The View from Orbit: Hydrothermal Deposition in a Large Impact Crater on Asteroid Ceres

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Keywords: *hydrothermal, planetary, Ceres, Occator, carbonates, ice.*

ABSTRACT

Mapping of hydrothermal deposits in the 92-km Occator impact crater on Ceres provide a unique opportunity to examine hydrothermal processes and deposits from a planetary perspective. Bright deposits of carbonates and hydrated salts occur on the central uplift and in a cluster of isolated bright spots on the eastern crater floor. Formation was likely by innumerable small seeps of brine that coalesced to form larger contiguous deposits. Isolated bright spots also occur on the crater rim, and small domes and pits occur elsewhere on the floor but are not common, indicating hydrothermal output was spatially limited. Occator and its hydrothermal deposits are considered a prime target for future exploration.

1. OCCATOR CRATER, CERES

1.1 Observations and Geologic Context

NASA's Dawn mission acquired global stereo imaging of Ceres at ~35 m pixel scales and dedicated high resolution stereo over Occator at 3.5-8 m pixel scales, enabling high resolution topographic mapping (Figure 1). Compositional constraints come from lower resolution Dawn gamma ray mapping of elemental abundances and near- to mid-IR spectroscopic mapping of mineralogies at 100-m scales. The lack of surface outcrop mapping and sampling requires that indirect inferences be made from these orbital data products.

Occator crater (~92 km in diameter) is the youngest large crater (perhaps <10 myr) on the dwarf planet and largest asteroid Ceres and retains most of its prime impact morphologies and deposits, including hydrothermal deposits (Figure 1). With a density of ~2.16 g/cm3 and diameter of ~940 km, Ceres is ice-rich with a surface composition that includes ammoniated phyllosilicates, carbonates, and hydrated chloride salts. Ceres is thus unusual in the relatively high volatile mixture of its outer rocky layers.

Detailed mapping of terrestrial impact craters reveals extensive hydrothermal deposition driven by impact heat, most densely concentrated in the central uplift, along the crater rim, and other areas where fractures and porosity concentrate hydrothermal fluids. Hydrothermal activity has been identified also in some large martian craters as well. In eroded Earth craters these often take the form of hydrated and carbonate- silica- or salt-rich alteration minerals along rock fractures. The presence of carbonates and salts in similar locations at Occator crater on Ceres suggests the deposition of mineral deposits from the extrusion and deposition of brines from the interior after impact. High resolution mapping was targeted to explore this hypothesis.

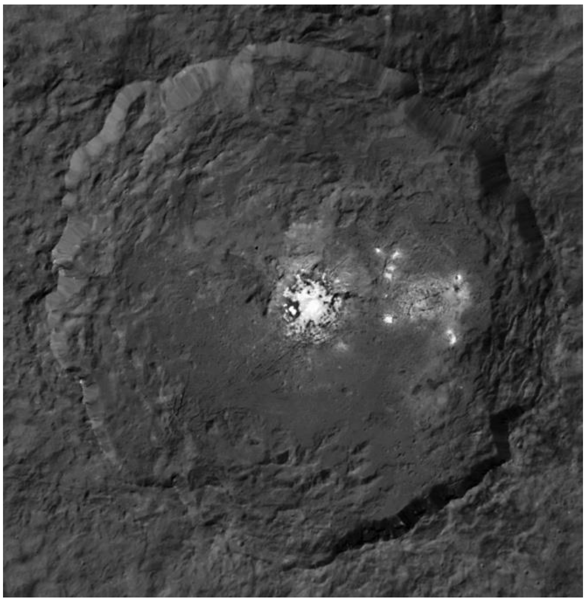

Figure 1a: Image mosaic of 92-km-wide Occator crater, Ceres, at 35 m pixel scales, showing bright central carbonate deposits and flanking bright deposits on eastern crater floor.

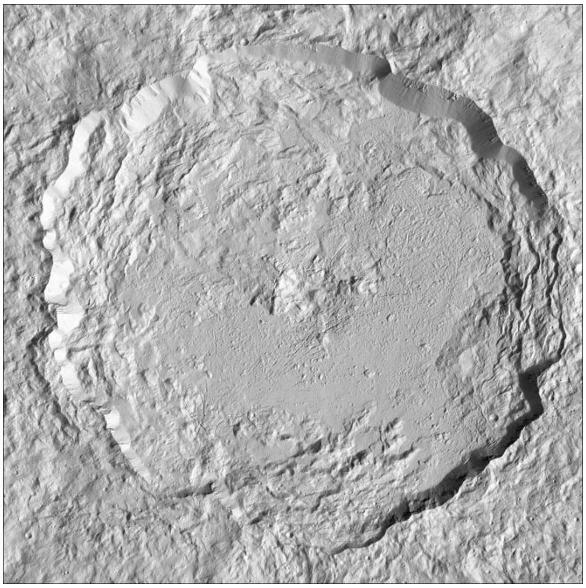

Figure 1b: Shaded relief view of Occator crater, Ceres, based on high resolution topography, highlighting central depression and the rim massifs to east and west.

