TILTED BLOCKS AS A WINDOW TO THE EVOLUTION OF CHARON.

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Introduction: Although Charon's surface is ~4 Ga old, the youngest terrain is the smooth plains of Vulcan Planitia, which covers much of the encounter hemisphere [1-4]. The plains stand in contrast to the heavily dissected Oz Terra region, which has crustal blocks hundreds of kilometers across bounded by troughs [1-4]. At the margin of these two terrains, there are large chasma and tilted blocks (Fig. 1, 2) [1-4].

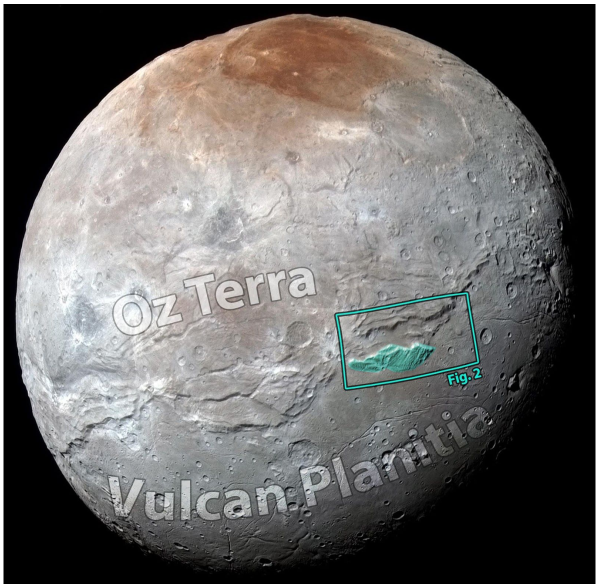

Fig. 1. Charon. Example of tilted block in blue. Modified from: [5].

Tilted crustal blocks may provide the evidence needed to understand how Charon's current surface features formed (Fig. 2). The formation mechanism for the fractured crustal blocks and smooth plains has implications for the interior and orbital evolution of the Pluto-Charon system [3].

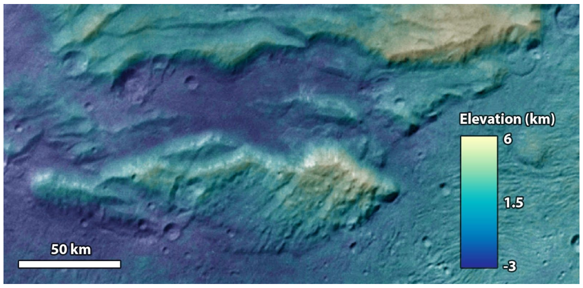

Fig. 2. Titled block near Serenity Chasma. Modified from: [2].

One proposed model for the formation of these blocks is that the fractured brittle crustal blocks foundered in a low density underlying layer [3]. Another model proposes the blocks were tilted before or during the eruption of cryomagma from the depths of a freezing ocean [1, 3].

These formation mechanisms suggest different sources for the plains material. Under the foundered block model, the plains are proposed to be a buoyant near-surface layer, giving us an unprecedented glimpse into the interior of an icy satellite [3]. Under the cryovolcanism model, the plains would be sourced from deep subsurface ocean material with implications for the timescales associated with ocean freezing and the initial chemistry (especially NH_3) of Charon [3]. This could help us understand the bulk chemistry and evolution of Charon as well as trans-Neptunian and Kuiper Belt objects more broadly. Additionally, tilted blocks are found on other icy moons, most notably Ariel [2, 3]; the processes which formed tilt blocks on Charon may be important for shaping the surfaces of a wide range of icy bodies.

We use a combination of numerical and experimental methods to test whether the cryovolcanism model could produce the tilted blocks, explain the age of the smooth plains, and be consistent with the plains morphology observed on Charon.

Methods:

1. Timing of Cryovolcanic Eruption

We use a simplified model to get a first order estimate of the freezing time required for a significant fracture of the ice shell to form. Specifically, we calculate the time needed to achieve maximum stored elastic energy in a Charon-size freezing water sphere [6]. Although this calculation neglects Charon's core, ocean chemistry, and internal heat budget, it nonetheless provides a first order constraint on the plausibility of a freezing ocean to generate Vulcan Planitia and the associated geologic features. This calculation is tested with experimental work [6, 7].

2. Formation of Tilted Blocks

In order to form a tilted block, a discrete crustal block must be formed through fracturing. Therefore, there should be a relationship between fracture density or regional concentration of fractures and the presence of crustal blocks; this may also control the scale of the blocks. Once formed, the block must be tilted. On Charon, tilting likely occurs due to global expansion forces from the freezing of an ocean [3, 8]. There may be a certain degree of expansion, and correspondingly ice shell thickness, needed to tilt crustal blocks to the degree observed on Charon. We test this by freezing spheres of water from the outside in as an analog for a freezing ocean world [7]. As the ice shell grows inward, we can observe the overall evolution of the water spheres as well as their surface features [7].

