

Global Tectonics

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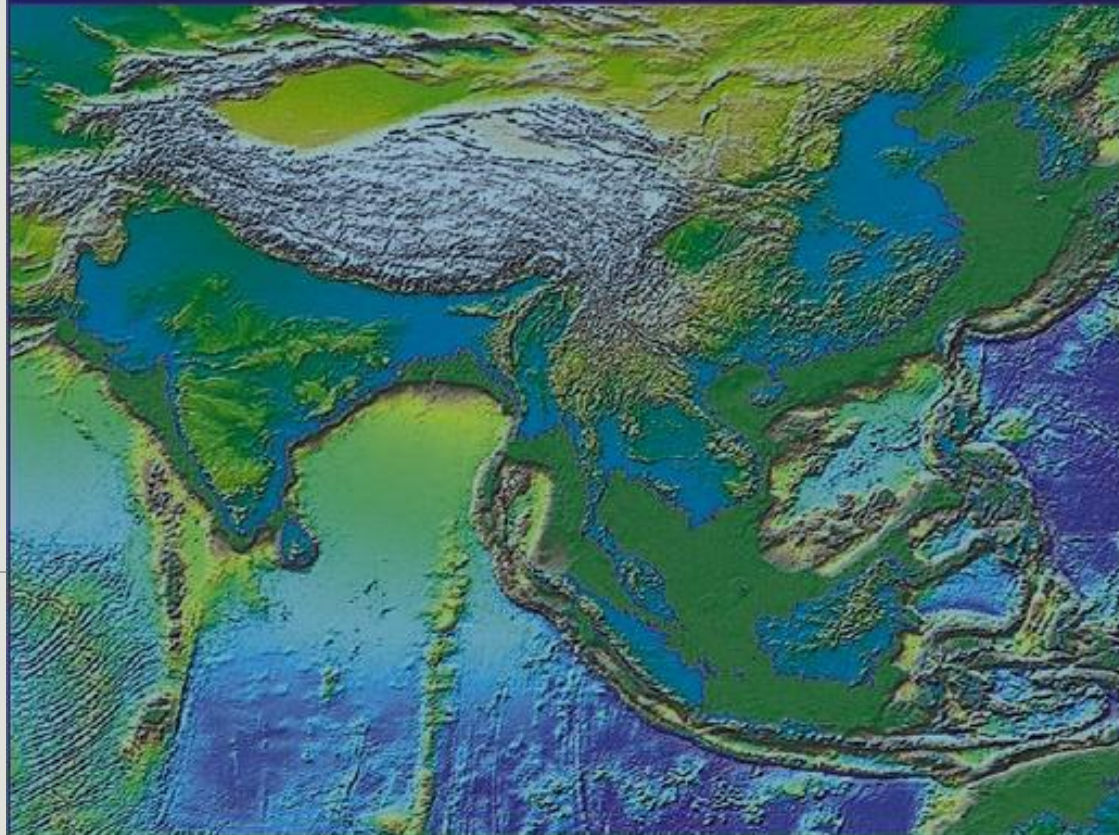
Lecture-5

Instructor

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THIRD EDITION

Global Tectonics



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Chapter 5 – **The Framework of Plate Tectonics**

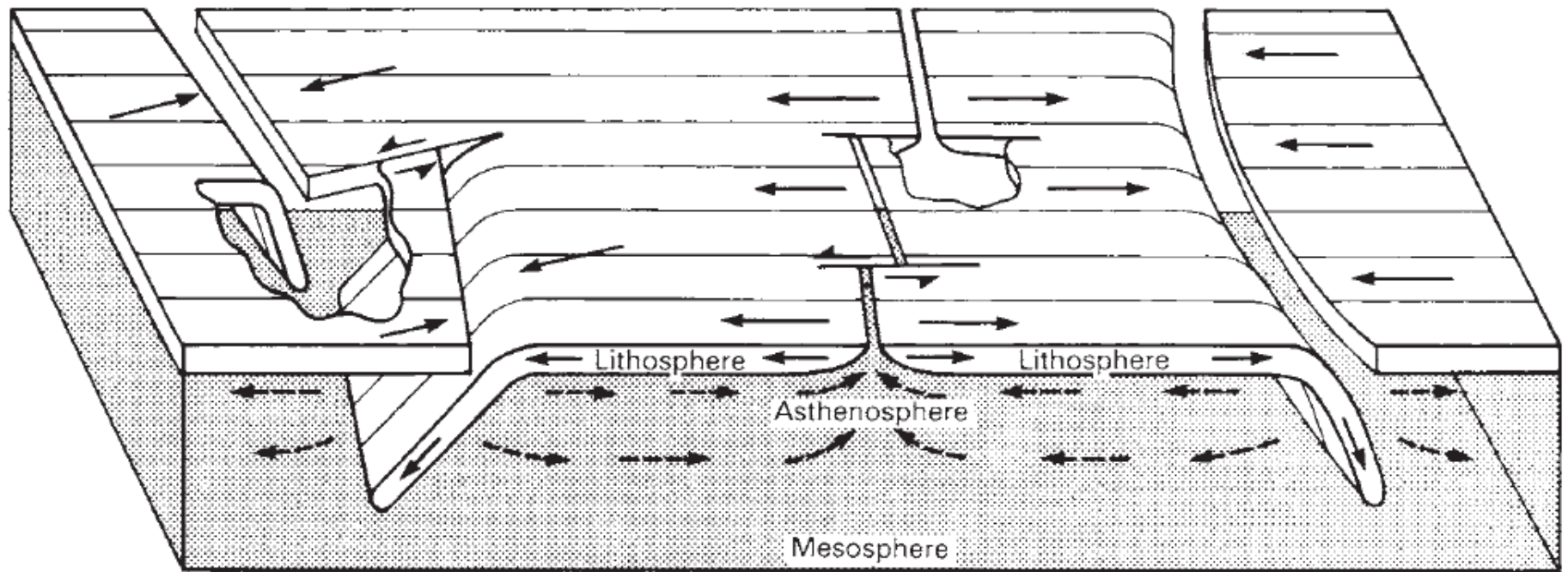
This chapter provides a comprehensive overview of plate tectonics, covering the classification of plate boundaries, the distribution of earthquakes, relative and absolute plate motions, hotspots, true polar wander, the Cretaceous superplume, direct measurement techniques, finite plate motions, and the stability of triple junctions.

The framework integrates geologic, geophysical, and geodetic data to explain plate tectonics, emphasizing the dynamic nature of plate interactions, the role of hotspots, and the methods used to quantify plate motions. It is essential for understanding Earth's past and present tectonic activity.

Plates and Plate Margins

Definition of Plates: The lithosphere is divided into rigid plates that interact at their boundaries. Plate boundaries are classified into three types based on their motion:

- **Divergent (Constructive) Boundaries:** Ocean ridges where plates move apart, creating new oceanic lithosphere through upwelling magma (e.g., Mid-Atlantic Ridge).
 - **Convergent (Destructive) Boundaries:** Trenches where plates collide, leading to subduction (e.g., Pacific Ring of Fire) or continental collision (e.g., Himalayas).
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- **Transform (Conservative) Boundaries:** Faults where plates slide past each other (e.g., San Andreas Fault).
- **Intra-Plate Deformation:** While plates are generally rigid, deformation can occur within continental interiors (e.g., rifts, orogenic belts).

