

The mystery of **EARTH'S** missing lead

DEEP WITHIN EARTH'S MANTLE, PRESSURE-STABILISED SULFIDE MINERALS MAY HIDE A LONG-SOUGHT RESERVOIR OF ANCIENT LEAD, SUGGESTS SIMON REDFERN, OFFERING A NEW EXPLANATION FOR ONE OF GEOCHEMISTRY'S OLDEST PARADOXES

FOR MORE THAN half a century, geochemists have wrestled with an uncomfortable problem. Earth appears to be missing some of its lead. Not literally, of course, lead is abundant in ore deposits, occurs in volcanic rocks, and has been mined and used by humans for thousands of years. But when scientists compare the composition of lead's various forms (or isotopes) in Earth's crust and mantle with the composition expected from the meteorites that formed the Solar System, something does not add up.

The lead preserved in rocks from

Earth's surface appears too radiogenic. There seems to be too much lead produced by radioactive decay and not enough primordial, unradiogenic lead left over from the early Solar System. Somewhere, geochemists reasoned, there must be a hidden reservoir containing the 'missing' unradiogenic lead. This puzzle became known as the 'lead isotope paradox', and it has shaped thinking about Earth's chemical evolution for decades.

My recent research carried out with colleagues at Nanyang Technological University, Singapore, offers a possible solution (Liu et al., 2026). Using high-pressure crystal structure prediction and quantum mechanical calculations, we find that unusual lead-sulfur minerals may become stable deep within Earth's mantle under immense pressure. Could

these minerals lock away ancient lead for billions of years, effectively hiding it from the rest of the planet? The work brings together mineral physics, geochemistry and planetary science, and suggests that Earth's deep interior may host previously unknown minerals capable of influencing the isotopic evolution of the entire planet.

Reading Earth's history

Lead isotopes are among the most powerful tools available to geochemists. They preserve information about the timing of planetary differentiation, crust formation, mantle evolution and recycling processes operating over geological time. Three isotopes of lead, ^{206}Pb , ^{207}Pb and ^{208}Pb , are produced by the radioactive decay of uranium and thorium isotopes. A fourth isotope, ^{204}Pb , is non-radiogenic and remains unchanged through time. By comparing ratios such as $^{206}\text{Pb}/^{204}\text{Pb}$ and $^{207}\text{Pb}/^{204}\text{Pb}$, geochemists can reconstruct how different parts of Earth evolved chemically.

The problem is that Earth's mantle and crust appear more radiogenic than expected if the planet formed from material with a chondritic composition similar to primitive meteorites, representative of the building blocks of the Solar System. Somewhere, a complementary reservoir rich in unradiogenic lead seems to be missing. →

“The ‘lead isotope paradox’ has shaped thinking about Earth’s chemical evolution for decades”

New calculations show that unusual lead-sulfur minerals may become stable deep within Earth's mantle, potentially locking away ancient lead for billions of years. Small amounts may be episodically remobilised into the convecting mantle, as illustrated by this artist's impression of Earth's internal structure © Planetary Visions Ltd / Science Photo Library

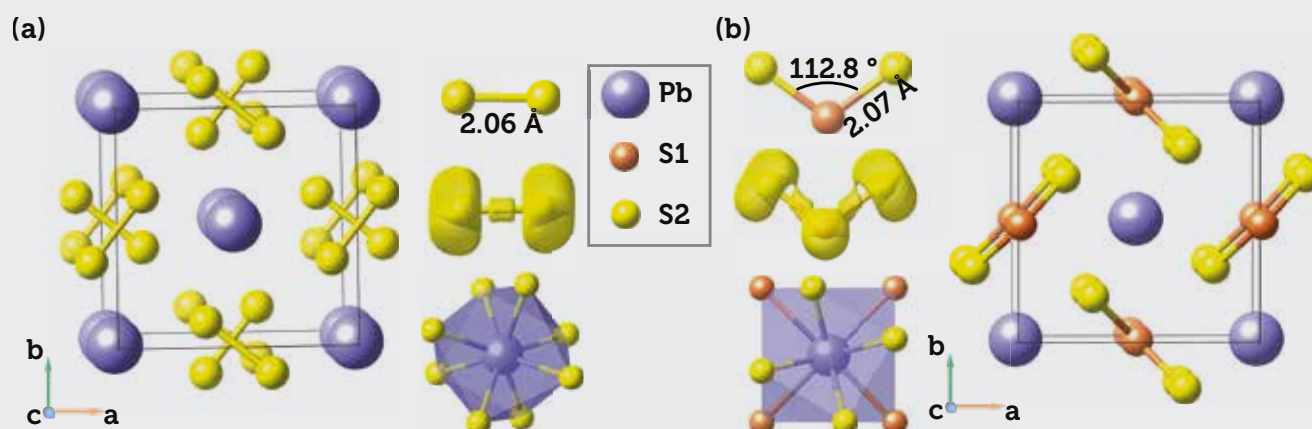


Figure 1 | Crystal structures of lead polysulfides. Crystal structures of PbS_2 at 10 GPa (a) and PbS_3 at 30 GPa (b), along with the calculated electron localization function of polysulfur units. Large purple, small orange, and small yellow spheres represent lead (Pb) and sulfur (S_1 and S_2) atoms, respectively. (Figure reproduced from Liu et al. (2026) Nat. Commun. 17, 2913; doi.org/10.1038/s41467-026-69772-8, published under a CC BY-NC-ND 4.0 licence)

