Using Icelandic Pit Chains to Constrain Regolith Thickness on Saturn's Moon Enceladus. E. S. Martin[1] and J. L. Whitten[1], Smithsonian Institution, National Air and Space Museum, Center for Earth and Planetary Studies, Washington DC, 20013.

Introduction: The surface of Saturn's moon Enceladus is mantled with a layer of regolith sourced by both impact cratering and fallback from the south polar plumes [1]. A layer of unconsolidated regolith across Enceladus's surface may act to mute surface morphology, erase small craters [2], and may have an insulating affect [3–6]. In particular, the insulating effects of such 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 Enceladus's regolith to better constrain thermal models, plume activity, and perhaps the longevity of Enceladus's plume and global ocean.

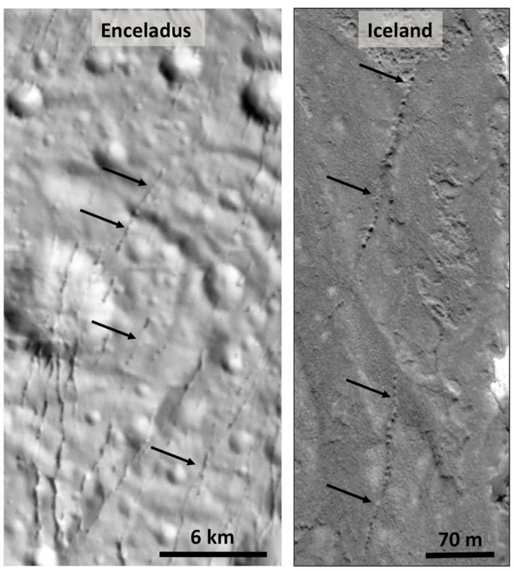

Figure 1: Pit chains on Saturn's moon Enceladus (left) and Iceland (right).

A proxy to probe regolith depth. The distribution and thickness of regolith can be assessed using pit chains as a proxy for regolith depth on Enceladus. Previous work [7] has shown that pit chains (Fig. 1) may be used to probe local regolith depths adopting a method established by [8]. Images obtained from orbital spacecraft can be used to measure the depth of individual pits by assuming each pit is a cone and the depth of the pit can be calculated based on geometric relationships (Fig. 2). Pit chains are linear assemblages of circular to elliptical pits that form in regolith (either from impact cratering and/or plume activity) and are observed on planetary bodies across the solar system [9], including the Earth. There are a variety of processes that may form pit chains, including venting and lava tube collapse [8]. Pit chains on Enceladus, however, can also form via another process, where pits form in regolith overlying extension fractures [8, 10–12]. 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.

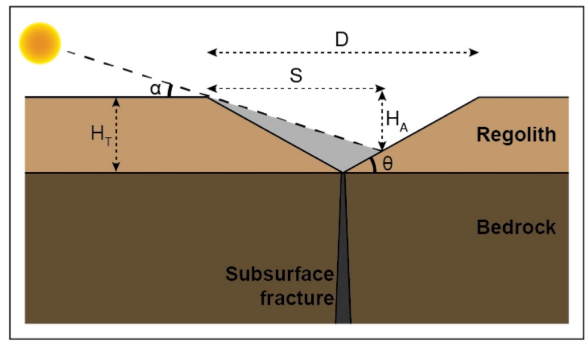

Figure 2: The diameter of a pit (D) is geometrically related to the depth of the pit, or its true height (H_T). Measured values include the length of the shadow cast by the sun (S), the pit diameter (D), and the sun angle (α), and the calculated values of apparent height (H_A) and the angle of the pit wall (θ) Modified from [8] Figure 3a.

Pit chains in Iceland. Pit chains have been identified in various locations on Earth [e.g. 13], but pit chains around the Krafla volcano in northern Iceland may serve as a representative analog for Enceladus's pit chains [11, 12] (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 soil that rests on top of the basalts drain into the underlying crack [11]. The cold icy crust of Enceladus behaves in much the same way as the basaltic bedrock in Iceland making it an ideal material analog for the water ice and snow-like regolith across Enceladus. The ice sheets across the Earth are too warm and behave too ductility to be appropriate analogs for Enceladus in this case.

Motivation: Previous work has applied the technique from [8] using geometric relationships to estimate pit depth on Enceladus [7]. 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 full depth of the regolith layer the measured pit depth is a minimum estimate of regolith depth.

Here, we ground truth this proxy by making measurements and observations of terrestrial pit chains in Iceland to determine (1) if the geometric relationships from Fig. 2 accurately predict pit depth and (2) verifying whether the depth of the soil is equivalent to the depth of the pit.

