Geological mapping of impact melt deposits at lunar complex craters
Jackson and Tycho: Morphologic and topographic diversity and relation to the cratering process

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1. Introduction

Crater floors are the largest repositories of impact melt deposits at impact craters. The floor region also exhibits a chaotic landscape owing to its continuous evolution during the cratering process, starting with the compression of the material at the impact point and immediate vicinity, followed by rapid expansion into a transient cavity aided by the excavation and displacement of material (along with melting) and finally taking shape during the modification processes wherein the displaced and melted material, that failed to escape, starts to accumulate on the crater floor as the crater units take form e.g. (Gault et al., 1968; Grieve et al., 1977). Additional levels of complexity and disturbance are incorporated during the formation of complex craters and basins with the formation of terraces, central peaks, peak rings and rings, e.g. (Melosh, 1982; Melosh and Ivanov, 1999; Head, 2010; Baker et al., 2011; Potter, 2015). The morphological characteristics of impact melt and their spatial distribution around craters have been extensively studied to understand the process of cratering, especially the relationship of melt movement and emplacement with various cratering parameters, e.g. (Howard and Wilshire, 1975; Hawke and Head, 1977; Krüger et al., 2013). Several studies have utilized impact melt deposits to obtain estimates of their physical properties, e.g. (Onorato et al., 1976; Simonds et al., 1976; Bray et al., 2010; Denevi et al., 2012; Xiao et al., 2014).

The floors of impact craters present a complex geological setting with wide variations in the morphology and topography which is, at first glance, difficult to interpret. Geological mapping is a fundamental technique to explore complex terrains by sequentially grouping together material with similar morphological attributes. The resulting geological map forms the primary set of information to understand and interpret the geological history of the region. Impact craters provide a challenging environment and geological mapping has been extensively used to understand their character e.g. (Schmitt et al., 1967; Wilhelms and McCauley, 1971; Ohman and Kring, 2012; Kramer et al., 2013).

Here, we map the complexity of impact melt deposits on the floor regions of Jackson and Tycho craters (Fig. 1) in great detail utilizing high spatial resolution datasets in order to understand the morphological diversity and spatial distribution of the various melt units. In addition, we identify interesting trends in the mapped units and utilize them to understand the probable impact conditions at each of the mapped craters as well as the subsequent
emplacement dynamics of the impact melt as the crater floor evolved.

2. Motivation and major objectives

High spatial resolution datasets from recent missions including LRO, Kaguya/SELENE and Chandrayaan-1, e.g. (Chin et al., 2007; Ohtake et al., 2008; Goswami and Annadurai, 2009) have revealed a rich diversity in the morphological form and wide distribution of impact melt deposits on the Moon, e.g. (Plescia and Cintala, 2012; Stopar et al., 2014). Apart from panchromatic imagery, near infrared and radar datasets have added new dimensions to the study of impact melt deposits, e.g. (Carter et al., 2012; Neish et al., 2014; Wöhler et al., 2014). In certain cases, entirely new perspectives on the character of impact melt have been presented. The recent discovery of a mineralogically distinct sinuous impact melt deposit on the floor of Copernicus crater has revealed crater scale mineralogical heterogeneity in lunar impact melts (Dhingra et al., 2013). In addition, the sinuous melt feature does not have any detectable morphological signature, which is in contrast to the conventional use of morphological criteria for the identification of impact melt deposits. In this vein, it is an entirely new perspective on the occurrence of impact melt deposits which needs to be included in the identification criteria. Another example of new insight is the impact melt affiliation of a large olivine-bearing deposit that is spectrally similar to an olivine-bearing lithology of primary origin (Dhingra et al., 2015a). This finding has highlighted the importance of geologic context for crystalline lithologies on the Moon that are often assumed to be always of primary origin.

Panchromatic imagery provides the highest spatial resolution views of the lunar surface and forms the baseline dataset for enhancing the interpretation of information from other datasets (viz. near-IR, radar datasets). The rich morphological diversity of impact melt deposits observed in the visible imagery is the product of the rapid succession of events that took place during the impact process, something that is beyond the current modeling capabilities and that has not yet been replicated in a controlled environment in the laboratory. The natural exposures of impact melt deposits at various craters are, therefore, the most accessible source of information available to decode the rapid time steps involved in the cratering process. Besides, the widespread occurrence of impact melt deposits makes them an important crater unit that needs to be characterized in detail. This forms our fundamental motivation for the work presented here. Geological mapping provides a systematic way to document the sequence of events that lie overprinted in the impact melt deposits. The major objectives of this study are the following:

(i) Systematically document the various morphological forms of impact melt on the crater floors of Jackson and Tycho.
(ii) Analyze the spatial distribution of various impact melt-associated units with respect to each other within a crater and contrast the characteristics across the craters.
(iii) Explore the possibility of using the mapped crater units for understanding the cratering process and the parameters controlling the melt formation, distribution and its morphological character.

