ANALYZING PIT CHAINS IN ICELAND TO CONSTRAIN REGOLITH THICKNESS ON ENCELADUS.
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Introduction: The surface of Enceladus is mantled with a layer of regolith hypothesized to be sourced from both impact cratering and fallback from the south polar plumes [1]. This layer of unconsolidated regolith may contribute to muting surface morphology, obscuring or erasing small craters [2], and insulating the surface [3-6]. In particular, the insulating effects of a regolith layer would raise the effective surface temperature and have a significant influence on thermal models of Enceladus [6]. Therefore, it is important to understand the distribution and depth of regolith on Enceladus to better constrain thermal models, plume activity, and perhaps the longevity of the south polar plume and a global subsurface ocean.

Measuring Regolith. The regolith distribution and thickness can be assessed on Enceladus using pit chains. Pit chains are linear assemblages of circular to elliptical depressions that form in regolith and are observed on planetary bodies across the solar system [7], including Earth. There are a variety of processes that may form pit chains [8], but pit chains on Enceladus typically form where regolith overlies extension fractures [8-11].

Previous work [12] has shown that pit chains (Fig. 1) can be used to measure local regolith depths, adopting a method established by [8] for terrestrial planetary bodies. The assumption of this technique is that a pit reaches the base of the regolith layer, thus pit depth is a proxy for regolith depth. Since the pit may not necessarily penetrate the entire regolith layer, the measured pit depth is a minimum estimate of regolith depth. Orbital images can be used to measure the depth of individual pits by assuming each pit is a cone and its depth can be calculated based on geometric relationships with the pit diameter [8].

Here, we ground truth this proxy by making measurements and observations of terrestrial pit chains in Iceland to determine (1) if the geometric relationships [8] accurately predict pit depth and (2) verifying whether the depth of the soil is equivalent to the depth of the pit. Measuring the distribution of regolith thickness across Enceladus using pit chains is a necessary first step in separating the contribution of plume materials from impact cratering in regolith production, and ultimately understanding the persistence of plume activity.

On Earth, pit chains have been identified in various locations [e.g. 13] and those around the Krafla volcano in northern Iceland serve as a representative analog for pit chains on Enceladus [10,11] (Fig. 1). As extension cracks on Enceladus dilate, regolith drains into the existing void forming pits along the trace of the crack. Similarly, in Iceland cracks form in the underlying basalt, and the overlying soil drains into the underlying crack [10]. The cold icy crust of Enceladus behaves in much the same way as the basaltic bedrock in Iceland, making these basalts an ideal material analog for the water ice and snow-like regolith across Enceladus. Ice sheets across the Earth are too warm and behave too ductilely to be appropriate analogs for pit chain formation on Enceladus.

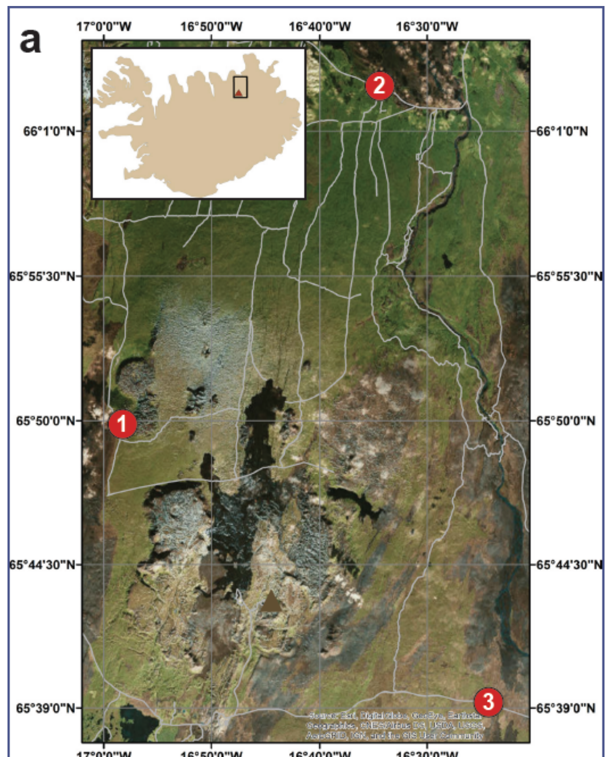

Figure 1: Location of the three study sites in Iceland. Inset: Black rectangle denotes the location of the larger image. Brown triangle marks the location of Krafla volcano.