Proceedings 47th New Zealand Geothermal Workshop
11 -13 November 2025
Rotorua, New Zealand
ISSN 2703-4275

1.2 Carbonate Deposition – Cerealia Facula

Occator is a central pit crater featuring a 12-km-wide 1-km-deep partially rimmed depression (or pit), with a 2-km-wide ~700 m high central dome (Figure 2). The most prominent hydrothermal deposits within Occator crater are the extensive bright carbonate and salt-rich surface deposits that cover most of this central depression (Figure 3-8).

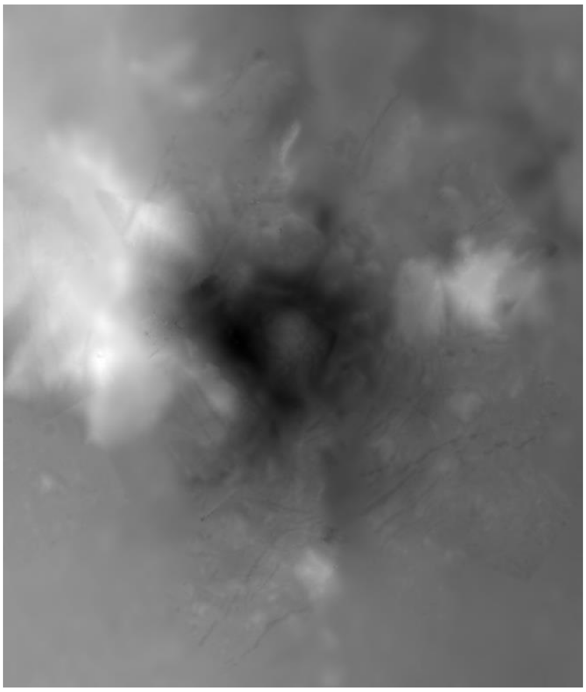

Figure 2: Topographic map of central depression (pit) and dome of Occator crater. Bright is high, dark low; 2 kilometers of relief are shown.

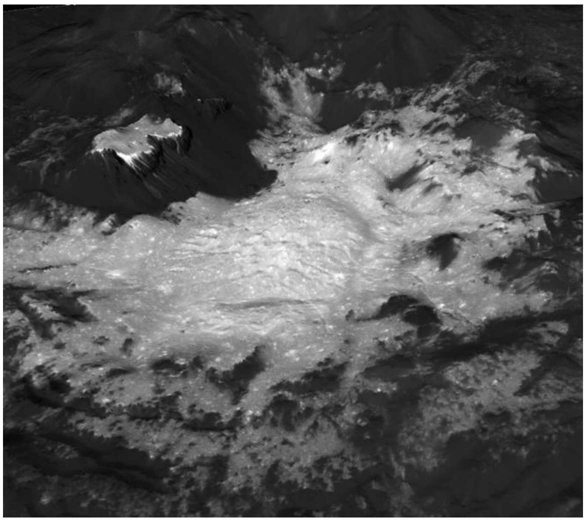

Figure 3: Perspective view across central depression (pit) and dome of Occator crater showing bright carbonate deposits. Block-shaped carbonate-topped plateau at upper left and downslope streaks at upper center.

All of the central dome and most of the central depression (pit) are covered in a contiguous carbonate deposit that grades outward into gradually more dispersed spots of up to 25 m size. Carbonate deposits occur on many different slopes and surfaces, from flat-topped mesas to the steep slopes of the central pit, to narrow inter-ridge valleys (Figures 4-8). Several discrete spots can be identified on the steep inner wall of the central depression, and on the crests of small dark mounds (Figure 6). Although small pits are abundant, most are attributable to post-formation micro-cratering. No discrete vents or constructional edifices anywhere on the deposits can be confidently identified, although irregular pitting on the crest of the central dome (Figure 4) could be sites of either collapse of venting.

