REVIEW OF THE SEISMICITY ON MARS AS RECORDED BY INSIGHT.

D. Giardini[1], S. Ceylan[1], S. C. Stähler[1], J. F. Clinton[2], D. Kim[1], A. Khan[1], G. Zenhäusern[1], N. Dahmen[1], C. Duran[1], A. Horleston[3], T. Kawamura[4], M. Plasman[4], C. Charalambous[5], M. Knapmeyer[6], R. F. Garcia[7], P. Lognonné[4], M. P. Panning[8], W. T. Pike[5] and W. B. Banerdt[8], [1]Institute of Geophysics, ETH Zurich, Switzerland (domenico.giardini@erdw.ethz.ch), [2]Swiss Seismological Service, ETH Zurich, Switzerland, [3]University of Bristol, UK, [4]Université Paris Cité, Institut de physique du globe de Paris, CNRS, Paris, France, [5]Imperial College London, UK, [6]German Aerospace Center, Berlin, Germany, [7]Institut Supérieur de l'Aéronautique et de l'Espace SUPAERO, France, [8]Jet Propulsion Laboratory, CA, USA.

Introduction: The InSight mission [1] collected an astounding seismic dataset from Mars during more than four years (∼1450 sols) of operation until it was retired on 21 December 2022. The mission deployed the first seismic station (SEIS) on the ground of Mars [2, 3], including a very-broadband (VBB) and a short-period (SP) seismometer. Additional instruments in the payload were a set of wind and pressure sensors for observing the Martian atmosphere and providing crucial evidence for discriminating seismic events from other noise sources, the $\mathrm{HP^3}$ temperature probe [4], and the robotic arm and cameras used to deploy SEIS on the ground [1].

Marsquakes are located by the Marsquake Service (MQS) [5] determining distance and back-azimuth. When phases are confirmed to be P and S arrivals or their surface reflections (PP and SS, respectively), the event distance is computed following a probabilistic single-station location algorithm [6, 7] using new interior models based on the inversion of multiple body wave phases [8]. In addition, a first order determination of distance and origin time was obtained by visually aligning low SNR events with well-located high-SNR events. The event backazimuth was obtained using polarization analysis of the primary body waves [7, 9].

MQS [5, 10] detected more than 1300 events of seismic origins [11]. Two of these events (S1000a and S1094b) were later confirmed as distant impacts [12, 13] (Figure 1), with magnitudes of $\mathrm{M_W^{Ma}}$ 4.0 and 4.2 and crater diameters of 130 and 150 m, respectively [13]. For six seismic events closer than 300 km, dispersive acoustic signals propagating along an acoustic waveguide were detected in the form of chirps with strong elliptical polarization pointing toward the impact source [14, 15]. Finally, the largest marsquake (S1222a, $\mathrm{M_W^{Ma}}$ 4.6) that occurred during InSight's lifetime[16] was recorded on May 4, 2022 (Figure 1).

The first overview and interpretation of the seismicity on Mars was provided by Giardini et al (2020)[17]. Here, we present the current understanding of the Martian seismicity and the different types of events we observed on Mars, based on the data collected over the whole mission.

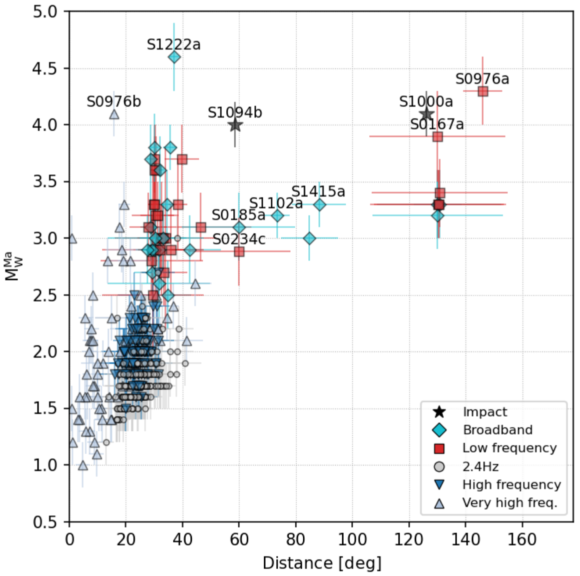

Figure 1: Mars-calibrated moment magnitude ($\mathrm{M_W^{Ma}}$) vs. distance distribution of the seismic events. The symbols together with colors indicate different event types. The two distant impacts are shown as stars.

Low-frequency (LF) and broadband (BB): Since early in mission, we distinguish different event classes based on the their frequency content.

The LF family of events include energy predominantly below 1 Hz. They are similar to teleseismic events observed on Earth, where P and S waves are often identified; a few LF events have broad-band frequency content up to 2.4 Hz (BB). The hypocenter is known for about half of the recorded LF-BB events, owing to the difficulty of determining back-azimuth and in some cases also distance for the smaller events. The following elements are now understood:

- Seismicity appears to be located only in few spots around Mars (Figure 2) and no tectonic events were located within 25° from the InSight station.
- A large number of LF-BB events are located 26–30° from the station, interpreted to be associated with the active dynamics of the volcanic Cerberus Fossae area [18–20]. These marsquakes show relatively clear P and S energy.
- A group of events show only a weak S-wave energy and are aligned using the P-wave and length

of its coda in the spectral envelopes around 46°. Their tectonic origin is yet unknown, but the lack of S-wave energy is attributed to mantle structure.

