Mantle-lithosphere interactions: Plate tectonics & subduction

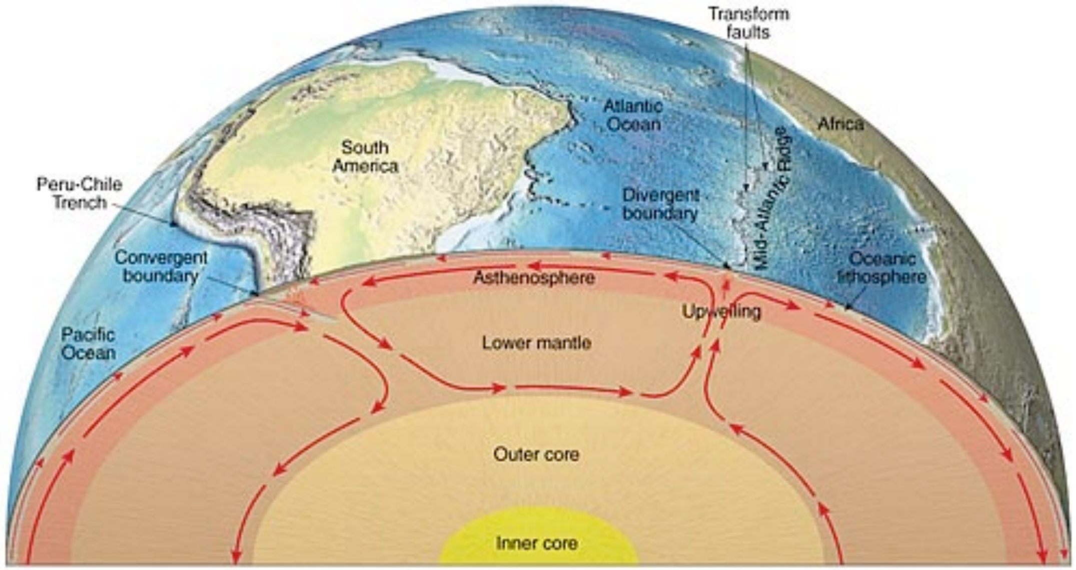
(651-4008-00 G)

Schedule

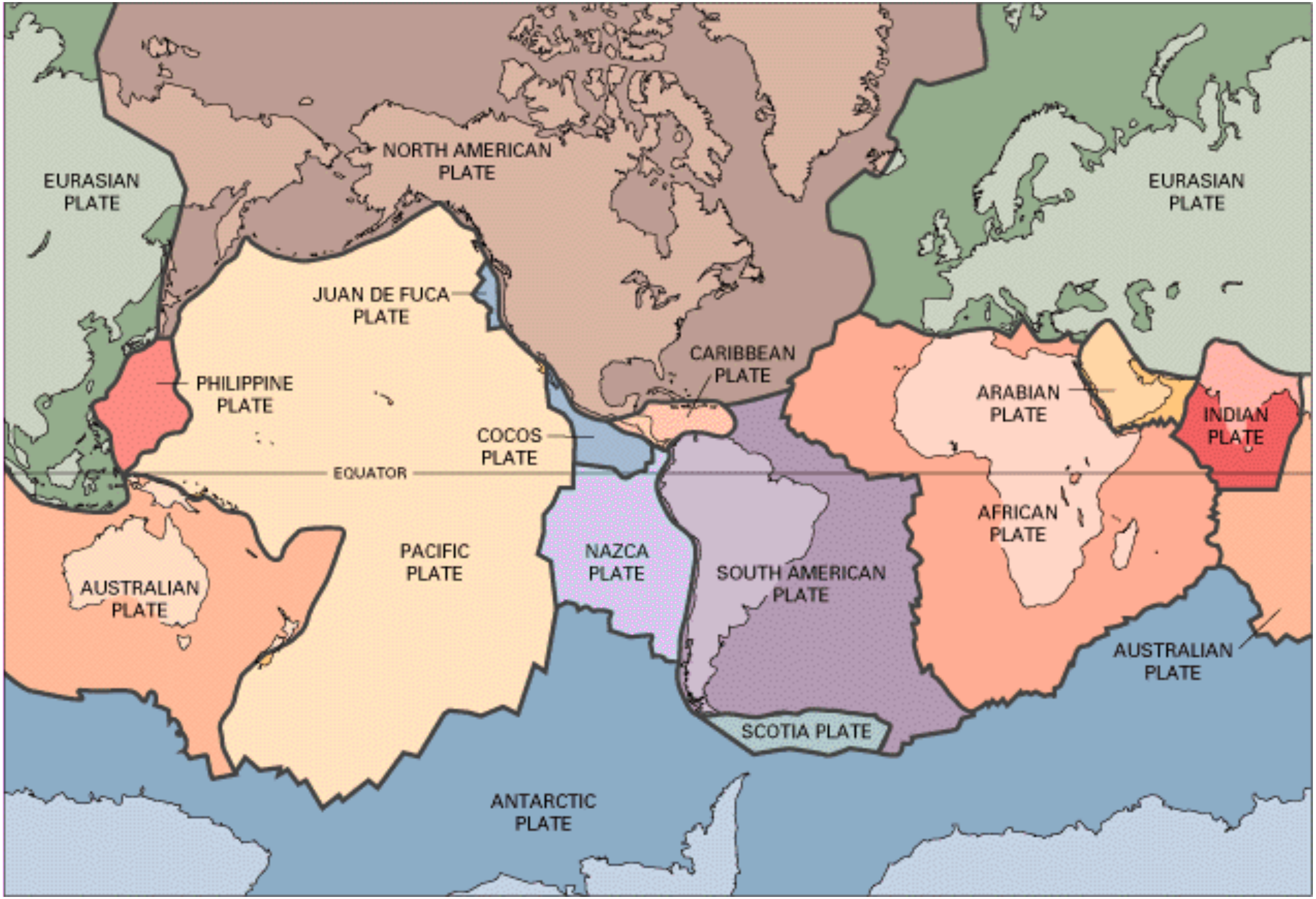
- Tectonics and plate boundaries
- The process of subduction
- Forces associated with subduction
- Subduction related observables
- Insights from laboratory and numerical experiments
- Reconciling observations and models
- Some unresolved problems in tectonics

Tectonics

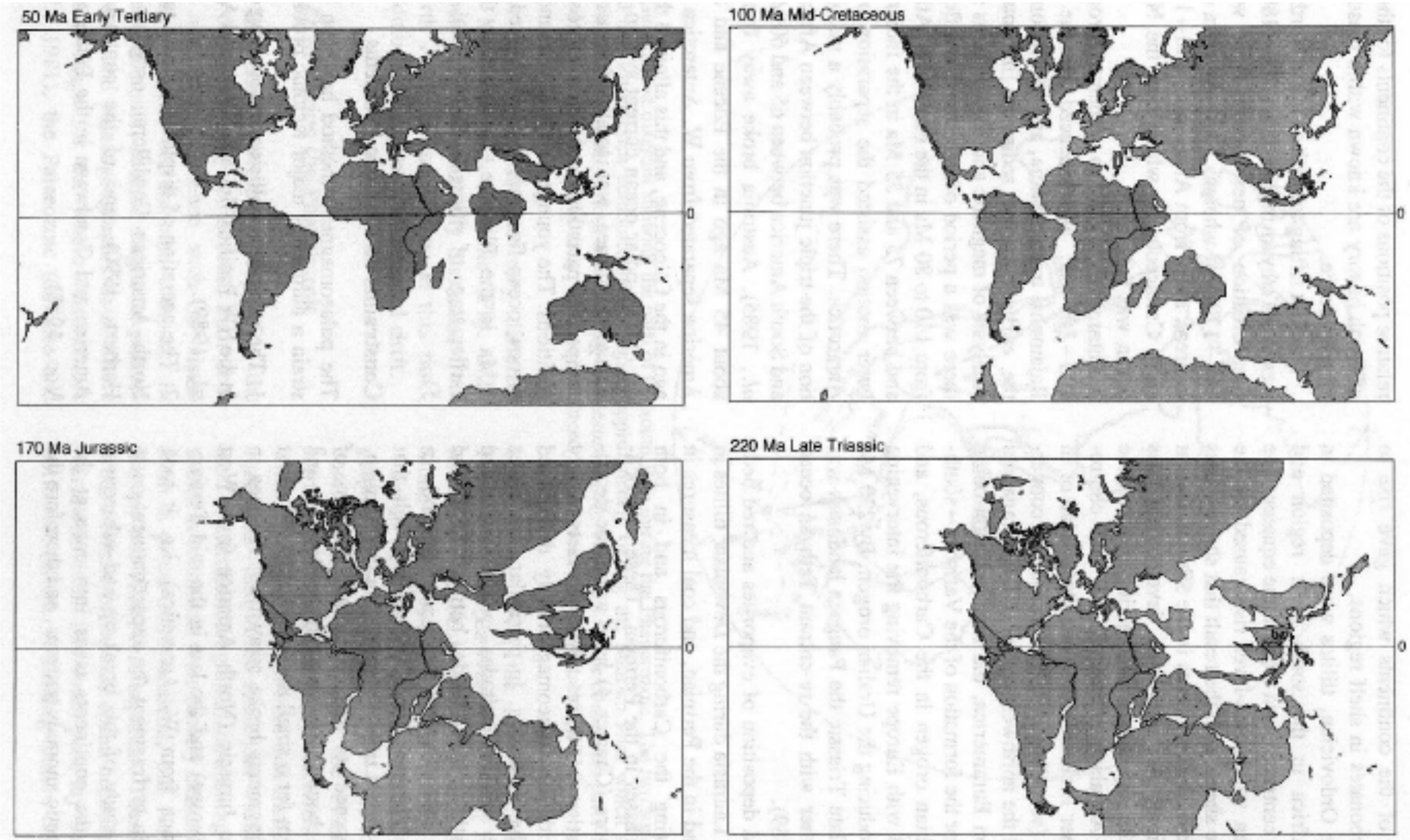
- Set of “rigid” plates drifting over a convecting viscous mantle
- Heat released from the core and internal radiogenic elements
- The mantle cools over time by thermo-chemical convection and conduction
- Plate tectonics is the most efficient way to remove heat from the Earth’s interior



Major plates

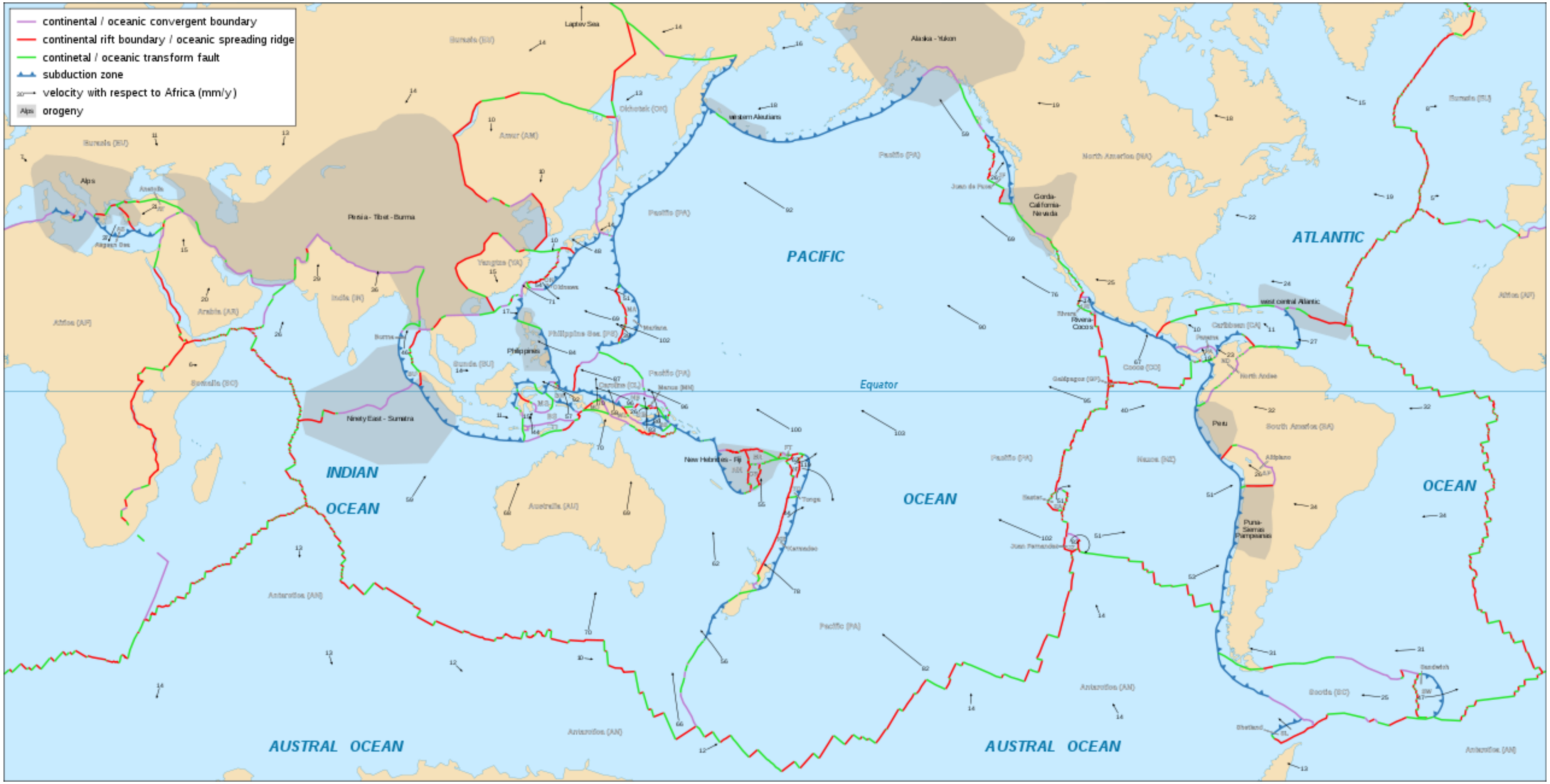


Convection and continents



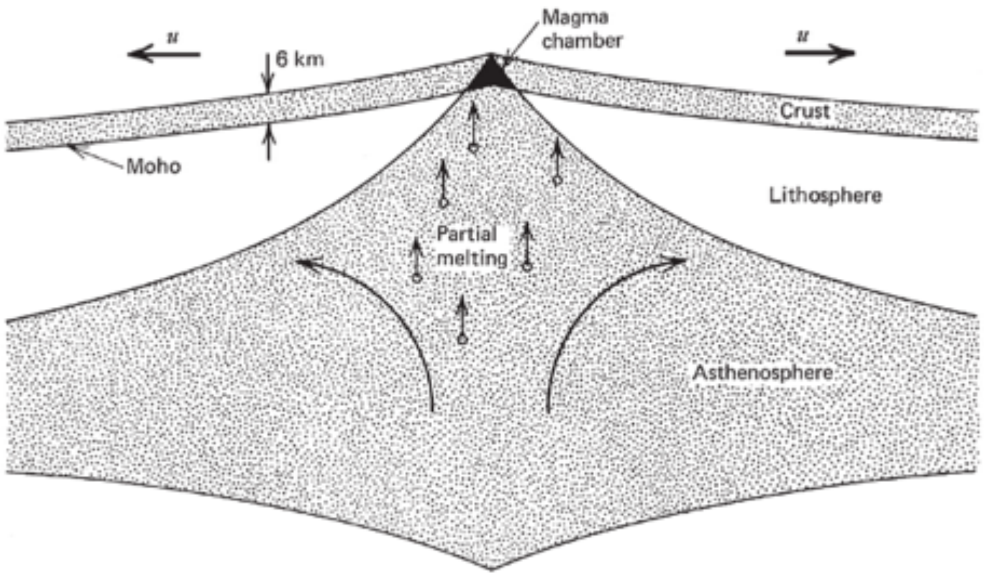
Breakup of Pangaea *(Windley, 1995)*

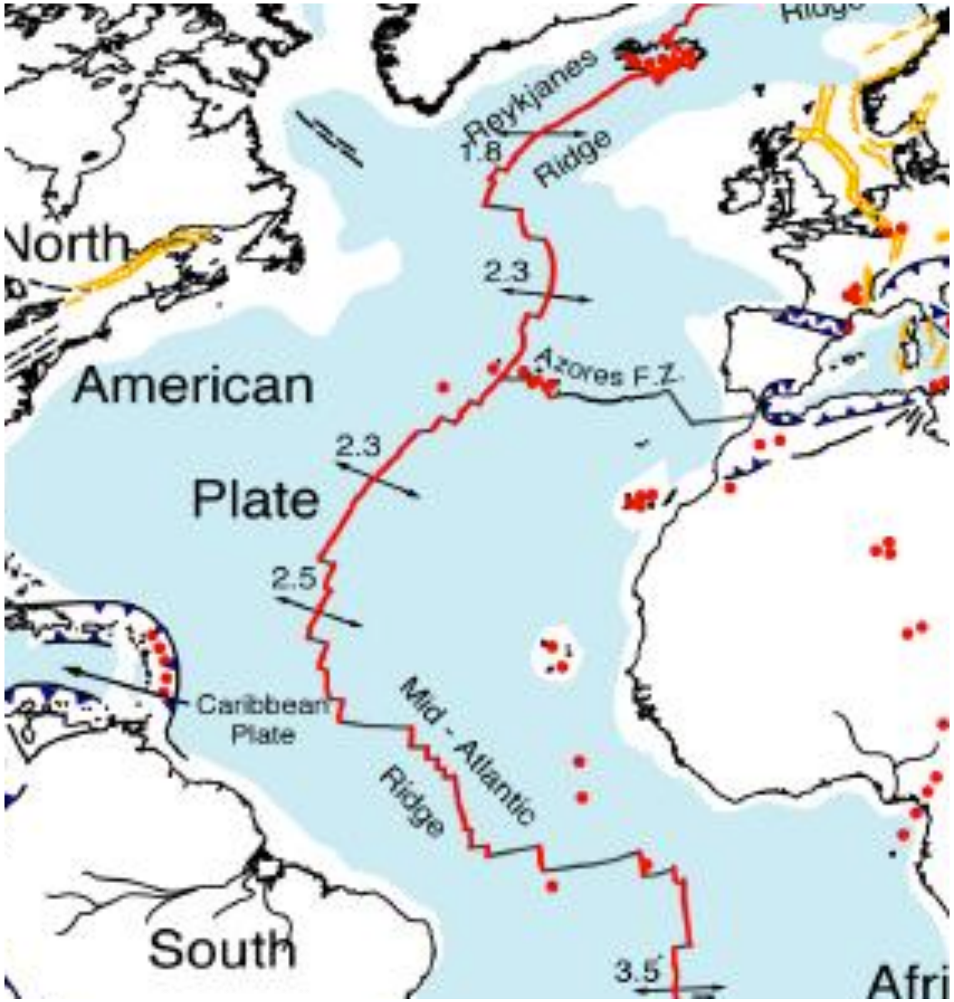
Plate boundary classification



1 Ridges
2 Trenches
3 Transforms

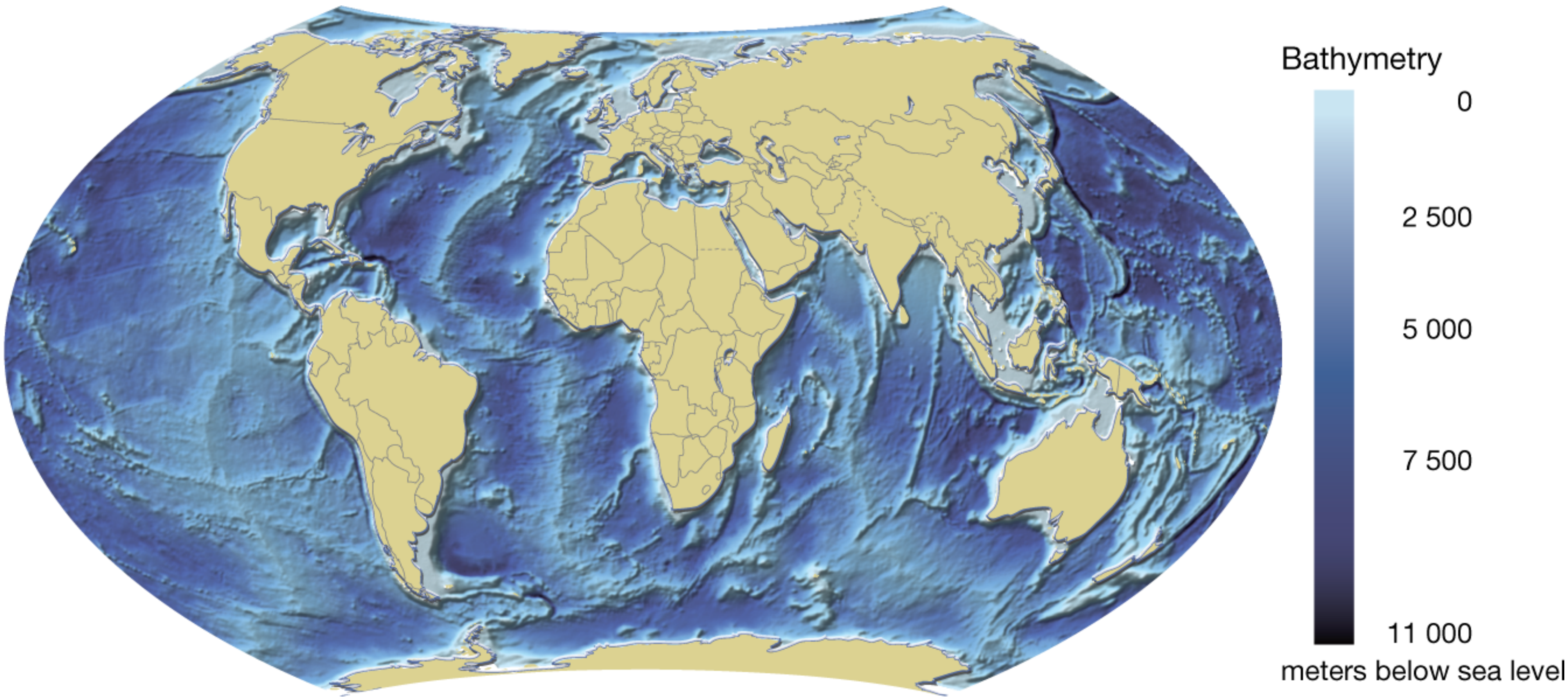
Ridges





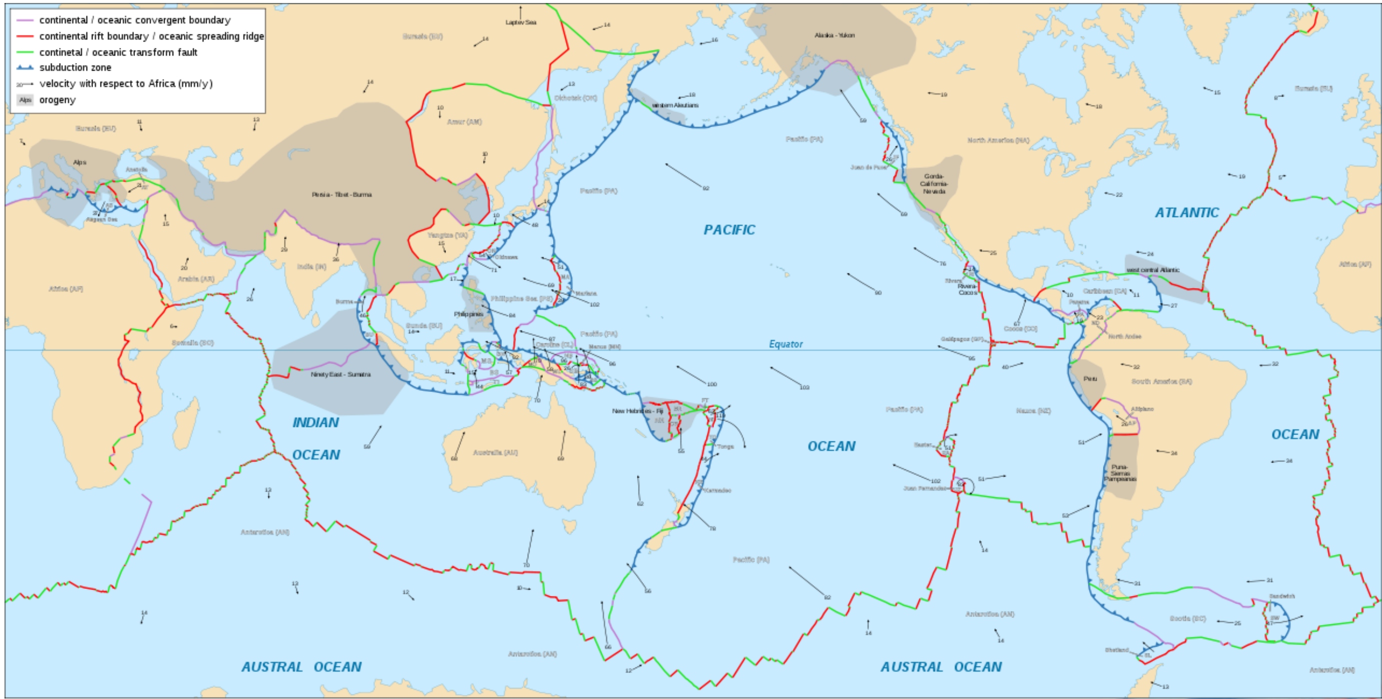
- Spreading center
- Divergent boundary
- Accretionary plate boundary
- Oceanic plate creation

