A Thermal Origin for Most Marsquakes

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Key Points:

- Daily and seasonal heat conduction under the InSight landing site is modeled.
- Daily temperature variation over 1 K occurs only within the depth of 25 cm.
- The highest absolute rate of temperature appears around sol 440, coincident with the dominant season of marsquakes observed around sunset.
- Thermal-mechanical simulations indicate that more potential afternoon marsquakes might exist but be covered by the wind noise.
- Most high-frequency and low-magnitude marsquakes are likely thermal in origin.

Abstract

The thermal response of the martian subsurface due to solar forcing lacks direct measurements. The InSight mission provides the best opportunity to detect the thermal behavior of the subsurface since it was equipped with both air temperature sensors and a subsurface heat flow probe. Here, we model heat conduction under the InSight landing site based on the measured subsurface thermal parameters and air temperature records, which provide insights into heat flow in the martian subsurface. Daily temperature variation over 1 K occurs only within 25 cm under the ground surface. The highest absolute rate of temperature change appears around sol 440, which coincides closely with the season of the dominant number of marsquakes observed around sunset. Thermal-mechanical finite-element method simulations indicate that more potential afternoon marsquakes might exist but be covered by the wind noise. Our results indicate that most high-frequency and low-magnitude marsquakes are likely thermal in origin.

Plain Language Summary

The mechanism of some marsquakes might not be tectonic in origin, but thermal, related to its large diurnal temperature difference. However, lack of comprehensive near-surface observation makes the thermal investigation challenging. We model the heat conduction beneath InSight based on the measured subsurface thermal parameters and air temperature records. Diurnal and seasonal variations of subsurface temperature and the rate of temperature change are analyzed. Daily temperature variations of >1 K only occur in the top 25 cm of the subsurface. In summer, the absolute rate of temperature change reaches its peak, which is also notably the dominant season of marsquakes observed around sunset. Thermal-mechanical simulations indicate that the heat-induced ground motion is evidently stronger in the daytime than that in the nighttime. Covered by the wind noise, more potential marsquakes might exist in the afternoon through the entire martian year. Our results indicate that high-frequency marsquakes are related to thermal conduction in the top 10 cm of the ground.

1 Introduction

The daily variation of temperature on Mars can reach up to 80–100 K [*Banfield et al.*, 2020]. Such a large thermal range can strongly influence both the weather variability and the thermal behavior of the subsurface. Satellite measurements can be used to estimate the thermal parameters from the ground surface to high altitudes [*Ahern et al.*, 2021; *Mellon et al.*, 2000], but they can only provide large-scale and intermittent observations. It is difficult to maintain a permanent weather station on the surface of Mars and to perform continuous underground observation, even though both are necessary for understanding the thermal behavior of subsurface materials. The InSight mission was equipped with both an air temperature gauge on the lander [*Spiga et al.*, 2018] and a deployable subsurface heat flow probe, the Heat Flow and Physical Properties Package (HP^3) [Spohn et al., 2018], which provides the best opportunity to detect the thermal behavior of subsurface materials due to the variation of near-surface temperature. The HP^3 mole successfully bored 20–30 cm deep [Good *et al.*, 2021] and performed direct detection on critical thermal parameters of the shallow martian subsurface.

Here, we perform a series of numerical simulations to infer the heat conduction process under the InSight landing site, based on the measured subsurface thermal parameters and the air temperature records. We further analyze the daily and seasonal variations of subsurface temperature and the rates of temperature change. Thermal-mechanical coupling finite-element simulations reveal the daily variation of the temperature and the strain in the subsurface. Our results indicate that underground heat conduction on Mars has been critically overlooked in the interpretation of marsquakes.

