Initial results from the InSight mission on Mars

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Abstract

The primary objectives of NASA's InSight mission are to determine the interior structure, composition, and thermal state of Mars, as well as constrain present-day seismicity and impact cratering rates. These advances are key for understanding both Mars' initial differentiation and subsequent thermal evolution, and thus the forces that shape surface geology and volatile processes. As of 30 September 2019, 174 seismic events have been recorded by the InSight seismometer, including over 20 events of magnitude 3-4. An assessment of events to date indicates that Martian seismicity is similar to terrestrial intraplate seismic activity for events below $M_w \sim 3$, but produces relatively fewer larger quakes; no quakes with $M_w \geq 4$ have been observed. Two of the larger events occurred near Cerberus Fossae, an active fracture system that has produced volcanism in the last 10 My. No unambiguous seismic signatures of new impact craters have been identified. A suite of instruments (two cameras, atmospheric pressure, temperature and wind sensors, a magnetometer and a radiometer) were primarily designed to support seismometer noise characterization, but are also producing unique and important science results individually and synergistically. A surface magnetic field 10× greater than measured from orbit indicates significant crustal magnetization at length scales <100 km. Continuous meteorological measurements have detected signals of a dynamic atmosphere, including unexpectedly large baroclinic waves, and surprisingly ubiquitous gravity waves and convective vortices. Combined observations of an atmospheric vortex from multiple instruments on the lander and in orbit allow its remote characterization and an estimate of the rigidity of the martian surface.

NASA's InSight mission (Interior exploration using Seismic Investigations, Geodesy and Heat Transport) landed in Elysium Planitia, Mars on 26 November 2018. Here we report the first 10 months of comprehensive geophysical observations of the planet. From the seismic data acquired through 30 September 2019, it is clear that Mars is a seismically active planet. The first magnetic field measurements on Mars' surface reveal crustal magnetization variation at spatial scales undetectable from orbit and exhibit fluctuations that can be used to probe the resistivity of the interior. Continuous high-rate meteorological measurements are providing new insights into atmospheric dynamics and boundary layer processes and, coupled with seismic data, are used to reveal the mechanical structure of the near-subsurface. InSight measurements of crustal thickness, core size, density and state, rates of seismicity and impacts, and heat flow will provide new information on the compositional and thermal evolution of Mars. With extended observations over an entire martian year or more, we anticipate unprecedented insights into the history of differentiation on Mars.

This paper provides a brief mission overview and reports key discoveries to date. We present the first measurement of seismic activity rate, which fundamentally constrains the geological vigor of the planet (note that this study is part of the first set of InSight science reports; two addition papers[1;2] also include interpretation of InSight seismic data[3;4]). The data acquired thus far also enable the characterization of Mars seismic background and upper crust structure, a preliminary analyses of the basic character of seismicity, local geology, atmospheric processes at the surface, and the characteristics of the surface magnetic field[1;2;5–7]. InSight's payload (Table 1) is similar to that deployed on the Moon by Apollo astronauts and consists of three primary investigations: Seismic Experiment for Interior Structure (SEIS)[8]; the Heat Flow and Physical Properties Package (HP^3)[9]; and Rotation and Interior Structure Experiment (RISE)[10]. These provide a synergistic view of the martian interior, as seismology is most effective in delineating the outer layers of a planet (crust and mantle) whereas determination of the rotational dynamics by RISE is particularly well-suited for probing the properties of the deep core. Heat flow measurements provide insight into the dynamics of the interior, which is complementary to the structural information from SEIS and RISE. HP^3 and RISE have not yet collected sufficient data for meaningful analysis; thus their results will not be discussed here. As originally planned, InSight is expected to require upwards of 24 months ($\sim$1 Mars year) to achieve all of its objectives.

The Auxiliary Payload Sensor Suite (APSS) supports these investigations, including a deployment system and a set of sensors intended to measure sources of seismic noise (Table 1). A unique aspect of these sensors is that because they were designed to have performance commensurate with SEIS (e.g., the pressure sensor has a sensitivity in the seismic frequency band sufficient to measure variations that can cause ground deformations that appear in the seismic data), they are well-suited for providing diverse simultaneous measurements of phenomena both endogenic and exogenic (see Table 1).

Data are acquired continuously at 100 sps for SEIS and 20 sps for APSS, but only a fraction of this data can be returned due to transmission limitations. High-rate data are stored on the lander for $>$1 month, while sub-sampled continuous data sets for SEIS and APSS are returned daily and evaluated rapidly on the ground by the science team. The science team then submits 'event requests' for the lander to return full-rate data for specific time intervals that contain seismic, atmospheric, or magnetic events of interest.

Upon landing, InSight began immediately acquiring images, followed soon after by APSS, radiometer, and SEIS Short Period (SP) observations, along with multiple RISE

X-band tracking passes each week. The first three weeks were dedicated to choosing the best locations on the ground for placement of the SEIS and HP^3 instruments[5]. Installation of SEIS and its wind shield was completed on sol 70 (a sol is a Martian day). SEIS data was acquired prior to this time (including on the deck), but it did not achieve full performance until completion of its calibration and tuning around sol 85. Currently SEIS is performing significantly better than its design requirements at frequencies between 0.2 and 2 Hz, with a noise floor of $\sim 3\times10^{-9}$m/s^2/Hz$^{1/2}$ for the SP sensors and slightly above 1×10^{-10} m/s^2/Hz$^{1/2}$ for the very broad band (VBB) sensors during the early evening when the atmosphere is still[1].

Geologic Context and Shallow Structure of the Regolith

InSight landed in western Elysium Planitia (4.502°N, 135.623°E, elevation -2.613 km; see Figure 1), a volcanic plain with surface ages ranging from 3.7 By to 2.5 My[5]. Cerberus Fossae, approximately 1600 km to the east, contains faults, volcanic flows and liquid water outflow channels with ages as recent as 2-10 My and possibly younger from impact crater counts[11;12]. The lander sits in a ∼25 m diameter degraded impact crater, informally named Homestead hollow, filled with impact-generated sediments that have been transported and modified by wind. The local depth to a rocky layer inferred to be ancient lava flows is approximately 3-5 m based on the depth at which nearby impacts have excavated boulders[13;14].

