Formation Mechanisms of Cryovolcanoes in the Solar System

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I. Problem

Cryovolcanoes are found on moons and other icy bodies in the outer reaches of the solar system. These volcanic edifices generally occur on planetary bodies beyond the "frost line", which is the boundary in the solar system where volatile compounds are solid at the low surface temperatures (McCord, 2005). This line occurs in the asteroid belt between Mars and Jupiter (fig. 1). Various planetary bodies past the frost line are suspected to have had or currently have cryovolcanic eruptions.

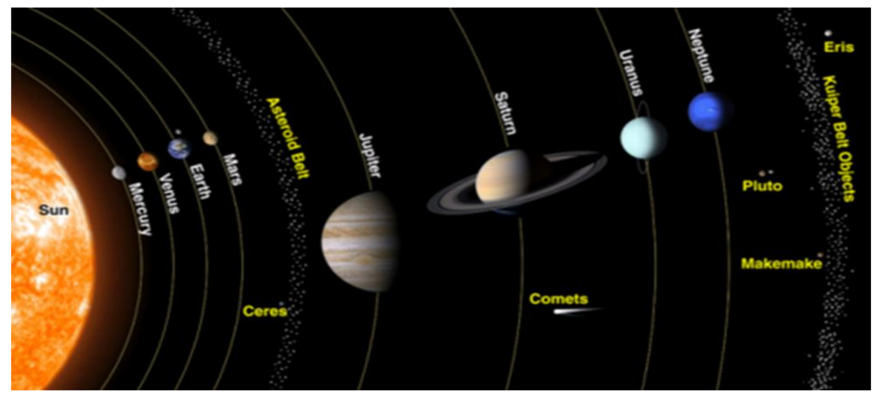


Figure 1: From SolarStory.net

Cryovolcanoes are volcanoes that erupt volatile fluids such as water, nitrogen, and methane rather than the silica-based molten rock that erupts on earth. These volatile fluids solidify on or near the surface due to low surface temperatures (Lopes, 2013).

Cryovolcanoes are thought to be the product of tidal heating- when rotational and orbital energy of the planetary body is dissipated as heat within the interior. This heat melts part of the surface ice, creating a pocket of liquid similar to a magma chamber. This fluid is then vented to the surface.

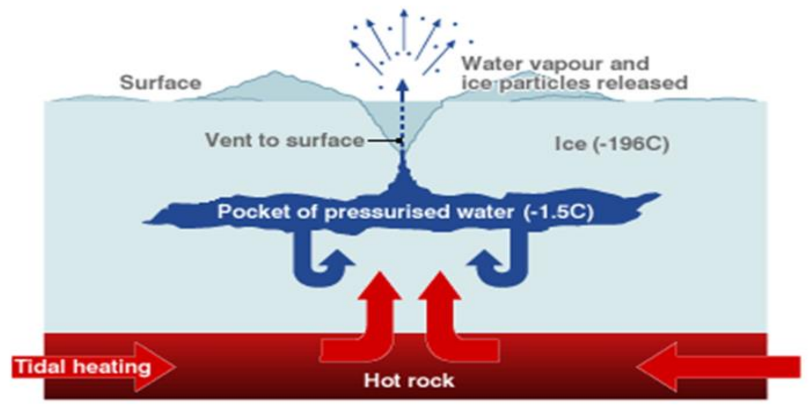


Figure 2: Image from NASA/JPL/SSI.

II. Hypotheses

1. Geomorphic characteristics such as the height/radius ratios of cryovolcanoes will reflect their mechanism of formation.
2. Relationships between geomorphic characteristics and material properties (viscosity, density, etc.) based on Earth volcanoes can be developed and applied to evaluate material properties on cryovolcanoes.

III. Volcano Morphology

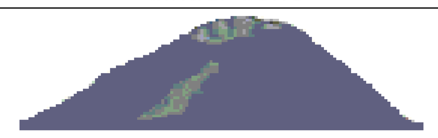
Volcanic Profile	Aspect Ratio	Relative Viscosity
 Shield Volcano	Less than 0.18	Low
 Caldera	Less than 0.18	Low
 Cinder Cone	Median 0.2	High
 Lava Dome	Greater than 0.2	High

Table 1 data received from (Perez-Lopez, 2010), and Google Earth.

