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Comparisons of fresh complex impact craters on Mercury and the Moon: Implications for controlling factors in impact excavation processes

Zhiyong Xiao [a,b,*], Robert G. Strom [b], Clark R. Chapman [c], James W. Head [d], Christian Klimczak [e], Lillian R. Ostrach [f], Jörn Helbert [g], Piero D'Incecco [g]

[a] Planetary Science Institute, Faculty of Earth Sciences, China University of Geosciences (Wuhan), Wuhan, Hubei 430074, China
[b] Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85719, USA
[c] Department of Space Studies, Southwest Research Institute, Boulder, CO 80302, USA
[d] Department of Geological Sciences, Brown University, Providence, RI 02912, USA
[e] Department of Terrestrial Magnetism, Carnegie Institution of Washington, Washington, DC 20015, USA
[f] School of Earth and Space Exploration, Arizona State University, AZ 85281, USA
[g] Institute of Planetary Research, Deutsches Zentrum für Luft- und Raumfahrt, 12489 Berlin, Germany

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ABSTRACT

The impact cratering process is usually divided into the coupling, excavation, and modification stages, where each stage is controlled by a combination of different factors. Although recognized as the main factors governing impact processes on airless bodies, the relative importance of gravity, target and projectile properties, and impact velocity in each stage is not well understood. We focus on the excavation stage to place better constraints on its controlling factors by comparing the morphology and scale of crater-exterior structures for similar-sized fresh complex craters on the Moon and Mercury. We find that the ratios of continuous ejecta deposits, continuous secondaries facies, and the largest secondary craters on the continuous secondaries facies between same-sized mercurian and lunar craters are consistent with predictions from gravity-regime crater scaling laws. Our observations support that gravity is a major controlling factor on the excavation stage of the formation of complex impact craters on the Moon and Mercury. On the other hand, similar-sized craters with identical background terrains on Mercury have different spatial densities of secondaries on the continuous secondaries facies, suggesting that impactor velocity may also be important during the excavation stage as larger impactor velocity may also cause greater ejection velocities. Moreover, some craters on Mercury have more circular and less clustered secondaries on the continuous secondaries facies than other craters on Mercury or the Moon. This morphological difference appears not to have been caused by the larger surface gravity or the larger median impact velocity on Mercury. A possible interpretation is that at some places on Mercury, the target material might have unique properties causing larger ejection angles during the impact excavation stage. We conclude that gravity is the major controlling factor on the impact excavation stage of complex craters, while impact velocity and target properties also affect the excavation stage but to a lesser extent than gravity.

1. Introduction

Mercury's surface is populated by numerous impact craters, giving it a first-order appearance similar to the Moon (Murray et al., 1974). Fresh impact craters with pristine morphology (i.e., little eroded, distinct rims, and few superposed craters) and the distribution of their secondary craters (secondaries are formed by impacts of high velocity ejecta; Shoemaker, 1965) are windows into studying the factors that affect the impact cratering process, such as the presence of an atmosphere, surface gravity, target and projectile properties, and impact velocity. Mercury and the Moon are airless bodies and thus are not affected by atmospheres, making these bodies ideal laboratories for comparative studies of impact processes (Gault et al., 1975; Schultz and Singer, 1980).

The impact process can be divided into the coupling, excavation, and modification stages (e.g., Gault et al., 1968; Melosh, 1989). The coupling stage begins at the instant when the impactor strikes the target surface and its kinetic energy is transmitted into the target material, inducing impact melting and vaporization. Outside the melting and vaporization zone, the expanding shock wave front severely damages and ejects the target material, marking the onset of the excavation stage. The shock fronts weaken

* Corresponding author at: Planetary Science Institute, Faculty of Earth Sciences, China University of Geosciences (Wuhan), #388 Lumo Road, Hongshan District, Wuhan, Hubei 430074, China.
E-mail address: xiaobeary@gmail.com (Z. Xiao).

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rapidly with increasing distance from the melting and vaporization zone, accompanied by a rapid decrease of ejection velocities. The transient crater forms at the end of this stage. During the modification stage, the ejected material falls back to the surface and the transient crater collapses due to gravitationally unstable crater walls. As a result, the crater diameter grows while the depth decreases. The modification stage can take a longer time relative to the coupling and excavation stages (Melosh, 1989).

Early studies comparing the morphology and scale of craters on Mercury to the Moon focused primarily on crater interior structures, such as central peaks, crater depth, rim height, rim scallops, and wall terraces (e.g., Head, 1976; Oberbeck et al., 1977). Opinions have differed over the role of the above described factors on the size and morphology of impact structures on the Moon and Mercury. For example, Murray et al. (1974) suggested that for a similar-sized projectile, the larger median impact velocity on Mercury could overcome the greater surface gravity and form a larger crater as compared to the Moon. Gault et al. (1975) suggested that the primary cratering variable between the Moon and Mercury was gravitational acceleration. They considered different target-physical properties, impact velocities, possible thermal history, etc., to have potentially contributed to some degree, but thought the influence of those variables to be of second-order importance. Head (1976), Cintala et al. (1977) and Malin and Dzurisin (1978) argued that target properties might be one of the controlling factors, at least for the development of crater terraces and for the simple-to-complex crater transition diameter. Cintala et al. (1976) and Smith and Hartnell (1978) concluded that gravity, terrain type, and impact velocity were all important in affecting crater sizes on the terrestrial planets.

