Inner Mars revealed

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The interior of a planet holds important clues to its origin and thermal and dynamic evolution. Exploring a planet's deeper layers offers insights into questions such as: How did the planet accrete and differentiate into layers? Does its core sustain a geodynamo creating a magnetic field? What is the origin of any tectonic and volcanic activity? New clues are now uncovered for Mars.

Humanity has a long history looking up to the skies and observing the stars and solar system. Looking beneath the surface is a lot more involved. The subsurface can be probed with recordings of seismic waves that propagate through the planet after an earthquake. For Earth, the first measurement of waves diving deep through the mantle was made in 1889 in Germany originating from an earthquake in Japan (von Rebeur-Paschwitz, 1889). Global seismology is thus a relatively young science. In the first decades of the 20th century, seismologists discovered the main layers of the Earth, e.g. the boundaries between the crust and the mantle 30 km down (Mohorovičić, 1910), the mantle and core roughly halfway to the center (Oldham, 1906) and the small inner core (Lehmann 1936).

Now, about a century later, Knapmeyer-Endrun et al., Khan et al. and Stähler et al. (*this issue*) present the first findings of the interior structure of Mars based on data from the InSight mission. These studies provide the first direct observations of the crust, mantle and core structure on another rocky planet, for which the results and implications can be compared and contrasted to Earth. Mars also allows us to study planetary puzzles different to Earth, including observations of an extinct magnetic field, a strong hemispherical topographical dichotomy, and localized long-lived volcanism. Understanding Mars' planetary evolution sheds light on these puzzles.

In a great feat of engineering, InSight landed on Mars in November 2018. Its seismometer, SEIS, started recording marsquakes in February 2019. The measurement of ground movements on Mars comes with a range of challenges. Although the sensitive sensors in SEIS measure ground movement along three axes and across frequencies, its recordings are only obtained at a single location. This limits how well it can constrain marsquake epicenters and timings. And while a protective shield surrounds SEIS, its sensors still record perturbations caused by weather variations, including atmospheric pressure waves and dust storms. These signals give interesting insights into the Martian atmosphere and its daily and seasonal variability (e.g. Banfield et al. 2020), but for those studying marsquakes and Mars' interior, these signals are generally considered 'noise'. The geology of Mars also complicates observations. Its rocky soil surface disperses seismic energy near the seismometer, complicating the identification of waves.

Results from the InSight mission have already demonstrated that Mars is seismically active; marsquakes are plentiful, albeit small in magnitude (e.g. Giardini et al. 2020). All marsquakes observed in the two years of recording are estimated to have magnitudes below 4.0, which humans would only notice within several kilometers of the epicenter. The vast majority of marsquakes originates in the crust and creates strong reverberations within, making individual waves difficult to identify (e.g. Giardini et al. 2020). A smaller number are generated below the crust and their appearance resembles tectonic events on Earth. The studies discussed here use data from about ten of these sub-crustal marsquakes to reveal the inner structure of Mars.

To overcome the challenges of working with noisy and sparse seismic data, the authors prepared and benchmarked a range of data analysis techniques, exploring signals in different frequency ranges and combining data from multiple marsquakes. For all three studies, independent research groups applied their methods of expertise to come to robust results or provide complimentary constraints. Importantly, seismologists worked together with a broad team of planetary scientists specializing in petrology, geochemistry, mineral physics and geodynamics to understand the results and the implied structure and evolution of Mars. Seismic data were combined with compositional constraints from Martian meteorites, and also other geophysical observables such as surface topography and heat flow, gravity and geodetic data, and observations of crustal magnetization.

While the detection of waves from small marsquakes is far from trivial, waves bouncing off a Martian core will be even weaker and are thus more challenging to observe. Stähler et al. *(this issue)* report the first observations of faint signals bouncing off the boundary to the Martian core. They determine that the core starts about 1560 km deep, nearly halfway to the center. The core is on the large end of previous estimates. Given the known mass and moment of inertia of Mars, this implies the core is less dense than previously thought and its iron-sulfur alloy must be further enriched in light elements. The strength of the bouncing waves confirms the core is still in a liquid state, as has been suspected from Mars' tidal response (e.g. Yoder 2003) and for an iron-sulfur alloy at estimated Martian core temperatures above 1800 K (e.g. Stewart et al. 2008).