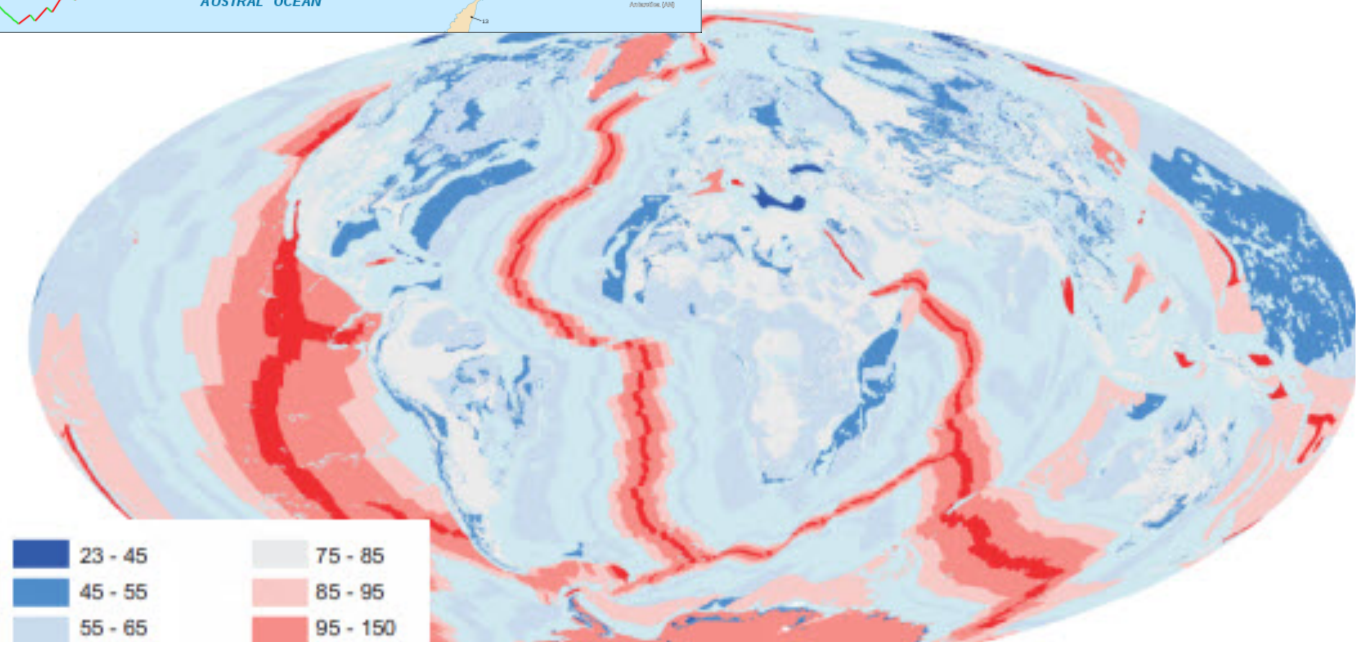
Ridges



- Topographic highs in the ocean
- High heat flow

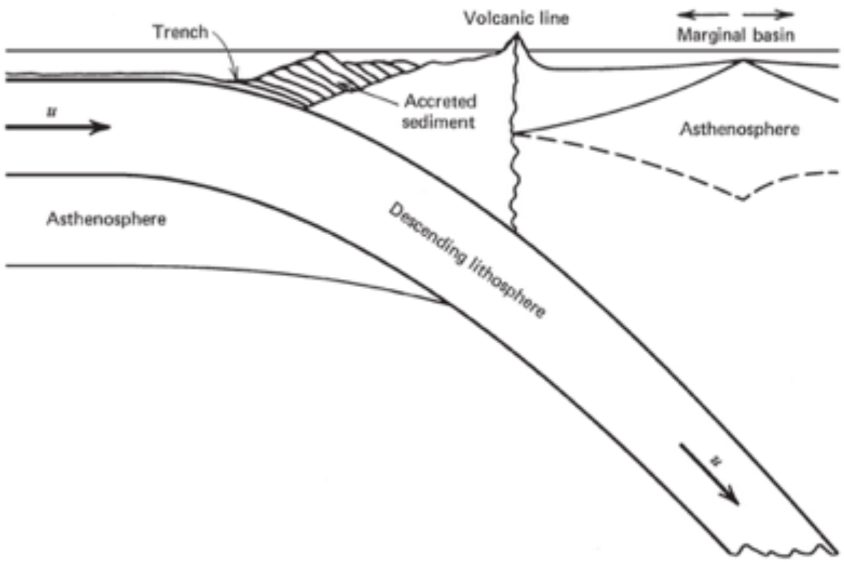
Ridges





- Topographic highs in the ocean
- High heat flow

Trenches



- Convergent plate boundary
- Oceanic plate destruction

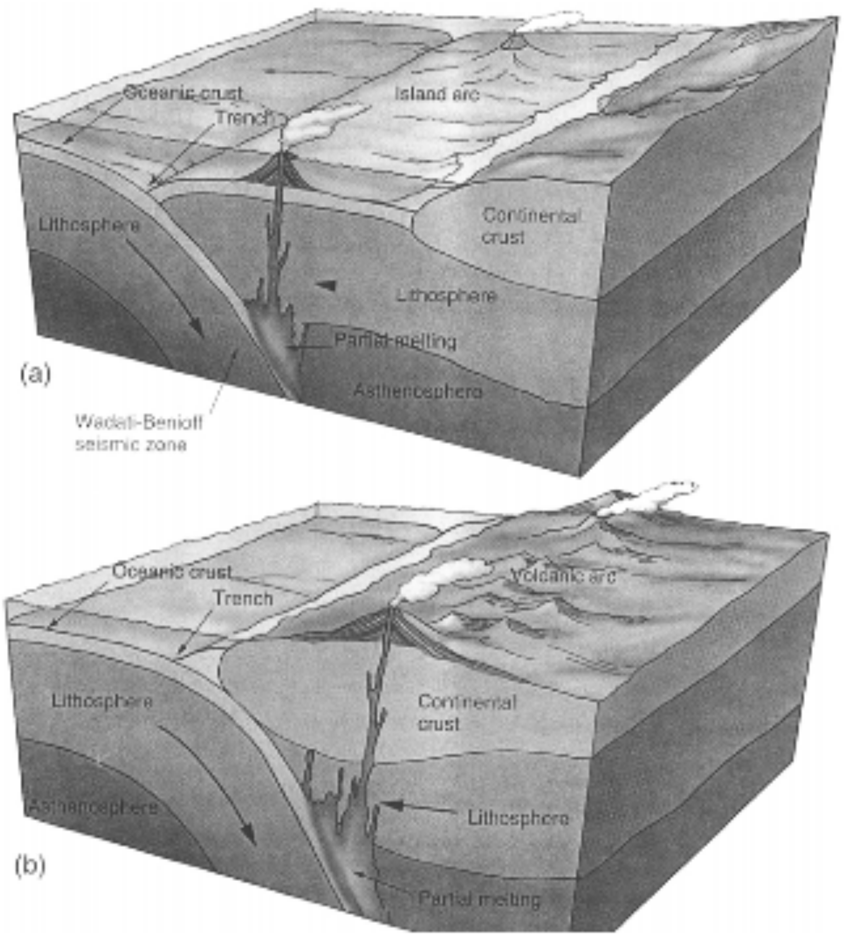
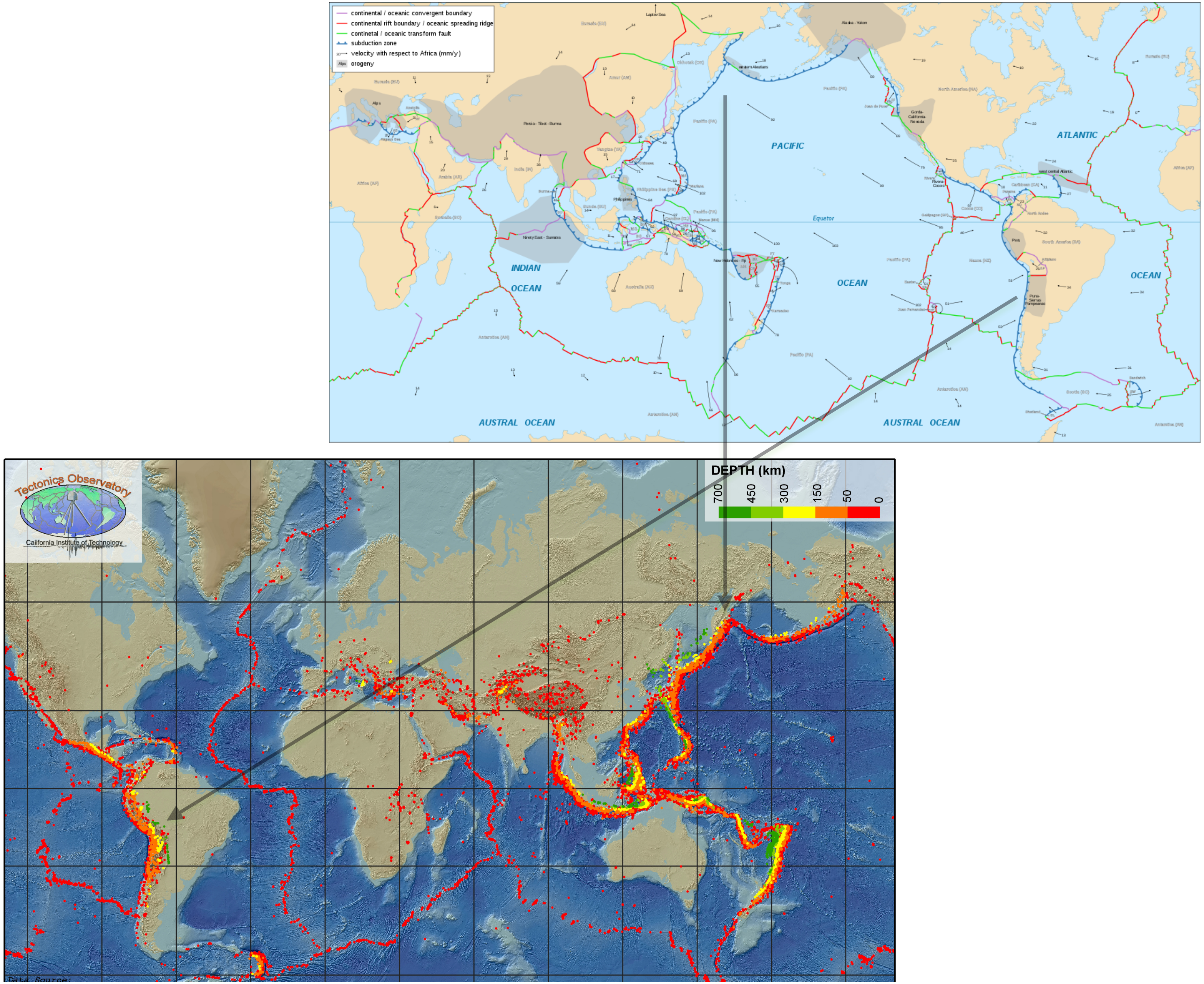


Figure 2.21. Schematic of (a) oceanic lithosphere subducting beneath oceanic lithosphere and the creation of a volcanic island arc, and (b) oceanic lithosphere subducting beneath continental lithosphere and creation of a volcanic chain on the continent. After Tarbuck and Lutgens (1988).

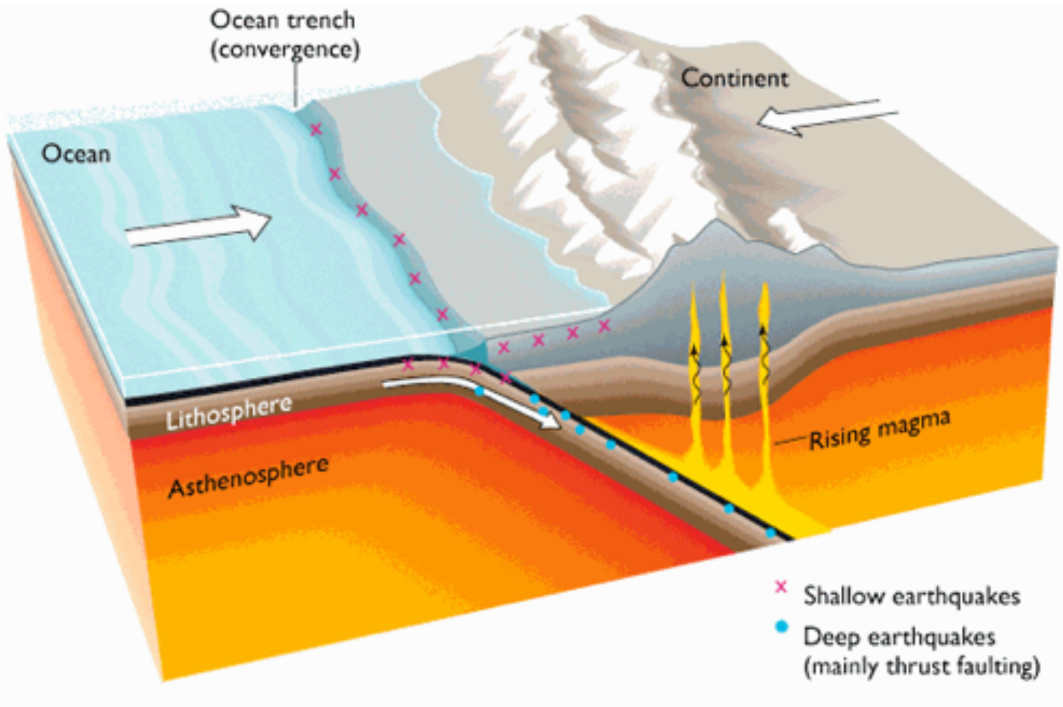
Trenches

- Seismicity
- Volcanism
- Curvature



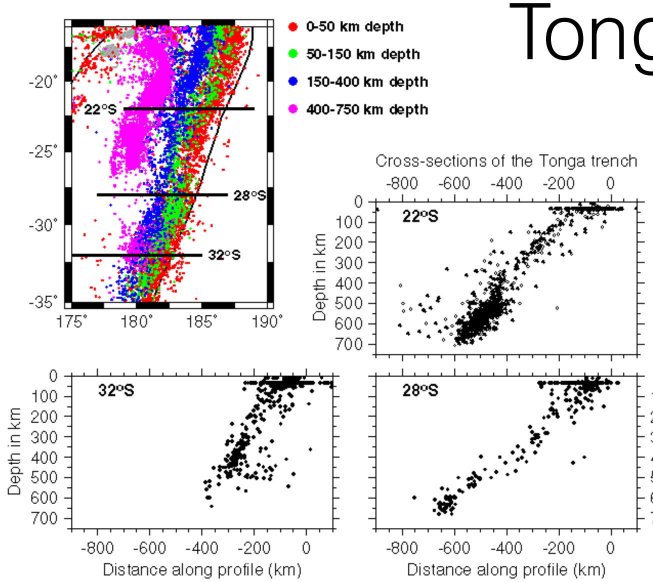
Trenches

- Seismicity
- Volcanism



http://www.earth.northwestern.edu/people/seth/107/Ptdev/Image80.gif

Tonga



Japan

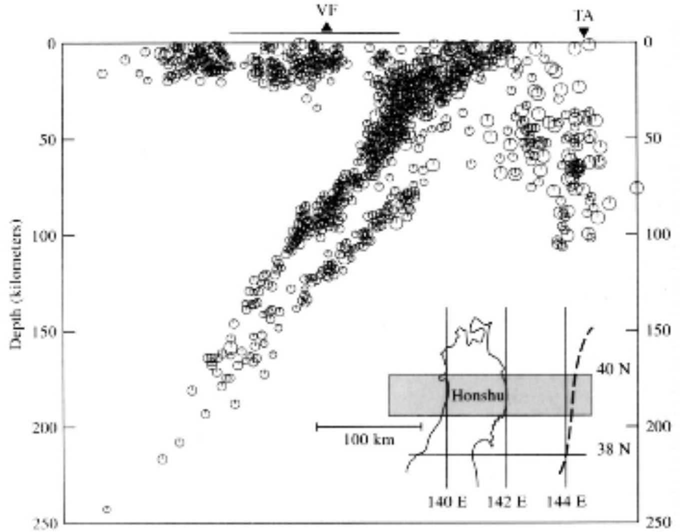


Figure 2.20. Double Benioff zone marking subduction at the Japan arc. Circles are foci of earthquakes recorded in 1975 and 1976. VF = volcanic front, TA = Japan Trench axis. After Hasegawa et al. (1978b). Redrawn from Bolt (1993).

Transform faults

- Shearing (or slip) boundary
- Fault is 90 degrees to ridge axis (e.g. parallel to the spreading direction)
- May posses vertical offsets
- Physical origin is poorly understood

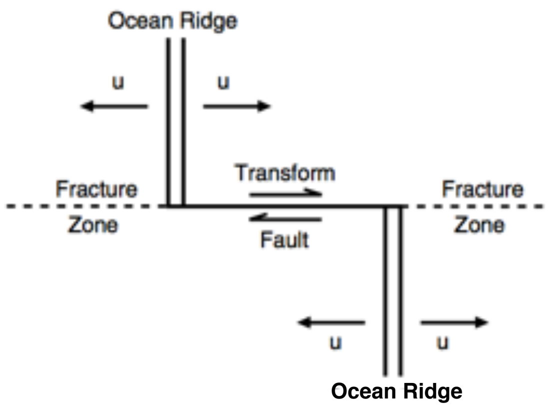


Figure 2.13. Segments of an ocean ridge offset by a transform fault. The fracture zones are extensions of the transform faults into the adjacent plates.

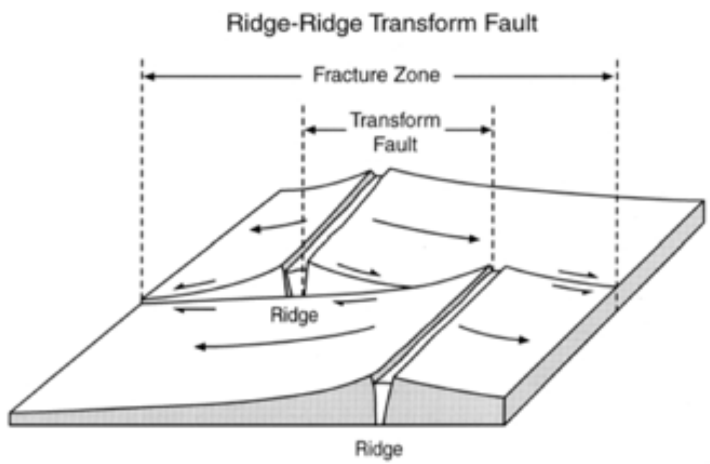


Figure 2.14. Sketch of a ridge–ridge transform fault showing exaggerated differential vertical subsidence across the fault.

Transform faults

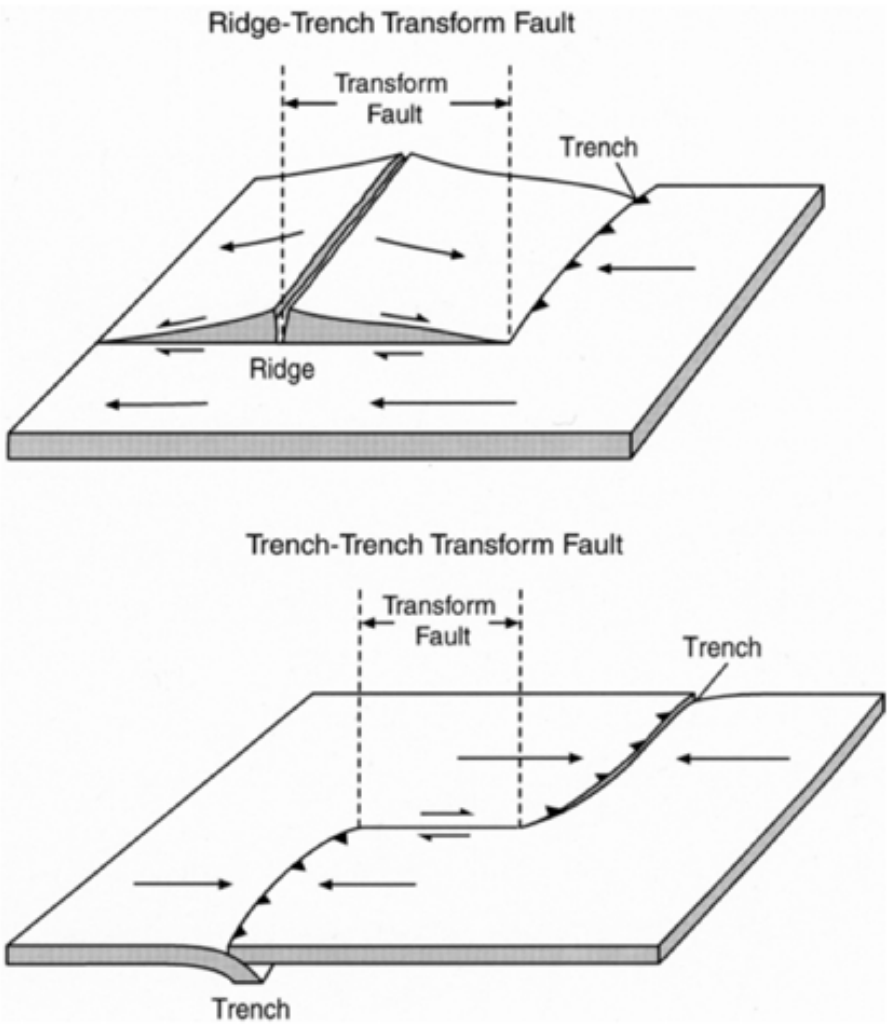
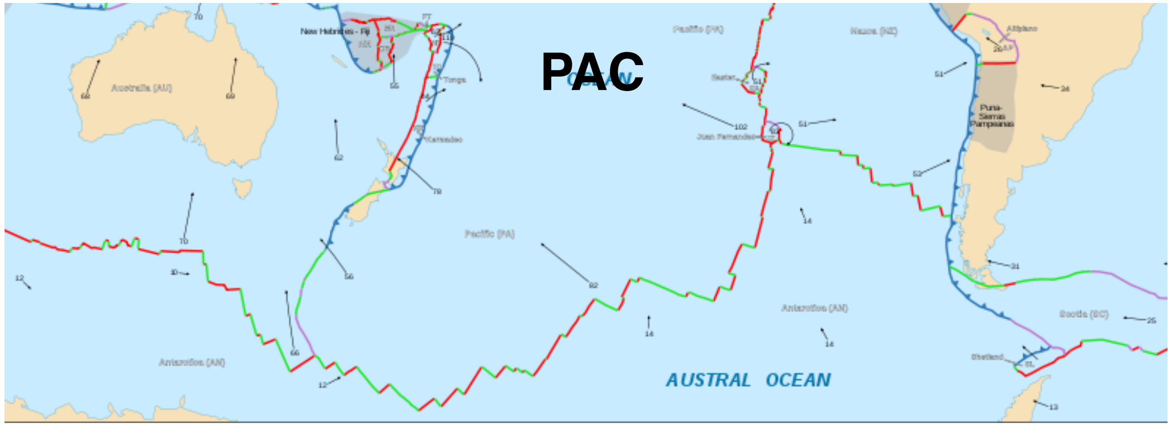
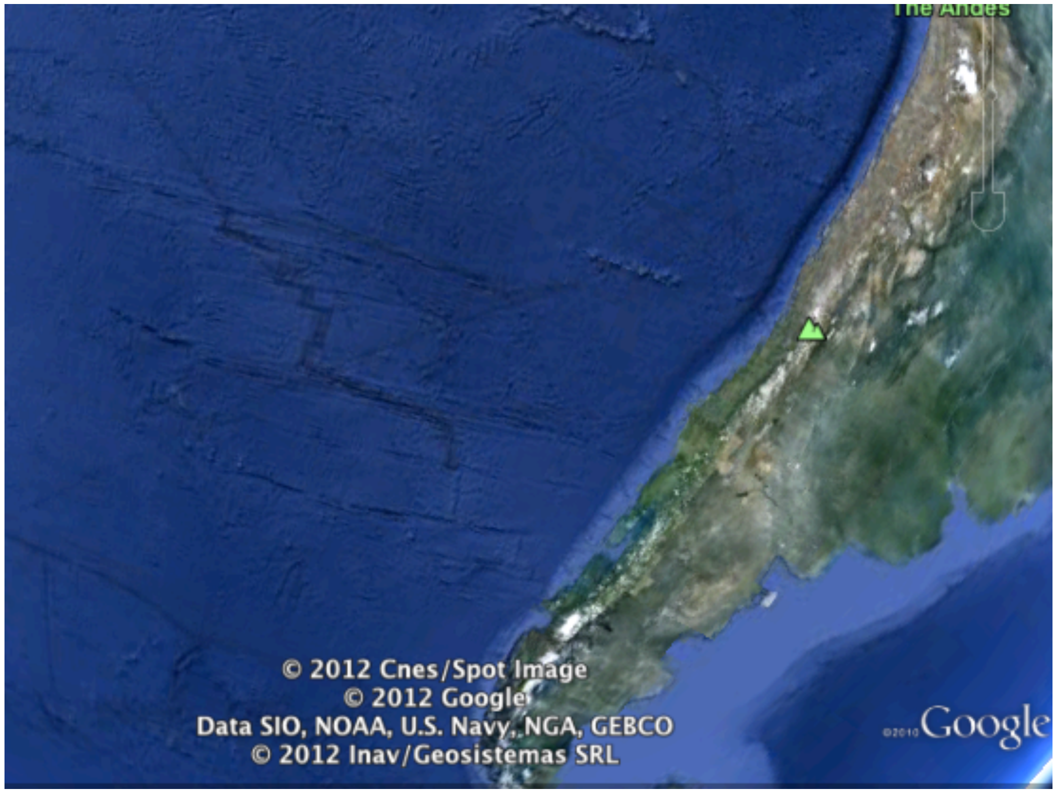


Figure 2.15. Sketch of ridge–trench and trench–trench transform faults.

