**THE HONEYCOMB TERRAIN ON THE HELLAS BASIN FLOOR, MARS: ARGUMENTS FOR SALT OR ICE DIAPIR SCENARIOS**

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**Introduction:** The so called "honeycomb" terrain (HC) is an enigmatic and unique landscape of up to ~14 km long, mostly ellipse-shaped depressions that are arranged in a regular, dense pattern [e.g., 1]. The HC is located on the northwestern Hellas basin floor (Fig. 1), ~150 km southwest of Badwater crater (lowest point on Mars) and occupies elevations between -7,000 and -7,500 m. A wide variety of interpretations of the HC, all with drastically different geologic and climatic implications, have been brought forward: iceberg imprints [2], igneous diapirs [3], salt diapirs [3,4], fossilized impact melt convection cells [4], and ice diapirs [5]. Independently from any possible associations between the HC and the adjacent "banded" terrain, we evaluate these five models plus a thermokarst scenario. We offer arguments for an interpretation of the HC as the surface expression of a canopy of either salt or ice diapirs.

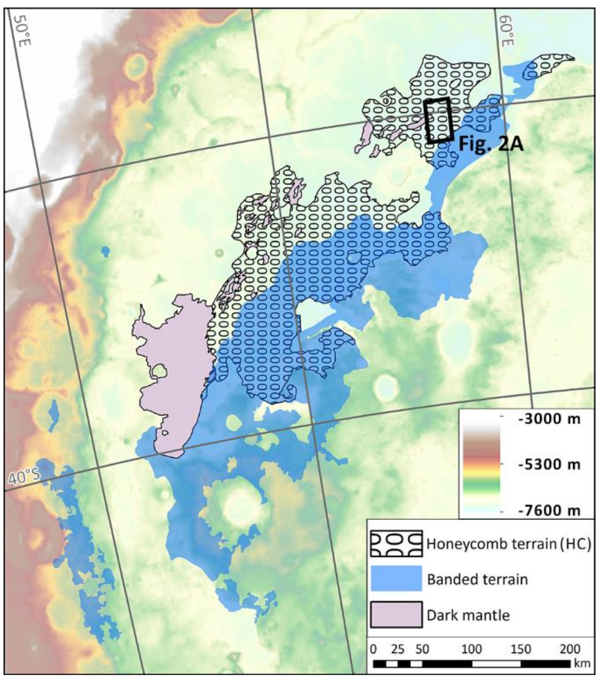


**Figure 1:** MOLA DEM showing the northwestern part of the Hellas basin (derived from the map by [1]).

**Data and methods:** The extent of the HC, as well as its geologic and stratigraphic context (including the partially superposing banded terrain) are based on a recently published photogeological map of the entire Hellas basin floor [1]. Additionally, we used Mars Orbiter Laser Altimeter (MOLA) data and created Context Imager (CTX)-based digital elevation models (DEM) to analyze the HC in detail. We then studied potential terrestrial analogs using Landsat 7 and 8 TerraColor mosaics, GeoEye-1 images, as well as DEMs by the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) and the U.S. coastal relief model (CRM).

**Observations**: The HC has an area of ~36,000 km$^2$ (Fig. 1) and is formed by a mostly regular and dense assemblage of cell-like depressions, which never occur individually (Fig. 2A). The depressions are mostly elliptical, up to ~170 m deep, ~14 km long, and ~6 km wide. Overall, cell diameters do not deviate more than ± ~30% from the average of ~10.5 x 4 km. In the eastern half of the unit, the honeycombs are morphologically well pronounced and their habitus is comparatively symmetrical, whereas in the west, coverage by dark mantling material, as well as banded terrain is more prevalent. Cells are separated by up to 10s of meters high and ~300 m to ~3 km wide ridges. They are often divided into subparallel, only 10s of meters wide, self-similar subridges, while other cell rim parts are covered by dark mantling material that sometimes transitions into <2 km wide, inverted polygons.