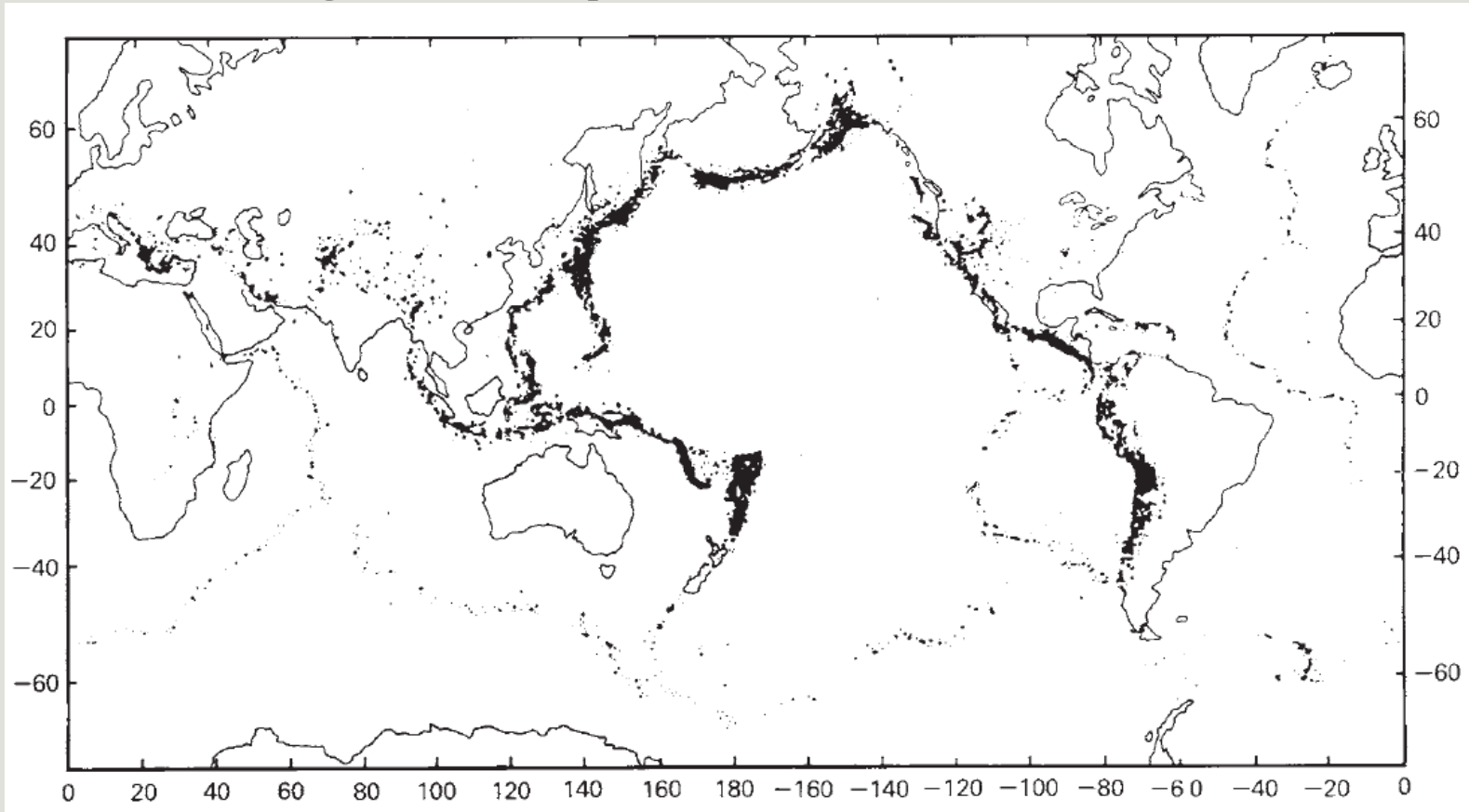


Block diagram summarizing the principal features of plate tectonics. Arrows on lithosphere represent relative motions. Arrows in asthenosphere may represent complementary flow in the mantle

Distribution of Earthquakes

Earthquake: Shallow earthquakes (0–70 km) occur at ridges and rifts, intermediate (70–300 km) and deep (>300 km) earthquakes are associated with subduction zones (Benioff zones).

Seismic Activity: Most earthquakes align with plate boundaries, but intra-plate earthquakes also occur, indicating stress within plates.



Worldwide distribution of epicenters of large magnitude earthquakes
($m_b > 4$) for the period 1961–67

Relative Plate Motions

Relative plate motion describes how plates move with respect to each other at their boundaries. This is the most straightforward way to quantify plate movements because it relies on observable geologic and geophysical data.

• **Euler's Theorem:** Plate motion is described as rotation around an Euler pole.

Methods to determine relative motion:

- **Transform Fault Orientation:** Small circles centered on the Euler pole.
 - **Spreading Rates:** Vary with angular distance from the pole.
 - **Earthquake Slip Vectors:** Less precise but useful for convergent boundaries.
- **Global Plate Models:** Studies (e.g., DeMets et al., 1990) refine plate motions using large datasets, showing Pacific plates shrinking while Atlantic/Indian Ocean plates grow.

Methods for Determining Relative Motion

1.Transform Fault Orientations (Small Circle Geometry)

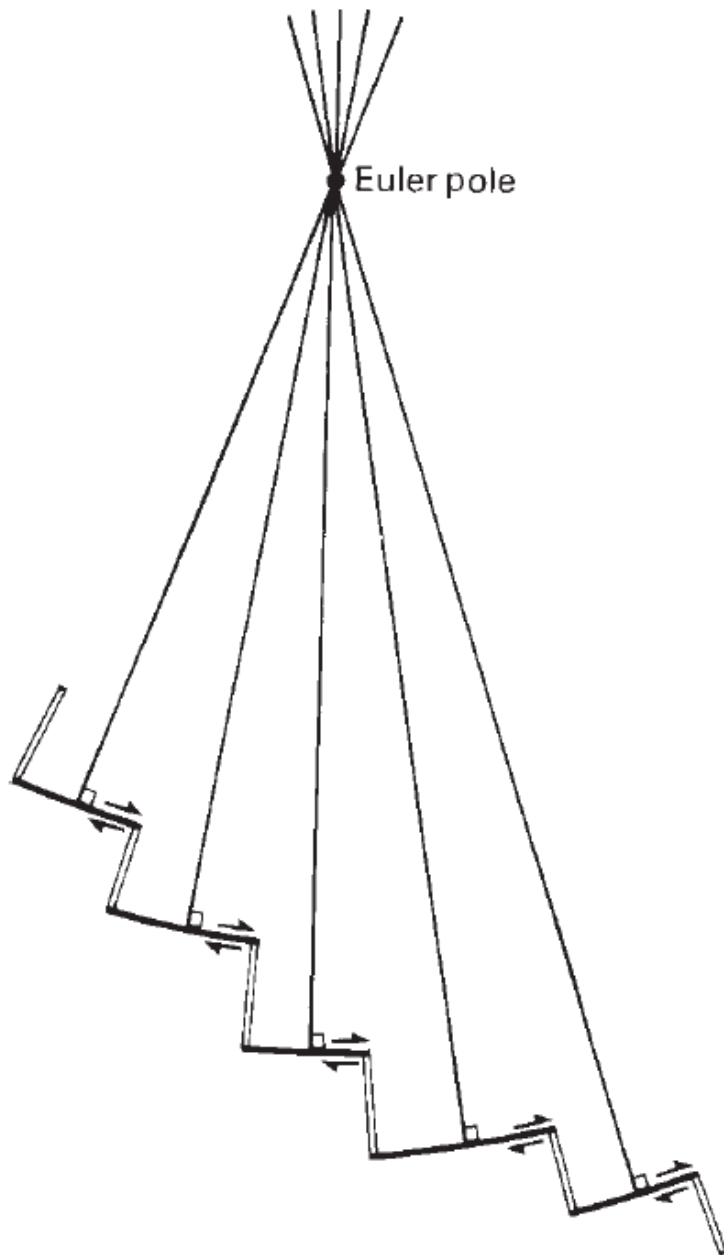
Transform faults (e.g., the San Andreas Fault) follow small circles centered on the **Euler pole** (the axis of rotation for two plates). By analyzing the strike of transform faults along mid-ocean ridges, the Euler pole can be determined. Example: The Pacific and North American plates rotate around a pole near Alaska, causing the San Andreas Fault to have a predominantly strike-slip motion.

2.Spreading Rates at Mid-Ocean Ridges

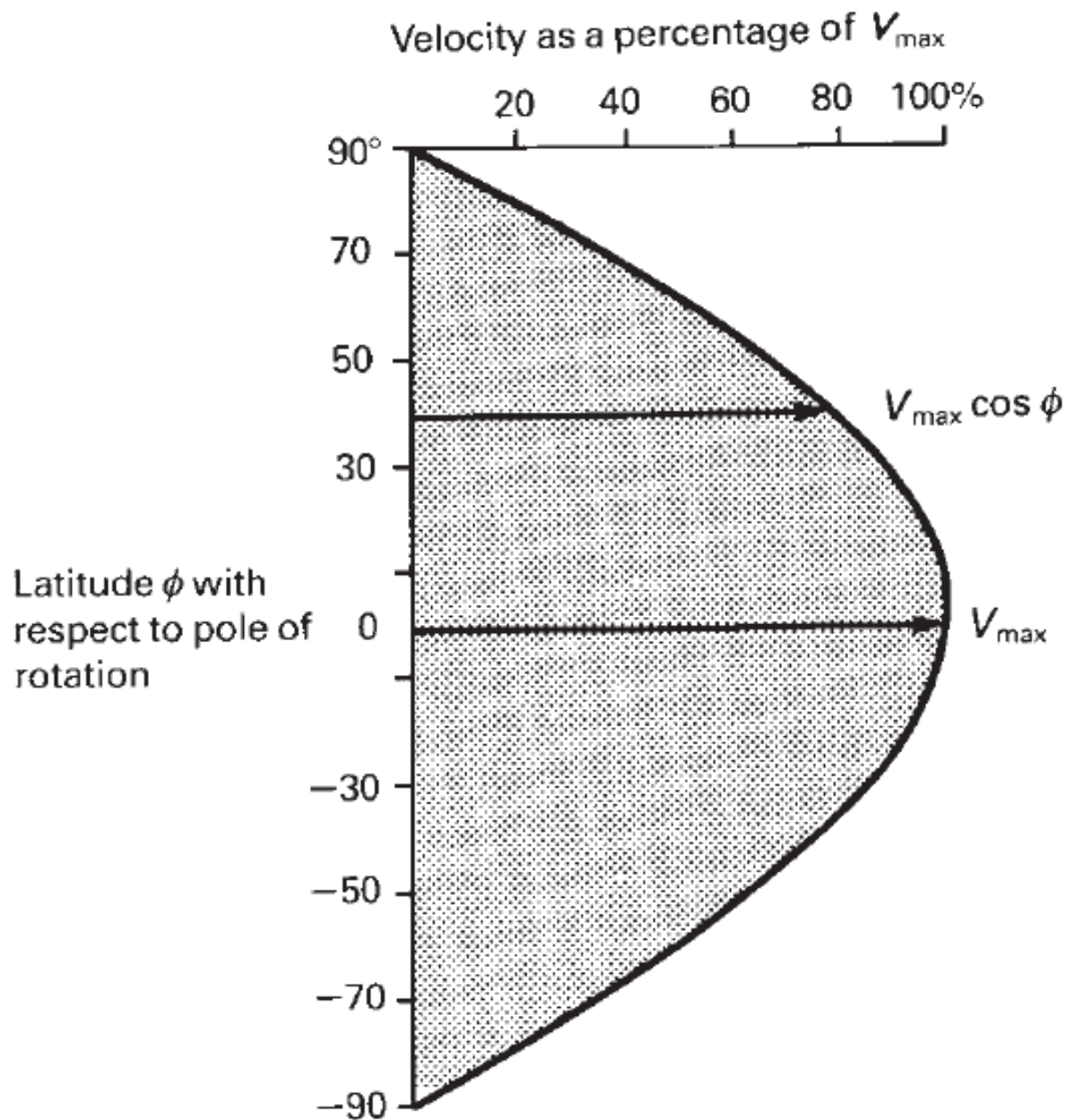
The rate of seafloor spreading varies with latitude relative to the Euler pole. Spreading is fastest at the "equator" of rotation (90° from the pole) and slows toward the pole. Measured using magnetic anomalies (e.g., the distance between anomalies of the same age on either side of a ridge).

