PIT CRATER MORPHOLOGY IS NOT UNIQUE TO SETTING OR FORMATION. C. L. Kling[1] and P. K. Byrne[2], [1]Center for Earth and Planetary Studies, National Air and Space Museum, Smithsonian Institution, Washington, D.C. 20560 (clkling@ncsu.edu), [2]Department of Earth and Planetary Sciences, Washington University in St. Louis, St. Louis, MO 63130.

Introduction: Pit craters have been identified on nearly every planetary surface imaged in our Solar System, from our home planet [1–3], to Venus [4], Mars [4], asteroids [4] and even icy moons [5]. Often the identification of pit craters is linked to a formational process and subsequently used for piecing together the surface history of that region. *However, identification of pit craters alone does not necessarily indicate a particular formational process, and careful consideration of the factors that can influence pit crater formation is important to determining what the presence of pit craters on a planetary surface actually tells us.*

Pit craters are also being looked at as possible entrances to a sustainable underground refuge for future astronauts visiting the Moon or Mars [6]. Pit Craters often are attributed to faulting [3], therefore, it is critical to understand the mechanical make-up of these surface features to be able to safely utilize them in the future.

We present the largest amalgamation of pit crater morphometric data to date, together with a statistical analysis investigating the differences in pit crater depth/diameter ratios. This work is motivated [7] by the fact that pit craters can assume similar morphologies from different processes and are therefore not necessarily straightforward to interpret, so we aim to provide simple ways to describe pit craters and the information they contain about the settings in which they form.

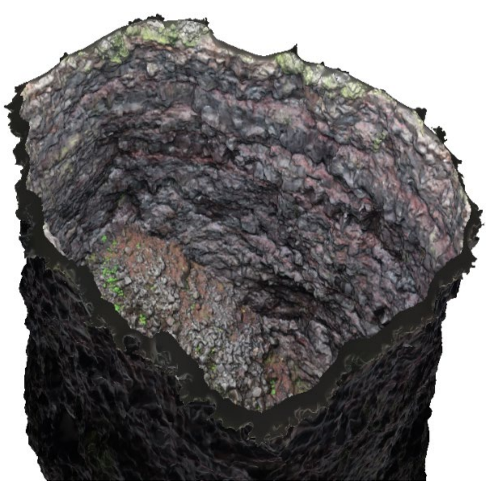

Figure 1. Three-dimensional model of Devil's Throat pit crater in Hawaii Volcanoes National Park showing steep, straight walls and stacked lava flows. This model was derived from handheld camera photos taken in October 2018.

Data: This project utilizes a data set from [7, 8] that contains morphometric data of 583 pit craters, from a multitude of sources. This catalog includes data from Earth (Iceland) (*n = 58*) [2, 3], Mars [7 (*n = 216*), 9 (*n = 260*)], and Nyx Mons, Venus (*n = 49*) [7].

Morphology: Pit craters can be split into two morphological groups based on appearance: cylindrical (Figure 1) and inverted conical (Figure 2). Cylindrical pits have sharp rims that represent the top of the cylinder, and generally straight walls that can have overhanging portions (especially near the pit top). The bases of pits are often irregular due to caving in of material from the walls and/or preferential accumulation of wind-blown sediments. Inverted conical pits have sloped walls, often at the angle of repose, and are usually smoother than the walls of the cylindrical pits.

For both types of pit, their walls often contain useful information about the geological environment in which they formed, information that is not necessarily available from surface observations alone. If a pit wall is vertical to near vertical, the materials making up the pit walls are likely mechanically strong (i.e., rigid and/or coherent) and able to accommodate slope angles above the angle of respose for extended periods of time. If the walls of a pit are sloped, this generally indicates that the walls are made of mechanically weak materials.

The geological environments that pits form in often influence these shapes and should be taken into consideration when describing how a pit may have formed. For instance, in settings of stacked lava flows, i.e., mechanically strong wall material, pit craters will likely have cylindrical shapes. In contrast, environments that feature abundant ashfall deposits, uncemented sediments, loose cinder, etc. (that is, mechanically weak material), pit craters will often have inverted conical shapes. These inverted cone pits are smooth because the materials comprising the walls are relatively small grains, not cobble-to-boulder-sized clasts commonly seen on the floors of cylindrical pits.

However, pits *can* have traits of both shapes, leading to a spectrum of pit morphologies with cylindrical and inverted conical as two endmember styles. This spectrum of pit shapes is why identification of a pit crater alone does indicate a particular geological environment.

