**THE EFFECT OF TARGET PROPERTIES ON IMPACT CRATER SCALING AND THE LUNAR CRATER CHRONOGLOGY**

K. Wünnemann[1], S. Marchi[2], D. Nowka[1], P. Michel[3], [1]Museum für Naturkunde, Leibniz Institute at the Humboldt-University, D-10115 Berlin, Germany, [2]NASA Lunar Science Institute, Boulder, CO, USA, [3]University of Nice-Sophia Antipolis, CNRS, Côte d'Azur Observatory, Nice, France (Contact: kai.wuennemann@mfn-berlin.de).

**Introduction:** The surfaces of all planets, satellites, and other objects are more or less scarred by impact structures. The size-frequency distribution (SFD) and the morphology of impact craters are known to be important observations to determine the age of surfaces and to estimate the change of properties and composition of the crust with depth. For the dating of planetary surfaces by the SFD of impact craters the lunar crater record is key as it is the only surface where direct radiometric dating of Apollo and Luna samples enables an absolute age calibration of terrains with a given crater density. Empirical lunar chronologies [e.g., 1] have been derived based on the assumption that the effects of target properties on the cratering on different terrains are negligible.

The lunar crater chronology can be exported to other planetary surfaces by modeling the flux of impactors and the formation of craters [1]. For the latter so-called scaling laws are required that relate the kinetic energy of an object (diameter *L*, mass *m*, velocity *U*) to the size (diameter *D*, depth *d*, volume *V*) of the crater formed after impact. Based on many experimental [e.g. 2] and numerical modeling studies [e.g. 3, 4] Pi-group scaling is probably the most successful approach in dimensional analysis of impact crater scaling [5] and has been successfully used to theoretically model the lunar crater production function [6,7]. However, existing scaling laws predict the size of the transient crater (not the final crater) only for a homogeneous target with material properties that can be approximated by analogue modeling on a laboratory scale [8]. Numerical modeling of crater formation enables more systematic parameter studies to analyze the effect of material properties such as porosity $\phi$, cohesion *Y*, friction *f* [4] and impact angle [9] on crater size. Here we present a suite of numerical cratering experiments to develop new refined scaling relationships for layered targets to approximate more realistically the conditions for the lunar crust. Recent high resolution images (Kaguya, Lunar Reconnaissance Orbiter) of young lunar crater records reconfirmed that differences in target properties affect crater size and, thus, probably also the determination of crater SFD-ages on lithologically different terrains [10].

**Numerical experiments:** We conducted a suite of numerical experiments of crater formation on the Moon with the hydrocode iSALE [11 and reference in there]. iSALE was successfully validated against laboratory experiments [14] and systematic numerical scaling studies [4] show good agreement with scaling-laws derived from laboratory experiments [2]. We modeled vertical (90°) impacts of asteroids with a diameter range of 12-1000m and an impact velocity of 12.6 km/s (the velocity was chosen to approximate the most likely scenario of a 45° impact at 18 km/s by a 2D model of a 90° impact with a velocity corresponding to the vertical velocity component of the 18km/s oblique impact [15,9]). A suite of 3D models of oblique impacts into homogeneous targets is also available to estimate the effect of the impact angle [8]. The projectile is composed of the same material as the target and we use a Tillotson EoS for basalt to model the thermodynamic response of material to shock wave compression. In a separate study we found that a more sophisticated ANEoS for basalt produced similar results. The target is composed of a 50m thick regolith layer overlying megaregolith that gradually transitions into fully intact basement material at 1000m depth.

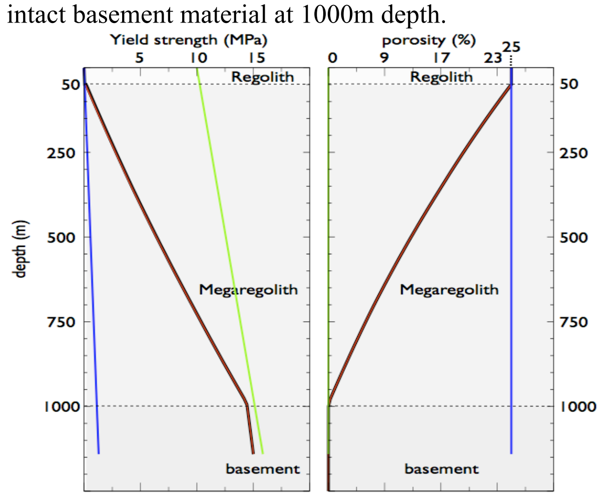


**Fig. 1** Initial target strength and porosity as a function of depth for three different cases: (1) 3-layer model (regolith-megaregolith-basement, red), (2) 1-layer (regolith, blue), (3) 1-layer (basement, green). For details on material parameters see [13]:$Y_{dam}$=3 KPa, $f_{dam}$=0.35 (regolith); $Y_{dam}$=70/15 KPa, $f_{dam}$=0.7, $Y_{int}$=10 MPa, $f_{int}$=1.2 (megaregolith/basement). Note, we assume a pre-impact damage grdient in the megaregolith with *Dam*=1 (totally damaged) at the top and *Dam*=0 (intact) at the bottom.

We account for the differences in porosity and material strength in the three different layers by using a porosity compaction model [11] and a strength model described in [13]. Fig. 1 shows the change of strength and porosity as a function of depth for three different target types we investigated: (1) 3-layer model (regolith-megaregolith-basement, red), (2) 1-layer (regolith, blue), (3) 1-layer (basement, green). Due to the large number of numerical experiments required for this study the resolution in all models is only 10 cells per projectile radius which causes an error for crater diameters of approximately 10% [14].

