are an exception — they rely mainly on the ICS pathway. Functional versions of the newly identified enzymes, apart from BEBT, are absent in these species, highlighting evolutionary divergence in the mechanisms of salicylic-acid biosynthesis across plant lineages.

Gaining a deeper understanding of the production of salicylic acid in a wide range of crops might provide opportunities for agricultural innovation. For example, Zhu *et al.* showed that expressing higher than normal levels of *OSD1* in rice plants boosts the levels of salicylic acid and enhances resistance to infection by the bacterium *Xanthomonas oryzae*, which is a substantial threat to this crop. This increased resistance was achieved without any differences in the usual number of rice branches (tillers) and panicles, the structures from which rice grains form. This result highlights the potential of fine-tuning the PAL pathway to improve crop defences without compromising growth.

These discoveries open many doors to future research and raise complex questions. How are these newly identified enzymes regulated? How do they integrate with other plant-defence networks? The way in which the molecules move between cellular compartments and organelles during the biosynthesis process is unknown.

It is also unclear how the production of salicylic acid is coordinated across various tissues to enable an immune response throughout the plant, a defence mechanism known as systemic acquired resistance (SAR)[13]. SAR depends mainly on the production of salicylic acid away from a localized infection site, and it enables uninfected parts of the plant to strengthen their defences against disease-causing agents. Although the production of salicylic acid is relatively well understood at infection sites, its regulation in tissues away from an infection site, which is required for SAR[14–18], remains to be understood, especially for species that depend mainly on the PAL pathway.

Ultimately, these findings do more than just solve a long-standing puzzle, they highlight how evolution established two distinct routes, the ICS and PAL pathways, to achieve the same outcome of salicylic acid production. The research also highlights the value of integrating genetic, biochemical and evolutionary approaches to unravel complex biological questions. This new understanding provides a robust foundation for advancing plant-defence research and developing strategies for crop improvements that can be tailored to different species and environments.

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1. Desborough, M. J. R. & Keeling, D. M. *Br. J. Haematol*. **177**, 674–683 (2017).
2. Liu, Y. *et al. Nature* **645**, 201–207 (2025).
3. Zhu, B. *et al. Nature* **645**, 218–227 (2025).
4. Wang, Y. *et al. Nature* **645**, 208–217 (2025).
5. Jia, X. *et al. Mol. Plant* **16**, 245–259 (2023).
6. Rekhter, D. *et al. Science* **365**, 498–502 (2019).
7. Torrens-Spence, M. P. *et al. Mol. Plant* **12**, 1577–1586 (2019).
8. Hong, K. *et al*. Preprint at bioRxiv https://doi.org/10.1101/2025.03.03.641121 (2025).
9. Yalpani, N., León, J., Lawton, M. A. & Raskin, I. *Plant Physiol*. **103**, 315–321 (1993).
10. Pallas, J. A., Paiva, N. L., Lamb, C. & Dixon, R. A. *Plant J*. **10**, 281–293 (1996).
11. Bussell, J. D., Reichelt, M., Wiszniewski, A. A. G., Gershenzon, J. & Smith, S. M. *Plant Physiol*. **164**, 48–54 (2014).
12. León, J., Shulaev, V., Yalpani, N., Lawton, M. A. & Raskin, I. *Proc. Natl Acad. Sci. USA* **92**, 10413–10417 (1995).
13. Fu, Z. Q. & Dong, X. *Annu. Rev. Plant Biol*. **64**, 839–863 (2013).
14. Zheng, X.-Y. *et al. Proc. Natl Acad. Sci. USA* **112**, 9166–9173 (2015).
15. Hartmann, M. *et al. Cell* **173**, 456–469 (2018).
16. Yildiz, I. *et al. Plant Physiol*. **186**, 1679–1705 (2021).
17. Cao, L. *et al. Science* **385**, 1211–1217 (2024).
18. Hyun, J. *et al*. Preprint at bioRxiv https://doi.org/10.1101/2025.07.17.664945 (2025).

