Large mineralogically distinct impact melt feature at Copernicus crater – Evidence for retention of compositional heterogeneity

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[1] Despite several lines of evidence for efficient mixing of impact melt in complex craters, we document mineralogical heterogeneity in impact melt deposits on a scale of tens of kilometers on the Moon in the 96 km-diameter Copernicus crater. This heterogeneity is in the form of a large, sinuous impact melt feature on the floor and northern wall that is spectrally distinct from melt in its immediate vicinity. This melt feature spanning >30 km in length and 0.5–5 km in width has relatively short-wavelength, narrow ferrous absorption bands near ~900 nm and ~2000 nm indicating a more Mg-rich pyroxene composition as compared to impact melt deposit in the vicinity which is relatively rich in Fe/Ca-pyroxenes. This distinction provides evidence for the preservation of compositional heterogeneity in impact melt in complex craters on the Moon and documents an example of inefficient mixing of melt during the cratering process. Citation: Dhingra, D., C. M. Pieters, J. W. Head and P. J. Isaacson (2013), Large mineralogically distinct impact melt feature at Copernicus crater – Evidence for retention of compositional heterogeneity, Geophys. Res. Lett., 40, doi:10.1002/grl.50255.

1. Introduction

[2] Impact cratering is known to be a very rapid and dynamic process and is divided into three stages: (1) contact and compression, (2) excavation, and (3) modification [e.g., Gautel et al., 1968]. Impact melt formation and emplacement are important components of the excavation and modification stages [e.g., Grieve et al., 1977], and there is abundant evidence that impact melt is mobile during the short-term modification stage of the transient cavity [e.g., Hawke and Head, 1977; Bray et al., 2010; Osinski et al., 2011]. Highly chaotic and dynamic movement of superheated impact melt is predicted from theoretical considerations [e.g., Melosh, 1996]. Further, homogeneity of impact melt is reported in some terrestrial craters with diverse target substrates [e.g., Floran et al., 1978; Zieg and Marsh, 2005] suggesting highly turbulent mixing that would homogenize any initial compositional heterogeneities [e.g., Phinney and Simonds, 1977]. In contrast, some of the recent studies of terrestrial melt sheets have revealed heterogeneities associated with specific target lithologies [e.g., Darling et al., 2010]. Heterogeneities in impact melt have also been reported for craters in sedimentary targets [e.g., Osinski et al., 2008]. We report here the occurrence of a large impact melt feature at lunar crater Copernicus that is mineralogically distinct from surrounding impact melt deposits.

[3] Copernicus is a 96 km diameter, young complex impact crater (~779 m.y.; e.g., Hiesinger et al., 2012) located on the lunar near-side, extensively studied using telescopic [e.g., Pieters, 1982; Lucey et al., 1991; Pinet et al., 1993] and spacecraft observations [e.g., Pieters et al., 1994; Le Mouëlic and Langevin, 2001; Ohtake et al., 2009; Bugiolacchi et al., 2011]. The pre-impact stratigraphy (top to bottom) has been suggested to be [Schmitt et al., 1967]: (1) mare basalts, (2) Imbrium ejecta (Fra Mauro Formation), and (3) upper crustal material (pre-Imbrian megaregolith and anorthosites) [e.g., Hiesinger and Head, 2006, Figure 1.20]. Later, Earth-based spectroscopic measurements detected an olivine-bearing lithology in the central peaks [Pieters, 1982]. A noritic, thin upper crust and olivine-rich peak material from lower crust or even mantle was suggested by Pieters and Wilhelms [1985]. The crater shows a north-south compositional heterogeneity with more basaltic components detected along the southern wall [e.g., Pieters et al., 1994]. Recently, proposed east-west differences [Arai et al., 2011] and identification of Mg-spinel [Dhingra and Pieters, 2011] at Copernicus have expanded this diversity. Impact melt deposits are extensively present in various parts of the crater, in the form of smooth ponds, debris-laden deposits and flows, some of which contain quenched glass [Smrekar and Pieters, 1985].

2. Newly Identified Impact Melt-Related Feature

[4] Spectral reflectance analysis for the Copernicus crater interior has been carried out using high spectral resolution data from the Moon Mineralogy Mapper (M3) instrument on board Chandrayaan-1 mission [Goswami and Annadurai, 2009]. M3 is a VIS-NIR imaging spectrometer [e.g., Pieters et al., 2009] operating between 460 and 3000 nm in 85 spectral bands at a spatial resolution of 140–280 m. The data has been corrected for viewing geometry, thermal emission, and ground truth. Supplementary datasets include data from the Terrain Camera (TC) [Haruyama et al., 2008] onboard Kaguya mission, data from the Lunar Reconnaissance Orbiter Camera (LROC) [Robinson et al., 2010] and the Lunar Orbiter Laser Altimeter (LOLA) [Smith et al., 2010] onboard LRO mission.

