IMPACT SPALL AND FRAGMENTATION BY NEAR-SURFACE STRESS WAVE INTERACTIONS. H. J. Melosh[1] B. C. Johnson[2] and T. J. Bowling[3], [1]Earth Atmospheric and Planetary Sciences Department, Purdue University, 550 Stadium Mall Drive, West Lafayette, IN 47907 USA (jmelosh@purdue.edu), [2]Department of Earth, Environmental, and Planetary Sciences, Brown University, 324 Brook Street, Providence, RI 02912, USA. [3]Department of the Geophysical Sciences, University of Chicago, 5734 S. Ellis Avenue, Chicago, Illinois 60637, USA.

Introduction: The impact ejection of fast, lightly shocked material is one of the important insights stemming from the discovery of meteorites that originated on Mars and the Moon [1]. The sizes of such fragments as a function of ejection velocity is presently one of the most poorly understood aspects of impact cratering, in spite of its importance for meteoritics as well as the sizes of secondary craters. To better understand this process we have carefully studied the interaction of the stress wave with the free surface at very high resolution in a simplified impact scenario. In addition, we present a new model for impact fragmentation of rock overtaken by a sudden compressional shock wave and deduce its consequences.

Modeling near-surface stress waves: We used the iSALE computer code to model a vertical impact of a 10 km diameter Al projectile onto a planar Al target at 20 km/sec at a resolution of 6.25 m/cell. We chose Al because it lacks high pressure phase transition that might complicate the free-surface interactions and because we have an accurate (and simple) Tillotson equation of state that we can solve analytically. Figure 1 illustrates the pressure contours 0.36 sec after the impact, when the projectile is still penetrating the target and the shock wave adjacent to the target is already damped by near-surface interacions beginning at the complex region near the projectile's edge.

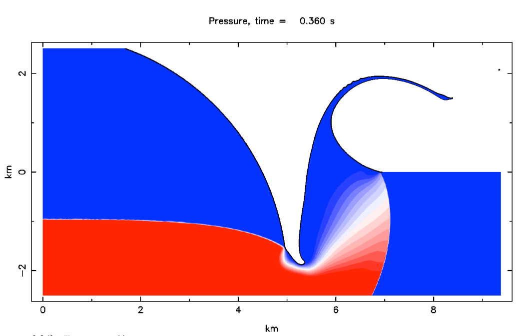

Figure 1. Pressure near a vertical Al on Al impact at 20 km/sec. Highest contour is 150 GPa, lowest is 0.

We traced the time evolution of the shock front and pressure contours, shown in Figure 2. Note that the area of pressure relief forms a near-triangle beginning at the former edge of the projectile. This region is known as an "irregular reflection" and is created by rarefaction waves propagating downward from the free surface through previously shocked material. The angle Ψ of the steepest contour is approximately given by [2]

$$\tan\Psi = \frac{\sqrt{c^2-(U-u)^2}}{U}$$

where c is the sound speed behind the shock, U is the shock velocity and u is the particle velocity. For Al at 150 GPa the tangent equals 0.7, implying an angle of 35°, close to that in Figure 2.

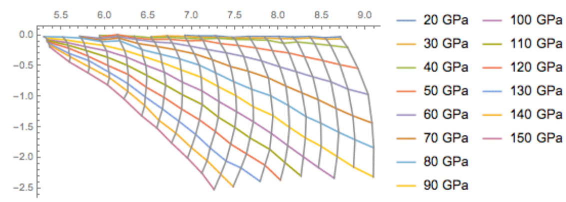

Figure 2. Contours of maximum shock pressure ever achieved (color) in the irregular reflection region and successive shock front positions (black) at intervals of 0.02 sec. Scale is in km.

The maximum shock pressure in this region is given approximately by $Pmax = 150 * z/s * \tan\Psi$, where z is depth below the surface and s is horizontal distance from the projectile edge (at 5.0 km on the left). This estimate is not valid very close to the surface, where numerical problems may have arisen from iSALE's interface tracking algorithm—in any case, no Eulerian code does an adequate job close to a free surface because it cannot resolve the surface to better than one cell. We are currently exploring a Lagrangian code to better define this important region.

Figure 1 shows that the maximum pressure is only achieved for a short time. After the arrival of the sharp shock front, the pressure decays gradually through a stepwise release that is often approximated as a Prandtl-Meyer expansion fan [3], even though this is strictly not applicable because the flow is entirely subsonic (within the rapidly moving material) behind the shock. The pressure release fan forms an angle of about 45° to the vertical in these computations, so near-surface material is decompressed quickly as the shock sweeps outward at 10.4 km/sec, while deeper material resides longer at high pressure.

Compressional fragmentation at the shock front: Although the iSALE computation did not implement a fragmentation model (none exists for crushing, so far, and the basalt HEL at 2 GPa is exceeded at nearly all depths this close to the impact), the stress history of material at different depths invites us to attempt to construct a post-processing algorithm for dynamic fragmentation.

