LIMITS ON CHAOS INCEPTION ON MARS. Neil Coleman and Christopher Coughenour, University of Pittsburgh at Johnstown (Department of Energy & Earth Resources, Johnstown, PA 15904; ncoleman@pitt.edu).

Introduction: Chaotic terrain is a landform unique to Mars. Chaos have been described on Europa, but those ice features are not analogous to those on Mars. Powerful insights about the upper crust of Mars can be gained from studying its deep chasmata, chaos, and fissure systems. This paper focuses on the chaotic terrain and pressure limits on their inception. A curious paradox posed by some chaos is discussed.

Global Distribution: So far, 30 chaoses have been assigned formal IAU names, but many small areas of chaos are unnamed. Most chaos exist in a narrow belt of latitude clustered in lowlands near the equator, between 19°S and 16°N. Over 90% of the chaos by area lie in Xanthe and Margaritifer Terra (Unit Ht in Fig. 1), spatially associated with larger outflow channels (Simud, Tiu, & Ares) that flowed into Chryse Planitia.

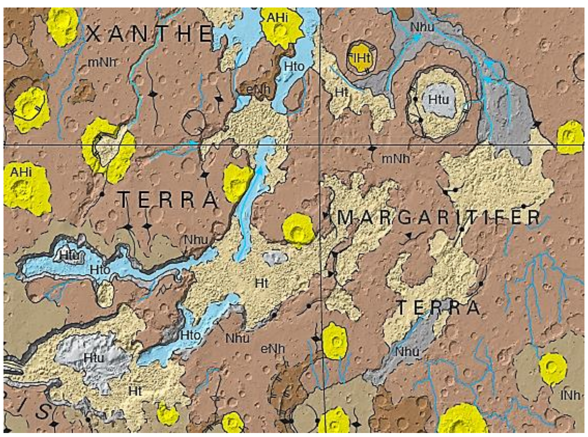

Fig. 1. Geologic map [1] showing main chaos areas.

The largest region of chaos includes the adjacent Aurorae and Aureum Chaos, at the eastern mouths of Ganges-Capri and Eos Chasmata, which are clearly linked to megafloods sourced from paleolakes in the Valles Marineris (VM). Those floods incised Simud and Tiu Valles. Farther east, extensive chaos (Iani and Margaritifer) contributed discharges to Ares Valles.

Eos Chaos lies at 17°S. Chaos occur on the floor of Simud Valles as far north as 16° and within the nearby Shalbatana Vallis up to 12°N (i.e., Xanthe Chaos). Ister Chaos lies on the floor of Maja Valles at 12-13°N. Nilus Chaos at 25°N lies along the western flank of Kasei Valles. Of named features, Galaxias Chaos, NW of Hecates Tholus, is farthest from the equator at 34°N. The nearby volcanic edifice and former heat source likely explains why this chaos appeared so far north.

Source-Area Elevations: The chaos birth areas were low-lying, based on the approximate rim elevations along the chaos margins. Examples include:

Chaos	Adjacent Land Elev.	Collapse Depth (≤)
Hydraotes C.	-1.5 km	3.5 km
Aromatum C.	0 km	2.5 km
Aureum C.	-2 km	3 km
Pyrrhae C.	-1.2 km	2.8 km
Hydaspis C.	-1.5 km	2.2 km
Aurorae C.	-0.5 km	3.5 km
Iani C.	-2 km	2 km

The very low elevations at which chaos formed are consistent with regions that would have experienced large overpressures in aquifers confined beneath the cryosphere. The high pressures arose from recharge occurring in higher elevation areas, accumulating over time as excess pressure beneath lowland cryospheres. At their peak, the groundwater potentiometric surfaces could have stood well above the Martian land surface.

Pressures in the Crust: Pressure relations in the crust provide keen insights about how and where chaos formed, and also place limits on the depth of inception. Fig. 2 compares hydrostatic and lithostatic pressures on Earth vs. Mars. "Hydrostatic" simply refers to the increasing pressure of water with depth in a well, open to the atmosphere. "Lithostatic" refers to increasing rock pressure with depth. A crustal density of 2.67 g/cc is used for Earth. A slightly higher 2.7 g/cc is assumed for Mars given a crust dominated by basalts. Due to lower gravity, the lithostatic plot for Mars nearly coincides with the hydrostatic plot for Earth.

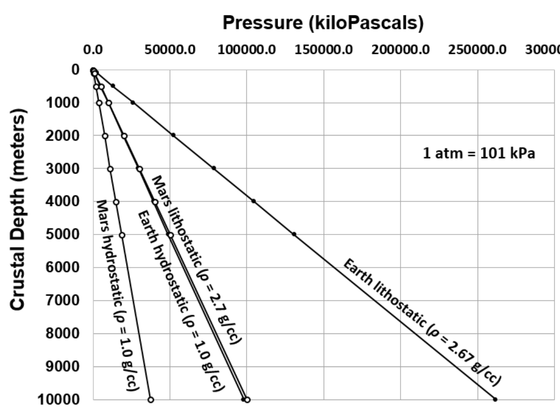

Fig. 2. Pressure scenarios for Earth vs. Mars. Hydrostatic plots assume a liquid water column.

Limits on Chaos Inception: Pressure plots for the Martian crust (Fig. 3) reveal that chaos formation was limited to zones where confined aquifer pressures could exceed lithostatic loads. This would have occurred in the crust at depths limited by the peak heights of recharge zones, mostly limited to depths of ≤3.5 km.

