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Mega-ejecta on asteroid Vesta

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[1] Asteroid 4 Vesta, sometimes called the "smallest terrestrial planet", will be orbited next July by NASA's Dawn mission. This will be the first time a small planet is visited by a spacecraft, and novel geological structures are expected. A key issue regarding Vesta (mean diameter 530 km) is to what extent its geology is dominated by the ~460 km diameter impact basin on its southern hemisphere. We model the basin's formation using a very high resolution 3D smooth-particle hydrodynamics simulation to establish some of the major impact-related aspects of Vesta's geology. The goal is to provide a framework for interpreting anticipated observations of landforms. A collision of this magnitude (a ~50 km diameter impactor at ~5 km/s) exposes many deep strata from within the planet and offsets the center of mass by ~10 km from the center of figure. Vesta spins every 5.3 hr, so that a hemispheric-scale impact evolves in a non-inertial frame, and deposits variably-shaped, multiply-folded and abruptly-terminated ejecta sequences of regional scale. Since little of this ejecta would have been molten, these massive sequenced deposits could be mistaken in images of Vesta for other geologic forms such as thrusts and folds. Detailed mapping, and the piecing-together of mega-ejecta via impact models, will enable an informed understanding of the interior geology of Vesta.

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1. Introduction

[2] Although 20,000 times less massive than the Earth, asteroid 4 Vesta has a similar uncompressed bulk density (~4 g cm^{-3}) [*Kovačević*, 2005] and a basaltic crust [*McCord et al.*, 1970; *Drake*, 1979], indicating a global composition that sets Vesta apart from known asteroids [*Keil*, 2002]. Vesta's spectral type is rare, something that is surprising given the expectation that many early asteroids were differentiated silicate bodies with basaltic surfaces. With the exception of 17 km diameter Magnya (which probably originated on a different parent body [*Lazzaro et al.*, 2000]) nearly all other asteroids with basaltic-dominated surfaces can be dynamically linked to Vesta [*Binzel and Xu*, 1993; *Marzari et al.*, 1996]. Vesta's giant crater, its morphology, its global-scale deposits, its ejected V-type asteroids, and the basaltic and ultramafic meteorites which presumably sample Vesta's crust and upper mantle, lead to a fascinating large-scale collisional experiment [*Asphaug*, 1997] to be studied using astronomical, dynamical and impact modeling techniques – and soon in the context of detailed geologic images.

[3] While it is not unusual to see planet-sized impact craters on asteroids [*Thomas*, 1999; *Asphaug*, 2008] this structure is truly gigantic – a depression ~460 km diameter and ~13 km deep [*Thomas et al.*, 1997]. Because it wraps around almost half the circumference of the planet, the depression is actually convex at the longest wavelength. There may be no better place in the Solar System to see the exposure of the interior structure of a terrestrial planet, since even after removing most of the crust from the impacted hemisphere the giant crater did not collapse to the extent that it would on a Mars-sized body [e.g., *Marinova et al.*, 2008; *Nimmo et al.*, 2008]. Beyond the impacted hemisphere, ejecta from tens of km deep, and the tectonic aftermath of global-scale crater collapse, are expected to dominate Vesta's landscape. Since the event, spin relaxation has reoriented the planet so that the depression aligns with the southern pole [*Schmidt and Moore*, 2010]. The original orientation of the impact with regard to the spin axis is presently unknown, but as we shall see, can probably be deduced from images of mega-ejecta distribution.

[4] An earlier numerical simulation of Vesta's impact structure [*Asphaug*, 1997] used gravity-regime scaling to derive an impactor diameter of 42 km striking head-on at a velocity of 5.4 km/s, as being responsible for the crater. This assumed a rocky impactor with density 2.7 g/cm^3. Adopting the same impactor in the case of a head-on impact, we achieve good agreement using our code for the size and structure of the final crater. Because the present study is in 3D it allows for the more probable case of off-axis impacts, which we consider here. Since the impact contributes rather small net angular momentum to Vesta (no more than 5% of the present angular momentum) we are to assume that the target was spinning at close to the present period of 5.3 hrs. There being no hard and fast scaling rule for mega-cratering collisions (and certainly not into rapidly spinning targets) we use a slightly larger impactor of 50 km diameter for typical 45° impacts and show that the model finishes with a crater of similar depth, profile and diameter.

