# News & views

Planetary science

## Deep Mars is surprisingly soft

Suzan van der Lee

Two analyses of seismic waves that traversed Mars paint the clearest picture yet of the red planet's core and deep mantle — and rationalize the puzzling implications of a previous interpretation of the seismological data. **See p.712 & 718**

In 2019, Mars became only the third body in the Universe, after Earth and the Moon, to have a seismological study carried out of its deep interior. The InSight Mars Lander used an instrument called the Seismic Experiment for Interior Structure (SEIS) to record seismic waves passing through Mars's interior. The seismometer collected data during nearly three years of marsquakes, including two seismic events caused by meteorite impacts. Writing in *Nature*, Samuel *et al.*[1] (page 712) and Khan *et al.*[2] (page 718) present analyses of these seismic signals. Their findings improve our understanding of the layers of Mars that lie deep beneath the crust, and help to put the structure and origins of the Martian interior into context with formation and evolution scenarios for rocky (terrestrial) planets in the Solar System.

Most surprisingly, both studies conclude that the liquid iron–nickel core of Mars, which reaches no farther than halfway to the surface, is surrounded by an approximately 150-kilometre-thick layer of soft, essentially molten rock (Fig. 1). The molten state of this layer suggests that its temperature must be at least 2,000 kelvin. This could be a sign that Mars had a turbulent interior following its formation[3], rather than a calmer one that more gently transported and shed heat to interplanetary space. Samuel *et al.* favour the turbulent scenario, whereas Kahn *et al.* favour the calmer alternative. Samuel and colleagues' model of Mars therefore has a core that is hundreds of kelvin hotter than a core that evolved from the calmer alternative, and a mantle that is hundreds of kelvin cooler.

Three main seismological clues indicated the existence of this molten rock layer. The first was the observation of slow longitudinal seismic waves (called P waves) that traversed the bottom of the mantle but did not make it into the core, and which were generated by a meteorite impact about one-third of a planetary circumference away from the InSight lander. The second hint came from the finding that transverse seismic waves (called S waves), produced by marsquakes nearer to the lander, propagated through the mid- and uppermost mantle with an efficiency suggestive of a relatively cool solid. And the third clue was the observation of strong reflections of S waves from the top of the molten layer. S waves can exist only in solids, and so the InSight team originally interpreted these reflections as evidence of a large liquid iron–nickel core[4], and did not consider that the base of the mantle could be molten.

The previous estimate[4] of the core radius (1,830 kilometres), inferred from a subset of the InSight seismic data, indicated that the volume of the core was about 30% bigger than Samuel *et al.* and Khan *et al.* now suggest. This implied that Mars's core would contain much less iron per unit of volume than Earth's core does, and instead would have surprisingly large amounts of lightweight elements such as sulfur, oxygen, carbon and hydrogen. These light elements do combine reasonably well with heavyweight liquid iron[5], but are not likely to have been available in sufficient quantities in planetesimals — the bodies that combined to form the terrestrial planets of the Solar System — to explain the core density implied by the previous estimate. This is especially true when the differentiation process that separates heavy elements from lighter ones in planetary bodies is taken into account.

The new estimates[1,2] of the core radius (1,650–1,675 km), density (6,470–6,650 kilograms per cubic metre) and iron composition (about 80–90%) are more compatible with the proportions of elements that occurred in planetesimals, and with values known to be achievable from studies involving high-pressure experiments and theoretical and computational modelling[5]. Samuel *et al.*