2 Diurnal and Seasonal Variations of the Subsurface Heat Conduction Beneath InSight

The heat conduction equation can describe the thermal process of a given model with several controlling parameters (Text S1). In our numerical calculations, we use typical values of these parameters obtained from the heating experiments from HP^3 [*Grott et al.*, 2021] as follows: soil density $\rho = 1211$ kg m^{-3}, specific heat $c = 630$ J kg^{-1} K^{-1}, and thermal conductivity $k = 0.039$ W m^{-1} K^{-1}. Thus, the thermal diffusivity $\kappa = k/(\rho c)$ at the InSight landing site can be estimated as 5.1×10^{-8} m^2 s^{-1}. The air temperature sensors are on the deck of the InSight lander, ~1 m over the ground. We correct the air temperature to the ground temperature according to the recorded air temperature and ground temperature from the Martian Climate Database [Forget *et al.*, 1999] (Text S2; Fig. S1). Daily subsurface heat conduction calculation results (Text S3; Fig. S2) for the annually average sol show that the ground surface (depth of 0 cm) reaches its highest temperature (~290 K) at ~15:00 local mean solar time (LMST) and drops to the lowest temperature (~180 K) slightly before ~06:00. In contrast, at a depth of ~3 cm, the highest temperature (~250 K) appears slightly after ~16:00 and drops to the lowest temperature (~195 K) slightly after ~06:00, yielding 1 hr and <1 hr time delays compared to the surface, respectively. At a depth of 7 cm, where the maximum daily variation is only ~15 K, the highest temperature appears at ~19:00 and the lowest temperature appears at ~11:00, yielding 4 hr and 5 hr time delays compared to the surface, respectively. Thus, time delays of the lowest and highest temperature (<1 hr cm^{-1}) can be seen at different depths. Diurnal temperature variations of over 1 K only occur within the top 25 cm. This indicates that we can focus on the shallowest 25 cm for analyzing the diurnal variations of subsurface temperature, especially for the shallowest 10 cm, below which daily temperature variations are less than 15 K.

Similar to the annually averaged data and model, we can further calculate the real-time heat field under the InSight landing site day by day with measured thermal parameters and daily ground temperature. Figure S3 presents the daily temperature at different depths in the first martian year after InSight landed. The daily ground temperature exhibits several characteristics, such as the lowest daily temperature at ~06:00 (around sunrise), the highest daily temperature at ~14:00, and the highest absolute rate of temperature change at ~18:00 (around sunset). Figure 1 presents the temperature profile at these moments for each sol. We mark a zone with temperature over ~230 K (black isolines) as the “hot zone” and the other as the “cold zone”. We can see that the “hot zone” at 14:00 has depths within 6 cm, varying from ~4 cm during sols 0–300 down to ~6 cm around sol 500 (Fig. 1b). At 18:00, the “hot zone” is deeper than that at 14:00, varying from ~6 cm in depth during sols 0–300 down to ~10 cm around sol 550 (Fig. 1c). In sols 230–610, the top of the “hot zone” is 2 cm in depth, which indicates dramatic increases of temperature in this zone.

