SUBSURFACE VOLUME LOSS AND SURFACE COLLAPSE BY SALT-DISSOLUTION OF TERMINAL CAVI IN OSUGA VALLES.
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Introduction: Geologic depressions on Mars are suggested to be the surface expression of volume loss resulting from magmatism [1], tectonic processes [2], cryosphere withdrawal and aquifer breach [3]. Void-forming karst dissolution processes have not been similarly explored, though some depressions may be associated with buried salt deposits [4,5]. Some depressions on Mars, located at the source of outflow channels are known as chaotic terrains. The volume of these chaotic terrains is commonly inferred to have been lost as released groundwater and excavated load [3]. In Osuga Valles, a catastrophic outflow channel site [6], the flood morphologies can be tracked from their chaotic origins down to terminal depressions or cavi (centered around 14°50'S and 37°25'W Fig. 1). The association between the channels and cavi implies a genetic link between the inflowing floodwater and cavi formation, possibly related to subsurface salt dissolution. Exploring the formation mechanism, as constrained by the channel-cavi association, may contribute to a better understanding of possible depression formation mechanisms on Mars. Such understanding may constrain subsurface stratigraphy, past climate, and hydrology, with astrobiological implications.

Materials and Methods: We mapped the cavi, the channels, and the chaotic source terrains. The boundaries of the mapped region overlap the –15037 quadrangle (12.5-17.5° S., 35-40° W.), other than at its western boundary, which closely follows the estimated watershed of the studied basin. We used ESRI's ArcMap® 10.6, utilizing data from CTX, HiRISE, and THEMIS. Geologic features were mapped at a scale between 1:50,000 and 1:100,000, and locally at a scale between 1:1,000 and 1:10,000.

Channel, chaotic origin and cavi volumes were calculated using ArcGIS® 10.6 by summing the elevation differences (multiplied by pixel area) between Mars Global Surveyor's Mars Orbiter Laser Altimeter (MOLA) DEM (463 m per pixel; [7]) and an interpolated preexisting surface. The calculated channel volume, under an assumption of 5-20% sediment load, was used to provide a lower bound on the volume of water discharged in the floods that carved the channels in the Osuga system.

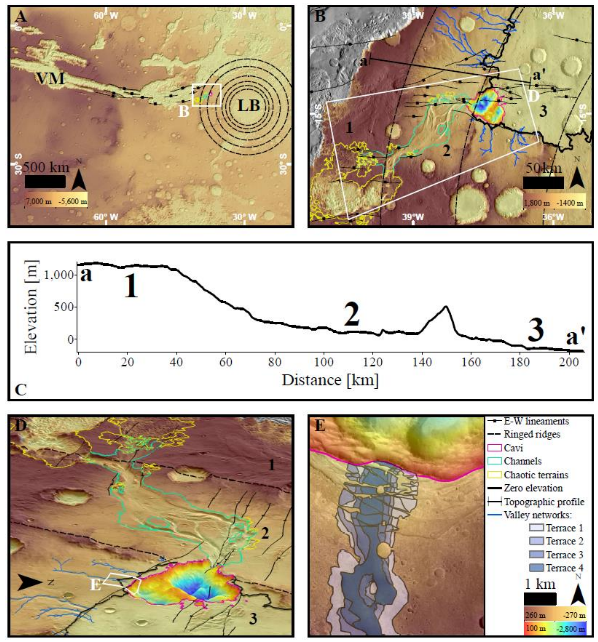

Figure 1: Study site and geologic setting. A) Two regional geologic structures overlap in the study site: LB are the proposed ring-ridge remnants of Ladon Basin, and VM are the proposed extended fracture and fault system of Valles Marineris. The structures are shown on MOLA hillshaded DEM. B) The effect of these regional geologic structures on the study site. Numbers mark three topographic stairs. The background is MOLA DEM overlying THEMIS Day IR. The color bar of the area enclosed within the cavi is in panel E. C) A MOLA DEM-based elevation profile (~25 times vertically exaggerated) along the three topographic stairs (profile track is shown in panel B). D) A perspective view of Osuga's three segments and their transition through LB along VM features. The background is MOLA DEM overlying THEMIS Day IR with elevation color-coded as in panel B. E) A morphological map of a valley network channel that is cut by Osuga Cavi. The background is CTX underlying HRSC DEM. Note that the range of elevations represented by the brown color palette differs between figure panels.

Using the calculated volume of water, we estimated the maximal volume of salts that could have been dissolved, under an assumption of saturation of the water with the salts of interest (i.e., sufficiently long residence times of the water in contact with the salts). Given typically low rates of water flow in subsurface conduits, this assumption seems reasonable. We included mineral families detected on Mars [8], considering a wide range of salts within those families. Solubility product constants were taken from [9,10,11].

