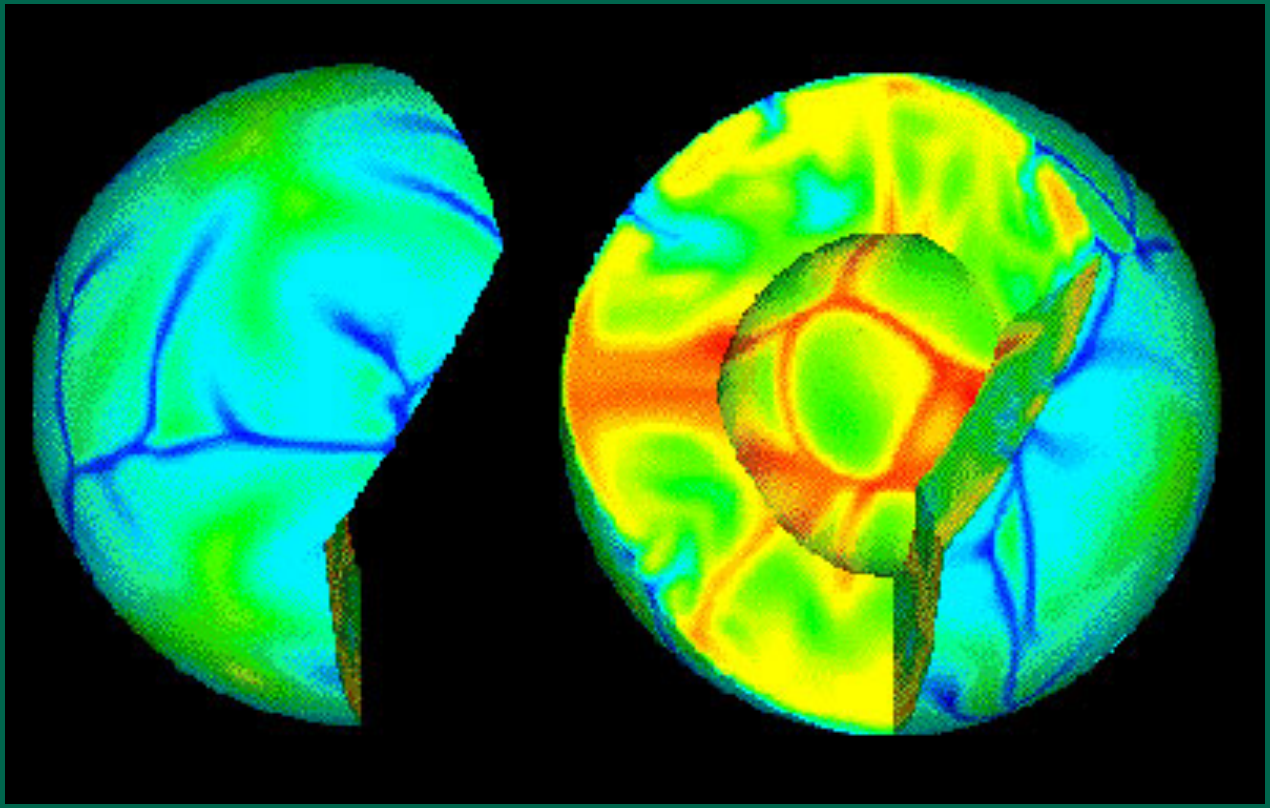
Lecture 14: Mantle convection and driving forces of global tectonics

Read chapter 12 in KK&V



Simulation of mantle convection; JPL-NASA

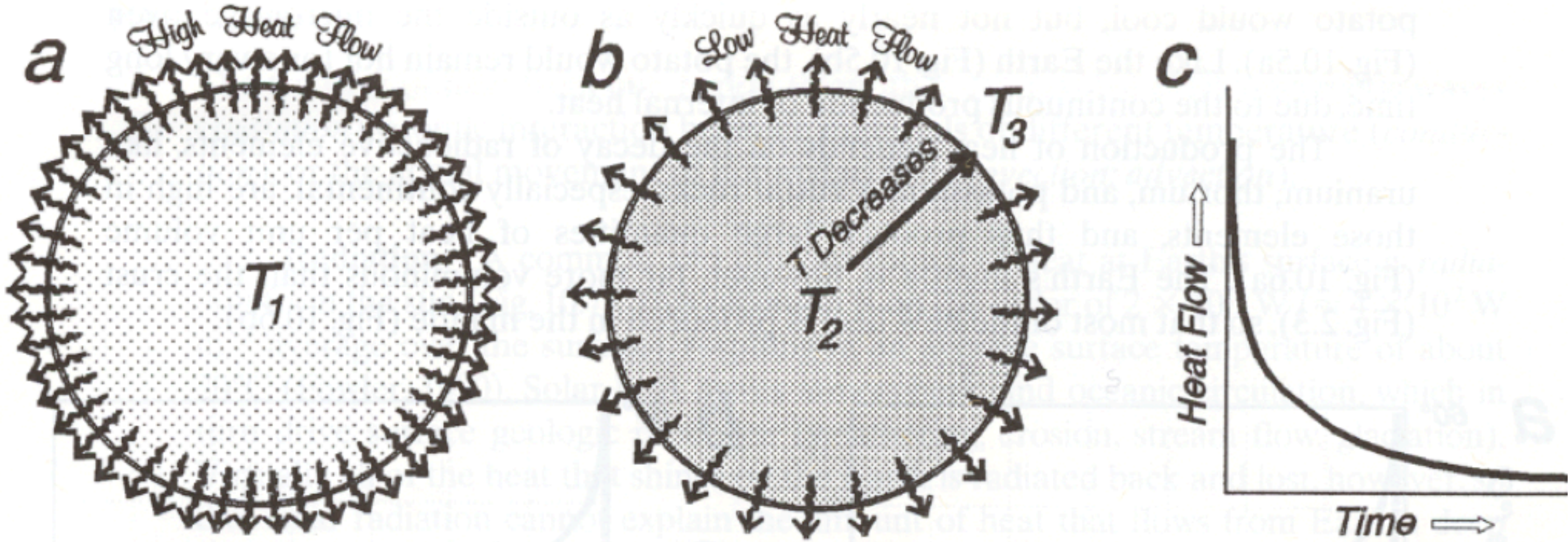
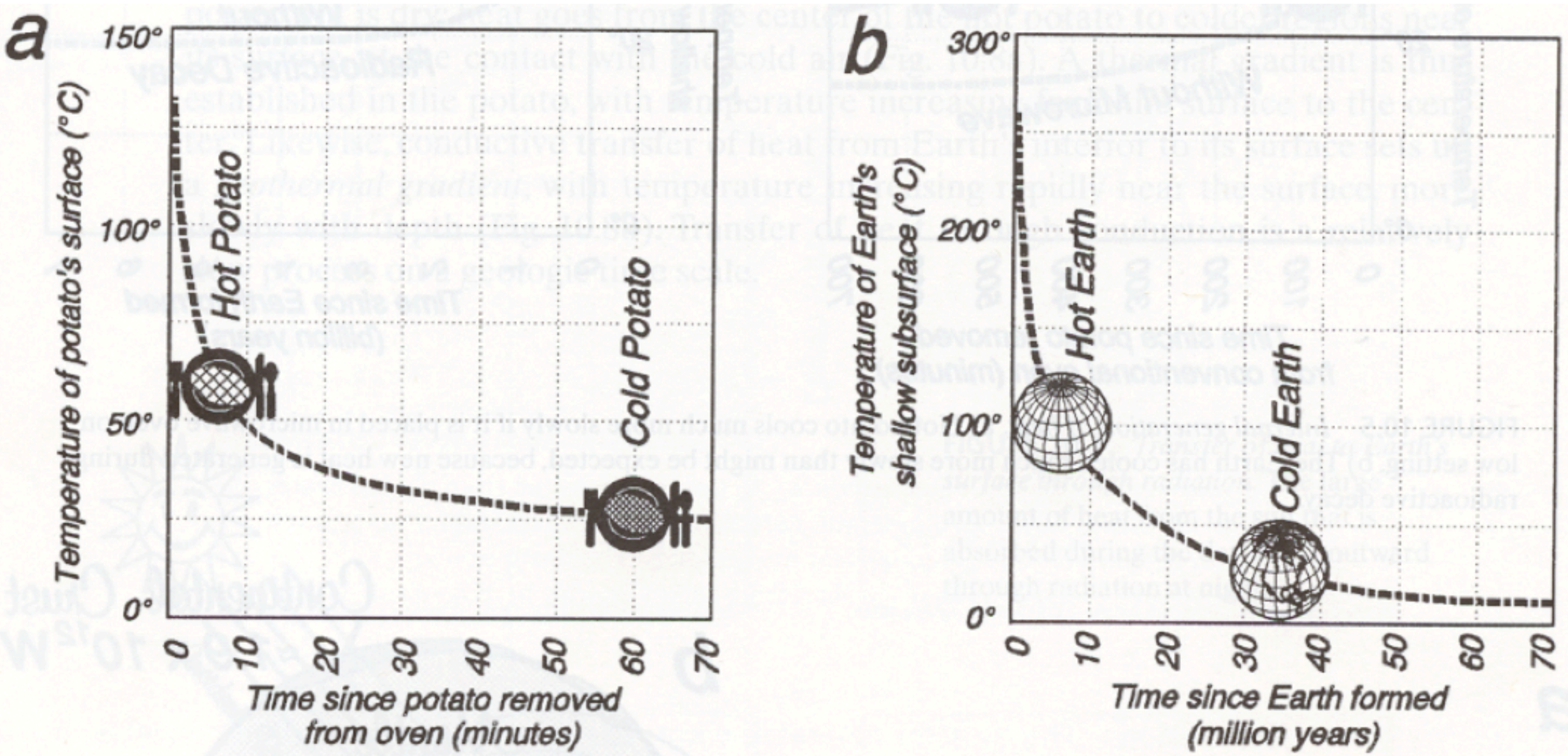


FIGURE 10.3 *Cooling of Earth through time.* a) Original temperature of the Earth (T_1), in a molten state at the time of its formation. b) As heat is lost through the surface, the temperature drops throughout; it is highest near the center (T_2) and decreases outward (to T_3). c) The rate of heat flowing across the surface also decreases through time; the average heat flow across the surface was thus used by Kelvin to estimate the age of the Earth.

Cooling of the earth through time by conduction from an initial state T_1 to a later state T_2. The rate of heat flowing across the earth's surface decreases exponentially with time.

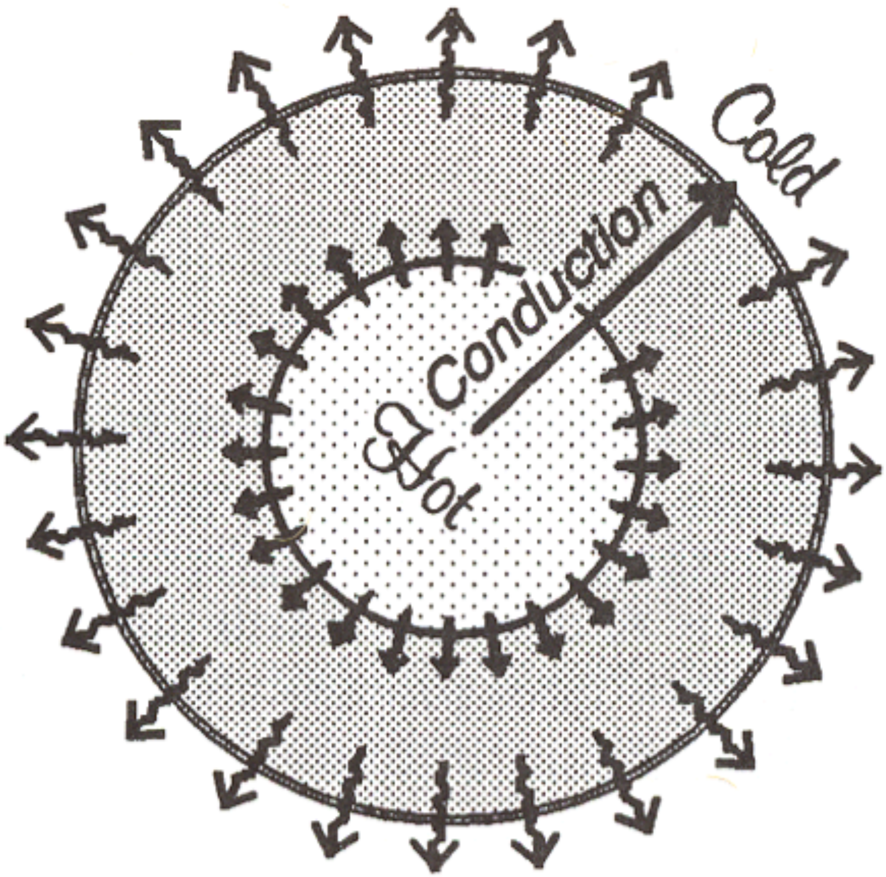


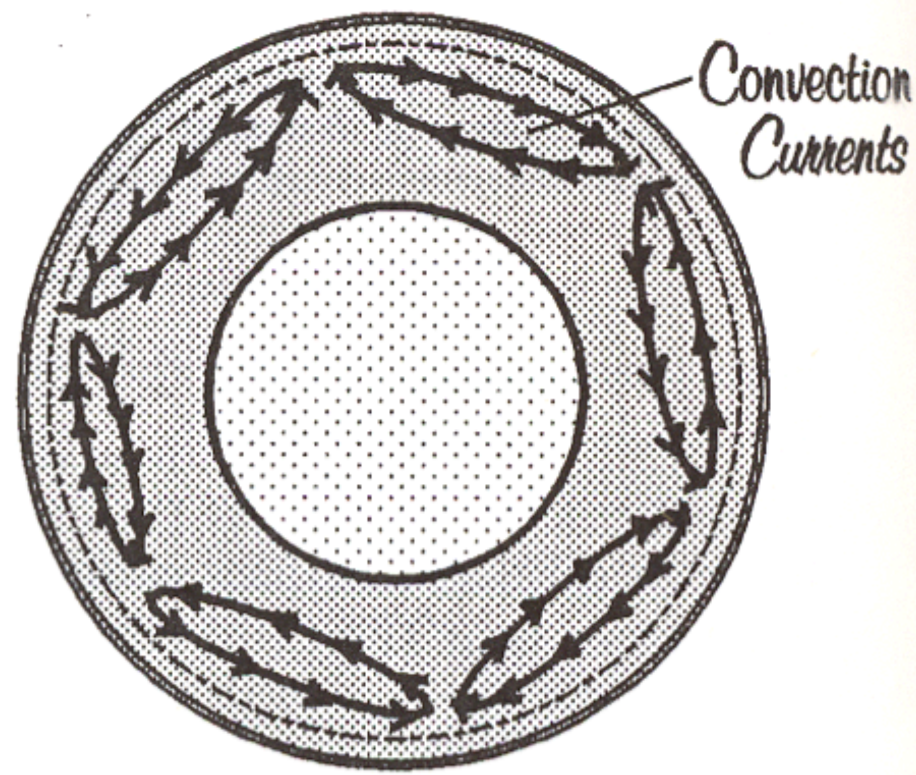
Loss of heat through conduction. For example the surface temperature of a potato suggests the time since it was removed from an oven. Assuming no new heat generation or convective heat loss, the temperature at about 1 km depth indicates the earth's age (60 –70 million years).

Global tectonic theories pre-dating plate tectonics:

- Contracting Earth
  - Contraction by cooling is not sufficient to explain the crustal shortening observed in mountain belts
  - Fails to explain extensional tectonics
- Expanding Earth
  - A decrease in the gravitational constant G is not sufficient to double the Earth's radius
  - The moment of inertia hasn't changed over the last 400 My
  - Paleomagnetic data do not indicate that the Earth's radius changed significantly over geologic time

Mechanisms for heat to escape from the interior of the Earth





Conduction (inefficient)

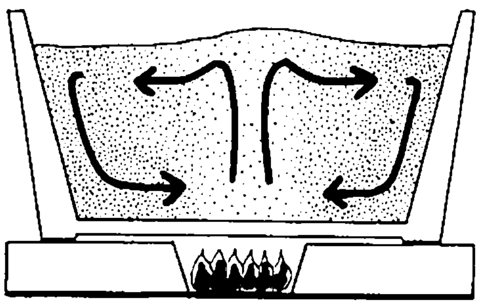
Convection (much more efficient)

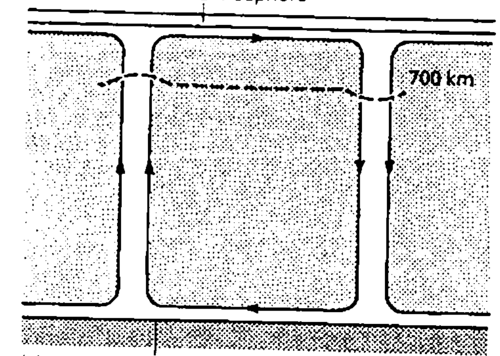
Driving Forces

Thermal convection: primary process responsible for plate motions

Heat at bottom causes a temperature gradient
Hot material rises, cold material sinks at edges

Earth: additional sources of heat in mantle
Variable viscosity between lithosphere, asthenosphere, mantle





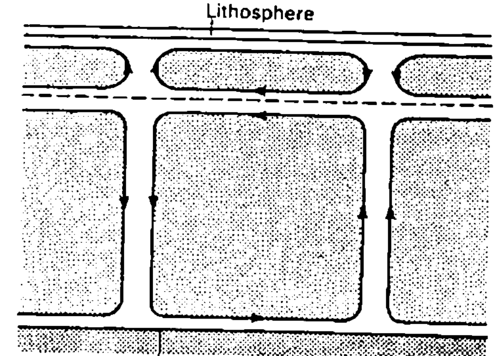


Figure 10-1.
Single convection cell: The kitchen stove experiment.

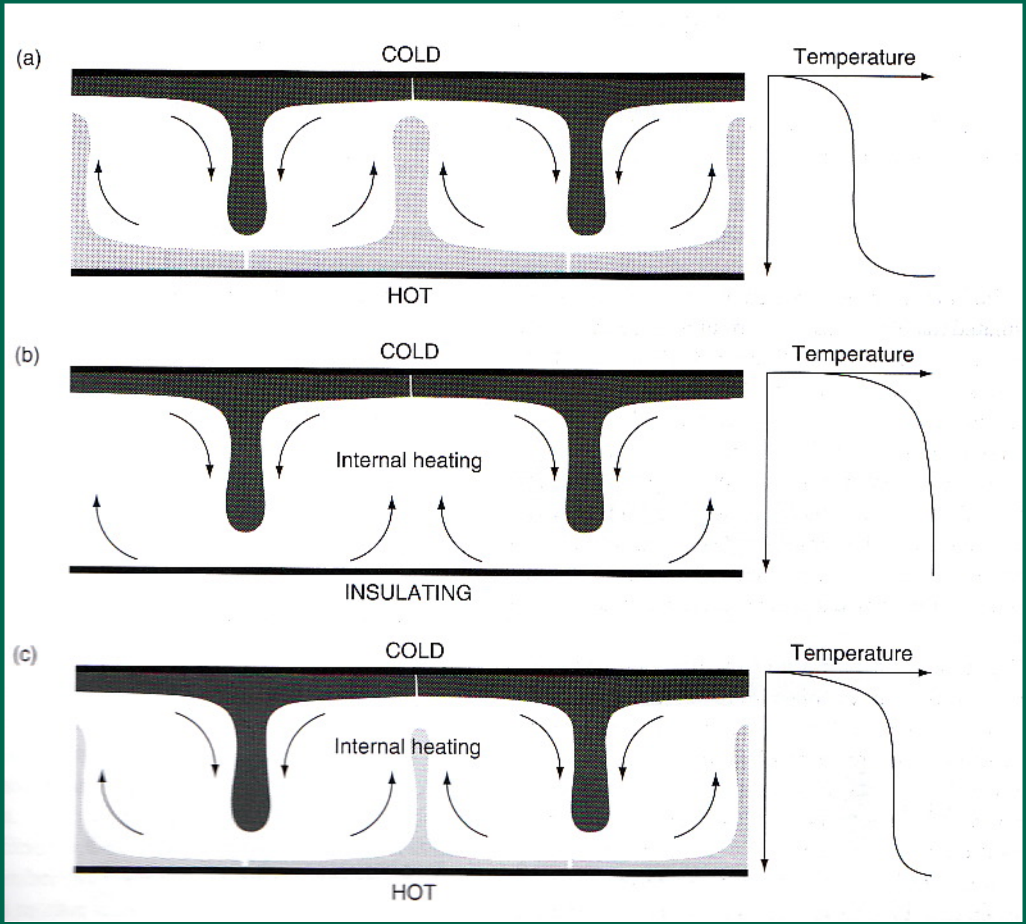
Figure 10-2.
Multiple convection cells over distributed heat source.

Cox and Hart (1986)

Kearey and Vine (1996)

Issue: Form of mantle convection:
- Whole mantle convection?
  - Transition zone is a phase boundary which can be traversed
    - Plumes come from deep mantle
    - Favored by recent seismic tomography
- Or: Two layer convection?
  - Transition zone represents a chemical boundary
    - Plumes come from upper mantle

Some conceptual models …



The temperature profiles (right) show that when there is internal heating (cases b and c) there is a greater temperature drop across the upper boundary layer. This will strengthen the upper boundary layer

KK&V Fig 12.5

Three different conditions of the thermal boundary layers in a convecting fluid

a) Cold top, heated bottom, no internal heating

b) Cold top, insulated bottom (no heat), internal heating

c) Cold top, heated bottom, internal heating

In a) convection is driven equally by more dense downwelling from top and less dense upwelling from bottom

In b) cold, dense fluid from top drives convection; upwelling is passive

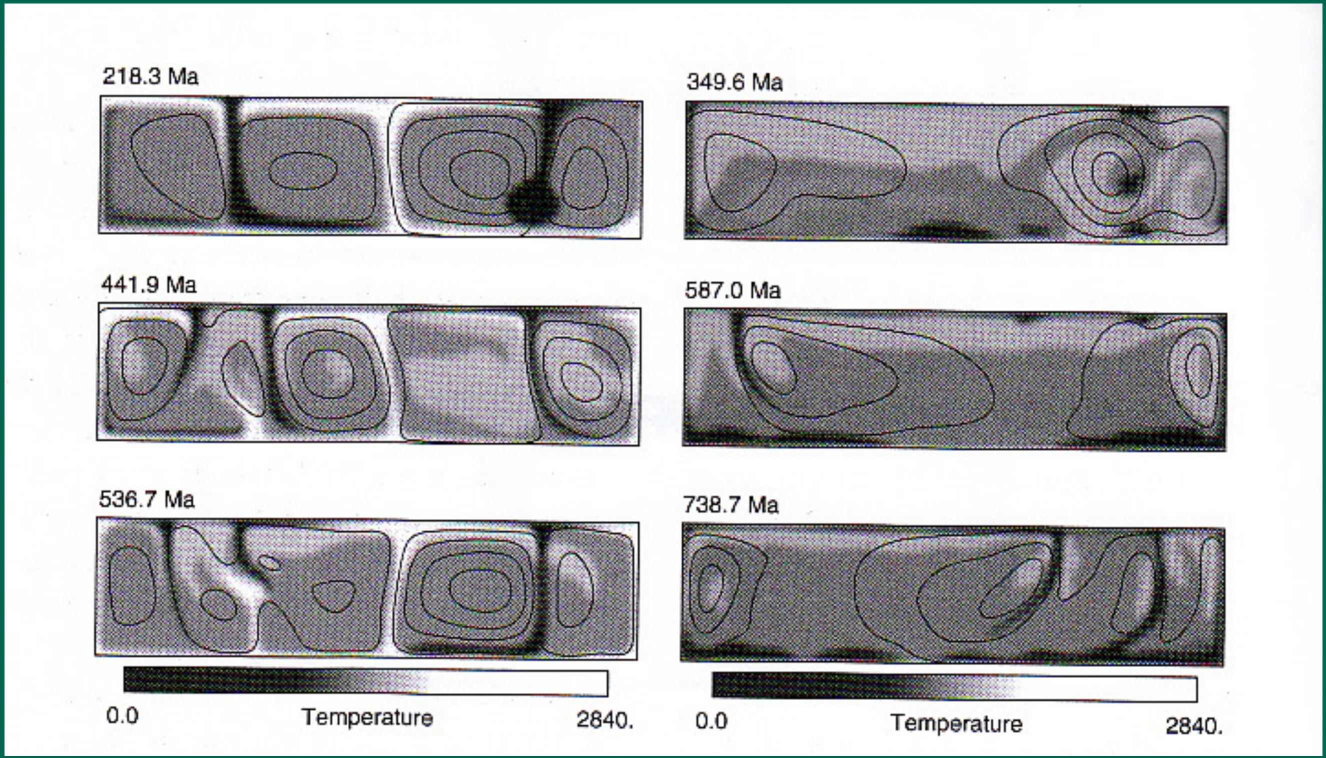
In c), some upwelling from bottom but weaker than in a)

