

From Waveform Inversion to Deep-Earth Anomalies:

A Formal Working Paper on Membranous High-Pressure Structures,
Observational Limits, and the Epistemic Status of Speculative
Geophysical Models

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AI-assisted formulation from a structured dialogue; not a claim of empirical proof

July 2026

Abstract

This paper formalizes a speculative but non-arbitrary line of reasoning concerning the epistemic limits of human knowledge about the deep Earth. The central claim is not that a literal hollow Earth or inhabitable underground world exists. Rather, the paper asks whether complex, high-pressure, multi-layered, shell-like or membrane-like anomalous regions could be under-resolved or over-smoothed by present geophysical inverse models. The argument begins from an observation: human knowledge of the mantle, core-mantle boundary, outer core, and inner core is overwhelmingly indirect, mediated by seismic waves, gravity fields, magnetic fields, normal modes, heat-flow constraints, mineral physics, and model-based inversion. This makes planetary interior science powerful but not equivalent to direct inspection.

We introduce the *Membranous Deep-Earth Anomaly Hypothesis* (MDEAH): under billions of years of high pressure, high temperature, convection, phase transitions, slab subduction, partial melting, chemical segregation, and core-mantle coupling, the interior may contain multi-scale, layered, shell-like, high-pressure anomalies whose true geometry may be more complex than current smoothed velocity or density models suggest. The hypothesis is distinguished from a literal hollow-Earth claim. It is framed as a testable residual hypothesis: if such structures exist, they should appear as systematic residuals in seismic travel times, waveform scattering, normal-mode splitting, gravity-density inversions, geomagnetic coupling, and eventually neutrino tomography.

Mathematically, the paper uses the language of forward modeling and inverse problems, showing that geophysical observations satisfy equations of the form $d = F(m) + \epsilon$, where m is an internal Earth model, F is a forward operator, and ϵ is noise and modeling error. Because F^{-1} is generally non-unique and resolution-limited, the absence of a feature in a model is not equivalent to a proof that no such structure exists. At the same time, large low-density voids are strongly constrained by mass, moment of inertia, seismic-wave propagation, and pressure stability. Thus, the scientifically defensible version of the speculation is not an empty cavity, but a high-P anomalous domain: a complex, possibly shell-like, partially molten, dense, low-velocity, anisotropic, or otherwise exotic region that may be simplified by current inversions.

The conclusion is deliberately balanced. Present evidence strongly disfavors literal large empty caverns below it, but it does not eliminate the possibility that deep-Earth anomalies are structurally richer than current models can resolve.

The value of the hypothesis lies not in claiming discovery, but in converting intuition into falsifiable questions, residual tests, and multi-observable predictions.

1 Purpose and Epistemic Position

This paper is a formalization of a reasoning process that began with an apparently speculative question: if humans cannot directly reach the mantle, outer core, or inner core, how strong is the claim that the deep Earth contains no large, hidden, shell-like, or cavity-like structures? The goal is not to defend an old hollow-Earth model. The goal is to formulate a more careful question:

Could present waveform-based and field-based geophysical inversions under-resolve, average out, or misclassify layered, high-pressure anomalous structures whose true geometry differs substantially from the smooth layered models usually presented to the public?

The question has scientific legitimacy because geophysical models are not photographs. They are inverse solutions obtained from finite, noisy, unevenly distributed data. Seismic tomography, for example, reconstructs Earth structure by inferring elastic and density variations from travel times, waveforms, amplitudes, attenuation, scattering, and normal modes [6, 7]. The underlying problem is an inverse problem and is therefore subject to non-uniqueness, regularization, finite resolution, and prior assumptions [8].

The epistemic position of this paper is therefore:

1. Current geophysical models are powerful, empirically constrained, and not arbitrary guesses.
2. These models are nonetheless not identical to the deep Earth itself.
3. Large literal empty cavities are strongly disfavored by multiple independent constraints.
4. Complex deep anomalies, including layered, shell-like, partially molten, dense, low-velocity, and anisotropic structures, are scientifically plausible and already appear in related forms in the literature.
5. A speculative hypothesis becomes scientifically meaningful only when it is translated into definitions, equations, constraints, and predictions.