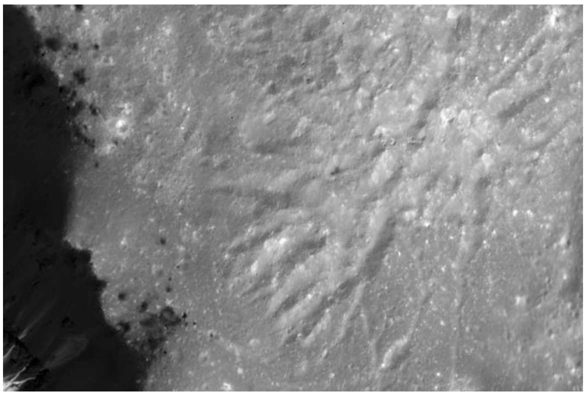

Figure 4: Close-up view across central depression (pit) and dome (upper right quadrant) of Occator crater. Bright deposits are carbonate depositions from hydrothermal activity. Radial fractures emanate from dome center. Scene width is 2 km.

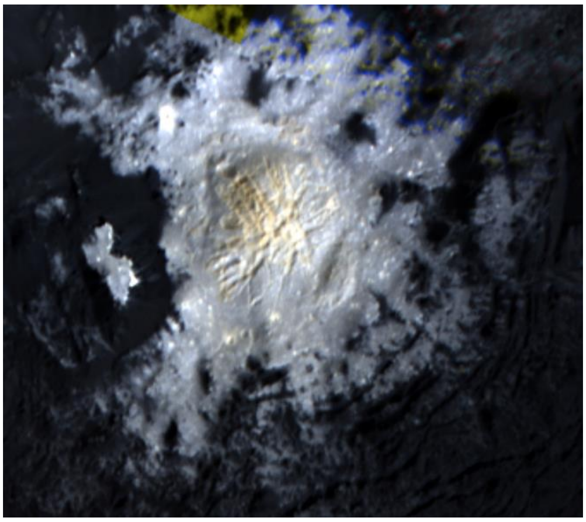

Figure 5: Color view of central dome and depression of Occator showing more yellowish signature of fractured crest of dome. Scene width is 10 km.

Most of the carbonate deposits have a bland coloration in visible colors. A major exception is the yellow-reddish coloration along the crest of the central dome (Figure 5). The dome is fractured (Figure 4), just as central domes are on the large icy moons Ganymede and Callisto. The compositional distinction at Occator's dome is unclear but could indicate exposure of deeper or different materials during the uplift and fracturing event. Dome fracturing is likely due to inflation of the solid surface due to either freezing of subsurface fluids or intrusion of new fluids into the dome interior.

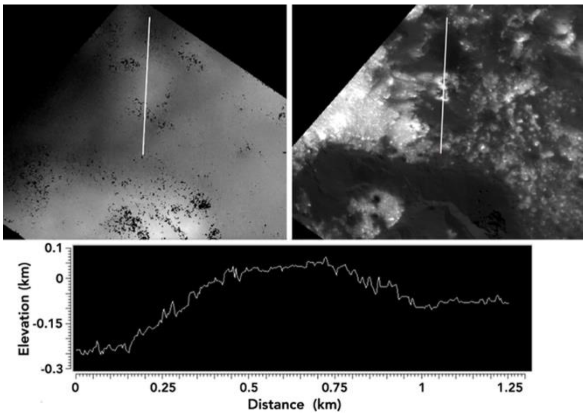

Figure 6: Example of a bright-topped dark mound in the outer portions of Cerealia Facula, Occator, Ceres. Topographic map at left, image at right, topographic profile at bottom.

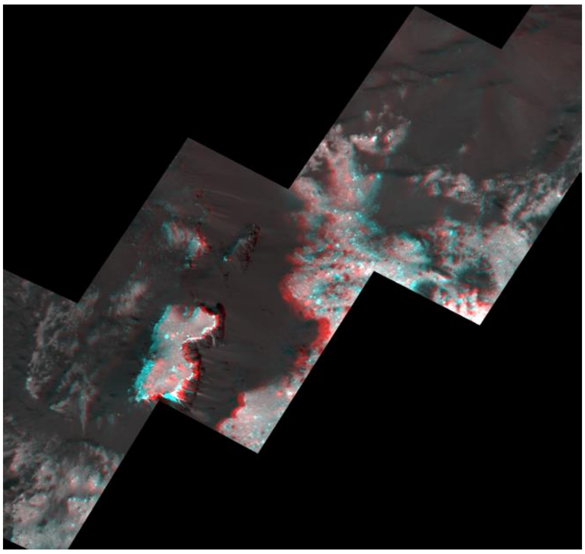

Figure 7: Stereo anaglyph of carbonate deposits on western rim of Occator central depression. Note block-shaped carbonate-topped plateau at center left and downslope streaks at upper center. Central dome is out of view at bottom. Scene is ~2 km across.

