The Physics of How a Blast Front Causes Craters in Material

Excerpted from "Impact Cratering: An Overview of Mineralogical and Geochemical Aspects" (http://www.univie.ac.at/geochemistry/impp.html) Although the cited reference deals with geological impact craters, the physics model described is general enough to apply to a wide variety of high energy impacts.

For a thermodynamical treatment of shock fronts traveling through matter, the so-called Hugoniot equations are used (see Melosh, 1989). These equations link the pressure P, internal energy E, and density r in front of a shock wave (uncompressed: P_0, E_0, ρ_0) to values after the shock front (compressed: P, E, ρ). The density is also expressed as the specific volumes $V = 1/\rho$ and $V_0 = 1/\rho_0$ for the compressed and uncompressed cases, respectively. Initial pressure, energy, and density before the shock are known values, while the respective values after the shock are unknown quantities, as are the shock velocity U and particle velocity u_p behind the shock front. The Hugoniot equations are then written as:

$$\rho(U - u_p) = \rho_0 U$$

$$P - P_0 = \rho_0 u_p U$$

$$E - E_0 = (P + P_0)(V_0 - V)/2$$

These equations express the conservation of mass, momentum, and energy across the shock front to reduce the number of unknown variables from five to two. For a derivation of the Hugoniot equations, see Appendix 1 in Melosh (1989), and Boslough and Asay (1993). In the uncompressed material, the initial particle velocity should be zero, and the initial pressure P_0 can be neglected, yielding the approximation $E - E_0 = u_p^2/2$. In addition to the three equations mentioned above, a fourth one, the equation of state, is necessary to specify conditions on either side of the shock front. This equation links pressure, specific volume (density), and internal energy: $P = (V,E)$. Equations of state have been determined experimentally for a large number of different materials (e.g., Marsh, 1980).

The shock wave equation of state data can be plotted in pressure versus specific volume (Fig. 1) or shock velocity versus particle velocity diagrams. The curves in these diagrams are not equivalent to conventional equilibrium in thermodynamical P,V diagrams, but represent loci of several individual shock events, i.e., each point on a curve is the result of one particular shock wave compression event. The HEL appears as a kink in the shock curve, indicating yielding at the maximum stress of the elastic wave (Fig. 1).

After the shock wave passes, the high pressure is released by a so-called rarefaction, or release, wave, which trails the shock front. The rarefaction wave is a pressure, not shock, wave and travels the speed of sound in the shocked material. As it moves faster than the shock wave, it gradually overtakes the shock front and causes a decrease in pressure with increasing distance of propagation. While the pressure behind a rarefaction wave may drop to near zero, the residual particle velocity actually accelerates material, leading to impact crater excavation. In addition, the rarefaction wave does not only conserve mass, energy, and momentum (as the shock wave does), but also entropy. Thus, rarefaction is a thermodynamically reversible adiabatic process, while shock compression is thermodynamically irreversible. During shock compression, a large amount of energy is being introduced into a rock. Upon decompression, the material follows a release adiabat in a pressure versus specific volume diagram. The release adiabat is located close to the Hugoniot curve, but usually at generally somewhat higher P and V values, leading to excess heat appearing in the decompressed material, which may result in phase changes (e.g., melting or vaporization). The effects of the phenomena described above can be observed in various forms in shocked minerals and rocks.

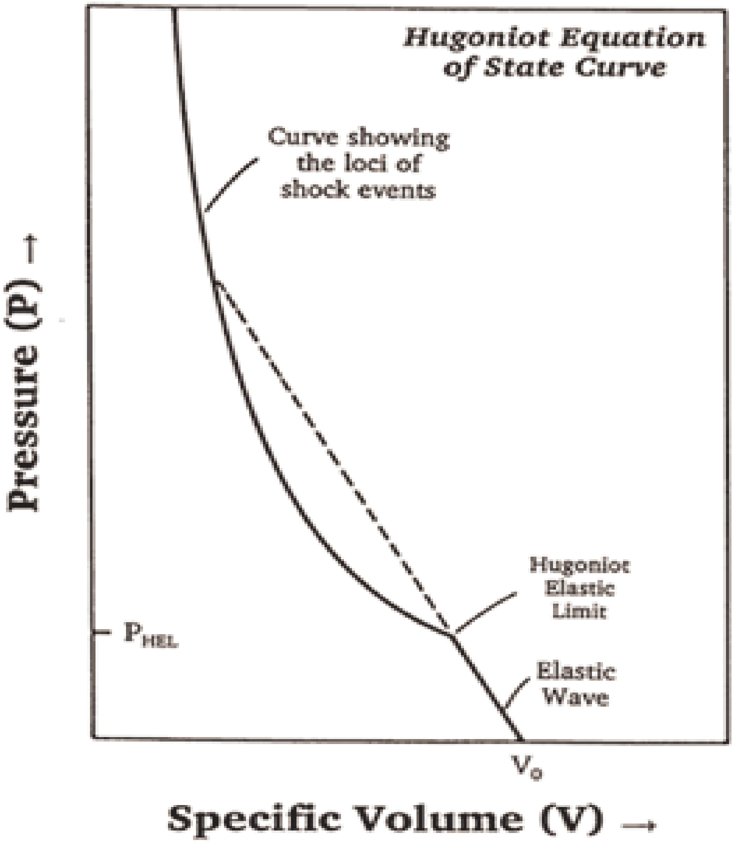

Fig. 1. Idealized representation of a Hugoniot equation of state curve. The Hugoniot curve does not represent a continuum of states as in thermodynamical diagrams, but the loci of individual shock compression events. The yielding of the material at the Hugoniot Elastic Limit is indicated. See text for detailed discussion.

References

Melosh, H. J., 1989, Impact cratering: A geologic process: New York, Oxford University Press, 245 p.

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Marsh, S.P., 1980, LASL Shock Hugoniot Data. University of California Press, Berkeley, 658 pp.