- A few events are located around 60° with relatively emergent P- and S-wave energy.
- Two large events (S0976a and S1000a) lie beyond the core shadow and have PP and SS phases [21]. MQS located S0976a in the Valles Marineris region 146° away from InSight, whereas S1000a has now been confirmed to be the result of a meteoritic impact[13].
- A number of events of uncertain location and previously located around 80–100°, have now been realigned using their S-wave coda length and are believed to be clustered in the same range distance and tectonic region, around 100-120° distance.
- LF family events have the largest magnitudes with S1222a reaching $\mathrm{M}_\mathrm{W}^\mathrm{Ma}$ 4.6 and a few others at or above $\mathrm{M}_\mathrm{W}^\mathrm{Ma}$ 3.5.

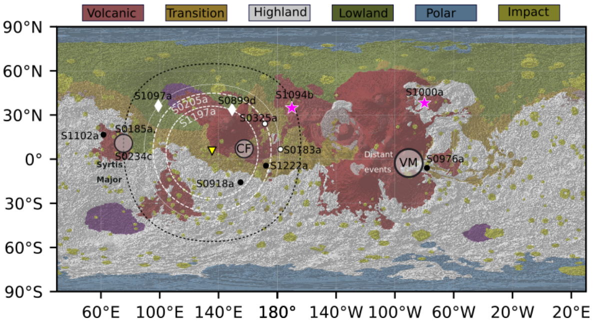

Figure 2: Interpretation of Martian seismicity after alignments. The geological units are after [22]. The purple stars denote the two distant confirmed impacts.

High-frequency (HF): The HF family of events are predominantly at and above 2.4 Hz. A large number of weaker HF events are visible only on the 2.4 Hz amplification, and are termed as 2.4 Hz events. The excitation of the 2.4 Hz resonance is interpreted as trapped energy within the layered Martian crust [17, 23]; therefore, these phases are labelled as Pg and Sg, respectively, following the phase naming nomenclature for Earth. The first comprehensive analysis of [23] and the alignment show that the HF events all originate from a distance range of only a few degrees, in the 25–30° range, with magnitudes below $\mathrm{M}_\mathrm{W}^\mathrm{Ma}$2.5. Stähler et al. (2022) found that the HF events have also similar backazimuth and propose that all HF events originate from a single area in the central Cerberus Fossae region, as very shallow events associated to large active volcanic dykes[19].

Very high frequency (VF): A small number of HF events are characterized by higher frequency content, up to 20–30 Hz with a notable amplification on the horizontal components at very high frequency, and are termed VF events. The amplification is plausibly explained by the local subsurface structure [24] These events are observed only close to the lander. While a few larger events have been detected up to a distance of 35°, the majority of them a located within 26° distance. Remote imaging of recent craters and the presence of a distinctive signal confirmed that the closest events were produced by meteoric impacts[14]. Investigations are being conducted to understand if other VF events can be confirmed as impacts[25].

Acknowledgments: The InSight seismic event catalog [11] and waveform data [26, 27] are available from the IPGP Datacenter, NASA-PDS and IRIS-DMC.

References: [1] Banerdt W. B. et al. (2020) *Nat. Geosci.*, 13(3):183–189. [2] Lognonné P. et al. (2019) *Space Sci. Rev.*, 215(1):12. [3] Lognonné P. et al. (2020) *Nat. Geosci.* [4] Spohn T. et al. (2022) *Advances in Space Research*, 69(8):3140–3163. [5] Clinton J. F. et al. (2021) *Phys. Earth Planet. Inter.*, 310:106595. [6] Khan A. et al. (2016) *Phys. Earth Planet. Inter*, 258:28–42. [7] Böse M. et al. (2017) *Phys. Earth Planet. Inter*, 262:48–65. [8] Stähler S. C. et al. (2021) *Science*, 373(6553):443–448. [9] Zenhäusern G. et al. (2022) *Bull. Seismol. Soc. Am.*, 112(4):1787–1805. [10] Clinton J. et al. (2018) *Space Sci. Rev.*, 214:133. [11] InSight Marsquake Service , Mars Seismic Catalogue, InSight Mission; V13 2023-01-01 (2023), *ETHZ, IPGP, JPL, ICL, Univ. Bristol*, 10.12686/a19. [12] Kim D. et al. (2022) *Science*, 378(6618):417–421. [13] Posiolova L. V. et al. (2022) *Science*, 378(6618):412–417. [14] Garcia R. F. et al. (2022) *Nat. Geosc.*, 15(10):774–780. [15] Daubar I. J. et al. (2023) *LPSC.* [16] Kawamura T. et al. (2023) *Geophys. Res. Let.*, e2022GL101543. [17] Giardini D. et al. (2020) *Nat. Geosci.* [18] Brinkman N. et al. (2021) *J. Geophys. Res.: Planets*, 126(4):e2020JE006546. [19] Stähler S. C. et al. (2022) *Nat. Astronomy*, 6(12):1376–1386. [20] Jacob A. et al. (2022) *Tectonophysics*, 837:229434. [21] Horleston A. et al. (2022) *The Seismic Record.* [22] Tanaka K. L. et al. (2014), 48. [23] van Driel M. et al. (2021) *J. Geophys. Res.: Planets*, 126(2):e2020JE006670. [24] Carrasco S. et al. (2023) *Geophys. J. Int.*, 232(2):1293–1310. [25] Wójcicka1 N. et al. (2023) *LPSC.* [26] InSight Mars SEIS Data Service , SEIS raw data, Insight Mission. IPGP, JPL, CNES, ETHZ, ICL, MPS, ISAE-Supaero, LPG, MFSC (2019), 10.18715/SEIS.INSIGHT.XB_2016. [27] InSight Mars SEIS Data Service , InSight SEIS Data Bundle. PDS Geosciences (GEO) Node (2019), 10.17189/1517570.