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Occurrence and mechanisms of impact melt emplacement at small lunar craters

Julie D. Stopar[a,*], B. Ray Hawke[b], Mark S. Robinson[a], Brett W. Denevi[c], Thomas A. Giguere[b,d], Steven D. Koeber[a]

[a] School of Earth and Space Exploration, Arizona State University, Tempe, AZ 85287, USA
[b] Hawaii Institute of Geophysics and Planetology, University of Hawaii, Honolulu, HI 96822, USA
[c] The Johns Hopkins University Applied Physics Laboratory, Laurel, MD 20723, USA
[d] Intergraph Corporation, Box 75330, Kapolei, HI 96707, USA

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ABSTRACT

Using observations from the Lunar Reconnaissance Orbiter Camera (LROC), we assess the frequency and occurrence of impact melt at simple craters less than 5 km in diameter. Nine-hundred-and-fifty fresh, randomly distributed impact craters were identified for study based on their maturity, albedo, and preservation state. The occurrence, frequency, and distribution of impact melt deposits associated with these craters, particularly ponded melt and lobate flows, are diagnostic of melt emplacement mechanisms. Like larger craters, those smaller than a few kilometers in diameter often exhibit ponded melt on the crater floor as well as lobate flows near the crater rim crest. The morphologies of these deposits suggest gravity-driven flow while the melt was molten. Impact melt deposits emplaced as veneers and "sprays", thin layers of ejecta that drape other crater materials, indicate deposition late in the cratering process; the deposits of fine sprays are particularly sensitive to degradation. Exterior melt deposits found near the rims of a few dozen craters are distributed asymmetrically around the crater and are rare at craters less than 2 km in diameter. Pre-existing topography plays a role in the occurrence and distribution of these melt deposits, particularly for craters smaller than 1 km in diameter, but does not account for all observed asymmetries in impact melt distribution. The observed relative abundance and frequency of ponded melt and flows in and around simple lunar craters increases with crater diameter, as was previously predicted from models. However, impact melt deposits are found more commonly at simple lunar craters (i.e., those less than a few kilometers in diameter) than previously expected. Ponded melt deposits are observed in roughly 15% of fresh craters smaller than 300 m in diameter and 80% of fresh craters between 600 m and 5 km in diameter. Furthermore, melt deposits are observed at roughly twice as many non-mare craters than at mare craters. We infer that the distributions and occurrences of impact melt are strongly influenced by impact velocity and angle, target porosity, pre-existing topography, and degradation. Additionally, areally small and volumetrically thin melt deposits are sensitive to mixing with solid debris and/or burial during the modification stage of impact cratering as well as post-cratering degradation. Thus, the production of melt at craters less than ~800 m in diameter is likely greater than inferred from the present occurrence of melt deposits, which is rapidly affected by ongoing degradation processes.

1. Introduction

The distribution and occurrence of melt rocks and melt-bearing deposits associated with impact craters provide insight into the amount of energy involved in an impact as well as the deposition of energy into the target. On Earth, where melt rocks might be most accessible to study, it is difficult to identify surficial melt deposits due to extensive weathering and erosion (e.g., Grieve et al., 1977; Osinski, 2004; Osinski et al., 2011; Kalleson et al., 2013). Therefore, many details concerning the production, ejection, and cooling of impact melt are still poorly constrained. Fortunately, many details of impact melts are preserved on the surfaces of other Solar System bodies, particularly the Moon, where both physical and chemical weathering rates are relatively low. In the vacuum environment of the Moon, the destruction of landforms and

* Corresponding author. Address: Lunar Reconnaissance Orbiter Camera Science Operations Center, Box 873603, Tempe, AZ 85287, USA.
E-mail address: jstopar@asu.edu (J.D. Stopar).

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materials exposed at the surface is, in part, driven by meteoroid bombardment (e.g., Hörz et al., 1971; Gault et al., 1972).

Remotely acquired images reveal well-preserved details of melt deposits in and around lunar craters, including those that formed as thin surficial veneers, sprays, ponds, sheets, and lava-like flows (e.g., Shoemaker et al., 1968; Howard and Wilshire, 1975; Hawke and Head, 1977; Heather and Dunkin, 2003; Bray et al., 2010; Osinski et al., 2011; Ashley et al., 2012; Denevi et al., 2012; Öhman and Kring, 2012; Plescia and Cintala, 2012). Here, we summarize the occurrence and distribution of impact melt deposits in and around simple craters smaller than 5 km in diameter using LROC observations. We also discuss how the improved characterization of melt distribution and occurrence advances our current understanding of melt production and emplacement.

2. Background

Impact melt forms during the cratering process as a result of shock (e.g., Gault et al., 1968; recent review by Osinski, 2013), where melting is generally initiated as shock pressures rise above ~40–50 GPa with corresponding post-shock temperatures exceeding ~1000 °C. At extreme pressure and temperature (i.e., above 100 GPa), vaporization of target materials commences (e.g., Stöffler, 1971; Ahrens and O'Keefe, 1972; Hörz and Cintala, 1997; French, 1998). Detailed reviews of the impact cratering process and the mechanisms of impact melting on the Moon and other planetary bodies are available in a variety of previous works (e.g., Grieve et al., 1977; Wilhelms, 1987; Melosh, 1989; Hörz et al., 1991; Cintala and Grieve, 1998; Osinski et al., 2011; Collins et al., 2012; Osinski and Pierazzo, 2013; Osinski, 2013); thus, only a brief overview is provided here. Principally, the energy available to produce impact melt depends on target properties such as porosity and volatile content, impactor properties such as size and density, and impact parameters such as velocity and angle (e.g., Gault et al., 1972; O'Keefe and Ahrens, 1977; Kieffer and Simonds, 1980; Hörz and Cintala, 1997; Cintala and Grieve, 1998; Pierazzo and Melosh, 2000a; Osinski et al., 2008, 2011; Wünnemann et al., 2008). Therefore, in general, denser, higher angle, and faster impactors generate larger volumes of impact melt than less dense, lower angle, and slower projectiles of the same size. However, the melting points of individual target components also play a role in melt generation (e.g., Ahrens and O'Keefe, 1972).