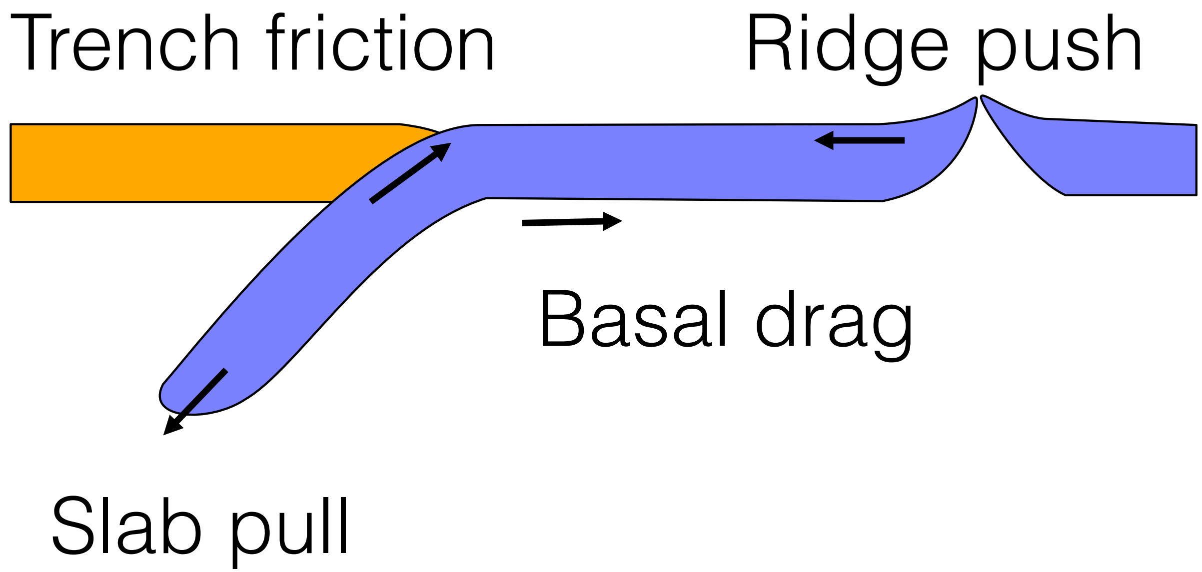




Driving forces of plate tectonics

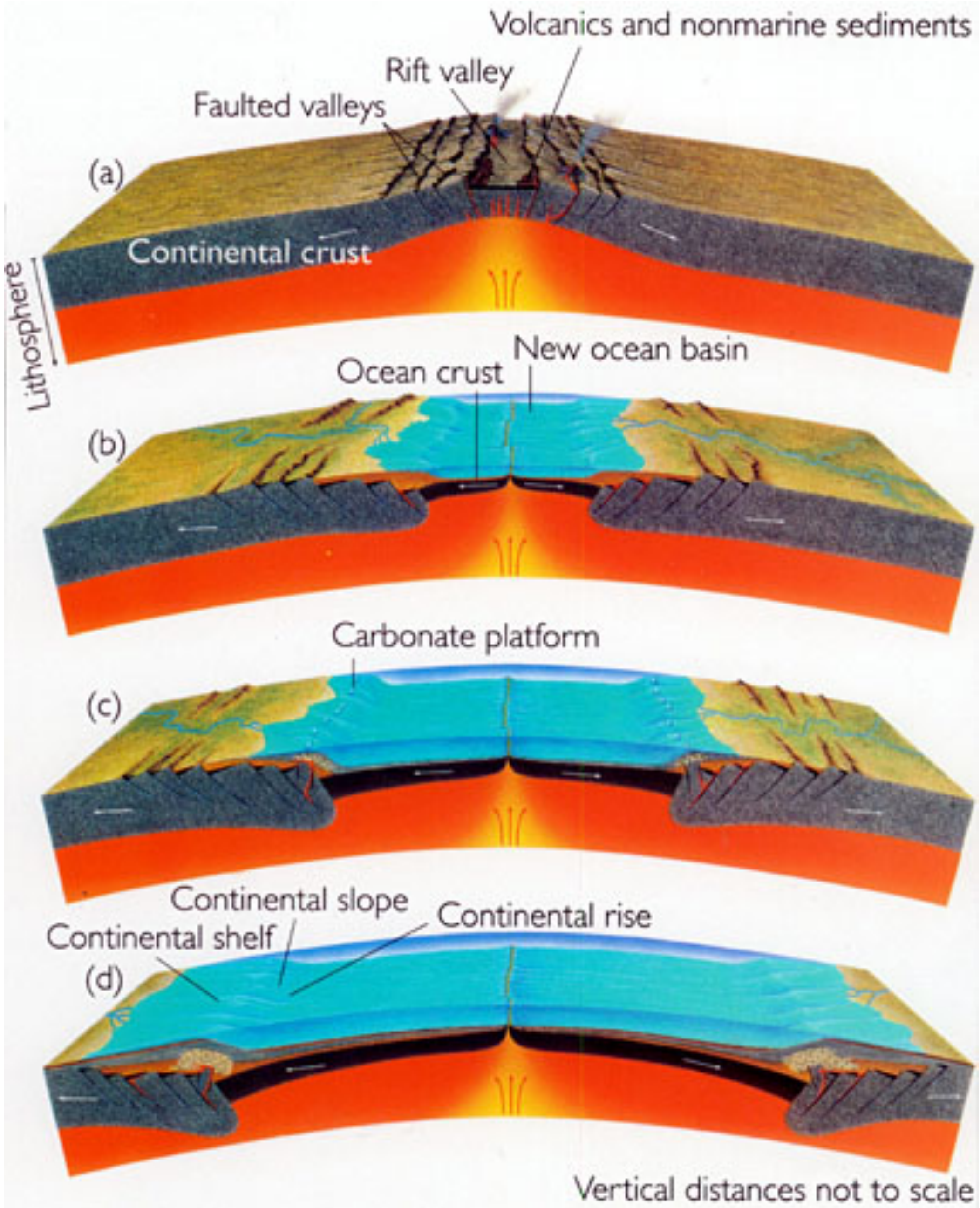
- Driving forces
  - ridge push
  - slab pull

- Resisting forces
  - Trench friction
  - Basal drag
  - Suction in the mantle

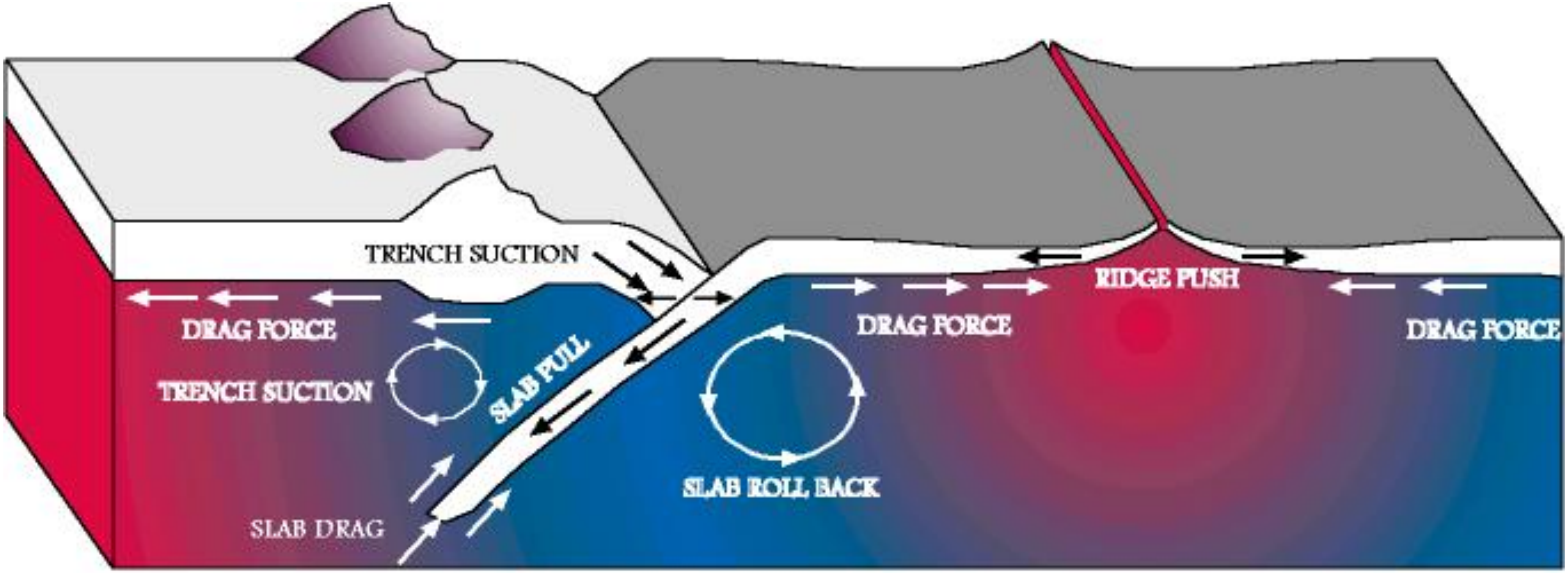


Ridge push

- Ridge push or "gravitational sliding"
- Plate moves from ridge, continuing to cool and thus thickens
- Cooling causes density increase and subsidence w.r.t the ridge axis
- Relative elevation difference creates horizontal buoyancy force pointing outwards from ridge axis

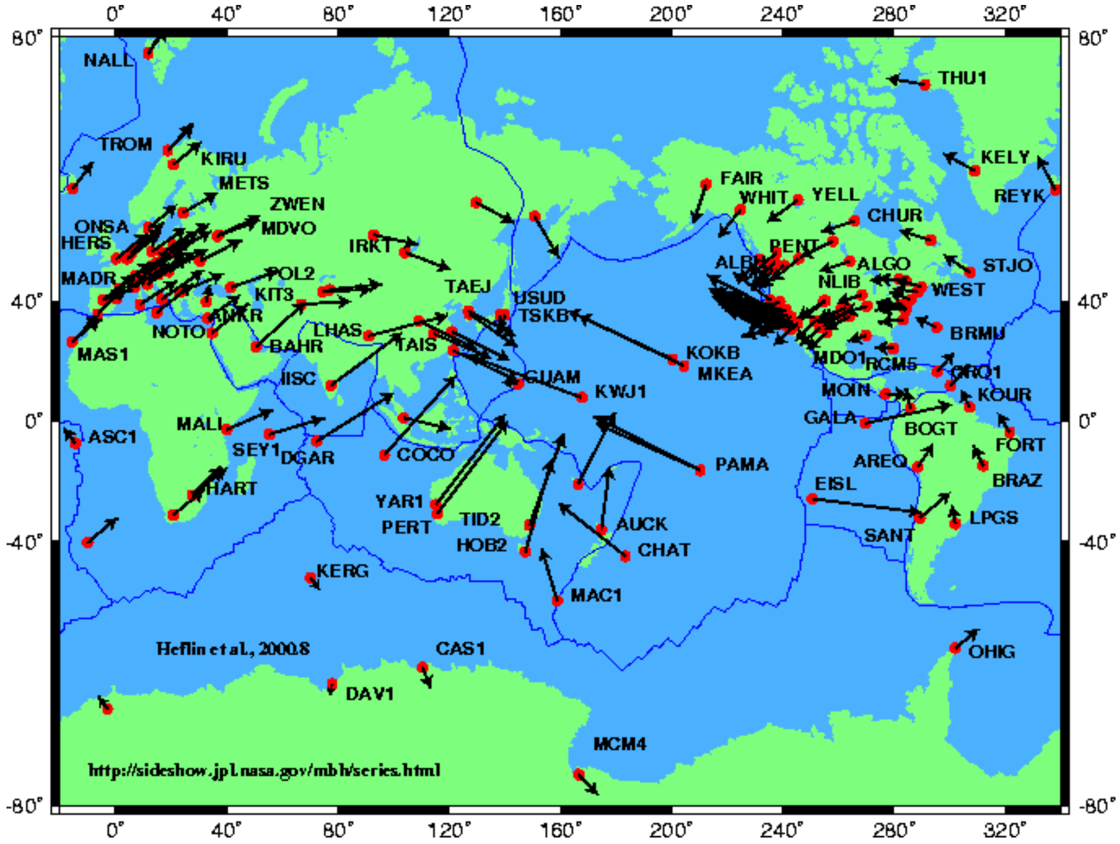


Which force dominants?



Available data

- GPS velocities
- Plate geometries
- Estimates on trench, ridge, transform lengths



Looking for correlations
The Forsyth & Uyeda 1975 study

"*On the relative importance of the driving forces of plate motion*"
Donald Forsyth and Seiya Uyeda,
Geophys. J. R. astr. Soc. (1975), 43, 163—200

Methodology

- Forces
  - Act on bottom surface of plates
  - Act along plate boundaries (ridge, trench, transform)
- Plate inertia negligible
  - implies dynamic equilibrium
  - implies net torque equal zero on each plate
- Determine size of forces which minimizes net torque on each plate via an inversion

Methodology

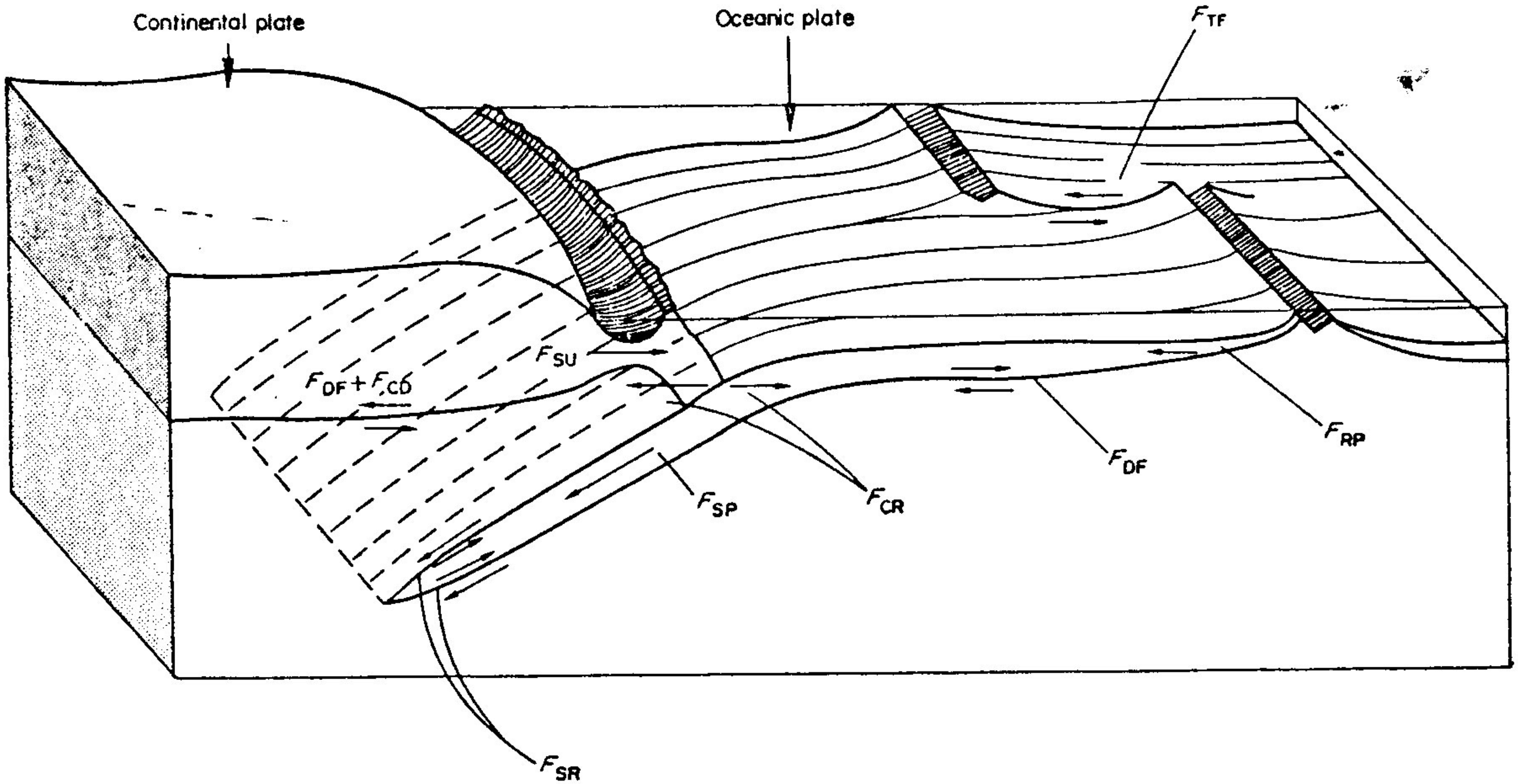


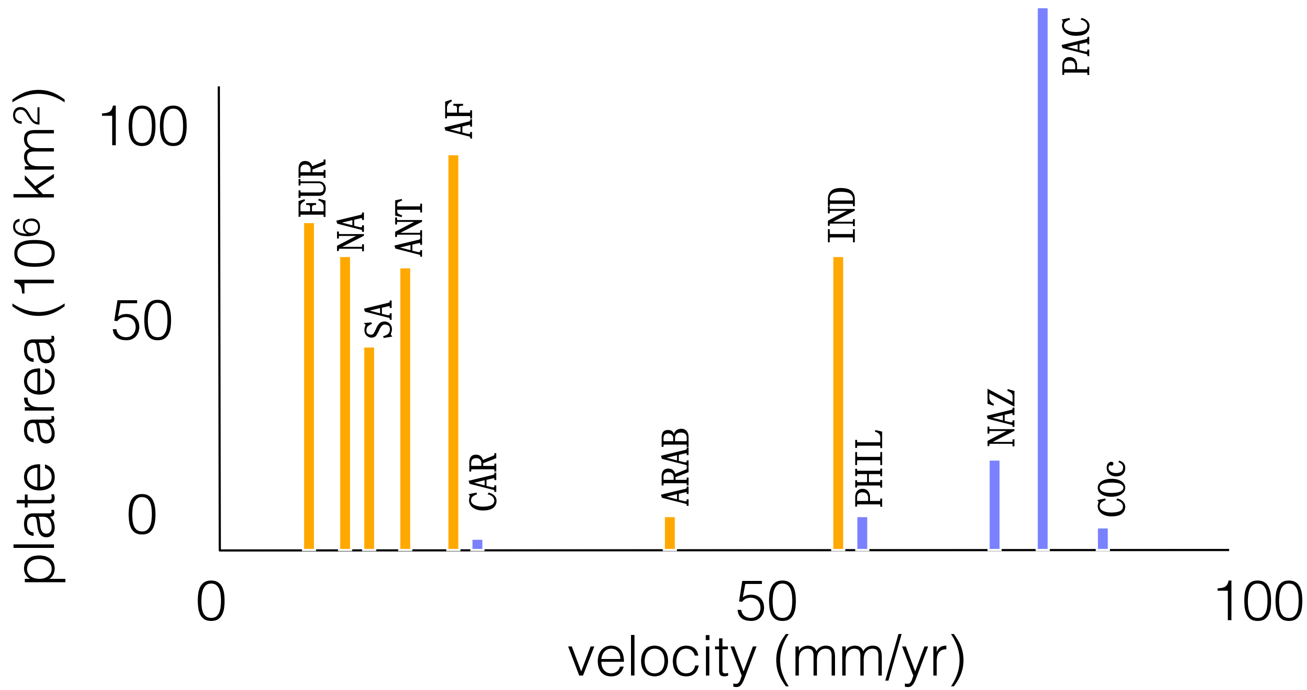
FIG. 1. Possible forces acting on the lithospheric plates. The forces and abbreviations are defined in the text.

Assumptions

- Mantle drag proportional to surface area and relative velocity
- Ridge push proportional to length of the ridge. Ridge push is independent of plate velocity
- Slab pull is a function of density of slab and slab volume (length of trench). Slab pull is independent of plate velocity.

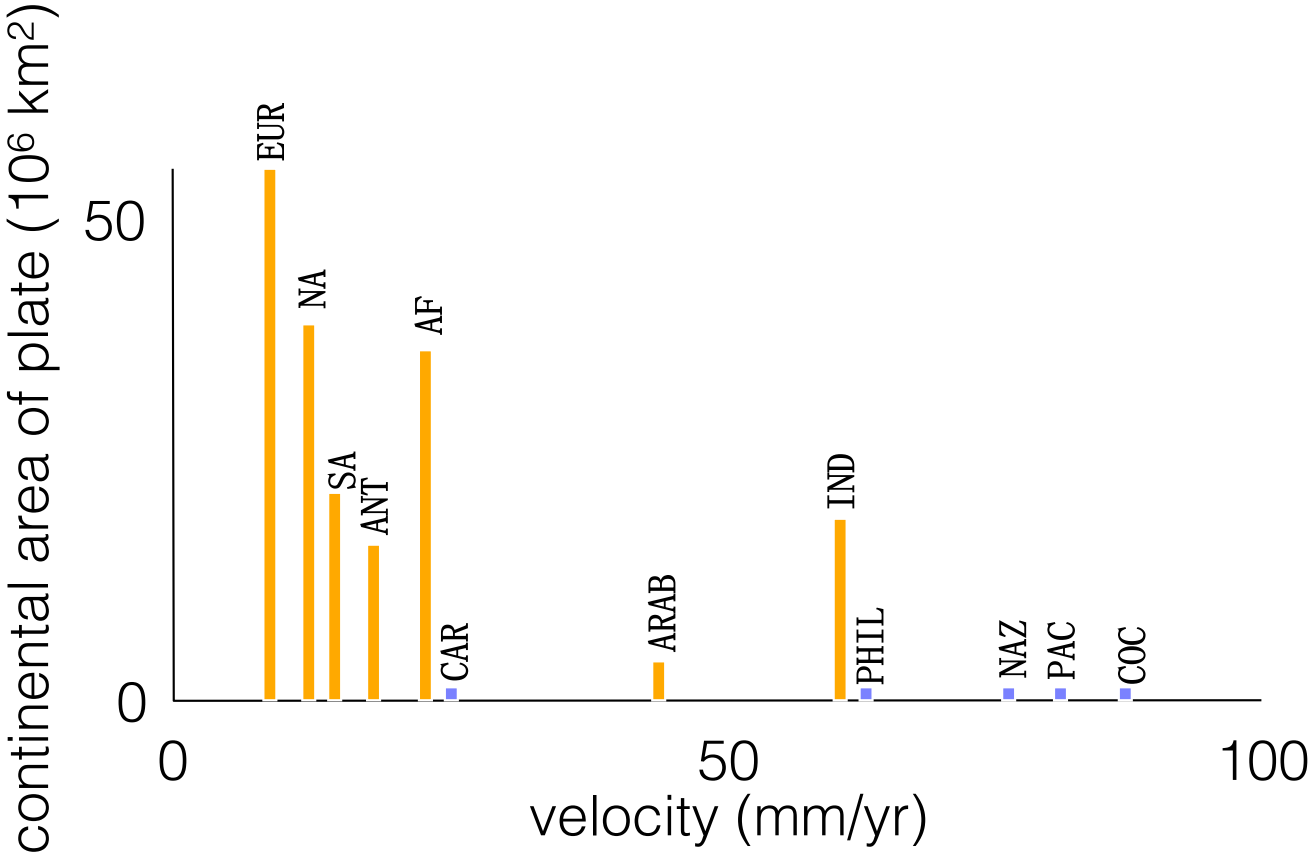
Mantle drag?

- *Expect correlation between plate area and velocity*
- No correlation observed.
- Truly oceanic plates do appear to be faster (less mantle drag)
- *—> mantle drag not the major driving force*



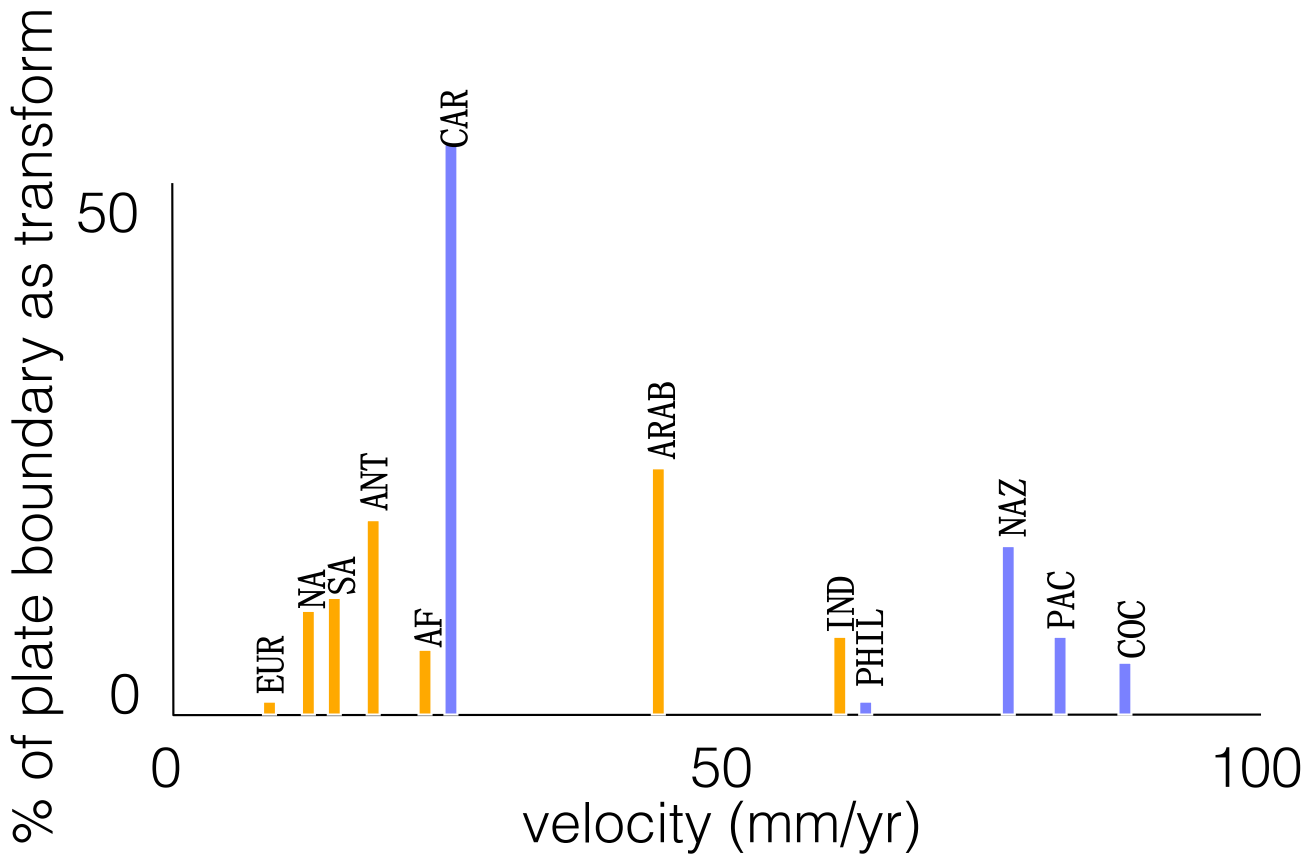
Mantle drag?

- *Expect correlation between plate area and velocity*
- Plates with larger continental areas do appear to move slower
- —> higher mantle drag?



Friction along transform faults?

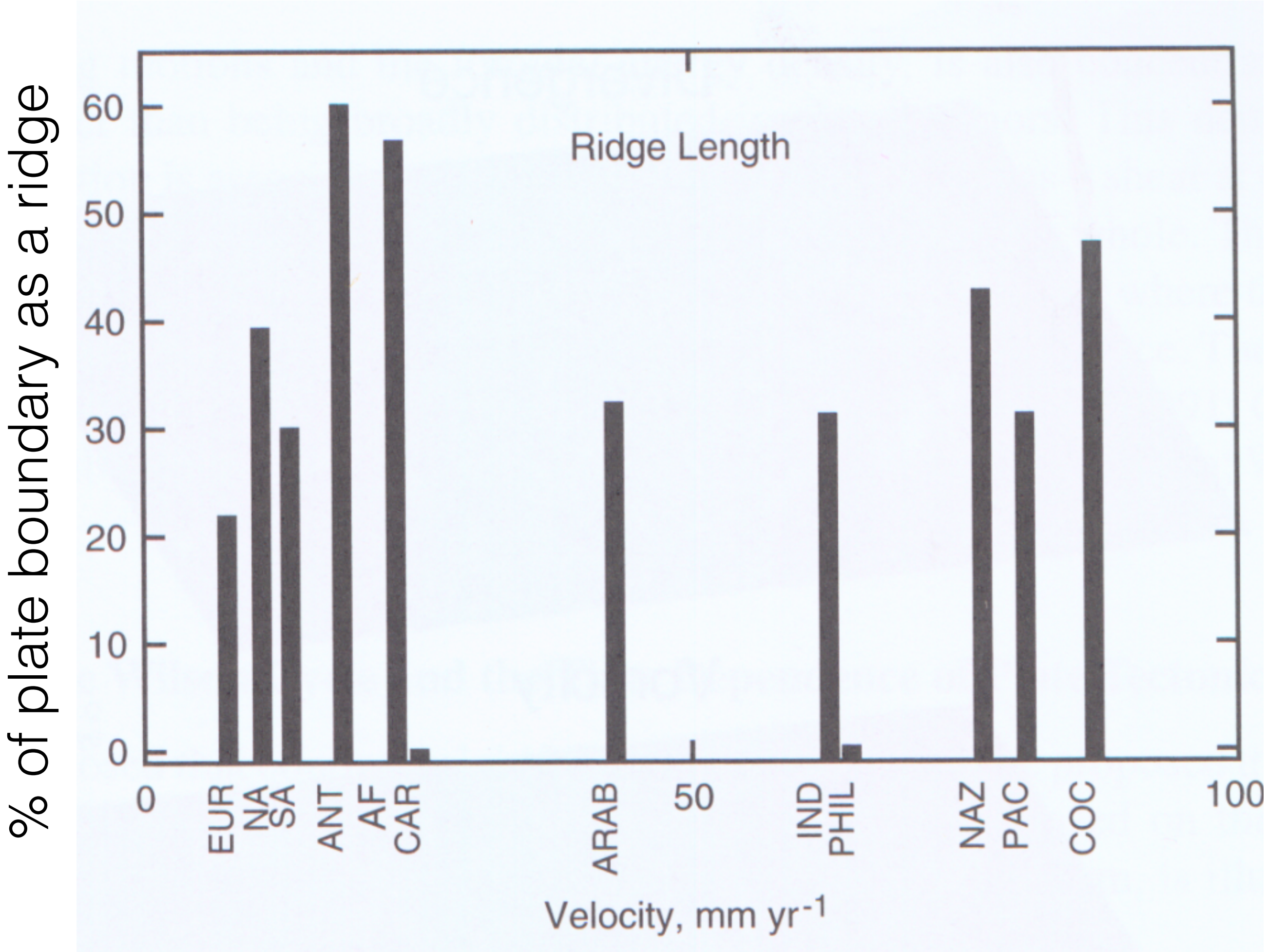
- *Expect transform length - velocity correlation*



- No obvious correlation observed

Ridge push?

