IMPACT EJECTA EMPLACEMENT ON TERRESTRIAL PLANETS. G. R. Osinski[1], L L. Tornabene[2], and R. A. F. Grieve[1], [1]Departments of Earth Sciences/Physics and Astronomy, University of Western Ontario, 1151 Richmond Street, London, ON, N6A 5B7, Canada, [2]Center for Earth and Planetary Studies, National Air and Space Museum, Smithsonian Institution, Washington, DC 20560-0315, USA (gosinski@uwo.ca)

Introduction: Impact cratering is one of the most fundamental processes responsible for shaping the surfaces of solid planetary bodies. One of the principal characteristics of impact events is the formation and emplacement of ejecta deposits. An understanding of impact ejecta deposits, and their components, is critical for the results of planetary exploration; particularly future sample return missions. Their compositional and physical characteristics provide fundamental information about the sub-surface of planets. Current models of ejecta emplacement, however, do not account for several important observations of planetary ejecta deposits; in particular, the presence of double or multiple layers of ejecta. Further, there is also no universal model for the origin and emplacement of ejecta on different planetary bodies. Here, we present a new working model for the origin and emplacement of ejecta on the terrestrial planets, in which ejecta is emplaced in a multi-stage process.

Critical observations from the terrestrial planets: It is generally acknowledged that proximal ejecta deposits around impact craters on airless bodies, such as the Moon and Mercury, are emplaced via the process of ballistic sedimentation – this results in the incorporation of local material (secondary ejecta) in the primary ejecta, via considerable modification and erosion of the local external substrate [1]. A typically overlooked, but critical, observation is that proximal ejecta may consist of more than one layer.

Moon and Mercury. On the Moon, melt ponds on the rim terraces of complex lunar craters and overlying parts of continuous ejecta have been documented since the 1970s [2] (Fig. 1a). The interpretation is that these deposits consist of impact melt that has flowed and pooled according to local slopes, after its initial emplacement as ejecta. This is consistent with observations from the Lunar Reconnaissance Orbiter Camera (LROC) (Fig. 1b). Images recently returned by the Messenger spacecraft show the presence of what is interpreted as melt ponds around several Mercurian impact craters [3]. If ballistic sedimentation followed by radial flow accounts for the emplacement of the continuous ballistic ejecta, it begs the question as to the origin of this overlying melt-rich ejecta observed around many lunar and Mercurian craters.

Venus. The relative increase in the volume of impact melt produced on Venus, for a given transient crater size, compared to the Moon is manifest as spectacular melt outflows exterior to Venusian craters [4]. Several factors complicate the interpretation of these outflows around Venusian craters and not all may have the same origin; however, they share many traits with exterior lunar impact melt deposits and ponds.

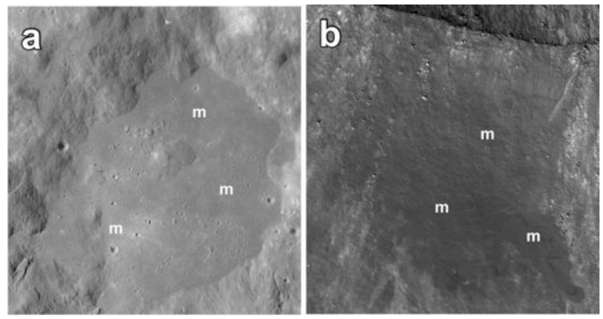

Fig. 1. (a) Large impact melt ("m") pond around King Crater crater. Portion of Apollo 16 image 1580 (NASA). (b) A portion of LROC NAC image pair (M106209806RE) of melt overlying the continuous ejecta blanket at Giordano Bruno crater (NASA/GSFC/ASU).

Earth. Ejecta deposits are relatively rare due to high rates of erosion on Earth; however, given the ability to ground truth, any model must be consistent with the interpretation of the characteristics of ejecta deposits on Earth, if it is to be generally applicable.

The nature, lithological and stratigraphic relations of ejecta at several buried complex structures are known only from drill core but indicate the presence in the proximal ejecta of a low-shock, lithic breccia overlain by melt-bearing deposits. Some of the best-preserved and exposed ejecta deposits on Earth occur at the Ries structure, Germany [5]. The Ries clearly displays a distinctive two-layer ejecta deposit (Fig. 1a) with a series of impact melt-bearing breccias (suevites), and impact melt rocks overlying the continuous ejecta blanket (Bunte Breccia). Studies of the Bunte Breccia strongly support the concept of ballistic sedimentation [6].