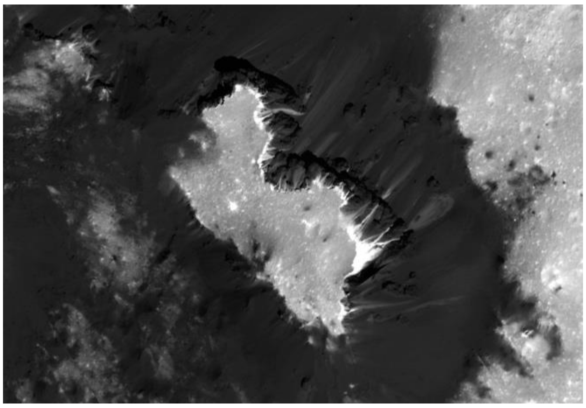

Figure 8: Close-up of western rim of central depression (pit) at Occator crater. Bright deposits are carbonate depositions from hydrothermal activity. Scene is ~1 km across.

A large flat-topped mesa occurs on the western edge of the central pit (Figures 5, 7, 8). Bright carbonate deposits up to 10 m thick cover the undulating top of this mesa despite being ~1 km above the pit floor. Bright streaks on the right-edge of plateau are either seepage of brines from the crest of the mesa or downslope talus of bright materials or both. The presence of deposits at these elevations might seem incongruous but also occur along the outer margins of the central depression at similar elevations. They do require permeability across most of the depression for brines to reach these locations at different elevation.

The lack of large constructional edifices and the varied outcrop locations all suggest formation by thousands of individual seeps producing thin deposits that coalesce into a contiguous unit where mostly densely concentrated. Subsurface fractures and localized permeability likely played a key role in both the concentration within the central structure and the highly localized outcropping of these deposits.

1.3 Carbonate Deposition – Vinalia Facula

The only other major outcroppings of extended bright carbonates occur in the group of 8 or so bright spots of Vinalia Facula (Figure 9-11) approximate half way between the central depression and the rim. These deposits occur within the large impact melt sheet discussed below. The large spots appear to be comprised of thousands of individual bright spots a few 10s of meters across that become more densely spaced and coalesced toward the centers of each major spot.

Outcrops of carbonates exhibit a variety of landforms in Vinalia, mostly as surface coating on shallow elongate depressions. In some cases, the deposits also cover one flank of a ridge suggesting direction deposition, such as by fountaining, but the exposures are too inconsistent to make this emplacement likely. Layering is not observed but is likely below the resolving power of the imaging. The only candidate constructional edifice is a low knobby dome <1 km across, that could be viscous material extruded onto the surface (Figure 11).

The large bright spots of Vinalia Facula are spatially associated with a set of through-going or cross-cutting fractures (Figures 9-10). These extend all the way across the crater to the southwestern rim but do not otherwise appear to be associated with any outflow or deposition. They cut into the carbonate deposits at Vinalia and hence may post-date deposition, although it is noted that fracture widening likely occurred due to mass wasting. Outcrops of the deposits along the rims of elongate cross-cutting fractures indicate local thickness of 10-15 meters (Figure 10), but in most outlying areas the deposits appear to be thinner.

As at Cerealia Facula, the coalescence of smaller dispersed carbonate outcrops into the larger Vinalia Facula bright spots, with limited thickness of no more than a few 10's of meters also suggests that deposition is through brine seepage at small, localized vents. The larger spots likely occur when seepage is more highly concentrated at the contiguous major spots. Permeability and fracture density, and fluid availability are thus highly variable across Occator. Why these occur only on the eastern floor and not the southeastern floor where impact melt is also relatively thick is unknown but plausibly related to deep fracture systems or preexisting subsurface structures.