IV. Cryomagma Composition

Table II: Properties of candidate cryomagmas (eutectic compositions).

Liquid	Liquid Composition, Mass %	Melting Point, K	Liquid Density,	Viscosity of Liquid, poise	Solid Composition, Mass %	Solid Density,
Water	H_2O 100%	273	1	0.017	Ice 100%	0.917
Brine	H_2O 81.2% $MgSO_4$ 16% Na_2SO_4 2.8%	268	1.19	0.07	Ice 50% $MgSO_4 * 12H_2O$ 44% $Na_2SO_4 * 10H_2O$ 6%	1.13
Ammonia-Water	H_2O 67.4% NH_3 32.6%	176	0.946	40	$NH_3 * 2H_2O$ 97% $NH_3 * H_2O$ 3%	0.962
Ammonia-Water and non-polar gas	H_2O 67% NH_3 33% CH_4 0.1-2%	176	0.94	40	$NH_3 * 2H_2O$ 97% $NH_3 * H_2O$ 3%	0.96
Ammonia-Water-Methanol	H_2O ~47% NH_3 ~23% CH_3OH ~30%	~153	~0.978	~40,000	$NH_3 * H_2O$ ~46% $CH_3OH * H_2O$ ~54%	
Nitrogen-Methane	N_2 86.5% CH_4 13.5%	62	0.783	0.003	$N_2 * CH_4$ 100%	

Data from Kargel (1994).

Table III: Composition and Surface Temperature on Planetary Bodies.

Planetary Body	Composition	Temperature, K	Applicable Eutectoid Composition
Ceres	Water, salts, and mud	160	Water, Brine
Titan	Water and Ammonia	98	Ammonia-Water
Charon	Ammonia hydrates and water	53	Ammonia-Water
Pluto	Nitrogen, water, and methane	46	Nitrogen-Methane

Data received from (McCord, 2006)[Titan], (Ruesch, 2016)[Ceres], and (Desch, 2016)[Pluto and Charon].

When comparing J.S. Kargel's compositions to those derived from spectrometers, we can see that the compositions do not exactly align but it does provide a range of values for density, viscosity, and melting temperatures to use. This experiment additionally provides the opportunity to further refine estimates on edifice composition. When testing models of formation with estimated compositions or even compositions with atmospheric interference we can test if the characteristics of the given compositions can actually result in the topography observed. If the topographic profile cannot result from the given composition it could indicate that current composition estimates are inaccurate.

V. Formation Models

Static Dome Model:

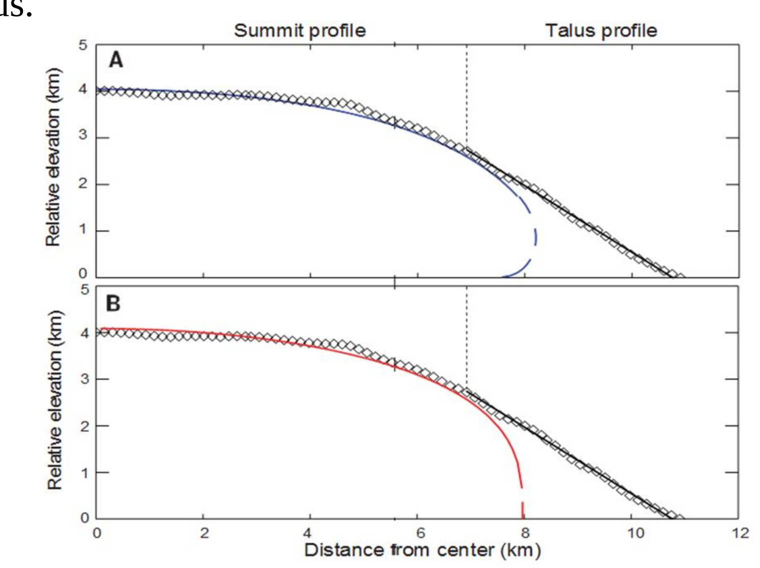
$$D = \frac{1}{h}\sqrt{\frac{\sigma t}{\rho g}}$$

Where h is the pressure head in meters (m) at the apex of the dome. The density, ρ, g is the gravity of the body, the carapace thickness, t, is estimated as a range based on the width of the dome and assuming that it is symmetrical, σ is tensile strength of the carapace.

