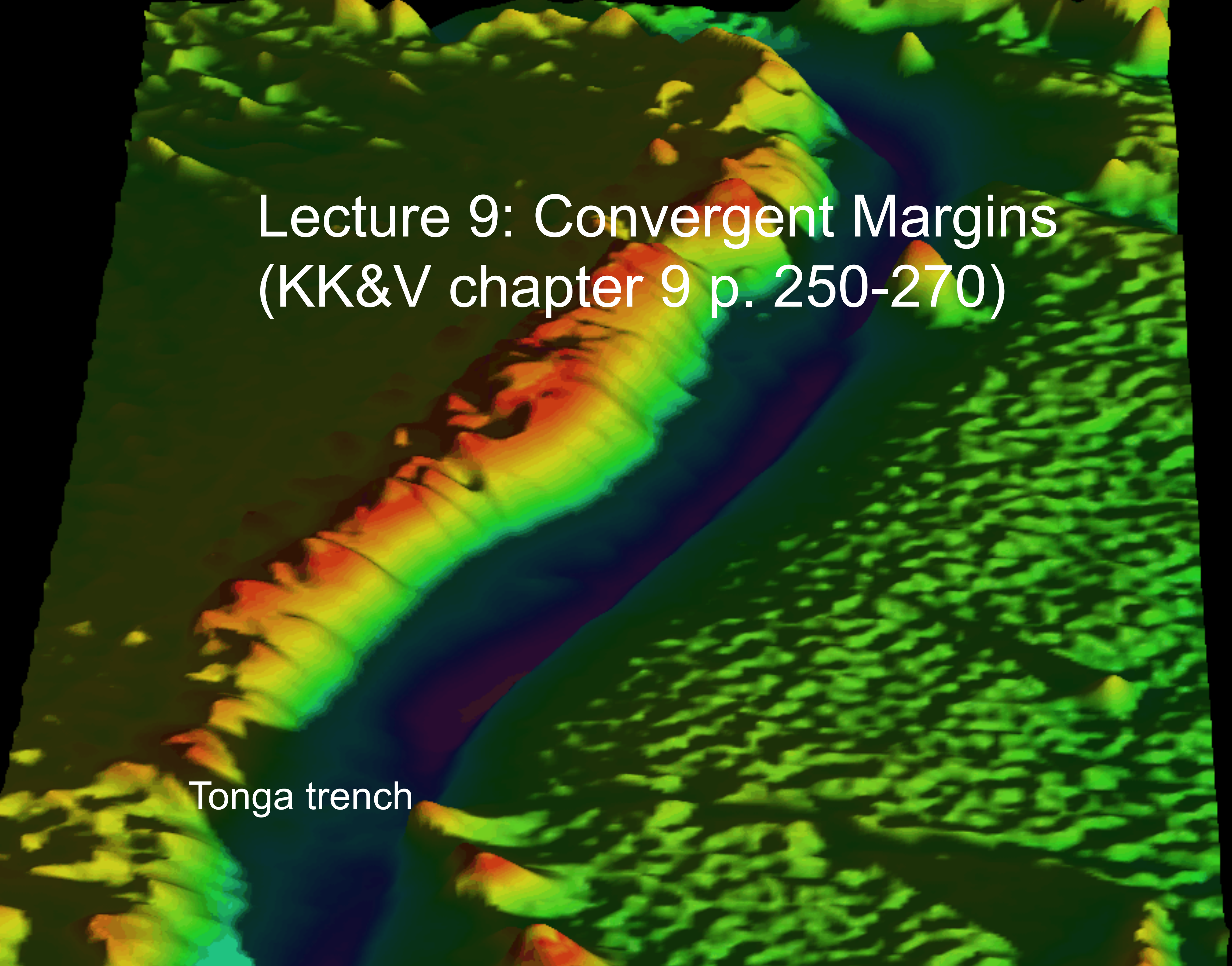
Lecture 9: Convergent Margins
(KK&V chapter 9 p. 250-270)