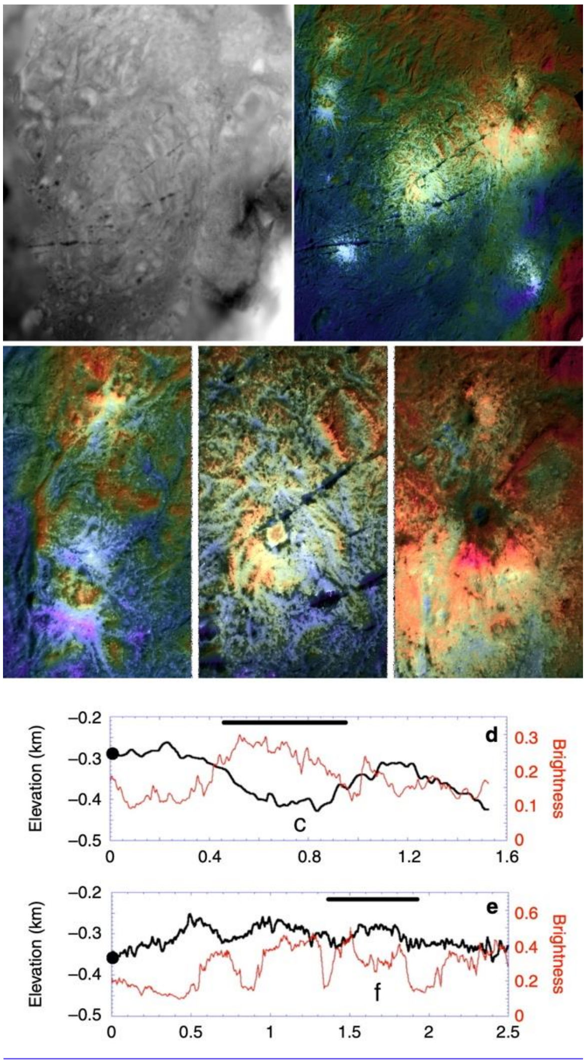

Figure 9: Vinalia Facula, Occator crater. Top row: topographic and mosaic color coded for topography showing overview of 7 major spots (scene width 30 km). Middle row: closeups of several major spots, color-coded for topography. Bottom row: profiles of brightness (red) and topography (black) showing general correlation of bright carbonate deposits and local depressions.

1.5 Hydrothermal Activity - Melt Sheet

The southeastern floor of Occator is dominated by a thick lobate deposit interpreted as impact melt ponded on the lowest part of the crater floor (Figure 1). This melt sheet is several hundred meters thick near its center and has a ropey surface texture at multi-kilometer scales in the northern quadrant but a more knobby texture in the southwest.

Most of the surface of the melt sheet is covered in multitudes in small barely resolved pits interpreted to be micro-impact craters. The degree to which some or even many of these pits could be exhalation pits due to vapor or water release as the melt sheet cooled and solidified, exsolving minerals and volatile gasses is plausible but not known.

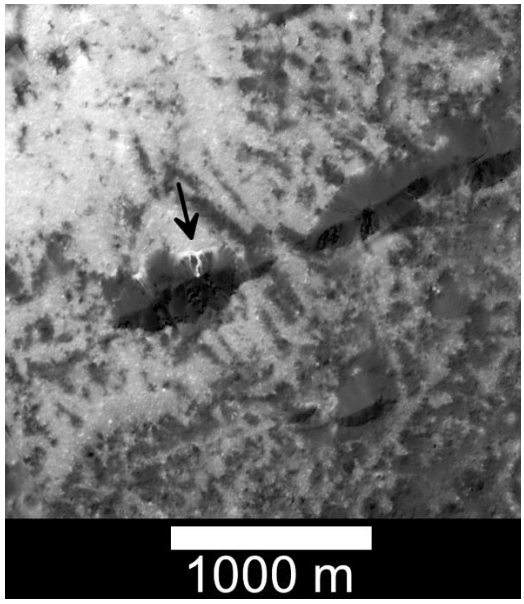

Figure 10: Close-up of large bright spot highlighting the sinuous and isolated bright spots that coalesce toward the center of the major spot at upper left. Arrow highlights a scarp exposing the thickness of the bright deposits (~10 m).

