IMPACT MELTING AND THE ROLE OF SUBSURFACE VOLATILES: IMPLICATIONS FOR THE FORMATION OF VALLEY NETWORKS AND PHYLLOSILICATE-RICH LITHOLOGIES ON EARLY MARS.

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Introduction: Observations from the Mars Reconnaissance Orbiter (MRO) are providing new insights into the aqueous history of Mars. The High Resolution Imaging Science Experiment (HiRISE) and supporting images from the Context Imager (CTX), suggest volatile-rich impact melt-bearing features, which appear to be the source of surface runoff by liquid water, are present in Mojave and other geologically recent and well-preserved craters [1, 2]. The Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) has identified additional phyllosilicate-rich lithologies on Mars [3, 4]. Together with the previous detections made by OMEGA [5, 6], it is apparent that all occur in the heavily cratered Noachian Martian highlands. It is worth mentioning that the highlands are also the geographic province with the highest concentration of Martian valley networks. The presence of both “dewatering” volatile-rich impact melt-bearing features in geologically recent craters and the detection of phyllosilicates in the most heavily impacted region have substantial implications for the volatile and aqueous activity on Mars.

Here we present the results of a comprehensive study of geologically recent and well-preserved craters and their morphologic features using primarily HiRISE with other datasets. For brevity, we will use the term “fresh” to describe these craters, although some appear less fresh and more infilled than others. In addition, we provide a synthesis of these new observations with previous observations from Mars (both visual and spectral) and Earth (field relations and lab analyses) to further our understanding of: 1) generation of volatile-rich impact-melts, 2) the release of post-impact liquid water, and 3) the possible relationship between impact melt and clays with implications for the OMEGA- and CRISM-detected phyllosilicate occurrences on Mars.

Targeting additional fresh craters: In addition to the craters used in our preliminary study (see [1]), craters where chosen based on their morphology in available imagery and thermophysical signature as seen in THEMIS nighttime thermal infrared images. Fifty-four craters (including the craters from [1]) have been identified from a survey of Mars from latitudes 65°N to 65°S. Where CTX and HiRISE are not yet available, THEMIS VIS and MOC images were used to assess each candidate crater. Six of these craters appear to have substantial post-impact aeolian deposits that make the identifications of fresh morphologic features difficult. The remaining 48 fresh craters appear to be good candidates for closer examinations with HiRISE and CTX, which are currently being planned.

Observations from HiRISE, CTX and other datasets of fresh craters: Here we give a general overview of the properties and occurrence of fresh crater morphologic features based on a preliminary study of the 48 candidate craters (note that at the time of writing this abstract only 5 of the 48 had HiRISE and/or CTX coverage: Hale, Mojave, Tooting, Zunil and Zumba; D ~125x150, 60, 29, 10, 3.3 km, respectively). Specific examples and details of these features from Tooting Crater are presented in our companion abstract in this conference [7].

Ponded Materials: There are two types of ponded materials found in the fresh craters studied here: Pitted and Fractured (Fig. 1a-b). Pitted materials are by far more abundant and are commonly found in areas of low-lying topography such as the crater floor, terraces, on the ejecta, and beyond the distal ejecta rampart. In a few cases, they can be found ponded on the flanks of the central uplift (e.g., Tooting). The pits are quasi-circular, rimless, do not bear ejecta, and are often found in coalescing groups under which the surface has subsided. This suggests that these features are not impact or explosion craters, but formed by a non-explosive mechanism such as collapse (possibly from the loss of volatiles). The fractured materials are most commonly found on the crater floor and less frequently on the terraces and ejecta (e.g., Tooting see [7]). The fractured materials are also seldom free of pits, which suggest a genetic relationship between the two types. Fractures appear to be cooling-contraction cracks and can both emanate and cross-cut the pits (Fig. 1b).

In several cases, the ponded materials display morphologic features suggestive of having once flowed under the influence of gravity and local topography. Ponded materials on the terraces often appear to linked from one pond to the next, likely *en route* to the crater floor, and can even be seen flowing around obstacles that are in some cases “streamlined”. Ponded materials have been tentatively identified in all 48 candidate craters (using THEMIS visible and MOC images), but many of these will need to be confirmed with HiRISE and CTX images. If these are indeed some of the youngest, most recent craters on Mars, it is apparent that these ponds are common in fresh Martian craters and can be linked to the impact process.