[5] In a mega-impact there is a gradation from crater formation in the impacted hemisphere, to contiguous ejecta deposition over the rest of the planet. The discontinuous ejecta in this case escaped to become V-type asteroids and associated meteorites. Because of the rapid spin rate, the dynamical deposition of ejecta on Vesta is not hemispherically symmetric, but takes place over one or more rotations, with the planet rotating underneath the fallback. Sheets of ejecta tens of km thick are sheared in the non-inertial frame, forming massive overturned flaps (even a doubly-overturned flap in the example below) and other complex stratigraphic structures. Given that this ejecta is in the solid phase (a regolith), the final layer structure is not

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Table 1. Porosity and Friction Parameters Used in the Simulations[a]

$P_{elastic}$ (dyn/cm^2)	P_s (dyn/cm^2)	α_0	P_{crush} (dyn/cm^2)	μ_s	μ_2	I_0	d (km)
2.0E+08	1.0E+9	1.1	2.0E+08	0.382	0.642	0.279	5.0

[a]Note that the initial distention α_0 and the porosity ϕ (0) are related as ϕ (0) = 1 − 1/α_0. The distention α (P) is equal to unity for $P > P_s$.

expected to undergo much further evolution, other than overturn and excavation by subsequent impacts. Clearly the stratigraphic record of Vesta is going to be complex, and possibly ambiguous owing to this level of redistribution and overturning. Our future work shall be to change the impact angle and impactor diameter to obtain the best possible match to the observed crater and these resultant structures, in order to study in great detail the global processes resulting from this event.

2. Numerical Method

[6] We use a smoothed particle hydrodynamics (SPH) code [*Benz and Asphaug*, 1994, 1995] to model the impact event. Recently this impact code was extended to include a model adapted for porous materials [*Jutzi et al.*, 2008, 2009]. Central gravity is used to model gravity as an external force; this speeds up the calculation dramatically compared to a self-gravity approach, allowing for millions of particles, and is appropriate for this class of impact, where the target remains mostly intact throughout the collision.

[7] In our current implementation of this model, we do not model brittle failure and assume instead that the material is initially fully damaged (but can have some porosity). Previously, our SPH code has treated the behavior of fully-damaged material by reducing the deviatoric stress to zero, modeled as a liquid. For studies of meteorite ejection from Vesta [*Asphaug*, 1997] such an approach is reasonable, since final crater structure is not the question, just the ejecta sizes and velocities. For studies of the impact-related geology of Vesta, an approach is required that allows for a crater bowl to freeze into place, since otherwise the final crater takes the form of the equipotential, resulting in a featureless topography. This also regards the final topography of the ejecta that are layered upon the surface. A number of past treatments on impact-induced fluidization have been proposed, one being that of *Melosh and Ivanov* [1999], where the impact stress leaves behind an acoustic signal that decays over time, and which allows for material to slip. We adopt the treatment of dense granular flow by *Jop et al.* [2006], which is easier to implement in a continuum model and which we have now tested against a variety of laboratory and analytical scenarios.

[8] *Jop et al.*'s [2006] model is inspired by the two main characteristics of granular liquids: (1) a critical shear stress below which flow is not possible, and (2) a complex dependence on shear rate when flowing. Granular material is described as an incompressible fluid with the internal stress tensor given by

$$\sigma_{ij} = -P\delta_{ij} + \tau_{ij} \quad \text{and} \quad \tau_{ij} = \eta(|\dot{\gamma}|, P)\dot{\gamma}_{ij} \qquad (1)$$

where P is the isotropic pressure, $\dot{\gamma}_{ij}$ the strain rate tensor and $|\dot{\gamma}|$ the second invariant of $\dot{\gamma}_{ij}$. The effective viscosity η ($|\dot{\gamma}|$, P) is related to the friction coefficient μ (I) by

$$\eta(|\dot{\gamma}|, P) = \mu(I)P/|\dot{\gamma}| \quad \text{and} \quad I = |\dot{\gamma}|d/(P/\rho_s)^{0.5} \qquad (2)$$

