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How the Deep Earth Moves, and Why It Matters for Energy

The rock beneath our feet is not still. The mantle is solid, yet over millions of years it deforms and flows, creeping a few centimetres a year in slow convection cells. That flow reorganises the rock's internal structure: olivine crystals rotate until their fast axes line up with the flow, the way a combed carpet's fibres point one way, and the combed mantle becomes seismically anisotropic. A shear wave crossing that fabric splits into a fast and a slow component whose delay, around a second, surface instruments record directly. Two numbers per measurement (the fast-polarisation azimuth and the delay time) form a compact, physically grounded readout of deep flow. Coupling geodynamic flow models to observed splitting turns scattered measurements into a self-consistent regional story, and that story sets boundary conditions operators care about: lithospheric heat flow governs source-rock maturation and geothermal gradient, and the regional stress orientation decides which natural fractures conduct fluid and which seal. EarthScan's contribution is turnaround: deep-learning estimators with calibrated uncertainty and surrogate models make a read-out that once took a multi-year regional study repeatable in hours, with honest error bars attached.

Tannistha Maiti
Senior AI Researcher

MANTLE-DYNAMICS / SEISMIC-ANISOTROPY / SHEAR-WAVE-SPLITTING / GEOTHERMAL-ENERGY / SUBSURFACE-AI / ENERGY-TRANSITION

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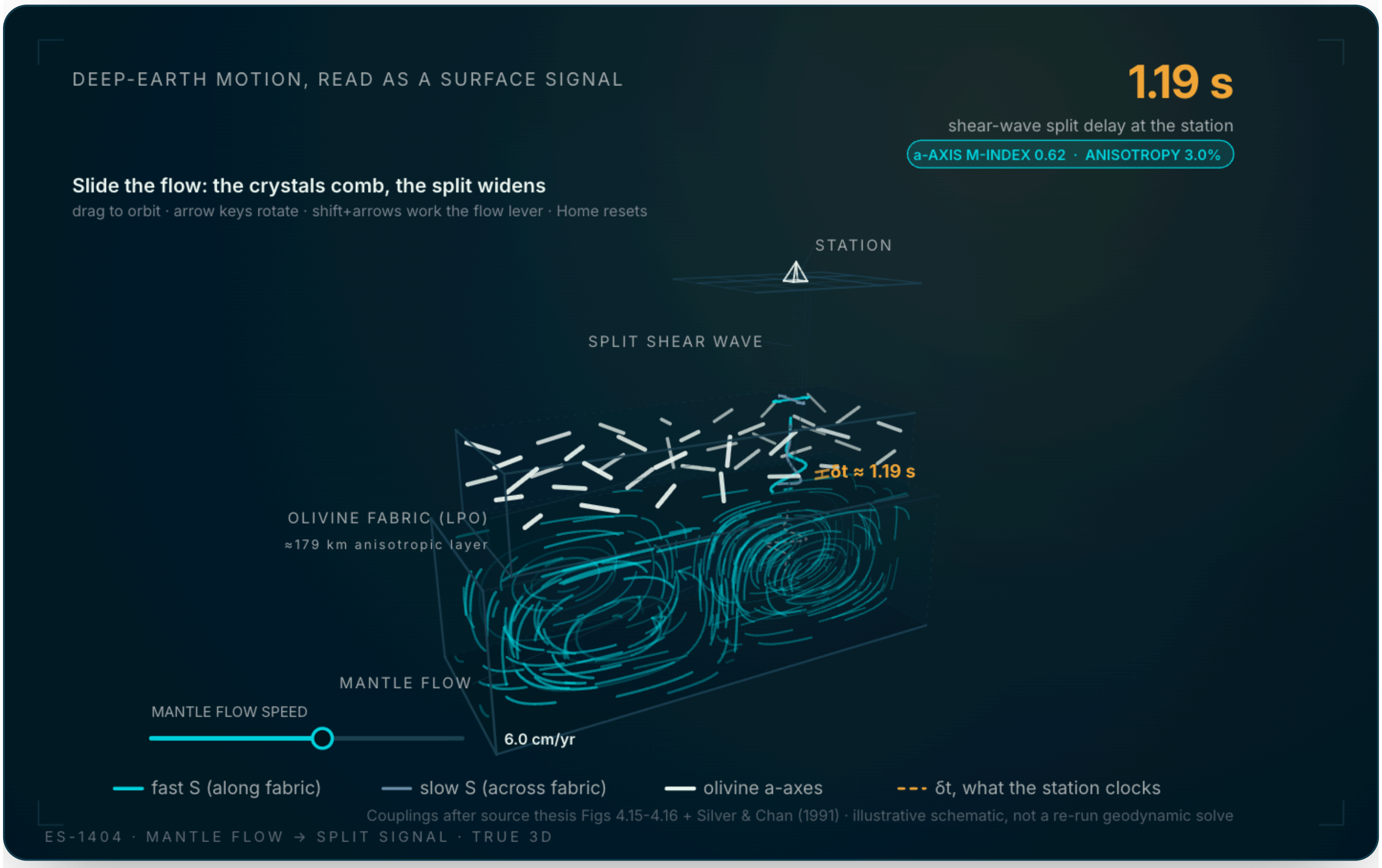
The rock beneath our feet is not still. Roughly 100 to 300 kilometres down, the mantle flows like extremely stiff toffee, creeping a few centimetres a year. You cannot see it, drill to it, or feel it, but you can *hear* it, because that slow flow leaves a fingerprint on every earthquake wave that passes through. This whitepaper explains, in plain terms, how deep-Earth motion turns into a measurable seismic signal, why that chain matters for anyone who develops the subsurface for energy, and how EarthScan turns the signal back into an estimate of what the deep Earth is doing.