3. Data and methods

In this study, we have evaluated impact melt properties at complex craters Jackson and Tycho (Fig. 1). The craters have similar size (71 km and 85 km, respectively), both are Copernican in age (evident from their bright-rayed nature) e.g. (Wolfe et al., 1975; Arvidson et al., 1976; Neukum and König, 1976; König, 1977; Lucchitta, 1977; Drozd et al,1977; van der Bogert et al., 2010; Hiesinger et al., 2012) and have formed in a predominantly highlands terrain. These set of similarities help simplify the interpretations which may otherwise be complicated by different crater size, target lithology and age. These similarities also allow the exploration of other factors/processes that may be playing a role in the emplacement dynamics of the impact melt. Accordingly, these two craters make a good pair for comparing and contrasting the nature of impact melt deposits for highland craters. Both the craters also have an extensive ray system, have prominent central peaks, and show extensive impact melt occurrences.

3.1. Geologic setting

3.1.1. Jackson

Crater Jackson (22.4°N 163.1°W; 71 km) is located on the lunar far side, east of Mare Moscoviense and north of the South Pole Aitken basin (Fig. 1). The crater has a spectacular ray system, has well-formed terraces as well as a cluster of central peaks with varying degrees of morphological freshness. Jackson’s location in the deep far side highlands in the feldspathic highland terrane (Jolliff et al., 2000) suggests its principal geologic setting to be feldspathic in nature. The crater diameter suggests an excavation depth of about 6 km (e.g. Cintala and Grieve, 1998).
3.12. Tycho

Tycho (43.29°S 11.22°W, 85 km) is located in the southern highlands region on the lunar near side (Fig. 1). However, some large mare basalt exposures can be observed in the north and west of the crater about 200 km away. Tycho has an extensive ray system that is observable with the naked eye, a prominent central peak and spectacular impact melt deposits that occur almost everywhere on the crater including the rim, walls, floor and even the central peak, e.g. (Howard and Wilshire, 1975; Hawke and Head, 1977; Dhingra and Pieters, 2011; Carter et al., 2012). Tycho is also known for its dark halo observable under high Solar Illumination which has been suggested to represent quenched glass (e.g. Smrekar and Pieters, 1985). The crater diameter suggests an excavation depth of about 7 km, e.g. (Cintala and Grieve, 1998).

3.2. Geological mapping

Impact melt deposits at both the craters have been mapped based on their morphological character on a scale of 1:25,000 using ArcGIS® software. The geographical extent of the mapping effort in this study covers the crater floor. The primary data used to map the impact melt deposits is Kaguya Terrain Camera (TC) at a spatial resolution of ~10 m/pixel (Haruyama et al., 2008). We have used the ortho-rectified and map projected version (TCO) of the TC dataset in our study. The data was downloaded as image tiles from the SELENE data archive (http://tdb.selene.darts.isas.jaxa.jp/) and subsequently imported into ArcGIS for generating the base image for impact melt mapping. The morphological details mapped out in this study are dependent on the illumination geometry. We have therefore taken care that images selected for mapping have comparable illumination conditions across the two selected craters. We have also utilized elevation information from LRO lunar orbiter laser altimeter (LOLA) e.g. Chin et al. (2007), Smith et al. (2010) for defining the floor units, thus increasing the information content of the geological map. The data was obtained from the LOLA PDS data node (http://imrenium.mit.edu/BROWSE/LOLA_GDR/) in the form of a digital elevation model (DEM) at a resolution of 512 pixel per degree. In addition, we have used LRO WAC derived topography (Robinson et al., 2010) through the LROC Quick Map functionality (http://target.iroc.asu.edu/q3/). We also used this online tool for extracting selected elevation profiles across the crater floor as well as general crater profiles. We show that integrating elevation information in the geological mapping provides additional scientific insights compared to the morphological details alone.

3.2.1. Mapping rules

There is a certain set of rules which were followed while mapping the impact melt units to ensure a systematic and effective approach. In an effort to avoid over-interpretation of the datasets, ambiguous impact melt regions were not mapped and were included in the undivided category. This category comprises of regions which were too complex to be sub-divided into the geological mapping framework adopted in this study or regions that have inadequate morphological detail to be classified meaningfully. However, it should also be recognized that the mapping effort is always a mix of objective criteria and subjective intuition that builds over time. We describe below the general rules that were followed while mapping:

(i) The unit boundaries are primarily defined based on the differences in physical characteristics such as albedo, texture and structure. In this study, we also used regional elevation differences as an additional criterion.

(ii) The morphological units should have sufficient spatial coherence in order to be mapped as a unit. Chaotic units that display a mixed character on small spatial scales are classified as ‘undivided’. In cases where one unit transitions into the other, the unit with the larger extent is used for assigning unit classification.

(iii) The morphological units are broadly classified into floor and peak sub-units for simplicity and to accommodate variability that may be specific to these broad units. This convention is followed even when certain units on the floor and the peaks share similar morphological character.