2 Background: Human Access to the Deep Earth

Humans have not directly sampled the mantle in a general, controlled, vertical path through ordinary continental crust, and they have not directly sampled the outer or inner core. Existing boreholes are shallow relative to Earth's radius. Hence, knowledge of the interior is based mostly on indirect evidence. The standard picture of crust, mantle, liquid outer core, and solid inner core arises from a convergence of multiple observables, especially seismic waves.

The important distinction is between *direct access* and *indirect constraint*. Lack of direct access does not imply ignorance; indirect constraints can be extremely strong. However, indirect constraints are model-mediated. They restrict the set of possible internal structures but do not reveal every local detail.

3 Known Deep-Earth Complexity

The interior is not a simple uniform sphere. Modern seismology has revealed continent-scale structures, especially the large low-shear-velocity provinces (LLSVPs) under Africa and the Pacific. These structures occur in the lowermost mantle and are thousands of kilometers wide and hundreds of kilometers high in many models [2, 3]. They are widely discussed as thermochemical piles, reservoirs, or anomalous domains rather than ordinary homogeneous mantle.

Ultra-low velocity zones (ULVZs) near the core-mantle boundary are another example. ULVZs are marked by strong reductions in seismic velocities and often by density anomalies [4, 5]. Their origins remain debated, with possible interpretations including partial melt, iron enrichment, chemically distinct material, subducted materials, or other high-pressure phases.

These examples already support the first half of the reasoning developed here: the deep Earth contains large, complex, incompletely understood structures. The controversial part is not whether such structures exist; they do. The controversial part is how far one may extrapolate from them.

4 The Inverse Problem: Why Waveform Knowledge Is Powerful but Limited

Denote by m an Earth model, including density $\rho(\mathbf{x})$, elastic moduli $K(\mathbf{x}), \mu(\mathbf{x})$, attenuation $Q(\mathbf{x})$, anisotropy parameters $A(\mathbf{x})$, and boundaries or discontinuities Σ_i . Let d denote observed geophysical data: seismic travel times, waveforms, normal modes, gravity coefficients, magnetic-field data, and heat-flow constraints. Then a generic forward model is

$$d = F(m) + \epsilon, \quad (1)$$

where F is the physical forward operator and ϵ collects noise, measurement error, and modeling error.

The inverse task is to estimate m from d :

$$\hat{m} = \arg \min_m \left\{ \|F(m) - d\|_{C_d^{-1}}^2 + \lambda R(m) \right\}, \quad (2)$$

and C_d the data covariance, $R(m)$ a regularization functional, λ controlling the strength of regularization. This equation makes the epistemic issue explicit: the recovered model $\hat{m}$ is shaped by data, physics, and regularization.

In a linearized setting around a reference model m_0 , write

$$d - F(m_0) \approx G\delta m + \epsilon, \quad (3)$$

with G the sensitivity kernel matrix and $\delta m = m - m_0$. A damped least-squares solution has the form

$$\widehat{\delta m} = (G^T C_d^{-1} G + \lambda L^T L)^{-1} G^T C_d^{-1} (d - F(m_0)). \quad (4)$$

The resolution matrix is

$$\mathcal{R} = (G^T C_d^{-1} G + \lambda L^T L)^{-1} G^T C_d^{-1} G. \quad (5)$$

If $\mathcal{R} = I$, the model is perfectly resolved. In reality, $\mathcal{R} \neq I$, meaning true structure may be blurred, smeared, or averaged.

