

Research Article

Coherent Vortices in the Mantle: A Scaling Theory for LLSVPs and the Iceland Plume

Lays Schneider¹, Mike Wofsey², L. Merritt³

1. Independent researcher; 2. PhD Thermodynamics, University of Alabama, United States; 3. University of Michigan, United States

Large Low-Velocity Provinces (LLVPs) in the lowermost mantle exhibit sharp lateral boundaries, internal heterogeneity, isotopic anomalies indicative of early Earth reservoirs, and prolonged spatial stability.^[1] In this paper, we propose that LLVPs are fossilized “mantle hurricanes”—relics of large, coherent vortices that developed during early planetary cooling when the mantle was partially molten. In this scenario, rotational flow organized fluids into spiral, banded, or vortex-shaped domains which subsequently became compositionally locked in as the mantle crystallized, preserving the geometry of ancient fluid motion, like a fossil. This interpretation provides a unified explanation for the longevity of LLVPs and predicts that LLVPs should contain evidence of past rotational shear, including azimuthally organized anisotropy and spiral compositional structure. It further suggests that locations such as Iceland represent active boundary-breach sites, where residual vortex cores weaken the thermal boundary layer and permit ascent of deep mantle materials. The hypothesis is testable through integration of seismic tomography, anisotropy mapping, thermochemical convection modeling, and geochemical datasets. If validated, it implies that the solid Earth retains a structural memory of early dynamical organization and that present-day mantle plumes and tectonic patterns are influenced by “fossil vortices” formed billions of years ago.

Correspondence: papers@team.qeios.com — Qeios will forward to the authors

I. Introduction

Large low-shear-velocity provinces (LLSVPs) are among the most enigmatic features of the deep Earth. Seismic tomography reveals two continent-scale regions of reduced shear-wave speed at the base of the

mantle beneath Africa and the Pacific, with lateral dimensions of several thousand kilometers and heights up to 1,000 km above the core–mantle boundary (CMB)^[2]. Their margins appear sharp, their internal structures heterogeneous, and their spatial configuration has remained broadly stable over hundreds of millions of years^[2]. They have been interpreted as thermochemical piles, the remnants of ancient subducted slabs, dense basal reservoirs, or compositional stratification associated with partial melting at the core–mantle boundary^[3].

In rotating, thermally driven fluids, coherent vortices are a natural and often long-lived outcome^[4]. In planetary atmospheres and oceans, rotation and buoyancy together organize convection into columnar or spiral structures that can persist for timescales far exceeding individual turnover times^[5]. Giant vortices such as Jupiter’s Great Red Spot provide a familiar example of long-lived vortex behavior in a stratified rotating fluid. Because the mantle is internally heated, compositionally variable, and rotating, its effective dynamics may permit analogous flow structures. That coherent vortices might form in the mantle has been raised indirectly within the broader framework of rotating convection and plume dynamics^[6].

We propose that LLSVPs may represent the fossilized remnants of coherent vortex structures that formed earlier in Earth’s thermal evolution within a molten or weakly viscous mantle. With cooling, these vortices would have eventually frozen into large-scale geometries that fossilized systems of organized rotational flow. Rather than axisymmetric, large “mantle storms” commonly develop strongly directional, non-axisymmetric geometry more similar to an atmospheric supercell than a hurricane.

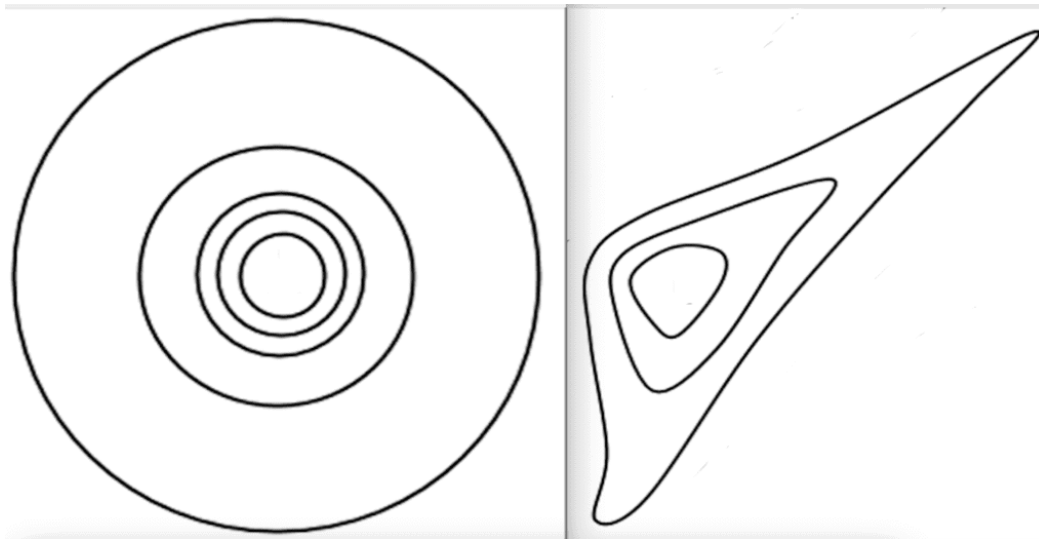


Figure 1. Symmetric versus directional vortex geometry. Idealized axisymmetric vortices (left) contrast with directional, bonded vortices (right) that are elongated and embedded within a larger flow field.

If coherent vortices exist in the mantle, they may interact with thermal boundary layers, producing localized upwellings where vortex-organized buoyant material approaches or crosses the mantle to surface transition region. We suggest that the Icelandic plume may represent a modern example of upwelling linked to deep vortex dynamics capable of penetrating the upper thermal boundary layer. Iceland's unusually high buoyancy flux^[7], broad geochemical diversity^[8], and apparent connection to deep mantle structures make it a natural test case. Focusing on physical plausibility rather than comprehensive proof, we ask a narrow, testable set of questions:

1. Under what mantle conditions can coherent vortices form and persist?
2. Are these conditions compatible with mantle data?
3. Are LLSVPs consistent with the expected imprint vortices?
4. Does Iceland exhibit signatures consistent with a vortex interacting with the thermal boundary layer?