The temperature drop at the base of the top boundary layer is the greatest in c, thereby strengthening the top boundary layer

Mantle is like c)

Problem: assumes uniform viscosity throughout mantle

Some actual calculations …



KK&V fig 12.6

Numerical convection simulations

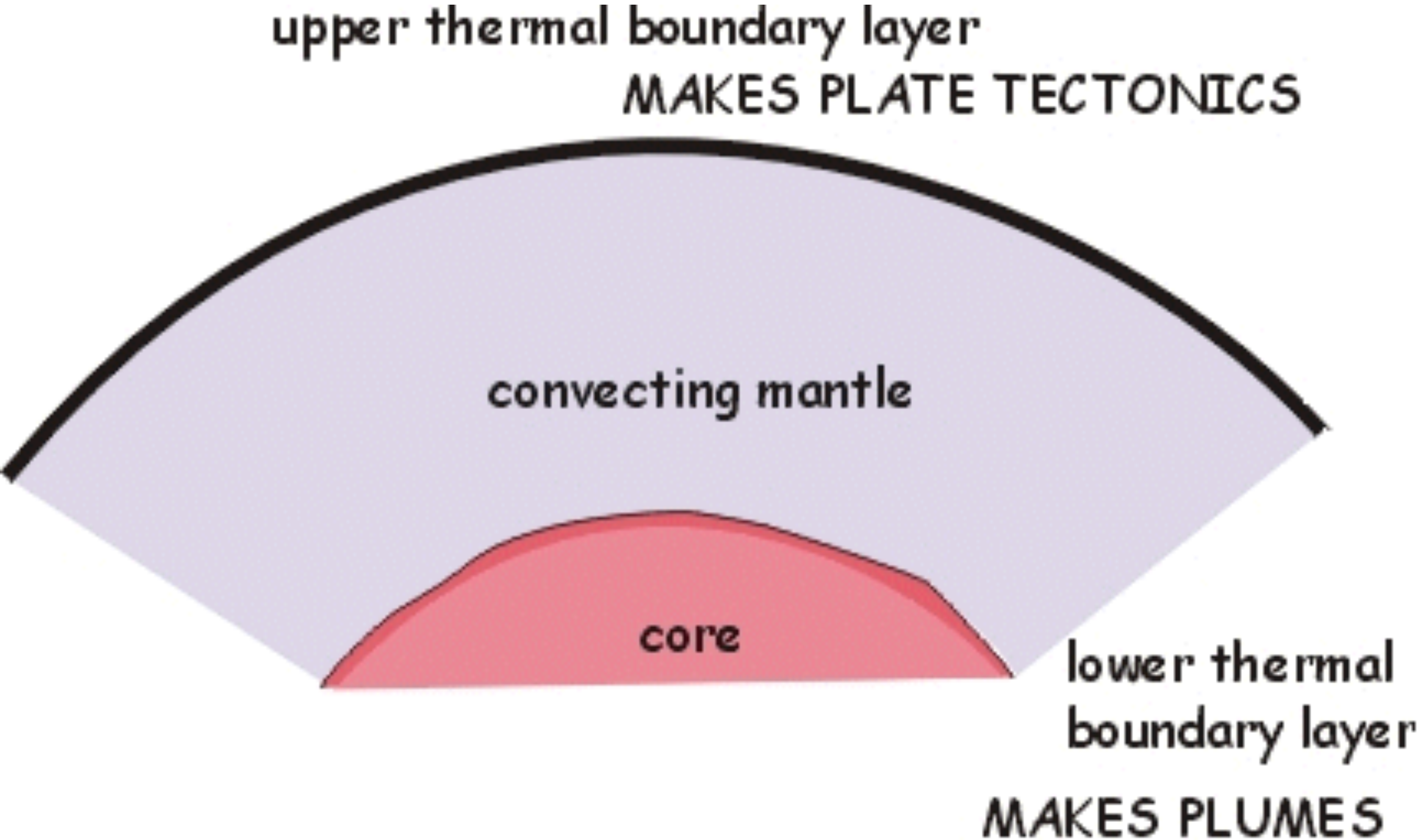
Left: heated from below
Right: heated internally, no heat from below

In case where heated from below but no internal heat (left) see downwellings and upwellings (like case a)

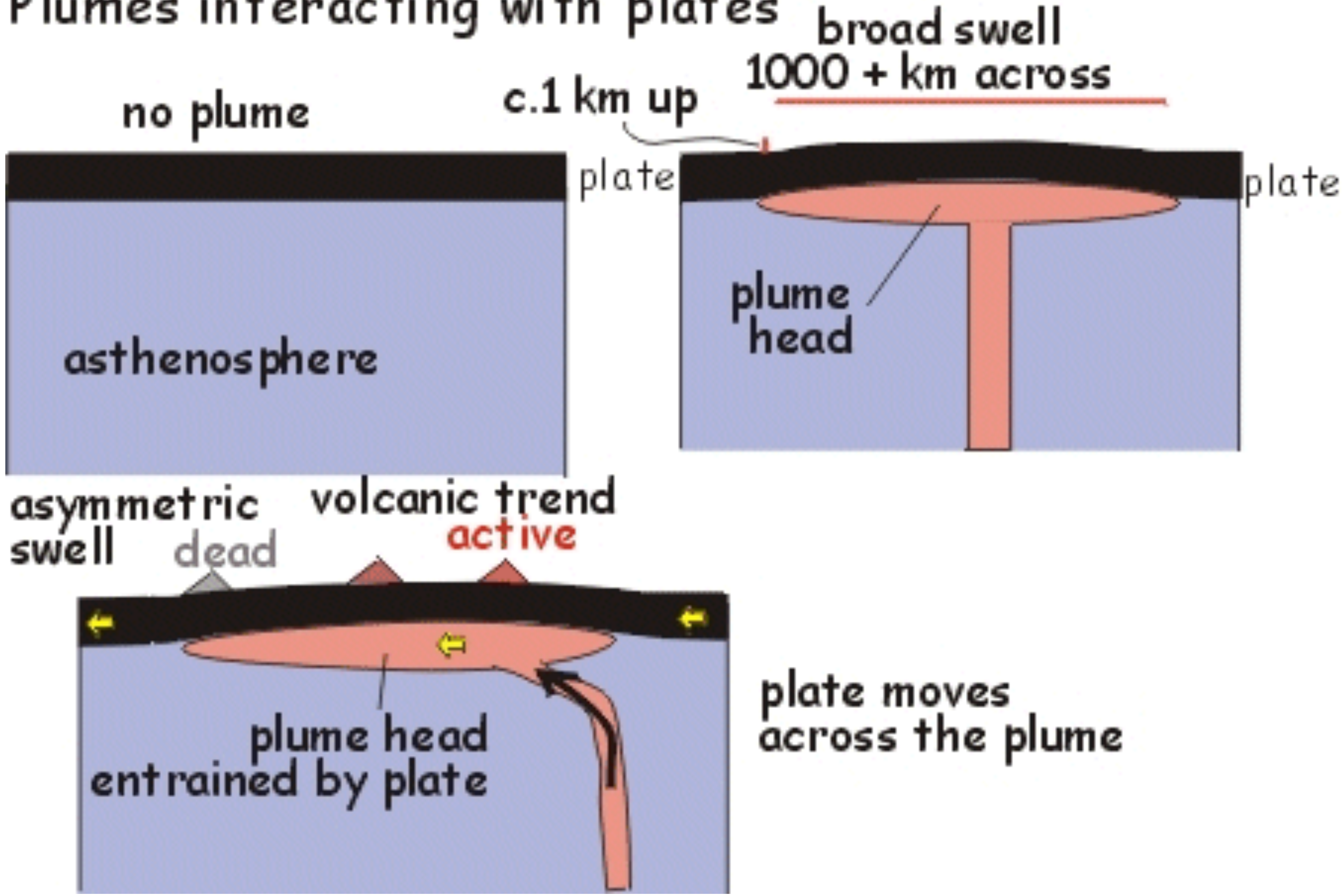
In case where heated internally and no heat from below (right, like case b) see strong downwellings and only weak upwellings

The later is thought to be more like the Earth's mantle, although neither example is like case c

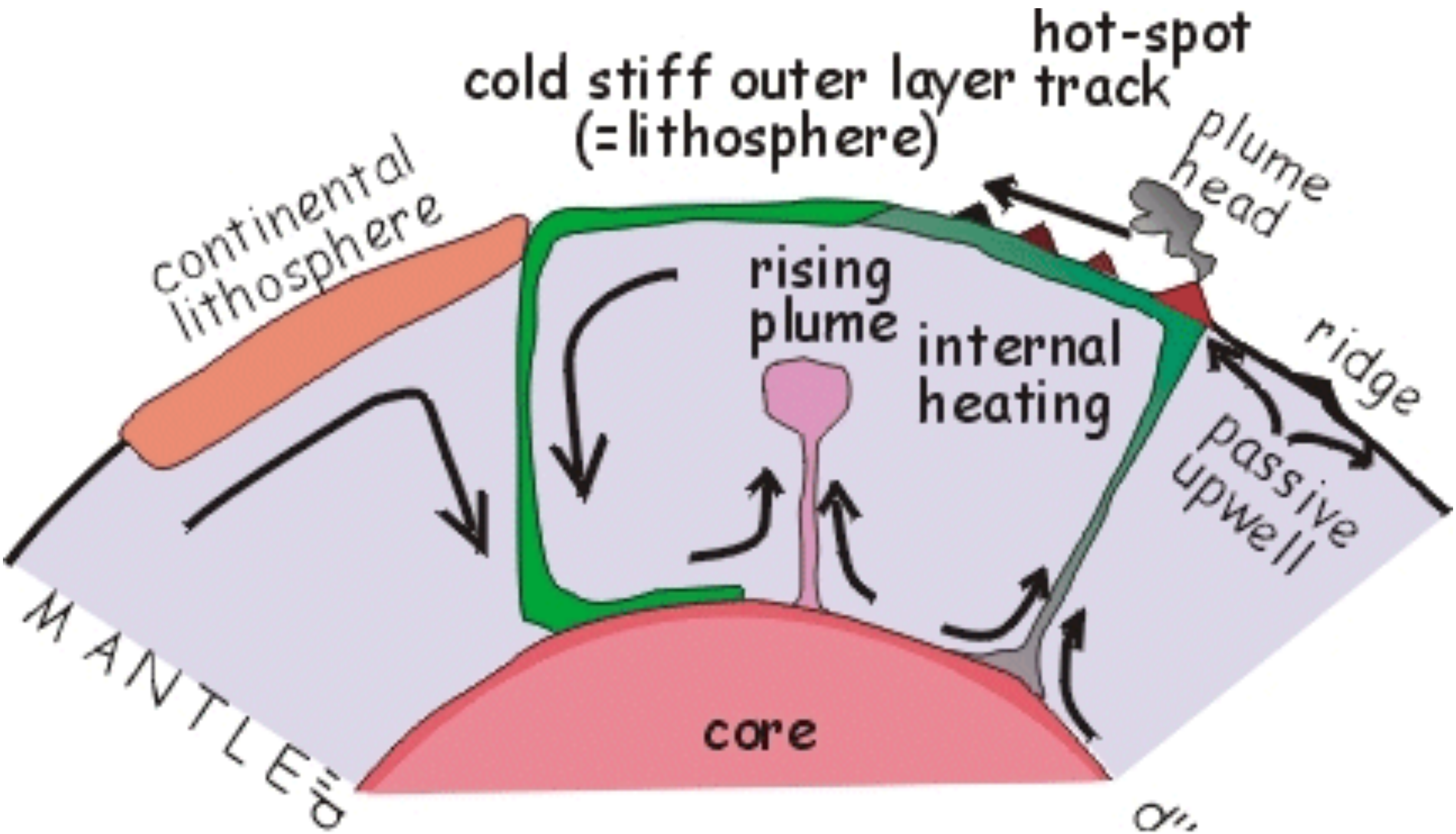
Still missing in models:
Variable viscosity with depth
Phase changes


upper thermal boundary layer
MAKES PLATE TECTONICS
convecting mantle
core
lower thermal
boundary layer
MAKES PLUMES

Plumes interacting with plates



This leads to the idea that it is not the upwelling beneath the mid-ocean ridge axis, but the upwelling in mantle plumes that is important in the thermal cycle. Mid-ocean ridges and sea-floor spreading may in fact be entirely **passive** phenomena.



Summary comparison of active versus passive plates

1) Passive plates (old idea):

Convection cells are prime movers

Ridges form at upwellings

Trenches at downwellings

Subduction occurs because a slab is pulled down by a dense sinking limb of a convection cell

Distance between ridges and trenches is determined by characteristic length scale of convection cell

2) Active plates (plate tectonics; edge forces)

Plate is an instrinsic part of a convection cell

Subduction occurs because the slab <u>is</u> the dense, sinking limb of the cell

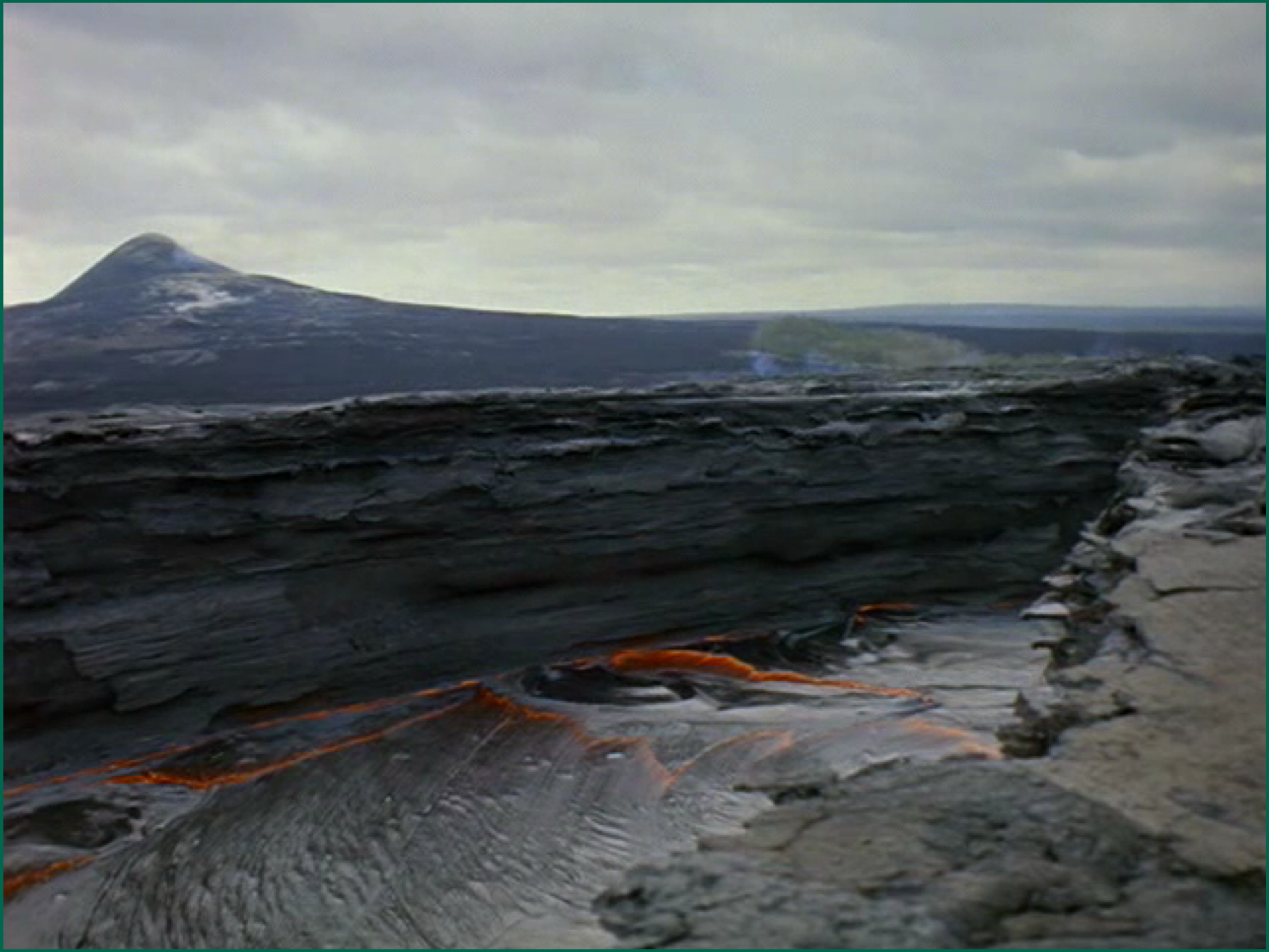
Ridges are simple cracks between diverging plates filled from local sources (spreading ridges are passive)

Analogy: Diverging ices sheets on a pond
Sea ice in the Arctic

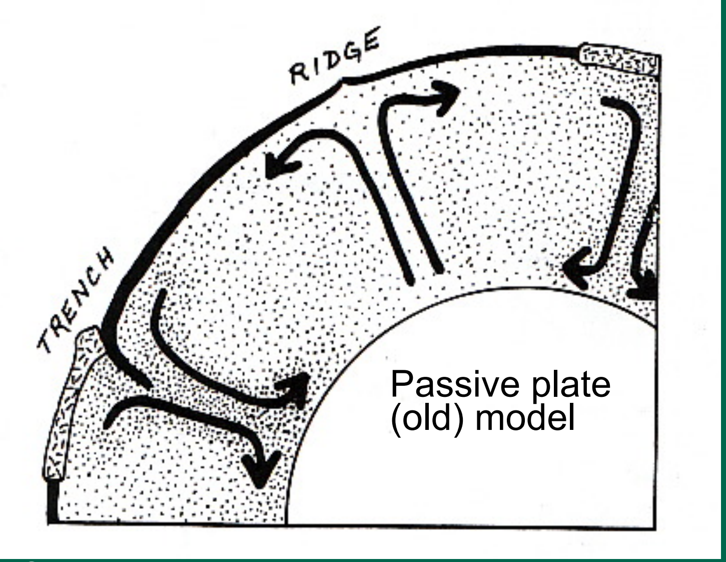
Also called: Orowan-Elsasser type convection

A little confusing:
active plates = passive spreading

Another analogy: lava lake (note recycling of solid crust on top)



Three tests of passive versus active plates



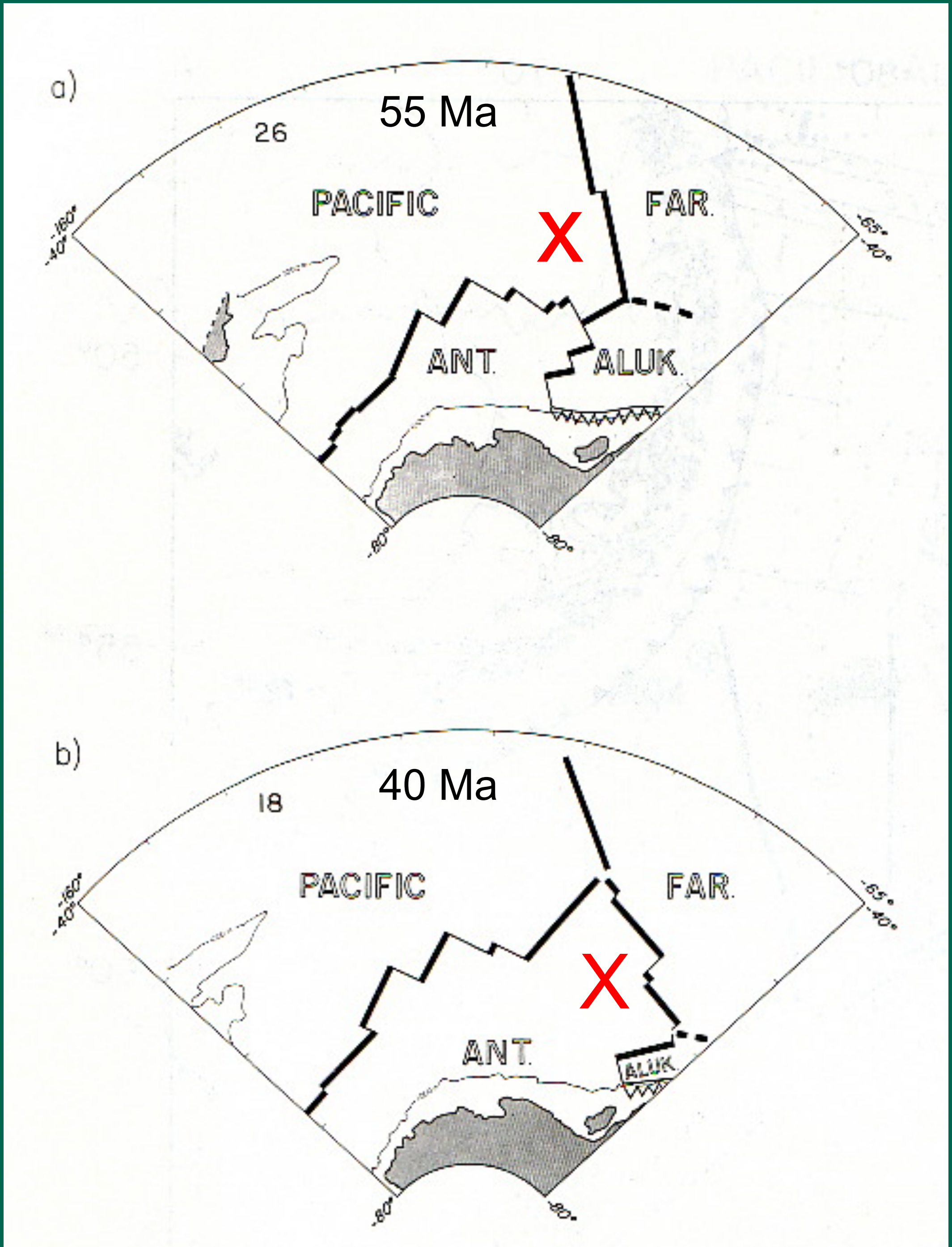
Cox and Hart

Test 1:
Large ridge jumps:

Passive plate model (old) requires that a large ridge jump corresponds to a major reorganization of the mantle convection pattern

Active plates: Plate can simply break into pieces like a large ice floe

Example: Early Cenozoic plate reorganization in Southeast Pacific: large piece of Pacific plate (X) is captured by Antarctic plate

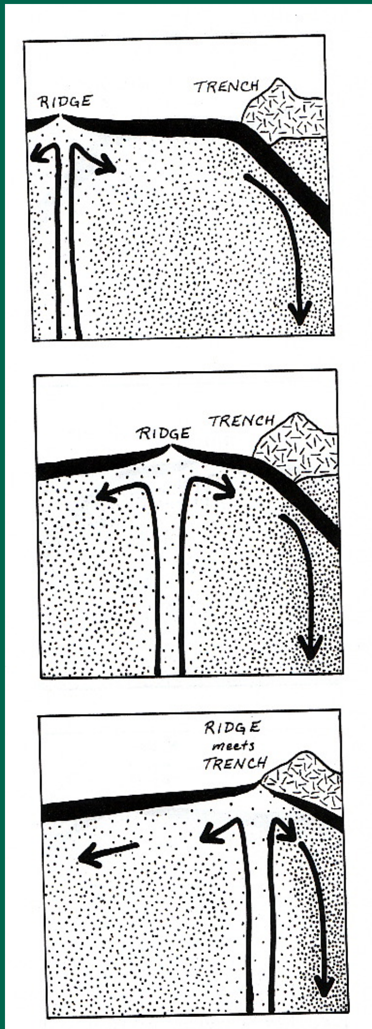


Test 2: What happens when a ridge collides with a trench?