3.2.2. Geologic units

The various morphological forms of impact melt deposits identified on the floors of craters Jackson and Tycho are shown in Fig. 2 and explained below. We use an umbrella term ‘megaclasts’ for meter to kilometer-sized boulders which occur along with (usually embedded in) the melt deposits on the crater floor. We believe that some of these rocks represent broken-up fragments resulting from fracturing of rocks during the cratering process. Some of them could also represent displaced sections of crater walls or the central peaks. Megaclasts occur in variety of settings and at different spatial scales. Accordingly, they have been sub-divided into three units based on their relative sizes as Hummocky Unit, Isolated Mounds and Large Blocks (Fig. 2c, d and e respectively). The megaclast units are embedded in impact melt to different extents, similar to clasts in the impact melt and hence we use the term megaclasts, to emphasize the nature of this relationship between the boulders and the melt. However, there is a difference in terms of the spatial scale (mm to cm sized clasts in hand samples of impact melt, versus kilometer-size boulders embedded in impact melt here). Accordingly, the megaclasts should not be confused with the conventional small-size usage of the term ‘clast’. We use a ratio of area to the perimeter (each measured in meters) as a measure of the megaclast size in each of the mapped megaclast units (i.e. Hummocky Unit, Isolated Mounds and Large Blocks). The ratio is calculated by obtaining measurement statistics stored in ArcGIS for all of the mapped individual megaclasts in a given unit. Each mapped unit has a size range as is the case with any measurement. In addition, due to the variable melt-cover, the discrete nature of megaclasts within a unit is at times, hard to discern. This factor also expands the size range. The purpose of defining the area to perimeter ratio is to have a simple metric that can be used for making broad scale comparisons between different megaclast units. Accordingly, for any given megaclast unit, we have obtained an average value. However, the units are not mutually exclusive. There is some overlap in the size range between the megaclast units since in many cases there are transitions from one unit to the other. In cases, where a given megaclast has size in the overlap range between two units, then, it will be grouped in the unit (amongst the two) which is closest to it. This strategy avoids creating unnecessary small islands of a given unit, which by itself, will not be useful in the scientific analysis.

We use a combination of morphological character, surface albedo and elevation information to define the various impact melt units on the floors of craters Jackson and Tycho. Although majority of the units are common to the two craters, there are a few geological units that occur at one crater but are not observed in the other crater. We describe below the various impact melt morphological units:

(i) Smooth Unit: This unit is usually devoid of any megaclasts (Fig. 2a) and is therefore the smoothest among all the mapped impact melt deposits with minimal, if any, relief. We have sub-divided the Smooth Units based on their relative elevation on the crater floor as well as surface albedo differences. These are named as (a) Low Elevation Low Albedo Smooth Unit, (b) High Elevation Low Albedo Smooth
Unit and (c) Low Elevation Intermediate Albedo Smooth Unit.

(ii) Intermediate Unit: This unit has an intermediate morphology between smooth and rough (Fig. 2b). It is comprised of a topographically subdued megaclast population where individual clast boundaries are indistinct and they occur more as a continuous unit with low but observable relief. We have divided the Intermediate Unit into two sub-units based on differences in albedo and surface elevation within the unit: (a) Low Elevation High Albedo Intermediate Unit; (b) High Elevation Low Albedo Intermediate Unit.

(iii) Hummocky Unit: The unit is comprised of abundant megaclasts along with a relatively smaller proportion of smooth material (Fig. 2c). There is a high contrast in relief due to the hummocks and intervening low areas. This unit covers the smallest size range of megaclasts with an average area to perimeter ratio of ~50. The Hummocky Unit usually occurs as a pervasive unit but sometimes is also observed to be interrupted by, and interspersed among other units.

(iv) Isolated Mounds: This unit is comprised of megaclasts that stand out distinctively on the crater floor due to their relatively high relief and considerable spacing between individual megaclasts (Fig. 2d). This unit covers the intermediate range of megaclast sizes with an average area to perimeter ratio of ~200. This unit displays an identifiable coating of melt on individual megaclasts. In many cases, cooling cracks are distinctively observable in the melt layer.

(v) Large Blocks: This unit is comprised of very large blocks (or likely aggregates in some cases) on the crater floor (Fig. 2e)
that attain the size and elevation characteristics comparable to the central peaks (a few kilometers in size and a few hundred meters in elevation). However, in contrast to the central peaks, the individual blocks in this unit are generally more topographically subdued with gentler slopes and extensive melt cover. The **Large Blocks** cover the largest size range of megaclasts with an average area to perimeter ratio of $\sim 400$. In contrast to other megaclast units, this unit has the least number of individual megaclasts. At the same time, each megaclast in this unit has a much larger areal extent compared to other megaclast classes (as highlighted by their sizes). Individual megaclasts in this unit are sometimes located very close to the central peaks, while in other cases they are located much closer to the crater walls (along the periphery of the crater floor).

