THE FORMATION AND TIMING OF NEAR-SURFACE NA-CARBONATE DEPOSITS ON CERES: EVIDENCE FOR DIVERSE, WIDESPREAD, AND GEOLOGICALLY RECENT EMPLACEMENT.

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Introduction: Characteristics of Na-carbonate exposures on the surface of Ceres indicate their emplacement recently in Ceres' past [1]. The source and timing of the Na-carbonate-forming fluids in Ceres remains an open question: are surface deposits recently formed from brines, are they ancient deposits that have only recently been excavated, or both? Several mechanisms have been invoked for the formation of Na-carbonate deposits: 1) impact-induced melting of icy crustal material [1-4, 5]; 2) upwelling of brines from the deep interior via fractures [6]; or 3) exhumed precipitation products of brines in the crust [4]. The formation of Na-carbonate-bearing brines via impact heating has been a focus since Dawn's arrival at Ceres due to extensive Na-carbonate exposures on the floor of Occator Crater [1], but hundreds of faculae, many of which also contain Na-carbonate, dot the surface of Ceres [4,7,8]. Most of these are located on the rims and walls of geologically recent craters [4], and some are at least as spatially extensive as the deposits in Occator crater. Understanding the source of these deposits is critical to unraveling the mechanism(s) and timing of the emplacement of Na-carbonate deposits on Ceres, as well as understanding how recent and widespread brines were in Ceres' crust.

Observations of Rim Deposits: Spatially significant deposits of Na-carbonates on crater rims and walls were identified using thermally corrected and denoised images from Dawn's Visible and Infrared Spectrometer (VIR) collected a spatial resolutions up to ~100 m. Deposits were identified on the rims of dozens of craters, including nearly contiguous spans over extents as long as 8-32 km in Azacca, Xevioso, Oxo, Ikapati, Kupalo, Haulani, Dantu, and several other craters (referred to as "large" deposits).

Potential Sources of Rim Deposits: Possible scenarios to generate crater rim exposures of Na-carbonate include 1) heating of ices during the formation of the impact crater in which the Na-carbonates are exposed; 2) exposure of buried Na-carbonate that formed in previous impacts via impact heating or impact-induced upwelling of brines; 3) exposure of the precipitation products of brines that have been in Ceres since its differentiation. We rule out the first scenario because impact models indicate that impact heat in craters of this size would not be close to the eutectic temperature of the progenitor materials for Na-carbonate exposed on crater rims [2]. Therefore, we use observations and computational modeling to investigate the relative timing and plausibility of scenarios 2 and 3, and propose a set of geophysical models to investigate the mechanism(s) that mobilize subsurface Na-carbonate and whether the mobilization occurs as a liquid or solid.

Constraints on Age of Present-Day, Near-Subsurface Na-Carbonates: Because crater rims expose large deposits of shallowly buried Na-carbonate, the Na-carbonate must have been emplaced recently enough that it has not been removed by impacts. To investigate the lifetime of near-subsurface Na-carbonate deposits, we generated a grid with the surface area of Ceres and populated it with cylinders of varying width and thickness representing subsurface Na-carbonate deposits. This grid was populated in Myr timesteps with craters sourced from the Ceres crater production function. During each timestep, the volume of the cylinder intersected by each impact was removed. The simulation was run >1,000 times for each cylinder geometry.

We first considered near-subsurface Na-carbonate deposited at the end of the Late Heavy Bombardment (LHB, ~3.7 Ga) (Fig 1). Results indicate that to 3σ confidence, a single subsurface Na-carbonate deposit (and hence any rim exposure) could be no larger than 32 km across (the scale of the largest observed rim deposits) after ~3.2 Ga if the subsurface deposit started with a diameter of <100 km. That is, after ~500 Myr of cratering, a 100 km wide near-subsurface deposit could be no more than 32 km across. Multiple model runs show that for a 32 km-size subsurface Na-carbonate deposit to survive to the present (i.e. at the 3σ upper size limit) it must be emplaced no earlier than ~1.3 Ga, i.e. 2.4 Gyr after the LHB. Collectively, simulations indicate that the largest exposures of Na-carbonate on crater rims are sourced from material that was emplaced in the shallow subsurface no more than ~1.3 Ga. Future work will examine the plausibility of subsurface Na-carbonate deposits greater than 100 km in extent.

Source and Timing of Youthful Near-Subsurface Na-Carbonate: Additional impact models of the persistence of Na-carbonate at different depths in the crust indicate that a significant proportion of material near or below the base of the crust likely remains unmixed by impacts since differentiation and could provide a source for Na-carbonate-bearing material to rise toward the surface, consistent with previous work [6] that invokes the upwelling of brines from a deep reservoir [9] in the formation of Cerealia Facula.

