OBLIQUE IMPACT AND ITS EJECTA – NUMERICAL MODELING.
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Introduction: It is well known that impact events strike planetary surfaces at an angle from the surface. Assuming an isotropic flux of projectiles, probability theory indicates that the most likely angle of impact is 45^o regardless of the body's gravitational field [1-2]. While crater rims appear circular down to low impact angles, the distribution of ejecta around the crater is sensitive to the angle of impact and currently serves as the best guide to obliquity of impacts. A fair amount of numerical modeling of vertical impacts has been carried out from the early 60-s [3] to the present time [e.g., 4-5 and references herein]. In vertical impacts, the axial symmetry of the process allows the simplification of the model to two dimensions (2D). Oblique impact modeling requires 3D hydrocodes and, hence, much more powerful computers. The first documented detailed oblique impact studies were carried out at Sandia National Labs' supercomputers less than 10 years ago to describe the 1994 collision of comet SL9 with Jupiter [6-7]. Since then, substantial progress in computer science has made 3D modeling a reachable objective for the scientific community.

Hydrocodes. The hydrocodes that are mostly used by the planetary impact cratering community for modeling oblique impacts are CTH [8], and SOVA [9]. Both are two-step Eulerian codes that can model multidimensional, multimaterial, large deformation, and strong shock wave physics. Both can be coupled with sophisticated equations of state models, and both have distinctive features: CTH allows for a sophisticated treatment of strength; SOVA contains a procedure to describe particle motion in an evolving ejecta-gas plume.

Melt production is a strong function of angle of impact. However, scaling laws for oblique impacts are still not well constrained. Pierazzo & Melosh [10] found that for typical rocks the amount of impact melt produced decreases with impact angle. For impacts from 90^o to 45^o the decrease is less than 20%, whereas for impacts at 30^o the volume of melt drops to about 50% of the vertical case, declining to less than 10% for a 15^o impact. In this study, the projectile volume was kept constant. For geological studies, however, it may be more useful to focus on crater volume. Ivanov and Artemieva [12] found that for relatively high impact velocities (>20 km/s) the efficiency of the cratering excavation, based on the maximum volume of the transient cavity, for a 45^o impact appears to be comparable with that of a vertical impact. Early on, the application of standard scaling laws for crater size to oblique impacts [11] suggested that for impact angles between 30^o and 90^o the melt ratio is more or less constant, with deviations within 20% of the average. Published laboratory data [13, 14] show that cratering efficiency in an oblique impact varies with impact velocity and projectile-target materials.

Complex targets must be treated with care. While the overall target melting seems to follow the general behavior described above, Stoffler et al [15] found that the amount of melting of finite thickness layers scales with the projectile's cross section (D^2), not its volume (D^3), as is the case for the overall melting. Furthermore, melting of near surface layers increases with impact angle decrease.

Fate of the projectile Oblique impacts show a downrange focusing of projectile material, becoming predominant at low impact angles [16]. Furthermore, most of the projectile is ejected from the opening crater in the early stages of the impact, and a significant amount of projectile material carries a downrange/upward velocity larger than escape velocity. Shock melting and vaporization in the projectile also decreases with impact angle [16,17].

Distal ejecta – tektites and meteorites from other planets. It is now widely accepted that both SNC-meteorites and tektites are produced by impact events. Geophysical and geochemical properties of tektites are consistent with an origin from high-temperature melt from the top few hundred meters of the Earth's surface that solidified in the upper atmosphere (low oxygen content) [18]. Martian meteorites originate from the upper layers of the youngest martian terrains [19, 20]. Different in their nature, both types of ejecta have a similar place of origin (upper target layers) and require high velocities (to travel distances of hundreds of km – tektites – or to escape Mars gravity – SNC meteorites). The main difference between them is in the degree of shock compression they must have experienced: melting must occur for tektites while, on the opposite end, meteorites must experience modest shocks. Since they are formed by the same mechanism, impact cratering, from the numerical modeling point of view both SNC and tektites may be treated in similar ways.

Transformation of continuum material into discrete particles is crucial for modeling ejecta during the late stages of impact cratering, when the properties of individual particles (i.e., mass, size, shape, individual velocity) become important. Modeling of ejecta as a continuum is a reasonable assumption only in the early stages of impact cratering. The trajectories of discrete particles in the atmosphere should be defined by a two-phases hydrodynamics that includes the interaction of the particles with the post-impact gas flow. Various processes influence the size and shape of individual particles [e.g., 21,22,23]. The approach of representative tracer particles [9,24,25] is used to avoid limitations due to computer capacity. A simplified treatment models material disruption when the material is subject to tension. The hydrodynamic cell velocity defines the initial particle velocity, and the particle's initial position within the cell is randomly defined. An empirical size distribution for solid particles is adopted from experimental studies of high-energy chemical explosions, where particle sizes range from 1 mkm to 10 cm. The diameter of molten particles ranges from 1 to 3 cm, while particle size drops to 0.01 cm when produced by condensation from a two-phase mixture.

Tektites. Tektites (high-temperature, high-velocity melt from surface layers) are consistent with a production by relatively high-velocity (>20 km/s) impact into silica-rich, possibly porous and volatile-rich, targets with impact angles around 30^o -50^o [26]. In particular, very oblique impacts must be excluded, since they tend to produce target melt that is highly contaminated with projectile material. In [15] a numerical modeling study was performed to evaluate whether a single collisional event (a 30^o impact) could have been responsible for the formation of the Ries and Steinheim craters and the moldavite tektite strewn field. The modeled spatial particle distribution shows promising similarities with the observed one (Fig.1), like the formation of a relatively narrow tektite distribution fan, symmetric with respect to the downrange direction, and a modeled mass of tektite-type material that is within a factor of two of that estimated for the Ries-related tektites.