To address these questions, we develop a scaling framework for vortex formation in rotating convection using the Navier–Stokes equations under the Boussinesq approximation coupled with thermal evolution. We evaluate key dimensionless numbers—including the Rayleigh, Ekman, and Rossby numbers—to identify parameter regimes conducive to coherent vortex formation and long lifetimes relative to

diffusive and viscous timescales. We then compare these theoretical expectations with seismological, geodynamic, and geochemical characteristics of LLSVPs and with observations from the Iceland hotspot.

A central implication of this framework is that rotation may locally organize flow into coherent structures. In such regimes, vortices can concentrate heat and composition, steepen lateral gradients, and promote the development of sharp boundaries—features strikingly similar to those observed in LLSVPs^{[4][2][1]}. If portions of the lower mantle were partially molten or significantly weaker earlier in Earth history, vortex formation and subsequent “fossilization” by cooling and viscosity become plausible outcomes.

If LLSVPs are mantle storm fossils, we expect to observe internal fabrics or anisotropic signatures consistent with rotational flow, arcuate or spiral planform geometries, and compositional patterns reflecting organized, rather than random, mixing. If Iceland is an active example of boundary-penetrating vortex-driven upwelling, we expect time-variable asymmetry in plume structure, potential precession or drift of the upwelling center, and specific geochemical signatures related to mixed deep reservoirs^[5]. Conversely, the absence of such signatures where data coverage is good would challenge the hypothesis. The vortex-fossil hypothesis is intended as a stimulus to further modeling, observation, and debate regarding the dynamical history of Earth’s deep interior.

2. Mantle Supercell Hypothesis

Mantle convection is commonly modeled as buoyancy-driven flow in a viscous, slowly deforming medium^[9]. Temperature differences arising from internal heating and basal/core heat flux generate density contrasts that drive upwellings and downwellings^[10]. Rotation can influence convective organization even when inertial forces are weak^[4]. Buoyant convection tends not to occur as random, unorganized motion. Instead, rotation introduces a preferred alignment, encourages columnar flow parallel to the rotation axis, and suppresses lateral dispersion of vorticity^[4]. Rotation can act as an organizing principle, producing long-lived vortical structures and banded flow patterns^[6].

Across many nonequilibrium rotating systems, energy transport often self-organizes into vortical or spiral pathways, producing recurring geometric motifs across scales. Coherent vortices are localized regions of swirling motion that maintain their identity for longer than the characteristic eddy turnover time of the surrounding flow^[5]. These structures can arise through nonlinear interactions, vorticity stretching, and shear instabilities, and they can be stabilized by rotation, stratification, or viscosity

contrasts^[6]. In planetary atmospheres, large anticyclones such as Jupiter's Great Red Spot represent vortices that persist for millennia while interacting with surrounding turbulence^[11].

The defining properties of coherent vortices include: (1) concentrated vorticity relative to the background flow, (2) a characteristic spiral or circular geometry, (3) internal mixing of temperature and composition distinct from their surroundings, and (4) resilience to disruption^[4]. These same properties, expressed in a high-viscosity, solid-state convecting medium, would be expected to produce long-lived, compositionally distinct domains with sharp margins—features qualitatively similar to those attributed to LLSVPs. The term “mantle storm” used here is metaphorical, but the underlying fluid-dynamical concept is simply that of a stable, coherent vortex in a rotating convecting system.

The persistence of vortices depends on the competition of processes. Maintenance processes include rotational alignment and vorticity stretching, and destructive processes include viscous diffusion of vorticity and thermal or compositional homogenization^[4]. In a cooling planet, viscosity increases with time, convective vigor declines, and the capacity for large-scale reorganization is progressively reduced^[10]. Under such conditions, heterogeneities formed earlier in Earth history may become effectively “frozen” into the mantle. If coherent vortices formed when the mantle was hotter, partially molten, or more weakly viscous, their internal compositional or thermal anomalies could have been locked in as the system cooled^[10].

Current interpretations of LLSVPs emphasize thermochemical piles, dense basal reservoirs, or regions enriched in iron or incompatible elements. Many models invoke long-term accumulation of subducted slabs or basal melting to explain their density and seismic characteristics^{[2][12][13]} (Davies et al., 2012). These explanations successfully account for several features, including stability and geochemical reservoir behavior, but they typically treat LLSVPs as largely static, topographically controlled accumulations rather than the preserved imprint of a dynamic flow structure^[1].

The vortex-fossil hypothesis allows that LLSVPs may indeed be compositionally distinct or dense; however, it proposes that the spatial organization of these provinces arises from coherent flow during earlier mantle evolution. In this framework, thermochemical heterogeneity is not accumulated passively but is actively structured by rotational dynamics, producing characteristic geometries such as arcuate margins, lobate domains, or internally wrapped heterogeneity. Such behavior is consistent with the known properties of coherent vortices, which can maintain long-term structural integrity while mixing internally^[5], and the stable longevity of LLVPs^[14].

A key element of deep mantle dynamics is the interaction between convective flow and thermal or rheological boundary layers^[10]. Strong viscosity contrasts across the mantle transition zone and the lithosphere–asthenosphere interface can impede, redirect, or localize upwellings^{[15][16][17]}. When buoyant material organized within a vortex approaches such a boundary, localized stresses may lead to focused plume formation, deflection, or intermittent breakthrough rather than diffuse ascent^[18].

Iceland and other mantle plume regions may reflect this style of localized penetration, where deep-seated, rotationally organized buoyancy finds a pathway through the upper boundary layer. In this context, a “breaking through” event does not imply violent disruption but rather progressive, focused delivery of heat and material along preferred pathways established by underlying flow geometry. The observable surface expression is a hotspot or plume-like feature characterized by unusually high buoyancy flux and pronounced compositional diversity, consistent with seismic and geochemical interpretations of Iceland^{[7][8]}.