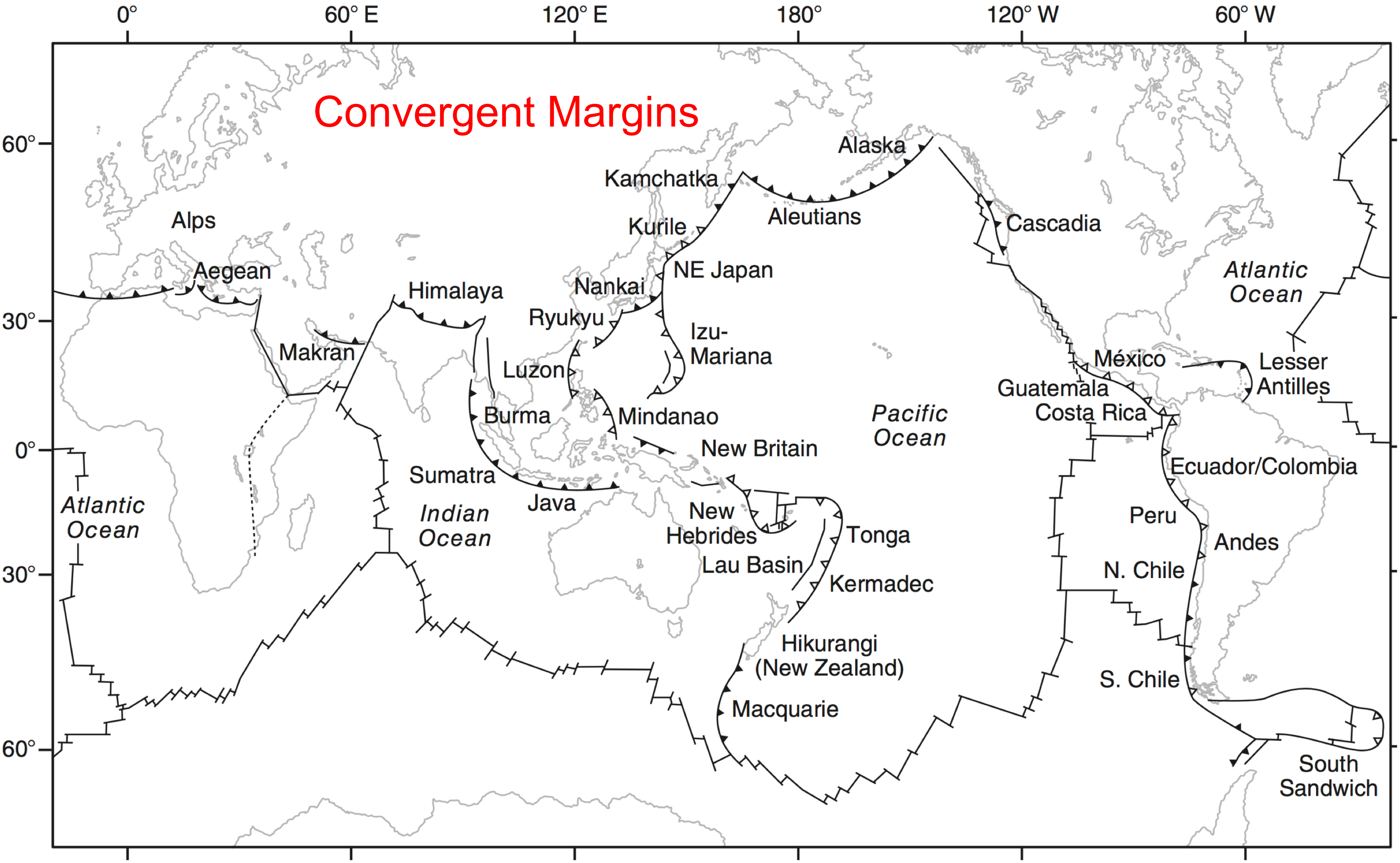


Tonga trench

Convergent Margins (destructive margins, subduction zones)

- Oceanic trenches (deepest depressions at the Earth surface)
- Megathrust earthquakes (largest on Earth)
- Benioff zones (Wadati-Benioff zones, dipping seismicity down to 600 km, deepest earthquakes)
- Large negative gravity anomalies
- Volcanic arcs on the overriding plate

