NUMERICAL SIMULATIONS OF COMPLEX CRATER FORMATION WITH DILATANCY: IMPLICATIONS FOR GRAVITY ANOMALIES OF LUNAR AND TERRESTRIAL CRATERS G. S. Collins, Impacts and Astromaterials Research Centre, Dept. Earth Science and Engineering, Imperial College London, SW7 2AZ, UK (g.collins@imperial.ac.uk).

Introduction: The most characteristic geophysical signature of an impact crater is a circular negative gravity anomaly, centred over the crater [1]. The cause of the gravity low is dilatancy: fracturing and brecciation, induced by the passage of the shock wave and comminution during crater formation, creates pore space between fragments and fractures, reducing the bulk density of the sub-crater material. Calculation of damage accumulation is routine in modern numerical impact cratering simulations [e.g., 2]; accounting for dilatancy is not [3]. As a result, most impact cratering simulations do not correctly predict density changes beneath an impact crater, which limits the scope for comparing model results with geophysical data.

Here I describe a semi-empirical approach to account for dilatancy—the creation of pore space in a shearing granular material—in numerical models of impact crater formation. I then use this method to investigate porosity generation in complex craters on Earth and the Moon.

Method: A simple approach to account for dilation during shear failure in impact cratering simulations is to supplement the pressure computed by the equation of state with a "dilatancy pressure," representing the outward force of grains moving passed one another, in cells where shear failure has occurred [4]. This additional pressure effectively shifts the pressure-density relationship for the dilatant material up (to a higher pressure) so that when the material unloads the density drops to a (dilated) bulk density that is below the reference density of the pristine material. A limitation of this approach is that the porosity of the material is not modified, which implies that temporary density reduction caused by heating cannot be easily separated from permanent density reduction by shear bulking.

Here I propose a refinement of this approach where both the distension (porosity) and the pressure are modified during shear failure. Shear failure leads to a prescribed increase in distension (porosity), depending on a semi-empirical function for the dilatancy angle, which describes the tendency for the target rock to dilate. Through the ε-α porosity model [5, 6] this porosity increase acts to increase the pressure by an amount proportional to the incremental plastic shear strain and the tangent of the dilatancy angle. In this work the dilatancy angle is defined as a function of porosity, pressure and temperature, based on measurements from soil and rock mechanics experiments [7,8,9]. The maximum dilatancy angle occurs at zero porosity, pressure, and temperature and decreases as any of these three variables increase. This approach ensures that, after impact, the increase in distension caused by shear failure is preserved. The final sub-crater porosity distribution can be compared with observations at terrestrial craters and used to make predictions about the gravity anomalies over terrestrial and lunar complex craters.

The dilatancy model was implemented in the iSALE shock physics code [2,5,10] and used to predict post-impact porosity distribution beneath craters on the Moon and Earth. Suites of simulations, spanning a range in impactor size, were performed for typical impact conditions on Earth and the Moon. Impacts on Earth assumed an impact velocity of 15 km/s, a surface gravity of 9.81 m/s^2 and a crustal thickness of 30 km. Impacts on the Moon assumed the same impact velocity and a surface gravity of 1.63 m/s^2; two lunar crustal thickness scenarios were considered, a thin crust of 30 km and a thick crust of 60 km. In all simualtions the impactor and target mantle were modeled using a material model for dunite; the crust was modelled using a material model for grantite. Equation of state tables generated using ANEOS were used to describe the thermodynamic state of both materials, while material strength was modeled using the approach described in [2]. In all simulations the intial target was assumed to have zero porosity. To facilitate late stage collapse of the craters, the block-oscillation model was used [11]. A single choice of block model scaling constants, which produced simulated crater morphologies in reasonable agreement with observed morphometry trends of lunar and terretrial craters [12,13,14], was used to simulate impacts on both the Moon and Earth. Bouguer gravity anomalies were computed from the post-impact porosity and crustal thickness distributions beneath the simulated crater.

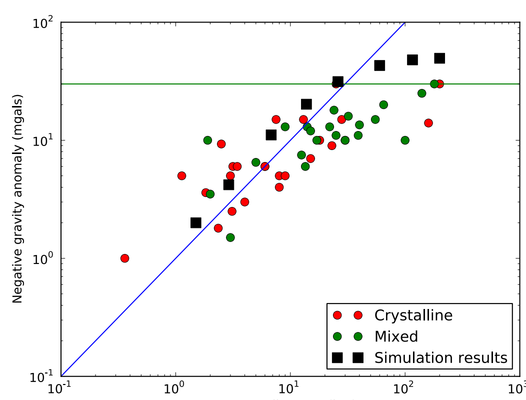

Figure 1 Magnitude of negative Bouguer gravity anomaly as a function of crater diameter for terrestrial impact structures (colored symbols). Numerical model predictions of negative gravity anomaly magnitude caused by dilatancy (black squares) are consistent with observation.