For length scales characteristic of LLSVPs (1,000–5,000 km), plausible mantle viscosities, and Earth’s rotation rate, the Ekman and viscous-diffusion timescales suggest that rotational constraints may be non-negligible even in a slowly convecting mantle and that vortex lifetimes may approach or exceed geological timescales^[10]. Under these conditions, large structures would be extremely resistant to erasure, consistent with the observed longevity and stability of deep-mantle anomalies^[2]. These estimates support the hypothesis that the observed size, sharpness, and stability of LLSVPs are consistent with the preserved imprint of coherent vortices in the deep mantle.

Small mantle vortices could be axisymmetric, but those potentially linked to LLSVPs are directional, supercell-like flow systems initiated by triple-junction convergence. The triple junction is potentially the densest part of the system and it’s located at the back of the storm. Likewise, LLVPs concentrate density near the CMB^[14]. At this junction, two opposing mantle flows merge, concentrating shear and vorticity and giving rise to a coherent vortex core, forming a rotating domain analogous to the mesocyclone of an atmospheric supercell. Beyond the vortex core, material exits the system as high-vorticity, shear-dominated outflow. The storm system therefore exhibits a well-defined upstream convergence, a central rotating structure, and a directional, high-vorticity dispersive region, imparting strong directionality and asymmetry to mantle deformation.

This topology predicts that large, fossilized mantle storms will leave behind curvilinear, lobate, and asymmetric structures, rather than circular piles. Such structures are consistent with the observed

planform complexity of LLSVPs, including irregular margins, internal heterogeneity, and apparent directional elongation^{[1][12]}. In this framework, LLSVPs represent the preserved rotating cores of ancient supercell-like mantle storms, while surrounding heterogeneity reflects turbulent mixing zones.

Because vorticity is generated at the triple-junction convergence rather than merely sustained by rotation, this mechanism provides a natural pathway for sustained entropy production and long-lived structural organization during early mantle evolution.

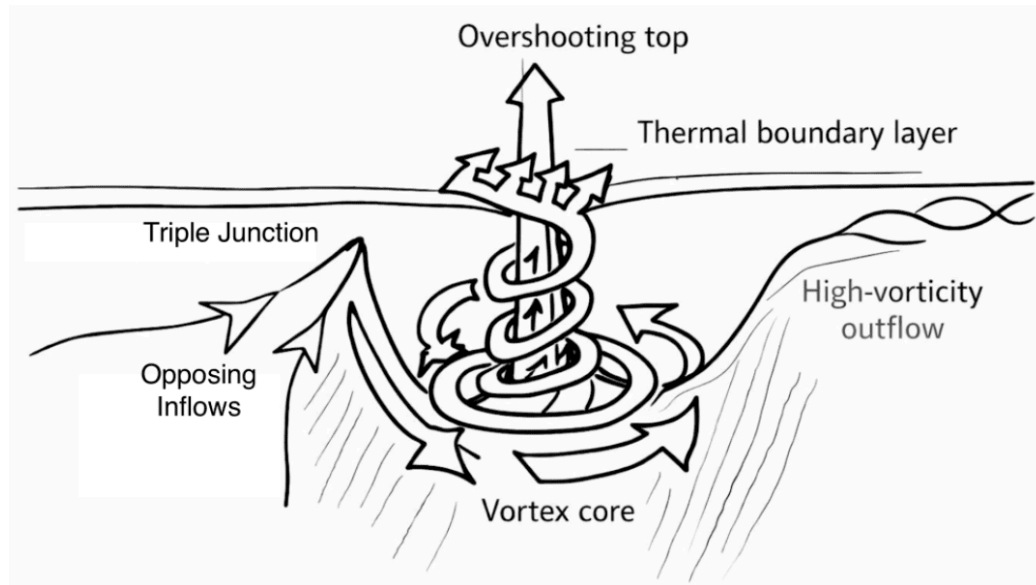


Figure 2. Conceptual model of a triple-junction-driven mantle supercell. Opposing mantle flows converge at a triple junction, generating an elongated, bonded vortex core with organized rotational flow. Within this configuration, vorticity is concentrated in an oblong central region rather than a circular axisymmetric pipe. Upward transport in the vortex can locally breach the thermal boundary layer, producing an overshooting top analogous to atmospheric supercells. Outflow maintains elevated vorticity and organized shear.

If LLVPs are the frozen remnants of large-scale, long-lived vortex structures in the early molten mantle, then they should preserve dynamical signatures distinct from those of purely thermal or purely compositional piles. The hypothesis predicts that LLVPs should exhibit coherent spiral or vortex-like internal geometry, and sharp lateral boundaries caused by shear-enhanced chemical segregation during vortex flow. We can expect internal anisotropy aligned tangentially, not radially, consistent with rotational motion, and radial chemical stratification wrapped azimuthally, rather than vertically stacked

layers. Current seismic tomographic images already hint at undulating margins, non-axisymmetric shapes, and internally heterogeneous but spatially coherent domains^{[11][19]}. Under the vortex-fossil model, these are not incidental irregularities but diagnostic relics of rotational dynamics in the early mantle.

Mantle hurricanes penetrating the thermal boundary layer should generate prolonged plume activity, maintain long-lived geochemical isolation, and produce surface expressions such as topographic swells, localized rifting, and narrow, buoyant upwellings. Iceland satisfies these expectations in several independent ways. Its volcanic products sample deep, primitive mantle reservoirs consistent with an LLVP source, as indicated by radiogenic and noble-gas isotope signatures^{[20][21]}. Seismic imaging reveals persistent plume head–tail structure beneath Iceland extending through much of the mantle since at least the Miocene^[7]. The region also exhibits strong mechanical and geochemical interaction with the Mid-Atlantic Ridge, influencing melt generation and ridge segmentation^[22], and is characterized by anomalously thick crust and elevated heat flow relative to typical ridge environments^[23]. Together, these observations are consistent with Iceland representing a long-lived boundary-penetration site associated with an underlying mantle storm. In the present framework, Iceland is interpreted as an active breach point where a coherent vortex forces material through the thermal boundary layer.