Early workers suggested that the upper surficial "suevite" ejecta at the Ries was deposited sub-aerially from an ejecta plume [5] and the term "fallout" was used to qualify the suevites. This is despite the fact that the surficial suevites are unsorted to poorly sorted, which is not predicted by subaerial deposition (i.e., fallout from an ejecta plume). More recently, it was suggested that the proximal surficial suevites were emplaced as surface flow(s), either comparable to pyroclastic flows or as ground-hugging volatile- and melt-rich flows [7, 8]. The most intransigent argument used to support an airborne origin for suevites at the

Ries are so-called "aerodynamically shaped" glass clasts and "gneiss-cored glass bombs" [5]. An airborne emplacement was offered as a possible explanation for their shape; however, such "morphologies" can be found in injection dikes of impact melt-bearing breccia that clearly cross-cut the lithologies of the crater floor of the Mistastin Lake impact structure, Canada (Fig. 2b). In this case, the "fladen" cannot be explained as aerodynamically-shaped, and are likely due to shaping during transport within a confined flow (cf., glass coatings on lithic clasts).

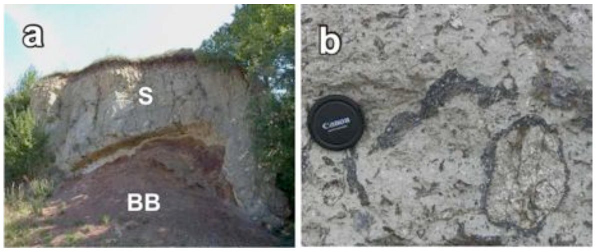

Fig. 2. (a) Impact melt-bearing breccias, or "suevites" (S) overlying Bunte Breccia (BB) at the Ries structure. Note the sharp contact between the two units. (c) Elongate, "aerodynamically-shaped" glass bombs and gneiss-cored glass "bombs". These features are widely cited as de facto evidence for airborne emplacement but these are actually from a dike of suevite in the crater floor of the Mistastin structure.

Mars. The Martian impact cratering record is notably more diverse than that of the Moon, Mercury or Venus. In particular, approximately one-third of all Martian craters ≥5 km in diameter possess discernable ejecta blankets, with over 90% possessing so-called layered ejecta that display single (SLE), double (DLE), or multiple (MLE) layer morphologies [9]. In general, MLE craters are typically larger and their ejecta are found at greater radial distances than SLE craters, when normalized to crater size. DLE craters remain enigmatic. Contrasting models have been proposed to account for these layered ejecta on Mars.

The working hypothesis: Based on the above observations that impact melt occurs outside the rim at both simple and complex craters, we suggest that the current view of impact ejecta emplacement, i.e., a one-stage and strickly ballistic process that occurs during the excavation stage, is incomplete. A multi-stage emplacement process that intimately links the generation of impact melt lithologies, allochthonous crater-fill deposits and ejecta is proposed:

1) *Crater excavation and ballistic emplacement* – The initial emplacement of a continuous ejecta blanket is via the process of ballistic sedimentation. Materials are derived from the excavated zone of the transient cavity and are of generally relatively low shock level. It is suggested that several parameters will affect the morphology and extent of this primary ejecta layer, in particular the volatile content and cohesiveness of surficial target materials.

2) *Late excavation – early modification and minor flow emplacement* – In simple craters, there is movement of highly shocked and melted materials initially down into the expanding transient cavity. Some of these materials are driven up and over the transient cavity walls and rim region, consistent with the presence of thin melt veneers around some simple lunar craters and impact melt rocks outside the rim at some terrestrial craters. Impact angle and preexisting topography can have a major influence during this stage.

3) *Crater modification and "late" flow emplacement* – The observations of impact melt-rich deposits overlying ballistic ejecta deposits and the sharp contact between these units, where observed, argue for the general late-stage emplacement of melt-rich ejecta. It is suggested that cavity modification, in particular uplift, imparts an additional outward momentum to the melt- and clast-rich lining of the transient cavity during the modification stage, resulting in flow towards and over the collapsing crater rim and onto the proximal ballistic ejecta blanket, forming a second thinner and potentially discontinuous layer of non-ballistic ejecta. For oblique impacts, an additional mechanism may be the emplacement of external melt in a process more akin to what is believed to occur at simple craters, i.e., by the late-stages of the cratering flow-field. In this case, the initial direction of the flows is preferentially downrange. The final resting place for the melt-rich deposits will be controlled to a large extent by the local topography of the target region.

4) *Minor fallback* – Fallback of material from the vapour-rich ejecta plume will occur during the final stages of crater formation on bodies with an atmosphere and will produce the very minor "fallback" material in the crater interior, which will be characteristically graded, such as observed at the Ries structure in the terrestrial environment.

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