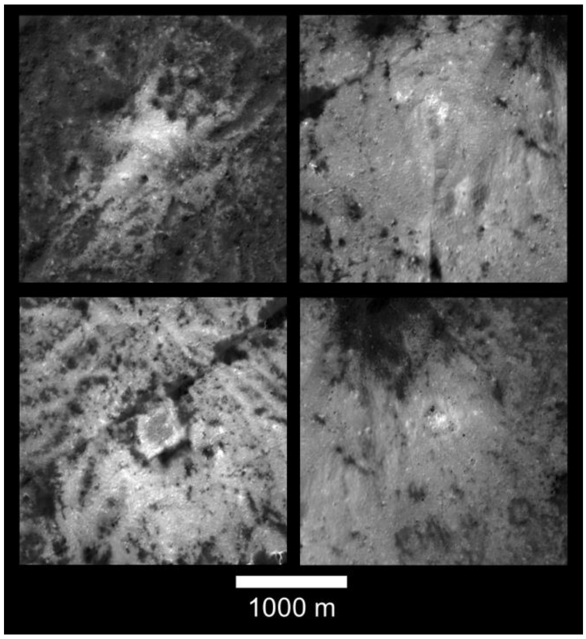

Figure 11: Close-up of large bright spots in Vinalia Facula highlighting the variety of manifestations. The sinuous bright tendrils in upper left view. mostly follow low topographic valleys between ridges. The contiguous sheet at upper right covers a variety of preexisting topographic features. The small bright feature at center of lower right view is a small low dome that might be the only constructional edifice thus far recognized.

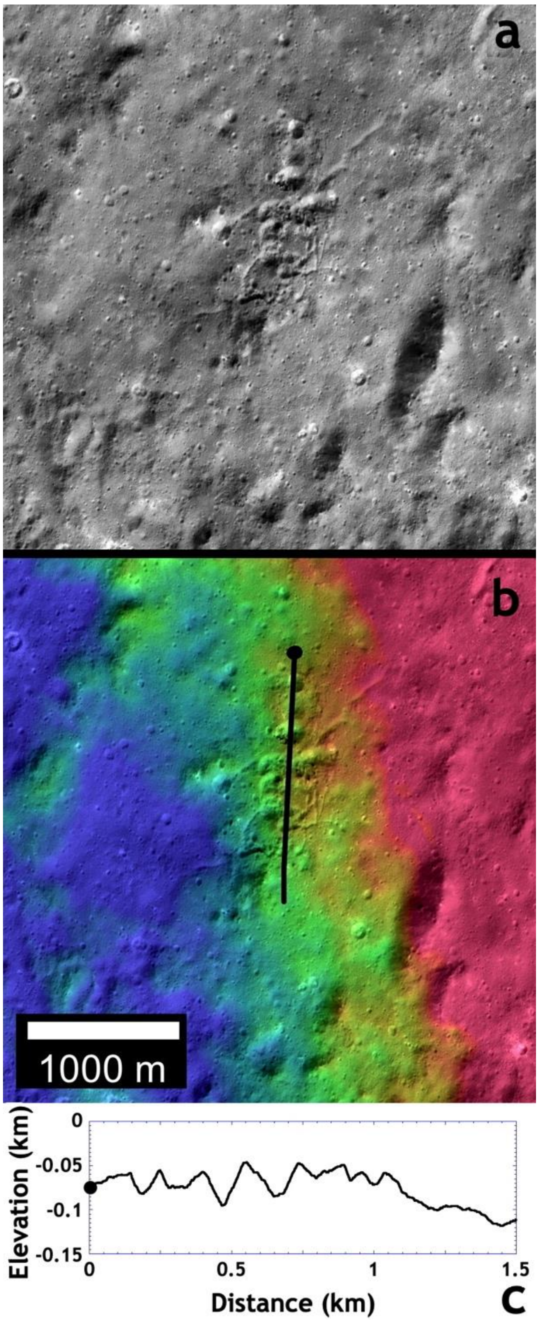

Figure 12: Close-up of unusual, clustered pits and fractures on floor of Occator. Top row: mosaic; Middle row: mosaic color coded for topography. Bottom row: topographic profile.

Several unusual features are definitively not impact related (Figures 12-15). Sinuous fractures abound but most may be related to contract cracking due to the solidification of the impact melt. Oval pits occur in at least two locations, one of which forms a tight cluster associated with connecting fractures that are the more prominent example of hydrothermal breaching of the surface (Figure 12). A shallow oval rimmed feature and a nearby yellow-colored promontory additional examples (Figure 13), yellow colors being the exception.