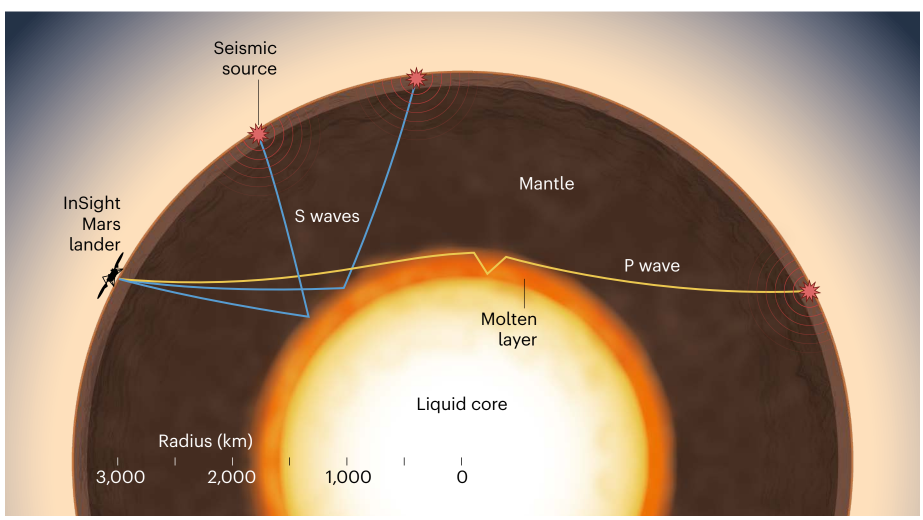


**Figure 1 | A model of Mars.** The InSight Mars Lander recorded seismic waves that were caused by marsquakes and meteorite impacts and traversed the interior of Mars. Shown here are two transverse seismic waves (S waves, blue), caused by marsquakes, and one longitudinal seismic wave (a P wave, yellow), produced by a meteorite strike. From their analyses of the seismological data, Samuel *et al.*[1] and Khan *et al.*[2] conclude that Mars' core is surrounded by a 150-kilometre-thick molten layer of mantle rock. The S waves reflected off this layer before they reached the lander, and the P wave travelled a complex path as a result of refraction at the top of the soft molten layer and reflection from the dense, liquid core. (Adapted from Fig. 1l of ref. 1).

estimate that sulfur makes up 14 to 17% of the core's mass; that oxygen and carbon account for about 3% and 1%, respectively; and that hydrogen constitutes less than 0.15%. Khan *et al.* estimate about two-thirds of these amounts for sulfur and oxygen, and more than double the amounts for carbon and hydrogen. The studies show that the incompressibility – a measure of how much a material resists changing volume when subjected to constant pressure – of the top of the liquid iron–nickel core is around 160 gigapascals, which corresponds to a longitudinal seismic-wave speed (P-wave velocity) of around 5 km $s^{-1}$.

The deep solid mantle that overlies the molten basal mantle layer is estimated to have a much lower density (4,000 kg $m^{-3}$) than the core's, but a much higher incompressibility and P-wave velocity (190 GPa and 9 km $s^{-1}$, respectively). Khan *et al.* estimate that the density and incompressibility of the molten layer itself are 4,000 kg $m^{-3}$ and 110 GPa, whereas Samuel *et al.* conclude that it is denser (4,800 kg $m^{-3}$) and less compressible (about 140 GPa).

A denser, less compressible layer of molten rock would be confined to the bottom of Mars's mantle and would not participate in convection of the solid mantle over geological timescales – thereby acting as a thermal boundary layer that prevents the core from solidifying and potentially generating a magnetic field. By contrast, a less dense, more compressible molten rock layer would be able to fuel volcanism, such as the lava flows that occurred at Mars' Tharsis plateau, and magmatic intrusions that are inferred to be below or within the crust in the Elysium Planitia region. Either way, the incorporation of a basal molten layer into models of Mars's mantle is an insightful addition that explains the paths, travel times and amplitudes of observed seismic waves, and also reconciles the core's size and composition with expectations for terrestrial planets.

Both Khan *et al.* and Samuel *et al.* conclude that the molten layer envelops the entire core of Mars. An important caveat is that the seismic waves from which the authors' inferences were drawn do not sample the entire planet. Rather, they provide a combination of regional snapshots that might not be representative of the whole planet. Further measurements of seismic waves, using instruments at different locations, will be needed to clarify this issue – although no such missions to Mars are currently planned.

