Feierberg et al., 1981

INTRODUCTION
The authors present IR spectra (0.9–2.5 µm) and narrowband photometry (3.0–3.5 µm) for low-albedo asteroids Ceres, Pallas, and Bamberga. The authors compare the major mineral absorption features to those found in primary carbonaceous chondrite matrix material (CCMM) and secondary alteration products. The observed differences between spectral reflectances between the three C-type asteroids are explained by (1) variations in the extent of aqueous alteration of CCMM and (2) compositional differences between the asteroids.

AQUEOUS ALTERATION
Table 1 lists the CCMM components and alteration products that were examined in the IR spectra and narrowband photometry for each of the three low-albedo asteroids. In general, Ceres is found to be dominated by clay minerals with some hydrated salts. The spectrum of Pallas is dominated by Fe-poor clay minerals. Finally, Bamberga shows signatures for some Fe-rich clay minerals and an abundance of magnetite, which is an alteration product of iron-rich clays.

ALBEDO VS. HYDRATION
Fig. 1 illustrates the relationship between the 2.2-µm albedo and the 3-µm reflectance for Ceres, Pallas, and Bamberga. Ceres is the only asteroid that falls below the mixture trend line and this is likely due to the presence of salts. Hydrated salts and opaques have inherently weaker 3-µm absorptions due to lower optical densities.

<table>
<thead>
<tr>
<th>Primary Components</th>
<th>Spectral Reflectance Properties</th>
<th>1 Ceres</th>
<th>2 Pallas</th>
<th>3 Bamberga</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe-rich clay minerals</td>
<td>strong absorption features in uv due to iron cations and at 3 µm due to water molecules</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Carbon</td>
<td>low-albedo opaque suppresses absorption features of other components</td>
<td>?</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>Fe-poor olivine, pyroxene</td>
<td>low optical density, spectrally featureless</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Alteration Products</td>
<td>Changes in Spectral Reflectance</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Fe-poor clay minerals</td>
<td>absorption feature in uv due to iron cations much weaker</td>
<td>+</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>Magnetite</td>
<td>low-albedo opaque, can be distinguished from carbon by its 1-3 µm spectrum</td>
<td>?</td>
<td>?</td>
<td>+</td>
</tr>
<tr>
<td>Hydrated salts</td>
<td>high albedo, low optical density, strong absorption feature at 3 µm</td>
<td>+</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1. Table 1 from Feierberg et al., 1981. Spectroscopic evidence for aqueous alteration products on the surfaces of low-albedo asteroids. Key to symbols: + evidence for its presence; – evidence against its presence; ? could be present, no evidence for or against.
Fig. 1. Fig. 5 from Feierberg et al., 1981. The 3-µm band depth dependence on 2.2-µm albedo for laboratory samples and asteroids. The dashed line is the trend for the clay minerals as they are mixed with increasing amounts of carbon black.

We discussed how chlorites and serpentines do not change much in the presence or absence of water. This is because hydroxyl is very stable, and the structuring of these minerals does not allow for the interlayering of water as seen with smectites. Montmorillonite, a swelling clay, changes because water is pulled water out of the interlayer region, causing the 3-µm absorption feature to decrease. In contrast, when water is removed from a salt such as MgSO₄, an actual phase change occurs. Therefore, salts behave differently than clays do (in which water can come and go with an actual phase change). Thus overall the presence and spectral “detections” of salts can be rather non-unique.

**SALTS, ICE OR AMMONIATED CLAYS?**

In the literature, three proposed phases to explain the 3-µm feature on Ceres include (1) salts, (2) water ice, and (3) ammoniated clays. We discussed the implications of each of these possibilities.

While the presence of salts is consistent with the spectrum of Ceres, as discussed previously, it can be very non-unique. This solution can thus be rather unsatisfying if salts are “detected” on the basis of a non-detection.

Other researchers have suggested that the 3-µm feature can be attributed to the presence of water ice. We discussed, however, that this option does not seem very plausible given that thermal models demonstrate that water ice is not stable on long-term time scales at the surface of Ceres, with the possible exception of some of Ceres’ polar permanently shadowed regions that have remained shadowed even through its cycles of obliquity shifts. Given that reflectance spectroscopy takes measurements of the optical surface, water ice would not be stable at this surface, and thus it is unlikely that a global signature of water ice would produce this 3-µm feature in the spectrum of Ceres.

Finally, it is possible that Ceres contains ammoniated clays. We discussed the concept that the presence of ammoniated clays may imply that Ceres is a Kuiper Belt Object (KBO) that migrated inward to the main belt. We questioned whether this concept would be disproved if New Horizons observed two KBOs for which the acquired spectral data did not resemble those of Ceres. However, we would not expect the spectrum of Ceres to look like that of a current KBO anyway, because Ceres has (theoretically) migrated inward and has had a completely different geologic history. As Ceres traveled inward past the ammonia snowline, the ammonia from ice mobilized. Because ammonia is no longer stable, aqueous alteration begins to occur in the presence of liquid, and ammoniated clays are formed.

We also discussed that the presence of ammonia does not necessarily equate to the idea that Ceres is a KBO. Cometary impacts could alternatively be a source for providing ammonia to the surface of Ceres. There is, however, likely a limit to how much ammonia comets can deliver via impacts. Therefore, there may be a specific threshold of how much can be detected on the surface of Ceres before ruling out this hypothesis as a plausible source for the ammonia on the basis of impact population and the cratering history for Ceres.
ALTERATION OF CCMM
The authors conclude that the surface compositions of Ceres, Pallas, and Bamberga are unlike one another, and furthermore, unlike the compositions of any carbonaceous chondrites in the laboratory collections. Differences in the degree of alteration of the primary CCMM minerals is invoked to explain these differences. We discussed that as a result of these major differences, CCMM material is not an adequate meteoritic analogue for these asteroids. Thus, when doing studies of Ceres, for example, it is most appropriate to create your own laboratory mixtures to reproduce the appropriate spectral features (e.g., Milliken and Rivkin, 2009).

