CRYOVOLCANICALLY SOURCED METHANE ON CHARON. S. M. Menten[1] (smenten@purdue.edu), A. M. Bramson[1], M. M. Sori[1], [1]Purdue University, West Lafayette, IN

Introduction: Cryovolcanism is a process occurring on icy solar system bodies that is not fully understood but is a potentially important process in a planetary body's geological evolution. Charon, Pluto's largest moon, exhibits possible evidence of cryovolcanism. Charon's best observed hemisphere appears to have been geologically active until about 4 Ga. There are two main geologic units identified on the observed hemisphere of Charon, Oz Terra and Vulcan Planitia (Figure 1). Oz Terra is an older unit thought to contain pieces of the original surface of Charon. Oz Terra includes Mordor Macula, a red polar region thought to have been created through the migration and processing of methane. Vulcan Planitia, an area of smooth plains in the south, is likely a younger unit that may have resulted from cryovolcanic activity [1,2].

Vulcan Planitia could have formed during a freezing episode of Charon's subsurface ocean. One proposed idea is that this subsurface ocean underwent fractional differentiation, creating a viscous, ammonia-rich fluid that resurfaced the Planitia as a cryoflow, which has an estimated surface area of 480,000 km^2 [2]. Previous research has theorized that the red polar region of Charon, Mordor Macula, was formed exogenically [3]. Grundy et al. (2016) hypothesized that Mordor Macula formed by the accumulation and processing of molecules escaping from Pluto's atmosphere [3]. Here, we propose endogenic sources originating from the emplacement of Vulcan Planitia for the formation of Mordor Macula. We hypothesize that Mordor Macula was formed endogenically through the migration and processing of volatiles sourced from the cryolava flows forming Vulcan Planitia. To test this idea, we estimate the volume of Vulcan Planitia and the amount of methane it released to determine if it was sufficient to create Mordor Macula.

Methods: We constrained Vulcan Planitia's thickness using four different geologic features: craters, montes, troughs, and grooves (Figure 1). We conducted an analysis of all craters on Vulcan Planitia to determine if any pre-existing craters might be infilled with cryolava flows using imagery and topography data from the New Horizons' Long-Range Reconnaissance Orbiter (LORRI) [4]. Charon contains a total of 306 craters visible on the encounter hemisphere [5]. Craters that demonstrated evidence of a cryolava flow were used to topographically constrain the thickness of the Vulcan Planitia unit at that location. Mons and troughs were topographically used to constrain thickness by looking at trough depth surrounding the mons features. Tectonic grooves (narrow fracture channels) on the surface of Vulcan Planitia were used to constrain thickness by examining their depth compared to Vulcan Planitia's surrounding surface height. These features may have originated as fractures resulting from Vulcan Planitia freezing. All techniques included consideration of uncertainty in the topography dataset [4], and we only considered cases where calculated thicknesses were greater than uncertainty. After thickness was constrained, the total volume of Vulcan Planitia was estimated using the thickness measurements and the surface area. This volume estimate is a minimum constraint on the unit's volume on Charon due to uncertainties of the three techniques used and the fact that other similar units may exist on parts of Charon that were observed with lower resolution. The volume estimate of Vulcan Planitia was used to calculate the total molecules of methane released per unit of cryovolcanism during the eruption of this cryoflow assuming it is an ammonia-water mixture [6] with 0.5% methane [7].

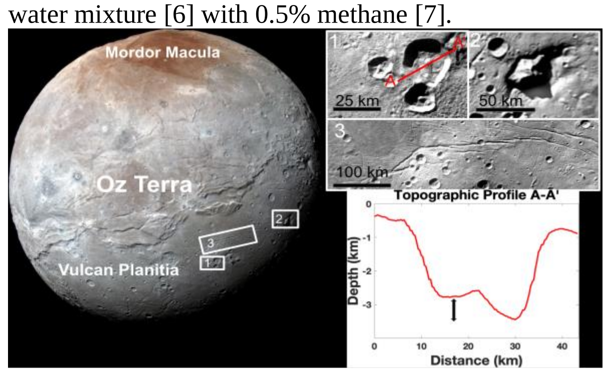

Figure 1. *Examples of the four geologic features used to constrain the thickness of Vulcan Planitia, along with labelled images of the two main geologic units on Vulcan Planitia. Box 1 is an example of a crater with possible cryoflow infill shown by the A-A' cross section. Thickness was estimated by finding the difference between the top of the flow and presumed depth of the underlying floor (represented by the double-headed arrow). Box 2 shows a mons feature surrounded by troughs. Box 3 shows the grooves that are found across Vulcan Planitia's surface.*

Results: We found 8 craters with possible evidence of infilled cryolava flows. Vulcan Planitia thickness from crater estimates ranged from a few hundred meters to a kilometer. Figure 1 showcases a topographic profile of a crater in Vulcan Planitia containing a possible cryoflow. The thickness estimates from two mons features along with four troughs were much larger than crater estimates, ranging from a kilometer to two kilometers in thickness. Tectonic grooves examined showed similar thickness values to the crater analysis, with no thickness estimates larger than a few hundred meters. Interpolation of all these thickness constraints resulted in an average thickness for Vulcan Planitia of just over a kilometer. Figure 2 shows the interpolated thickness map of Vulcan Planitia.

