SEIS achievement for Mars Seismology after 1000 sols of seismic monitoring. P.Lognonné[1], W. B. Banerdt[2], D.Giardini[3], M. P. Panning[2], W.T.Pike[4], S. Barkaoui[1], M. Böse[3] , N. Brinkman[3] , C. Charalambous[4] , N. Compaire[13], N. Dahmen[3] , M. Drilleau[13] , B. Fernando[10], R. Garcia[13], M.T. Hobiger[3] , Q. Huang[22], K. Hurst[2] , A. Jacob[1], F. Karakostas[22,30] , T. Kawamura[1] , S. Kedar[2] , A. Khan[3] , D.Kim[22,3] , B. Knapmeyer-Endrun[16] , M. Knapmeyer[21] , J. Li[8] , S. Menina[1] , N. Murdoch[13] , K. Onodera[1] , C. Perrin[9], L. Pou[20], A. Rajšić[27] , H.Samuel[1], D. Savoie[28] , M. Schimmel[29] , D. Sollberger[3], S.Stähler[3], A.Stott , G. Szilar , M. van Driel[3], N. Wojcicka[4]. P. Zweifel[3], C. Beghein[8], E.Beucler[9], D.Antonangeli[5], D.Banfield[7], N. Bowles[10], E. Bozdag[11], U. Christensen[12], J. Clinton[3], G. Collins[10], I.Daubar[14], J. Irving[15], R. Lorenz[17], L. Margerin[18], C. Michaut[19], D. Mimoun[13], F. Nimmo[20], C.Perrin[9], A-C Plesa[21], N. Schmerr[22], S.Smrekar[2] , A.Spiga[23], N. Teanby[15], J. Tromp[23], R. Weber[24], M. Wieczorek[6], C.Agard[25], E.Barrett[2],J.L.Berenguer[6], S. Ceylan[3], V.Conejero[1], C.Duran[3], N.Dahmen[3], M.Froment[1], A.Horleston[15], C.Ferrier[25], N.Fuji[1], T.Gabsi[1], E.Gaudin[26], B.Jaillant[26] A.Jullien[25], F.Meunier[25], C.Pardo[1], J.ten Pierick[3], M.Plasman[1], L.Rochas[25], G.Sainton[1], E.Stutzmann[1], Z.Xu[1], C.Yana[25], G. Zenhäusern[3] and the InSight/SEIS Science Team; [1]Université de Paris-Institut de physique du globe de Paris-CNRS (lognonne@ipgp.fr), [2]Jet Propulsion Laboratory, California Institute of Technology, [3]ETH-Zürich, [4]Imperial College, [5]IMPMC-Sorbonne Université, [6]Obs. Côte d'Azur, [7]Cornell, [8]UCLA, [9]LPG Nantes,[10]Oxford, [11]CO School of Mines, [12]MPS, [13]ISAE-SUPAERO, [14]Brown University,[15]Bristol University, [16]Univ. Cologne, [17]JHU-APL, [18]IRAP-Univ. Toulouse, [19]ENS Lyon, [20]UCSC, [21]DLR-Berlin, [22]UMD, [23]LMD-Sorbonne Université, [23]Princeton, [24]MSFC,[25]CNES, [26]Telespazio, [27]Curtin University, [28]Observatoire de Paris,[29]Geosciences Barcelona,[30]Istituto Nazionale di Geofisica e Vulcanologia, Bologna.

Introduction: The InSight mission landed on Mars on November, 26, 2018 [1]. The Seismic Experiment for Interior Structure (SEIS) [2] started continuous monitoring with VBBs and SPs on February, 14th, 2019. Only a few 10s of sols are missing since then for VBBs, with monitoring interruptions made only during the first conjunction and during lander safe mode period, and the VBBs are now close from 1000 sols of data acquisitions. We review here the main finding of SEIS in terms of Mars seismology performed in 2021.

Mission goals achievements: The achievement of SEIS with respect to the InSight mission goals are summarized in the Table below. All mission objectives have been addressed successfully and SEIS has been able to provide the first model of the interior of Mars down to the core-mantle boundary of Mars as well as the determination of Mars seismicity.

