

Key Points:

- The Heat Flow and Physical Properties Package (HP3) measured the average thermal conductivity of the martian soil
- Average soil thermal conductivity in the 0.03–0.37 m depth range is $0.039 \pm 0.002 \text{ W m}^{-1} \text{ K}^{-1}$
- This implies that 85%–95% of all particles are smaller than $104\text{--}173 \mu\text{m}$

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Thermal Conductivity of the Martian Soil at the InSight Landing Site From HP³ Active Heating Experiments

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Abstract The heat flow and physical properties package (HP³) of the InSight Mars mission is an instrument package designed to determine the martian planetary heat flow. To this end, the package was designed to emplace sensors into the martian subsurface and measure the thermal conductivity as well as the geothermal gradient in the 0–5 m depth range. After emplacing the probe to a tip depth of 0.37 m, a first reliable measurement of the average soil thermal conductivity in the 0.03–0.37 m depth range was performed. Using the HP³ mole as a modified line heat source, we determined a soil thermal conductivity of $0.039 \pm 0.002 \text{ W m}^{-1} \text{ K}^{-1}$, consistent with the results of orbital and in-situ thermal inertia estimates. This low thermal conductivity implies that 85%–95% of all particles are smaller than $104\text{--}173 \mu\text{m}$ and suggests that soil cementation is minimal, contrary to the considerable degree of cementation suggested by image data. Rather, cementing agents like salts could be distributed in the form of grain coatings instead. Soil densities compatible with the measurements are $1211_{-113}^{+149} \text{ kg m}^{-3}$, indicating soil porosities of $63_{-9}^{+4}\%$.

Plain Language Summary The heat flow and physical properties package (HP³) of the InSight Mars mission is an instrument package that was designed to measure soil temperature as well as the soil's ability to transport heat, the so called thermal conductivity. After the probe was inserted to a depth of 0.37 m a first measurement of the soil's thermal conductivity was performed. The soil was found to be a poor thermal conductor with average conductivity close to $0.039 \text{ W m}^{-1} \text{ K}^{-1}$. As thermal transport properties in sands are related to grain size, the latter can be estimated based on the performed measurement. We find that particles must be smaller than about $150 \mu\text{m}$, corresponding to fine sand that may be intermixed with dust. Further, salts in the soil can act as cementing agents, which connect individual sand grains and thus increase the strength of grain-to-grain contacts and therefore thermal conductivity. However, given the low thermal conductivity determined here, the amount of such cement must be minimal, contrary to what is suggested by image data. Finally, we find that the soil must have significant porosity of about 60% to be compatible with our measurements.

1. Introduction

The martian near surface layer consists of sand-sized as well as dust-sized particles (Christensen & Moore, 1992) interspersed with larger rocks, and its detailed structure depends on the deposition process as well as subsequent surface modifications by eolian and fluvial activity. Under present martian atmospheric conditions sand-sized particles in the $100\text{--}600 \mu\text{m}$ size range can be moved by winds through saltation (Kok et al., 2012), and dust particles of typical sizes around $1.5 \mu\text{m}$ are suspended in the atmosphere and can reach the ground in the form of airfall (Lemmon et al., 2019), such that aeolian processes are generally recognized to be the prevalent surface modification process on Mars today.

The thermal conductivity is a fundamental physical property of the surface material and determines the rate at which heat can be transferred from the interior to the surface and vice versa. Heat is transported

through grain-to-grain contacts, conduction through the pore-filling gas, as well as radiation between individual grains, and the conductivity of the martian soil holds information on the soil's bulk porosity, composition, grain size (Presley & Christensen, 1997; Presley & Craddock, 2006; Piqueux & Christensen, 2009a), as well as the state of cementation or induration (Presley et al., 2009; Piqueux & Christensen, 2009b). Thermal properties of the martian soil can thus provide critical information to better understand the local, regional and global geologic processes modifying the surface of Mars, including material redeposition as well as soil-atmosphere interactions. The latter can result in cementation or induration by salts, which may be common on Mars (Banin et al., 1992; Ditteon, 1982; Haskin et al., 2005; Hurowitz et al., 2006; Moore et al., 1999; Mutch et al., 1977) and can have a significant influence on thermal properties by increasing the contact area between individual grains (Piqueux & Christensen, 2009a).

Thermal properties of the martian soil have primarily been estimated from remote sensing infrared observations conducted from orbit (Golombek et al., 2008; Kieffer et al., 1977; Mellon et al., 2000; Palluconi & Kieffer, 1981; Putzig & Mellon, 2007), but some investigations have also been performed on the ground (Ferguson et al., 2006; Golombek, Warner, et al., 2020; Hamilton et al., 2014). In general, thermal inertia

$$\Gamma = \sqrt{k\rho c_p} \quad (1)$$

is derived from measurements of the surface brightness temperature, where k is thermal conductivity, ρ is density, and c_p is specific heat capacity. Globally, thermal inertia was found to have a bimodal distribution (Kieffer et al., 1977; Mellon et al., 2000; Putzig & Mellon, 2007), with peaks around 75 and 250 $\text{J m}^{-2} \text{K}^{-1} \text{s}^{-1/2}$, representing dust covered and dust free surfaces, respectively. Higher thermal inertia units are associated with impact craters and their ejecta as well as intercrater dunes, the latter potentially due to larger average particle sizes (Mellon et al., 2000). Further, outflow channels and valleys consistently show higher thermal inertias than the surrounding terrain (Mellon et al., 2000). Finally, it has been argued that high thermal inertia may be related to soil induration (Jakosky & Christensen, 1986; Mellon et al., 2000), often referred to as duricrust.

Thermal conductivity can be interpreted in terms of soil grain size (e.g., Hamilton et al. (2014)) by a comparison with results from laboratory experiments (Presley & Christensen, 1997; Presley & Craddock, 2006). Estimates of grain size were found to be robust if cementation of the soil is minimal and indurated surface layers are much thinner than the diurnal skin depth. Edwards et al. (2018) compared orbital and rover results with grain size estimates derived from direct microscopic imaging at a dune field in Gale Crater and found that particle sizes derived from the different datasets yield consistent results, indicating that grain sizes of homogeneous material derived from temperature measurements are reliable. The determination of grain size from thermal conductivity is enabled by a strong dependence of conductivity on pore size, which in turn results from the mean free path of gas molecules being similar to pore size under current martian atmospheric conditions (Piqueux & Christensen, 2009a). Gas flow in the martian soil occurs in the transitional flow regime, resulting in a much stronger dependence of conductivity on pore size (and thus grain size) than in either the slip flow or the free molecular flow regimes, which are encountered for higher and lower pressures, respectively. Note, however, that thermal conductivity is expected to be only weakly dependent on grain size in cemented soils, in which case conduction through the gas phase becomes less important when compared to conduction through the soil matrix (Piqueux & Christensen, 2009b).

Out of the few measurements from the ground, most have been performed using radiometric methods, and thermal inertia at the Mars Exploration Rover landing sites was determined using the mini-TES instrument for a number of bedforms (Ferguson et al., 2006). Particle sizes derived from these measurements were 45–415 μm and were generally found to be consistent with those derived from Microscopic Imager data. Although some discrepancies in the data analysis remained, results indicated that in most cases the relationship between thermal inertia and effective particle size as determined in the laboratory (Presley & Christensen, 1997) also holds for the mini-TES observations (Ferguson et al., 2006).