3.Earthquake Slip Vectors (Focal Mechanisms)

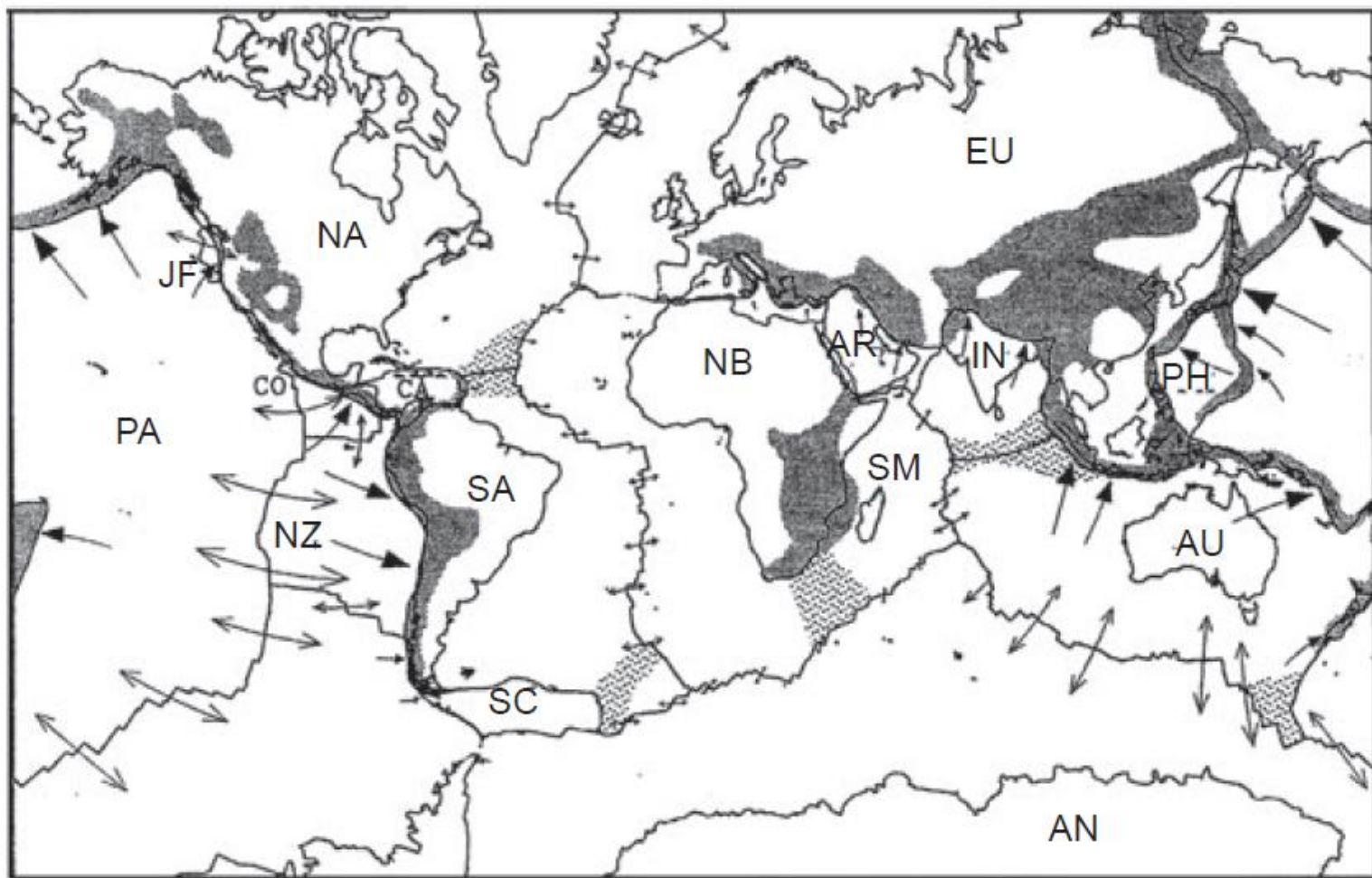
The direction of slip in earthquakes at convergent boundaries indicates the relative motion between plates. Less precise than transform fault or spreading rate methods because of complex fault geometries



Determination of the Euler pole for a spreading ridge from its offsetting transform faults that describe small circles with respect to the pole.



Variation of spreading rate with latitudinal distance from the Euler pole of rotation.



Map showing the relative motion between the major plates, and regions of diffuse deformation within plates (shaded areas). Solid arrowheads indicate plate convergence, with the arrow on the under thrusting plate; open arrowheads indicate plate divergence at mid ocean ridges. The length of the arrows represents the amount of plate accretion or subduction that would occur if the plates were to maintain their present relative velocities for 25 Ma. Note that, because of the Mercator projection, arrows at high latitudes are disproportionately long compared to those at low latitudes. AN, Antarctica; AR, Arabia; AU, Australia; CA, Caribbean; CO, Cocos; EU, Eurasia; IN, India; JF, Juan de Fuca; NA, North America; NB, Nubia; NZ, Nazca; PA, Pacific; PH, Philippine; SA, South America; SC, Scotia Sea; SM,

Global Plate Motion Models

- NUVEL-1A (DeMets et al., 1990, 1994):** A widely used model averaging plate motions over the past 3 million years. Predicts Pacific Plate subduction at ~ 80 mm/yr under Japan, matching geologic observations. Shows the Pacific Plate shrinking as subduction outpaces spreading at the East Pacific Rise.

Challenges in Relative Motion Studies

- Oblique Subduction:** At trenches like the Aleutians, motion isn't perpendicular to the boundary, complicating slip vector analysis.
- Diffuse Boundaries:** Some plate boundaries (e.g., the Himalayan collision zone) are wide and deform internally rather than along a single fault.

Absolute Plate Motions

Absolute plate motion describes how plates move relative to a fixed reference frame, such as Earth's deep mantle or hotspots. This helps understand large-scale mantle dynamics.

- Reference Frames:

- Hotspot Frame: Assumes hotspots (e.g., Hawaii) are fixed relative to the mantle.

- No Net Rotation (NNR) Frame: Minimizes global lithospheric rotation.

- Challenges: Hotspots may not be entirely fixed, and discrepancies exist between Pacific and Indo-Atlantic reference frames.

1. Hotspot Reference Frame

Assumes volcanic hotspots (e.g., Hawaii, Iceland) are stationary relative to the deep mantle. Plate motion is inferred from the age progression of hotspot tracks (e.g., the Hawaiian-Emperor seamount chain,).

Problems: Some hotspots may move slowly (~ 5 mm/yr, Müller et al., 1993), and discrepancies exist between Pacific and Atlantic hotspot tracks.

2. No Net Rotation (NNR) Frame

1. Assumes the lithosphere has no net rotation relative to the mantle.
2. Used in space geodesy (GPS, VLBI) to minimize global torque.
3. Differs slightly from the hotspot frame but generally agrees for most plates.

3. Paleomagnetic Reference Frame

1. Uses Earth's magnetic field (assumed axial and dipolar) to reconstruct past plate positions.
2. Combined with hotspot tracks to study **True Polar Wander**.

Findings in Absolute Motion

Pacific Plate: Moves northwestward over the Hawaiian hotspot at ~ 100 mm/yr.

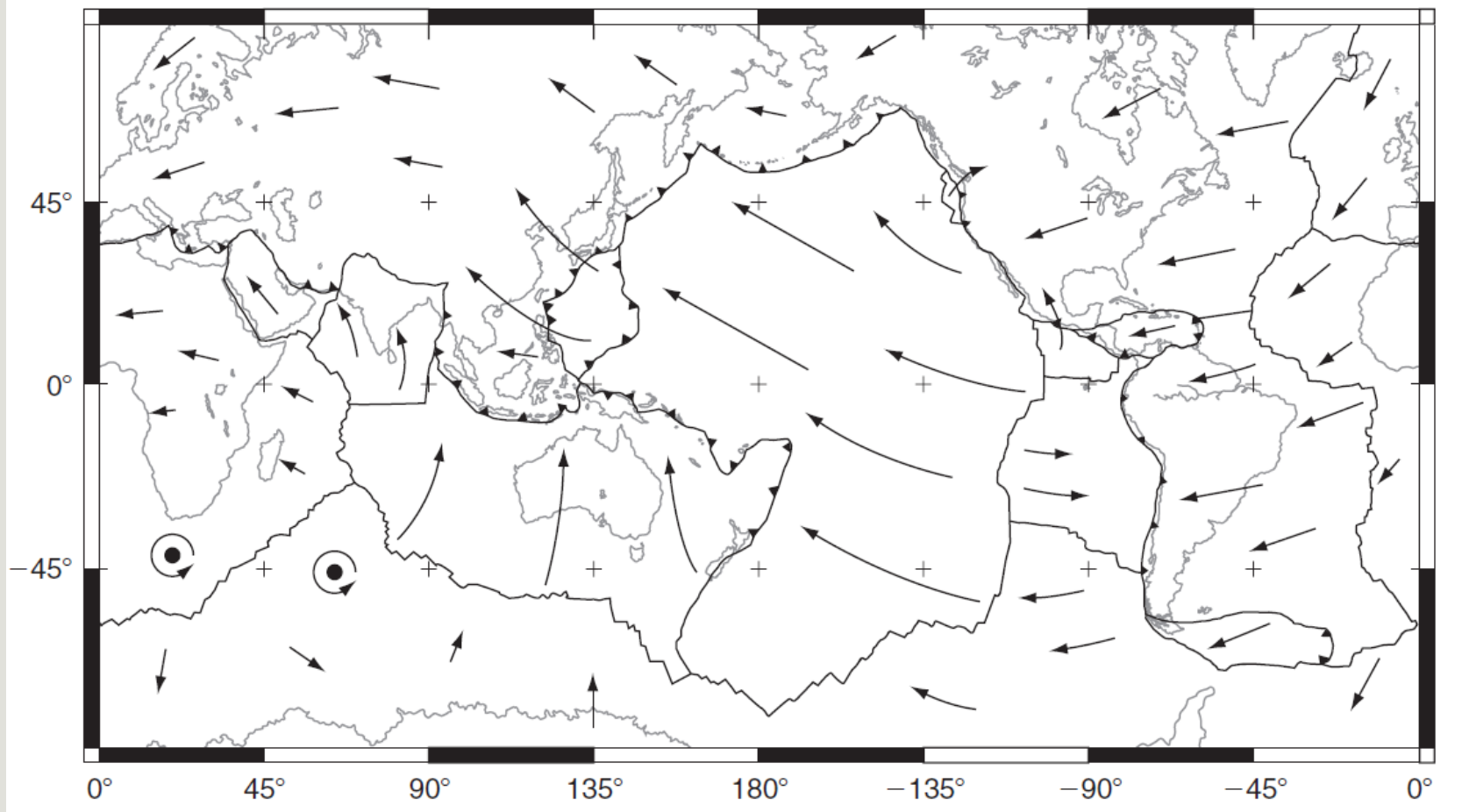
African Plate: Nearly stationary in the hotspot frame, explaining uplift and volcanism (e.g., East African Rift).