Lava flow-like materials: HiRISE images have revealed the presence of flows near the rim crest of Zumba and Tooting (see [7]). They are similar in appearance to lava flow-like features interpreted to be impact melt flows seen on the rim of several lunar craters (e.g., [8]). These features are quite distinct in that they do not appear to emanate from an observable source vent or fissure and

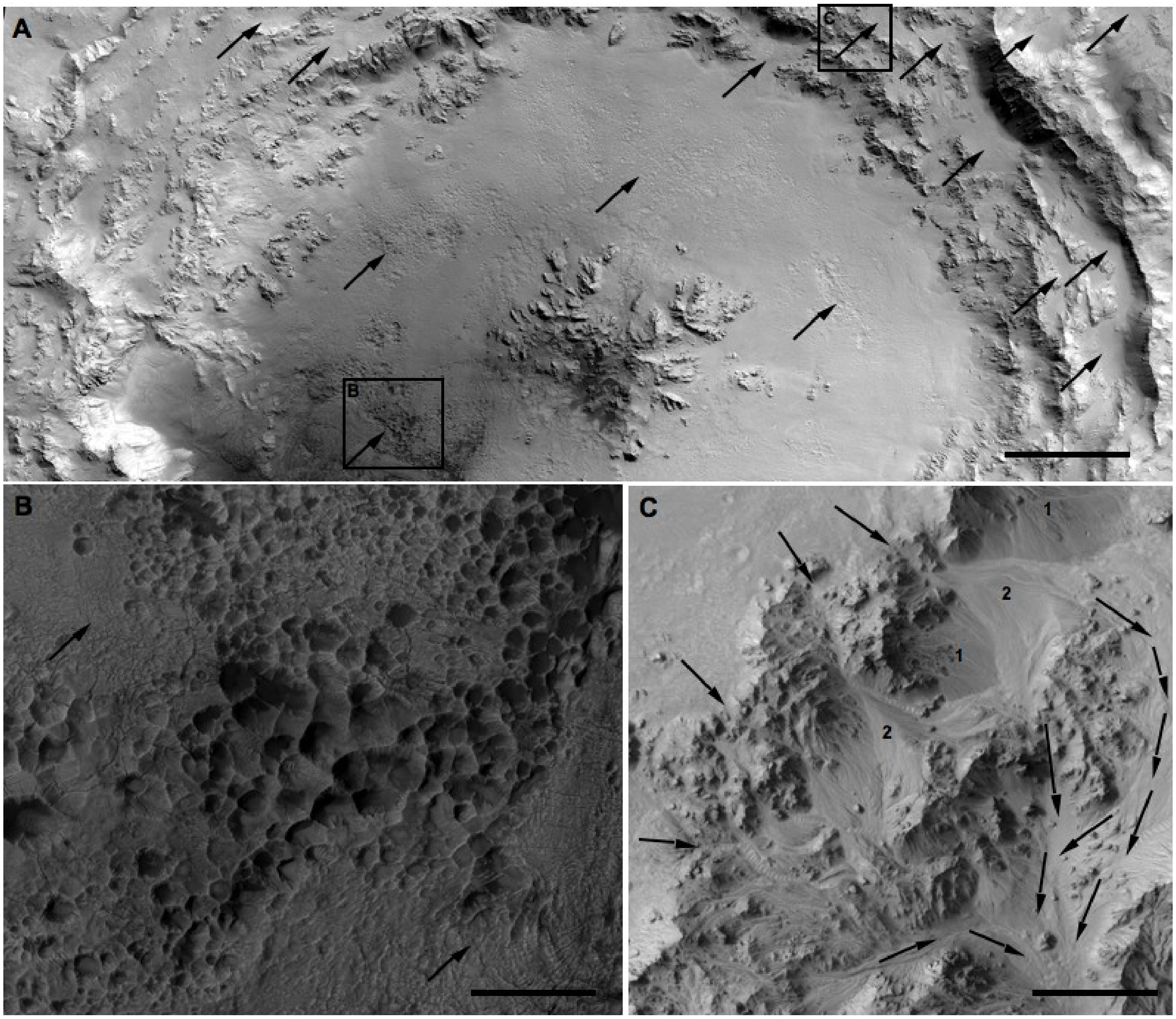

Fig 1. Examples of morphologic features in Mojave crater a) CTX image showing the distribution of ponded materials (arrows) and location of HiRISE sub images. North is towards the upper right. Scale bar is ~ 6 km. b) HiRISE image of both pitted and fractured (arrows) ponded materials on the floor of Mojave. North is up. Scale bar is ~ 1km. c) HiRISE image of Ponded materials are in the upper right. Several channels appear to be directly fed by the ponded materials as no channels or fans overlie them, but emanate from them. Arrows give a sense of the source regions and apparent flow direction. Fans labeled 1 and 2 refer to the older and younger generations of fans, respectively. North is up. Scale bar is ~500 m.

flow around and into topographic highs and lows, respectively.