Methods: In August, 2017 and May, 2018, we traveled to northern Iceland, just north of the Krafla volcano, to make morphometric measurements of individual pits within pit chains. Three study sites were chosen, two in basalt flows (Sites 1 and 3) and one in delta materials (Site 2) (Fig. 1). Pit diameter was measured along strike and perpendicular to strike to characterize potential ellipticity [i.e. 8]. Pit depth was measured using a TruPulse 200 laser rangefinder instrument, and images were collected to generate digital elevation models of pits to assess the validity of using a cone to represent pit shape.

In addition, soil depth was measured with both a ground penetrating radar (GPR) system and a tiling probe to more completely constrain the soil depth measurements. We used a GSSI SIR-3000 control unit with a 200 and 400 MHz antenna to collect GPR tracts adjacent to several of the measured pits (both sub-parallel and perpendicular tracks). The 200 and 400 MHz antennas were selected because they would be sensitive to the estimated regolith-bedrock boundary, rather than smaller-scale variations within the regolith like layering, rocks, or other debris.

Results: Data were collected from pits based on the preservation of their walls and floor to ensure accurate diameter measurements. As a result, all of the pits measured in Iceland were located at the tips of their fractures where the least amount of extension has occurred, rather than in the central, or widest, portion of the fracture. Due to the similar location of measured Icelandic pits along the fractures, the pits encompass a relatively narrow diameter range, ~5-8 m (Fig. 2).

Comparing the ratio of pit depth and diameter values with those measured for pits on Enceladus [12] and other planets (Mars [8], Earth [10]), Icelandic basalt pits from this study are deeper than calculated on Enceladus using the proxy. The Icelandic delta pits depth to diameter ratios plot substantially closer to a 1:1 line compared with the other planetary bodies (Fig. 2). Additional data are required of both smaller and larger pits to more thoroughly test whether they are consistently deeper, or if the method for inferring depth of Enceladus pits needs refinement. Differences that are visible in these data may also be due to variations in the material properties of basalt regolith and Enceladus's 'snow' regolith.

Summary: We find that the proxy accurately predicts the depth of an individual pit within a chain as long as the regolith is unconsolidated. Measurements from Site 2 are consistent with proxy predictions, while the measurements from Sites 1 and 3 are not (Fig. 2).

The calculated pit depth from the proxy does only a modest job of predicting an accurate estimate of the regolith depth. For unconsolidated regolith (Site 2) that generally follow the expected depth-diameter relationship proposed using the geometric proxy [8], the depth of the pit cannot be used to accurately determine the thickness of the regolith. Depth measurements represent minimum regolith thickness estimates in the Iceland delta materials. For more consolidated regolith (Sites 1 and 3), the measured depth of pits more closely matches up with the regolith thickness. However, the expected depth-diameter relationship is not observed for this material type, making use of the proxy irrelevant.

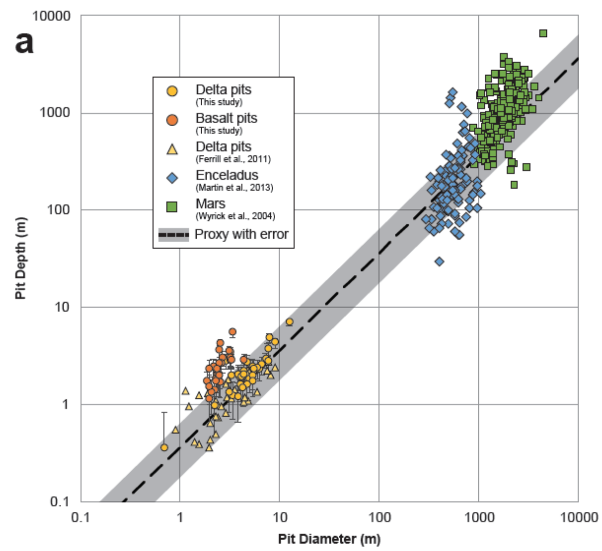

Figure 2: Depth-diameter relationship of pits on Earth, Mars, and Enceladus. Individual measured pits on each planetary surface. Only those Icelandic pits that form in basaltic materials (orange circles), with the clay-rich soils and vegetation (Sites 1 & 3), do not fall within the proxy size predictions.

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