TECTONIC CAVES: THE ROLE OF DILATIONAL FAULTING.

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Introduction: Subterranean void spaces on planetary bodies are a critical area of study for both astrobiology and *in situ* resource utilization (ISRU). Common cave forming mechanisms such as lava tubes are being studied as subsurface areas of interest and have been interpreted on the moon and Mars. However, lava tubes are relatively rare in the solar system, and where found, often limited in spatial extent (e.g., lava tubes are typically confined to a single lava flow). Alternatively, the ubiquitous nature of extensional fractures, normal faulting, and pit crater chain formations found on terrestrial planets, asteroid and icy moons [1] suggests that dilational faulting may be the dominate formation mechanism for creating subsurface void space.

Dilational faulting can occur when extensional strain is applied across mechanically stratified layers, or where hybrid mode failure (Mode I opening combined with either Mode II sliding and/or Mode III tearing) occurs under low differential stress [2,3]. Mechanical stratigraphy influences where faults nucleate, the type of failure mode, the strike/dip geometry, and the degree and distribution of displacement along the fault [3,4]. In particular, the stratigraphic layering of mechanically strong rock (e.g., basalt flow) with relatively weak rock (e.g., non-lithified pyroclastic deposits, unconsolidated regolith) often found on planetary bodies lends itself to the formation of dilational faults [5,6,7]. The geometry of these dilational faults in the subsurface have a significant influence on the flow and storage of fluids and volatiles as well as mineral deposition on earth [8] and likely plays a similar role on solid bodies in our solar system. Thus characterizing dilational faulting will yield insight into the subsurface permeability architecture of planetary bodies of interest, allowing a better understanding of the potential for fluids and volatiles to flow and become trapped in these voids spaces over geologic time. Whether the target is groundwater/ice, methane, metals, minerals or other vital ISRU, dilational fault systems play a major role in controlling where these resources may be found [8,9].

Fortunately, dilational faults often reveal themselves in the form of collapsed pit crater chains [1,5,6,10], which can often be identified in visual imagery (Fig 1). Additional topographic datasets (e.g., LOLA, MOLA) can help to quantify the geometry of the fault zone and the magnitude of displacement that has occurred. These analyses can, in turn, help constrain the degree of potential void space available in the subsurface as well as help define the permeability architecture [11,12,13].

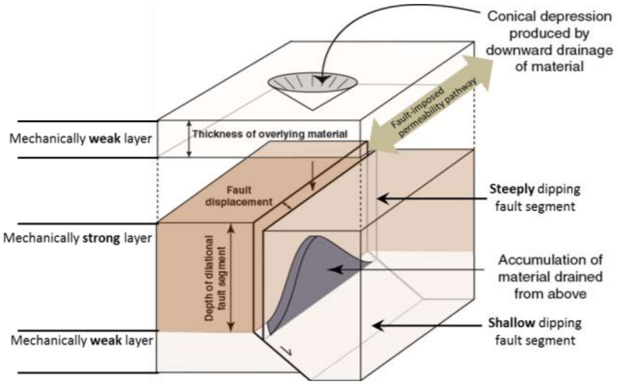

Figure 1. Schematic illustrating a subsurface dilational fault segment. The subsurface volume is a function of the thicknesses and mechanical strength of the stratigraphic layers, which in turn controls the depth and dip of the fault segment. The degree of dilation controls the size of the subsurface void, which can become large enough for overlying weaker material to collapse into the fault segment, creating a pit crater at the surface (modified from [6]).

Dilational Fault "Caves": Pit crater chains on Earth have been observed forming over dilational normal faults [14,15], illustrating the large volume of void space that exists within the subsurface dilational fault segment beneath the surface pit crater features (Fig 2). These same terrestrial dilational faults become permeability pathways for groundwater flow and storage (Fig 1,2), suggesting that similar features observed on other planetary bodies may also provide volatile and fluid transport and potential reservoirs. On Mars for example, outflow channels have been mapped directly emanating from pit crater chains, which are interpreted to have been structurally controlling the groundwater in the region [16]. Understanding these structural controls on groundwater, minerals, and volatiles is critical toward understanding what resources may be available both for astrobiology and future human exploration.

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 and dilational faulting on these wide ranging bodies – from small asteroids to icy moons to large terrestrial planets – raises important questions regarding the near-surface crustal porosity of solid bodies in our solar system and their capacity to store vital resources. The ubiquitous nature of dilational faulting and their signature pit crater chains make them an easily identifiable target on many planetary bodies of interest, providing a peek into the subterranean environment that may exist.

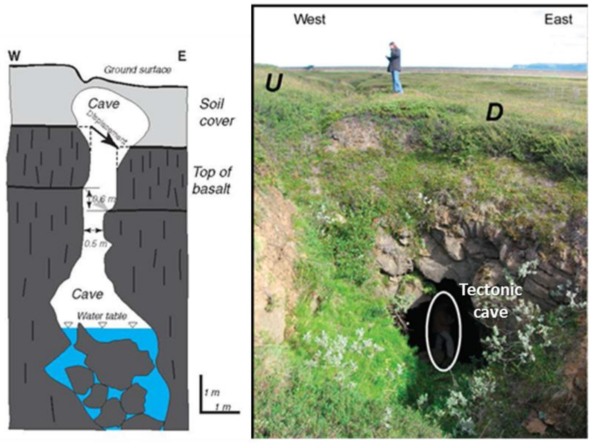

Figure 2. (left) Schematic cross-section of a tectonic cave associated with a dilational fault segment that channels the groundwater. (right) Image showing a pit crater above a dilational fault in the subsurface. Note person at surface mapping pit crater while person (white oval) maps the subsurface dilational fault segment for scale. From [14].

Implications: Understanding the relationship between pit crater chains, dilational faulting and subsurface voids space will be critical in future solar system exploration. Dilational faulting, and the tectonics caves they can produce, have direct implications for the transport and storage of volatiles and fluids in the lithosphere on Earth. Pit crater chains on Mars appear to have also provided permeability pathways for groundwater, and may be regions of ground ice storage today. Similarly, pit crater chain identification on the moon and other small bodies suggest that there may be significant subsurface void space to sequester volatiles and ices [10]. Because pit crater chains are a more easily observed surface feature, they can serve as good proxy indicators of dilational faulting and subterranean cavernous tectonic voids.

Identifying fracture void spaces has potential implications for human exploration, as the need for in situ resource utilization becomes a driver for exploration targets. Near-Earth Asteroids (NEA) are considered the most likely early candidates for these exploration activities. Finding water and other volatiles on site in these asteroids is considered vital toward in situ resource utilization. While water is relatively common on the C-type asteroids, it is unlikely to be abundant on the S-type NEAs. However, there might be water ice trapped in the impact-formed fracture systems, brought in by the impactor. Even other asteroid types (C-type or the water-bearing D-type) would also benefit from the mapping of their void spaces, as the fractured regions would likely be where the valuable volatiles would be most easily accessible.

Other types of in-situ resource identification would also benefit by extensive void space mapping and measurement. Determining the viability of asteroid mining is becoming a priority as it becomes clear that many key elements important to industry will be depleted on Earth within the next 50-60 years. S-type asteroids, the most common type of NEA [17, 18, 19, 20], could potentially provide important metals, such as nickel and cobalt. M-type asteroids contain far more of these materials than S-type, but are considerably more rare. Meanwhile, C-type asteroids could contain useful carbon and phosphorus, as well as water. Identifying existing void spaces would make accessing these resources easier and less time consuming.

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