2.1. Geologic Setting of the Study Region

[5] The geologic context of the area is illustrated in Figures 1a–d. The geological map of Copernicus shown in Figure 1a delineates two floor units that have been interpreted as impact melt deposits (ft = textured floor
material, magenta color; fh = hummocky floor material, red color). Figure 1(b) shows an image of the crater from the Wide Angle Camera (WAC) onboard LRO. Note the relatively smooth northwestern crater floor which is believed to be comprised of thick melt deposits. The area outlined in black in both Figures 1(a) and 1(b) corresponds to the study region for which M3 data were analyzed (Figures 1c and 1d). The newly identified melt-related feature is not easily discernible in the albedo images and is outlined in red in the sketch of the study region (Figure 1d) based on M3 spectral data.

2.2. Characteristics of the Proposed Sinuous Melt-related Feature

2.2.1. Spectral and Compositional Properties

The character of the melt-related feature is best represented in a RGB color composite (Figures 2a–b). The red channel represents albedo variations at 1489 nm, green shows absorption band strength variations across the 2000 nm, while blue captures band strength variations around 1900 nm (see Table 1 in Supporting Information for band parameter algorithm). The sinuous melt-related feature appears cyan-blue color, while two fresh craters located west of this feature (but still within impact melt) appear green in this color composite. The spatial extent of the sinuous melt-related feature is marked with solid and broken lines based on the clarity of the spectral boundaries. Various perspectives of the region shown in Figure 2(b) provide better understanding of the geological setting and the relationship of the melt feature with the surroundings. The parameter images can be observed individually in Figures 2d–f. The feature can also be seen in independent color composite of Kaguya MI multispectral data presented by Arai et al. [2011], although the authors did not comment on the possible origin of this feature.

The broad spectral variations observed in the color composite were further analyzed by obtaining representative spectra and studying the differences in shape, strength, and center of the absorption bands. As mentioned above, the mineralogical diversity at Copernicus crater has been well studied. M3 spectra for these key lithologies are illustrated in Figure 3(a). We also include the recent detection of...
Mg-spinel (R4 in Figure 3a and marked by a green arrow in Figure 2a) at Copernicus [Dhingra and Pieters, 2011], a new component in the existing diversity.

Apart from diverse primary lithologies, impact melt deposits at Copernicus also exhibit compositional variability with some areas displaying relatively strong absorption bands while others having either weak or no absorptions altogether. Materials excavated by relatively young craters or exposed at steeply sloped surfaces have little soil accumulation and are referred here as “fresh surfaces”. Representative spectra from fresh surfaces (A2, A3; Figure 3b, c) within the newly identified melt feature have band centers at shorter wavelengths and a narrower 1 μm absorption band compared to spectrum (A1) from the fresh crater located outside the sinuous melt feature in the northwestern thick melt deposits (see Figure S1 in Supporting Information for location). The observed difference in band center implies a different pyroxene composition [e.g., Adams, 1974; Burns, 1993; Klima et al., 2007, 2011], specifically more Mg-rich pyroxenes for the sinuous melt feature and more Ca- and Fe-rich pyroxenes for the fresh crater to the west in widespread impact melt deposits. The broader 1 μm absorption for #A1 may be solely due to the presence of clinopyroxene; however, an additional component such as olivine or quenched glass is also possible. Although fresh material outside the sinuous melt feature is less common, the #A1 spectrum (Figures 3b and c) from impact melt deposit appears to be representative (see Figure S2 in Supporting Information for various sampling locations used to validate compositional differences, Figure S3 for spectra and Section 1 for discussion on representative nature of sampling).

To further assess the compositional variability of the region, we sampled soils from various locations on the floor (see Supporting Information, Figure S1) since soil reflects a relatively well-mixed composition of an area (aided by micro-meteorite impact gardening processes) and is therefore a more representative spectral sample (though it has weaker spectral bands). Spectra of soils sampled within the sinuous melt feature (6-8; Figures 3d and S4 in Supporting Information) have a very consistent spectral character with short wavelength pyroxene bands comparable to those observed.

Figure 2. (a) RGB color composite based on spectral parameters prominently captures the sinuous impact melt feature as distinct unit (marked with solid and broken lines). Here, R = albedo at 1489 nm, G = IBD 2000 nm, and B = BD 1900. Green arrow points to the location of newly identified Mg-Spinel lithology. (b) Various perspectives of the study area. Here, M3 data is draped over LOLA topography. (c) The M' 1489 nm albedo image provides context, but does not explicitly show the sinuous impact melt feature. (d) The IBD1000 parameter highlights the central peaks and fresh craters on the floor. (e) and (f) BD1900 and IBD2000 parameter images show the sinuous feature.
for fresh surfaces (A2, A3; Figures 3b and 3c) in the melt feature, indicating more Mg-rich pyroxene composition. Spectra of soils elsewhere within impact melt deposits either have no discernible absorptions or have very broad bands around 1000 nm. The latter (2, 3; Figure 3d and located outside of the melt feature) suggests the presence of quenched glass which is consistent with telescopic observations [Smrekar and Pieters, 1985]. A soil from the hummocky southern floor [1; Figure 3d] exhibits pyroxene features but has a distinct composition in view of the different 2 μm band position when compared to spectra of soils inside the sinuous melt feature [6–8; Figure 3d].