**Discussion:** *Iceberg imprints.* Terrestrial grounding structures left by icebergs can be up to ~1 km wide and ~30 m deep keel scours as well as decameter-scale, irregular "wallow craters" imprinted during jökulhlaups [e.g., 6-8]. There are no known terrestrial examples of massive, stationary icebergs floating on a gradually disappearing lake and slowly subsiding into a soft substrate as it was suggested for the HC [2]. A similar scenario is the formation of few 100s of meters wide "till rings" formed by subsiding dead-ice blocks resting on wet sediments [9]. Assuming typically dense (~2 g/cm$^3$) wet sediments, ~170 deep honeycombs would thus imply ~340 m thick dead-ice blocks (subsidence until isostatic equilibrium). However, compared to the honeycomb terrain, all the considered terrestrial ice-imprint structures are 1) almost two orders of magnitude smaller, 2) usually irregularly shaped, 3) do not form continuously dense, regular arrangements of more than ~1 km$^2$, and 4) display a large variation in size within a given occurrence (usually more than one order of magnitude).

*Thermokarst depressions.* Clusters of thermokarst depressions occur on Earth and Mars (often referred to as "scallops") [e.g., 8,10,11]. Similar to the HC are their cell-diameters (up to ~15 km), cluster-extents (10s of 1,000s of km$^2$), aligned elliptical shapes, and occurrence in the mid-latitudes of Mars [e.g., 8,10-13]. In contrast to the HC, however, thermokarst holes are 1) always arranged chaotically, sometimes overlapping each other or leaving spaces in excess of their diameters; 2) have diameters varying by two orders of magnitude within a cluster; and 3) are never deeper than few 10s of meters.

*Fossilized impact melt convection cells.* Convection is the most efficient mode of heat dissipation in a superheated impact melt being cooled from above [e.g., 14].

Thus, convection is inevitable until the temperature of a melt surpasses the liquidus [14,15]. Below the liquidus, however, conduction becomes more efficient for dissipating heat, causing laminar upwelling, i.e., convection to cease [14]. While flow patterns can be fossilized during this final phase of solidification, e.g., in some lunar melt pools [16], convection does not take place anymore, and its patterns can therefore not be preserved [e.g., 15].

*Igneous diapirs.* Swarms of large terrestrial igneous diapirs (or "batholiths") are likely formed by Archean back-arc volcanism [e.g.,17]. They can form mostly granitic, dense canopies which can result in roughly HC-like curvilinear, cell-like surface patterns, albeit without strong topographic surface expressions [e.g., 18]. In certain cases, batholiths can also result in ~10-100 km wide ridge-bound basins via thermal subsidence and/or more erosion-resistant surrounding contact aureoles [e.g., 19,20]. However, on Earth such basins only occur relatively isolated and never form regularly spaced assemblages [e.g., 20]. Furthermore, absent back-arc volcanism, the formation of a large batholith swarm on Mars remains a poorly-founded concept.

*Ice diapirism.* Upwelling of subsurface ice bodies does not occur on Earth, but has been suggested for Mars, Triton, and Europa [21-23]. Assuming 1) a surface temperature of 220 K, 2) an above-average geothermal gradient in the thinner crust of the Hellas basin floor (50 K $km^{-1}$) [24,25], and 3) taking into account the high thermal conductivity of ice-saturated soils [25], water ice could be stable down to ~2 km. As its density is only half that of rock salt, an only ~1 km thick ice layer (see following section on salt diapirism), i.e., ~36,000 $km^3$, would be sufficient to form the cells of the HC.

*Salt diapirism.* Upwelling of salts is a well-studied phenomenon on Earth and has also been proposed for certain locations on Mars [e.g., 26-29]. Terrestrial salt diapirs can form canopies resulting in vast assemblages (in excess of 200,000 $km^2$), e.g., on the Sigsbee nappe in the Gulf of Mexico [e.g., 26]. Here, ~10-25 km wide and ~50-600 m deep salt withdrawal basins form a dense, regular pattern strongly resembling the HC (Fig. 2B). The amount of salt required to form such a canopy, however, has been the main argument against interpreting the HC as salt diapirs [3,4]. The most effective wavelength of overturn (i.e., the average honeycomb short-axis of 4 km) in an inverted-density setting is ~2.6 times the overburden thickness [30] (most of which has likely been eroded). As the density ratio between salt and materials like basalt or sandstone is ~0.75-1, both the salt layer and the overburden should each have been ~1.5-2.5 km thick (implying a mean salt volume of ~72,000 $km^3$). Such an amount of salt is contained in ~5.2 x $10^{17}$ liters of salt-saturated brine (~0.1% the water evaporated for the Zechstein formation [28,30,31]), which would take ~2 Ma to evaporate if simply assuming terrestrial arctic evaporation rates [32]. The circum-Hellas highlands are rich in chlorides [33,34] and the source of numerous channels leading into the Hellas basin (whose stratigraphy-based age of >3.8 Ga might be congruent with that of the HC) [1]. We therefore suggest a scenario of recurring, salt-rich (melt-)water influx sequentially depositing evaporites in the basin and thus potentially enabling the formation of the HC.

