MODELING COMPLEX CRATER COLLAPSE. G. S. Collins and E. P. Turtle, Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721, (Contact: gareth@lpl.arizona.edu, or turtle@lpl.arizona.edu).

Introduction: Impact crater collapse is the gravitationally driven modification of the cavity generated during the early stages of an impact event. It is the last major stage in the formation of an impact crater and has the most profound influence on the final morphology of the crater. The aim of this paper is to summarize the robust conclusions drawn from modeling crater collapse and highlight the questions that remain unanswered, particularly those that will require the collaboration of modelers and observers to answer.

Why do modeling? Abstract computer simulations provide one of the only feasible methods for studying complex crater collapse. There has been no direct observation of complex crater collapse in recorded history; large impact events are, perhaps fortunately, too infrequent. In addition, the scale of experimental studies is somewhat inappropriate for drawing conclusions about the collapse of the largest craters in the Solar System. The dominance of gravity in influencing the collapse stage of crater formation implies that the results of the small-scale laboratory collapse experiments cannot be extrapolated meaningfully to the scale of complex craters. Similarly, underground nuclear explosions, although extremely valuable in elucidating the principal features of the excavation stage, are also not of an applicable scale.

Modeling complex crater collapse: The fundamental procedure behind all numerical models of complex crater collapse is the same. First, the physical situation being simulated is simplified and divided into manageable portions, in which all properties are constant. In other words, a grid (mesh) of points and cells is defined to represent the geometry and material properties of the target. Next, the effect of external and internal forces on each of these points and cells is determined, assuming that these forces are constant during a very short interval of time, known as the time step. The mesh is then adjusted to account for the displacements induced by the net effect of the calculated forces for the duration of the time step. Repeating this process of calculating the forces acting on each cell and then adjusting the mesh allows the solution to be advanced in time until the end of the simulation.

Impact crater collapse is controlled by the competition between the gravitational forces tending to close the excavated cavity and the inherent material strength properties of the post-shock target. Thus, to simulate crater collapse, a detailed knowledge of the strength and rheologic behavior of the collapsing material is required. This is the fundamental difficulty in simulating complex crater collapse: numerous studies [for example, 1-7] have concluded that crater collapse controlled by the well-understood standard strength models for rock materials does not involve any uplift of material from beneath the crater floor, which precludes the formation of a central peak, peak ring, or external rings; or the slumping of the transient crater walls, which precludes formation of terraces and significant widening of the crater. In other words, to reproduce the observed morphologies of complex craters, collapse requires significant, but temporary, weakening of the target material beneath the crater floor.

Several processes act during an impact event that might help explain the transient weakening associated with crater collapse. These include wholesale fracturing of the target, bulking (the decrease in density associated with the fracturing of a material and the movement of broken rock debris), acoustic fluidization (the reduction in ambient overburden pressure due to the presence of high-frequency vibrations remnant from the initial impact), melt production, thermal softening (the reduction in strength of material close to its melting temperature) and shear melting in regions of strain localization (pseudotachylite formation). Most, if not all, of these processes have been implemented and tested in numerical models of complex crater collapse; however, the relative importance of each mechanism is still poorly constrained. Thus, there is little agreement on the nature of this weakening.

Results: The impact modeling community is in strong consensus about the need for increased mobility of the target rocks surrounding large craters. Recent modeling work has constrained the required effects of the target weakening mechanism associated with complex crater collapse [6,7,8,9]. The weakening mechanism must: (1) Reduce the strength of the target material surrounding the crater by an order of magnitude or more; (2) weaken the target material surrounding the crater sufficiently for a volume of material at least equal to the crater volume to flow during collapse; and (3) in the case of peak-ring craters, mobilize this material enough such that during collapse the central uplift may overshoot the target surface, which implies an effective viscosity for the collapsing material less than $\sim10^9$ Pa s for craters less than ~200 km in diameter.

There is also close agreement between the different modeling groups on the details of the collapse flow. Figure 1 illustrates the current paradigm for complex crater formation derived from recent modeling work [6,7,8,9]. Regardless of the weakening mechanism, simulation results support the observation that central peaks are the result of uplift of material originally well below the crater floor, and that peak-rings are the result of uplift and collapse of the central region. Figure 2 illustrates the subsurface structure of a generic peak ring crater, as inferred from various numerical simulations of complex crater collapse [7].

