PIT CRATER CHAINS ACROSS THE SOLAR SYSTEM. D. Y. Wyrick[1], D. L. Buczkowski[2], L. F. Bleamaster[3], and G. C. Collins[4], [1]Department of Earth, Material, and Planetary Sciences, Southwest Research Institute® (6220 Culebra Rd., San Antonio, TX, 78238-5166, USA; dwyrick@swri.org); [2]Johns Hopkins University Applied Physics Laboratory; [3]Planetary Science Institute; [4]Wheaton College.

Introduction: Pit crater chains are lines of circular to elliptical depressions, which in many cases coalesce into linear troughs (Fig. 1). Pit craters lack the elevated rim, ejecta deposits, or lava flows that are typically associated with impact craters or calderas. Individual pits most commonly have a conical shape, with or without a flat floor, or in some cases, an elliptical plan shape with the long axis parallel to the chain orientation. Pits are often bounded by a graben (down-dropped block bounded by normal faults), and pit chains are often in alignment with a regional fault and fracture system [1]. The pits are generally agreed to have formed by collapse into a subsurface cavity, although the exact formation mechanisms hypothesized vary from planet to planet. Pit crater chains have been identified on several solid planetary bodies throughout the solar system including Venus [2], Earth [3,4,5], the Moon [6], Mars [1,4,5], Phobos [7], Eros [8,9], Gaspra [10], Ida [11], Enceladus [12], and Europa.

Very few endogenic geologic processes operate across-the-board on such a wide variety of planetary bodies with disparate lithologies and geologic histories. The identification of pit chains on these wide ranging bodies – from small asteroids to icy moons to large terrestrial planets – raises important questions regarding both the potential geologic formation mechanisms and near-surface crustal properties of solid bodies in our solar system:

- Are pit chains formed by the same mechanisms on all of these different planetary bodies?
- If so, what geologic formational mechanisms are shared by all bodies and what are the implications for the geologic histories of these bodies?
- What inference regarding the near-surface crustal properties of these disparate bodies can be drawn from the presence of pit crater chains?

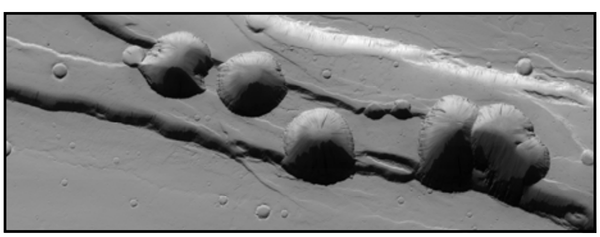

Figure 1. Pit crater chain in the Tractus Catena region, Mars. Image credit: NASA/JPL/Univeristy of Arizona

Hypotheses regarding the formation of pit crater chains vary across different solar system bodies. On Venus, dike intrusion and dike swarms are the most commonly interpreted hypotheses [2,13,14,15,16], whereas on small asteroid bodies such as Phobos [7] and Eros [8,9], it is drainage into extensional fractures. Martian pit crater chains have variously been interpreted to be a result of dike swarms [17,18,19,20]; dike swarms associated with collapsed magma chambers [21]; karst dissolution [22]; fissuring beneath loose material [23,24,25]; and dilational faulting [1,4]. On Earth, fractures [3], dikes [3], dike injection into preexisting normal faults [26], karst dissolution [27], and dilational faulting [4,5] have all been proposed. On Enceladus, dilational faulting has been suggested for pit crater formation [12].

Venus: Pit chains on Venus are linear to curvilinear collections of individual pit craters (circular to elliptical, shallow, steep-sided depressions) that range from tens to several thousands of kilometers long and have widths ranging from 10 km down to the resolution of the best Magellan radar data (75 m/pxl; pit chains and pits must be ~150-200 m in width for positive identification). They occur across the spectrum of Venusian terrains, including the plains, within tessera, on volcanic rises, but especially in association with chasmata and coronae. They are generally straight, but in some cases show minor undulations along their trend, typically reflecting adjacent topography; pit chains at the summits of volcanic rises are often concentric around the central crater, or caldera. The general characteristics of these features suggest that they form by collapse following the removal of subsurface support; however, the mechanism responsible for the loss of this support remains in question [2].