At Gale Crater (4.59°N, 137.44°E) thermal inertia was determined using the REMS GTS sensor (Gómez-Elvira et al., 2012), and thermal properties of loose material, mudstone, and sandstone could be clearly distinguished (Vasavada et al., 2017). While the bedrock component showed thermal inertia as high as 650–1700 $\text{J m}^{-2} \text{K}^{-1} \text{s}^{-1/2}$ at mudstones sites, it was approximately 700 $\text{J m}^{-2} \text{K}^{-1} \text{s}^{-1/2}$ at sandstones sites. Inertia of loose

material along the Curiosity rover's traverse ranged from 265 to 375 J m⁻² K⁻¹ s^{-1/2} (Hamilton et al., 2014). Furthermore, thermal inertia was found to be 180–215 J m⁻² K⁻¹ at a sand patch called Rocknest. Using thermal inertia as a proxy for grain size and comparing results with those from laboratory experiments (Presley & Christensen, 1997), thermal inertia of loose material was found to be generally consistent with particle sizes determined from images (Edgett et al., 2013; Yingst et al., 2013). Millimeter sized particles dominate along the rover's traverse, and thermal inertia at Rocknest indicates particle sizes around 200 μm.

To date, the only direct thermal measurement using needle probes was performed by the thermal and electrical permittivity probe (TECP) during the Phoenix mission, which landed in Vastitas Borealis at 68.22°N 234.25°E and investigated the martian polar regions in a search for subsurface ice (Mellon et al., 2009). TECP measurements indicated a thermal conductivity of 0.085 W m⁻¹ K⁻¹ and an average ρc_p equal to $1.05 \cdot 10^6$ J m⁻³ K⁻¹ (Zent et al., 2010). The dry material above the ground ice was therefore found to be a good thermal insulator, protecting the ice from large temperature excursions during noontime.

Here we report on direct thermal conductivity measurements at the InSight landing site in Homestead hollow, located in the Elysium Planitia region (4.50°N, 135.62°E) (Banerdt et al., 2020). In the region, the regolith is estimated to constitute a 3–17 m thick layer of broken up material (Warner et al., 2017), and regolith thickness at the landing site itself is estimated to be close to 3 m (Golombek, Kass, et al., 2020). The stratigraphy exposed underneath the InSight lander indicates layering consistent with a surficial dust layer over thin unconsolidated sand, underlain by a cohesive duricrust, which appears to be at least 5–10 cm thick (Golombek, Warner, et al., 2020) and may be underlain by unconsolidated cohesive sand mixed with rocks (Hudson et al., 2020).

Thermal inertia at the landing site was found to be 160–230 J m⁻² K⁻¹ s^{-1/2} (Golombek, Warner, et al., 2020), consistent with estimates obtained by the Thermal Emission Spectrometer (TES) (Mellon et al., 2000; Putzig & Mellon, 2007), which determined inertias of ~200 J m⁻² K⁻¹ s^{-1/2} from orbit. Further, the Thermal Emission Imaging System (THEMIS) of the Mars Odyssey mission showed a high homogeneity of thermal properties at the 100 m scale and a median thermal inertia of around 180 J m⁻² K⁻¹ s^{-1/2} near the landing site (Golombek et al., 2017; Golombek, Kass, et al., 2020), indicating that measurements performed by the InSight radiometer are representative of the regional soil properties. In addition, the lack of significant seasonal variations in thermal inertia suggest the same material extends down to a few tens of centimeters depth.

2. Probe Emplacement

The InSight Mars mission (Banerdt et al., 2020) landed in the Elysium Planitia region on Mars (Golombek et al., 2018; Golombek, Warner, et al., 2020; Golombek, Williams, et al., 2020) on November 26, 2018, and installed a geophysical and meteorological station at the landing site. One of InSight's payloads is the Heat Flow and Physical Properties Package (HP³), which was designed to make the first direct measurement of the martian planetary heat flow (Grott et al., 2007, 2019; Spohn et al., 2018). To determine heat flow, HP³ was designed to emplace 14 temperature sensors to a target depth of 5 m using a self-hammering penetrator called “the mole”. During descent, the depth of the sensors is determined from the attitude of the mole with respect to vertical using static tiltmeters, while simultaneously measuring the amount of paid-out tether. Furthermore, a profile of subsurface thermal conductivity was planned to be determined at 50 cm depth intervals using the mole as a modified line heat source (Hammerschmidt & Sabuga, 2000).

After an initial phase of surface characterization, first the InSight seismometer and then the HP³ were deployed onto the surface by the lander's robotic arm (Golombek, Williams, et al., 2020). HP³ then started hammering on Sol 92 of the mission (February 28, 2019), but the depth sensor did not show significant progress despite the fact that 3,600 hammering strokes had been executed. Hammering was recommended at the next opportunity, and an additional 5,000 strokes were executed on Sol 94 (March 2, 2019). At this point it became clear that the probe did not penetrate as expected. In an attempt to resolve the anomaly the HP³ support structure was removed from above the mole, exposing the probe for further investigation on Sol 209 (June 29, 2019).

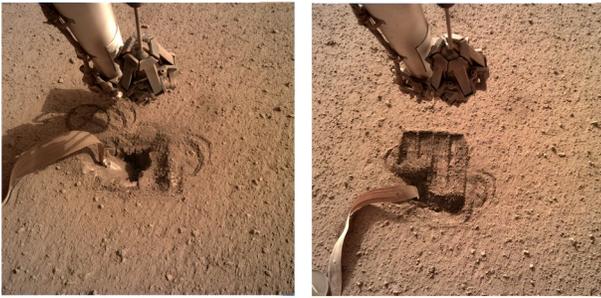


Figure 1. Left: Mole configuration on Sol 598 before scraping soil into the mole pit. Note steep walls of the pit indicating cohesive duricrust. Right: Sol 674 after filling the pit and after retracting the robotic arm. The active heating experiment reported here was conducted in this configuration.

Insufficient friction to compensate for recoil during hammering was identified as the basic cause of the penetration anomaly (Hudson et al., 2020). Using the lander's robotic arm, friction was provided by first pressing on the side of the mole (Sol 302 to Sol 407; October 2, 2019, to January 18, 2020) and later recoil was compensated by pressing directly onto the back of the mole (Sol 427 to Sol 557; February 8, 2020, to June 20, 2020). In this way, it was possible to bury the back of the mole step-wise to approximately 3 cm below the surface using an additional 1,700 strokes in total. The average penetration rate during this time was 0.15 mm per stroke. Together with a mole length of 40 cm and a mole inclination of 30° with respect to vertical, this depth corresponds to a mole tip depth of approximately 37 cm. Therefore, the measurements presented here represent average thermal conductivity in the 0.03–0.37 m depth range.

