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USING PAHOEHOE CRUST GROWTH RATES TO CONSTRAIN LAVA CHANNEL FORMATION EVENTS AND TIMING

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INTRODUCTION

Volcanic rootless cones (VRCs) are a volcanic structure commonly found in Iceland, formed from steam explosions as lava flows over water or saturated sediment (Thorarinsson, 1951). The water breaks through the solid lower crust of the lava flow, interacting with the liquid lava in the flow center, resulting in phreatomagmatic activity (Thorarinsson, 1951). After the initial breach of the lower crust, explosive activity continues at the site of the breach, throwing ash, tephra, and lava fragments into the air until either the lava or water supply has been exhausted (Fagents and Thordarson, 2007). This results in the formation of a tephra cone which closely resembles a true volcanic crater, distinguishable by the fact that it is not a vent which lava has erupted from (hence the term “rootless”).

VRCs in Iceland are typically found in clusters where sheet-like lava flows have flowed over highly saturated areas (Hamilton et al, 2010a). VRCs can also be formed from a lava channel flowing over saturated sediment, causing erupted material to be deposited on either side of the channel as the central material is carried away by the flowing lava (Hamilton et al, 2010a). In this case the formation is called a “paired half-cone”. Rootless cones have recently been identified on the surface of Mars, making them a particularly interesting object of study in the hopes of learning more about martian magmatic processes and water history on the planet (Keszthelyi et al, 2004).

FIELD SITE

The area of focus of this study is located in the Laki flow’s southern branch, just north-east of the mountain Leidolfsfell and the Skafta river gorge. The field site is centered on a large, channel-fed paired half-cone surrounded by multiple smaller VRC clusters, lava flows, and side channels. The paired half-cone complex is over 1 km in length (E-W) and 1.5 km wide (N-S). The lava channel which runs through the cone is between 35 and 140 m wide, with the narrowest section occurring as it passes through the major cone structure.

The tephrastratigraphy of the cone is not constant throughout the entire cone, with layers thinning, thickening, and disappearing at various locations on both sides. Additionally, layers cannot be easily matched up between the two sides, indicating a

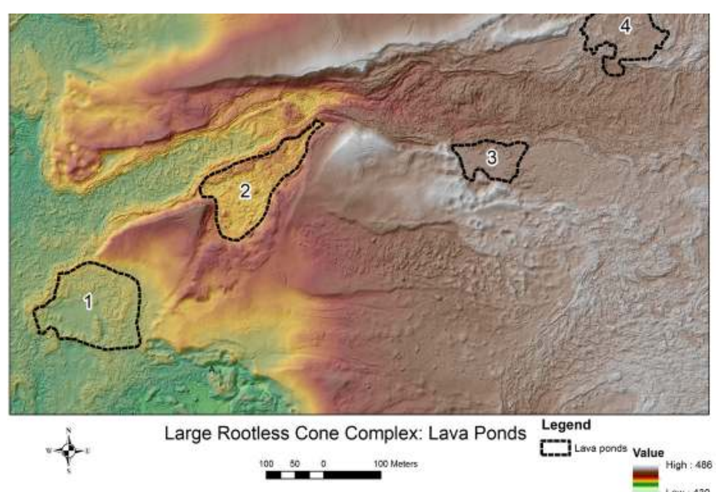

Figure 1. Map of the large rootless cone field area with pond locations outlined. Areas are labelled as they are referred to in text and in Table 1. The background is a hillshade image constructed from the project DEM overlain with a color ramp corresponding to elevation, ranging from a low of 430 meters (green) to a high of 486 meters (white). The relatively smooth topography in the middle of the image are tephra and VRC deposits, with the main channel flowing through the middle from right to left (E-W).

complex series of rootless eruptions with multiple eruption centers, rather than just a single eruptive center from which all tephra material was erupted.

The surface morphology of the channel material is characterized by a rubbly pahoehoe surface (Guilbaud et al, 2005) composed of pieces ranging in shape from equant blocks to crustal slabs and columnar joints. A series of pressure ridges (Guilbaud et al, 2005) disrupt the surface, rising up to five meters above the channel surface, oriented perpendicular to the flow direction up-flow from the cone. Additionally, a series of similarly shaped lateral pressure ridges are formed along the edge of the channel, running parallel to the flow direction, both up-flow and down-flow from the cone. There are multiple areas where lava has overflowed the sides of the channel and formed spillover zones or areas of ponded lava as the result of fluxes in the volume of lava being delivered through the channel (Harris et al, 2009). The distribution, direction, and timeline of lava flows seems to be controlled by the pre-existing topography, source vent lava output, and formation of rootless cones providing new topographic barriers.