where d is the particle size, ρ_s is the particle density and I is the inertial number. It can be shown that the material flows only if $|\tau| > \mu_s P$ so that a Drucker-Prager-like yield criterion results in the limit of infinitesimal shear rate; this leads to a static solution at the angle of repose. As for the friction coefficient μ (I), we follow *Jop et al.* [2006] and use the friction law

$$\mu(I) = \mu_s + (\mu_2 - \mu_s)/(I_0/I + 1) \qquad (3)$$

where μ_s is the critical value of the friction coefficient at zero shear rate, μ_2 is the limiting value at high I, and I_0 is a constant.

[9] The pressure which is used to define the effective viscosity η ($|\dot{\gamma}|$, P) corresponds to the one which is computed from the equation of state, but with an upper limit of P = min(P, P_{crush}), where P_{crush} roughly corresponds to the stress at which the granules start to break.

[10] The granular rheology as described above has been applied to test beds including: the flow of granular material through a chute, for which it gives the right characteristic velocities; collapse of a granular pile to give the expected angle of repose; and the formation of an impact crater in dry sand to give good fits to crater opening velocity and final shape. The results of these tests will be detailed in a forthcoming paper (M. Jutzi et al., manuscript in preparation, 2010).

3. Impact Simulations

[11] Table 1 shows the material parameters used in the simulations. As for the grain size, we use d = 5 km which is comparable to the SPH particle smoothing length, which is 3 km in our simulations. In practice a highly battered planetary body such as Vesta will evolve to have a regolith and megaregolith ranging from kilometer-sizes to micron-sizes, with most of the mass at depth being in the larger sizes. It is important to note that the results shown here are not very sensitive to this choice of parameter, and indeed without any granular rheology at all (a liquid target) we obtain very similar results for crater formation and ejecta emplacement, but the final crater structure and the ejecta-deposited landforms disappear with time.

[12] About 5 × 10^6 SPH particles are used in the impact simulations. We assume a completely differentiated target of D = 540 km diameter with a iron core of D_c = 240 km. Porosity ϕ (h) as a function of depth h is constant for small depth (ϕ (h) = ϕ (0) = 10%), as long as $P_{overburden} < P_{elastic}$, and then decreases as a function of depth according to a porosity profile which is similar (in terms of overburden pressure) to the lunar megaregolith [*Clifford*, 1981]. The pressure $P_{elastic}$ corresponds to the elastic pressure of our porosity model [*Jutzi et al.*, 2008]. We first let the target self-gravitate to its hydrostatic equilibrium before the projectile is released. The projectile is a basalt sphere of a diameter d = 42 km (for an impact angle of α = 90°) and d = 50 km (α = 45°), respectively. The impact velocity is