Integrated analysis of fresh surfaces and soils in the study area indicate that the sinuous melt feature has a composition consistent with relatively Mg-rich pyroxenes (commonly associated with norites) as compared to more Fe-and Ca-rich pyroxenes (commonly associated with basalts) in the surrounding melt deposit.

2.2.2. Surface Morphology and Texture

Topography derived from LOLA data shows a net relief of ~250 m on the crater floor with the newly identified sinuous melt feature being located in a broad depression (blue region, Figure 4a). High spatial resolution images (10 m/pixel) from Kaguya TC were studied (Figures 4b and 4c) to identify brightness variations that may be linked with topographical differences between the sinuous melt feature and surrounding impact melt deposits. Subtle variations were noted in the northern part of the melt feature (also observed in Figure 1c, yellow arrow), but no differences were discernible in the central and southern part, suggesting overall low relief in the area.

Radar observations at 12.6 cm wavelength from both ground (Arecibo) and spacecraft (LRO Mini-RF [Nozette et al., 2010] total power images at higher spatial resolution) suggest a similar degree of roughness within and outside the sinuous melt feature making it indistinguishable from the surrounding melt deposit [B. Campbell and L. Carter, Pers. Comm.].

3. Discussion

There are several possible causes for the observed mineralogical heterogeneity including (1) melting of a heterogeneous target and insufficient time for mixing, (2) isolation of an impact melt component during initial stages of melt movement and its later incorporation to the floor, (3) variable cooling and differentiation of the melt perhaps due to volume differences and/or abundance and mineralogical variability of lithic clasts, and (4) impactor debris contamination [e.g., Schultz et al., 1998].

We interpret the observed differences in the mineralogy of the sinuous melt-feature (Mg-rich pyroxenes) and the surrounding impact melt deposits (Fe-Ca-rich pyroxenes) on the crater floor as due to inefficient mixing of melt during the cratering process. Terrestrial examples of heterogeneous melt deposits [e.g., Kring et al., 2004; Lambert, 2010] support this possibility. The two melt compositions are essentially mimicking pre-impact target composition (basalt, norite), which is known to be heterogeneous [e.g., Pieters et al., 1994]. Therefore, heterogeneity of impact melt in the present case likely represents the original composition of the target rocks. Although some fractionation of the melted material may occur [e.g., Vaughan et al., 2013], in

![Figure 3. (a) Spectral diversity at Copernicus. R1- Olivine + Crystalline Plagioclase, R2-High Ca-pyroxene, R3-Low Ca-pyroxene, R4- Mg-spinel, R5-Olivine. (b) Fresh surface spectra of impact melt deposit within (A2, A3) and outside (A1) sinuous melt feature. (c) Spectra in Figure 3b with continuum removed (derived after dividing the spectra with a straight line continuum between 730 nm and 1618 nm). (d) Continuum removed spectra of soils within and outside the sinuous melt feature (See Supporting Information Figure S4 for soil spectra without continuum removal).](image-url)
the present case, compositional differences have not been observed to be linked to sampling depth (which would be expected in case of differentiation), and therefore we favor preservation of the target heterogeneity (#1 and #2 above) as the likely cause. In this scenario, the sinuous melt feature likely represents preservation of an outwardly (radial) streaming zone of impact melt derived from a mineralogically distinct (noritic) horizon of the target substrate. The observed sinuous nature could be attributed to deformation accompanying melt drain-back during the modification stage of the cratering event. Furthermore, the spatial relations are intriguing and may offer insights into melt dynamics; the sinuous melt feature occurs on the floor and crater wall, north of the central peaks but no evidence is seen for the continuation of this feature on the floor to the south of central peaks.

4. Conclusions

[15] The spectroscopically identified sinuous impact melt feature at Copernicus has provided a view of compositionally heterogeneous lunar impact melt on a scale of several tens of kilometers. There are at least two mineralogically distinct varieties of impact melt (Mg-rich pyroxene vs Fe-Ca-rich pyroxene) occurring in close proximity on the floor of Copernicus, over a distance of ~30 km. Pre-impact target stratigraphy plays an important role in the type and form of impact melt produced in a cratering scenario where an outward (radial) streaming melt (and its later drain-back) preserves the character of the source lithology. The Copernicus region thus provides compelling evidence for the preservation of impact melt heterogeneity in the context of an extremely dynamic cratering process, strengthening its potential as a future exploration site.

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