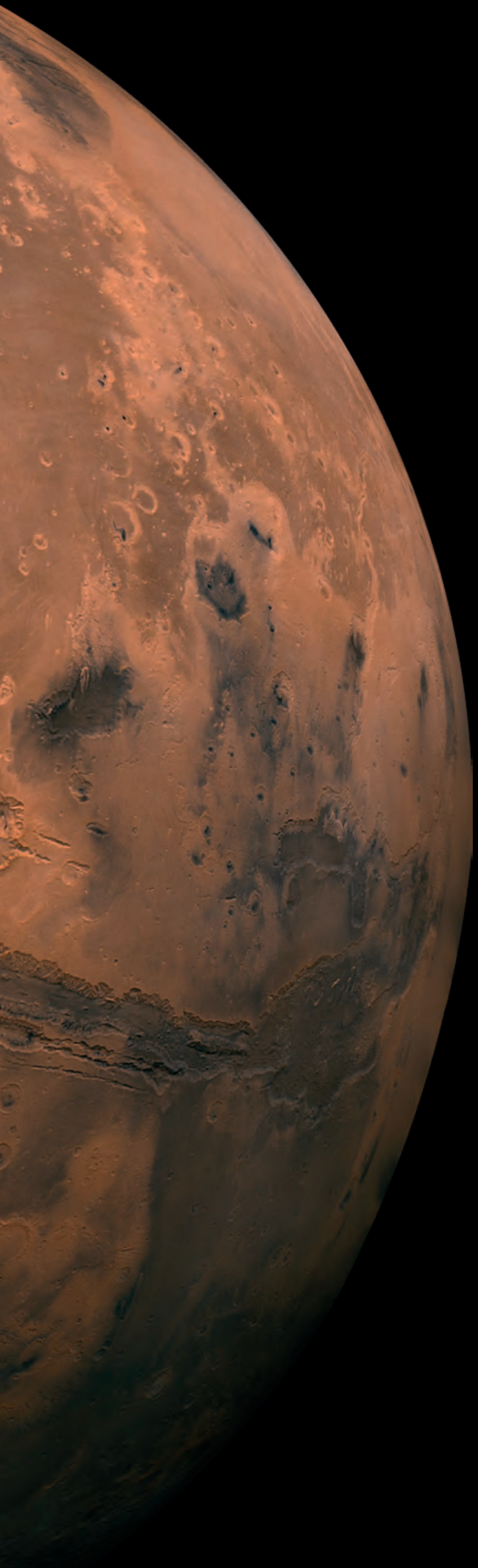
WHAT LIES BENEATH

Since February 2019, the InSight lander has been collecting geophysical data that allow us to peer inside the red planet. The data reveal a vast molten core, but thinner-than-expected crust, as Anna Horleston and Jessica Irving explain

The Valles Marineris Hemisphere of Mars.
(Image credit: NASA/JPL-Caltech)



IT TOOK SEVERAL CENTURIES of theorisation and many decades of seismic data collection and analysis to determine Earth's internal structure. However, we now have a good understanding of the layering seen within our planet: from the crust – oceanic and continental – through the upper mantle, transition zone, lower mantle and liquid outer core, all the way to the solid iron heart of Earth.

Thanks to the seismic data recorded as part of the Apollo missions, we also know that the Moon has both a solid inner core and a liquid outer core, but what of Mars' interior? Understanding the formation, evolution and structure of a terrestrial planet is a big goal for a little lander, but NASA's InSight is rising to the challenge.

InSight on Mars

InSight (Interior Exploration using Seismic Investigations, Geodesy and Heat Transport; Fig. 1) is the first dedicated geophysics mission sent to another planet. The lander is equipped with not only a highly sensitive seismometer, but also wind, pressure, temperature, and magnetic sensors that were all designed to allow us to determine the internal structure of the red planet.

After a successful landing in November 2018, the seismometer (SEIS; Fig. 2) was carefully deployed onto the surface of Mars (rather than being left on the deck of the lander as in the 1970s Viking mission). After it was protected with a wind and thermal shield, continuous seismic recording began in February 2019 and SEIS has been recording and transmitting data with very few interruptions ever since (Banerdt et al., 2020).