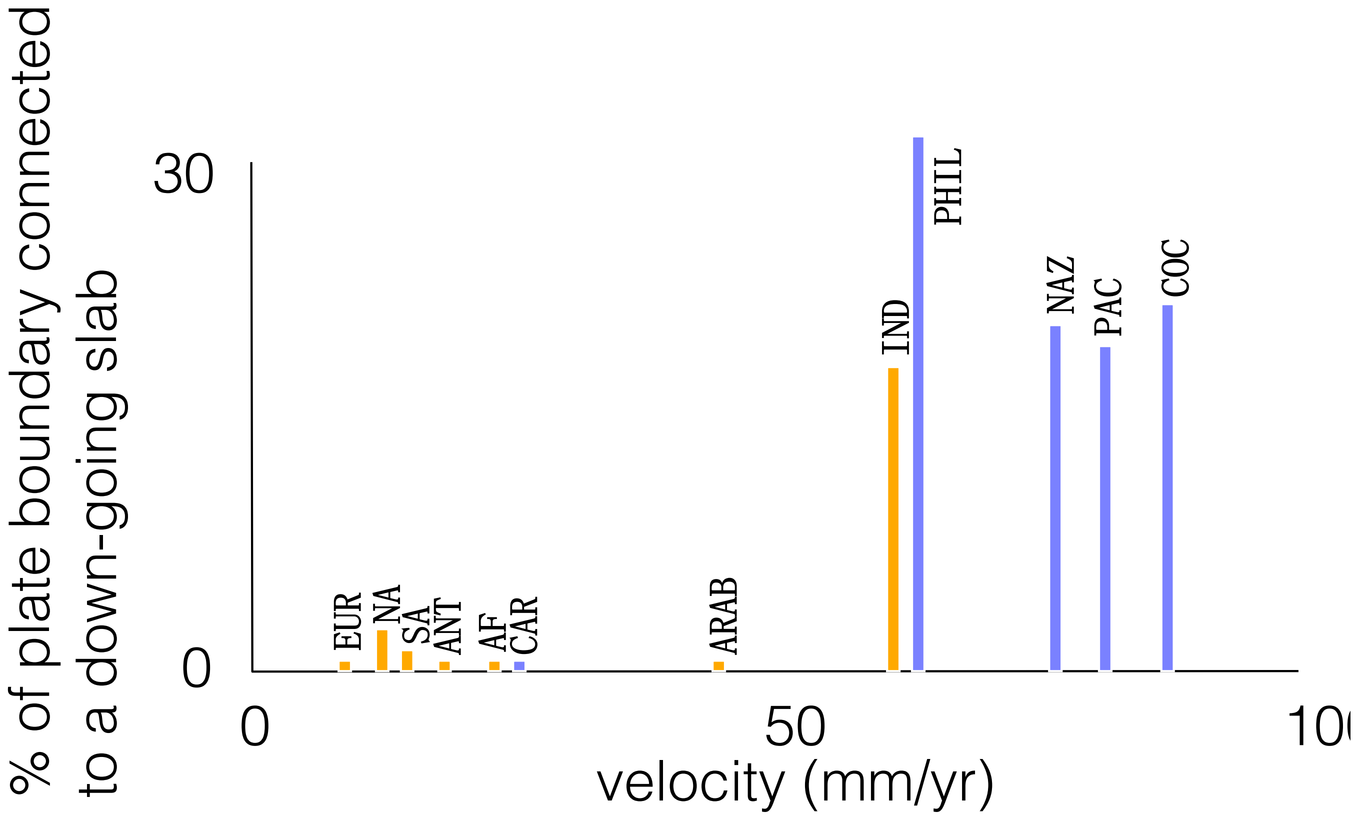
- *Expect plates with more effective length (e.g. length not cancelled by another ridge) to move faster*



- "Top plates" Antarctic, Africa, Cocos, Nazca
- Correlation does not appear to be very strong

Slab-pull?

- *Expect plates with more larger length connected to trench to move faster*
- Strong correlation between velocity and length of trench
- —> slab-pull is a major factor in determine plate velocity



Correlation summary

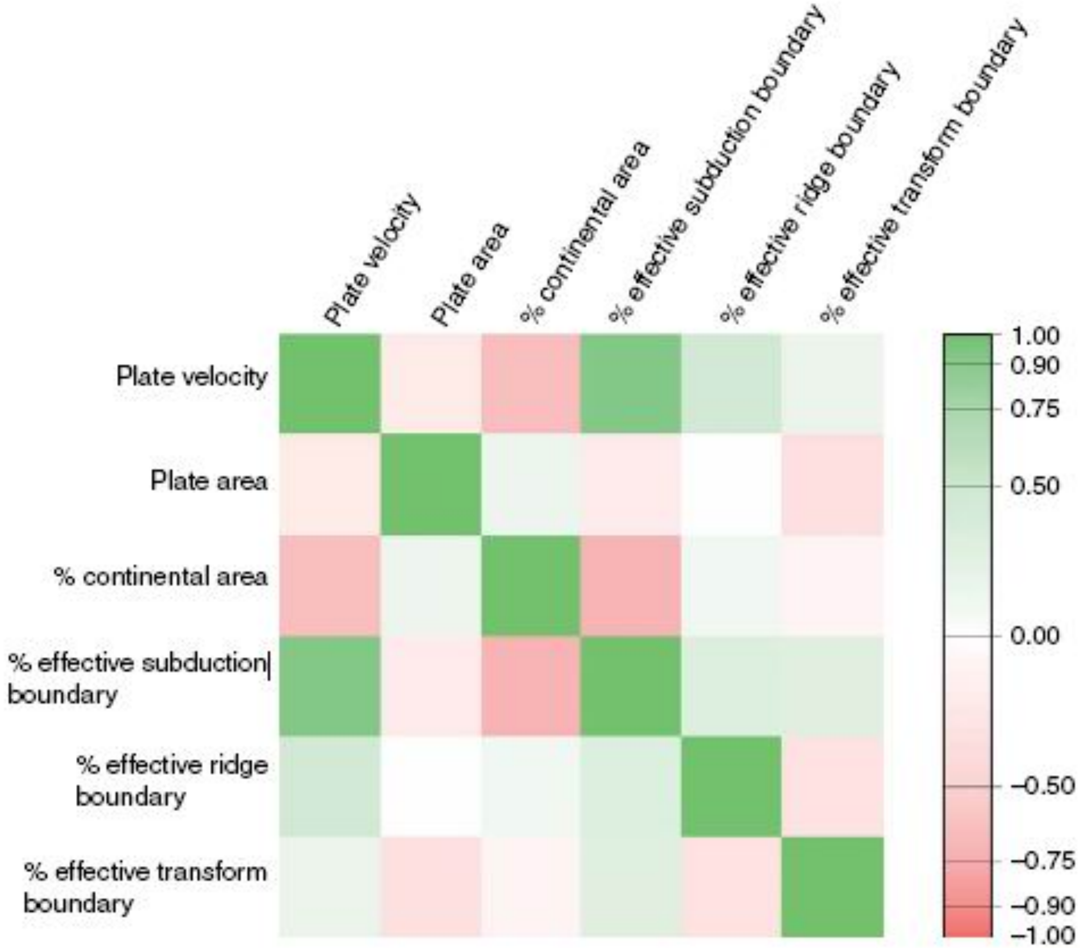


Figure 1 Color shading of the covariance matrix for selected plate geometry characteristics from Forsyth and Uyeda (1975) (see table 1 of Forsyth and Uyeda). The percentage of subduction zone, ridge, and transform fault boundary are the effective percentages (as defined by Forsyth and Uyeda), where the effects of boundaries that occur on opposing sides of the plate are assumed to cancel out and are not included in the percentage of length of that type along the boundary. Green is strong positive correlation, red is strong negative correlation.

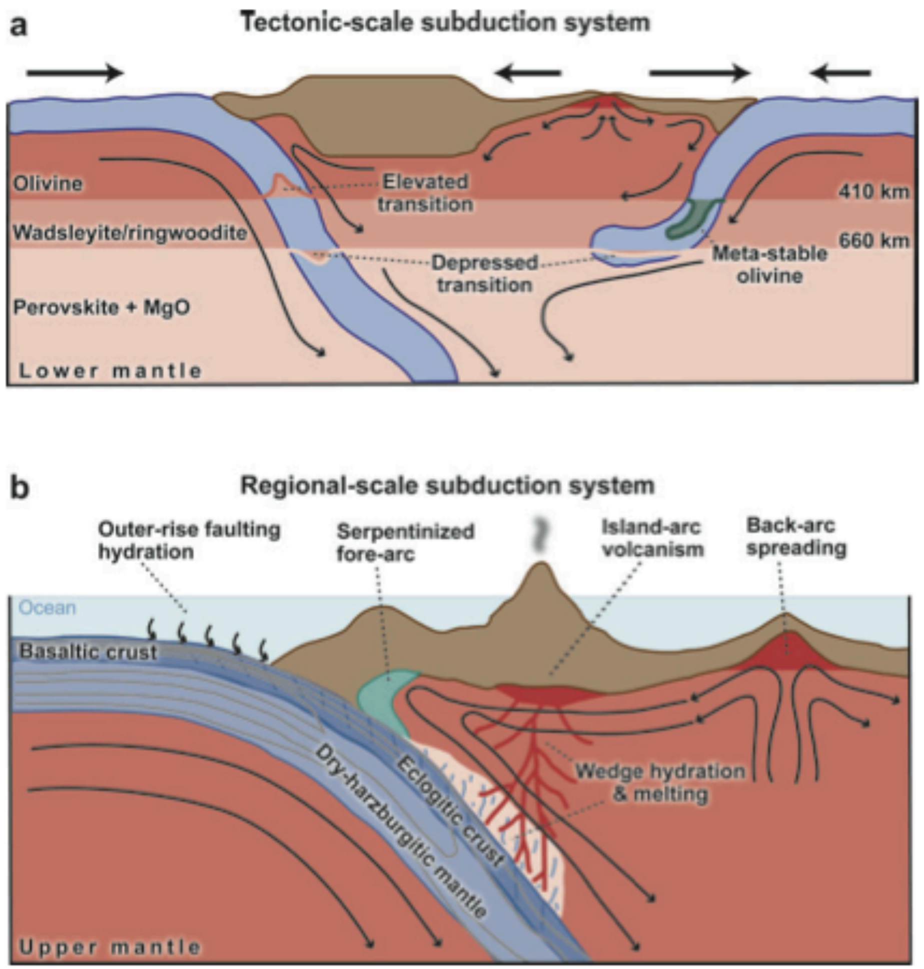
Conclusions of Ueyda

- Plate velocity is a function of the total area of the continental lithosphere and the percentage of the plate boundary which is connected to a subducting plate
- In other words,
    - continental plates are slow (due to increased drag)
    - and oceanic plates that are attached to subduction zones are fast

- *These results imply that slab pull is the primary driving force of plate motion*

Importance of subduction

- Subduction provides the main force driving plate motion and flow in the Earth's mantle
- With respect to the evolution of slabs, we interested in understanding;
    - the role of rheology
    - the role of slab geometry
    - nature of flow field associated with subduction

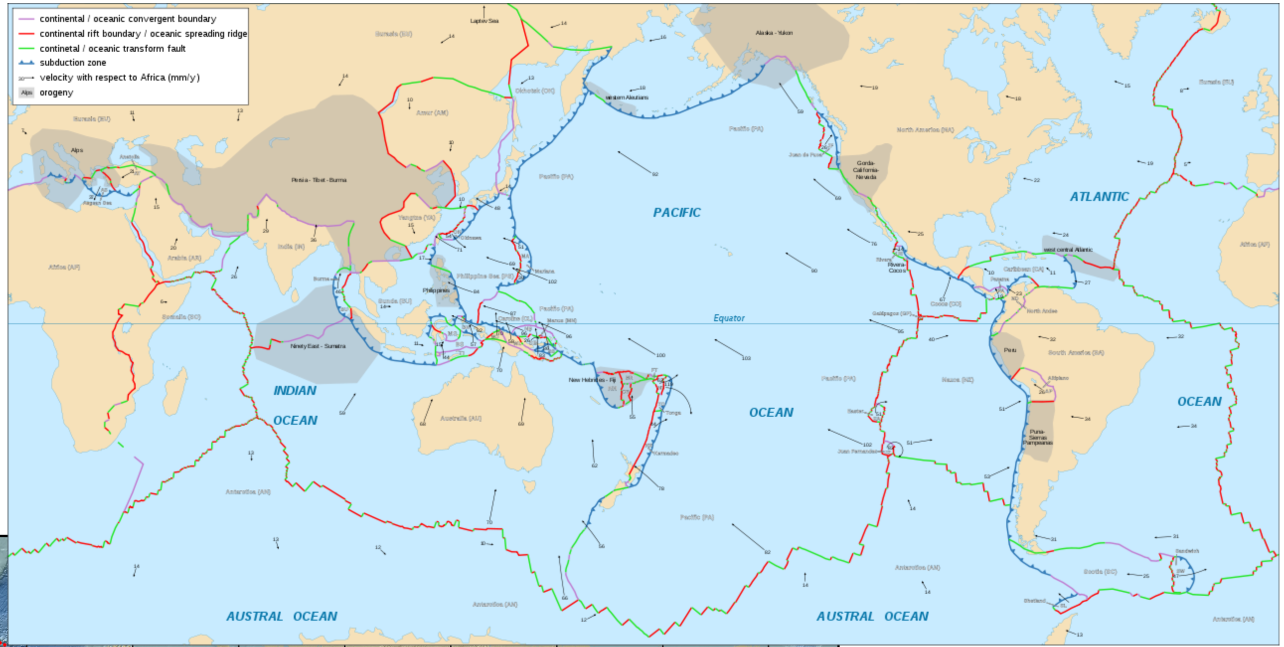


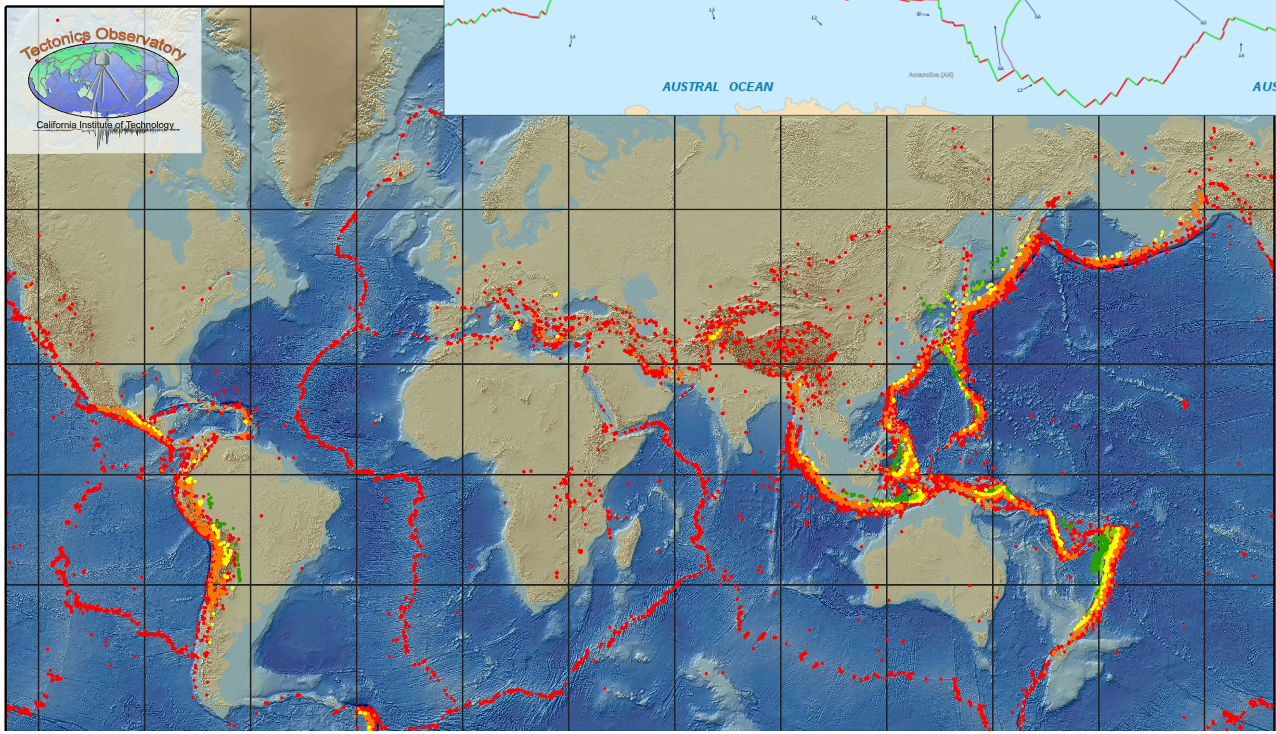
(Billen, Annuv. Rev. EPS, 2008)

Subduction processes: Observations

Surface data

- Trench location
- Active seismicity (shallow and deep)
- Volcanism

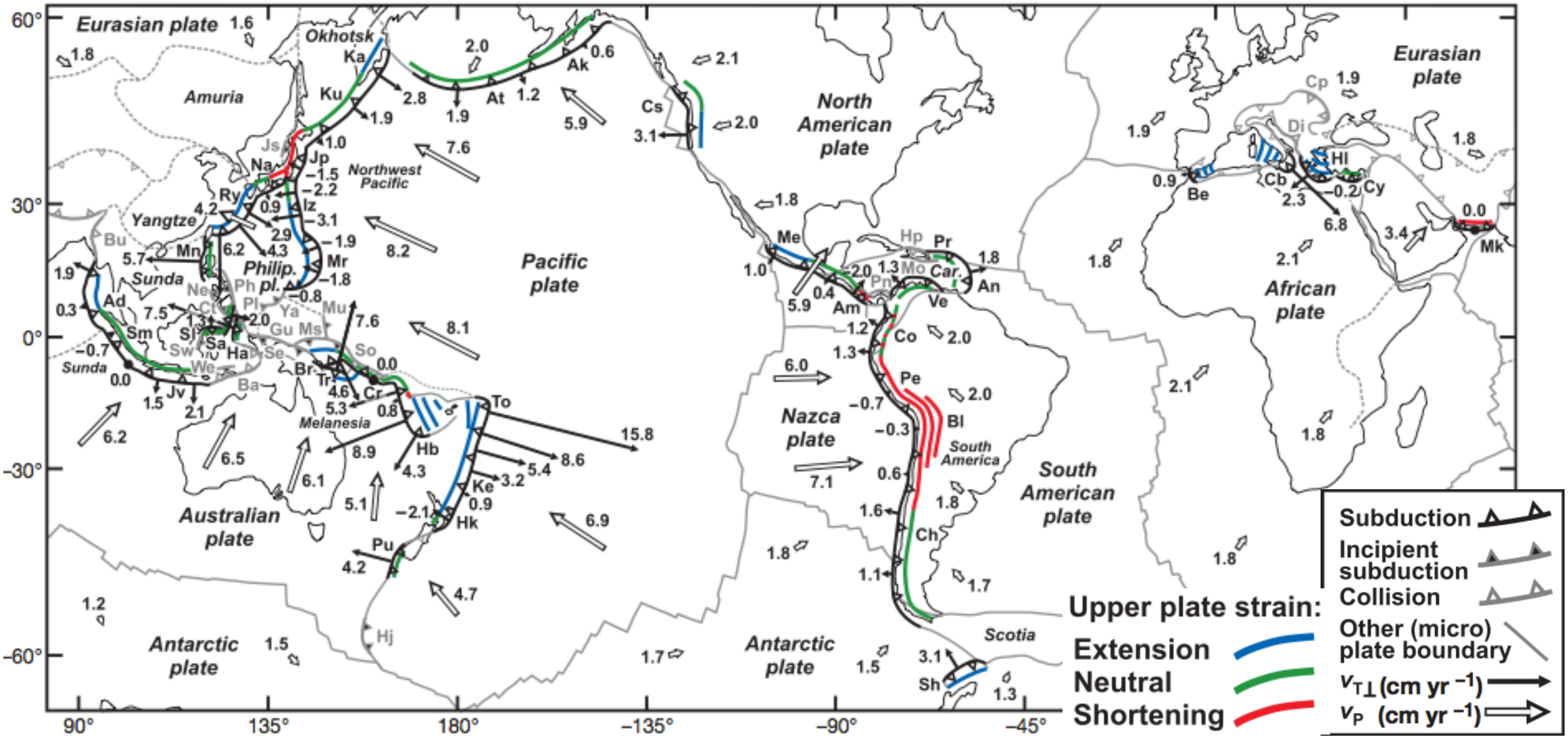




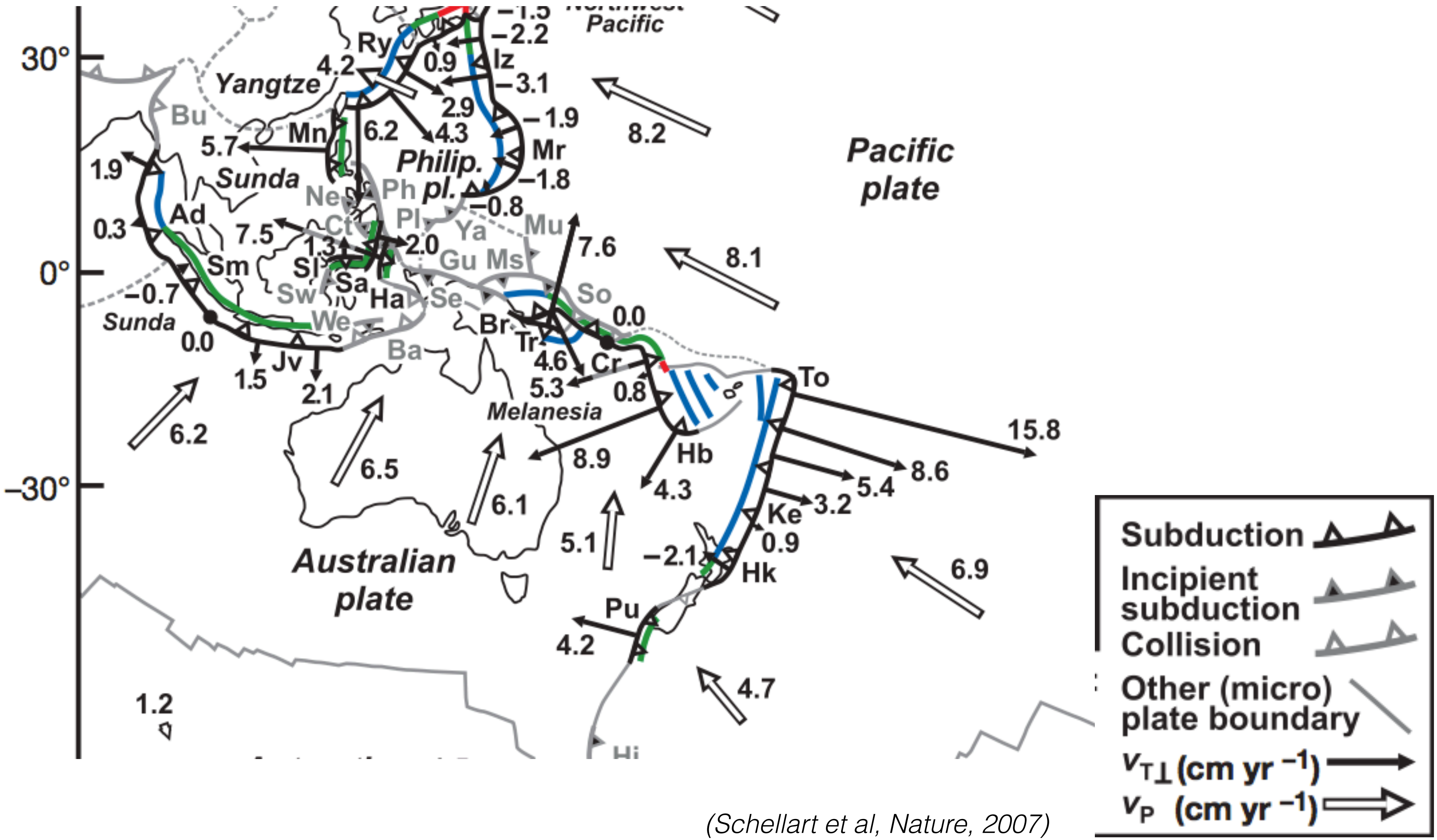
Surface data

- Geometry (length, curvature)
- Velocity (advance, retreat)

(Schellart et al, Nature, 2007)



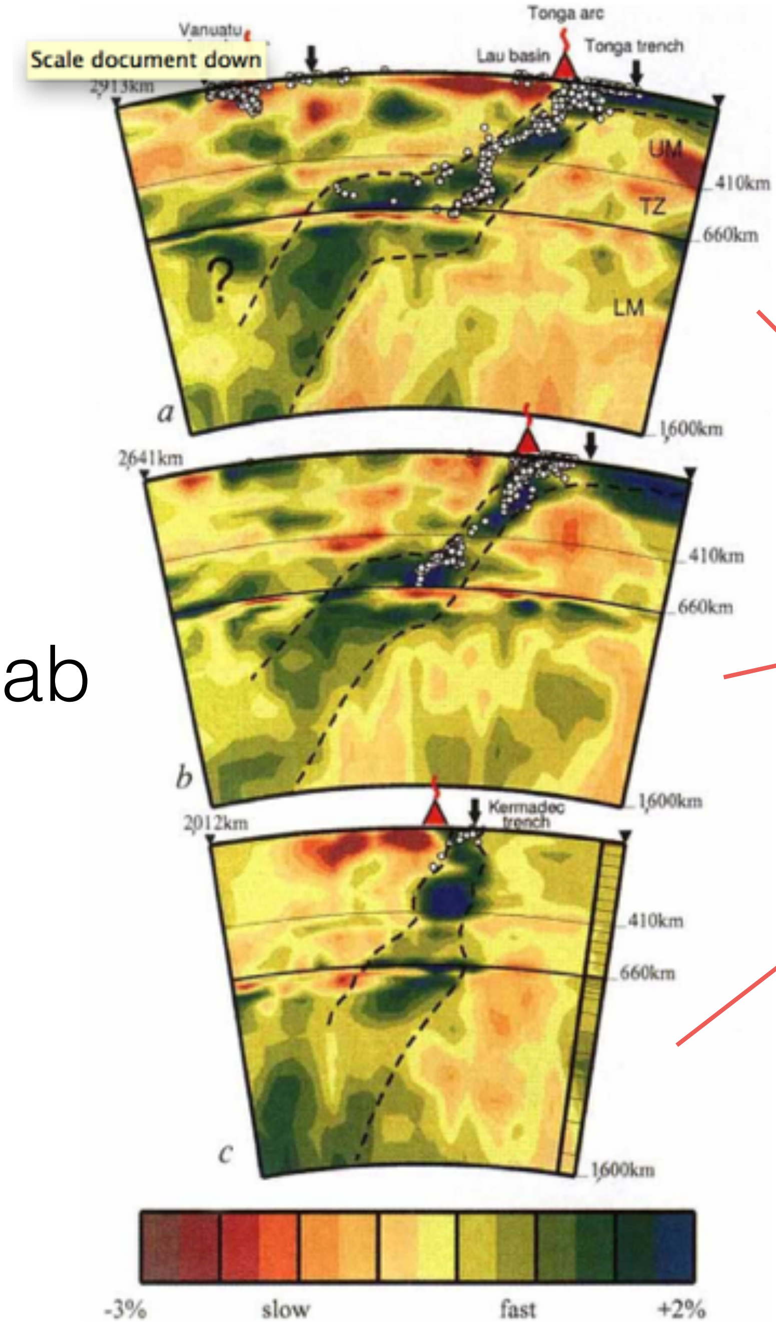
Surface data

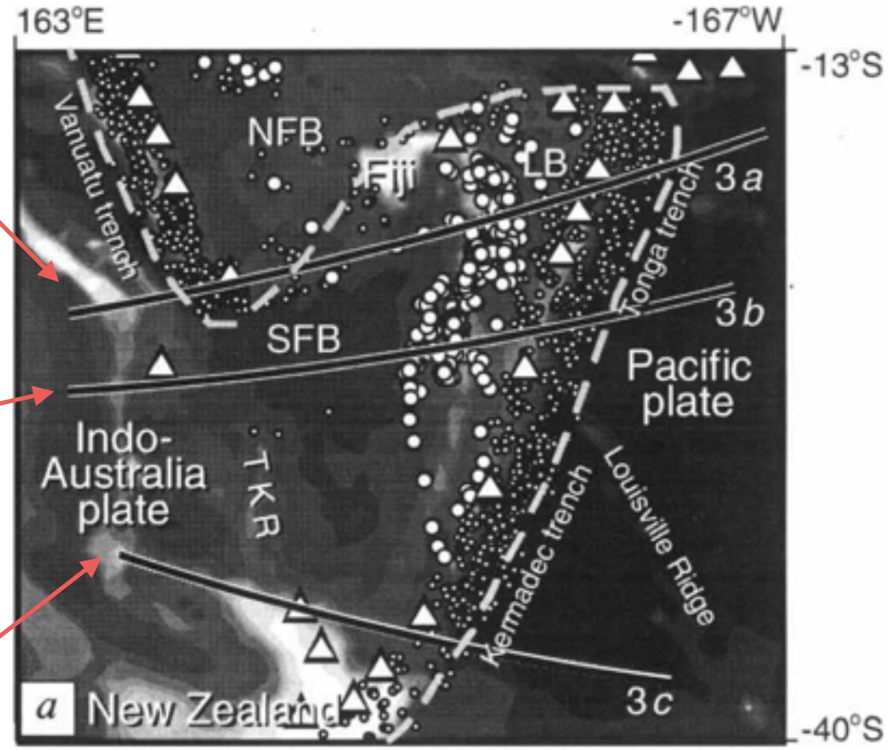


(Schellart et al, Nature, 2007)