Formation Processes: Pit craters can be formed in a multitude of ways: lava tube collapse [10, 11], dike-tip related processes [12, 13], and dilational faulting [3,

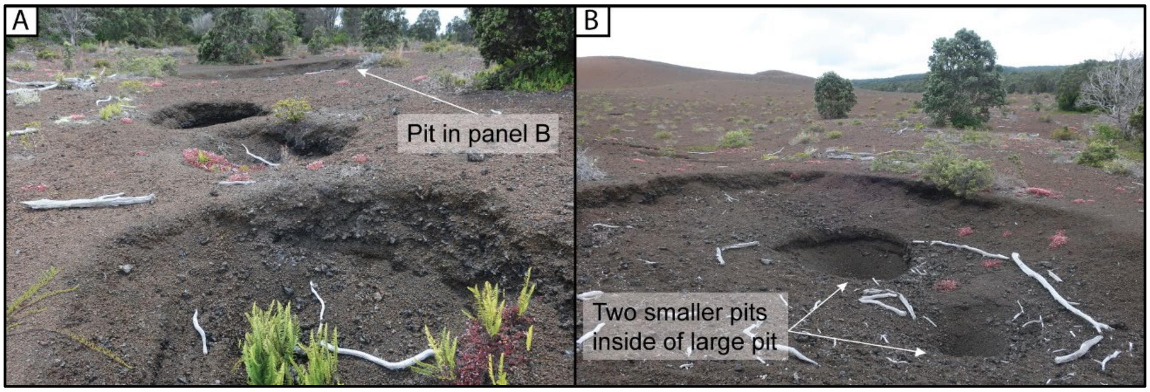

Figure 2. Photographs of inverted conical pit craters located along a caldera ring fault located on the Kilauea Volcano, Hawaii. A) Photograph looking south with four pit craters in view; B) Photograph looking north showing larger pit crater, itself hosting two smaller pits.

9] have all been proposed as potential source processes contributing to the formation of pit craters. Pit craters of lava tube origin have clear surficial expressions that meander along with the course of the tube itself. Pit craters of dike and fault origin are not easy to separate due to the co-occurrence of faults and dikes whenever dike tips come close to the surface. Additionally, in volcanic settings, there are a multitude of process that can lead to faulting such as caldera widening (dilational faulting on a caldera ring fault, **Figure 2**), and lithospheric loading.

Statistical analysis: To assess the morphometric data we compiled, depth/diameter ratios were calculated for each pit crater population to account for differences in scale and, then compared with the MATLAB™ function multcompare. Multcompare runs an analysis of variance (ANOVA) test of separate datasets, and reports which (if any) are statistically similar one another. Only those data from Noctis Labyrinthus, Mars [7, 8], global Mars [9], Nyx Mons, Venus [7], and Iceland [2, 3] were compared in these analyses. The Hawaiian data set [8] was not included because of their small sample size, which cannot be accurately analyzed with the multcompare function. The results of the ANOVA are shown in **Figure 3**, which indicate that the Icelandic [2, 3] and global Mars [9] pit crater data sets have similar depth/diameter ratios, whereas the Noctis Labyrinthus and Nyx Mons, Venus data sets [7] are dissimilar from the other pit crater populations.

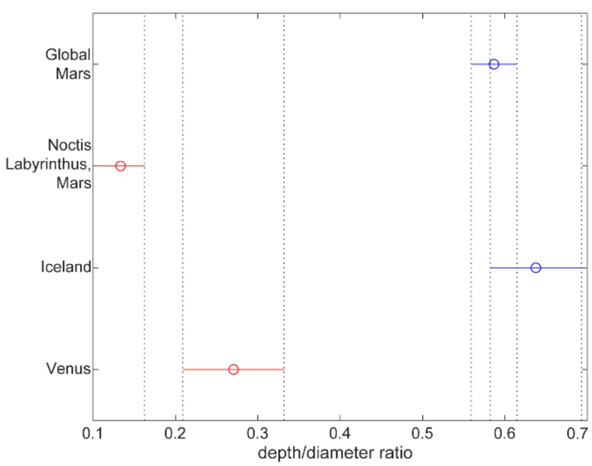

Figure 3. ANOVA results for datasets with a sufficient number of observations. Red indicates groups that are dissimilar, and blue indicates groups that are statistically similar.

Although it is useful to make morphological comparisons across planetary surfaces, the results of this analysis show that pit craters on different planetary surfaces can, *but do not always*, have similar morphologies when regarding depth and diameter. Careful interpretation of formation mechanism(s) is therefore required. On Earth, pit craters most likely do not reach the large sizes seen on other planetary surfaces due to the effects of an active hydrosphere, which will erode and mask pit craters before they can reach the sizes of their counterparts on Mars or Venus [3]. The depth/diameter ratios for Icelandic pits, which form in basaltic sediments, *do* have similar depth/diameter ratios to the global data set of Martian pits mapped by [4], suggesting that perhaps both pit crater populations are similar in how they form.

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