The observation of a relatively thin mantle means Mars lacks the dense, insulating layer of the bridgmanite mineral that becomes stable under large pressures in the Earth's mantle. The absence of this mineral would have led to more rapid cooling of the early Martian core, potentially driving a geodynamo creating a magnetic field. This geodynamo has since ceased and is now only evidenced by magnetized older crustal rocks (Stevenson, 2001). The magnetometer on InSight observed that the magnetization in the crust observed at the surface is 10x stronger than modeled based on satellite data and Mars' early geodynamo must have been similar in strength to Earth's present-day geodynamo (Johnson et al. 2020).

Instead of using waves bounced off the core, Khan et al. *(this issue)* use waves that travel directly to the seismometer, or bounce off the surface, to reveal shallower Martian mantle structure. The travel times and amplitudes of these waves show that the seismic shear-wave speed decreases gradually in the Martian mantle down to depths of 400-600 km. This reduction in seismic wave speed could be caused by the thermal structure in a static, thick outer shell (the lithosphere) on top of a convecting mantle. Closer to the surface, Knapmeyer-Endrun et al. (*this issue*) image the local Martian crustal structure by identifying energy conversions from shallow layers through a range of methods. The study remains agnostic as to whether there is a 2-layer crust of 20 km thick, or 3-layered crust of 39 km thick at the Insight landing spot. Both crustal thickness models point to the sub-surface crust being less dense than the surface materials to different degrees, indicating the material has been highly altered over time.

These three studies provide important constraints on the present-day structure of Mars, and are also key for improving our understanding of how the planet has formed billions of years ago and evolved through time. Knapmeyer-Endrun et al. and Khan et al. both model the cooling and differentiation history of Mars, and test which parameters result in the proposed crustal and thick lithospheric structure. They find that the crust must be 13-21 times more enriched in radioactive heat-producing elements compared to the mantle, more than estimated by measurements of the surface materials. This puts new bounds on crustal composition and its formation. The models also find that the mantle beneath the thick stagnant lithosphere convects sluggishly.

The observations of a highly enriched crust, a thick thermal lithosphere, a sluggish mantle, and the lack of an insulating lower mantle, will now have to be investigated further in dynamical mantle models. Such models will test whether internal dynamics, instead of a giant impact, could have caused the strong topographic dichotomy of Mars (e.g. Zhong & Zuber 2001, Elkins-Tanton 2008), or whether a single mantle plume could produce the volcanism beneath the broad Tharsis Rise (e.g. Harder & Christensen, 1996). These kinds of dynamic processes control the rate of volcanism, volatile outgassing and (early) habitability.

The decrease in seismic velocities across the shallow mantle and the presence of a relatively large core both contribute to more bending of seismic energy from marsquakes deeper into the planet. This predicts the existence of so-called seismic shadow zones - less direct or no seismic energy would arrive at greater distances from a marsquake. SEIS would not be able to observe marsquakes at certain distances, thus underestimating the seismic activity on Mars. Crucially, due to the larger core, SEIS lies in the seismic shadow zone for seismicity in the tectonically and volcanically active Tharsis Rise. On the positive side, the preliminary models of the Martian mantle presented in this issue will help locate more sub-crustal marsquakes, and identify more core-bouncing waves and possibly even core-traversing waves. With the mission currently extended until the end of 2022, the number of high quality observations is expected to double, leaving plenty of opportunity for adding detail and improving models of Mars.

Direct seismic observations on Mars represent a major leap forward in planetary seismology. The size of the Martian core, the crustal layering and thick lithosphere provide important insights into the thermal and dynamic evolution of Mars. Over the coming years, as more marsquakes are measured, scientists will work to refine these models of the red planet and reveal more of Mars' enigmatic mysteries.

