CRYOVOLCANISM ON DWARF PLANETS. M. Neveu[1], S. J. Desch[1], E. L. Shock[1,2], and C. R. Glein[3,4], [1]School of Earth & Space Exploration, Arizona State University, Tempe, AZ 85281, USA. [2]Department of Chemistry and Biochemistry, Arizona State University, Tempe, AZ 85281, USA. [3]Geophysical Laboratory, Carnegie Institution, Washington, DC 20015, USA. [4]Department of Earth Sciences, University of Toronto, Toronto, ON M5S 3B1, Canada. Email: mneveu@asu.edu.

Introduction: Extrusion of cold material from the interior of icy bodies, or cryovolcanism, has been observed on Enceladus and perhaps Triton, Europa, and Ceres. It may explain the seemingly young surface on Pluto's moon Charon. Further evidence may be gathered in 2015 during the visits of Ceres and the Pluto system by the *Dawn* and *New Horizons* spacecrafts, respectively. As observations of cryovolcanic material may provide a unique window into the physics and chemistry of dwarf planet interiors and their potential present or past habitability, understanding the potential for cryovolcanic processes is of major astrobiological interest. Here, we evaluate four prerequisites for cryovolcanism on dwarf planets.

1. Subsurface liquid water: Thermal evolution models of the dwarf planets Charon, Pluto, and Ceres suggest that they should have differentiated into a rocky core and an icy mantle, and possibly retained a liquid water layer for several Gyr [1-5]. Antifreezes, whether primordial volatiles (ammonia, methanol) or salts, enhance the persistence of liquid on Pluto and enable liquid on Charon and Ceres.

2. Fracturing of the ice: Subsurface liquid can communicate with the surface provided cracks develop in the ice shell. A potent fracturing mechanism is the pressurization of liquid reservoirs upon freezing, due to the lower density of water ice I compared to liquid water [6]. Global cooling and freezing is expected on dwarf planets 1-2 Gyr after accretion, as heat loss by conductive and/or convective transport and radiation to space exceeds radiogenic heat production [1-5]. Freezing just 1% of the ice over-pressurizes a water pocket by ~1 MPa; such stresses can overcome the strength of ice [7]. Cracks are expected to remain open for (much) longer than fluid ascent timescales (see below and [7]) if the ice viscosity exceeds ~10^{10} Pa s. Although the ice viscosity decreases exponentially with increasing temperature, even Ceres' interior (warmer than its mean surface temperature of ~170 K at which the ice viscosity is > 10^{15} Pa s [4]) should be cold enough to prevent crack healing before material reaches the surface.

3. Ascent mechanism: Water can ascend in cracks up to the water/ice hydrostatic level, but cannot progress further unless the negative buoyancy of water in ice is overcome. A way for this to happen is if cryovolcanic fluids contain enough gas to become positively buoyant. During ascent up to the hydrostatic level, the headspace pressure (difference between surrounding hydrostatic and crack water column pressures) inside cracks decreases. This can lead to the exsolution of volatiles from water to make a low-density fluid [7,8]. The exsolution of non-polar volatiles such as H_2, N_2, Ar, CH_4, CO, and to some extent CO_2 allows crack propagation by positive buoyancy. However, exsolution would not happen if a primordial ice-rock crust is retained, as modeled by [4]: crust acts as a pressure seal to keep the volatiles dissolved [7].

4. Reaching the surface before freezing: Even if cracks propagate to the surface, cryovolcanic fluids must rise faster than they freeze onto the channel walls. Antifreeze in the liquid delays the freezing time, but a water-ammonia solution driven to its eutectic has a high viscosity (10 Pa s), which slows it down near the walls. However, for a water-ammonia liquid, we calculate ascent times of 10^5 s (about 1 day), shorter than freezing times of 10^6 s [7].

Conclusions: Cryovolcanism seems possible on dwarf planets, although exsolution-driven ascent could be unlikely if these objects retained an undifferentiated crust. Surface evidence to be gathered by Dawn and New Horizons for past or present cryovolcanism, in addition to potential plumes, could provide a valuable window into the interiors of Ceres, Pluto, and Charon. The mysterious bright spots observed by Dawn prior to its capture into Ceres orbit might be a first hint of such evidence. Understanding how cryovolcanism works on dwarf planets may allow us to confirm the presence of liquid in their interiors, which would render many more worlds potentially habitable than currently thought.

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