Controversies: The Hawaiian hotspot may have moved southward ($\sim 15^\circ$ latitude) between 80–43 Ma (Tarduno & Cottrell, 1997). The Indo-Atlantic and Pacific hotspot frames disagree before ~ 40 Ma, possibly due to plate boundary reorganizations.

Relative motion is well-constrained by seafloor spreading and transform faults, providing precise plate boundary kinematics.

Absolute motion helps link plate tectonics to mantle convection but relies on assumptions about hotspot fixity.

Discrepancies between models (e.g., NUVEL-1A vs. GPS) may reflect recent changes in plate speeds or measurement errors. This dual framework—relative and absolute—is essential for reconstructing past plate movements and predicting future tectonic activity.



The absolute velocities of plates, assuming the hotspot reference frame. The arrows indicate the displacement of points within the plates if the plates were to maintain their current angular velocities, relative to the hotspots, for 40 Ma. Filled circles indicate the pole (or antipole) of rotation for the plate if this occurs within the plate. The medium solid lines are approximate plate boundaries; where barbed, they indicate subduction zones with the barb on the overriding plate. Note that, because of the Mercator projection, arrows at high latitudes are disproportionately long compared to those at low latitudes

Comparison of Relative vs. Absolute Motion

Aspect	Relative Motion	Absolute Motion
Definition	Movement between two plates	Movement relative to deep mantle/hotspots
Key Methods	Transform faults, spreading rates, earthquakes	Hotspot tracks, paleomagnetism, NNR frame
Primary Use	Understanding boundary interactions	Studying mantle dynamics and plate driving forces
Limitations	Doesn't show whole-Earth movement	Hotspot drift, reference frame uncertainties

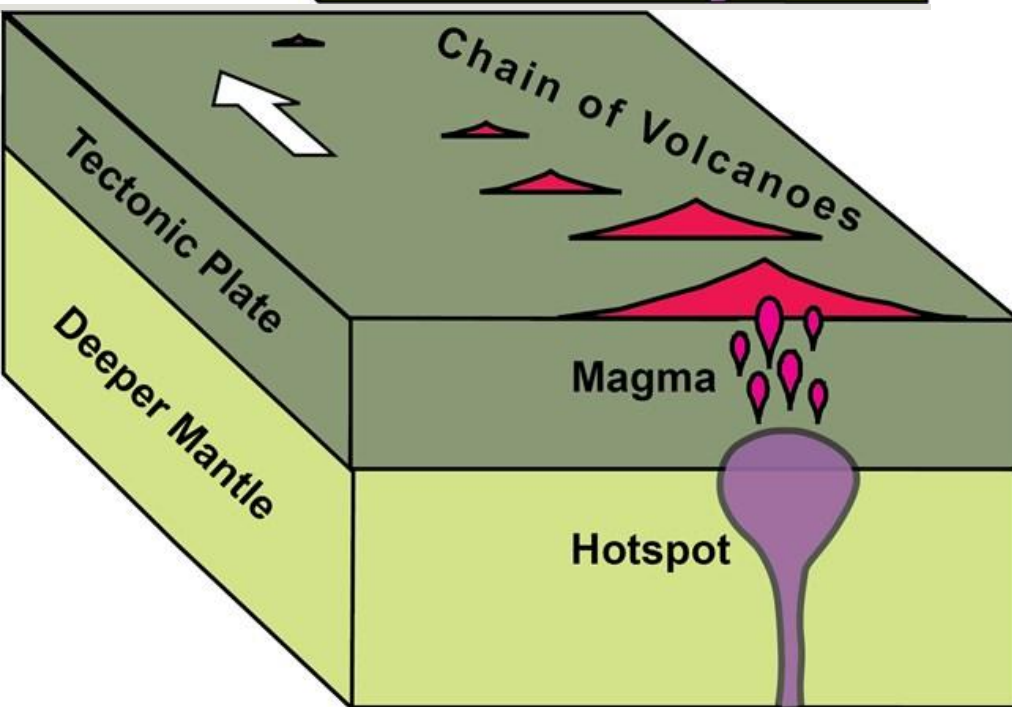
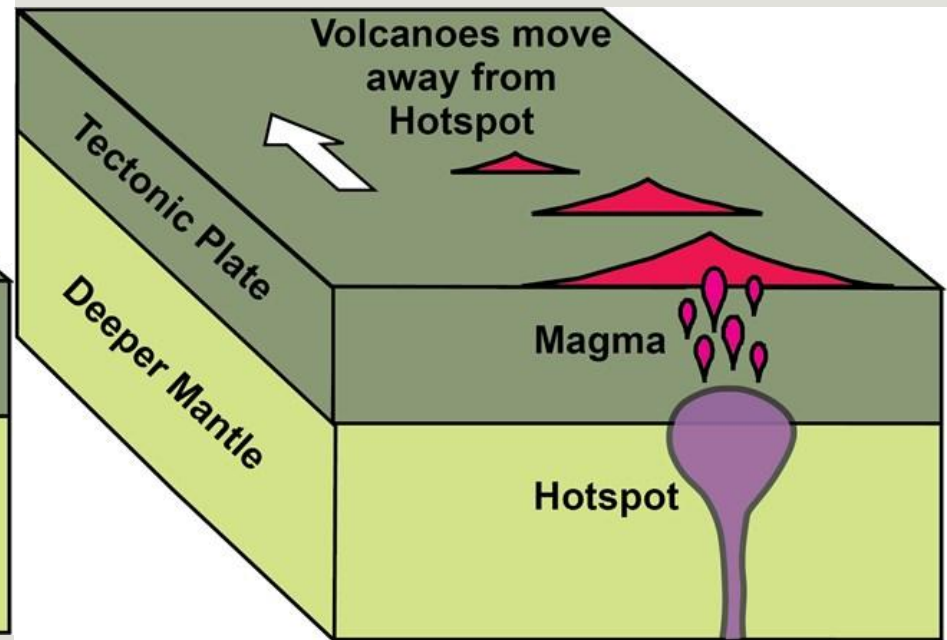
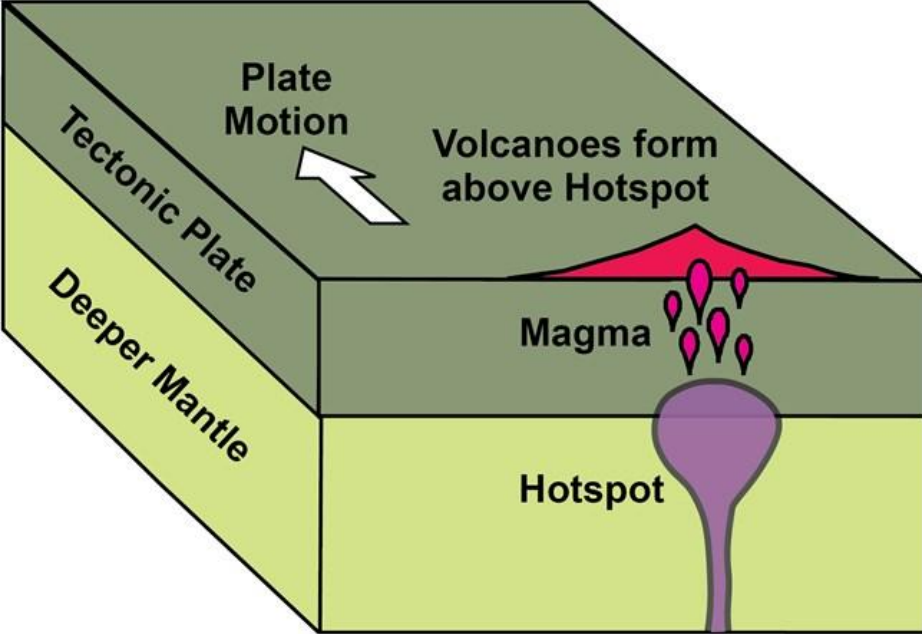
Hotspots

Hotspots are localized volcanic regions not directly associated with plate boundaries, where mantle-derived magma rises to the surface, creating volcanoes, seamounts, and large igneous provinces (LIPs). They provide critical insights into plate motions, mantle dynamics, and Earth's thermal evolution.