In the supercell mantle storm framework proposed here, vortex formation proceeds through a sequence of dynamically distinct but connected stages. Upstream, convergent mantle flows at a triple junction concentrate shear and vorticity, initiating organized rotational motion. The resulting vortex core represents a transition zone between convergent and divergent flow regimes and is the location of maximum mixing, entropy production, and effective volumetric expansion within the system. Within this rotating core, enhanced entropy and reduced density promote upward buoyancy, making the vortex a natural site for thermal boundary-layer penetration. This process is analogous to the overshooting top of an atmospheric supercell, where organized rotation enables material to breach an otherwise stable stratification^[24]. The ongoing volcanic activity in Iceland is consistent with this expectation. Persistent eruptions imply continuous entropy production and heat transport at the surface boundary, as predicted by the mantle storm model. Rather than representing a transient plume pulse, Iceland is interpreted here as the surface expression of sustained vortex-driven boundary breach.

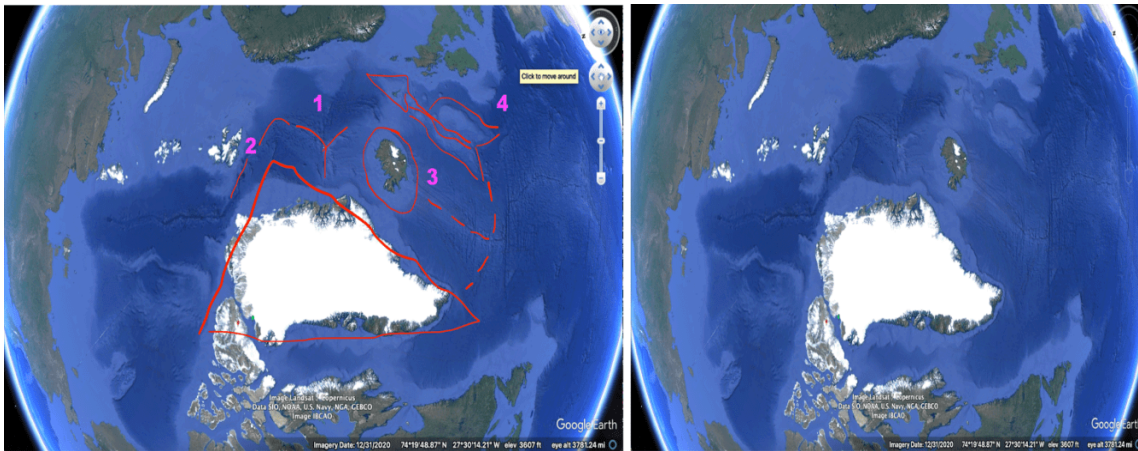


Figure 3. Annotated bathymetric and crustal features illustrate geometric elements interpreted within the mantle-storm framework: (1) a triple-junction-like convergence of structural trends, (3) an elongated, oblong domain centered on Iceland consistent with a bounded vortex core and localized vertical expression associated with plume activity, and (4) directionally organized flow patterns extending away from the core region. The oblique orientation of Greenland relative to these structures is consistent with interaction along an inclined stress field imposed by long-lived deep-mantle organization.

Material exits the storm as directional high-vorticity outflow. This outflow may organize into adjacent laminar streams that maintain rotational coherence even as turbulence increases. Such a configuration provides a mechanism for sustaining vortex longevity while simultaneously generating surrounding heterogeneity. This structure predicts that fossilized mantle storms will preserve a rotating core (observed as LLVPs), asymmetric margins, and regions of mixed composition, while active boundary breach sites—such as Iceland—mark locations where vortex cores currently intersect the upper thermal boundary layer.

This mechanism also provides a natural explanation for asymmetric tectonic response in adjacent continental blocks. The oblique translation and rotation of Greenland are consistent with lateral forcing imposed by a boundary-penetrating vortex beneath Iceland^[25], producing shear and sliding along an inclined stress field^{[26][27]}. In this view, Greenland's motion is not incidental but reflects the mechanical consequence of deep, organized mantle dynamics interacting with continental lithosphere.

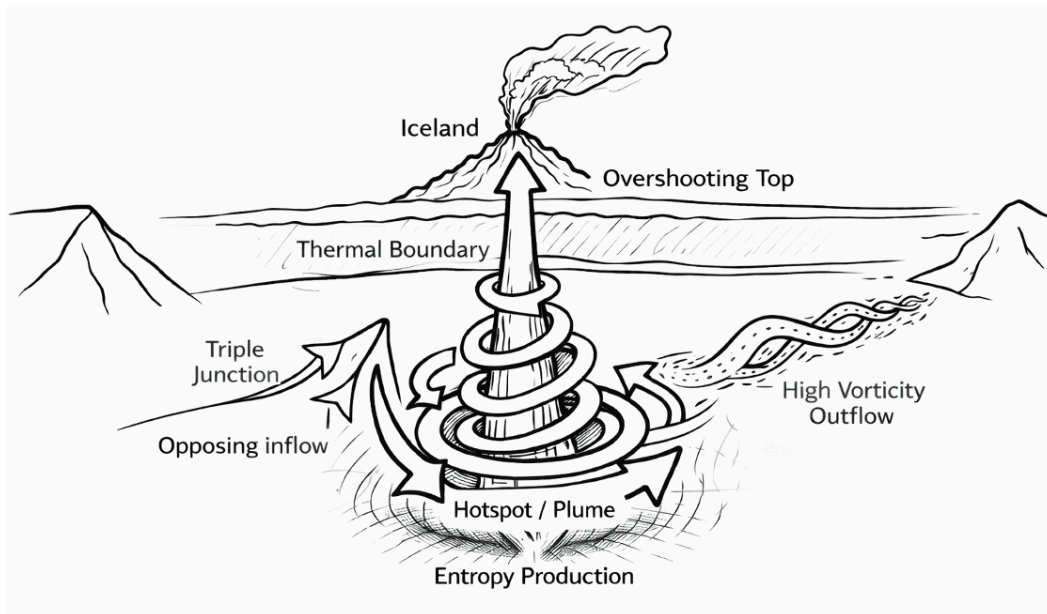


Figure 4. It presents a schematic cross-section through a triple-junction–driven, oblong mantle vortex, illustrating how organized rotational flow can locally weaken and breach the thermal boundary beneath Iceland.