Methods: In August, 2017 we traveled to northern Iceland near the Krafla volcano (Fig. 3) to make morphometric measurements of individual pits within pit chains (Fig. 4). Pit diameter was measured along strike and perpendicular to strike as laboratory analogs of pit formation show that pits become more elliptical with increasing dilation [8]. Pit depth was measured using a laser ranger, and images were obtained to generate digital elevation models of pits to assess the validity of using a cone as a representation of pit shape.

Soil depth was measured with both a ground penetrating radar (GPR) system as well as a tiling probe to manually verify the GPR measurements. We used a GSSI SIR-3000 control unit with a 400 MHz antenna to collect 15 GPR tracts near-parallel to several of the measured pits. The 400 MHz antenna was used because it would be sensitive to the estimated regolith-bedrock boundary, rather than the smaller-scale variations within the regolith like layering, rocks, or other debris.

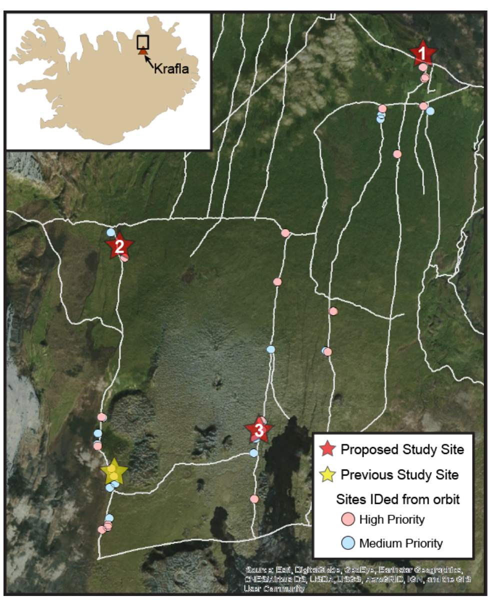

Figure 3: Pit chain study region, with individual pit chains identified from orbit ranked by priority. Stars indicate August 2017 (yellow) and summer 2018 (red) field sites.

Preliminary Results: Data were collected from pits that were selected based on the preservation of their walls and floor. This was to ensure accurate measurements of pit diameter. As a result, all of the pits measured in Iceland were located the tips of their fractures where the least amount of extension has occurred, rather than in the central, or widest, portion of the fracture. Those pits located in the widest part of the fractures analyzed in August 2017 have merged together making individual pit identification difficult, compromising depth and diameter measurements.

Figure 3: Pit chains in Northern Iceland.

Due to the similar location of measured Icelandic pits along the fractures, all of the pits are of approximately the same dimeter, ~5–8 m. Comparing the ratio of pit depth and dimeter values with those measured for pits on Enceladus [7], Icelandic pits are deeper than inferred on Enceladus. Additional data are required of both smaller and lager 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 the preliminary data may also be due variations in the material properties of basalt regolith and Enceladus's 'snow' regolith.

Future Work: We will present processed GPR data of regolith depth near the 15 measured pits and compare Icelandic results with those inferred for Enceladus.

We are returning to Iceland in the summer of 2018 to finish collecting data the same lava fields around the Krafla volcano in northern Iceland. Additional measurements will be made in deltaic deposits along the northern coast of Iceland to characterize how the material properties of the regolith can affect the shape of a pit.

References: [1] Kempf, S. et al. (2010) *Icarus,* 206, 446–457. [2] Kirchoff M. R. & Schenk P. (2009) *Icarus, 202,* 656–668. [3] Passey Q. R. & Shoemaker E. M. (1982) in *Satellites of Jupiter,* pp. 379–434. [4] Squyres S. W. et al. (1983) *Icarus, 53,* 319–411. [5] Passey Q. R. (1983) *Icarus*, 53, 105–120. [6] Bland M. T. et al. (2012) *GRL, 39,* L17204. [7] Martin E. S. & Kattenhorn S. A. et al. (2013) *LPSC XXXXIV*, abs #2047. [8] Wyrick D. et al. (2004) *JGR, 109,* E06005. [9] Wyrick D. Y.et al. (2010) *LPSC XXXXI*, abs #1413. [10] Ferrill D. A. et al. (2004) *GSA Today, 14,* 4–12. [11] Ferrill D. A. et al. (2011) *Lithosphere, 3,* 133–142. [12] Martin E. S. et al. (2017) *Icarus,* 294, 209–217. [13] Okubo C. H. & Martel S. J. (1998) *J. Volc. Geotherm. Res., 86,* 1–18.