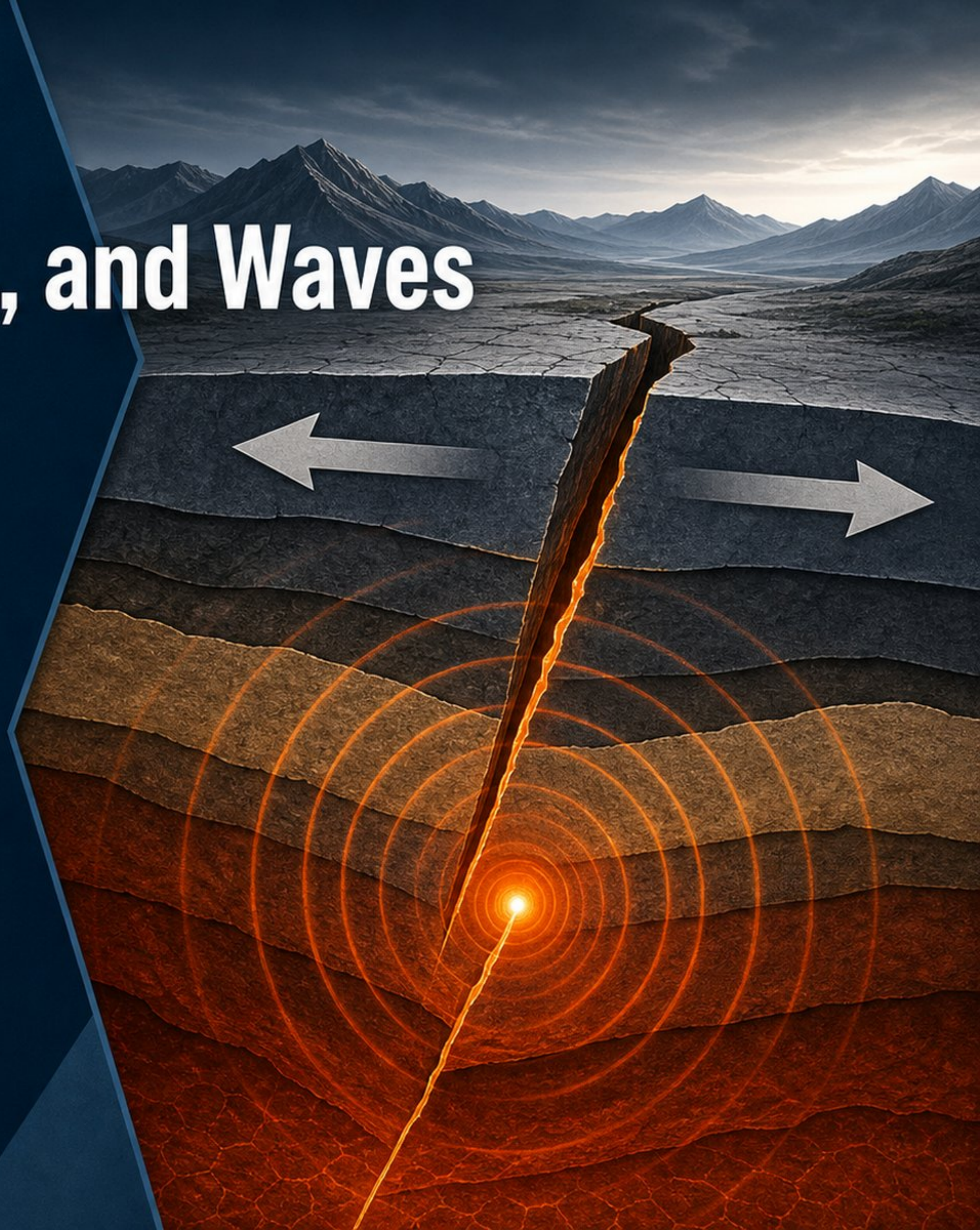
Earthquakes: Faults, Plates, and Waves

- Earthquake: sudden fault slip releasing stored energy as seismic waves
- Plate motion builds stress → stress exceeds fault strength → rupture
- Seismic waves radiate outward, causing ground shaking at the surface
- Training spans subsurface drivers to surface impacts and hazard awareness



Earth’s Interior and the Foundation of Plate Tectonics

- Lithosphere: cold, rigid shell moving atop the hot, ductile asthenosphere
- Mantle convection and slab pull drive plate motion across geological time
- Earth's surface is divided into 15 major tectonic plates like Pacific and Eurasian
- Plates move continuously, carrying continents and oceans with them