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Planetary science

Marsquakes point to a solid planetary inner core

Nicholas C. Schmerr

An analysis of seismic waves propagating through Mars finds evidence that the planet has a small, solid inner core, which challenges existing planetary models. **See p.67**

In December 2018, for the first time since 1976, a seismometer station was deployed on the surface of Mars. For four years, NASA's Interior Exploration using Seismic Investigations, Geodesy and Heat Transport (InSight) mission[1] recorded seismic waves from 'marsquakes', which built a picture of the inner structure of the red planet. On page 67, Bi *et al.*[2] report analysis of InSight data that reveals evidence of a small, solid inner core at the centre of Mars. This finding challenges current models of the planet's evolution and present-day structure.

Rocky planets such as Earth and Mars contain solid and liquid layers that have distinct compositions. When seismic waves propagate into the interior of these planets, they partition into reflected and refracted waves at the layer boundaries. A seismometer on the surface of the planet might detect signals from seismic waves that took different paths through the interior — these signals are called seismic phases.

In 1936, the seismologist Inge Lehmann used recordings of compressional seismic waves, which are called P waves, to show that Earth has a solid inner core[3]. Bi and colleagues used P waves to look for evidence of a Martian solid inner core but, whereas studies of Earth's interior can combine data from many seismic stations, Bi *et al.* had only one. The InSight seismometer station, which is called the Seismic Experiment for Interior Structure (SEIS), has recorded tectonically generated marsquakes, as well as meteoroid impacts and background vibrations, which are dominated by wind and atmospheric motions.

Previous analysis of the InSight data unveiled the structure of the outermost solid, rocky layers of Mars[4], called the crust and mantle, and also measured the size of the metal core, which is at least partially liquid[5]. However, a full picture of the deep interior of Mars has remained elusive.

The researchers used seismic phases detected by InSight to build a picture of the structure of the Martian core (Fig. 1). Of the seismic phases that pass through the core, they focused on two, called P′P′ and PKKP. These are P waves that travel from a marsquake source, through the crust and the mantle and enter the core. P′P′ waves travel through the core and reflect at the surface on the other side of the planet, whereas PKKP waves are reflected inside the core at the core–mantle boundary. If an inner core is present, a third phase, called PKiKP, will also be generated by P waves that reflect from the outer–inner-core boundary.

To search for these waves, Bi *et al.* used a method called seismic array analysis[6]. Typically, this approach combines seismometer measurements, called seismograms, from several instruments. The analysis can distinguish seismic phases that arrive at different incidence angles and at different speeds. For the InSight data, Bi *et al.* turned this approach around, using data from 23 marsquakes to identify P-wave phases that had travelled into the deepest parts of the Martian core.

Bi *et al.* observed waves that were consistent with the predicted properties of the