Fixed Mantle Plumes: The traditional Wilson-Morgan model (1963–1971) suggests hotspots are fed by stationary mantle plumes rising from the core-mantle boundary (D'' layer). Alternative models propose they result from lithospheric cracking or edge-driven convection.

Surface Features:

- **Island/Seamount Chains** (e.g., Hawaiian-Emperor chain).
- **Flood Basalts** (e.g., Deccan Traps, Columbia River Basalts).
- **Oceanic Plateaus** (e.g., Ontong Java Plateau).



A chain of volcanoes (hotspot track) forms as a tectonic plate moves over a plume of hot mantle material (hotspot) rising from deep within the Earth.



Continental Hotspot



Oceanic Hotspot

Hotspot Types (Courtillot et al., 2003)

Hotspots vary in longevity and origin. Only ~7–12 are considered primary (deep-sourced), while others are secondary (shallow or fracture-related).

Type	Examples	Origin	Duration
Primary	Hawaii, Iceland, Réunion	Deep mantle plumes (core-mantle boundary)	>100 Myr
Secondary	Galápagos, Afar	Upper mantle upwellings or edge-driven convection	<50 Myr
Ridge-Centered	Azores, Tristan da Cunha	Enhanced melting at mid-ocean ridges	Variable



World-wide distribution of hotspots

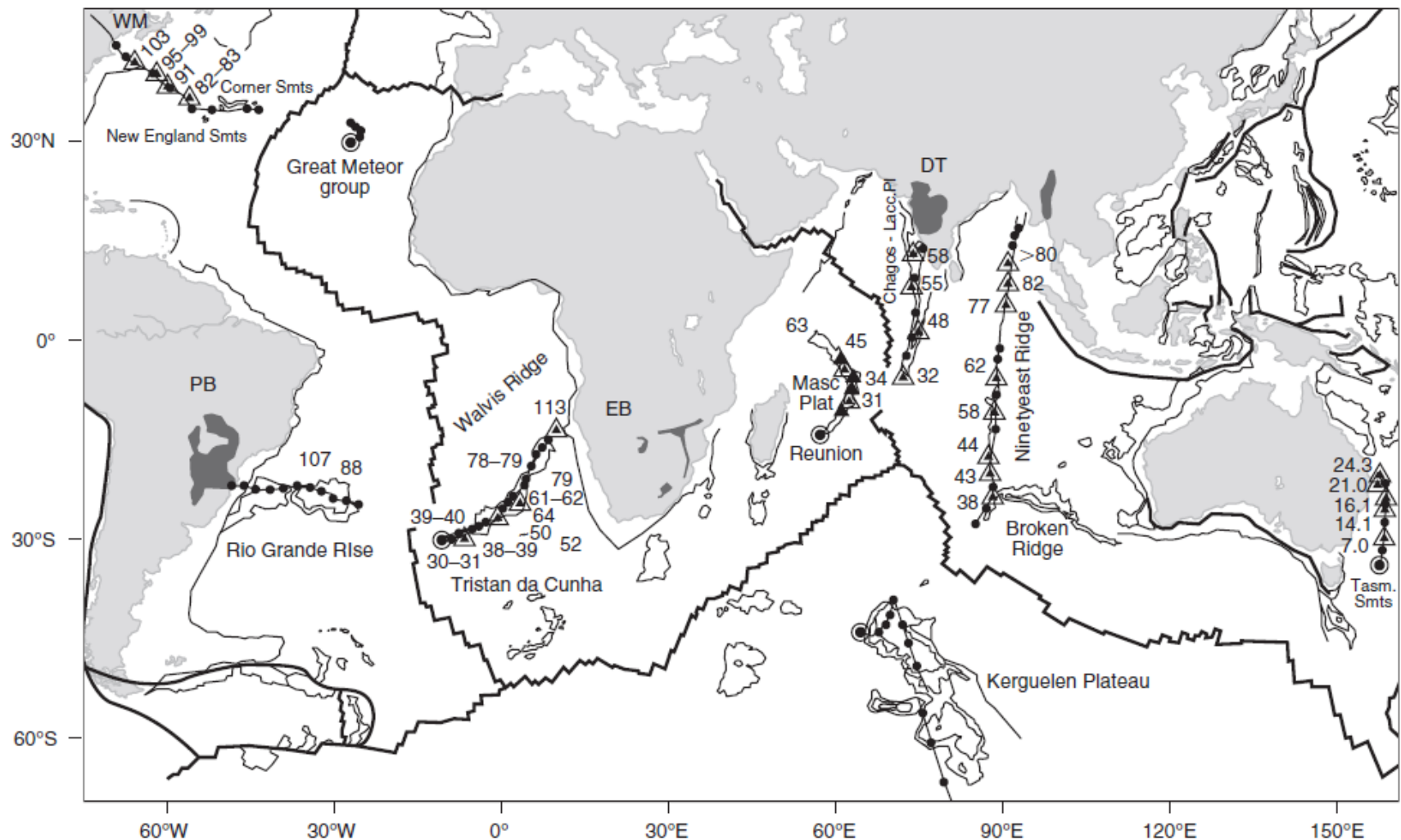
Hotspot Tracks and Plate Motion

Hotspot tracks record absolute plate motion if plumes are fixed. **Examples**

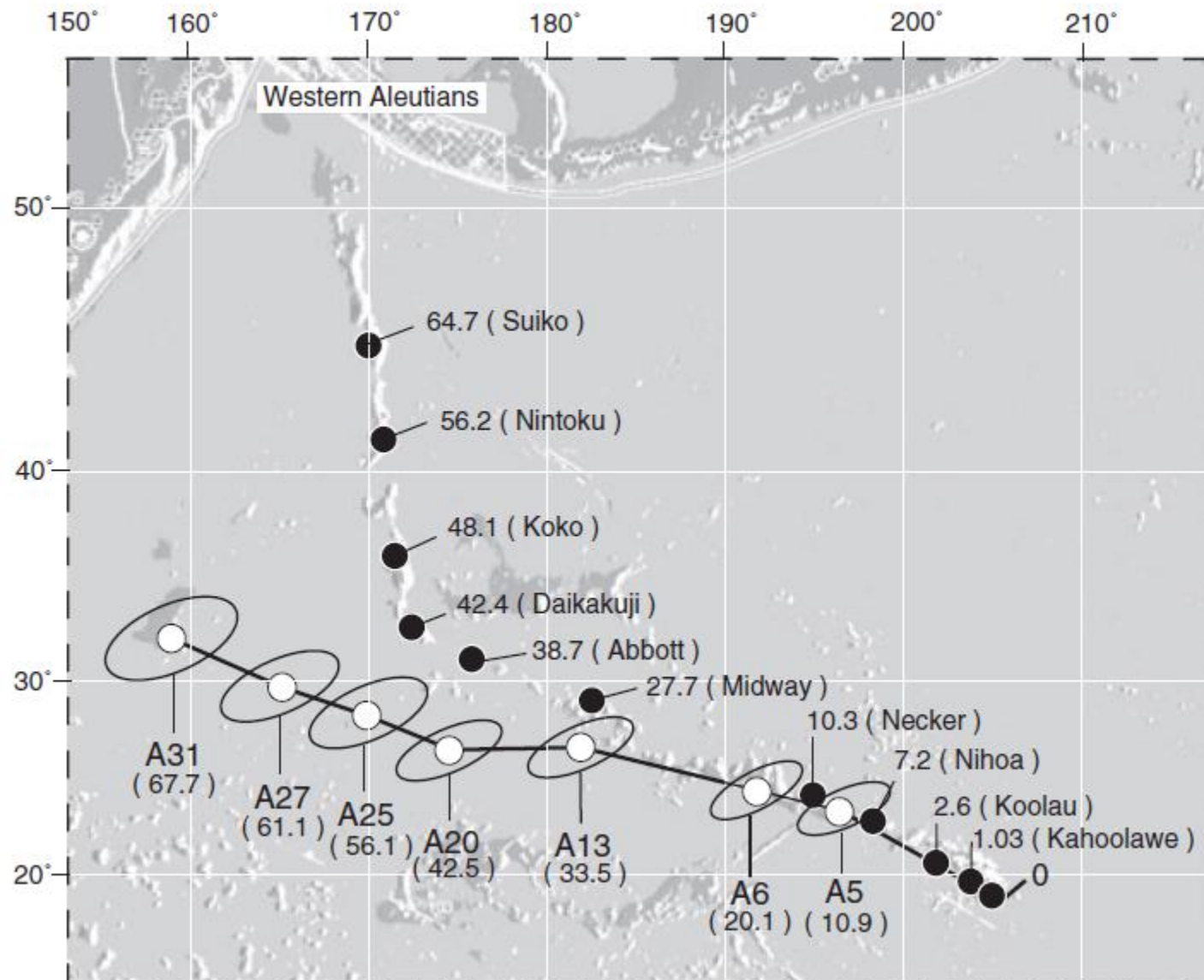
1.Hawaiian-Emperor Chain (Pacific Plate) Age Progression: Active volcanoes at Hawaii (0–0.5 Ma) → extinct seamounts (e.g., Midway, ~27 Ma) → Emperor Seamounts (~80–47 Ma). **Bend at 47 Ma:** Reflects a change in Pacific Plate motion (or hotspot drift). Recent studies suggest the Hawaiian plume moved southward (~15° latitude) before 47 Ma (Tarduno & Cottrell, 1997).

