Constraints on the Martian crust away from the InSight landing site. J. Li[1], C. Beghein[1], S. M. McLennan[2], A. C. Horleston[3], C. Charalambous[4], Q. Huang[5], G. Zenhäusern[6], E. Bozdag[5], W. T. Pike[4], M. Golombek[7], V. Lekić[8], P. Lognonné[9], and W. B. Banerdt[7]. [1]Department of Earth, Planetary, and Space Sciences, University of California, Los Angeles, CA (jli@epss.ucla.edu), [2]Department of Geosciences, Stony Brook University, [3]School of Earth Sciences, University of Bristol, [4]Department of Electrical and Electronic Engineering, Imperial College London, [5]Department of Geophysics, Colorado School of Mines, [6]Institute of Geophysics, ETH Zurich, [7]Jet Propulsion Laboratory, California Institute of Technology, [8] Department of Geology, University of Maryland, [9]Université Paris Cité, Institut de physique du globe de Paris.

Introduction: Since the first seismological constraints on the Martian crustal structure were obtained beneath the InSight lander [1,2], the nature of the crustal layers and whether they represent local geological structures or global features has been debated [3,4]. To partially answer this question, we do not necessarily have to wait for additional seismometers to be placed on the Martian surface.

In this study, we made use of seismic wave precursors, i.e., underside reflections off a subsurface discontinuity halfway between the marsquake and the instrument to constrain the crustal structure away (about 4,100 - 4,500 km) from the InSight landing site [5].

Seismic Observations: We chose the most distant marsquake recorded, event S0976a, which occurred on the 976th InSight Mars solar day (i.e., August 25th, 2021). Its epicentral distance is estimated at 146.3 ± 6.9° and its back azimuth is 101 ± 25° [6]. The epicenter is located near the western end of Valles Marineris (Fig. 1a), east of the Tharsis region.

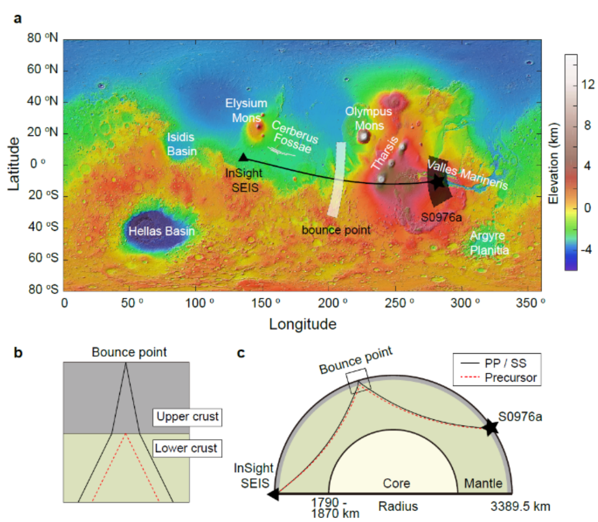

Figure 1: Locations of the marsquake, seismic station, and bounce point.

The PP phase arrived 1,013 s after the origin time (i.e., 2021-08-25 03:32:20) on the vertical component (Fig. 2a). There is an early-arriving signal 10.2 ± 0.2 s before the PP phase (Fig. 2a). We interpret this signal to be the crustal PP precursor reflected off the crustal interface beneath the bounce point (Fig. 1b and c).

The SS phase arrived 1,856 s after the origin time on the tangential component (Fig. 2b). With a polarization filtering technique [7], which enhances the linearly polarized signals, most wave trains arriving before the SS phase are attenuated except for one signal at about 19.3 ± 0.5 s relative to the SS phase (Fig. 2b). We interpret this early-arriving signal to be the crustal SS precursor.

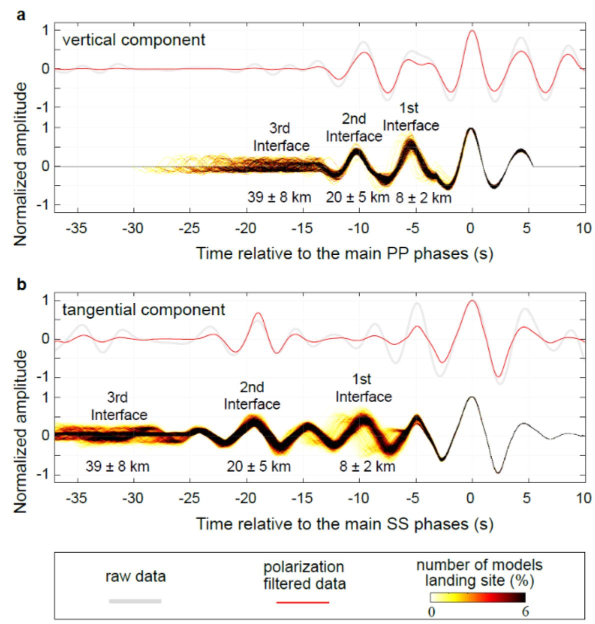

Figure 2: Seismic observations of the PP and SS waves, and synthetic waveforms using the models at the InSight landing site.