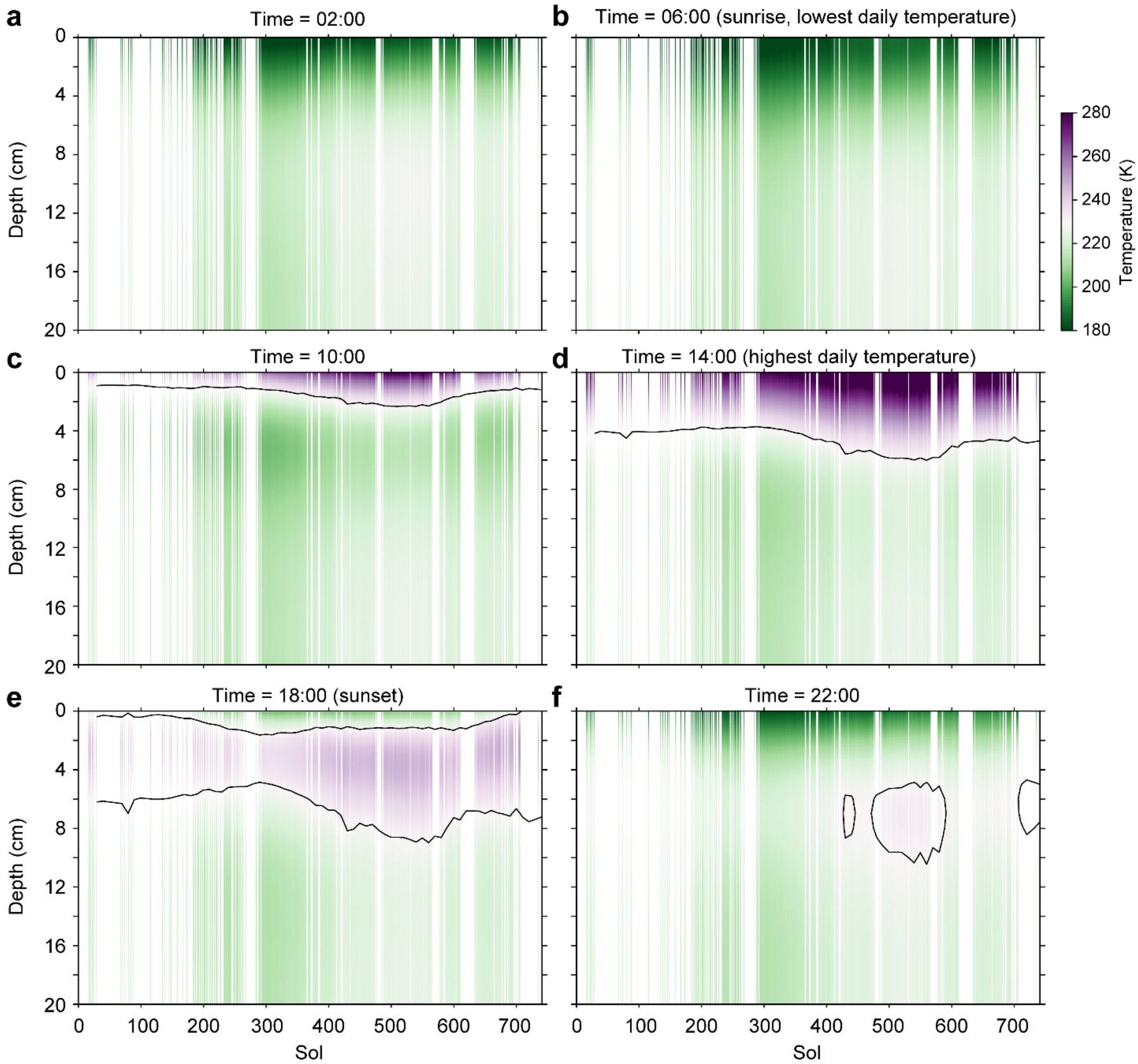

Figure 1. Temperature as a function of both depth and mission days (sol) at characteristic moments of day. Vertical white spaces indicate data gaps due to solar conjunctions or machine stoppages. Black lines denote the isolines of 230 K.

3 Correspondence Between Rate of Temperature Change and Ground Motion Around Sunset

Using seismic data recorded by InSight's seismic experiment for interior structure (SEIS) [*Lognonné et al.*, 2019] deployed on the ground at the InSight landing site, a number of marsquakes have been detected [*Ceylan et al.*, 2021; *Clinton et al.*, 2021; *Giardini et al.*, 2020]. Strikingly, the timing of marsquakes is highly non-uniform, with no observed diurnal or seasonal dependence (Fig. 2). About 49% of marsquakes occur within a 2 hr time window near sunset (17:00–19:00) and 70% of them occur within a 4 hr time window near sunset (16:00–20:00) (Table S1). Furthermore, nearly all the remaining minority of events occur at nighttime after sunset and twilight (Fig. S4). The strong wind noise precludes the detection of potential weak marsquake signals during the daytime or in the dust-storm season. Nevertheless, larger magnitude marsquakes, were they to occur during the windy daytime or dust-storm season, should still be detectable, thus making their absence conspicuous. That is, if large magnitude marsquakes are tectonic in origin, they should occur at more or less random times of day and year, assuming that tectonic marquakes are similar to earthquakes (e.g., *Hao et al.* [2019]). However, only several high quality marsquakes have been detected in an entire martian year [*Khan et al*., 2021], far lower than the frequency of moonquakes [*Garcia et al*. 2019].