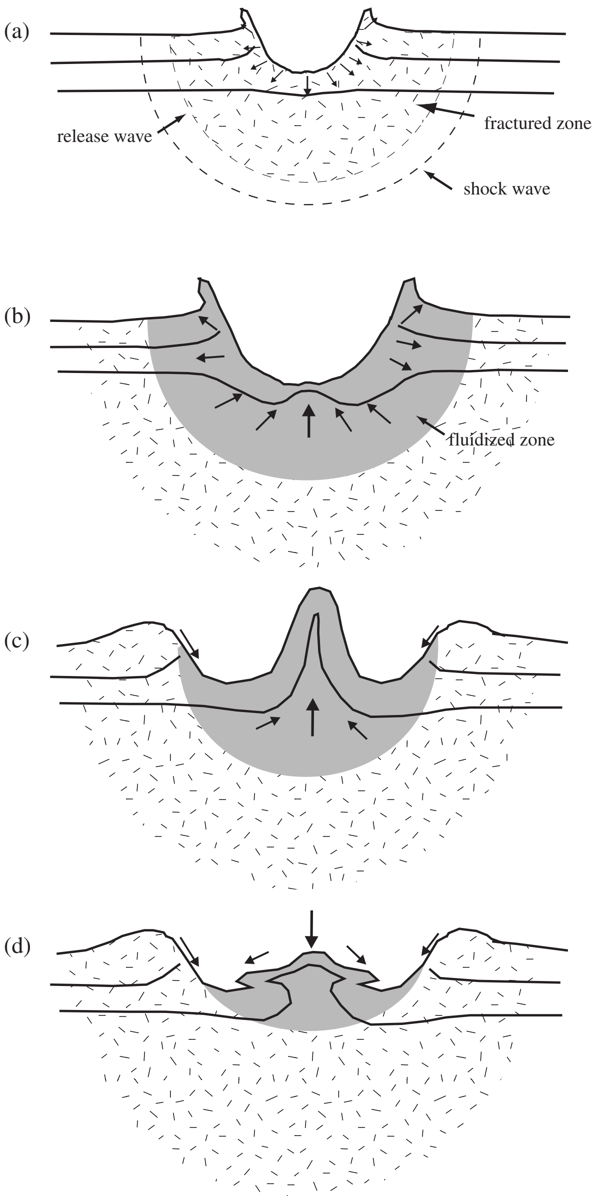

Figure 1 Illustration depicting the current paradigm for how a complex crater collapses to produce its final morphology. (a) During the early stages of the impact the outward propagation of the shock wave and subsequent release wave comprehensively fractures a large region of the target (stippled) and initiates the excavation of the crater. (b) A weakened, mobile region of the target surrounding the crater (grey) enables the onset of collapse, in the form of uplift below the crater and slumping of the walls. The extent of this fluidized region decays with time, effectively freezing the crater morphology in place. In small craters the collapse is frozen before the central uplift gets too high: a central peak crater is formed. (c and d) In large impacts, however, the uplift overshoots the target surface before collapsing back down and out to generate a peak ring.

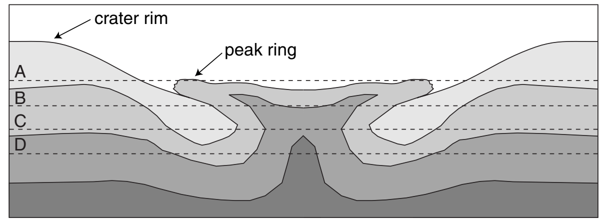

Figure 2 Illustration depicting the subsurface structure of a generic peak ring crater as derived from our simulation results. The dashed lines labeled A-D refer to possible stages in the erosion of an initially fresh crater. Note that the vertical scale has been exaggerated; the illustration has an aspect ratio of 1:2. Thus, the pre-impact thickness of the stratigraphic layers is on the order of D/20, where D is the final crater diameter.

Models of crater collapse have also elucidated the mechanism responsible for the formation of multiple concentric scarps around large impact structures [9]. Simulations based on the ring-tectonic theory [10] have demonstrated that inward flow of a low-viscosity layer (with effective viscosities comparable to that of the weakened material within the transient crater) is an effective way of forming rings around large craters. The mechanism responsible for this low-viscosity behavior and the degree to which it is controlled by the target structure and composition, or the impact process itself, are still not well understood.

Conclusion: Impact modeling has produced a robust paradigm for how complex craters must collapse. However, current models do not provide a complete explanation for why large impact craters collapse in this manner. Developing a complete model for the collapse of large impact craters will, therefore, require close collaboration between impact modelers, and observers. More work needs to be done to: (1) understand better each potential target weakening mechanism; and (2) establish under what conditions each mechanism may be important—does field evidence support one or more weakening mechanism? Collaboration should also concentrate on the testing and refining of numerical models of peak-ring and external-ring formation based on geological observation, geophysical data and drill cores.

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