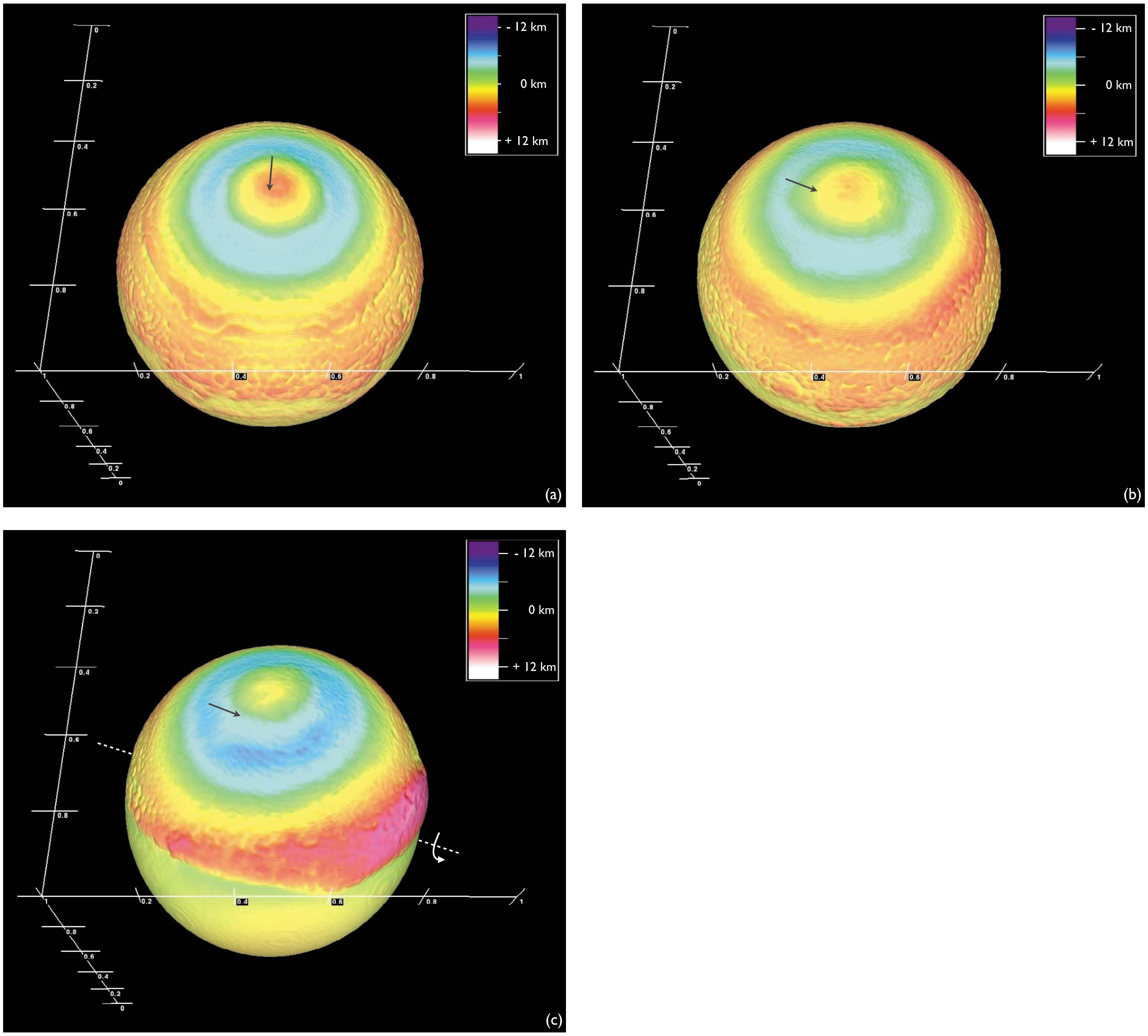

Figure 1. Heights (km) above mean surface level. (a) impact angle $\alpha = 90°$, no rotation, (b) $\alpha = 45°$, no rotation, (c) $\alpha = 45°$, with rotation. Targets are rotated so that the crater is on top. The axis scale is 700 km. The dashed line and the arrow indicate the rotation axis and the impact direction, respectively. In all three cases, the crater diameter is roughly 400 km and the central peak of the crater is about 8–12 km above the deepest part of the floor. The effect of an obliquity is only small while pre-impact rotation has a huge effect on the outcome (see also Figure 2).

v_{impact} = 5.4 km/s. In one simulation (see Figure 1) we start with a rotating planet with rotation period $P = P_{vesta}$ = 5.342 h [*Thomas et al.*, 1997].

[13] The simulations stop at the time t = 7000 s which corresponds to a few dynamical times of $(G\rho)^{-1/2} \sim 2000$ s, which is a few dozen sound-crossing times. Crater formation is finished and most of the ejected material has either escaped or landed on the surface of Vesta. Only a small fraction of the non-escaping ejected material is still on ballistic trajectories. Figure 1 shows the outcome of our simulations. In all three cases investigated, the resulting crater dimensions are slightly smaller, but still roughly consistent (given the large uncertainties) with the observed ones [*Thomas et al.*, 1997; *Kattoum and Dombard*, 2009]. In Figure 2, the initial depth of the ejecta is shown for the simulation with pre-impact rotation. While in the simulations without rotation, the ejecta distribution is symmetric (head-on impact) or only slightly asymmetric (45° impact), an impact in a rotating Vesta leaves highly asymmetric, variably-shaped and abruptly-terminated ejecta depositional sequences. At the impact crater, material from depth as deep as 50 km is exposed. In all three cases investigated, we find an inverse layering of the ejecta next to the crater (an "overturned flap") with ejecta coming from depths <30 km. Interestingly, the impact in a rotating target even leads to a "double overturned flap" in a certain area (see Figure 3). The maximal rim height (height above mean surface level; Figure 1) in this case is of the order of 15 km.

