PERSPECTIVES

PLANETARY SCIENCE

The interior of Mars revealed

Direct seismic observations provide clues to the red planet's structure and evolution

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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 can reveal how a planet accreted and differentiated into layers, whether its core sustains a geodynamo that creates a magnetic field, and what the origin is of any tectonic and volcanic activity. New clues are now uncovered for Mars. On pages 438, 434, and 443 of this issue, Knapmeyer-Endrun *et al.* (*1*), Khan *et al.* (*2*), and Stähler *et al.* (*3*), respectively, present the first findings of the interior structure of Mars based on data from the NASA lander InSight (Interior Exploration using Seismic Investigations, Geodesy and Heat Transport). 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 with the characteristics of Earth.

A planetary subsurface can be probed with recordings of seismic waves that propagate through the planet after a quake. For Earth, the first measurement of waves diving deep through the mantle was made in 1889 in Germany from an earthquake in Japan (*4*). Global seismology is thus a relatively young science. In the first decades of the 20th century, seismologists discovered the main layers of Earth—that is, the boundaries between the crust and the mantle 30 km below Earth's surface (*5*), the mantle and core roughly halfway to the center (*6*), and the small inner core (*7*).

In a great feat of engineering, InSight landed on Mars in November 2018. Its seismometer, SEIS (Seismic Experiment for Interior Structure), 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 although 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 clues about the martian atmosphere and its daily and seasonal variability (*8*), but for those studying marsquakes and Mars' interior, these signals are generally considered "noise." The geology of Mars also creates challenges. 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 (*9*). All marsquakes observed in the 2 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 originate in the crust and create strong reverberations within, making individual waves difficult to identify (*9*). A smaller number are generated below the crust, and their appearance resembles tectonic events on

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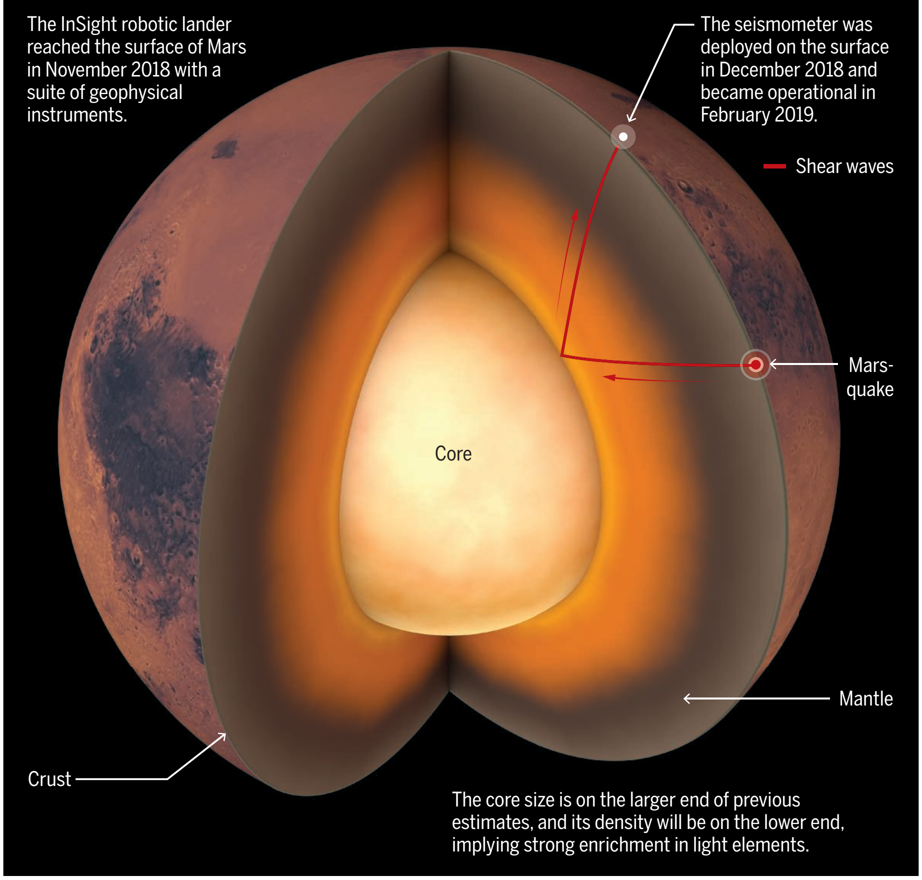
Martian core measurements

