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Impact ejecta emplacement on terrestrial planets

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ABSTRACT

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 which is critical for planetary exploration. Current models of ejecta emplacement, however, do not account for several important observations of ejecta deposits on the terrestrial planets, in particular, the presence of more than one layer of ejecta. Furthermore, there is also no universal model for the origin and emplacement of ejecta on different planetary bodies. We present 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. The generation of the continuous ejecta blanket occurs during the excavation stage of cratering, via the conventional ballistic sedimentation and radial flow model. This is followed by the emplacement of more melt-rich, ground-hugging flows – the "surface melt flow" phase – during the terminal stages of crater excavation and the modification stage of crater formation. Minor fallback occurs during the final stages of crater formation. Several factors will affect the final morphology and character of ejecta deposits. The volatile content and cohesiveness of the uppermost target rocks will significantly affect the runout distance of the ballistically emplaced continuous ejecta blanket, with impact angle also influencing the overall geometry of the deposits (e.g., the production of the characteristic butterfly pattern seen in very oblique impacts). Ejecta deposited during the surface melt flow stage is influenced by several factors, most importantly planetary gravity, surface temperature, and the physical properties of the target rocks. Topography and angle of impact play important roles in determining the final distribution of surface melt flow ejecta deposits with respect to the source crater. This working hypothesis of ballistic sedimentation and surface melt flow provides a framework in which observations of ejecta at impact craters can be compared and placed in the context of the respective terrestrial planets.

1. Introduction

Meteorite impact craters represent an important geological landform in the solar system and are among the highest priority scientific targets for the international exploration of the Moon and Mars (e.g., Barlow, 2010; Hiesinger and Head, 2006). It has become apparent over the past two decades that meteorite impact events also have played an important role throughout Earth's history, shaping the geological landscape, affecting the evolution of life (e.g., Kring, 2000) and producing economic benefits (e.g., Grieve, 2005). Despite the ubiquitous occurrence of impact craters, however, important aspects of the processes and products of their formation remain poorly constrained. One such process is the emplacement of impact ejecta deposits and the provenance of their components, in particular, impact melt. As with all impactites, the record on Earth is the only source of ground truth data on ejecta. 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. A prime example is on Mars, where the presence of so-called fluidized (or layered) ejecta deposits was the initial evidence to infer the presence of subsurface ice (e.g., Carr et al., 1977).

This contribution synthesizes field and laboratory data on Earth impact products and structures and combines them with planetary remote sensed observations. These provide the input for a working hypothesis for the origin, nature and emplacement of ejecta around simple and complex impact craters on the terrestrial planets. We do not discuss multi-ring basins here due to a current lack of observations and overall understanding of their formation. It should also be noted that current numerical simulations are unable to reproduce all the observations from planetary impact craters in terms of ejecta deposits (Artemieva et al., 2009). Some recent work has

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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 (Artemieva and Morgan, 2009; Goldin and Melosh, 2009). A driving paradigm of this work is that the overall processes involved in the generation of impact ejecta and crater-fill deposits and their *initial* emplacement are, in principle, essentially the same on all the terrestrial planets. Planetary gravity, atmospheric, and target properties have secondary, but important, effects on the nature of ejecta and account for detailed differences in ejecta between the terrestrial planets. We briefly discuss the unique Martian scenario of impacts that involve appreciable ground ice in the target, but note that a complete discussion is outside the scope of this paper. In support of the working hypothesis, we first present some critical observational evidence from the terrestrial planets.

2. Critical observations from the terrestrial planets

Impact ejecta deposits are defined here as any target materials, regardless of their physical state, that are transported beyond the rim of the *transient* cavity formed directly by the cratering flow-field (Fig. 1a, b). In complex craters, therefore, ejecta deposits occur in the crater rim region interior to the final crater rim. We focus on proximal ejecta deposits, which are, by definition, found within 5 crater radii of the source crater (Stöffler and Grieve, 2007). Fresh impact craters on all the terrestrial planets are typically surrounded by a “continuous ejecta blanket” that extends approximately 1 to 2 crater radii beyond the crater rim (Melosh, 1989). This continuous ejecta blanket is thickest at the rim. Beyond this, the deposits are typically thin and patchy. For a full discussion of the characteristics of continuous ejecta blankets (e.g., structural rim uplift, overturned flaps, and clast size distributions, etc.), the reader is referred to Chapter 6 in Melosh (1989).

2.1. The Moon and Mercury

Continuous ejecta blankets around lunar craters are typically blocky and of high albedo, when fresh (Melosh, 1989). Radial textures and patterns are common and the ejecta blanket thins with increasing radial distance. The maximum diameter of boulders in an ejecta blanket increases with crater size (Bart and Melosh, 2007). It is generally acknowledged that the continuous ejecta blanket, and proximal ejecta deposits in general, on airless bodies, such as the Moon and Mercury, are emplaced *via* the process of ballistic sedimentation. The ballistic emplacement of primary crater-derived ejecta produces secondary cratering, which results in the incorporation of local material (secondary ejecta) in the primary ejecta, via considerable modification and erosion of the local external substrate. The characteristics of this ballistic sedimentation model for proximal ejecta, namely increasing source depth and incorporation of secondary local substrate materials with increasing radial range (Oberbeck, 1975), are a tenet in the interpretation of lunar samples (Heiken et al., 1991). A typically overlooked, but critical, observation is that proximal ejecta may consist of more than one layer.

