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Impact spallation processes on the Moon: A case study from the size and shape analysis of ejecta boulders and secondary craters of Censorinus crater

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ABSTRACT

Impact spallation is a fundamental process responsible for formation of ejecta boulders from impact craters. Although theoretical spallation models were developed about three decades ago, only limited geological observations have been made so far to test these models. The 3.8 km Censorinus crater on the Moon provides an excellent opportunity for studying the impact spallation processes associated with a fresh simple crater formed by oblique impact. Using the Lunar Reconnaissance Orbiter Narrow Angle Camera images, we prepared the ejecta boulder distribution map of Censorinus crater and measured the boulder sizes and shapes. Mapping of about 242,000 ejecta boulders enabled us to document the size distribution of boulders both radial and concentric to the impact crater. Larger size boulders dominate the crater rim areas, while they become smaller away from the crater. The boulder distribution exhibits a radial asymmetry suggesting Censorinus is a oblique impact, in which the uprange ejecta have smaller ranges with larger concentration of boulders near the southwestern crater rim, while the downrange ejecta are in general characterized by smaller boulders with high spatial dispersion. The cumulative size–frequency distribution (CSFD) of boulders shows a highly variable fragmentation history in which the uprange boulders suffered more complex fragmentation. The ejecta boulders also exhibit a variety of shapes that are gleaned from their axial ratios and edge angle characteristics. There is a general decrease of axial ratios away from the crater rim. Rectangular boulders dominate the crater rim and they become more equant away from the crater. In addition to the boulder sizes, the boulder shape distribution also exhibits a mild asymmetry in response to the oblique impact. Small size fresh impact craters (84,000 craters) are abundant on the Censorinus ejecta and post-date Censorinus. These craters are found in two morphologic types in which a large majority of craters have subdued ejecta (rayless craters), while some possess bright-rayed ejecta (bright-rayed craters). The CSFD of rayless craters show a steep power-law slope with a b-value of -4.0, similar to the secondary craters produced by the impact of ejecta from primary craters. We therefore interpret the rayless craters as the secondary craters of Censorinus. On the other hand, the CSFD of bright-rayed craters have smaller power-law slope (b value -2.7) which is a characteristic of primary craters, and thus provide 3 Ma age for Censorinus crater. When the characteristics of Censorinus boulders are compared with the theoretical spallation models that are sensitive to the petrophysical properties of the target (lunar highland), the models generally agree with the Censorinus boulders. However, the observed shape and size characteristics of the Censorinus boulders are found to be more complex than the theoretical spallation models. The ejecta boulders suffered more complex fragmentation and asymmetric distribution in response to the oblique impact. The spallation models accounting oblique impacts have not yet been developed. Therefore, our Censorinus boulder observations can be used to develop and validate the new theoretical spallation models for the effects of oblique impacts.

1. Introduction

Impact cratering is the most important geological process that has modified the entire surface of Moon. The ejecta deposits are