**vi) Melt Fronts**: These are large (several kilometers in length and width), continuous sheet-like structures (Fig. 2f) with clearly identifiable leading edge, generally having a lobate character. These features recently described by Dhingra et al. (2015b) generally tend to occur in clusters but occasionally, isolated **Melt Fronts** have also been observed. Some morphological features identified by previous workers (e.g. El-Baz and Roosa, 1972; Howard and Wilshire, 1975; Schultz, 1976) bear some similarities (viz. superposition relationship) with the **Melt Front** features mapped in this study. This unit is observed in different parts of the crater floor and wall-floor interface. The surface elevation characteristics of this unit highlight its perched nature with some of the melt fronts located at least a few hundred meters above the local floor elevation and emplaced on the slopes of the central peaks (e.g. Jackson crater). In other cases, the perched occurrences have been noticed on the crater wall-floor interface (e.g. Tycho crater). The **Melt Fronts** are far fewer in number and more localized compared to the previously described units. We define a sub-unit of **Melt Fronts** and name it as **Melt Front Striations**. This sub-unit has a morphology that is similar to the melt fronts. However, in this case, only the leading edge of the melt front is identifiable while the trailing side is merged with the background floor melt deposits (Fig. 2g).

**vii) Central Peak Low Albedo Coating**: This unit is fairly thin (sub-surface undulations are visible), has a low albedo and is principally associated with the central peaks although not all peaks host this impact melt unit (Fig. 2h). This unit is relatively smooth in texture with no observable cooling cracks. It has also been determined to be mineralogically distinct [e.g. Tompkins, 1997; Ohtake et al., 2009]. This unit is only observed at Jackson crater.

**viii) Central Peak Boulder Regions**: This central peak unit is comprised of boulder fields that are pervasive over the peak region (Fig. 2i). The mapped boulders are at the limit of image resolution and so are expected to be few 10s of meters in size or less. As a consequence, instead of mapping individual boulders, large boulder clusters were mapped.

**ix) Central Peak Unconfined Perched Deposits**: This central peak impact melt unit is principally defined as a smooth, perched deposit that is not confined by high standing topography on all the sides (Fig. 2j). This lack of complete topographic confinement makes these deposits different from impact melt ponds that otherwise occur in close proximity to this unit. This unit generally occurs on the slopes of the peaks but also sometimes occurs in relatively flat regions on the central peaks.

**x) Smooth Ponds**: These are flat deposits with usually smooth surfaces (negligible clasts if any) that are confined on all sides (Fig. 2k) by high standing topography. (xi) **Flows**: These are elongated features with lobate ends, generally occurring along the crater wall–floor interface in this study (Fig. 2l).

4. Impact melt morphological diversity on crater floors

The impact melt deposits on the floors of craters Jackson and Tycho display spectacular diversity in their morphological form, the relationships among various units and the overall hierarchy of complexity. The young age of the two craters allows confident identification of a variety of impact melt deposits located on the crater floor. Our detailed mapping of the floor impact melt deposits, the single largest impact melt unit in any typical crater, provides useful information about the character of the melt and the processes controlling impact melt formation and emplacement. We describe here the properties of these impact melt deposits.

4.1. Jackson

The floor of Jackson crater provides a diverse variety of impact melt units. We have mapped 15 geological units on the crater floor based on the surface texture, albedo and surface elevation. The latter was included due to a distinct elevation pattern observed on the crater floor (Fig. 3). There are five large melt units on the floor forming the base unit framework onto which the remaining units are overprinted (Fig. 4). The three most extensive units are **Low Elevation High Albedo Intermediate Unit** (N and NW crater floor), **High Elevation Low Albedo Intermediate Unit** (N and E crater floor) and **Low Elevation Low Albedo Smooth Unit** (SW crater floor). Each unit usually occurs as a coherent entity when viewed at the crater scale but may be locally interrupted by smaller units. In the case of the **Low Elevation Low Albedo Smooth Unit**, it appears to extend into the **Low Elevation High Albedo Intermediate Unit**. Relatively smaller-scale continuous units include the **Smooth Unit** and **High Elevation Low Albedo Smooth Unit**. These units are more limited in their spatial extent and are principally located in parts of the southern and eastern crater floor.

The second important set of mapped geological units includes the sparsely populated megaclasts. The largest megaclast unit represented by the **Large Blocks** (average area/perimeter ratio $\sim 400$) has a size range comparable to the central peaks. There are two **Large Block** units mapped at Jackson crater, one located in the northern crater floor and the other is close to the crater center. The latter is far away from the crater walls but is in close proximity to the central peaks. We interpret this spatial relationship to mean that the **Large Block** located near the crater center could potentially be a subdued central peak section. Both the **Large Block** units are extensively draped with impact melt with the latter showing an extensively fractured melt layer (Fig. 5a, b).