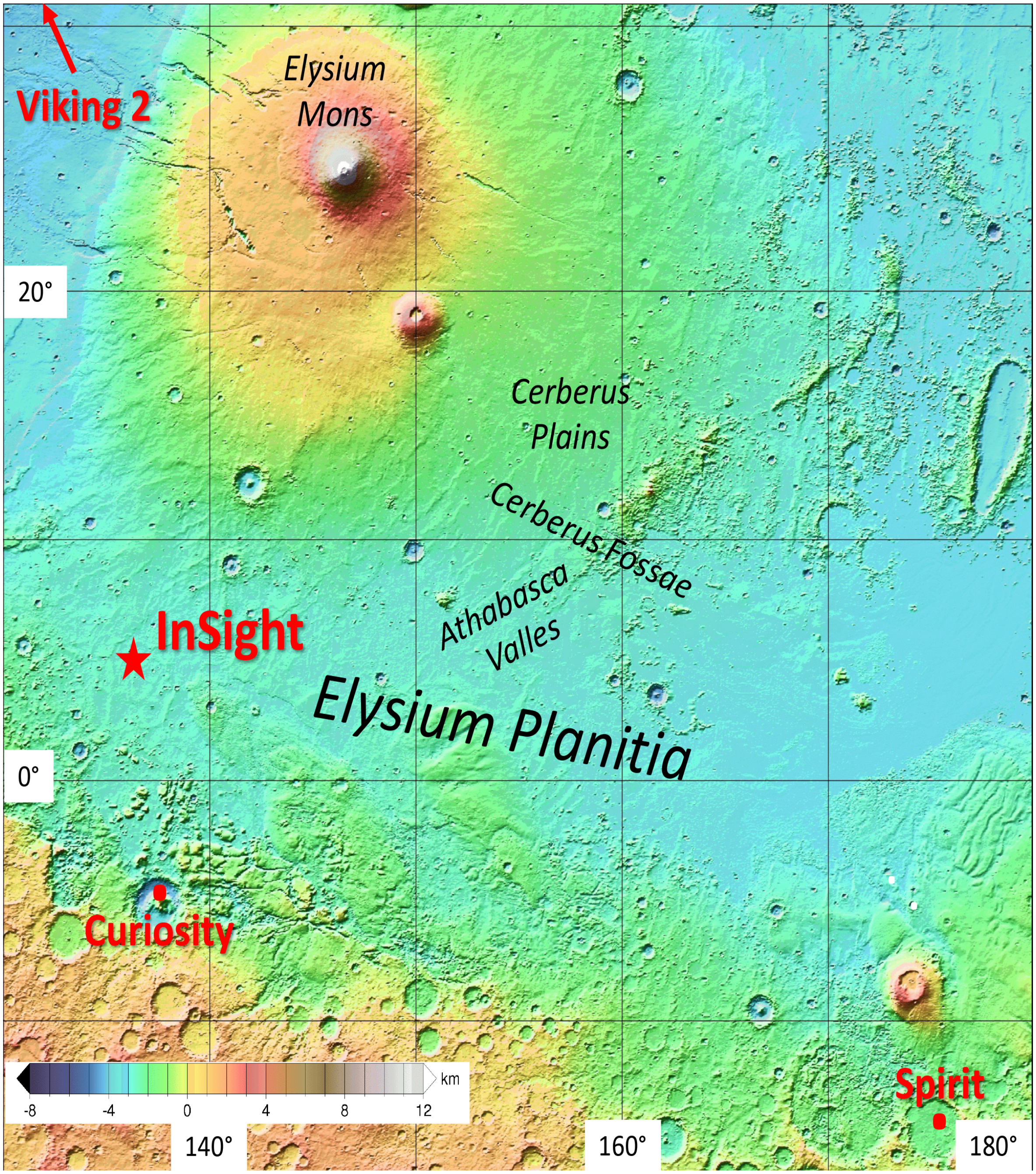

Figure 1: InSight (shown as a star) landed on an ancient volcanic plain south of Elysium Mons and north of the martian hemispheric dichotomy. The locations of the Curiosity and Spirit rovers, and the Viking 2 lander, along with major geologic features are shown on a topographic map[15].

Coordinated synergistic observations by InSight's instruments are providing new ways of characterizing the near-subsurface of Mars. The seismic recording of the HP^3 hammer strokes[16] and of seismic signals due to atmospheric vortices[17;18] sound the first few meters of the subsurface adjacent to the lander, confirming a high-porosity, low-rigidity layer of ∼3 meters, above a much more rigid layer[1]. Independently, a unique joint observation of a dust devil vortex using orbital imaging with the lander's cameras, pressure sensor and seismometer yielded a measurement of Young's modulus of 270 MPa in the upper few meters (see Box and Supplementary Discussion). This value, which is localized at a distance of ∼20 m from the lander, is larger than that immediately adjacent to the lander. This is consistent with the latter having an upper layer of relatively unconsolidated eolian material which filled Homestead hollow after its formation. Finally, the infrared radiometer has measured the thermal inertia of the near-surface[5] to be 160-230 $J/m^2/s^{1/2}/K^1$, consistent with expectations of a poorly-consolidated, sandy surface layer[13;19].

Atmospheric and Magnetic Measurements

Although in-situ meteorological measurements have been made previously, InSight's continuous and simultaneous, well calibrated, high-rate, high-precision pressure, wind and air temperature data provide an unprecedented view of Mars' surface environment. The characteristics of the bulk atmosphere and boundary layer phenomena are sampled on time scales of seconds to months[6;20] (Figure 2). And, as discussed above, the sensitivity of SEIS to both wind- and pressure-induced signals[1;18;21–25] make it a unique complementary meteorological sensor for short-time-scale phenomena.

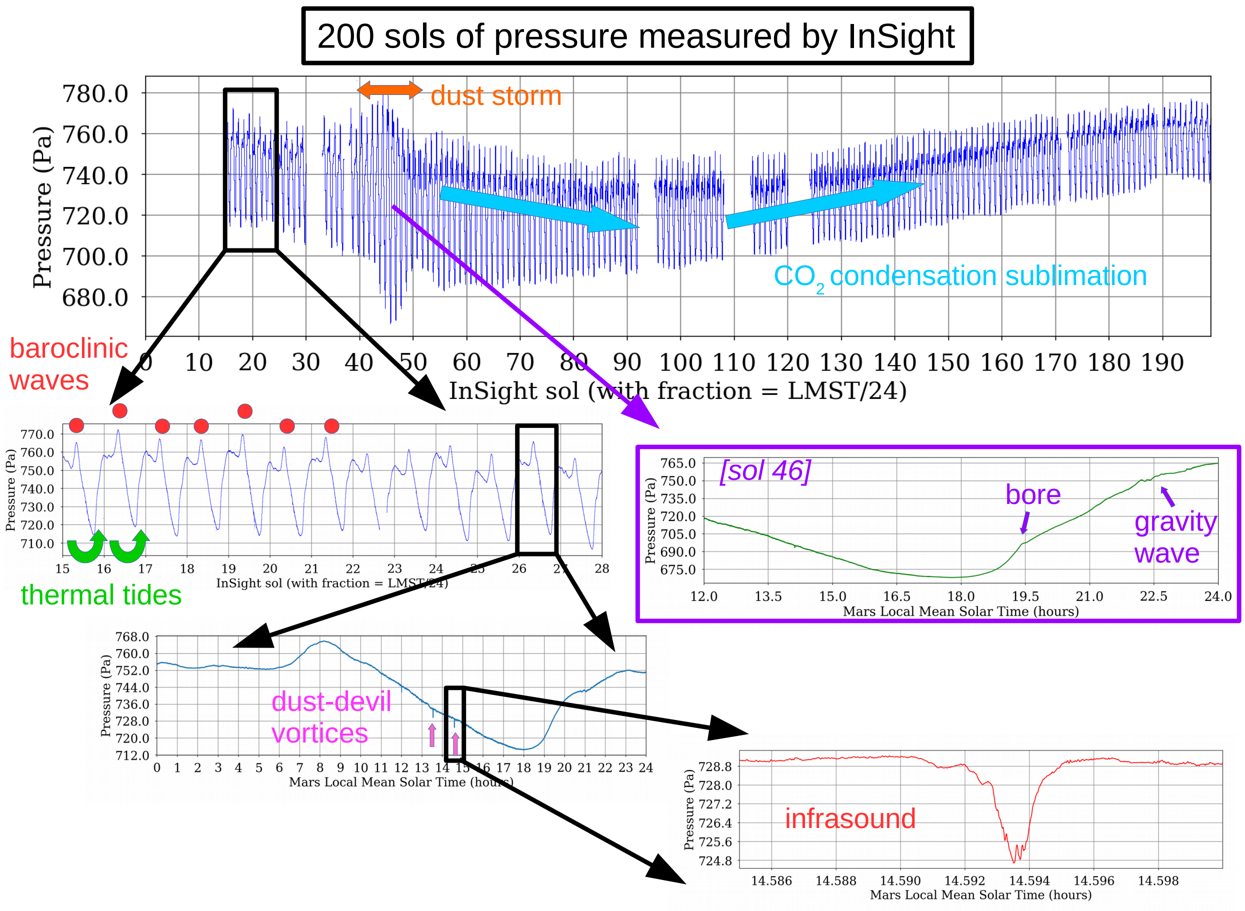

Figure 2: The InSight weather station's continuous high-frequency coverage monitors the atmospheric activity from large-scale weather to small-scale turbulence. The first 200 sols reveal seasonal processes (polar cap CO_2 condensation/sublimation, dust storm), daily variations (baroclinic waves), diurnal variability (thermal tides), mesoscale phenomena (gravity waves, bores), turbulence (dust-devil-like convective vortices) and infrasound.