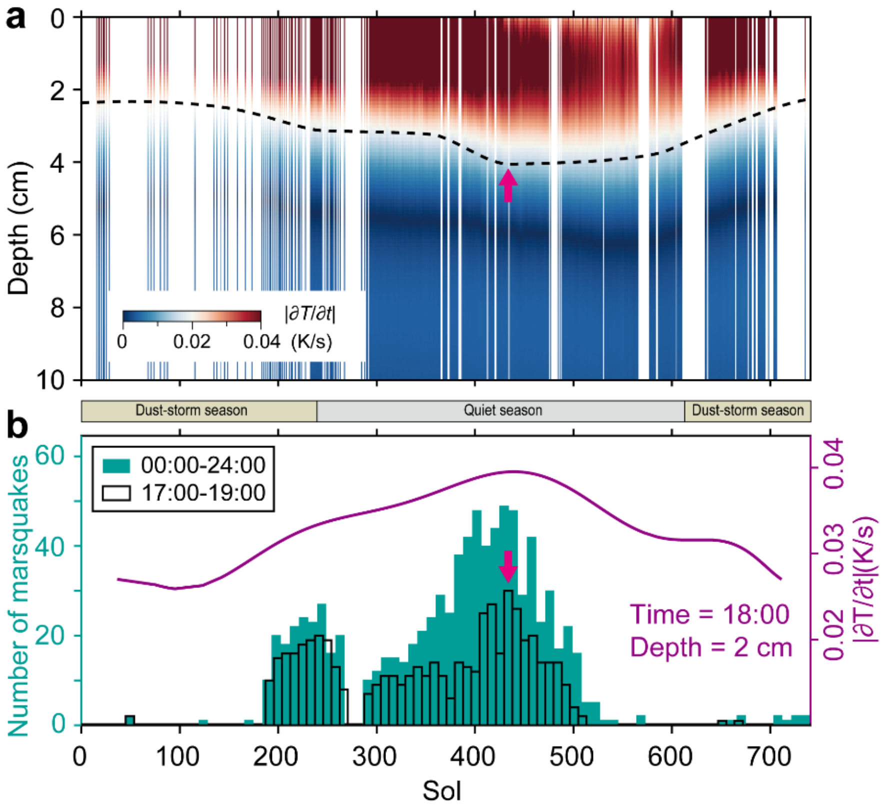

Figure 2. **Rate of temperature change and the ground motion around sunset.** (a) Comparison between the absolute rate of temperature variation at 18:00 LMST and number of events in high-frequency family (see below). The dashed line indicates the boundary of ~0.02 K s^{-1}. (b) Green filled and black framed bars indicate marsquakes during 00:00–24:00 LMST and 17:00–19:00 LMST, respectively. The purple line is the temperature variation at the depth of 2 cm at 18:00 LMST. Temperature variations at other depths are shown in Figure S5. Only marsquakes in the high-frequency family (HF, VHF, and SHF) [*InSight Marsquake Service*, 2021] are plotted. See all types of marsquakes in Figure S6.

It is well known that rapid temperature change can cause thermal expansion and contraction and even cracks in rock, which would change its mechanical properties. It has been suggested that marsquakes might be related to thermal cracking of the subsurface [*Dahmen et al.*, 2021], like thermal quakes on the tectonically dormant Moon [*Duennebier and Sutton*, 1974; *Sens-Schönfelder and Larose*, 2010]. Thus, based on our calculated temperature field and the

InSight marsquake catalog [*InSight Marsquake Service*, 2021], we analyze the correspondence between the seasonal variations in thermal conduction with the occurrences of marsquakes. Figure 2 shows the absolute rate of temperature change $|\partial T/\partial t|$ at 18:00 and the number of marsquake events in the high-frequency family [*InSight Marsquake Service*, 2021] during 17:00–19:00. This low-wind time window is the quietest, thus providing the most reliable record of marsquakes (Fig. S4).

It is evident that the absolute rate of temperature variation $|\partial T/\partial t|$ at 18:00 and the number of high-frequency events (high frequency (HF), very high frequency (VHF), and super high frequency (SHF)) are essentially synchronous during an entire martian year (except the dust-storm season), and both reach their peak values at around sol 440 (in summer). It is notable that marsquakes do not occur more frequently during the peak temperature (around sol 540); instead, they occur more frequently around sol 440, corresponding to the peak rate of temperature change. The absolute rate of temperature change on sol 440 was >0.02 K s^{-1} within a depth of ~4 cm (Fig. 2a). This indicates that high-frequency events might be related to thermal conduction within only the top several centimeters of the subsurface.