Proposition 1 (Model absence is not direct nonexistence). *Let $s(\mathbf{x})$ be a true internal structure and $\hat{s}(\mathbf{x})$ its reconstructed image under an inverse operator with resolution kernel $K(\mathbf{x}, \mathbf{x}')$. Then*

$$\hat{s}(\mathbf{x}) = \int K(\mathbf{x}, \mathbf{x}') s(\mathbf{x}') d\mathbf{x}' + n(\mathbf{x}). \quad (6)$$

If K is broad, anisotropic, or poorly sampled in a region, then $\hat{s}$ may fail to represent the sharp geometry of s . Therefore, absence of a sharp structure in $\hat{s}$ is not by itself a proof of absence in s .

None of this is a license to assert arbitrary hidden worlds. It is a formal statement about inverse problems. The degree of plausibility must be judged by how the proposed structure interacts with all available constraints.

5 A Formal Version of the Motivating Hypothesis

The underlying intuitive picture can be translated from “membranes” and “cavities” into a more scientific hypothesis.

Hypothesis 1 (Membranous Deep-Earth Anomaly Hypothesis, MDEAH). *Over geological time, high pressure, high temperature, mantle convection, phase transitions, subducted slabs, partial melting, chemical segregation, and core-mantle coupling may form multi-layered, shell-like, membrane-like, or compartmentalized anomalous domains in the lower regions near the core-mantle boundary. These domains need not be empty cavities; they may consist of high-pressure fluids, partially molten material, viscoelastic solids, dense thermochemical piles, anisotropic layers, or presently unresolved high-pressure phases. Due to finite resolution and inverse non-uniqueness, their true geometry may be simplified in current models as low-velocity provinces, ULVZs, D'' structures, density anomalies, or smooth mantle heterogeneity.*

The crucial revision is that the scientifically defensible object is not a low-pressure hollow cavern, but a *high-pressure anomalous domain*. This distinction matters because low-P voids are strongly disfavored by stability considerations and seismic-wave behavior, whereas high-pressure anomalous domains are consistent with the general logic of deep-Earth research.

6 Why Literal Empty Cavities Are Strongly Constrained

A literal empty cavity at great depth faces severe constraints. Denote by $P(r)$ the lithostatic pressure at depth. A cavity of radius a embedded in material with density ρ and gravity $g(r)$ experiences surrounding pressure roughly of order

$$P(r) \sim \int_r^R \rho(r') g(r') dr'. \quad (7)$$

At such depths, P is enormous. A low-pressure cavity would require a shell whose strength exceeds the differential stress over geological timescales. If the surrounding material behaves viscoelastically with effective viscosity η and stress σ , deformation occurs on a timescale roughly

$$\tau_{\text{creep}} \sim \frac{\eta}{\sigma}. \quad (8)$$

Over 4.5×10^9 years, even very viscous materials may deform under sustained stress.

A large empty cavity also introduces a density deficit. Consider V_c as the cavity volume and $\Delta\rho$ as the density contrast relative to the surrounding matrix. The missing mass is

$$\Delta M = \Delta\rho V_c. \quad (9)$$

For a spherical cavity of radius a ,

$$\Delta M = \frac{4\pi}{3} a^3 \Delta\rho. \quad (10)$$

A large a produces a large mass anomaly. Such a mass anomaly would affect the gravity field, moment of inertia, and normal modes unless compensated by an unusually dense shell. But a dense shell would itself affect seismic velocities and gravity.

The hypothesis therefore cannot be a simple empty hole. It must be a compensated, high-pressure, physically interacting anomalous domain.

7 High-Pressure Cavities Versus Empty Cavities

The strongest form of the intuition is that a “cavity” might not be empty. It may be pressure-filled, dynamically supported, and seismically ambiguous. Write Ω_A for the anomalous region and $\partial\Omega_A$ for its boundary. Its mechanical stability requires approximate stress balance:

$$\nabla \cdot \boldsymbol{\sigma} + \rho \mathbf{g} = 0, \quad (11)$$

for $\boldsymbol{\sigma}$ the stress tensor. Across the boundary,

$$\mathbf{n} \cdot (\boldsymbol{\sigma}_{\text{out}} - \boldsymbol{\sigma}_{\text{in}}) = \mathbf{f}_{\partial\Omega_A}, \quad (12)$$

where $\mathbf{f}_{\partial\Omega_A}$ is any boundary traction or effective membrane force.

