BOULDERS UNTANGLE PRIMARY FROM SECONDARY CRATERS. G.D. Bart, H.J. Melosh, *Dept. of Planetary Science, Univ. of Arizona, Tucson, AZ 85721 (gwenbart@lpl.arizona.edu).*

Summary: Impact fracture theory predicts that secondary craters, which result from lower velocity impacts than primary craters, produce larger ejecta fragments than primary craters. A high-resolution study of 15 lunar craters, including small primary and distant secondary craters, verifies this expectation. This observation provides a tool for distinguishing between primary and secondary craters in high resolution planetary images. Boulder size distributions can help constrain primary production rates of small craters and improve surface ages based on small craters.

Introduction: Planetary surface ages differentiate sequences of geologic events, revealing clues to that planet's evolution. The crater density dating method is reliable for large craters over broad surface areas. However, spacecraft are beginning to return images at meter scale or better resolution, permitting counts of smaller craters. Can these small craters be used for determining the age of a surface? Some small craters are secondary craters, meaning that the impactor was launched as ejecta from a nearby crater, rather than falling from interplanetary space. Secondary craters near their primary crater can be distinguished by their morphology, because the impact velocity was significantly slower than that of a meteorite impact. Distant secondary craters, however, are morphologically indistinguishable from small primary craters because the ejecta-impactor was launched at much higher velocity. How many of the small craters at a given location are secondary craters? Which ones are the secondary craters? The answer is crucial for reliable age determination.

If most of the small craters are primaries, as some have assumed [1], their production is random in time and space, and hence they can be used to determine surface ages. However, both old lunar results [2] and recent results from Europa [3, 4] and Mars [5, 6] indicate that the small crater population is dominated by secondary craters. Because secondary craters are clustered in time and space, they do not provide a reliable chronometer.

Here we report a quantifiable difference between the ejecta fragment size distributions of primary and distant secondary craters, providing a diagnostic tool for distinguishing between the two. Identification of distant secondary craters will help constrain primary production rates of small craters and improve surface age determination of small areas based on small crater counts.

Identification of Distant Secondary Craters

The first distant secondary craters unambiguously identified are those from Pwyll on Europa [3]. Because Europa's surface is so young, relatively few primary craters exist on its surface. Craters are spatially associated with the crater rays, indicating that they are secondary craters. On Mars, distant secondary craters of Zunil are identified by a distinctive thermal inertia signature of the secondary crater's ejecta, as well as by association of the secondary crater with Zunil's rays [5].

We interpret a cluster of lunar mare craters associated with a ray from the crater Burg as distant secondary craters. Burg is a 39.1 km diameter crater with distinct rays extending across Mare Serenitatis [7]. We identify these lunar craters as distant secondary craters because of their association with the Burg ray, their apparent similar age, and their proximity to one another. Figure 1 shows the location of these craters with respect to Burg.

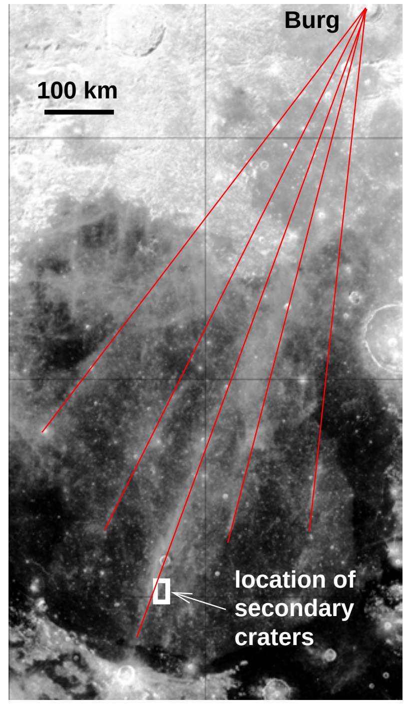

Figure 1: A *Clementine* basemap image shows the rays from Burg crater extending across Mare Serenitatis; the location of the distant secondary craters is indicated.

This cluster of craters lies at a distance, R, of 890 km from Burg. As secondary craters of Burg, their ejection velocity must be less than the Moon's escape velocity. We compute their ejection velocity assuming a spherical Moon and obtain a value of 1080 m/s. This value is comfortably less than the lunar escape velocity of 2380 m/s.

