NUMERICAL MODELING OF SHATTER CONES DEVELOPMENT IN IMPACT CRATERS

D. Baratoux[1] and H.J. Melosh[2], [1]Observatoire Midi-Pyrénées, UMR5562, 14 Avenue Edouard Belin, 31000 Toulouse, France, david.baratoux@cnes.fr, [2]Lunar and Planetary Laboratory, University of Arizona Tucson, AZ 85721, USA, jmelosh@lpl.arizona.edu

Introduction: Shatter cones are the characteristic forms of rock fractures in impact structures. They have been used for decades as unequivocal fingerprints of meteoritic impacts on Earth [1,2]. The abundant data about shapes, apical angles, sizes and distributions of shatter cones for many terrestrial impact structures should provide insights for the determination of impact conditions and characteristics of shock waves produced by high-velocity projectiles in geologic media. However, previously proposed models for the formation of shatter cones do not agree with observations. For example, the widely accepted Johnson-Talbot mechanism [3] requires that the longitudinal stress drops to zero between the arrival of the elastic precursor and the main plastic wave. Unfortunately, observations do not support such a drop [2,4]. A model has been also proposed to explain the striated features [5] on the surface of shatter cones but can not invoked for their conical shape. The mechanism by which shatter cones form thus remains enigmatic to date. In this paper we present a new model for the formation of shatter cones. Our model has been tested by means of numerical simulations using the hydrocodes SALE 2D enhanced with the Grady-Kipp-Melosh fragmentation model [6].

Constraints from field observations : Our model must be consistent with all the following constraints from the observations of shatter cones in various high-pressure shocked materials, including natural impact structures and explosion experiments. Shatter cones range in size from few centimeters to 12 meters and all the cones seem to point toward the shock wave source area in both natural impact structures and explosion experiments. Apical angles are distributed between 60° and 120° [1]. Generally, shatter cones are observed inside a restricted pressure range from 2 to 6 GPa [7]. This range of pressure has been reported from both explosion experiments and estimation of peak pressure in natural impact craters. For impact craters, the pressure decreases with the distance from the center of the cavity.

New model for the formation of shatter cones: Our model relies on the interaction between an elastic wave scattered by a rock heterogeneity and the tensional hoop stress that occurs behind a shock front expanding in a spherical geometry (see figure 1). When the shock front encounters a heterogeneity having a lower sound speed, (lower bulk modulus or higher density), an extensional wave is generated that propagates radially from the heterogeneity. As the shock front propagates forward, the hoop stress becomes tensional if the wave's rise time is not too short. At a given time, the tensional hoop stress is increased at the locus of its intersection with the scattered wave, the interference producing a tensional stress which may exceed the resistance of the material in tension. According to this model, fractures occur at the locations indicated by filled-circles in figure 1, outlining approximately a conical region while the domain inside the cone is preserved from fracturing.

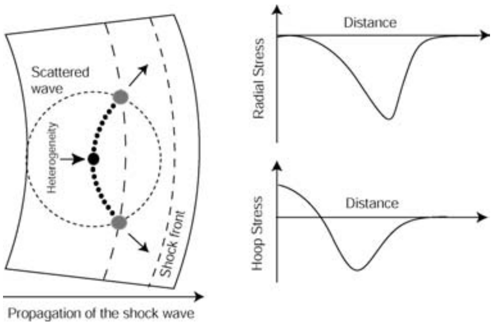

Figure 1. New model for the formation of shatter cones (left) and patterns of stress for a propagating wave in the spherical geometry (right). Compression is taken to be positive.

Numerical Modeling : The Navier Stokes equations are solved using the 2-dimensional hydrocode SALE 2D enhanced with the Grady-Kipp-Melosh fragmentation model.

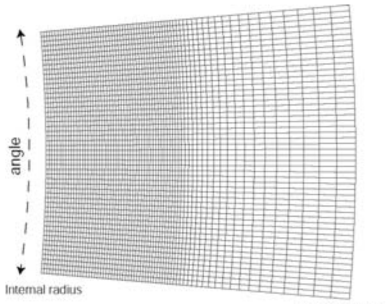

Figure 2. Scheme of the mesh. The internal radius is defined from the distance of the axis of symmetry in the cylindrical geometry.

A radial section of the mesh, in axisymmetric geometry, is presented in figure 2. The grid is defined by its dimension (100*150 cells), the internal radius (10m), the angle (20°) and radial dimension of the cells (2 cm). Larger cells are used for the larger radius leading to the prolongation of the grid in order to simulate a continuative outflow boundary and to avoid any reflected stress waves from the external boundary. For those cells, the size ratio of the next cell to the previous one is 1.1.

