FRICTIONAL MELT FORMATION AROUND LARGE CRATERS. L. E. Senft[1] and S. T. Stewart[1], [1]Dept. of Earth & Planetary Sciences, Harvard University, 20 Oxford St., Cambridge, MA 02138 (lsenft@fas.harvard.edu).

Introduction: Frictional melts (pseudotachylites) are observed around many large impact craters and may play a role in aiding crater collapse. Here we use numerical modeling to predict where frictional melts should form and compare results to field observations.

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) [1-6]. This reduction occurs in two stages (with a strengthening regime in between): (1) flash heating along asperities (melting occurs along a 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 [2,7]. Lab measurements of low friction are in agreement with field estimates of co-seismic friction [3], suggesting that frictional melting plays an important role in determining the strength along some faults.

Cratering Simulations: Crater formation is simulated using a quasi-static strength-damage model for rocks with dynamic strength reduction due to frictional melting. The quasi-static strength-damage model of Collins et al. [8] is implemented in the CTH shock physics code [9]. In this model, the shear yield strength is degraded from an intact strength to a damaged strength, which is controlled by motion along fractures. The damaged strength follows a friction law, $Y_d = Y_c + \mu P$ (Y_d is the damaged strength, Y_c is the cohesion, μ is the coefficient of friction, and P is the pressure), where μ is 0.85 for low pressures and 0.6 for higher pressure and Y_c is 0 [10]. Tensile strength is a function of damage, and void is added when a cell is failing in tension to simulate tensile crack formation. As an approximation of frictional melting effects, when (1) the shear strain rate (in terms of the square root of the second invariant of the deviatoric strain rate tensor, $II'_{\dot{\epsilon}}$), (2) the damage, and (3) the integrated plastic shear strain times the projectile diameter are above certain cutoff values ($\dot{\epsilon}_{cut}$, d_{cut}, and ϵ_{cut}), then the coefficient of friction is reduced to a new value (μ'). μ' is some complex function involving a number of factors, including velocity, rock type, fault geometry, and slip distance, but we approximate it by a single value for exploratory purposes. We choose $\dot{\epsilon}_{cut} =$ 0.01 s^{-1} and $\mu' = 0.2$ based on lab data of frictional melting. To restrict frictional melting to fractured material, we choose $d_{cut} = 0.9$. An integrated strain cutoff is necessary because even if strain rates are high, a threshold amount of slip must occur to generate enough energy for melting. Note that the slip must be scaled by some length parameter (otherwise frictional melting will occur at craters of all sizes, because the strains are similar even though the displacements are not). This parameter should be the fault length, however this is impossible to ascertain during the simulation. Instead we scale by the projectile diameter, based on the assumption that longer faults are produced around larger craters. We experimented with a range of choices for ϵ_{cut} and chose a value (1 m) that precluded frictional melting around small, simple craters (where fault displacements are too small for frictional melting), while allowing it around larger craters. This value is consistent with lab measurements of the slip needed to generate melting (>1 m) in rocks.

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 (Chicxulub-size; a geotherm and lithostatic pressure are included). The target and projectile are basaltic. The target is well resolved: 125 meters per cell (80 cells across the projectile). A-D show areas (red) where frictional melting is occurring and E-H show integrated plastic shear strain.

During shock wave expansion and crater excavation (E) conical (concave down) shear localizations (which we interpret as fractures or fracture networks) are formed behind the shock wave. The strain rates and displacements are high enough during their formation to generate frictional melts (A). Note that spontaneous localization of deformation is seen in all calculations whether or not frictional melting effects are accounted for; however, it is the additional decrement of the friction 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. After passage of the shock wave, the strain rates decay and frictional melting temporarily ceases. The stresses created by the transient crater's gravitationally unstable shape build up until new fractures are generated with strain rates high enough to undergo frictional melting. Vertical fractures under the floor (labeled 1 in B) aid floor uplift and shallow listric fractures in the wall (labeled 2 in B) aid wall collapse. At later times, slip transfers from the vertically oriented fractures under the floor to a set of steeply dipping concentric fractures under the crater (labeled 3 in C), which shallow as the crater collapses (labeled 4 in D). The frictional melting that appears to be occurring along the x=0 boundary in C and D is an artifact resulting from the centerline boundary condition. 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 than the calculation; artificial viscosity and the eulerian meshing spreads the deformation across multiple cells.

Comparison with Field Observations: The model predictions for where frictional melting should occur are broadly consistent with the location and orientation of pseudotachylites around terrestrial craters. The most extensively studied impact related pseudotachylites are around Vredefort Dome (>250 km diameter), South Africa and the Sudbury Structure (>200 km diameter), Canada. Note that the term "pseudotachylite" indicates a melted zone but does imply a genetic origin; pseudotachylites at impact craters may be shock induced and/or friction induced melts [11]**.** Pseudotachylites around Sudbury are concentrated into three large rings (with randomly oriented smaller networks in between); the first ring encircles the central uplift and the second two appear to be related to wall and terrace collapse [12]. Our model shows a zone of frictional melting surrounding the central uplift (features labeled 1 in B, 3 in C and 4 in D), and a zone of shallowly dipping listric faults undergoing frictional melting at and beyond the rim area (features labeled 2 in B). This is consistent with the zones observed at Sudbury. The floor directly under the central uplift is not observable at Sudbury; however this area is well exposed at Vredefort. Pseudotachylites are abundant in the crater floor at Vredefort, and while they do not show any preferred orientation, most have steep to vertical dips [13]. It is possible that the observed pseudotachylites were formed during shock wave expansion (A) and/or as vertical faults during floor collapse (features labeled 1 in B).