The left hand panel of Figure 1 shows the configuration of the mole after reaching the maximum depth possible using direct support from the robotic arm to compensate recoil. Tilt of the mole as well as a highly cohesive soil layer and a sizeable pit surrounding the mole are apparent. After filling some material into the pit the robotic arm pressed on the mole, but the following hammering attempts between Sol 618 and Sol 645 (August 22 to September 19, 2020) showed no clear indication of significant (>1 cm) further depth progress. Subsequent activities focused on filling the pit to increase friction between the mole and soil, but no additional hammering was performed before the TEM-A measurement on Sol 680.

During the period of mole recovery activities, a number of active heating experiments to determine the thermal conductivity of the soil were performed (Sols 97, 116, 211, 380, and 536). However, all of these suffered from the fact that the mole was not fully buried, thus providing reduced thermal contact to the soil. In addition, direct solar illumination induced a large background temperature variation superimposing the heating curve with a strong diurnal signal and complicating data analysis. In contrast, the mole was fully buried during the measurement conducted on Sol 680, and the corresponding configuration is shown in the right hand panel of Figure 1. During the measurement, the mole was protected from direct insolation and the residual diurnal temperature amplitude was only 4 K at the effective depth of the temperature sensors in the mole. In the following we report on the results of the Sol 680 measurement and the average soil thermal conductivity in the 0.03–0.37 cm depth range.

3. Modeling

3.1. Data Reduction

HP³ measures thermal conductivity by operating the mole as a modified line heat source (Hammerschmidt & Sabuga, 2000; Jaeger, 1956). During a measurement, a specified constant heating power is provided to the mole's outer hull and the resulting temperature rise is monitored as a function of time (Grott et al., 2019; Spohn et al., 2018). Soil thermal conductivity can then be determined from the rate of self heating, where a fast temperature increase corresponds to low thermal conductivity and vice versa. Note that this method is slightly different from the dual needle technique applied by the TECP probe (Zent et al., 2010), which generates a heat pulse at one needle and measures the temperature rise at a second needle.

Before the active heating experiment was started on Sol 681, the background temperature drift was monitored for 2 Sols. Operations were then timed such that heating started at 21:00 local true solar time (LTST), thus allowing temperature perturbations induced by direct insolation to decay, while at the same time maximizing the time before sunrise. Furthermore, care was taken to ensure that sources of shadow like the robotic arm did not move during the experiment to minimize day-to-day temperature variations. The heating power of the probe was set to 2 W to increase the temperature rise during the heating phase to the greatest possible amount, thereby increasing the signal-to-noise ratio with respect to background temperature variations.

Temperature data obtained for the active heating experiment conducted between Sols 680 and 682 are shown in Figure 2a, where temperature is given as a function of LTST and color-code indicates the Sol of

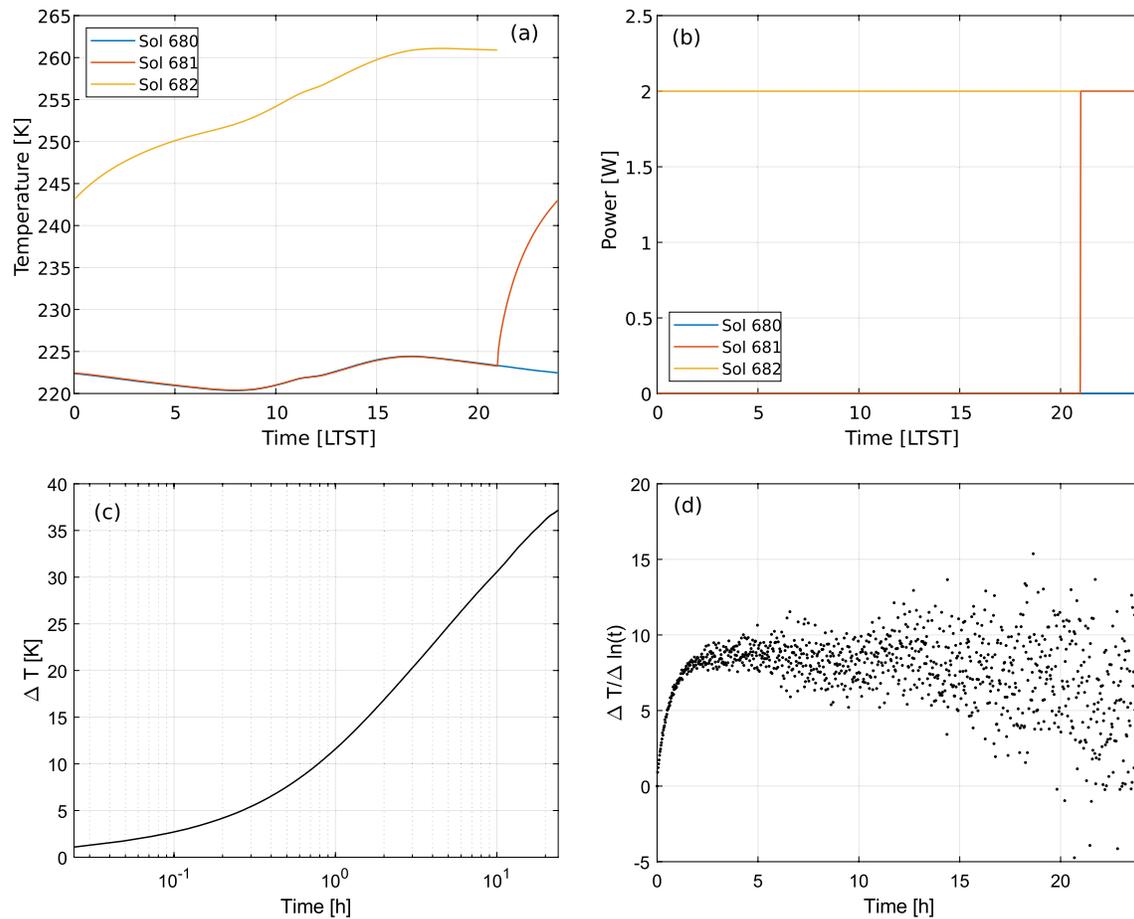


Figure 2. Illustration of steps taken during data reduction. (a) Temperature as a function of local true solar time (LTST) for the three Sols of the experiment. Heating was activated on Sol 681 at 21:00 LTST and continued for 24 h. (b) Heating power as a function of local time for the same time frame. (c) Heating curve (temperature rise as a function of time) extracted from the data shown in (a) (see text for details). (d) Logarithmic time derivative of the temperature rise shown in (c) as a function of time.

the measurement. The heating power dissipated in the probe is shown in panel (b) of the figure for the same time frame, demonstrating that heating power was kept constant by the control loops in the HP³ electronics during the experiment. As shown, temperature was monitored on Sol 680 and Sol 681 before switching on the heaters at 21:00 LTST on Sol 681. The background temperatures show a diurnal amplitude of 4 K, with maximum temperatures reached at 16:40 and minimum temperatures at 8:00 LTST. As is evident from the figure, background temperatures are highly repeatable, and we found day-to-day variations to be smaller than 80 mK.

