IMPACT EJECTA EMPLACEMENT: OBSERVATIONS FROM THE TERRESTRIAL PLANETS, THE MOON, AND VESTA. G. R. Osinski[1,2], R. A. F. Grieve[1,3], L L. Tornabene[1], [1]Dept. of Earth Sciences/Centre for Planetary Science and Exploration, University of Western Ontario, London, ON, Canada, [2]Dept. of Physics and Astronomy, University of Western Ontario, London, ON, Canada, [3]Earth Sciences Sector, Natural Resources Canada, Ottawa, ON, Canada (gosinski@uwo.ca)

Introduction: One of the principal characteristics of impact craters throughout the Solar System is the presence of impact ejecta deposits. Despite this, the formation and emplacement of ejecta deposits remains actively debated, particular for the Earth and Mars. Here, we provide results from observations of craters on all 4 terrestrial planets as well as the Moon and Vesta. This builds upon earlier with in which we outlined a unifying working hypothesis for the origin and emplacement of ejecta on the terrestrial planets, in which the ejecta are emplaced in a multi-stage process [1]. A driving paradigm of this work is that the overall processes involved in the generation of impact ejecta deposits and their initial emplacement must, in principle, essentially the same on all the terrestrial planets. Planetary gravity, atmospheric, and target properties will have secondary, but important, effects on the nature of ejecta and account for detailed differences in ejecta between the terrestrial planets.

At present, numerical simulations are unable to model the emplacement of proximal ejecta deposits. Some recent work has started to address this but, to-date, the published simulations have focused on the emplacement of very distal ejecta deposits related to the K-Pg impact [2, 3]. Thus, our approach is to synthesize field observations and sample studies from craters on Earth with remote sensing data from other planetary objects.

Formation of continuous ejecta blankets: On airless bodies, such as the Moon, it is generally accepted that continuous ejecta blankets are emplaced via the process of ballistic erosion and sedimentation [4]. In this model, ejecta is deposited ballistically, which results in the incorporation of local material (secondary ejecta) in the primary ejecta, via considerable modification and erosion of the local substrate *external* to the transient cavity. Studies of the Bunte Breccia at the Ries impact structure, Germany, strongly support this concept of ballistic sedimentation [5]. Thus, it seems plausible that the emplacement of the continuous ejecta blankets around craters on all terrestrial planets, rocky moons, asteroids, etc., is via this process.

The problem of multiple ejecta layers: Early studies of lunar craters recognized the presence of material interpreted to be impact melt ponded on rim terraces and parts of the ballistic continuous ejecta deposits [6] (Fig. 1; Table 1). These melt ponds are, by definition, impact ejecta. Critically, this ejecta morphology – i.e., patchy, discontinuous deposits of ejecta *overlying* the continuous ejecta blanket (Fig. 2) – has recently been shown to occur on Mercury [7] and Vesta [8] (Table 1). We also showed that this morphology occurs on Mars [1] (Table 1).

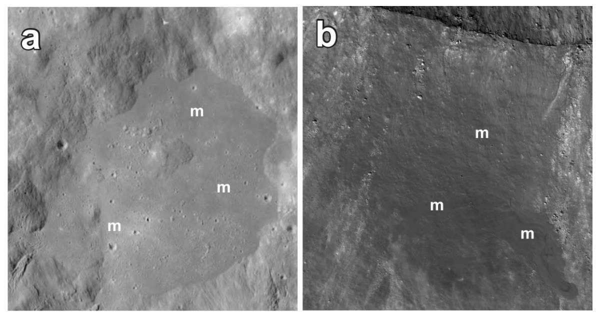

Fig. 1. (a) Large impact melt ("m") pond around King Crater crater. Portion of Apollo 16 image 1580 (NASA). (b) A portion of LROC NAC image pair (M106209806RE) of melt overlying the continuous ejecta blanket at Giordano Bruno crater (NASA/GSFC/ASU).