Forward modeling: The SS (or PP) phase and its precursor share almost the same ray paths except for the regions near the bounce point (Fig. 1c); thus, the differential arrival time and amplitude ratio mainly reflect the structure beneath the bounce point.

We first used the receiver-function-derived models beneath the landing site [2] to calculate the synthetic arrival time and amplitude of the PP and SS precursors using ray theory (Fig. 2). Synthetic waveforms show that such precursors are observable for a single event.

Contrary to terrestrial studies [8], where stacks of hundreds of seismic records are needed to enhance the signal, stacking is not required here owing to the relatively high velocity (or impedance) contrast across the intra-crustal interface on Mars.

The interface at the base of the second layer (at ~ 20 km) beneath the lander can generate PP and SS precursors with similar arrivals and amplitude as observed in the data (Fig. 2). However, the signature of the shallowest layer seen at the landing site (which should produce another strong precursor at around -6 s for the PP wave and -10 s for the SS wave), is absent from the recorded waveforms after polarization filtering. We also found that the velocity contrast across the base of the third layer (i.e., the Moho) is too small to generate significant precursors.

Crustal Variations: The forward modeling results (Fig. 2), based either on the raw data or the polarization-filtered data, consistently show that the Martian crust at the bounce point shares a similar discontinuity with the second intra-crustal interface beneath the InSight landing site, i.e., at ~ 20 - 25 km [2].

If present at the bounce point, the shallowest interface (at 8 ± 2 km, discovered at the landing site) should produce another strong precursor. However, although energy is visible in the raw data between the main PP/SS phase and the major precursor (i.e., 19.3 s for SS and 10.2 s for PP), it is strongly attenuated after polarization filtering. Since this filter should enhance the linearly polarized body-wave signals, the weak signal in the polarization-filtered seismogram indicates the absence of such a shallow layer at the bounce point, or that the velocity contrast across it is not as significant as beneath the lander. Because of this inconsistency between raw data and polarization-filtered waveforms, we cannot confidently evaluate the regional variations in the uppermost crustal structure of Mars based on these results.

The third interface (i.e., the Moho) detected at the landing site has a limited impedance contrast. If this discontinuity exists at the precursor bounce point with similar depth and property as at the landing site, it cannot generate detectable SS or PP precursors (with an amplitude ratio of less than 20%, in Fig. 2). Considering that the structure at the bounce point can be different, we also searched for the earlier precursors in a longer time window. However, we did not find any consistent precursors associated with the crust-mantle discontinuity.

The "20-km" discontinuity on Mars: This "20-km" discontinuity, first discovered beneath the lander, is not a local geological structure but more likely a regional feature near the dichotomy boundary or possibly even a global feature.

A variety of mostly non-mutually exclusive factors could play a role in the origin of this seismic interface at the bounce point.

At the InSight landing site, [3] favored a hypothesis involving the removal of pore space by viscous deformation at depth. On the Moon, impact cratering has been suggested as the cause of low seismic velocities or crustal porosity [9]. If it is the same on Mars, [10] proposed that porosity should have been removed at depths greater than about 12 – 23 km since then. This range of the porosity-removal depth overlaps with the depth estimation of the '20-km' discontinuity beneath both the lander and the bounce point.

If such an intra-crustal seismic interface reflects a transition from porous to non-porous Martian crustal materials, the velocity difference above and below the pore closure depth can be explained by a porosity reduction of about 10 - 16%, assuming a pore aspect ratio of 0.1 [5].

Summary: We show that the Martian crust at the bounce point between the lander and the marsquake is characterized by a discontinuity at about 20 km depth, similar to the second (deeper) intra-crustal interface seen beneath the InSight landing site. We propose that this 20-km interface, first discovered beneath the lander, is not a local geological structure but likely a regional or global feature, and is consistent with a transition from porous to non-porous Martian crustal materials.

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