We then extracted the heating curve between Sol 681 21:00 LTST and Sol 682 21:00 LTST by subtracting the background temperatures from Sol 680 21:00 LTST to Sol 681 21:00 LTST from the data, and temperatures were then referenced to the start of the heating interval at 21:00 LTST on Sol 681 to obtain the temperature rise ΔT as a function of time, which is shown in Figure 2c. Furthermore, data was downsampled from 5,548 to 1,000 points by linear interpolation to save computing time. A slight change of slope caused by background temperature fluctuations is visible during the final hours of heating, and we disregard data at times later than 21 h 40 min after start of heating for the data inversion below. Furthermore, data before 1 h was also not considered, as this part of the heating curve is most sensitive to the unknown contact conductance between probe and soil. Therefore, to reduce uncertainties associated with the unknown contact conductance, we performed inversions between 1 and 21 h 40 min only. Figure 2d shows the logarithmic time derivative of the heating curve to illustrate the amount of scatter, which is caused by short-term temperature fluctuations resulting from the diurnal temperature forcing. Therefore, rather than using the logarithmic

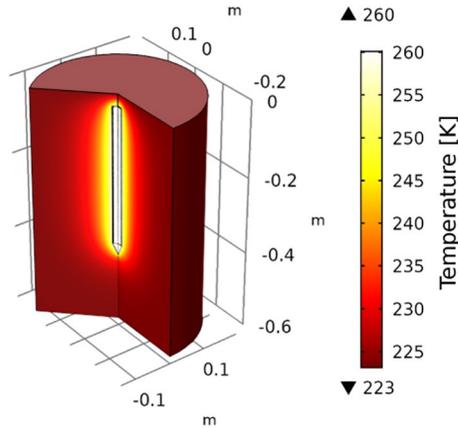


Figure 3. Illustration of the temperature distribution in the finite element model at the end of the heating period. The soil thermal conductivity used in the model was $0.04 \text{ W m}^{-1} \text{ K}^{-1}$, heating power was 2 W, the back of the mole was assumed to be 3 cm below the surface.

time derivative as a fitting function (Grott et al., 2019; Spohn et al., 2018), we use the heating curve itself to determine soil thermal conductivity in the following.

3.2. Data Inversion

We used forward modeling of the heating curve to determine the admissible range of soil parameters. The temperature response to heating of the mole was modeled using a finite element model in cylindrical geometry. The model encompasses a reduced thermal model of the mole including the hull, motor, hammering mechanism, heaters, the science tether connecting the mole to the electronics, and the surrounding soil. The model solves the initial value problem posed by the heat conduction equation and associated boundary conditions starting from thermal equilibrium, and thermophysical properties of the mole and soil need to be prescribed. In addition, thermal contact conductance between the mole and soil is explicitly taken into account, as this can have a significant influence on the temperature rise during the first part of the experiment (also compare Grott et al. (2010) for the lunar case). Details of the finite element model are given in Grott et al. (2019).

To determine the range of admissible soil parameters, we ran Monte Carlo simulations varying soil thermal conductivity k , soil density ρ , as well as thermal contact conductance between probe and soil H to determine parameter combinations which allowed us to fit the heating curve within admissible limits. The latter were defined based on the observation that background temperature drift was reproducible to within 80 mK on consecutive sols. Furthermore, probe calibration may have drifted as a consequence of being exposed to diurnal temperature cycles. Temperature drift can result in an additional 0.4% uncertainty for temperature difference measurements (Grott et al., 2019), and given a temperature rise of 37.3 K during the measurement, potential sensor drift adds an additional uncertainty of 150 mK. Assuming Gaussian uncertainty propagation, total admissible uncertainty δT is then given by

$$\delta T = \sqrt{\delta T_{\text{var}}^2 + \delta T_{\text{drift}}^2} \quad (2)$$

where δT_{var} and δT_{drift} are the uncertainty contributions stemming from day-to-day variations and potential sensor drift, respectively. Therefore, we require the forward model to reproduce temperatures to within $\delta T = 170 \text{ mK}$.

For each model run of the Monte Carlo simulation, the modeled temperature $T_{\text{mod}}(t, k, \rho, H)$ was then compared to the measured temperature rise $T_{\text{dat}}(t)$ and the root mean square deviation between the two quantities was determined according to

$$\Delta T_{\text{rms}}(k, \rho, H) = \left(\sum_{i=1}^n (T_{\text{mod}}(t_i, k, \rho, H) - T_{\text{dat}}(t_i))^2 / n \right)^{1/2} \quad (3)$$

Here, $n = 1,000$ is the number of measurement points, and $t_1 = 1 \text{ h}$ and $t_n = 21 \text{ h } 40 \text{ min}$ correspond to the beginning and the end of the inversion interval, respectively (see above). In case $\Delta T_{\text{rms}}(k, \rho, H) < \delta T$, the combination of parameters k , ρ , and H was considered admissible

An illustration of the results of the finite element model is shown in Figure 3, where the color coded temperature field is shown for the best fitting model. Heating was active for 21 h 40 min at a heating power of 2 W, and soil thermal conductivity was assumed to be $0.039 \text{ W m}^{-1} \text{ K}^{-1}$. Although heat transport is primarily in the radial direction, some heat is also lost along the mole axis, illustrating the need to consider a probe with finite length in contrast to analytical solutions for this type of heat conduction problem (Jaeger, 1956).

The computational domain has a diameter of 0.4 m, large enough to minimize boundary effects, and the heat from the mole penetrates a few centimeters into the soil.

An additional constraint that can be considered to restrict the range of admissible models is posed by the surface thermal inertia, which is sensitive to the upper ~ 0.07 m of the soil and ranges from 160 to 230 J m⁻² K⁻¹ s^{-1/2} at the landing site (Golombek, Warner, et al., 2020). If soil parameters are assumed to be constant as a function of depth, parameter combinations determined here should also satisfy this additional constraint. Here we assume a soil specific heat capacity c_p of 630 J kg⁻¹ K⁻¹ (Morgan et al., 2018) to convert density and thermal conductivity into thermal inertia Γ , and models satisfying the additional constraint $160 \leq \Gamma \leq 230$ J m⁻² K⁻¹ s^{-1/2} (Golombek, Warner, et al., 2020; Piqueux et al., 2021) will be discussed in addition to the models fitting the heating curve only.

4. Results

4.1. Monte Carlo Simulations

We calculated forward models of the heating experiment varying the soil thermal conductivity k , density ρ , as well as the thermal contact conductance between probe and soil H , searching for models which fit measured temperatures within error bounds and within the constraints posed by the surface thermal inertia. To reduce the number of Monte Carlo simulations, we first conducted a series of test calculations, varying thermal conductivity between $0.01 \leq k \leq 0.1$ W m⁻¹ K⁻¹, soil density between $600 \leq \rho \leq 1,800$ kg m⁻³, and contact conductance between $3 \leq H \leq 250$ W m⁻² K⁻¹ to narrow down the parameter space. We found that only conductivities between 0.034 and 0.045 W m⁻¹ K⁻¹ yielded admissible models, such that the full Monte-Carlo run was restricted to these conductivities in the following. In total, 45,000 models were calculated and parameters were assumed to be equally distributed in the above intervals. For each draw of parameters, the resulting model was compared with the data and 229 models reproduced measured temperatures within error bounds. Out of these models, 102 satisfied the additional constraint posed by the surface thermal inertia.