The short version: the mantle writes its motion into rock fabric, the fabric bends seismic waves in a predictable way, and modern deep-learning tools read that bending as a map. For energy operators, that map constrains the deep stresses, temperatures, and boundaries that shape everything shallower, from basin heat flow to the orientation of natural fractures.



The whole causal chain in one block of Earth, in true 3D: mantle convection (aqua streaks, two counter-rotating cells) creeps at centimetres a year and combs the olivine crystals in the fabric slab into a common orientation; a shear wave crossing the combed fabric splits into a fast packet polarised along the fabric and a slow packet polarised across it; the amber bracket is the delay between them, and it is the number a surface seismometer actually records. Drag to orbit the block, use the lever to speed the flow up or down, and watch alignment, anisotropy and the split delay move together. Couplings follow the source thesis's mantle-flow models and Silver and Chan (1991); the scene is an illustrative schematic, not a re-run geodynamic solve.

The mantle is a fluid on geological time

Ask most people what the mantle is and they will say "molten rock." That is wrong, and the mistake matters. The mantle is solid. You could stand on it. But over millions of years it deforms and flows like a fluid. This dual nature has a name in engineering: a material that is elastic on short timescales and viscous on long ones. Push it for a second and it springs back; push it for a million years and it slowly gives way. The flow is driven by heat: hot, buoyant rock rises, cool rock sinks, and the whole system churns in slow convection cells that also drag the tectonic plates around above them.