2.Réunion Hotspot (Indo-Atlantic): Deccan Traps (66 Ma): Massive flood basalts linked to India's breakup. **Mascarene Plateau:** Tracks India's northward drift.

•**Iceland Hotspot (North Atlantic): North Atlantic Igneous Province (60 Ma):** Triggered North Atlantic rifting. **Controversy:** Some argue Iceland is a shallow anomaly, not a deep plume (Foulger, 2010).



Hotspot tracks in the Atlantic and Indian Oceans. Large filled circles are present day hotspots. Small filled circles define the modeled paths of hotspots at 5 Ma intervals. Triangles on hotspot tracks indicate radiometric ages. WM, White Mountains; PB, Parana flood basalts; EB, Etendeka flood basalts; DT, Deccan.



Predicted Hawaiian hotspot track (solid line) from plate reconstructions assuming that the Indo-Atlantic hotspots are fixed. Ages in Ma

Evidence for Deep Mantle Plumes

1. Seismic Tomography

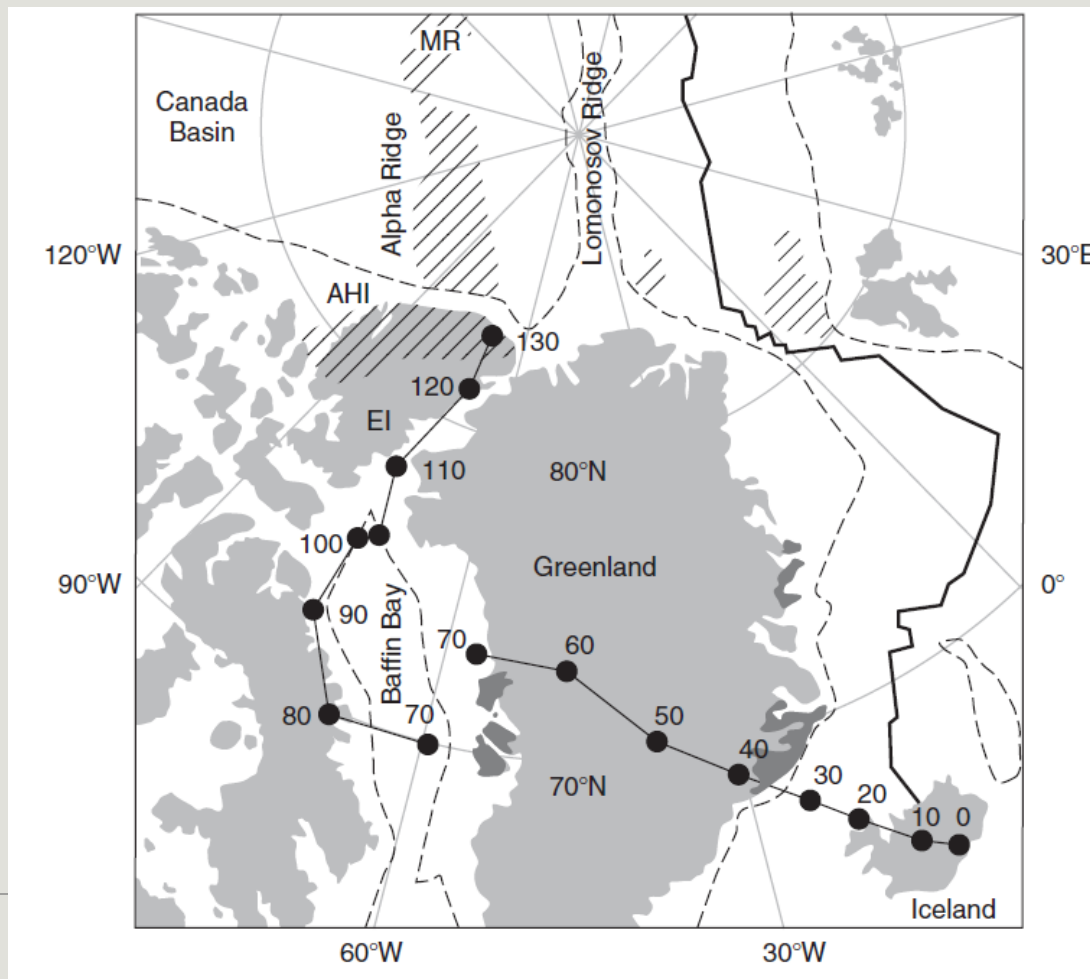
- Low-velocity zones beneath Hawaii, Iceland, and Afar suggest **hot, upwelling mantle** (Montelli et al., 2004).
- Some plumes (e.g., Hawaii) appear rooted at the core-mantle boundary.

2. Geochemistry: Hotspot lavas have distinct isotopic signatures (e.g., high $^3\text{He}/^4\text{He}$) indicating **primitive, undepleted mantle** sources. (note: nuclear physics and chemistry, ^4He and ^3He refer to two different isotopes of the element helium. An isotope is a variant of a particular element that has the same number of protons but a different number of neutrons in its nucleus. The number in the superscript (4 or 3) is the mass number, which is the total number of protons and neutrons in the nucleus.)

3. Crustal Swells: Hotspots elevate the lithosphere (e.g., Hawaiian swell rises ~1 km above surrounding seafloor).

Economic and Geologic Significance

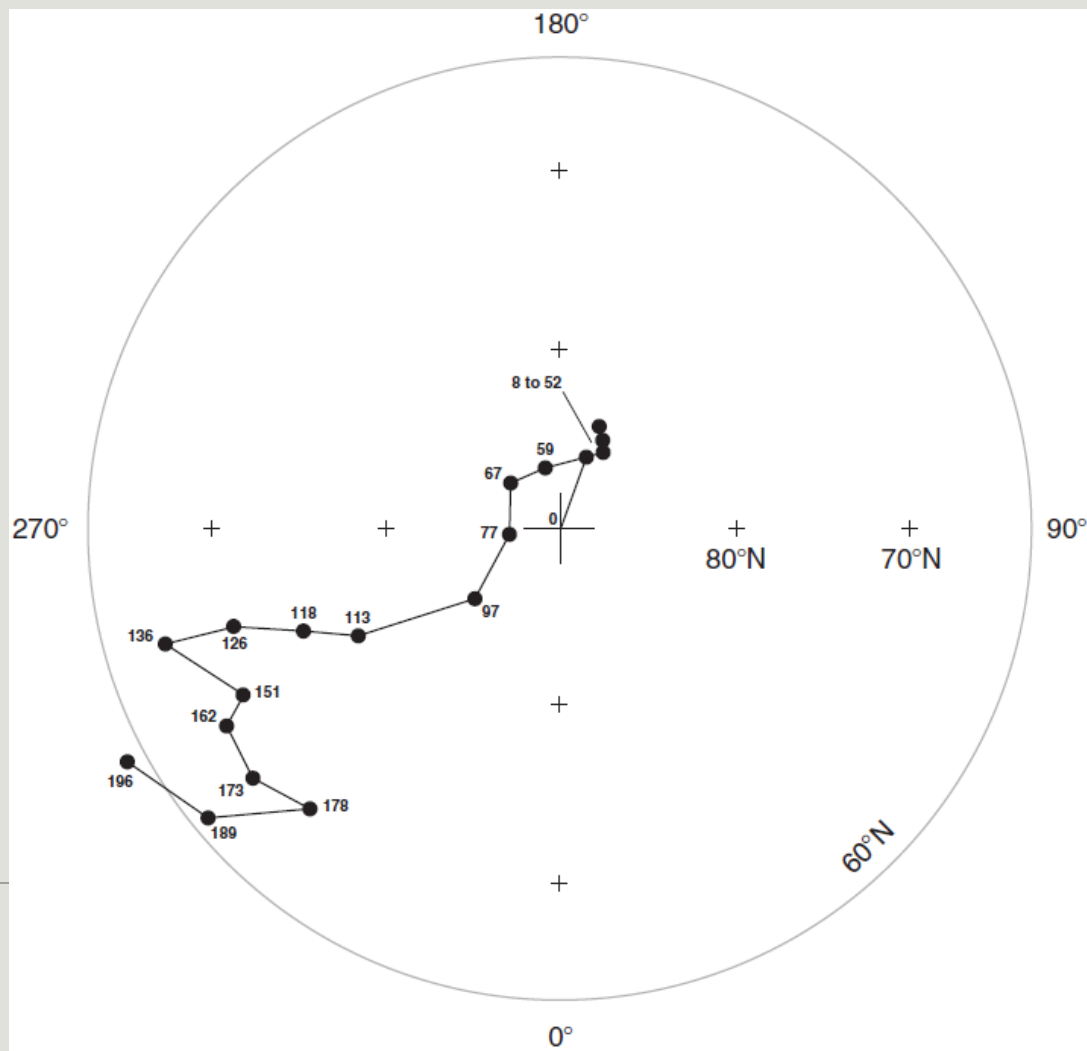
- ❑ **Mineral Deposits:** Kimberlites (diamonds) and Ni-Cu-PGE deposits are linked to plume activity.
- ❑ **Mass Extinctions:** LIP eruptions (e.g., Deccan Traps) may have contributed to the K-Pg extinction.
- ❑ **Oil/Gas Reservoirs:** Hotspot-related uplift creates traps (e.g., North Sea volcanism).



Predicted hotspot track assuming that the Iceland hotspot is fixed relative to the other Indo-Atlantic hotspots . Position of hotspot at 10 Ma intervals is indicated by solid dots. AHI, Axel Heiberg Island; EI, Ellesmere Island; MR, Mendeleyev Ridge. Dashed line, continent–ocean boundary based on bathymetry. Gap between 70 Ma positions results from sea floor created after the passage of the Labrador Sea Ridge over the hotspot at 70.