Results of the calculations are shown in Figure 4, where the best fit model is shown together with the data and associated uncertainties in panel (a). As is evident, the model fits the data excellently, and the residual root mean square misfit is only 60 mK. The logarithmic time derivative of the data is shown together with the best fit model in panel (b), demonstrating that the model also fits the time derivative well on average. Histograms of admissible thermal conductivities are shown in Figure 4c, where the histogram for models fitting the heating curve is shown in light green (1- σ), while models satisfying the additional constraint posed by the observed surface thermal inertia are shown in red. For the two cases considered, thermal conductivity is $k = 0.0395 \pm 0.0006$ and $k = 0.0395 \pm 0.0008$ W m⁻¹ K⁻¹, respectively. Overall, only a very small range of thermal conductivities fits the data, allowing us to put tight constraints on the admissible values.

Histograms for the admissible soil density are shown in Figure 4d, and a large range of admissible values is visible. The Median density for models satisfying the heating curve constraint is 1,007 kg m⁻³ and the 25th and 75th percentile are given by 993 and 1,184 kg m⁻³, respectively, corresponding to an interquartile range or midspread of 191 kg m⁻³. For models satisfying the additional constraint posed by the surface thermal inertia, the median density is 1,211 kg m⁻³ with 25th and 75th percentiles of 1,098 and 1,360 kg m⁻³, corresponding to a midspread of 262 kg m⁻³. Finally, contact conductances compatible with the available constraints have median contact conductances of 70 and 28 W m⁻² K⁻¹ for models satisfying the heating curve and the thermal inertia constraint, respectively (not shown). The 25th and 75th percentiles are 30 and 121 W m⁻² K⁻¹ and 19 and 37 W m⁻² K⁻¹, respectively. For comparison, 10 W m⁻² K⁻¹ corresponds to the conductance across a 1 mm wide, CO₂ filled gap, whereas 2 W m⁻² K⁻¹ would correspond to purely radiative coupling at 220 K. Therefore, contact conductances needed to fit the data are reasonable.

4.2. Uncertainty Error Budget

The total measurement uncertainty for the determination of thermal conductivity from HP³ active heating experiments was estimated by Grott et al. (2019) to be 3.7%. However, it was assumed that the influence of the unknown soil density and contact conductance would be small due to the fact that the logarithmic time derivative of the temperature rise at large times t could be used for the fitting. As this is not the case

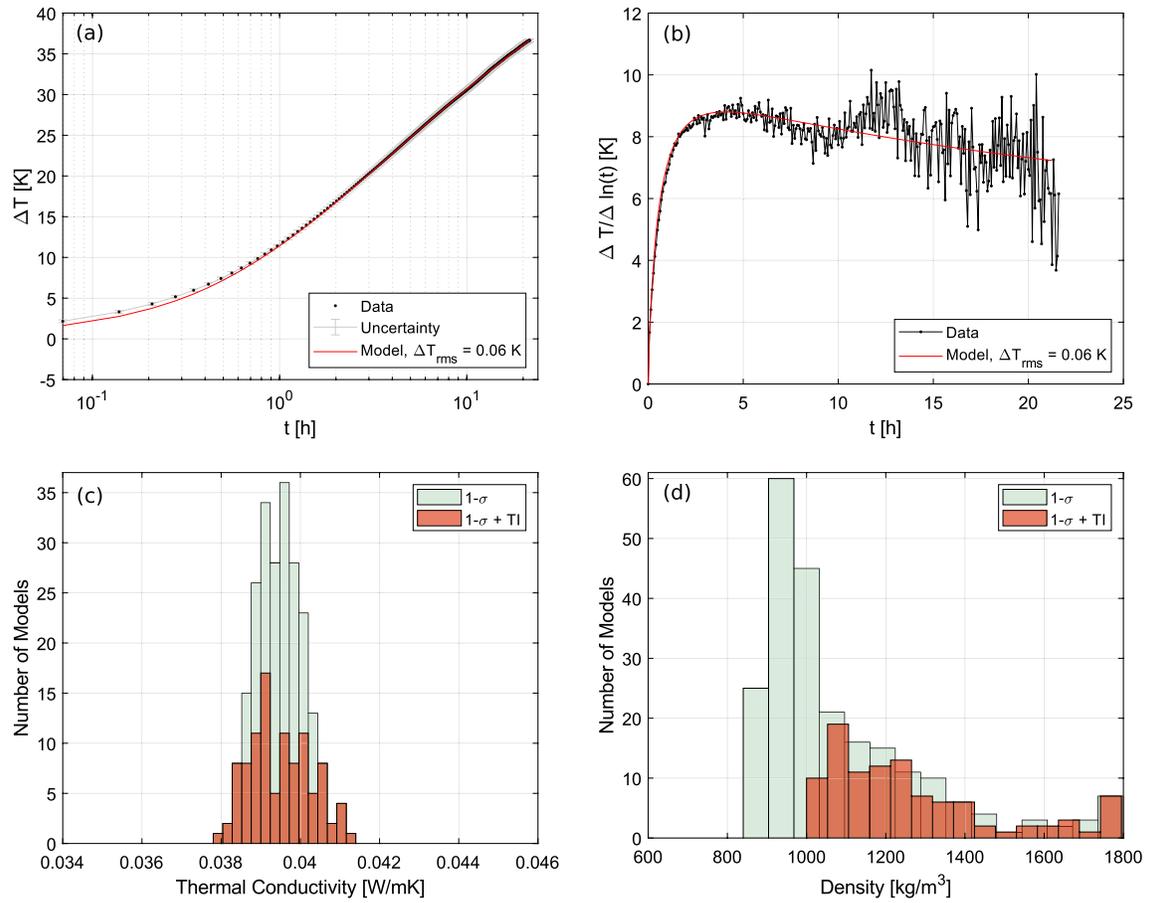


Figure 4. Result of the Monte-Carlo inversion. (a): Temperature rise as a function of time (black) together with the associated measurement uncertainty (gray) during the Sol 680–682 active heating experiment together with the best fit model (red). (b) Logarithmic time derivative of the temperature rise as a function of time (black) together with the best fit model (red). (c) Histogram of thermal conductivities for the models fitting the prescribed uncertainty within error bounds (1- σ , light green) as well as histogram of models also fitting the constraint posed by the surface thermal inertia (red). (d) Same as (c), but showing the histogram of admissible soil densities.

for the data set considered here, the contributions of unknown soil density and contact conductance to the uncertainty budget need to be reassessed.

Total measurement uncertainty for the determined thermal conductivity σ_k is given by Gaussian error propagation, and

$$\sigma_k = \left(\sigma_Q^2 + \sigma_{reg}^2 + \sigma_{mod}^2 + \sigma_{THS}^2 \right)^{1/2} \quad (4)$$

Here, σ_Q is the uncertainty associated with determining the heat input into the TEM-A foils, σ_{reg} is the contribution stemming from the allowable spread of models determined using the Monte Carlo simulations above, and σ_{mod} is the uncertainty associated with the imperfections of the finite element model representing the mole. The latter has been estimated during instrument calibration by a comparison with measurements in a low thermal conductivity granulate (Grott et al., 2019). Finally, σ_{THS} is the uncertainty of the reference measurement originally used to calibrate the finite element model (Hammerschmidt & Sabuga, 2000). The numerical values of these contributions are summarized in Table 1, and a total 1- σ uncertainty of 3.9% is obtained for the conductivity determined here. Given a best fit thermal conductivity of $0.039 \text{ W m}^{-1} \text{ K}^{-1}$, this corresponds to an uncertainty of $\pm 0.002 \text{ W m}^{-1} \text{ K}^{-1}$.

