THERMAL AND COMPOSITIONAL EVOLUTION OF A BRINE RESERVOIR BENEATH CERES' OCCATOR CRATER: IMPLICATIONS FOR CRYOVOLCANISM AT THE SURFACE.

Lynnae C. Quick[1], Debra L. Buczkowski[2], Jennifer E. C. Scully[3], Ottaviano Ruesch[4.5], Julie Castillo-Rogez[3], Carol A. Raymond[3], Paul M. Schenk[6], Hanna G. Sizemore[7], Mark V. Sykes[7], [1]Center for Earth and Planetary Studies, National Air and Space Museum, Smithsonian Institution, Washington, DC 20560, QuickL@si.edu, [2]Johns Hopkins University Applied Physics Laboratory, Laurel MD 20723, [3]Jet Propulsion Laboratory, California Institute of Technology, Pasadena CA 91109, [4]NASA Goddard Space Flight Center/USRA, Greenbelt MD, 20771,[5]ESTEC, European Space Agency, 2221 Noordwijk, The Netherlands, [6]Lunar and Planetary Institute, Houston TX, 77058, [7]Planetary Science Institute, Tucson AZ, 85719.

Introduction: The Dawn spacecraft has imaged several putative cryovolcanic features on dwarf planet Ceres [1-6], and several lines of evidence suggest past cryovolcanic activity at Occator crater [1-2, 5-9]. Thus, cryovolcanism may have played a key role in delivering carbonate and/or chloride brines to Ceres' surface in the geologically recent past. The presence of low-density material beneath Occator is one possible explanation for the negative Bouguer anomaly detected beneath it [10-11]. If this region is a partially crystallized reservoir, it may be a remnant of a past global ocean on Ceres [12]. Excess pressures caused by gradual freezing of the reservoir, or by stresses from the Occator-forming impact, could have delivered cryolavas from this reservoir, to Ceres' surface. We have investigated the progressive thermal and compositional evolution of such a crystallizing reservoir beneath Occator, and implications for the emplacement of Cerealia and Vinalia Faculae (Fig. 1).

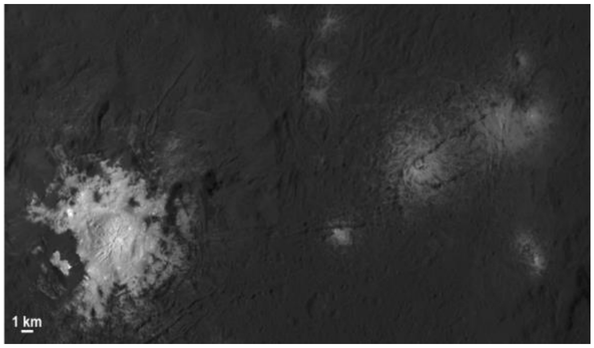

Fig. 1. Bright spots in Occator crater. Cerealia Facula (left) is the brightest deposit on Ceres. The wispy Vinalia Faculae (right) are located to the east of Cerealia Facula.

Cryomagma Reservoir Evolution: The temperature, T, of a crystallizing reservoir as a function of time, may be described by:

$$T = T_c + (T_o - T_C)e^{-3\kappa t/r^2} \qquad (1)$$

[13-14]. Assuming that the dimensions of the reservoir are commensurate with those of Occator, (i.e., radius, r = 45 km), Fig. 2 shows the reservoir's temperature as a function of time, and the cooling sequence of various cryomagmatic solutions, when T_c = 150 K and $\kappa = 10^{-6}$ m^2/s are the average temperature and thermal diffusivity of Ceres' lithosphere, and T_o = 273 K is the initial temperature of the reservoir [15-16]. Fig. 2 shows that for the first 85,000 years of cooling, the reservoir will maintain an average temperature of ~273 K. Due to these elevated temperatures, cryolavas of various compositions may be transported to the surface during this time. However, by the time the reservoir has undergone 4 Myr of cooling, briny solutions rich in carbonate and chloride salts will be depleted, while those rich in NH_3 will be depleted after 33 Myr of cooling (Fig. 2).

