STRUCTURAL UPLIFT SCALING FOR COMPLEX CRATERS FORMED BY OBLIQUE IMPACTS
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Introduction: Complex impact craters are almost ubiquitous on solid planetary surfaces with substantial surface gravity. They are characterized by a broad central core of uplifted rock beneath the crater floor that can protrude through the surficial impact melt sheet as a central peak or peak ring. On Earth, erosion often means that this central uplift is the only vestige of the impact structure preserved today.

Uplift of deeply derived strata and its exposure at the surface is an important consequence of large impacts. Complex craters provide natural probes of deep crustal materials, exposing otherwise inaccessible rocks to remote observation. Uplift of dense, hot rock from depth also has implications for impact-related crustal structure, hydrothermal circulation, economic resources and geophysical anomalies. It is therefore important to understand how the dimensions of structural uplifts relate to crater diameter as well as impactor and target parameters.

Observations at terrestrial craters have been used to establish scaling relationships for the diameter [1] and height [2] of uplift, but any dependence of these metrics on impactor parameters is not known. Moreover, connections between asymmetries and offsets in the central uplift and impact angle and direction have been investigated [3-6], but these have not been widely tested by simulation.

Here we use oblique impact simulations of complex crater formation on Earth to investigate relationships between impact angle, impactor size and speed and the size and morphometry of structural uplift beneath complex craters.

Modeling: The numerical simulation results we interrogate were previously described by Davison and Collins [7]. In that work, oblique incidence impact events were simulated using the iSALE3D shock physics code [8-11]. The target was composed of a 33 km thick granitic crust overlying a dunite mantle, with Earth’s gravity. Both materials used an ANEOS-derived tabular equation of state [12, 13]. The acoustic fluidization “block model” was used to allow late-stage collapse of the transient crater [14]. Impactors had diameters of 6, 9 and 14 km, and impact angles ranged from 30 to 90°. Impact velocity was varied between 10 and 30 km s⁻¹. The impacts produced final craters ranging in diameter from 60 to 170 km. All models had a resolution of 14 cpr (cells per projectile radius), achieved by cells sizes of 222.2, 320 and 500 m for the three different impactor sizes. In previous work [7], we analysed these simulation results to quantify the effect of impact angle, impact speed and impactor size on crater dimensions. Here, we extend this analysis to investigate the influence of the same impactor parameters on subsurface structural deformation.

To quantify structural deformation beneath the floor of the simulated complex craters, we analysed the displacement of three marker horizons—planes of Lagrangian tracer particles—initially located at depths of 0.125D, 0.15D and 0.175D below the target surface (where D is final crater diameter). These horizons are below the maximum excavation depth and above the transient crater depth, ensuring that all three surfaces image different levels within the central uplift. From the final morphology of the deformed middle horizon we defined several metrics describing the geometry of the central uplift (Fig. 1), including the amount of structural uplift SU, the diameter of the central uplift DSU, the offset of the structural uplift from the crater center LSU and the uprange and downrange structural uplift slopes S_UP and S_DOWN. The ratio of these slopes S_DOWN/S_UP measures the asymmetry in structural uplift, with higher values indicating a preferential uprange dip of deformed strata.

Figure 1: Structural uplift beneath a 60-km diameter simulated complex crater formed by a 6-km diameter asteroid impacting Earth at 20 km/s and an angle of 30° to the horizontal. Shown is the deformation of three strata at initial depths of 0.125D, 0.15D and 0.175D. The labelled dimensions of the structural uplift are analyzed in this work. Tracer peak temperature is used to identify the melt sheet/central uplift transition.
**Results and Discussion:** The main dimensions of the central uplifts produced by all our simulations are consistent with terrestrial observations: $SU \approx 0.1D$ [2], $D_{SU} \approx 0.3D$ [1]. The amount of structural uplift $SU$ and the diameter of the central uplift $D_{SU}$ are insensitive to impact angle, impact speed and impactor size within the parameter ranges investigated (Fig. 2). An analysis of central peak dimensions of Venusian craters also found no correlation between peak diameter and impact angle [3].

In the simulations, there is a tendency for a small downrange (-ve) offset of the center of the structural uplift from the crater center, which increases in amplitude as the impact angle gets shallower but exhibits considerable scatter (Fig. 2). This trend is clearer if data from the smallest impactor size (6 km) and fastest impact speed (30 km/s) are excluded, suggesting that a systematic downrange offset in the center of the central uplift may be more prevalent in large complex craters formed at typical asteroidal impact speeds. No systematic offset in central peak or peak-ring center and crater center was found in analysis of Venusian central peak [3] and peak-ring craters [4], which suggests that variations in target properties or topography may exert a greater influence on central uplift formation than impact angle.

**Figure 2:** Dimensions of the central structural uplift of simulated complex craters relative to crater diameter as a function of impact angle. Shown are structural uplift of the horizon originally located at a depth of 0.15D, the diameter of the region where strata is uplifted above its preimpact location and the offset of the center of the central uplift (-ve downrange; +ve uprange). Dimensions are normalized by the diameter of the crater measured at the preimpact level.

Other measures of asymmetry of the central uplift do not show a clear dependency on impact angle. For the range of impact angles considered (30-90°), there is little asymmetry in the dip of strata on the up- and downrange side of the central uplift and the planform of the central uplift is close to circular. At intermediate impact angles there is a slight tendency for more steeply dipping strata on the uprange side, but this reduces as impact angle shallows. This suggests that established structural indicators of oblique impact found in central uplifts [e.g., 5, 6] require impact angles shallower than 30° to the horizontal.

**Conclusions:** Three-dimensional numerical simulations of complex formation by oblique impact suggest that central uplift formation is principally an axisymmetric process for impact angles steeper than 30° to the horizontal. Structural uplift and the diameter of the central uplift are consistent with terrestrial observations and insensitive to impact angle. The central uplift planform is close to circular and the dip of strata away from the uplift is close to axisymmetric. Obvious structural asymmetries in the central uplifts of impact craters are likely to indicate an impact angle shallower than 30° to the horizontal.

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