Terrestrial craters: The decrease in dilatancy angle with increasing pressure has three important effects on porosity creation in impacts. While a small amount of dilation (bulking) occurs during tensile failure behind the shock wave, in general the high pressures in the shock wave suppress the generation of porosity as it propagates through the target rocks. Moreover, at depths exceeding about 10 km on Earth the confining pressure is sufficient to suppress porosity generation during much of the crater formation time. As a result, the majority of the impact-generated pore space is created by shearing near the surface and late in the crater formation process--during excavation and collapse. Finally, in complex craters, where deep rocks are raised to the surface in a central uplift, dilatancy is also suppressed in the central region because of the high pressure in the convergent flow. As a consequence, the central gravity high in many terrestrial complex craters may be caused, at least in part, by suppression of dilatancy, rather than uplift of dense rocks [1].

The simulations of terrestrial impact craters predict porosity and Bouguer gravity anomalies with magnitudes consistent with observation, provided that the maximum dilatancy angle is only a few degrees (Fig. 1). A pronounced change in slope in the relationship between negative gravity anomaly magnitude and crater diameter is also predicted to occur at a crater radius approximately equal to the depth at which dilatancy is suppressed (10-km on Earth; Fig. 1).

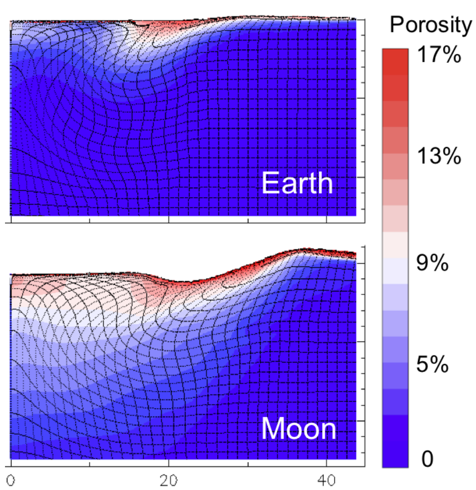

Figure 2 Comparison of predicted porosity distribution beneath a 60-70 km diameter crater on Earth and the Moon (formed by 5-km diameter impactors at 15 km/s).

Lunar craters: The lower confining pressure at a given depth on the Moon implies that impact crater formation is more effective at generating porosity on the Moon than on Earth (Fig. 2). Dilatancy is not suppressed until depths >60 km on the Moon (c.f. 10 km on Earth). Pervasive impact-generated porosity may explain the high porosity of the lunar crust inferred from GRAIL gravity maps [15].

The magnitude of negative gravity anomalies predicted by the numerical models of lunar crater formation are greater than observed because of the assumption of no pre-impact porosity in the lunar crust. Nevertheless, the shape of the predicted Bouguer anomalies is broadly consistent with observation (Fig. 3). A central high, caused by mantle uplift, is predicted for craters greater than ~150 km in regions of thin crust and for craters greater than ~300 km in regions of thick crust. The central high is predicted to be a positive anomaly for peak ring craters and basins with diameters >250 km (thin; 400 km thick). The surrounding gravity low is caused by a combination of crustal thickening and porosity creation by dilatancy benath the peak ring and anular trough.

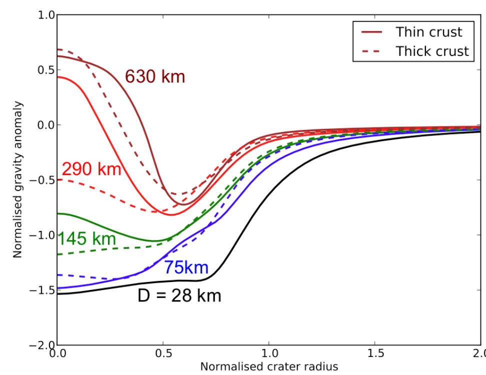

Figure 3 Numerical model predictions of the shape of gravity anomalies over lunar craters for both a thin (30 km) and a thick (60 km) crust. Gravity anomaly magnitude is scaled in proportion to the crater diameter.

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