The InSight landing site exhibits strong daytime turbulence, being the most active site among previous and current landed missions to date for dust-devil-like vortices. The pattern of turbulence and calm is strongly periodic, repeating daily over the time span thus far observed. This pattern defines the low-noise windows for SEIS marsquake observations[1;2]. Conversely, the dynamic atmosphere provides vibrational and ground tilt signals that can be used both to help characterize the meteorological phenomena and to probe the mechanical structure of the upper few meters of the regolith (see

Lognonné et al.[1] and Supplementary Discussion). On synoptic scales, InSight detects surprisingly large signals from mid-latitude baroclinic waves (with periods of 2-7 sols, similar to those detected by previous landers and from orbit), in addition to the expected diurnally repeating solar-driven pressure variations from thermal tides and the longer timescale signature of CO_2 seasonal condensation (which matches in shape that measured from prior landers). A few months after landing a regional storm changed the weather at the InSight landing site, with wind direction shifting diametrically. Other mesoscale phenomena include gravity waves (regular oscillations in pressure, wind or air temperature driven by buoyancy oscillations and with periods >100 s), which are more ubiquitous than previously thought, and the first detections of bore events (soliton-like waves) and infrasound on Mars[25]. All of these phenomena are interesting from an atmospheric science perspective, but also must be well-understood to properly isolate atmospheric effects from true seismic sources.

The InSight Fluxgate magnetometer (IFG) is one of the auxiliary instruments that monitor environmental conditions for the SEIS experiment. It is also the first magnetometer on the surface of Mars and allows studies of static and time-varying magnetic fields (Figure 3). Although the lander itself produces both such fields, signals of Martian origin can contribute to understanding the atmosphere and ionosphere regionally, as well as the interior structure of Mars. Joint studies of InSight and MAVEN magnetic field data, using new observations from the MAVEN spacecraft above InSight, will provide unique opportunities for studying how external fields measured in and above the ionosphere are manifest on the ground.

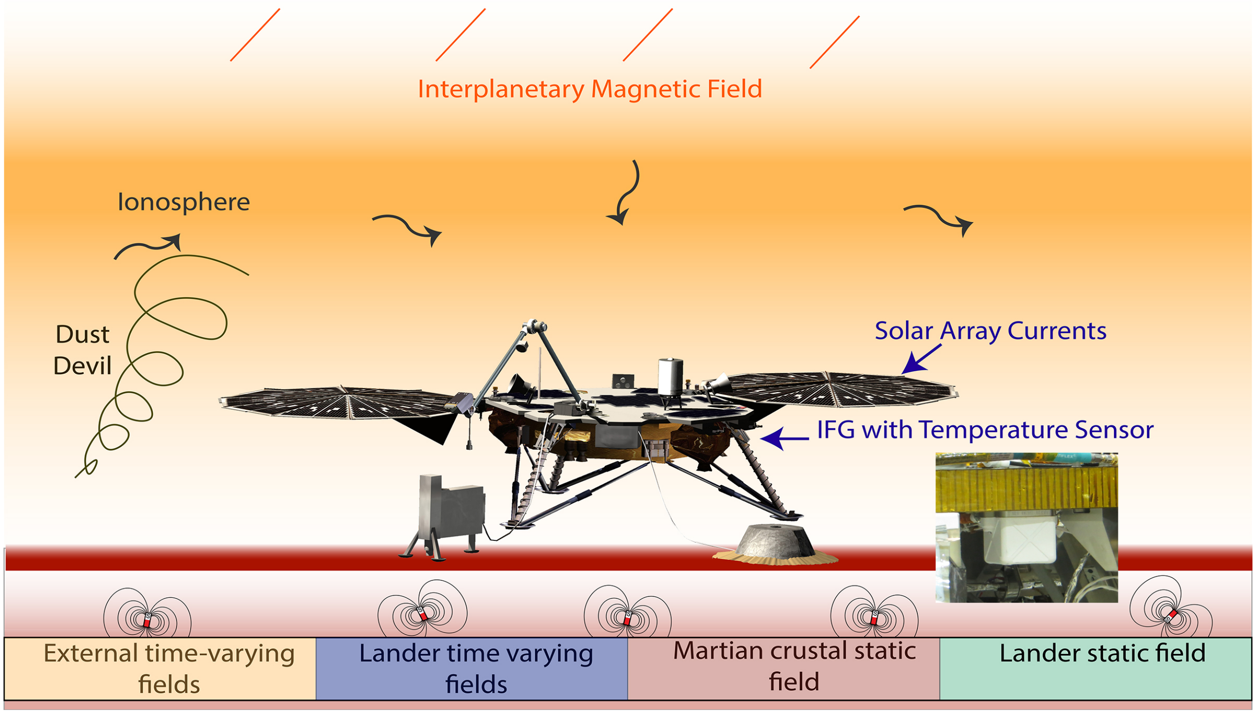

Figure 3: Multiple phenomena contribute to the magnetic field measured by the IFG. Time-varying fields (orange) can be of external origin, including the interplanetary magnetic field, ionospheric currents and weather events such as dust devils; they can also be of lander origin (blue), e.g., due to movement of the robotic arm, RISE or UHF communications, solar array currents, or temperature variations causing deformation of the lander. The martian static crustal field (red) results from crustal magnetization, represented schematically here as subsurface dipoles. A DC field is also associated with the lander itself (green).

Satellite missions have measured crustal magnetization acquired in an ancient global field[26]. However, only surface measurements can identify weak and/or small-scale magnetizations that provide key constraints on crustal structure. The static crustal field measured by InSight has a strength of 2013 $\pm$ 160 nT, and points south-east and upward. The field strength exceeds predicted surface fields at this location from combined MAVEN and MGS satellite measurements by an order of magnitude[27–29] and hence implies locally strong magnetization with wavelengths less than $\sim$150 km. Furthermore, the inferred magnetization is consistent with an Earth-like ancient dynamo field and is probably carried within a layer at least 3.9 Ga old[7].

So far, time-varying signals that have been confidently detected are diurnal variations and shorter period pulsations (100-1000 s). Peak-to-peak amplitudes of diurnal variations are $\sim$20 nT and exceed those expected from the interplanetary magnetic field alone, indicating contributions from ionospheric currents. IFG has also detected transient signals possibly related to atmospheric or space weather. With a longer time-series, we expect to find signals with seasonal and/or annual variations and 26-sol cyclicity that results from solar rotations and the resulting periodic changes in the interplanetary field at Mars. More details are provided in Johnson et al.[7].