Dynamic Dome Model:

$$h(r,t) = \frac{4V}{3\pi r_0^2}\frac{1}{(1+\frac{\theta}{t})^{\frac{1}{4}}}\left[1-\frac{r^2}{r_0^2}\frac{1}{(1+\frac{\theta}{t})^{\frac{1}{4}}}\right]$$

The equation gives height, h, and radius, r, as a function of t, time. It incorporates the viscosity increase over time (due to cooling) through the parameter θ. Where V is volume and r_0 is initial radius.

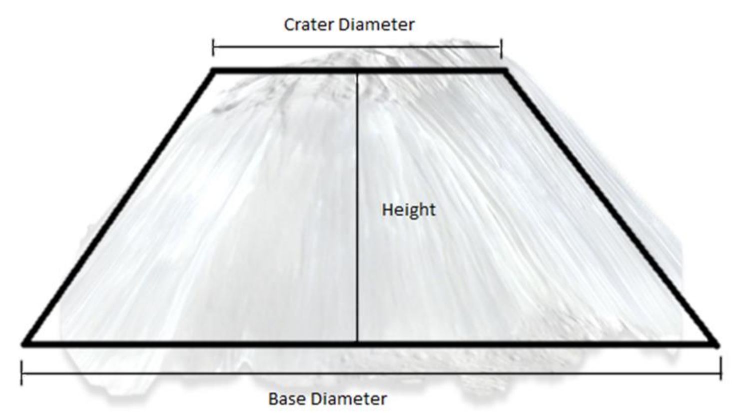


The Dynamic and Static are consistent with the actual profile of Ahuna Mons on Ceres, suggesting behavior consistent with volcanic brittle domes found on Earth (Ruesch, 2016).

Lava Flow models:
Lava will flow when the fluid shear stress ($t = \rho gds$) exceeds
The yield stress of the magma: $t_{eff} = (t - t_{yield})$

Where ρ equals cryomagma density, g is gravitational acceleration, d is flow depth, and S is gradient.

VI. Methods



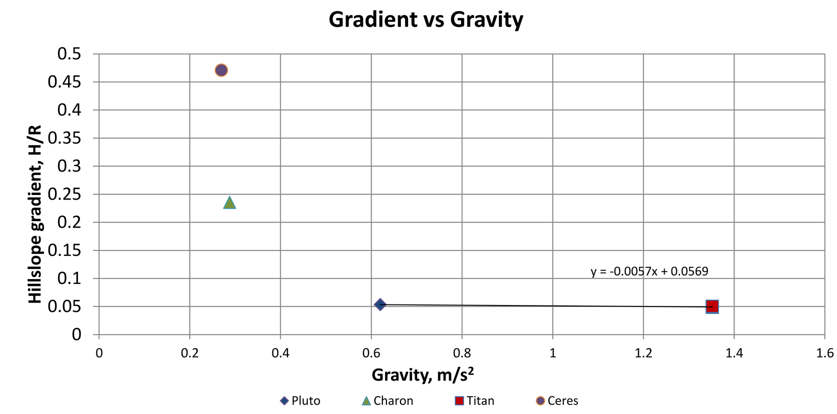
1. Morphological data were compiled from reviewed and referenced data sources which is then analyzed.

