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The disappearance of a colossal amount of ancient lead makes Earth appear much younger than primordial meteorites indicate

An NTU Singapore-led team predicted that the lead-sulphur compound PbS_3 forms under conditions usually found deep in the Earth's mantle. Credit: David Zherdenovsky / Pexels

by Guillermo Carvajal

For decades, geochemists have used the different varieties of lead as a kind of infallible geological clock to date the formation of rocks and understand the processes of planetary accretion that shaped Earth more than 4.5 billion years ago.

However, this method, considered one of the most robust tools in planetary science, carries with it a glaring contradiction that has kept the scientific community on edge: calculations indicate that a colossal amount of ancient lead is missing from Earth's crust, a mismatch so significant that, on paper, makes our planet appear much younger than primordial meteorites attest.

A recent study led by the Asian School of the Environment at Nanyang Technological University (NTU) in Singapore and published in the journal *Nature Communications* has proposed a solution to this paradox that does not require searching for the missing metal in the inaccessible core, but rather in the crushing pressures of the Earth's mantle, where the behavior of lead in the presence of sulfur reveals a chemistry far more complex and stable than previously assumed.

The missing lead paradox is based on the existence of four isotopic forms of this element. Three of them —lead-206, lead-207, and lead-208— are radiogenic in nature, which means they are generated continuously from the radioactive decay of uranium and thorium.

This process of atomic decay operates at a fixed and immutable rate, providing researchers with a precise nuclear chronometer: if a rock contains a high proportion of lead derived from uranium compared to the original lead, it is classified as geologically young, whereas a high abundance of primordial lead relative to radiogenic lead indicates an ancient age.

The fourth isotope, lead-204, is non-radiogenic and constitutes the “original” lead that has been present since the formation of the Solar System. The conflict arises when comparing the composition of rocks from Earth’s surface with that of ancient meteorites that served as building blocks of the planet.

Crustal rocks display an inexplicable excess of “young” or radiogenic lead, which implies, by inverse logic, a severe deficit of primordial lead that should be distributed throughout the planet. For a long time, the prevailing hypothesis to explain this absence proposed that this original lead sank toward the molten iron core during early planetary differentiation, a model that, while elegant, never managed to satisfactorily describe the exact physicochemical mechanism that would allow lead to remain sequestered in the core over eons without leaving a clear trace in the surrounding mantle.

The research team, led by Professor Simon Redfern and former postdoctoral researcher Dr. Liu Siyu of NTU, decided to examine this issue by focusing on lead’s natural affinity for sulfur, an element abundant within Earth. The initial premise considered lead sulfide as the most likely candidate to act as a deep storage vehicle for the missing lead.

Through the intensive use of advanced computational simulations, the scientists subjected this compound to the conditions of extreme pressure that prevail hundreds or thousands of kilometers beneath the surface. The modeling results revealed a crucial and until now underestimated thermodynamic property: lead sulfide acquires extraordinary stability under such pressures, remaining in a solid state even at temperatures approaching 5,000 degrees Celsius, a thermal threshold that far exceeds the actual conditions estimated for the lower mantle.

This structural robustness suggests that, during the formative stages of Earth, massive reservoirs of ancient lead may have formed in the depths of the mantle, encapsulated in solid mineral phases that completely isolated them from the uranium and thorium present in the crust. As a direct consequence of this isolation, that sequestered lead has not participated in the surface geochemical cycle nor contributed to the mixing of isotopes that scientists measure in volcanic and continental rocks, thus generating the false impression of an Earth depleted in primordial lead and artificially enriched in radiogenic lead.

The computational predictions, carried out with the specialized software CALYPSO —an algorithm designed to predict stable crystalline structures solely from chemical composition and external thermodynamic conditions— were not limited to confirming the stability of conventional lead sulfide, but led the team to identify two completely new lead–sulfur mineral structures that science had not previously described.

These are two polysulfides, designated PbS_2 and PbS_3, whose existence is predicted to be viable in regions of the mantle locally enriched in sulfur. High-temperature atomic dynamics simulations confirmed that these theoretical compounds are not mere curiosities of computational laboratories, but thermodynamically feasible phases capable of persisting in the face of the intense convective movement of Earth's interior over billions of years.

Each of these new compounds exhibits different behavior under mantle conditions. The first of them, PbS_2, would presumably maintain a solid state within the pressure ranges corresponding to the upper mantle. The second compound, PbS_3, presents a dynamic characteristic of great geological relevance: its melting point is comparatively low, which implies that under certain thermodynamic circumstances it could undergo partial melting and transform into a less dense liquid.

This liquid, driven by its own buoyancy, would slowly rise through the solid rock of the mantle, acting as an efficient albeit minute transport agent. This mechanism of deep material "dripping" or "leakage" toward the surface offers a coherent and chemically grounded explanation for a phenomenon empirically observed by volcanologists: the sporadic appearance of isotopic signatures of extremely ancient lead in modern volcanic rocks, an anomaly that until now lacked a clear mechanism of origin.

The implications of this finding extend beyond the mere resolution of an old terrestrial geochemical puzzle. The research redefines the role of sulfur in the distribution and sequestration of heavy metals within rocky planets. Understanding how a volatile element such as sulfur can anchor dense lead so effectively in the depths of Earth's mantle provides a new theoretical framework for evaluating the chemical evolution of other planetary bodies in the Solar System, such as Mars.

Differentiation processes and the distribution of elements within the Martian interior could be reevaluated in light of this new high-pressure polysulfide chemistry, allowing planetary scientists to refine models of how terrestrial planets segregate their metallic and silicate components during their youth. The computational work by NTU demonstrates that the answers to some of the most fundamental questions about the history of Earth do not lie in distant cosmos, but in the quantum behavior of atoms confined under unimaginable pressures at the heart of the planet we walk upon.

Experimental verification of these theoretical predictions constitutes the next logical and immediate step in the research team's agenda. The scientists aim to recreate the pressure and temperature conditions of Earth's mantle in the laboratory using diamond anvil cells and laser heating techniques, with the goal of physically synthesizing the polysulfides PbS_2 and PbS_3 and confirming their structural stability *in situ*.

At the same time, they will continue refining computational models to obtain a more precise chronology of the separation events of the internal layers of the primitive Earth. Likewise, a systematic search will be undertaken for physical evidence of these exotic minerals in mantle xenoliths and in samples of ultramafic rocks brought to the surface by tectonic and eruptive activity, in an effort to capture the elusive traces of that ancestral lead that has remained hidden beneath our feet since the dawn of the planet.

SOURCES

Nanyang Technological University

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