FIELD-BASED ASSESSMENT OF PIT CRATER CHAINS. Corbin L. Kling[1], Paul K. Byrne[1], Danielle Y. Wyrick[2], and Karl W. Wegmann[1], [1]Planetary Research Group, Department of Marine, Earth, and Atmospheric Sciences, North Carolina State University, 2800 Faucette Drive, Raleigh, NC 27695, USA, [2]Southwest Research Institute, 6220 Culebra Road, San Antonio, TX 78238, USA.

Introduction: Pit craters and pit crater chains are structures found on numerous rocky planets, icy satellites, and asteroids in the Solar System, as well as on Earth [1]. Pit craters are distinguished from impact craters due to the lack of their raised rim, are circular to elliptical, and often form in linear chains [2]. Numerous pit crater formation mechanisms have been proposed [2], but few have been tested via detailed examination of pits in different geological settings on Earth [3, 4]. Dilational normal faulting, extensional faulting above a dike tip, and explosive formation are all proposed mechanisms for pit formation [2]. The pits on Earth, though often smaller than those found on other planetary surfaces, offer an opportunity to study pit formation processes *in situ*, including, for example, the role of mechanical stratigraphy in the development of these structures [5].

Here, we report on active pit formation on the flank of the Kilauea caldera in Hawaii, as well as morphometric analyses of pit craters at Craters of the Moon National Monument and Preserve in Idaho (CRMO), with a view to better understand the nature and origin of these structures. Diameter-versus-depth scaling shows morphological similarities in pit craters on Earth that are conical in shape, whereas pit craters on Mars seem to scale slightly different than from those studied on Earth.

Field Sites: We use a combination of field observations, ground-based, and airborne lidar datasets to describe pit occurrence in Hawaii. Pit craters there are related to extension along the southeastern and southwestern rift zone of Kilauea [2]. Devil's Throat, southeast of Kilauea caldera, is an example of a straight-walled pit tens of meters across and deep and formed within lava flows along the southeast and southwest rift zones of Kilauea. In contrast, the flank of Kilauea Iki hosts meter-scale, conical pits within cinder deposits.

Pit craters at CRMO are also rift related and hosted within basaltic lava flows and cinder deposits. The lava flows are 2000–5000 years old, with numerous cinder cones and fissure eruptions present [6]. Previous work has interpreted King's Bowl, the most studied and one of the largest pits at CRMO, as the result of a phreatomagmatic explosion that post-dated the lavas in which it is situated [7]. The pits at Yellowjacket Waterhole, located within the main park, are previously unstudied pit craters that are hosted within volcaniclastic material and lava flows, and are bounded by extensional fractures.

King's Bowl and Yellowjacket Waterhole topographic data were collected using Unmanned Aerial Systems (UAS) stereo photogrammetry techniques. A DJI Matrice 600 UAS was used to collect the data, and Agisoft Photoscan v1.2.6 was used to produce 5 cm /px digital surface models (DSMs) and RGB orthomosaics. Ground control points were surveyed using an Emlid Reach RS+ RTK GPS system.

Field Observations in Hawaii: We made initial field observations of the Hawaiian pits in April 2018, one week prior to the lower east rift zone eruption and Kilauea caldera collapse. Devil's Throat is a straight-walled pit and tens of meters across and deep. Fractures were noted along the northeastern side of Devil's Throat.

No substantial change was noted at Devil's Throat pit crater as a result of the flank eruption from visual inspection, but minor changes in shape can be seen between the 2004 lidar survey and the 2018 lidar surveys. These changes are evident along the edge of the pit, where calving of material has widened the pit in several places.

To the southwest of Kilauea Iki, there is a chain of pit craters aligned N–S with the caldera wall (**Figure 1**). There are ~8 pits that are all easily accessible and relatively well preserved; additional pits are located to the south but are heavily vegetated and not easily accessed.

We identified substantial change at the Kilauea Iki pit chain upon a follow-up visit in October 2018, after the bulk of eruptive activity had ended. Pit 6 had

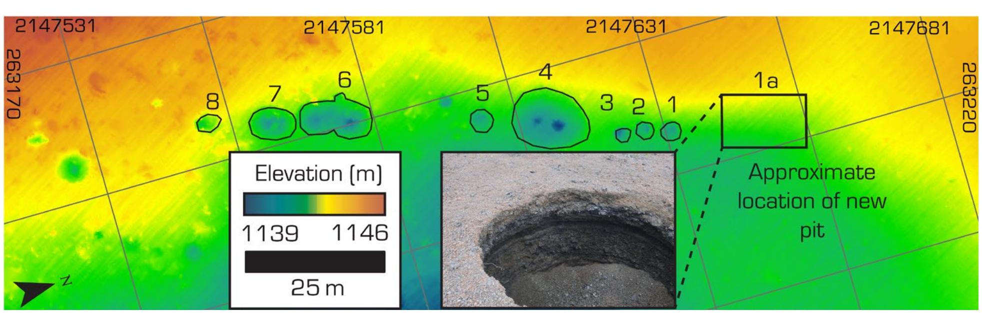

Figure 1. *July 2018 Hawaiian lidar survey showing Kilauea Iki pit chain. Inset photo shows pit observed in October 2018 that does not appear in either the June 2018 lidar surveys. Coordinates in UTM zone 5N north.*