Buczkowski et al., 2016

INTRODUCTION
The authors present a new geologic map derived from Dawn Framing Camera data. They detail interesting geomorphological features on the surface of Ceres, including impact craters, Occator crater, floor-fractured craters (FFCs), polygonal craters, linear structures, domes and mounts, and lobate flows. Overall, the crater morphology suggests that Ceres has a strong crust and a rock-dominated crust with contributions of ice or salt. Evidence for sub-surface ice includes possible cryovolcanism and cryomagmatism as suggested by Ahuna Mons, Occator dome, and floor-fractured craters.

LOBATE FLOWS
We discussed the range of mass-wasting flows that are observed across the surface of Ceres, and how the differences in morphology may suggest differences in sub-surface ice content. For example, Type 1 flows are lobate in nature and are similar to ice-core and ice-cemented flows on Earth. These flows are typically found in the higher latitudes on Ceres (Fig. 2). Type 2 flows are longer and thinner in nature with fan-shaped deposits, while Type 3 flows tend to be broad sheets of smooth material and even thinner.

Fig. 2. Fig. 8D from Buczkowski et al., 2016. Location of lobate flows on Ceres. Blue crosses represent Type 1 flows, green triangles are Type 2 flows, and yellow dots are Type 3 flows.
than Type 1. The authors show the global distribution of these features in Fig. 2.

We discussed that the latitudinal distribution of these features is overall not completing convincing. The distribution in Fig. 2. does show that the Type 1 flows tend to be restricted to higher latitudes, however, examples of these flows are also identified as far south as ~40°N/S. Furthermore, the distribution of Type 2 and Type 3 flows is particularly non-linear (Fig. 2.), even though we would expect more fluidization toward the equator under the authors’ argument that these features are showing progressively more amounts of mass wasting of ground ice. Overall, these arguments would have been strengthened with a quantitative analysis.

**CRUSTAL HETEROGENEITY**

There is a distinct lack of large-scale craters on the surface of Ceres. It is possible that long-wavelength topography has viscously relaxed away. We discussed the possibility that different amounts of ice in the crust leads to heterogeneities. Furthermore, the Gamma Ray and Neutron Detector (GRAND) instrument on Dawn has indicated a general enhancement in hydrogen detection toward the poles, suggesting that subsurface ice-content increases with latitude.

**CRUSTAL COMPOSITION**

Overall, the crust is likely too strong to be dominated by ice, which is indicated by the presence of polygonal craters and long-lived lineations. But there is evidence for the importance of ice is some localized locations, such as relaxed craters, FFCs, and Ahuna Mons.

**Hiesinger et al., 2016**

**INTRODUCTION**

The authors present observations of Ceres’ surface revealing a heavily cratered surface and heterogeneous crater distribution. There is an apparent lack of large craters that may indicate viscous relaxation or overprinting. The depth-to-diameter (d/D) ratios of smaller craters suggest that the crust is an ice-rich-rock mixture.

**SIMPLE-TO-COMPLEX TRANSITION**

![Fig. 3. Fig. 2 from Hiesinger et al., 2016. (A) Simple-to-complex crater transitions on Ceres (small red circles represent simple craters; large red circles represent complex craters) occur at diameters of 7.5 to 12 km. Moon (black line) and those of the icy bodies Dione (blue circles), Tethys (green triangles), and Ganymede (blue open circles) are shown for comparison. (B) Taking into account its surface gravity, the depth/diameter ratio of Ceres (red triangle) follows the same trend as other icy bodies (green triangles). The transition diameters to complex craters of rocky bodies (brown circles) are shown for comparison.](image-url)
Fig. 3. Shows the simple-to-complex transition diameters of impact craters on Ceres and selected icy moons and rocky bodies. We discussed the fact that taking into account its surface gravity, the transition diameter of Ceres (red triangle in Fig. 3.) follows the same trend as other icy bodies (green triangles). However, d/D ratios are also similar to those of the dry Moon (black line in Fig. 3a). To reconcile this, the crust is neither purely icy nor rocky.

ICE SHELL STRIPPING
One concept entertained in our discussion was whether or not we would expect to see the extensive record of impact cratering if Ceres once was encapsulated by an ice shell that has since been stripped away. We discussed that this would depend on the timing of when the stripping occurred relative to the history of impact bombardment. For example, if the stripping occurred early on in solar system history, possibly within the first 10 Myr as has been suggested by certain models, then we would still expect to see the full extent of craters on Ceres that is recorded on the dwarf planet’s surface today. Thus one of the major caveats of the ice stripping model is that it is very difficult to test. All potential evidence of it has been erased, and it was stripped away early enough to still allow for an extensive cratering record.

A COMPLEMENTARY STORY
The work of Heisenger et al. (2016) complements that of Buczkowski et al. (2016) and suggests that Ceres is a body composed of rock and ice. The proportion of rock and ice likely varies vertically with depth. Since these papers were published, the overall story has not changed much with newer LPSC results. Data from Dawn indicate that Ceres is not a purely rocky body like Vesta, but is instead a rather complicated dwarf planet in the asteroid belt.

References