Flow leaves a fabric

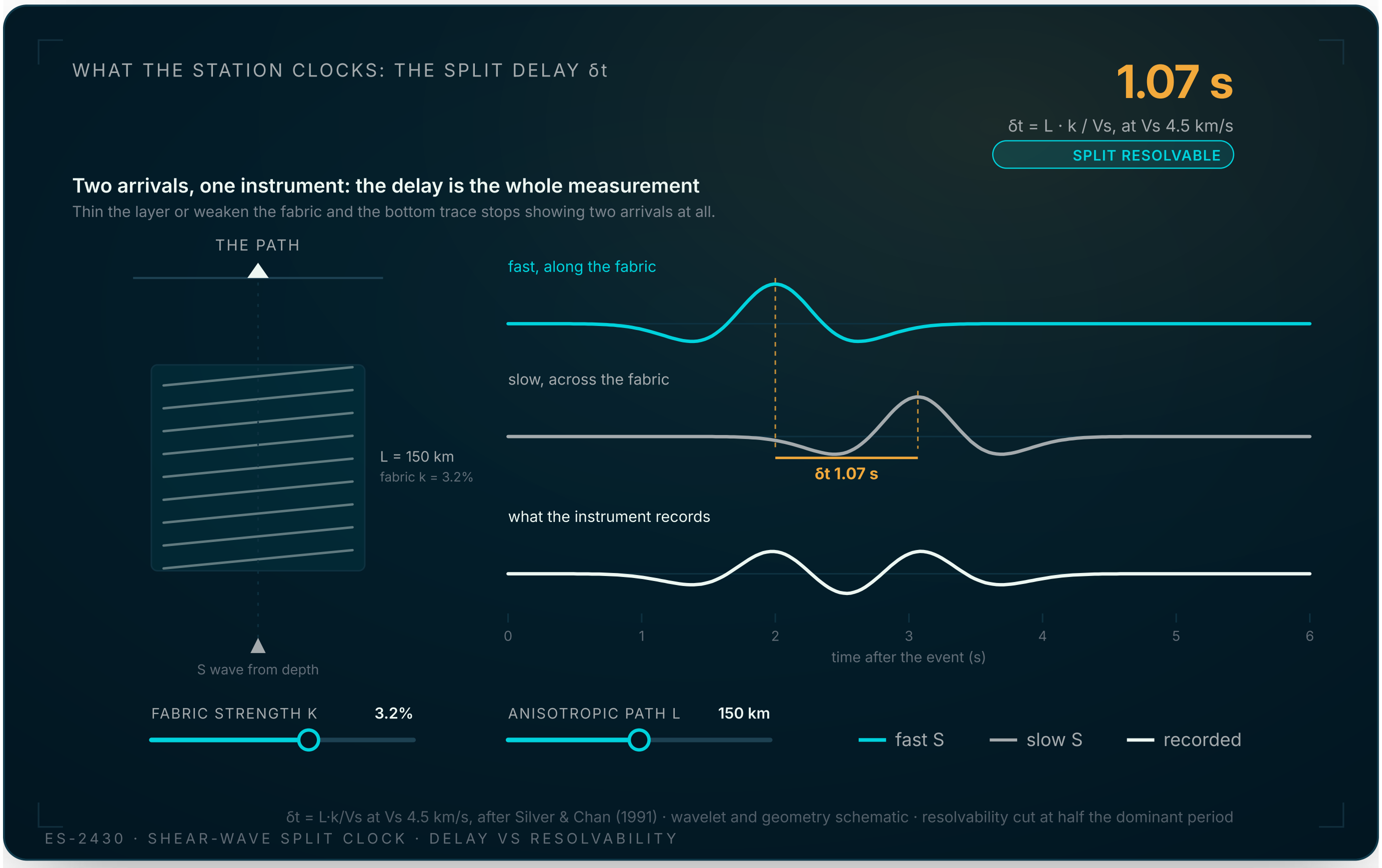
Here is the key idea most non-specialists miss. When the mantle flows, it does not just move rock from A to B. It *reorganises* the rock's internal structure. The dominant mantle mineral is olivine, and olivine crystals are shaped a bit like matchsticks: they have a long, "fast" axis and shorter, "slow" axes. As the mantle strains, these crystals rotate so their fast axes line up with the flow direction. Geologists call this lattice-preferred orientation, or LPO; you can think of it as combing a shag carpet so all the fibres point the same way. Once the carpet is combed, the mantle is no longer the same in every direction. It has become *anisotropic*.

Anisotropy is a directional speed limit

Anisotropy simply means a property depends on direction. In an anisotropic mantle, a seismic wave travels faster along the combed fabric than across it. The difference can be several percent, which sounds small but is enormous by seismological standards. The analogy is wood: a saw cuts easily along the grain and struggles across it. Mantle fabric gives seismic waves a "grain," and the direction of that grain is a direct readout of the direction the mantle was flowing when the fabric froze in.

The signal: shear-wave splitting

The cleanest way to read the grain is *shear-wave splitting*. A shear wave is a wiggle that shakes the ground sideways. When such a wave enters anisotropic rock, it splits into two: a fast component polarised along the fabric and a slow component polarised across it, exactly like light splitting in a birefringent crystal. The two arrive at the surface separated by a delay time called δt (delta-t), typically around one second. Two numbers fall out of a splitting measurement: the fast-polarisation direction (which way the mantle is combed) and δt (how strong the fabric is, integrated along the path). Together they are a compact, physically grounded summary of deep flow.