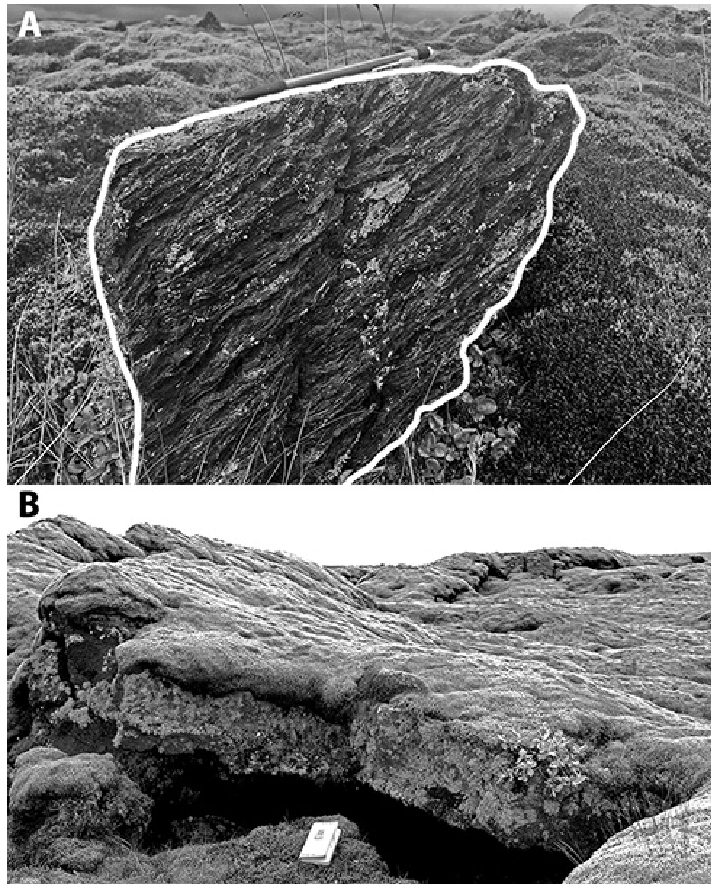

Figure 2. Example of crust segments that were measured in the field. Crust A is from pond 3, and is one of the thin (3.3 cm, pencil for scale) segments that is oriented vertically with respect to the pond surface. Crust B (field book for scale) is from pond 4, location d. The horizontal orientation and smooth continuation from the visible crust to the surrounding topography indicates that it is in-situ.

RESULTS

There are four distinct locations in the field area (Fig. 1) which represent areas in which lava overflowed the channel walls and ponded, allowing the lava to cool in place. These areas are distinguished by their unusually flat, undisrupted surfaces. In places where the surface of the lava has been disrupted in the process of solidifying, crustal segments of varying thickness can be found (Fig. 2). The thickness of these pieces is a function of the amount of time which the lava has been cooling before being disrupted, as given by Equation 1 (Hon et al, 1994).

$$t = 164.8\ C^2$$

A total of 379 crust measurements were taken from the four areas, with measurements grouped and marked with GPS locations. Field notes were taken to note the orientation and setting of the pieces, with additional field photographs taken of some samples. From the orientation and position of the crust segments you can infer the processes which led to their disruption. Pieces which are in-situ (oriented horizontally or attached to the containing barrier of a pond) were likely disrupted and exposed when the lava pond or lobe broke open, allowing the lava to flow out and deflating the solidified crust. Crust segments which are overturned or not horizontal were likely deformed from an application of pressure, either from the lava pushing against a barrier or from pulses of lava flowing into the area, applying pressure from below the crust (Guilbaud et al, 2005).

Data from the four studied ponded areas is presented in Table 1. Measurements from areas 1 and 2 followed a normal distribution. Measurements from area 3 followed a bimodal distribution with two distinct peaks of thickness frequency. This bimodal distribution was recognized in the field as well as a distinct difference in orientation of the corresponding pieces, and measurements were divided into their

Area	# of Measurements	Mean (cm)	Std. Dev. (cm)	Max (cm)	Min (cm)	Cooling Time (hours)
1	65	18.4	8.1	40	6	5.7
2	17	13.6	2.9	20	8	3.1
3	109	6	4	19	0.5	0.6
3a	42	10.2	3.1	19	4	1.8
3b	67	3.3	0.9	6	0.5	0.2
4	134	46.1	15.5	80	14	35.8
4a	19	47.4	12.6	80	23	37.8
4b	20	43.5	8.4	62	29	31.9
4c	22	60.7	9.6	80	42	62.0
4d	20	44.8	9.2	62	21	33.8
4e	20	34	17.4	77	14	19.5
4f	20	40.6	19.9	75	16	27.8
4g	13	52.5	8.3	67	42	46.4

Table 1. Crust measurement data from each of the areas studied, with associated estimated cooling hours necessary to form a crust of the given mean measured size.