**Results:** We determined the diameter of transient crater $D$ in the numerical experiments at the time when the crater volume reaches its maximum [8]. Note, for large craters (several tens of km) gravity driven collapse uplifting the crater floor may occur while the crater is still growing in radial direction which results in an erroneous determination of the transient crater. Following Pi-group scaling [5] the measured crater diameter is expressed in terms of the dimensionless ratio $\pi_D = D(\rho/m)^{1/3}$ where $\rho$ is the density of the target. Despite variations of density due to porosity in the layered target we use $\rho$=2.65 kg m$^{-3}$ to determine $\pi_D$ for all data points. In Fig. 2 $\pi_D$ is plotted versus the gravity-scaled size $\pi_2=1.61gL/U^2$ where $L$ is the projectile diameter and $g$ is the gravity of the Moon. The diagram shows the results from numerical modeling of crater formation in the lunar crust for the 3 different cases described above.

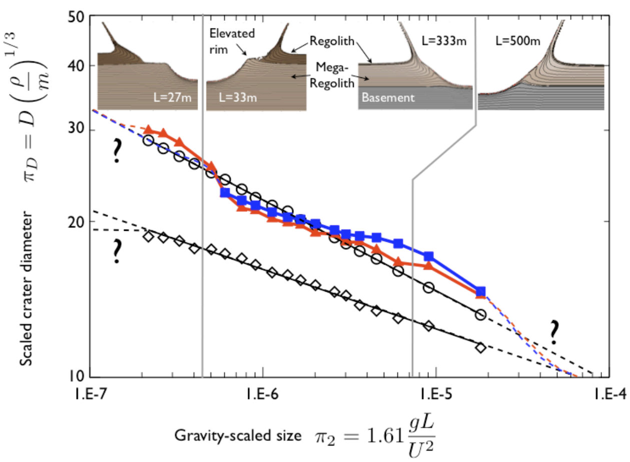


**Fig. 2** Gravity-scaled size $\pi_2$ vs. scaled crater diameter $\pi_D$ for 3 different target conditions (see caption Fig.1). The red and the blue curve correspond to the 3-layer type (Fig.1, red, with slightly different material properties), the circles represent the 1-layer regolith target (Fig.1 blue) and the diamonds the 1-layer basement target (Fig.1, green). Dashed lines indicate estimated extrapolation beyond the available data range. Vertical grey lines mark the transition from a "nested crater" to the onset of excavation of the 2$^{nd}$ layer, and the transition where the transient crater reaches into the basement. Snapshots of the transient crater for different projectile diameters $L$ are shown for the different regimes.

**Discussion:** The preliminary results show that target properties significantly affect the scaling of crater dimensions. For the range of projectile diameters ($\pi_2$-values) all craters are dominated by gravity. For smaller $\pi_2$-values crater scaling may transition into the strength regime. Corresponding models are currently in progress; however due to the small crater efficiency at small $\pi_2$-values such models make high demands on computation time. While craters in homogeneous targets can be scaled by power-laws (straight lines), craters formed in layered targets show a much more complex scaling relationship between $\pi_2$ and $\pi_D$; however, the curves roughly follow the scaling line for regolith (the upper most layer). Due to an overemphasized contrast in strength properties between the regolith and megaregolith in our models smaller craters (small $\pi_2$-values) show morphologies similar to so-called "nested craters" (Fig.2, upper left snapshot). The radial extent of those craters may exceed the size of craters in pure regolith targets as the projectile can penetrate less deep into a layered target where strength increases significantly at the transition into the megaregolith layer.

Our preliminary results show that the scaled crater size for a layered target differs up to 20% from craters in a homogeneous target of basement material and up to 7% from craters in a homogeneous target of regolith, respectively, for the same impact conditions. This difference, as well as the change in the shape of the crater scaling law, may significantly affect the crater retention age determination. In a next step we plan to use the new scaling laws for crater formation in layered targets to reproduce the crater production function for the Moon.

**Acknowledgements:** This work was funded by the Helmholtz-Alliance "Planetary Evolution and Life" (WP3200).

**References:** [0] Neukum, G., and Ivanov, B. A. (1994), in Hazards Due to Comets and Asteroids, Univ. Arizona Press, 359-416; [1] Schmidt, R. M. and Housen, K. R. (1987) IJIE, 5, 543-560; [2] O'Keefe J.D. and Ahrens T.J. (1993), JGR, 17,011-17,028; [3] Wünnemann et al. (2011), Proc. 11th HVIS 2010, 1-14; [4] Holsapple K.A. (1993), Annu. Rev. Planet. Sci. 12:333-73; [5], Marchi S. et al. (2009), Astro. J., 137: 4936–4948; [6] Marchi S. et al. (2011), Planetary and Space Sci., 59: 1968-1980; [7] Holsapple, K. A., Housen, K. R. (2007) Icarus, 187: 345–356; [8] Elbeshausen et al. (2009), Icarus 204: 716-731; [9] van der Bogert et al. (2010), LPSC XLI, abstrac# 2165; [10] Wünnemann K., Collins G.S., Melosh H.J. (2006), Icarus, 514-527; [11] Chapman, C. R. and McKinnon, W. B. (1986), Satellites, Univ. of Arizona Press, 492-580; [12] Collins G.S. et al. (2004), M&PS, 39: 217-231; [13] Pierazzo et al. (2008), M&PS 43:1917-1938; [14] Chapman, C. R. and McKinnon, W. B. (1986), Satellites, Univ. of Arizona Press, 492-580;