
Introduction: The “honeycomb” terrain is a Noachian-aged cluster of ~7 km wide linear cell-like depressions located on the northwestern floor of Hellas basin, Mars [1] (Fig. 1). A variety of origins have been proposed for the honeycomb terrain, including deformation rings of subglacial sediment [2], frozen convection cells from a Hellas impact melt sheet [3], a swarm of igneous batholiths [4], salt diapirism [1], and ice diapirism [1, 5].

Recent work has shown that the salt or ice diapirism scenarios (Fig. 2) appear to be most consistent with the morphology and morphometry of the honeycomb terrain [1]. The salt diapirism hypothesis requires a climate with either temporary or prolonged warm conditions and large volumes of saline water to flow into Hellas and then evaporate or freeze. The ice diapirism scenario, on the other hand, requires either a predominantly cold climate with intermittent warming periods to produce liquid water in Hellas (which would later freeze), or alternatively, a cold climate with a source of glacial ice to be buried and eventually form the diapirs. The salt and ice diapirism scenarios have different implications for the ancient martian climate and hydrological cycle, and so distinguishing between the two scenarios is critical.

Testing salt and ice diapirism scenarios: In this study, we specifically test whether the honeycomb terrain is consistent with a salt or ice diapir origin. Diapirism requires a density inversion, i.e., that a sufficient thickness of salt or ice is present beneath an overburden layer with a greater density (Fig. 2). This configuration is gravitationally unstable, and the density contrast between these two layers acts as a driving force for upwelling of the less dense diapir-forming layer (Fig. 2). The thickness of the salt/ice and overburden determines the resulting (and observable; Fig. 1C and 2) wavelength of the diapirs [6]. Because the melting temperature of salt/ice is reached at some depth below the martian surface due to the geothermal gradient, the depth of stability of salt/ice offers a constraint on the thickness of a diapir-forming layer. Therefore, assessing the depth of thermal stability of salt/ice in concert with analytic models for diapir wavelength offers a way to test whether salt and ice diapirism are viable mechanisms to produce the honeycomb terrain.

Thermal constraints: We use thermal modeling to assess the stability limits on the thickness of an ice or salt diapir-forming layer at depth within the Hellas basin. This offers a constraint on the maximum thickness of salt/ice and the overburden which allows diapirism to occur.

Diapir wavelength constraints: We also apply analytical models for diapir formation [6] to evaluate the predicted diapir wavelengths in order to compare with observations (Fig. 1C). By evaluating the parameter range in which salt/ice diapirism is predicted to produce the observed diapir wavelength and initiate diapirism, we can evaluate the viability of the diapirism scenario.

We evaluate the case of halite, gypsum, and kieserite salt diapirism, in addition to ice diapirism for a range of surface temperatures predicted for Hellas in the Late Noachian [7]. We also evaluate sedimentary and basaltic compositions for the overburden. Details of these models can be found in [6, 8].

Figure 1. The honeycomb terrain is located in Hellas (A), and is composed of a cell-like depressions (B, C) that are morphologically similar to salt diapir terrains on Earth (D, E).

Figure 2. Schematic diagram showing the geometry of diapirism and the thermal/diapir wavelength model configuration and variables [1].
Figure 3. Model results showing the diapir-forming layer thickness as a function of overburden thickness for surface temperatures of 200 K (left panels), 225 K (middle panels), and 250 K (right panels). Permissible regions of ice diapirism are shown in shaded black/dotted regions, gypsum diapirism in red, halite diapirism in blue cross-hatched region, and kieserite diapirism in zigzag region. Top panels: sediment overburden models. Bottom panels: basaltic overburden models. Textured/colored regions show the zones in which diapirism is predicted to (1) produce the correct wavelength, (2) allow the diapir-forming layers to be thermally stable in the subsurface (3) and allow diapirism to initiate.

**Model results:** Ice diapirism is generally predicted to reproduce the observed honeycomb wavelengths for ~100 m to ~1 km thick ice deposits (Fig. 3). Gypsum and kieserite diapirism are generally predicted to reproduce the observed honeycomb wavelengths for ~0.6-3 km thick salt deposits, but only with a basaltic overburden. Halite diapirism generally requires ~1-3 km thick halite deposits in order to reproduce the observed honeycomb wavelengths (Fig. 3).

**How much water is required to form the honeycomb terrain?:** Because water must fill an equipotential surface to at least the elevation of the honeycomb terrain in order to deposit salt, the elevation of the honeycomb terrain and model results offer a constraint on the total volume of water required if the salt or ice deposits are remnant from a standing body of water in Hellas. We find that an equipotential surface -6300 m below the datum represents the minimum water level required to deposit salt across the entire area of the honeycomb terrain (Fig. 4). Adopting the salt thickness range derived from our models (~1-3 km) and salt contents of 3.5-20 wt% salt, yields a cumulative water volume of 119-2045 m global equivalent layer (GEL) required to deposit sufficient salt to form the honeycomb terrain. If deposited solely through groundwater inflow from a vertically integrated hydrologic system, this would require the entire volume of pore space within the martian crust to cycle through Hellas basin approximately two times. For comparison, an ice diapir layer between 100 m and 1 km thick would require 0.29-2.4 m GEL water.

**Implications for the early martian climate:** The plausibility of an ice diapir mechanism is dependant up-on the climate, and generally requires temperatures ≤250 K within Hellas in order to reproduce the observed diapir wavelength. Conversely, the viability of the salt diapir mechanism requires sufficiently thick evaporite deposits to accumulate in Hellas (~1-3 km). On the basis of our analysis, we conclude that ice diapirism is more likely due to the thin deposits (~0.1-1 km) and low water volumes required (0.3-24 m GEL), and the potential for either glacial deposits or a frozen ocean to supply the necessary ice. Salt diapirism requires thick evaporite deposits and much higher water volumes than formed the valley networks [9], and thus appears less likely.