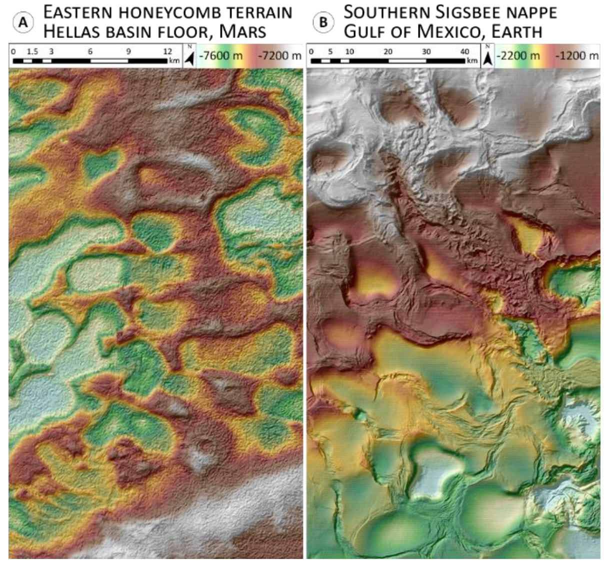


**Figure 2:** A) CTX DEM of a portion of the eastern honeycomb terrain (location shown in Fig. 1). B) CRM DEM of the southern Sigsbee nappe showing the basin-ridge assemblage formed by salt withdrawal basins.

**Conclusions:** Based on our findings, we favor diapirism, either of salt or ice, as formation process for the HC. We propose the withdrawal basin assemblage formed by a salt canopy on the Sigsbee nappe in the Gulf of Mexico as the closest morphological analog to the HC on Earth. We also conclude that it is feasible to provide the required amounts of salt (~72,000 $km^3$) assuming recurring evaporation sequences as they occurred on Earth. Ice diapirism might be an alternative and would just require ~36,000 $km^3$ of buried water ice. However, it would then remain an open question as to why we can identify only one single ice diapir canopy on Mars.

**References**: [1] Bernhardt et al. (2016) *Icarus* 264; [2] Moore and Wilhelms (2001) *Icarus* 154; [3] Mangold and Allemand (2003) *Int. Conf. Mars#3047*; [4] Kite et al., (2009) *LPSC#1249*; [5] Diot et al. (2016) *JGR* in print; [6] Syvitski, et al. (1983) *Geosci. Canada* 10; [7] Allen (1982) ISBN: 978-0-444-41935-4; [8] Benn and Evans (2010) ISBN: 0340905794; [9] Eyles et al. (1999) *Sed. Geol.* 123; [10] Lefort et al. (2010) *Icarus* 205; [11] Zanetti et al. (2010) *Icarus* 206; [12] Grosse et al. (2013) ISBN: 9780123747396; [13] Ulrich et al. (2010) *JGR* 115; [14] Worster et al. (1990) *EPSL* 101; [15] Zieg and Marsh (2005) *GSA* 117; [16] Bray et al. (2010) *GRL* 37; [17] Kusky (1998) *Geology* 26; [18] Ramsay (1989) *JSG* 11; [19] Hickman (1983) ISBN: 0724487921; [20] Blight et al. (1996) map sheet SF 50-1; [21] Brand et al., (2008) *LPSC#1641*; [22] Schenk and Jackson (1993) *Geology* 21; [23] Rathbun et al., (1998) *GRL* 25; [24] Zuber (2001) *Nature* 412; [25] Hoffman (2001) *Int. Conf. Mars#6008*; [26] Lehner, 1969 *AAPG* 12; [27] Jackson et al., 1990 ISBN: 0-8137-1177-0; [28] van Gent et al. (2011) *JSG* 33; [29] Pozzobon et al. (2015) *LPSC#2142*; [30] Turcotte and Schubert (2002) ISBN: 9780521186230; [31] Taylor (1998) doi: 10.1002/9781444313413.ch6; [32] Babkin (2009) ISBN: 978-1-84826-475-5; [33] Osterloo et al. (2008) *Science* 319; [34] Jensen and Glotch (2011) *JGR* 12