Example of active plate subduction: Southern Chile:

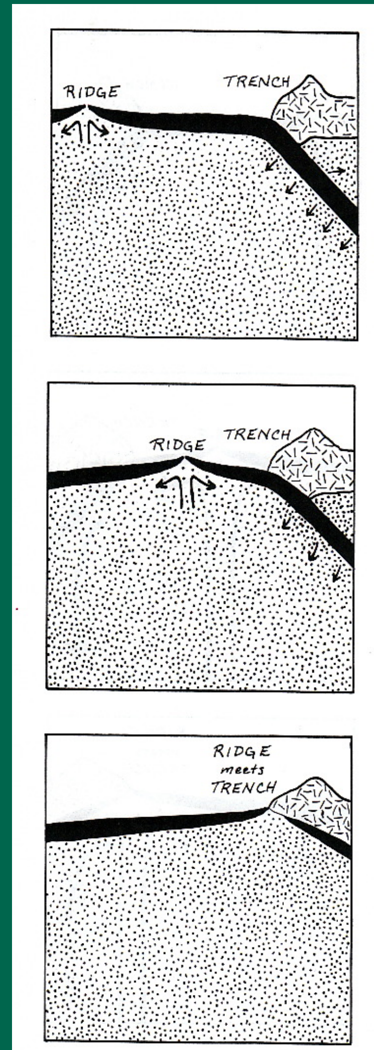
South America is overriding Chile (Nazca-Antarctic) ridge

Antarctic plate continues to subduct south of the triple junction

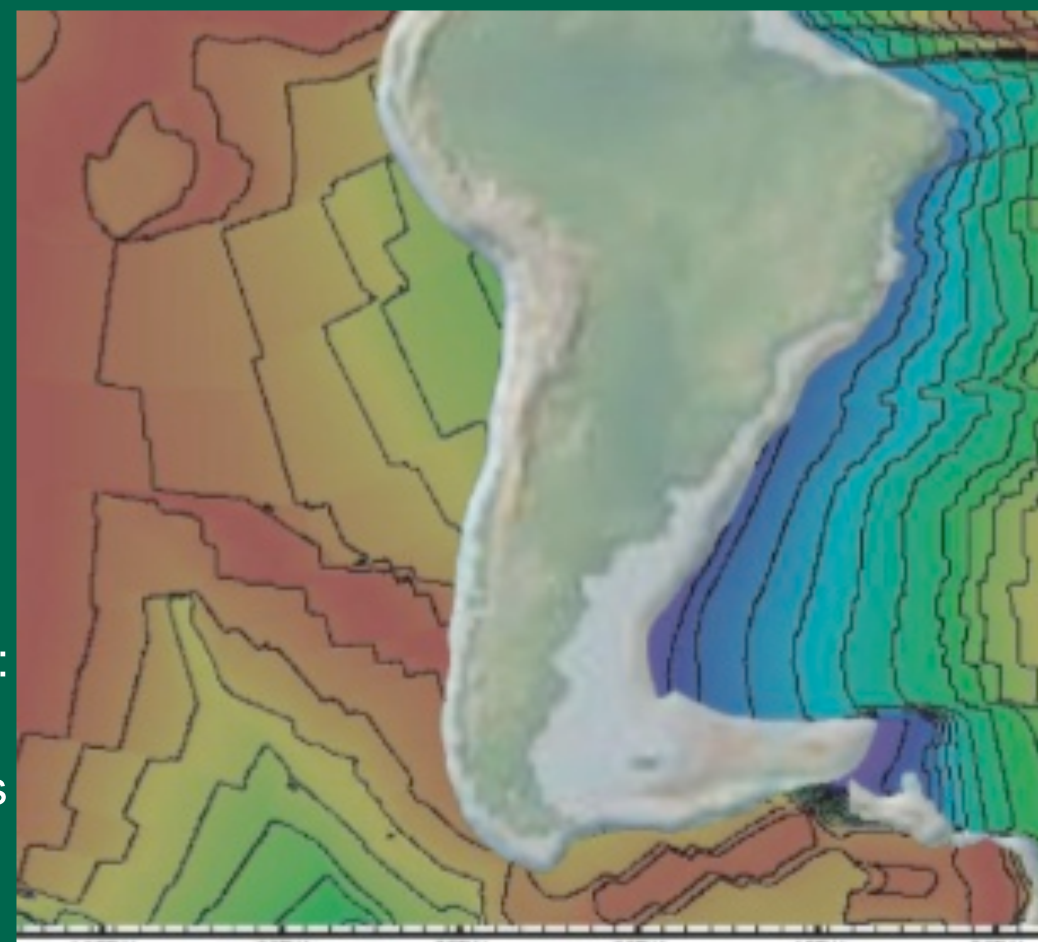


Cox and Hart

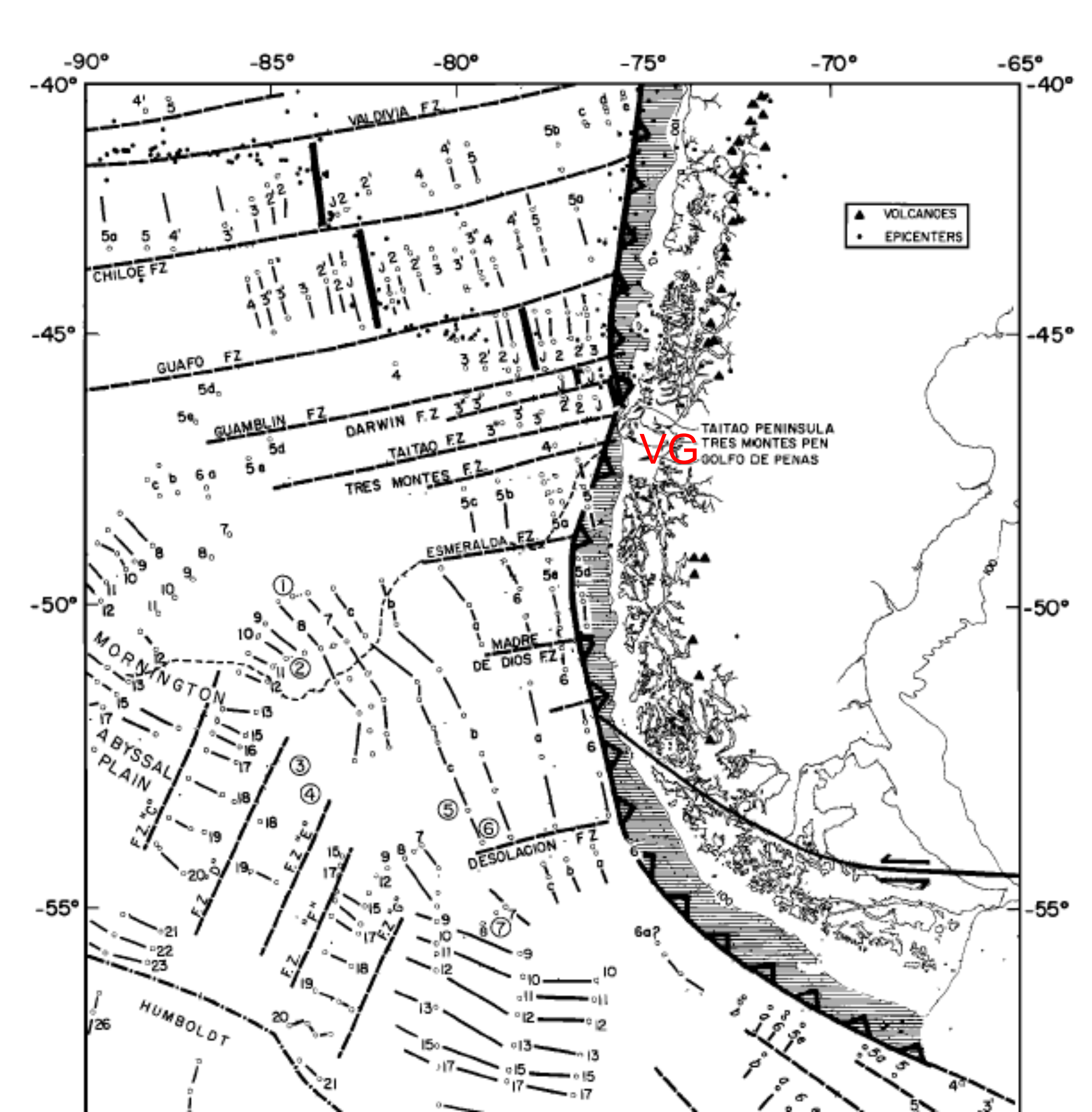
Passive plate model: ascending and descending ends of convection system meet. Convection system ends

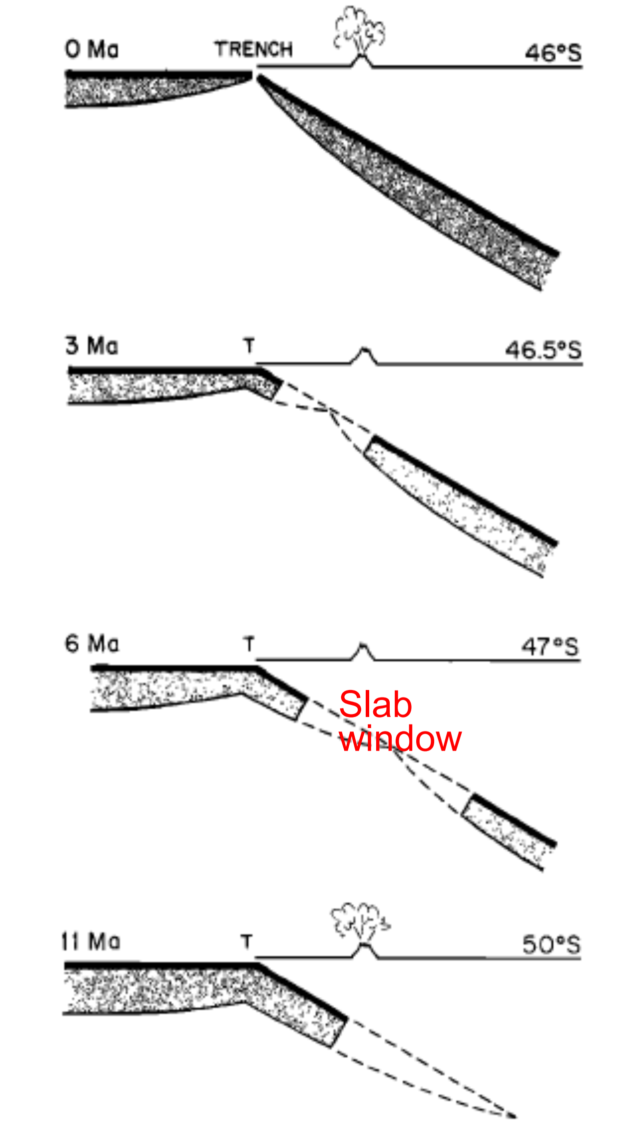


Active plate model: Ridge slips beneath trench. Trailing plate starts subducting



After the ridge "collides" with the trench along the southern Chile margin, the "trailing" plate (Antarctica) starts subducting and the location of a "slab gap" can be followed down the subduction zone



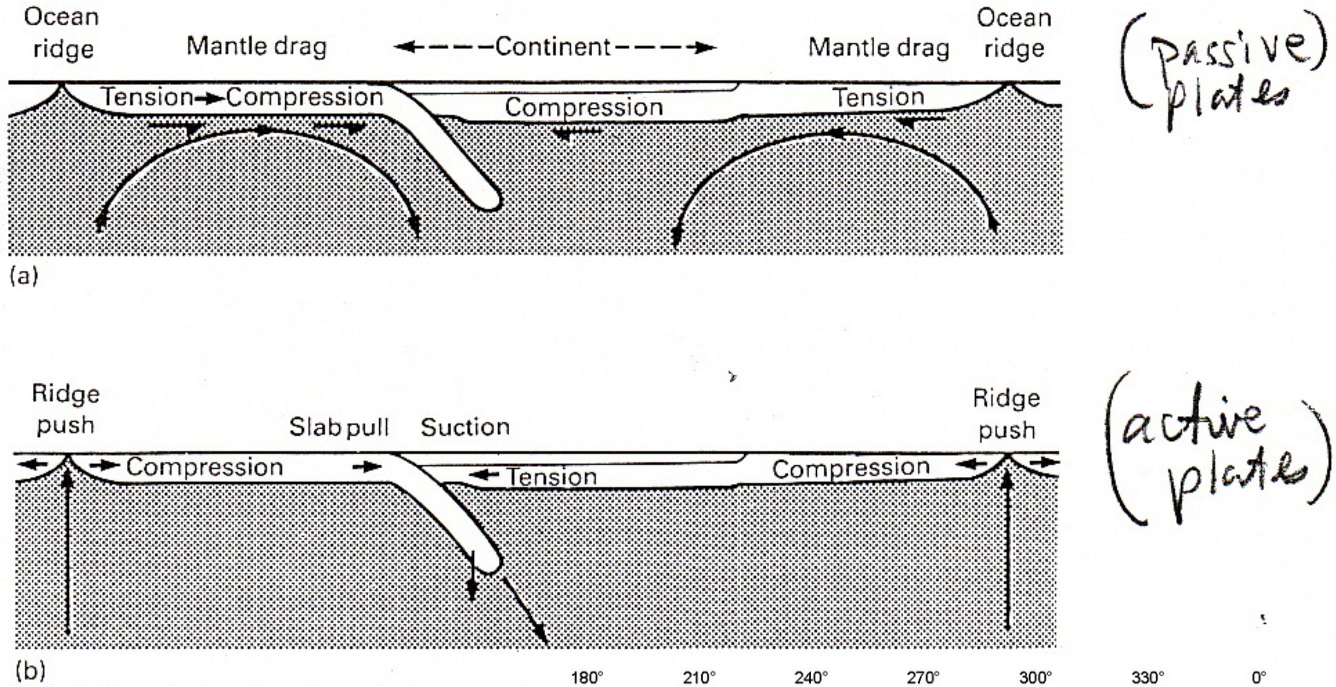


There is a gap in volcanism (VG) south of the triple junction corresponding to the segments where the "gap" between the leading and trailing plates passes beneath the volcanic arc.

Test 3:

Two models predict very different states of stress within the lithosphere

Stress conditions in the oceans (based mostly on focal mechanisms) are more like the bottom panel (active plates)

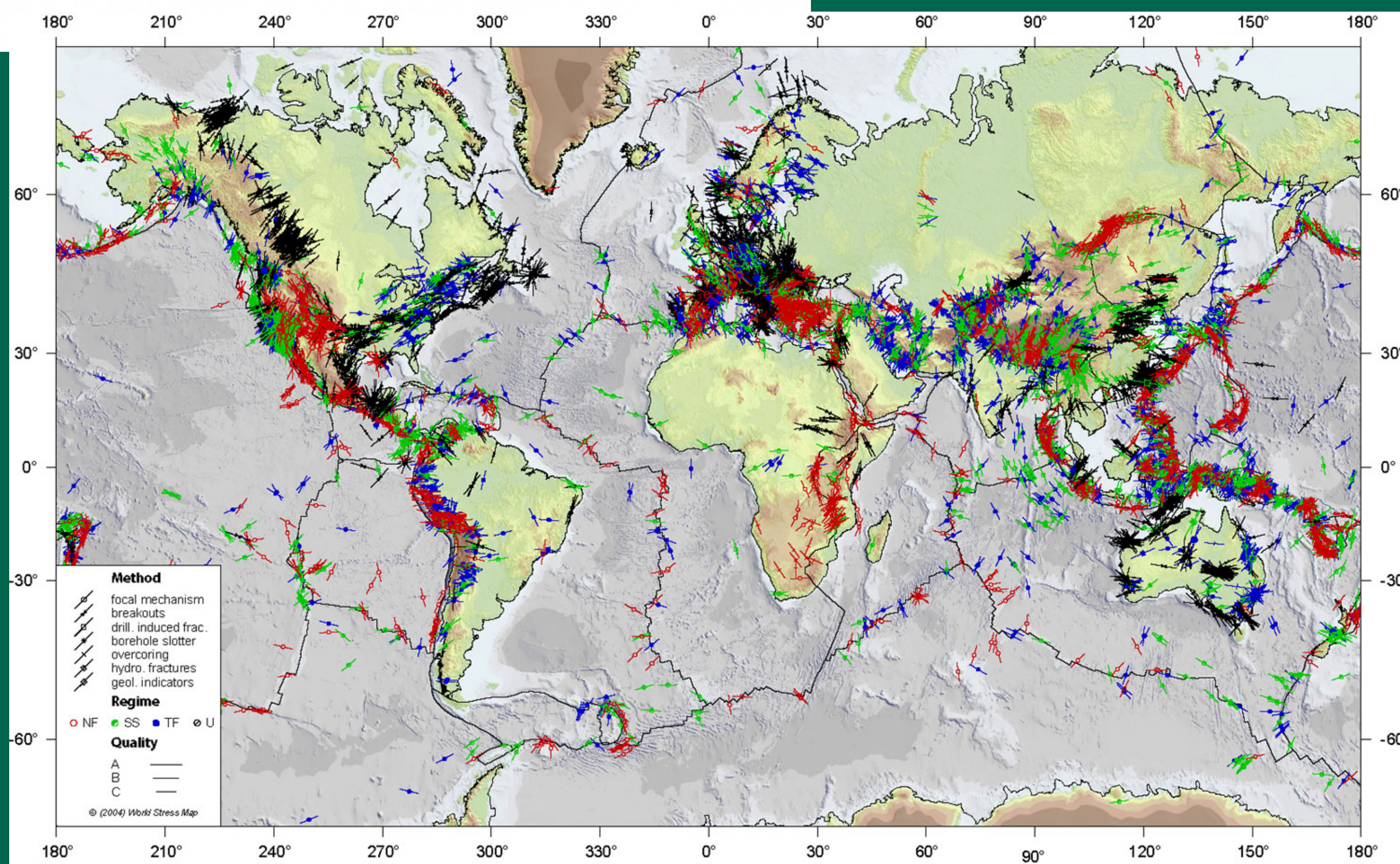


KK&V Fig. 12.9

World stress map – 2004

Blue = thrust faulting = compression

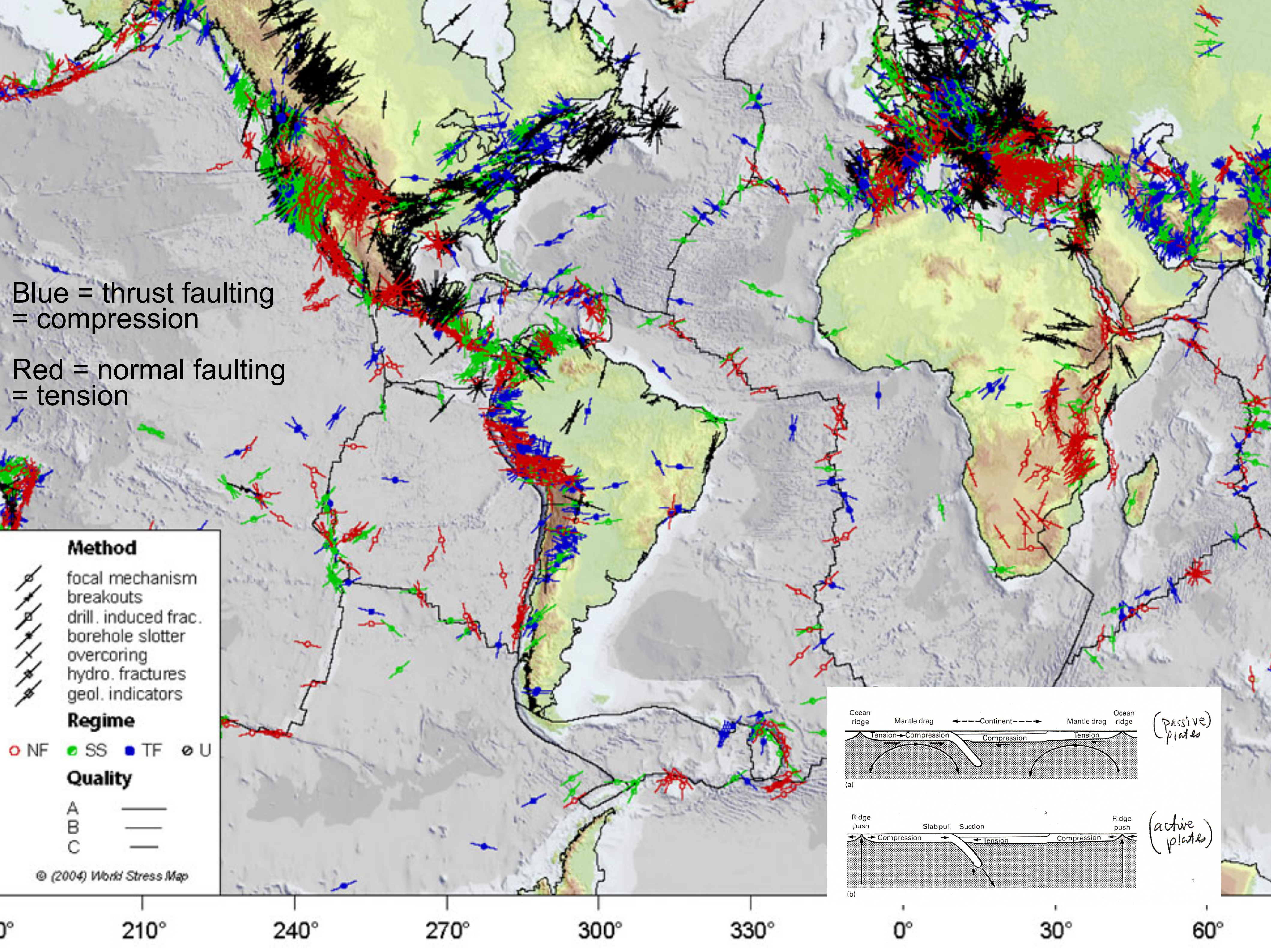
Red = normal faulting = tension



Heidbach et al. (2010)

Blue = thrust faulting
= compression

Red = normal faulting
= tension



Forces acting on plates

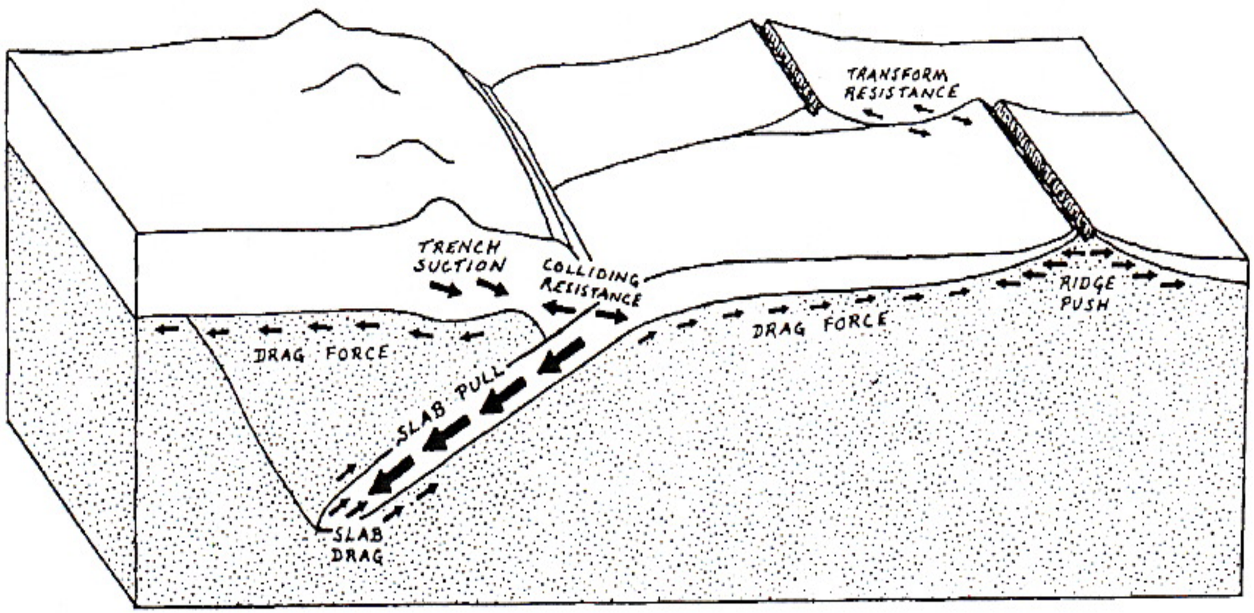


Figure 10-6.
Forces acting on plates.

Cox & Hart

Slab Pull (Slab drag)
Ridge push
Mantle Drag
Continental Drag (deep root)
Trench suction
Transform fault resistance

Slab Pull - F_{SP}

Force generated because cold subducting slabs are denser than the asthenosphere and therefore sink through it. However, "pull" is a misleading word. Plate is too weak to be "pulled." Plate is not under tension in an absolute sense; rather, there is a reduction in the pressure that would exist at a given depth. Think of the descending limb of cold water in a convection cell, which "pulls" the water behind it (rather than the misleading analogy to a wet tablecoth). Should be independent of the rate of convergence.

