NUMERICAL MODELING OF METEOR CRATER: SIMPLE CRATER FORMATION IN A LAYERED SEDIMENTARY TARGET

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Introduction: Meteor (aka Barringer meteorite) Crater, Arizona, was the first impact crater to be discovered on Earth [1] and is arguably the most intensively studied simple crater in the Solar System. Despite being the subject of the first numerical simulations of impact crater formation [2] and several subsequent modeling efforts (*e.g.*, [3]) numerical simulations are yet to satisfactorily match all observational constraints. Here we describe numerical simulations of Meteor Crater formation that reproduce the observed final crater structure [4] and gravity anomaly [5]. The models constrain the relative contribution of impact-induced compaction and generation of pore-space, as well as the impactor parameters, dimensions of the transient crater and degree of enlargement by rim collapse.

Methods: Meteor Crater simulations used the iSALE2D shock physics code [6], including algorithms to account for impact induced porosity changes from compaction [6] and dilatant shear deformation [7]. Impactor parameters (speed, density and size) were based on previous numerical simulations of the early stages of the Meteor Crater impact [8,9], which suggest that the iron impactor was moderately decelerated and disrupted by atmospheric entry, and likely impacted the surface as a cloud of fragments, rather than as a contiguous, dense mass. We considered a range of impactor speeds (12-18 km/s) and modeled the impactor as a distended mass of iron, with a bulk density up to three times lower than solid iron. The two-dimensional, cylindrical geometry of the model enforced a simplifying assumption of vertical impact, implying that our best-fit impactor mass is likely to be a lower limit. The Meteor Crater pre-impact target [10] was represented using a simplified, four-layer structure. From top to bottom, the target comprised: 8.5 m porous (18%) dry sandstone, representing the Moenkopi sandstone units; 80 m porous (19%) dry limestone, representing the Kaibab units; 37.5 m porous (22%) dry sandstone, representing the Toroweap and upper Coconino formations; a lowermost layer of wet sandstone, representing water-saturated Coconino and Supai formations below the water table at 126 m. Material model parameters for dry sandstone and limestone were based on previous impact simulations in similar target rocks [11] and experimental measurements of strength and dilatancy [12]. Wet sandstone was approximated using the same material model as for dry sandstone, but with reduced porosity to account for water in the pore spaces and no compaction, reflecting the more efficient transmission of shock energy in water-saturated materials.

Results: Numerical model results were compared with the observed crater morphometry, structural deformation and Bouguer gravity anomaly. Our best-fit model, which assumed a (post-entry) impact speed of 15 km/s, impactor mass of 10^8 kg and damaged target cohesion of 50 kPa, matched to within 10% the final crater radius, rim height and the depth to the top and bottom of the breccia lens [4, 10]. Four Bouguer gravity profiles [5] across the crater center at different azimuths (N-S, E-W, NW-SE and SW-NE) were replotted, subtracting the regional Bouguer anomaly, normalized by the radius of the crater rim along each profile, and averaged to give a single, mean residual Bouguer profile and uncertainty envelope. The residual Bouguer anomaly has a maximum negative amplitude of -0.5 mgals at the crater center, with a local mimimum of similar amplitude beneath the crater rim. An inferred local maximum at ~0.7 crater radii is attributed to uplift of denser Coconino sandstone in the crater wall. The final subcrater density distribution in the numerical simulation is broadly consistent with this gravity anomaly, provided that dilatancy, rather than compaction, dominates during breccia lens formation. Given the relatively high initial porosities in the Meteor Crater target rocks, this constrains the efficiency of impact compaction in natural craters. Formation of a thick breccia lens at Meteor Crater, which occupies about half the depth of the transient crater, requires substantial collapse of the transient crater rim. Our numerical simulations predicit a transient crater diameter of 0.85 km and a transient-final crater diameter enlargement factor of 1.4, substantially greater than the canonical value of 1.25.

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