

THE CHALLENGE OF OCEAN-SOURCED CRYOVOLCANISM ON CHARON. A. R. Rhoden¹, M. L. Rudolph², and M. Manga, ¹Southwest Research Institute, 1050 Walnut St., Boulder, CO; alyssa@boulder.swri.edu, ²Dept. of Earth and Planetary Sciences, UC Davis, Davis, CA, ³Dept. of Earth and Planetary Science, UC Berkeley, Berkeley, CA.

Introduction: Charon's surface displays canyons (referred to as chasmata), fractures, and smooth deposits that have been interpreted as cryovolcanic flows (e.g., [1]). Charon's cratering record reflects an ancient surface despite being less heavily cratered than ancient surfaces in the inner solar system [2]. Although the dynamical evolution of Pluto and its moons is unresolved, most models indicate that Charon's orbit rapidly circularized and synchronized due to tides [e.g., 3]. The loss of tidal heating after this evolution caused an initial subsurface ocean to freeze out, which would have generated large tensile stresses in the ice shell and pressurized the ocean (e.g., [1][3]). Thus, a freezing ocean has been proposed as the driver for 1) initiating fractures that transit the entire ice shell to provide conduits for ocean water, 2) erupting ocean material onto Charon's surface due to pressure in the ocean, and 3) creating canyons in response to the volumetric expansion of a growing ice shell. Here, we use a numerical toolkit, previously applied to Europa and Enceladus [4], to determine whether a freezing ocean would, in fact, create fractures that penetrate the entire ice shell and the effectiveness of driving surface eruptions via ocean pressurization. Full details of our study are provided in [5].

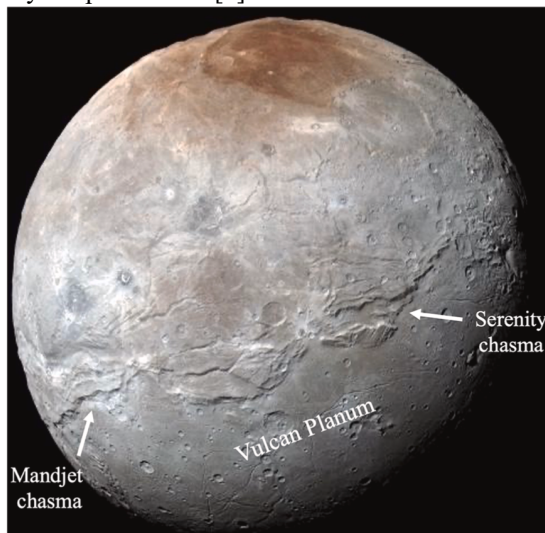


Figure 1: Charon's ancient surface has extensive canyons that have been attributed to the volumetric increase that occurs when a subsurface ocean freezes. Cryovolcanic flows have also been suggested to be ocean-sourced. Here, we investigate whether ocean freezing can form both feature types.

Methodology: We used the numerical model developed for analysis of Europa and Enceladus [4] to track stress and pressure in Charon's ice shell and ocean, determine when and at what depth failure occurs, track crack propagation, and determine the height to which ocean material can be driven through fractures that reach the ocean. We explored a range of ice shell thicknesses, basal ice shell viscosities, and failure strengths, as previous studies have shown that these parameters values exert the largest controls on the fracture and eruptive processes [4][6][7]. Given the potential presence of ammonia in Charon's subsurface ocean, we adapted the code to account for the effects of ammonia on freezing and the density of melt, and we vary the amount of ammonia within the ocean. Parameter values that are kept constant across all simulations are given in Table 1. Varied parameters and their outcomes are listed in Table 2.

Table 1
Parameters held constant across all simulations.