Earth: Long linear chains of collapse pits are rare on Earth, but have been documented in Hawaii, Israel/Jordan, and Iceland. Pit chains were identified along Kilauea's east and southwest rift zone with the conclusion that collapse along a typical Hawaiian dike could not account for the large aperture of the pit craters [3]. Large opening-mode fractures were likely caused by ''magma pressure and tensile stresses associated with the seaward sliding of Kilauea's south flank'' [3]. Although magma flow through a preexisting fracture might enlarge the fracture and associated pit craters, it was not required to create them; regional extension alone produced open fractures [3]. Smaller-scale collapse pits are also found near Kilauea-Iki where the near-surface stratigraphy consists primarily of unconsolidated tephra deposits. Pit craters and ovoid fissures have been mapped in rift zones in Iceland [5,26]. In studies of Iceland, normal faulting and dike injection occur simultaneously during rifting episodes, but field evidence conflicts with dike-generated fracture models [4,5,28,29]. Normal faulting with open dilational fault segments near the surface is common in rift zones and accommodates much of the extensional deformation in the upper crust [30]. The Dead Sea pull-apart basin has produced hundreds of collapse pits along the coastlines of Israel and Jordan [27]. These pits form long linear clusters in plan view. Although the collapse is facilitated by dissolution of a buried salt layer, the pit chains' orientations and distributions are controlled by active, subsurface normal faults [27].

Mars: More than 1500 pit chains were mapped on Mars, primarily in relation to the Tharsis region [1]. Individual pits range in size from tens of meters (the limit of image resolution) to 4.5 km [1]. Martian pit chains are found in areas that show features of local or regional extension, with a strong correlation to tectonic grabens and volcanic edifices. Martian pit chains are often found within, or transitioning into, grabens and normal faults. Pit chains also occur in *en echelon* (segmented, laterally stepping) arrays, and a few display curved tips similar to interaction at the tips of *en echelon* faults [31] or extension fractures [32]. Fault systems and pit chain traces on Mars bear a striking resemblance to fault systems on Earth, including geometric features such as horsts and grabens [33], relay ramps and breached relay ramps, and *en echelon* arrangement of faults and grabens.

Eros and other small bodies: A number of different types of linear structural features – including pit crater chains – were observed on the surface of Eros by the Multi-Spectral Imager (MSI) onboard the Near-Earth Asteroid Rendezvous (NEAR)-Shoemaker spacecraft (e.g., [8]). A database of all Eros lineaments was created to determine the distribution of these features and the interior structure of the asteroid [9].

One set of similarly oriented linear structures consists of a high concentration of pit crater chains and beaded grooves, as well as fractures and flat-floored troughs [9]. When compared to the volume of low-velocity ejecta from Shoemaker crater [34], it is observed that the pit chains occur only where the lineation set overlaps a region of moderate regolith thickness [35]. While the geomorphology of the entire data set of linear structures in the [9] map has yet to be evaluated, all other pit crater chains identified on Eros are associated with areas of moderate regolith thickness.

Pit chains have also been observed on Phobos [7], Gaspra [10], Ida [11], and possibly the asteroid Steins [36]. Some potential formation mechanisms for the pit chains on these bodies have been discussed, but given the resolution of the observations, no detailed geomorphic analysis has been undertaken to date.

Enceladus, Europa, and other icy moons: Groups of parallel pit crater chains are commonly observed in the cratered plains of Enceladus [12]. They are often associated with larger graben-like structures, supporting a dilational faulting origin for the pit chains. The full range of morphologies is observed, from individual pits to merged pits, with pit diameters in the range of 100-400 m. Most pits are ~150 m in diameter, which may indicate that the cratered plains are covered by a loose regolith layer ~150 m deep [37]. Immediately adjacent to the cratered plains is highly tectonized terrain with very low crater densities, corresponding to surface ages of ~1-10 Ma [38]. Pit chains are observed within the cratered plains in close proximity to the younger terrain, but none have been found in the younger terrain. This may be due to lack of a thick, loose regolith layer on the younger terrain.

Pit chains have also been observed in high resolution images of Europa, though they have not yet been described in the literature. Several are found within the matrix material of chaotic terrain, but evidence is less certain in ridged plains, which may have implications for the nature of Europa's regolith and the formation of chaos. Candidate pit chains have also been casually observed on Ganymede and Dione, but no detailed study has been undertaken to assess these features.

Discussion: The origin and evolution of pit crater chains, some of the which are among the youngest surface geologic features on Mars and Enceladus [1,4,12], are fundamental components of and constraints on a large variety of surface tectonism and volcanism models. Although pit chains are a common feature on these planets and moons, they remain relatively poorly understood. An improved understanding of pit chains would result in a better understanding of crustal characteristics and conditions on several solid bodies in the solar system. Pit craters also provide a unique insight into the layered mechanical inhomogeneities of the near surface crust and offer clues about subsurface processes that current data cannot directly measure. The analysis of pit crater chain features may provide an improved understanding of the relationship between pit chain formation, faulting and fracturing processes, and igneous intrusion as well as producing quantitative values of the mechanical properties of the near surface, with implications for processes on Venus, Earth, the Moon, Mars, Phobos, Eros, Gaspra, Ida, Europa, Enceladus, and other bodies where pit chains may be discovered.

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