[14] In all cases investigated, the impactor gets pulverized and is partly distributed over the target. The fraction f of the impactor mass which becomes part of the ejecta depends on the impact angle (the effect of the rotation is negligible).

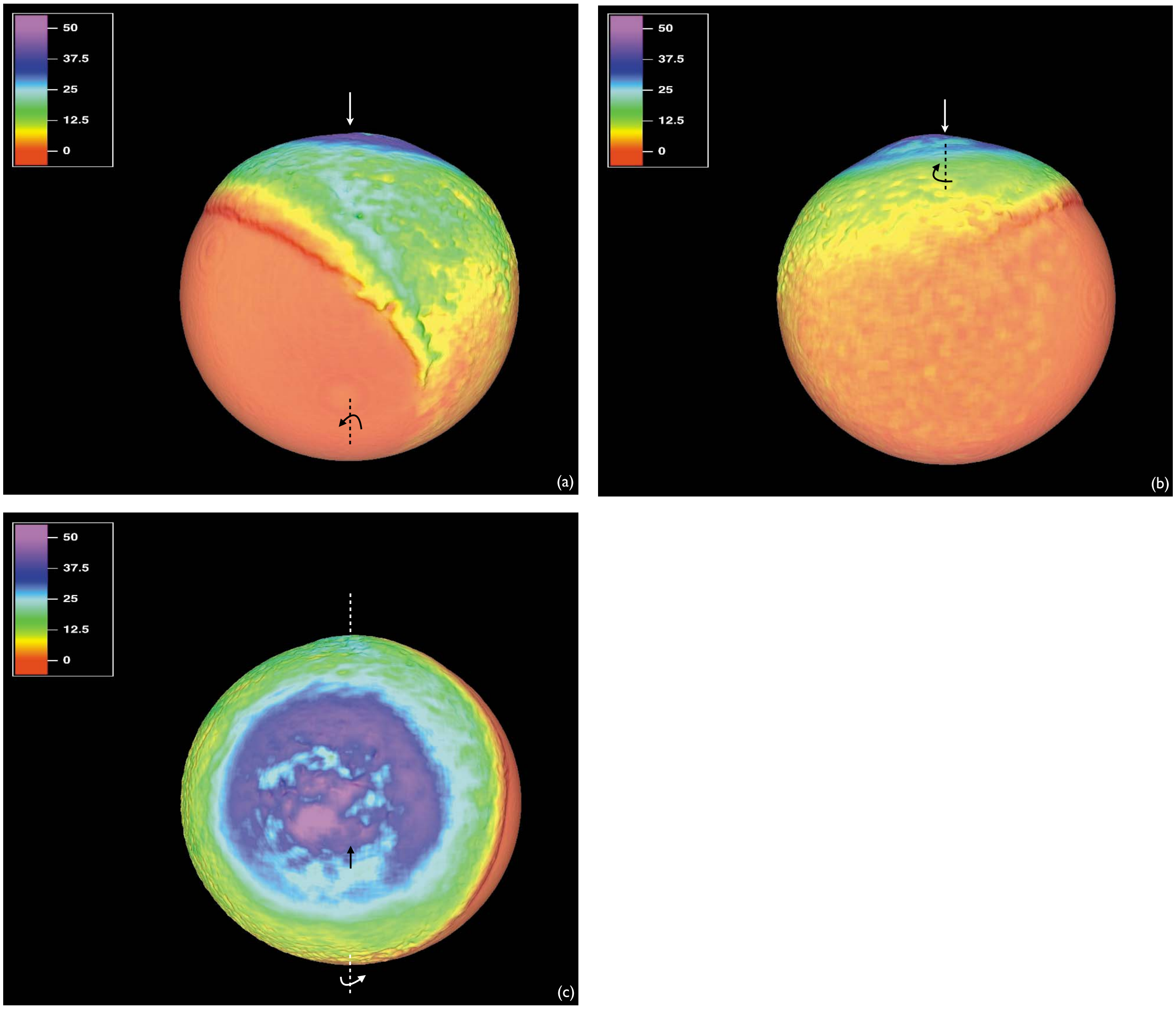

Figure 2. Initial depth of the ejecta (0 to 50 km). The case α = 45° *with rotation* is shown. Vesta is shown (a, b) from two opposite sides and (c) from the top. The dashed line and the arrow indicate the rotation axis and the impact direction, respectively.

For the head-on impact this fraction is small ($f \sim 0.1$; that is, 90% of the impactor is accreted by Vesta) while for the 45 degree impacts $f \sim 0.5$.

[15] At the antipodal site of the impact, the maximal particle velocities resulting from the impact event (the shock wave and detached stress wave) are of the order of ~5 m/s. However, our resolution of ~3 km may not be sufficient to meaningfully resolve impact generated effects at the antipode.

4. Conclusions

[16] Vesta, and its associated family of smaller asteroids and associated meteorites, is a fabulous collisional relic of planet formation. We have performed the highest resolution simulations to date, using a 3D impact hydrocode with realistic target structure, spin state, and material response. While much work remains to be done, particularly in the aftermath of the Dawn mission discoveries at Vesta [*Rayman et al.*, 2006; *Russel et al.