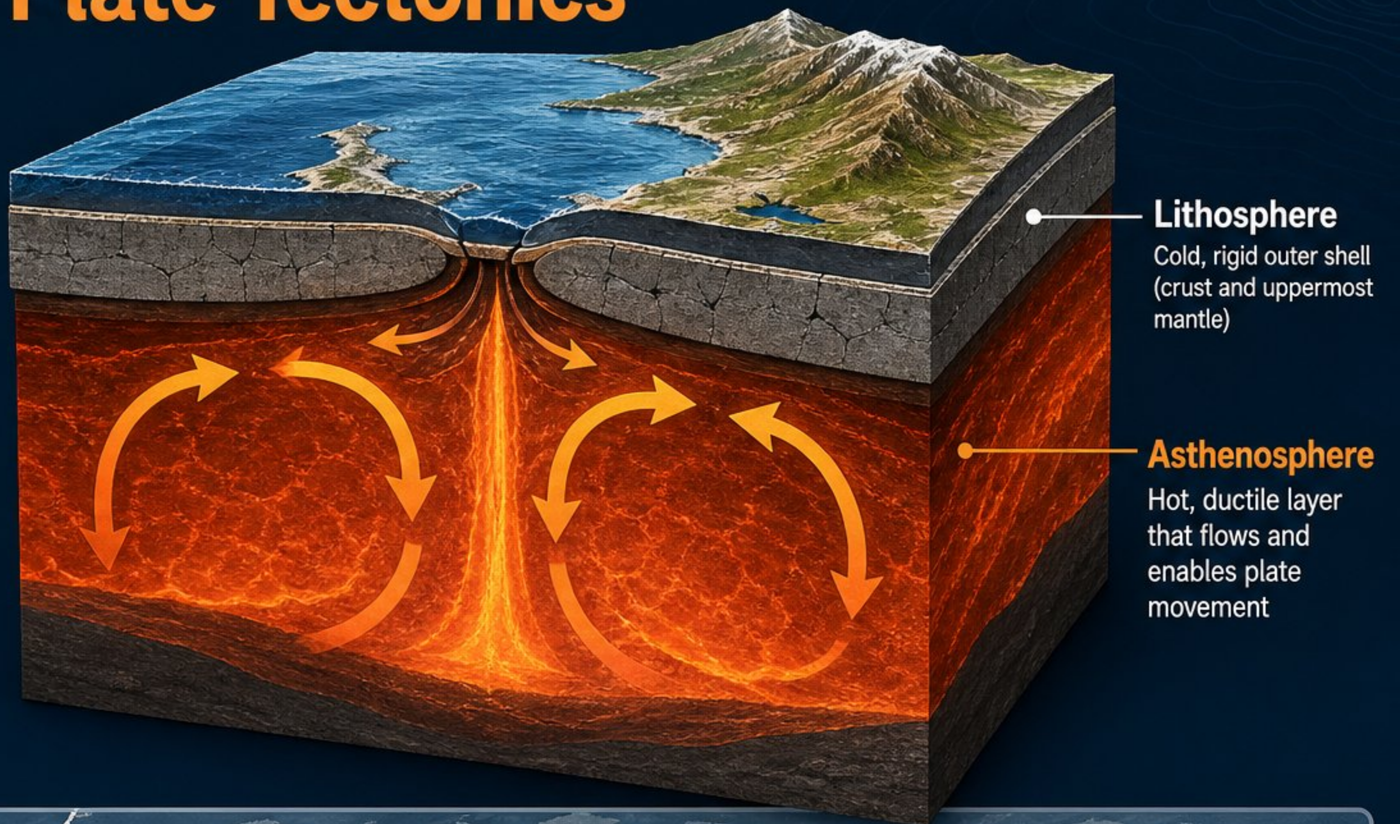
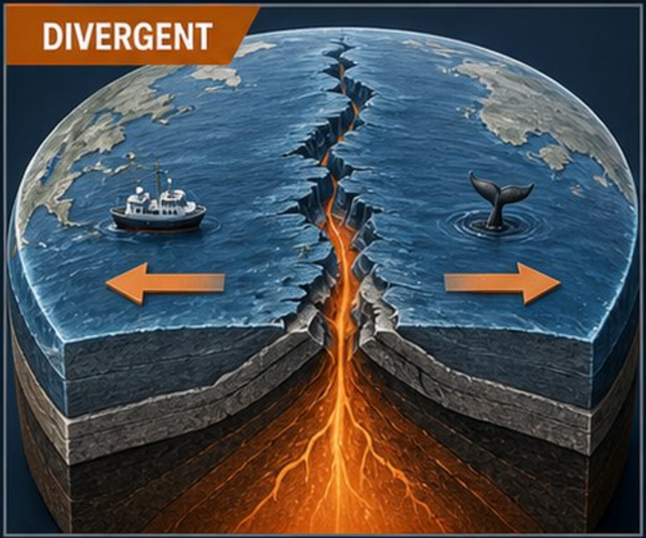
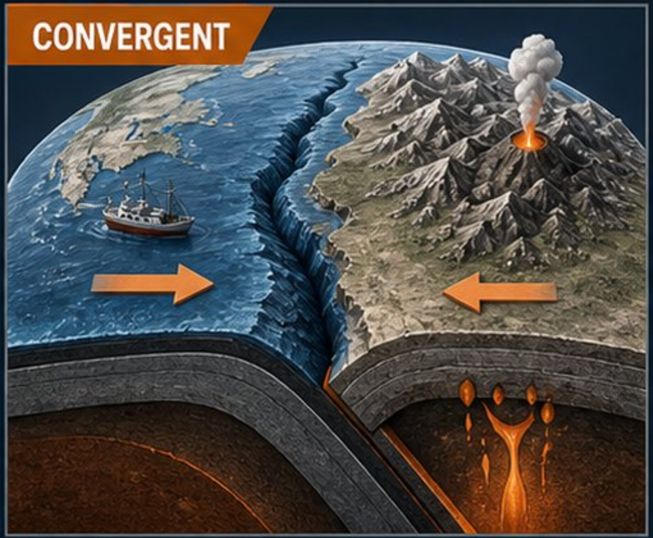
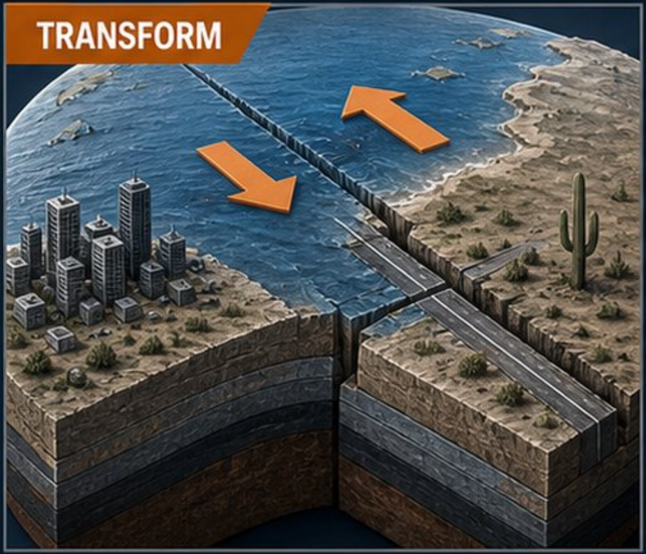
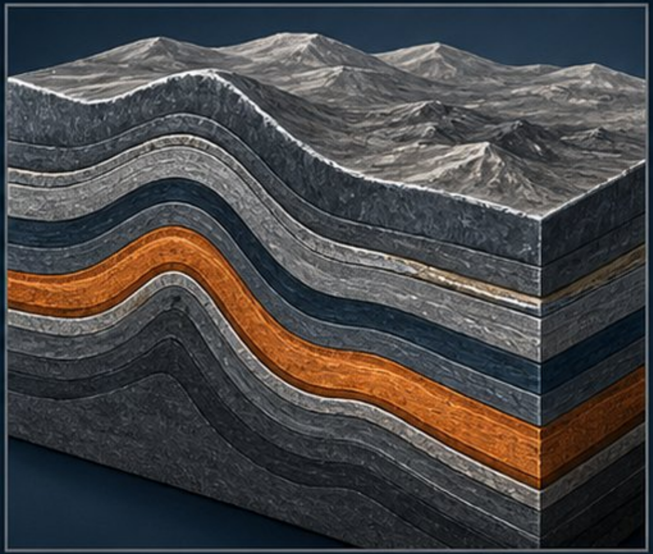