If Ω_A contains high-pressure material rather than vacuum, then

$$P_{\text{in}} \approx P_{\text{out}} \quad (13)$$

may hold, and collapse is not immediate. That interpretation is the mathematically meaningful one of the user’s intuition that pressure could “hold up” a structure. The region then becomes a high-pressure inclusion, not an empty cavern.

The seismic response is governed by effective velocities. For an isotropic elastic solid,

$$v_P = \sqrt{\frac{K + \frac{4}{3}\mu}{\rho}}, \quad v_S = \sqrt{\frac{\mu}{\rho}}, \quad (14)$$

with K the bulk modulus, μ the shear modulus, and ρ the density. For a fluid, $\mu = 0$, so

$$v_S = 0. \quad (15)$$

That property is why the liquid outer core is inferred from shear-wave behavior. But a partially molten, viscoelastic, anisotropic, or layered material can produce more subtle behavior than a simple solid/fluid binary. That subtlety is where the MDEAH has a defensible conceptual space.

8 Residuals as the Correct Scientific Target

A hypothesis becomes scientific when it produces residuals that can be tested. Let m_{std} be a standard model such as PREM-like radial structure [1] plus tomographic perturbations. Let m_A be a model containing a membranous anomaly. Then the observable difference is

$$\Delta d = F(m_A) - F(m_{\text{std}}). \quad (16)$$

The hypothesis is meaningful only if Δd has systematic features exceeding uncertainty:

$$\Delta d^T C_d^{-1} \Delta d > \chi_\alpha^2. \quad (17)$$

Potential observables include:

1. frequency-dependent travel-time residuals;
2. anomalous ScS, PcP, PKP, or SKS phases;
3. waveform scattering and multi-pathing;
4. normal-mode splitting inconsistent with smooth models;
5. gravity-density residuals;
6. geomagnetic coupling anomalies near the core-mantle boundary;
7. future neutrino tomography residuals.

The paper therefore does not defend speculation by denying data. It converts speculation into data-driven residual predictions.

9 A Bridge to Broader Waveform Thinking

The dialogue that motivated this paper also considered quantum observation, black holes, string theory, and Einstein-Rosen bridges. These are not used here as evidence for deep-Earth cavities. Rather, they provide an analogy: whenever a region is inaccessible, humans infer structure from signals. In black-hole physics, the interior is not directly accessible; in quantum measurement, observation is not passive inspection; in deep-Earth science, the interior is inferred through waves.

The analogy can be expressed as

$$\text{Reality} \xrightarrow{\text{propagation medium}} \text{signal} \xrightarrow{\text{inverse model}} \text{interpreted structure}. \quad (18)$$

Errors or blind spots may enter at propagation, measurement, inversion, or interpretation.

This is why the underlying reasoning is not merely science fiction. The scientifically valid part is not the assertion of a hidden world, but the methodological claim: signal-derived models must be distinguished from directly inspected reality.

10 Relation to Emergent Spacetime and ER=EPR

The more speculative side of the discussion involved whether space, time, and matter may be understood as stable patterns or wave-like structures. This resonates, at the level of analogy, with research in emergent spacetime and ER=EPR. Van Raamsdonk argued that spacetime connectivity is deeply related to quantum entanglement [10]. Maldacena and Susskind proposed that entangled black holes may be interpreted as connected by Einstein-Rosen bridges [9]. Gao, Jafferis, and Wall later showed that certain quantum couplings can make otherwise non-traversable wormholes traversable in special settings [11].

These works do not imply that the planetary interior contains wormholes or hidden worlds. Their relevance is conceptual: they show that, in frontier physics, geometry may be less fundamental than the relational, informational, or entanglement structure underneath it, and even the semiclassical observer picture may be limited by gravitational decoherence [12]. This supports the broader philosophical claim that geometry and material appearance may be emergent from deeper patterns. It does not prove the geophysical hypothesis.