Identifying and measuring P and S waves through Mars' interior is fraught with uncertainty. Nevertheless, the authors were able to identify and measure a striking number of seismic waves (more than 130), thanks to the high quality of the lander's seismometer, and by using sophisticated seismogram interpretation and modelling tools that were developed for Earth but specifically adapted for use on Mars. It is remarkable that both studies arrived at similar models for the planet's deep interior, given that the two teams used slightly different measurements of seismic waves, and distinct approaches to modelling the effects of composition, state and temperature on the density and incompressibility of the molten interior of Mars.

Samuel *et al.* and Khan *et al.* agree on the molten state of the mantle's bottom 150 km, as well as on the size, state and average density of the core. However, they disagree on the density, incompressibility, composition and origin of the molten mantle layer. They also draw different conclusions about the extent to which oxygen and sulfur lower the core's incompressibility, and whether the core's P-wave velocity rises or falls with increasing amounts of these elements. To clarify these points, it will be necessary to achieve better alignment between computational and experimental data for representative alloys and minerals at the appropriate temperatures and pressures.

The current results provide the most accurate and precise estimates so far of Mars' core and mantle structure. The findings show that combining seismological observations with knowledge of terrestrial-planet formation and evolution – and with data on planetary size, shape, rotation and gravitational field – offers invaluable perspectives on Mars's past, present and future dynamics. The combination also limits the range of models that are compatible with all of the data. The inferred connections between the current interior structure and the potential evolution of Mars[1,2] provide crucial context for understanding terrestrial planets, such as Earth, more generally.

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1. Samuel, H. *et al. Nature* **622**, 712–717 (2023).
2. Khan, A. *et al. Nature* **622**, 718–723 (2023).
3. Elkins-Tanton, L. T., Zaranek, S. E., Parmentier, E.M. & Hess, P. C. *Earth Planet. Sci. Lett.* **236**, 1–12 (2005).
4. Stähler, S. C. *et al. Science* **373**, 443–448 (2021).
5. Steenstra, E. S. & van Westrenen, W. *Icarus* **315**, 69–78 (2018).

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Virology

# Learn from the past to predict viral pandemics

**Nash D. Rochman & Eugene V. Koonin**

The COVID-19 pandemic highlighted the need to understand the emergence of viral variants, given that these can have implications for vaccination success. A bioinformatics tool offers a way to predict viral evolution. **See p.818**

The COVID-19 pandemic, the first epidemic to affect society on a global level since the influenza pandemic in 1918, has put the problem of predicting viral evolution at the forefront of biomedical research. On page 818, Thadani *et al.*[1] present a tool for making such predictions.

The evolution of viral sequences is an inherently random process that provides the raw material for the process of natural selection. The number of different sequences that are theoretically available for an evolving viral genome is almost unimaginably vast. For example, for a typical coronavirus genome of 30,000 nucleotides, there are $4^{30,000}$ possible sequence variants, which is much greater than the number of elementary particles in the Universe[2]. Evidently, a vanishingly small fraction of all of the possible viral genome sequences even encode a functional virus. Determining precisely the particular few that will emerge during the course of evolution is simply impossible. Fortunately, however, most of the time, the predictions of viral evolution that are actually needed are more realistically achievable.

So, a pertinent question to address might be, instead, what vaccine using messenger RNA that targets particular strains of the SARS-CoV-2 virus will be designed within the next six months? Thadani and colleagues propose a computational framework called EVEscape, which the authors use to demonstrate that predictions of this type might indeed be feasible, and that the key to future success relies on remembering the past.

The long-term persistence of a virus depends on the continual availability of newly susceptible individuals through either birth or the loss of immunity that was originally conferred through prior infection or vaccination. Loss of immunity can result from limited host