Table 1
Error Sources Taken Into Account for Determining the Thermal Conductivity Uncertainty Budget

Error source	Value [%]	Distr.	σ [%]	Remarks
Sensor Heat input	0.1	normal	0.1	Grott et al. (2019)
Soil density, thermal contact	2	normal	2	This paper
Modeling	4	uniform	2.3	Grott et al. (2019)
Reference method	2.5	normal	2.5	Grott et al. (2019)
Total 1σ uncertainty			3.9	

Note. Uncertainty, distribution function, as well as error contribution σ are given together with an indication of how the individual contributions were derived. Following the relevant standards (VIM, 2004; GUM, 2008), uniformly distributed uncertainties propagate into the total error budget weighted by one over the square root of three. Stated uncertainties are 1σ confidence limits.

4.3. Particle Size

Thermal conductivity determined from the active heating experiment can be interpreted in terms of soil grain size (e.g., Ferguson et al., 2006) by a direct comparison with laboratory measurements under martian atmospheric conditions (Presley & Christensen, 1997; Presley & Craddock, 2006), and such estimates have been shown to be robust if the material is homogeneous and any indurated surface layers are much thinner than the diurnal skin depth (Edwards et al., 2018). Given soil thermal conductivity k in units of [$\text{W m}^{-1} \text{K}^{-1}$], particle diameter d in units of [μm] can be estimated from

$$d = \left(\frac{k}{CP^{0.6}} \right)^{-1/(0.11 \log(P/K))} \quad (5)$$

where P is atmospheric pressure in torr, and $C = 0.0015$ and $K = 8.1 \cdot 10^4$ are empirical fitting constants (Presley & Christensen, 1997). Equation 5 is valid for thermal conductivities less than $0.1 \text{ m}^{-1} \text{K}^{-1}$, while larger conductivities are more difficult to interpret. Presley and Craddock (2006) have shown that the thermal conductivity of soils which include a variety of particle sizes is dominated by the largest grains, and Equation 5 should provide a reasonable estimate of the size for which 85%–95% of the particles are smaller than the size determined using the above equation. A thermal conductivity-derived particle size is therefore closer to a maximum particle size, rather than an average or modal size. Errors in deriving particle sizes with this method are expected to be less than 10%–15% (Presley & Christensen, 1997), provided cementation does not significantly increase conductance between grains.

Results of applying Equation 5 to the thermal conductivity range of $0.01\text{--}0.05 \text{ W m}^{-1} \text{K}^{-1}$ (corresponding to thermal inertias of $100\text{--}240 \text{ J m}^{-2} \text{K}^{-1} \text{s}^{-1/2}$ assuming $\rho c_p = 10^6 \text{ J m}^{-3} \text{K}^{-1}$, Neugebauer et al. [1971]) are shown in Figure 5, where particle diameter is shown as a function of thermal conductivity (solid line) together with a 15% uncertainty interval (gray). Grain sizes corresponding to a thermal conductivity of $0.039 \pm 0.002 \text{ W m}^{-1} \text{K}^{-1}$ are $136_{-32}^{+37} \mu\text{m}$, corresponding to very fine to fine cohesionless sand.

Images taken by the InSight Instrument Deployment Camera (IDC, Maki et al., 2018) show that steep walls can be supported by the soil at the landing site. This indicates that the assumption of cohesionless sand may be an oversimplification. Rather, soil properties appear to be similar to those at the Phoenix landing site, for which trenches scraped by the robotic arm's scoop exhibited steep walls (Mellon et al., 2009).

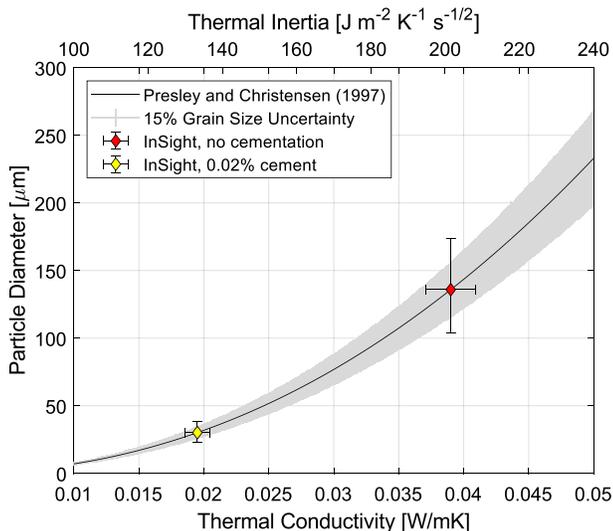


Figure 5. Particle diameter as a function of soil thermal conductivity according to the model of Presley and Christensen (1997) (black). The estimated 15% particle size uncertainty of the model is indicated by the shaded area. The grain size derived from the thermal conductivity determined here is indicated in red, while the grain size derived assuming 0.02 vol% of cement forming necks between particles is indicated in yellow. For reference, the thermal inertia corresponding to the considered thermal conductivities assuming $\rho c_p = 10^6 \text{ J m}^{-3} \text{K}^{-1}$ (Neugebauer et al., 1971) is also given.

Overall, cohesion at the InSight landing site was estimated to be at least 1–1.9 kPa (Golombek, Warner, et al., 2020), but may be as high as 14.5 kPa (Marteau et al., 2021), and the influence of cementation by, for example, clays, carbonates, and chloride bearing minerals and salts (see Piqueux & Christensen, 2009b and references therein) should also be considered.

Depending on the distribution of cementing agents, tiny amounts of cement can increase inter-grain contact and thus thermal conductivity. Assuming cement to primarily form pendular rings at necks between grains, ~0.02 vol% of cement would increase thermal conductivity by a factor of two according to the model of Piqueux and Christensen (2009b). This would reduce the uncemented soil thermal conductivity from about $0.04 \text{ W m}^{-1} \text{ K}^{-1}$ to about $0.02 \text{ W m}^{-1} \text{ K}^{-1}$ which, using Equation 5, would correspond to grain sizes of $30_{-7}^{+8} \mu\text{m}$ (see Figure 5). Therefore, lightly cemented, dust-sized particles would also be consistent with the thermal conductivity of $0.039 \pm 0.002 \text{ W m}^{-1} \text{ K}^{-1}$ determined here.

5. Discussion

Thermal conductivity values determined here are more than a factor of two smaller than those determined with the TECP instrument on the Phoenix Mars mission (Zent et al., 2010), for which a thermal conductivity of $0.085 \text{ W m}^{-1} \text{ K}^{-1}$ was determined for the upper few centimeters of the soil. This may not be surprising given the presence of near surface ground ice as well as the abundant presence of cementing agents like perchlorate salts at the polar Phoenix landing site (Hecht et al., 2009; Kounaves et al., 2014). However, overall even $0.085 \text{ W m}^{-1} \text{ K}^{-1}$ is relatively small, and both values indicate that the martian soil is a poor thermal conductor.

