NUMERICAL INVESTIGATION OF IMPACT-INDUCED SEISMIC SIGNALS IN MARTIAN CRUST.

Katarina Miljković[1], Gareth S. Collins[2], Andrea Rajšić[1], Natalia Wojcicka[2], Tanja Neidhart[1], Foivos Karakostas[3,4], Nick A. Teanby[5], Ingrid J. Daubar[6], Philippe Lognonné[3], Mark A. Wieczorek[7] and the InSight Team. [1]Space Science and Technology Centre, School of Earth and Planetary Science, Curtin University, Perth, Australia, [2]Imperial College London, UK, [3]Institut de Physique du Globe de Paris, France, [4]University of Maryland, USA [5]Bristol University, UK, [6]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA, [7]Observatoire de la Côte d'Azur, Nice, France (Katarina.Miljkovic@curtin.edu.au).

Rationale: Impact-generated seismic waves are not well-understood. We use the state-of-the-art numerical impact modelling code iSALE-2D [1] to simulate meteoroid strikes on Mars, in the size and speed range detectable during the InSight mission lifetime [2]. We aid analyses of seismic signals generated by meteoroid strikes by understanding the shock, plastic and elastic deformation in target materials representative of the uppermost martian crust. For our first numerical impact validation results, see [3, this issue].

Introduction: The InSight (Interior exploration using Seismic Investigations, Geodesy and Heat Transport) mission [4] is a geophysical station landed on the surface of Mars in November 2018. This space mission is set to investigate the crust and interior structure of Mars.

The seismic instrument SEIS (Seismic Experiment for Interior Structure) on-board InSight will quantify the seismic activity of the planet, which could be caused by a number of processes, from tectonic activity to meteorite impacts [5]. InSight aims to record meteoroid impacts on the surface of Mars through seismic responses of the atmosphere and ground [2, 5-6]. The estimated meteoroid impact rate on Mars [7] suggests that impact-generated seismic signals could be one of the primary signals recorded by SEIS.

Impact is a complex physical process in which a part of the impactor's momentum and energy are transferred to the target. For small impacts (impactors smaller than 100 m diameter) on planets with a dense atmosphere, like Earth or Venus, almost all of the impactor's kinetic energy is transferred to the atmosphere. For planetary bodies lacking an atmosphere (such as the Moon), the impactor transfers all its energy into the ground [2,5]. Mars is intermediate between these two cases [2], where the kinetic energy of meter-scale impactors is transferred to both the atmosphere during its brief passage and to the ground at the final impact. Remote observations have shown that about half of the recent impact strikes formed as clustered craters [8]. The outcome of m-scale meteoroid impacts in the Martian atmosphere and crust needs to be understood to inform the interpretation of seismic signals recorded by SEIS. Newland *et al.* [9, this issue] present new models of meteoroid fragmentation in the Martian atmosphere. Here we focus on the impact-induced seismic effects in the crust.

Seismic signals from impacts differ from seismic signals from tectonic sources. For example, subsurface material properties have a larger effect in the case of impacts, because a source depth of essentially zero means the signal travels through the shallow subsurface twice, enhancing the effects of e.g. a porous or fractured upper layer [5]. In seismic terms, the martian crust and mantle are expected to be between the Earth and the Moon, but more similar to the Earth's upper and lower mantle than to the Moon [10].

One way to investigate the relationship between impact events and impact-induced seismic signals is via seismic efficiency and quality factor of impact-induced seismic waves:

Seismic efficiency k: The kinetic energy of an impactor (*KE*) is largely released as heat during impact with a small portion converted to seismic energy. The seismic efficiency, k, is defined as the ratio of the seismic energy produced by an impact (*Eseis*) to *KE* [11, and refs therein]. Estimated k values for Mars in the literature span five orders of magnitude, from 10^{-6} to 10^{-1}. These uncertainties can be attributed to incomplete coverage of the seismic wave field or frequency limitations of the recording seismic instruments. It is also likely that k may depend on the impactor and target material properties as well as impact scale [12, and refs therein].

Seismic quality factor Q: A seismic wave attenuates with distance by geometric spreading and absorption as it propagates through the target material. This is considered an inelastic damping and can be quantified by the seismic quality factor Q. Q is thought to depend on the rock type, porosity, etc, although it should not be dependent on scale of the impact. For example, competent rocks with low porosity have high Q-values ranging from 500 and 1000, while highly porous and fractured rocks have low Q-values ranging 10 and 100 [12, and refs therein].

