**QUANTIFICATION OF SEISMIC SIGNALS GENERATED BY HYPERVELOCITY IMPACTS FROM NUMERICAL MODELING AND LABORATORY EXPERIMENTS.** N. Güldemeister[1] and K. Wünnemann[1], [1]Museum für Naturkunde, Leibniz-Institute for Research on Evolutions and Biodiversity, Invalidenstrasse 43, 10115 Berlin, Germany. (nicole.gueldemeister@mfn-berlin.de).

**Introduction:** Upon impact of a meteorite on a planetary surface the vast majority of the kinetic energy of the impactor is transferred to the target by compressing the target material to high shock pressures. The energy that goes into the elastic shaking is assumed to be only a very small fraction of the impact energy, that is not very well constrained, so far. Elastic waves have previously been recorded as seismic signals in several explosion experiments [1], during hypervelocity impact experiments [2] and in hydrocode models, e.g. of the Chicxulub crater [3]. Seismic signals are characterized by several parameters such as the seismic attenuation factor and the seismic efficiency, both of which strongly depend on material properties such as composition, density, strength and porosity. The attenuation of the seismic wave is commonly described by the so-called seismic quality factor $Q$, which is a typical characteristic of rocks and depends on porosity and water saturation [4]. The smaller $Q$ the faster the seismic wave attenuates. How much of the impact energy $E_{kin}$ is transferred into seismic energy $E_{seis}$ can be expressed by the so-called seismic efficiency $k=E_{seis}/E_{kin}$. The seismic efficiency also depends on material properties, but is not very well known. It has been roughly estimated between $k=10^{-3}$ and $10^{-5}$ [1, 5]. A better quantitative understanding of the characteristics of seismic signals ($k$ and $Q$) generated by impact is important (1) to better estimate the environmental consequences of impact in terms of induced earthquakes and (2) to better analyze the lunar seismic data record where small impacts or the strike of missile stages were used as seismic sources.

In this study we present a combined approach of laboratory impact experiments performed within the *Multidisciplinary Experimental and Modeling Impact Research Network* project (MEMIN) [6] and numerical simulations. The main objectives of this work are: (1) the calibration of the numerical model with regard to real-time measurements of the wave velocity and pressure amplitudes by recording the acoustic emission and the usage of pressure gauges; (2) the quantification of seismic parameters (quality factor $Q$ and seismic efficiency $k$) by using the calibrated numerical models.

**Methods:** To record seismic signals, experimentally as well as numerically, a suite of laboratory and numerical impact experiments have been performed within the MEMIN project [6]. Here we focus on impact experiments using a target block size of 80x80x50cm edge length and iron or steel projectiles of 12mm impacting into a quartzite, sandstone (~23% porosity), tuff (~43% porosity), and water saturated sandstone (50% and 100% saturation) target with a velocity of 4.6 km $s^{-1}$. The impact experiments have been equipped by several diagnostics one of which was an array of acoustic emission sensors. This method enables to record acoustic signals to determine the wave velocity [7]. Note, as these sensors were not calibrated it was not possible to translate the measured amplitudes in the actual acceleration or pressure amplitude of the wave. Therefore, the sandstone target block was also equipped with pressure gauges, developed at EMI Freiburg [8]. The measured pressure amplitudes allow for the determination of the attenuation of the signal with distance. To simulate the laboratory experiments we used the iSALE-2D shock physics code [9]. iSALE uses the equation of state model ANEOS to simulate the thermodynamic response of the materials (iron, quartz) to shock wave compression [10]. Additionally, the ε-α porosity model [9] was employed to account for the effect of porosity. The propagation velocity and attenuation of the amplitude of the generated waves including the elastic part are very sensitive to the parameters of the porosity compaction model (ε-α porosity model) and it is essential to determine the parameters through detailed calibration of the models against experimental observations. A crucial parameter is the dependency of the elastic wave velocity on porosity. The ratio of the wave velocity of a porous material and a solid material is defined by the ratio of the speed of sound in the solid component ($C_{solid}$) and the bulk material with porosity ($C_{por}$), ($\chi=c_{por}/c_{solid}$). The model further defines a critical volumetric strain $\varepsilon_e$ when pore space starts to collapse (elastic threshold value), which has a significant effect on pressure amplitudes. These parameters can be calibrated by using the laboratory observations. We carried out a suite of numerical simulations using numerical gauge points with distances between 20 and 60 cm to the point of impact to record thermodynamic and mechanical parameters as a function of time during the impact simulation. In order to determine the seismic attenuation factor and the seismic efficiency, we focused on the recording of the elastic wave, in particular its first-arrival-time, velocity and pressure amplitude.

**Results:** *Calibration of the numerical model.* By using the experimentally determined wave velocities the parameter $\chi$ was determined for different porosities. We find $\chi$=0.46 for tuff and $\chi$=0.6 for sandstone. To define the correct threshold where pore space starts to collapse, we varied the $\varepsilon_e$-value in our models until the pressure amplitude matched the recorded values in a sandstone target experiment. Pressure amplitudes of about 51, 42, and 32 MPa were reached at distances of 25 cm, 35 cm, 45cm. Considering a threshold value of $-7.5 \cdot 10^{-2}$ which corresponds to relatively small resistance against pore space crushing and is consistent within an error of 2-10 GPa with the values obtained in [8] (Fig.1).