A vortex-fossil model predicts spiral segregation of iron-rich and iron-poor material, long-lived heterogeneity rather than whole-mantle homogenization, and isotopic “memory” of early Earth differentiation. Specifically, LLVP material should exhibit elevated Fe/Mg relative to surrounding mantle, preservation of ^{182}W , ^{142}Nd , and noble-gas isotopic anomalies associated with early Earth differentiation, and correlation between chemical domains and seismic LLVP outlines^{[2][12][28][29][30][21][20]}. These features are widely discussed for the African and Pacific LLVPs and are reinterpreted here as natural consequences of hurricane-like sorting in a slowly cooling planetary interior.

If LLVPs are ancient dynamical fossils, surface geological behavior should correlate with their deep-mantle geometry rather than being randomly distributed. Within this framework, large igneous provinces are expected to concentrate preferentially along LLVP margins, where shear and boundary interactions are strongest. Continental rifting and breakup may similarly align with spiral boundaries or shear zones inherited from the underlying vortex structure, while long-lived hotspot corridors trace the arms of persistent mantle storms. In addition, regions above vortex cores or organized outflow zones may experience localized preservation or development of anomalous continental or proto-continental

crust, reflecting prolonged interaction between deep, structured mantle flow and the overlying lithosphere.

Instead of random distribution, volcanism and tectonics are expected to follow the template imposed by the frozen vortex structure. In this sense, the deep interior acts as a guiding blueprint for surface geology. The proposed existence of submerged continental crust surrounding Iceland (“Icelandia”) provides a potential example of such coupling, where anomalous crustal preservation or development may reflect long-lived interaction between deep mantle structure and surface tectonics rather than purely shallow processes^{[31][32][33]}.

The East African Rift System (EARS) overlies the African Large Low-Velocity Province and associated deep mantle upwellings, a spatial relationship that has long been recognized in seismic tomography and geodynamic studies^{[34][35][36]}. Broad low-velocity structure rising from the core–mantle boundary beneath Africa connects to upper-mantle anomalies beneath the Ethiopian Plateau, Afar, and the segmented rift system, consistent with sustained deep-mantle influence on surface tectonics and long-wavelength dynamic uplift^{[37][38]}.

In the context of the hurricane-fossil hypothesis, this relationship is reinterpreted as the surface expression of a long-lived, organized mantle vortex rooted within the African LLSVP. Rather than representing diffuse thermal buoyancy alone, upwelling beneath East Africa may reflect structured ascent along vortex cores or shear zones established during early mantle evolution. The observed segmentation of the rift system, long-wavelength uplift of the African continent, and persistence of plume-related volcanism are consistent with continued interaction between lithosphere and a spatially coherent, deep-mantle flow structure.

This interpretation does not negate tectonic or lithospheric controls on rift evolution, but suggests that rifting in East Africa has been conditioned by a deep, ancient dynamical template. In this view, the African LLSVP acts as a fossil mantle storm whose internal geometry continues to guide where and how surface extension, volcanism, and uplift are focused. Continental rifting, upwelling, and dome structures are consistent with a breakup aligned with boundaries or shear zones inherited from an underlying vortex structure. A detailed geometric comparison between EARS and the internal structure of a mantle storm—including oblong vortex cores and triple-junction-bonded flow—is beyond the scope of this study and will be addressed in future work.

This model is explicitly falsifiable. It would be disproven if Large Low–Velocity Provinces lack coherent internal geometry or show no evidence of organized, non–axisymmetric structure. The hypothesis would also fail if geochemical signatures within LLVP footprints do not preserve isotopic memory of early Earth differentiation, or if mantle anisotropy does not exhibit tangential or spiral alignment consistent with rotational flow. Finally, if Icelandic magmas are shown not to sample deep, LLVP–like mantle reservoirs, the interpretation of Iceland as a boundary–penetration site associated with a fossil mantle storm would be untenable.

3. Analysis of Thermodynamic Pathways

We analyze a possible thermodynamic pathway from the Earth’s core to the lithosphere. We use a spatial projection from a Large Low Shear Velocity Province (LLSVP) from the core’s rotational center to the lithosphere. We use a conic projection with flat conic intersections, and we approximate correction factors from these flat surfaces to spherical caps. We treat the LLSVPs as areas of discontinuous propagation of thermal phonons, such that thermal transitions around the perimeter of the LLSVP peak are due to lateral phonon transport normal to the axis height of the cone at planar intersection. This thermal transport is demonstrated in the following illustration.