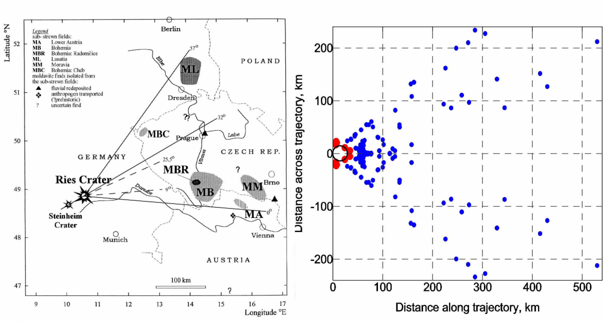

Fig.1 Observed (left) and modeled (right) distributions of moldavites.

Martian meteorites. The number of ejection events required to represent the known Martian meteorites (in the past 20 Ma) [19] combined with the known Martian cratering rate [27] suggest the need of parent craters of 1 to 3 km in diameter. Modeling studies [28] have shown that oblique impacts (15^o to 60^o) are much more efficient than vertical ones [29] at producing Martian meteorites. However, the modeled crater sizes are too large (>10 km) or particles should be larger than 20 cm in diameter to keep escaping velocity in upper atmosphere [28] (the idea of large pre-entry size of martian meteorites has been confirmed independently by measurements of ^{80}Kr produced by epithermal secondary cosmic-ray neutrons of 30-300 eV energy [30]). In our study, solid, modestly shocked material (6-7% of the projectile mass) is ejected to velocities >5 km/s from a thin surface layer (~1/10 of the projectile diameter), where the peak shock pressure is distinctly limited to about 9 to 45 GPa. This pressure range is essentially confirmed by the observations [31]. Thus, recent hypotheses [32, 33] that Martian rocks can reach the Earth without being intensely shocked and heated are incorrect or at least questionable.

References: [1] Gilbert G.K. (1893) *Bull. Philos. Cos. Wash. (D.C.) 12*, 241–292**.** [2] Shoemaker E.M. (1962) In *Physics and Astronomy of the Moon* (Z. Kopal, Ed.), pp. 283–359. [3] Bjork R. L. (1961) JGR 66, 3379-3387. [4] O'Keefe J.D. and Ahrens T.J. (1999) *JGR 104*, No. E11, 27,091. [5] Melosh H.J. and Ivanov B. (1999) *Annu. Rev. Earth Planet. Sci.*, 27:385–415 [6] Crawford et al. (1994) *Shock waves* 4, 47-50. [7] Boslough et al. (1994) *GeoRL* 21, 1555-1558. [8] McGlaun J.M.et al. (1990) *Int. J. Impact Eng. 10*, 351–360. [9] Shuvalov V.V. (1999) *Shock Waves 9*, 381-390. [10] Pierazzo E. and Melosh H.J. (2000) *Icarus 145*, 252–261. [11] Gault D.E. and Wedekind J.A. (1978) *Proc. Lunar Planet. Sci. Conf. 9th*, 3843–3875. [12] Ivanov B. and Artemieva N. (2002) *GSA Special paper 356*, 619-630. [13] Burchell M.J., and Mackay N.G.(1998) *JGR 103*, p. 22761–774. [14] Hayhurst C.J. et al. (1995) *Int. J. Impact Eng 17*, 375–386. [15] Stoffler et al. (2002) M&PS 37, in press. [16] Pierazzo E. and Melosh H.J. (2000b) M&PS 35, 117-130. [17] Artemieva, N.A. and Shuvalov V.V.(2001) in *Geological and biological effects of impact events,* Buffetaut & Koeberl Eds. (Springer-Verlag), 249-263. [18] Koeberl C. (1994) *GSA Special Paper 293*,133-151. [19] Warren P.H. (1994) *Icarus 111*, 338-363. [20] Nyquist L. E. et al (2001) *Space Science Reviews 96,* 105-164. [21] Melosh H.J. and Vickery A.M. (1991) *Nature 350*, 494-497. [22] Melosh H.J. (1984) *Icarus 59*, 234-260. [23] O'Keefe J.D. and Ahrens T.J. (1986) *LPSC 17*, 1004-1005. [24] Teterev A.V. and Nemtchinov I.V. (1993) *LPSC 24*, 1415-1416. [25] Shuvalov V.V. (2001) *LPSC 32*, #1126. [26] Artemieva A.N. (2002) in Lecture Notes in Earth Physics. In press. [27] Hartmann W. K. and Neukum G. (2001) *Space Science Reviews 96*, 165-194. [28] Artemieva N. and Ivanov B. (2002) *LPSC 33*, #1113. [29] Head J. and Melosh H.J. (2002) *LPSC 31*, #1937. [30] Eugster O. et al. (2002) *LPSC 33*, #1096. [31] Fritz et al. (2002) *LPSC. 33*, # 1504. [32] Weiss, B.P. et al. (2000), *Science, 290*, 791-795. [33] Mileikowsky. C. et al. (2000), *Icarus*, *145*, 391-427