Mission Objectives	SEIS achievements	References
Crustal Thickness	20-35 km below InSight	[3,4,5,6]
Crustal Stratification	Altered crust in the first 10 km, possible second layer between 20 and 35 km	[3,5,6,7,8,9]
Mantle seismic velocity	7.8 ±0.2 km/s	[10,11,12,13]
Liquid/core state	Liquid at the core/mantle boundary	[14,12]
Core radius	1830±40 km	[14,12,15]
Core density	6000±300 kg/m^3	[14,12,15]
Heat flow	14-29 mW/m^2	[10,12]
Seismic activity	Between Earth and Moon	[16,17,18, 19]
Location of seismic zone	Larger activity in Cerberus	[20,21,22, 23]
Meteorite flux	Improvement by 2 of the pre-launch knowledge	[24]

Deep interior: More in detail, the first interior of Mars inverted from the analysis of SEIS data suggest from the top to the bottom:

- a 10 km low velocity zone with a significant seismic anisotropy [8], likely related to a highly porous zone of the planet, possibly related to cracks associated to impact cratering history [9] and in which alteration occurred in the past. This zone is however today relatively dry, and is characterized with highly scattered waves and low intrinsic attenuation [3,17,25,26],
- A Martian crust/mantle discontinuity either at 20±5 km or 38±8 km, the first model being characterized by a larger porosity and smaller densities (<2700 kg/m^3) as the second one (< 3100 kg/m^3) [3,4,5,6],
- A Martian mantle, with a thick thermal lithosphere of 500±100 km generating a low Shear velocity zone at the base of that lithosphere but relatively constant P velocities [10,12] and with a broad transition zone between 800-1100 km [13],
- A relatively large liquid core of 1830±40 km, making the mantle transition from spinel to dominated bridgmanite impossible [14,12]. Due to its size and the geodetic constrains this core is furthermore associated to low densities, confirming a volatile rich accretion scenario [15].

Crustal inversions were made by using Receiver function analysis of Marsquakes or auto-correlation of seismic noise, while the mantle and core analysis were made with travel time analysis.

Subsurface: The subsurface below the landing site has been constrained either by compliance measurements, from the joint inversion of ground deformation measured by SEIS and pressure loading measured by APSS [27,28], by the measurement of the HP3 signal by SEIS [29] or by the H/V inversion of a seismic signal resonance located at 2.4 Hz [30]. The models obtained from the two first approaches are however not compatible with those obtained from the last one and further works will be necessary to unify them. Climatic variation in autocorrelation have nevertheless been observed, likely related with the temperature variation of the ground [31].

Seismic noise: Despite all efforts in the installation of SEIS by InSight, the noise remains controlled by the wind. Wind sensitivity has been therefore modeled fairly well by comodulation techniques [32,33] or by monitoring lander resonances [34]. In addition, thermal glitches remain an importance source of noise, with non-stochastic character [35] generating potential pitfalls in autocorrelation techniques [36] or a large thermal noise masking Phobos tide signal [37]. Further noise studies have been able to correct for artefact associated to the temperature acquisition [38], to better constrain the SEIS sensor assembly resonances [39], to monitor the ground tilt [40] and quantify orientation errors of SEIS [41].

Seismic activity and Meteor detections: By January 1st, 2022, the current Mars Quake catalog [16,18] comprises almost 1000 distant marsquakes [19], including High Frequency events [17] with significant climatic variability in the occurrence rate [45] and more than 1000 events likely associated with thermal cracking. Cerberus is confirmed as a very active area of Mars and the source mechanism has been constrained for several quakes [21,22], providing new seismo-tectonics constraints [22,23,24] and a recalibration of the prelanding Magnitude estimation [46]. None of the recent landing have generated seismic or acoustic signals strong enough to be detected [42,43,44]. The search for natural impacts continue [47], as well as for events related to infrasounds [47,48] and impact modeling [50,51].

Education and Data access: SEIS data continue to be distributed to about 100 middle and high schools in 15 countries. All SEIS data and MQS activity catalogues until January, 1st, 2022, are available at the SEIS website (http://seis-insight.eu) as well as IRIS and NASA-PDS depository. An access to most of the reference cited in this abstract can also be found in the SEIS website and [52] list SEIS publications made in 2020.

Acknowledgments: The SEIS team acknowledges the supports of NASA, CNES, ANR, UKSA SSO and DLR for the experiment funding and of the InSight operation team for delivering SEIS data and operating the InSight mission.