Plate Boundaries: Where the Action Happens





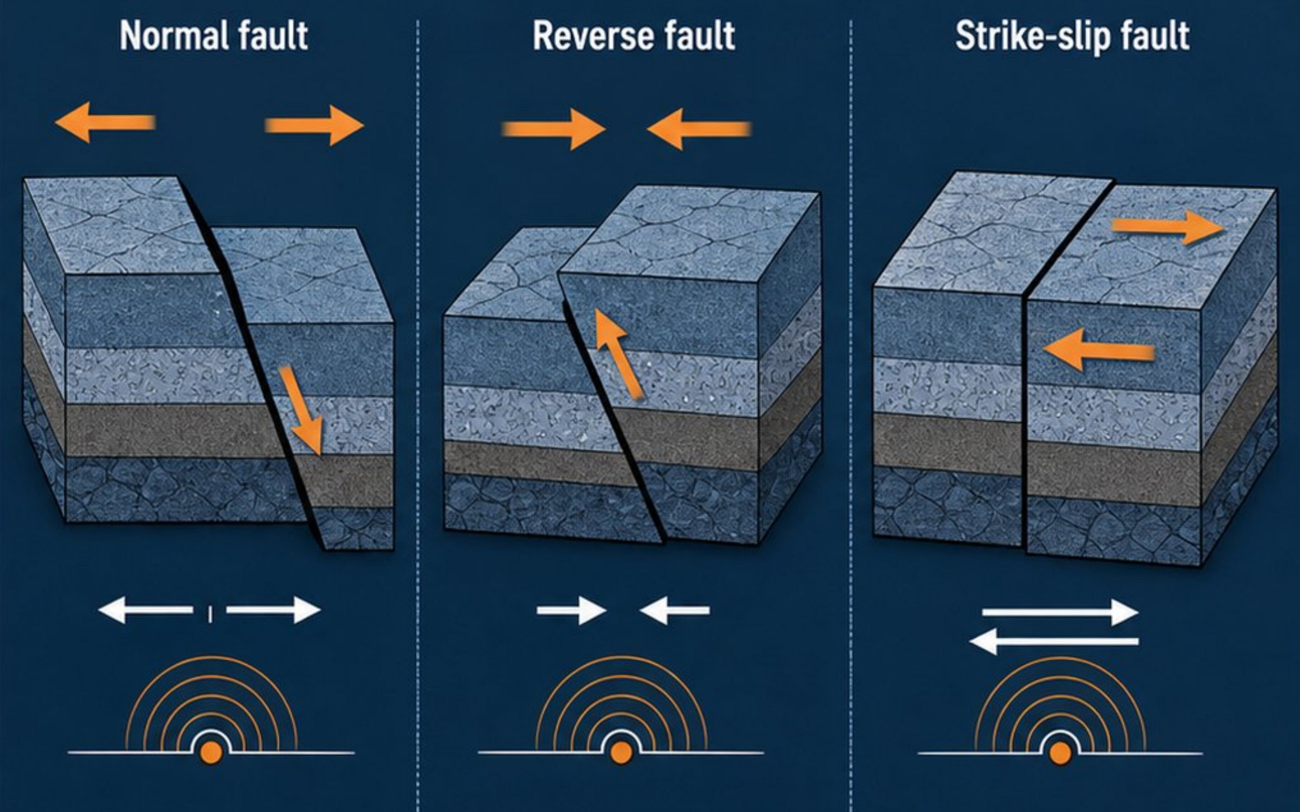


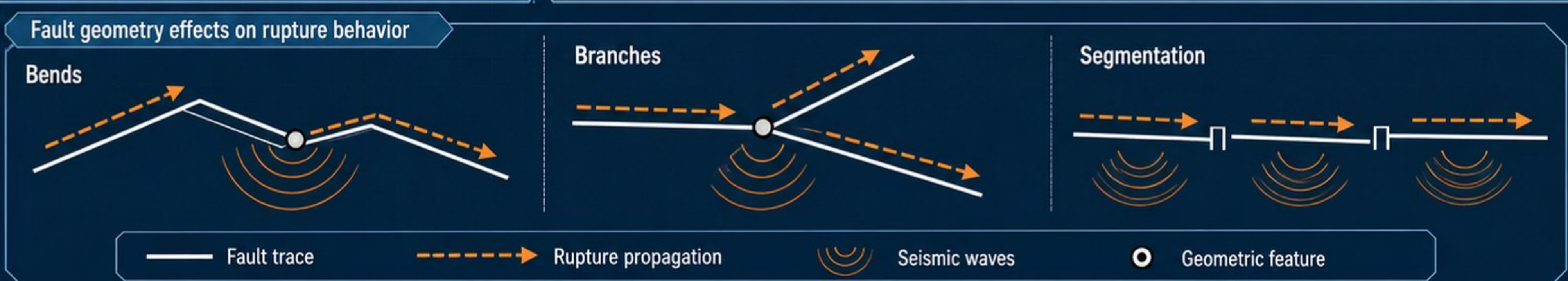


- - Divergent: plates pull apart, new crust forms at mid-ocean ridges
- - Convergent: plates collide; one subducts or crust crumples into mountains
- - Transform: plates slide horizontally past each other, building shear stress
- - Boundary type controls earthquake depth, mechanism, and magnitude potential
- - Key examples: Mid-Atlantic Ridge, Japan Trench, San Andreas Fault

Faults: The Fractures That Generate Earthquakes

- A fault is a fracture zone where crustal blocks move, accumulating elastic strain that powers future earthquakes
- Normal faults (extension), reverse/thrust faults (compression), and strike-slip faults (shear) match three stress regimes
- Subduction zones host megathrusts; continental transforms show strike-slip segmentation; rift zones display normal faulting
- Fault geometry controls rupture behavior—bends, branches, and segmentation influence slip distribution and shaking intensity





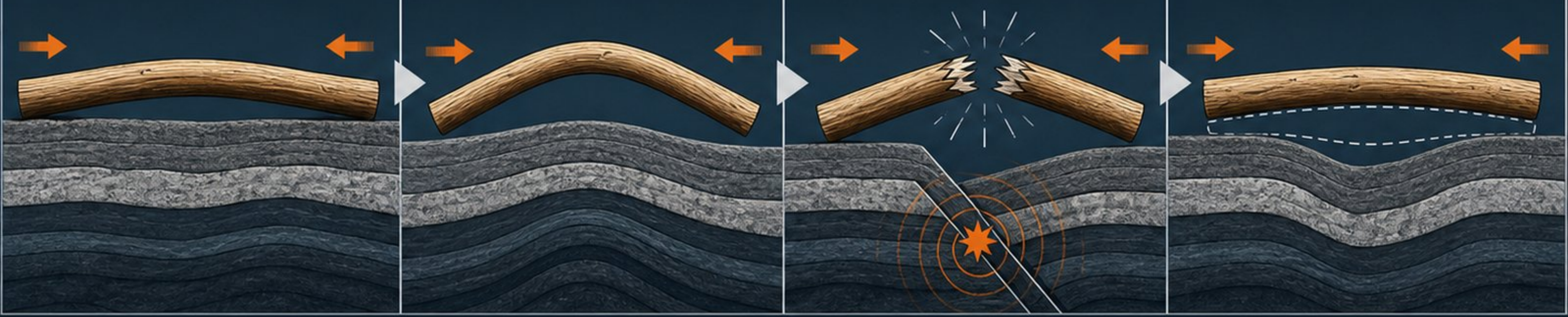
The Elastic Rebound Theory: How Strain Becomes Rupture