The next megaclast unit in terms of size is comprised of **Iso-lated Boulders** (average area/perimeter ratio $\sim 200$). This unit is largely located in the western part of the crater floor at Jackson. As reported for the **Large Blocks**, the **Isolated Mounds** also appear to be covered with impact melt with some showing an overlapping **Melt Front** (Fig. 5c). It is interesting to note that a similar relationship has also been observed earlier using lunar orbiter data [e.g. Schultz, 1976; plate 33b] where it was inferred that either the mounds protruded through the cooling melt or the melt had contracted and slipped off from the boulder due to gradual cooling. We have added a third possibility in this context based on the occurrence of these **Melt Fronts** elsewhere in the crater as well as at Tycho (Dhingra et al., 2015b). The lobate margins of these features could be indicating an advancing sheet of impact melt that was stalled due to higher elevation of the boulder in its path. However, further studies are required to develop a more robust interpretation of these morphologic features. Many of the mapped
4.2. Tycho

The impact melt on the floor of Tycho occurs at two different elevations with the western crater floor at a relatively higher elevation (> 200 m difference) than the eastern crater floor (Fig. 3f, g, h). This difference in elevation has also been noted earlier by Margot et al. (1999) using Earth-based radar observations. This two floor-level setting is similar to Jackson which contains a relatively elevated eastern crater floor as compared to the western floor (Fig. 3b–d). It is also interesting to note that the spatial extent of the two floor sections at Tycho (at different elevations) correlates roughly (but not exactly) with the spatial extent of the floor as divided by surface roughness (e.g., Pohn, 1972) (also see Fig. 3e and f). Based on the broad scale surface roughness of the crater floor, the western crater floor is hummocky while the eastern crater floor is smooth which is consistent with the geologic map of Pohn (1972) based on lunar orbiter IV and V images. However, we have been able to subdivide the floor into additional geologic units. We have mapped 15 geologic units on the crater floor of Tycho with four extensive units and 11 units of limited extent or discontinuous nature (Fig. 6). Among the four continuous units, two units (High Elevation Low Albedo Intermediate Unit and Low Elevation Intermediate Albedo Smooth Unit) have protrusions into nearby units (High Elevation High Albedo Intermediate Unit and Low Elevation Intermediate Albedo Intermediate Unit). Seven units amongst the 11 discontinuous or limited extent units are interspersed between the extensive units stated above. The remaining four units are located on the central peaks. We describe below several interesting trends in the distribution of the mapped units. While some units have similar trends as at Jackson crater, certain other units display a contrasting trend.

Among the megaclasts (viz. Hummocky Unit, Isolated Mounds and Large Blocks), the Isolated Mounds Unit is largely concentrated in the northern crater floor at Tycho while the Large Blocks Unit is mostly located in the western part of the crater floor (Fig. 6). The Hummocky unit is observed to be quite extensive on the crater floor (∼7% of the floor area) and this trend is in contrast to the relatively limited extent of this unit (∼3% of the floor area) at Jackson crater (Fig. 7). In addition, the low elevation region on the eastern crater floor of Tycho, with the exception of the Low Elevation Intermediate Albedo Smooth Unit (Fig. 6; brown color), has a notably higher concentration of the Hummocky Unit (Figs. 6 and 7; magenta color) as compared to the high elevation region on the west. The High Elevation Low Albedo Smooth Unit (Fig. 6; light pink), located in the southwestern crater floor is almost devoid of the Hummocky Unit and Isolated Mounds Units.

The observed contrast in the density of the Hummocky Unit between the eastern and western crater floor sections at Tycho, if taken by itself, will make the eastern crater floor rougher compared to the western crater floor. This is in stark contrast to our earlier observations and crater floor unit assignments in geologic map of Tycho by Pohn (1972) where on broad scale, the western crater floor is hummocky while the eastern crater floor is smooth.
Fig 4. Impact melt units at Jackson crater. (a) Albedo image from Kaguya Terrain Camera (TC) [Image Id: TCO_Map_02_N24E195N21E198SC]. (b) Geological map of impact melt units on the crater floor. (c) Geological map draped over the albedo image.
This observation highlights the scale dependent interpretation of surface roughness which may help identify multiple factors and processes at work.

The crater floor has some Large Blocks located in the western part that are draped completely by the impact melt. Although they are large and coherent in nature, these Large Blocks appear relatively subdued as compared to the observations of this unit at Jackson crater. Tycho also displays Flows and Melt Fronts (and Melt Front Striations), mostly along the periphery of the crater floor.

The central peaks of Tycho display notable melt cover. Central Peak Unconfined Perched Deposit is the most common unit on the peak region. There is also a large melt pond in the northern section of the main central peak unit. Many impact melt locations on the peak display an extensive set of cooling cracks. The Central Peak Boulder Regions are mostly located at the distal ends of the mapped melt occurrences at Tycho.

5. Insights into the cratering process

The diverse array of relationships observed between the mapped impact melt units and their contrast at the two craters Jackson and Tycho provides us the opportunity to utilize this knowledge in interpreting some of the details of the cratering process. Here, we assimilate all the observations to understand the various aspects of the cratering process.