The time-varying magnetic fields are key to future studies of electrical conductivity structure, that acts as a probe of interior temperature, mineralogy and volatile content. The crustal magnetization and future electrical conductivity sounding therefore contribute directly to the overarching mission science goals.

Seismic Activity of Mars

The InSight marsquake catalog (through 30 September 2019) contains 174 events[2;4], 150 of which have a high-frequency character (with significant energy only above $\sim$1 Hz) and are not yet fully understood in terms of distance and magnitude. The other 24 have dominantly low-frequency content, compatible with distant tectonic events, and three of these have sufficiently high SNR to be clearly located. Assuming similar signatures between these three events and another ten with lower SNR, rough distances and moment magnitudes can be computed for 13 events (see Table 1 in Giardini et al.[2]). At least two of these events are located in the Cerberus Fossae region, consistent with the interpretation from orbital imaging of an active volcano-tectonic system.

Figure 4 shows two examples of these low-frequency marsquake signals compared to two terrestrial events at similar distances from the receivers. S0235b has clearly defined P- and S-wave arrivals. The time difference between these arrivals along with their measured polarization allows location of the epicenter of the quake and determination of its moment magnitude. P and S arrivals for lower SNR signals such as S0105a are difficult to pick from simple inspection of the time series, and are estimated using spectral density envelopes (see Giardini et al.[2] for details). Compared to terrestrial quakes, marsquakes show relatively long codas after each seismic arrival, indicative of strong scattering in the crust, and lack surface waves. Whether the latter is due to deep sources, crustal scattering, or other reasons is yet unknown.

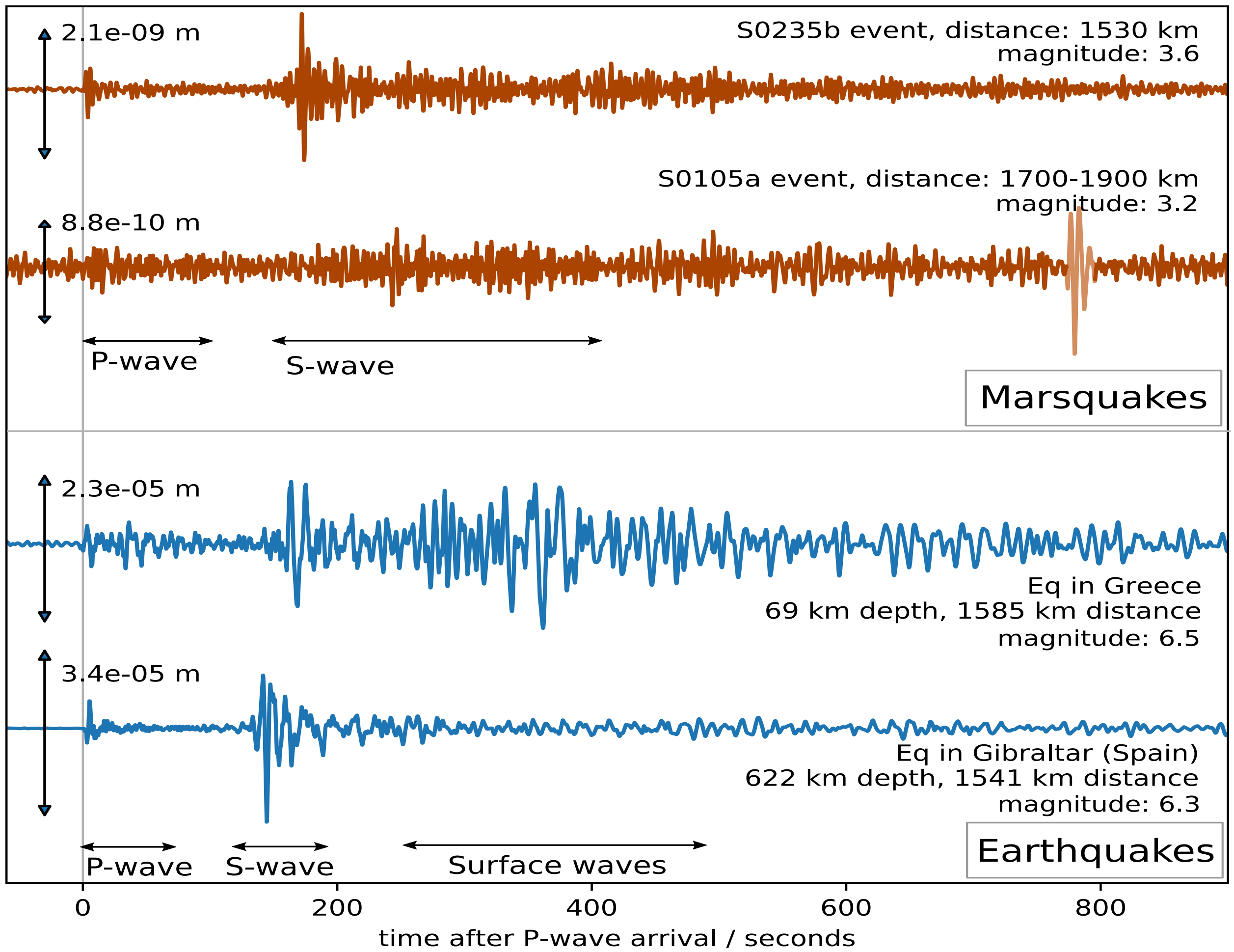

Figure 4: Marsquakes have similarities and differences with earthquakes. The upper frame shows displacement times series for two marsquake signals (brown). S0235b has the highest SNR thus far observed and shows clear P-wave and S-wave arrivals. S0105a is an example of a lower SNR event; for such events P and S arrivals are determined using power density function envelopes[2]. Note the different amplitude scales. The lower frame shows two earthquake signals at a similar distance, recorded at stations FIESA and DAVOX of the Swiss Seismic Network[30]. The shallow earthquake in Greece has visible surface waves, which are not visible for either the deep earthquake or the marsquakes. All waveforms were corrected for instrument response and filtered between 2 and 8 second period (marsquakes) or 2 and 30 seconds (earthquakes). For the marsquakes, the instrument noise exceeds the signal at about 10 second period, hence the different filter.

Meteoroid impacts are an additional expected source of seismic events, and can be used to both probe the crust and constrain the impact flux. In theory, factors such as the direction of first motion, the occurrence of surface waves or depth phases, the amplitude ratio of P/S waves, and frequency spectrum can all be used to discriminate between impacts and endogenic sources[31]. Impact detections of up to 10 per Earth year were predicted[31]. Using the measured ambient seismic noise[1], the updated predicted annual detection rate is ~8 (0.1-200) for SEIS-VBB and ~2 (0.2-20) for SEIS-SP[32]. All estimates have roughly an order of magnitude uncertainty due to factors such as unknown impact-seismic efficiency, attenuation and scattering in the martian interior.

No impacts have been unequivocally identified to date, possibly due to the scattering[1] that can obscure surface waves and depth phases[2]. Thus we cannot definitively rule out an impact origin for any particular event. However the similarity of observed waveforms points to a common seismic origin[2]. To actively guide the search for candidate events in the seismic record, orbital images are being analyzed for new albedo features characteristic of recent impacts. InSight has also begun using its cameras for night time imaging to search for meteors. None have yet been identified[33].

The level of seismic activity is crucial for investigating interior structure and understanding Mars' thermal and chemical evolution. Martian seismicity predictions are based on evidence of faulting[34;35] and thermal evolution models that directly link seismicity to lithospheric cooling[36–38]. Prior to InSight, the only direct constraint was the absence of unambiguous event detections by the Viking 2 seismometer[39;40]. This restricted activity to be lower than a few percent of global terrestrial seismic activity.