noticeable calving of walls, and in pit 4 (previously coalesced), two new, small pits had formed in the base. Additionally, a new pit north of the previously northernmost pit 1, had formed, marked as “1a” in **Figure 1**. The new pit is ~1 m deep and wide, as has straight walls. This new pit must have formed after July 2018, as the lidar campaigns to monitor the Kilauea Caldera and lower east rift zone did not capture the pit in June or July of 2018. The resolutions of the lidar surveys are 50–100 pts/m^2, more than sufficient to capture a 1×1 m pit.

The change seen at the Kilauea Iki pits is coeval with the 2018 eruption event and caldera collapse, suggesting that the seismic activity contributed both to the growth of the pits already present and to the creation of the new pit. The alignment of the pit chain with the caldera wall suggests that the material could be draining into a fracture that is involved in the caldera widening.

Field Observations in Idaho: The King’s Bowl pit crater in CRMO displays flows oriented perpendicular to the surface, suggesting either drainage of lava into the fissure or a source from below. This indicates that King’s Bowl was once part of the fissure system feeding the flows. There are many smaller subsidiary pits and depressions to the north and south of King’s Bowl. Extensional fractures are found east and west of the pits, and cross cut flows at this pit as well as older flows that the King’s Bowl fissure erupted onto.

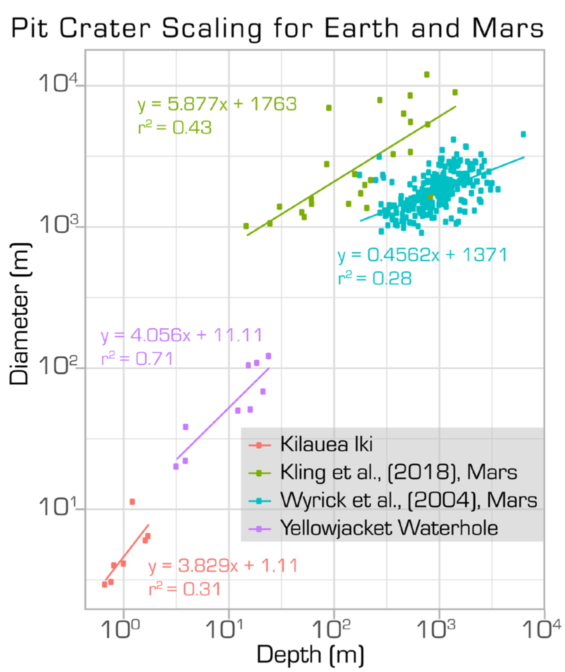

Figure 2. *Diameter versus depth scaling plot for Earth pits in this study and Mars pits from previous studies [2, 8]. Only conical-shaped pits are plotted due to uneven infilling of straight-walled pits.*

The pits at Yellowjacket Waterhole in CRMO are morphologically different from King’s Bowl itself. The Yellowjacket Waterhole pits occur in unconsolidated volcaniclastic material and the lava flows within the walls are much less well defined. Additionally, the Yellowjacket Waterhole pits are aligned in a chain, and bounded on either side by extensional fractures that can be seen in orthomosaics and DEMs from the UAS surveys. These pits range in size but can be up to tens of meters in width and depth, similar to the main pit at King’s bowl, but the Yellowjacket Waterhole pits are more conical than both King’s Bowl and Devil’s Throat, and show few to no vertical wall segments.

Outlook: Figure 2 shows a diameter-versus-depth plot of pit crater populations studied at these field sites as well as from other studies on Mars. One key takeaway when comparing the Earth-borne pits with those from Mars is the differing scales. Pits on Mars are larger than pits we see on Earth, in part a function of the resolution of available imagery for Mars, *but Earth has no pits that are as large as the pits on Mars* [2, 8]. In terms of mechanical stratigraphy, pits in unconsolidated material form conical pits, whereas pits in consolidated material tend to form straight walled pits. Conical pits are abundant on other planetary surfaces, but there are much fewer straight walled pits.

These field analogue sites provide three mechanisms for pit crater formation: 1a) extensional fracturing and subsequent drainage of material (Kilauea Iki, and Yellowjacket Waterhole); 1b) extensional fracturing above a dike tip leading to collapse of material (Devil’s Throat) and 2) phreatomagmatic explosion leading to pit formation and subsequent collapse (King’s Bowl). King’s Bowl seems to be an outlier in comparison to other pits observed in this study, suggesting that phreatomagmatic explosions are not a dominant formation mechanism for pit craters. These formation mechanisms are all plausible for pit formation on other planetary bodies, but fracture infilling seems to be the most prevalent and can also explain pits on smaller bodies such as asteroids, shallow intrusive (dike) related processes presumably do not occur.

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