5.1. Structural evolution of the crater floor

The crater floors of both Jackson and Tycho have been shown to be composed of coherent sections that lie at different elevations (\( \geq \text{200 m} \) difference in elevation). We have previously also documented a toponographic low on the floor of Copernicus crater (Dhingra et al., 2013). In view of these observations from craters located in widely different regions of the Moon, we suggest that elevation differences on the crater floors may be a relatively common phenomenon. There could be multiple causes for the observed differences in floor elevation within a crater: (a) differential subsidence of the floor during cooling of the melt column (e.g. Wilson and Head, 2011), (b) collapse of a wall section that could pile up material on the adjacent crater floor (e.g. Hawke and Head, 1977, Margot et al., 1999), (c) impact conditions including impact direction, impact angle, pre-impact topography (e.g. Hawke and Head, 1977) and (d) structural failure of the floor section along a major plane of weakness. We provide here some observations that could help in evaluating the dominant cause of the elevation differences on the crater floors of Jackson and Tycho.
Fig 6. Impact melt units at crater Tycho. (a) Albedo image from Kaguya Terrain Camera (TC) [Image ids: TCO_MAP_02_S42E345S45E348SC, TCO_MAP_02_S42E348S45E351SC]. (b) Geological map of impact melt units on the crater floor. (c) Geological map draped over the albedo image.
Scenario 1. Subsidence due to melt cooling: Cooling of the melt column causes contraction in lateral and vertical directions leading to subsidence (e.g. Bratt et al., 1985; Wilson and Head, 2011). In view of the highly energetic nature of the impact cratering process, large scale slumping of material occurs along with melting and the floor is expected to be a dynamically created mixture of melt and rock lacking spatial coherence. As a consequence, subsidence of crater floor due to the cooling of melt column should lead to elevation differences on the local scale (irregular topography) due to varying amounts of impact melt and rock mixtures at different locations in the crater. However, such small scale topographic variations do not dominate at Jackson or Tycho at the available spatial resolution. Instead, we observe that the floor is divided into two very large sections (several hundred square kilometers), each occurring at a different elevation (>200 m; also see selected topographic profiles shown in 3c, 3d and 3g, 3 h). In such a scenario, subsidence due to melt cooling seems to be an unlikely dominant cause for the crater scale elevation differences.

However, a special case where cooling-induced subsidence could be important is where the impact melt column has substantial differences in the melt-clast ratio in different geographical sections of the crater floor. Such a setting may lead to a significant subsidence in clast-poor section of the floor (due to higher volume of molten material and therefore greater contraction) compared to the clast-rich section. One such scenario could involve late stage crater wall collapse which would contribute significant clast volume to the melt-column in the immediate vicinity but not much to the melt-column located further away. It is further discussed as a separate scenario in the next section. In principle, we could always invoke a hybrid scenario where subsidence due to cooling complemented by crater wall collapse led to the observed elevation differences.

Scenario 2. Crater wall collapse: If crater wall collapse played a dominant role in causing the observed elevation differences on the crater floor, then such an event would contribute abundant rock fragments on the adjacent floor section raising its elevation e.g. (Margot et al., 1999). The distribution of megaclasts (Hummocky Unit, Isolated Mounds and the Large Blocks) at the two craters can be used as a measure of the rock fragment abundance in different floor sections. In the case of Jackson, the higher elevation eastern crater floor section has a distinctly lower proportion of megaclasts when compared to the low elevation western floor section which is contrary to the expectation that wall collapse should add rock fragments to the nearby floor region. The wall collapse scenario is thus not favored at Jackson to explain the floor elevation differences.

The trends at Tycho seem to support crater wall collapse as a probable cause. The higher elevation western floor section has an abundance of megaclasts with respect to the lower elevation eastern floor section. The western floor section has distinctly higher proportion of intermediate size megaclasts, namely Isolated Mounds Unit. In addition, all the large size megaclasts, namely Large Blocks Unit, are also concentrated mostly within the western floor section. These collective insights prompt us to suggest that wall collapse could have possibly played an important role in causing the observed floor elevation differences at Tycho. This inference is supported by independent set of observations by Hawke and Head (1977), Margot et al. (1999) and more recently by Krüger et al. (2013) who suggested wall collapse in the SW crater wall of Tycho based on parameters such as the distinctively gentler slope of the SW crater wall compared to the other sides, lower rim crest elevation and wider terraced walls in the western and south western parts of the crater.

Scenario 3. Impact conditions: Several parameters collectively define the impact conditions. These include direction and angle of impact, impactor velocity, pre-impact target topography and target material properties. While a detailed assessment of all the parameters is beyond the scope of this study, we present an evaluation of some important parameters. We infer the direction of impact based on either the observed zone of avoidance or other information such as spatial distribution of impact melt ponds on the crater rim (as reported in the literature). In the case of crater Jackson, we used the observed zone of avoidance which refers to a ‘no crater ejecta zone’ and is generally observed in the uprange direction of impact when the impact angle of incidence is less than 45° (but could also occur downrange at increasingly smaller impact angles) e.g. Gault and Wedekind (1978).

