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Structural evidence for oblique meteorite impacts at complex crater structures from 3D numerical modelling

K. Wünnemann and D. Elbeshausen
Museum für Naturkunde, Leibniz-Institute at the Humboldt-University Berlin, Germany (kai.wuennemann@mfn-berlin.de / Fax: +49-30-20938565)

1. Introduction

The vast majority of complex impact structures on planetary surfaces appear as relatively symmetric, circular depressions with a central peak at their geometric centre [1]. At first glance, this observation may seem incompatible with the majority of impacts being oblique to the target surface. The apparent discrepancy is explained by the fact that, in hypervelocity impacts, crater formation is the result of an expanding shock wave that originates from a "point source," analogous to the detonation center of an explosion [2]. The point source concept implies that the resulting crater structure has a symmetric shape and is circular in plan, regardless of the angle or direction of impact. Although the crater outline appears to be insensitive to impact angles >15° [3] other criteria to reconstruct the angle and direction of impact have been proposed [4-10]. The structural analysis of central peaks at terrestrial impact craters [11,12] and numerical modeling [13,14] suggested subsurface, structural asymmetries at the central peak of complex impact structures. However, it is unclear how these observations relate to different impact angles, and crater sizes. Here we present results of 3D numerical modeling focusing on the formation of central peak structures at oblique impacts.

2. Modelling of crater formation

We carried out a series of three-dimensional impact simulations with the hydrocode iSALE-3D [15] and varied the angle of incidence between 30° and 90° (measured from horizontal). We used a simple cohesionless Drucker-Prager model where shear strength Y is a linear function of pressure P, $Y = fP$, where f=0.8 is the coefficient of friction. Cohesion (strength at zero pressure) was neglected in our simulations. We assumed both projectile and target composed of granite and calculated the thermodynamic state with Tillotson's equation of state. To avoid the complication of material vaporization we kept the impact velocity constant at a relatively low value of U=6.5 km/s in all simulations. We assumed Earth-like gravity conditions of g=9.81 m/s^2. Acoustic fluidization [16] was used to simulate a temporary strength degradation of the target during crater formation. Brittle material failure was neglected.

3. Results

Figure 1 shows the final crater geometry in plain for 90°, 60° and 30° impacts of an asteroid 5 km in diameter. Our models show that (i) the inner crater is approximately circular in all three cases; (ii) with decreasing impact angle the central peak is shifted slightly downrange of the geometric centre; (iii) a "forbidden zone" occurs in the uprange portion of the proximal ejecta deposit with decreasing angle of impact; (iv) crater size and formation time of the central peak decreases with decreasing impact angle – the de-crease is proportional to the sine of the impact angle α [15].

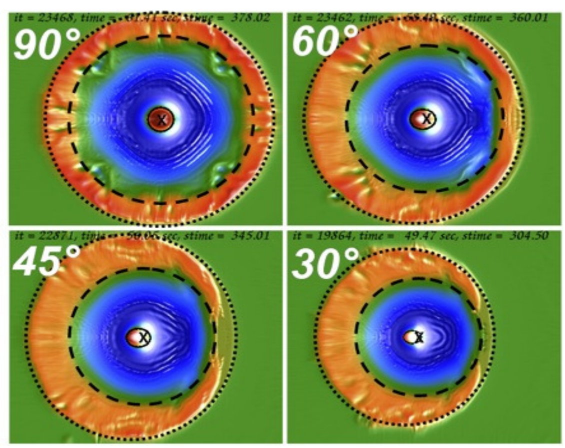

Figure 1: Plan-view of the final crater for different impact angles. Dashed line: inner boundary of the crater; X: geometric centre of the crater; the solid line: central peak, and the dotted line: extent of the proximal ejecta.

Figure 2 shows cross sections of the final crater. For impact angles between 30°<α<60° (a) no overturning of the uppermost strata in uprange direction occurs; and (b) the collapse of the central peak is more pronounced in uprange direction, resulting in an asymmetric central uplift beneath the surface.

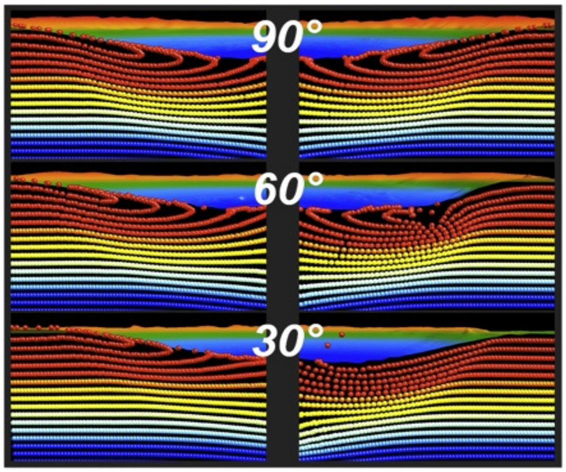

Figure 2: Post-impact stratigraphy below the downrange (left) and uprange (right) crater rim

The asymmetries in crater morphology shown in Fig. 1 are specific to a given crater size and a relatively simple material model and may differ significantly depending on material properties and size of the impact event. A broader parameter study over different crater sizes and using a more complex material model are required to judge whether the observations apply in general. Nevertheless, the models show that the internal structure of the inner most part of the crater is strongly asymmetric (Fig. 3). Crater collapse and the formation of the central peak can be characterized by different material flows indicated by arrows in Fig. 3: while deep-seated collapse originating from the deepest point of the transient crater is relatively symmetric (red arrow) inwards collapse of the crater is increasingly asymmetric closer to the surface (turquse arrow). Slumping along the crater walls (dashed white arrow) is much more pronounced in downrange direction.

4. Conclusions

Our modeling results suggest that apart from distribution of proximal and distal ejecta the surface expression of oblique impacts is still relatively symmetric. Slight displacement of the central peak towards downrange direction with decreasing impact angle may not be significant. In agreement with field observations [14,15] and previous modeling work [16], our simulations suggest that the internal structure of the central peak is very asymmetric and is diagnostic of impact direction. This observation is of particular relevance on Earth as most terrestrial impact structures have undergone a certain degree of erosion and provide insight into the internal structure of the central peak.

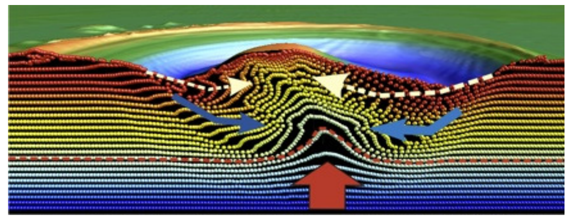

Figure 3: Central peak formed after an oblique (45°) impact event. Arrows show deep (red) and near-surface (blue) material flow and slumping (white).

Acknowledgements

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