FRICTIONAL MELTING AND COMPLEX CRATER COLLAPSE. S. T. Stewart and L. E. Senft, Dept. of Earth & Planetary Sciences, Harvard University, 20 Oxford St., Cambridge, MA 02138 (sstewart@eps.harvard.edu).

Introduction: The formation of complex craters requires a mechanism(s) to cause transient weakening of the target material to reproduce observed morphologies and structural deformation. Several processes have been suggested for the dominant weakening mechanism [1, 2, 3], with the most widely tested model to date being the block model approximation of acoustic fluidization [2, 4, 5, 6]. Here we investigate the possible role of frictional melting in the collapse of complex craters.

Frictional Melting in the Lab: It has long been recognized that slip at high velocities and high displacements may produce melt; recent experiments illuminate how frictional melt forms and affects the strength along a fault [7, 8, 9]. For example, Hirose and Shimamoto [7] demonstrate that frictional melting has a very strong influence on the coefficient of friction. Two stages of weakening are observed with increasing slip. The first stage is thought to be due to small amounts of frictional melting along asperities (also known as flash heating; melting occurs along a very small surface area of the fault). As melting continues, the friction increases (to a level lower than the initial dry friction), because melt patches tend to 'stick' as they form. Eventually, a continuous melt layer forms, and as this layer grows, a second weakening event is observed. Note that although the melt viscosity tends to increase during layer growth, the shear strain rate decreases sharply, leading to an overall weakening. Finally, widening of the layer due to melting is balanced by loss of melt from the system (in experiments, melt is squeezed out the sides of the sample; in the field, melt may be squeezed into surrounding fractures), leading to a steady state friction. The friction at steady state depends strongly on (1) the melt viscosity, and (2) the shear strain rate across the melt layer, which is determined by the thickness of the melt layer and, hence, the rate of melt loss.

Frictional Melting in the Field: Frictional melting may be an important process in reducing friction along high strain rate, large displacements faults. The total effect, however, is difficult to quantify. Rice [10] suggests that flash heating of asperities, along with pore fluid pressure effects, may explain the strengths observed along large crustal faults during seismic slip events. The drastic loss of strength associated with flash heating may halt the onset of large-scale melting for many faults, inhibiting the formation of pseudotachylites [10]. If the displacement and strain rates are large enough, melting will nonetheless proceed and the second weakening event discussed above may become relevant. However, it is difficult to say what the degree of weakening will be because the steady state friction (if it is reached) will depend strongly on the melt viscosity and the rate of melt loss.

Frictional Melting and Complex Crater Collapse: Field studies of complex craters suggest that collapse occurs largely by brittle deformation, as the crater walls collapse inward along faults [e.g. 11, 12]. Additionally, pseudotachylites (μm to km scale) have been observed around complex craters [13, 14]. Spray [15] estimated the viscosity of these melts to be very low; additionally, because pseudotachylites are not bulk melt but clast-melt suspensions, they may exhibit pseudoplastic behavior. Thus it is likely that both flash heating and large-scale melting contribute to reducing the coefficient of friction along faults during impact crater collapse. Note also that the presence of large-scale pseudotachylites is not a requirement for frictional heating effects (if the weakening is from flash heating of asperities).

The resolution of cratering simulations is much coarser than individual faults that are formed and/or are active during planetary-scale impact crater formation. In a continuum model, discrete deformation (fractures) is approximated by a nondimensional damage variable, where zero represents completely intact material and one represents completely fractured material. We use the strength-damage material model of Collins et al. [16], which we have implemented into CTH [17]. In this model, yield strength, Y_d, of the fractured rock is assumed to follow a friction law, $Y_d = \mu_d P$. When frictional melting occurs, the coefficient of friction, μ, is reduced. As a simplified approximation, when both the velocity and damage in a cell are above certain values (v_{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 as a single value here for exploratory purposes.

Fig. 1 shows results for impacts of a 1-km diameter asteroid at 17 km/s on Earth (nominal final rim-to-rim diameter of ~24 km). Three different cases are shown: crater formation (1) with no additional weakening mechanism, (2) with acoustic fluidization using parameters from [4], and (3) with frictional melting using v_{cut}=0.2 m/s, d_{cut}=0.9, and μ'=0.2 (higher values of v_{cut} and d_{cut} did not produce enough collapse and lowering d_{cut} did not have any significant effects). Note that a μ' of 0.2 is well within the range of friction coefficients determined experimentally.

The light and dark layers are the same material with the same strength properties; the layers are shown to illustrate the deformation. Similar final crater morphologies are observed in both cases, but the collapse processes are different. With acoustic fluidization, collapse appears to be driven by the uplift of the crater floor (and the walls slump in as a response), while with frictional heating, collapse appears to be driven by slumping from the walls (and the central peak forms as the wall collide). This results in different stratigraphy beneath the craters. In larger impact events, e.g., Chicxulub-scale, the central uplift is formed primarily by uplift of the crater floor using both acoustic fluidization and frictional heating, although some stratigraphic differences are apparent.