Morphological observations: Prior to the onset of catastrophic flood events, Ladon Basin's impact ring structure divided the study area into three main elevation levels or stairs (Fig. 1). The stairs are dissected by a superposing set of generally E-W trending fractures associated with the Valles Marineris stress field. Valley networks, which predate the catastrophic events, likely eroded the steeper slopes of the middle stair and dissipated at the transition to the plain of the lower stair. The cavi are situated within the lower stair, bounded to the south and west by the higher terrains that contain the older valley networks. The catastrophic channels originate in two separate chaotic terrains situated on the upper stair and then flow over the middle stair to merge into a single channel approximately at the transition between the middle and lower stair. Crosscutting relations imply that the later outflow event that originated from the southern chaotic terrains postdates outflows from the northern terrains and produced higher discharges. More minor chaotic source regions were identified within and around the flood channels. The convoluted drainages on the middle stair are morphologically distinct and linked by their spatial association, width, and depth, to different flood events. A set of shallower channels are incised by much deeper and wider channels, suggesting the existence of an early, higher-elevation drainage system. The shallower channel remnants can be linked to fluvial morphologies on some remnant collapsed blocks within the cavi. Prior to terminating at the cavi, the deeper channels merge at a cataract-like form, which is of much lower elevation than the upstream channels. The merged channel continues inside the primary cavus, but terminates where the depression's floor is cut by a nested depression that postdates the collapse of the primary cavus. Additional depressions, which we term peripheral cavi, are located to the east of the primary cavus. No inlets or outlets of water are identified for these peripheral cavi.

Our mapping suggests that subsurface volume loss and initial collapse resulted from infiltration of flood waters, possibly at the intersection of planes of weakness associated with the large-scale structures in the study region (the ringed ridge and the E-W fracture system). Subsequent collapse was likely due to additional, higher discharge flood events that drained directly into the forming depressions. Crater-counting model surface ages [12] are in agreement with this proposed sequence of events. Further work to quantify the catastrophic discharges in Osuga Valles and explore their implications is ongoing [13].

Proposed mechanism: A terrestrial analog to Osuga's terminal cavi may be the Ze'elim Fan Sinkholes along the Dead Sea shores. These sinkholes are located at flood channel termini, and their formation following flash flood drainage into pre-existing sinkholes has been documented [14]. The sinkholes are suggested to form by groundwater dissolution of a subsurface salt layer, which causes preliminary surface collapse. Subsequent floodwater draining into the collapsed region then becomes the dominant subsurface salt dissolution agent and induces further surface collapse [14]. In the case of Osuga Valles terminal cavi, it remains unclear whether infiltrating flood waters removed the substrate volume by subsurface salt dissolution or simply by physical excavation of subsurface fractures from rocks and melting ground ice. Nevertheless, the region hosts numerous older valley networks that terminate in a proposed sedimentary basin, possibly implying the preexistence of evaporite-rich sediments at this site. Our water volume and dissolution calculations suggest that magnesium sulfate minerals are the most likely candidates to explain the subsurface volume loss that led to formation of Osuga Cavi. These results are consistent with observations in outcrops in the relative vicinity of the Osuga system [4]. The crater counting model surface ages conducted by [12] is consistent with proposed ages of detected sulfate mineral deposition on Mars [15].

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References: [1] Michalski, J. (2018) *AGUFM*, P53F-3028M. [2] Wyrick, D. et al. (2004) *JGR*, *109*, E06005. [3] Rodriguez, J. A. P. (2015) *Scientific reports, 5(1)*, 1-10. [4] Gendrin, A. et al. (2005) *Science, 307(5715)*, 1587-1591. [5] Bishop et al. (2021) *Sci. Adv., 7(6),* eabe4459. [6] Naor, R. et al. (2019) *EPSC-DPS 2019* abs. #1443-2. [7] Smith, D. et al. (2001) *JGR Planets*, *106.E10*, 23689-23722. [8] Ehlmann, B. L. and Edwards, C. S. (2014). *Annu. Rev. Earth. Planet. Sci.*, *42(1)*, 291-315. [9] Johnson, J. et al. (2000) *Database "thermo. com. V8. R6. 230," Rev.* 1-11. Lawrence Livermore Natl. Lab. [10] Tosca, N. J. et al. (2005) *EPSL*, *240(1)*, 122-148. [11] Marion, G. M. et al. (2010) *Icarus*, *207(2)*, 675-685. [12] Spurling, R. et al. (2023) *LPSC 54th*. [13] Portillo, D. et al. (2023) *LPSC 54th*. [14] Avni, Y. et al. (2016) *JGR Earth. Surf., 121(1),* 17-38. [15] Bibring, J. P. et al. (2006) *Science, 312(5772),* 400-404.