True Polar Wander (TPW)

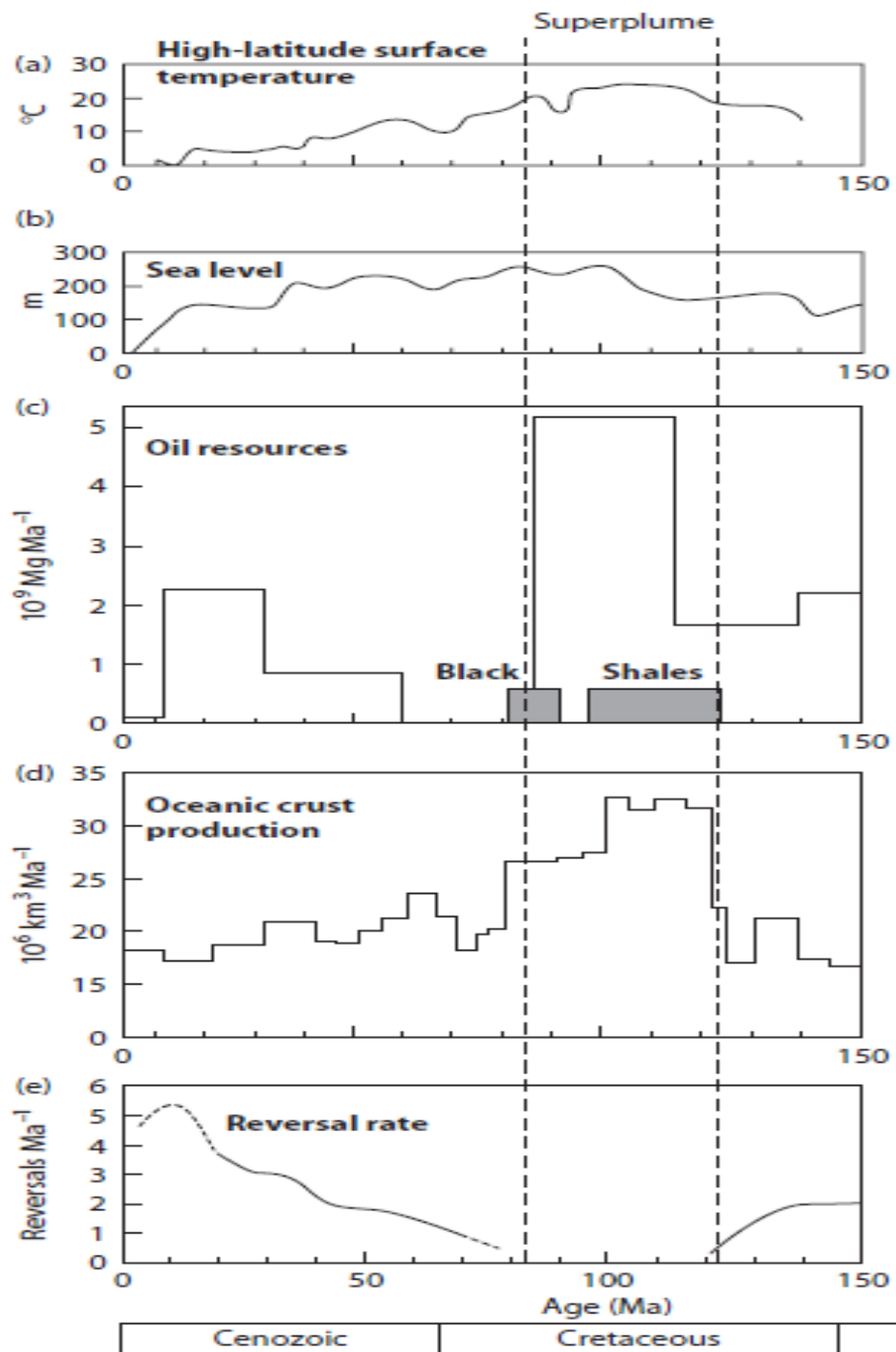
- **Definition:** Movement of Earth's spin axis relative to the mantle, detected by combining paleomagnetic and hotspot data. Episodic Motion, TPW occurred rapidly ($\sim 30^\circ$ in 200 Ma) with periods of stability (e.g., 10–50 Ma).
 - **Causes:** Mass redistribution from subduction, mountain building, or mantle convection.
-



True Polar Wander (TPW) path for the past 200 Ma. TPW is defined as the movement of the “geographic” pole of the Indo-Atlantic hotspot reference frame with respect to the magnetic pole defined by paleomagnetic data, the latter being equated to the Earth’s rotational axis.

Cretaceous Superplume

- **Hypothesis:** A massive mantle upwelling (~120–80 Ma) caused:
 - Increased oceanic crust production.
 - Elevated sea levels and global warming (greenhouse effect).
 - Geomagnetic quiet period (few reversals).
 - **Debate:** Some attribute these phenomena to plate reorganization rather than a superplume.
-



Phenomena associated with the mid-Cretaceous superplume

Direct Measurement of Plate Motions

Space Geodesy Techniques:

- ❖ **VLBI (Very Long Baseline Interferometry)**: Uses quasars to measure baselines.
- ❖ **SLR (Satellite Laser Ranging)**: Tracks satellite positions.
- ❖ **GPS (Global Positioning System)**: Most accurate for real-time plate motion.

Results: Modern measurements (e.g., REVEL-2000 model) align with geologic models (e.g., NUVEL-1A), confirming plate rigidity.

Finite Plate Motions: Finite plate motions describe the cumulative displacement of tectonic plates over geologic time, as opposed to instantaneous (current) motions. This concept is crucial for reconstructing past plate configurations and understanding long-term tectonic evolution.

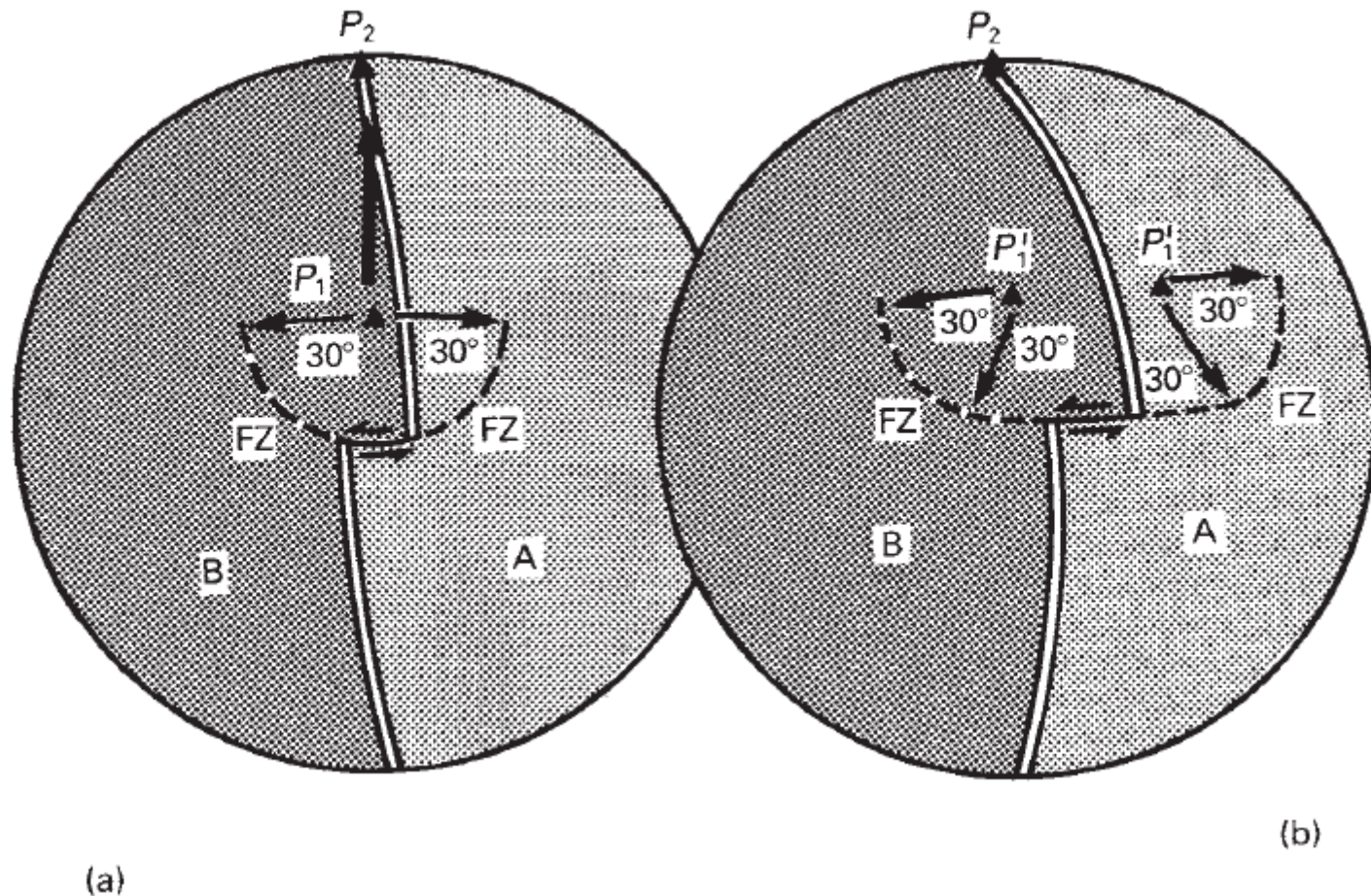
A. Finite vs. Instantaneous Motion

Instantaneous Motion: Current plate movement described by Euler poles (angular velocity vectors).

Finite Motion: Total displacement over millions of years, requiring integration of changing Euler poles.