1 TECTONIC LOADING
Crustal rock (stick) begins to bend under stress.

2 STRAIN ACCUMULATION
Continued loading increases bending and stores elastic strain energy.

3 RUPTURE (SLIP)
When stress exceeds fault friction, the stick snaps and sudden slip occurs.

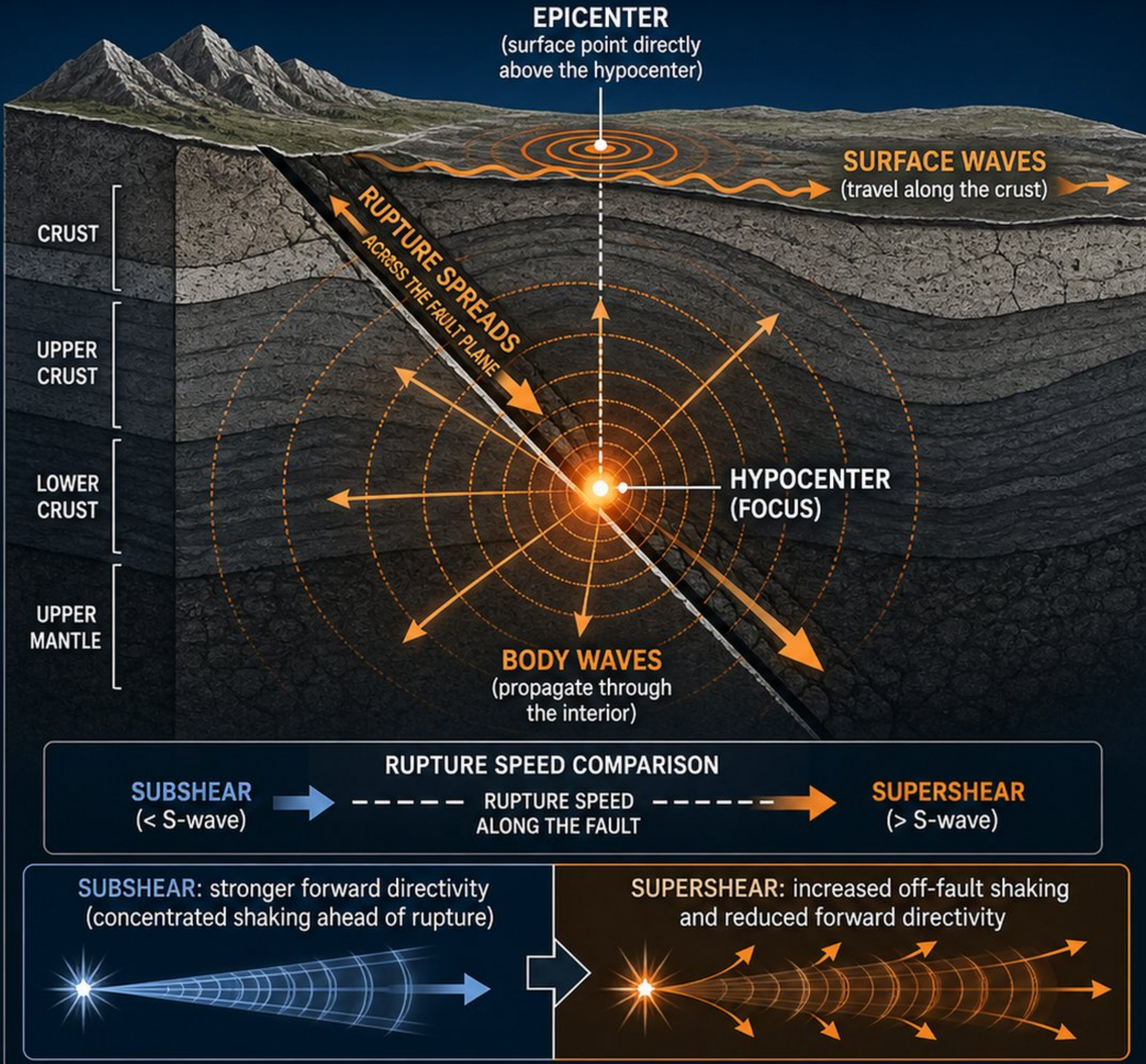
4 REBOUND & RELAXATION
The sides rebound to a new position; stress is reduced and strain is released.



- Tectonic loading elastically bends crustal rock over decades to centuries—like bending a stick
- When stress exceeds fault friction, sudden slip occurs and the sides rebound, releasing stored energy

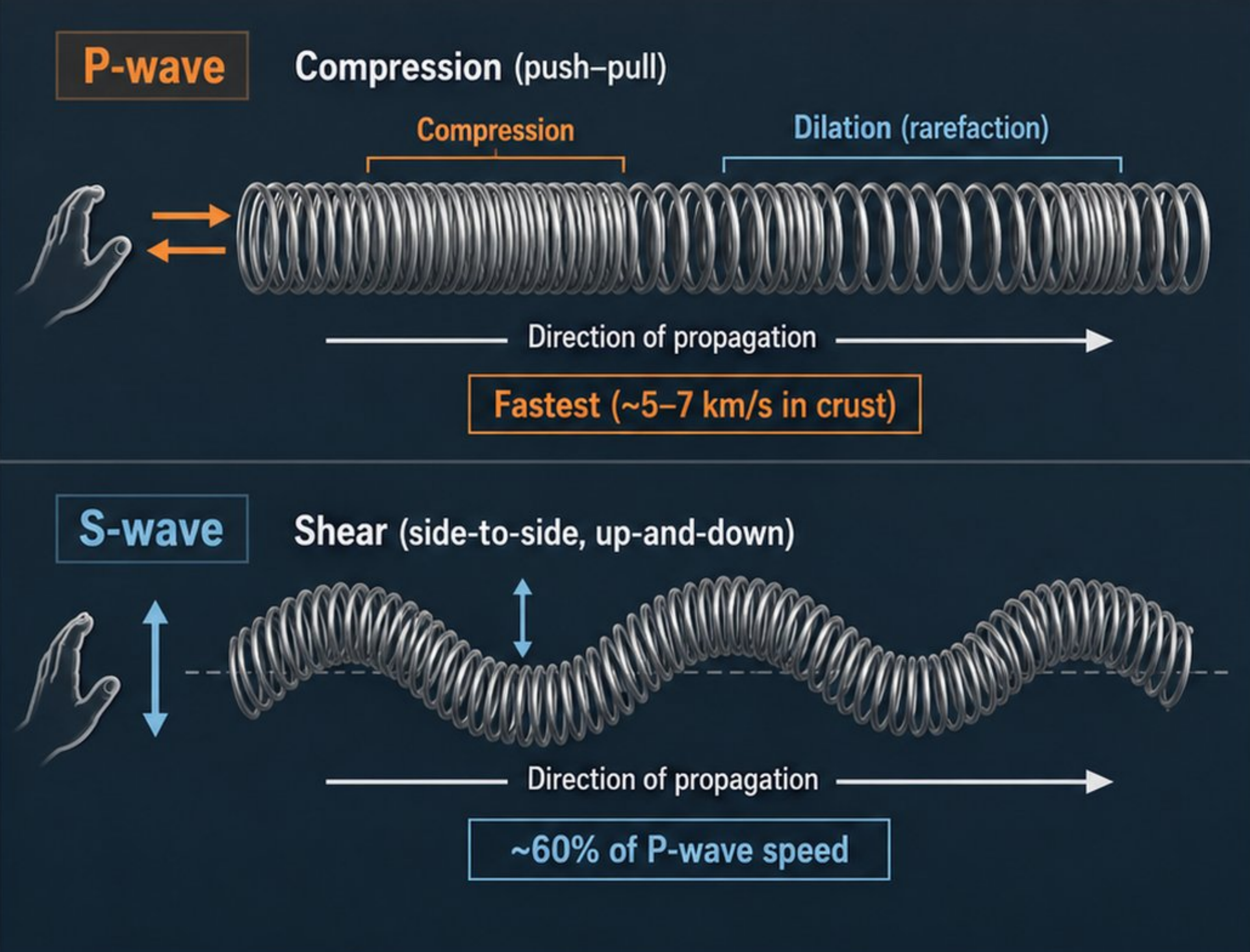
1. **INTERSEISMIC:** strain accumulation
2. **INTERSEISMIC:** strain accumulation
3. **COSEISMIC:** rupture and energy release (e.g., 2011 Tohoku, 2023 Türkiye events)
4. **POSTSEISMIC:** afterslip and relaxation redistribute stress

