HOLLOW-FORMING LAYERS IN IMPACT CRATERS ON MERCURY: MASSIVE SULFIDE OR CHLORIDE DEPOSITS FORMED BY IMPACT MELT DIFFERENTIATION?

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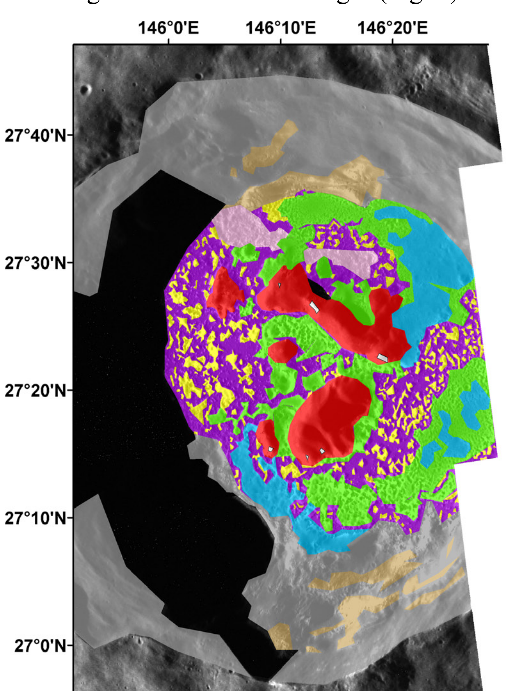
Introduction: MESSENGER observations from Mercury orbit show that unusually bright and comparatively blue deposits on the floors of large impact craters first observed during Mariner 10 and MESSENGER flybys of Mercury [1-4] are marked with irregular, shallow, fresh-appearing rimless depressions known as hollows that are associated with impact crater floors, central peaks, and wall terraces [5]. Hollows develop on equator-facing slopes [5] and resemble sublimation pits in the Mars south polar terrain [6-7], suggesting that they may form by space weathering and/or sublimation of a volatile-bearing layer.

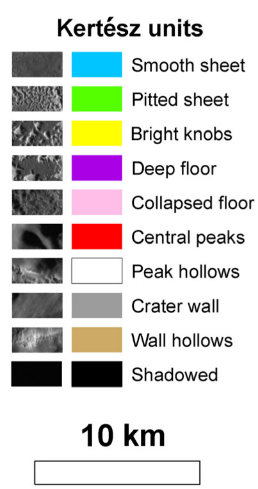
We map the geology of the heavily hollowed crater Kertész and show that hollows in this crater develop in an approximately 30-m-thick hollow-forming layer derived from impact melt. We investigate the possibility that this volatile-bearing layer represents a massive deposit of sulfide or chloride minerals formed by flotation of sulfide or chloride liquids unmixed from impact-melted crust.

Hollows in Kertész crater: Kertész (27.3° N, 146.2° E) is a 33-km-diameter crater on the western edge of Mercury's Caloris basin with a heavily hollowed, high-reflectance floor (Fig. 1). 13 high-resolution (average pixel dimensions of ~18 m) monochromatic images of Kertész crater and its immediate surroundings were obtained by the MESSENGER spacecraft's Mercury Dual Imaging System (MDIS) narrow-angle camera (NAC). We mapped the geologic units in Kertész on a mosaic of these high-resolution NAC images (Fig. 1).

Mapped smooth sheet units, characterized by their dark, flat surfaces and distribution about halfway between central peaks and crater walls, transition at their edges to pitted sheet units, which are marked by many shallow pits. These pits develop vertically to a maximum depth of ~30 m below the edges of the pitted sheet (as determined by shadow measurements and photogrammetry) and laterally, coalescing to produce the depressed deep floor unit, spotted with isolated, elevated bright knob units characterized by their concave cuspate and lunate edges. This deep floor may have developed preferentially around crater walls and central peaks. Small regions of collapsed floor on the north edge of Kertész have developed to a depth of ~60 m below the edges of the pitted sheet. The central peaks of Kertész appear to be draped by smooth material similar in appearance to the smooth sheet. Small, bright hollows develop on central peak slopes and crater wall terraces.

The continuous gradation between smooth sheet, pitted sheet, and bright knob/deep floor units suggests that the hollow-forming process transforms the smooth sheet unit to pitted sheet and bright knob/deep floor units. The entire Kertész crater floor may once have been covered with the smooth sheet unit. We call the component of the smooth sheet unit that develops hollows the hollow-forming layer (HFL). The observation that hollows across the Kertész floor everywhere develop to a maximum depth of ~30 m below the edges of pitted sheet units suggests that the crater floor hollow-forming layer is ~30 m thick.





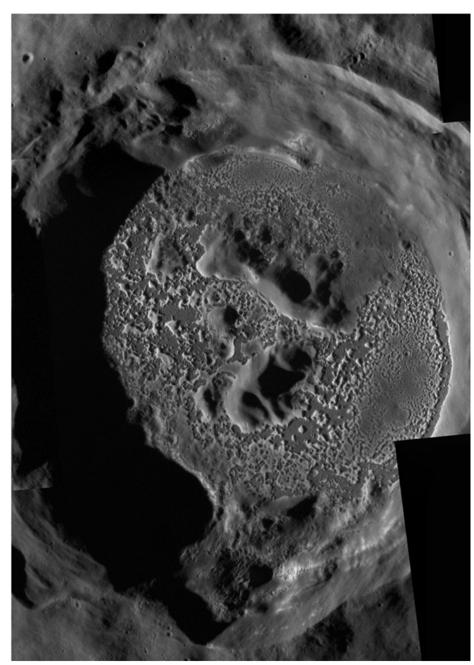


Figure 1. Geologic map of Kertész crater (at left) and unannotated Kertész mosaic (at right) with representative unit surfaces pictured.