The numerical model employed to determine thermal conductivity uses cylindrical symmetry, while the mole was inclined at an angle of 30° with respect to vertical. Therefore, a 3-dimensional model would in principle be needed, but since the distance probed by the heat pulse is only a few centimeters (compare Figure 3), the surroundings of the mole can be assumed to be homogeneous to a good approximation. Therefore, the influence of deviations from the ideal cylindrical symmetry is considered to be small.

Penetration of the probe inevitably disturbs the mechanical state of the soil surrounding it (see also Marshall et al. (2017)) and this disturbance was probably increased by the complex history of probe penetration (see Section 2). Soil around the mole is likely compacted to an unknown degree, such that strictly speaking the thermal conductivity values reported here need to be considered as upper limits. One method to quantify the influence of compaction would be to independently estimate thermal diffusivity from the amplitude of the diurnal temperature wave measured at the mole, but such an analysis is beyond the scope of this paper.

Thermal conductivity of the soil is expected to be temperature dependent (Morgan et al., 2018). Therefore, it would have been preferable to use less heating power and stimulate a smaller temperature response during the experiment, but this needed to be balanced against the desire to obtain a good signal to noise compared to the background temperature fluctuations. Therefore, it was decided to run the experiment using a heating power of 2 W, inducing a temperature rise of 37.3 K. This may have increased the measured thermal conductivity by up to 8% as compared to a measurement at the background temperature (Morgan et al., 2018).

By applying the experimental correlation between particle size and thermal conductivity (Equation 5) we have neglected the influence of soil density and particle shape on conductivity (Presley & Christensen, 1997; Presley & Christensen, 2010), which make the grain size estimate non-unique. In general, increased density will reduce conduction through the gas phase while at the same time increasing solid conductivity. Under martian atmospheric pressure conditions, the latter effect appears to dominate (Presley & Christensen, 2010), and a 30% increase of density was found to result in a conductivity increase of 15% in glass beads and crushed quartz (Presley & Christensen, 1997). Given that the experiments used to derive Equation 5 were performed at densities close to $1,700 \text{ kg m}^{-3}$ and that the soil density at the InSight landing site is $121_{-13}^{+149} \text{ kg m}^{-3}$, a similarly sized conductivity change could be expected. This would imply that grain sizes have been underestimated here, and the upper limit on particle size would increase to $184_{-44}^{+51} \mu\text{m}$.

It has been suggested that advective heat transport driven by subsurface gas flow may influence soil thermal transport properties. Such transport would be particularly important when considering temperature in

porous debris aprons (Antoine et al., 2011, 2017) or fractured volcano flanks (Lopez et al., 2012), but high permeabilities are required to make this process efficient. This is likely not the case for the fine-grained soil at the InSight landing site.

Further, as the mean free path of molecules in the soil is comparable to the size of the pores, forced convection may occur in areas of large temperature gradients (de Beule et al., 2014). Such flow may play an important role for transporting volatiles (de Beule et al., 2014) or moving particles that can drive dry avalanches, thus potentially causing the appearance of recurring slope lineae (Schmidt et al., 2017). However, such processes are too inefficient to significantly affect soil bulk thermal conductivity owing to the low heat capacity of the tenuous martian atmosphere. Using CO₂ mass flow rates as derived by de Beule et al. (2014), the advective contribution to the bulk thermal conductivity can be estimated to be smaller than $3 \cdot 10^{-4} \text{ W m}^{-1} \text{ K}^{-1}$. This can be safely neglected in the context of the present active heating experiment. Further, the forced convection would be strongest in the near surface layers at depths of only a few centimeters, further reducing the influence on our measurement in the 0.03–0.37 cm depth range.

As discussed in Section 4.3, the presence of cement can have a large influence on thermal conductivity. If present in the form of cementing necks, increased grain-to-grain contact areas will significantly increase thermal conductivity (Piqueux & Christensen, 2009b), and as little as 0.02 vol% of cement would increase thermal conductivity by a factor of two. As discussed, this would imply dust sized particles to be present. However, such small particle sizes seem to be implausible, as Homestead hollow appears to be filled by eolian deposits (Grant et al., 2020; Weitz et al., 2020) and the saltation limit for particles that can be mobilized by winds is 100–600 μm (Kok et al., 2012). Therefore, it seems more likely that cement present in the soil acts to increase cohesion but has only a small influence on grain-to-grain contact areas. This could for example be the case if cement is distributed in the form of grain coatings rather than cementing necks (Piqueux & Christensen, 2009b). In this case, thermal conductivity would increase linearly as a function of volumetric cement content (Martinez et al., 2020) rather than the very steep increase expected for deposition at particle contacts only (Piqueux & Christensen, 2009b).

Whether cement deposition in the form of particle coatings is sufficient to provide the soil cohesion necessary to create clods and to support steep walls remains to be investigated. At the InSight landing site, cohesion of at least 1–1.9 kPa is required (Golombek, Warner, et al., 2020), but may be as high as 14 kPa (Marteau et al., 2021). Lower bounds on cohesion are similar to values found for crusty to cloddy soil at other landing sites (0–4 kPa), whereas upper limits are similar to cohesion estimates for blocky, indurated soil (3–11 kPa, see Golombek et al. (2008); Herkenhoff et al. (2008) and references therein). Cohesion values determined at InSight are comparable to or higher than the $0.2 \pm 0.4 \text{ kPa}$ to $1.2 \pm 1.8 \text{ kPa}$ derived from trenching experiments at the Phoenix landing site (Shaw et al., 2009). Considering that perchlorate is present at a level of 0.6 wt% at the Phoenix site (Hecht et al., 2009; Kounaves et al., 2014), similar amounts of cement could be present at InSight. However, these would need to be distributed in the form of particle coatings to be compatible with the thermal constraints discussed above.

The underlying particle-scale process that provides the cohesive strength of the soil at the InSight landing site is not known. Nonetheless, it is likely a combination of inter-particle bonding by cementation, electrostatic attraction due to surface tension, and interlocking of the particles. In particular, a broad particle size distribution allows particles to interlock, providing mechanical bonds to create a supporting network which retains large pore spaces. Moreover, it was found in laboratory studies that low environmental pressure or hard vacuum result in a significant increase in cohesion of sands (Bromwell, 1966), which may help to explain the high cohesion apparent in the InSight images. Nevertheless, if soil cohesion is closer to the upper limit of 14 kPa (Marteau et al., 2021), these mechanisms may not be sufficient and particle cementation may be required to provide the necessary bonding.

In the light of the above discussion, grain size estimates based on a comparison with laboratory experiments of essentially cohesionless sand need to be interpreted with caution. Also, it should be kept in mind that the derived grain sizes are representative of the larger particles in the mixture, with 85%–95% of particles being smaller. Therefore, a significant amount of smaller, dust sized particles could be present, increasing soil cohesion and potentially explaining the presence of steep walls and clods. As the influence of cohesion on thermal conductivity remains poorly constrained, estimates of particle size remain uncertain. However,

it seems likely that 85%–95% of all particles are smaller than 104–173 μm based on a comparison with laboratory experiments (Presley & Christensen, 1997) and the fact that the investigated soil appears to be an eolian deposit (Grant et al., 2020; Weitz et al., 2020).

