TARGET WEAKENING AND TEMPORARY FLUIDIZATION IN LARGE IMPACT EVENTS. G. S. Collins, *Imperial College, University of London, London SW7 2BP, UK (gareth.collins@ic.ac.uk)*, H. J. Melosh, *Lunar and Planetary Laboratory, University of Arizona, Tucson AZ85721.*

Introduction: A predictive, quantitative model for complex crater collapse remains elusive [1]. Theoretical work [2, 3, 4] suggests that complex crater formation requires a prodigious change in target rheology to facilitate collapse. It would appear that, from a macroscopic point of view, the target must adopt a fluid-like rheology for the few minutes during which collapse occurs. The rheologic model that best represents the apparent behaviour of the target following a large impact event is the Bingham model. In this model the target behaves as a solid for stresses below a finite yield value. For stresses in excess of this value, the Bingham substance behaves as a fluid with a constant viscosity.

Recent numerical modeling [1, 5, 6, 7] has constrained further the requirements for complex crater collapse. Such studies indicate that: (1) the yield strength of the Bingham substance must be at least an order of magnitude lower than the yield strength of standard broken-rock material; (2) that the effective viscosity of the fluidized region must be an order of magnitude or more below the critical viscosity that precludes overshoot of the collapsing central uplift (given approximately by $\eta_{crit} \approx 0.14 \rho g^{1/2} D_t^{3/2}$, where g is gravity, ρ is the density of the target material and D_t is the diameter of the transient crater); and (3) that the volume of rock involved in the collapse must be on the order of the volume of the transient crater.

Here we compare the merits of several weakening mechanisms, postulated in the literature to explain complex crater collapse, in the context of the three requirements discussed above.

Impact melt production: Perhaps the most intuitive explanation for the change in rheology of the target is heat. Molten rock possesses the correct material properties; it is a Bingham fluid with a yield strength lower than that of standard rock debris by more than an order of magnitude. The viscosities of most magmas are sufficiently low to permit flow in the required time-scale. Moreover, there is direct geologic evidence for melting of the target in terrestrial complex craters; and the collapse time-scale appears to be limited by the cooling of a clast-rich impact melt [8]. However, scaling laws relating transient crater dimension to melt production, which have been derived from numerical modeling [9, 10], suggest that the volume of melt produced is comparable to the transient crater volume only in extremely large impact events ($D_t > 200$ km for terrestrial impacts). Melt production, therefore, cannot be the sole fluidizing agent facilitating the collapse of most complex craters.

Thermal softening: [11] propose a weakening mechanism that relies on temperature, without necessitating the melting of large volumes of the sub-crater region. This process of "thermal softening" is analogous to the effect the ductile behaviour of metals at high temperatures. [5] successfully simulate complex crater collapse using a thermal softening model where strength linearly approaches zero for temperatures in excess of 80% of the melt temperature T_m. However, work by [12] suggests that even for a Chicxulub-scale event, temperatures within the target are not extreme enough over a large enough volume for thermal softening to be the dominant collapse mechanism. In the thermal softening model, strength degradation of an order of magnitude or more requires the local temperature to be greater than $0.98T_m$; we suggest that thermal softening, like melt production, becomes relevant to crater collapse only in the formation of very large complex craters. More work on the effect of thermal softening is required.

Friction melting: [13] discuss friction melt as a weakening agent during the formation of multi-ring impact basins, based on observations from the Sudbury impact structure. The mechanism is based on the premise that, during deformation of the target, friction melt is generated as rock blocks slip over one another; the presence of this low-viscosity melt lowers the effective yield strength of the medium, thus facilitating collapse. Support for the theory comes from the fact that only a small amount of melt is required to lower the effective yield strength of the block-melt system by an order of magnitude; and that in regions of strain localization, melt layers 1-10 meters thick could easily be generated, lubricating the fault and expediting large displacements. Furthermore, rapid cooling rates, due to the presence of cold rock blocks and the composition of the melt, will arrest the collapse in the appropriate time-scale for complex crater formation [13]. However, the amount of friction melting observed at terrestrial impact structures suggests that the effective viscosity of the block-melt system, from a macroscopic point of view, will only be 1-2 orders of magnitude less than the viscosity of the solid rock blocks. An effective viscosity this high precludes fluidization of the target by friction melting.