Boulder Size and Impact Velocity: The size of boulders ejected from an impact crater depends on the size of the crater, the strength and condition of the substrate rock (whether it is initially fractured or jointed) and the impact velocity. Other factors being equal, the size of the ejected boulders is inversely correlated with impact velocity: craters produced by lower velocity impacts should produce larger boulders. The complete explanation of this relation is quite complex. Fragment sizes in rapidly crushed rock depend on both the size of the stress load as well as the loading rate [8, 9]. However, for a given

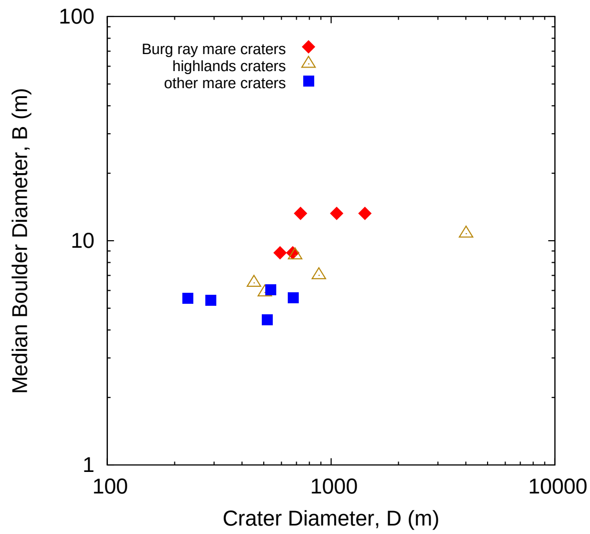

Figure 2: Plot of the median diameter of boulders around a crater vs. that crater's diameter. The secondary craters (red diamonds), formed on the mare, plot significantly higher than other mare craters (blue squares). The highlands craters (open triangles) plot in between, showing that attempts to compare boulder distributions from craters formed on different terrain types blurs the primary/secondary crater distinction. Thus boulder distributions permit differentiation between distant secondary and primary craters.

final crater size, lower velocity impacts produce both a lower peak stress as well as a lower loading rate, both of which favor larger fragments.

The shock pressure for a primary impact is more than 30 times larger than that for a secondary. This does not mean that boulders ejected from secondary craters of a given size are 30 times larger than those from primary impact craters of the same size, because the crater size also increases with increasing impact velocity, but it does indicate that, in general, the shock pressure is lower in craters produced by secondary impacts and, with lower peak shock pressures, we expect that the ejected boulders should be larger, as we have discovered observationally.

Method: To test whether secondary craters have larger boulder diameters than primary craters, we compare five of the Burg secondary craters with five additional mare craters and five highlands craters. These craters are observed in high resolution (1-4 m) images from *Lunar Orbiter III* and *V* and *Apollo 17*.

We used the computer program *ImageJ* [10] to measure the boulder diameters. Boulders were identified as bright pixel(s) on the sunward side of dark pixel(s) (shadows). To find the median boulder size ejected from each crater, we first eliminated all boulders from consideration smaller than 4.42 m, the limit of resolution of the lowest resolution image. We then computed the median diameter of the remaining boulders at each crater. This process eliminates bias toward lower median boulder sizes for higher resolution images. For the same reason, we also eliminated craters for which we couldn't resolve boulders as small as 4.42 m.

This technique only works for similar size craters, when all factors other than impact velocity are equal. It cannot be applied to compare craters on different terrain, which may be underlain by rocks of very different intrinsic strength. Thus, it is best used as a local discriminant of small crater origin. Nonetheless, this is precisely what is needed to make reliable counts of primary vs. secondary craters.

Result: For each of the 15 craters, we plot the median boulder size vs. crater diameter (Fig. 2). As previously mentioned, the secondary craters must be compared against other craters formed on the same terrain; because the Burg secondary craters formed on the mare, we first compare their median boulder sizes with those of the other mare craters studied. The Burg secondary craters (red diamonds) have significantly larger median boulder sizes than do the other mare craters (blue squares). Secondary craters thus have larger median boulder sizes than the other mare craters. A similar, but more scattered, relation is is apparent for the largest boulder around each crater. This result demonstrates a trait of secondary craters that may be exploited to distinguish primary from distant secondary craters.

The highlands craters we studied (open triangles) are also plotted for comparison. Although their median boulder diameters are lower than the secondary craters' boulder diameters, they are higher than the mare craters' boulder diameters, blurring the primary/secondary crater distinction. This result indicates the importance of comparing craters on similar terrain.

Conclusion: The larger boulder size associated with lower velocity impacts allows for a distinction between primary craters (higher velocity impacts) and secondary craters (lower velocity impacts). This method, which is possible only when very high resolution images are available, may rescue attempts to date very young planetary surfaces, even in the face of heavy contamination by secondary craters.

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