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The formation and timing of near-surface Na-carbonate deposits on Ceres

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Abstract

We present the extent of Na-carbonate deposits on Ceres and the mechanisms and timing of their formation.

1. Observations

Ceres' surface is dotted with 100s of exposures of Na-carbonate [1-3] with characteristics that indicate recent emplacement [1]. The source and timing of the fluids that formed Na-carbonate deposits in Ceres remains an open question: are surface deposits recently formed from brines, are they recently excavated ancient deposits, or both? Several mechanisms have been invoked for the formation of Na-carbonate deposits: 1) impact-induced melting of ices in the crust [1, 4-7]; 2) upwelling of overpressured brines from the deep crust or mantle via fractures [8]; or 3) exhumation of the precipitation products of brines in the crust [1]. Most of the Na-carbonate exposures on Ceres' surface are located on the rims and walls of geologically recent craters [1], some of which are at least as spatially extensive as the deposits in Occator crater. Understanding the source of these exposed deposits is critical to unraveling the mechanism(s) and timing of the emplacement of Na-carbonate on Ceres and the processes the mobilize material in the crust.

Spatially significant deposits of Na-carbonates on crater rims and walls were identified using thermally corrected, denoised images from Dawn's Visible and Infrared Spectrometer (VIR) collected at up to 100m/px spatial resolution. Deposits >1 km across were identified on the rims of >40 craters, including nearly contiguous spans over 5-32 km in Kupalo, Haulani, Azacca, Ikapati, Dantu, Oxo, and several other craters (termed "large deposits") (Fig. 1A).

2. Potential sources of rim deposits

Possible sources of Na-carbonate on crater rims include: 1) heating of ices during the formation of the crater in which the Na-carbonates are exposed; 2) exposure of the precipitation products of brines that have been in Ceres' shallow subsurface since its differentiation; 3) exposure of shallowly buried Na-carbonate that formed in previous impacts by impact heating or transport to the surface via impact-induced solid state deformation or brine upwelling; 4) exposure of shallowly buried Na-carbonate brought to the surface from the deep crust or upper mantle by brine upwelling or solid state deformation independent of impact events. We rule out the first scenario because impact models indicate that impact heating would not exceed the eutectic temperature of the progenitor materials of Na-carbonate at crater rims [5]. We rule out the second scenario based on models that indicate large, shallow Na-carbonate deposits must have been emplaced geologically recently (see §3). We investigate the plausibility of the third and fourth scenarios by searching for structures associated with or resulting from those processes. In scenario 3, rim deposits should sit in older, still visible impact basins. In scenario 4, rim deposits may be near domes or other surface features resulting from subsurface material transport.

Approximately half of the large Na-carbonate rim deposits are within older impact basins that could have concentrated the now-exposed Na-carbonates via heating or mobilized them to the surface via an Occator-like process (Fig. 1B). The remaining large rim deposits, which are not in discernible impact basins, are anomalously close to domes relative to all surface points and the other group of large Na-carbonate deposits (Fig. 1B). The absence of older impact basins associated with these deposits leaves processes not directly related to impact cratering, such as solid state diapirism and/or upwelling of overpressured brines, as a more plausible source of their Na-carbonates (scenario 4). Furthermore, the close spatial association of these deposits with domes suggests that the same process(es) responsible for the emplacement of Ceres' domes may have brought Na-carbonate to the shallow subsurface, or that the conditions that favor the formation of domes also favor proximal mobilization of Na-carbonate. The viability of solid-state deformation or brine upwelling as a source of the Na-carbonates must still be tested with geophysical models (see §4).

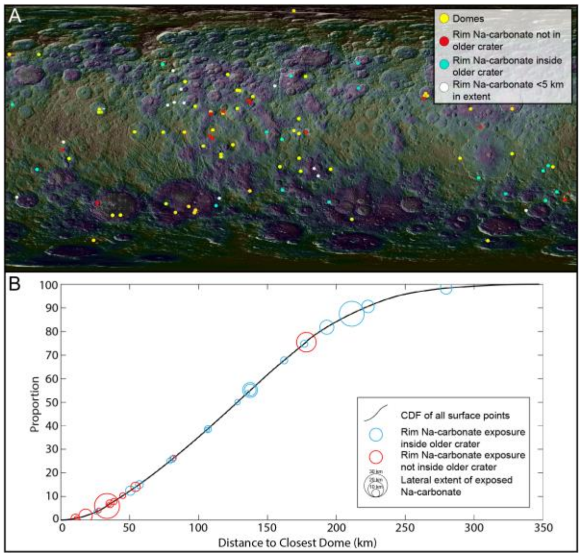

Figure 1: A) Map of all domes [9-10] and > 1 km Na-carbonate crater rim deposits on Ceres. B) Comparison of the distance of Na-carbonate rim deposits to domes.

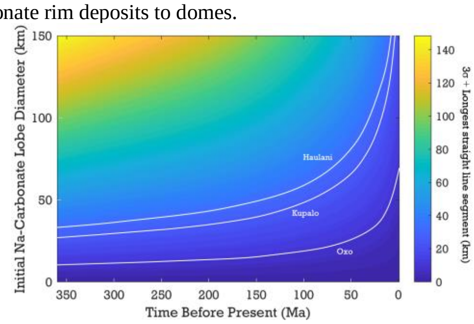

Figure 2: A) Simulated extent of contiguous subsurface Na-carbonate plus three standard deviations as function of time before present for different starting geometries. Contours are large rim Na-carbonate deposits. Start time 1 Ga.

3. Constraints on age of present-day near-surface 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 populated a grid of Ceres' surface area with cylinders of varying width and thickness representing subsurface Na-carbonate deposits. The 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 geometry.

We first considered near-subsurface Na-carbonate deposited at the end of the Late Heavy Bombardment (LHB, ~3.7 Ga). Results show that to 3σ confidence, a single subsurface Na-carbonate deposit of 32 km (like Haulani) would not exist after 500 Ma of bombardment, i.e. would be destroyed by 3.2 Ga, even if the subsurface deposit started with a diameter of 150 km. Only in scenarios beginning 1 Ga or later do deposits >20 km survive to the present at the 3σ limit (Fig. 2).

4. Summary and Conclusions

Large rim exposures of Na-carbonate were emplaced in the shallow subsurface within the last ~1 Ga, likely by a combination of Occator-like impact heating (mechanism 3) and upwelling of Na-carbonate-bearing material from the deep crust or upper mantle (mechanism 4). Additional modeling is required to address the central question of Na-carbonate deposits on Ceres: were they mobilized and emplaced recently in solid form, or as brines? One plausible scenario for mechanism 4 is that Na-carbonate-bearing brines that froze early in Ceres' history were concentrated in the deep crust [11] and later mobilized by solid-state deformation or compositional diapirism [e.g. 12-13]. Models after [13] show that deep (below 15 km) concentrations of low-density ice that entrain Na-carbonate may be unstable to km-scale perturbations over geologically short timescales. More work is required to understand whether resulting diapirs could progress to the surface, or if the mobilization of deep brines [8-9, 14] is required to explain the recent emplacement of shallowly buried Na-carbonate near domes.

Acknowledgements

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