Accounting for possible events that may be masked at noisier times and using source-spectral scaling to estimate magnitudes (see detailed analysis in Giardni et al.[2]), we determine magnitude- and distance-dependent detectability statistics and estimate the total annual seismic activity using the 13 confirmed events. We extrapolate the number of observed events to (i) one full year, assuming statistical stationarity of the seismicity release, (ii) to the full sol, taking into account the observed, highly variable noise profile, and finally (iii) to the full planet, accounting for the detectability of events of different magnitudes with distance (see Supplementary Discussion). For example, the handful of events with M_w 3.0-3.2 are the detectable fraction of an estimated several tens to a hundred events across the planet.

Our estimated global seismic event rate derived from observed events (Figure 5) indicates a moderately active planet, with a value far above that of the Moon[41] (for events believed to be of tectonic origin) and slightly below intraplate Earth[37;38]. We note that the activity is relatively close to the initial predictions[34] that were used to guide performance requirements and is within the uncertainty estimates of Knapmeyer et al.[37].

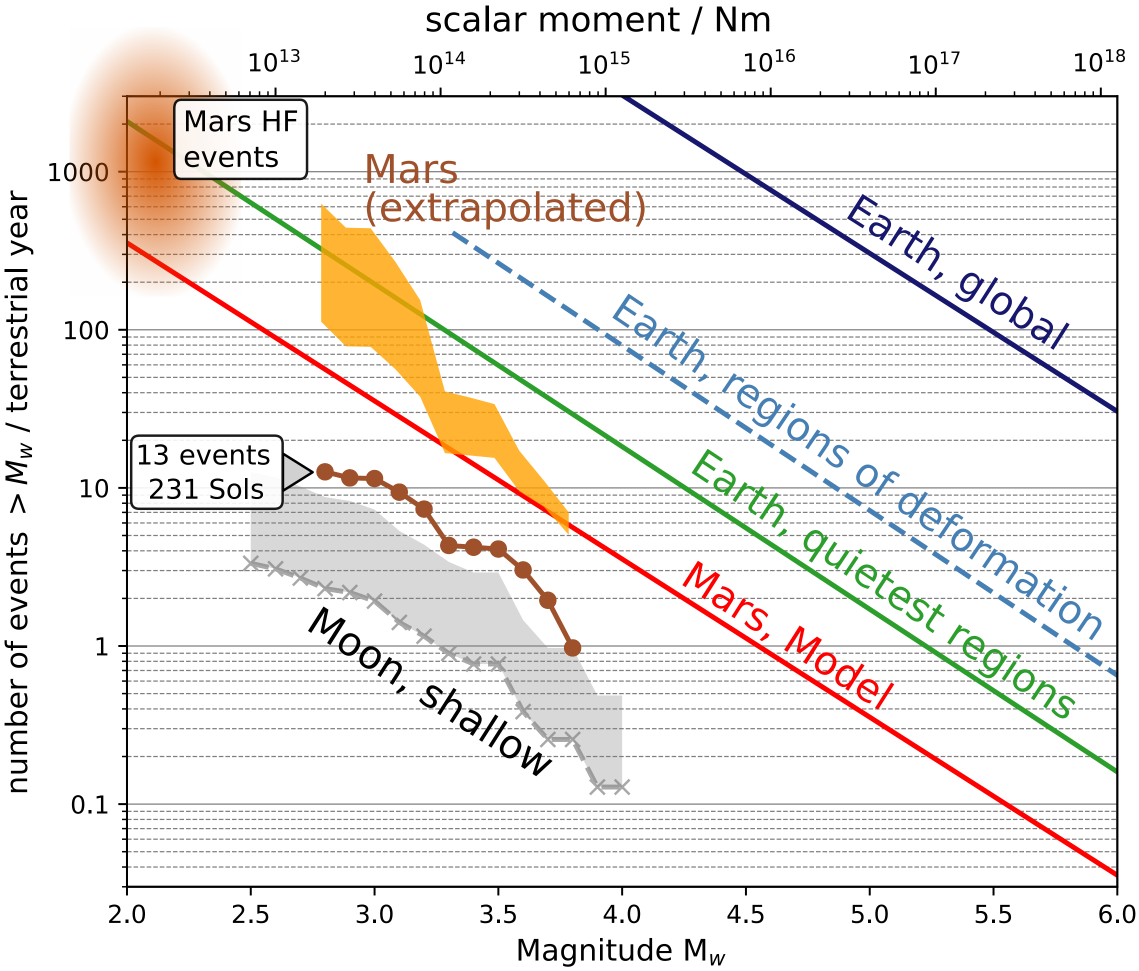

Figure 5: Cumulative annual activity rate for Mars compared to Earth, the Moon and pre-mission predictions for Mars. The brown curve shows the observed number of marsquakes as a function of magnitude from Giardini et al.[2]. The orange curve represents these data extrapolated to the entire planet, with the vertical spread of values representing the uncertainty in the completeness of observation for smaller distant events. The pre-InSight estimate of Mars seismic activity is from Golombek et al.[34]. Lunar seismicity is based on the analysis of shallow moonquake activity by Oberst[41], with the grey area representing the unknown completeness. The global seismicity of the Earth (dark blue line) is from the GlobalCMT catalogue, and is dominated by plate boundaries. The intraplate seismicity estimates separate tectonically deformed regions away from plate boundaries (blue) and stable continental interiors (green)[42]. Terrestrial curves are scaled to the surface area of Mars.

Another robust observation is the absence of events above $M_w \geq 4$. Compared to the Gutenberg-Richter magnitude distribution with $b \sim 1$ commonly observed on the Earth and the Moon (where b is the logarithmic slope of the cumulative magnitude-number curve; see Figure 5), the current distribution of events appears to be skewed to smaller events (b>1). On Earth higher b values are only observed in specific tectonic settings, such as normal faulting regimes[43] or extremely low-strain-rate oceanic intraplate earthquakes[44]. We note that the robust determination of b requires much larger datasets[45] and will only be possible later in the mission. To connect the seismicity to geodynamic modelling and the global heat budget[38] requires an estimate of the full planetary moment release, which is dominated by the largest events in the distribution[46].

First results from the InSight seismometer are beginning to unveil Mars' interior structure, rate of seismicity, and locations of current tectonic activity. Observations by other instruments reveal high crustal magnetization and unexpected atmospheric processes, such as high levels of vortex activity and strong mid-latitude baroclinic waves. With more than another year of planned observations, InSight's focus on interior processes utilizing its diverse suite of highly complementary instruments is expected to refine the rate and distribution of seismic activity and delineate the thickness of the crust, the size and density of the core, and bound the planetary heat flow. These observations should continue to lead to new discoveries and constraints on Mars' interior structure and geologic evolution, and processes of planetary differentiation and thermal evolution.

Methods

Estimating seismic activity rate from event statistics

The InSight Marsquake Service[47] has detected 174 seismic events, including 13 higher-quality regional and teleseismic (low-frequency or broadband) events (as of Septermber 30, 2019). These latter events were all detected during the quiet evening period and all but one (S0167a) has been determined to be closer than about 90 degrees (6000 km). To estimate the full seismic activity on Mars, we use only these events. The so called high-frequency events are of considerably smaller magnitude; their distance is probably <500 km, but with large uncertainty[2]. They therefore relate to local seismicity that would not be detected over larger distances and is not necessarily representative of the global seismic activity.

