Using the HP[3] mole on InSight to probe the thermal and mechanical properties of the Martian regolith

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The NASA InSight Lander on Mars includes the Heat Flow and Physical Properties Package HP[3] (see Spohn et al. (2018) for a description of the package) to measure the surface heat flow of the planet. The package uses temperature sensors that would have been brought to the target depth of 3–5 m by a small penetrator, nicknamed the mole. The mole requiring friction on its hull to balance remaining recoil from its hammer mechanism did not penetrate to the targeted depth. Instead, it reached a depth of 40 cm, bringing the mole body 1–2 cm below the surface. A discussion of the lessons learned from the penetration failure and suggestions for an improved mole have been given by Spohn et al. (2022). The root cause of the failure - as was determined through an extensive almost two years long campaign - was a lack of friction in an unexpectedly thick cohesive duricrust. (compare Figure 1)
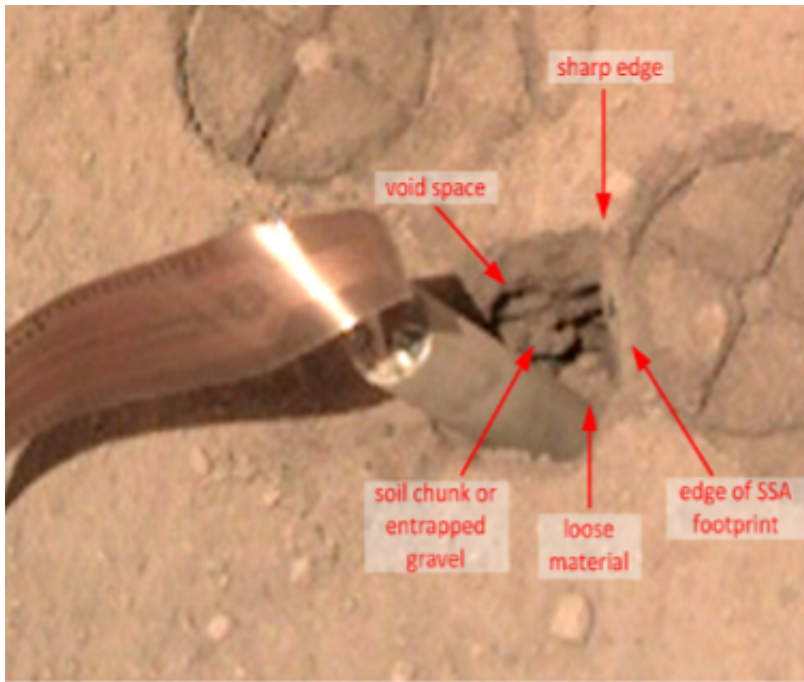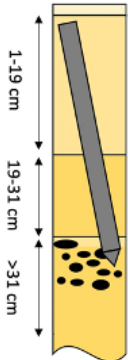
Figure 1. The HP[3] mole before complete burial and the properties of the hole that the mole had punched in the duricrust

During the campaign the mole penetrated further aided by friction applied using the scoop at the end of the robotic Instrument Deployment Arm and direct support by the latter. The mole reversed its downward motion twice during attempts to provide friction through pressure on the regolith instead of directly with the scoop to the hull. The penetration record of the mole and its thermal sensors were used to measure thermal and mechanical soil parameters such as the penetration resistance of the duricrust. These parameter values are summarized in Table 1 below. The combined data suggest a model of the regolith that has an about 20 cm thick duricrust underneath a 1 cm thick sand layer and above another 10 cm of sand. Underneath the latter, a layer more resistant to penetration and possibly consisting of debris from a small impact crater was found. The thermal conductivity increases from 14 mW/m K in the 1 cm sand layer to 34 mW/m K in the duricrust and the sand layer underneath the duricrust to 64 mW/m K in the gravel layer below. Applying cone penetration theory, the resistance of the duricrust was used to estimate a cohesion of the latter of 4 - 25 kPa depending on the friction angle of the crust. Pushing the scoop with its blade into the surface and chopping of a piece of crust provided another estimate of the cohesion of 5.8 kPa.

The hammerings of the mole were recorded by the seismometer SEIS and the signals could be used to derive a P-wave velocity and an S-wave as listed (see also Brinkman et al., 2022) representative of the topmost tens of cm of the regolith. Together with a density provided by a thermal conductivity and diffusivity measurement using the mole thermal sensors of about 1211 (Grott et al., 2021), the elastic moduli could be calculated from the seismic velocities.