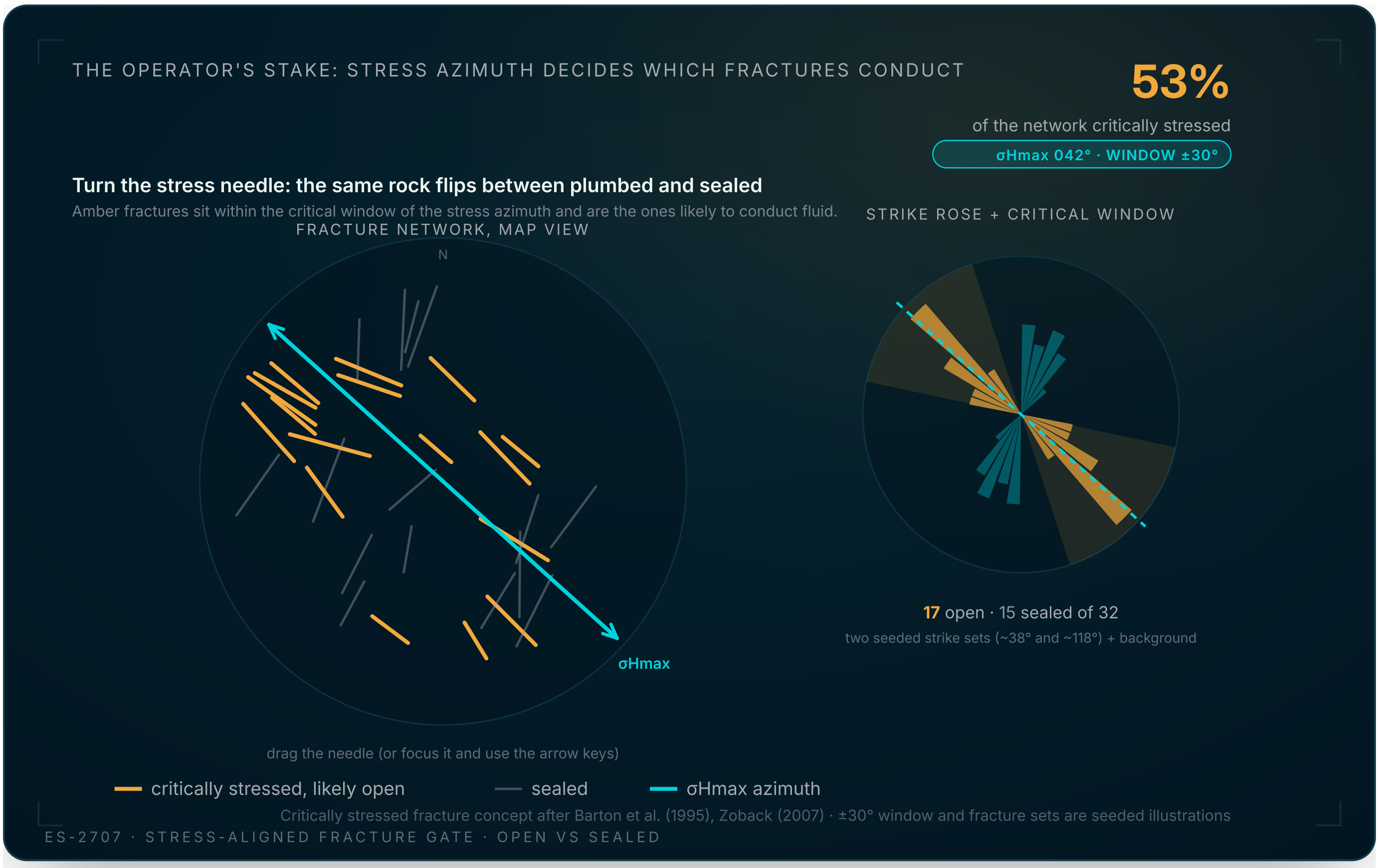
The measurement end of the chain. A shear wave crosses an anisotropic layer of thickness L and fabric strength k, splits, and reaches the station as two arrivals separated by dt = Lk/Vs. The top two traces are the fast and slow components; the bottom trace is their superposition, which is all the instrument actually records. Work the two levers: a long path through strong fabric gives a clean two-pulse record, while a thin layer or weak fabric drops dt below the pulse width and the arrivals merge into a single blob, a split that is physically present but observationally hidden. Couplings follow Silver and Chan (1991); the wavelet and geometry are schematic.