11 Distinguishing Science, Speculation, and Pseudoscience

The proposed reasoning avoids pseudoscience only if it accepts constraints. The following distinctions are essential:

Claim type	Status	Scientific treatment
Deep Earth has large anomalies	Strongly supported	Study via LLSVP, ULVZ, D'', tomography, mineral physics
Deep anomalies may be more complex than current models	Plausible	Test via residuals and multi-observable inversions
Membrane-like high-pressure anomalous domains	Speculative but formulable	Define parameters and predict wavefield signatures
Literal low-pressure giant hollow caverns	Strongly disfavored	Must overcome pressure, mass, gravity, and seismic constraints
Inhabited underground world	Unsupported	Not a geophysical conclusion

The scientific value lies in the middle rows, not in the extreme claim.

12 Predictions and Research Program

A serious research program derived from MDEAH would not search for “a hollow world.” It would search for under-resolved deep structure. The program could proceed as follows:

12.1 Prediction 1: Systematic path-dependent residuals

For seismic phase i , define

$$\Delta t_i = t_i^{\text{obs}} - t_i^{\text{pred}}(m_{\text{std}}). \quad (19)$$

If a deep membranous anomaly exists, then for paths intersecting Ω_A ,

$$\mathbb{E}[\Delta t_i \mid \gamma_i \cap \Omega_A \neq \emptyset] \neq 0. \quad (20)$$

12.2 Prediction 2: Frequency-dependent scattering

Layered structures of thickness h should interact differently with wavelengths λ . The anomaly becomes visible when

$$\lambda \sim h. \quad (21)$$

Thus the signal should be frequency-dependent rather than uniform across all bands.

12.3 Prediction 3: Coupled density-velocity inconsistency

If a region is interpreted as an ordinary velocity anomaly but actually has unusual density or phase structure, then velocity-derived density and gravity-derived density may disagree:

$$\rho_{\text{seis}}(\mathbf{x}) - \rho_{\text{grav}}(\mathbf{x}) \neq 0 \quad (22)$$

in a coherent region.

12.4 Prediction 4: Normal-mode anomalies

The planet's free oscillations integrate over global structure. A deep shell-like anomaly should produce small but systematic splitting or frequency shifts:

$$\delta\omega_{nlm} = \omega_{nlm}^{\text{obs}} - \omega_{nlm}^{\text{std}}. \quad (23)$$

The pattern of $\delta\omega_{nlm}$ should reflect the geometry of the anomaly.

12.5 Prediction 5: Future neutrino tomography

If neutrino tomography matures, it could test density distributions independently of seismic-wave elastic assumptions. A discrepancy between neutrino-inferred density and seismic-inferred density would be a key test.

13 Discussion: Why the Intuition Has Meaning

The reasoning has meaning because it challenges a common category error: treating an inverse model as though it were direct perception. Science advances by recognizing precisely such distinctions. The fact that present models strongly constrain hidden-cavity hypotheses does not mean that all unresolved deep structures are impossible. It means that a credible hypothesis must obey the constraints that already exist.

The key conceptual contribution is therefore not “there is a hollow Earth.” It is:

Knowledge of the interior is waveform-mediated and model-dependent; therefore the correct scientific question is not whether imagination may override data, but whether residuals, non-uniqueness, and finite resolution leave room for more complex high-pressure structures than our models currently display.

The question is legitimate. It belongs to the philosophy and methodology of geophysical inference as much as to geophysics itself.

14 Conclusion

This paper formalized a speculative intuition into a constrained hypothesis. Human knowledge of the interior is not direct. It is built from waves, fields, and inverse models. Existing evidence strongly disfavors literal large empty caverns below it, especially because of stability, seismic-wave propagation, gravity, mass, and moment-of-inertia constraints. However, existing evidence does not imply that current models capture every geometrical and material detail of the mantle, core-mantle boundary, or deep anomalies.