Previous work [4] adapted a model of Grady and Kipp [5] to successfully model tensional fragmentation long after the arrival of the initial compressional shock. This model envisages that tensile stresses activate Griffith crack-like flaws that then grow at the speed of sound to finally intersect and define a distribution of fragments, whose mean size is inversely proportional to the strain rate. Although such flaw-activation models are currently used in the fragmention literature [6], they are closely tied to estimates of the strain rate. However, as appears from Fig. 1, the strain rate across the shock is almost infinitely high and the time during the pressure jump is, in any case, too short for cracks to propagate from the activated flaws.

Here we propose a new model, constructed in the same spirit as the activated flaw models, in which we assume that the strain applied to the material jumps discontinuously during the shock (in reality it is merely very short compared to crack growth speeds), but that once the strain is applied, flaws are activated and grow at high speed until they intersect and form a network of fragments, as in the tensional case. We assume that the number N of flaws available for fracture is given by a Weibull distribution, $N = k\ \varepsilon^m$, but the material constants k and m are different for flaws in compression than in tension. Under compression the cracks may be held closed by friction until, as they begin to slide, they generate tensile wing cracks which then propagate, as is observed for quasi-static rock fracture in the laboratory [7]. Alternatively, at high confining pressure shear failure may occur by adiabatic shear bands [8], but even in this case the initial flaw description is appropriate, only the interpretation differs.

Whereas the power m is typically about 9 in tension, the commonly observed dependence of stress on the 2/3 power of the strain rate in compression [6, Figure 6] implies that m = 3/2 in this case. We then determined the constant k from the measured crushing strength at a characteristic strain rate. For basalt, with a strength of 200 MPa at a strain rate of 1000 $\sec^{-1}$ [6, Table 1], we find that $k = 2.6 \times 10^9\ m^{-3}$, much smaller than is typical for tension, where k is approximately 10^{32}.

Following a development similar to that for tension, but assuming a fixed strain instead of a constant strain rate, expressions for time to complete fracture and mean fragment size can be derived in terms of m and k. The final result for the mode of the fracture size distribution l in terms of a suddently imposed deviatoric strain ε_0 above the HEL(in uniaxial compression):

$$l = 4\left[\frac{(m+1)\,(m+3)^4}{8\pi\, k\,(m+2)^5}\right]^{1/3} \varepsilon_0^{-m/3}$$

This predicts, for example, that for a shock of 3 GPa (just above the Hugoniot Elastic Limit for basalt) the fragment size in basalt is about 1.1 cm and at 10 GPa, l is 3.5 mm. Unfortunately we do not presently have adequate fragmentation data to check this theory.

We apply this theory to the stresses in the irregular shock wedge in Figure 3. Note that the duration at high pressure exeeds the time for complete fracture at all depths, so any tensile stresses that would develop in this region are preceeded (and thus prevented) by the complete fragmentation under compression computed by this model. Fragment sizes are much smaller than the surface spall layer (defined as the region where the HEL of 2 GPa is not exceeded). We do not show ejection velocities directly here, but they are high, typically about 10 km/sec this close to the impact site.

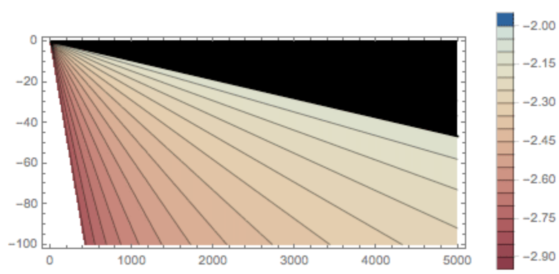

Figure 3. Log10 of fragment sizes in the irregular reflection wedge, all dimensions in meters. Intact spall shown in black at top. Contours for shock pressures above 50 GPa are not shown because the rock is melted, not fragmented. Note 50X vertical exaggeration.

Supported by NASA grant NNX15Al61G

References: [1] Melosh, H. J. (1984), *Icarus* 59, 234-260. [2] Kamegai, M. (1986) LLNL-20701, 42pp. [3] Falade, A. and Holt, M. (1978) *Phys. Fluids* 21, 1702-1708. [4] Melosh, H. J. et al. (1992) *JGR* 97, 14735-14759. [5] Grady, D.E. and Kipp, M. E. (1980) *Int. J. Rock Mech. Min. Sci.* 17, 147-157. [6] Ramesh, K. T. et al. (2015) *Planet. Space Sci*. 107, 10-23. [7] Ashby, M. F and Sammis, C.G. (1990) *PAGOPH* 133, 489-521. [8] Dodd, B. and Bai, Y. (2015) *Introduction to Adiabatic Shear Localization*, 456pp.