*Seismic signals.* Typical seismic signals for different target materials recorded at three distances as a function of time are shown in Fig. 1. The signals, regardless of their amplitudes, look very similar with an exception for the water-saturated material. The pressure amplitudes decrease with increasing porosity and water saturation. The attenuation of the wave is much stronger in porous and water-saturated material with the fastest decay in the target where water was present. Apparently, the determined quality factor significantly depends on the target properties. Based on the decay of amplitudes we determined by numerical modeling the seismic quality factor $Q$ between ~50 for the solid quartzite and 70 for the porous dry targets. It is much lower for water saturated target materials, $Q$=10. For the seismic efficiency we determined values of $k=3.4 \cdot 10^{-3}$ for quartzite, $k=2.6 \cdot 10^{-3}$ for dry sandstone, and $k=1.5 \cdot 10^{-4}$ for water-saturated sandstone by using

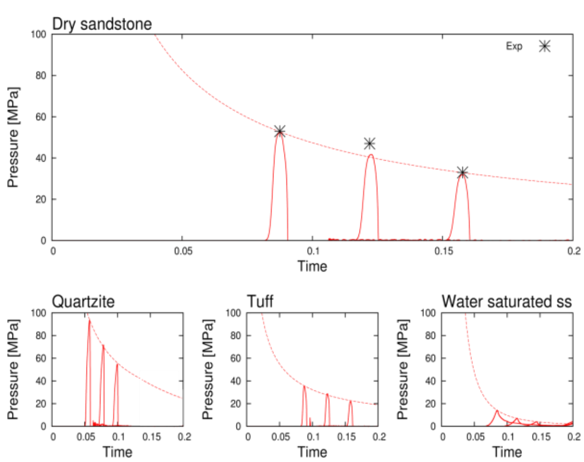


Fig. 1: Pressure signals as recorded by the numerical gauge points at three distances (25, 35, 45 cm) as a function of time. The experimental pressure amplitudes are included for the sandstone target. The wave decay is shown as a dashed line.

the method described in [1]. These results correlate with the range of literature values of $10^{-3}$ to $10^{-5}$ [5] and the experimentally determined values for the MEMIN experiments into sandstone ($k=2 \cdot 10^{-3}$[8]). Thus, we can conclude that the seismic efficiency decreases with porosity and water saturation. This may be explained by the fact that the crushing of pores consumes some fraction of the initial impact energy and less energy is converted into seismic energy. Preliminary results suggest a linear dependency of the seismic efficiency on target porosity.

**Discussion:** Numerical models allow for more systematic studies than it is possible with experiments. However, reliable numerical results depend on accurate calibration and rigorous validation, which enable to further investigate seismic signals in porous and water-saturated materials. The numerical material parameters are strongly dependent on wave velocities as well as pressure amplitudes. Taking the dependency of the wave velocity on porosity into account, we achieve very similar wave velocities in the experiment and the numerical simulations. The calibrated models then lead to reliable results considering different seismic parameters such as the seismic quality factor and the seismic efficiency. Both parameters are significantly affected by different target properties (porosity and water saturation). Further improvements of the material models, in particular for water-saturated materials, will allow for a more accurate determination of the signals. So far we used a mixed-material approach [11], which may not reproduce the actual process of the compaction of water-filled pores very well. Assuming a target of a defined porosity or water saturation and considering the determined range of seismic efficiency we can now make assumptions about the magnitude of a seismic wave. For a Chicxulub scale impact event, the determined seismic efficiencies lead to seismic magnitudes of 11 for a solid and porous target and to a magnitude of 10 for a water saturated target. Considering a smaller impact, the effect of different target properties on the seismic magnitude will increase.

**Acknowledgement:** This work was funded by DGF grant WU 355/6-2.

**References:** [1] Schultz, P.H. & Gault, D.E. (1975), Moon Planets, 12, 2, 159–177. [2] Richardson J. and Kedar S. (2002) *LPSC 44th*, Abstract #2863. [3] Ivanov B.A. (2004) Sol. Sys. Res., 39,381-409. [4] Winkler K. and Nur A. (1979) *Geophys.Res.Lett.*, 6, 1-4. [5] Melosh H. J. (1989), Oxford Univ. Press, New York, p. 245. [6] Kenkmann T. et al. (2011) *MAPS*, 46, 875-889. [7] Moser D. et al. (2013) *JAE*, 31, 55-66. [8] Hoerth T. et al. (2014) *JGR Planets*, 119, 2177–2187. [9] Wünnemann K. et. al. (2006) *Icarus*, 180, 514-527. [10] Melosh H. J. (2007) *MAPS*, 42, 2079-2098. [11] Güldemeister N. et al. (2012) *MAPS*, 48, 115-133.