For decades, many researchers suspected that the missing lead was hidden in Earth's metallic core. Lead has a moderate affinity for sulfur and metallic phases, so it was plausible that lead followed sulfur into the core during the violent differentiation of the early Earth. But there is a problem with that idea. Experimental measurements of how lead partitions between metal, sulfide and molten silicate suggest that the core cannot contain enough lead to balance the isotope budget on its own. That has led scientists to search for alternative hidden reservoirs elsewhere inside Earth.

Minerals at extreme conditions

One possibility is that the missing lead is stored in deep mantle sulfides. Lead is a chalcophile element, meaning it preferentially associates with sulfur. Near Earth's surface, lead commonly occurs as galena (PbS), the main ore mineral of lead. Sulfur-bearing minerals and melts are also known from mantle rocks, and sulfur is continuously cycled into Earth's interior through subduction. However, very little is known about how lead-bearing sulfides behave under the extreme pressures and temperatures of Earth's deep mantle. At

depths approaching the core–mantle boundary, pressures exceed 130 GPa (more than a million times atmospheric pressure), while temperatures may approach 4,000–5,000 K (3,700–4,700°C). Under such conditions, familiar minerals often transform into entirely new crystal structures.

Modern computational mineral physics allows researchers to explore these extreme conditions theoretically, even where experiments remain difficult. In our study, we used the computational method 'Crystal structure AnaLYsis by Particle Swarm Optimization' (CALYPSO) to predict crystal structures, combined with density functional theory calculations to search systematically for stable compounds in the lead–sulfur system at pressures up to 150 GPa.

Rather than assuming known structures, the calculations allow crystal structures to emerge naturally according to the laws

of quantum mechanics. The calculations recovered familiar lead sulfide phases but also predicted something unexpected: two previously unknown high-pressure lead polysulfides, PbS_2 and PbS_3 . These compounds become thermodynamically stable only under high pressure. Both contain unusual sulfur–sulfur bonding arrangements that do not occur in ordinary galena.

Exotic sulfur chemistry

One of the most striking aspects of the predicted minerals is the way sulfur behaves under compression. At ambient conditions, sulfur usually forms discrete molecules or simple sulfide ions. Under extreme pressure, however, sulfur atoms are forced much closer together and new bonding configurations become favourable.

In PbS_2 , sulfur forms paired S_2 units. In PbS_3 , sulfur forms bent trisulfur groups resembling tiny V-shaped molecular fragments embedded within the crystal structure (Fig. 1).

Calculations of the electron localization function, a way of visualising where electrons are concentrated within a crystal, show strong covalent bonding between sulfur atoms in these units. The effect is especially clear in PbS_3 , where the sulfur

“Deep planetary interiors host materials unlike anything familiar at the surface”

atoms behave very differently from sulfur in common sulfide minerals.

Pressure actually stabilises sulfur–sulfur covalent bonds. Compression increases the overlap of electron orbitals between neighbouring sulfur atoms. This stabilises the covalent bonds by widening the energy difference between bonding and antibonding states, and lowering the overall energy of the structure. This type of chemistry has become increasingly important in high-pressure materials science over the past decade. Similar pressure-stabilised polysulfides have been predicted or synthesised in several other systems, including calcium and barium sulfides. Our work suggests that lead may participate in comparable deep-Earth chemistry.

Surviving the deep mantle

Finding new crystal structures is interesting, but for geochemistry, the crucial question is whether these phases could actually survive inside Earth. To answer that, we calculated the pressure–temperature stability fields and melting behaviour of the different lead sulfides. The results were revealing (Fig. 2). Ordinary PbS remains stable over a huge pressure range and has an exceptionally high melting temperature. Even under conditions approaching those near the core–mantle boundary, our molecular dynamics simulations indicate that PbS would remain solid in a crystalline form rather than melt into a liquid.

That matters because a solid mineral trapped deep in the mantle can remain isolated for extremely long periods of time. If lead became concentrated in sulfide compounds early in Earth's history, these minerals could effectively shield lead from uranium and thorium, which remain preferentially associated with silicate rocks. Over billions of years, the surrounding mantle and crust would continue generating radiogenic lead through radioactive decay, while the isolated sulfide reservoir retained its original, unradiogenic isotopic composition. In other words, the deep mantle could preserve a hidden archive of primordial lead.