Birth of Seismic Waves at the Earthquake Source

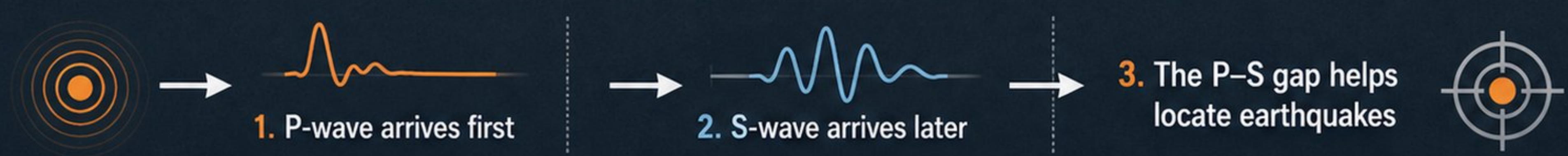


- Rupture starts at the hypocenter (focus) and spreads across the fault plane
- Epicenter: surface point directly above the hypocenter
- Two wave families emerge: body waves (interior) and surface waves (crust)
- Rupture speed varies: subshear (< S-wave) or supershear (> S-wave)
- Supershear boosts off-fault shaking and suppresses forward directivity

Body Waves: P-Waves and S-Waves



- P-waves (primary): compressional push–pull motion, fastest (~5–7 km/s in crust), arrive first
- S-waves (secondary): shear motion perpendicular to propagation, ~60% of P-wave speed, cannot travel through liquids
- The P–S arrival gap is used to locate earthquakes; S-waves carry higher amplitudes and cause more damaging shaking
- P-wave detection triggers early warning systems—alerts issued before slower, stronger S-waves and surface waves arrive

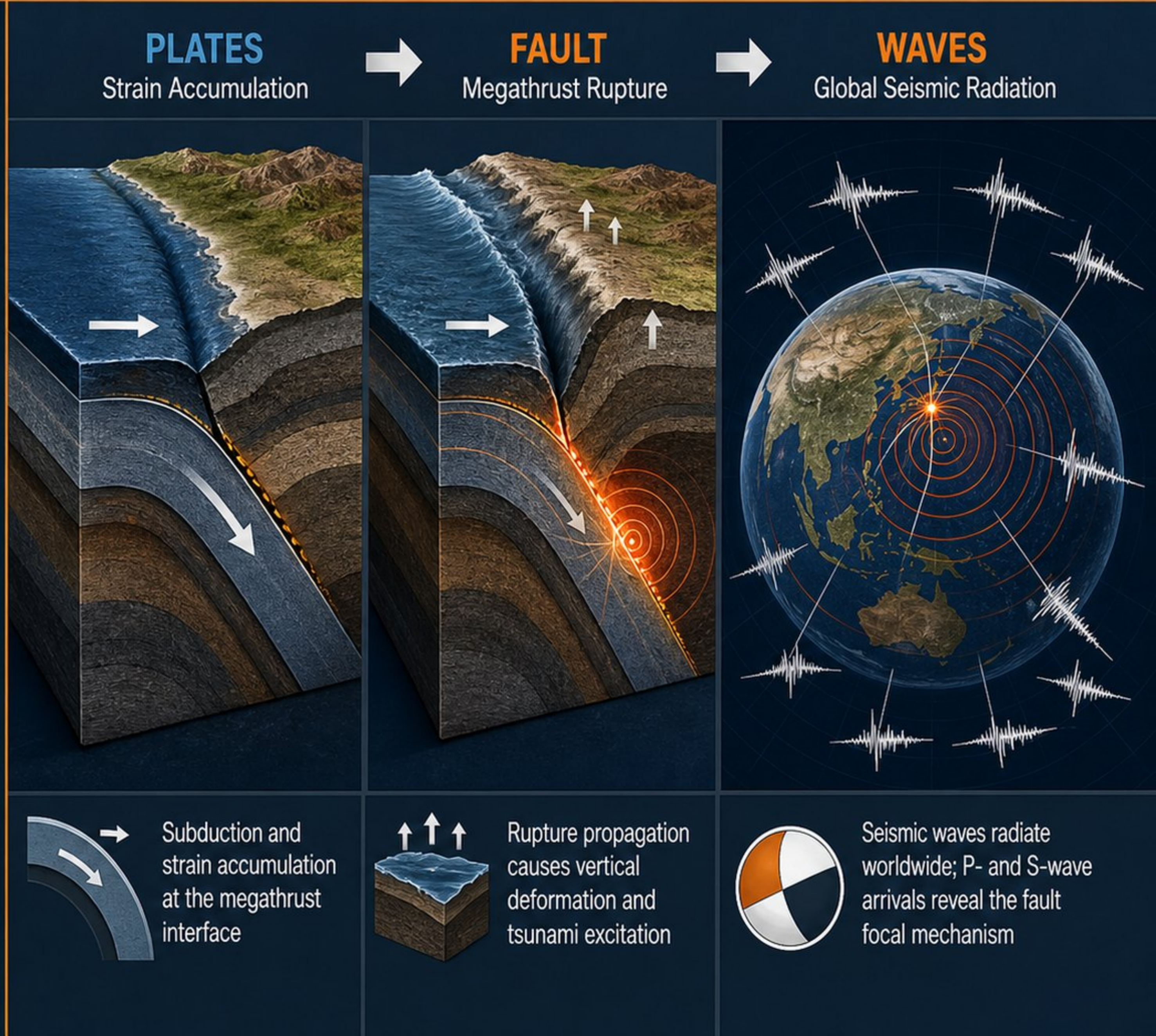


Surface Waves: Love Waves and Rayleigh Waves

- Love waves: horizontal, side-to-side shearing; trapped in upper crust, highly destructive
- Rayleigh waves: elliptical rolling motion, like ocean swells; cause long-period damage
- Slower than body waves but dominate distant seismograms; decay less with distance
- Surface waves cause most structural damage during earthquakes

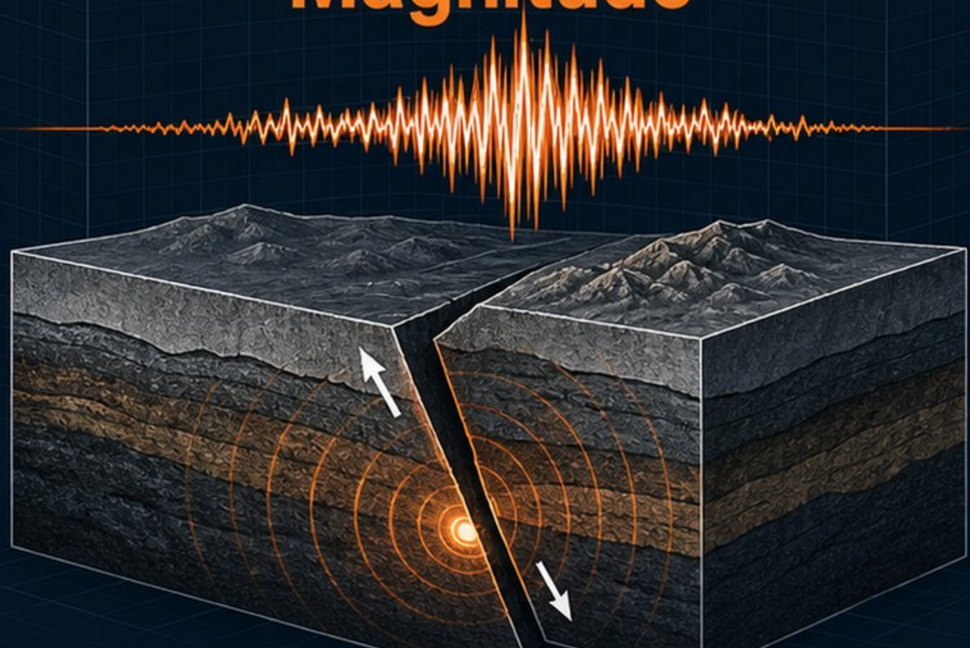
The Complete Rupture Scenario: Plates → Fault → Waves