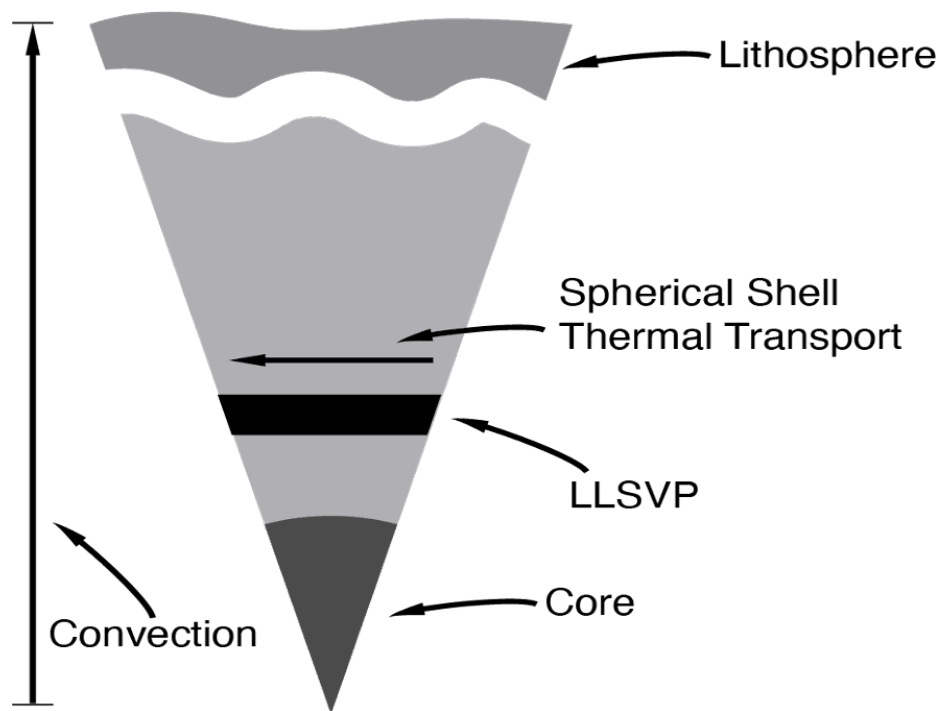


Figure 5. It presents a vertically stratified core to surface model of thermal transport based on conical projection. The LLSVP is an area of discontinuous propagation of thermal phonons. Thermal transitions around the perimeter of the LLSVP peak are due to lateral phonon transport normal to the axis height of the cone at planar intersection.

In detail, we model thermal transport through the LLSVP as shown ...

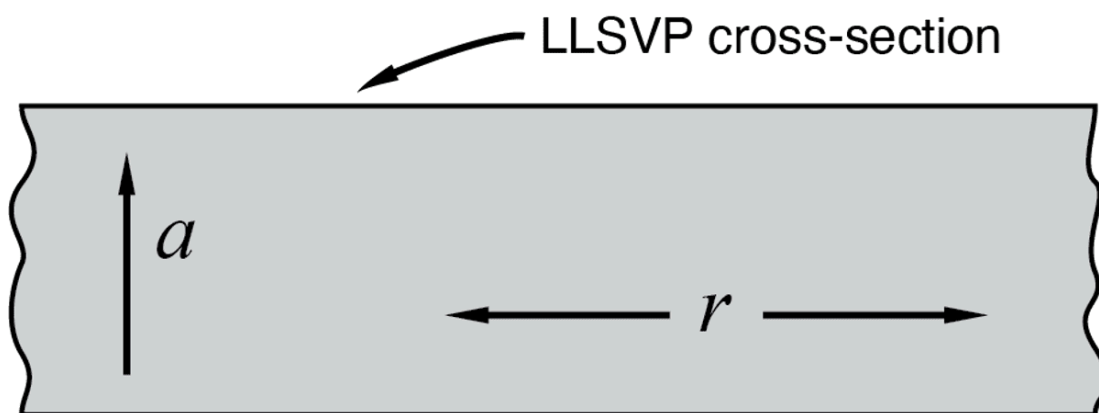


Figure 6. It presents thermal transport radially from the core through the LLSVP. a shows the thermal transport radially from the core, and r shows the direction of thermal transport through the LLSVP in a spherical shell normal to the radius.

Where a shows the thermal transport radially from the core, and r shows the direction of thermal transport through the LLSVP in a spherical shell normal to the radius. (Although the actual LLSVP is sufficiently irregular in shape that a planar approximation should be as accurate as a spherical shell.) For this work, it is sufficient to note that the increased mass density of the LLSVP relative to the surrounding mantle leads to a difference in thermal transport along the plane of the LLSVP.

Like a rock in a pot of boiling water that has reached thermal equilibrium with the water, both gas and thermal flow will show marked discontinuity along the edges of the rock. The projected cross section of the rock can be inferred from the surface thermal signature.

In this way, we model the LLSVP as a thermal projector for the lithospheric surface. We formulate the applied theory and compare currently measured areas of LLSVPs to surface characteristics.

To start we apply the conical symmetry of a single cone (we leave to later work the examination of mirror-symmetry of a second cone, apex to apex, through the core to examine venturi-like conduction across a given diameter). We form a single cone with a vortex at the center of the core.

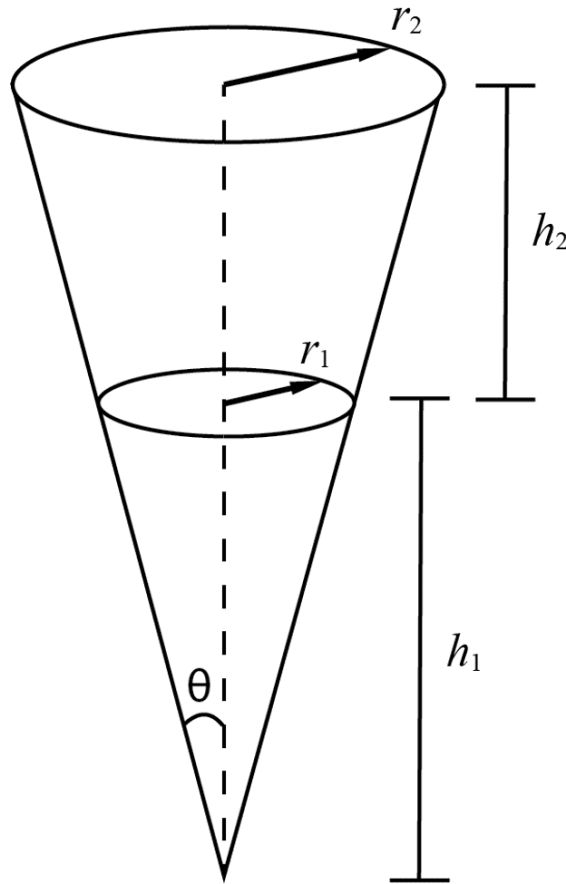


Figure 7.

We designate r_1 and h_1 the radius and the height of the planar intersection at the LLSVP. For the initial analysis, we neglect the thickness of the LLSVP. We designate r_2 and h_2 the radius and the height of the surface lithospheric feature, with h_2 the additional height of the surface feature above the LLSVP. As a first approximation, we use the average area of the LLSVP and map to a planar circle. We do the same for the surface feature, with radius r_1 and r_2 , respectively. Angle θ is noted between the vertical height and the conical angle.