Seismic signals from Mars

Though Mars has no tectonic plates, the first marsquakes were detected within months of InSight landing. It is challenging to detect quakes on Mars, not only because they are small, but also because the seismometer is subject to the extremes of the Martian weather, with seasonally changing daily windy periods that obscure hours of potential marsquake data, even with the wind and thermal shield in place. The wind and pressure sensors can help us distinguish between atmospheric and tectonic signals but, as yet, we have not found a way to remove the atmospheric effects from the seismic data.

Over the past three years, the marsquake service has catalogued over 900 marsquakes (InSight →

Marsquake Service, 2021; Fig. 3) and more are observed every day. The quakes fall into two distinct categories: high and lower frequency events (Clinton et al., 2021). High-frequency marsquakes have energy at or above 2.4 Hz and their seismic signal is scattered with emergent phases that slowly increase in amplitude, rather than having a sharp onset. These seismic signals are thought to originate in the crust and their complexity is caused by inhomogeneities in the crust causing the seismic energy to be reflected many times. Lower-frequency marsquakes look more like the classic tectonic quakes we might record on Earth. They are thought to originate in the upper mantle and it is these events that are used to determine the internal structure of the planet

Building a planet

Planets grow, or accrete, early in the life of a solar system. However, accretion is only one step in the planet-building process. Planetary interiors are not a uniform mix of their initial ingredients; they also undergo differentiation whereby lighter minerals 'float' towards the surface, whilst heavier components like iron sink towards the planet's centre. We expect that rocky planets like Mars should have an iron-rich core, a silicate mantle and an outermost crust, but, until now, the extent of each of these layers within Mars was unknown.

Various existing models, constrained by seismic, geodynamic, geophysical and mineral physics data (such as density, moment of inertia, phase equilibria and thermochemical parameters), offer a range of predictions for the internal structure and composition of Mars. In these models, varying the size and density of the core influences the composition of the mantle. The data from InSight allow us to test these models and thus more accurately determine the core size and density, as well as the mantle composition for the first time.

Finding the core

Although the presence of Earth's core was predicted in the 1770s from the Schiehallion experiment (Maskelyne, 1775), it wasn't actually detected until the early 1900s when a seismic shadow zone was observed in the seismic signals

Figure 1: InSight's first full selfie on Mars displays the lander's solar panels and deck. On top of the deck are its science instruments, weather sensor booms and ultra-high-frequency antenna. With the solar panels deployed, InSight has a length or 'wingspan' of ~6 m *(Image credit: NASA/JPL-Caltech)*

