ACTIVE TECTONICS ON MARS AS SEEN BY INSIGHT.

S. C. Stähler[1], J. F. Clinton[2], D. Giardini[1], S. Smrekar[3], M. Böse[2], N. Brinkman[1], S. Ceylan[1], C. Charalambous[4], M. van Driel[1], A. Horleston[5], A. Jacob[6], S. Kedar[3], T. Kawamura[6], A. Khan[1], M. Knapmeyer[7], M. Panning[3], C. Perrin[6], J. Robertsson[1], C. Schmelzbach[1], J-R. Scholz[8], P. Lognonné[6], W. T. Pike[4], B. Banerdt[1], E. Beucler[9], G. Mainsant[10], R. Garcia[10], U. Christensen[8], A. Spiga[6] (1) Institute for Geophysics, ETH Zürich, Zürich, Switzerland (simon.staehler@erdw.ethz.ch), (2) Swiss Seismological Service, Zürich, Switzerland, (3) Jet Propulsion Laboratory, California Institute of Technology, Pasadena, USA, (4) Imperial College London, UK, (5) University of Bristol, Bristol, UK, (6) Université de Paris, Institut de Physique du Globe de Paris, France, (7) Deutsches Zentrum für Luft- und Raumfahrtforschung (DLR), Berlin, Germany, (8) Max Planck Institute for Solar System Research, Göttingen, Germany, (9) Univesité de Nantes, Nantes, France, (10) ISAE-Supaero, Toulouse, France

Introduction: The InSight mission has delivered the first long-term geophysical observatory on the surface of Mars on November 26th, 2018 and it is fully operational since February 2019[1]. In the one year of operation of the seismometer package [2], over 300 seismic events were detected, of which 35 are interpreted as distant, tectonic marsquakes [3]. For 4 of those events, a location could be determined, which for 3 are close to the Cerberus Fossae graben system. We present an overview of the seismic dataset recorded by InSight, the procedures to detect and characterise seismic events and the tectonic interpretation that is possible with the data recorded so far.

Marsquake Service: The Marsquake Service (MQS), led by ETH Zürich, is tasked with reviewing all seismic and auxiliary data and detecting, locating and characterising potential marsquakes and other seismic events [4]. This task is shared by a team of seismologists from 5 institutes in Europe and Northern America and provides the InSight science team with fast bulletins of detected events. A separate review team works on detailed analysis and creates the reference marsquake catalogue of the mission, which is regularly distributed by IRIS / IPGP (InSight Marsquake Service, 2020) .

Marsquakes: The MQS detected 355 seismic events until January 5th. These events generally fall into two classes:
Low-frequency events: which have most energy below 1 Hz and show spectral characteristics compatible with a tectonic source, attenuated by propagation through the Martian mantle. Currently, 35 such events have been detected. The signal-to-noise ratio is generally so low, that seismic phases (compressional P-waves and shear waves) can only be clearly picked for four of them. For those events, distances could be determined with an uncertainty of less than 100 km. For three of those events, a direction could also be determined and they have been located near the Cerberus Fossae system of graben-like structures, 1400-2000 km east-northeast of the lander.
Analysis of similarity of the energy envelope allows estimation of the distance for about half of the other 32 events, and a significant number of them are also likely to have occured in the distance of Cerberus Fossae, while the others are distributed over the Martian hemisphere where InSight is located. For some events, the spectral character suggests a distance beyond the shadow of the Martian core, i.e. on the other hemisphere.
High-frequency events: These events have most energy above 1 Hz and spectral characteristics compatible with propagation in a low-attenuation, high-scattering medium, more similar to the uppermost lunar crust. So far, no absolute distances of these events could be determined, but the envelope shape allows picking of two distinct phases, suggestive of P- and S-waves. This allows determination of relative distances, which cluster and suggest a common source region. However, the waveform similarity is not so high, indicating that the events are not caused by the same exact source, as has been found for the tidally-triggered deep moonquakes.

Tectonic interpretation: The three low-frequency marsquakes located in Cerberus Fossae are the first geophysical observation of an active tectonic process on another terrestrial planet. This is the first observation of an active tectonic process on another planet and is in good agreement with pre-mission geological estimates from orbital imaging [5-7]. Modelling the waveform of the seismic signals allows estimation of the source mechanism of the quakes and thereby constrains the fault orientation.