4 A Thermal Origin for Most Marsquakes Inferred from Thermal-mechanical Simulation

Given the low heat conductivity in the martian subsurface, the rock-filled soil with a depth of 50 cm is considered in the simulation. Thus, we use a 2D thermal-mechanical coupling finite-element model (50 cm×100 cm) for the subsurface profile (Fig. 3a). The displacement boundary condition along the side and bottom boundaries is set as fixed in the normal direction and free in the tangential direction. Given that the thermal conduction dominates mainly in the top 10 cm of the subsurface, the top boundary is set as a free surface with corrected ground temperature, while the side and bottom boundaries are set as adiabatic. For the soil at InSight landing site, the S wave velocity, P wave velocity [Hobiger *et al.*, 2021] and density [*Grott et al.*, 2021] are set as 111 m s^{-1}, 200 m s^{-1}, and 1211 kg m^{-3}, respectively; the thermal diffusivity is set as 5.1×10^{-8} m^2 s^{-1}, obtained from the measured thermal parameters [*Grott et al.*, 2021]; thermal expansion is set as 2.4×10^{-4} K^{-1} [Molaro *et al.*, 2017]. For the rocks buried in the soil (Fig. 3a), the S wave velocity, P wave velocity and density are set as 1700 m s^{-1}, 3000 m s^{-1}, and 2760 kg m^{-3} [Morgan *et al.*, 2018], respectively, derived from terrestrial data obtained for fractured basalt [Planke *et al.*, 1999]; thermal diffusivity is set as 7×10^{-7} m^2 s^{-1} [Hartlieb *et al.*, 2016]; the thermal expansion is set as 1×10^{-5} K^{-1} [Molaro *et al.*, 2017]; and the volume ratio of the filled rocks is set as approximately 5 %.

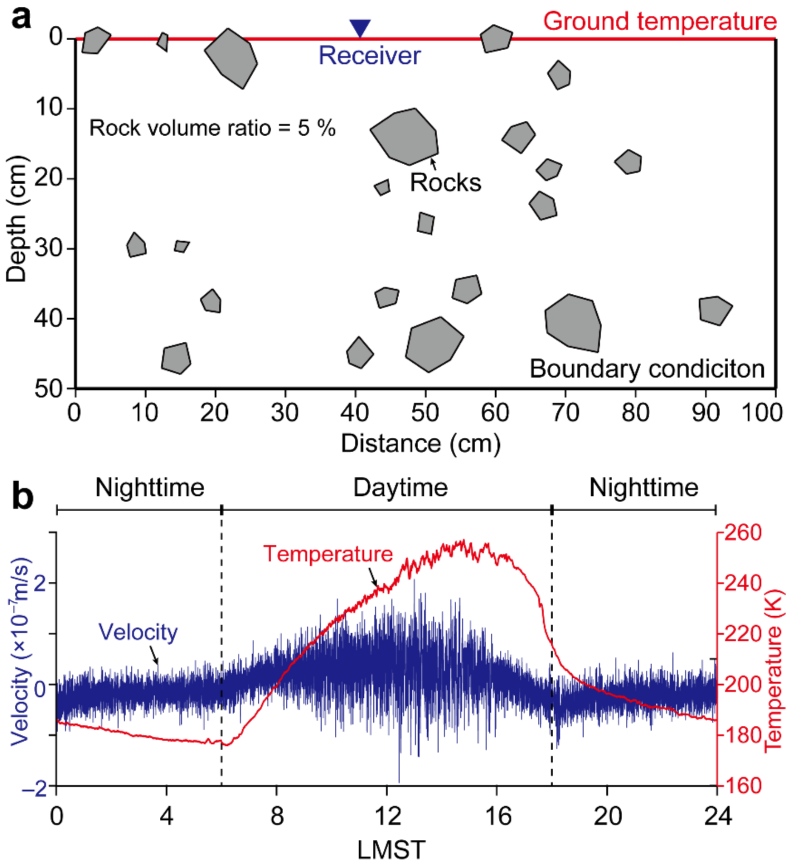

Figure 3. The 2D thermal-mechanical coupling finite-element model and the simulated ground motion. (a) The model with a depth of 50 cm and width of 100 cm. The polygons denote rocks in the soil and the reversed triangle on the ground denotes the receiver of seismic waves. (b) the input ground temperature, corrected from the InSight temperature record in sol 226 and the simulated ground motion (vertical velocity) at the receiver of seismic waves.

