A SPEED LIMIT FOR IMPACT-EJECTED SPALLS.

H.J.Melosh, Lunar and Planetary Lab, University of Arizona, Tucson,Az. 85721.

Large impact events eject a small amount (0.01 to 0.05 projectile mass) of the target as high-speed, lightly shocked spalls (1,2). These spalls, besides having the capacity of ejecting solid material from the target planet, also appear to produce the prominent secondary crater fields observed around fresh impact craters. Study of these secondary craters indicates that the size of the ejected fragments falls inversely as the velocity, in agreement with the model, until a cutoff velocity is reached, beyond which few large fragments seem to be ejected (3). The original spallation model (2) did not predict this velocity cutoff. I show below that the observed cutoff is actually a natural consequence of the model.

The impact of a solid body onto a planetary surface (the target) generates strong stress waves that propagate away from the impact site, weakening as they spread. The detailed structure of these stress waves is complex due to the effects of rarefactions from the (moving) free surface, structure in the target, and the complexity of the target's equation of state. However, several gross features can be extracted from numerical simulations. They correspond to distinct regimes in the flow of debris out of what will finally become the crater.

The first disturbance to reach any point in the near vicinity of the impact is a strong shock or stress wave. This shock's geometric form approximates a section of a sphere centered a small distance d below the planet's surface (d=2a, where a is the projectile's mean radius). The maximum pressure P and peak particle velocity v_p in the shock decline as the shock radius r increases according to the relation $P=\rho c_L v_p$ where c_L is the longitudinal sound speed in the target and

$$v_p = (U/2)(a/r)^{\alpha} \qquad (1)$$

Behind the shock wave the pressure falls rapidly to near-zero, but the particle velocity declines to 1/3 to 1/5 of its peak value (4,5). The shock wave forms a distinct structure called the "detached shock" (5). The low-velocity, nearly incompressible "excavation flow" develops behind the shock. This flow is responsible for removing most of the material from the crater: the detached shock moves so rapidly that little displacement of target material can occur during its passage.

Near the free surface the shock wave interacts with rarefactions to produce locally large pressure gradients at the intersection of the shock and surface (the pressure is exactly zero, of course, at the free surface). These pressure gradients accelerate the lightly shocked near-surface material to high speed in the form of spalls. The underlying, more heavily shocked material acquires less velocity: most of it forms part of the excavation flow although some, broken into fragments much smaller than the spalls, may be ejected immediately after the spalls.

The thickness of the spalled layer z_s can be estimated from the equation

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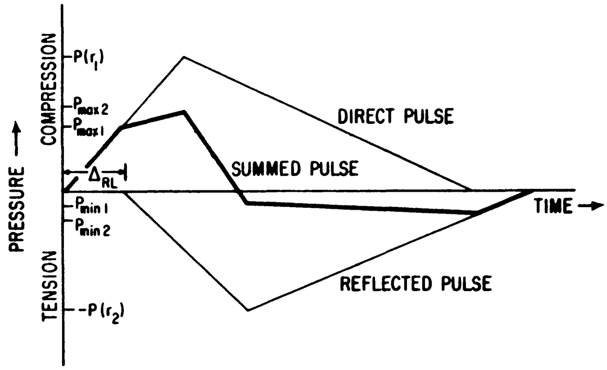
$$z_s = (\sigma_t/2P)\{r/(1-\alpha\, d/r)\} \qquad (2)$$

where σ_t is the dynamic tensile strength of the material. The ejection velocity v_E is approximately

$$v_E = 2v_P d/r \qquad (3)$$

It has been noted (especially clearly by K. Housen, Personal Communication, 1983) that z_s can become infinite if the denominator in equation (2) vanishes. This is always possible at some range s from the impact point ($r = \sqrt{d^2+s^2}$) if $\alpha > 1$. For $\alpha = 1.87$, the value reported by Perret and Bass (6), this occurs at $r_c = \alpha d = 3.74a$ (where d=2a is assumed), or at range s = 3.2a.

The meaning of this infinity is that the net pressure is still compressive when the tensile pulse reflected from the free surface reaches its peak P_{1min} (Fig.1). The net pressure pulse reaches its tensile minimum P_{2min} only much later. The inequality of P_{1min} and P_{2min} is due to attenuation of the pulse and the resulting inequality of the direct and reflected pressure pulses.



Although a spall does break off at this time with thickness $z_{s,delayed}$ of

$$z_{s,delayed} = (\sigma_t/2P)\, r, \qquad (4)$$

its velocity is very low, of order $v_{e,delayed} = \sigma_t/\rho c_L$. Such delayed spalls are caught up by the excavation flow field and do, in fact, attain significant velocities--but only 1/3 to 1/5 of the velocity that prompt spalls at this range could acquire. The fragment size vs. velocity curves should thus take a sharp downturn at an ejection velocity v_c corresponding to the radius of transition r_c between prompt and delayed spalls. This velocity is

$$v_c = (2d/r_c)(U/2)(a/r_c)^{\alpha} = 2U/(2\alpha)^{\alpha+1} \qquad (5)$$

For = 1.87, v_c = U/22. For impact velocities in the range of 10 to 30 km/sec, the maximum prompt spall velocity is 0.5 to 1.5 km/sec, agreeing well with observations.

REFERENCES

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