But countered by slab drag

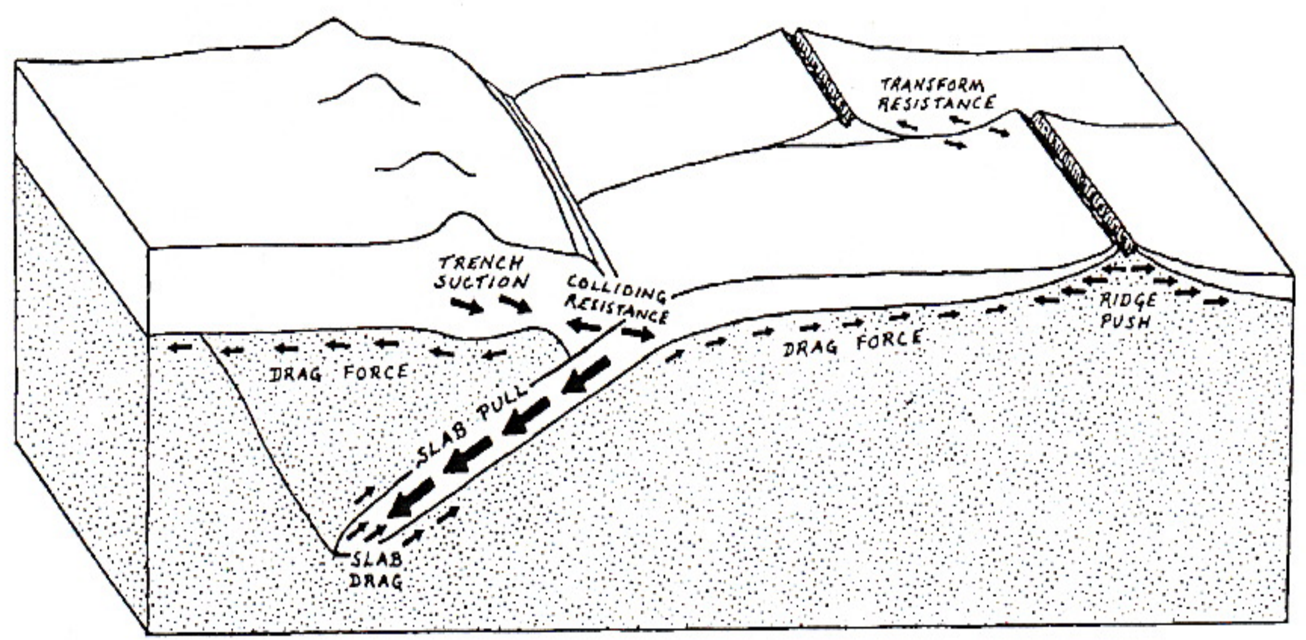


Figure 10-6.
Forces acting on plates.

Cox & Hart

Ridge Push - F_{RP}

Force due to the gravitational potential energy resulting from the relative height of ridges over areas of older crust. Think of a large glacier which flows slowly down hill. Force is generated over entire area of rise, but is greatest at the axis, goes to zero at the abyssal plains.

The principal way to explain motion of large plates with no slabs such as North and South America

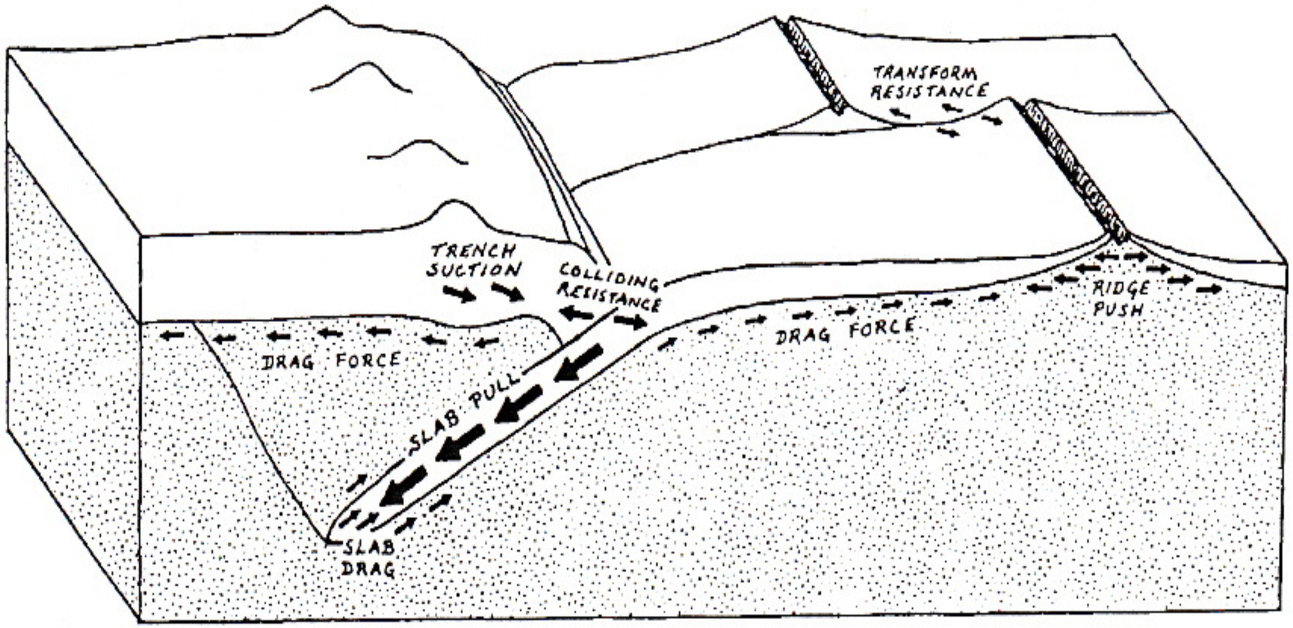


Figure 10-6.
Forces acting on plates.

Cox & Hart

Mantle Drag Force - F_{DF}

Force acting on the bottom of the plate due to viscous coupling between the plate and asthenosphere. Will be proportional to area of plate and its velocity relative to the asthenosphere. If a plate is passive, then the plate moves in the same direction as the asthenosphere beneath it, but at a slower rate. If plates are active, the drag force is resistive and in the opposite direction to the plate motion.

Continental Drag Force - F_{CD}

Additional drag force if there is greater drag under continents. May arise if the asthenosphere is more viscous under continents or if a root extends beneath a continent into the asthenosphere.

Force envisioned by early believers in continental drift like Arthur Holmes …

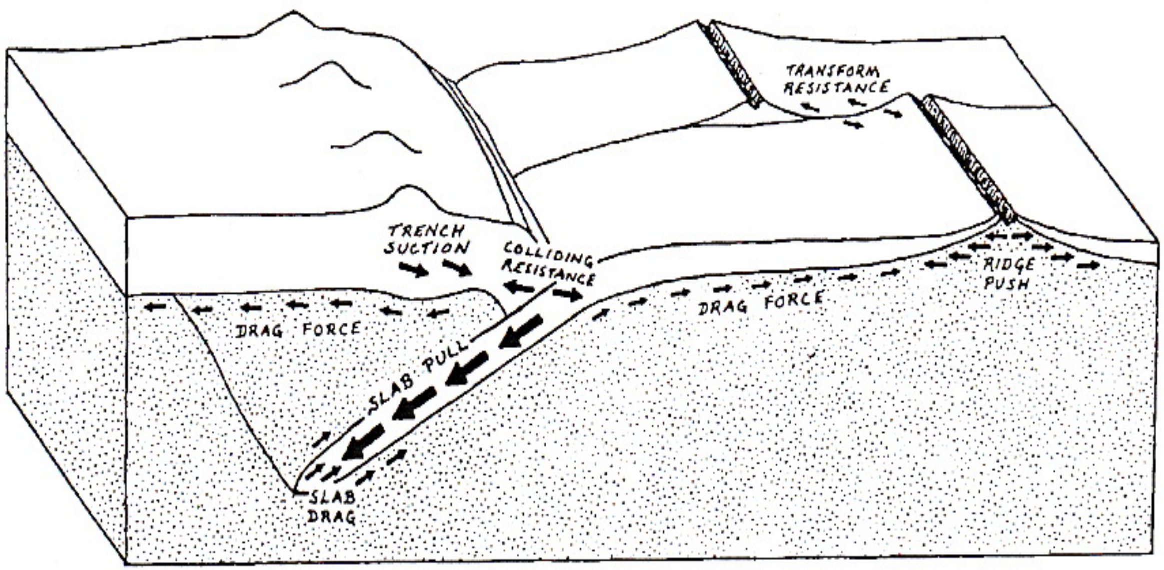
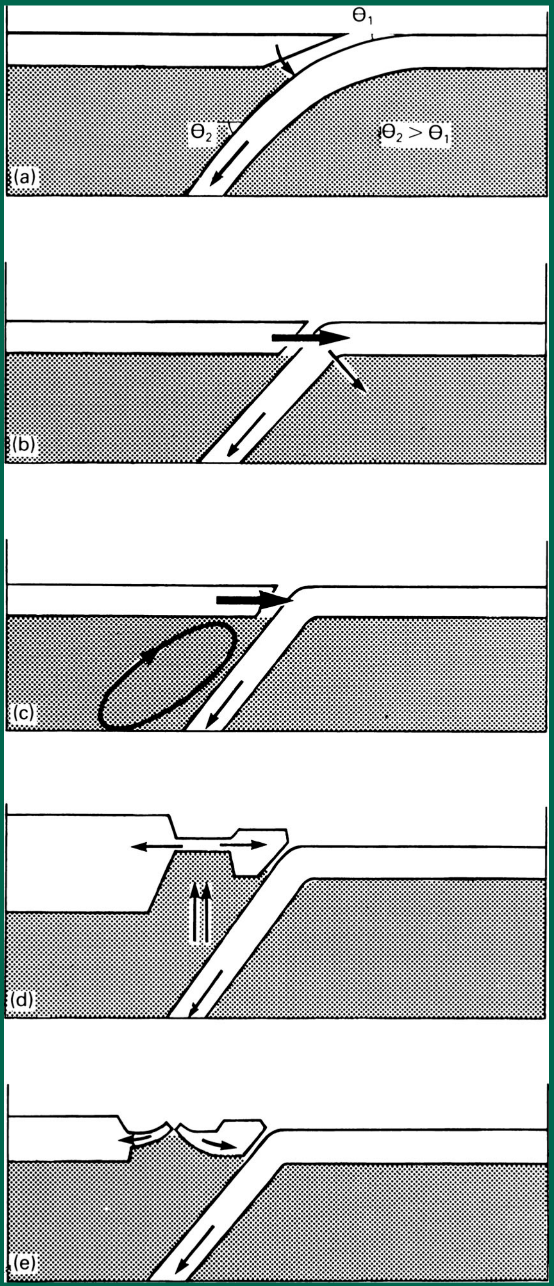


Figure 10-6.
Forces acting on plates.

Cox & Hart



KK&V Fig. 12.8

Suction Force - F_{SU}

Continents appear to be pulled toward the trench by a suction force. Perhaps because subducting slab produces an eddy-like flow in the asthenosphere or because the roll back motion of the slab creates a mass deficiency on the landward side of the slab, which sucks the continent towards it.

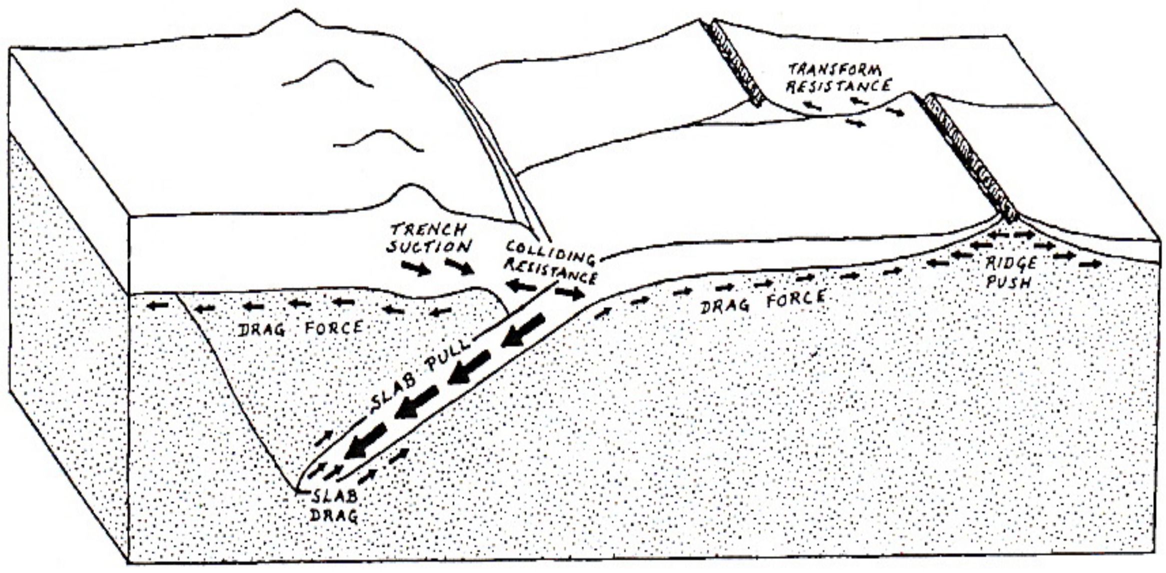


Figure 10-6.
Forces acting on plates.

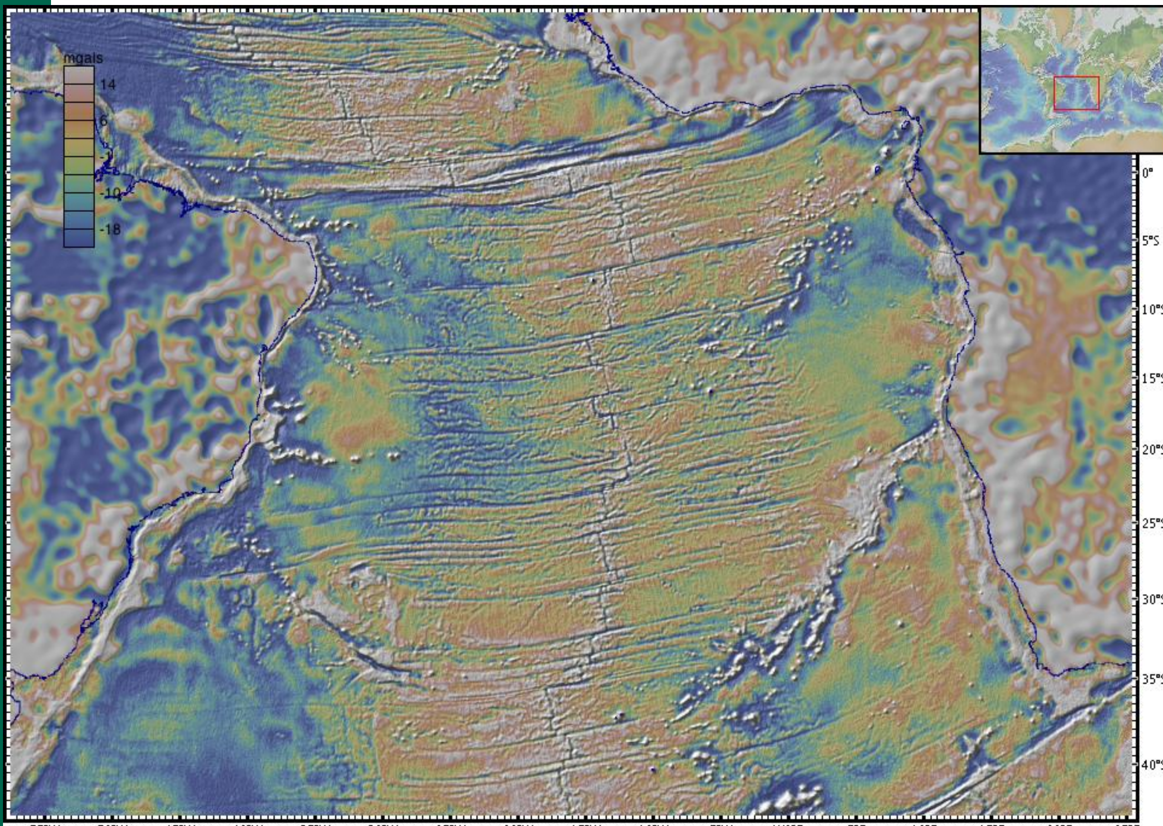
Cox & Hart

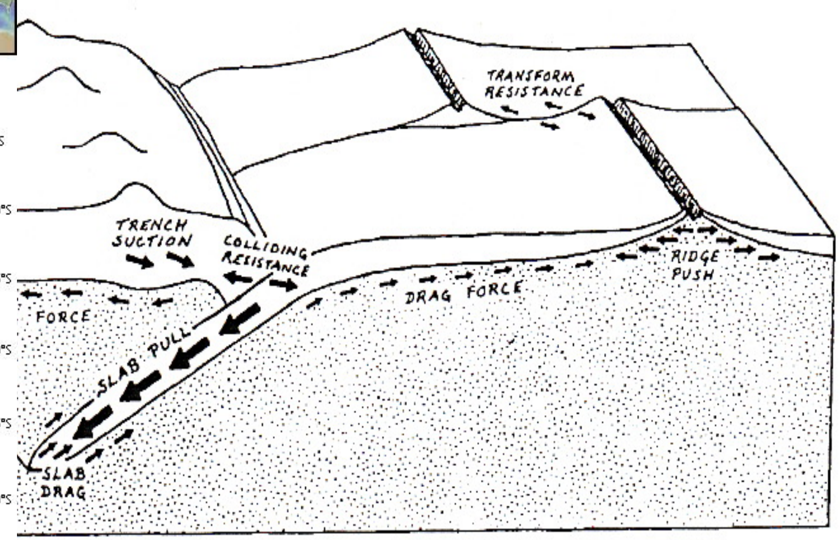
Transform Fault Resistance - F_{TF}

Friction along transform faults produce a resistive force as shown by presence of earthquakes. Function of stress in plate across transform. Independent of plate velocity.

Colliding Resistance - F_{CR}

Friction between plates tends to resist convergence as shown by presence of earthquakes. Faulting occurs when a critical yield stress is reached. Should be independent of velocity of convergence.



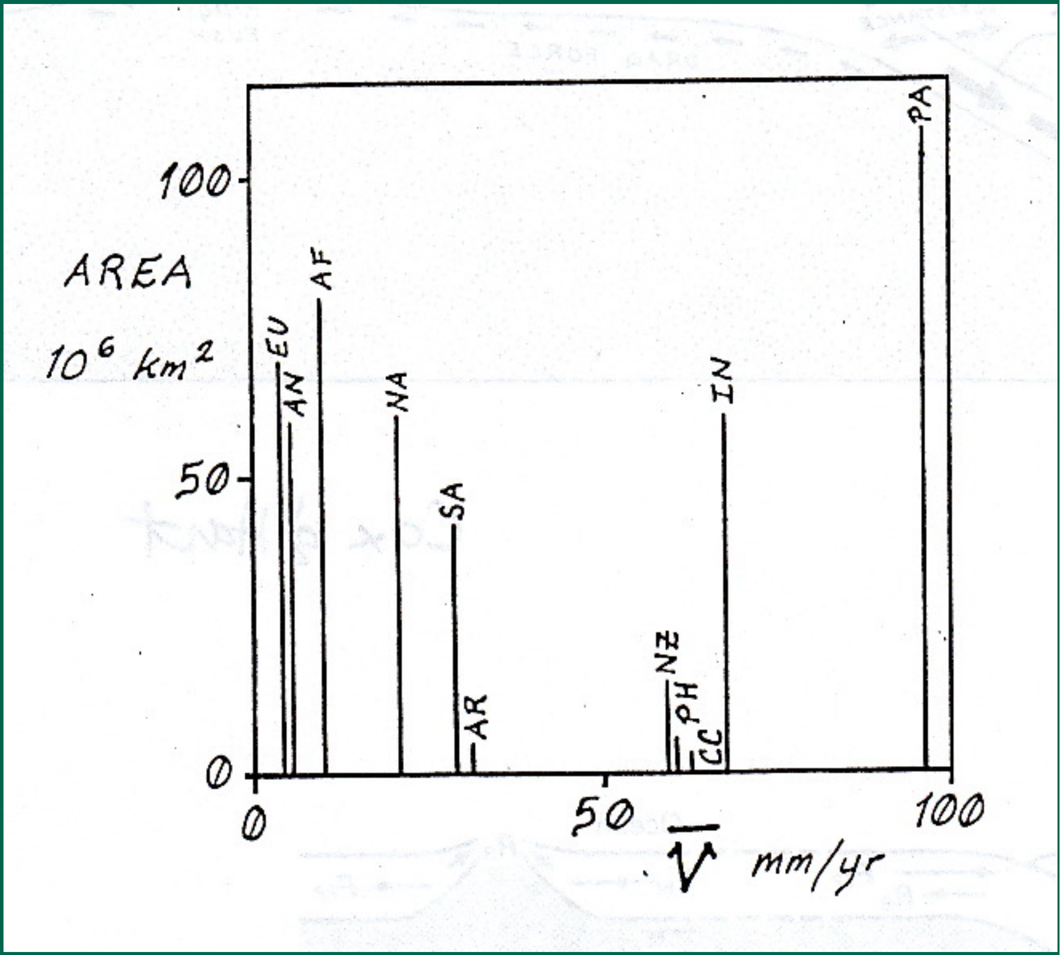


Cox & Hart

Classic study of Forsyth and Uyeda (1975) which evaluated possible driving forces

Plotted absolute velocities of 11 plates versus several parameters:

1) Area of plate
2) Area of continent
3) Percentage transform faults
4) Percentage ridges
5) Percentage trenches



1) Total area of plate versus absolute velocity:

No correlation – implies mantle drag force is small

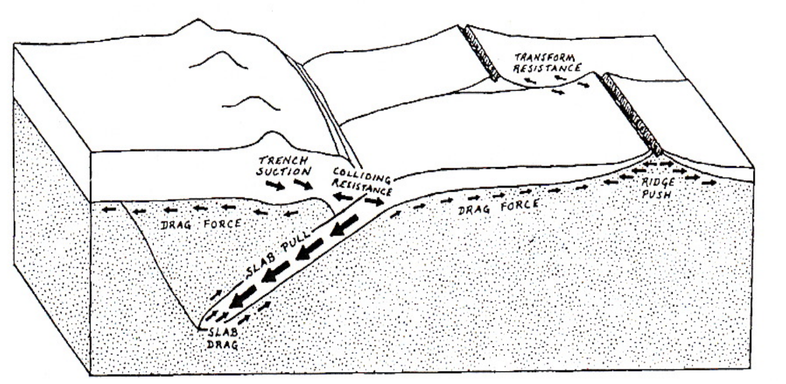
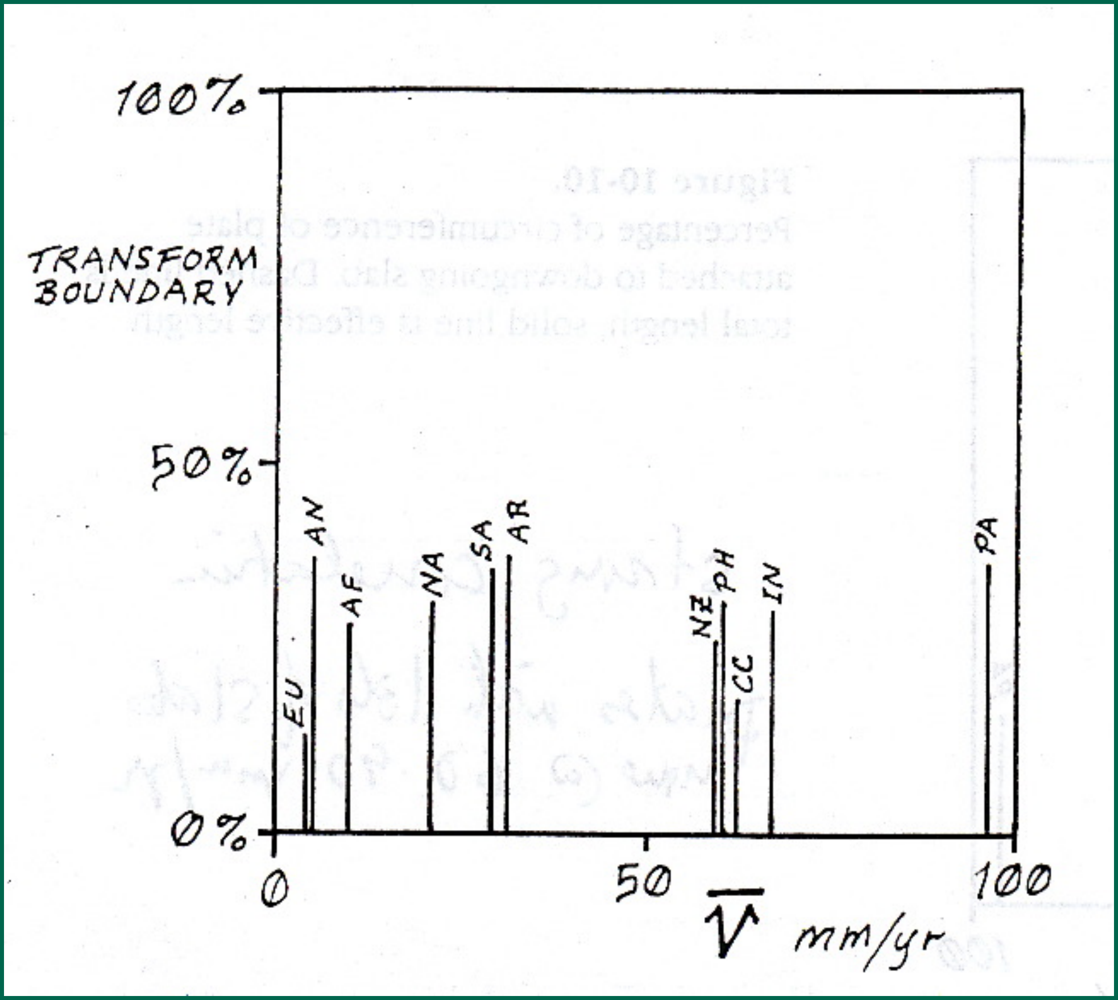


Figure 10-6.
Forces acting on plates.