References: [1] Banerdt et al., Nature Geoscience, 13, 183-189, 2021 ; [2] Lognonné et al., Space Sci Rev, 215, 12, 2019 ; [3] Knapmeyer-Endrun et al., Science, 373, 438-443, 2021 ; [4] Kim et al., J. Geophy. Res., Planets, in press, 2022 ; [5] Compaire et al. J. Geophy. Res., Planets, 126, e2020JE006498, 2021 ; [6] Schimmel et al. Earth and Space Science, 8, e2021EA001755, 2021 ; [7] Lognonné et al, Nature geoscience, 13, 213-220, 2020 ; [8] Li et al., LPSC, 2022 ; [9] Szilar & Nimmo, LPSC, 2022 ; [10] Khan et al, Science, 373, 434-438, 2021 ; [11] Drilleau et al., Geophysical Journal International, 226, 1615–1644, 2021 ; [12] Drilleau et al., submitted, J. Geophys. Res., Planet, 2022 ; [13] Huang et al., LPSC, 2022 ; [14] Stähler et al., Science, 373, 443-448, 2021 ; [15] Khan et al., EPSL, 578, 2022 ; [16] Giardini et al., Nature Geoscience, 13, 205-212, 2020 ; [17] van Driel et al. J. Geophy. Res., Planets,, 126, e2020JE006670, 2021 ; [18] InSight Marsquake Service, V9 2022-01-01, 2021 ; [19] Kawamura et al., LPSC, 2022 ; [20] Brinkman et al, J. Geophys. Res: Planet., 126, e2020JE006546, 2021 ; [21] Jacob, A. et al., submitted, Tectonophysics, 2022 ; [22] Perrin et al., J. Geophys Res., Planet, in press, 2022 ; [23] Kedar et al. J. Geophys Res., Planet, 126, e2020JE006518. 2021 ; [24] Garcia et al., LPSC, 2022 ; [25] Karakostas et al., Bull. Seism. Soc. America, 111, 3035–3054., 2021 ; [26] Menina et al., Bull. Seism. Soc. America, 111, 3016–3034, 2021 ; [27] Murdoch et al. J. Geophys Res., Planet, 126, e2020JE006410, 202 ; [28] Onodera et al Submitted, J. Geophys. Res., 2022 ; [29] Sollberger et al. Earth and Space Science, 8, e2020EA001234, 2021 ; [30] Hobiger et al. Nat Commun 12, 6756, 2021 ; [31] Compaire et al., Geophysic. Journal. Int., ggab499, 2021 ; [32] Charalambous et al., J.Geophys. Res.: Planet, 126, e2020JE006538, 2021 [33] Charalambous et al. J.Geophys. Res.: Planet, 126, e2020JE006757, 2021 [34] Dahmen et al., Bull. Seism. Soc. America, 111, 2924–2950, 2021 [35] Barkaoui et al., Bull. Seism. Soc. America, 111, 2964–2981, 2021 [36] Kim et al. , Bull. Seism. Soc. America, 111, 2982–3002., 2021 ; [37] Pou et al. Earth and Space Science, 8, e2021EA001669, 2021 [38] Zweifel et al., Bull. Seism. Soc. America, 111, 2909–2923, 2021 [39] Hurst et al., Bull. Seism. Soc. America, 111, 2951–2963, 202 [40] Stott et al., Bull. Seism. Soc. America, 111, 2889–2908, 2021 [41] Savoie et al., Earth and Space Science, 2021 [42] Fernando et al Earth and Space Science, 8, e2020EA001585, 2021 [43] Fernando et al. Nature Astron, 2021 [44] Fernando et al., Astronomy & Geophysics, 62, 6.22–6.25, 2021; [45] Knapmeyer et al., Earth and Planetary Science Letters, 576,117171, 2021; [46] Böse et al, Bull. Seism. Soc. America, 111, 3003–3015, 2021 [47] Garcia et al., LPSC, 2022 [48] Garcia et al., Bull. Seism. Soc. America, 111, 3055–3064, 2021 [49] Rajšić et al., Earth and Space Science, 8, e2021EA001887, 2021 [50] Rajšić et al., LPSC, 2022 [51] Wojcicka et al., LPSC, 2022 [52] Lognonné et al., LPSC, #2548, 2021