Sheet flow materials: Sheet flows are the least common type of flow feature observed thus far (see [7]). Large portions of the southern ejecta blanket of Tooting are covered by multiple thin "sheet" flows. The physical nature of these flows suggests that they were very fluid, very low viscosity materials when they were emplaced. The lowermost sheet flows possess pervasive dm- to m-scale fractures possibly suggestive of rapid cooling and contraction. Sheet flows on Tooting have also been observed to be associated with outflow channels and some fan development.

Channels, distributaries and alluvial fan deposits: Channels and distributaries can be seen in all 5 craters covered by HiRISE, with the highest order of channels and distributaries (up to 4th order) being observed in Mojave (Fig. 1c). Some of the first order channels originate high on local topography, which has led previous workers in the past to conclude that these features formed as a consequence of impact-induced precipitation [e.g., 8]. Importantly, two distinct generations of alluvial fans are observed in Mojave. The older generation consists of smaller fans, which often overlap one another with respect to the younger, larger generation of fans. The younger generations are sourced from the ponded materials, while the first generation sources appear to originate from higher up topography or are ambiguous due to overprinting. Fans in Tooting, Zunil, Zumba and Hale are scarce and less developed compared to Mojave fans. Like Mojave's younger generation of fans, they also appear to be exclusively associated with ponded materials and sheets flows, but are scarce in the crater interior, and relatively more common on the ejecta.

"Wet" debris flows: There are several lobate flows that we distinguish from the lava flow-like features above.

These flows appear to be mudflows with eroded alcoves and amphitheatres up-slope from the flow. This is unlike the lava flow-like features that do not appear to have a clear source. Also they occur on steep slopes whereas the sheet-flow and lava flow-like features are on more gentle slopes. These "wet" debris flows are most often seen on the central uplifts of fresh craters, but are also present on terraces and the ejecta blanket where steep slopes are present.

Discussion: Prior to the acquisition of HiRISE and CTX images of Tooting, the fractured ponded materials on the floor of this crater were suggested to be impact melt based on similar characteristics to lunar impact melts [9]. We further argue that the ponded materials, sheet and lava-flow features are most likely impact melt or melt-bearing deposits based on the following key HiRISE and CTX observations: 1) the similarity of these features to impact melt flows seen on the Moon (e.g., [10]) and Venus [11], 2) the repeated occurrence of these features in several examples of craters that appear to be "fresh", 3) all three features have attributes suggestive of being emplaced as a hot and low viscosity fluid that remained so sometime after emplacement, 4) sheet and lava-flow features do not have obvious sources, 5) materials "pond" in low-lying topography throughout the crater, and 6) the "flows" move around obstacles, not over them.

Are Impact melt-bearing bodies possible on Mars?: The generation of impact melts on Mars were once thought to be scarce due to lower impact velocities, lower gravity and a possibly dense mafic crust [12]. In addition, the presence of subsurface volatiles has been suggested to either impede or disperse impact melts [13]. At first glance the terrestrial record appears to corroborate the lack of melt in volatile-rich and sedimentary targets [14]. However, recent models indicate that impacts into ground-ice-rich targets should produce more impact melting than similar-size impacts into "dry" targets on Mars [15, 16], so that impact melts should be more common then once realized. This is consistent with recent studies of impactites from several terrestrial impact structures generated in sedimentary targets: these studies show that large volumes of impact melt are generated from impacts into volatile-rich targets (see [17] for an overview). For example, studies of the crater-fill impactites at the Haughton impact structure, Canada, indicate that they represent impact melt breccias with a volatile-rich melt groundmass–comprising carbonate, H_2O–CO_2-rich glass, and sulfate, which are genetically equivalent to coherent melt sheets formed in crystalline targets [18, 19]. Volatile-rich melts also form the bulk of the impact ejecta at Haughton and at the Ries impact structure, Germany. The groundmass of the Ries suevites (i.e., a melt bearing impactite) was once thought to comprise a groundmass of variously shocked and comminuted mineral and lithic clasts (e.g., [20]). However, detailed optical and scanning electron microscope (SEM) analyses of suevites from Ries and several other localities (including Haughton) indicate that the groundmass consists predominately of a series of volatile-rich impact melts, including H_2O-rich impact glasses and carbonates (as high as ~70 vol% in Ries suevites (e.g., [21]). These observations are consistent with the dispersal hypothesis put forth by [10].