We compare the location of zone of avoidance (that provides the direction of impact) and the elevation characteristics of the floor units to explore possible correlations. At Jackson, the inferred impactor direction is from NW based on the observed zone of avoidance (Fig. 8a). The lower elevation floor section is located in proximity to the uprange direction (Fig. 8b, c). The impact direction for Tycho is from SW (Fig. 8d) e.g. (Hawke and Head, 1977; Margot et al., 1999; Krüger et al., 2013). The lower elevation floor section is located in the downrange direction in this case (Fig. 8e, f). There are therefore, no consistent trends observed with respect to the impact direction and so it is unclear in the present context.
Fig 8. Regional distribution of crater rays and topographic relationships at craters Jackson and Tycho. (a) High Sun LROC WAC global mosaic derived image of crater Jackson showing the distribution of its extensive rays. Note the zone of avoidance on the NW rim which is almost devoid of rays and indicates the direction of the impactor. (b) LROC WAC derived topography (overlaid on WAC imagery) around the Jackson crater shows that the crater’s western edge lies at regional topographic boundary. (c) WAC derived regional topographic profile across crater Jackson confirms the W-E asymmetry. (d) High Sun LROC WAC image of crater Tycho showing the distribution of crater rays. (e) LROC WAC derived topography for the region around crater Tycho does not show large scale topographic differences as observed in the case of Jackson. (f) WAC derived regional topographic profile across crater Tycho. The black arrows in images (a) and (d) indicate the likely direction of impact based on the zone of avoidance (in the case of Jackson) and distribution of impact melt ponds (in the case of Tycho. Sourced from Krüger et al. (2013). The white dashed lines in (b) and (e) represent the geographic location of the profiles shown in (c) and (f).
whether impact direction alone could have caused the observed elevation differences on the crater floors.

Pre-impact topography has been shown to be an important parameter affecting the crater morphology and melt movement e.g. (Hawke and Head, 1977; Gulick et al., 2008; Neish et al., 2014). The regional topography at Jackson crater (Fig. 8b, c) indicates a NW–SE asymmetry with the NW section at the edge of a topographic low. The floor sections exhibit an E–W asymmetry in elevation with the western section at a lower elevation. These two observations seem to be correlated to certain extent. We make some additional observations. The higher elevation SE crater wall at Jackson is much wider than other wall sections of the crater, possibly hinting at a slumped wall section e.g. (Hawke and Head, 1977). As expected, the adjacent floor section also has a higher elevation but surprisingly there is a dearth of rock fragments that should have been produced by the wall slumping. Based on these observations, pre-impact topography may have affected the crater floor elevation differences at Jackson but there is ambiguity about the surface expression of the slumped material.

The available topography data for Tycho does not indicate a topographical asymmetry (Fig. 8e, f) on a regional scale (as observed in the case of Jackson) so any direct correlations of the observed floor elevation differences with the pre-impact regional relief is ruled out at this scale. However, it is known that pre-existing local topography did affect the distribution of exterior impact melt deposits around Tycho, e.g. (Margot et al., 1999).

Scenario 4. Structural failure along a major plane of weakness: The failure of coherent floor sections along substantially weak zones is conceivable in view of the massive structural damage taking place during the cratering process. This mechanism could be favorable in view of the observed trends in the spatial distribution of the Hummocky Unit at Tycho. If floor elevation differences were produced during the early stages of the crater formation, then melt will be expected to move towards the lower elevation floor unit thereby inundating the region and submerging any small-scale topography. Contrary to this expectation, the low elevation floor units at crater Tycho (i.e. the eastern crater floor) have an observationally high density of the Hummocky Unit (Fig. 7). We interpret this observation to suggest that floor elevation differences likely developed in the later part of the cratering process, probably during the final adjustment stages or even at a much later stage when the majority of the crater formation process came to rest. Structural failure could be one of the mechanisms still possible in the very late stages and may have caused the observed elevation differences. In such a scenario, the impact melt deposits would have acquired sufficient viscosity to not drain out from the high elevation section of the floor to the low elevation section, avoiding flooding of the low-lying units. Accordingly, the observed high density of the Hummocky Unit on the lower elevation floor section of Tycho could be maintained even after the development of floor elevation differences.

5.2. Possible origin of the smooth melt deposits

The smooth melt deposits (Smooth Unit and sub-units) provide an interesting contrast to the otherwise rough crater floor. We make a couple of interesting observations about the smooth melt deposits that may be related to the evolution of the crater floors. The smooth melt deposits have been observed to occur both at high elevations and low elevations on the floors of craters Jackson and Tycho. However, the Smooth Unit, the largest amongst the smooth melt deposits (light brown unit in the geological maps), has consistently been observed to be located within the floor sections at the lowest elevation in the case of both Tycho and Jackson craters. We interpret these units as the likely locations where the final dregs of impact melt ponded, flowing down from nearby regions at higher elevations, either on the floor or from the walls.