Results : We investigated the conditions for the formation of shatter cones from numerical modeling using plausible geologic material parameters. We varied the sizes of the heterogeneity and the peak pressure and rise time. The parameters that affect the formation of shatter cones include the material parameters (density, bulk modulus, Hugoniot Elastic limit) as well as the shape and the magnitude of the stress wave. We find that the sound velocity ratio between the heterogeneity and the embedding material has to be greater than 2 to allow the formation of shatter cones. We observe shatter cones for peak pressures ranging from 2 GPa to 6 GPa. These values, strikingly similar to the reported values from field observations support strongly our model. The rise time of the peak pressure also has to be short and less than the time required for the stress wave to travel across the heterogeneity. For a meter-scale shatter cone, the rise time should be a fraction of a millisecond.

We present below the detailed parameters and our result (figure 3) for one typical simulation of the formation of a shatter cone due to the presence of water ice in a basaltic target. The parameters of the materials are reported in table 1, the parameters of the shock wave are reported in table 2.

Target type	Basalt	Ice
Density (kg/m^3)	2980	900
Bulk Modulus (GPa)	60,1	0,2
Shear Modulus (GPa)	36,7	0,12
Murnhagan exponent	5,5	5,23
Crack velocity (m/s)	1790	7500
k^1 (m)	9,05	8,7
m^1 (m^{-3})	$3.05*10^{40}$	$3.2*10^{40}$

Table 1. Material Parameters for the target and the heterogeneity [8]. [1]Material parameters of the Weibull distribution : $N = k\varepsilon^m$ where N is the number of flaws per unit volume activated at or below tensile strain ε [6].

Pressure Max	Rise time	Decay time
3 GPa	0,01 ms	0,05 ms (triang. pulse)

Table 2. Parameters for the shock wave.

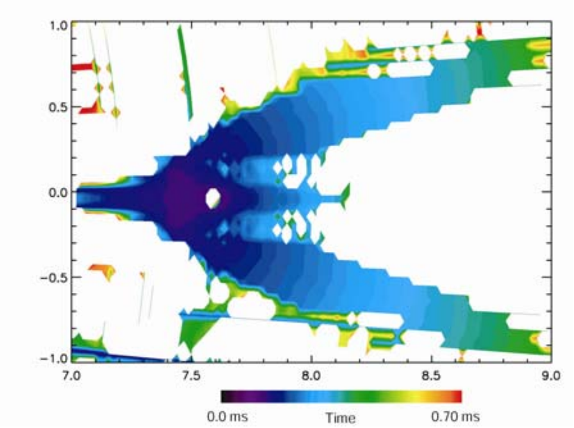

Figure3. Damage history. The duration of the computation is 0.70 ms. Distances along x and y axes are in meters. The fragmentation front expands for the cells along the boundary of the cone, and the hoop stress is consequently relieved after damage occurred, the cells inside the cone remain intact (white cells have not been fully damaged throughout the computation).

Conclusions : This new model for shatter cones formation operates over a wide range of conditions and for common geologic media for pressures between 2 and 6 GPa, in good agreement with estimates from most of the impact structures investigated. From this model, the size and distribution of shatter cones should be correlated with the pulse width and the size of heterogeneities. Centimeter-scale shatter cones imply that the rise time of the peak pressure in geologic media is shorter than previously thought.

References: [1] Dietz, R.S. (1960), *Science*, *131*, 1781-1784. [2] Milton, D.J. (1977), *in Impact and Explosion Cratering*, 703-714. [3] Johnson, G. And Talbot, R., *A theoretical study of the shock wave origin of shatter cones*, *M.s. Thesis, Air Force Inst. Tech*. [4] Grady, D. E. (1977) in M. H. Manghanani and S-I. Akimoto (Eds) *High Pressure Research : Application to Geophysics*, 389-438. Perret, W. R. (1967) Sandia National Laboratory Report VUF-3012 and VUF-3013. [5] Sagy, A., et al. (2002), *Nature*, *418*, 310-313. [6] Melosh, H.J. et al. (1992), *Journal of Geophysical Research, 97*, 14735-14759. [7] Roddy, D. and Davis, L.K. (1977), *in impact and explosion cratering,* 715-750. [8], Melosh, J.H, (1989) Impact cratering : a geologic process.

Acknowledgments: This work was performed during a visit of the first author to the Lunar and Planetary Laboratory, University of Arizona. HJM was supported by NASA grant NAG5-11493.