- Japan Trench megathrust: subducting plate accumulates strain, slips up to tens of meters, radiating body and surface waves worldwide
- Thrust ruptures produce strong vertical deformation and tsunami excitation; strike-slip ruptures cause horizontal shaking and surface faulting
- Rupture directivity amplifies shaking in the propagation direction; P- and S-wave arrival patterns encode the fault focal mechanism



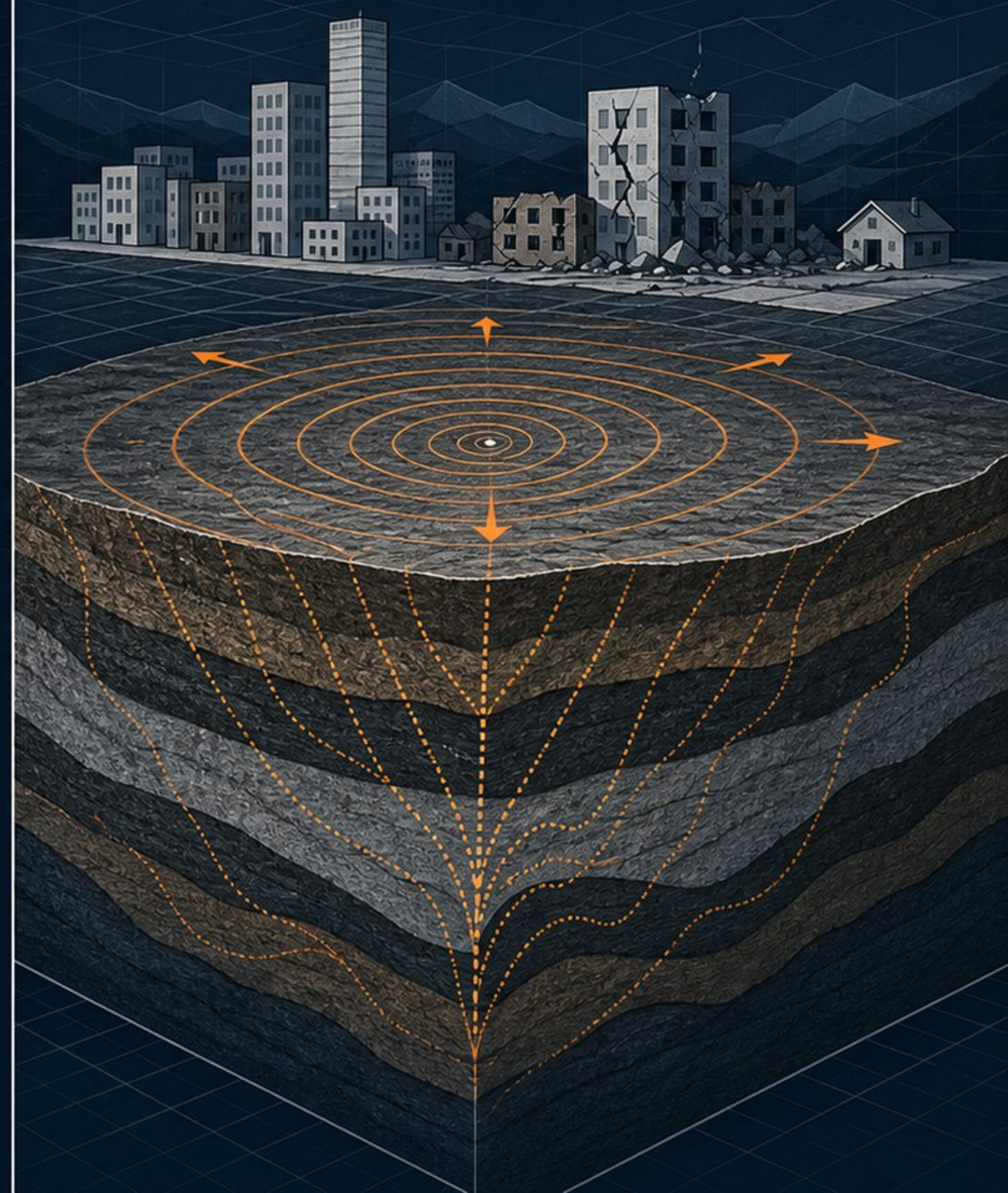
Measuring Earthquakes: Magnitude and Intensity

Magnitude



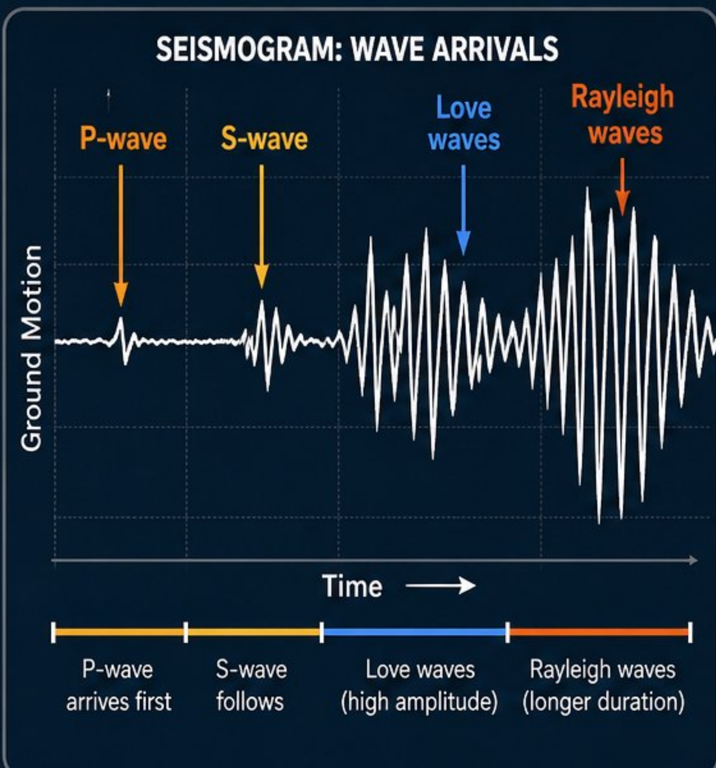
- **Magnitude** measures source energy; intensity describes local shaking and damage
- **Richter scale** (M_L) saturates for large events; **Moment Magnitude** (M_w) does not
- **Seismic moment:** M_0 = rock rigidity × fault area × slip distance
- **M_w** $= (2/3)(\log_{10} M_0 - 9.1)$; one M_w unit ≈ 32× greater energy release