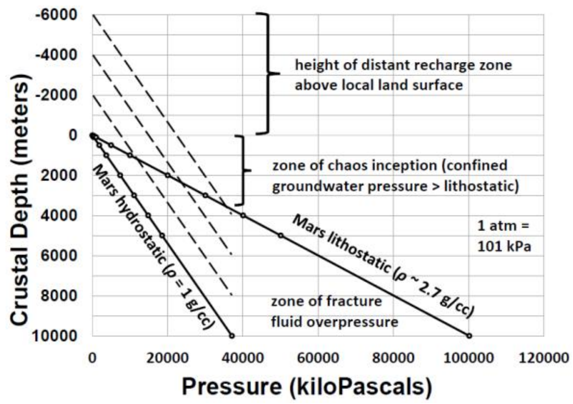

Fig. 3. Increases in hydrostatic pressures from recharge zones at a series of higher elevations (dashed lines). Example: recharge area 6 km higher than local surface could rupture the cryosphere at thicknesses ≤3.5 km.

Many chaos discharged groundwater at such large flow rates that deep fluvial channels were incised. Examples include Aromatum [2], Iani, Hydaspis [3], and Aram chaoses. Aram C. formed entirely within a crater. The power to erode deep channels was adequate to transport materials lost to form these chaos. Chaos inception likely also occurred during rapid thinning of the cryosphere by deep channel incision during megafloods (see Section 4 and Fig. 5 of [2]). However, outflows from these "secondary" chaos would not likely have been as great as discharges from chaos at heads of channels - significant aquifer depressurization would already have occurred.

Isolated Chaos: A curious paradox relates to chaos that are *isolated*, not apparently associated with outflow channels. Pyrrhae Chaos (Figs. 4 & 5) is one of the larger isolated chaos on Mars. *At first glance* there are no structural lineations or extensional rifts (such as seen in the VM) to account for the collapsed ground. Excluding the crater at its southeast end, Pyrrhae Chaos has a surface area of ~9,050 km^2, and the collapsed (cavity) volume lost is ~14,400 km^3. On average, the terrain collapsed 1.6 km for each km^2 of surface area.

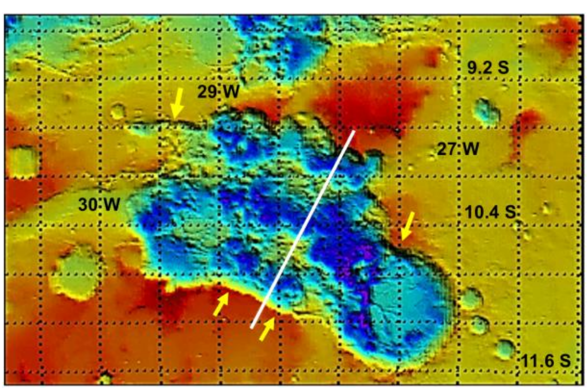

Fig. 4. Topography of Pyrrhae Chaos. White line is 100 km long. Image produced with Gridview [4].

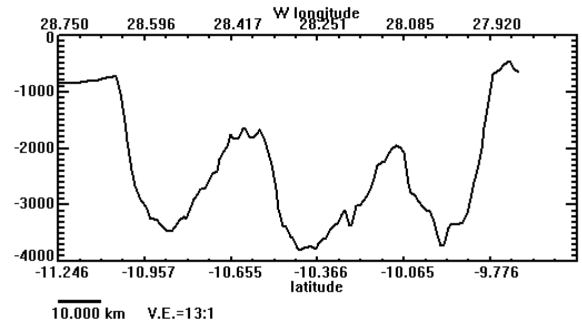

Fig. 5. Topographic profile along white transect in Fig. 4. Vertical axis is in meters, horizontal in degrees.

Fate of Material "Lost": An explanation is needed for the volume lost in the genesis of large isolated chaos like Pyrrhae. Dissolution of material like carbonates and sulfates is unlikely given that mineralogical mapping has shown that volcanic rocks, mainly basalts, dominate the crust. Similarly, the loss of such enormous volumes of *crustal* ice was unlikely because that would have required some lowland areas of Mars to have an icy upper crust like that of Europa, veneered with surface layers of basalts.

Although extensional rifting was not at first apparent, on closer examination, *normal faulting as seen in the VM can indeed account for most of the lost volume*. As shown in Fig. 4, there are three bands of deeper collapse (blue topography) that trend WNW, separated by two bands of much higher chaotic terrain. This structural trend parallels that of the main VM canyons. These bands clearly appear in the topographic profile of Fig. 5. There are also two long segments of chaos wall that parallel the observed topographic bands. Locations of these wall segments are shown using yellow arrows in Fig 4. An arrow also points to a western extension of the northernmost band of low terrain.

Conclusions: (1) Chaos are concentrated in low-lying areas where very high pressures caused by groundwater recharge in higher terrain could have accumulated in confined aquifers beneath the cryosphere. (2) Over 90% of the chaos by area lie at the eastern mouths of the VM canyons, linked to discharges that formed Simud, Tiu, and Ares Valles. (3) Chaos formed in zones where confined aquifer pressures could exceed lithostatic loads (i.e., in upper crust at depths of ≤3.5 km). (4) Evidence points to fault-related subsidence as the main cause of "lost" volume at Pyrrhae Chaos. (5) Pressure ratios reveal one reason why Mars, with its thick cryosphere, has chaos and Earth does not.

References: [1] Tanaka, K. et al. (2014), *USGS Sci. Invest. Map 3292*. [2] Coleman, N. (2005) *JGR Planets* 110, https://doi.org/10.1029/2005JE002419. [3] Coleman, N. (2015) *Geomorphology* 236, 90-108. [4] Gridview (2018) https://denali.gsfc.nasa.gov/gridview/.