IMPACT MELT BURIAL AND DEGRADATION THROUGH CRATER MODIFICATION IN SIMPLE LUNAR CRATERS.

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Introduction: Recent images acquired by the Lunar Reconnaissance Orbiter Camera (LROC) reveal new details of impact melt deposits in and around simple lunar craters. The size and location of melt deposits provide clues to impact parameters and target properties [e.g., 1-7]. Previous observations and models focused on craters larger than a few kilometers in diameter [e.g., 2,4-7]. Models based on earlier observations predict that impact melt production and ejection should rarely result in observable impact melt deposits in and around craters less than ~1 km in diameter (D). Here, we utilize LROC images to assess the frequency of impact melt occurrence in the floors of fresh simple craters (D<5 km), both as a function of crater diameter and degradation state (excluding heavily degraded craters).

Methods: The LROC consists of two Narrow Angle Cameras (NACs) and a Wide Angle Camera (WAC) that provide pixel scales of 0.5 m and ~100 m, respectively, from 50 km altitude. More than 850 youthful, randomly distributed, simple impact craters (D<5 km) were identified based on their maturity and reflectance. Selected craters have crisp rims, NAC images at suitable pixel scale (generally better than 1 m/p), favorable illumination, and >50% coverage. The WAC-based GLD100 provides regional topography sampled to 100 m [8]. NAC DEMs were created for several craters using established techniques [9] and provide crater profiles, crater depths, and slopes of melt materials that are used to assess the factors controlling observed distributions of melt. Impact melt was identified using the criteria of Plescia and Cintala [1].

Results and Discussion: Melt production and retention are still poorly understood for craters D<1 km. Recent LROC observations of small, fresh craters [1, 3] have shown that while melt ponds are rare on the floors of craters D<1 km, they are more abundant than previously recognized as most melt is expected to be ejected during cratering [e.g., 7]. Plescia and Cintala [1] suggested that impact melt ponds on the floors of some craters as small as D=170 m result from near-vertical impact angles. A near-vertical impact should result in conditions more favorable to the formation of a melt pond on the crater floor by producing more melt that is located deeper in the crater, thus both increasing the amount of melt produced and reducing the volume of melt ejected. If this is the case, the frequency of ponds in small fresh craters (Table 1) should reflect the expected frequency of near-vertical impacts.

For all fresh craters in this study, roughly half of the craters D<400 m have some melt present on the crater floor, but less than a third preserve a coherent melt pond. At crater D<300 m, melt ponds are found in <20% of all fresh craters, and more than half of the craters have no apparent melt at all. This is significantly less frequent than for larger craters; for example, ~70-80% of craters D>600 m have at least some melt. For craters in the range D=300-600 m, melt ponds are twice as frequent as for craters D<300 m.

Table 1: Frequency of melt occurrence on the crater floor as a function of crater diameter. "Some melt" includes melt veneer and puddles that do not form a coherent pond.

Diameter	n	Melt Pond	Some Melt	Total Melt	No Apparent Melt
100- 200 m	66	14%	12%	26%	74%
200- 300 m	88	17%	25%	42%	58%
300- 400 m	65	28%	20%	48%	52%
400- 500 m	67	36%	34%	70%	30%
500- 600 m	60	23%	20%	43%	57%
600- 700 m	62	45%	26%	71%	29%
700- 800 m	57	42%	32%	74%	26%
800- 1000 m	78	42%	28%	70%	30%
1.0- 1.2 km	64	45%	28%	73%	27%
1.2- 2.0 km	117	50%	31%	81%	19%
2.0- 3.0 km	71	59%	20%	79%	21%
3.0- 5.0 km	63	46%	29%	75%	25%

Table 2: Frequency of melt pond occurrence, limited to only craters less degraded than North Ray crater.

Diameter	n	Melt Pond
100- 200 m	59	15%
200- 300 m	76	13%
300- 400 m	49	31%
400- 500 m	55	35%
500- 600 m	42	33%
600- 700 m	33	61%
700- 800 m	34	59%
800- 1000 m	37	78%
1.0- 1.2 km	32	75%
1.2- 2.0 km	56	77%
2.0- 3.0 km	39	80%
3.0- 5.0 km	24	71%

Most impacts from a randomly-distributed bolide population are expected to occur near 45° from the surface with very few near vertical [10]. The lower frequency of melt pond occurrence in craters D<400 m is generally consistent with the low probability of a high angle impact. However, there may be other explanations for the reduced volume of apparent melt. For instance, there may be many more low velocity secondary impacts at smaller diameters [e.g., 10] and as is supported by the very low depth-to-diameter ratios of nearly all craters D<300 m across different lunar terrains [11]. Low velocity, low angle secondaries have virtually no excess energy for melting.

Many craters D<300 m occur in the upper regolith, which is less coherent than solid rock, and target strength influences melting, excavation, and crater modification processes. While porous target materials leave more energy for melt production [e.g., 12], the crater will be larger with more ejected material, possibly resulting in less melt retained within the crater.

Crater modification that occurs near the end of the cratering process in simple lunar craters consists primarily of wall failures [e.g., 13]. These wall failures modify the original transient crater cavity (expected depth-to-diameter ratio ~0.5) to the true crater cavity. The material shed from the crater walls forms a lens on the crater floor, resulting in a final depth-to-diameter ratio ~0.2. If crater depth is an important factor in preventing melt ejection, then deeper craters should preserve more melt ponds. However, NAC topographic data show that the presence of melt ponds is not correlated to the depth-to-diameter relationship. Some comparatively deep craters have no apparent melt pond (e.g., Linné). Additionally, some craters formed on steep slopes (at 20-30°) have shallow floors and significantly lower depth-to-diameter ratios, yet still preserve melt in the crater floor [3]. Therefore, if burial obscures some melt ponds, it does not appear to be enough material to significantly alter the depth-to-diameter ratio.