Volumetric models / data

Tonga slab

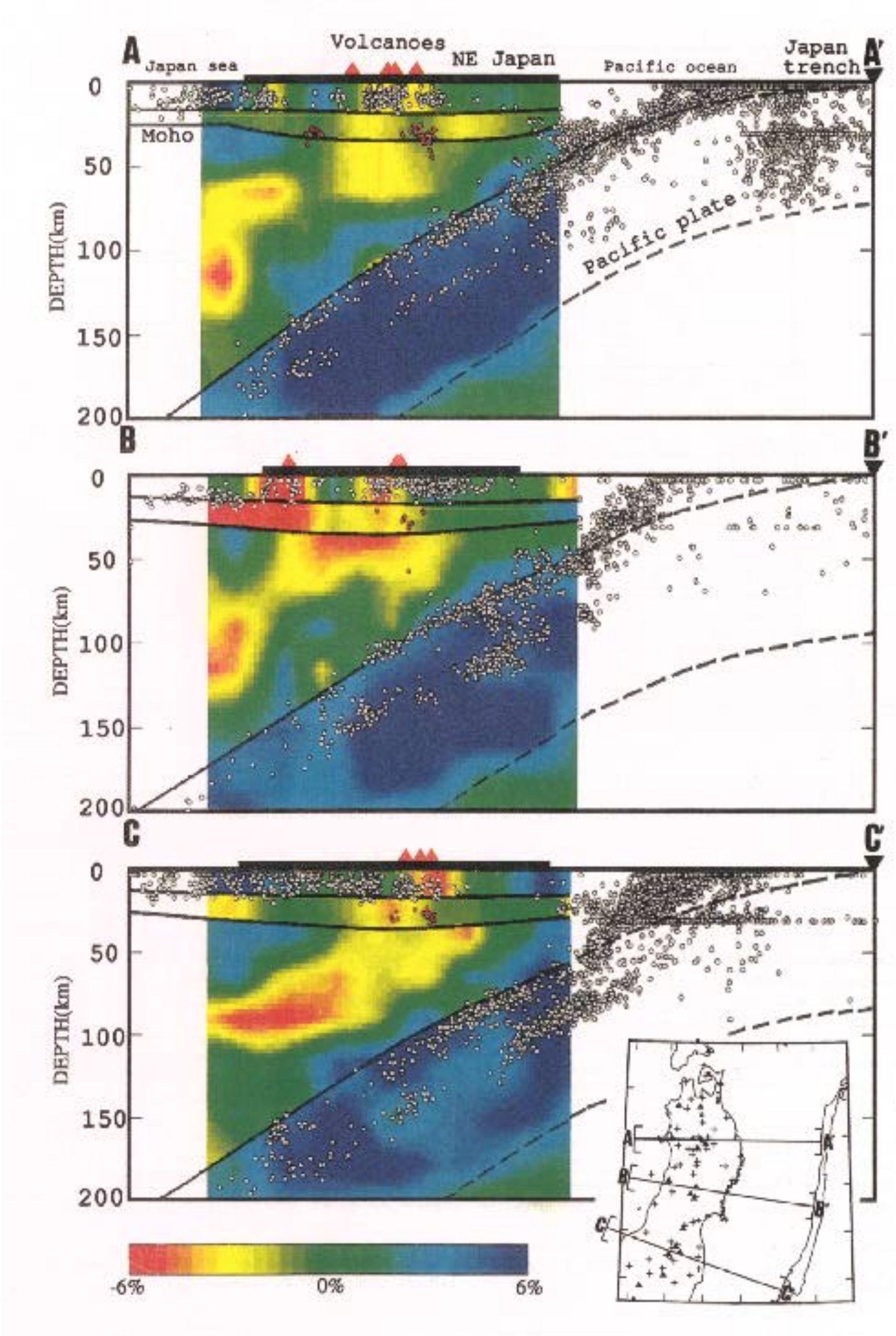




(Van der Hilst, Nature, 1995)

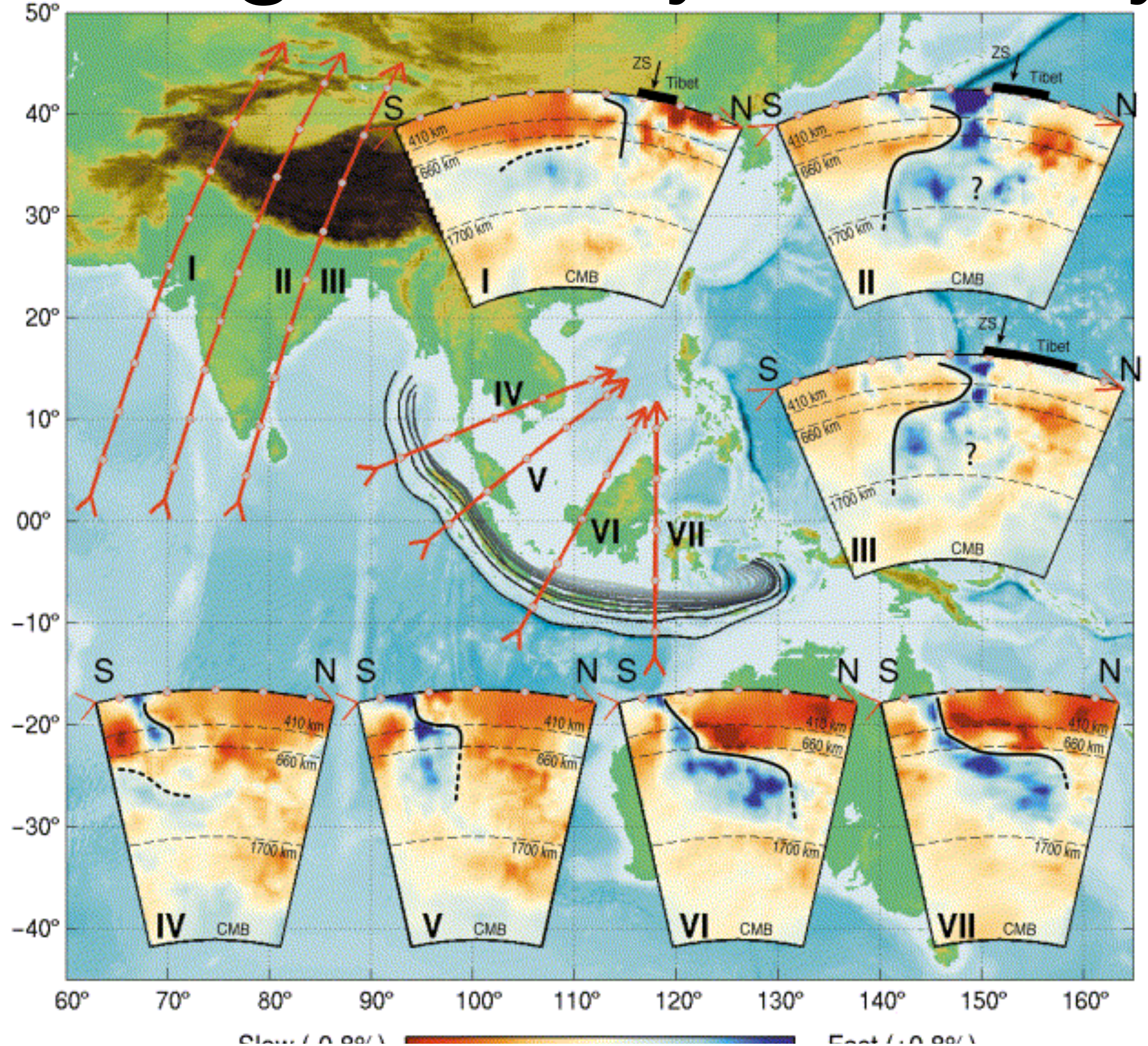
Slab interfaces

Japan



(Zhao et al, Nature, 1992)

Slab geometry diversity



“Slab detachment” — Break-off? gaps? tears?

Seismic gaps… tears?

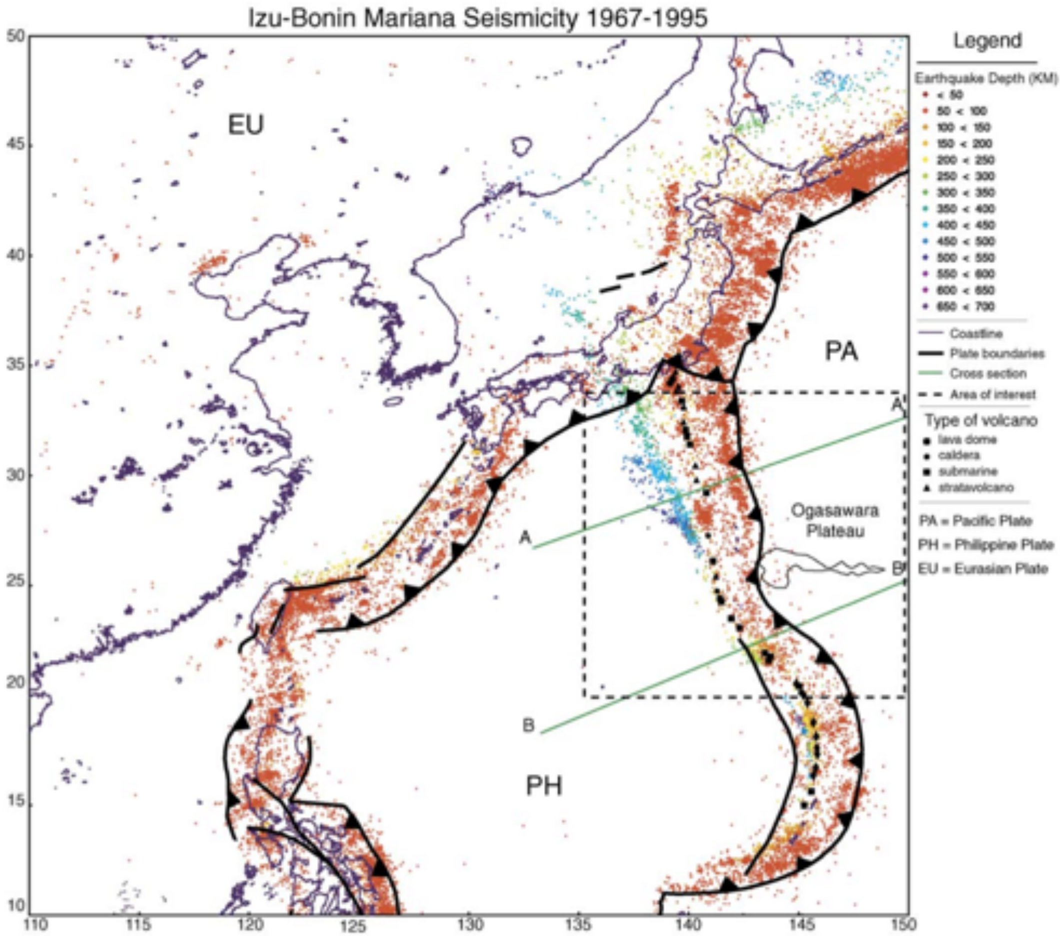
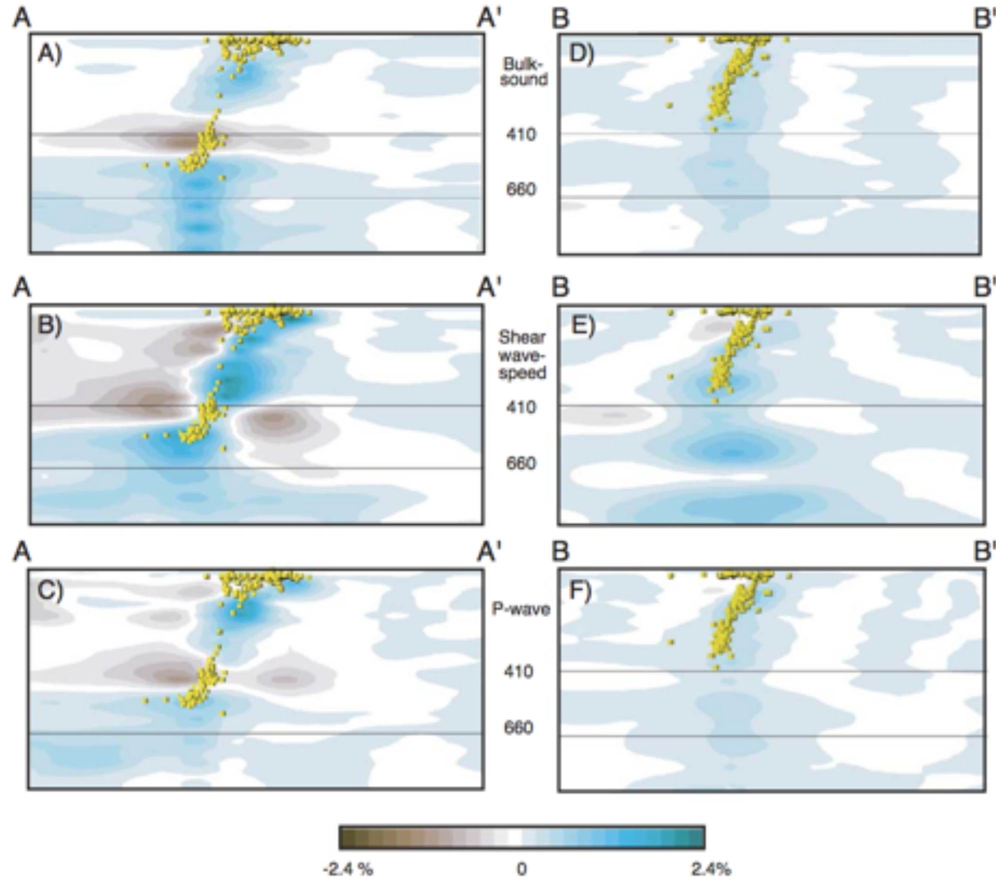


Fig. 1. Map of the Izu–Bonin–Mariana region with the major features of the area, hypocenters of events with magnitudes of 5.0 and greater from the NEIC catalogue, and location of the cross sections used in Fig. 4.



Observations

Seismic gaps… tears?

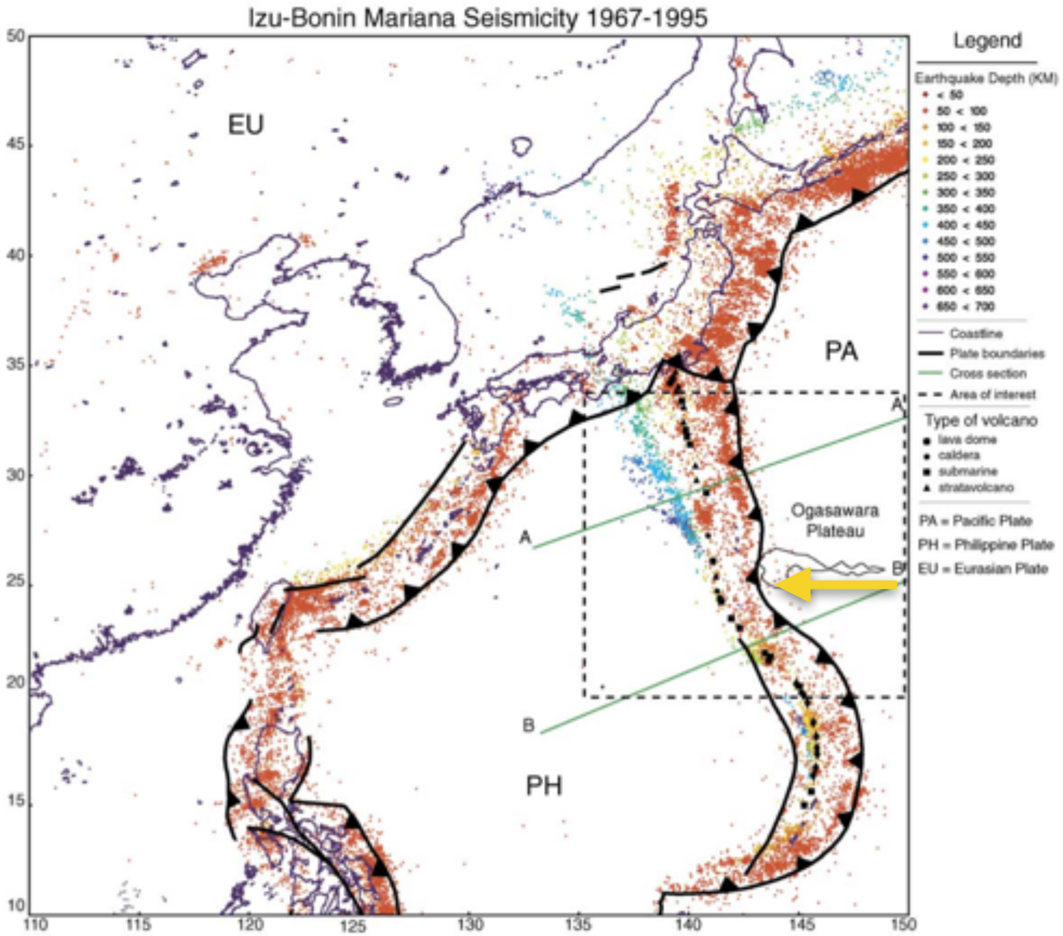
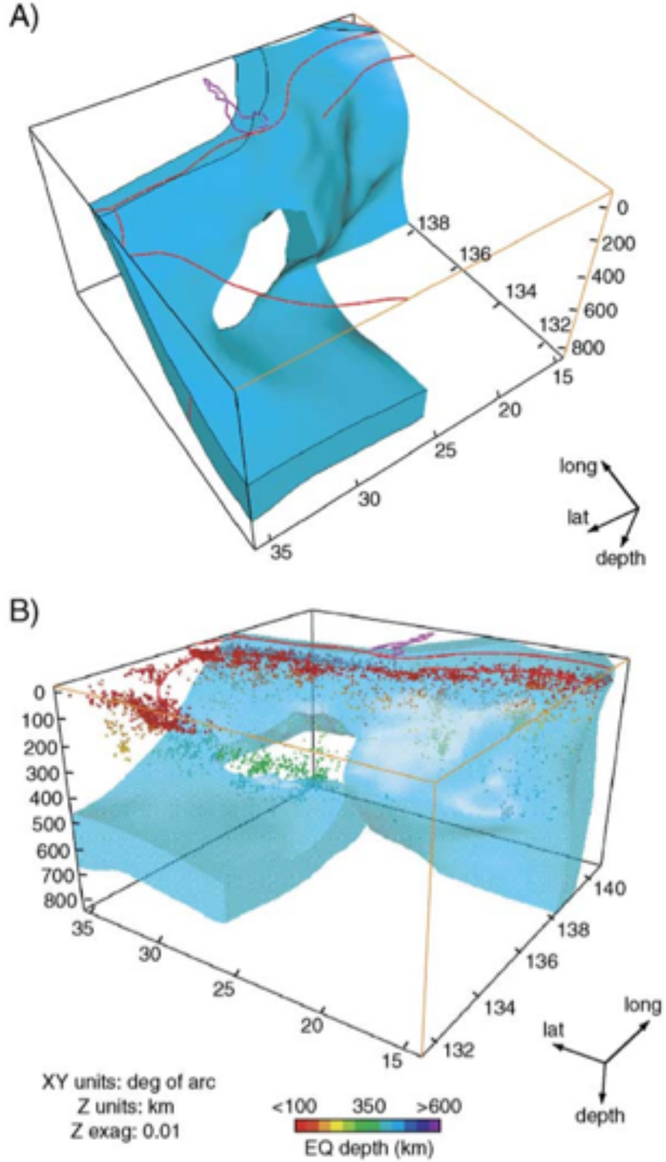


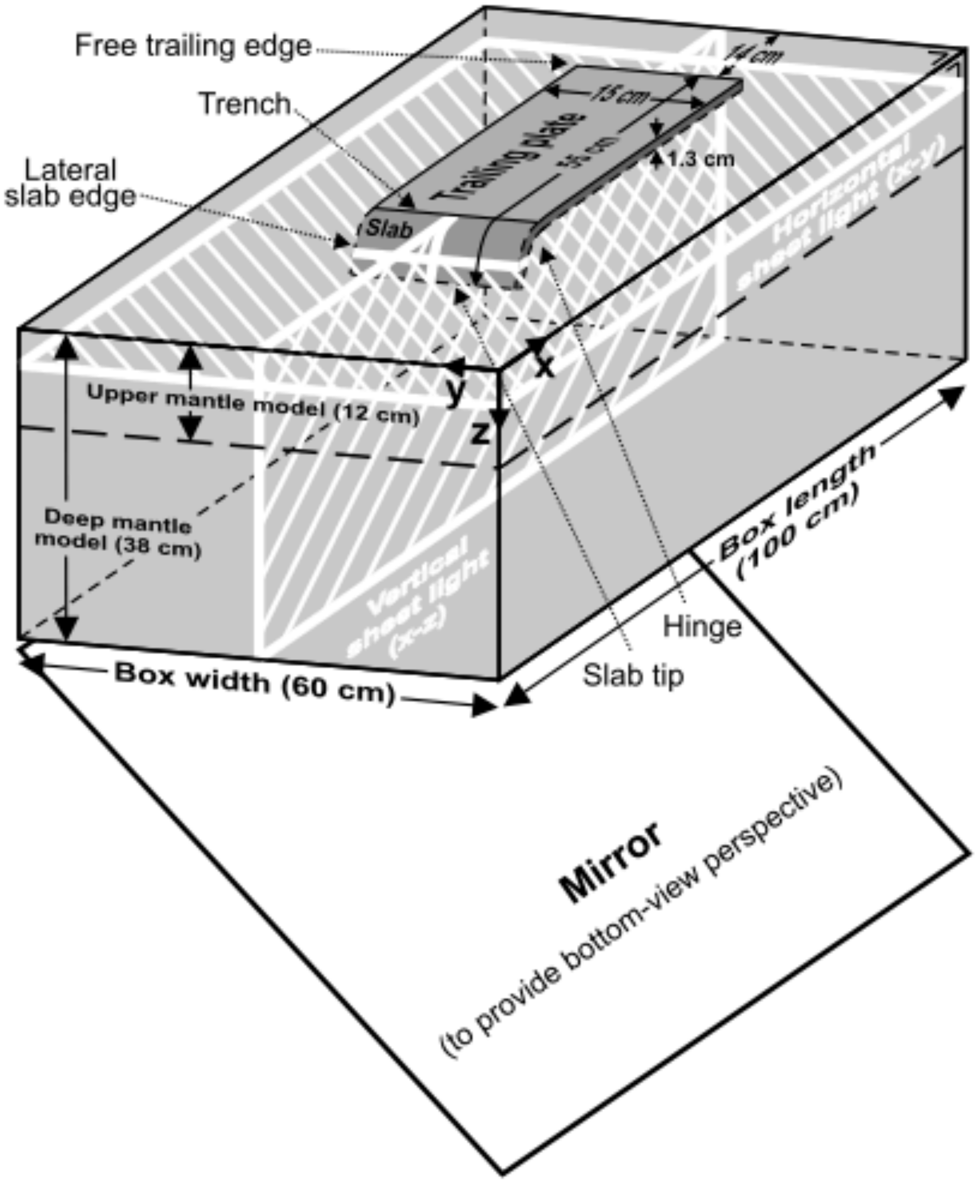
Fig. 1. Map of the Izu–Bonin–Mariana region with the major features of the area, hypocenters of events with magnitudes of 5.0 and greater from the NEIC catalogue, and location of the cross sections used in Fig. 4.