Another associated observation is the approximate correlation between the geographic locations of the Smooth Units and the inferred downrange impact direction. It is known that at impactor incidence angles less than 45°, preferentially larger volume of melt is focused in the downrange direction e.g. (Gault and Wedekind, 1978). This relationship has been utilized at crater Tycho to infer the impactor direction (from SW) based on higher abundance of mapped melt ponds on the NE crater rim e.g. (Krüger et al., 2013). We think that a larger melt volume focused in the down-range direction will also lead to the downrange region receiving relatively large volume of melt-fall back into the crater. As a result, melt may preferentially accumulate in the region that lies in the downrange impact direction, consistent with the observations. In addition, since draining of melt back into the crater, is a relatively late stage activity, significant melt movement after ponding may be limited, which may have helped in preserving this relationship. However, we would like to acknowledge that this is only one of the possibilities which seem to satisfy all the constraints. There may well be other aspects which could have also contributed to these observations.

5.3. Central peak–impact melt relationship

The central peaks represent a unique geological unit on the floor of impact craters. In contrast to their spatial proximity to the crater floor, they are believed to represent material from a different part of the crustal column and have therefore been extensively used in determining the mineralogy of deeper parts of the lunar crust e.g. (Tompkins and Pieters, 1999; Cahill et al., 2009; Song et al., 2013; Lemelin et al., 2015). Impact melt, on the other hand, represents a mixture of lithologies present in the crustal column which may not share any direct mineralogical link with the central peak lithologies. The two units represent different sampling depths: the impact melt is produced from an upper shallower part of the lithological column while central peaks have been suggested to form from material below the melted lithologic horizon e.g. (Cintala and Grieve, 1998).

Our mapping of impact melt deposits on the central peaks of Tycho and Jackson therefore documents a hybrid geological setting where material from different depths and physical form (melt vs un-melted peak material), that could conceivably be different in composition, is juxtaposed in various forms. It includes melt-draped surfaces, melt ponds and flows. This geologic setting therefore has obvious implications for the use of central peaks to decipher the sub-surface mineralogy. Similar observations of impact melt deposits on central peaks have also been made earlier e.g. (Ohtake et al., 2009; Dhingra et al., 2014) although systematic and detailed mapping of various impact melt deposits associated with the central peaks has been lacking so far. The mapping of impact melt exposures on the central peaks of Tycho and Jackson in this study highlights the fact that direct interpretations of the subsurface mineralogy based on central peaks could be misleading unless melt-free regions on the peaks are specifically chosen for determining the mineralogy. Systematic geological mapping of impact melt deposits of the central peaks could help identify such melt free regions for compositional analysis.

6. Summary and major conclusions

The detailed investigations presented in this study document the morphological properties of impact melt at two young, complex craters, Jackson and Tycho. The salient findings from this study are as follows:
(i) There is a rich morphological diversity in the impact melt deposits on the crater floors of Jackson and Tycho that hold clues to the understanding of the cratering process. The detailed mapping carried out in this study highlights the fact that there is a certain degree of order (or systematics) associated with the impact melt deposits which otherwise appear quite chaotic in the first look. Accordingly, scientifically significant trends could be inferred based on impact melt mapping studies to understand the cratering process in general and impact melt generation and emplacement in particular.

(ii) We observe elevation differences between coherent floor sections within both Jackson and Tycho and have also reported such differences in the case of Copernicus crater (Dhingra et al., 2013). These observations suggest the possibility that elevation differences between coherent floor sections may be a common phenomenon at many of the impact craters. We have evaluated several possibilities to understand the potential cause(s) for the observed elevation differences on the crater floors. We propose that late-stage wall collapse, structural failure of the floor along major weak zones and pre-impact topography could be the possible causes of observed elevation differences on the floor. However, additional observations at other large craters (e.g. Dhingra et al., 2016) could help validate these interpretations.

(iii) This study documents the occurrence of very large sized rock fragments (Large Blocks Unit) on the crater floor that have the size and elevation characteristics similar to the central peaks. Some of the mapped large blocks are located in close proximity to the central peak complex and could therefore be subdued sections of the central peak unit.

(iv) Our detailed mapping of impact melt deposits on the central peaks highlights the often overlooked fact that the central peaks may not always represent pristine exposures of the sub-surface crustal material and could be contaminated with impact melt deposits. As a consequence, the prevalent use of central peak units in deciphering mineralogy of deeper part of the crust needs to take this factor into consideration. This has implications not only for the Moon but for other planetary bodies as well where central peak mineralogical surveys have been carried out. Melt-free regions should be first identified through systematic geological mapping before deciphering the mineralogy of the peaks.

Acknowledgments

This research was supported by SSERVI grant no. NNA14AB01A. We thank the LRO and Kaguya mission teams for making high quality datasets available in the public domain. We would also like to thank the two anonymous reviewers and the editors for their thoughtful comments and suggestions.

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