy margins, vesicle bands and radial and columnar jointing are consistent with features of true pillows; however, this does not preclude their role in magmatic distribution. In Tasmania, pillows are shown radially propagating from the basal margins of a fully exposed megapillow at Plum Pudding Rock (Goto and McPhie 2004). Goto and McPhie note theirs is the only known three-dimensional exposure of a megapillow; it likely remains the most pristine example. They argue for a style of subaqueous pillow propagation in which pillows emerge and are fed from the base of megapillows (and/or sheet flows) which then override them, creating an upward gradation from pillow into massive lavas. The megapillows at Undirhlíðar, while exposed in three dimensions, are eroded and lie within a complex stratigraphic sequence of glaciovolcanic and later glacial material. They occur in contact with pillow rubble at their base, and although intact pillows are not apparent, they are geochemically and genetically related to the pillow units in which they are found; this is consistent with Goto and McPhie' model. The accumulation of plagioclase in megapillows may therefore be the result of dense, liquid magma filtering down out of the buoyant plagioclase phenocryst-rich interior of the megapillow and preferentially flowing into the pillows developing from its base.

CONCLUSIONS

At Undirhlíðar ridge, megapillows are among the features formed during a series of tindar-building glaciovolcanic eruptions. The outcrops occur in multiple stratigraphic units and are genetically and petrographically related to the pillow lavas in which they are found. They appear to be derived from multiple batches of magma proposed by Pollock et al. (2014), and plagioclase accumulation plays an important role in their development. Pillow rubble surrounds the outcrops, consistent with Goto and McPhie's (2004) model for pillow propagation resulting in an upward gradation from pillow to massive (megapillow) facies. Megapillows at Undirhlíðar may represent a significant mechanism for magmatic distribution: feeding and then overrunning pillows which propagate and are fed from their basal margins at the eruptive front.

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