For vertical to near-vertical impacts, the bulk of generated melt typically occupies the lower part of the transient cavity throughout crater excavation (e.g., Gault et al., 1968; Grieve et al., 1977), but a portion of the melt moves outward with the crater cavity. Some of this melt may be ejected, particularly when the growing crater encounters a topographic low such as another crater (e.g., Hawke and Head, 1977; Osinski et al., 2011; Denevi et al., 2012; Neish et al., 2014). After excavation, the transient cavity of a simple crater generally undergoes little modification, which includes relatively minor mass movements of wall debris (e.g., Melosh and Ivanov, 1999). Conversely, at complex craters (the simple-complex transition is ~15 km in diameter on the Moon), wall slumping, terracing, and central uplift occurring during crater modification significantly affect crater morphology and can facilitate melt mobility, including ejection (Dence, 1971; Hawke and Head, 1977; Osinski, 2013; Neish et al., 2014).

Both during and shortly after crater modification, impact melt lining the crater cavity can flow, driven by gravity, downslope toward the crater floor (e.g., Hawke and Head, 1979; Melosh, 1989; Cintala and Grieve, 1998; Melosh and Ivanov, 1999; Bray et al., 2010). Melt that flows back to the crater floor may mix with solid debris, additional melt, and/or breccias on the crater walls and floor (e.g., Cintala and Grieve, 1998). If enough melt is present on the crater floor, it forms a coherent pond of impact melt (e.g., Howard and Wilshire, 1975; Hawke and Head, 1979; Melosh, 1989). Ponded impact melt deposits, particularly those formed from the voluminous impact melt associated with larger craters such as Giordano Bruno (crater diameter ~22 km) and complex craters like King (crater diameter ~77 km) and Copernicus (crater diameter ~93 km) may remain molten and mobile for a significant time after cratering (e.g., Howard and Wilshire, 1975; Bray et al., 2010; Ashley et al., 2012; Wagner and Robinson, 2014). Ponds of molten melt either solidify to form flat-lying deposits, or they may mix with cool impact clasts and wall materials, as is the case for many complex craters where rebound, slumping, and deformation through uplift are believed to disturb melt ponds on the crater floor (e.g., Hawke and Head, 1977).

While complex craters are frequently associated with abundant impact melt deposits (e.g., Howard and Wilshire, 1975; Hawke and Head, 1977), melt ponds were only recently recognized inside craters less than 1 km in diameter (Plescia and Cintala, 2012). Influenced by a lack of observations of impact melt in and around small lunar craters, Cintala and Grieve (1998) calculated that craters in this diameter range generally should not produce enough melt to allow ponding on the crater floor. The predicted low volumes of melt production, when mixed with unmelted debris, were expected to result in rapid chilling of the melt. Yet, LROC-based observations of occasional ponded deposits on the floors of craters as small as 170 m in diameter suggest that melt may be more abundant or better retained in a subset of craters (Plescia and Cintala, 2012). Likewise, Denevi et al. (2012) calculated that melt associated with a single 3-km diameter crater is roughly 12 times more abundant than models of Cintala and Grieve (1998) predict. Radar observations of previously uncharacterized melt deposits from the Miniature Radar Frequency (Mini-RF) experiment onboard LRO as well as Earth-based Arecibo Observatory further emphasize that large volumes of melt may be present in the ejecta around many impact craters (Campbell et al., 2010; Carter et al., 2012; Neish et al., 2012; Bray et al., 2013).

Glass-coated blocks and rock fragments (Schaber et al., 1972; Wilshire and Moore, 1974) indicate that impact melt is commonly produced and scattered across the surface of the Moon; even small craters on the order of microns to centimeters exhibit impact glass (Hörz et al., 1971). Melt emplaced near the crater rim crest, usually within a few crater radii, can form a surficial veneer as well as ponded or lobate deposits (e.g., Howard and Wilshire, 1975; Hawke and Head, 1977; Denevi et al., 2012); however, there are several examples of craters where ponds and flows can be found at distances exceeding three crater radii (e.g., Robinson et al., 2011; Campbell et al., 2010; Carter et al., 2012; Neish et al., 2014). Observations suggest that a large proportion of impact melt could be distributed beyond the crater but is too thin or mixed with other debris to be readily recognized (Howard and Wilshire, 1975; Bray et al., 2013). Nonetheless, the thickest exterior melt generally occurs near the crater rim crest. Ejected melt is emplaced with some horizontal momentum resulting from impact, but local topographic slopes and depressions around the crater permit downslope flow of melt under the influence of gravity, potentially resulting in ponding and/or formation of lava-like flow lobes (Howard and Wilshire, 1975; Hawke and Head, 1977; Denevi et al., 2012). Melt deposits are reported as exhibiting lower albedo than the rest of the ejecta (Howard and Wilshire, 1975; Plescia and Cintala, 2012; Wöhler et al., 2014).

When lobate flow morphologies and ponded deposits were first observed at impact craters, many including El-Baz (1970), Strom and Whitaker (1971), Mattingly et al. (1972), and others, suggested that these deposits might result from volcanic eruptions. However,