FAULT WEAKENING AND SHEAR LOCALIZATION DURING CRATER COLLAPSE. R. V. Zucker and S. T. Stewart, Dept. of Earth & Planetary Sciences, Harvard University, 20 Oxford St., Cambridge, MA 02138 (rzucker@fas.harvard.edu).

Introduction: The observed morphologies of impact basins can only be explained by invoking dramatic weakening of the crater walls and floor during crater collapse, but the mechanism underlying the drop in strength is unknown. Here, we explore the possibility that strain-weakening along faults is the primary mechanism. We present a model of temperature- and pressure-dependant strain-weakening along faults during crater collapse.

Background: The depths of complex craters are far shallower than predicted using the quasi-static frictional strength of fractured rock [1, 2]. Therefore, some physical process must be causing transient weakening of the rock.

The mechanism responsible for this dramatic drop in strength remains unknown. Proposed explanations for weakening include acoustic fluidization [3], or dynamic weakening along faults, possibly caused by melt lubrication [4]. Acoustic fluidization has been modeled extensively [e.g. 1, 5, 6, 7], however, little work has been done on fault weakening [8].

Simulations of crater collapse including a simple model of dynamic strain weakening were performed by Senft and Stewart [8]. Their work was successful at producing the characteristic features of large craters (fig.1), indicating that fault weakening could explain the strength drop during crater collapse. However, the simplicity of their model presents some limitations. One of the limitations is that the criterion for weakening is not pressure-dependent. This asumption is not a problem in large craters because the pressures are high everywhere, but in smaller complex craters, strain weakening must account for pressure effects because the weakening criterion is not met everywhere. Another limitation is that detailed work on finding the average spacing between faults cannot be done reliably with such a simple model. Also, the thickness and other characteristics of the faults are not constrained. Therefore, a more sophisticated theory is necessary to apply a fault-weakening model to any size complex crater and to predict specific propeties of the faults, such as their spacing and thickness.

With the benefits of an improved model as motivation, the present work aims to improve upon the model by Senft and Stewart [8] by including temperature, pressure, strain rate, and localization effects in the simulations of fault-driven crater collapse.

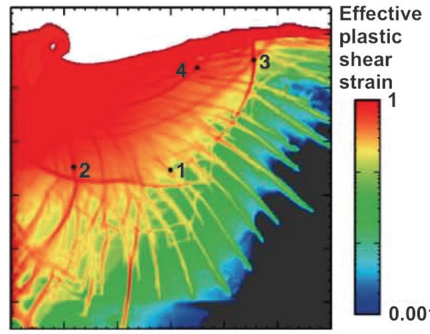

Figure 1: A simulation of an 8 km-diameter body impacting a rocky planet 140 seconds after impact by Senft and Stewart [8]. The color denotes total accumulated shear strain. Quasi-linear zones of localized shear strain are interpreted as fault zones. The numbers indicate the relative order of fault activation, with 1 being the earliest. Faults naturally arise in this model as rocks are damaged, and the final crater shape predicted using fault weakening is consistent with observations [8].

Fault weakening model: Friction experiments have shown that shear strength drops at high slip rates (see summary in Table 1 in [8]). In the 1950's, a theory of flash heating at frictional asperity contacts was developed to explain this weakening behavior in metals [9]. Rice [9, 10] has adapted this theory to explain weakening at high strain rates in rocks. The theory is that rough, frictional surfaces are actually in contact over only a fraction of their apparent area. During slip, the points of contact (asperities) are only exist for a short time before they slip apart. If the slip rate is low, the heat generated will have time to diffuse away from the asperity during its lifetime. If the slip rate is high, then heat cannot flow away fast enough and the asperity can become hot enough to fail plastically or melt locally, which is called "flash heating." Therefore, there is a critical slip rate for asperity weakening, v_w, which is set by the material weakening temperature, T_w, the current temperature on the fault, T, the size of asperities, D_a, and the ratio of nominal contact area to asperity contact area, s. The critical slip rate is given by:

$$v_w = \frac{\pi\alpha}{D_a}\left(\frac{\rho c_p(T_w - T)}{\tau_a}\right)^2,$$

where α is the thermal diffusivity, ρ is the density, c_p is the heat capacity, and τ_a is the shear strength of the asperity, which is estimated as

$$\tau_a = f\sigma_n s,$$

where σ_n is the normal stress across the fault. The derivations of these expressions are presented in [9].