Average soil thermal conductivity in the 0.03–0.37 m depth range determined here is very similar to that derived from surface thermal inertia measurements using the HP³ radiometer (Mueller et al., 2020). While a thin low conductivity layer of thickness below 4 mm is required to explain the surface temperature response to solar eclipses by the martian moon Phobos (Mueller et al., 2021), diurnal surface temperatures sensitive to the upper \sim 0.04–0.08 m of the soil are consistent with a thermal conductivity of $0.041 \pm 0.013 \text{ W m}^{-1} \text{ K}^{-1}$ (Piqueux et al., 2021). Therefore, the thermal data suggest that the soil is largely homogeneous to a depth of 0.37 m.

Soil densities compatible with the temperature data are $1210_{-102}^{+219} \text{ kg m}^{-3}$ if soil properties in the 0.03–0.37 m depth range are assumed to be similar to those derived from surface thermal inertia measurements (Golombek, Warner, et al., 2020). This falls within the range of density estimates for other martian landing sites with crusty to cloddy soils, for which values between 1,100 to 1,600 kg m^{-3} have been reported (Golombek et al., 2008). Furthermore, the range of admissible densities determined here is compatible with pre-landing estimates of 1,300 kg m^{-3} (Morgan et al., 2018). These estimates of soil density can be converted to an estimate of bulk porosity if the density of the constituent particles is assumed to be known. Here we assume particle density to be similar to that found for basaltic martian meteorites, which have densities of 3,100–3,400 kg m^{-3} (Britt et al., 2012; Coulson et al., 2007). This range is supported by petrological modeling, which indicates particle densities of 3,100 kg m^{-3} (Baratoux et al., 2014), such that the soil densities derived above correspond to a bulk porosity of $63_{-5}^{+4}\%$. While this may appear large, it is quite consistent with results obtained at the Phoenix landing site (55%, Zent et al. (2010)) as well as the fact that mole hammering created a significant hole by compacting void spaces during the early phases of probe insertion.

Experimental results on thermal conductivity as a function of porosity for various extra-terrestrial soil simulants under terrestrial atmospheric conditions are summarized by Becker and Vrettos (2016). Of the materials tested, three sands show grain-size characteristics similar to the soil encountered at the InSight landing site. These poorly graded sands with mean grain sizes between 0.2 and 0.3 mm exhibit a thermal conductivity around $0.2 \text{ W m}^{-1} \text{ K}^{-1}$ at a typical porosity of 50%. In order to extrapolate conductivity to Martian atmospheric conditions we scale the gas contribution to the conductivity to 20%–25% of the terrestrial value as suggested by the results of Huetter et al. (2008). Adopting the analytical model by Haigh (2012) for the extrapolation, we obtain a proportional reduction of the terrestrial conductivity value, resulting in predicted thermal conductivities close to $0.04\text{--}0.05 \text{ W m}^{-1} \text{ K}^{-1}$ under martian atmospheric conditions. This indicates that high porosities are compatible with the thermal properties determined above.

If radiometrically derived surface thermal inertia is not used as an additional constraint, soil density estimates are reduced to $1007_{-74}^{+176} \text{ kg m}^{-3}$, and resulting porosity estimates would increase to 68%. However, there are no strong indications of changing soil parameters in the depth range investigated here (Golombek, Warner, et al., 2020). Therefore, the larger density estimates of $1211_{-113}^{+149} \text{ kg m}^{-3}$ appear to be more appropriate. Note, however, that it has been argued that a transition to cohesionless sand may be present at a depth of 0.2 m (Hudson et al., 2020), but this is difficult to reconcile with the apparent similarity of thermal properties derived from radiometric measurements (Piqueux et al., 2021) and the results presented here.

The thermal conductivity measured here falls within the range of predictions used for designing the HP³ instrument (Grott et al., 2007; Spohn et al., 2018), which was $0.02\text{--}0.1 \text{ W m}^{-1} \text{ K}^{-1}$. Based on the measurement of soil thermal conductivity, the subsurface thermal gradient at the landing site can be derived given an estimate of surface heat flow. Global thermal evolution models predict heat flows of 19–24 mW m^{-2} (Plesa, Grott, Tosi, et al., 2016), consistent with analysis of lithospheric flexure (Egea-Gonzalez et al., 2021; Grott & Breuer, 2010), such that the subsurface thermal gradient is expected to be $0.45\text{--}0.64 \text{ K m}^{-1}$. This is well above the design limit of 0.2 K m^{-1} to guarantee an overall $1\text{-}\sigma$ heat flow uncertainty of 2.2 mW m^{-2} (Spohn et al., 2018). The relatively low thermal conductivity of $0.039 \pm 0.002 \text{ W m}^{-1} \text{ K}^{-1}$ further reduces the influence of perturbations to the subsurface heat flow, which can be caused by, for example, the InSight lander (Grott, 2009; Siegler et al., 2017), interannual variations of surface temperature (Grott et al., 2007), as well as surface temperature changes induced by martian dust storms (Plesa, Grott, Lemmon, et al., 2016). The

thermal conductivity determined here will therefore help to design future heat flow probes by providing important constraints on the thermophysical properties of the martian soil.

6. Conclusions

The heat flow and physical properties package (HP³) of the InSight Mars mission has conducted direct thermal conductivity measurements of martian soil, and average thermal conductivity in the 0.03–0.37 m depth range was found to be $0.039 \pm 0.002 \text{ W m}^{-1} \text{ K}^{-1}$. This falls within the expected conductivity range for uncemented martian soils, which is 0.02–0.1 $\text{W m}^{-1} \text{ K}^{-1}$ (Grott et al., 2007) and demonstrates that the soil at the InSight landing site is a poor thermal conductor.

Although particle sizes derived from thermal measurements must be interpreted with some caution, a particle diameter of 104–173 μm appears to be a robust upper limit for the vast majority of particles. Considering effects like cementation would only act to further decrease this value, such that the soil at the landing site is likely composed of fine sand intermixed with dust.

We find that median soil densities of $1211_{-113}^{+149} \text{ kg m}^{-3}$ are consistent with our data, which implies a bulk porosity of $63_{-9}^{+4} \%$. This is consistent with the fact that mole hammering created a significant hole by compacting void spaces during the early phases of probe insertion. Further, porosity well in excess of the canonical value of 42% for a random loose packing of monodisperse spheres (Scott, 1960) indicates that soil cohesion has played a role during soil deposition.

Finally, the derived soil thermal conductivities place strong constraints on the allowable degree of soil cementation, and only minor amounts of cement are consistent with the low thermal conductivities derived here. This is difficult to reconcile with the analysis of image data and the derived soil mechanical properties, which strongly suggest an indurated duricrust to be present (Golombek, Warner, et al., 2020; Marteau et al., 2021). This apparent discrepancy between the interpretation of the thermal and mechanical properties cannot be resolved here and certainly deserves further study.

Data Availability Statement

The numerical code and data necessary to reproduce the results of this paper have been made publicly available in Grott (2021).

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