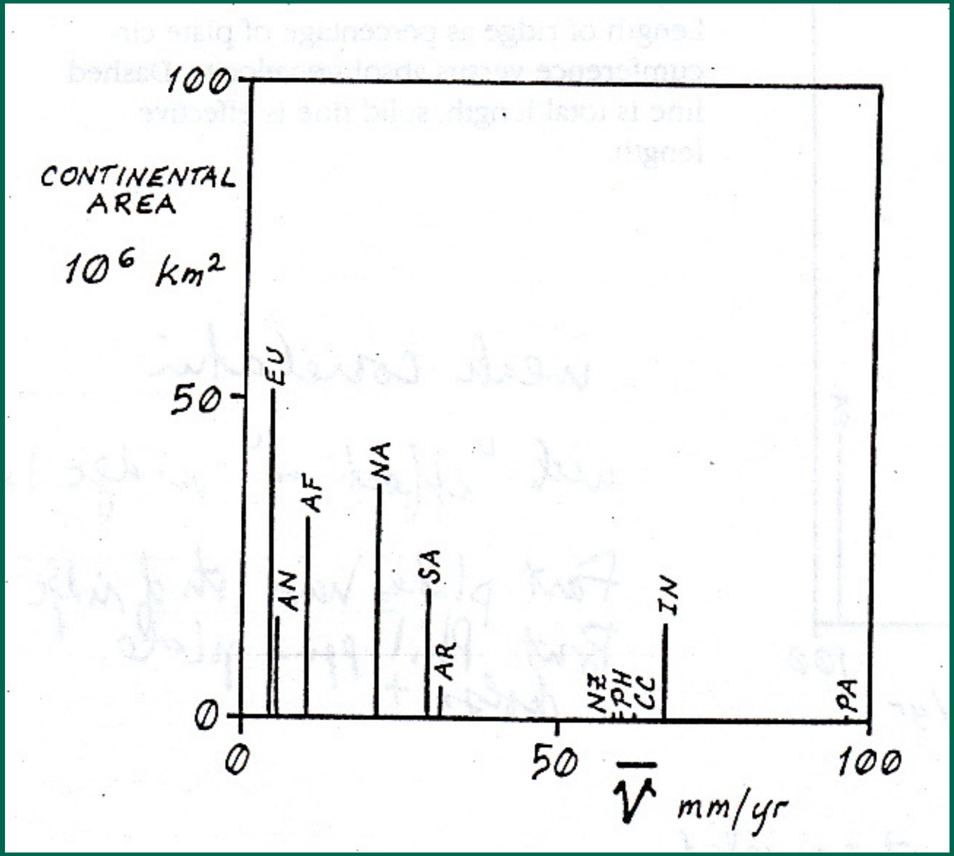


2) Transform boundaries:

No correlation between absolute velocities and percentage length of transform faults

Implies resistive force across transform faults is small

3) Continental area of plates:



Moderate correlation

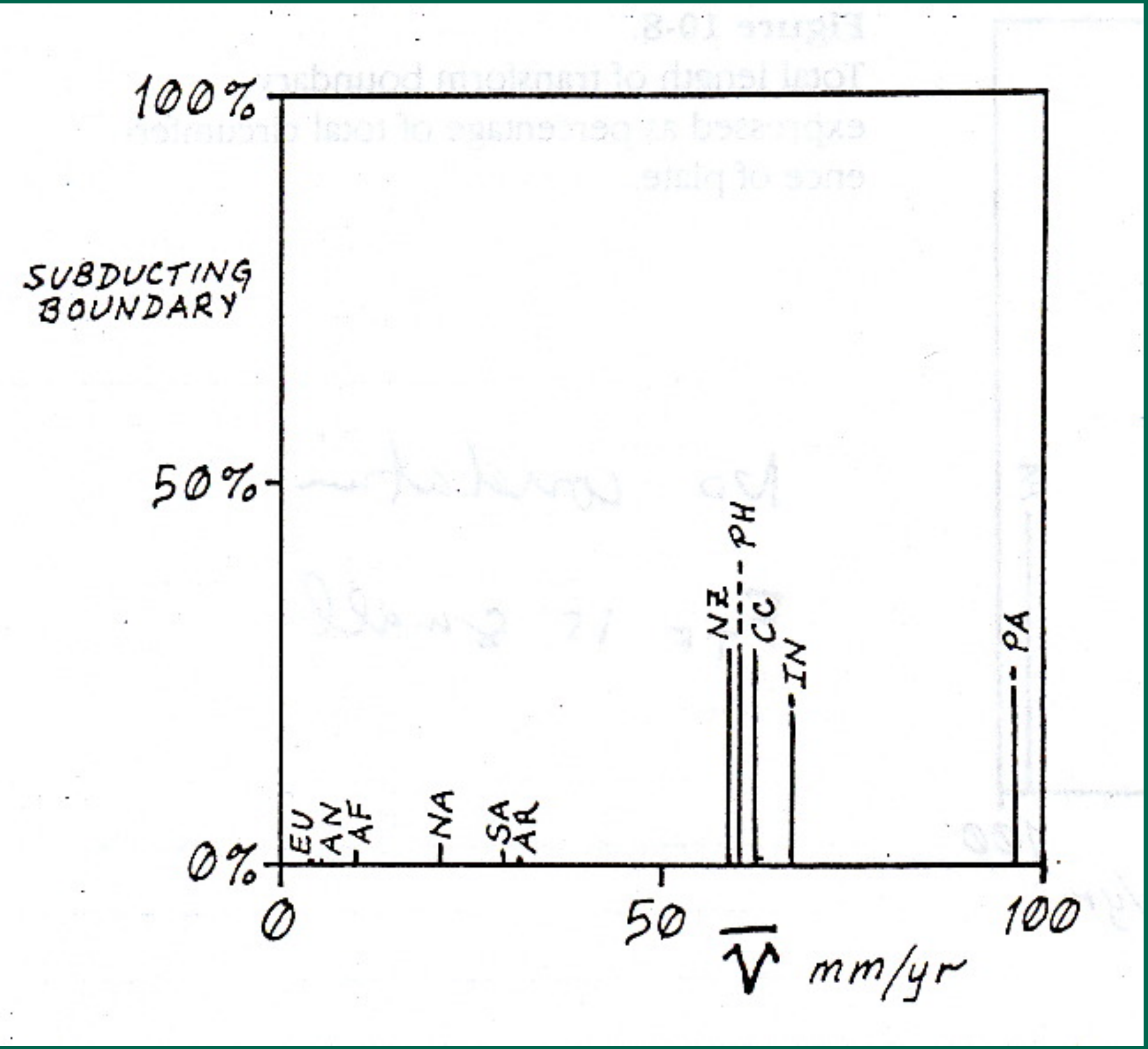
Note that India and Antarctic have same area but very different velocities

Implies:

Mantle drag is stronger beneath continents

Or – no slab attached to slow continents

(Fast motion of India is still a mystery)



4) Percentage of boundary attached to a downgoing slab

Strong correlation

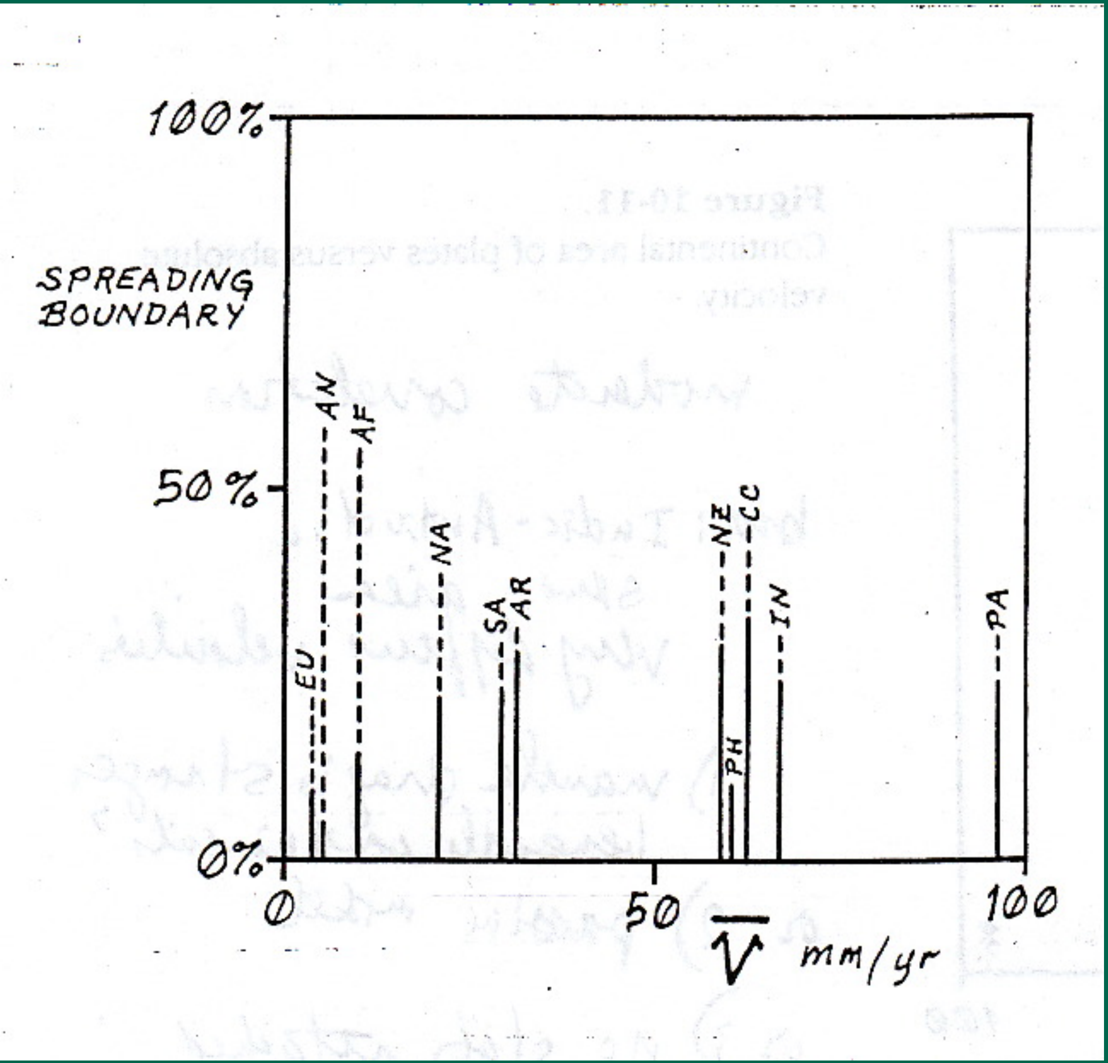
Plates with high percentage of slabs move @ 60 – 90 mm.yr

Implies:

Slab pull is primary force!

5) Length of ridges as percentage of boundary

How strong is Ridge push?



Need to look at “effective” ridge length. That is, part not cancelled by ridges on opposite side of plate – like around Antarctica and Africa

Weak correlation with effective ridge length

(note: most fast plates have lots of ridge but Philippine plate does not)

Mixed message

but clearly need ridge push to explain motion of plates with no slabs attached

Ridge push is about 1/10th of slab pull

Summary of driving forces

1) Mantle Drag is small.

2) Slab Pull is the largest force and is 10x greater than Ridge Push.

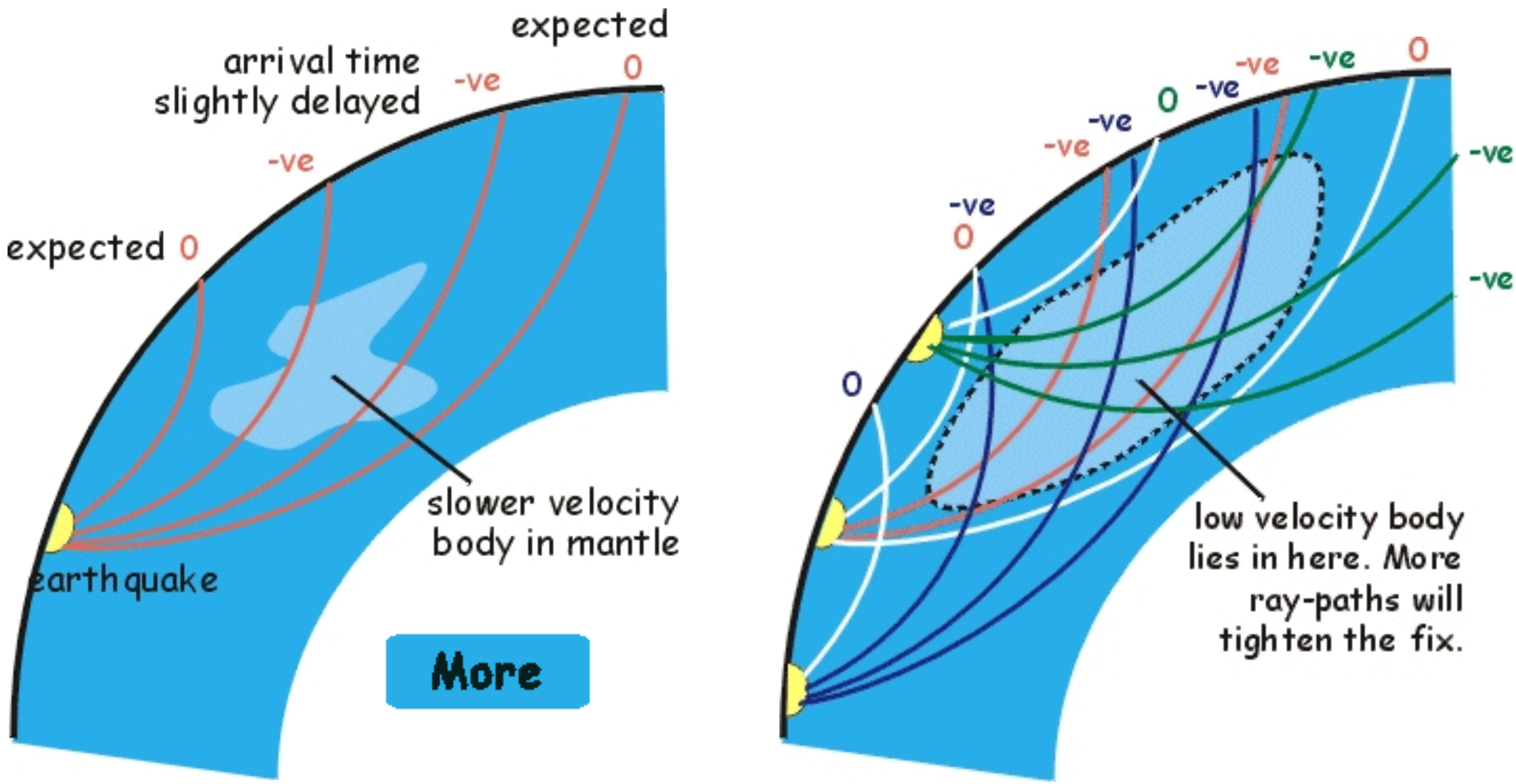
However,

3) Slab Pull is balanced by Slab Drag.

Consequently,

4) Ridge Push remains an important force in the overall scheme of things and may explain why North America moves.

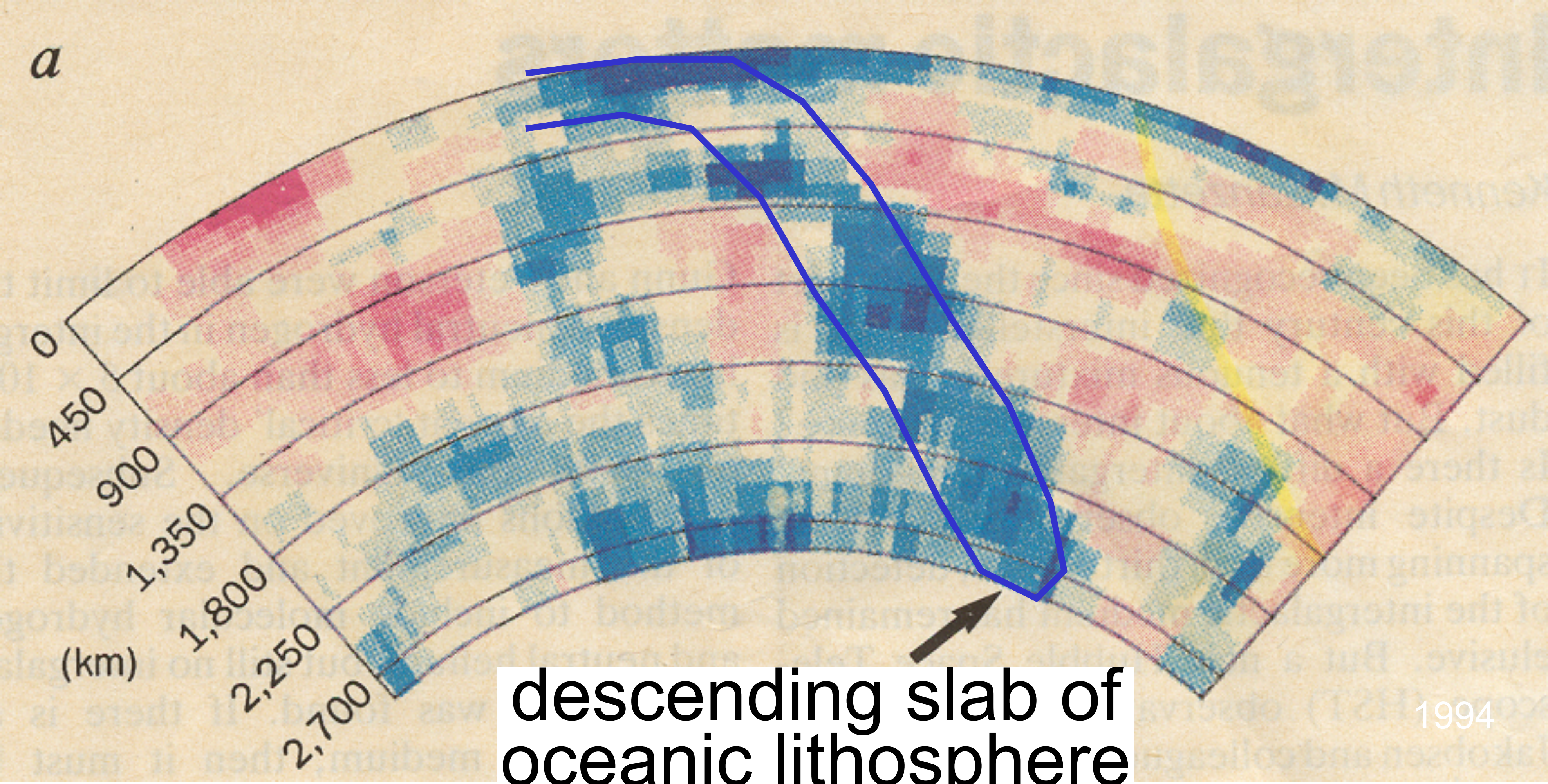
Tomography gives an image of the earth's interior by measuring the slowing or speeding of seismic waves.