Fragmentation and comminution: The extent of tensile failure in the target surrounding an impact crater has an important influence on the mechanics of complex crater collapse. The abrogation of the cohesive strength properties of the target permits debris sliding; however, the amount of weakening induced by tensile failure is not sufficient to explain complex crater collapse [2, 3, 4].

Pore pressure: Explosion craters on Earth are strongly influenced by the presence of subsurface fluids, namely water. Water saturated silts and clays behave like Bingham fluids and thus it is no surprise that craters produced in such materials on the earth resemble extraterrestrial complex craters. The exaggerated development of central peaks observed in many Martian craters may also be due to the presence of near surface water [14, p. 151]. Consequently, models have been proposed for complex crater collapse involving fluidization due to the presence of a fluid. However, fundamental problems exist with this theory: (1) water-mediated fluidization cannot be applicable on the Moon, Mercury, or Venus as there is no current evidence for significant quantities of subsurface fluid;

(2) when the target is fractured by the shock wave any pore pressure will be greatly reduced preventing any vestige of fluidization by water.

Acoustic Fluidization: The final physical mechanism with the potential to explain the temporary change in rheology is known as Acoustic Fluidization [15]. The physical basis for this model is that acoustic vibrations within a granular material, if violent enough, could temporarily relieve the overburden pressure and, hence, abrogate the internal frictional strength of the medium. The theory, therefore, predicts a rheology where stresses are supported without appreciable strain unless acoustic vibrations in the medium are strong enough to reduce the material's resistance to shear and let it flow as though it were a fluid.

From a theoretical point of view acoustic fluidization appears to offer the most robust explanation for temporary fluidization of the target surrounding an impact crater. Acoustically fluidized debris behaves as a fluid with an effective viscosity sufficiently low to permit collapse in the required time-scale [15]. Experimental evidence indicates that during the formation of small, shallow-buried explosion craters on Earth the acoustic noise generated has an amplitude that comfortably exceeds the overburden pressure within one crater diameter from the crater center [16]. After the acoustic vibrations have decayed away, the target regains its more familiar strength properties and would show no indication of the fluidization process at geological outcrop. Furthermore, hydrocode simulations of complex crater collapse using simplified models of acoustic fluidization [1, 6, 7] have also been successful in reproducing many of the characteristic features of large impact craters. However, it remains to be proven whether seismic energy generated during a large impact event can remain strong enough and last for the required time-scale to facilitate collapse. A thorough investigation of acoustic fluidization is required. Here we begin by implementing a new methodology for modeling the temporal behaviour of acoustically fluidized debris in a hydrocode.

Hydrocode Modeling of Full Acoustic Fluidization Formulation We present an implementation of the full acoustic fluidization formulation into the SALES_2 hydrocode [17]. The major improvement provided by this implementation is in modeling the temporal behaviour of the acoustic energy. Equation (2) from [18] describes the rate of change of acoustic energy per unit volume, as controlled by scattering, dissipation and regeneration of acoustic energy. A similar equation (differing only by a factor of $1/\rho$) exists for the acoustic energy per unit mass:

$$\frac{d\mathcal{E}_v}{dt} = \frac{\xi}{4}\nabla^2\mathcal{E}_v - \frac{c}{\lambda Q}\mathcal{E}_v + e\frac{\dot{\epsilon}\Pi}{2\rho}. \quad (1)$$

The first term on the right-hand side is the scattering term, where ξ is the scattering diffusivity, which has dimensions of a length times a velocity. The second term parameterizes conversion of elastic energy into heat. Q is defined as the ratio of the energy stored per cycle to the energy dissipated in the same period. The last term quantifies the energy generation during flow, where e is the fraction of the released acoustic energy that is available to regenerate the vibrations, $\dot{\epsilon}$ is the strain rate of the fluidized debris and Π is the deviatoric stress.

A potentially important aspect of this full model is that energy dissipated by shear in the flowing debris could itself generate acoustic energy. In static regions the vibrations might dissipate quickly by friction and the effective viscosity in those regions would rapidly rise; however, in flowing regions the regeneration of acoustic energy could permit flow to continue until the driving stresses are relieved.

We have adapted the SALES_2 solution algorithm to study the temporal behaviour of acoustic energy during complex crater collapse. We present our methodology and discuss preliminary results.

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