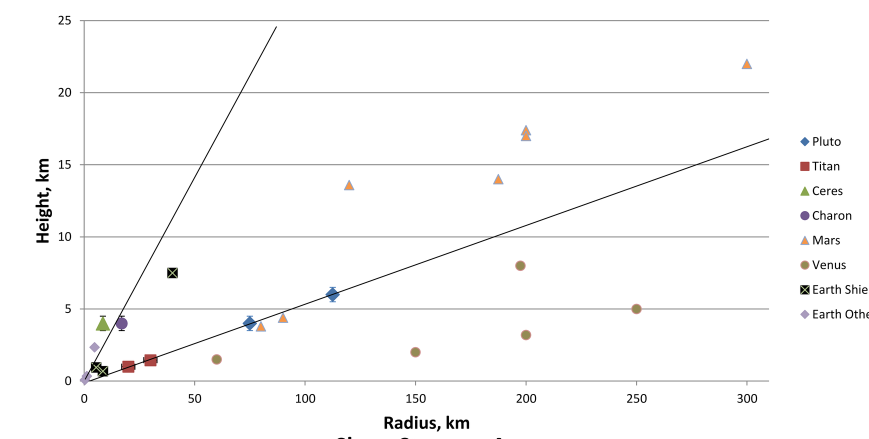
Satellite	Edifice	Radius, km	Height, km	Aspect Ratio	Gravity, m/s^2
Pluto	Wright Mons	75±0.65	4±0.5	0.053	0.62
Pluto	Piccard Mons	112.5±0.65	6±0.5	0.053	0.62
Charon	Kubrick Mons	17±0.4	4±0.5	0.235	0.288
Titan	Doom Mons	30±3	1.45±0.2	0.048	1.352
Titan	Erebor Mons	20±3	1±0.2	0.050	1.352
Ceres	Ahuna Mons	8.5 ± 0.14	4±0.5	0.471	0.27

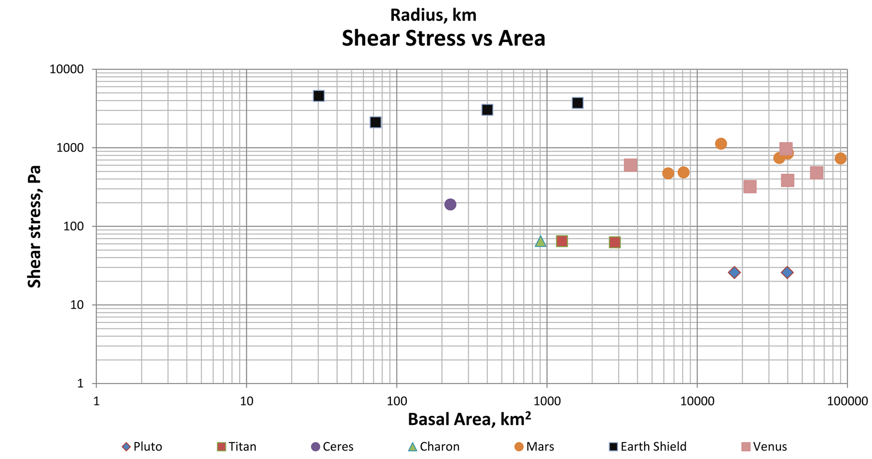
Data from (McCord, 2006)[Titan], (Ruesch, 2016)[Ceres], (Stern, 2015)[Pluto and Charon], (USGS, 2012)[Titan], and (Desch, 2016)[Pluto and Charon].

2. $Flow\ Shear\ Stress = \rho g d S$ was calculated for each site, assuming a flow depth of 10 m (Earth basalt flow average)

VII. Preliminary Results







These graphs shows that in relation to aspect ratio, Pluto and Titan volcanoes fall within the range of shield volcanoes, even when accounting for gravity. Ceres has an aspect ratio consistent with terrestrial domes. Charon has an aspect ratio that can fall within the range of a volcanic dome but also the range of a cinder cone.

Additionally, terrestrial volcanoes have a higher shear stress when assuming constant flow depth.

VIII. Future Work

1. Continue to gather information on Earth volcanoes.
2. Look for more cryovolcanoes with topographic data available (e.g. unnamed cryovolcanoes on Charon) and find a way to possibly include cryovolcanoes without topographic measurements in analysis (i.e. Europa and Triton).
3. Continue to refine definitions of volcano morphologies and their attributing variables.
4. Calculate dimensionless parameter D and graph.
5. Analyze the separation of terrestrial volcanoes and cryovolcanoes in relation to flow depth , shear stress, and yield stress.

IX. Conclusions and Feasibility

Preliminary data suggests that Earth volcanoes can serve as analogs for cryovolcanoes in terms of morphology and possible formation mechanism. Additionally, the differences in shear stress for similar basal areas suggests that Earth flows are significantly impacted by yield stress or that cryovolcanic flows are very thick.

X. References

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