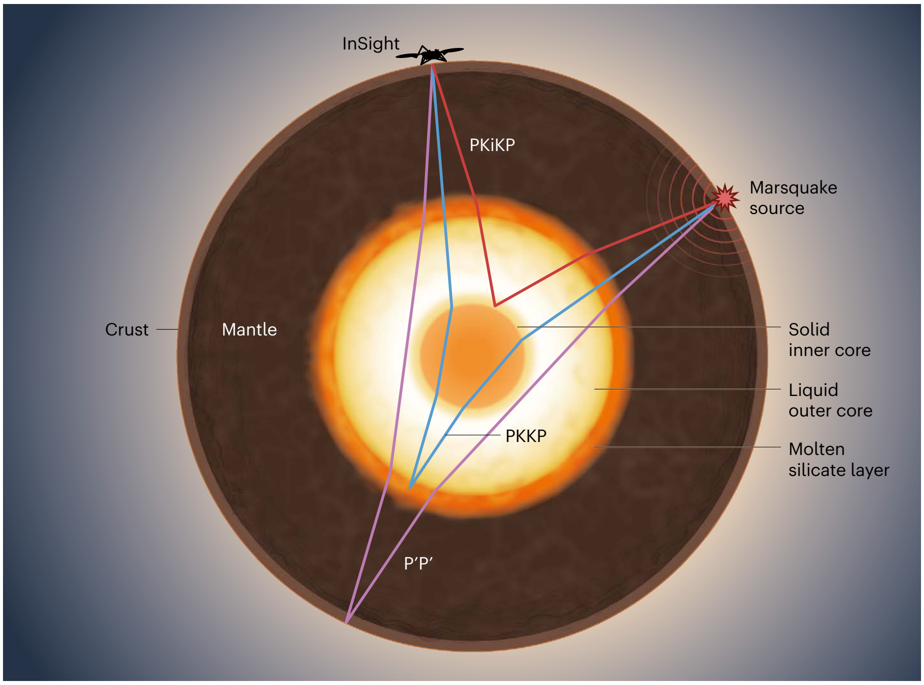

Figure 1 | Seismological evidence for a solid Martian inner core. When a seismic wave propagating through a planet encounter layers with different properties, part of the wave will reflect at the boundary, and part will refract into the next layer. This means that a single seismic wave can separate into multiple signals called 'seismic phases'. To determine the structure of the centre of Mars, Bi *et al.*[2] report measurements of seismic phases generated by marsquakes and collected by NASA's InSight mission. Mars comprises a solid crust and mantle, and a liquid outer core. There is also evidence of a molten silicate layer between the core and mantle. The researchers detected two seismic phases called P′P′ and PKKP, which pass through the core. They also detected another phase, called PKiKP, which would be present only if there is a solid inner core.

P′P′ and PKKP seismic phases. Intriguingly, the PKKP waves arrived at the seismometers 50–200 seconds earlier than would be expected if the core were purely liquid (P waves travel faster though solids than through liquids). The researchers also detected seismic waves that were identified as the PKiKP phase, which is direct evidence for the presence of an inner-core structure. Bi and colleagues supported their array analysis by identifying the suspected core phases in individual seismograms.

From their observations of the travel times and amplitudes of the measured seismic waves, the researchers performed an 'inversion' analysis to identify the Martian structure that best explained the data. They found that the Martian inner core has a radius of about 613 kilometres, which is about 18% of the planetary radius. The analysis also showed that Mars's density increases by about 7% and the P-wave velocity by 30% between the outer and inner cores. The uncertainties in the reported core properties were high because the analysis was limited to a handful of events that had sufficient amplitude to be differentiated from background signals, but these results nevertheless have important implications.

Rocky planets have dense metal-alloy cores that are mainly composed of iron and nickel. Bi and colleagues' measurement of the inner-core radius provides important information about the pressure and temperature required for the liquid core to partially crystallize to form a solid inner core. The researchers estimate the inner–outer-core boundary to have a pressure of 35 gigapascals and a temperature of 1,800–2,100 K. Any postulated Martian-core composition must be capable of crystallizing under these conditions.

Past analyses of core-traversing seismic waves[7], as well as gravity and solid-body tidal measurement of the properties of Mars[8], suggest that the planet's iron–nickel outer core is 'enriched' by lighter elements such as sulfur, oxygen, carbon and hydrogen. Bi *et al.* used their seismic inversions to constrain estimates of the abundance of these lighter elements. They found that an outer core comprising 12–16% sulfur, 6.7–9.0% oxygen and 3.8% or less carbon, surrounding an oxygen-enriched solid inner core, can match their seismic observations. This requires that the Martian core has a temperature of around 2,000 K. There are large uncertainties regarding the properties of iron alloys that contain lighter elements at Martian-core pressures, so alternative core compositions and higher temperatures remain possible.

Theories of the light-element composition and temperature profile of the core must also consider the previous detection from InSight of a molten-silicate layer at the Martian core–mantle boundary[9,10]. A Martian-core

From the archive

An experiment puts 'spoon bending' to the test, and a pioneer of industrial research gets the recognition she deserves.

50 years ago

We have investigated six young people who claimed the power of bending objects by stroking in the manner demonstrated on television recently by Uri Geller and others ... [W]e will call these people A, B, C, D, E, and F ... All six subjects were ... tested in Bath University's psychology laboratory. This laboratory has three large one-way mirrors behind which the experimenter can observe ... unseen by the subject ... [A]t no time did C bend anything for us while experimenters were watching. The others all succeeded in bending spoons ... The observers in the room were instructed to deliberately relax their vigilance at intervals after the first twenty minutes. The experimenters were specially alert during these periods and in all cases except C they observed and photographed cheating by the subjects ... We can assert that in no case did we observe a rod or spoon bent other than by palpably normal means.

