TESTS OF AN ENDOGENIC ORIGIN FOR MORDOR MACULA ON CHARON.

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Introduction: Pluto's moon Charon was revealed alongside Pluto from the New Horizons 2015 flyby to be a world which experienced varied geologic processes in its past that are well preserved due to a lack of current geologic processes that would erode ancient features away [1]. One preserved geologic process can be observed in Charon's southern hemisphere as the smooth geologic unit termed Vulcan Planitia, which is thought to be a cryovolcanic flow [1]. This cryovolcanism is thought to be the result of Charon's subsurface ocean freezing around 4 Ga [1].

Mordor Macula is a region of irradiated methane products at Charon's north pole. Previous research [2] has proposed the methane that sources Mordor Macula is exogenic – captured from Pluto's escaping atmosphere. Here, we instead test the hypothesis that Mordor Macula sourced its methane through the cryovolcanic eruptions that created Vulcan Planitia in Charon's southern hemisphere.

Previously, we found that Vulcan Planitia likely contained a sufficient amount of methane to source Mordor Macula [3], and through volatile transport modelling showed that sufficient amounts of methane would be transported to the pole and become cold-trapped. Figure 1 below presents the proposed scenario of the endogenic hypothesis.

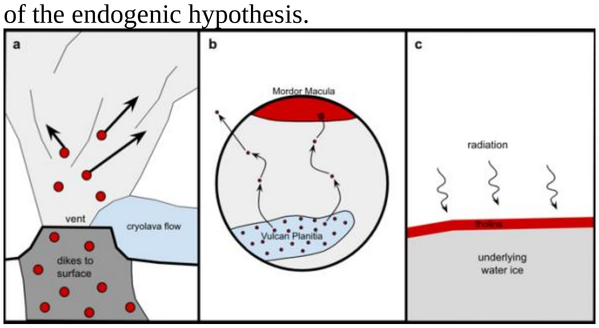

Figure 1. *Diagram demonstrating the proposed scenario of the formation of Mordor Macula. In panel* ***a****, the Vulcan Planitia cryoflow erupts onto the surface and degasses methane contained within the flow. Each methane particle migrates with random initial velocities and trajectories.* ***b****, methane ballistically 'hops' across Charon's surface until either reaches Charon's poles and is cold-trapped or escapes to space.* ***c****, radiation processes the trapped methane into tholins over geologically long time scales.*

We found through a combination of geologic analysis and modelling that Vulcan Planitia contains around 2.38×10^{15} kg methane. Using a volatile transport model, we found that the vast majority (~95%) of this methane would migrate to a polar region within a Charon year, and that around 9 total meters of methane ice would accumulate at each of Charon's poles cumulatively over Charon's history. Therefore, the Vulcan Planitia cryovolcanic eruption is a potential candidate source of methane for the Mordor Macula region.

Here, we conduct further tests of the feasibility of a cryovolcanic origin of Mordor Macula. We considered constraints on the age of Mordor Macula from crater size-frequency distributions, the degassing efficiency of methane from an ammonia-water cryoflow, and the effects geothermal heat might have on volatile stability.

Geologic Observations: Some craters within the Mordor Macula region appear to completely punch through the tholin layer and expose the underlying water ice. Vulcan Planitia and Mordor Macula, if emplaced simultaneously, should share similar crater densities. Differently from previous work, we assume Mordor Macula was sourced endogenically and thus only craters which have excavated water ice material with no irradiated methane products layered on top of the crater should be considered in the crater density evaluation. Geologic analysis reveals that of the 66 craters above 60 degrees latitude, 16 appear to be have exposed the water ice underneath the thin tholin layer and meet the specified criteria. Figure 2 pictured below showcases all 16 identified craters used in this analysis within the Mordor Macula region.

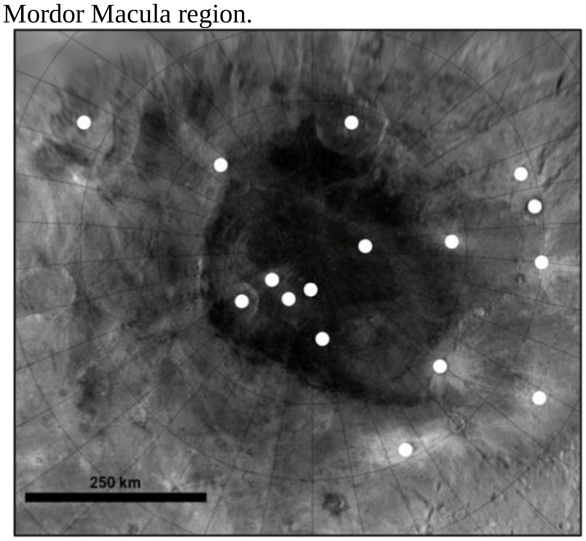

Figure 2. *Polar projection of Charon's north pole including Mordor Macula in a New Horizons image mosaic. White circles denote identified craters that have*

punched through Mordor Macula's thin tholin layer at the surface to expose the underlying bright water ice.