The results show that driven by the diurnal air temperature variation, the ground motion is evident and highly correlated with the magnitude of temperature changes. The amplitude of the vertical velocity is evidently larger in the daytime than that in the nighttime (Fig. 3b), which has similar trend with the measured vertical ground motion by InSight's SEIS. The peak ground acceleration of the simulated heat-induced (Fig. S7) is comparable to the average amplitude of high-frequency marsquake events identified by SEIS [*Ceylan et al.*, 2021] in the sunset (10^{-9} − 10^{-8} m s^{-2}), which indicates that the heat variation might be adequate to induce thermal marquakes.

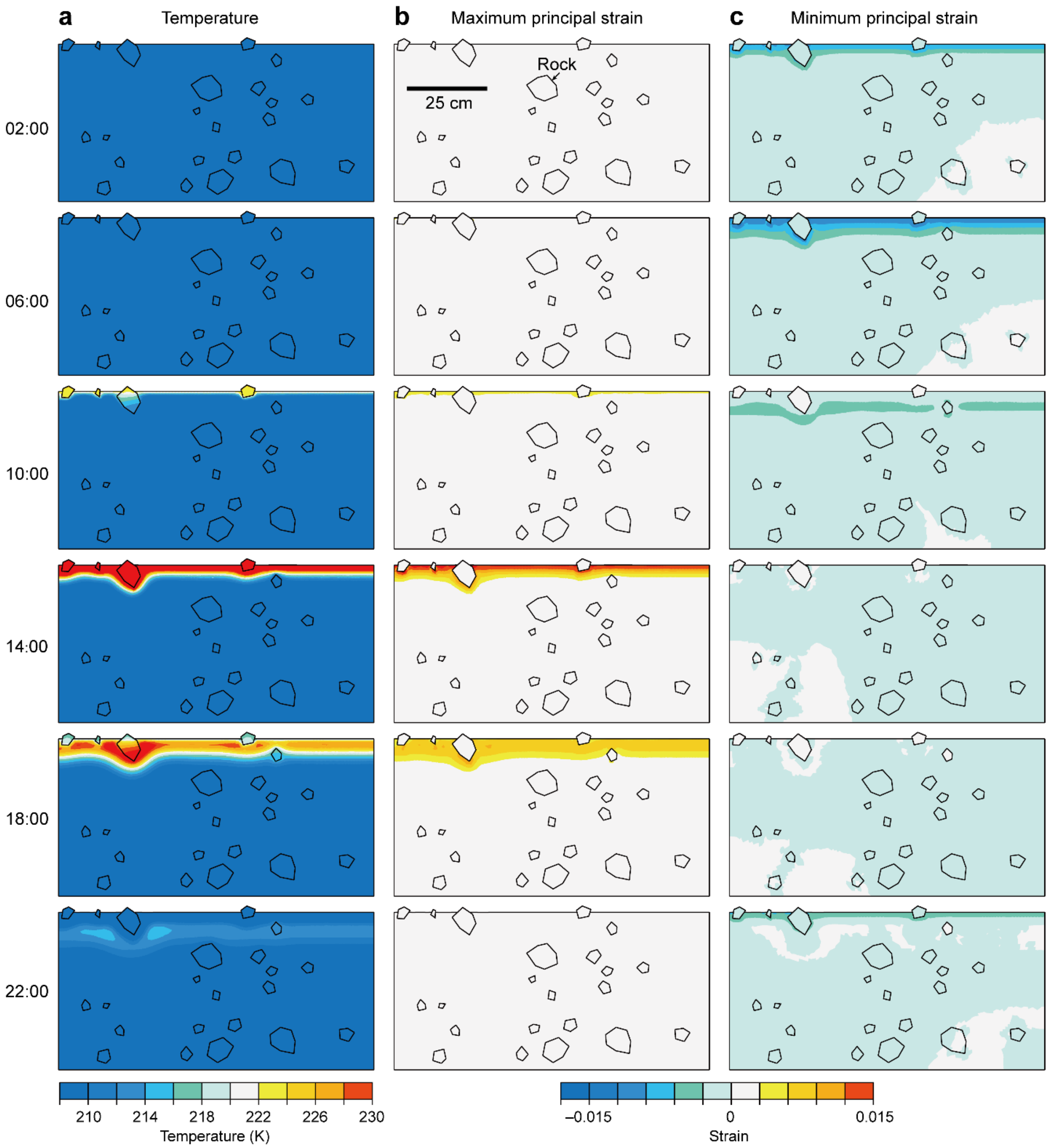

Figure 4. Representative snapshots of temperature and strain. (a) Temperature; (b) Maximum principal strain; (c) Minimum principal strain. The 6 rows from the top to the bottom denote the snapshots at 02:00, 06:00, 10:00, 14:00, 18:00 and 22:00 LMST, respectively.

Time-varying temperature distribution shows that the subsurface temperature varies mainly within the top ~ 10 cm and is strongly affected by the part-buried rocks (Fig. 4a). In the early morning (e.g., 02:00 and 06:00), the minimum principal strain (Fig. 4c) reaches its lowest values (~-0.01), which indicates that the subsurface is compressed due to low temperature. In the afternoon (e.g., 14:00 and 18:00), the maximum principal strain (Fig. 4b) reaches its peak values (~0.01) in the top ~10 cm, which indicates the failure or fracture of the subsurface. This is consistent with the frequently recorded sunset marsquakes. This indicates that more potential afternoon marsquakes might exist but be covered by wind noise before the sunset (e.g., 14:00), during which the maximum strain is even higher than that in the sunset.

5 Discussions

We simulated the ground motion induced by daily temperature variation in the subsurface. The amplitude of simulated acceleration is ~5×10^{-8} m s^{-2} in the representative sol (Fig. S7), which is much smaller than that of the observed acceleration by SEIS (< 10%) in the same sol. However, their trends are basically consistent, which are strong in the daytime but weak in the nighttime. These indicate that other sources (e.g., wind) besides temperature variation might dominate the surface ground motion. If the wind was further considered in the simulation, the heat-induced ground motion would be exaggerated and gain a higher amplification on the amplitude of acceleration. More work is needed in the future by considering the coupling process between thermal activity and wind shaking.