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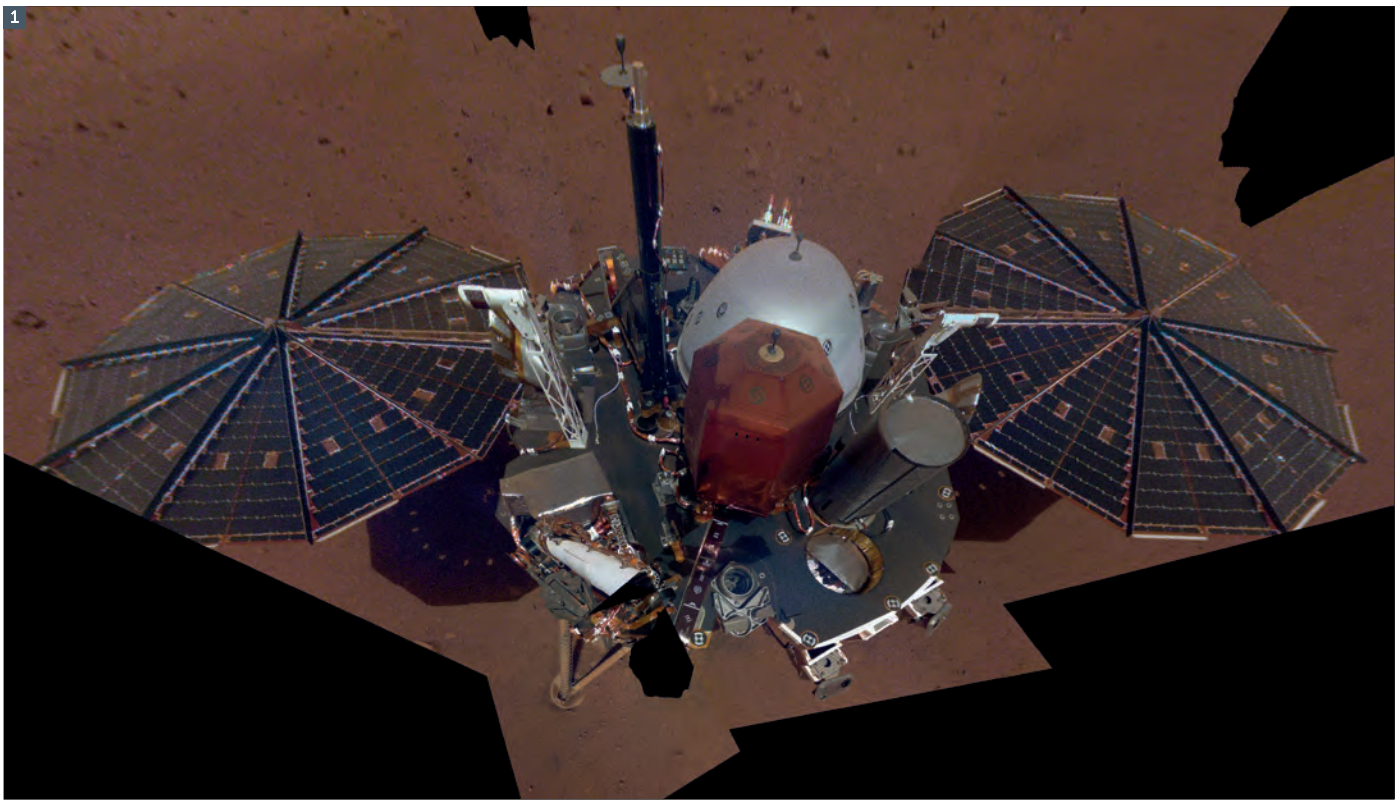

“Though Mars has no tectonic plates, the first marsquakes were detected within months of InSight landing”

from large earthquakes travelling through the planet (Oldham, 1906). On Mars, we have not detected any large quakes from the far side of the planet. Instead, we rely on shear waves that are reflected at the boundary between the core and mantle (the seismic phase ScS) to measure the Martian core. Of the hundreds of marsquakes detected so far, only six provide clearly identifiable ScS phases suitable for estimating the core radius.

By analysing the ScS phases (together with other direct and reflected seismic phases), the radius of Mars’ core was constrained to be 1,830 $\pm$ 40 km (Stähler et al., 2021; Fig. 4). This is huge! It sits at the upper end of pre-mission estimates and means that the core occupies just over half of the planet’s radius. A comparison of the amplitude of the ScS phase to that of directly detected seismic phases also confirmed that the core is liquid.

Mars’ large metallic core, combined with estimates of the core density, requires a large proportion of lighter elements to be alloyed with iron inside the Martian core. It is tricky to pin down the exact composition of the core, but the best interpretation points towards an iron-nickel core with 10 – 15 wt% sulphur, <5 wt% oxygen and <1 wt% hydrogen and carbon. The bounds on oxygen, hydrogen and carbon are upper limits, but demonstrate the need for more light elements to balance the core size and density with the bulk composition of Mars.

Mineral physics experiments show that liquid iron alloys containing this much sulphur are unlikely to solidify at the pressures and temperatures we expect at the centre of Mars’ core, so it is unlikely that the red planet has an inner core. The lack of an inner core may help to explain why there is no planet-wide magnetic field on Mars today, unlike on Earth.