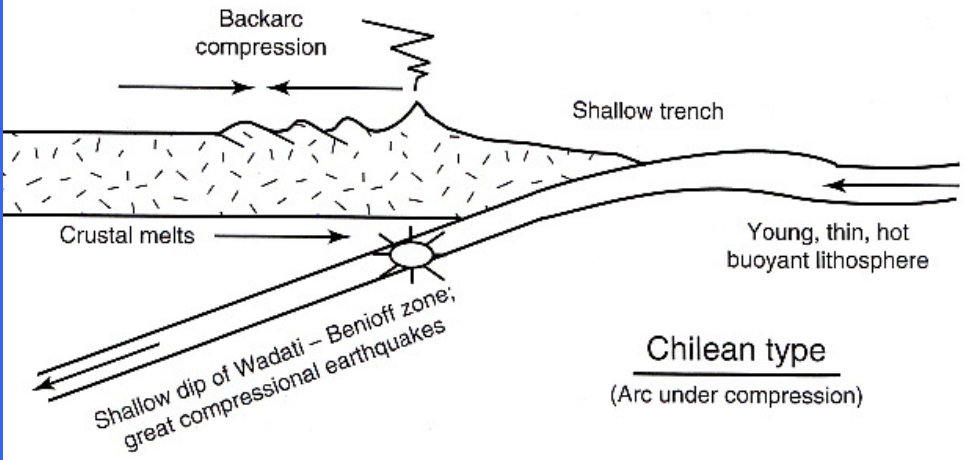
Convergent Margins



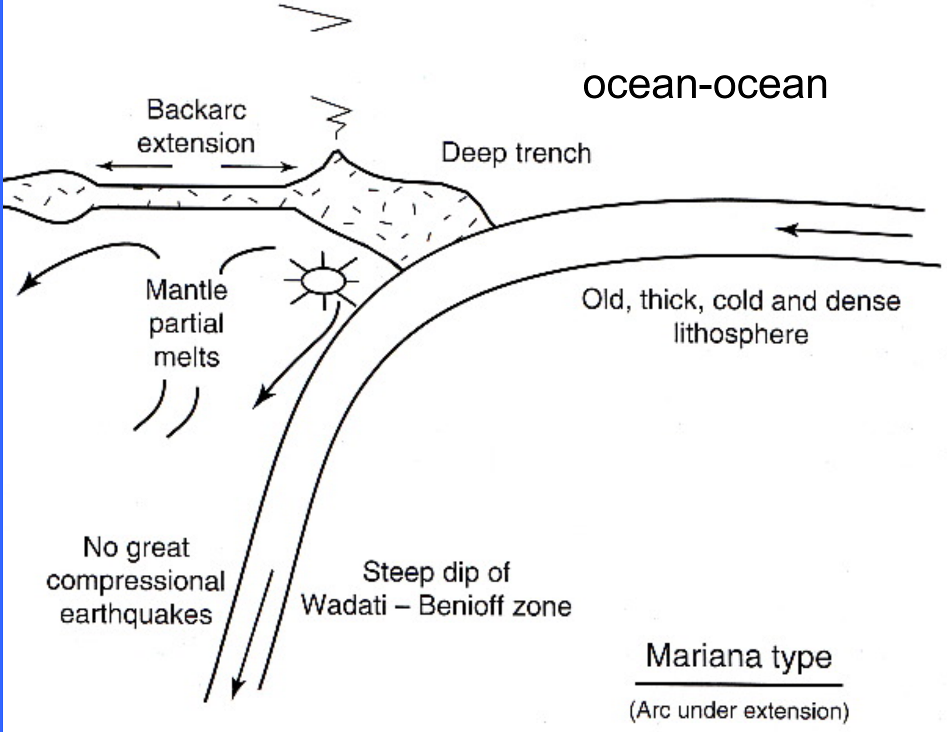
accretionary margins: solid triangles ("barbs")
erosive margins: open triangles

