NUMERICAL SIMULATIONS OF OBLIQUE IMPACTS: THE EFFECT OF IMPACT ANGLE AND TARGET STRENGTH ON CRATER SHAPE. G. S. Collins[1], T. Davison[1], D. Elbeshausen[2] and K. Wünnemann[2], [1]Impacts and Astromaterials Research Centre, Dept. Earth Science and Engineering, Imperial College London, London SW7 2AZ, UK (g.collins@imperial.ac.uk), [2]Museum für Naturkunde, Leibniz-Institute at the Humboldt University, D-10099 Berlin, Germany.

Introduction: Current understanding of impact cratering is based, in large part, on numerical models and experiments where the impactor strikes perpendicular to the target surface. In reality, such events are extremely unlikely to occur; the most common impact angle is 45° to the target plane and over 90% of all impacts are oblique (<70°) [1]. It is therefore vital to understand how oblique impacts differ from vertical impacts. Here we investigate the influence of impact angle on crater shape in targets of different strengths.

Background: The effect of impact angle on crater ellipticity (and other measures of crater asymmetry) has been investigated directly by experiments [e.g., 2,3,4] and indirectly by remote sensing [e.g., 5,6]. Impacts at low angles (measured with respect to the target plane) produce elliptical craters elongated in the direction of the projectile's horizontal movement. Above a certain threshold angle, however, all impacts produce a near-circular crater.

Bottke et al [6] define an elliptical crater as a crater with an ellipticity (length divided by width) of 1.1 or more. Applying this definition, they examined the cratering record of Mars, Venus and the Moon, and found that 5% of craters on these bodies were elliptical. As 5% of impacts occur at <12° to the horizontal, this proportion of elliptical craters is consistent with an elliptical crater transition angle of 12° [6]. In other words, 5% of all craters should be elliptical if impacts at an angle of 12° (or less) produce craters with an ellipticity of 1.1 (or more). However, an elliptical crater transition angle of 12° is not entirely consistent with experimental observation (as noted by [5] & [6]).

The seminal experimental work of Gault and Wedekind [2] demonstrated that the relationship between impact angle and crater ellipticity depends on the target material. Results from their impact experiments into sand suggest that the transition from circular to elongated craters occurs at an impact angle of less than 5° to the target plane. Specifically, an impact at 4.75° produced a crater with an ellipticity (length divided by width) of 1.1. However, for impacts at similar velocities into granite targets [2] found that circularity is only maintained for angles steeper than ~30°. The impact velocities for these experiments ranged from 2-7 km s^{-1}.

More recent laboratory impact experiments, using ductile metal targets, demonstrate that in these materials elliptical craters are produced at impact angles up to ~30-40°. Christiansen et al. [3] found that the threshold angle between circular and elliptical craters is approximately 25° from the horizontal for impacts into an aluminum target at between 5.5 and 6.2 km s^{-1}. Burchell and Mackay [4] also present results of laboratory oblique impact experiments for several different metallic projectile and target material combinations. These data show complex, nonlinear relationships between impact angle and crater ellipticity, with threshold angles for elliptical crater production as high as 40-50°. In this case, the threshold angle for elliptical craters in aluminum-aluminum impacts was 35-40°.

The threshold angle below which an elliptical crater is produced on a planetary surface (12°) is intermediate to the threshold angle in sand (5°) and that in high-strength targets such as metal and rock (~30-40°). Bottke et al. [6] suggested that this trend might be explained by the different cratering efficiency (the ratio of crater size to impactor size) in each case. The impact experiments in sand had a high cratering efficiency, producing craters up to ~60 times larger than the impactor [2]. The impacts in aluminum targets, on the other hand, had a very low cratering efficiency, typically producing craters only 3-5 times larger than the impactor [3,4]. Cratering efficiency in planetary-scale impacts is not fully understood; however, Pi-group crater scaling laws [e.g., 7] suggest that km-scale impacts on planetary surfaces typically produce craters that are 10-20 times larger than the impactor, which is intermediate to the cratering efficiency in sand and metal/rock observed in experiments. Hence, according to the hypothesis of [6], the larger the cratering efficiency, the better the approximation of an impact as a point source of energy and momentum, and the smaller the influence of impactor properties such as shape and trajectory on crater formation.

To test this hypothesis, and to further investigate the influence of impact angle on crater shape in targets of different strengths, we used the newly-developed iSALE-3D impact code [8] to simulate oblique impacts in low and high strength targets. In the process, we also validated iSALE-3D against experimental data from lab-scale oblique impacts in aluminum [4].

Numerical Simulations: iSALE-3D [8] is a multi-material, finite-difference shock physics code for simulating impact processes and follows a similar approach to the 2D code iSALE (see [9] for a description of the history of iSALE's development). Like iSALE, iSALE-3D inherits some of its underlying structure from the SALE/SALE3D hydrocodes [10,11], and from extensions to SALE/SALE3D for impact applications by Boris Ivanov and Jay Melosh [e.g., 12,13,14].

To test the ability of iSALE-3D to reproduce laboratory-scale cratering, we performed a suite of simulations with conditions identical to the aluminum-aluminum impact experiments of [4]. The impact velocity in each model was kept constant (5 km/s), as was the impactor diameter (1mm). The Tillotson equation of state for aluminum [15] was used for the target and projectile material. A Von Mises yield criterion, with a shear strength of 200 MPa, together with a simple thermal softening model, was used to model the strength of the aluminum. Impacts were simulated at a range of impact angles between 90° (vertical) and 10° to the target surface.