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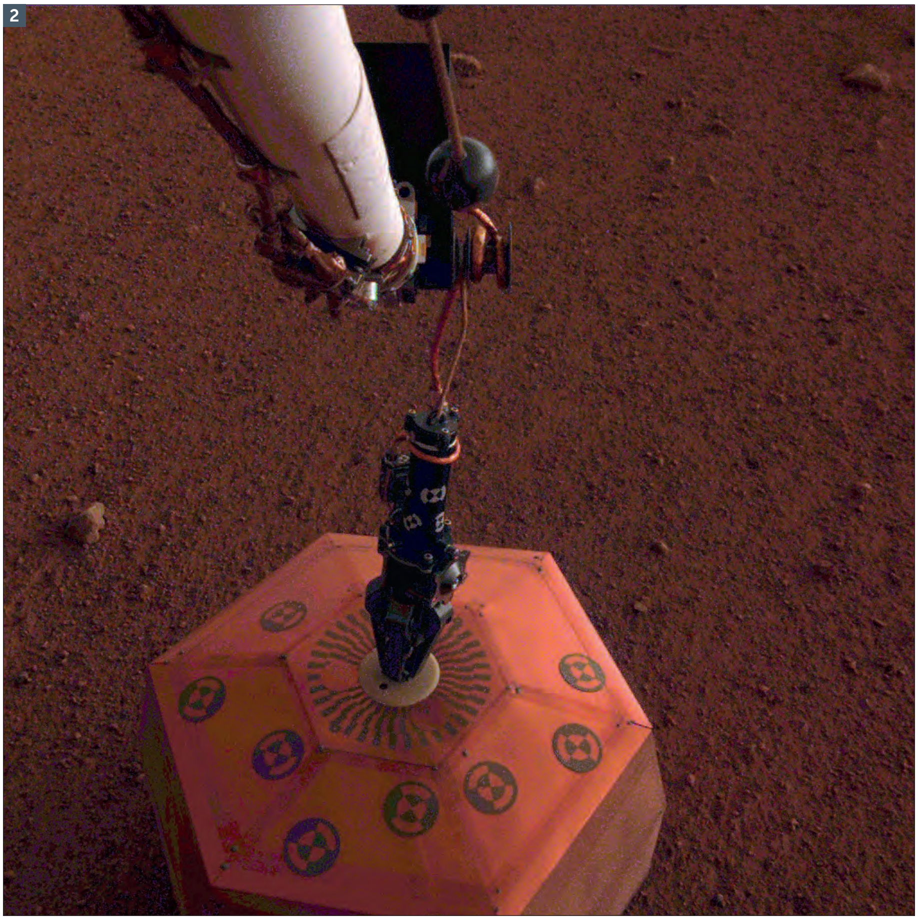

Figure 2: InSight placed its seismometer onto the Martian surface on 19 December 2018, marking the first time a spacecraft has robotically placed a seismometer onto the surface of another planet. *(Image credit: NASA/JPL-Caltech)*

The mantle

Eight of the marsquakes recorded show seismic phases that have been reflected from the surface, as well as direct P and S phases. These phases travel through different regions of the mantle and allow us to test models of the upper mantle structure. The results suggest that Mars has a thermal lithosphere that is 400 to 600 km thick (Khan et al., 2021). This is twice the thickness of Earth’s lithosphere. Models of the Martian mantle also show that the velocity of shear seismic waves increases at around 1,050 km depth, in line with previous work that suggested →

a potential mantle transition zone within Mars. This is similar to the 410 km discontinuity seen on Earth, where olivine transforms into wadsleyite.

If the core-mantle boundary is located at a depth of 1,520 to 1,600 km within Mars, the pressure here will be about 18 – 19 GPa and the temperature around 1900 – 2000 K. These conditions are not favourable for the stabilisation of bridgmanite — the mineral that comprises most of Earth's lower mantle. So, effectively, Mars' lower mantle is mineralogically comparable to Earth's mantle transition zone and not the dense, thermally insulating lower mantle that we see on Earth.