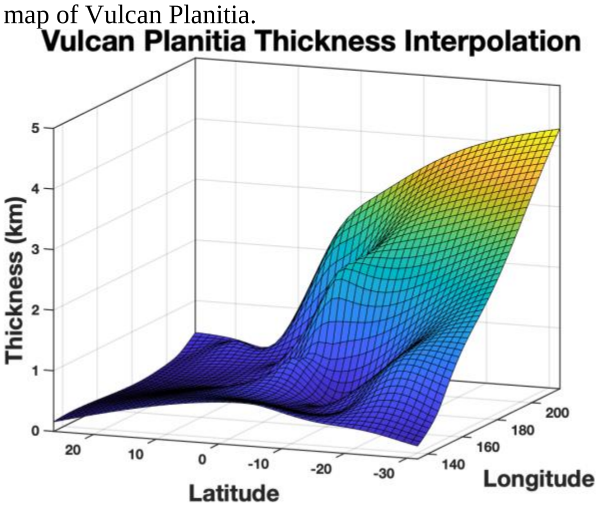

Figure 2. *A thickness interpolation plot of all thickness points acquired from Vulcan Planitia. Vulcan Planitia ranges in thickness from a few hundred meters to almost 4 kilometers.*

Average thickness found from the interpolation of all data points was used to calculate volume, methane content, and methane release rate resulting from the emplacement of Vulcan Planitia. Table 1 showcases three different volume scenarios of Vulcan Planitia. "All Data Points" uses every thickness value calculated and is our nominal value of Vulcan Planitia's volume and methane content. "Mons and Trough Only" estimates represent upper limits, and "Craters and Grooves Only" represent lower limits.

Estimated Values	All Data Points	Mons and Trough Only	Craters and Grooves
Volume of Vulcan Planitia (m^3)	5.19e14	7.57e14	2.81e14
Molecules CH_4	8.93e40	1.30e41	4.84e40
Rate of CH_4 Release (molecules/m^2s)	6.45e14	9.42e14	3.50e14

Table 1. *Calculated values from the interpolation plot of Vulcan Planitia's estimated volume, molecules of methane, and rate of methane release assuming that Vulcan Planitia is emplaced over 1 Myr*.

Discussion: Grundy et al. (2016) found that 2.7 × 10^{11} molecules m^{-2} s^{-1} is a sufficient rate of CH_4 arriving at Charon from Pluto necessary to source the material being processed at the north pole to form Mordor Macula [3]. Here, we have considered Vulcan Planitia instead of Pluto's escaping atmosphere as a potential source for the CH_4 necessary to create Mordor Macula. Our nominal estimate of the methane release rate globally averaged over Charon is 6.45 × 10^{14} molecules m^{-2} s^{-1} (which assumes Vulcan Planitia is emplaced over 1 Myr), which is sufficient to make an endogenic source of Mordor Macula through cryovolcanism viable. These rates are comparable to Titan's current rate, whose methane-rich atmosphere also might be sourced from cryovolcanism [8,9].

Even being conservative by using a volume of Vulcan Planitia calculated with craters and grooves constraints only and assuming that Vulcan Planitia is emplaced over 1 Gyr yields a rate of released methane of 3.50 × 10^{11} molecules m^{-2} s^{-1}. This rate compares favorably to Grundy et al.'s and is likely sufficient to provide the source of methane responsible for the creation of Mordor Macula. An important note is that Vulcan Planitia is likely larger than is currently observed due to a lack of resolution from spacecraft data. Therefore, our nominal methane release rate may be a lower limit.

This methane release from the emplacement of Vulcan Planitia could have created a thin, transient atmosphere globally across Charon. Cryovolcanically produced atmospheres on icy bodies are not currently understood. Volcanism is an important source of atmospheres on rocky planets and understanding whether cryovolcanism similarly represents a significant mechanism of interior/surface exchange on icy bodies (such as Europa or Enceladus) will be important in understanding their geological evolution.

Conclusions and Future Work: We find that the amount of methane released from a cryovolcanically emplaced Vulcan Planitia is likely sufficient to represent an endogenic source for Mordor Macula. Our next step is to create thermal and ballistic transport models with the estimated volatile release volume to determine how the methane and other released volatiles from Vulcan Planitia would behave and migrate over geologic timescales. This simulation will track the transport and loss of these volatile molecules over time to determine the likelihood of their migration to the pole.

References: [1] Moore et al. (2016), *Science* 351, 1284–1293. [2] Schenk et al. (2018), *Icarus* 315, 124–145. [3] Grundy et al. (2016), *Nature* 539, 65–68. [4] Beyer et al. (2019), *Icarus* 323, 16–32. [5] Robbins et al. (2019), *JGR: Planets* 124, 155–174. [6] Moore and McKinnon (2021), *Annual Review of Earth and Planet. Sci.*, 49, 173–200. [7] Lorenz (1996), *Icarus* 44, 1021–1028 [8] Lopes et al. (2007), *Icarus* 186, 395–412. [9] Tobie et al. (2006), *Nature* 440, 61–64.

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