The defensible hypothesis is therefore not a hollow-Earth claim, but a *Membranous Deep-Earth Anomaly Hypothesis*: deep, high-pressure, multi-layered, shell-like, partially molten, dense, low-velocity, anisotropic, or otherwise exotic regions may be more complex than current smoothed inversions reveal. Such a hypothesis is meaningful only if translated into testable predictions: systematic waveform residuals, scattering signatures, normal-mode shifts, gravity-density inconsistencies, geomagnetic coupling anomalies, and future neutrino-tomography discrepancies.

The broader philosophical lesson is simple: observation and reality are not identical; observation is a mediated encounter with signals. Where humans cannot directly go, science must infer. Inference can be powerful without being omniscient. That is the space in which disciplined speculation has value.

Acknowledgment

This working paper was generated from a long-form dialogue exploring quantum observation, black holes, time, string-theoretic waveforms, Earth interiors, and the epistemic limits of indirect measurement. The final framing deliberately separates defensible scientific hypotheses from unsupported literal claims.

References

- [1] Dziewonski, A. M., & Anderson, D. L. (1981). Preliminary reference Earth model. *Physics of the Earth and Planetary Interiors*, 25(4), 297–356. [https://doi.org/10.1016/0031-9201\(81\)90046-7](https://doi.org/10.1016/0031-9201(81)90046-7)
- [2] McNamara, A. K. (2019). A review of large low shear velocity provinces and ultra low velocity zones. *Tectonophysics*. Seismic tomography reveals two extensive low-velocity regions in the lowermost mantle beneath Africa and the Pacific, with scales of thousands and hundreds of kilometers in width and height. <https://doi.org/10.1016/j.tecto.2018.04.015>

- [3] Wang, W., et al. (2021). Formation of large low shear velocity provinces through the decomposition of oxidized mantle. *Nature Communications*. <https://doi.org/10.1038/s41467-021-22185-1>
- [4] Hansen, S. E., et al. (2023). Globally distributed subducted materials along the Earth's core-mantle boundary. *Science Advances*. <https://pmc.ncbi.nlm.nih.gov/articles/PMC10075969/>
- [5] Pachhai, S., Li, M., Thorne, M. S., Dettmer, J., & Tkalčić, H. (2022). Internal structure of ultralow-velocity zones consistent with origin from a basal magma ocean. *Nature Geoscience*, 15(1), 79–84. <https://doi.org/10.1038/s41561-021-00871-5>
- [6] Rawlinson, N., Fichtner, A., Sambridge, M., & Young, M. K. (2014). Seismic tomography and the assessment of uncertainty. *Advances in Geophysics*. <https://rses.anu.edu.au/~malcolm/papers/pdf/Rawlinson-etal-2014.pdf>
- [7] Ahmed, S. M. S., & Güneşli, H. (2025). The evolution of seismic tomography in earth sciences—advancements, limitations, and its AI-enabled future (A critical review). *Earthquake Research Advances*. <https://doi.org/10.1016/j.eqrea.2025.100425>
- [8] Fichtner, A., et al. (2025). On tomographic resolution, uncertainty, and model preference in geodynamic reconstructions. <https://arxiv.org/abs/2501.14301>
- [9] Maldacena, J., & Susskind, L. (2013). Cool horizons for entangled black holes. *Fortschritte der Physik*. <https://arxiv.org/abs/1306.0533>
- [10] Van Raamsdonk, M. (2010). Building up spacetime with quantum entanglement. <https://arxiv.org/abs/1005.3035>
- [11] Gao, P., Jafferis, D. L., & Wall, A. C. (2017). Traversable wormholes via a double trace deformation. <https://arxiv.org/abs/1608.05687>
- [12] Pikovski, I., Zych, M., Costa, F., & Brukner, C. (2015). Universal decoherence due to gravitational time dilation. *Nature Physics*. <https://arxiv.org/abs/1311.1095>