*, 2006], we note one stunning and unexpected aspect of these impact simulations, namely the degree to which a mega-impact on a rapidly rotating planet leaves behind mega-ejecta forms which confuse the stratigraphy and can resemble massive endogenic constructs such as folds or thrusts. Similar forms might have been produced by impacts on other solar system bodies that (a) are spinning fast (or were spinning fast a time of the impact event) and (b) are large enough so that a significant amount of the ejected material gets re-accumulated. The formation of a broad central peak structure and raised rims, in overall agreement with the Hubble-based topography modeling [*Thomas et al.*, 1997], suggests that the model does a good job at predicting final topography. Our results indicate that Vesta will reveal clear signatures for the impact parameter relative to the original spin axis, contained in the geologic features of mega-ejecta deposition. This will allow revised models that are tuned to reconstruct the interior of Vesta (from which the mega-ejecta derived), and also the trajectories, velocities, and source depths of Vesta's family of asteroids and meteorites.

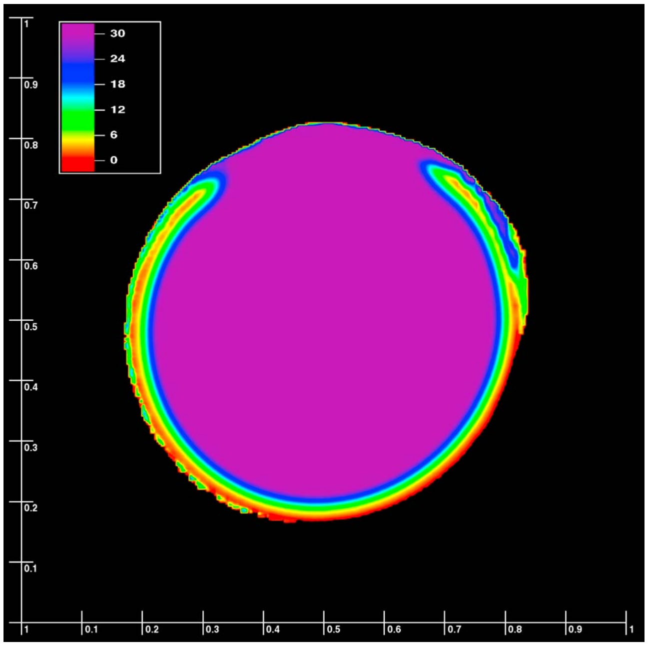

Figure 3. Initial depth of the ejecta (0 to 30 km) shown as two dimensional slice. The plot shows a vertical cut through the mid-plane of Figure 2b. The doubly-overturned ejecta flap is seen. The axis scale is 700 km; the thickest part of the ejecta sequence is ~15 km.

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