Interpretation

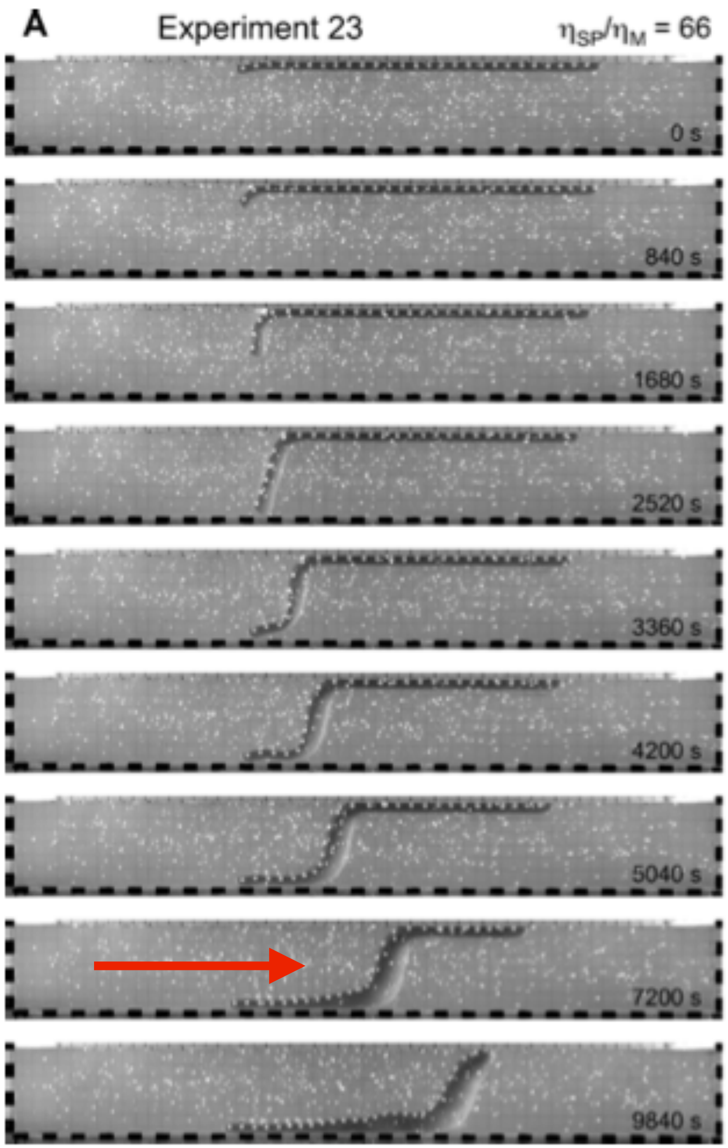
Subduction processes:
Laboratory experiments

Laboratory experiments

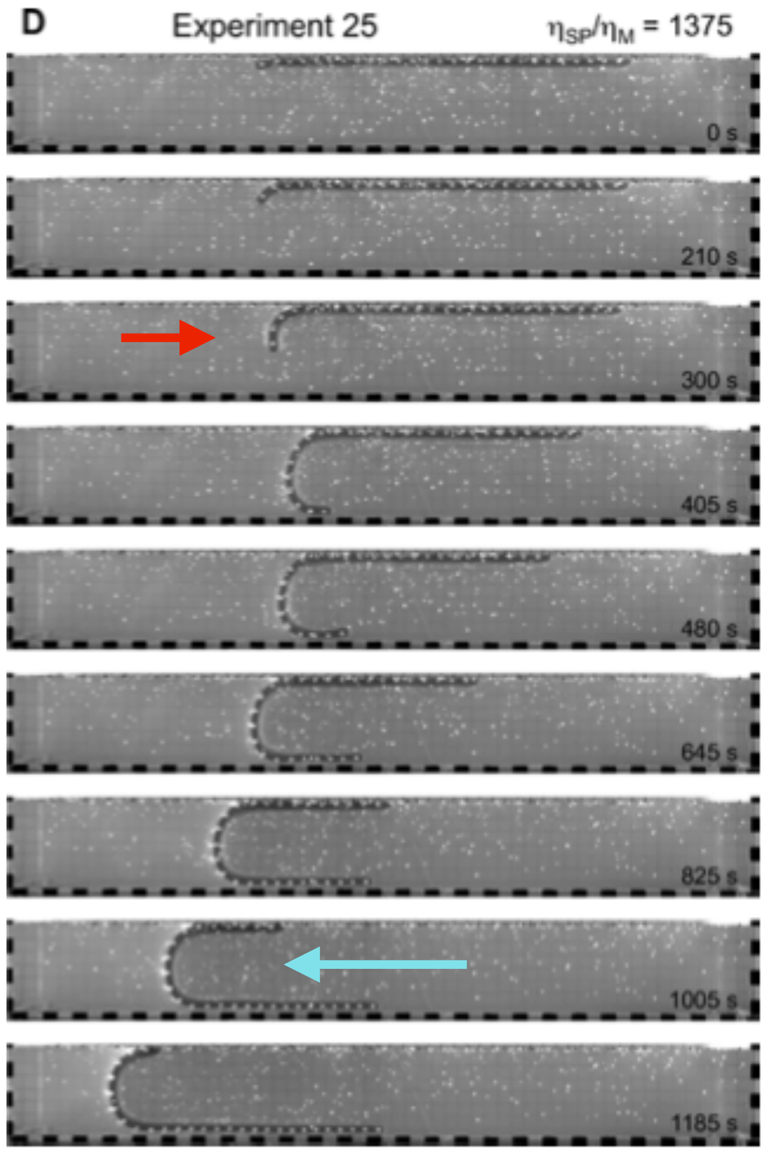


- No over-riding plate
- No ridge push
- Driven solely by "slab pull" (imposed perturbation)
- Viscous rheology
    - "slab" — silicone
    - "mantle" — glucose

Free-subduction



- "Upper mantle" models: scaled tank depth ~720 km
- Vary the viscosity contrast between the slab and mantle



slab retreat

slab retreat then ac

Shallow mantle models

Movie upper mantle experiment 23 (side-view perspective)

$\eta_{SP} / \eta_{M} = 66$

W.P. Schellart, *Geochemistry Geophysics Geosystems* [2008]

Movie upper mantle experiment 22 (side-view perspective)

$\eta_{SP} / \eta_{M} = 709$

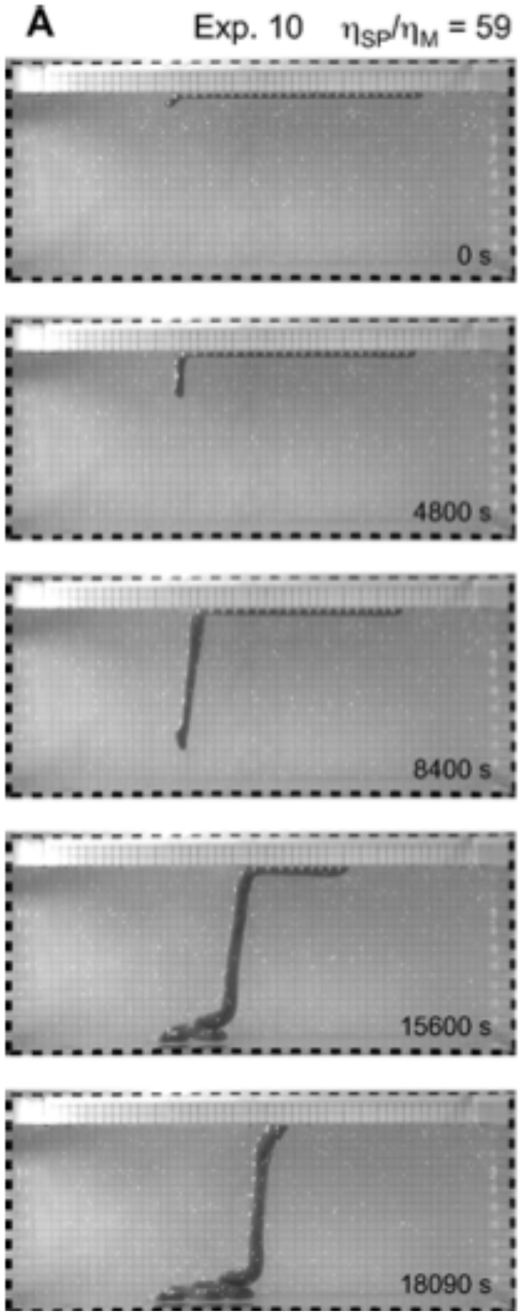
W.P. Schellart, *Geochemistry Geophysics Geosystems* [2008]

Movie upper mantle experiment 25 (side-view perspective)

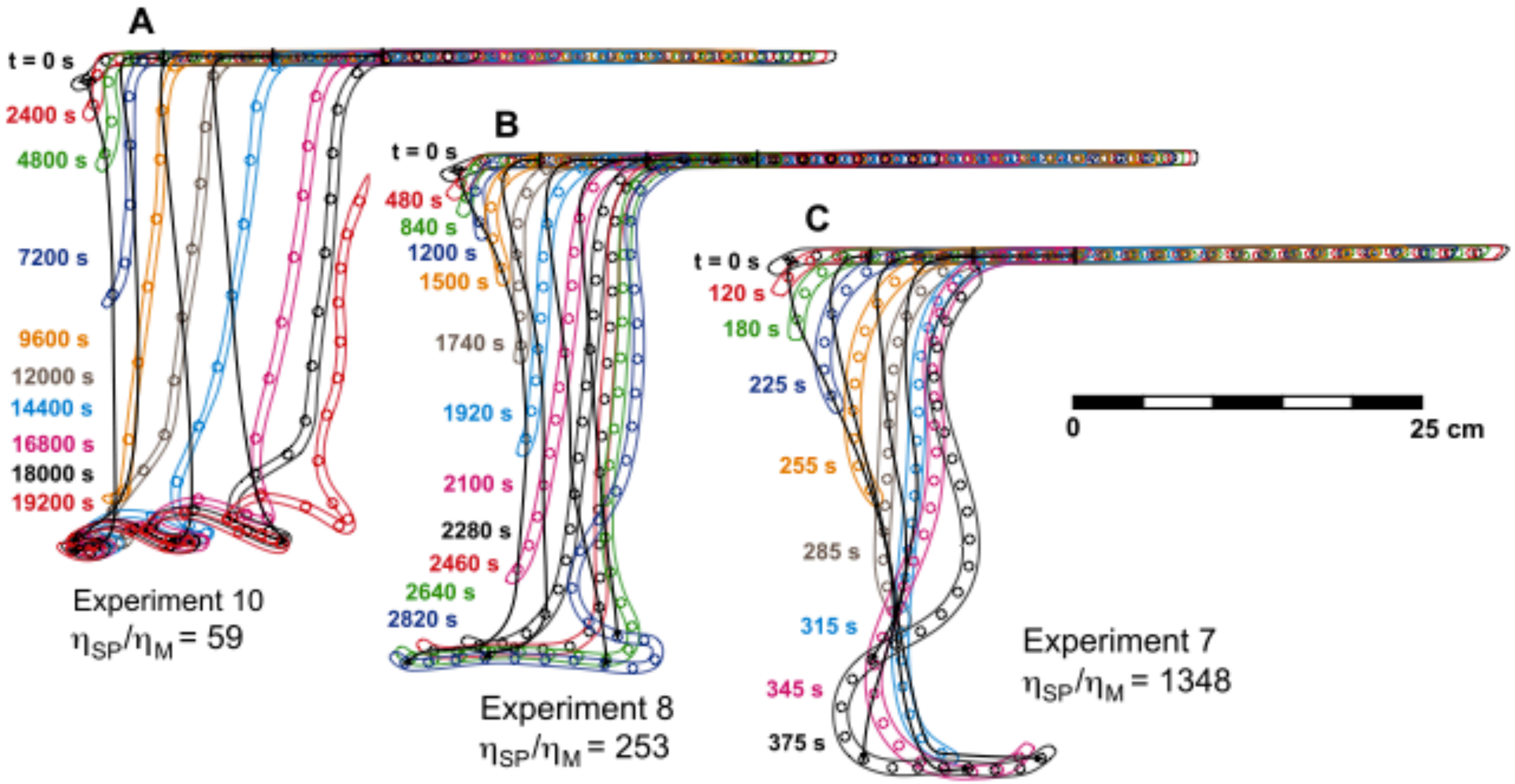
$\eta_{SP} / \eta_{M} = 1375$

W.P. Schellart, *Geochemistry Geophysics Geosystems* [2008]

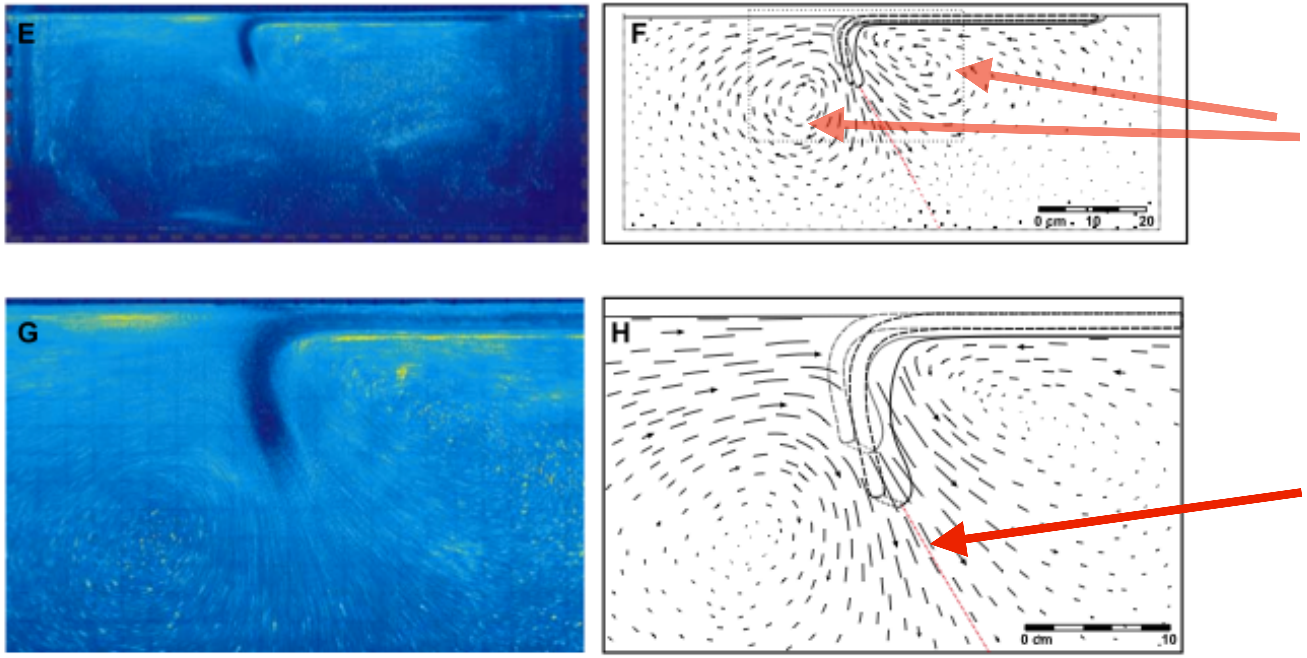
Deep mantle models



- “Upper-lower mantle” models: scaled tank depth ~2280 km

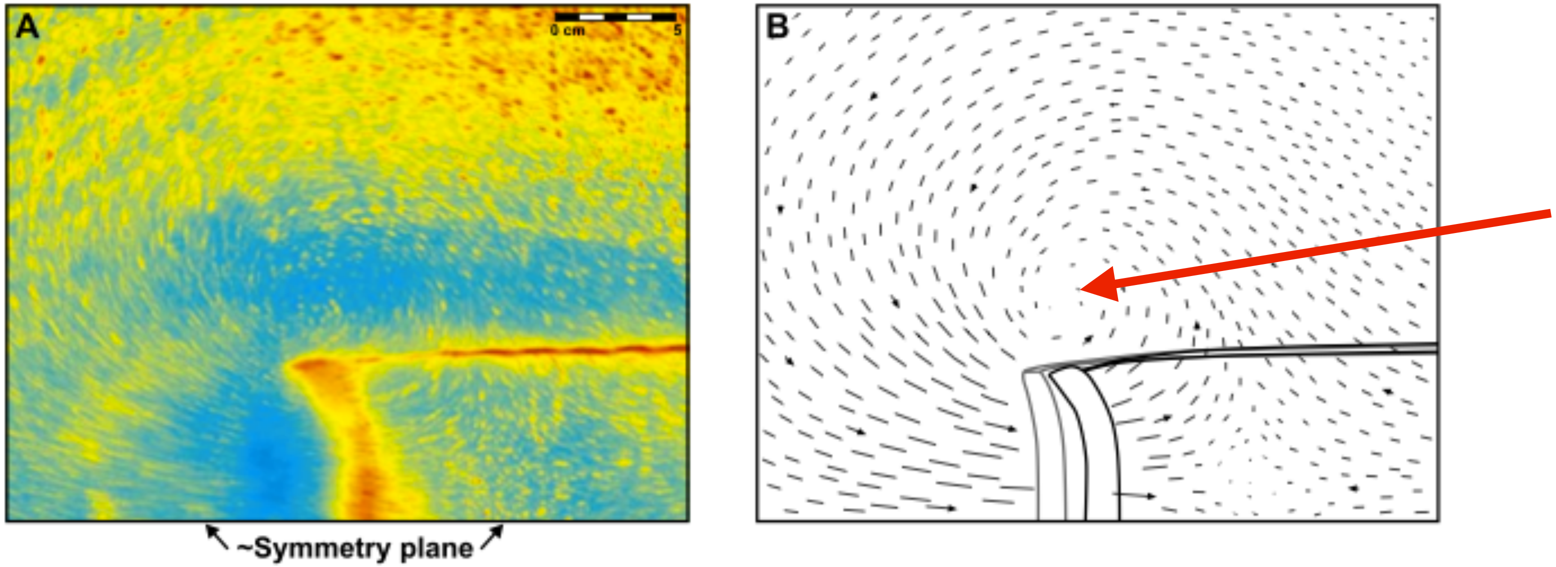


Flow field



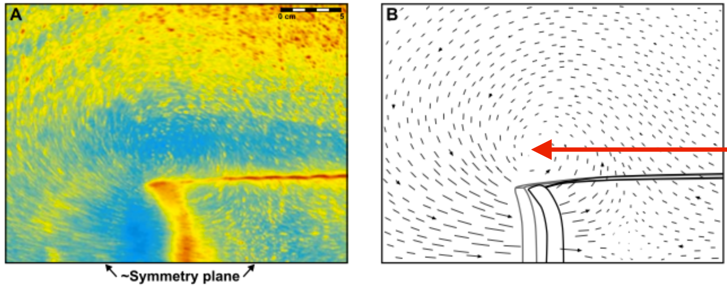
Strong poloidal mantle flow

No slab tip poloidal mantle flow



Strong toroidal flow around slab edges within the mantle

Flow field



Strong toroidal flow around slab edges within the mantle

Movie upper mantle experiment 19

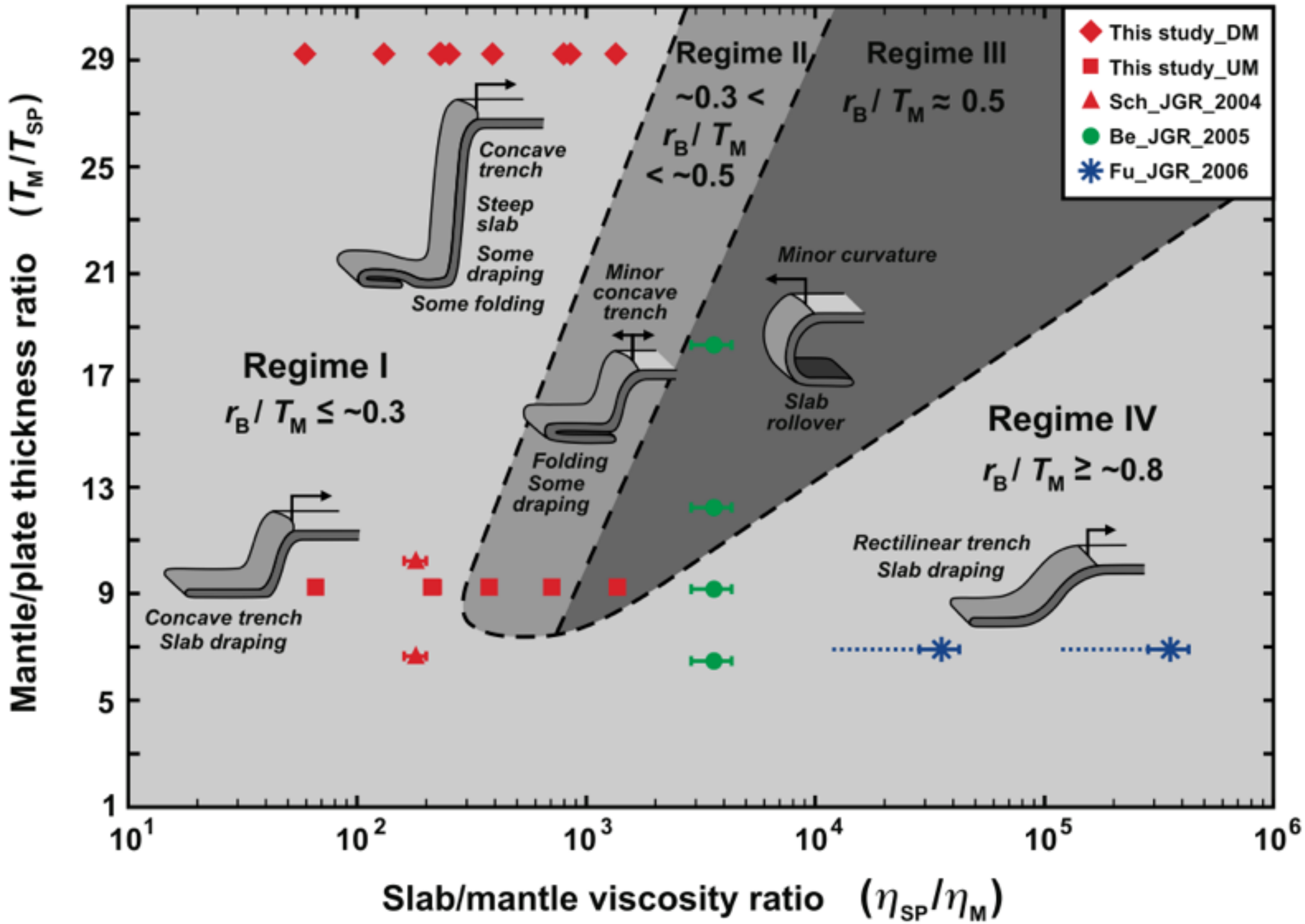
(bottom-view perspective)

$\eta_{SP} / \eta_{M} = 217$

W.P. Schellart

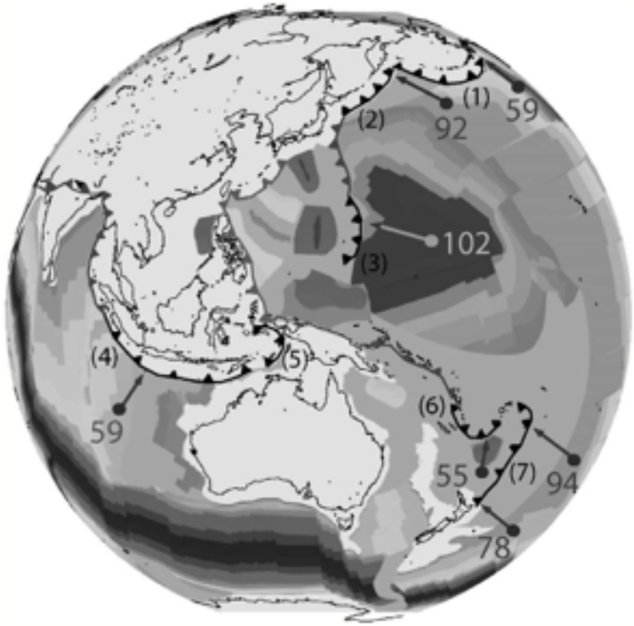
***Geochemistry Geophysics Geosystems* [2008]**

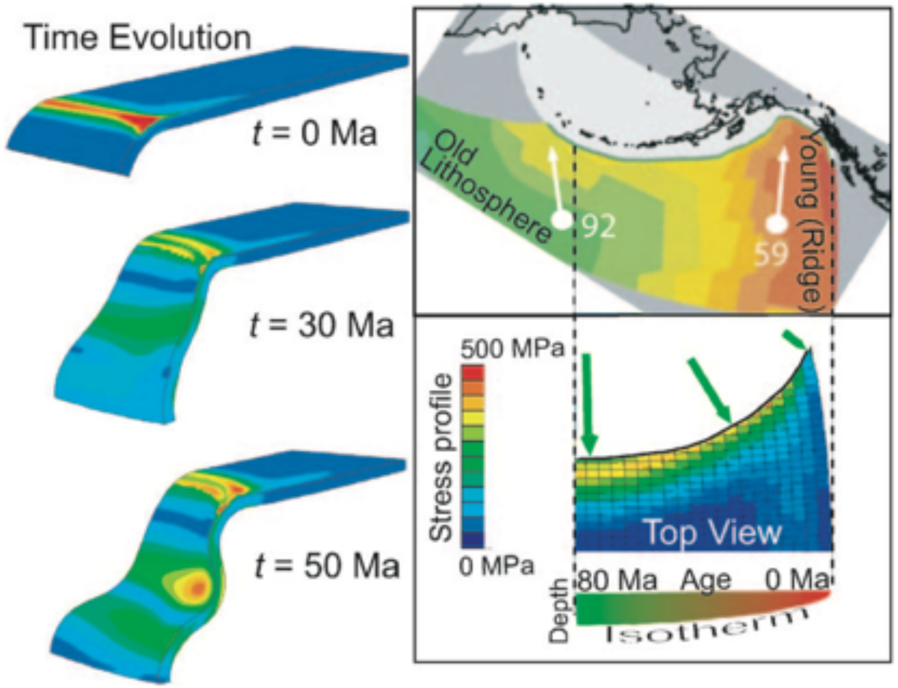
Subduction regimes



Subduction processes: Insights from numerical experiments

Slab curvature





- Curvature of ocean arcs previously attributed to spherical nature of Earth
- Curvature can arise from
  - feedback between migrating lithosphere and mantle flow (lower bound)
  - internal heterogeneities (upper bound)

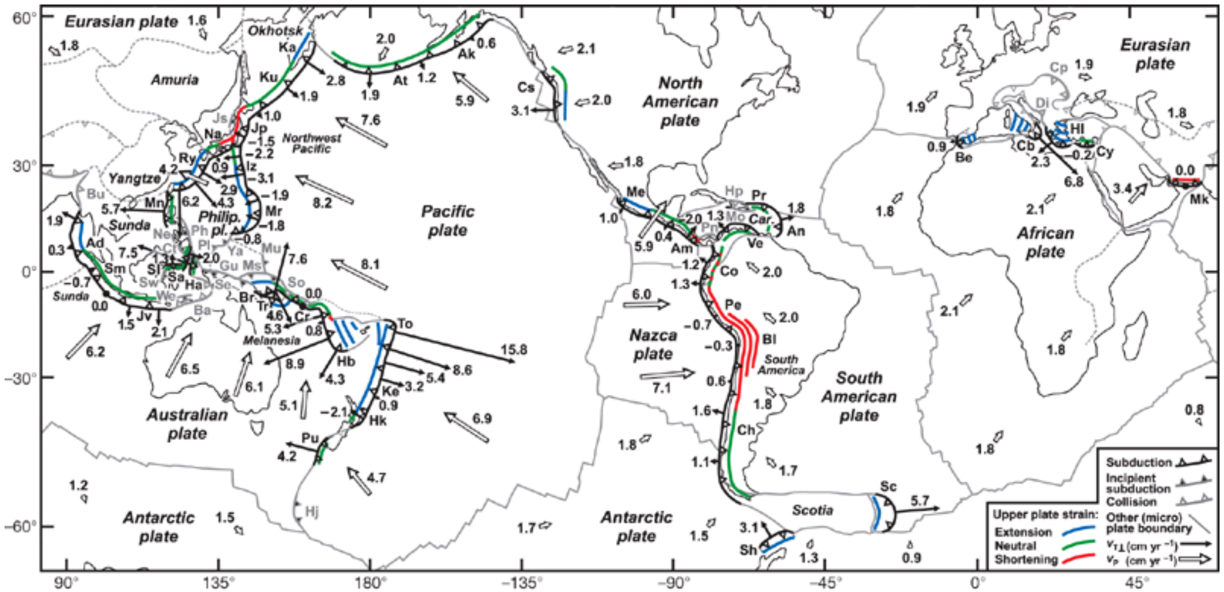
Slab curvature

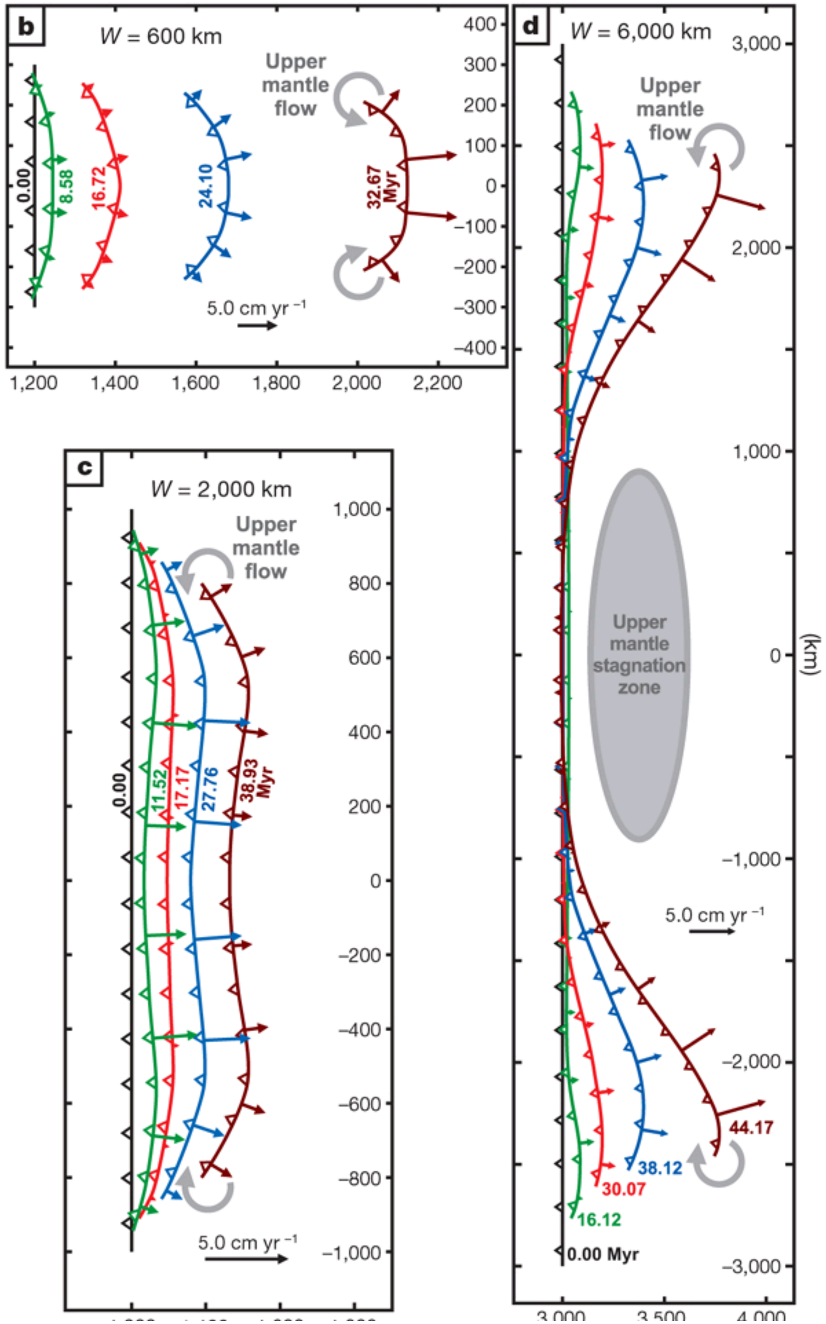
(Schellart et al, Nature, 2007)