Interior structure & global parameters		
Charon's radius	R	606 km
Silicate interior thickness	r_c	376 km
Hydrosphere thickness	$R-r_c$	230 km
Surface gravity	g	0.279 m/s ²
Ice shell properties		
Temperature at ice shell base (H ₂ O ocean)	T_M	273 K
Young's modulus	E	5×10^9 Pa
Poisson ratio	ν	0.3
Density of ice	ρ_i	900 kg/m ³
Freezing/melting parameters		
Coefficient of linear thermal expansion	α_l	3×10^{-5} K ⁻¹
Compressibility of water	β	4×10^{-10} Pa ⁻¹
Activation energy	Q	40 kJ/mol
Heat capacity of ice	C_p	2100 J kg ⁻¹ K ⁻¹
Latent heat of fusion	L	3.34×10^5 J kg ⁻¹

Results: We find that cracks can only fully penetrate Charon's ice shell if it is thinner than 10 km (Table 2). Once fully cracked, liquid can enter the fracture and flow upward until nearly at the surface. The liquid is not actually extruded onto the surface in this simplified treatment. Deep fractures that do not reach the ocean continue to form throughout ocean freezing. The addition of ammonia does not substantively change our results.

Discussion: Models of Charon's thermal evolution predict a short-lived, thin ocean beneath an ice shell that is ~100 km thick at a minimum (e.g., [1][3]), which is an order of magnitude too thick to enable fractures from cooling stresses to connect the ocean and the surface.

While there is some uncertainty in the magnitude of heat available to warm Charon, this large disparity seems to rule out ocean freezing as a mechanism for enabling ocean-sourced material to reach the surface. Even if through-going cracks could form, and liquid were brought to the surface, an additional process (such as gas expansion and exsolution [8]) would be needed to extrude the material in order to generate surface flows. Given the rapid freezing that occurs after tidal heating is diminished, all activity related to ocean freezing should cease very early in Charon's history, which is consistent with the inferred age of putative cryovolcanic flows [1].

Table 2
Test cases and outcomes.

	Surface temp (K)	Ice viscosity μ_b (Pa-s)	Failure strength (MPa)	Cutoff for conduits (km)
Charon 100% H ₂ O	40	1.00E+13	1	2.9
	60	1.00E+13	1	2.5
	40	1.00E+14	1	3.3
	60	1.00E+14	1	3.0
	40	1.00E+13	3	8.5
	60	1.00E+13	3	7.3
	40	1.00E+14	3	9.3
	60	1.00E+14	3	8.4
	Surface temp (K)	Ice viscosity μ_b (Pa-s)	Failure strength (MPa)	Cutoff for conduits (km)
Charon 90% H ₂ O 10% NH ₃	40	1.00E+13	1	3.0
	60	1.00E+13	1	2.5
	40	1.00E+14	1	3.2
	60	1.00E+14	1	3.0
	40	1.00E+13	3	8.2
	60	1.00E+13	3	6.5
	40	1.00E+14	3	9.1
	60	1.00E+14	3	8.0

Charon's chasmata are more likely candidates for structures that result from ocean freezing and ice shell thickening. If Charon's ice shell had thinned substantially more than models predict, the larger ocean would provide additional volumetric increases as it froze out. In that case, we would expect to see more canyons than have been thus far identified. Hence, the extent of ocean freezing may be further constrained by future observations of Charon.

Interestingly, canyons are observed on only a handful of icy moons (e.g., Tethys), even though many more moons are thought to have had past oceans that froze partially or fully (e.g., Dione, Mimas). The existence of canyons, or lack thereof, may be useful for constraining the extent of ocean freezing within a moon. However, more work is needed to elucidate the connection between radial fractures that form from a freezing ocean and the laterally-expansive canyons we observe.

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output files related to this work can be found at: <https://zenodo.org/record/7336096#.Y3gG3-zMKgk>.

References: [1] Spencer et al., 2021, In: The Pluto System After New Horizons. [2] Singer et al., 2019, Science 363, 955-959. [3] Bagheri et al., 2022, Icarus 376, 114871. [4] Rudolph et al., 2022, GRL 49. [5] Rhoden et al., 2023, Icarus 392, 115391. [6] Rudolph and Manga, 2009, Icarus 199, 536-541. [7] Hemingway et al., 2020, Nat Astro 4, 234-239. [8] Crawford and Stevenson, 1988, Icarus 73, 66-79.