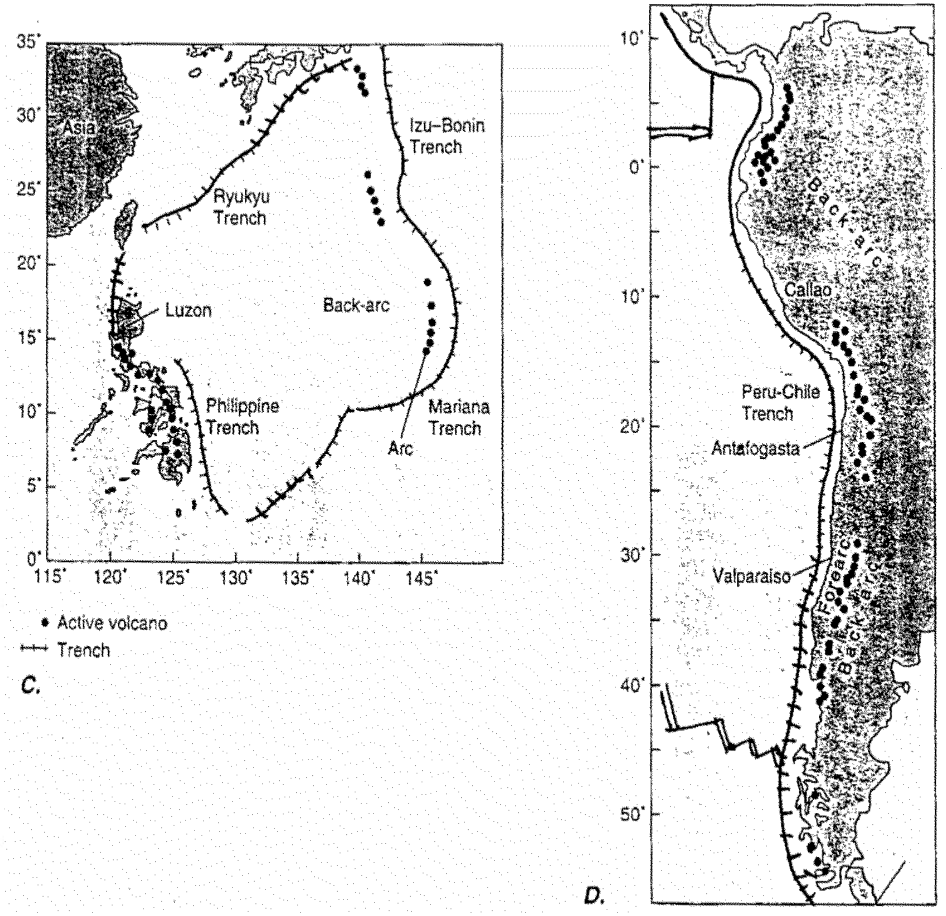
KK&V Fig 9.1

ocean-continent