The area of the planes are:

$$A_1 = \pi r_1^2 \quad A_2 = \pi r_2^2$$

Where r_1 is derived from measured data of the LLSVP, and r_2 is the projected radius at the surface. We note that

$$\tan \theta = r_2 / (h_1 + h_2) \quad \text{and} \quad \tan \theta = r_1 / h_1.$$

We then find that

$$r_2 / (h_1 + h_2) = r_1 / h_1, \text{ so that}$$

$$r_2 = r_1 (h_1 + h_2) / h_1.$$

We then use measured averages for the Pacific LLSVP, with an approximate diameter of 3,000 km, so that

$$r_1 = 1.5 \times 10^6 \text{ m}$$

$$h_1 = 3500 \text{ km} = 3.5 \times 10^6 \text{ m}$$

$$h_2 = 6.4 \times 10^6 \text{ m} - 3.5 \times 10^6 = 2.9 \times 10^6 \text{ m}$$

This produces $r_2 = 2.7 \times 10^6 \text{ m}$.

Adjusting for the spherical cap, $r_2 \approx 3 \times 10^6 \text{ m}$.

As a first approximation, we extend r_2 outward in a circle with the island of Kiribati at the approximate center.

We then apply the generally accepted approximate metrics for all three LLSVPs ...

LLSVP	Center of mass Diameter km	r_1 meters	r_2 meters (adj spherical cap)	Approx Geographic Center	r_2 miles
Pacific	3,000	1.5×10^6	3×10^6	Kiribati	1,860
African	4,000	2×10^6	4×10^6	Dassen Island	2,500
Icelandic	2,000	1×10^6	2×10^6	Iceland	1,200

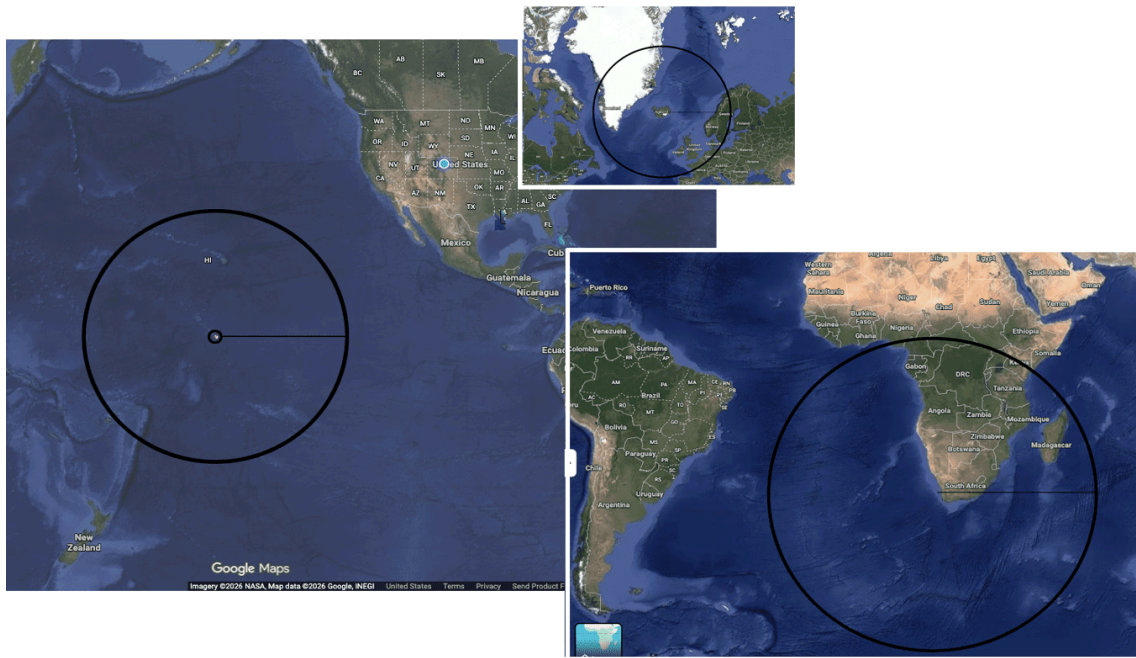


Figure 8. It presents the predicted thermodynamic areas based on our conical projection model to determine thermal signature.

4. Methods for Detection and Analysis

To evaluate the hypothesis that LLVPs represent fossilized mantle hurricanes and that features such as Iceland mark active boundary breakthrough sites, we outline a set of analytical approaches integrating seismology, geodynamics, and geochemistry. The emphasis is not on a single decisive test, but on the convergence of multiple independent indicators consistent with vortex-fossil dynamics.

We propose quantitative analysis of LLVP geometry using global seismic tomography, including extraction of LLVP margins from P- and S-wave velocity models, identification of curvilinear or spiral patterns, and comparison with synthetic vortex geometries from rotating convection models. Pattern recognition methods may involve curvature analysis, spectral descriptors of azimuthal periodicity, and topological techniques to identify spiral arms or vortex cores. Under the hurricane-fossil hypothesis, LLVPs should depart from simple dome-like morphologies and instead exhibit coherent rotational structure or wrapped internal layering.

We will examine mantle anisotropy datasets to identify deformation fabrics inherited from past flow. The method consists of 1) integrating SKS splitting and surface-wave anisotropy databases, 2) mapping fast-

axis orientations relative to LLVP boundaries, 3) testing whether orientations trend tangential to LLVP margins, indicating historical rotational shear. Finite-strain ellipsoid reconstructions from anisotropy patterns provide a tool to distinguish between vertical plume upwelling models, stagnant dense piles, and rotational vortex flow with azimuthal shearing^[39]. A predominance of tangential fabrics would support the vortex interpretation.

Numerical simulations of early mantle convection will be used to assess whether hurricane-like vortex structures naturally emerge during rapid planetary cooling, using established thermochemical convection frameworks^[2]. We specifically test scenarios with 1) initially molten or partially molten mantle, 2) strong radial temperature gradients, 3) rotation and Coriolis effects, 4) iron enrichment feedback on density and viscosity. Outputs of interest include persistence timescales of vortices, spiral segregation of composition, and solidification patterns at the freezing front. LLVP-like features that survive for billions of years in these models would strongly support a fossil origin.