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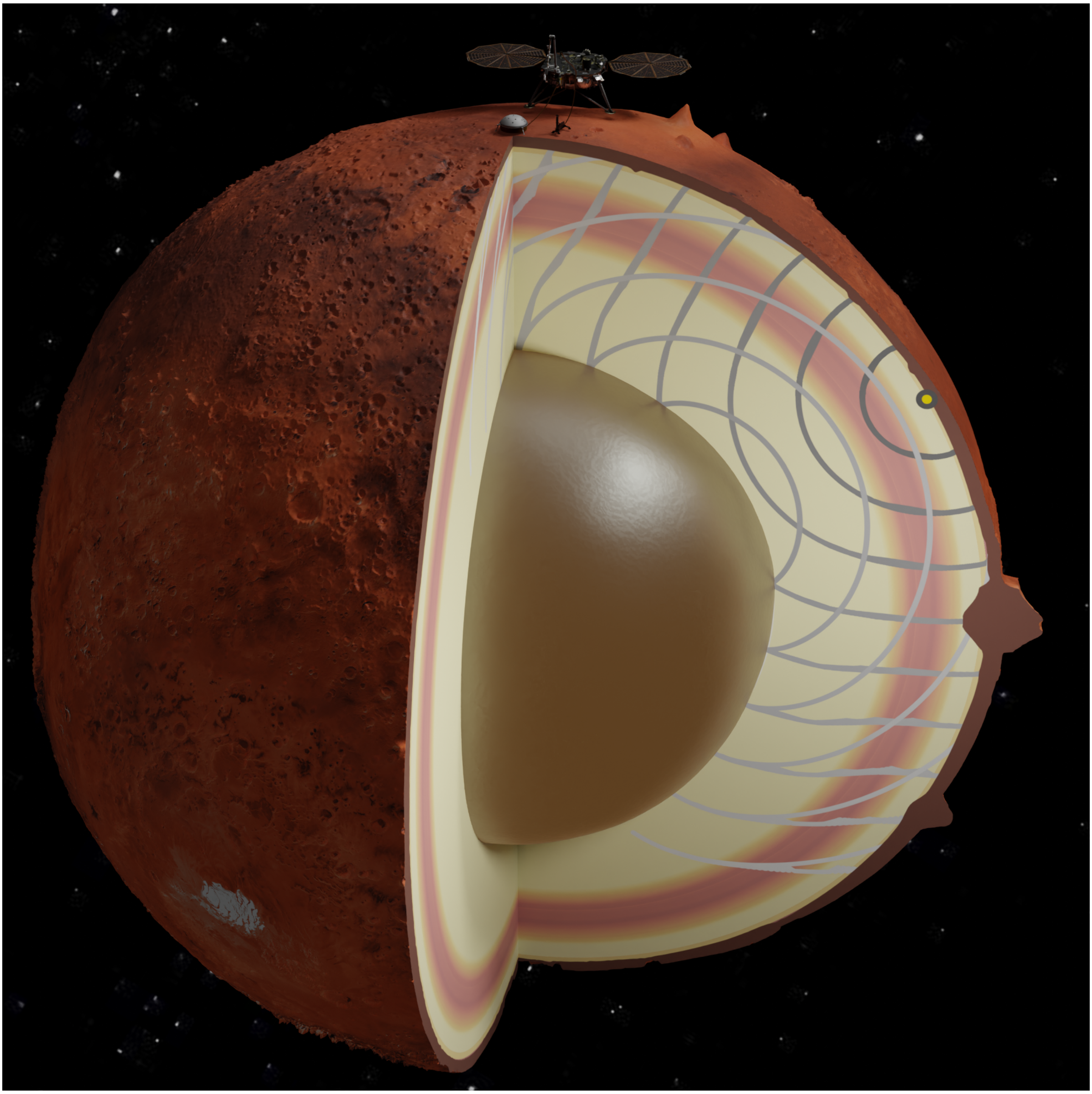
"Figure #1"



"Figure #2"