It is likely therefore that Mars' core lost a lot of heat early in its history and had a thermally driven dynamo that would have caused the remnant crustal magnetisation currently observed on Mars. Local to InSight the crustal magnetic field has been measured to be twice as strong as that observed from orbit (Johnson et al., 2020), suggesting that at some stage in its evolution Mars had a magnetic field as strong as Earth's present-day field.

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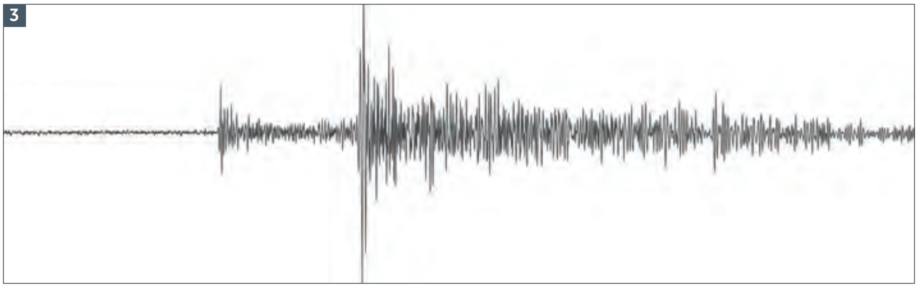

Figure 3: Marsquakes are recorded as seismograms. Variations in the frequency, amplitude, and onset (emergent compared to sharp) of the signals reflect complexities in the seismic source regions and travel paths for the seismic waves that allow geophysicists to make inferences about the structure and character of the planet. This seismogram was recorded on 25 July 2019, the 235th Martian day, or sol, of InSight's mission and shows an event with a sharp onset, originating in the upper mantle. *(Image credit: NASA/JPL-Caltech)*

The crust

Whatever lies beneath, the crust of Mars is proving somewhat enigmatic. Receiver-function analysis combined with analysis of the ambient noise field was used to determine the crustal structure beneath InSight (Knapmeyer-Endrun et al., 2021). However, initial results point to two different possible solutions: either a two-layer crustal model with a total thickness of 20 $\pm$ 5 km or a three-layer model with a thickness of 39 $\pm$ 8 km. Extrapolating from this using global gravity and topography maps gives an average Martian crustal thickness between 24 and 72 km, which rules out some previous models that suggested an average crustal thickness of up to 100 km.

Towards a unified model

Combining the core, mantle and crustal models still leaves some uncertainty as to the exact composition of Mars' interior. For example, if the crust is thin, it must not only be less dense than previously thought, but must also be enriched in heat-producing elements (by about 21 times more than the primitive mantle). If the crust is thick, on the other hand, it would have to be about 13 times more enriched in heat-producing elements and would then have a density that is more in line with surface observations. Both models would fit with a surface heat flux between 20 and 25 mWm^{-2} (as previously predicted by Wänke & Dreibus, 1994) and both would support the possibility of present-day melting that is only occurring beneath the Tharsis volcanic province and not more widely across the planet.

Other mantle models (Khan et al, 2021) suggest a heat flux of between 14 and 29 mWm^{-2} and crustal enrichment of heat-producing elements by a factor of 13 to 20, which is compatible with predictions from either crustal thickness, thick or thin.

The future

There is much more that can be done with the seismic and other geophysical data from InSight. For example, the Rotation and Interior Structure Experiment (RISE) aboard the lander is recording the exact location of InSight in space as Mars orbits, tracking not only the orbital path, but also the precession or 'wobble' of Mars. Knowing precisely how much Mars' North Pole 'wobbles' will further help us to constrain the size, state and composition of Mars' core.