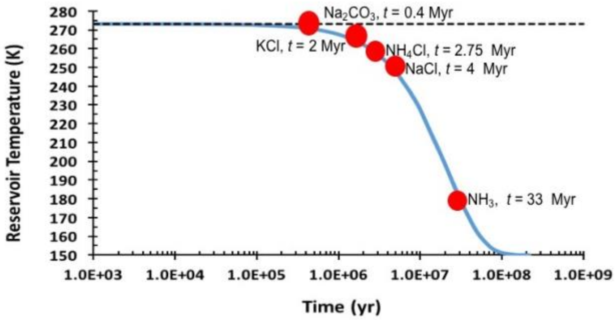

Fig. 2. Reservoir crystallization and the depletion of aqueous solutions enriched in salts or NH_3. The dashed line denotes a 273 K reservoir temperature. The red dots indicate the eutectic temperatures of respective solutions.

Formation of the Vinalia Faculae: Excess pressures caused by the gradual freezing of the reservoir may have generated fractures capable of delivering cryolavas to Ceres' surface [cf. 17-19]. Owing to the very low vapor pressure of aqueous solutions, any cryolava emplaced on Ceres' surface will initially boil violently until a coherent, insulating ice crust forms atop the flow. During this time, the liquid portion of the brine will condense into icy particles, which will be deposited onto the surface, along with salts ejected from the brine during liquid condensation. The Vinalia Faculae may have formed from multiple episodes of salt deposition during the initial boiling phase of cryolava eruptions, or, when fractures containing volatile-rich, salty solutions breached Ceres' surface [6, 20]. The bright mantling that makes up the largest Vinalia bright spots is ~5-6 km in diameter (Fig. 1). Ballistically-emplaced salt particles would therefore have to have been launched on trajectories that allowed them to reach maximum radial distances of 2.5-3 km from a central source.

The eruption velocity for a mixture of gas and particles expanding in a low-pressure environment is:

$$v_E = \sqrt{\frac{2nR_gT_g\gamma}{m(\gamma-1)}} \tag{2}$$

where n is volatile mass fraction, R_g is the universal gas constant, T_g = 273 K is the temperature at which gas expansion begins, $\gamma = c_p/c_V$ is the ratio of specific heats of the driving volatile, and m is its molecular weight [21-22]. The maximum radial distance, R, that particles travel is described by $R = v_E^2 \sin 2\theta/g$ [23], where θ is the particle eruption angle [22-23]. It is clear from Fig. 3 that regardless of eruption angle, less than 1 wt % of a driving gas is required to launch particles on trajectories with dimensions consistent with the largest Vinalia bright spots (Fig 3).

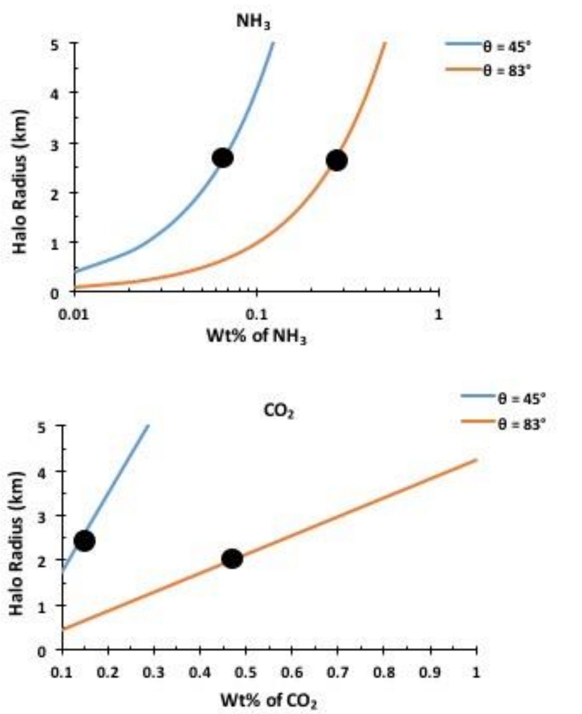

Fig. 3. Radial extent of Vinalia halos as a function of volatile content. The black dots represent the 2.5 km radius of the largest Vinalia bright spots.