From single station to a coupled model

A single splitting measurement is one arrow on a map. The scientific leap, and the subject of the source thesis behind this note, is to *couple* the whole chain end to end: run a geodynamic model of mantle flow, predict the olivine fabric that flow would produce, forward-model the seismic anisotropy, and compare the predicted splitting to what real stations observe. When the predicted map matches the observed map, you have a self-consistent story linking deep motion to surface data. The thesis's mantle-flow velocity models (its Fig. 4.15-4.16) are exactly this kind of coupling: flow fields on the left, testable seismic predictions on the right.

Why an energy operator should care

Deep flow is not an academic curiosity for the energy sector. The mantle sets the thermal state of the lithosphere above it, and heat flow governs source-rock maturation, geothermal gradient, and the depth of the brittle-to-ductile transition. Mantle flow also organises the large-scale stress field, and stress orientation controls which natural fractures are open and permeable versus closed and sealing: a first-order input for geothermal reservoirs, CO_2 storage integrity, and induced-seismicity risk. Knowing the deep boundary conditions does not replace a site survey, but it tells you which regional story your local data should be consistent with.



Map view of a fracture network with two dominant strike sets. Drag the aqua needle, the azimuth of maximum horizontal stress that regional dynamics (mantle flow included) helps set. Fractures striking within the critical window of the needle are critically stressed and likely to conduct fluid (amber); the rest stay sealed. Watch the open share swing from a handful to most of the network as the needle turns: same rock, different plumbing. That swing is why geothermal, storage, and injection screening starts from the regional stress story before a single well is planned. Concept after Barton et al. (1995) and Zoback (2007); the fracture sets and the window are seeded illustrations.

What EarthScan adds

Historically, this coupled analysis was a multi-year PhD effort per region. EarthScan's contribution is to make the read-out repeatable and fast: deep-learning models trained on synthetic and observed waveforms estimate splitting parameters with calibrated uncertainty, surrogate models stand in for the expensive geodynamic solver until precision is genuinely needed, and the whole pipeline runs as a screening loop rather than a bespoke study. The physics is unchanged. We are still reading olivine fabric. But the turnaround shrinks from years to hours, and every estimate ships with an honest error bar.

Results at a glance

STAGE IN THE CHAIN	PHYSICAL QUANTITY	WHAT IT TELLS AN OPERATOR	TYPICAL SCALE
Mantle flow	Velocity field (cm/yr)	Direction and vigour of deep convection	1-10 cm/yr
Olivine fabric (LPO)	Fast-axis orientation	Frozen-in flow direction	fabric strength 0-100%
Seismic anisotropy	% velocity contrast	Strength of the "grain"	1-5%
Shear-wave splitting	φ (fast azimuth), δt	Measurable surface signal	δt ≈ 0.5-2.0 s
Coupled estimate	Calibrated flow map	Regional boundary condition	+ uncertainty band

WHAT THIS WHITEPAPER ARGUES

1. The mantle flows like a fluid on geological timescales, and that flow is measurable, not hypothetical.
2. Flow imprints a directional fabric on olivine, making the deep Earth seismically anisotropic in a predictable way.
3. Shear-wave splitting (phi and delta-t) is a compact, physically grounded read-out of that fabric.
4. Coupling flow models to splitting observations turns a scattered dataset into a self-consistent regional story.
5. Deep boundary conditions, heat flow and stress orientation, propagate upward into decisions operators actually make.
6. Deep learning makes the coupled read-out fast and repeatable while preserving the underlying physics and reporting honest uncertainty.

References

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[4] Source PhD thesis (2018): receiver-function imaging of the Moho/LAB, seismic anisotropy, and geodynamic modelling, Fig. 4.15-4.16.

EarthScan offers consulting engagements that couple regional flow models to your local seismic and stress data. Talk to us about a scoping call.

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