Seismic activity level of Mars: The 35 distant events that were detected are just a subset of the total seismicity of Mars. The ambient and instrument noise levels are considerably lower than their design requirements, but nevertheless, atmospheric noise prohibits detection of marsquakes smaller than magnitude 4 during the day, even for distances like Cerberus Fossae or less. We simulated an underlying

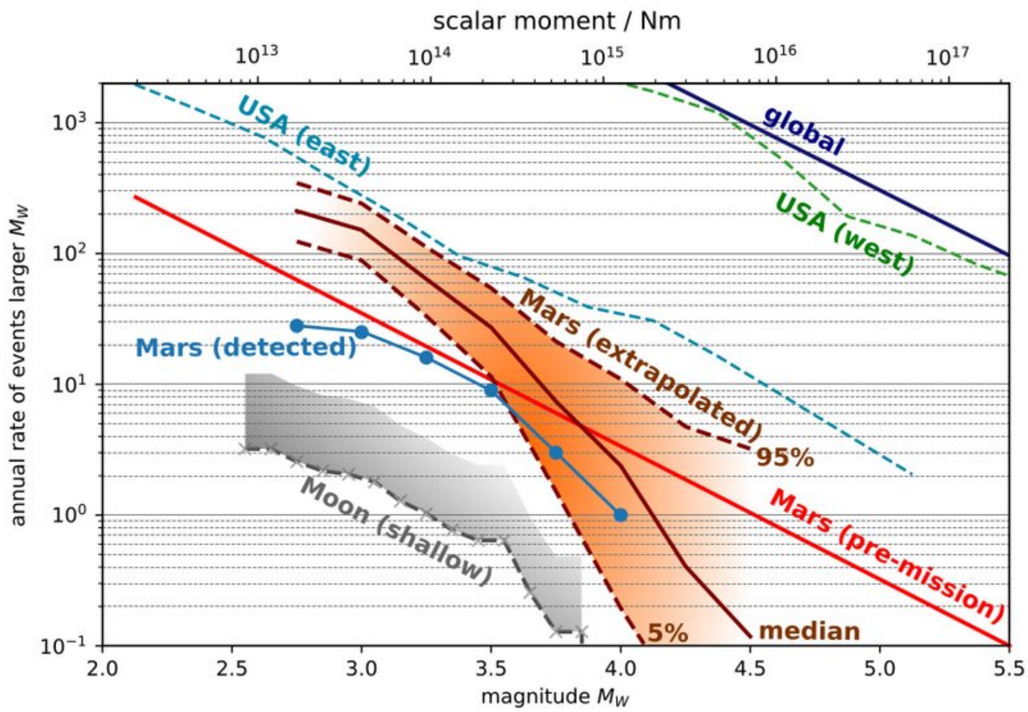

Figure 1: Extrapolated annual seismic activity rate, assuming the 30 detected marsquakes, as well as a distance-magnitude-dependent detection probability curve based on the noise observed so far in the mission. For reference, the rate of lunar events [8] and terrestrial events is shown, as well as the rate in the United States west and east of the Rocky Mountain front. All rates have been scaled to the surface of Mars.

global annual activity rate, modulated with the distance-dependent detection probability to estimate the global activity rate and find that it is significantly above the estimates of Golombek (1992) and in the upper range of Knapmeyer (2006), or slightly below tectonically deformed intraplate regions on the Earth (see fig. 1).

Acknowledgments: The InSight seismic waveform data [9] and seismic event catalogue [10] are available from the IPGP Datacenter and IRIS-DMC. Waveforms are also on NASA PDS.

References:

1. Banerdt, W. B. et al. Early Results from the InSight Mission: Mission Overview and Global Seismic Activity. *Nature Geoscience, submitted*

2. Lognonné, P. L. et al. First constraints on the shallow elastic and anelastic structure of Mars from InSight seismic data. *Nature Geoscience, submitted*

3. Giardini, D. et al: The seismicity of Mars. *Nature Geoscience, submitted*

4. Clinton, J. F. et al. The Marsquake Service: Securing Daily Analysis of SEIS Data and Building the Martian Seismicity Catalogue for InSight. *Space Sci. Rev.* 214, 133 (2018).

5. Knapmeyer, M. et al. Working models for spatial distribution and level of Mars' seismicity. *J. Geophys. Res. Planets* 111, 1–23 (2006).

5. Taylor, J., et al. Estimates of seismic activity in the cerberus fossae region of mars. *J. Geophys. Res. Planets* 118, 2570–2581 (2013).

6. Roberts, G. P., et al. Possible evidence of paleomarsquakes from fallen boulder populations, Cerberus Fossae, Mars. *J. Geophys. Res. Planets* 117 (2012),

7. Golombek, M. P., Banerdt, W. B., Tanaka, K. L. & Tralli, D. M. A prediction of Mars seismicity from surface faulting. *Science* 258, 979–81 (1992).

8. Oberst, J. Unusually high stress drops associated with shallow moonquakes. *J. Geophys. Res.* 92, 1397–1405 (1987).

9. InSight Mars SEIS Data Service. (2019). SEIS raw data, Insight Mission. IPGP, JPL, CNES, ETHZ, ICL, MPS, ISAE-Supaero, LPG, MFSC. https://doi.org/10.18715/SEIS.INSIGHT.XB_2016

10. InSight Marsquake Service (2020). Mars Seismic Catalogue, InSight Mission; V1 2/1/2020. ETHZ, IPGP, JPL, ICL, ISAE-Supaero, MPS, Univ Bristol. Dataset. http://doi.org/10.12686/a6