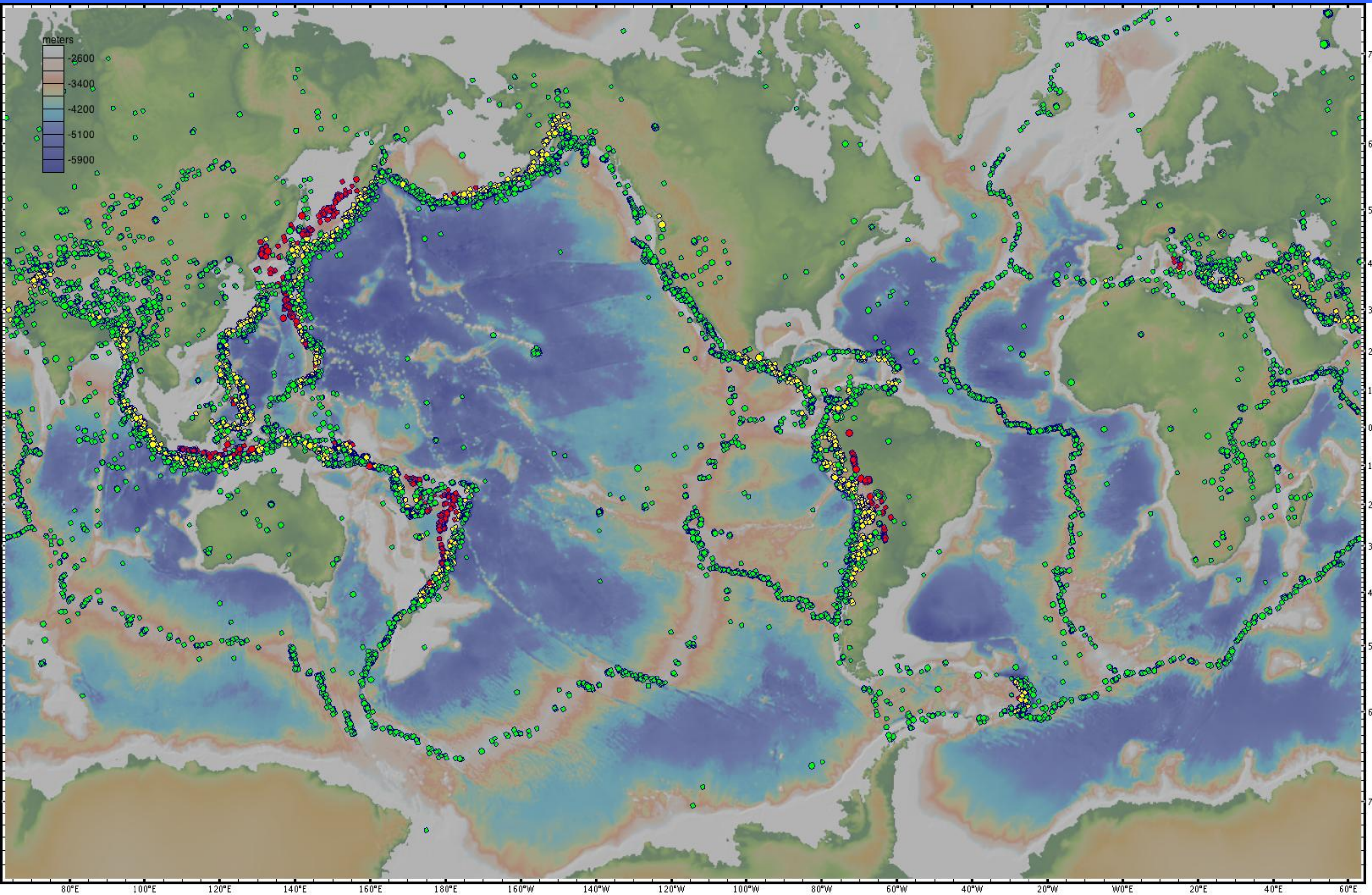
ocean-ocean

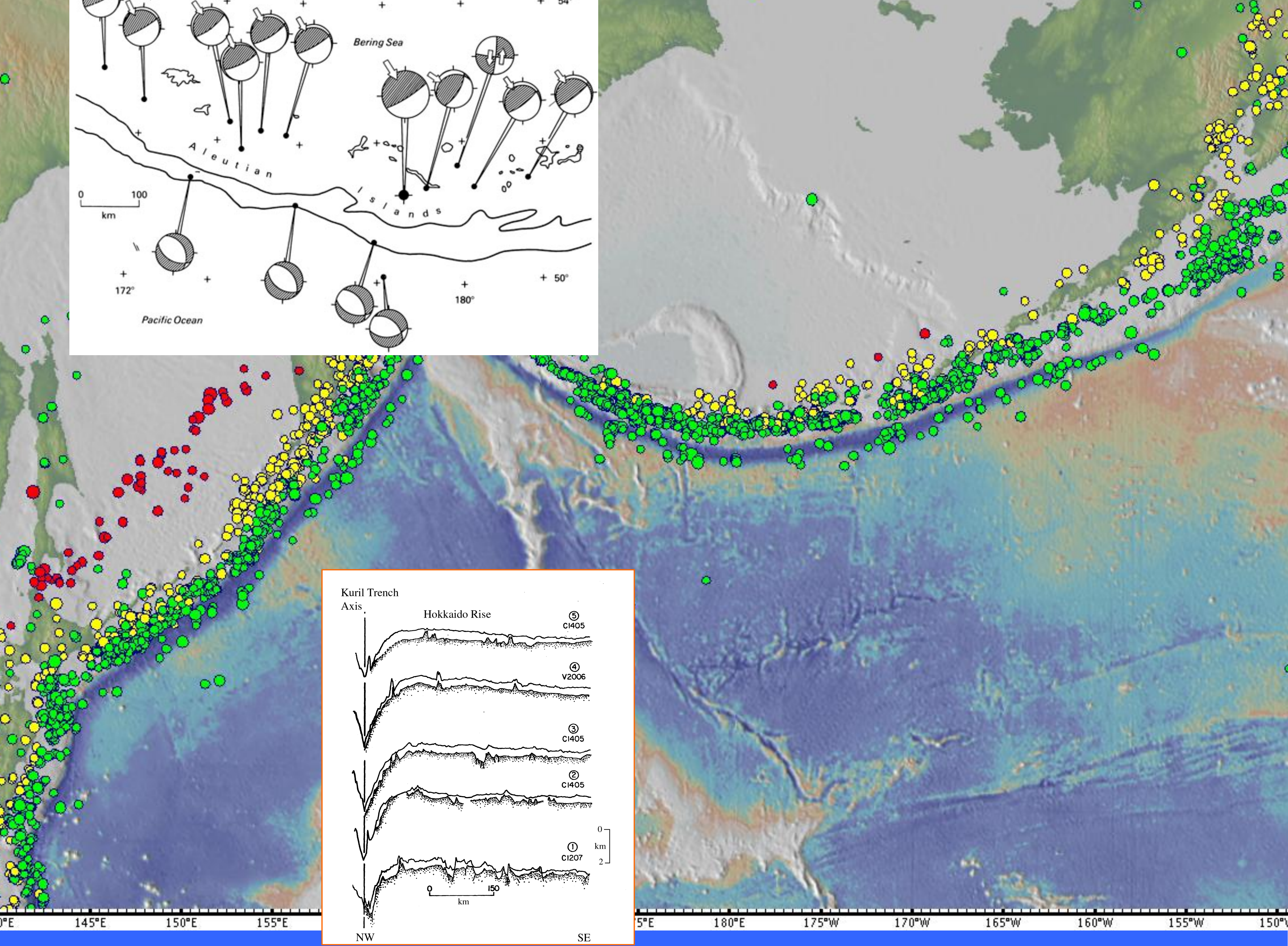