Our current experiments show that the marsquakes occur at the zone with high strainin the subsurface. Given that the sunset is away from the highest rate of temperature change in the sol, we expect that more potential thermal quakes may exist at the other time periods (such as 14:00-16:00 LMST, Fig. 4). However, the wind noise in these times is too strong to detect the weak signals.

6 Conclusions

Taking the ground temperature and subsurface heat properties observed by InSight as boundary conditions, we performed a series of numerical simulations based on heat conduction equation. From the analyses of subsurface temperature and the rate of temperature change, we infer that the depth of daily temperature variation over 1 K occurs only within 25 cm under the ground surface. This indicates that the strong daily temperature variation (up to 80–100 K) has little influence on the underground materials below this depth. Peak absolute rate of temperature change appears around sol 440 (in summer), which is strikingly coincident with the peak number of marsquakes observed starting at sunset. This temporal correspondence may suggest that the highest absolute rate of temperature change triggers thermal marsquakes. We infer that the thermal marsquakes mainly happen at the depth of <10 cm, over the zone of daily temperature variation with a threshold as little as 15 K, especially at the uppermost several centimeters with absolute rate of temperature change >0.02 K s^{-1}. Thermal-mechanical finite-element method simulations indicate that the heat-induced ground motion is evidently stronger in the daytime than that in the nighttime. In the afternoon, the maximum principal strain reaches its peak values in the top ~10 cm of the subsurface, which indicates the failure or fracture of the subsurface. The peak ground acceleration of the simulated heat-induced is comparable to the average amplitude of high-frequency marsquake events identified by SEIS in the sunset, indicating that these marquakes might have thermal in origin.

Acknowledgments

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