Planetary and Space Science 160 (2018) 39–55

Contents lists available at ScienceDirect

Planetary and Space Science

journal homepage: www.elsevier.com/locate/pss

Preliminary laboratory investigations of ejecta emplacement dynamics and morphology with planetary applications

Kirby D. Runyon[a,*,1], Olivier S. Barnouin[b]

[a] The Johns Hopkins University Department of Earth & Planetary Sciences, Baltimore, MD, USA
[b] The Johns Hopkins University Applied Physics Laboratory, Laurel, MD, USA

ARTICLE INFO

Keywords:
Impact cratering
Ejecta
Experimental methods

ABSTRACT

The preponderance of impact craters and the associated crater ejecta facies are leading agents of geomorphic change across the Solar System. Interpretation of planetary landscape evolution, sample provenance, and regolith gardening all benefit from a thorough understanding of ejecta emplacement dynamics. Constraining the type and range of these dynamics has eluded experimentation even as the effects of primary impacts have become well-constrained from experiments and numerical simulations and have been shown to follow power law scaling relationships. To address the knowledge gap surrounding granular ejecta emplacement, we built and characterized a novel ejecta emplacement catapult and showed it to accurately reproduce the ejecta mass and velocity profiles predicted for in-flight natural ejecta curtains. Based on this dynamic similarity to larger, natural systems, we proceeded with a preliminary exploratory suite of experiments to constrain runout and erosion efficiencies of flowing ejecta. Our quantitative results at low speeds may suggest a new set of scaling relationships for erosion via ballistic ejecta versus crater formation and erosion from hypervelocity clustered projectiles. Our results also show significant ejecta runout efficiencies of ~1–2 (only slightly below the efficiencies of terrestrial debris flows 12 decades more voluminous) with important erosive efficiencies of ~2–4%. Our qualitative results reveal a stochastic and heterogeneous system: ejecta "saltation" and implantation, and regolith exhumation, erosion, and shearing. Together with the initial results showing ejecta emplacement to be violently dynamic, the development of this new laboratory technique will enable more detailed studies to better inform interpretations of sample provenance, ejecta stratigraphy, and geochemical boundaries.

1. Introduction

Impact cratering is the most common geologic process that influences the surfaces of solid worlds across the solar system (Shoemaker, 1962; Gault et al., 1968; Oberbeck, 1975; Housen and Holsapple, 2011). It follows that on worlds where the gravity is sufficient to retain ejecta, the emplacement of the crater ejecta might be just as influential a process, given that the surface area of ejecta deposits is typically large relative to its source crater (Fig. 1). Compared to the extensive studies exploring cratering mechanics and crater geomorphology (e.g., Holsapple, 1993; Melosh, 1989; Barnouin-Jha et al., 2007), few investigations have addressed the dynamics of ballistic ejecta emplacement, especially within a few crater radii from the rim (e.g., Oberbeck et al., 1975; Pieters et al., 1985; Schultz and Gault, 1985).

Ejecta does not simply remain where it lands: Oberbeck (1975) introduced the concept of ballistic sedimentation in which deposited ejecta creates secondary craters, erodes, and incorporates itself with the original pre-impact regolith. Evidence from striae, polish, and detachment folds in limestone ejecta fragments at Germany's Ries Crater (Chao, 1974, 1976; Hörz et al., 1983; Kenkmann and Ivanov, 2006; Kenkmann and Schönian, 2006) indicate that ballistic ejecta slide while eroding local material, yet this sliding has been largely ignored or, early on, even contested (Oberbeck et al., 1975) when considering ejecta on other planets, including the Moon and Mars. Ghent et al. (2016) used radar and near infrared observations of lunar ejecta to strongly suggest post-depositional runout to explain abrupt boundaries of radar haloes around craters, agreeing with the observations of ejecta runout in radar images of Venusian crater ejecta (Schultz, 1992). In the case of Mars, ejecta deposits that show contiguous ramparts and lobate deposits (e.g., Carr, et al., 1977; Mouginis-Mark, 1979; Schultz, 1992; Barlow, 1994;