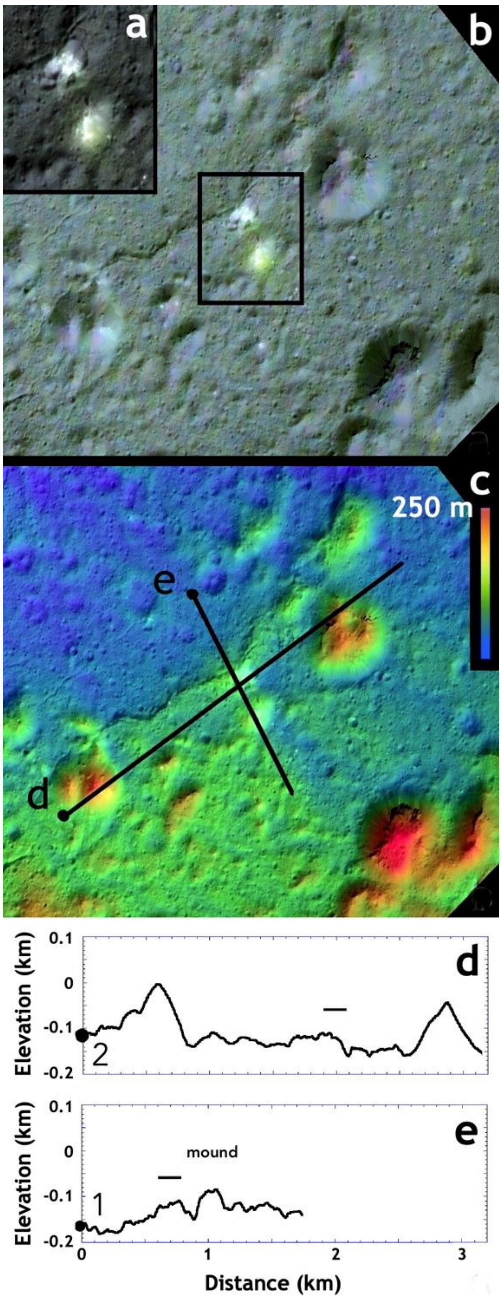

Figure 13: Small shallow oval rimmed feature adjacent to bright yellow mound within impact melt sheet on Occator crater. Top row: color image; middle row: mosaic color coded for topography; Bottom row: topographic profiles across oval feature and small mound (horizontal bars). Scene width 3 km.

Mapping reveals additional pits and troughs but suggest a widespread (Figures 14-15) but very low-density distribution of hydrothermal exhalation features across the crater floor, indicating that most of the floor did not experience hydrothermal outflow on the surface. This is in contrast to the more prodigious output at Cerealia and Vinalia Faculae and suggests that the overall output was less than at other smaller Ceres impact craters and that the floor of the crater may have been resistant to fluid flow except at the highly fractured uplift at crater center and the side center at Vinalia (where lateral subsurface fractures or layering may have enhanced fluid flow).

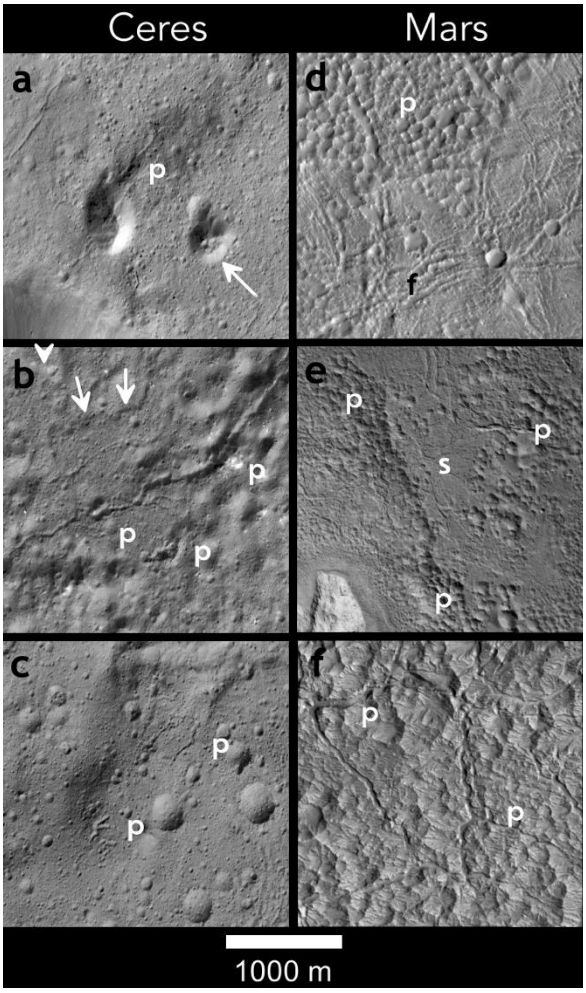

Figure 14: Close-ups of isolated pit (p) and trough structures on Occator (left) and large crater Mojave om Mars (right). Of special interest are the oval pits in center left view linked by through-going fracture. Arrows point to possible flow front in center left or pitted mound (top left).