In summary, studies of terrestrial craters together with numerical modeling, suggest that large volumes of impact melt should be generated during impacts into volatile-rich target rocks on Earth and Mars. Suevites or impact melt-bearing breccias are likely to be the main impactite produced. Given the likely volatile-rich nature of the Martian subsurface (e.g., [22]), suevites should be common on Mars (c.f., [17]). Synthesizing these studies with our observations of fresh Martian impact structures, we suggest that volatile-rich terrestrial suevites are a good analogue for the ponded materials on Mars. This is based on the following observations: 1) field, optical and SEM observations of the Ries suevites indicate that this ejecta was emplaced a series of flows [21, 23-24], 2) the suevite flows remained molten after emplacement [22], 3) Ries suevites have been observed in the field to overlie and infill the low-lying topography of the irregular and hummocky ballistic ejecta materials (i.e., the Bunte Breccia at the Ries structure [20]) (Fig. 2), 4) abundant vesicles in the groundmass melt glass and the occurrence of degassing pipes (which may be an analogue for the pits seen on Martian ponded materials) indicate that volatiles continued to exsolve and be released after emplacement [21, 23-24].

Fig. 2 Volatile melt-rich suevites (yellowish-green) overlying ballistic ejecta (reddish–brown), Ries impact structure, Germany. Suevites can be seen infilling pre-existing topography formed by the deposition of the irregular and hummocky ballistic ejecta deposits.

We have argued that the ponded materials may be volatile-rich melt-bearing suevite-like bodies, but what of the nature of the fractured ponded materials, the sheet flow and lava flow-like features? If the ponded and pitted materials indeed comprise a mix of melt, volatiles and lithic clasts, it stands to reason that the fractured materials may be relatively volatile-poor coherent impact melts, or impact melt breccias, while sheet and lava-flow like features may represent a more pure melt end member that may possess less mineral and lithic clasts. The presence of volatile-poor impact melts and volatile-rich suevite-like materials at the same impact crater may sound surprising, but this is the case at the Ries [23, 25] and Chicxulub [26] impact structures. Because these materials are emplaced hot and remain liquid for some period of time, melt may flow under the influence of gravity and local topography, thereby creating a series of impact melt features as observed here.

If these materials in fresh Martian craters are indeed volatile-rich impact melts, the emplacement of numerous and more voluminous hydrous impact melts in the Noachian have possible implications for hydrothermal environments, Martian valley networks and the recently detected phyllosilicate-bearing lithologies. Below we discuss these topics in more detail. For some discussion of the relationship between impact melts and hydrothermal systems, see our companion abstract in this conference [7].

Implications for the formation of Martian valley networks: Martian valley networks are pervasive in the ancient southern highlands of Mars (e.g., [27]). This has led many workers to conclude that Mars once possessed an active hydrological system, and may have even been Earth-like. Our observations of fluvial channels and alluvial fans formed by surface runoff within fresh craters suggest that some of the Martian valley networks may have been a consequence of heavy bombardment and the formation of large impact basins as suggested by [28]. Although some of the surface run-off of water could have been produced from impact-induced precipitation (e.g., the older generation of fans in Mojave; Fig. 1c), this may not be the only impact-induced explanation. Based on our observations, we suggest that some component of the surface runoff is derived from melt-bearing ponded materials (e.g., Tooting, Zunil, Zumba and the older generations of fans in Mojave). In addition, a recent impact model into ice-rich targets [29] indicates that a substantial subsurface ice layer can be “squeezed” out and liberated, thus producing a substantial surface runoff component that would move across the terraces and the ejecta blanket during and post the modification stage.