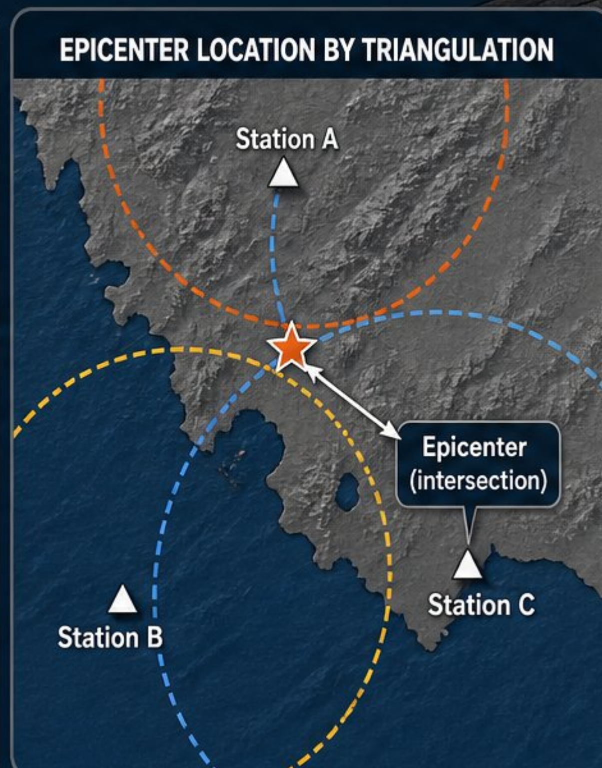
Intensity

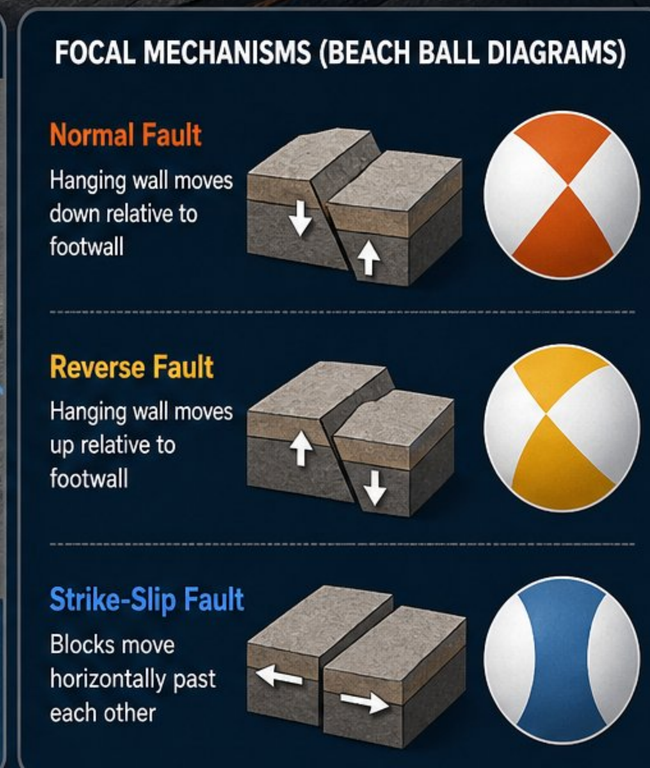


Reading Seismograms: The Fingerprint of Faulting

- P-wave arrives first, S-wave follows, then high-amplitude surface waves
- S–P interval gives epicenter distance; three stations triangulate location
- First-motion polarities reveal fault slip direction (normal, reverse, strike-slip)
- Beach ball diagrams visualize focal mechanisms from push/pull patterns

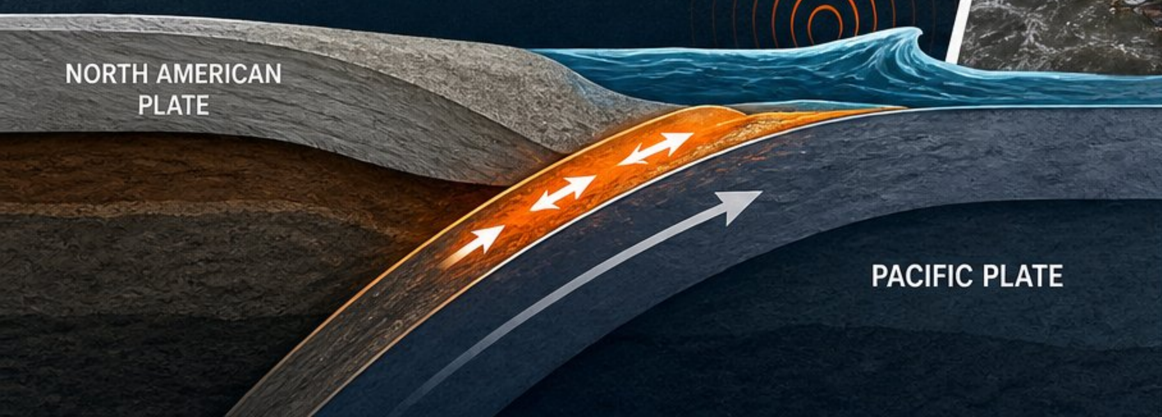






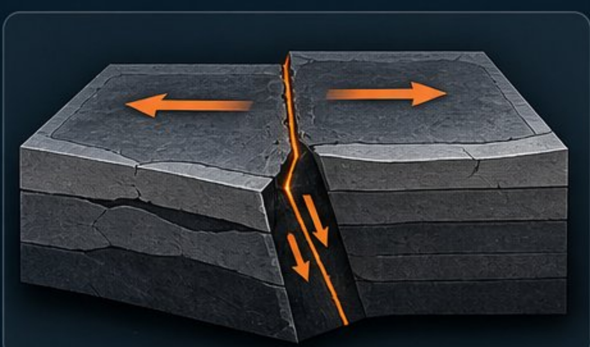
Real-World Case 1: The 2011 Tohoku Megathrust (Japan)

- Mw 9.0–9.1 reverse faulting on Japan Trench; Pacific Plate subducts beneath North American Plate
- Shallow near-trench slip exceeding 50 m drove devastating tsunami & strong long-period shaking
- Slow initiation (~45 s), then explosive up-dip rupture; bilateral expansion & deep afterslip followed
- Peak slip ~60 m; rupture ~150 s; seafloor uplift near trench triggered trans-Pacific tsunami