“Pressure-stabilised sulfides may influence chemical evolution on other planetary bodies”

PbS₂ and PbS₃ behave differently. PbS₂ has a melting temperature near or above the temperature profile of the deep mantle, suggesting that it could also remain crystalline and stable. PbS₃, however, has a lower melting temperature and may exist in molten form under some deep mantle conditions. This distinction turns out to be potentially important.

Releasing ancient lead

One of the longstanding challenges of the lead isotope paradox is explaining not only where unradiogenic lead could be stored, but also how traces of it occasionally reappear in volcanic rocks derived from the mantle. Some ocean island basalts and mantle xenoliths contain unusually unradiogenic lead isotope signatures that seem to require interaction with ancient, isolated reservoirs. Our calculations suggest a possible mechanism.

PbS could act as a stable long-term store of lead deep within the mantle. Under sulfur-rich conditions, however, some PbS might react with additional sulfur to form PbS₃. Because PbS₃ melts more readily, it could become mobile and migrate upward through the mantle. As pressure decreases during ascent, PbS₃ eventually becomes unstable and decomposes, potentially releasing small amounts of ancient unradiogenic lead back into the convecting mantle. This provides a plausible route for episodic remobilisation of lead from deep hidden reservoirs into shallower mantle regions, from which the primordial lead could find its way to Earth's surface through volcanic activity.

Importantly, our work does not prove that this process definitely occurs inside Earth. Many factors remain uncertain, including the density of sulfide melts in mantle rocks and how the melts move through or between mineral grains. Whether sulfides form interconnected

networks or isolated pockets strongly affects their mobility. But our calculations do demonstrate that pressure-stabilised lead sulfides are thermodynamically viable under realistic mantle conditions. That alone significantly expands the range of possible deep-Earth lead reservoirs.

Beyond lead

To non-specialists, the idea of missing lead isotopes may sound obscure. Yet the implications reach far beyond one element. Differences in the ratios of an element's isotopes underpin much of our understanding of how planets evolve. They allow scientists to estimate the timing of core formation, reconstruct mantle convection and crustal recycling, and infer the chemical evolution of Earth over billions of years. If part of Earth's lead inventory has been hidden away in deep mantle sulfides since the earliest history of the planet, that changes how geochemists interpret isotopic records preserved in volcanic rocks.

More broadly, such work highlights how mineral physics and geochemistry increasingly intersect. For many years, deep Earth geochemistry was constrained largely by the minerals that could be synthesised experimentally at moderate pressures. Advances in computational methods now allow researchers to predict entirely new classes of materials stable only under extreme conditions. These hidden minerals may play major roles in controlling the distribution of volatile elements, in influencing the patterns of isotopes of an element that act as geological fingerprints, and affecting redox-sensitive species inside planets.

The implications extend beyond Earth. Sulfur-rich planetary interiors occur elsewhere in the Solar System, including within Mercury and some differentiated asteroids. Pressure-stabilised sulfides →