Implications for phyllosilicate terrains: The detection of phyllosilicates (e.g., clays) within Noachian outcrops on Mars appears to bolster the idea that water was sustained on Mars for long periods of time (e.g., [5, 6]). This seems to be a simple matter of the kinetics of clay formation, which requires sustained long-term contact between primary volcanic phases and liquid water. However, studies of hydrous impact melt glasses and clay materials in terrestrial impactites indicate that clays can form in one of two ways: 1) from the direct devitrification of a metastable hydrous melt glass or, 2) by secondary aqueous alteration of glasses into clays. The first mechanism does not require long-term contact with water as the clays form from the solid-state transformation of hydrous impact glasses. This is more common in terrestrial melt-bearing breccias and can be clearly distinguished by both chemical and textural analyses [e.g., 21].

Given our hypothesis for the presence of abundant impact melt within in young Martian craters, the formation of phyllosilicate clays by devitrification of hydrous melt glasses in terrestrial analogues, we suggest that some Martian phyllosilcate-bearing lithologies may have been derived in a similar fashion (i.e., primary generation during impacts into volatile-rich terrains). This is corroborated by the following observations: 1) the preponderance of phyllosilicate detections in the heavily impacted southern highlands [3-6], 2) detections of hydrous glasses (e.g., [30]) in association with phyllosilicates, and 3) their proximity to large impact basins (e.g., Chryse, Isidis, Hellas and Argyre) to phyllosilicate localities. In addition, our observations and inferences from terrestrial analogues are consistent with the division of time based on mineral detections by OMEGA [6], that is the occurrence of hydrous-bearing phyllosilicate and sulfates within seemingly discrete periods with different climatic conditions. This division may reflect the transition from an impact-dominated (i.e., heavy bombardment) Noachian period to a relatively quiescent volcanic-dominated surface in the Hesperian.

Concluding statements Observations of impact melt features within and around impact structures with HiRISE, CTX and other datasets, has important implications for early conditions on Mars. Surface-runoff sourced from impact melts and ponds within fresh craters are suggestive of the formation and emplacement of volatile-rich melt-bearing bodies, which may have contributed to the formation of the Martian valley networks. In addition, the consequence of clay formation by devitrification of hydrous melt glasses is that it does not require sustained contact with water. If our interpretations using HiRISE and CTX observations presented here are correct, this will further weaken arguments for the possibility that Mars was warmer, wetter and more Earth-like in the past.

References: [1] Tornabene et al. (2007) *LPS XXXVIII*, #2215. [2] McEwen et al. (2007) *submitted to Science*. [3] Pelkey et al. (2007), *LPSC XXXVIII*, #1994. [4] Grant et al. (2007), *LPSC XXXVIII* [5] Poulet et al. (2005), *Nature*, 623-627. [6] Bibring et al. (2006) *Science*, 400-404. [7] Mouginis-Mark et al. (2007), *this conference*. Hawke and Head (1977). [8] Williams et al. (2004), *LPSC XXXV*, 1415. [9] Mouginis-Mark and Garbeil (2007) *MAPS, in press.* [10] Hawke and Head (1977), *In Impact and Explosion Cratering*, 815-841. [11] Grieve and Cintala (1995), *Icarus*, 68-79. [12] Pope et al. (2006), *Icarus*, 1-9. [13] Kieffer and Simonds (1980) *Revs. Geophys. Space Phys.*, 143 – 181. [14] Cintala and Grieve (1998), *MAPS*, 889-912. [15] Pierazzo et al. (2005), *In Large meteorite impacts III*, 443-457. [16] Stewart and Ahrens (200), *JGR*, doi:10.1029/2004JE002305. [17] Osinski (2006), *MAPS*, 1571-1586. [18] Grieve (1988) *MAPS*, 249-254. [19] Osinski et al. (2005) *MAPS*, 1789-1812. [20] Engelhardt (1990), *Tectonophys.*, 249-254. [21] Osinski et al. (2004) *MAPS*, 1655-1683. [22] Boynton et al. (2001), *Science*, 81-85. [23] Newsom et al. (1986), *JGR*, 239-251. [24] Newsom et al. (1990), *GSA special paper 247*, 195-205. [25] Osinski (2004), *MAPS*, 529-543. [26] Jones et al. (2000), *In Impacts and the Early Earth*, 343-361. [27] Gulick et al. (2001), *Geomorph.* 241-268. [28] Segura et al. (2002), *Science*, 1977-1980. [29] Senft and Stewart (2006), *AGU fall*, #P31A-0121. [30] Ehlmann et al. (2007), *LPSC XXXVIII*, #2078.