From the environmental noise evolution between 0.1 and 0.8 Hz from sols 80-240, and the modelling of source spectra described by Giardini et al.[2], the fraction of observation time during which an event of a given magnitude and distance would have been observable has been estimated (Figure M-1).

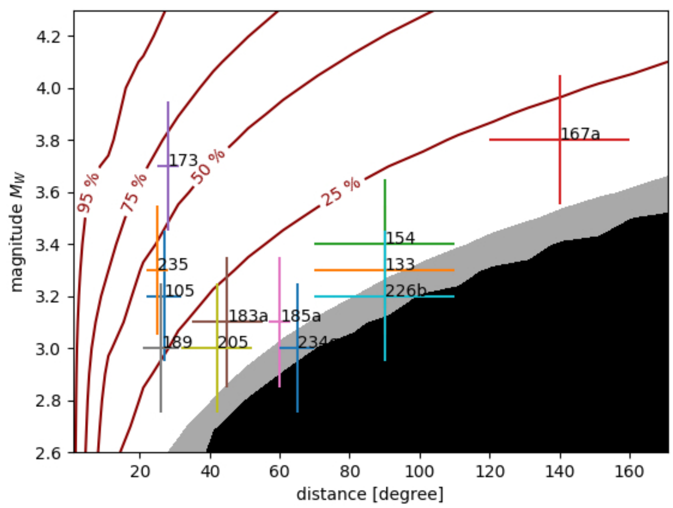

Figure M-1: Probability to detect a marsquake of a certain distance and magnitude, given the expected source spectrum[2] and the distribution of ambient noise over sols 85-325. The colored crosses mark the 13 events described in the main article with their uncertainty on distance and magnitude M_{w}. The black region is where the event would have never surpassed the ambient noise, the grey region is where it would have been observable only 10% of the time.

We use these detectability statistics to estimate the total annual seismic activity of Mars from the 13 observed events. These 13 events form **rate A** of our estimate. Extrapolation to full seismicity is done in three steps:

(a) **Extrapolation to one year.**

The events were detected during 231 sols of high quality operations. Under the assumption of seasonal temporal stationarity, we estimate the annual (with respect to Earth years) activity by multiplying the number of events by 365/231. This results in **rate B**.

(b) **Extrapolation to full sol.**

The ambient noise of Mars varies widely over the course of a sol and none of the events could have been detected during the noisy, turbulent wind periods of late morning and early afternoon. Therefore, each event is counted $n_i = 1/p_i$ times, where p_i is the ratio of time in which the event SNR would have been >1 (see Figure M-1). This factor n_i varies between 1.25 for the strongest event (S0173a) and 5 for the weakest ones. To increase stability, 4 event groups have been formed, with $p_i = (20\%~, 25\%~, 40\%~, 75\%)$; see Table M-1. This assumes the events are stationary in time over the duration of one sol. The result is an estimate of the set of events that would have been observed if the noise was at its quietest over the whole mission. In total, it increases the number of events by ~ 4, resulting in **rate C**.

(c) **Extrapolation to full planet.**

The most distant event is a magnitude 3.8 event at an epicentral distance of about 150 degrees, and is about 10 dB above ambient noise. We therefore conclude that the lowest magnitude that can be detected on the whole planet is about 3.5, under best noise conditions. For smaller distances, a threshold magnitude has been estimated from Figure M-1. This means that, for example, only on 25% of the surface of the planet could magnitude 3.1 events have been detected. Assuming homogeneous distribution of events over the surface of Mars, 75% of the magnitude 3.1 events would therefore remain undetected, even in the quietest periods of the sol. We therefore divide the number of events in each magnitude bin by the fraction of the surface of the planet corresponding to that bin (Table M-2), resulting, for example in a factor of 4 for the bin around M_{w}=3.0.

This results in **rate D**. Since this process is highly sensitive to the minimum magnitude for each distance, it is repeated with $M_{\mathrm{min}} \pm 0.2$ to estimate uncertainties, resulting in the orange range in Figure M-2.

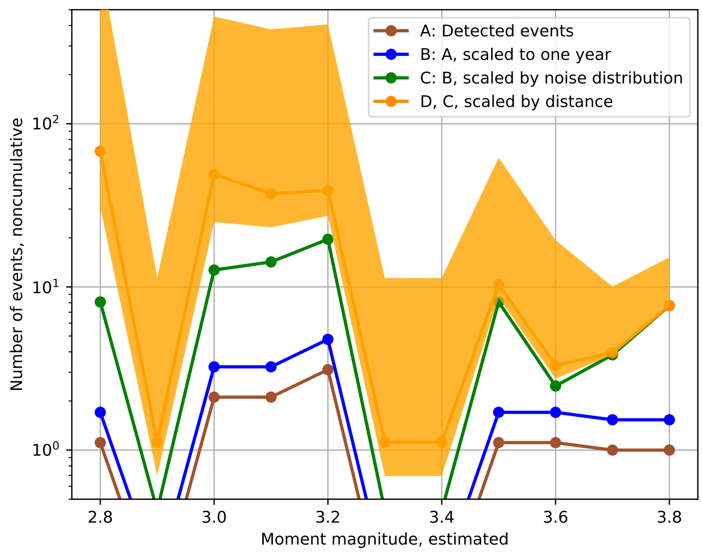

Figure M-2: Non-cumulative distribution of events with the corrections described in the text. To reflect the uncertainty in magnitude, each event is represented by a boxcar function of 0.5 M width and height 0.2.

Together, the three extrapolation steps result in an estimated annual rate of 100-500 seismic events above M_{w}=2.9. This number is at the upper end of pre-mission predictions[35;37] and almost 100× higher than shallow lunar seismicity[41]. Comparisons to terrestrial seismicity require us to take the lack of martian plate boundaries into account. Global catalogues find about 0.5% of the quakes (M_w>4.5) on Earth in truly intraplate settings (i.e. in non-deformed continental interiors[42]. This assumption has been previously used in the InSight context[48], but it was not always scaled to the smaller surface area of Mars. The estimate of Martian total seismicity presented here is 25-100% of this "terrestrial, intraplate" value for magnitudes <3. At the same time, marsquakes of magnitudes >3.2 are significantly underrepresented in our current catalog compared to a Gutenberg-Richter distribution with a logarithmic slope b=1. We recognize that there are different possible scenarios for the distribution of seismic activity on Mars. For example, the Tharsis area may be more active than the southern highlands[38]. Indeed if we detect large, locatable events we will test scenarios that link surface age to interior activity. For now we make the simplest assumption of uniform activity.