---

* Corresponding author.
E-mail address: kirby.runyon@jhuapl.edu (K.D. Runyon).
[1] Now at The Johns Hopkins University Applied Physics Laboratory, Laurel, MD, USA.

https://doi.org/10.1016/j.pss.2018.03.014
Received 14 August 2017; Received in revised form 22 March 2018; Accepted 28 March 2018

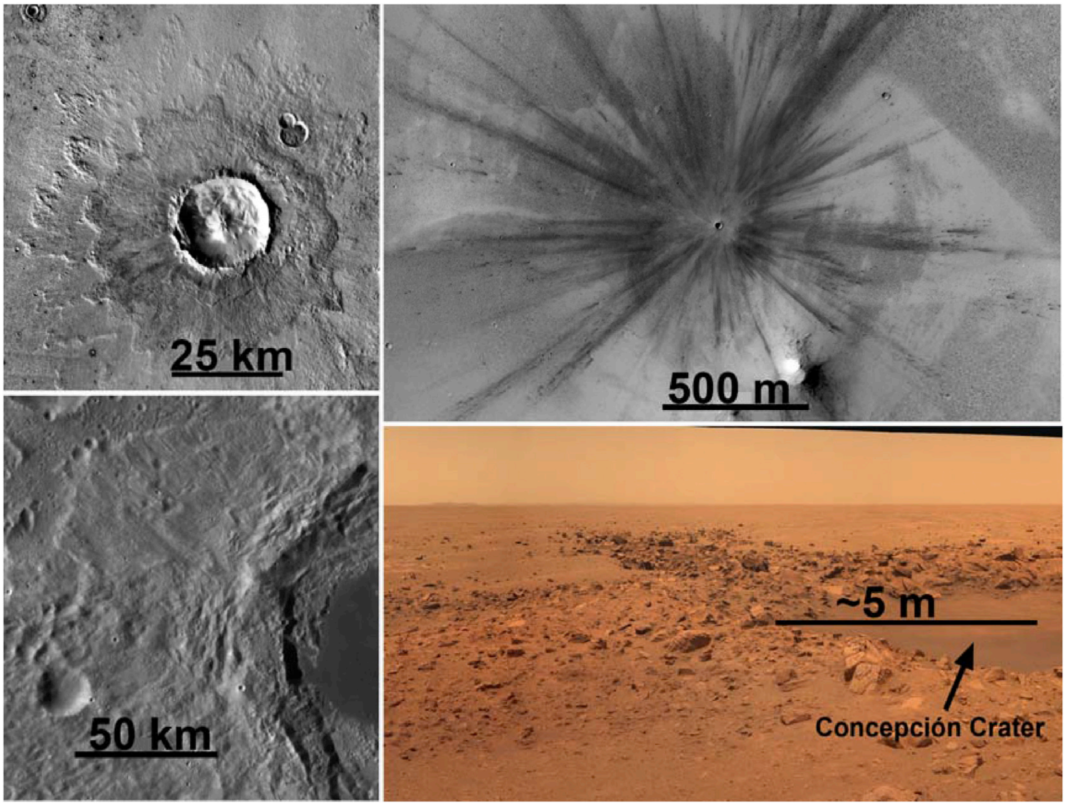

Fig. 1. Examples of crater ejecta on planetary surfaces at a range of spatial scales. *Top left:* Bacolor Crater, Mars, features multi-layered ejecta with distal ramparts; THEMIS image credit: NASA/ASU (33° N, 118.6E). *Top right:* A new impact crater with extensive dark ray ejecta on Mars. HiRISE image ESP_034285_1835 (3.7N, 53.4E) credit: NASA/UA. *Bottom left:* Rare lunar lobate ejecta to the northwest of Tsiolkovsky Crater; LROC WAC mosaic (18S, 124E), credit: NASA/GSFC. *Bottom right:* Proximal ejecta blocks from Concepción Crater on Meridiani Planum, Mars, as imaged by the rover *Opportunity*; Credit: NASA/JPL/Cornell.