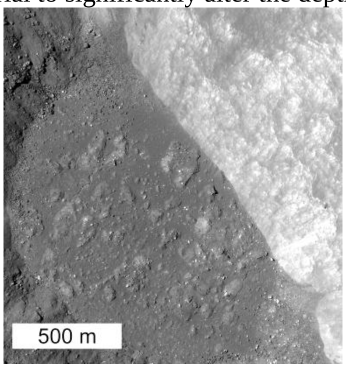

Fig. 1: Floor of a simple crater where a melt pond embays the wall failures (northeast wall, top right) formed during crater modification near the end of the cratering process.

Observations of modification-stage wall failures embayed by melt ponds (e.g., Fig. 1) suggest that wall failures do not prohibit the formation of a melt pond when sufficient melt is present. However, there must be a lower limit of melt volume that can survive disruption by wall debris and still remain coherent [e.g., 7]. For example, a thin melt pond associated with a crater D<300 m is relatively easy to destroy or bury with wall material during crater modification while also not significantly shallowing the crater.

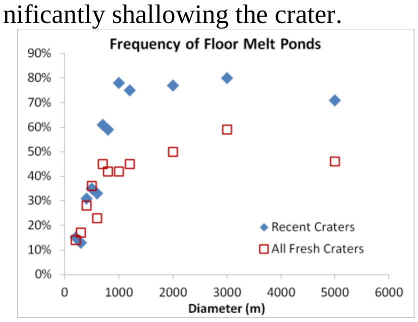

Fig. 2. Plot showing difference between Table 1 and Table 2.

To quantify the effects of post-cratering modification, craters were compared to the visual state of degradation of the ~50 Ma [14] North Ray crater near the Apollo 16 landing site. Table 2 provides the frequency of occurrence of impact melt ponds for recent impact craters, i.e., those less degraded than North Ray, and Fig. 2 compares these frequencies to those derived above for all fresh craters in this study. Exclusion of the more degraded craters from the calculation removes the inherent bias toward the inclusion of older craters at larger diameters due to the differential evolution of craters with increasing diameter [e.g., 15]. There are four resulting melt pond frequency populations: at D=100-300 m, ~10-20% of all fresh craters have a melt pond on the crater floor; at D=300-600 m, ~30% have a melt pond; at D=600-800 m, ~60% have a melt pond; and at D=800m-5km, ~80% of recent craters have a melt pond.

Fig. 3 shows the pond of a relatively small crater largely buried by a post-cratering landslide. The frequency of apparent melt ponds at crater D>800 m decreases by ~40% with only a limited amount of overall crater degradation (Fig. 2). Post-cratering landslides, which can bury crater floors, are more predominant in craters D>800 m, with many craters showing evidence for recent movement of granules and boulders.

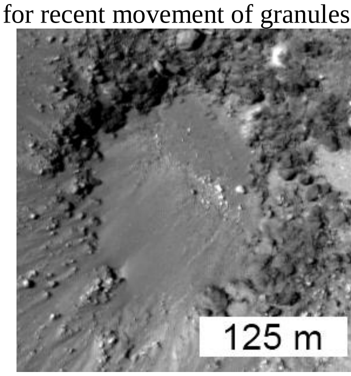

Fig. 3: A melt pond more than half buried by wall debris during a post-cratering landslide (from southeast wall, bottom left).

Conclusions: There are three possible explanations for the scarcity of melt ponds in craters less than a few hundred meters in diameter: 1) the melt was not produced, i.e., secondary impacts dominate at small crater diameters; 2) the melt was ejected, i.e., a porous target and/or low angle impact; or 3) the melt was disrupted and/or buried, as in the case of many craters with wall failures both during and after impact. In the latter case, a relatively thin layer of debris can obscure melt ponds in craters D<5 km without overt shallowing. Therefore, the number of small craters producing significant melt at diameters less than a few km is likely significantly larger than presently observed due to burial and disruption of melt ponds during crater modification.

References: [1]Plescia and Cintala (2012) *JGR* 10.1029/2011JE003941. [2] Denevi et al. (2012) *Icarus* **219**:665-675. [3] Stopar et al. (2012) *LPSC* #1645. [4] Howard and Wilshire (1975) *J.Res.U.S.Geol.Surv.* **3**, p.237-251.[5] Hawke and Head (1977) in *Impact Explos. Cratering*, p.889-912. [6] Hawke and Head (1979) *LPSC*, p.510-512. [7] Cintala and Grieve (1998) *Met.Plan.Sci*. 33:889-912. [8] Scholten et al. (2012) *JGR* 10.1029/2011JE003926. [9] Burns et al. (2011) *AGU Fall* #P43D-1706. [10] Shoemaker (1962) in *Phys. Astron. Moon*, p.283-359. [11] Stopar et al. (2012) *LPSC* #2729. [12] Wünnemann et al. (2008) *EPSL* **269**: 530-539. [13] Melosh and Ivanov (1999) *Ann. Rev. E. Plan. Sci.* 27:385-415. [14] Stöffler and Ryder (2001) *Sp. Sci. Rev.* **96**: 9-54. [15] Basilevskiy (1976) *Proc. LSC*, p.1005-1020.