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Author contributions

The scientific results of the InSight mission are the result of a team effort, with all the listed authors contributing to aspects of the design, implementation and analysis of results. W.B.B. and S.E.S. are Principal Investigator and Deputy Principal Investigator, respectively, of the InSight mission, and jointly and equally supervised and participated in the work described in the manuscript, as well as contributied substantially to writing the manuscript. P.L., along with D.G. and W.T.P., co-led the design and implementation of the SEIS experiment. The following people contributed to the design and implementation of SEIS: U.C., D.M. and J.T.; and contributed to seismic data analysis: C.B., E.B., J.C., J.I., S. Kedar, B.K.-E., M.K., L.M., A. Mocquet, F.N., M.P., A.-C.P., M.P., N.S. and R.W.. D.B. and A.S. co-led the atmospheric science investigation and contributed to writing the manuscript, with input from N.B., M.L. and C.N.. J.-A.R.-M. contributed to the design, implementation and analysis of the atmospheric science investigation. R.G. and R.L. contributed to the joint interpretation of the seismic and atmospheric science investigations. J.M. led the imaging experiment and contributed to interpretation of results. M. Golombek led the geology investigation and contributed to writing the manuscript, with input from J. Garvin, J. Grant, S.R. and N.W.. C.J. and C.T.R. co-led the magnetic investigation and contributed to writing the manuscript, with input from P.C., M.F. and A. Mittelholz. I.D. led the impact cratering investigation, interpretation of results, and write-up for this manuscript, with contributions from G.C. and N.T.. V.D. and W.F. co-led the geodesy investigation and contributed to interpretation of results, with contributions from S.A.. T.S. led the heat flow investigation and contributed to writing the manuscript. M. Grott, J. Grygorczuk, T.H., G.K., P.M., N. Müller, S.N., M.S. and S.E.S. contributed to the design, implementation and analysis of the heat flow investigation. C.P. led the analysis and the writing of the regolith properties from ground deformation described in the Supplementary Discussion, with contributions from N. Murdoch, M.D., S.R., M.L., E.S., T.K., P.L., A.S. and D.B.. S. Stähler led the analysis and writing of the seismic activity estimate described in Methods, with contributions from M.K., M.vD. and D.G.. D.A., S. King, S.McL., C.M., S. Stanley and M.W. contributed to the interpretation of the planetary interior results.

Competing interests

The authors declare no competing interests.

Data availability

The data shown in the plots within this paper and other findings of this study are available from the corresponding author upon reasonable request. The InSight Mission raw and calibrated data sets are available via NASA's Planetary Data System (PDS). Data are delivered to the PDS according to the InSight Data Management Plan available in the InSight PDS archive. All data sets can be accessed at https://pds-geosciences.wustl.edu/missions/insight/index.html. The data of terrestrial stations CH.DAVOX and CH.FIESA are part of the Swiss Seismic Network[30]. These data, as well as InSight seismic data are accessible from the Incorporated Resarch Institutes for Seismology (IRIS) at https://www.iris.edu/hq/.

References

[1] Lognonné, P., et al. Constraints on the shallow elastic and anelastic structure of mars from insight seismic data. *Nat. Geosci.*, (submitted), 2020.

[2] Giardini, D., et al. The seismicity of Mars. *Nat. Geosci.*, (submitted), 2020.

[3] InSight Mars SEIS data Service et al. SEIS raw data, InSight Mission. *Other/Seismic Network*, 2019. doi: 10.18715/SEIS.INSIGHT.XB_2016.

[4] InSight Marsquake Service et al. Mars Seismic Catalogue, InSight Mission; V1 2/1/2020. *Dataset*, 2019. doi: 10.12686/a6.

[5] Golombek, M., et al. Geology of the InSight landing site, Mars. *Nat. Comm.*, (submitted), 2020. doi: 10.1130/abs/2019am-336461.

[6] Banfield, D., and Spiga, A., et al. The atmosphere of mars as observed by insight. *Nat. Geosci.*, submitted, 2020.

[7] Johnson, C. L., et al. Crustal and time-varying magnetic fields at the InSight landing site on Mars. *Nat. Geosci.*, (submitted), 2020.

[8] Lognonné, P., et al. SEIS: InSight's seismic experiment for internal structure of Mars. *Space Sci. Rev.*, 215(12), 2019. doi: 10.1007/s11214-018-0574-6.

[9] Spohn, T., et al. The Heat Flow and Physical Properties Package (HP3) for the InSight mission. *Space Sci. Rev.*, 214(96), 2018. doi: 10.1007/s11214-018-0531-4.

[10] Folkner, W. M., et al. The Rotation and Interior Structure Experiment on the InSight mission to Mars. *Space Sci. Rev.*, 214(100), 2018. doi: 10.1007/s11214-018-0530-5.

[11] Vaucher, J., et al. The volcanic history of central Elysium Planitia: Implications for martian magmatism. *Icarus*, 204(2):418–442, 2009. doi: 10.1016/j.icarus.2009.06.032.

[12] Burr, D. M., Grier, J. A., McEwen, A. S., and Keszthelyi, L. P. Repeated aqueous flooding from the Cerberus Fossae: Evidence for very recently extant, deep groundwater on Mars. *Icarus*, 159(1):53–73, 2002. doi: 10.1006/icar.2002.6921.

[13] Golombek, M. P., et al. Selection of the InSight landing site. *Space Sci. Rev.*, 211:5–95, 2017. doi: 10.1007/s11214-016-0321-9.

[14] Golombek, M. P., et al. Geology and physical properties investigations by the InSight lander. *Space Sci. Rev.*, 214(84), 2018. doi: 10.1007/s11214-018-0512-7.

[15] Smith, D. E., et al. Mars Orbiter Laser Altimeter: Experiment summary after the first year of global mapping of Mars. *J. Geophys. Res. Planets*, 106(E10): 23689–23722, 2001. doi: 10.1029/2000JE001364.

[16] Kedar, S., et al. Analysis of regolith properties using seismic signals generated by InSight's HP3 penetrator. *Space Sci. Rev.*, 211:315–337, 2017. doi: 10.1007/s11214-017-0391-3.

[17] Lorenz, R. D., et al. Seismometer detection of dust devil vortices by ground tilt. *Bull. Seismol. Soc. Am.*, 105(6):3015–3023, 2015. doi: 10.1785/0120150133.

[18] Kenda, B., et al. Modeling of ground deformation and shallow surface waves generated by martian dust devils and perspectives for near-surface structure inversion. *Space Sci. Rev.*, 211:501–524, 2017. doi: 10.1007/s11214-017-0378-0.

[19] Morgan, P., et al. A pre-landing assessment of regolith properties at the InSight landing site. *Space Sci. Rev.*, 214(104), 2018. doi: 10.1007/s11214-018-0537-y.

[20] Spiga, A., et al. Atmospheric science with InSight. *Space Sci. Rev.*, 214(109), 2018. doi: 10.1007/s11214-018-0543-0.

[21] Teanby, N. A., et al. Seismic coupling of short-period wind noise through Mars' regolith for NASA's InSight lander. *Space Sci. Rev.*, 211:485–500, 2017. doi: 10.1007/s11214-016-0310-z.

[22] Mimoun, D., et al. The noise model of the SEIS seismometer of the InSight mission to Mars. *Space Sci. Rev.*, 211:383–428, 2017. doi: 10.1007/s11214-017-0409-x.

[23] Murdoch, N., et al. Evaluating the Wind-Induced Mechanical Noise on the InSight Seismometers. *Space Sci. Rev.*, 211:429–455, 2017. doi: 10.1007/s11214-016-0311-y.

[24] Murdoch, N.. Alazard, D., Knapmeyer-Endrun, B., Teanby, N. A., and Myhill, R. Flexible mode modelling of the InSight lander and consequences for the SEIS instrument. *Space Sci. Rev.*, 214(117), 2018. doi: 10.1007/s11214-018-0553-y.

[25] Banfield, D., et al. InSight Auxiliary Payload Sensor Suite (APSS). *Space Sci. Rev.*, 215(4), 2019. doi: 10.1007/s11214-018-0570-x.

[26] Acuña, M. H., et al. Global distribution of crustal magnetization discovered by the Mars Global Surveyor MAG/ER experiment. *Science*, 284(5415):790–793, 1999. doi: 10.1126/science.284.5415.790.

[27] Mittelholz, A., Johnson, C. L., and Morschhauser, A. A new magnetic field activity proxy for Mars from MAVEN data. *Geophys. Res. Lett.*, 45(12):5899–5907, 2018. doi: 10.1029/2018GL078425.

