FROM SUBSONIC TO SUPERSONIC COLLISIONS ONTO MAGMA OCEANS. L. Allibert[1], M. Landeau[2], R. Röhlen[1], A. Maller[2], V. Lherm[3], K. Wünnemann[1,4] and M. Nakajima[3]. [1]Museum für Naturkunde, Berlin, leibniz Institute (Invalidenstraße 43, Berlin, Germany, *Laetitia.allibert@mfn.berlin*), [2]Institut de Physique du Globe de Paris, Université Paris Cité (1 rue Jussieu, Paris, France), [3] University of Rochester, Department of Earth and Environmental Sciences, Rochester, NY, United States. [4]Freie Universität Berlin

Introduction: Terrestrial planet formation is characterized by multiple large collisions between planetary embryos [e.g. 1, 2, 3]. Each of these energetic events induced shock waves that propagate through the target causing widespread melting, which is thought to result in the formation of magma oceans covering the entire surface of a given planetary body and extending deep into the mantle [e.g. 4, 5, 6]. Impacts onto magma oceans have been studied using numerical modeling [e.g. 4, 7] and analog laboratory experiments [e.g. 9]. There are pros and cons to both methods. Laboratory experiments on the impact of a liquid onto another liquid produce the small scales that are needed to quantify the mixing of the impactor into the magma ocean. However, such experiments are limited in impact velocities. The effects of the shock wave cannot be investigated in these experiments. Holsapple and Schmidt [8] proposed a scaling law that relates crater dimensions with impactor parameters over 6 orders of magnitude with respect to the Froude number (relative importance of inertia to gravity forces, inverse of π_2). The scaling law is based on impact experiments of solid pyrex spheres into a water target at hypervelocity and water drop experiments [8]. However, it remains unclear whether interpolating across such a large velocity range holds true. To further explore the velocity effect, we vary both the Mach number (ratio of impact velocity to sound velocity in the material) and the Froude number, independently from one another in numerical and laboratory water impact experiments. We focus on the transitional regime between subsonic and hypersonic impacts combining numerical modeling and laboratory experiments. First, we validate impact simulations with the iSALE shock physics code against laboratory experiments of impacts of water drops into water targets at low velocities. In a second step iSALE is used to increase progressively the impact velocities and explore the change in the cratering processes. We investigate the influence of the Mach number on the maximum crater depth and on the partitioning of energy.

Methods: We use (1) analog laboratory experiments, and (2) numerical simulations with iSALE.

1) Liquid impact experiments. In our experiments a spherical water volume of radius R impacts onto a water pool. The impacting water volume is initially contained in a latex balloon that is pierced shortly before impacting the target surface. The dropping height of the balloon controls the impact velocity and hence the Froude number. The impact speed is much lower than the sound speed. We use two experiments with Fr=6 and Fr=93 respectively. Further details of the experimental setup are presented in [9]. Neither the density difference between the target and the impactor, nor the viscosity difference are varied here.

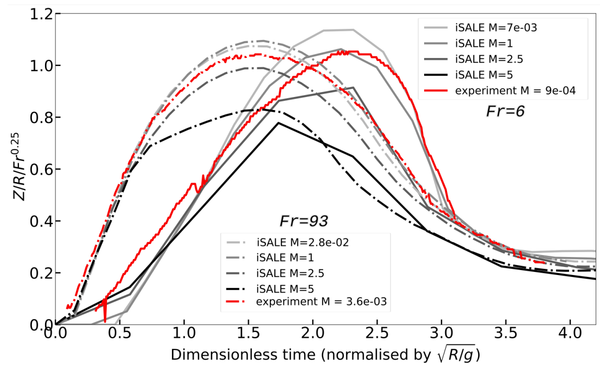

Figure 1: Crater depth Z_c as a function of time during the impact of a water volume of radius R into a water pool for two Froude numbers, Fr. The black curves denote experiments while the other curves correspond to iSALE simulations for different Mach numbers, M. The crater depth is normalized by $RFr^{0.25}$, which is a pure energy scaling for the maximum crater depth [13].

2) *Numerical modeling.* The code iSALE is a grid-based shock physics code well suited for modeling planetary impacts [10, 11, 12]. We use this code to investigate water-into-water impacts from subsonic to hypersonic conditions (up to M=9). We assume a purely hydrodynamical behavior with no material strength and we focus on head-on collisions. Due to cylindrical axis-symmetric geometry of the vertical impacts 2D simulations are sufficient. We use the Tillotson equations of state of various materials (water, aluminum, iron and basalt) to make our study of the cratering process more general and systematic. Since we do not consider large impactor and target radii, we use planar targets in the simulations. The space resolution is of 25 CPPR (cells per projectile radius).

Validation of the numerical model at low velocities: Figure 1 shows that the numerical models reproduce the crater depth (*Z*) growth as a function of time of the two laboratory experiments with different Fr when M<1. Note that the time is normalized by the square root of the impactor's radius, R, to gravity, g , ratio. The crater depth is normalized to the impactor's radius, R and the Froude number, Fr, *to the power 0.25,* *value corresponding to a pure energy scaling*. For M>1 crater growth deviates from the laboratory experiments resulting in different maximum crater depths.