Figure 15: Close-up of bright spots and pit chains of possible hydrothermal origin on northern floor of Occator crater. Scene width 2 km.

1.4 Hydrothermal Activity - Rim

Smaller highly localized bright deposits occur near the crest of the crater rim (Figure 16). These occurrences are perhaps incongruous relative to the mapped subsurface outcrops in large terrestrial craters where hydrothermal seepage is localized near the base of crater rims. How hydrothermal fluids would find their way up to the top of the rim scarp is unknown and they may instead be outflow or downslope creep of exposed preexisting localized concentrations of carbonates or salts.

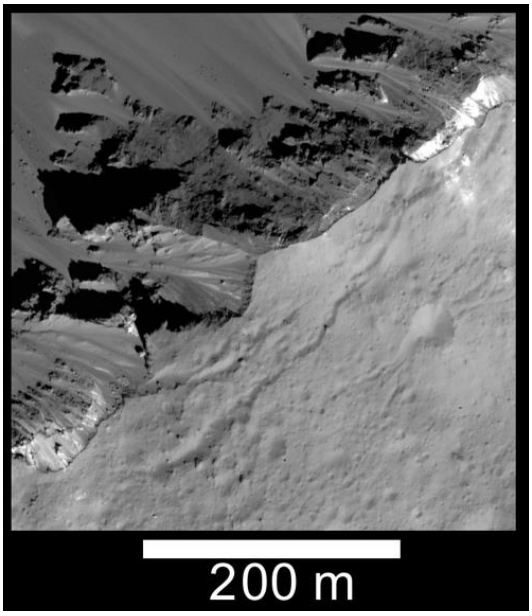

Figure 16: Close-up of rim scarp of Occator, highlighting bright carbonate deposits in rim.

2. CONCLUSION

The mechanisms of deposition of carbonates and salts on the surface of Occator craters remain partially unresolved. Despite this it is evident that most of these bright materials likely form by the direct precipitation of minerals from brines that outflowed or seeped onto the surface from innumerable small vents (e.g., Figure 17). Pingo development within the melt sheet resulting from possible subsurface fluid freezing has been proposed but observational evidence is weak and this process was probably not widespread. Activity across the crater floor was sporadic and low intensity. Most activity was concentrated at crater center (Cerealia Facula) and in several large spots on the eastern floor (Vinalia Facula) where carbonate deposits follow local contours that partially fill local valleys but some are on the flanks of low hills or ridges indicating venting occurred in any local setting. Deposits coalesced into large contiguous surface coatings at major centers.

Concentration of hydrothermal outflow and deposition in the central areas is consistent with impact modeling showing preservation of liquid waters for protracted periods only in the subsurface conical area of the central warmest regions, which then refroze forcing fluids to the surface. Indirect evidence suggests that the central warm fluid-rich zones may also have tapped deeper brine layers.

The duration of hydrothermal activity at Occator remains uncertain but could have been as long as a few million years. That it was localized in several highly active areas and not pervasive, as observed on some martian craters, is likely due to impact into a high standing but abnormally volatile-poor plateau or formation of a low permeability cap-rock material such as impact melt during the impact event.

Figure 17: Example of low travertine deposit from brine seep at Jemez Springs, Valles Caldera, New Mexico, USA. Photo by author.

The formation of hydrothermal deposits on such a small airless ice-rich body was unexpected but is consistent with hydrothermal activity in large craters early Earth (and Mars), resulting in local transient environments favourable to and possibly contributing to the early development of life. The mixed ice-rock-carbonate crustal composition on Ceres played a key role in making hydrothermal activity possible. The degree to which such activity occurred elsewhere, such as Callisto or Ganymede, is unknown at present but occurrence on Ceres indicates this process may have been very common and widespread in other planetary systems as well.

Plans are being developed for a possible future landed mission and sample return from the carbonate-hydrothermal sites on Ceres. Sample analysis and in situ surface mapping would allow direct mineralogical study of the deposition process and brine composition. Such investigations would allow direct study of the important processes of brine mobilization and hydrothermal alteration of planetary bodies in an alien setting.

ACKNOWLEDGEMENTS

The authors thank NASA and the Discovery Data Analysis Programs for supporting these investigations.

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ISSN 2703-4275