InSight is currently nearly halfway through its second Martian year of operations; the mission, originally funded for one Martian year, was extended in January 2021 for a second Martian year. Since the publication of these results earlier this year, more marsquakes have been

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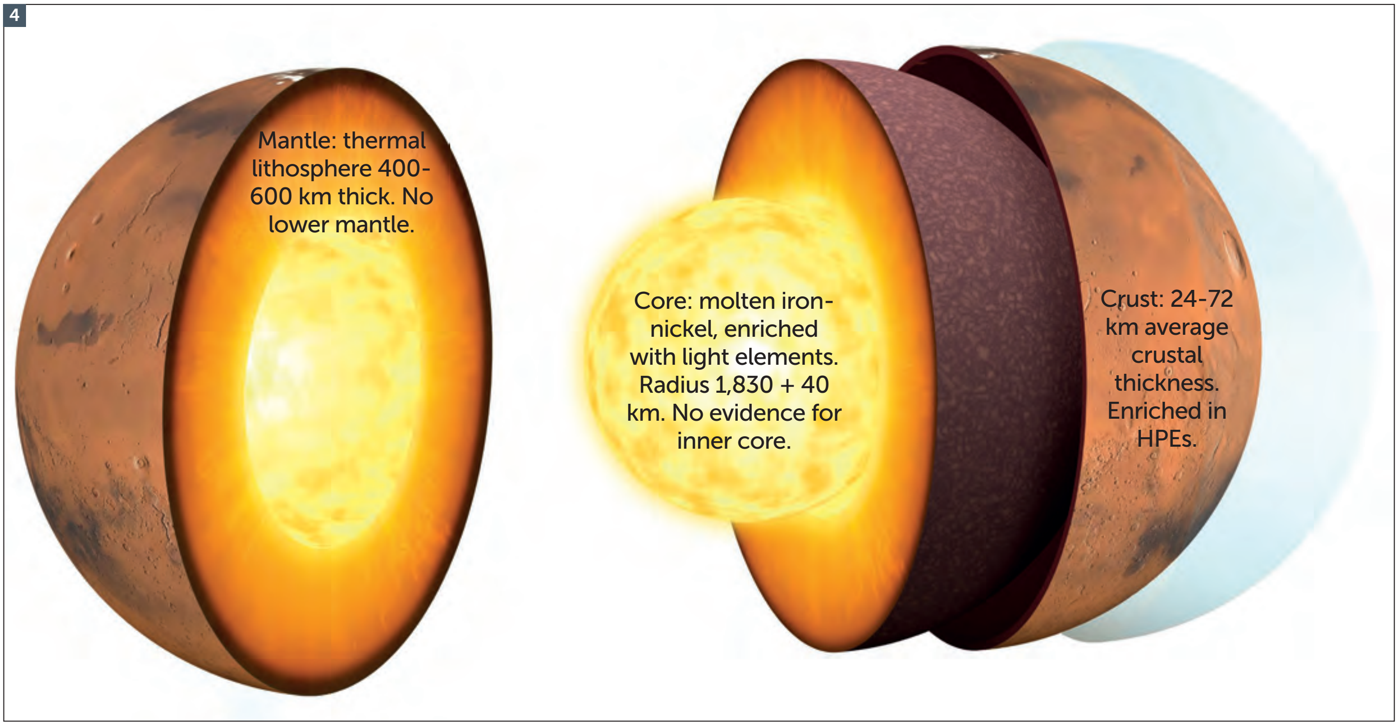

Figure 4: Illustration of the interior structure of Mars. The mostly iron-nickel molten core has a radius of ~1,830 km, which is just over half the planet's radius (3,389.5 km). Mars' lower mantle is mineralogically comparable to Earth's mantle transition zone, while the thermal lithosphere is 400 to 600 km thick – twice the thickness of Earth's lithosphere. The crust has an average thickness of 24 to 72 km (HPEs, heat-producing elements)

detected, and their seismic signals contain further potential reflected and converted phases. These data will be integrated into the existing inversion workflows to improve or verify the interpretations of the internal structure.

Despite the caveats and complexities of the modelling systematics, the results from InSight are a great leap forward in planetary science. Never before have we truly looked inside another planet and here, with one seismometer, we have placed bounds on the structure of Mars from direct measurements. In the future, seismometers will be deployed on the far side of the Moon as part of the Artemis mission and Dragonfly will place a seismometer on Titan in the mid-2030s. All of these experiments will help us understand more about how planets form and evolve; seeing deep into Mars is one piece of a solar system-sized puzzle. G

FURTHER READING

A full list of further reading is available at geoscientist.online.

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