We will compare the spatial extent of LLVPs with geochemical datasets from plume-related volcanism^[20]. The method includes 1) compiling plume-source basalt geochemistry (OIBs and flood basalts) 2) mapping ^{182}W , ^{142}Nd , He-isotope ratios, and noble gases relative to LLVP boundaries, 3) testing for preservation of early Earth differentiation signatures within LLVP-projected regions. The hurricane fossil model predicts that such domains retain ancient, poorly mixed reservoirs, consistent with early segregation rather than late subduction accumulation. To evaluate Iceland's role as a boundary breakthrough location, we analyze 1) seismic imaging of the Iceland plume conduit, 2) crustal thickness and gravity anomalies, 3) high- $^3\text{He}/^4\text{He}$ and other deep-source isotopic signals, 4) time history of melt production and plume-ridge interaction. We test whether Iceland is best interpreted as a typical plume independent of LLVP structure, or a localized failure point in the thermal boundary layer induced by a fossil vortex core beneath the North Atlantic. If the latter, we expect alignment between Iceland's upwelling pathway and underlying LLVP geometry.

Finally, to distinguish coincidence from causality, we will perform statistical tests linking 1) hotspot locations, 2) large igneous provinces, 3) supercontinent breakup margins, 4) LLVP boundaries and spiral features. Monte Carlo or rotational randomization tests can be used to determine whether observed alignments exceed chance expectation.

5. Discussion

The perspective developed here reframes LLVPs, not as passive, dense “piles” at the base of the mantle, but as relics of organized, rotating flow established during early planetary cooling. This interpretation naturally explains several otherwise puzzling properties including their extreme longevity despite convection, sharp, laterally coherent boundaries, strong internal chemical heterogeneity and association with plume generation and large igneous provinces. In a hurricane-fossil framework, these are not independent anomalies requiring multiple separate explanations, but linked outcomes of the same dynamical origin—long-lived vortical circulation in a partially molten, thermochemically stratifying mantle.

If LLVPs are fossil vortices produced during early cooling, they imply that significant fractions of the mantle once participated in large-scale rotational flow. Moreover, solidification did not erase dynamical structure, but froze it in. This suggests that chemical segregation was flow-structured rather than layer-cake stratified. This contrasts with traditional views of gradual, near-homogeneous solidification and subsequent mixing. Instead, the early mantle may have behaved more like a planetary ocean with embedded storms, where crystallization preserved motion patterns as compositional architecture.

In the hurricane-fossil hypothesis, plumes are not random buoyant instabilities; rather, they preferentially nucleate at vortex cores, shear zones along vortex boundaries, and points of enhanced thermal boundary weakening. This provides a unified explanation for the persistent observation that many hotspots align with LLVP margins, that deep-plume geochemistry samples LLVP-like reservoirs, and that some plumes—such as Iceland and Hawaii—appear unusually deep-rooted and long-lived^[20]^[36] (Torsvik et al., 2006). Vortex fossils therefore act as preconditioned launch sites for plume ascent.

If deep mantle structure was established early and has remained largely preserved, then plate tectonics is not purely self-organized at the surface. Instead, surface tectonics may inherit preferred rifting patterns from frozen deep structures, cluster breakup along underlying spiral arms or shear zones, and experience repeated plume events at persistent locations through time. In this framework, supercontinent cycles are not entirely stochastic but partially guided by deep, ancient templates — the “ghosts” of primordial mantle hurricanes.

This hypothesis is not mutually exclusive with other LLVP models. Dense thermochemical piles, subducted material accumulation, and basal heating may all contribute to present-day properties. What is added here is the proposal that initial geometry and composition were imprinted early by vortex

dynamics, and subsequent convection modified but did not erase these structures. Thus, fossil vortices may provide the initial conditions onto which later mantle evolution has been superimposed.

Interpreting Iceland as a present-day example of boundary breakthrough links surface volcanism directly to deep fossil structure. If correct, Iceland becomes a window into LLVP composition, a test case for vortex-aligned anisotropy, and a natural experiment in boundary layer failure. Future high-resolution seismic and geochemical work around Iceland, combined with mapping of LLVP geometry beneath the North Atlantic, has strong potential to discriminate between conventional plume-plus-ridge interaction models and the hurricane fossil boundary-breach model presented here.

This study is conceptual and integrative rather than purely computational. Important next steps include 1) 3-D geodynamic modeling including phase changes and solidification, 2) explicit simulation of spiral chemical segregation, 3) improved tomographic imaging of internal LLVP architecture, 4) targeted sampling of plume-related basalts predicted to intersect vortex arms, or active or frozen fluid bands. The purpose of this paper is to open a new interpretive pathway, not to claim finality. The decisive question is empirical: *do LLVPs behave like supercell storm fossils when examined across seismic, geodynamic, and geochemical lines of evidence?* The predictions outlined here provide a framework for quantitative testing using global tomography, mantle anisotropy, and plume–LLVP correlation analyses, which will be explored in future work.

The vortex-fossil hypothesis implies that the deep mantle retains a structural memory of early planetary dynamics and that this memory continues to influence present-day surface tectonics, plume distribution, and supercontinent evolution. Rather than being erased by convection, early organization may have guided the subsequent history of mantle flow. This framework is testable. It can be supported—or falsified—through integrated analysis of tomographic geometry, mantle anisotropy, geodynamic modeling, and isotopic geochemistry. The hypothesis does not reject existing models; instead, it reframes LLVPs as initially dynamical entities whose present thermochemical properties are the cumulative product of early vortex formation and later mantle evolution. If correct, this interpretation shifts the way we think about planetary interiors. The deep Earth is not only a convecting fluid but also an archive of ancient motion, where long-dead storms remain imprinted as the architecture of the lower mantle and continue to shape the geological systems we observe today.

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