Methodology: We use the iSALE-2D finite-difference shock physics code developed to simulate behavior of geologic materials under impact conditions. This includes elasto-plastic constitutive models, fragmentation, compression and compaction of pore space, and various equations of state [13-15].

In this work, we model meteoroid impacts in the martian regolith (37%, 44% and 65% porosity) and non-porous bedrock, using a basaltic equation of state [16] and previously investigated material models with these porosity values [17]. We consider an impact parameter range such that the effective crater size range is up to 30 m (which is on the large end of those impacts currently occurring). Preliminary results are obtained by using impactors of the order of 1-2 m and impact speed under 10 km/s.

We investigate the evolution of an impact-generated pressure wave: amplitude decay, the resulting Q and k, and their dependence on target material properties. Our work adopts the methodology used in impact experiments and numerical impact modeling [12], where the pressure wave amplitude and duration, at various ranges, were used to determine Q and k.

Results: Figs. 1 and 2 show the iSALE-2D results from a simulation of a meteoroid strike on Mars that is expected to be typical within the lifetime of the InSight mission.

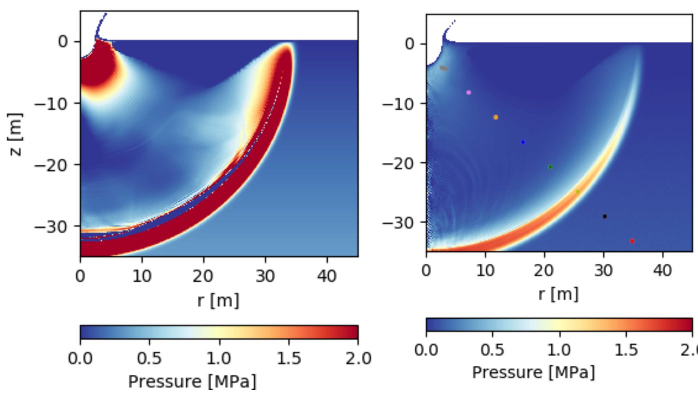

Fig. 1: Typical output from an iSALE-2D example showing progression of the pressure wave caused by a 1-m projectile impacting vertically at 5 km/s into non-porous (left) and 37% porous (right) basaltic target. Radial distribution of pressure gauges are color-coded on the right.

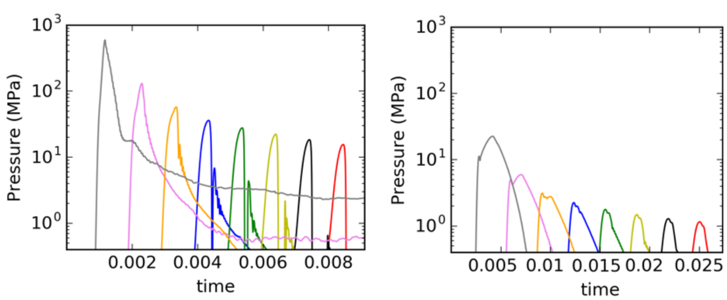

Fig. 2. Pressure pulses measured in color-coded gauges, as indicated in Fig. 1, for a non-porous (left) and 37% porous (right) basaltic target.

Attenuation of the pressure wave with distance follows a much steeper decay in the shock and plastic domain (permanent deformation) than when the wave becomes elastic. Therefore, we can observe the transition between plastic and elastic regime via pressure wave decay with distance. The shock (plastic) wave attenuation depends on the target material, and the rate of decay with distance increases as a function of target porosity [12]. The pressure attenuation slope turns linear once the pressure wave becomes elastic [e.g., 12].

Fig. 2 shows that for the same impactor size and speed (the same *KE*), the pressure wave amplitude is larger and the wave travels faster if the target is non-porous, while the duration of the pressure wave is longer in porous targets. This was also reported in [12].

Preliminary numerical investigation (for impact energies ranging 10^7-10^{12} J) suggested the values of k range from 10^{-4} for porous rocks (we tested 37%, 44%, and 65% porosity values) to 10^{-3} for non-porous rocks, analogue for martian regolith and bedrock, respectively. This is comparable to the value of $5x10^{-4}$ that [2] favors.

Simulations also suggest that Q ranges 30-60 for a Mars analog rock and soil of up to 65% porosity. These values are in agreement with previous impact experiments [12].

Conclusions: Seismic properties of martian regolith and bedrock are yet to be fully investigated; SEIS data is needed. Until then, we have developed a methodology to connect the properties of impacts (anticipated during the InSight lifetime) and target (typical for martian equatorial region) with properties of a seismic wave via seismic efficiency k and quality Q.

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