In addition to these validation simulations, we also simulated oblique impacts into aluminum targets with reduced shear strengths of 20 & 2 MPa to examine the effect of target strength on oblique impact cratering.

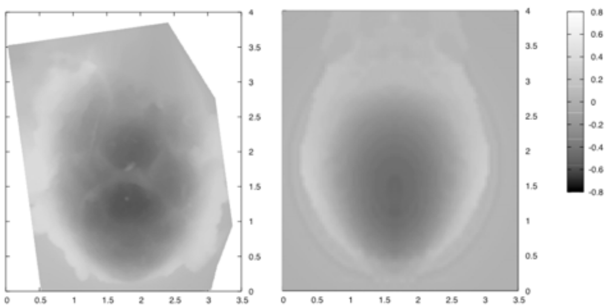

Figure 1 Surface maps of lab experiment (left) and simulated (right) craters formed by impact at 20° to the horizontal. Laboratory experiment data from [4]. Distances normalized by impactor diameter.

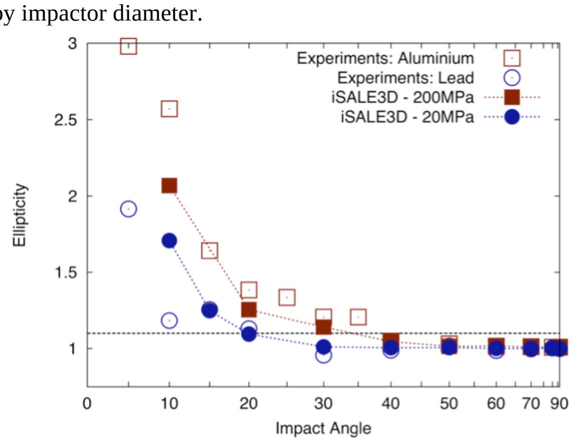

Figure 2 Crater ellipticity as a function of impact angle for Al-Al impacts at 5 km/s. Shown are data from the laboratory experiments of [4] and data from iSALE-3D simulations using two different target strengths.

Validation of iSALE3D: Using a shear strength of 200 MPa, our numerical simulations of Al-Al impacts produce craters with dimensions that are in good agreement with the corresponding experiments (Fig. 1). In particular, the relationship between impact angle and crater ellipticity from our simulation results is consistent with data from the experimental results (Fig. 2).

The effect of target strength on crater shape: The threshold impact angle for elliptical crater formation is 30-40° for our simulated impacts into aluminum with a shear strength of 200 MPa. This compares well to the 35-40° angle for the corresponding experimental data. Cratering efficiency (here defined as the ratio of crater diameter to impactor diameter) in these high-strength targets was ~3. Our simulations that used a lower strength of 20 MPa for the aluminum target give a threshold impact angle for elliptical craters of 15-20° (Fig. 2), comparable to the value for impact experiments into Lead targets [4]. In this case, cratering efficiency was ~6. The shear strength of Pb is about an order of magnitude smaller than that of Al. Thus, impact experiments [4] and our numerical simulations suggest that the threshold impact angle for elliptical craters decreases with decreasing target strength (and cratering efficiency). This supports the hypothesis that the larger the cratering efficiency, the smaller the influence of impactor properties such as shape and trajectory on crater formation. Further simulations in the gravity regime will differentiate between the effect of strength and cratering efficiency.

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References: [1] Shoemaker, E.M. (1983) *Earth. Ann. Rev. Earth Planet. Sci.* 11, 461-494. [2] Gault, D.E. & Wedekind, J., (1978) in *Proc. Lunar and Planet. Sci. Conf. 9th*, pp. 3843-3875. [3] Christiansen, E.L., Cykowski, E., & Ortega, J. (1993) *Int. J. Imp. Eng.* 14, 157-168. [4] Burchell, M.J. & Mackay, N.G. (1998) *JGR* 103 (E10), 22761-22774. [5] Schultz, P.H. & Lutz-Garihan, A.B. (1982) *JGR* 87, A84-A96. [6] Bottke, W.F., Love, S.G., Tytell, D., & Glotch, T. (2000) *Icarus* 145 (1), 108-121. [7] Holsapple, K.A. (1993) *Ann. Rev. Earth Planet. Sci.* 21, 333-373. [8] Elbeshausen, D., Wunnemann, K., & Collins, G.S. (2007) *LPS XXXVIII*, Abstract #1952. [9] Wünnemann, K., Collins, G.S., & Melosh, H.J. (2006) *Icarus* 180 (2), 514-527. [10] Amsden, A.A., Ruppel, H.M., & Hirt, C.W., (1980) Los Alamos National Laboratory Report LA-8095. [11] Amsden, A.A. & Ruppel, H.M., (1981) Los Alamos National Laboratory Report, LA-8905. [12] Melosh, H.J., Ryan, E.V., & Asphaug, E. (1992) *J. Geophys. Res.* 97 (E9), 14735-14759. [13] Ivanov, B.A. & Kostuchenko, V.N. (1997) *LPS XXVII*, Abstract #1655. [14] Ivanov, B.A. (2005) *Solar System Research* 39 (5), 381-409. [15] Tillotson, J.H., (1962) General Atomic Report, GA-3216.