The Moon represents an end-member case with respect to the terrestrial planets. Low planetary gravity and lack of atmosphere result in cratering efficiency, for a given impact, that is higher than on the other terrestrial planets. Cratering efficiency is defined as the ratio of the mass of the target displaced to the mass of the impactor (Melosh, 1989). As a portion of the transient cavity formed in an impact event that is due to the excavation of target materials, the cratering efficiency of equivalent impacts (same sized and type of impactor, same type of target and same impact velocity) is relatively lower on planetary bodies with higher surface gravities. Similarly, as gravity is an acceleration and acts to retard excavation, cratering efficiency is relatively lower for larger impact events (i.e., more time is required to complete excavation) on the same planet, given equivalent impact velocity and impactor and target types.

Planetary gravity has little effect on the volume of impact melt produced in a given impact event, beyond its effect on impact velocity (Grieve and Cintala, 1997). As a result, the relative volume of impact melt to transient cavity on the Moon is the lowest among the terrestrial planets for a given-sized cavity (Cintala and Grieve, 1998). Nevertheless, what is generally interpreted to be impact melt ponds on the rim terraces of complex lunar craters and overlying parts of the continuous ejecta blanket have been documented since the 1970s (Hawke and Head, 1977; Howard and Wilshire, 1975) (Fig. 2A,B). The interpretation is that these generally flat and smooth surfaced ponds consist of impact melt that has flowed and pooled according to local slopes, after its initial emplacement as ejecta. More recently, the Lunar Reconnaissance Orbiter Camera (LROC) has captured spectacular images of impact melt forming ponds and veneers within the crater interior and the terraced crater rim region (Fig. 2C), overlying ballistic ejecta deposits (Fig. 2C,D), and draping central uplifts (Fig. 2E–G) within and around many complex lunar craters. These melt deposits show intricate surface textures and morphologies indicative of flow, such as channels and arcuate cracks and ridges. Such impact melt deposits also are visible in radar imagery, where they appear to be associated with larger craters (>40 km in diameter) (Campbell et al., 2010). For craters formed from oblique impact, such as the 85 km diameter Tycho crater, it is apparent that more melt is present in the downrange direction (Hawke and Head, 1977).

With the increased resolution provided by LROC, it is apparent that some small, simple craters also preserve dark deposits consistent with

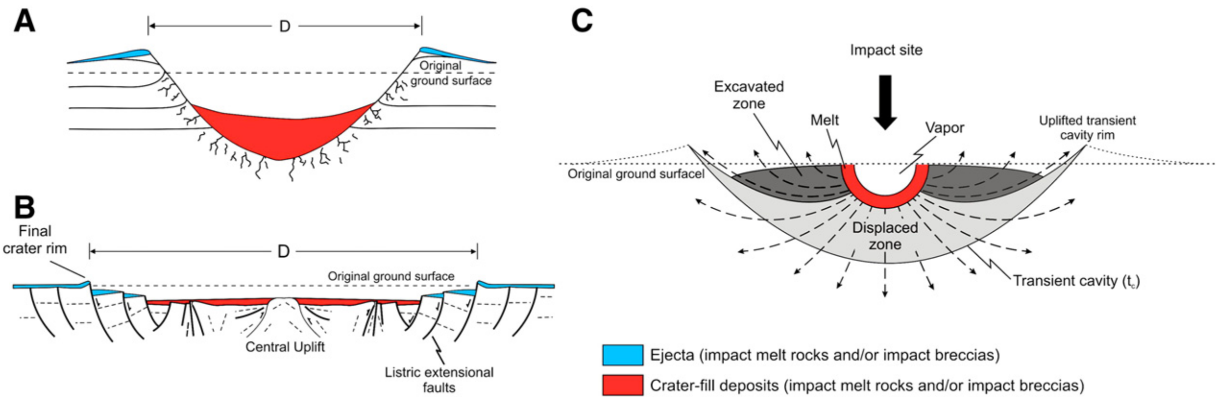

Fig. 1. Typical schematic cross sections of simple and complex craters and of a transient cavity. A. Simple impact crater. B. Complex impact crater. Note that ballistic ejecta is present inside the crater rim because it originates from the transient cavity, which is largely destroyed during crater collapse. Also note that typical cross sections, such as this, in the literature, do not show multiple ejecta layers. “D” represents the rim (or final crater) diameter, which is defined as the diameter of the topographic rim that rises above the surface for simple craters, or above the outermost slump block not concealed by ejecta for complex craters (Turtle et al., 2005). C. Theoretical cross section through a transient cavity showing the locations of impact metamorphosed target lithologies. Modified from Melosh (1989).