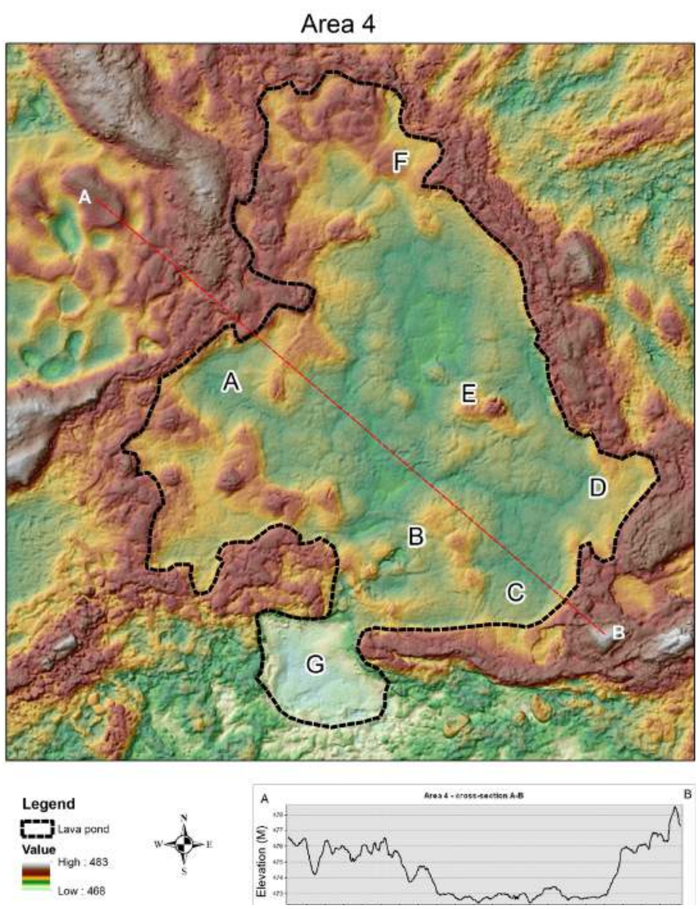

Figure 3. Close-up image of Area 4, with individual locations labelled (as referred to in text and Table 1). The pond edge is shown by the black dashed line. The background is a hillshade image constructed from the project DEM overlain with a color ramp corresponding to elevation, ranging from a low of 468 meters (green) to a high of 483 meters (red). Location G is inferred to be the spot where the pond was breached and emptied into the main channel.

respective groups when collected. Data for each of these subgroups, labelled 3a and 3b are also included in Table 1 and each follow a normal distribution. Measurements from area 4 were collected from seven distinct locations within the ponded area (Fig. 3). The data from the whole area covered a wide range of thicknesses and did not follow a normal distribution, however measurements from each individual location predominately followed normal distributions with smaller ranges of values. Data for each subgroup has been included in Table 1, labelled 4a to 4g.

DISCUSSION

Areas 1 and 2

Areas 1 and 2, the two ponded areas down-flow from the central cone, were found to have cooling times of 5.7 and 3.1 hours respectively. The crust segments found in these areas were oriented in-situ or only slightly disrupted, suggesting that the crust in these areas was only deformed when the still-molten lava was emptied from the pond, causing the surface crust to deflate. The lava likely re-entered the channel after leaving the pond, possibly as a result of a lowering of the flow level in the channel and the lava exiting through the same point which it entered, or from breaking through a constraining barrier and re-entering the channel. The difference in estimated cooling times of the crust, combined with the geographic separation and elevation differences of the ponds suggests that these ponds formed as the result of separate lava level increase in the channel.

Area 3

Area 3, located on the up-flow side of the central cone, was observed to have a bimodal distribution of crust segment thicknesses, with average thicknesses of each group corresponding to estimated cooling times of 0.2 and 1.8 hours. Additionally, all of the thinner crustal segments were oriented vertically, while the thicker pieces were horizontal and in-situ. This suggests that the original surge of lava was undisrupted for 0.2 hours (12 minutes), after which a second, stronger surge entered the area, breaking apart the thin upper crust and leaving it sticking out of the now uncovered liquid lava. This was followed by a 1.8 hour period of time in which the lava was allowed to cool undisrupted, resulting in the formation of the 10.2 cm crust which was left in-situ when the pond was emptied.

Area 4

Measurements from area 4 encompass a wider range of crust thicknesses than the other areas, and represents a more complex history of pond formation. The geographic distribution of mean crust thicknesses for each of the seven locations in the area and the corresponding cooling times (Fig. 3) supports a model of the pond forming from lava input into different zones over an extended period of time, similar to the lobe-by-lobe emplacement described as being common in the Laki flow by Guilbald et al. (2005). The differences in mean crustal thickness at the different locations may not seem large, but they represent differences of up to thirty hours in estimated cooling time of the crust before the pond was emptied and deflated. Similar to areas 1 and 2, the crust in this area was largely in-situ and undisturbed other than by deflation features (e.g. tumuli and collapse), suggesting there was no large influx of magma or other disturbance to the surface of the pond once the crust began forming.

The location of areas 3 and 4, directly up-flow from the central cone and narrowest section of the channel, suggests that these ponds may have been formed as the result of a blockage or partial blockage of the main channel, causing a buildup and overflow of lava (Harris et al, 2009). The subsequent failure of this blockage and the ensuing lava input into the channel down-flow from the cone may have been the cause of the lava ponds in areas 1 and 2 (Patrick and Orr 2012). Due to the vastly different cooling times of the two ponds, different channel blockages would have caused the formation of each, rather than a single blockage forming both.

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