Boyce and Mouginis-Mark, 2006; Barnouin-Jha et al., 2005; Robbins and Hynek, 2012; Barlow et al., 2014; Wada and Barnouin-Jha, 2006) show abundant evidence for surface flow and underscore the importance of understanding the detailed mechanics of ballistic ejecta emplacement and subsequent lateral flow after its initial deposition (Carr et al., 1977; Schultz, 1992; Ivanov et al., 1994, 1997; Wada and Barnouin-Jha, 2006). Numerous geomorphologies in ejecta facies on Mars and some icy moons suggest post-depositional flow emplacement such as distal ramparts in Martian ejecta, which appear to divert around obstacles or otherwise flow (e.g, Carr et al., 1977; Schultz, 1992; Mouginis-Mark, 1979; Baloga et al., 2005; Barlow, 2005; Boyce and Mouginis-Mark, 2006; Wada and Barnouin-Jha, 2006; Boyce et al., 2010).

Besides addressing the observed flow of ejecta and the resulting morphologies, a better understanding of the range of possible transport histories of ejecta and regolith parcels also will aid in petrologic and provenance interpretation of samples and remote sensing datasets. For instance, compositional mixing across physiographic boundaries on the Moon remain difficult to explain. Detailed investigations of the processes associated with regolith mobilization and mixing ("gardening") by ejecta should provide needed clarity, given that such processes are often invoked to explain multispectral and morphological observations (Oberbeck et al., 1975; Li and Mustard, 2000, 2003, and 2005). Such investigations of ejecta dynamics should also illuminate how transportation of geologic materials away from their source lithologies influence sample provenance interpretation, geochronometry, and other geochemical investigations. To wit: recent analyses of Apollo and Luna samples suggest Imbrium ejecta dominates the sample collections (Haskin, 1998; Cohen et al., 2018), yet knowing the range of possible transport histories for ejecta parcels could aid in the Imbrium provenance interpretation.

Historically, cratering experiments and nuclear explosions, along with data from a few lunar craters, have led to a commonly used model where ejecta thickness decays with distance from a crater rim as a power law with a slope of −3 assuming ejecta does not flow along the ground after deposition (e.g., McGetchin et al., 1973; Housen et al., 1983; Sharpton, 2014; Rice and Warner, 2016). Crater scaling relations (Housen et al., 1983) predict such a relationship for gravity-controlled craters where target strength is not important. Rather, the crater scaling relationship provide estimates for the amount of ejecta delivered to a given distance with some bulking. Conversely, some studies assume that the origin and volume of the ejected material in the deposit can be directly traced back along ballistic trajectories to source regions within the crater (Hartmann, 1985).

Many investigations (e.g., Hörz et al., 1983; Chao, 1974; Oberbeck, 1975, 1976; Kenkmann and Ivanov, 2006; Kenkmann and Schönian, 2006) indicate that it is not so simple to trace ballistic paths from the ejecta blanket back into the crater to determine ejecta provenance. Recent topographic and radar data from the Moon reveal that ejecta topography and thickness (e.g., Stickle et al., 2016) often show wide variation in the power-law slope of ejecta thickness as a function of distance from the crater. Experiments similarly show variation in ejecta thickness decay as a function of impactor angle and also impactor density (Goldberg et al., 2013). Settle and Head (1977) used orbital Apollo stereo photogrammetry to show that ejecta thickness decay curves did not follow a simple scaling relation. These thickness variations are thus likely evidence for post-depositional flow and near surface gardening, such as would happen during surface erosion and mixing. A detailed assessment of the dynamics of ejecta emplacement would help quantify the degree of mixing between primary ejecta and target and how much lateral displacement to expect. This assessment would better link observed ejecta thicknesses and the volumes of ejecta excavated from craters. For those ejecta facies where significant local material has not been