The timing of the emplacement of shallow subsurface Na-carbonates alone does not immediately favor or rule out their formation due to impact heating, upwelling of overpressured brines [10], or solid state diapirism of ices, but provides a constraint for geophysical models evaluating the plausibility of these mechanisms for the mobilization of Na-carbonates (future studies). In turn, these models will improve knowledge of the timing of Na-carbonate emplacement by refining the plausible extent of subsurface deposits.

Surface Clues of Na-carbonate Sources: If shallow subsurface Na-carbonate was emplaced geologically recently by scenarios 2 or 3, their exposures may be proximal to features that could provoke or result from the mobilization of Na-carbonate-bearing brines or ices. Two such features are 1) domes that could result from the upwelling of brines or solid state diapirism of ices from the deep crust; 2) large impact basins that could produce or tap overpressured brines that rise to the surface and form evaporites.

There are at least 31 domes on Ceres [11,12]. Nearly half of the large rim deposits of Na-carbonate, including in Azacca, Oxo, Xevioso, and Haulani craters, are closer to a dome than >85% of surface points (Fig 2). The closest domes to these deposits have been dated to ages of 280-640 Ma ADM [12]. Of these deposits, those in Azacca, Xevioso and a nearby crater, and Haulani do not sit inside other impact basins. Given that the modeled timescale for the removal of large, near-subsurface Na-carbonate deposits is faster than the expected degradation rate of large craters, the absence of large impact basins associated with these deposits leaves processes not directly related to cratering, such as solid state diapirism, as a more plausible source of the Na-carbonates, though the viability of these mechanisms must still be tested with geophysical models (future studies).

Only about half of craters with large rim Na-carbonate deposits are inside larger, older impact basins (Fig 2). Although some of these craters are abnormally close to domes (Oxo, Xevioso), most are not. Of those deposits that are not proximal to domes but are inside older impact basins, previous impacts may have produced Na-carbonate deposits in a manner similar to that hypothesized for the bright spots in Occator crater.

Future Studies: Additional modeling is required to distinguish between scenarios 2 and 3 and address the central question of Na-carbonate deposits on Ceres: were they mobilized and emplaced recently in solid form, or as brines? Perhaps the most plausible scenario for mechanism 3 is that Na-carbonate-bearing brines froze early in Ceres' history, were concentrated in the deep crust [13], and later mobilized by solid-state compositional diapirism [14, 15]. Given a sufficient viscosity and density contrast, perturbations of deep, low density ices may produce instabilities that allow them to rise slowly through the denser overlying crust [15]. Initial models indicate that ices that may be heterogeneously concentrated in the crust, H_2O and $CH_4{\cdot}5.75H_2O$, are unstable to 1 km perturbations over 1 Gyr timescales at the base of the crust. Future modeling will explore whether denser Na-bearing phases can be entrained in less dense ices that carry them toward the surface, as well as the geometry, duration, and range of these putative diapirs. Another scenario for mechanism 3 is that overpressured Na-carbonate brines were transported to the near-subsurface from the mantle or deep crust [10]. We will investigate whether this could plausibly occur. In either scenario, model results must be consistent with the surface morphology surrounding these deposits and the modeled timescales for their deposition.

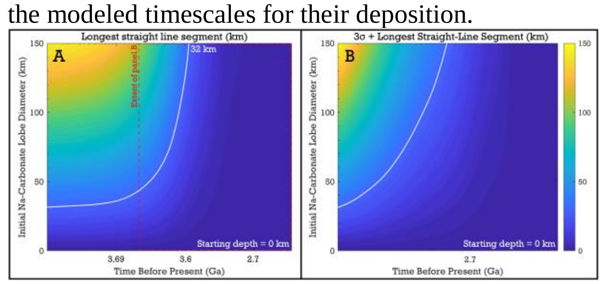

Figure 1: A) Simulated extent of contiguous subsurface Na-carbonate as a function of time before present for different initial lobes sizes. Contour denotes largest rim Na-carbonate deposit. Simulation starts after LHB. B) A plus three standard deviations in modeled subsurface Na-carbonate extent.

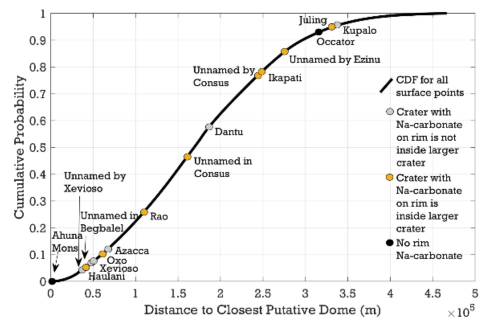

Figure 2: Distance between the largest crater rim Na-carbonate deposits and the nearest dome. Color denotes whether the rim deposits sit in a larger, older crater.

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