Maximum crater depth, effects of Froude and Mach numbers: In line with previous studies [e.g. 8, 9], the maximum crater depth (Z_c) increases with increasing Fr number. In addition, all simulations with M<1 agree with scaling law predictions of the crater depth in water targets. For M>1 (supersonic regime), our modeling results deviate from the experiments and scaling law predictions. To quantify this deviation, we systematically varied the Froude and Mach numbers as two independent variables. We show in Figure 2 the scaled maximum crater depth normalized by the Froude number as a function of dimensionless time. It shows that our numerical simulation data are well described by a function of the form $(Z_c/R)/Fr^{0.25}=a(1+bM^2)^{-c}$ [13], where Z_c is the maximum crater depth and a, b and c are best-fit coefficients.

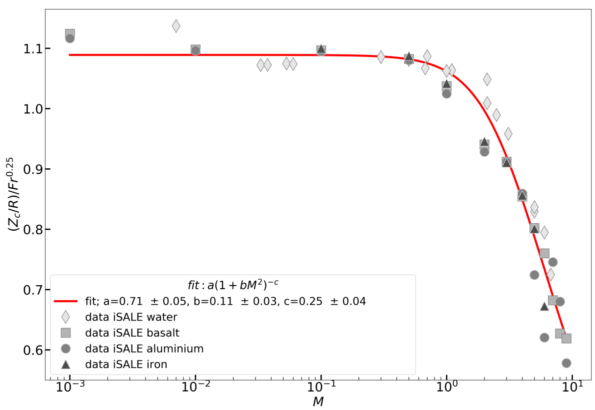

Figure 2: Maximum crater depth Z_c, normalized by the pure energy scaling $RFr^{0.25}$, as a function of the Mach number M. Data from numerical simulations using the equations of state of various materials are plotted. The data are fitted by a function of the form $a(1+bM^2)^{-c}$ with a, b and c the fit coefficients. Our best fit is shown by the red curve, and the associated coefficients are displayed in the legend.

Discussion: The proposed equation relating the subsonic to the hypersonic regime is based on an energy balance reasoning. The rather straight line observed for the subsonic regime suggests that the kinetic energy of the impactor is almost completely transferred into kinetic energy in the target, and then into gravitational potential energy in the crater. In this case, only a small negligible amount of energy is partitioned into internal energy (heating and compression). This changes for M>1 (hypervelocity regime) such that increasingly more energy is transferred into heating and compression and less energy is available for the excavation of the crater. As a consequence the resulting gravitational potential energy decreases or, in other words, the relative crater size decreases. Thus, previous scaling laws [8] for impacts into water connecting laboratory experimental data over more than 6 orders of magnitude with respect of the Froude number only allows for a first order approximation of the crater size. For more accurate predictions the effect of the Mach number has to be taken into account. This is illustrated in figure 3.

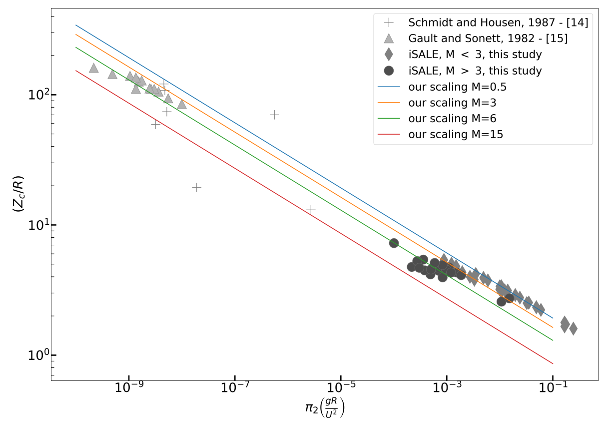

Figure 3: Normalized maximum crater depth as a function of π_2 (i.e. 1/Fr). The data from previous studies [14, 15] are shown along with different lines corresponding to our fit for different values of the Mach number.

Conclusion: iSALE reproduces well the cratering processes observed in water drop experiments for subsonic impacts and can be confidently used to explore the regime transition between subsonic and hypersonic collisions. The maximum crater depth is ultimately fitted as a function of both the Froude and the Mach number and translates well into the understanding of the energy partitioning during an impact.

Acknowledgments: This work was funded by the Deutsche Forschungsgemeinschaft (SFB-TRR170, subprojects C2).

References: [1] Chambers J. E. (2004) *EPSL, 223,* 241-252. [2] Raymond S. N. et al. (2009) *Icarus, 203,* 644-662. [3] Walsh K. J. et al. (2011) *Nature, 475,* 206. [4] Tonks W. B. and Melosh H. J. (1993) *JGR: Planets, 98,* 5319-5333. [5] Nakajima M. et al. (2021) *EPSL, 568,* 116983. [6] Manske L. et al. (2021) *Icarus, 357,* 114128. [7] Kendall J.D. and Melosh H. J. (2016) EPSL, 448, 24-33. [8] Holsapple K. and Schmidt R. (1982) *JGR: Solid Earth, 87,* 1849-1870. [9] Landeau M. et al. (2021) *EPSL, 564,* 116888. [10] Amsden A. et al. (1980) *Technical Report Los Alamos Lab,* NM. (USA). [11] Collins G.S. at al. (2002) Icarus, 157, 24-33. [12] Wünnemann K. et al. (2005) *Large meteorite impacts III, 384*, 67-83. [13] Miranda C. S. and Dowling D. R. (2019) *Icarus, 325,* 84-93. [14] Schmidt R. M. and Housen K. R. (1987) *International Journal of Impacts Engineering, 5(1-4),* 543-560. [15] Gault D. E. and Sonett C. P. (1982) *Geological Society of America,* Special Paper 190.