The hollow-forming layer covers the crater floor, drapes crater central peaks, and fills crater rim terraces. There is a close correspondence between the distribution of this layer and the distribution of impact melt in complex craters [8]. We therefore suggest that the hollow-forming layer may be derived from impact melt.

Identity of the hollow-forming layer: There are several chemical constraints on the identity of the hollow-forming layer. First, the hollow-forming layer is volumetrically substantial: a layer filling the 22-km-diameter floor of Kertész to a thickness of 30 m has a volume of ~11.4 km^3. This layer comprises ~11.4% of the ~100 km^3 impact melt (estimated from [8]) that floods the Kertész crater floor. Therefore, the hollow-forming layer must be chemically related to the impact melt, and, accordingly, the upper crust. Second, no BCFDs or hollows have been observed on planetary bodies other than Mercury. This observation could be a consequence of Mercury's distinctive crustal chemistry [10]. Third, there must be some differentiation mechanism able to fractionate the HFL from impact melt. Fourth, since the hollow-forming layer appears to sublime very slowly (~0.1 μm/year [5]) to form hollows, the melting temperature of the minerals comprising the hollow-forming layer should be somewhat above the maximum daytime surface temperature of Mercury.

Could the HFL be a massive sulfide deposit? Sulfides satisfy the first three constraints above. First, sulfur is a major element on Mercury. MESSENGER X-Ray Spectrometer (XRS) analyses have shown that some regions of Mercury's crust contain up to 4 wt. % sulfur [10]. Second, high surface concentrations of sulfur are unique to Mercury among the terrestrial planets. The upper continental crust on Earth, for instance, contains less than 0.1 wt. % S on average. Third, sulfides can fractionate from impact melts. For instance, massive sulfide deposits are associated with terrestrial ultramafic intrusions [11]. These deposits, well understood because of their economic importance, are thought to form by a two-stage process [12]. First, a sulfide liquid unmixes from a sulfur-saturated silicate liquid [13]. Second, unmixed and disseminated dense Ni, Cu, and platinum group element (PGE) sulfide blebs sink to form massive ore bodies [14-15]. The two-stage process of sulfur immiscibility and settling could operate in impact-melted, sulfur-rich portions of the crust to produce massive sulfide hollow-forming layers. Heavily hollowed craters may thus indicate the presence of sulfur-rich crust.

Sulfur may be insoluble in melts on Mercury. Magnesian melts at low oxygen fugacities (~2 log units below the iron-wüstite buffer, IW-2) and at a range of elevated temperatures and pressures produce silicate melts containing less than 4000 ppm S by weight [14, 16]. Because some of Mercury's crust contains up to 4 wt. % S [10], an order of magnitude more sulfur than is soluble in melt of such crust, almost all of the sulfur in the bulk melt may unmix to form blebs of sulfide liquid. However, more than 4 wt. % S can dissolve in silicate melts at very low oxygen fugacities (<IW-3) [17]. If the surface of Mercury is extremely reducing, sulfur may not unmix from even the most sulfur-rich silicate melts.

The mineral species present in the sulfide deposits formed from terrestrial, iron-rich ultramafic melts are dense metal sulfides [12]. The low abundances of iron and other metals on the surface of Mercury [10], however, imply that sulfide deposits formed from melts of Mercury's crust cannot contain mainly dense metal sulfides. By analogy to the mineralogy of enstatite chondrites [18], these sulfide deposits may contain alkali monosulfides, principally CaS (oldhamite) and MgS (niningerite), as previously inferred from positive correlations between Ca/Si, Mg/Si, and S/Si ratios measured by the MESSENGER XRS [10]. Alkali sulfides (and presumably alkali sulfide liquids) have low densities (CaS, ~2.5 g/cm^3) [19] and float in magnesian silicate liquids. Alkali sulfide blebs unmixed from sulfur-saturated silicate melt could rise to form a massive sulfide hollow-forming layer as a flotation crust.

However, the melting points of pure CaS and MgS are >2000 °C (although melting points may be as low as 1000 °C in solid solutions), temperatures well in excess of Mercury's surface temperature. The high abundance of sulfur in Mercury's crust may itself argue for sulfide stability. These observations present difficulties for the hypothesis of a sulfide hollow-forming layer.

Could the HFL be a massive chloride deposit? Magnesium and calcium chlorides, species suggested to form in reduced anhydrous chlorine-rich mafic melts [20], have melting points between 700 and 800 °C, sufficiently high for these materials to sublime slowly on Mercury's surface. MESSENGER XRS analyses suggest that Mercury's crust contains up to 0.2 wt. % chlorine [10]. Earth's upper continental crust contains only ~0.02 wt. % Cl. Although the behavior of chlorides in reduced anhydrous mafic melts is not well understood [20-21], chlorides and chloride liquids have low densities ($CaCl_2$, 2.15 g/cm^3; $MgCl_2$, 2.32 g/cm^3) and could potentially unmix from chlorine-saturated silicate melts to form a massive chloride HFL as a flotation crust.

Summary: The geology of the heavily hollowed crater Kertész suggests that hollows in this crater develop in a hollow-forming layer derived from impact melt. We hypothesize that this layer is a massive sulfide or chloride deposit formed by flotation of sulfides or chlorides unmixed from impact melts of Mercury's crust. We are investigating the applicability of this model to other hollow occurrences [22] and performing experiments on sulfur- and chlorine-rich melts to test this hypothesis.

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