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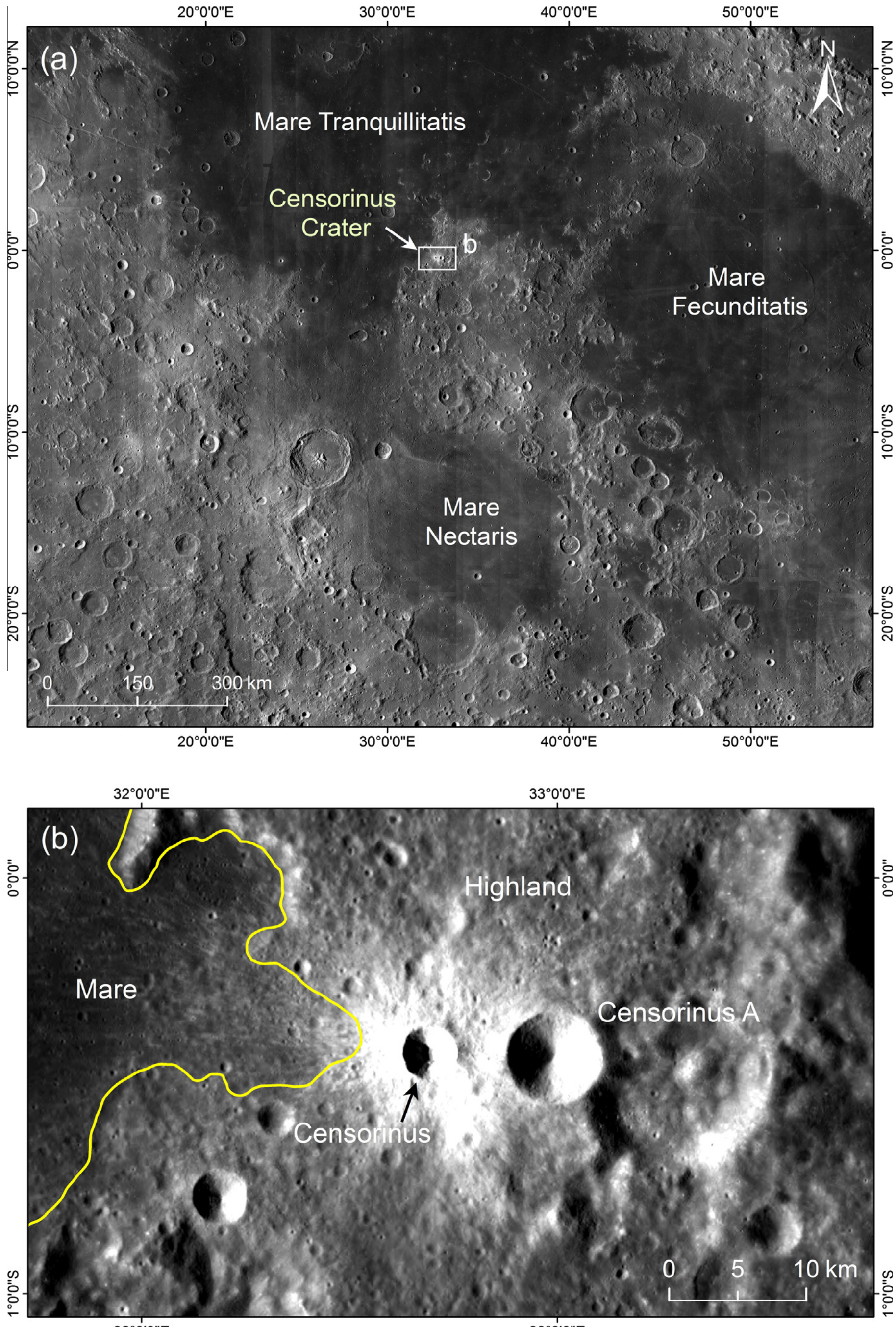

Fig. 1. (a) The LRO WAC image mosaic showing the location of 3.8 km diameter Censorinus crater. (b) Censorinus crater and its bright ejecta. The crater to the east is 7-km diameter Censorinus A. Censorinus crater impacted the lunar highland. The mare basalt materials are seen to the west of Censorinus.

one of the important products of the impact cratering process and are largely responsible for the global distribution of lunar regolith. The ejecta deposits are distributed around all impact structures such as simple craters, complex craters, peak-ring basins and multi-ring basins. They are made up of angular fragments of the target materials, shock-metamorphosed materials, impact melt rocks, and occasionally the projectile debris. The ejecta deposits provide significant insights into the impact cratering processes, particularly the nature of projectile and target materials, formation conditions, and energy and angles of impacts (Oberbeck and Morrison, 1974; Gault and Wedekind, 1978; Pierazzo and Melosh, 2000; Anderson et al., 2003, 2004; Osinski et al., 2011). Housen and Holsapple (2011) have summarized the results of various laboratory impact experiments and presented a set of scaling laws for the ejecta emplacement. In general, the continuous ejecta blanket forms during the excavation stage of impact cratering through ballistic sedimentation and radial flow of the excavated materials from the impact site (Osinski et al., 2011). Emplacement of impact melt rich materials and ground-hugging flows occur during the terminal stages of crater excavation and the modification stage of crater formation. Minor fallback occurs during the final stages of crater formation. Boulders are one of the major