Several factors complicate the interpretation of Venusian craters; however, spectacular outflows around many Venusian craters share many traits with exterior lunar impact melt deposits and ponds [9] (Table 1). On Mars, in addition to the discontinuous second layer of ejecta, continuous layers ejecta overlying the continuous ejecta blanket occur, displaying both double (DLE) and multiple (MLE) layer morphologies [10] (Fig. 2).

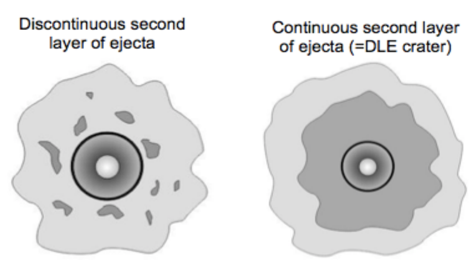

Fig. 2. Schematic representation of craters with discontinous (or patchy) and continuous second layers of ejecta.

Table 1 provides an overview of 3 major properties – distribution, melt content, and provenance (i.e., depth of origin in the target) – of ejecta deposits on various planetary bodies. It is clear from this that all the terrestrial planets, the Moon, and Vesta, all show similar ejecta morphologies. Therefore, any model for the formation of ejecta deposits must account for this and cannot be due to some feature only present on a particular planetary object (e.g., ice) or at one individual impact site (e.g., a lake).

A final important consideration is that the second discontinuous layer of ejecta around several craters on Earth (e.g., Haughton [11], Ries [12], Mistastin [13]) and Mars [1] possess the same physical and chemical characteristics and share the same provenance as the crater-fill impactites in said craters.

How to form multiple ejecta layers? The widely ejecta emplacement model of ballistic sedimentation and erosion [4] can only form one layer of ejecta. Thus, an alternative model is required in order to form continuous and discontinuous second layers of ejecta. At the Ries structure, the origin of the overlying second layer of ejecta remains contentious, with early workers suggesting fallout from an ejecta plume [12]. Subsequently, we proposed a surface flow origin for these deposits [14] based on field studies and the first – and still only – detailed microanalytical study of the groundmass of these impact melt-bearing breccias. Most recently a new model invoking the explosive reaction ("fuel-coolant interaction (FCI)) between a temporary impact melt pool with water and volatile-rich sedimentary target rocks [15]. However, as shown by Grieve et al. [16, 17] the FCI model for the Ries suevite is not supported by field or petrological observations. The FCI model also fails to account for the fact that the stratigraphy and properties of the Ries ejecta are not unique as noted above.

The working hypothesis. Based on the above observations we propose that the multi-stage emplacement model for impact ejecta emplacement [1] remains the best working hypothesis to date:

1) *Crater excavation and ballistic emplacement* – The initial emplacement of an ejecta blanket is via the process of ballistic sedimentation [4]. Materials are derived from the excavated zone of the transient cavity and are of generally relatively low shock level.

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.

3) *Crater modification and "late" flow emplacement* – 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 discontinuous layer of non-ballistic ejecta. On Mars and Venus, where melt volumes can be potentially higher in this layer, this layer can become continuous to form, e.g., DLE craters on Mars.

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.

Acknowledgements: G.R.O. is support by an Natural Sciences and Engineering Research Council of Canada (NSERC) Industrial Research Chair sponsored by MDA Space Missions and the Canadian Space Agency (CSA).

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Table 1. Properties of two-layered ejecta deposits on various planetary bodies.

Planetary body	Properties of the lower layer			Properties of the upper layer		
	Distribution	Melt content	Provenance	Distribution	Melt content	Provenance
Mercury	Continuous	Low	?	Discontinuous	High	?
Venus	Continuous	Low	?	Continuous / Discontinuous	High	?
Moon	Continuous	Low	?	Discontinuous	High	?
Earth	Continuous	Low	Shallow	Discontinuous	High	Deep
Mars	Continuous	Low	Shallow	Discontinuous Continuous	High ?	Deep Deep
Vesta	Continuous	Low	?	Discontinuous	High	?