FRICTIONAL MELTING AND COMPLEX CRATER COLLAPSE.

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Introduction: The formation of complex craters requires a mechanism(s) to cause transient weakening of the target to reproduce observed morphologies and structural deformation. Several processes have been suggested for the mechanism [1-3], with the most widely tested being acoustic fluidization [2, 4-6]. Here we investigate the possible role of frictional melting in the collapse of complex craters.

Background: Lab and field measurements have demonstrated that there is a significant reduction in friction along a fault at high slip rates (~1 m/s) and long displacements (>1 m) [7-12]. This reduction occurs primarily in two stages (with a strengthening regime in between): (1) flash heating along asperities (melting occurs along a very small surface area of the fault), and (2) generation of a continuous melt layer along the fault. The friction during stage (2) is determined by a balance between melt production, melt loss, and melt viscosity. Lab measurements of low friction are in good agreement with field estimates of co-seismic friction [9], suggesting that frictional melting plays an important role in determining the strength along faults.

Frictional melting as a complex crater collapse mechanism has been largely rejected based on (1) the lack of pervasive pseudotachylites around many complex craters, and (2) stability calculations (using plasticity theory) suggesting that the friction angle must be much smaller than observed along faults (< 2º) [13-15]. However, the presence of large scale pseudotachylites is not a requirement for frictional heating effects: if the weakening is a result of flash heating of asperities, any melt will be microscopic, and even a thin (microns) melt layer may dominate the effective strength of the target, without the bulk viscosity being that low. Furthermore, melt may drain away from faults after formation. Additionally, the stability studies mentioned above all analyzed the stability of a static transient crater; in reality, the crater wall is in outward motion and the crater floor is in downward motion at this point during formation, creating a dynamic pressure field. We verified that the code we are using reproduces the results of the plasticity calculations, and then found that significant collapse of a dynamic transient crater can occur at much higher friction angles (~10-15º).

Cratering Simulations: We use the strength damage model of Collins et al. [16], which we have implemented into CTH [17]. In this model, the shear yield strength is degraded from an intact strength to a damaged (strength controlled by motions along preexisting fractures) strength. The damaged strength is assumed to follow Byerlee's law, $Y_d = \mu P$ (Y_d is the damaged strength, μ is the coefficient of friction, and P is the pressure), where μ is 0.85 for low pressures and 0.6 for higher pressures [18]. As an approximation of frictional melting affects, when both the shear strain rate (in terms of the square root of the second invariant of the deviatoric strain rate tensor, $II'_{\dot{\varepsilon}}$) and damage in a cell are above certain values ($\dot{\varepsilon}_{cut}$, d_{cut}), then the coefficient of friction is decreased to a new value (μ'). This is based on the assumption that the strength in these cells is being determined by slip along faults undergoing some form of frictional melting. In actuality, μ' is some complex function involving a number of factors, including velocity, rock type, fault geometry, and slip distance, but we approximate it here as a single value for exploratory purposes.

Results: Figure 1 shows the results for the impact of a 10-km in diameter impactor hitting the Earth's surface at 17 km/s (analogous to the Chicxulub impact; a geotherm and lithostatic pressure are included). In this simulation, the target is highly resolved: 62.5 meters per cell, or 160 cells across the projectile. $\dot{\varepsilon}_{cut}$ was 0.01, d_{cut} was 0.9, and μ' was 0.2 (well within the values measured in laboratory frictional melting experiments). The plots show integrated plastic shear strain in the form of II'_{ε}. Fracture generation is usually an unresolved process in cratering calculations, and only recently have codes tried to resolve them. Here we see two types of shear localizations ("fractures"): conical (concave down features labeled A at 150s) and listric faults (concave up features labeled B at 150s). The conical fractures are initiated with the passage of the shock wave, and the listric ones form at late times, during crater collapse. Spontaneous localization of deformation is seen to some degree in all calculations whether or not frictional heating effects are accounted for; however, it is the additional decrementation of μ due to these effects that allows the fractures to grow. Because the fracture zones are weak, slip occurs preferentially along them; this causes stress to concentrate at the tip of the fractures until failure and extension occur. Thus the conical features extend during excavation of the transient crater to accommodate shear during the downward and outward displacement of material. These features are continuous in a 2D simulation, but may not be so in 3D. The width, spacing, and number of fractures is resolution dependent; however, their basic presence and orientation is not. Note also that the actual fractures will be thinner that what is seen in the calculation: artificial viscosity spreads the deformation across multiple cells.

