IMPACT CRATERING: SCALING LAW AND THERMAL SOFTENING. B. A. Ivanov[1], and D. Kamyshenkov[1,2], [1]Institute for Dynamics of Geospheres, RAS, 119334, Moscow, Russia (baivanov@idg.chph.ras.ru,boris.ivanov@univie.ac.at), [2]Moscow Institute of Physics and Technology, Institutskii per. 9, Dolgoprudny, Moscow Region, 141700, Russia (kdv88@yandex.ru).

Introduction: Impact cratering scaling laws (ICSL) [1] are widely used in planetology to connect impactor parameters (mass/size and impact velocity) with impact crater parameters (both for transient cavities and for final craters). The importance of ICSL is evident in (1) extrapolation of experimental data to natural large scale events, (2) interplanetary comparisons for different impact velocities and surface gravity values, (3) the comparison of observed asteroids and modern cratering populations on various planetary bodies (see, e.g., the review [2]). The ISCL form is derived from first principles and parameterized with mostly laboratory scale experiments with relatively low impact velocities. Numerical modeling of the impact cratering allows us to test the consistency of known ICSL and to estimate probable deviations due to nonlinear behavior of real geomaterials. Here we present a kind of a reconnaissance in the issue.

Dry Friction: Dry friction (typical for crashed rocks) is not included explicitly in the basic parameter set in [1]. Implicitly dry friction is included in the dry sand experiments and theirs scaling. However the dry sand scaling is referred often as the porous media scaling. In contrast the numerical modeling [3] confirms that lower value of the exponent in pi-based ICSL results from the presence of dry friction in crashed material and does not connected entirely to the material porosity. We repeat numerical modeling of impact cratering in model materials with a dry friction without dilatancy and acoustic fluidization. Details of the hydrocode (SALEB) and strength models are published in [4-6]. The vertical impact of spherical and elliptic (e=0.5) projectiles is modeled. For "low" impact velocities (~5 kms^{-1}) our results are close to [3] with small deviations, we believe, due to differences in assumed EOS'es (Fig. 1-3).

The lack of porosity in modeling together with exponents in pi-based ICSL close to experimental dry porous sand values put forward the question how impact velocity scaling looks like in our model materials.

Velocity scaling and thermal softening: We extend the model impact velocity range to 30 kms^{-1} and find the systematic deviation of scaled transient cavity parameters both from dry sand scaling and "hydrodynamic" strength-less scaling (see pi-scaled data in Figs. 1-3). We find that for π_2 below 10^{-6} scaled crater parameters are close at all investigated impact velocity range (5 to 30 kms^{-1}). As the impact velocity increases scaled transient crater parameters go well above the low velocity scaling toward the "hydrodynamic" strength-less scaling often cited as "non-porous rock" scaling derived in [1] from cratering in water saturated sand. Extrapolating pi-base power relationships for 6.5 kms^{-1} modeling for various friction coefficients (from zero to 0.7) [3], we can interpret our high-velocity data as cratering in materials with the *effective* friction below the initial level. Without any acoustic fluidization (or similar friction-softening mechanisms) the main suspected agent is the thermal softening of material by shock wave heating around the growing impact cavity

Thermal softening. The thermal softening was proposed and briefly discussed by O'Keefe and Ahrens [7] as strength decrease under "shock weakening". In [7] only metal-like plastic strength without dry friction is discussed.

Discussion and conclusions: To facilitate the perception of scaled parameters shown in Figs. 1-3 we compile Table 1 listed the range of "scale of impact" π_2 for main planetary bodies of interest. We use estimated average impact velocities [2] for spherical asteroids with diameters from 100 m to 10 km. Roughly this range corresponds to transient craters with diameters from 2 to 3 km for 100 m projectiles to 70 to 100 km for 10 km projectiles. Around π_2 of 10^{-6} (the smaller limit of available modeling with CPPR of 20 and better) scaled transient crater depths are close while scaled volumes and radii of a transient cavity appreciably grow for larger impact velocities. Around π_2 of 10^{-4} scaled crater radii approach the limiting "hydrodynamic" strength-less case while scaled transient crater depth is twice larger at 30 kms^{-1} than at 5 to 6 kms^{-1}. This put forward the next problem for future study how the variation in depth-diameter relations influences the following crater collapse and the final complex crater depth and diameter. It may be important while we compare impact craters on Mercury (impact velocity ~30 kms^{-1}) and on Mars (impact velocity for modern asteroids of 7 to 10 kms^{-1}).

The separated study (not presented here) of a planar shock 1D modeling with the same hydrocode reveals that the material shock heating occurs due to (1) hydrodynamic compression/release cycle AND (2) plastic work at the shock front. The second process make shock temperature estimates to be depended not only from the EOS, but from the model strength behavior as well. Here we find one more field of activity to verify existing models.