Type	Density [kg/m³]	Cohesion [kPa]	Penetration Resistance [MPa]	Thermal Conductivity [mW/mK]	Seismic wave velocities [m/s]	Elastic Properties
Unconsolidated Dust/Sand	1300	-	-	Increasing from 14 to 34		Bulk Modulus 9.84±6.54 MPa
Duricrust	1100	4 − 25 @ 30°≤ ϕ ≤ 40°	0.5 − 1.2	34	Compressional $V_P = 114^{+40}_{-19}$ Shear $V_S = 60^{+10}_{-7}$	Shear Modulus 4.32±1.01 MPa
Sand	1300		-			Young's Modulus 11.30±2.87 MPa
Sand/ Gravel	1600	-	5.3	62		Poisson Ratio 0.31±0.15

(Depth ranges shown at left of column: 1-19 cm, 19-31 cm, >31 cm)

Table 1. Model of the InSight landing site regolith

After burial, the mole was used to measure the thermal conductivity of the regolith as a function of the solar longitude (the seasons on Mars). The variations of the thermal conductivity are consequences of the variations in atmosphere pressure with the seasons and the contribution of atmosphere gas in the porous regolith contributing to the thermal conductivity.
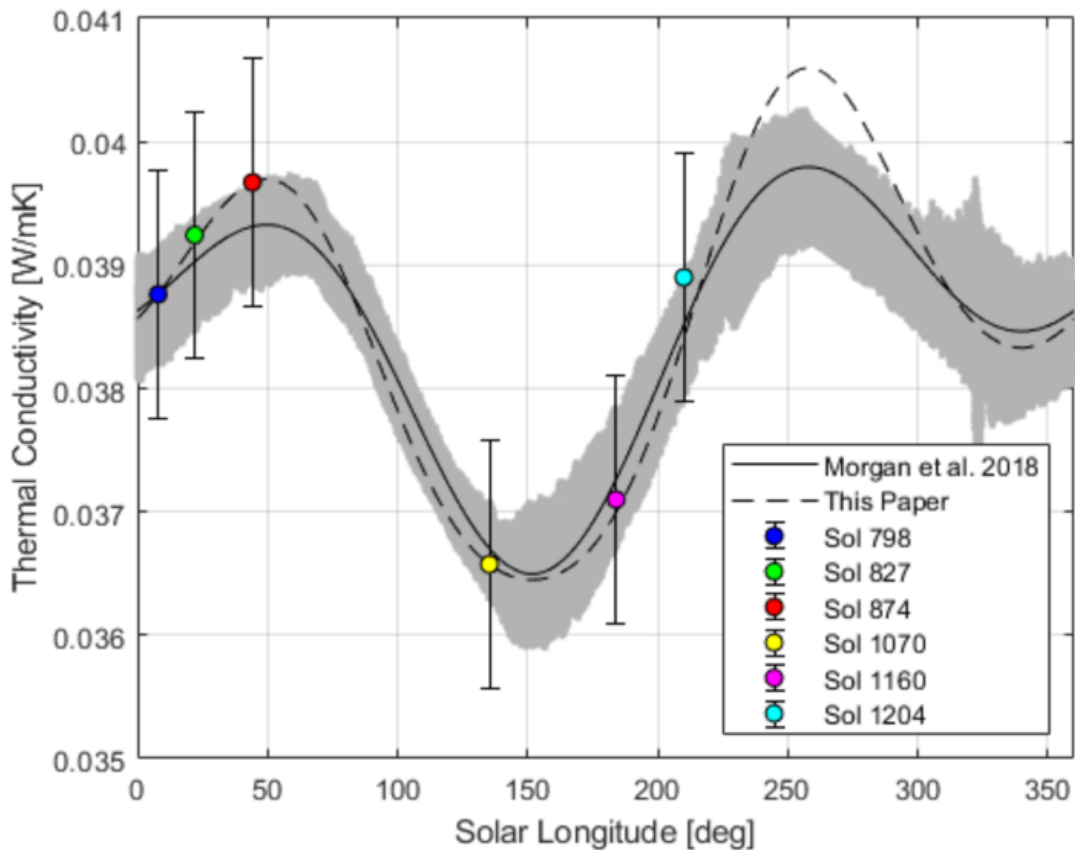
Figure 2 Thermal conductivity in the regolith top 40 cm as measured by sensors on the HP^3 mole as a function of the solar longitude (seasons on Mars).

Brinkmann et al. (2022), submitted to J. Geophys. Res. Planets

Grott et al. (2021), Planet and Space Sci, DOI: 10.1029/2019EA000670

Spohn et al. (2018), Space Sci Rev, DOI:10.1007/s11214-018-0531-4

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