Evolution and diversity of subduction zones controlled by slab width

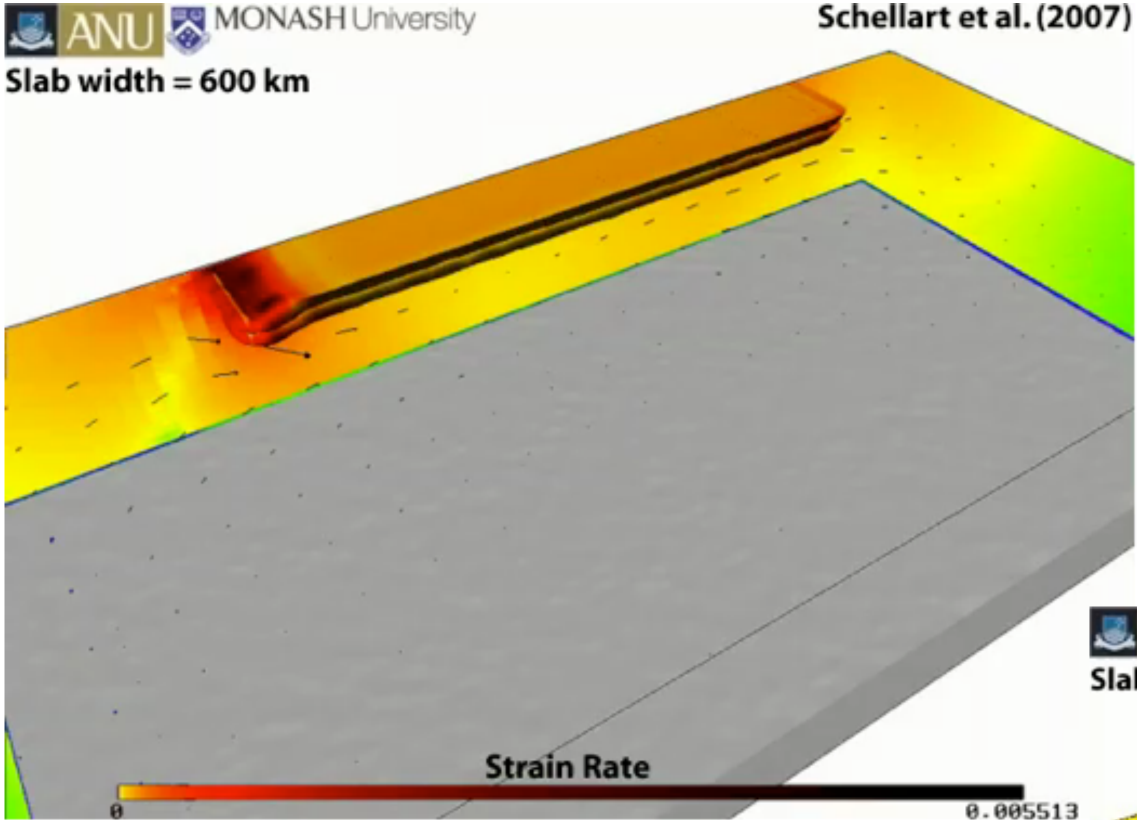
W. P. Schellart[1], J. Freeman[1], D. R. Stegman[2], L. Moresi[2] & D. May[2]

Subducting slabs provide the main driving force for plate motion and flow in the Earth's mantle[1–4], and geodynamic, seismic and geochemical studies offer insight into slab dynamics and subduction-induced flow[3–15]. Most previous geodynamic studies treat subduction zones as either infinite in trench-parallel extent[3,5,6] (that is, two-dimensional) or finite in width but fixed in space[7,16]. Subduction zones and their associated slabs are, however, limited in lateral extent (250–7,400 km) and their three-dimensional geometry evolves over time. Here we show that slab width controls two first-order features of plate tectonics—the curvature of subduction zones and their tendency to retreat backwards with time. Using three-dimensional numerical simulations of free subduction, we show that trench migration rate is inversely related to slab width and depends on proximity to a lateral slab edge. These results are consistent with retreat velocities observed globally, with maximum velocities (6–16 cm yr^{-1}) only observed close to slab edges (<1,200 km), whereas far from edges (>2,000 km) retreat velocities are always slow (<2.0 cm yr^{-1}). Models with narrow slabs (≤1,500 km) retreat fast and develop a curved geometry, concave towards the mantle wedge side. Models with slabs intermediate in width (~2,000–3,000 km) are sublinear and retreat more slowly. Models with wide slabs (≥4,000 km) are nearly stationary in the centre and develop a convex geometry, whereas trench retreat increases towards concave-shaped edges. Additionally, we identify periods (5–10 Myr) of slow trench advance at the centre of wide slabs. Such wide-slab behaviour may explain mountain building in the central Andes, as being a consequence of its tectonic setting, far from slab edges.

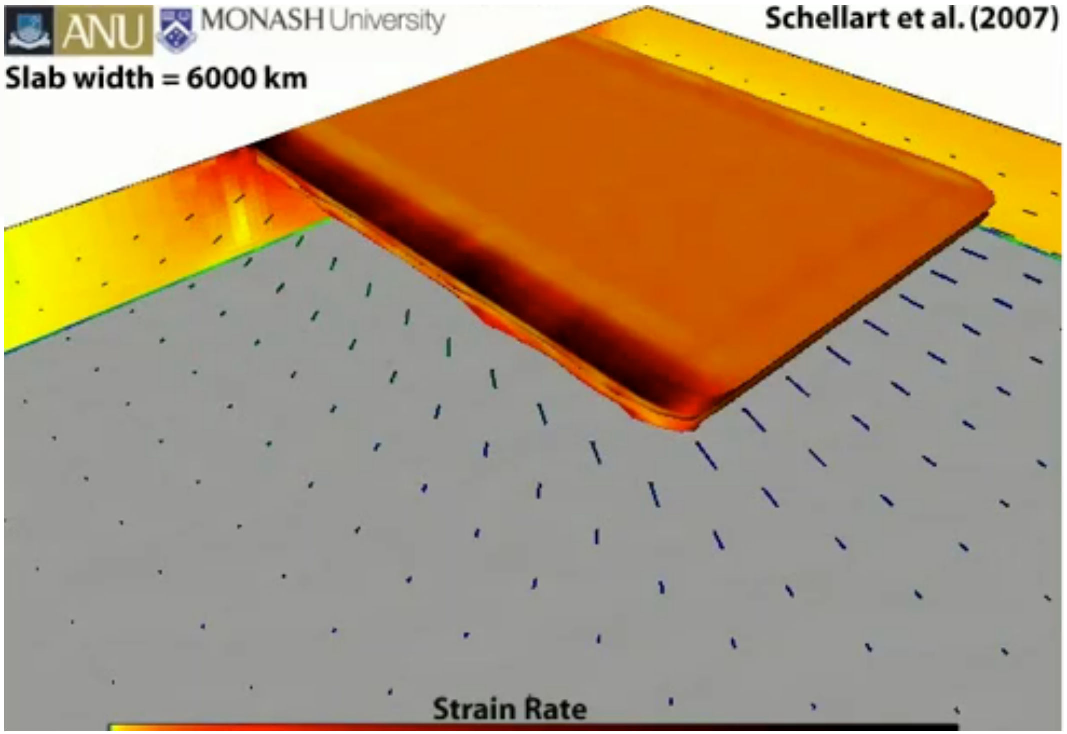




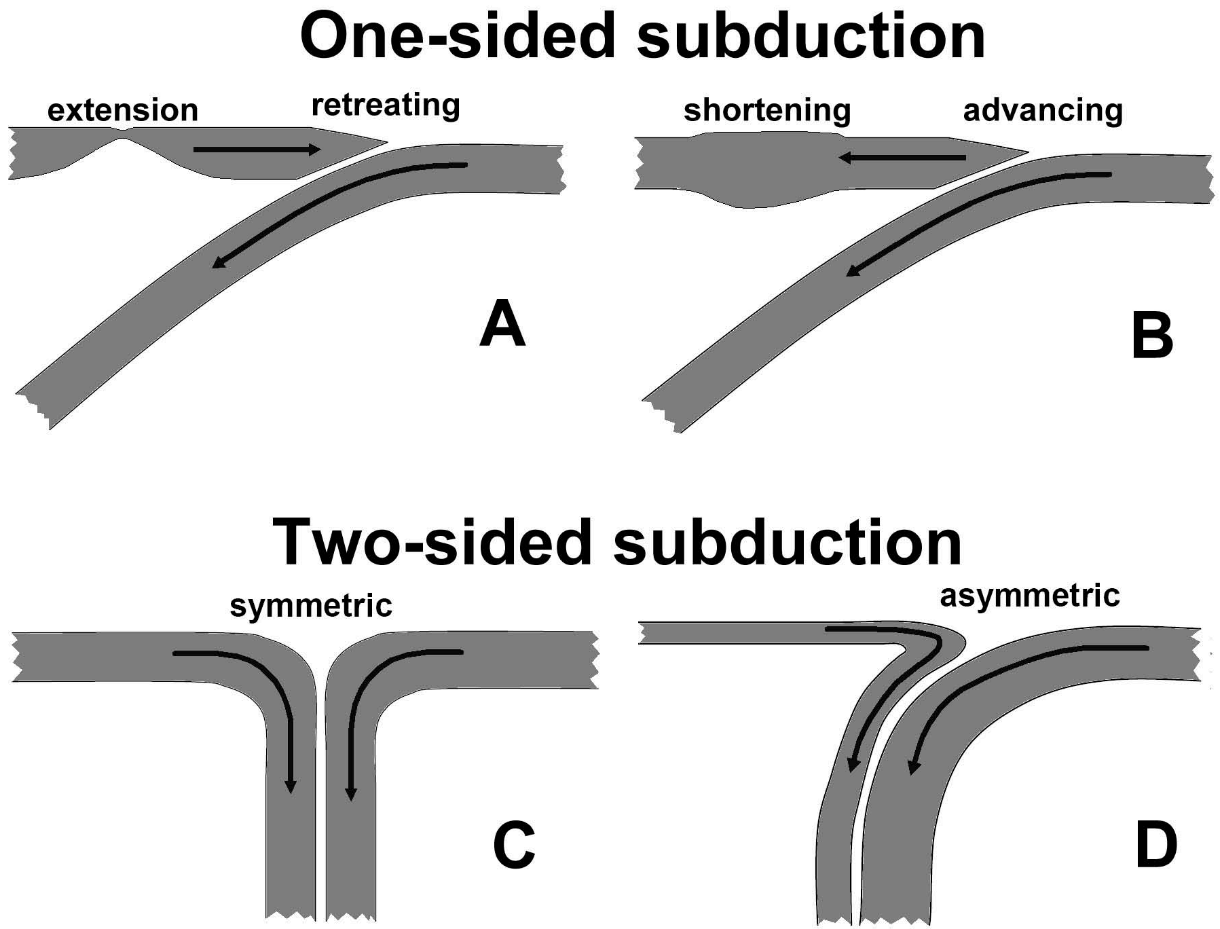
Slab curvature



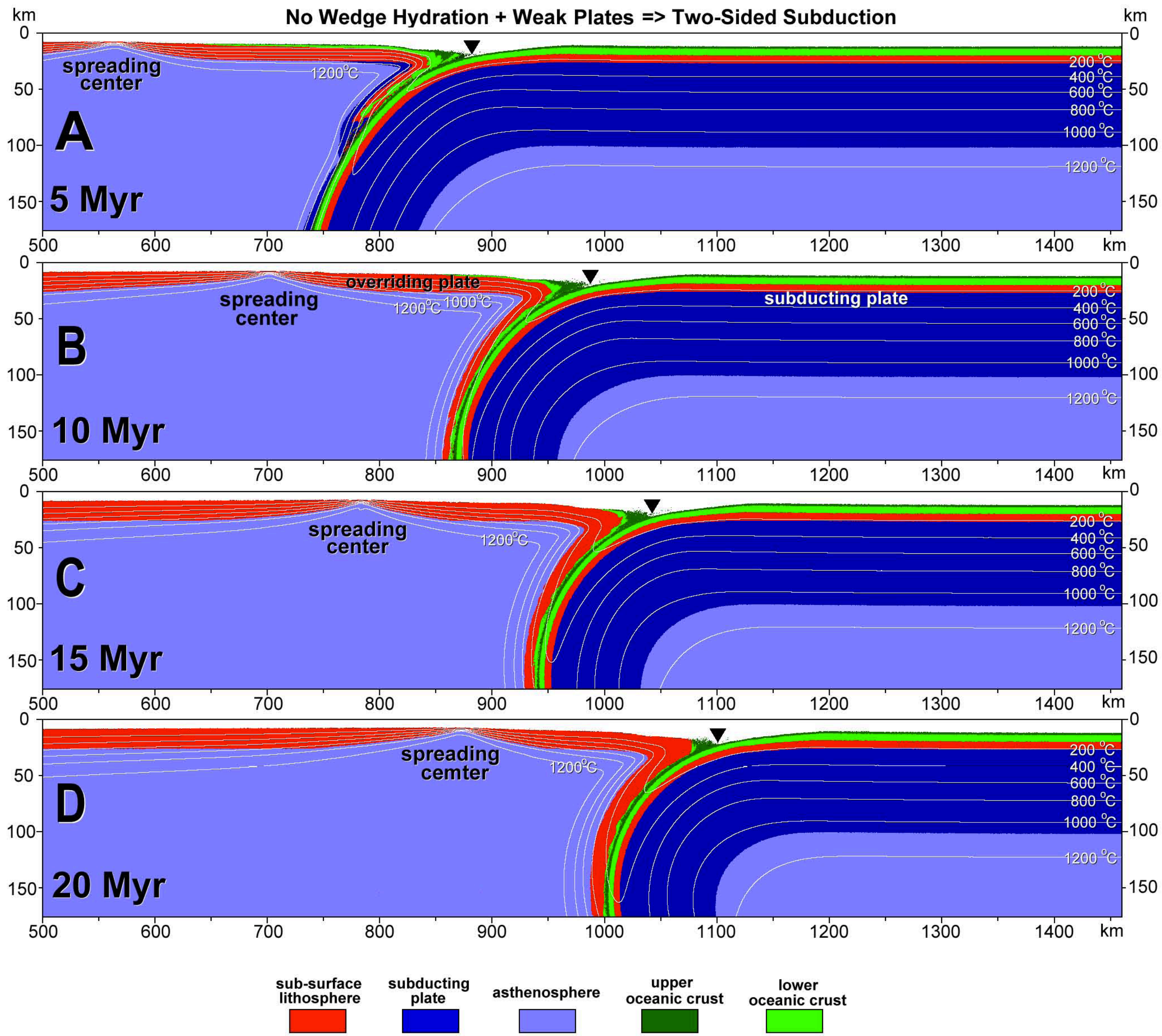
(Schellart et al, Nature, 2007)