The controlling factors in each stage of a cratering event are not the same (e.g., Holsapple, 1993). Correspondingly, the morphology and size of different parts of an impact crater are controlled by different factors, i.e., the zonal approach described by Schultz (1976). For example, interior structures of fresh craters are initially formed by the impacts and subsequently modified by mass wasting or other processes (Melosh, 1989); crater interior structures record the effect of factors from the coupling to modification stage. In this sense, most of the earlier reported morphological differences between craters on the Moon and Mercury can only be used to study the relative importance of the different factors on the overall impact cratering process. However, a full understanding of impact processes requires studying the controlling factors in each of the three cratering stages and those for different crater terrains. For example, the controlling factors of the coupling stage are reflected in the amount of impact melt and vaporization (e.g., Cintala, 1992), and those of the modification stage are reflected in the size and morphology of interior structures (e.g., crater terraces; Pike, 1980).

Exterior structures of fresh impact craters (i.e., continuous ejecta deposits and secondaries field) form from the emplacement of excavated material and these structures are less affected by the later modification stage compared with crater interior structures. They precisely record the impact excavation process and are ideal for studying the controlling factors in this stage. Previous studies compared crater exterior structures between lunar and mercurian craters and argued either that both gravity and impact velocity control the scale of these features (e.g., Pike, 1980; Schultz, 1988) or that gravity is the only controlling factor (Gault et al., 1975; Schultz and Singer, 1980). However, these studies used radial distances to represent the extents of crater exterior structures, which are usually not precise due to the asymmetric distribution of impact ejecta, and thus may bias the interpretation.

Early studies used Mariner 10 data to compare lunar and mercurian craters (e.g., Murray et al., 1975; Gault et al., 1975; Cintala et al., 1977). Mariner 10 data were of limited resolution and coverage (∼45% of the surface at 1 km/pixel on average; Murray et al., 1974) and included a large number of low incidence angle (>60°, measured from horizon) images (Strom, 1979), which restricted morphological analyses of impact craters. After three flybys, the MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER; Solomon et al., 2001) spacecraft was successfully inserted into the orbit about Mercury in March 2011. The Mercury Dual Imaging System (MDIS; Hawkins et al., 2007) onboard MESSENGER has been carrying out systematic global imaging augmented by high-resolution targeted observations. At the conclusion of the one Earth-year primary mission, MESSENGER images covered over 99% of Mercury's surface. Images returned by MESSENGER have higher-resolution and better illumination conditions than the Mariner 10 imagery thus allowing an improved assessment of crater morphologies and associated landforms and, hence, providing a better basis to obtain insights into the impact process in the innermost parts of the Solar System.

In this study, we seek to investigate the importance of gravity, impact velocity, and target properties in the impact excavation process on the Moon and Mercury using the gravity-regime crater scaling laws and comparative studies. To achieve this goal, we measure the sizes of crater exterior structures for similar-sized craters on the Moon and Mercury using high-resolution images obtained by both the Lunar Reconnaissance Orbiter Camera (LROC; Robinson et al., 2010) and MDIS.

2. Objectives and methodology

2.1. Background and scope of the study

We focus on the excavation stage of impact cratering, schematically illustrated in Fig. 1, to better constrain its controlling factors. The impact process removes target material from the excavation cavity and deposits it beyond the crater rim. Earlier authors have used different methods to subdivide crater deposits into radial regions. For example, Gault et al. (1975) divided crater ejecta deposits into continuous ejecta and discontinuous facies. Schultz and Singer (1980) divided crater exteriors into continuous ejecta deposits, secondary chains, and discontinuous secondary fields. Here we adopt the method of Schultz and Singer (1980) and divide a fresh impact crater into four components radial to the crater center (Fig. 2): crater interior, continuous ejecta deposits, continuous secondaries facies, and discontinuous secondaries facies.

The continuous ejecta deposits exhibit no secondary clusters or chains. It starts at the rim crest of the primary crater, which consists of hummocky terrain, and grades outward into a radially ridged facies (Schultz and Singer, 1980). These two facies have no sharp boundaries and together they comprise the continuous ejecta deposits. The continuous secondaries facies is composed of secondary crater chains and/or clusters. Beyond a certain distance from the parent crater, secondaries are more isolated and they do not always occur in chains or clusters. This is the boundary between the continuous and discontinuous secondaries facies. The discontinuous secondaries facies is composed of relatively isolated secondaries that are caused by ejecta of relatively large ejection velocities, which are launched during the early excavation stage. Individual secondary craters in the discontinuous secondaries facies can be globally distributed (e.g., Melosh, 1989).

The layout and extent of ejecta deposits around impact craters are not only related to the excavation process, lateral ballistic sedimentation caused by the landing of ejecta (e.g., Oberbeck, 1975) and later modification processes (e.g., crater wall retreat; Gault et al., 1975) may also affect them. For fresh craters, the extents of their continuous ejecta deposits and continuous secondaries facies are mainly controlled by the trajectories of the emplaced materials. The trajectory properties on airless bodies include