GEOLOGY OF DWARF PLANET CERES AND METEORITE ANALOGS

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Introduction: Although no known meteorites are thought to derive from Ceres, CI/CM carbonaceous chondrites are potential analogs for its composition and alteration [1]. These meteorites have primitive chemical compositions, despite having suffered aqueous alteration; this paradox can be explained by closed-system alteration in small parent bodies where low permeability limited fluid transport. In contrast, Ceres, the largest asteroidal body, has experienced extensive alteration accompanied by differentiation of silicates and volatiles [2].

The ancient surface of Ceres has a crater density similar to Vesta, but basins >400 km are absent or relaxed. The Dawn spacecraft's GRaND instrument revealed near-surface ice concentrations in the regolith at high latitudes [3], exposed on the surface locally in a few craters [4]. The VIR instrument indicates a dark surface interpreted as a lag deposit from ice sublimation and composed of ammoniated clays, serpentine, MgCa-carbonates, and a darkening component [5]. Elemental analysis of Fe and H abundances in the non-icy regolith are lower and higher, respectively, than for CI/CM chondrites [3]. A few young craters and a dome expose Na-carbonates and salts [6], possibly precipitates resulting from recent hydrothermal and cryo-volcanic activity. Aliphatic organic matter has also been detected in several regions [7], and the C abundance in the regolith may be greater than in carbonaceous chondrites [3]. Abundances of K and Ni/Fe are consistent with chondritic values [3, 8].

The moment of inertia factor of 0.37 confirms that Ceres is partially differentiated [9]. Its bulk density of 2162 kg/m^3 falls between rock and ice, suggesting 17-27 wt.% ice. Various two-layer models of the interior [9, 10] have a rocky mantle overlain by a 40-50 km icy shell. Isostacy models suggest densities for the icy shell and rocky mantle of ~1250 and 2400 kg/m^3, respectively [10]; the inferred mantle density is close to CI/CM chondrites and implies hydration of the deep interior. Based on limited viscous relaxation of craters <400 km, the icy outer shell is estimated to contain ~70 vol.% solids [11] including phyllosilicates, salts, and gas clathrate hydrates.

Why Is Ceres Different?: Ceres (diameter 930 km) is spectrally distinctive but not unique among the largest asteroids. Hygiea (444 km) and Interamnia (307 km) have similar spectra [12], which may also reflect advanced degrees of alteration that produced similar mineralogy to Ceres. We posit that the thermal history and alteration intensity of Ceres is related to its large size, where the effective water:rock ratios are greater due to hydrothermal convection and inability to vent to space via fractures [13]. Low thermal conductivity in the outer shell promoted by clathrate hydrates and redistribution of ^{40}K during alteration may account for temperatures warm enough to allow a subsurface brine reservoir at present that could periodically erupt [14].

The ammoniated clay in Ceres may reflect extensive alteration, when the NH_3 in chondritc organic matter [15] was released by heating. Mg-rich serpentine has replaced Fe-rich cronstedtite, as observed in the most altered CI/CM chondrites [16], and the relative proportion of carbonate in Ceres was likewise increased at the expense of organics, also noted during progressive chondrite alteration [17].

Conclusions: Ceres shows that differentiation, albeit of ice and rock, can accompany aqueous alteration on the largest carbonaceous chondrite-like bodies, and subsurface hydrothermal activity may persist to the present day. Impact-excavated samples of the icy crust of Ceres are unlikely to survive as meteorites, but Dawn's exploration has told us what mineralogy to look for.

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