ASYMMETRIC STRUCTURE OF LUNAR IMPACT CRATERS DUE TO OBLIQUE IMPACTS?

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Introduction: It has long been a matter of debate whether there exist any characteristic features in crater morphology diagnostic for oblique impacts [e.g. 1,2]. The vast majority of impact craters are almost circular in plain view, although it is well known that most impacts occur at an oblique angle of incidence [3]. Impact events may be approximated as a stationary point source of energy and momentum buried at a certain depth in the target, analogous to the detonation center of an explosive source [e.g. 4]. In accordance to this analogy the observed crater structures on planetary surfaces are relatively symmetric. Nevertheless there exist many morphological features in crater structures deviating from perfect symmetry and may be used to reconstruct the direction and obliquity of impact: The most conclusive feature to determine the direction of impact is the asymmetric shape of the ejecta blanket. In an oblique impact the preferential concentration of ejecta occurs downrange and a "forbidden" ejecta zone develops uprange (Fig. 1,2). These observations are based on remote sensing studies [5], laboratory impact experiments [6] and numerical modeling [7]. However, ejecta blankets are rarely preserved in particular at terrestrial craters and other criteria are required to determine the direction of impact.

Based on the remote sensing and laboratory experiments [8] proposed enhanced rim collapse, and offset of the central peak, downrange breaching, and an enlarged central uplift as being indicative for oblique impacts. However, [9] studied Venusian craters and found that an uprange offset is statistically unwarranted for assessing an oblique impact. They conclude that asymmetries occur due to heterogeneities in the target.

Numerical modeling of oblique impacts and subsequent crater collapse [10,11] and field studies of the subsurface at eroded terrestrial crater structures [12,13] revealed structural asymmetries as a criteria to decipher impact incidence. Moreover, detailed study of material flows during crater collapse in numerical models hints at structural asymmetries in the surface expression of complex craters in oblique impacts [10,11,14]. In this study we use Lunar Orbiter and Clementine data to investigate deviations of the position of the central peak in complex craters from the geometric centre of the crater.

Methods: To avoid target heterogeneities as a possible explanation for observed offsets of central uplifts we restricted our study area to the basalt flooded lunar mare basins. Complex crater morphologies occur on the Moon for craters > 10-15 km [15], whereas craters >~80 km exhibit peak rings. We chose only craters within this size range (20-80 km). A second criteria for the selection of our crater database was the preservation-stage of the ejecta blanket. Mapping of the ejecta distribution is crucial for the reconstruction of the impact direction. First a mosaic of Clementine data [16] (resolution: 200 m/px) was used to search and preview craters that fall into the given size range and exhibit a well-preserved ejecta blanket. Additional information like the preservation of the ejecta blanket and, in particular, higher resolution images (60 m/px) were taken from the Lunar Orbiter Digitalization Project [17]. To avoid distortion of craters due to their location at high latitude we used a sinusoidal projection. A total number of 140 craters were pre-selected but due to in part poor preservation of ejecta blankets, and low quality of the images only 20 craters could be used for further investigation.

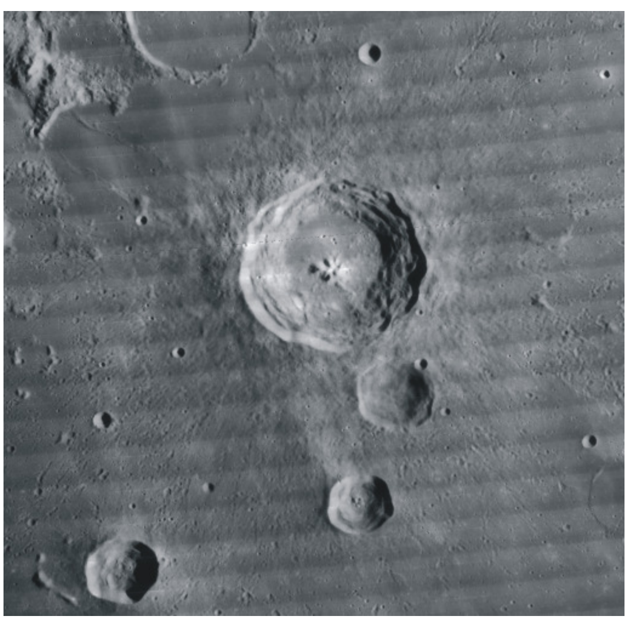

Fig.1: *Lunar orbiter data of the crater Bullialdus, Mare Nubium, 20.7S/22.2W, Diameter: 60km*