3. Formation of the Vulcan Planitia Rilles

Vulcan Planitia has many rilles, most near the boundary with Oz Terra; the rilles are thought to be formed in extensional tectonism with ~1.5% areal strain [3]. We model the thermal stresses generated by a cooling layer of cryoflow. An important aspect of this calculation is using an appropriate value for the thermal expansion coefficient of an ammonia-water liquid. Therefore, it is critical to know the composition of the erupted cryo-material [9]. Previous estimates have assumed ~20% ammonia, because ammonia should concentrate in the liquid portion of a freezing ocean [3]. However, such elevated concentrations may not be physically plausible. Thus, we model the concentration of ammonia as it is excluded from a growing ice shell, with a starting concentration of 1% [10, 11]. To give an upper limit, we assume that ammonia is perfectly excluded during the freezing process and use estimates of the core and silicate interior radii from previous studies [12]. Then we follow the procedure from previous studies' calculations of areal strain, calculating the thermal stress generated by cooling a thin layer of cryo-material from 240K to 175K [3].

Results:

1. Timing of Cryovolcanic Eruption

We find a maximum energy timescale of ~0.54 G.a. If we assume Charon began freezing soon after its formation and if the plains are associated with a large fracture caused by the freezing of Charon's ocean, then this timescale would give Vulcan Planitia an age of ~4 Ga. Additionally, we find that the timescale calculation predicts well the large surface disruption which occurs in our experimental analog water spheres [7].

2. Formation of Tilted Blocks

Preliminary experiments show that discrete crustal blocks can form on freezing water spheres and can be tilted (Fig. 3). Preliminary results suggest that these blocks are more likely to form when there is an increased number of fractures and greater global expansion. We find that the block width and height (normalized by sphere radius) are consistent with the range of those on Charon. We also find that the dip of the blocks are consistent with the range of dips measured for blocks on Charon.

3. Formation of the Vulcan Planitia Rilles

For a freezing ocean with an initial ammonia content of 1%, more than 93% of the ocean must freeze in order to achieve ammonia concentrations as high as 20% and strain of ~6.5% [3, 9]. However, large fractures which should erupt cryo-material on the surface should occur much earlier in the freezing process. Assuming an ice thickness consistent with the maximum energy timescale, we find likely ammonia concentrations of ~2% with a corresponding thermal expansion coefficient of ~2 * 10^{-4} K^{-1} [9] and areal strain of ~2.6%.

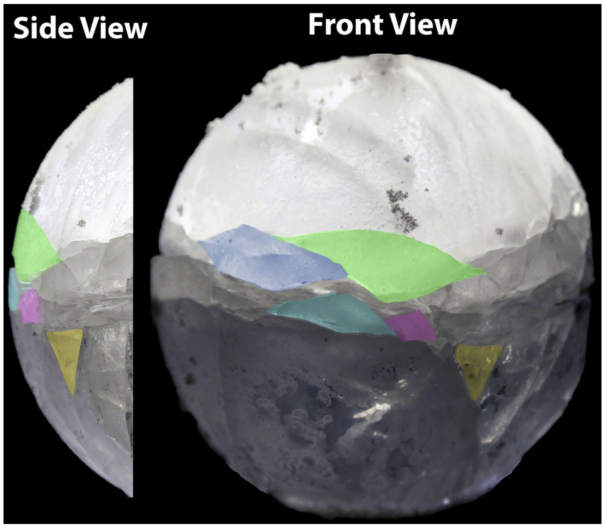

Fig. 3. Example of tilted blocks on an ice sphere (radius: 3.5cm). Some crustal blocks are colored for easy identification in both views. In the side view, blocks are measurably tilted and separated by a chasm.

Discussion and Conclusions:

1. An estimate of time of maximum stored energy based on a freezing timescale agrees with the crater age of Vulcan Planitia [1, 4].
2. Experiments confirm that tilted and non-tilted crustal blocks can be generated on freezing water spheres. More experiments are needed to constrain possible relationships between the formation of tilted blocks and experimental variables such as sphere size, number of fractures, ice shell thickness, and ocean volatile content.
3. Calculations of thermal stresses for an erupted cryoflow are sufficient to generate the observed rilles. We find much more observationally consistent coefficients of thermal expansion than previous work by using a model for ammonia concentration in a freezing ocean.

Future work is needed to test the foundered block model; thus far results show that the cryovolcanism model is plausible when we account for a more realistic freezing process.

References: [1] Robbins et al. (2019) *JGR: Planets*, 124(1). [2] Beyer et al. (2017) *Icarus*, 287. [3] Beyer et al. (2019) *Icarus*, 323. [4] Moore et al. (2016) *Science*, 351(6279). [5] NASA/Johns Hopkins University Applied Physics Laboratory/Southwest Research Institute. [6] Wildeman, et al. (2017) *Phys. Rev. Letters*, 188. [7] Nathan et al. (2019) *LPSC 50*, #1572. [8] Manga & Wang (2007) *GRL*, 34. [9] Croft et al. (1988) *Icarus*, 73(2). [10] Cook et al. (2007) *The Astrophysical Journal*, 663. [11] Holler et al. (2017) *Icarus*, 284. [12] Rhoden et al. (2015) *Icarus*, 246.