We then determined the crater density of these young, water ice excavating craters within the polar region. Results from the crater density analysis are shown in Table 1. For craters 20 km in diameter and greater, our calculations reveal densities similar to the densities found from previous work [4] in Vulcan Planitia within uncertainty. For craters 5 km in diameter and greater, the density of craters that excavate through Mordor Macula is significantly lower than the density of the same sized craters in Vulcan Planitia. However, there is very likely observational bias involving image resolution and incidence angle [4] that hinders our ability to analyze craters at the ~5 km scale in Mordor Macula. Therefore, we interpret our calculations to show that the age of Mordor Macula's tholins and the age of Vulcan Planitia cannot be confidently stated to be different with statistical significance.

Region	N(5) km^{-2}	N(10) km^{-2}	N(20) km^{-2}	N(30) km^{-2}	N(50) km^{-2}
Mordor Macula	6.61×10^{-5}	4.13×10^{-5}	2.06×10^{-5}	1.24×10^{-5}	8.26×10^{-6}

Table 1. *Calculated crater densities solely for the craters which have punched through Mordor Macula's tholin layer, for craters greater than 5, 10, 20, 30, and 50 km in diameter.*

Cryovolcanic Degassing: Creation of an ammonia-water cryoflow results from preferential freezing of water ice in a liquid water ocean [1], which increases the overall saturation of water with ammonia. Similarly, this freezing process of Charon's subsurface ocean would allow for methane and other volatiles to become more concentrated and reach much closer to the saturation point. Methane solubility in water under pressures around 300 bars is 5×10^{-3} mole fraction [5].

Methane solubility in water decreases exponentially with decreasing pressure [5,6]. This decrease in solubility will aid in allowing methane in solution within a cryoflow to degas and release the majority of its methane to a body's surface. Previous experimental work [6] measured methane solubility under increasing pressure conditions. Based on these studies, we calculate that as the Vulcan Planitia cryoflow erupts onto the surface, the solubility of methane in the flow would decrease to $<3 \times 10^{-4}$ from depressurization, allowing for methane to degas efficiently from the cryoflow onto Charon's surface.

Effects of Geothermal Heat: As surface temperature decreases due to lower received solar insolation, the geothermal heat flux of a body has a greater effect on its surface temperature. We used a geothermal heat flux of 3 mW m^{-2} when determining Charon's surface temperature through our thermal model. To ensure maximum accuracy, we tested endmember geothermal heat fluxes of 0 mW m^{-2} and 10 mW m^{-2}. We found that at Charon's higher temperatures (i.e., ~60 K) near the equator and during Charon summers, changes in the geothermal heat flux only minorly effect surface temperature, usually less than 1 K. In colder regions (i.e., Charon's poles during winter) geothermal heat flux does effect surface temperature, but by no more than 2–3 K. Charon's poles in winter remain well below the cold-trapping temperature for methane (~35 K) even with this uncertainty. Therefore, we conclude that uncertainty in Charon's geothermal heat flux will not alter the conclusions of our volatile transport modelling.

Conclusions: We find through the additional analysis of crater densities of Mordor Macula and through determining the solubility and thus degassing of methane in ammonia-water cryomagma during depressurization, our hypothesis of Mordor Macula sourced from the cryovolcanic eruption resulting in Vulcan Planitia is viable. Crater density analysis reveals that Mordor Macula and Vulcan Planitia cannot be determined to have a different age with statistical significance, implying they could have been emplaced on Charon's surface around the same time. These results do not imply that an exogenic origin [2] of Mordor Macula is implausible, but do show that exogenic methane would have to accumulate sufficiently slowly to not replenish the tholin layer over craters that have exposed underlying water ice. A hybrid origin, where Mordor Macula sourced methane from both cryovolcanism and Pluto's atmosphere, is also possible. Observations of other Kuiper Belt Objects (KBOs) similar to Charon in size but that do not orbit a Pluto-like body reveal irradiated methane products on their surfaces [7], so cryovolcanism as an endogenic mechanism to source volatiles to the surface of KBOs could be a common process on bodies within the Kuiper Belt.

References: [1] Moore et al. (2016), *Science* 351, 1284–1293. [2] Grundy et al. (2016), *Nature* 539, 65–68. [3] Menten et al. (2021), *LPSC LII*, Abstract #1047. [4] Robbins et al. (2017), *Icarus* 287, 187–206. [5] Lunine and Stevenson (1985), *The Astrophysical Journal* 58, 493–531. [6] Culberson (1951), *Petrol. Trans.* 192, 223–336. [7] Brown et al. (2015), *The Astronomical Journal* 149, 105.