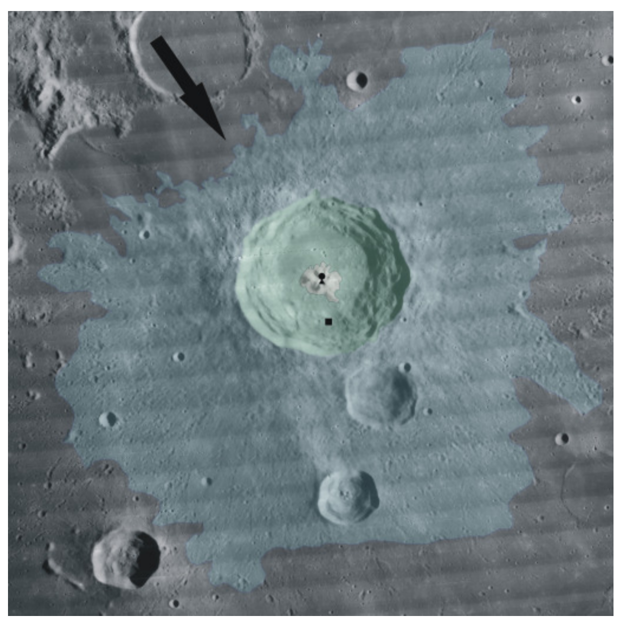

Fig.2: *Mapping of the ejecta blanket (turquise), the crater outline (green) of the Billialdus crater. The circle marks the geometric centre of the crater, the triangle the position of the central peak and the square the geometric centre of the ejecta curtain*

Fig.1 shows raw Lunar Orbiter image data of Bullialdus, located at the Mare Nubium in the southern hemisphere. As shown in Fig.2 we used ArcGis 9.2 by ESRI to map the outlines of the crater rims, central peaks and ejecta blankets of the selected craters and determined the barycenter of each shape.

Results: We used the shape and distribution of the ejecta blanket to estimate the direction of impact and defined an axis of symmetry by visual inspection. Other criteria are the position of a “forbidden” zone where less ejecta is deposited indicating the uprange direction, and a higher concentration and extent of ejecta on the opposite side indicating downrange. At highly oblique angles, “butterfly” ejecta blankets form, where the majority of ejecta is distributed cross range. Due to the poor preservation of the ejecta blanket in some cases this method is very subjective and presumably the biggest source of error.

Fig.3 shows the location of the central peak relative to the geometric center of the outline of the crater. The distances are scaled by the radius of the crater. The craters were rotated so that the impact direction is on the left side in the figure. Our preliminary results show that for all craters the central peak is shifted out of the geometric center. There seems to be a slight trend towards an offset of the central peak in downrange direction. However, the offset is not clearly distributed along the trajectory of the impact but spread over an area on the downrange side. This observation becomes more apparent when plotting the number of craters where the central peak is offset to the geometric centre in a certain direction (Fig.4) in a rose diagram.

Discussion: Crater asymmetries occur as a superposition of at least two different effects: obliquity of the impact and target heterogeneities. On the other hand deviations from symmetric crater structure may be reduced due to asymmetric slumping of the transient crater.

Our results indicate a slight trend towards a downrange displacement of the central peak to the geometric centre of the crater. However, our current data base of only 20 craters is not very large and may not be sufficient for an unequivocally conclusion. As mentioned above, an inaccurate determination of the direction of impact results in incorrect angles between the impact direction and the offset of the central peak. Additionally, the distribution of the ejecta is also affected by the topography of the target.

In contrast to our results, Ekholm and Melosh found random distributions of the offset for Venusian crater populations [9]. However, target conditions on Venus may be less uniform as in the lunar mare areas. Moreover, the ejecta distribution on Venus may be more affected by topography.

Conclusively, our study shows hints that it might be possible to determine the trajectory of the impact from an offset of the central peak to the geometric center. However, an insufficient database does not allow for final conclusions.

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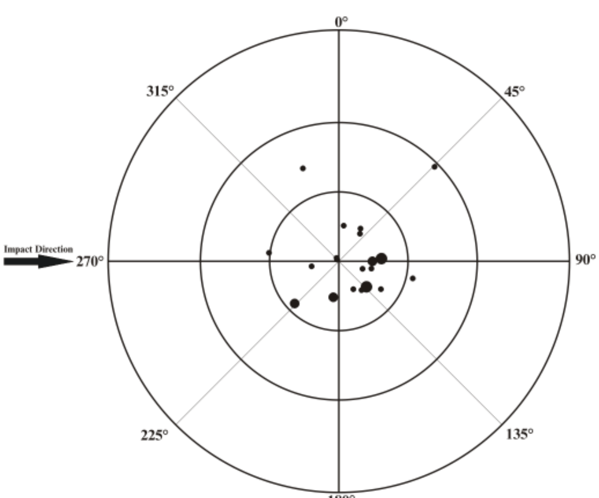

Fig. 3 *Location of the central peaks relative to the geometric center of the outline of the crater.*

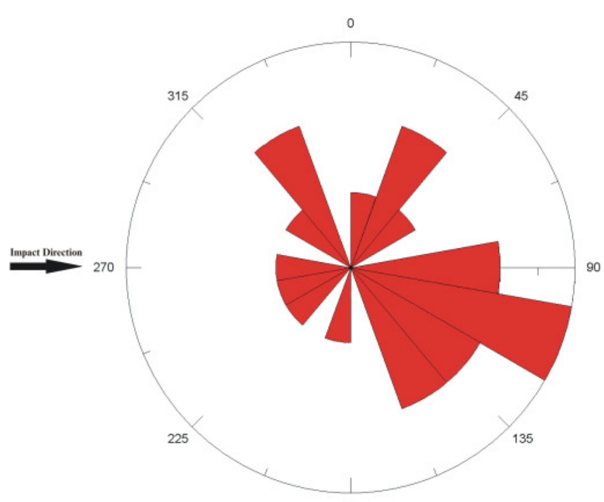

Fig. 4 *Number of craters with a central peak offset from the geometric center.*