[28] Smrekar, S. E., et al. Pre-mission InSights on the Interior of Mars. *Space Sci. Rev.*, 215(3), 2019. doi: 10.1007/s11214-018-0563-9.

[29] Langlais, B., Thébault, E., Houliez, A., Purucker, M. E., and Lillis, R. J. A new model of the crustal magnetic field of Mars using MGS and MAVEN. *J. Geophys. Res. Planets*, 124(6):1542–1569, 2019. doi: 10.1029/2018JE005854.

[30] Swiss Seismological Service (SED). National Seismic Networks of Switzerland. 1983. doi: 10.12686/sed/networks/ch.

[31] Daubar, I., et al. Impact-seismic investigations of the InSight mission. *Space Sci. Rev.*, 214(132), 2018. doi: 10.1007/s11214-018-0562-x.

[32] Teanby, N. A., et al. Impact detection with InSight: Updated estimates using measured seismic noise on Mars. *Lunar Planet. Sci. Conf. 50th*, abstract #1565, 2019.

[33] Daubar, I. J., et al. Impact science on the InSight mission – current status. *9th Int. Conf. Mars*, abstract #6198, 2019.

[34] Golombek, M. P., Banerdt, W. B., Tanaka, K. L., and Tralli, D. M. A prediction of Mars seismicity from surface faulting. *Science*, 258(5084):979–981, 1992. doi: 10.1126/science.258.5084.979.

[35] Golombek, M. P. A revision of Mars seismicity from surface faulting. *Lunar Planet. Sci. Conf. 33rd*, abstract #1244, 2002.

[36] Phillips, R. J., and Grimm, R. E. Martian seismicity. *Lunar Planet. Sci. Conf. 22nd*, abstract #1061, 1991.

[37] Knapmeyer, M., et al. Working models for spatial distribution and level of Mars' seismicity. *J. Geophys. Res. Planets*, 111(E11), 2006. doi: 10.1029/2006JE002708.

[38] Plesa, A. C., et al. Present-day Mars' seismicity predicted from 3-D thermal evolution models of interior dynamics. *Geophys. Res. Lett.*, 45(6):2580–2589, 2018. doi: 10.1002/2017GL076124.

[39] Anderson, D. L., et al. Seismology on Mars. *J. Geophys. Res.*, 82(28):4524–4546, 1977. doi: 10.1029/js082i028p04524.

[40] Goins, N. R., and Lazarewicz, A. R. Martian seismicity. *Geophys. Res. Lett.*, 6 (5):368–370, 1979. doi: 10.1029/GL006i005p00368.

[41] Oberst, J. Unusually high stress drops associated with shallow moonquakes. *J. Geophys. Res.*, 92(B2):1397–1405, 1987. doi: 10.1029/JB092iB02p01397.

[42] Okal, E. A., and Sweet, J. R. Frequency-size distributions for intraplate earthquakes. pages 59–71, 2007. doi: 10.1130/2007.2425(05).

[43] Petruccelli, A., et al. The influence of faulting style on the size-distribution of global earthquakes. *Earth Planet. Sci. Lett.*, 527(115791). doi: 10.1016/j.epsl.2019.115791.

[44] Sasajima, R., and Ito, T. Strain rate dependency of oceanic intraplate earthquake b-values at extremely low strain rates. *J. Geophys. Res. Solid Earth*, 121(6): 4523–4537, 2016. doi: 10.1002/2016JB013221.

[45] Marzocchi, W., and Sandri, L. A review and new insights on the estimation of the b-value and its uncertainty. *Ann. Geophys.*, 46(6):1271–1282, 2003. doi: 10.4401/ag-3472.

[46] Knapmeyer, M., et al. Estimation of the seismic moment rate from an incomplete seismicity catalog, in the context of the InSight mission to Mars. *Bull. Seismol. Soc. Am.*, 109(3):1125–1147, 2019. doi: 10.1785/0120180258.

[47] Clinton, J., et al. The Marsquake Service: Securing daily analysis of SEIS data and building the martian seismicity catalogue for InSight. *Space Science Rev.*, 214 (133), 2018. doi: https://doi.org/10.1007/s11214-018-0567-5.

[48] Panning, M.P., et al. Verifying single-station seismic approaches using Earth-based data: Preparation for data return from the InSight mission to Mars. *Icarus*, 527:230–242, 2015. doi: 10.1016/j.icarus.2014.10.035.

[49] Trebi-Ollennu, A., et al. InSight Mars lander robotics instrument deployment system. *Space Sci. Rev.*, 214(93), 2018. doi: 10.1007/s11214-018-0520-7.

[50] Maki, J. N., et al. The color cameras on the InSight lander. *Space Sci. Rev.*, 214 (105), 2018. doi: 10.1007/s11214-018-0536-z.

[51] Dell'Agnello, S., et al. LaRRI: Laser Retro-Reflector for InSight Mars lander. *Space Res. Today*, 200:25–32, 2017.

Table 1: Instrument Payload.

Instrument	**Measurement**
SEIS (Seismic Experiment for Interior Structure) [8]	Very-Broad-Band and Short-Period Seismometers - three-components of ground motion, 0.01–100 Hz, noise floor down to $\sim 10^{-10}$ m/s^2/Hz$^{1/2}$
HP^3(Heat Flow and Physical Properties Package) [9]	Mole and Science Tether – thermal gradient, thermal conductivity and mechanical properties in upper 5 m of regolith
	RAD (Infrared Radiometer) – ground surface temperature
RISE (Rotation and Interior Structure Experiment) [10]	X-Band Transponder – variations in planet rotation vector (direction and magnitude)
APSS (Auxiliary Payload Sensor Suite) [25]	TWINS (Temperature and Wind for InSight) – air temperature and wind direction and speed
	Pressure Sensor – atmospheric pressure
	IFG (InSight Fluxgate) – vector magnetic field
IDS (Instrument Deployment System) [49;50]	IDA (Instrument Deployment Arm) – ground mechanical properties
	IDC (Instrument Deployment Camera) – medium-resolution (FOV 45°) color camera (pointable)
	ICC (Instrument Context Camera) – wide-angle (FOV 120°) color camera (fixed)
LaRRI (Laser Retro Reflector for InSight) [51]	Passive retro-reflector array to support future precision laser ranging from Mars orbit

Table M-1: Correction of numbers of events for variable noise across observation window.

Event group	Event	M_W	p_i	n_i	Number of events in group		
					Detected (rate A)	Full year (rate B)	Full sols (rate C)
1 (highest p)	S0173a	3.2-4.2	0.75	1.2	1	1.8	2.2
2	S0235a	2.8-3.8	0.4	2.5	3	5.4	13.6
	S0105a	2.7-3.7					
	S0325a	2.7-3.7					
3	S0183a	2.6-3.6	0.25	4	3	5.4	22
	S0189a	2.5-3.5					
	S0205a	2.5-3.5					
4 (lowest p)	S0226b	2.7-3.7	0.2	5	6	10.8	55
	S0234c	2.5-3.5					
	S0133a	2.9-3.9					
	S0154a	2.9-3.9					
	S0167a	3.3-4.3					
	S0185a	2.6-3.6					
Sum					13	23	93

Table M-2: Minimum detectable magnitude for different distances, with the corresponding fraction of the surface of the planet.

Δ (degrees)	M_{min}	Fraction of the planet's surface
25	2.6	0.07
45	2.9	0.15
60	3.0	0.25
90	3.2	0.5
150	3.5	0.93