Conclusions: Real material properties make ICSL more complicated than it was originally proposed [1]. Still heavily model depended, the numerical modeling reconnaissance demonstrates that in model targets close to fragmented rocks non-linear strength behavior (here – thermal softening of rock friction) results in larger scaled transient crater parameters at higher impact velocities. This result may be important for interplanetary comparisons of crater morphology and cratering rate estimates.

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Table 1. π_2 range for various planetary bodies for spherical projectiles 100 m to 10 km in diameter at the average impact velocities estimated in [2].

Target	<v>, kms^{-1}	g, ms^{-2}	Dp=0.1 km	Dp=10 km
Mercury	35	3.7	4.86E-07	4.86E-05
Venus	24	8.9	2.49E-06	2.49E-04
Earth	19	9.8	4.37E-06	4.37E-04
The Moon	18	1.62	8.05E-07	8.05E-05
Mars	10	3.7	5.96E-06	5.96E-04
Vesta	5.5	0.22	1.17E-06	1.17E-04

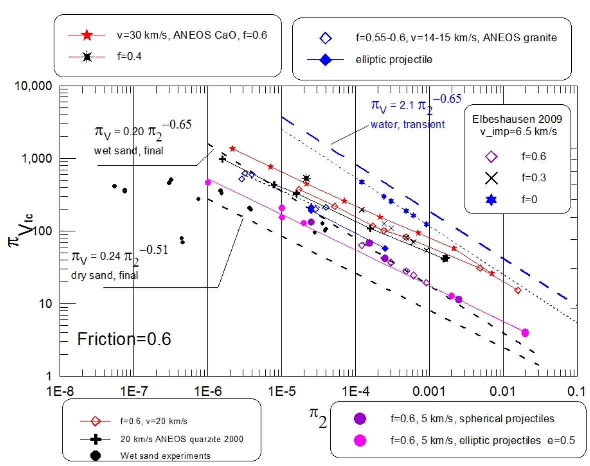

Fig. 1. Maximum transient cavity volume in cohesionless media with dry friction for various impact velocities and target material EOS'es in π_{Vtc}/π_2 coordinates. At "high" impact velocities (20 to 30 kms^{-1}) scaled transient crater volumes are significantly higher that at low impact velocities (5 to 6 kms^{-1}) approaching the "hydrodynamic" limit for stress- and friction-less targets. Graphic quality is enouh good to look details at 4x magnification in the Adobe reader.

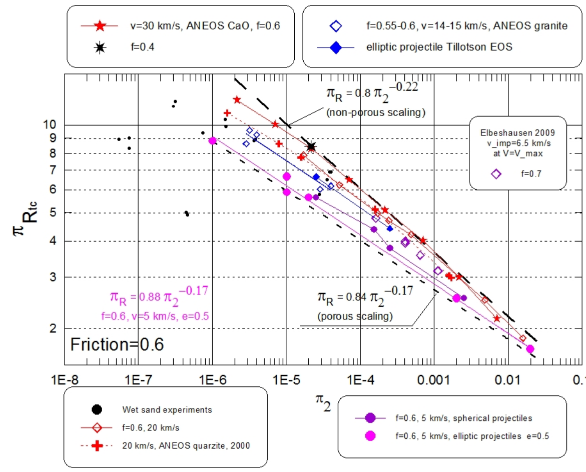

Fig. 2. The same as in Fig. 1 for the scaled transient crater radius. The transient crater radius here is defined as the radius at the pre-impact target level at the moment when vertical particle velocity component change the direction from upward (ejection) to downward (collapse).

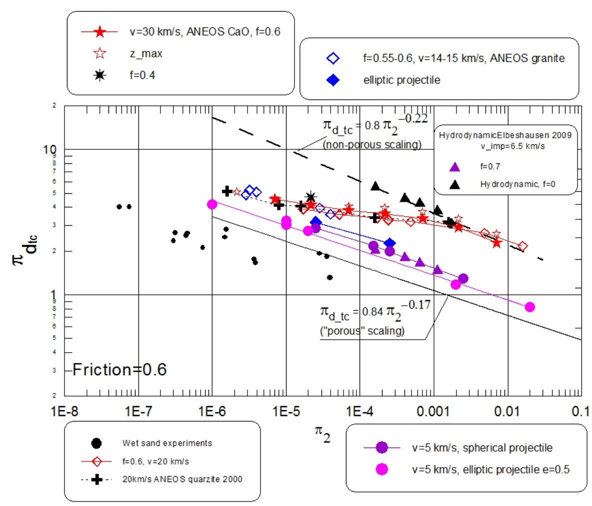

Fig. 3. The same as in Fig. 1 for the scaled transient crater depth. For selected model runs both maximum and the residual (after some elastic rebound) depth is shown.

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