First evidence for whole mantle flow

Pacific Ocean

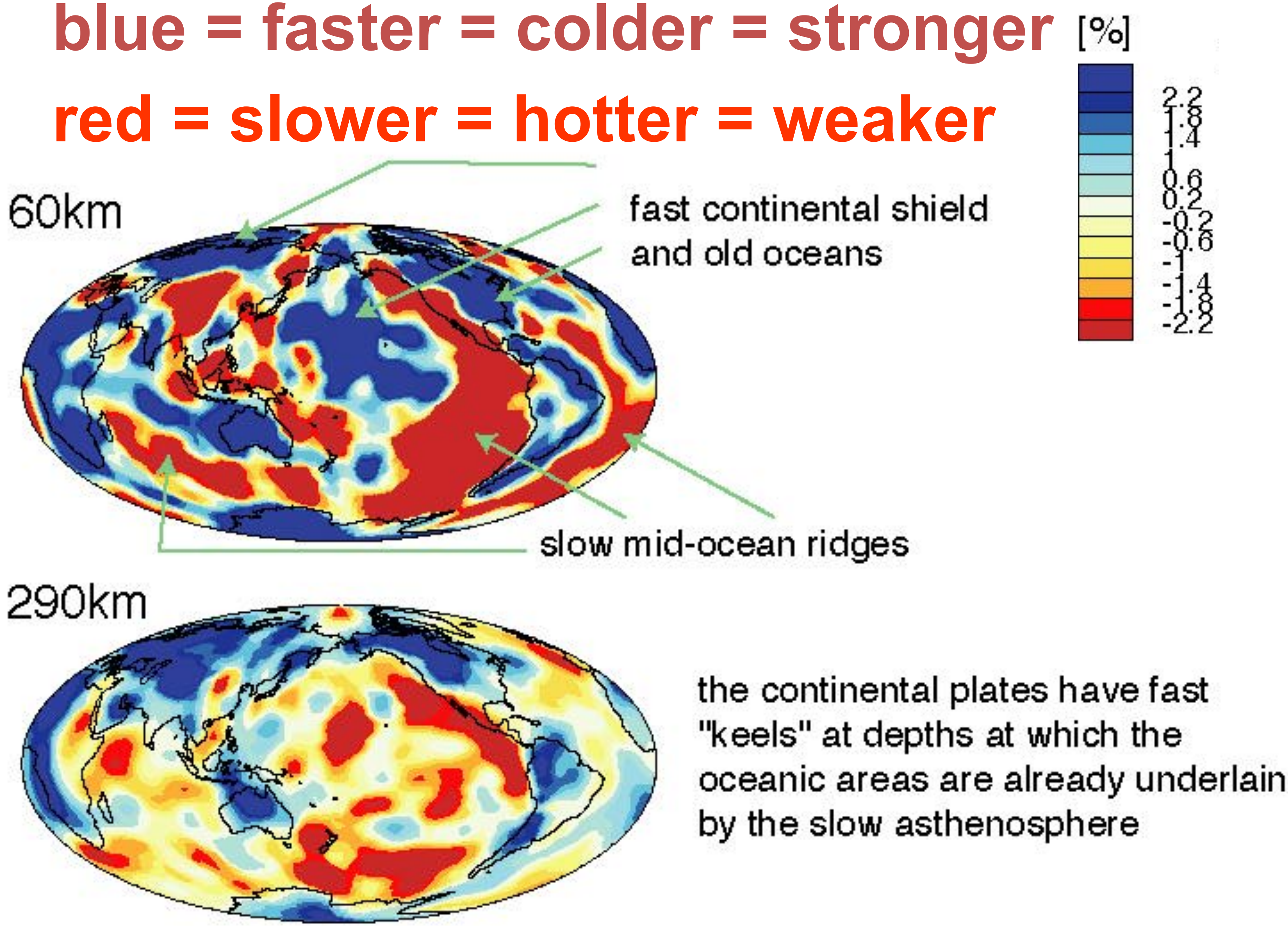
west coast of North America



seismic tomography permits a view of the earth's deep interior

blue = faster = colder = stronger

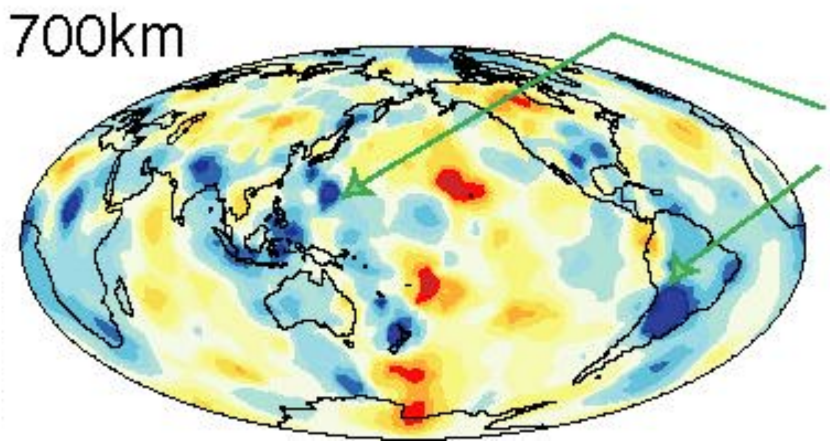
red = slower = hotter = weaker



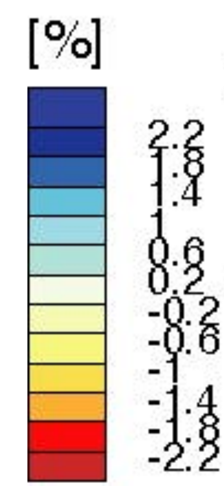
blue = faster = colder = stronger

red = slower = hotter = weaker

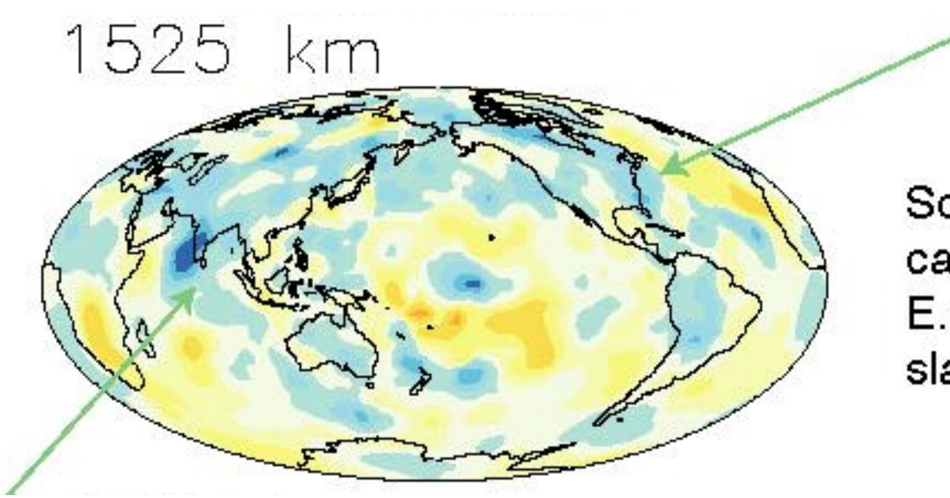
to the base of upper mantle



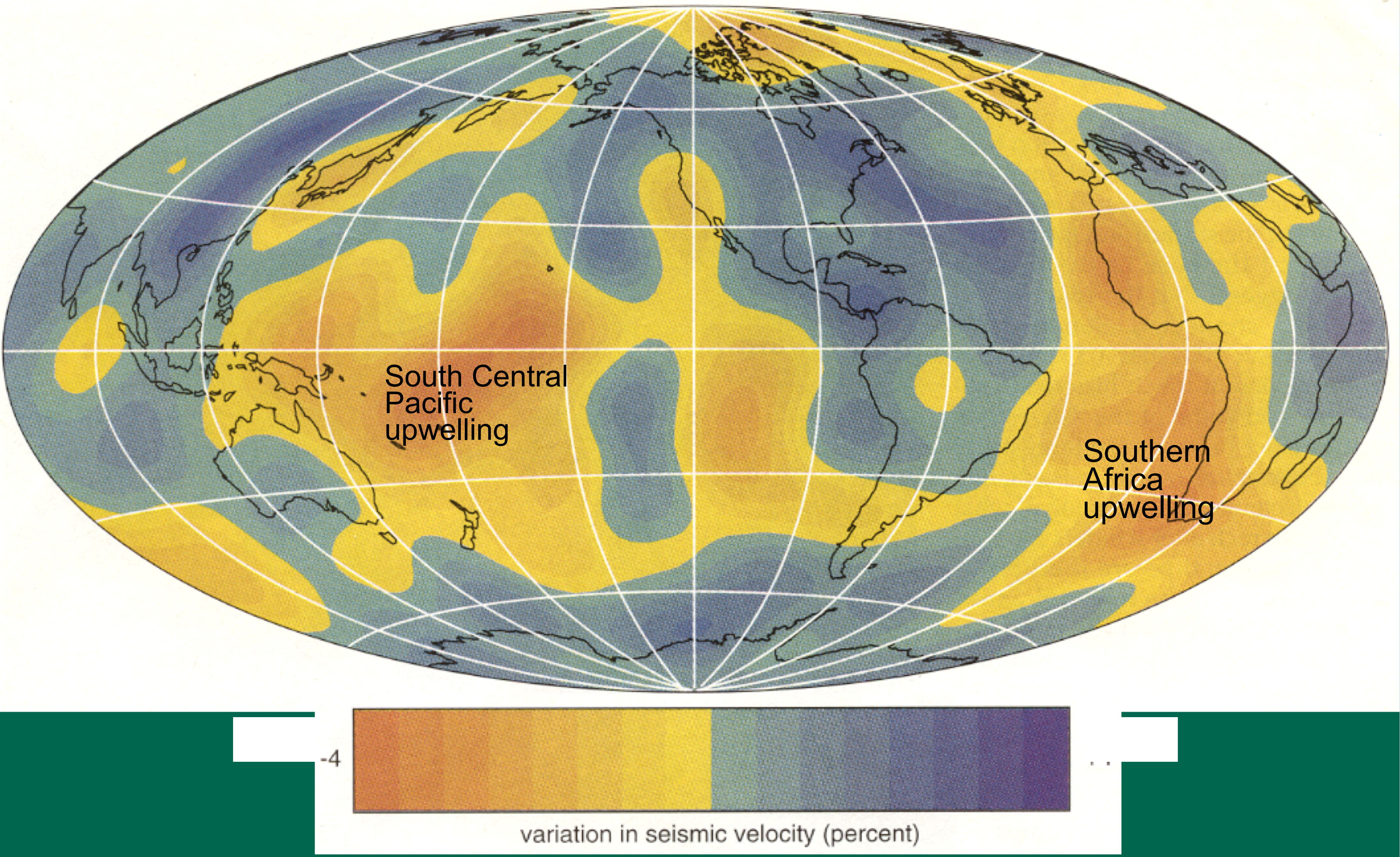
The "cold" subducting slabs show up as seismically fast areas. They pass the 670km discontinuity between upper and lower mantle and penetrate well into the lower mantle.



and even way down in the lower mantle

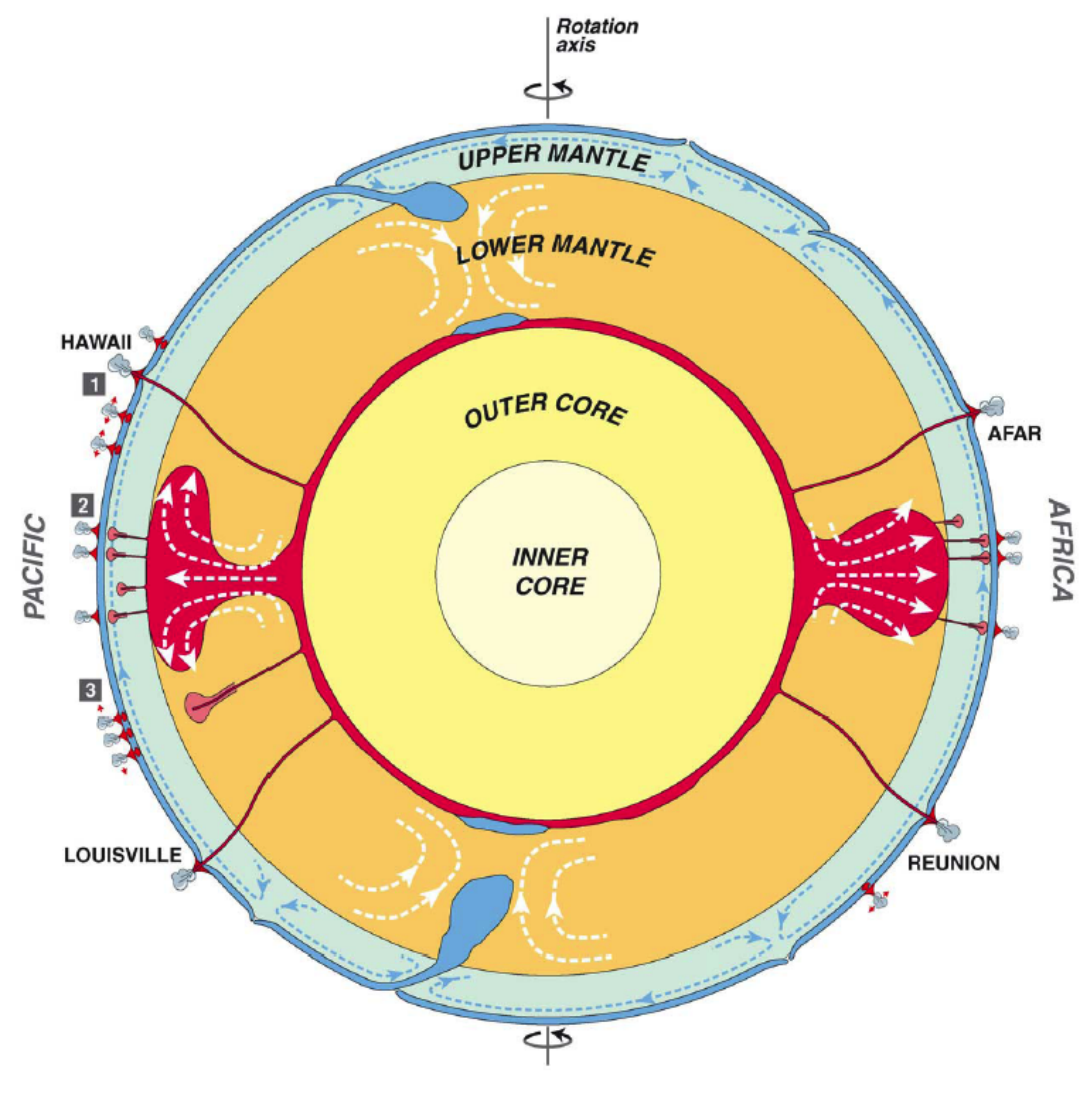


Some of the "cold" subducting slabs can be traced well into the lower mantle. E.g. old Farallon and Tethian subducting slabs.



Seismic tomography at the **base of the mantle** reveals continent-size structures and variations un-paralleled in magnitude except at the earth's surface.

High-velocities (blue) are cold rock
Low velocities (orange) are hot rock



Middle ground?

Not all hotspots come from deep mantle plumes

Some may come from the top of domes near the transition zone

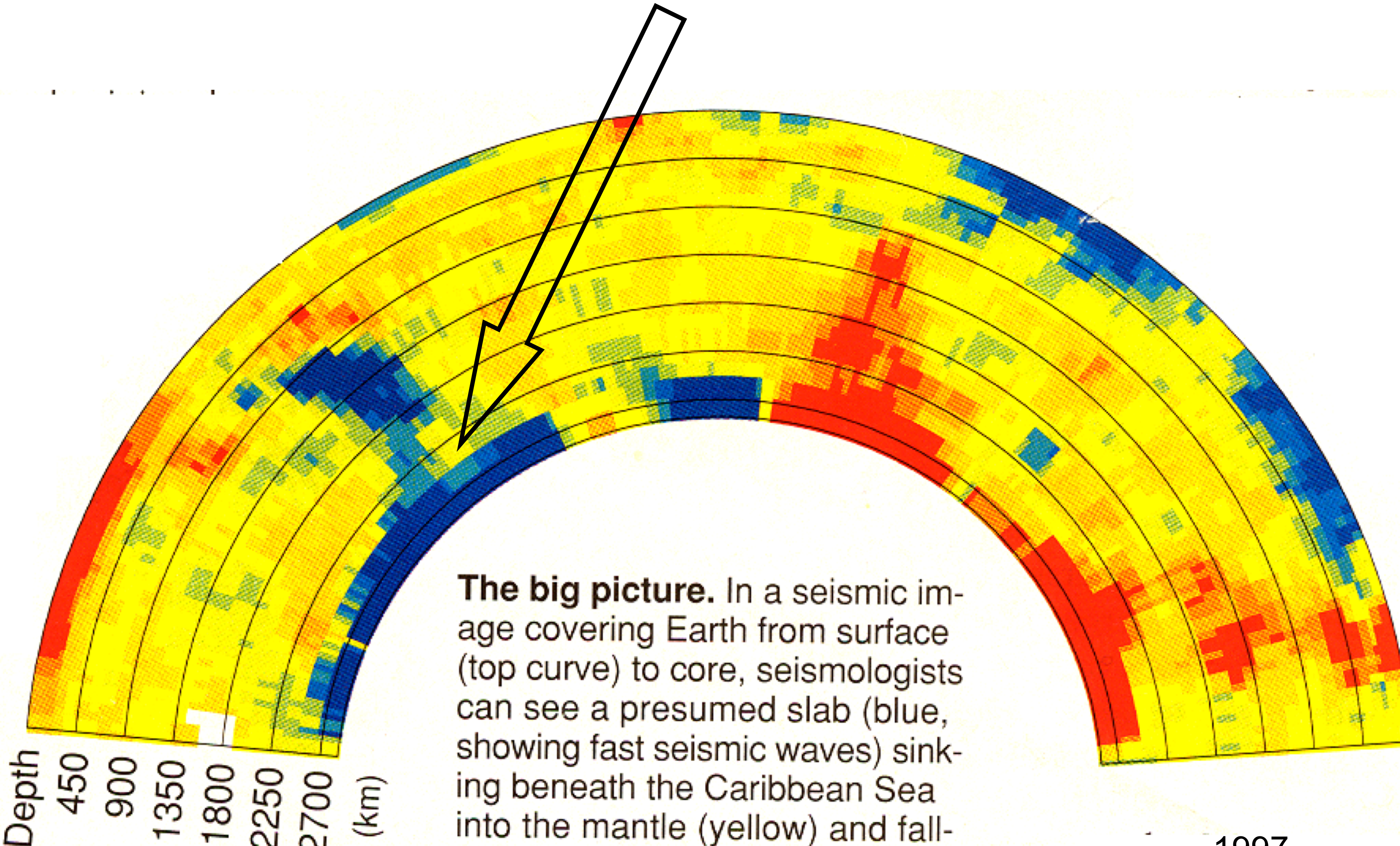
Still others may have a shallow origin due to cracks in lithosphere

Next: look at base of mantle

D”

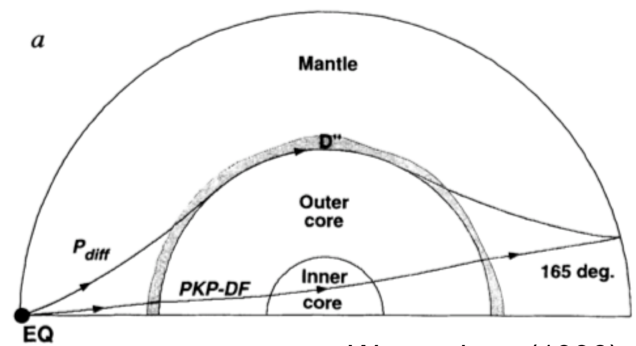
Courtillot et al. 2003

graveyard of cold lithosphere slabs at the base of the mantle?



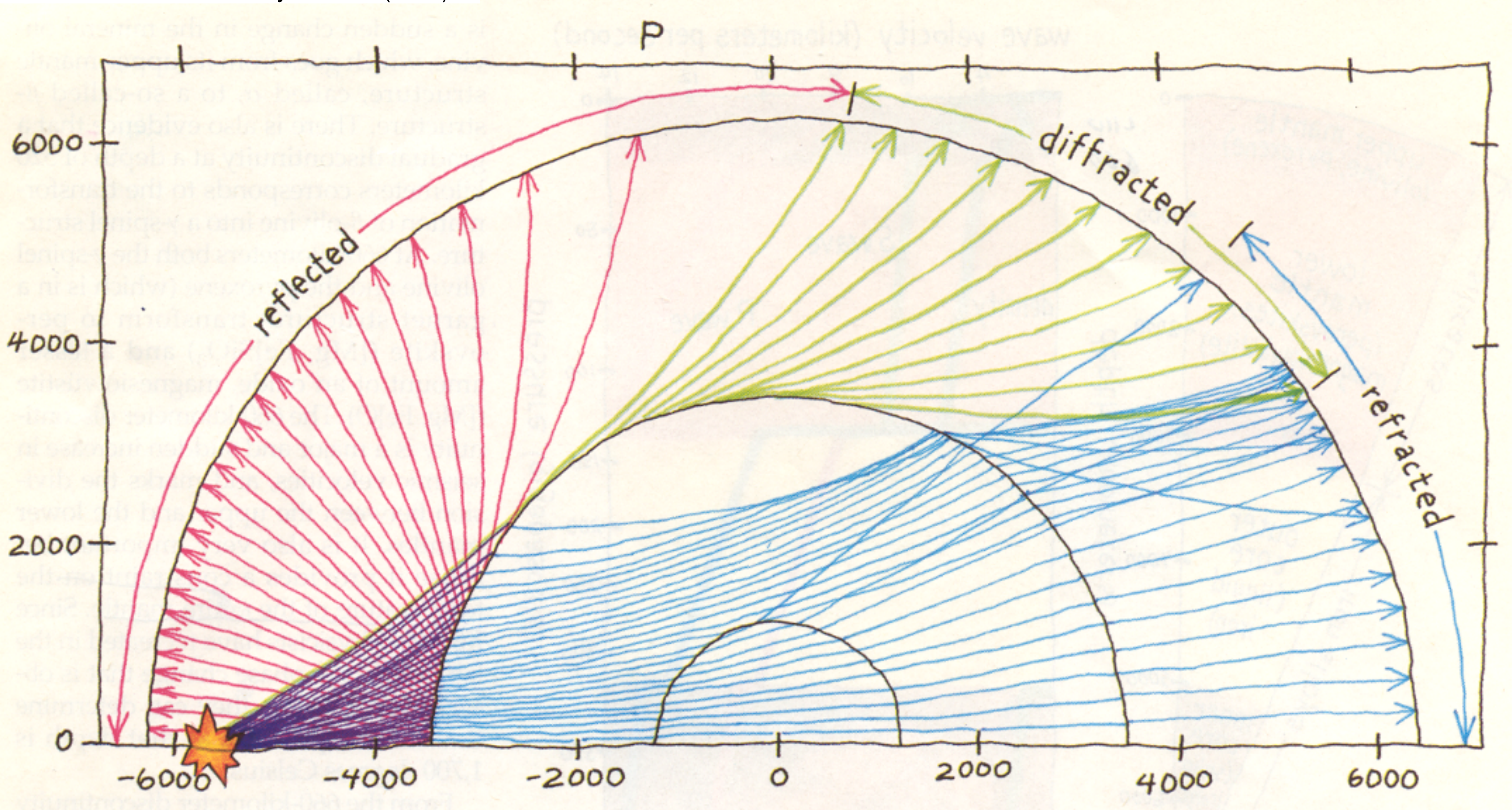
The big picture. In a seismic image covering Earth from surface (top curve) to core, seismologists can see a presumed slab (blue, showing fast seismic waves) sinking beneath the Caribbean Sea into the mantle (yellow) and falling into other slabs near the core.

1997



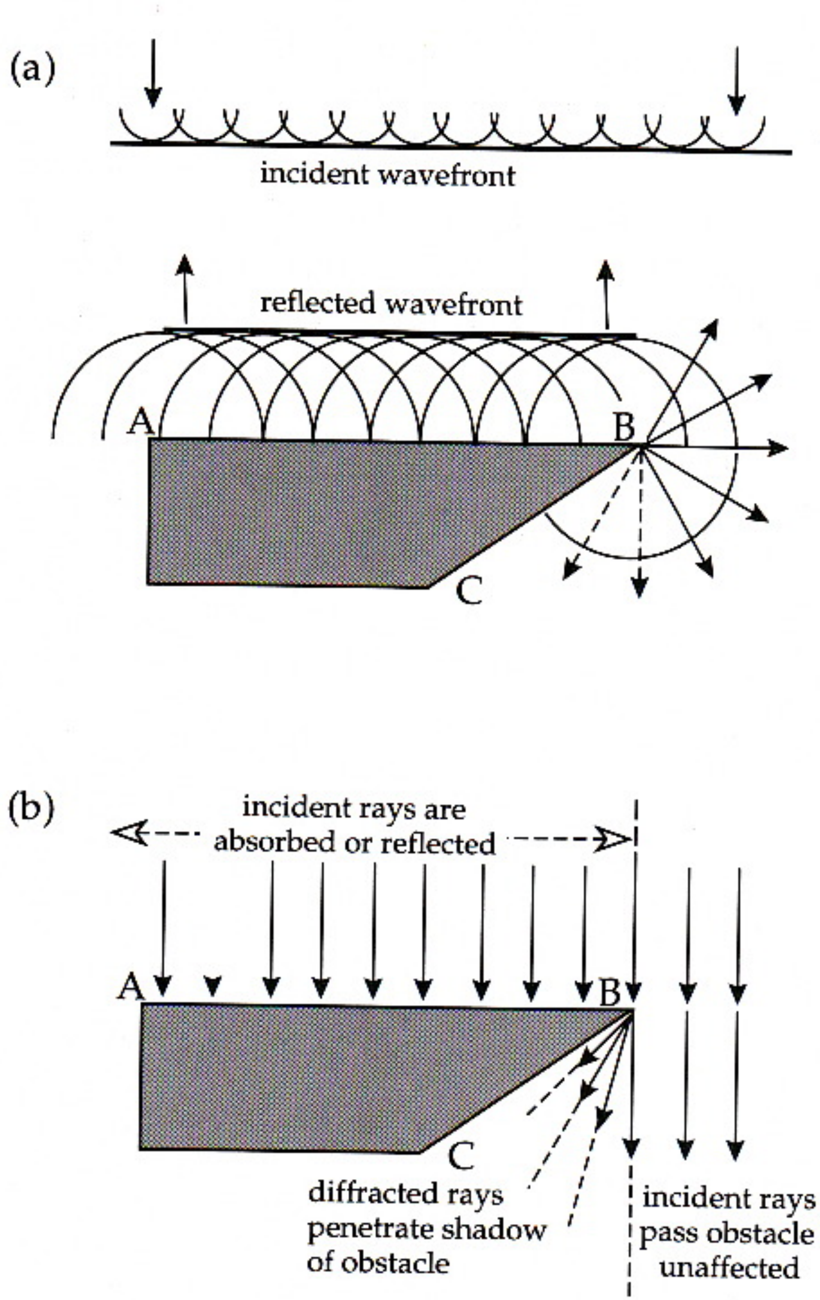
Wysessions (1996)

One EQ wave we haven't discussed yet are diffracted arrivals. Represents energy that has been refocused after hitting point or line barriers. Not usually used in seismology. However, these waves spend a lot of time grazing the core-mantle boundary and recently have been used to probe the structure of layer D".



Diffraction allows waves to bend around corners and point obstacles.

This is the reason we can hear people talking around the corner in another room.