Simulations of smaller complex craters (10's km in diameter) with frictional melting mainly display movement along deep seated concentric faults, such as those seen in C and D.

Summary: We performed cratering simulations with a simple proxy for frictional melting, with parameters constrained by lab results. The simulations predict the location and timing for frictional melt formation, and the results are in good agreement with field observations. Frictional melting may play a significant role during crater collapse. Finally, we note that the occurrence of frictional melting will depend on rock type; this abstract discussed only crystalline targets, but future work will consider sedimentary targets.

References: [1] A. Tsutsumi and T. Shimamoto (1997) GRL 6, 699. [2] T. Hirose and T. Shimamoto (2005) JGR 110, 2004JB003207. [3] G. DiToro et. al. (2006) Science 311, 647. [4] K. Mizoguchi et. al. (2007) GRL 34, 2006GL027931. [5] D. L. Goldsby and T.E. Tullis (2002) GRL 29(17), 2002GL015240. [6] G. DiToro, D.L. Goldsby, and T.E. Tullis (2004) Nature 427, 436. [7] H.J. Melosh (2005) in Impact Sudies, vol 6; eds C. Koeberl and H. Henkel [8] G.S. Collins and H.J. Melosh (2004) MAPS 39, 217. [9] L.E. Senft and S.T. Stewart (2007) JGR 112, 2007JE002894. [10] J. Byerlee (1978) Pure App. Geophys. 116, 615. [11] W.U. Reimold (1995) Earth Sci. Rev. 39, 247. [12] J.G. Spray, H.R. Butler, and L.M. Thompson (2004) MAPS 39, 287. [13] B.O. Dressler and W.U. Reimold (2004) Earth Sci. Rev. 67, 1.

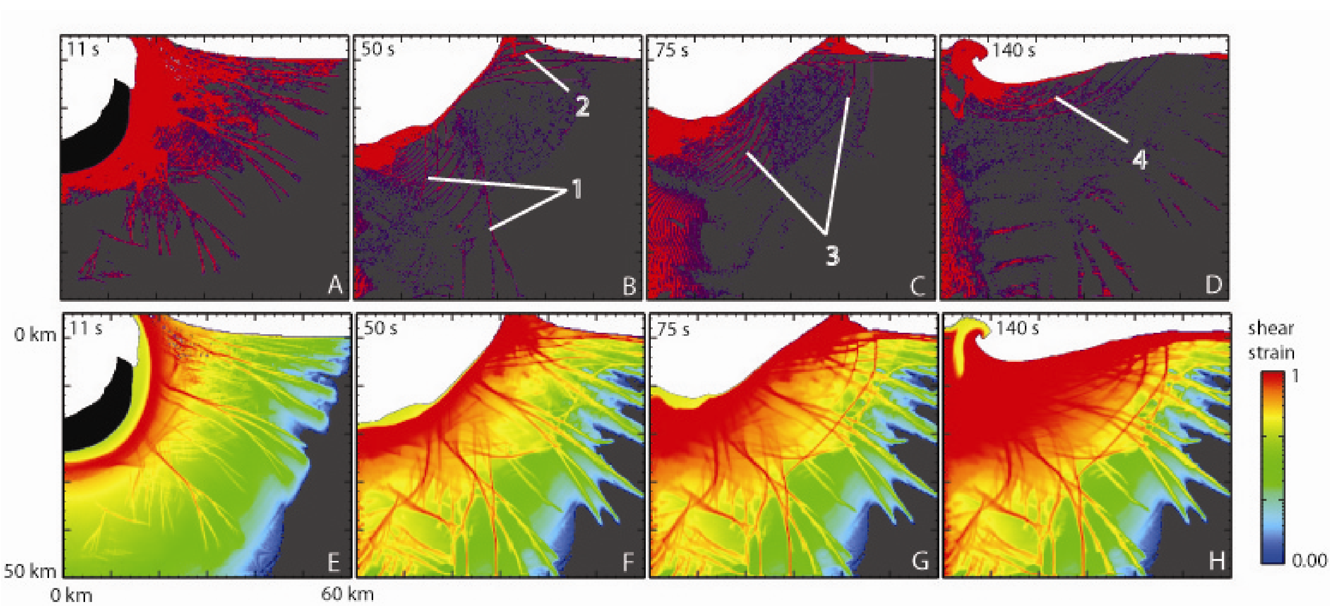

Figure 1: Impact of a 10-km diameter impactor onto a terrestrial basalt target at 17 km/s. Top row shows locations where frictional melting is occurring (in red); bottom row shows integrated plastic shear strain (color scale bar). The red areas have reduced friction and the gray areas have friction of typical fractured rock. The features along the centerline (x=0) are artifacts.