B. Euler's Theorem Applied to Finite Rotations

Any displacement of a rigid plate on a sphere can be described by a single rotation about a unique axis (Euler pole). For finite motions, this rotation has a finite angle (e.g., 30° over 50 Myr).



(a) Rotation of plates A and B about pole P_1 produces arcuate fracture zones with a radius of curvature of 30° ; (b) a jump of the pole of rotation to P_2 causes the fracture zones to assume a radius of curvature of 90° . P'_1 represents the positions of pole P_1 after rotation about pole P_2

Determining Finite Motions

Methods

1. Magnetic Anomaly Mapping

Fit conjugate magnetic lineations (e.g., Mid-Atlantic Ridge anomalies) to reconstruct past positions. Example: Matching Jaramillo anomaly (1.0 Ma) on both sides of a ridge.

2. Fracture Zone Geometry

Fracture zones mark small circles around past Euler poles. Changes in fracture zone orientation indicate Euler pole jumps.

3. Paleomagnetic Data

Apparent Polar Wander Paths (APWPs) track continental motions relative to Earth's spin axis.

4. Geologic Matching

Fit continental margins (e.g., South America and Africa) or orogenic belts.

Case Study: Pacific Plate

Five Spreading Phases: Each with distinct Euler poles, recorded by fracture zone segments. Implications: Pacific Plate motion changed episodically, not smoothly.

Triple Junctions in Plate Tectonics

Definition and Basics

A triple junction is a point where three tectonic plates meet. These are classified based on the types of plate boundaries involved (ridge=R, trench=T, transform=F). There are **16 possible combinations**, but only a few are stable over geologic time.

Stability Criteria (McKenzie & Morgan, 1969)

A triple junction is stable if its geometry can persist as plates move. Stability depends on velocity vectors of all three plates, Boundary orientations, and Relative motion directions

Only **RRR** junctions are always stable. **FFF** junctions are never stable. Other types require specific geometric configurations.

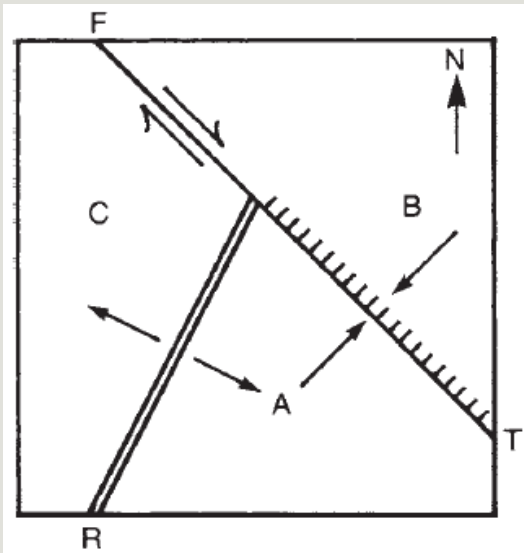
Kinematic Analysis: The velocity space method determines stability

1. Represent each plate's motion as a vector
2. Plot vectors in a triangle diagram
3. If all three velocity lines intersect at one point → stable
4. If not then junction will evolve into new configuration

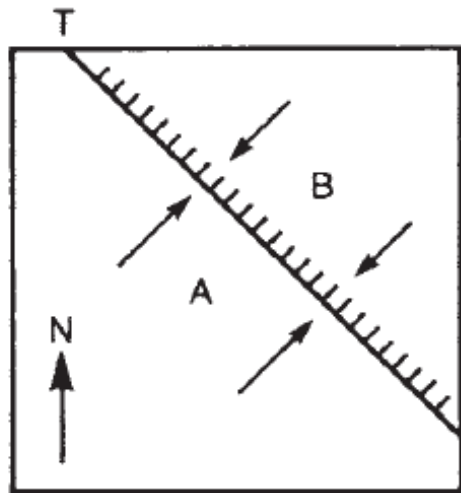
Types of Triple Junctions

Here are the 6 most geologically relevant types:

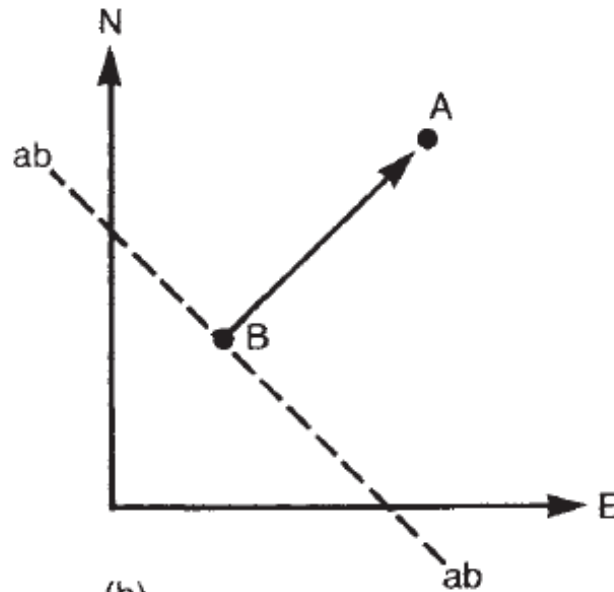
Type	Name	Example	Stability
RRR	Ridge-Ridge-Ridge	Galapagos Triple Junction	Always stable
TTT	Trench-Trench-Trench	Japan Trench-Kuril Trench-Philippine Sea Plate	Rarely stable
RTF	Ridge-Trench-Transform	Gulf of California	Conditionally stable
FFR	Transform-Transform- Ridge	Owen Fracture Zone- Carlsberg Ridge	Unstable
TTF	Trench-Trench-Transform	Chile Triple Junction	Conditionally stable
FFT	Transform-Transform- Trench	Mendocino Triple Junction	Unstable



Ridge (R)–trench (T)–transform fault (F)–triple junction between plates, A, B, and C.

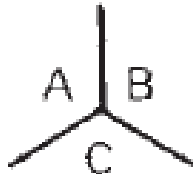
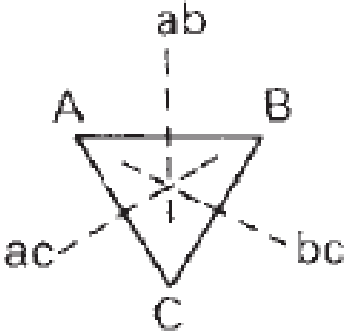
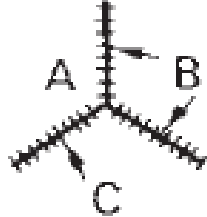
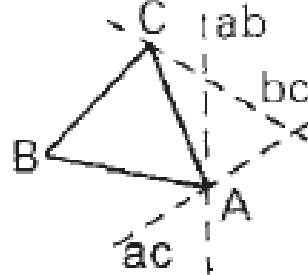
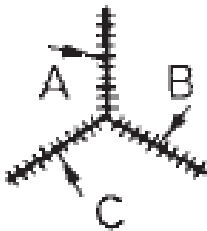
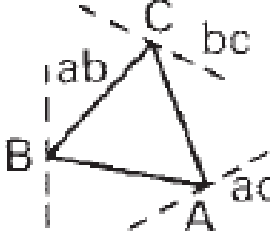


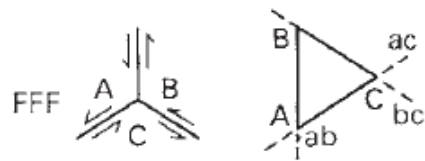
(a)



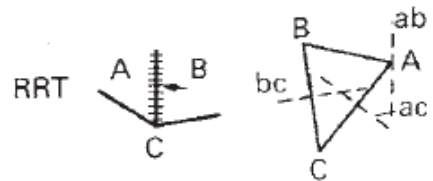
(b)

(a) Trench (T) between plates A and B; (b) its representation in velocity space with the velocity line *ab* corresponding to its related triple junction.

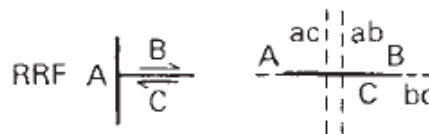
Type	Geometry	Velocity triangle	Stability	Examples
RRR			All orientations stable	East Pacific Rise and Galapagos Rift Zone Great Magnetic Bight
TTT(a)			Stable if ab , ac form a straight line, or if bc is parallel to the slip vector CA	Central Japan
TTT(b)			Stable if the complicated general condition for ab , bc and ac to meet at a point is satisfied	



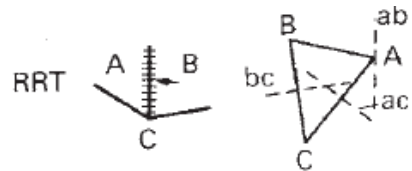
Unstable



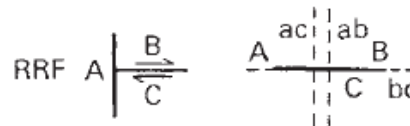
ab must go through circumcenter of ABC



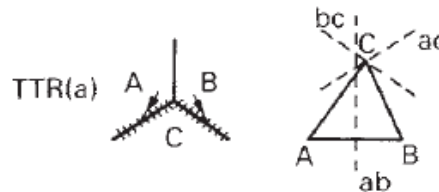
Unstable, evolves to FFR



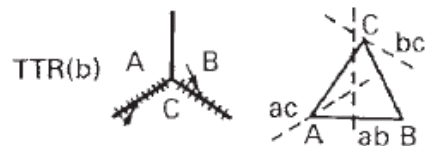
ab must go through circumcenter of ABC



Unstable, evolves to FFR



Stable if ab goes through C, or if ac, bc form a straight line



Stable if complicated general conditions are satisfied

Geometry and stability of all possible triple junctions