Seismic waves tell us about the properties and boundaries of a planet's interior. Shear waves that travel from a marsquake and reflect off of the iron-nickel core are detected by the InSight seismometer and give us an estimate of the core size. The strength of the reflected waves shows that the core is in a liquid state, which shear waves cannot propagate through.



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Earth. The studies of Knapmeyer-Endrun *et al.*, Khan *et al.*, and Stähler *et al.* used data from about 10 of these subcrustal marsquakes to reveal the inner structure of Mars (see the figure).

To overcome the challenges of working with noisy and sparse seismic data, the studies 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 complementary constraints. Notably, 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 as well as with other geophysical observables such as surface topography and heat flow, gravity and geodetic data, and observations of crustal magnetization.

"These three studies ...are also key for improving our understanding of how the planet formed billions of years ago..."

Although 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.* report the first observations of faint signals bouncing off the boundary to the martian core. They determined that the core starts about 1560 km deep, nearly halfway to the center. This is on the large end of previous estimates. Given the known mass and moment of inertia of Mars, this implies that the core is less dense than previously thought and that its iron-nickel alloy must be strongly enriched in sulfur and other light elements. The strength of the bouncing waves confirms that the core is still in a liquid state, as has been suspected from Mars' tidal response (*10*) and for a sulfur-enriched alloy at estimated martian core temperatures above 1800 K (*11*).

The observation of a relatively thin mantle means that Mars lacks the dense, insulating layer of the bridgmanite mineral that becomes stable under large pressures in Earth's mantle. The absence of this mineral would have led to a more rapid cooling of the early martian core, potentially driving a geodynamo to create a magnetic field. This geodynamo has since ceased and is now only evidenced by magnetized older crustal rocks (*12*). The magnetometer on InSight found that magnetization in the crust observed at the surface is 10 times stronger than that modeled on the basis of satellite data. These new observations imply that Mars' early geodynamo must have been similar in strength to Earth's present-day geodynamo (*13*).

Instead of using seismic waves that bounce off the core, Khan *et al.* used waves that either travel directly from the marsquake to the seismometer or bounce off Mars' surface to reveal the shallow 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 to 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.* imaged the local martian crustal structure by identifying energy conversions from shallow layers through a range of methods. The study was agnostic as to whether there is a 20-km-thick two-layer crust or a 39-km-thick three-layer crust at the InSight landing spot. Both crustal thickness models point to the subsurface crust as less dense than the surface materials to different degrees, indicating that 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 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 to 21 times more enriched in radioactive heat-producing elements compared with the mantle. This is greater than estimates based on measurements of surface materials and puts new bounds on Mars' crustal composition and 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, rather than a giant impact, could have caused the strong topographic dichotomy of Mars—the heavily cratered southern highlands and the smooth plains of the northern lowlands (*14*)—or whether a single mantle plume could have produced the volcanism beneath the broad Tharsis Rise, the most extensive topographic feature on the planet (*15*). 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 thus not observe marsquakes at certain distances, thereby underestimating the seismic activity on Mars. Crucially, because of 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 by these studies will help locate more subcrustal marsquakes and identify more core-bouncing waves, possibly even core-traversing waves. With the InSight 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 the thick lithosphere provide important insights into the thermal and dynamic evolution of Mars. Over the coming years, as more marsquakes are measured, scientists will refine these models of the red planet and reveal more of Mars' enigmatic mysteries. ■

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