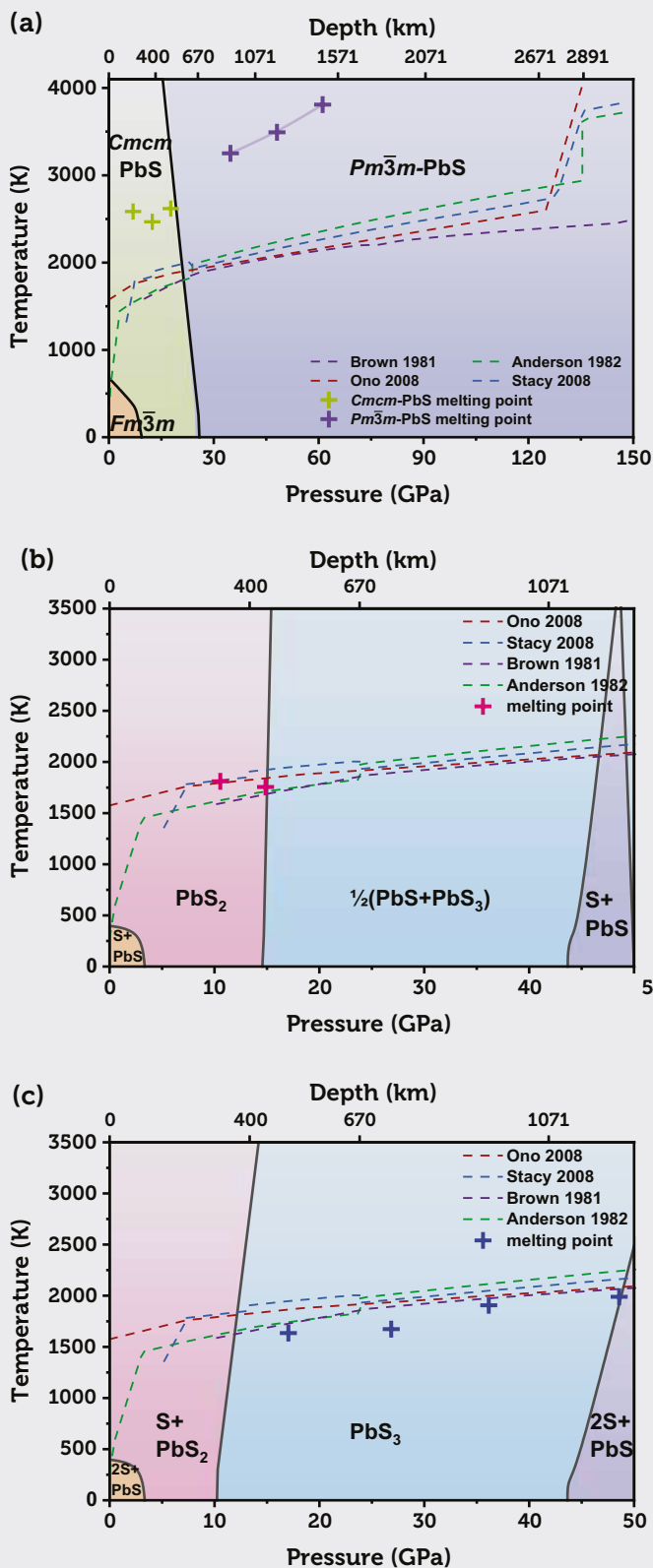


Figure 2 | Pressure-temperature phase diagram of Pb-S compounds. Phase diagrams of PbS (a), PbS₂ (b) and PbS₃ (c). Our simulations show that PbS has a melting point (+ symbols) well above the temperature profile of the deep mantle (dashed lines) and remains stable, in a solid crystalline form throughout the mantle (panel a, where purple and green indicate different crystalline configurations for PbS). PbS could therefore act as a long-term store of lead in the deep mantle. However, PbS₂ and PbS₃ behave differently. PbS₂ (pink, panel b) has a melting point near or above the temperature profile of the deep mantle, so could remain crystalline and stable. PbS₃ (blue, panel c) has a lower melting temperature and may exist in molten form under some deep mantle conditions. This provides a plausible route for the remobilisation of lead from deep, hidden reservoirs into the shallower mantle and surface via volcanism. Phase boundaries are indicated by grey solid lines. Dashed lines represent Earth's geotherm. Cmcm, Pm3m and Fm3m indicate different crystalline structures (space groups with different symmetry operations, lattice systems, atomic arrangement). (Figure modified from Liu et al. (2026) Nat. Commun. 17, 2913; doi.org/10.1038/s41467-026-69772-8, published under a CC BY-NC-ND 4.0 licence)

may therefore influence chemical evolution on other planetary bodies as well.

Deep Earth surprises

Earth's mantle occupies more than 80% of the planet's volume, yet much of its mineralogy remains uncertain. Over the past two decades, high-pressure mineral physics has repeatedly revealed that deep planetary interiors host materials unlike anything familiar at the surface. Minerals once thought exotic or impossible can become stable under compression. The discovery of pressure-stabilised lead polysulfides adds another example to that growing list.

Whether these exact phases exist abundantly in Earth's mantle remains to be tested experimentally. Future work combining high-pressure synthesis, synchrotron diffraction and isotope geochemistry will be needed to evaluate their abundance and behaviour more directly. Nevertheless, our calculations provide a physically plausible solution to one of geochemistry's oldest puzzles.

Far beneath our feet, hidden within Earth's deep mantle, ancient lead may have been quietly preserved for billions of years inside minerals that can exist only under enormous pressure. 

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FURTHER READING

A full list of further reading is available at [geoscientist.online](https://www.geoscientist.online).

- Anderson, O. (1982) Phil. Trans. R. Soc. Lond. A 306 (1492), 21–35
- Brown, J. & Shankland, T. (1981) Geophys. J. Int. 66, 579–596
- Halliday, A.N. & Canup, R.M. (2023) Nat. Rev. Earth Environ. 4, 19–35
- Hart, S.R. & Gaetani, G.A. (2006) Contrib. Mineral. Petrol. 152, 295–308
- Hofmann, A.W. (2008) Nat. Geosci. 1, 812–813
- Liu, S. et al. (2026) Nat. Commun. 17, 2913
- Ono, S. (2008) Phys. Earth Planet. Inter. 170, 267–273
- Stacey, F.D. & Davis, P.M. (2008) Physics of the Earth (4th ed.). Cambridge University Press