Discussion: Field observations affirm that shear deformation is localized around complex craters. Listric faults are easy to observe (because they intersect the surface), but it is harder to observe conical fault structures. However, nearly vertical faults are inferred along some central uplifts [e.g. 19-24].

The fractures generated occur in orientations that are favorable for aiding crater collapse. Upward motion along the conical fractures will facilitate uplift of the crater center, while motion along the listric faults will cause slumping of the crater wall. Although crater formation is not yet complete at 150s (it is time-consuming to run to long times at such high resolutions), lower resolution simulations to longer times indicate that significant collapse occurs.

Conclusions: Including a simplified proxy for frictional melting affects into a cratering code leads to the formation of fractures that are favorably oriented for crater collapse. We suggest that frictional melting may play a larger role in crater collapse than previously appreciated, and should be investigated further.

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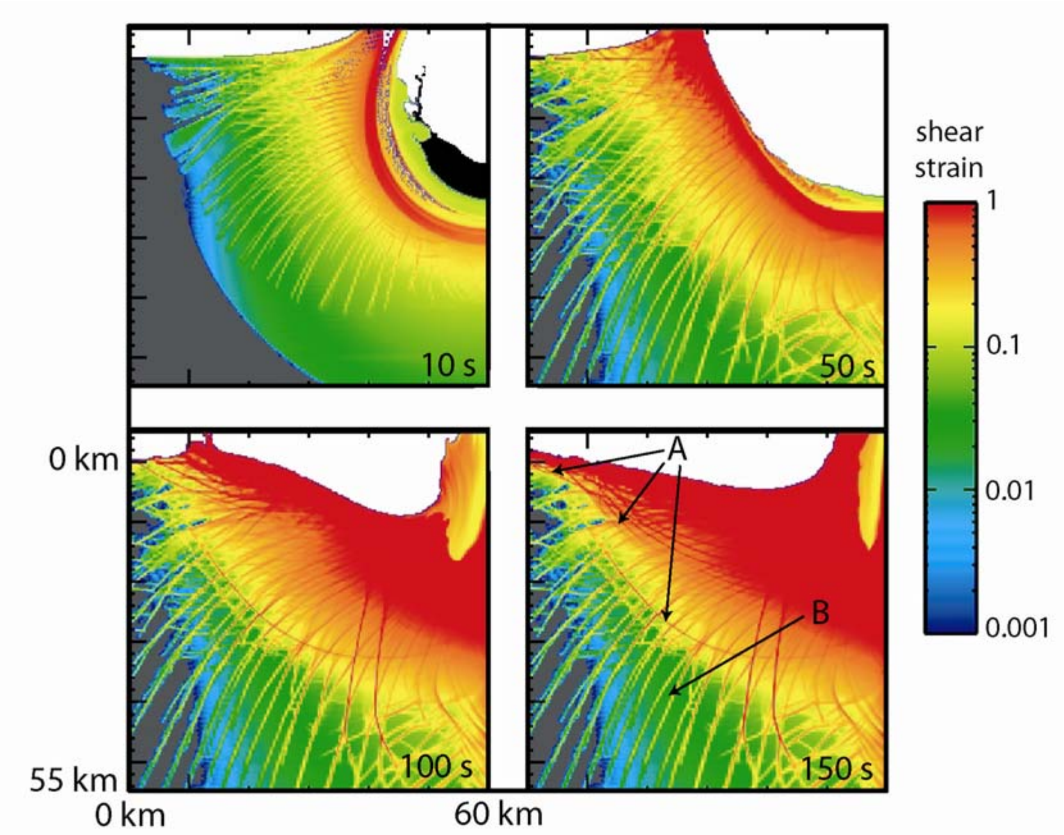

Figure 1: Integrated plastic shear strain for the impact of a 10-km in diameter impactor onto the Earth at 17 km/s (Chicxulub scale impact) at four times during crater formation. The scale is the same at all timesteps. Note that some of the features along the centerline are artifacts due to the 2d cylindrical symmetry boundary condition along the x=0 axis.