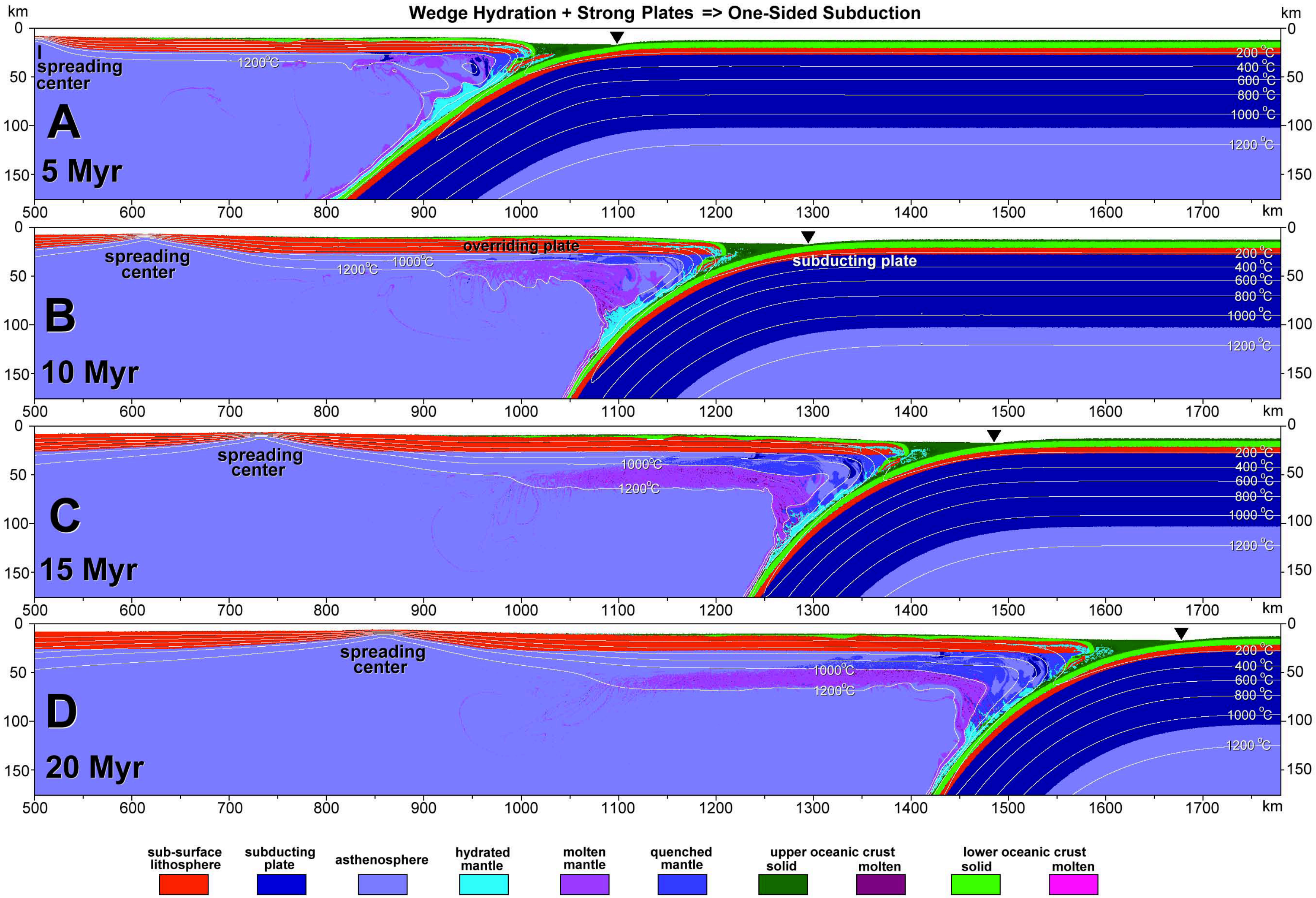
Subduction style



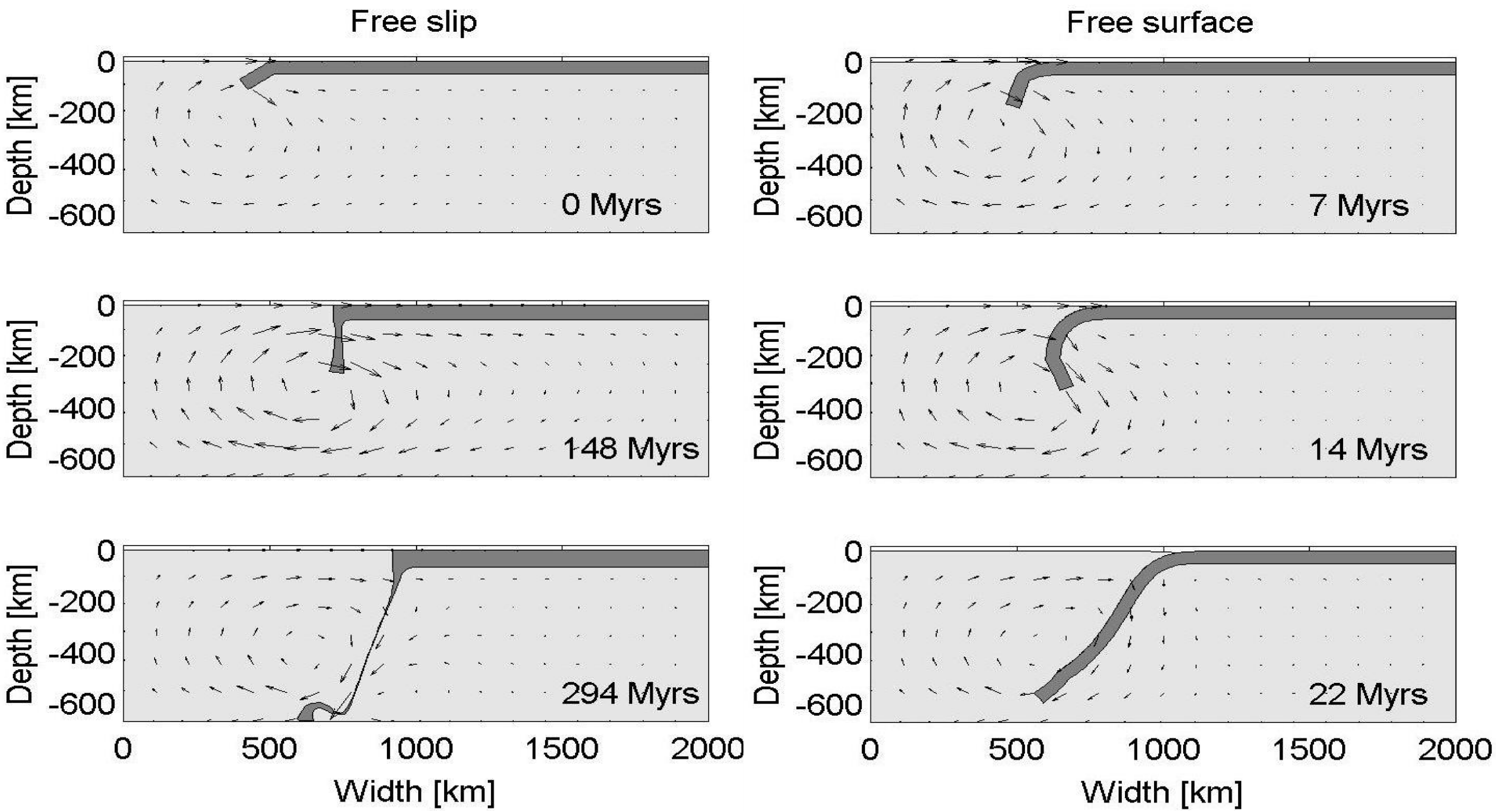
Subduction style



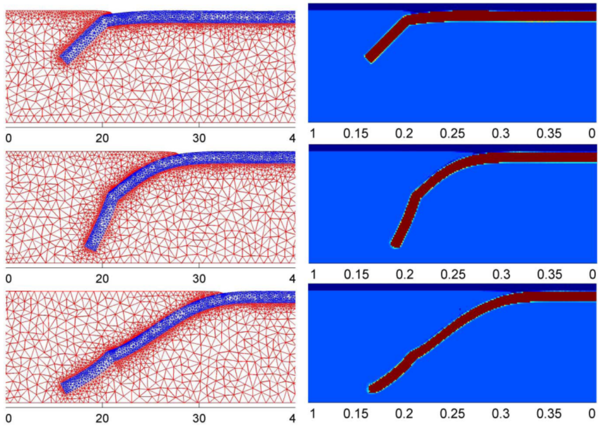
Subduction style



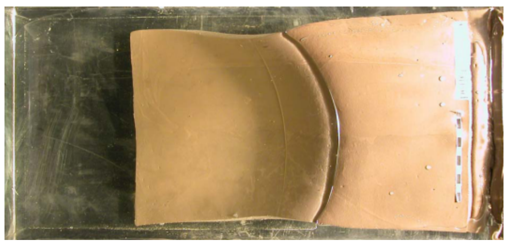
Subduction style



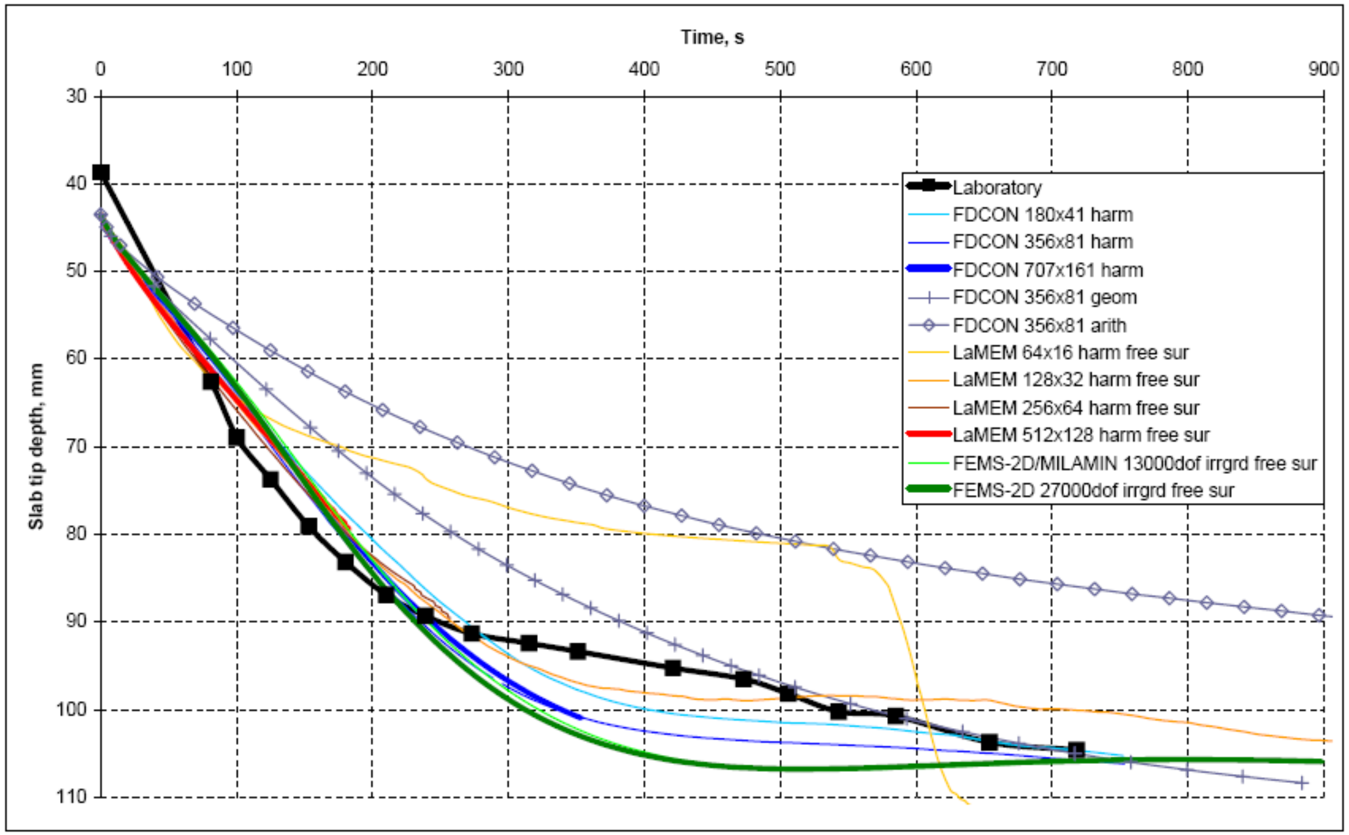
Lab versus numerics



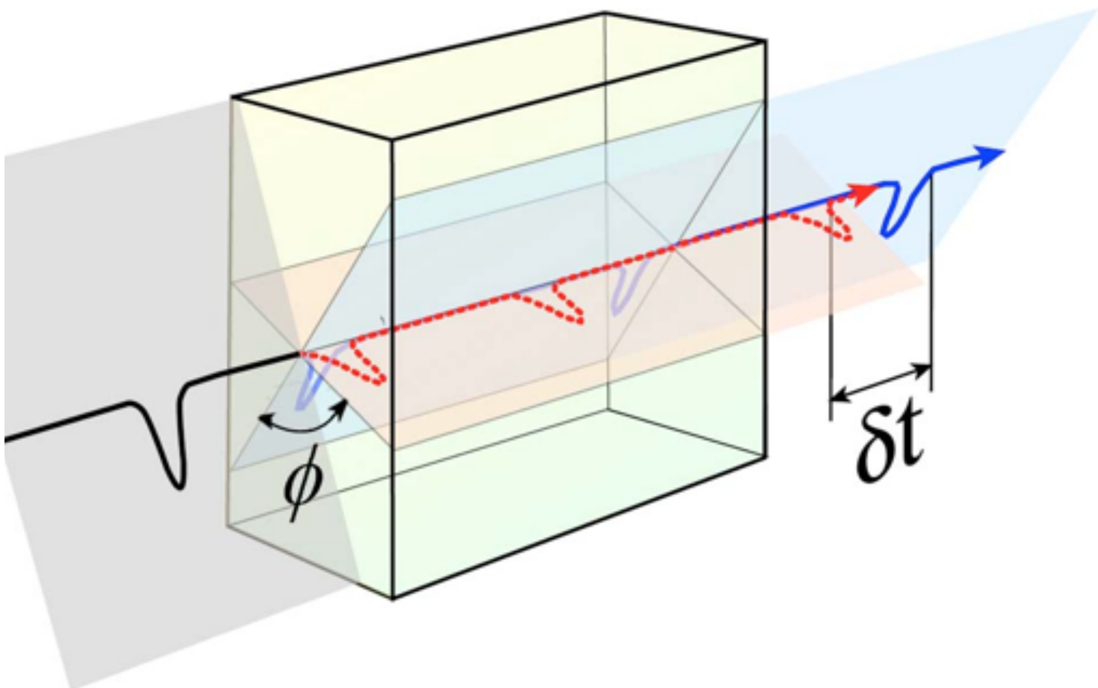
side view



bottom view



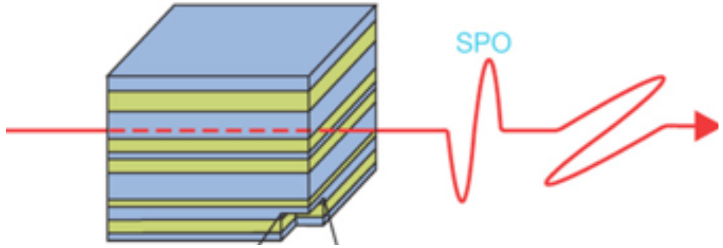
Seismic anisotropy



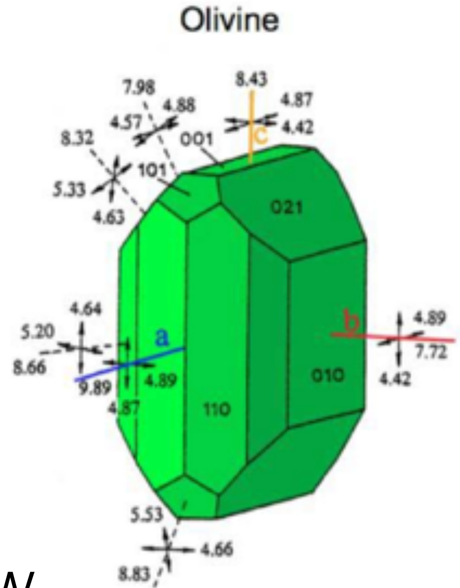
- Shear wave splitting in anisotropic material
- Polarized shear wave enters, two waves exit at different speeds and with a phase shift
- Delay and phase shift can be used to infer the nature of the effective anisotropic constitutive tensor

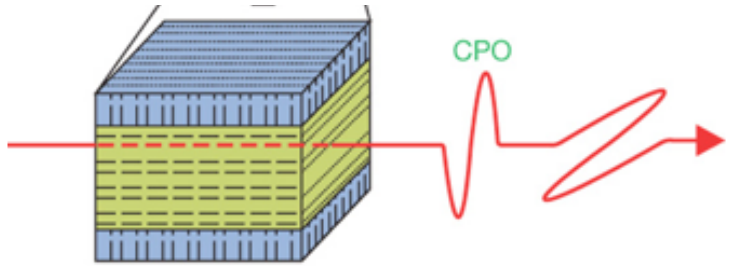
Sources of seismic anisotropy

- SPO (shape preferred orientation)
  - Due to material inhomogeneity, e.g. layering, aligned faults / cracks, aligned melt / fluid lenses

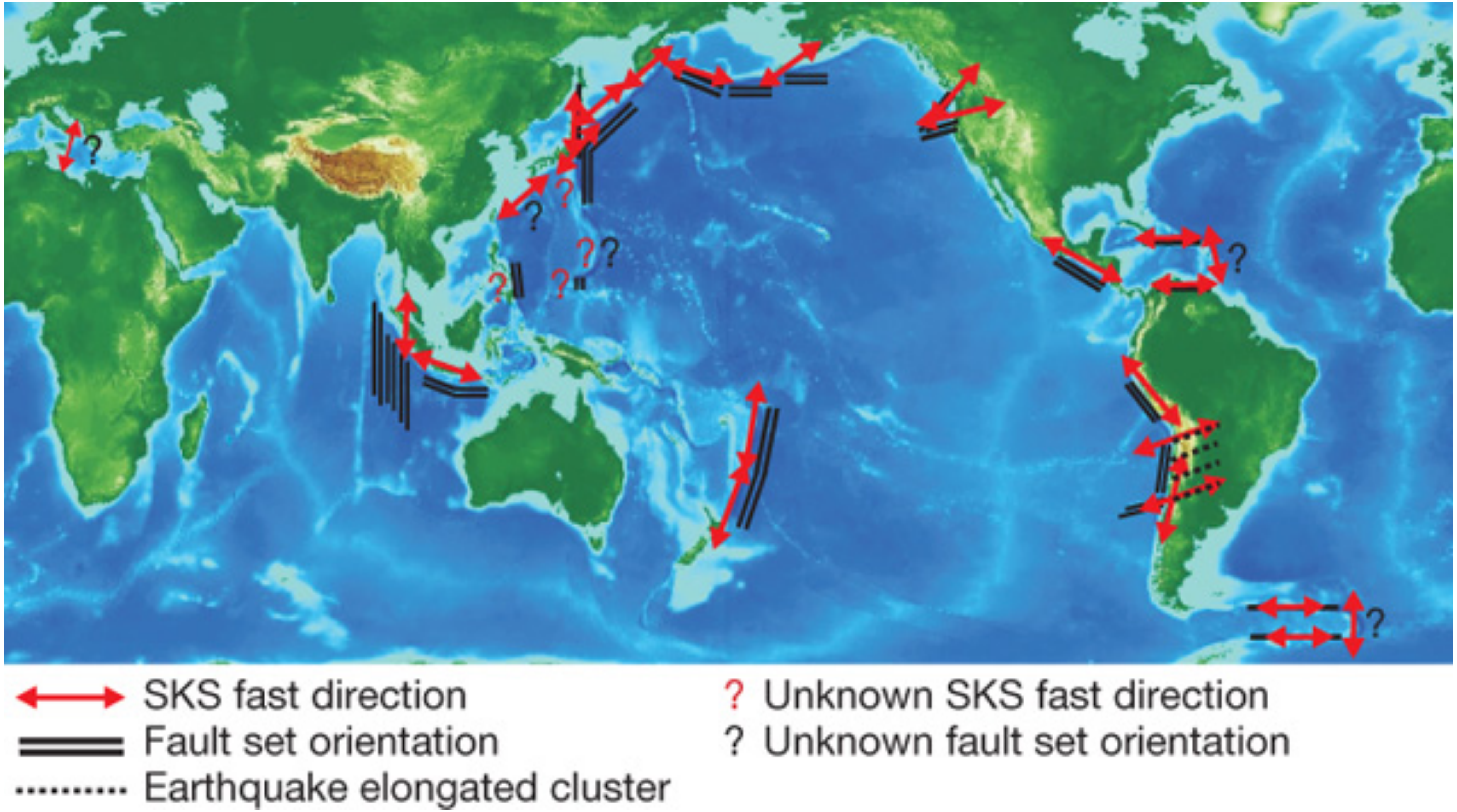


- CPO / LPO (crystal / lattice preferred orientation)
  - Olivine crystal is highly anisotropic
  - Under dry conditions, olivine aligns with its fast axis in the direction of flow

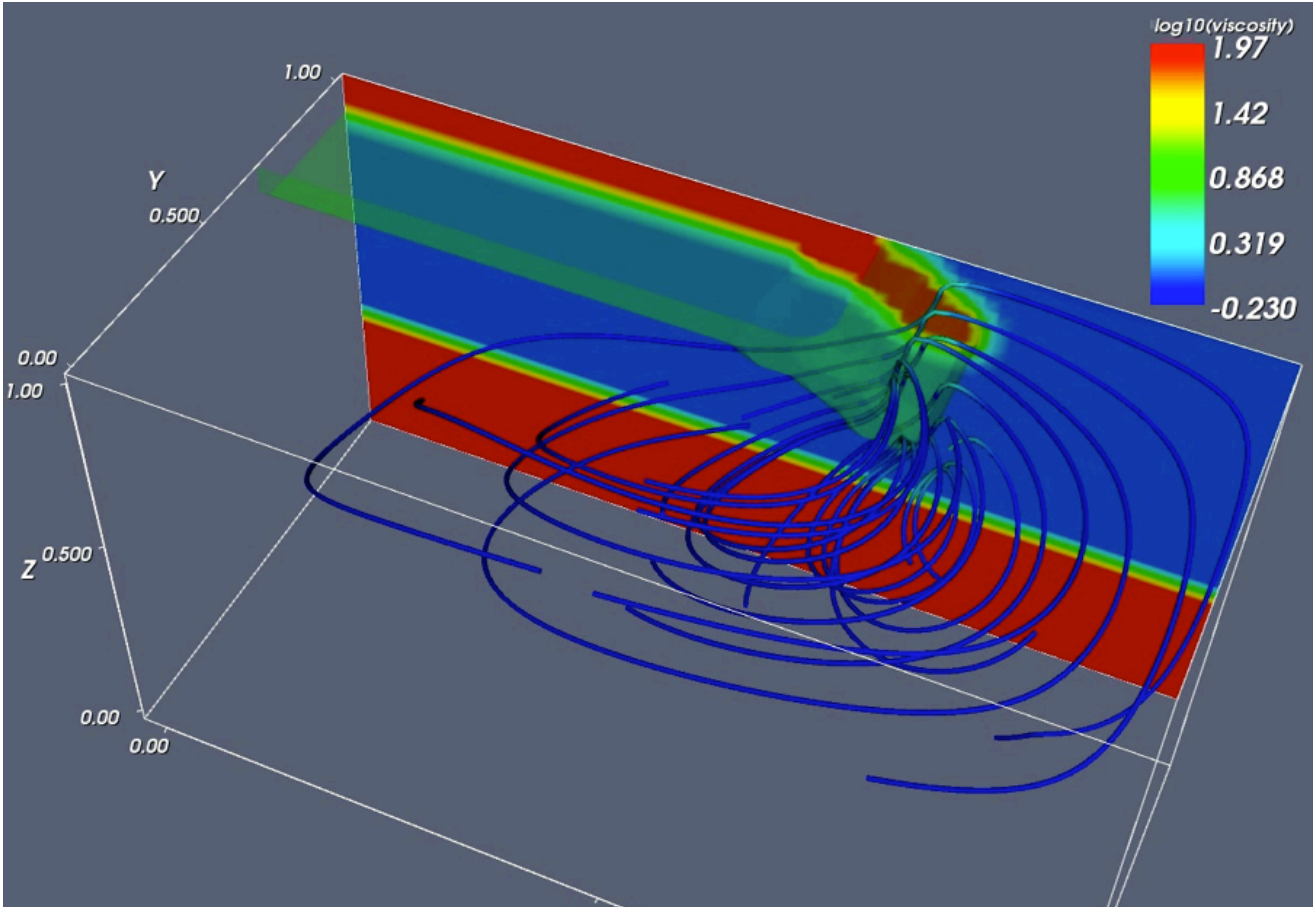




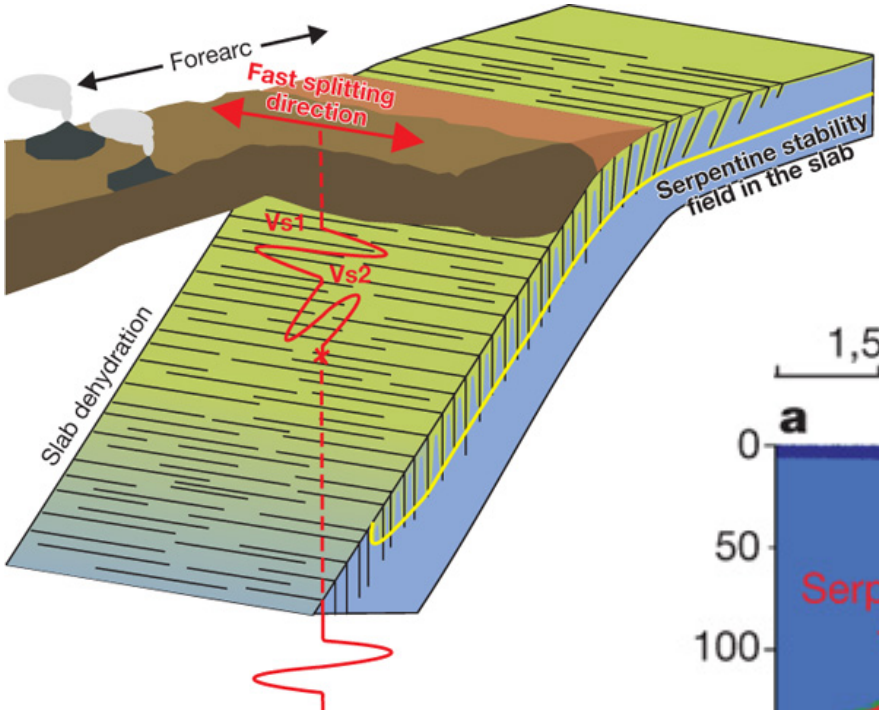
Anisotropy observations

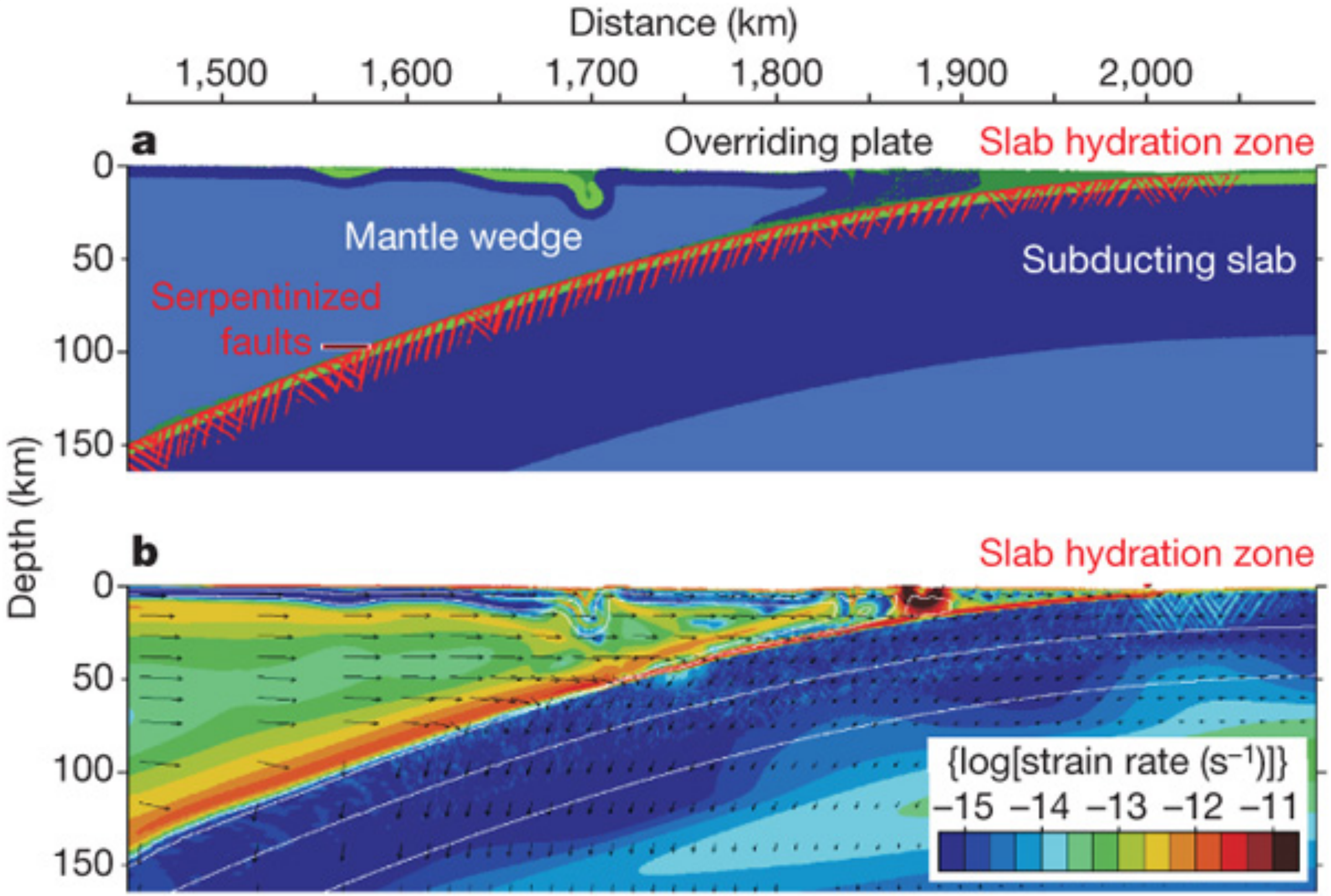


Trench parallel flow?



Trench parallel flow?





Trench parallel flow?

Jadamec & Billen, Nature 465, 338–341 (2010)

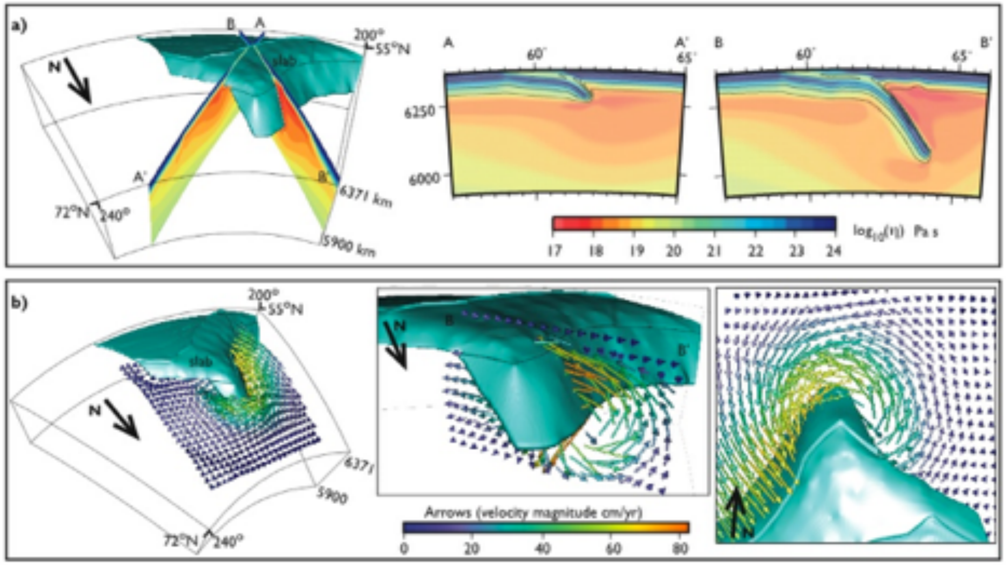


Figure 3: 3D mantle flow field and viscosity structure for slab$_{E115}$ model with composite rheology ($\sigma_y = 500$ MPa; PBSZ viscosity is 10^{20} Pa-s). (a) Isosurface and cross sections through composite viscosity show the strong slab and the low viscosity regions in the mantle wedge and beneath slab. Low viscosity regions correlate with high strain-rates. (b) Isosurface of viscosity with oblique, cross section, and radial slice through velocity field. Cross section BB' shows poloidal flow and along-strike flow. Map view slice shows counter-clockwise toroidal flow and an upward component of flow east of the slab edge.

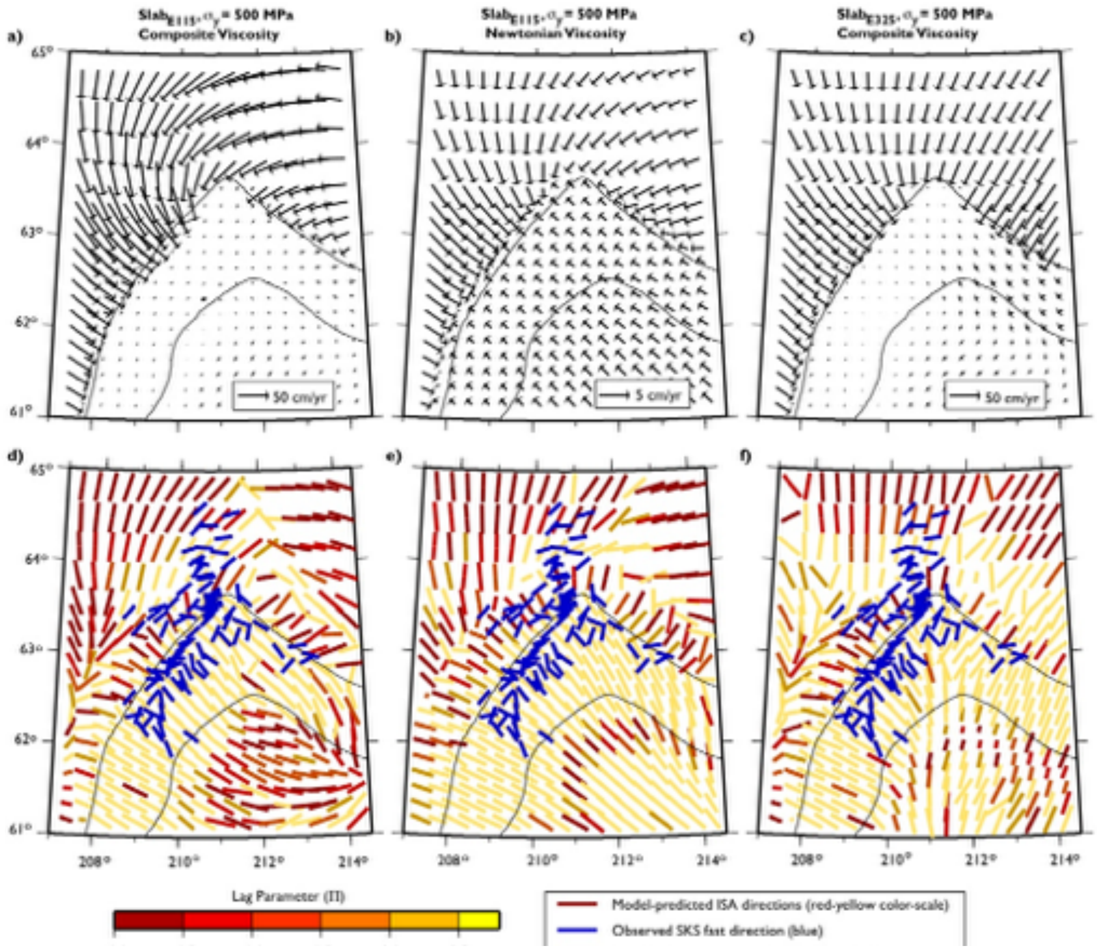


Figure 4: Velocity and ISA orientations at 100 km depth. (a) Velocity field shows a trench-parallel component of flow near the slab nose for slab$_{E115}$ with composite viscosity ($\sigma_y = 500$ MPa; PBSZ viscosity is 10^{20} Pa-s). (b) The Newtonian viscosity has a damping effect on the toroidal component of flow. (c) There is no toroidal flow above the slab nose for slab$_{E325}$. (d–f) ISA orientations colored by the lag parameter (Π). Superimposed are SKS fast-axis directions back-projected along the ray path to 100 km depth[5]. ISA orientation provides a good estimate of LPO for $\Pi < 1.0$.

On-going research topics

- Origin of seismic anisotropy near trenches
- Mechanisms required to initiate subduction
- Role of fluid and melt migration in subduction processes
- Factors which lead to the development of slab break-off, tears, gaps
- Topographic signature associated with slab detachment
- How the evolution of the landscape (erosion, deposition) influence styles of subduction
- Physical origin and rheology of transform faults
- Ultimate fate of subducted slabs