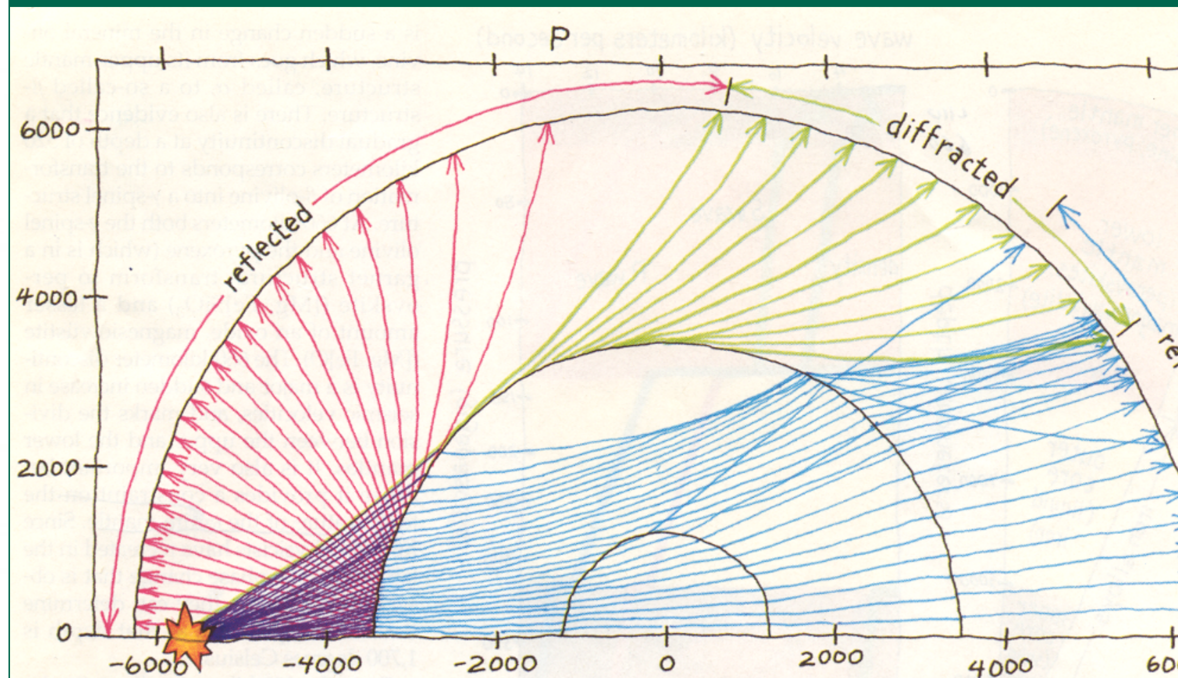
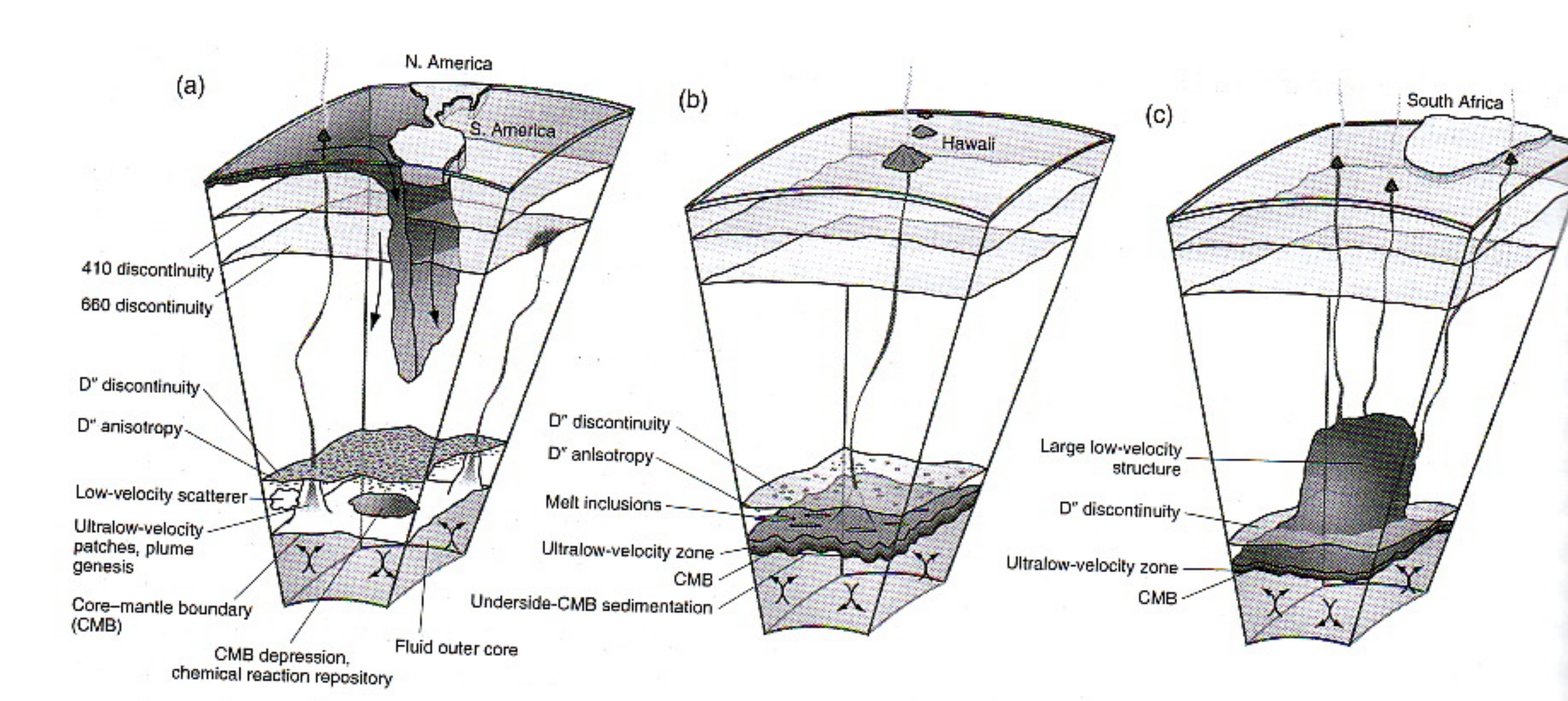


Figure 3. Seismic waves from large earthquakes (in this case one originating 5,730 kilometers from the earth's center) offer the be
map regions within the earth. In this example, waves emanating from the quake are represented as rays and show how they could b
study the core-mantle boundary, which is 3,500 kilometers from the earth's center. Seismometers, depending on their distance from t
quake, will detect waves that have been reflected off, diffracted around or refracted across the core-mantle boundary. A careful exa
of these waves reveals the structure of this boundary. Axes show distance from the center of the earth in kilometers; concentric lines
boundaries of the inner and outer core and the mantle.

Lowrie (1997)



D” is a thermal-chemical boundary layer at the base of the mantle

Recent seismic tomography reveals great complexity and vertical and lateral variability

KK&V Fig 12.11

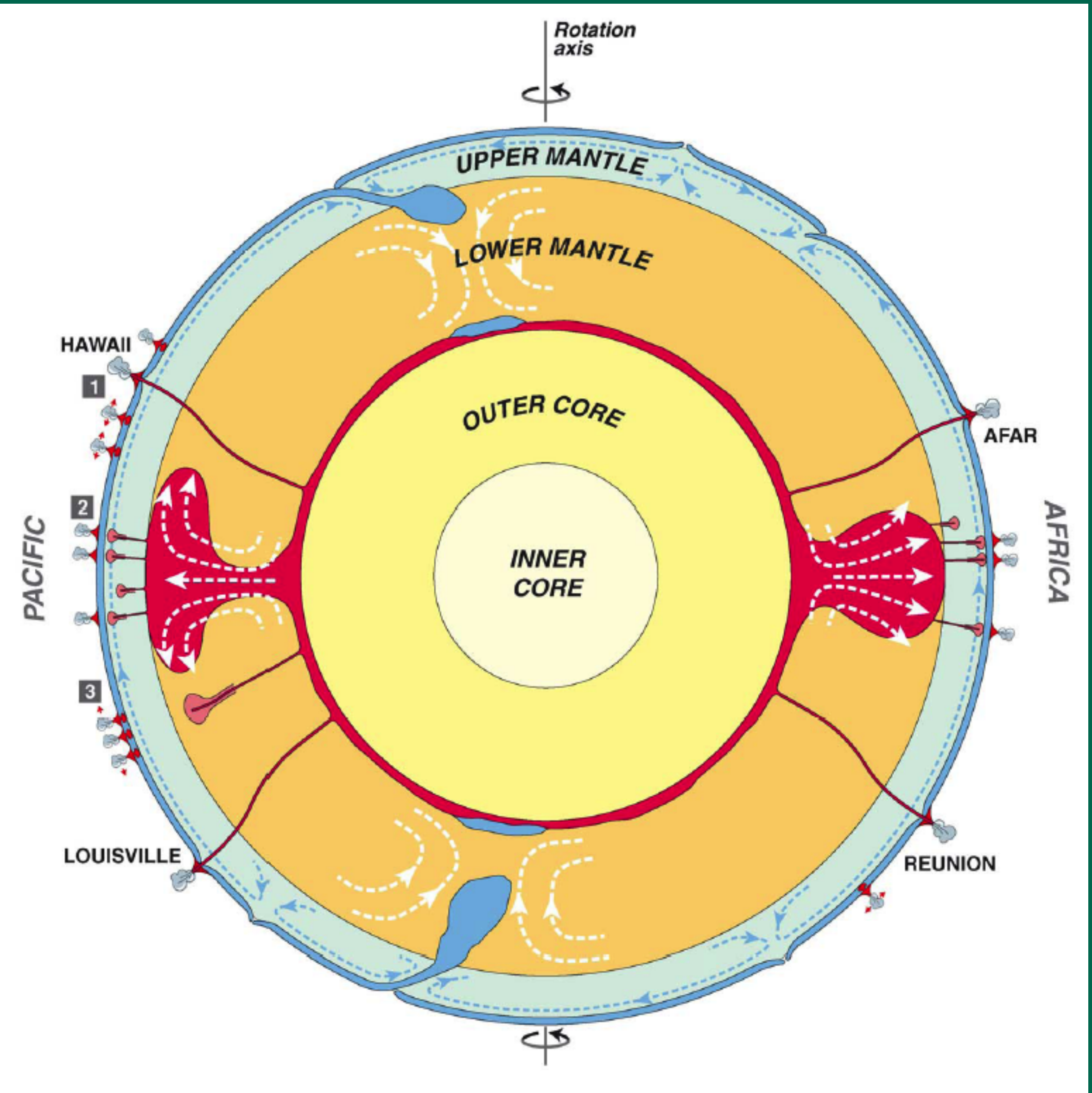
Three examples:

a) See a velocity increase beneath regions where we have subducting slabs

b) Beneath hotspots seismic velocities are decreased (an ultra low velocity zone or ULVZ) implying 15% partial melt
Probably chemical as well as thermal variations

c) See ULVZ’s beneath South African superswell

Nature of convection in the mantle



Can think of two complementary modes of convection

Plate mode cools the mantle; plume mode releases heat from the core

Driven by downwelling of cold plates and upwelling of hot plumes

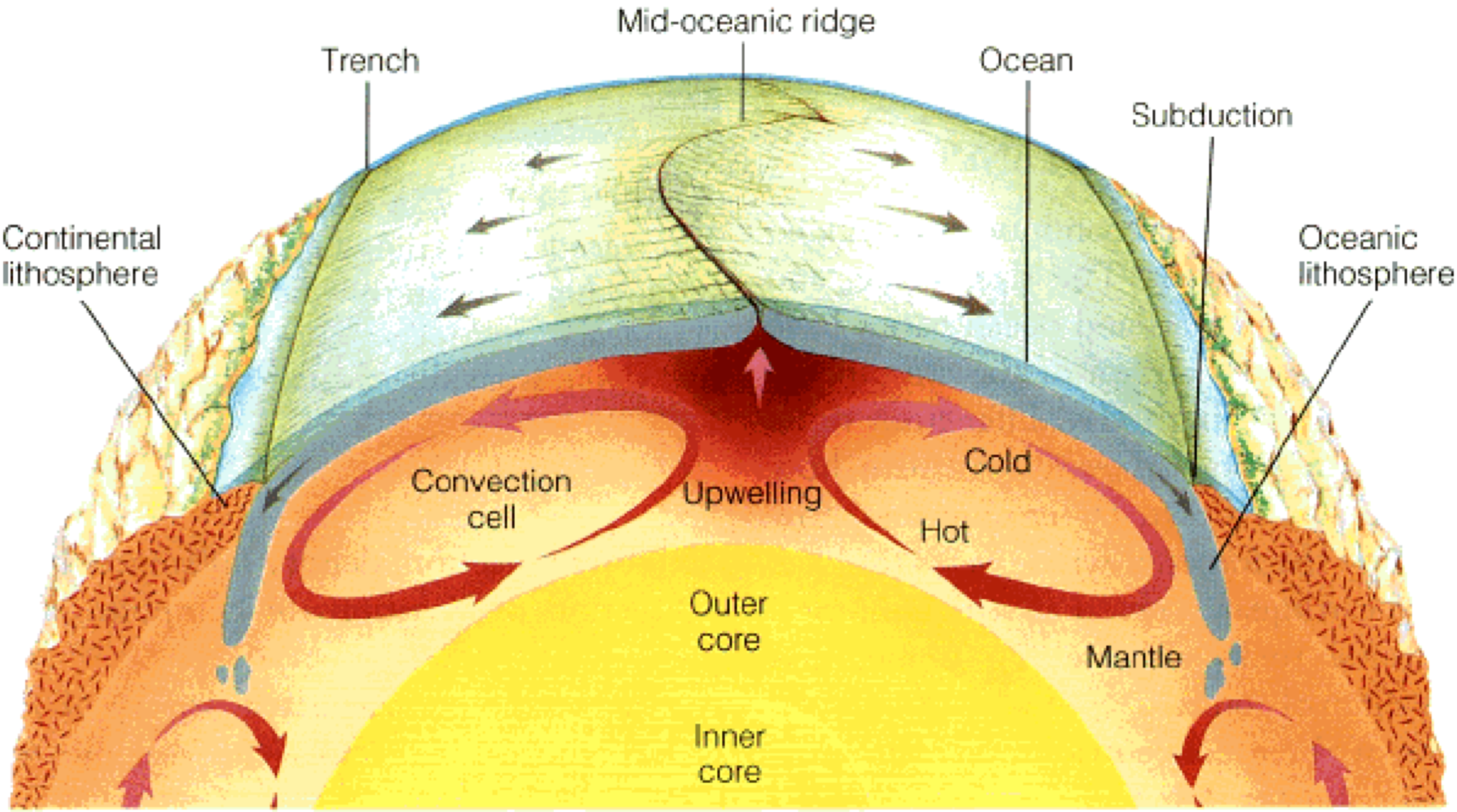
Two major areas of upwelling (from base-of-mantle tomography): one beneath southern Africa and the other beneath the south central Pacific

These two zones of upwelling do not correspond directly to mid-ocean ridges; instead they are at the center of rings of subducting slabs

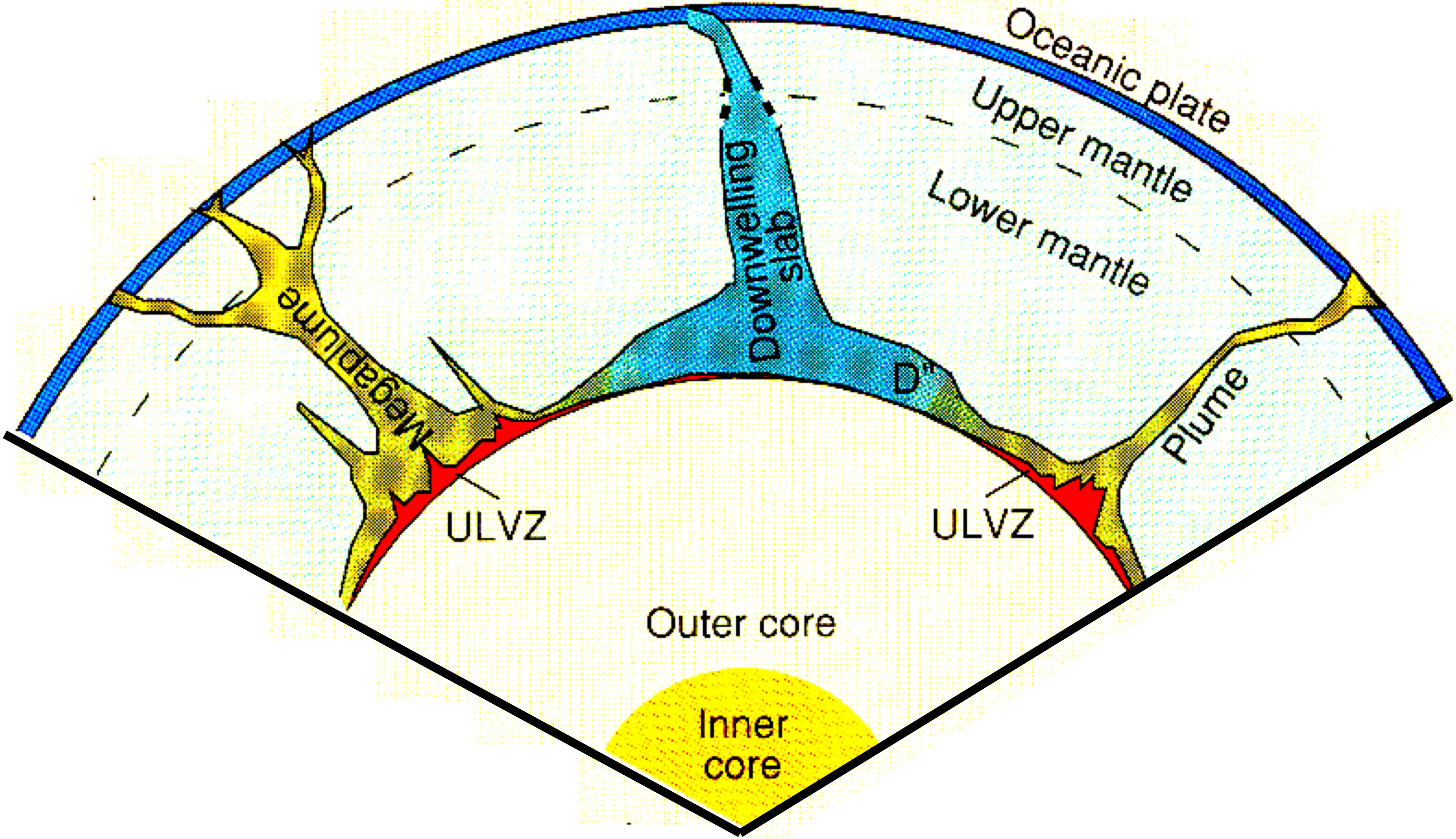
Primary plumes (like Hawaii) come from core-mantle boundary

Secondary plumes from top of superswells

Courtillot et al. (2003)



So, the early, simple picture of mantle convection in large bi-symmetric cells is not supported by observations and modeling.

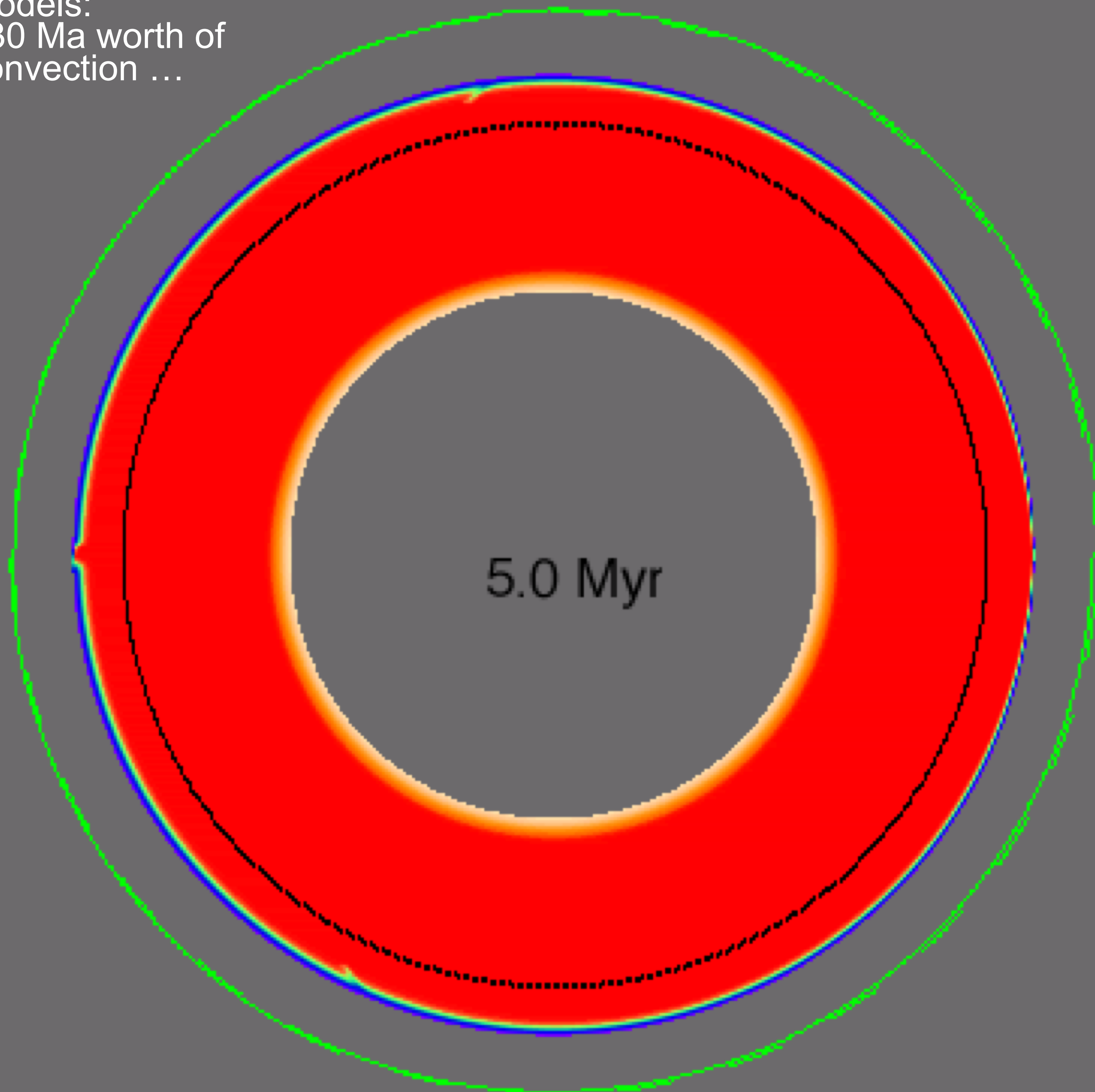


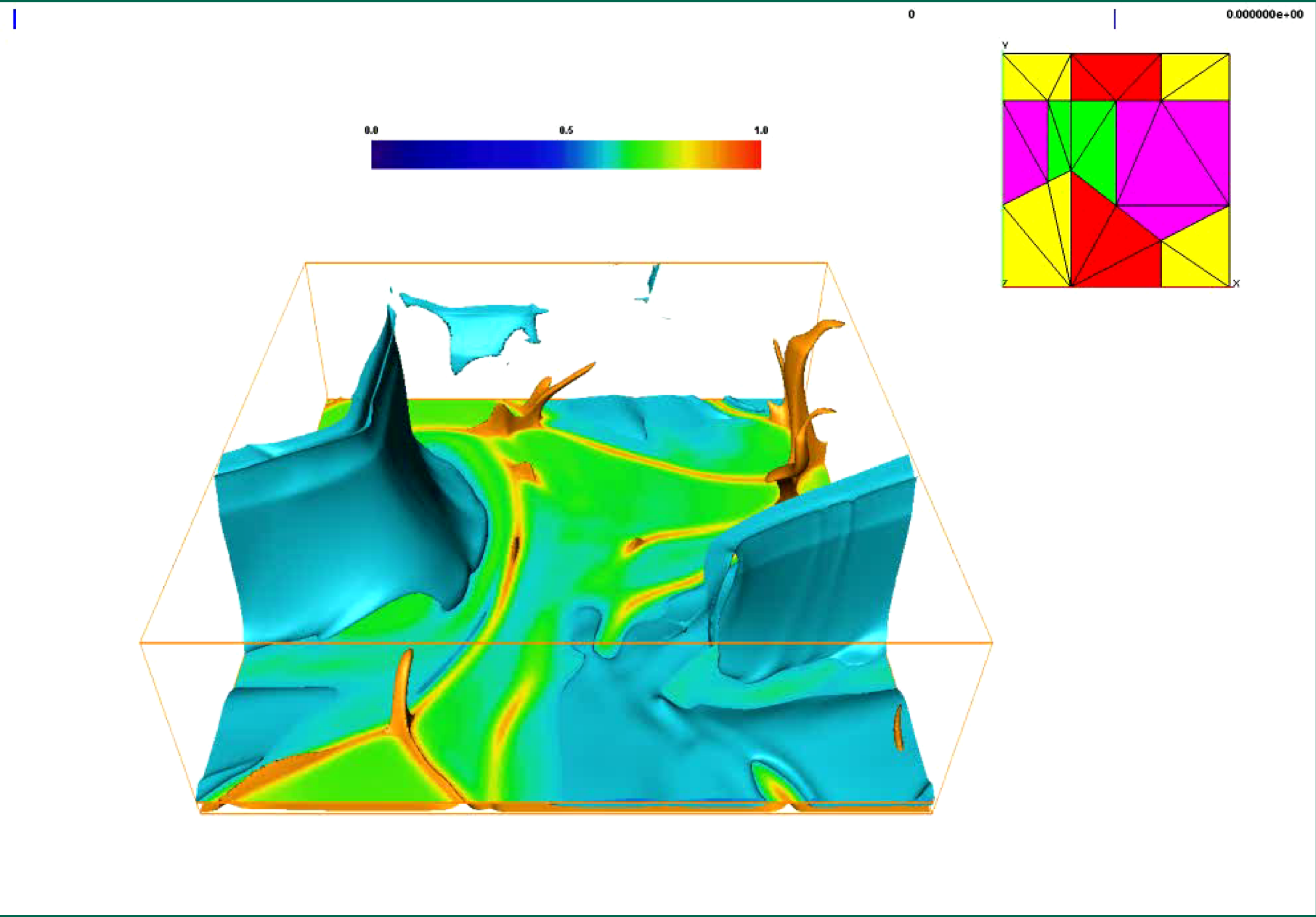
Instead we see convection in the form of rising, hot plumes and sinking, cold slabs. The plates are not passengers, but are actual limbs of the convecting cell.