Given this critical slip rate for weakening, the friction on a fault, f, is

$$f = (f_0 - f_w)\frac{v_w}{v} + f_w \qquad v > v_w$$

$$f = f_0 \qquad v < v_w$$

where f_0 is the quasi-static (slow) friction value, and f_w is the friction value in the limit of high slip rate [9].

This model for friction provides several advantages over previous models. First, the weakening criteria is variable and depends on the history of the deformation and state of a parcel, which is a major improvement over the model used in [8]. This feature makes it applicable to smaller craters as well as large ones. Second, it is testable, and matches experimental data very closely (fig. 2) [9, 11, 12]. Third, it provides a physical explanation for the weakening mechanism and all the parameters are at least in theory measurable. The highest uncertainly lies in the asperity size and contact area ratio, but these are constrained by experimental data and are roughly 5 μm for D_a and ~10 for s, so that τ_a ~ 3.0 GPa [9].

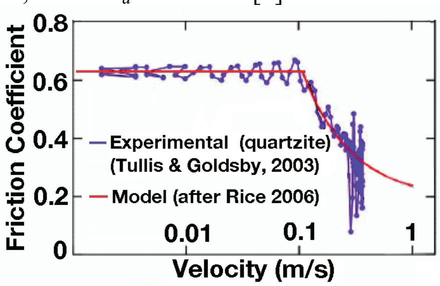

Figure 2: A comparison of experimental data from Tullis and Goldsby [11] with the model developed by Rice [9] for dynamic friction reduction is shown (after [9]). Experimental data for Arkansas Novaculite (~100% quartzite) is shown in blue, and the friction model is shown in red. The oscillations in the experimental data are believed to be experimental artifacts [11]. This plot shows the excellent agreement between friction data and Rice's model for a typical rock.

Given this friction model, the temperature on the fault can be calculated. Observations show that slip in rocks is usually not localized to mathematical plane, but is instead spread over a narrow volume around the fault, anywhere from 0.1 mm [13, 14] to 5 mm wide [9]. The width of this zone is the localization thickness, l. The main assumptions are that all the work from sliding is converted to heat via friction, that the heating rate and temperature is uniform within l, and that within a small time step, the friction and velocity are nearly constant. In an increment of time, dt, the heat produced per unit volume within l is

$$dw = dq = \frac{1}{l}\int_t^{t+dt} f(t\prime)\sigma_n v(t\prime)dt\prime = \frac{f\sigma_n v dt}{l}.$$

At short times, the thermal diffusion length, $\sqrt{4\alpha t}$, is less than l. When the diffusion length exceeds l, it replaces l in the expression for dq so that the heat can dissipate and the region can cool if it stops slipping.

The total heat on the fault is found by summing dq over the duration of slip. Diving by ρ c_p and accounting for the latent heat of melting converts total heat to a temperature.

Once enough heat has accumulated in the layer to partially melt it, the definition of dq changes so that the shear strength is given by assuming that the melt is a Newtonian fluid:

$$dq = \frac{\mu v^2 dt}{l^2},$$

where μ is the dynamic viscosity of the melt as a function of temperature.

Impact Simulations: Simulations of crater collapse using the strain-weakening model discussed above will be presented. The implementation of the model in the CTH hydrocode [15] is tested by comparing the calculated temperatures from simulations of a single fault with the temperatures found using the full theoretical solution. We will simulate a wide range of crater sizes and discuss the validity of this model for the mechanical behavior of rock during impact cratering events.

Summary: The development of dynamically-weakened faults may explain the extremely low strength of rock during crater collapse. We present a temperature- and pressure-dependant strain-weakening model for planetary materials that can be applied to any size crater. The model is testable by comparisons to observations of the spatial distribution of faults and the occurrence of friction-generated melts.

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