Cerealia Dome and Cerealia Facula: Previous workers have suggested that the Cerealia Dome (Fig. 1) is a cryovolcanic dome, formed by one or more episodes of viscous cryolava extrusion [5-6,9,20]. The formation of cryolava domes by viscous extrusions of cryolava was examined in [24-25]. The equation describing the flow profile of a radially expanding fluid, as a function of time as it relaxes into a domical shape, is:

$$h(r,\theta) = \frac{4V}{3\pi r_o^2}\frac{1}{(1+\phi/\tau)^{1/4}}\left(1-\frac{r^2}{r_o^2}\frac{1}{(1+\phi/\tau)^{1/4}}\right)^{1/3} \tag{3}$$

[24-25]. Here $\phi(t)$ is a time transformation variable obtained by assuming a time-dependent viscosity of the form $v(t) = v_o e^{t/T}$ [24-25]. Fig. 4 shows the solution of a radially spreading, Newtonian fluid with $v_o = 10^8$ m^2/s (equivalent to 10^{11} Pa s for cryolava density of 10^3 kg/m^3) at four times. The overall "shape" of the flow surface, as well as the aspect ratio at the final time, is very similar to the dimensions of the Cerealia Dome. Here the total relaxation time is ~ 9 months. Ruptures in the cryolava crust during and/or after the formation of the Cerealia Dome may have launched vapor, ice, and salts on ballistic trajectories, forming the central portion of Cerealia Facula. The diffuse edges may have formed when fractures containing volatile-rich fluids breached the surface.

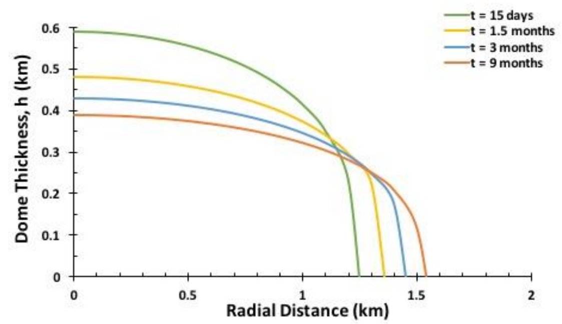

Fig. 4. Axially symmetric Newtonian fluid flow profiles obtained from (3).

Although endogenic models for faculae formation were presented here, these analyses do not preclude exogenic processes from also playing a role [11, 26]. Further modeling and continued analysis of Dawn data will provide additional clarity with respect to modes of faculae emplacement.

References: [1] Buczkowski, D. L. et al. (2016) *Science, 353*, aaf4332. [2] Buczkowski, D. L. et al. (2017) *Icarus*, In Press. [3] Buczkowski, D. L. et al. (2017) *Icarus*, Submitted. [4] Ruesch, O. et al. (2016) *Science, 353*, aaf4286. [5] Ruesch, O. et al. (2017) *48th LPSC*, Abstract #2435. [6] Ruesch, O. et al. (2017) *Icarus*, In Revision. [7] De Sanctis, M. C. et al. (2016) *Nature*, *536*, 54-58. [8] Krohn, K. et al. (2016) *GRL, 43*, 11994-12003. [9] Nathues, A., et al. (2017) *AJ, 153*, 112. [10] Ermakov, A., et al. (2017) *JGR Planets*, *122*, 11. [11] Scully, J. E. C., et al. (2018) *Icarus*, Submitted. [12] Castillo-Rogez, J. et al. (2017) *MAPS*, Submitted. [13] Marsh, B. D. (1982) *Am. J. Sci.*, *282*, 808-855. [14] Marsh, B. D. (1984) *JGR, 89*, B10. [15] Hobbs, P. V. (1974) *Ice Physics*. [16] Gibert, B. et al. (2003) *JGR*, *108*, B8. [17] Fagents, S. A. (2003) *JGR*, *108*, 5139. [18] Manga, M. & Wang, C.-Y. (2007) *GRL*, *34*, L07202. [19] Neveu, M. & Desch, S. J. (2015). *GRL*, *42*, 10,197–10,206. [20] Quick, L. C. et al. (2017) *Icarus*, In Revision. [21] Wilson, L. & Head, J. W. (1983) *Nature*, *302*, 663-669. [22] Fagents, S.A., et al. (2000) *Icarus*, *144*, 54-88. [23] Quick, L.C., et al. (2013) *P&SS*, *86*, 1-9. [24] Quick, L.C. et al. (2016) *JVGR*, *319*, 93-105. [25] Quick, L. C. et al. (2017) *Icarus*, *284*, 477-488. [26] Schenk, P. M., et al. (2017) *Icarus*, Submitted.