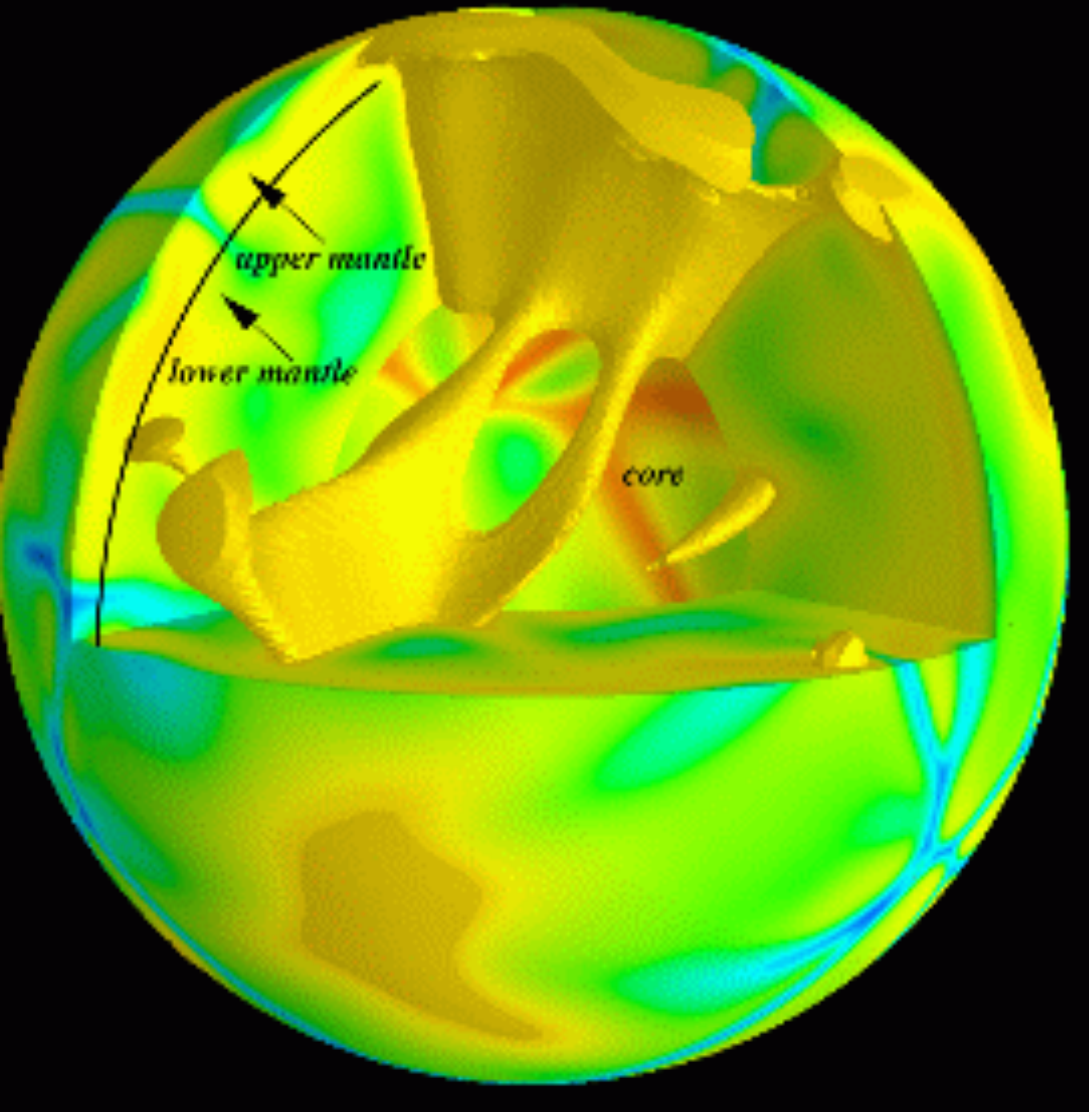
Bottom line

- Throw out the old (Holmes, Hess, etc.) concepts of mantle convection as cells rising beneath mid-ocean ridges and sinking at margins.
- Though phase changes produce abrupt density discontinuities in the mantle, lithospheric slabs are able to penetrate through these barriers.
- The base of the mantle collects old lithosphere and this lithosphere might re-cycle after it is warmed by the hot core.
- Hence plates are not passengers, but the cold part of the engine.

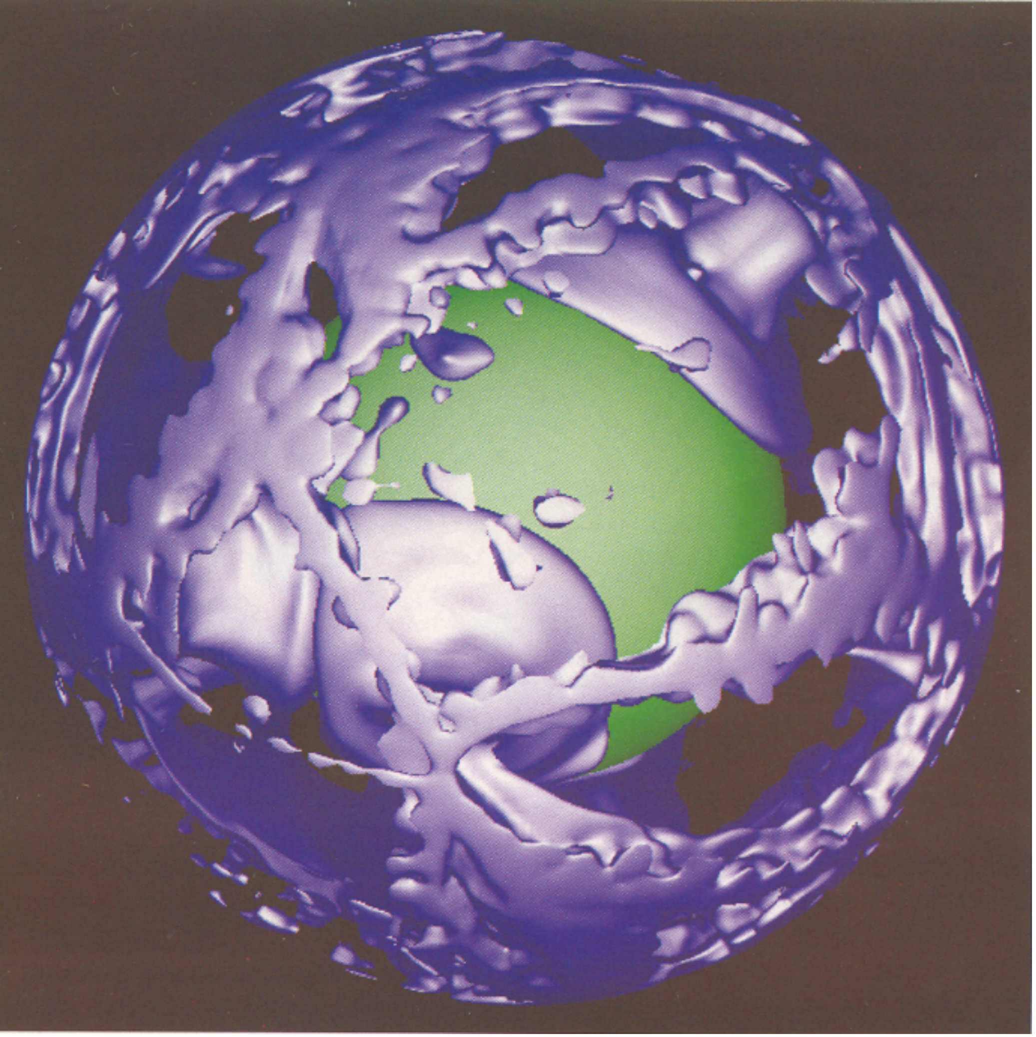
Geodynamic models:
230 Ma worth of convection …



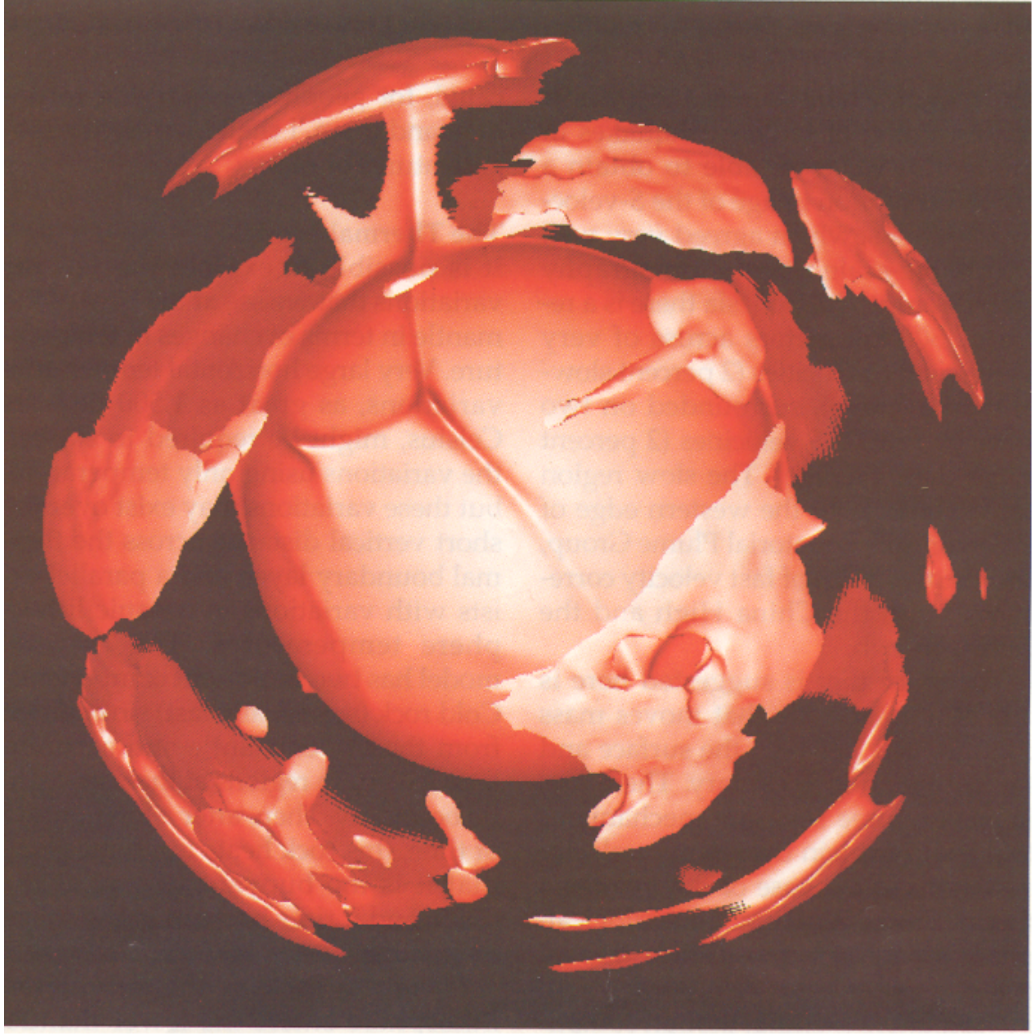

0
0.000000e+00
0.0
0.5
1.0



The tomography and computer simulation provide extraordinary view of mantle convection and how it is linked to the core-mantle boundary.

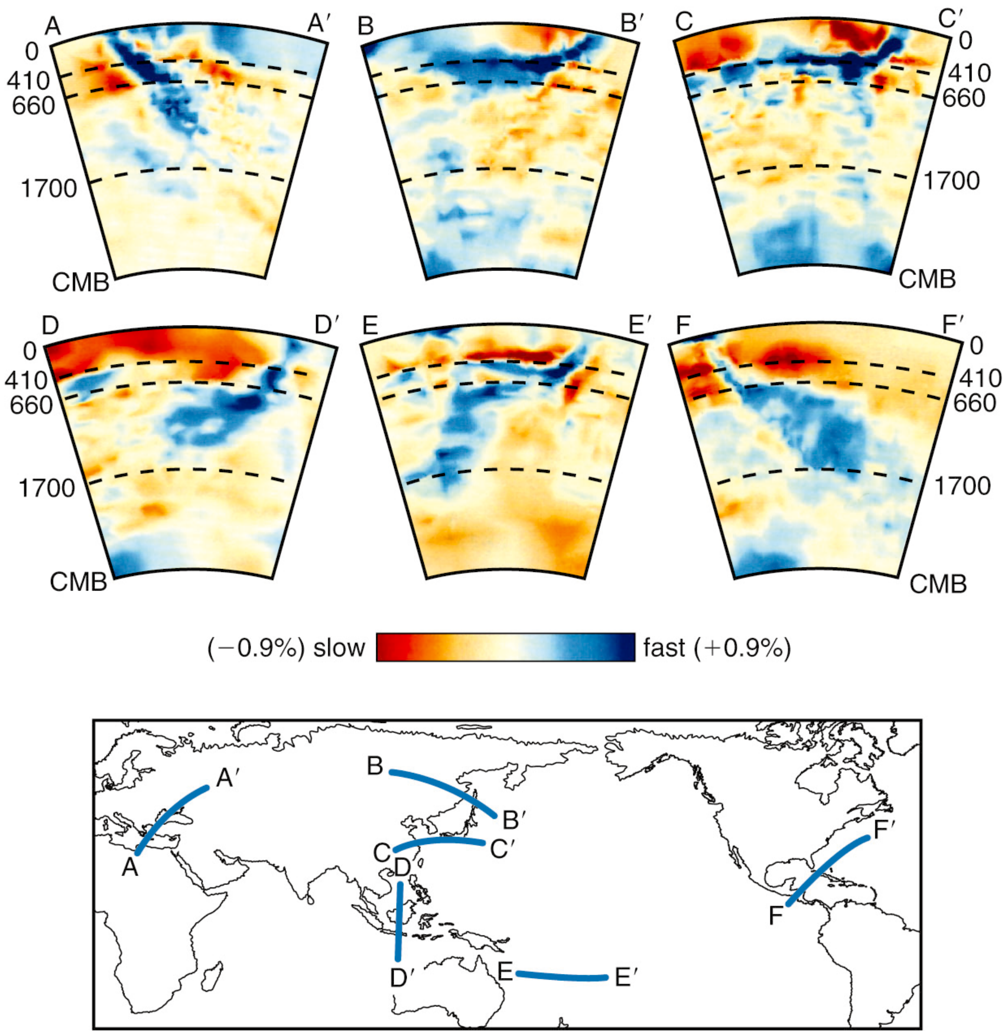


Cold mantle rock (blue) accumulates at the 660 km deep boundary, and occasionally penetrates into the lower mantle to rest on the top of the core.



Warm mantle rock (red) rises as plumes from the core-mantle boundary to return to the surface and complete the round trip. This is the principle escape route of the earth's internal heat.

Slab pull is all about negative buoyancy …



KK&V plate 9.2

Cross sections through the mantle from seismic tomography reveal subducted slabs penetrating into lower mantle

But only a few go straight down. Many "stall" at the 660 km transition zone.

This leads to all types of variations on the basic model of "slab pull"

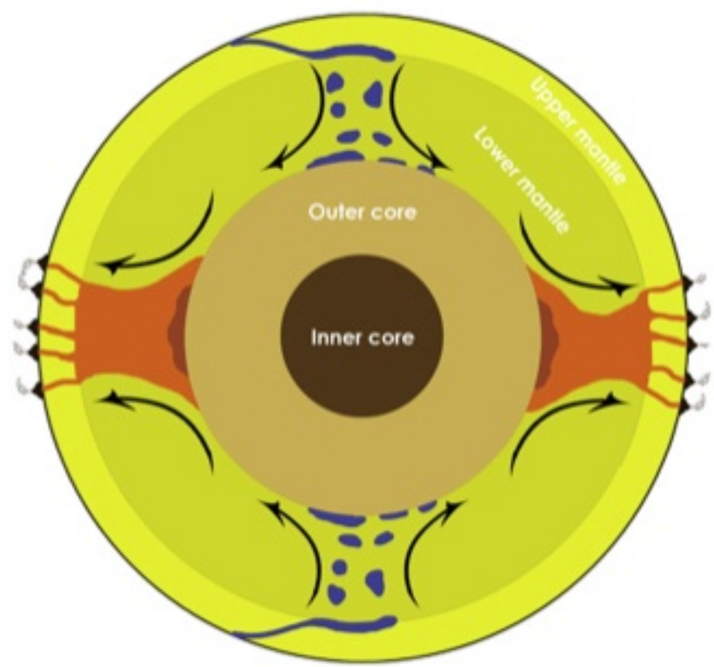
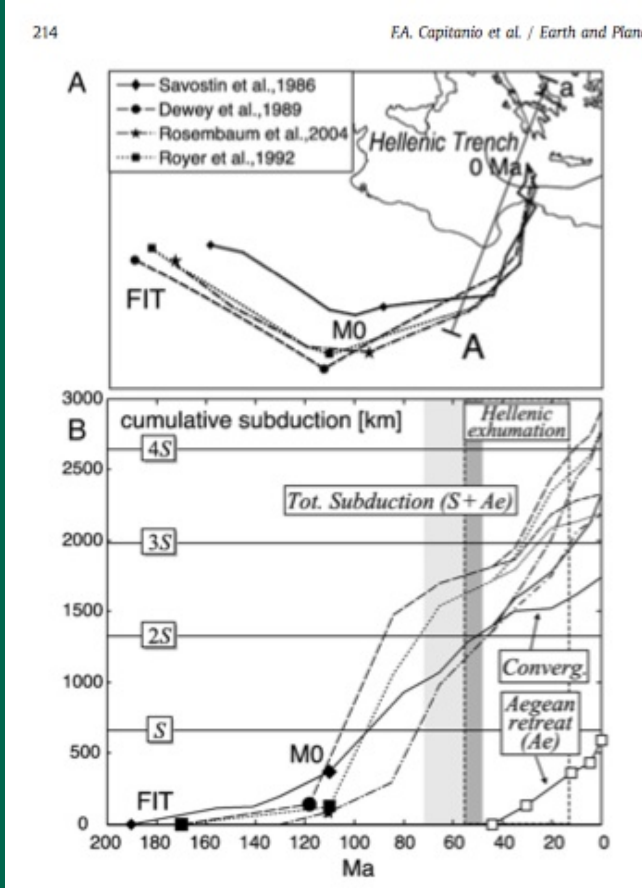
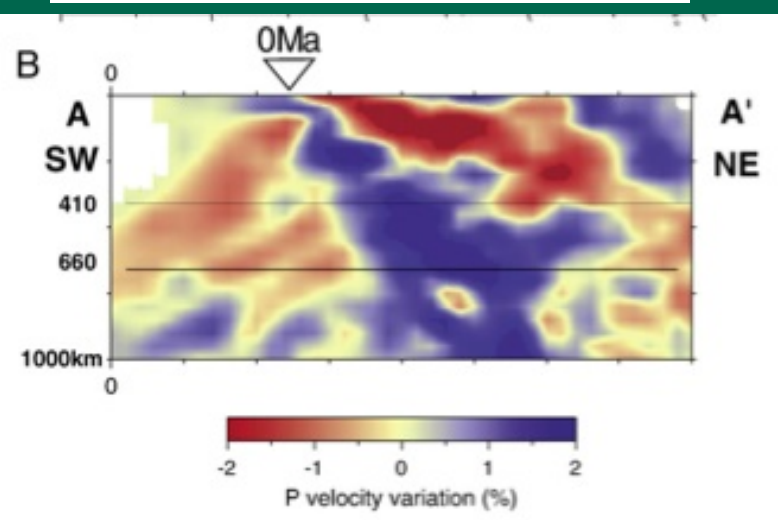


Fig. 10. A cartoon of the equatorial cross-section outlining the proposed circulation in the mantle. Note that the ponded slabs can be partly recirculated in the upper mantle.

Dziewonski et al. (2010)

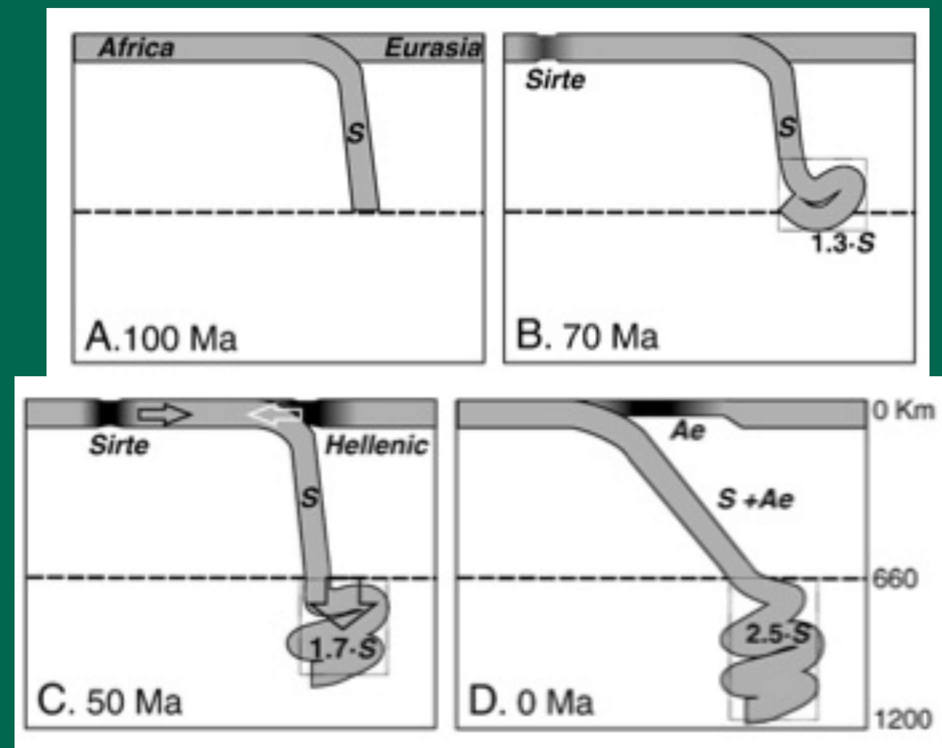




Seismic tomography cross section
Hellenic Trench (A-A')

Slab Avalanche?

A near hiatus in convergence between Africa and Eurasia in the early Cenozoic leads some geodynamic modelers to propose that the downgoing slab stalls at the upper mantle/lower mantle boundary, accumulates there and then suddenly, rapidly penetrates into the lower mantle …



1.3 s means 1.3 slab lengths, etc.

Capitanio et al. (2009)

Note: slabs stall at
transition zone;
Slab avalanche?