From *Nature* 4 September 1975

100 years ago

House Heating: a General Discussion of the Relative Merits of Coal, Coke, Gas, Electricity, etc., as alternative means of providing for Domestic Heating, Cooking and Hot Water Requirements, with Special Reference to Economy and Efficiency. By Dr. Margaret Fishenden — Dr. Fishenden has provided one of the most interesting books that has ever been written on a most important branch of domestic science. Her work has been known for a considerable time to all those who are ... interested in the performances of domestic heating appliances ... [A] wide public owes a debt of gratitude to Dr. Fishenden for having undertaken the task, and having carried it through so well ... It is to be hoped ... that this ... summary ... will be widely read ... [W]ithout such information it is only too likely that catch-words may take the place of principles in forming public opinion and inducing legislative action.

From *Nature* 5 September 1925

temperature between about 2,200 K and 2,900 K would be required to sustain this layer. The molten layer would also produce a blanketing effect, reducing heat flow from the core into the mantle — this is a pathway for heat escape that would normally drive cooling and crystallization in the core. The detection of the basal molten-silicate layer is therefore not easily reconciled with the evidence for the solid inner core. Further study of the core composition and its properties will be required to bring the two results into alignment.

Other geophysical observations of Mars provide a way to verify the existence of a solid Martian inner core. The inclusion of a small inner core would affect the 'geodetic' properties of Mars, which include the planet's shape, rotational orientation and gravity field. The inner-core properties proposed by Bi and colleagues would need to match the current geodetic estimates for the mean planetary density, moment of inertia and tidal deformation. Although previous experiments[7,8] that looked at geodetic properties did not find evidence for a small inner core, Bi *et al.* found that the inner core's properties can match the planet's moment of inertia and mean density within the measured uncertainties.

Unlike Earth, present-day Mars does not have a magnetic field, which further constrains the properties of the core. Magnetic fields are generated by flow inside the fluid metal part of the core, which can be influenced by the presence of an inner core. Magnetic fields are powered by a combination of planetary rotation, heat extraction from the core into the mantle and compositional differentiation inside the core. The presence of an inner core in Mars and the lack of a magnetic field in the present day suggests that the crystallization mechanism that drives the creation and evolution of the inner core is proceeding slowly, which means it cannot produce a magnetic field. Further geodynamical work on how the thermal and elastic properties of the core evolved as Mars cooled will be needed to shed light on the evolution of the planet's early magnetic field and how it relates to the current state of the core.

"The researchers used seismic phases to build a picture of the structure of the Martian core."

These factors mean that the question of the composition and layering structure of the Martian core is far from settled. Because the InSight mission ended in 2022, there will be no new recordings of marsquakes to improve the number of events seismologists can use to understand Mars's internal structure, at least until the next Mars seismic mission. However, this InSight data has given a tantalizing glimpse of the Martian interior. Further analysis of the existing seismogram data, numerical models and spacecraft missions will be needed to fully determine the red planet's deep interior.

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1. Banerdt, W. B. *et al. Nature Geosci.* **13**, 183–189 (2020).
2. Bi, H. *et al. Nature* **645**, 67–72 (2025).
3. Lehmann, I. *Publ. Bur. Cent. Seismol. Int. Strasbg* **14**, 87–115 (1936).
4. Khan, A. *et al. Science* **373**, 434–438 (2021).
5. Stähler, S. C. *et al. Science* **373**, 443–448 (2021).
6. Rost, S. & Thomas, C. *Rev. Geophys.* **40**, 1008 (2002).
7. Irving, J. C. E. *et al. Proc. Natl Acad. Sci. USA* **120**, e2217090120 (2023).
8. Le Maistre, S. *et al. Nature* **619**, 733–737 (2023).
9. Khan, A. *et al. Nature* **622**, 718–723 (2023).
10. Samuel, H. *et al. Nature* **622**, 712–717 (2023).

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