A simplified schematic of the similarly sized Haughton crater is shown for comparison [Fig. 2, from 20]. The maximum observable stratigraphic uplift is ~1450 m. This amount of uplift is more consistent with the frictional heating results; however, modifying the acoustic fluidization parameters can change the amount of uplift. Varying the frictional heating parameters produces a smaller range of possible structures compared to acoustic fluidization.

The central uplift at Haughton extends to about 5-6.5 km radially (Fig. 2); this is seen in both the acoustic fluidization and frictional heating simulations. Note that none of the simulations reach the predicted transient crater surface diameter from π-scaling (11.2 km predicted versus ~9 km in the simulations) [18]. According to complex crater scaling laws, a 9 km transient crater should collapse to a 16.3-20 km final rim to rim diameter crater [19], in agreement with both the acoustic fluidization and frictional heating cases.

Conclusions: Frictional melting may be an important mechanism in determining the strength during the collapse of complex craters. Simple numerical simulations show differences in the stratigraphy beneath simulations utilizing acoustic fluidization and frictional melting. Such differences may help to discriminate between collapse mechanisms.

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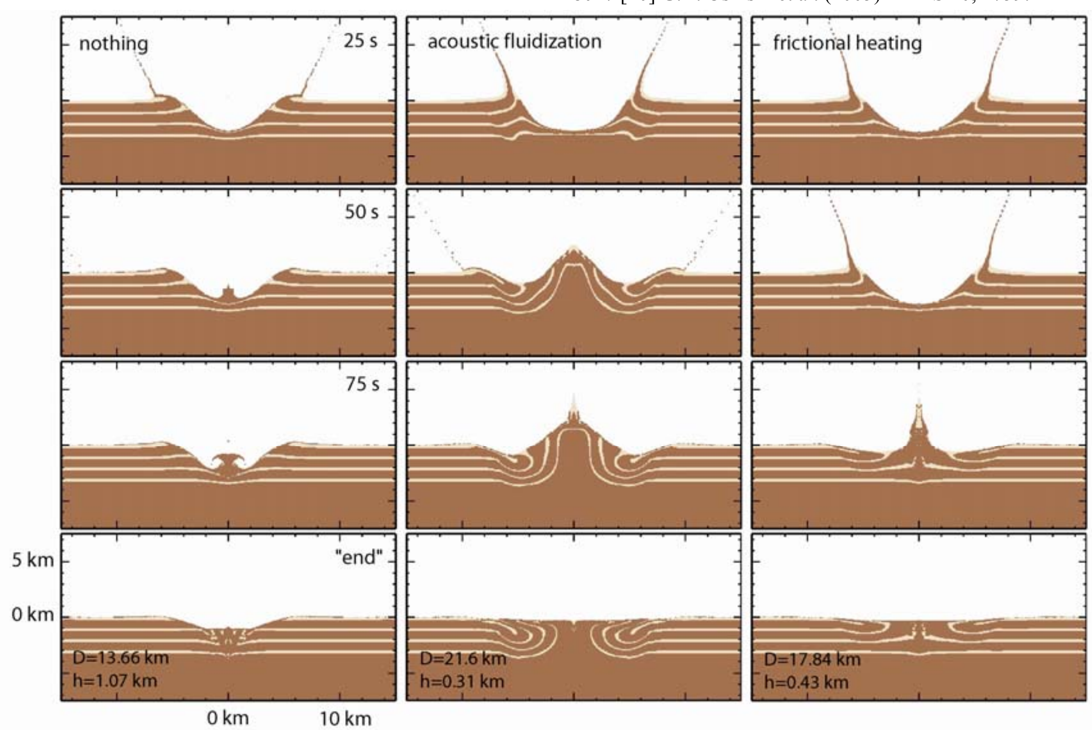

Figure 1. Crater formation from D=1 km asteroids impacts at 17 km/s on Earth for three different collapse scenarios. 2D cylindrically symmetric calculations. Final rim diameters and depths from the original surfaces are noted.

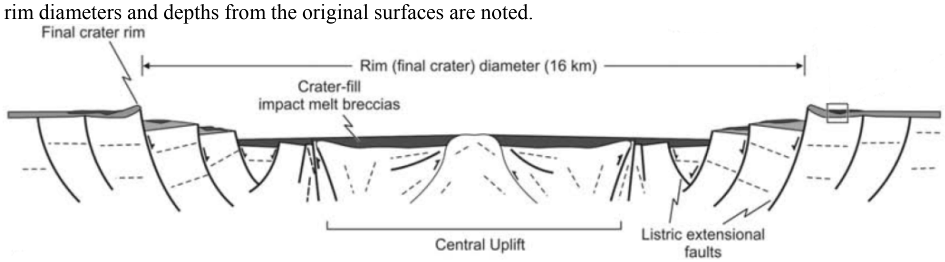

Figure 2. Simplified schematic of the Haughton impact structure, Devon Island, Canadian High Arctic [from 20].