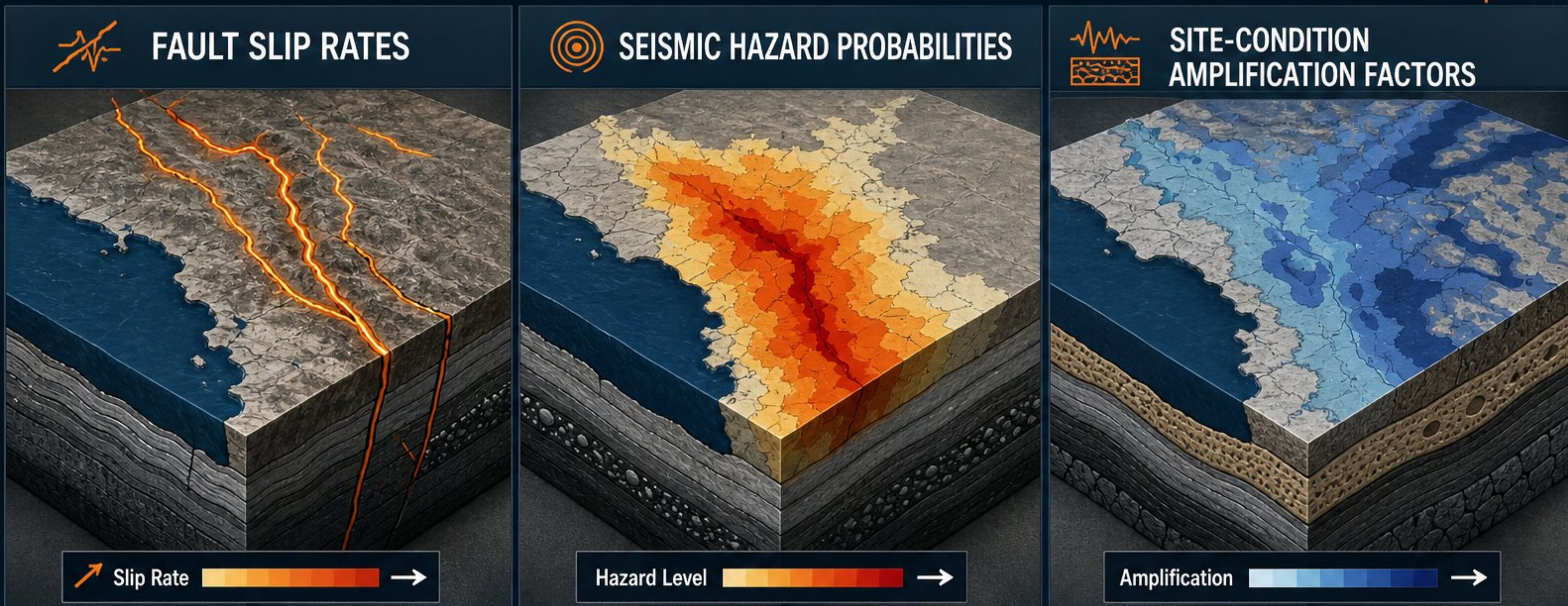


Real-World Case 2: The 2023 Türkiye Earthquake Doublet (Strike-Slip)

- Two Mw 7.8 & 7.7 left-lateral strike-slip quakes 9 h apart
- Ruptured the East Anatolian Fault Zone; ~59,000 fatalities
- Supershear rupture on some segments amplified shaking
- Stress transfer from the first event triggered the second
- Complex multi-fault cascade with extensive surface faulting



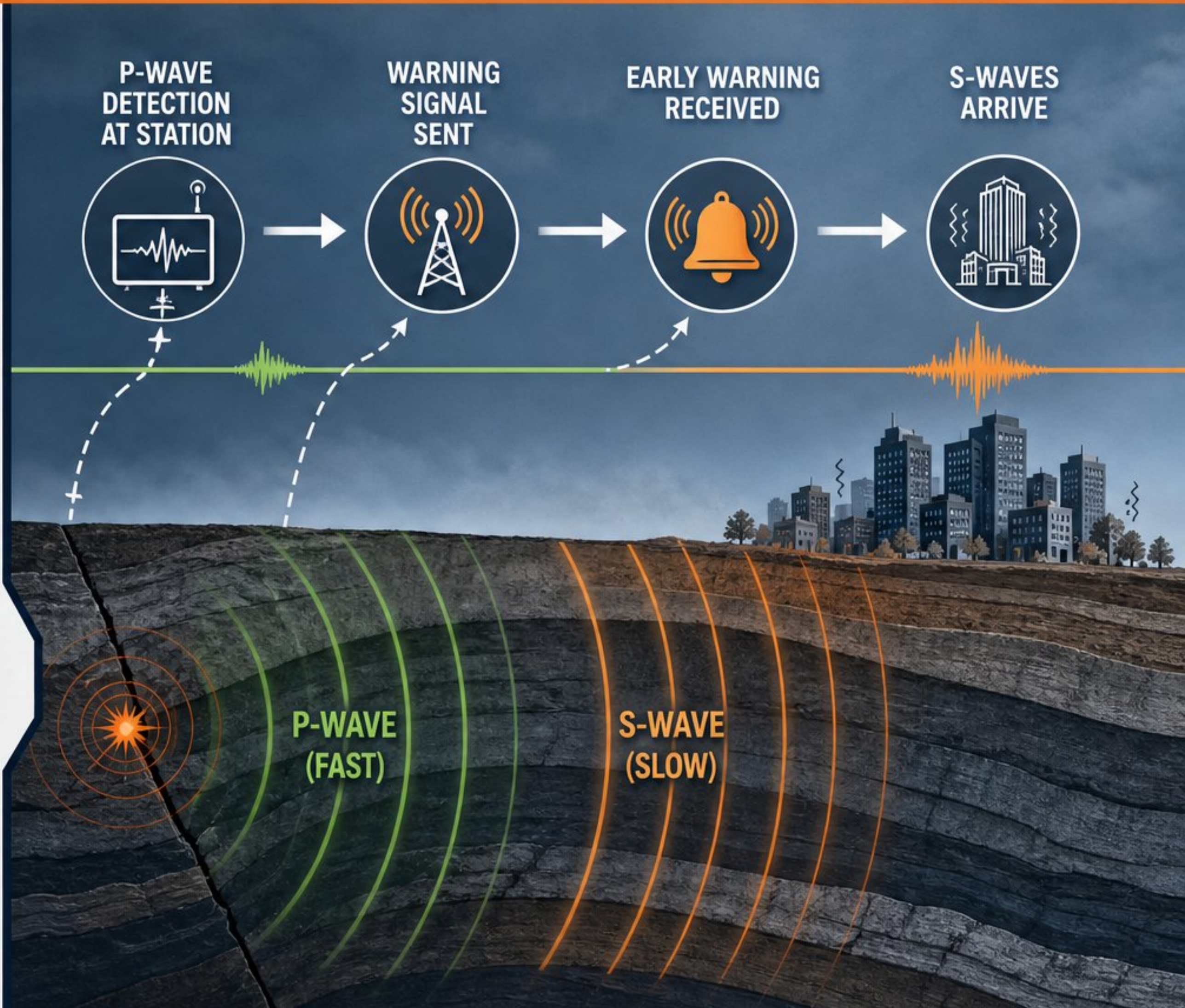
From Conceptual Links to Seismic Hazard Assessment



- Plate boundaries define source zones for hazard maps
- Fault slip rates constrain earthquake recurrence intervals
- Wave attenuation models predict shaking levels at distance
- PSHA integrates all three to forecast ground motion probability
- Soft soils amplify shaking; rigid bedrock minimizes it

Earthquake Early Warning: Exploiting the P–S Time Window

- EEW is not prediction; it detects the fast P-wave and alerts before damaging S-waves arrive.
- On-site systems predict S-wave shaking from P-wave amplitude within one second.
- Network-based systems require 3–4 stations and issue regional alerts within seconds.
- Lightweight CNNs detect P-waves on edge devices, reducing blind zones near the epicenter.
- Detection speed and accuracy govern available warning time and alert reliability.



Synthesis and Pathways Forward

- Plate motion builds stress on fault networks
- Elastic rebound triggers sudden rupture and slip
- Body and surface waves carry seismic energy outward
- Tohoku 2011 and Türkiye 2023 show timing, severity, secondary hazard patterns
- Building codes, early warning, and preparedness rely on the plates–faults–waves framework