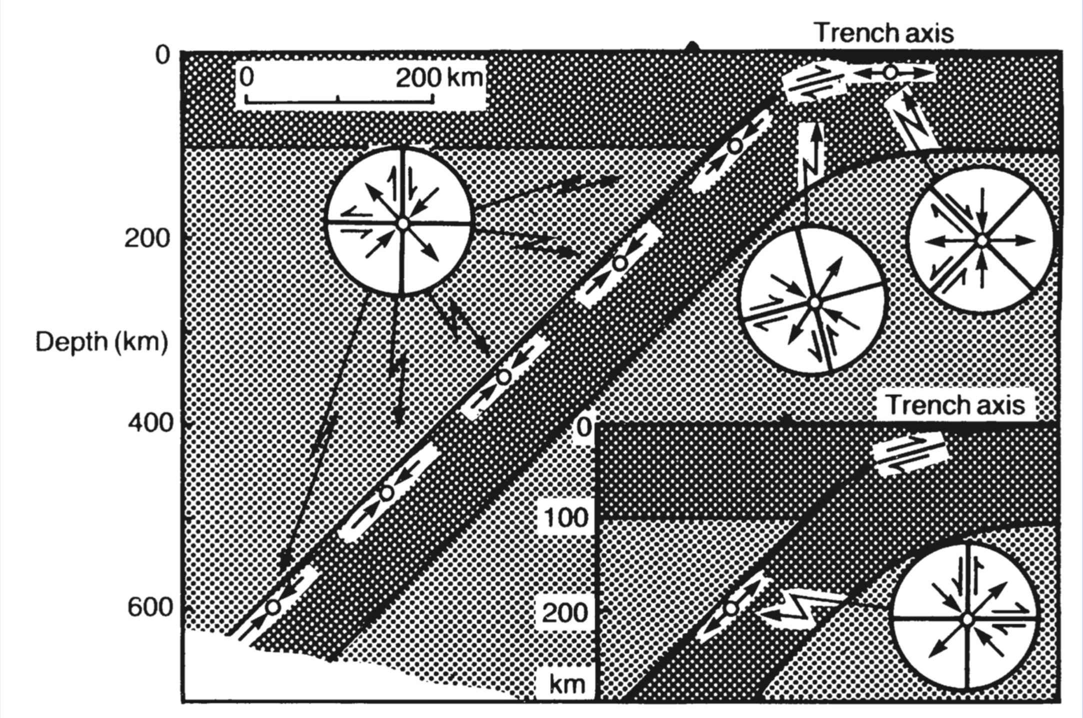
KK&V Fig 9.18

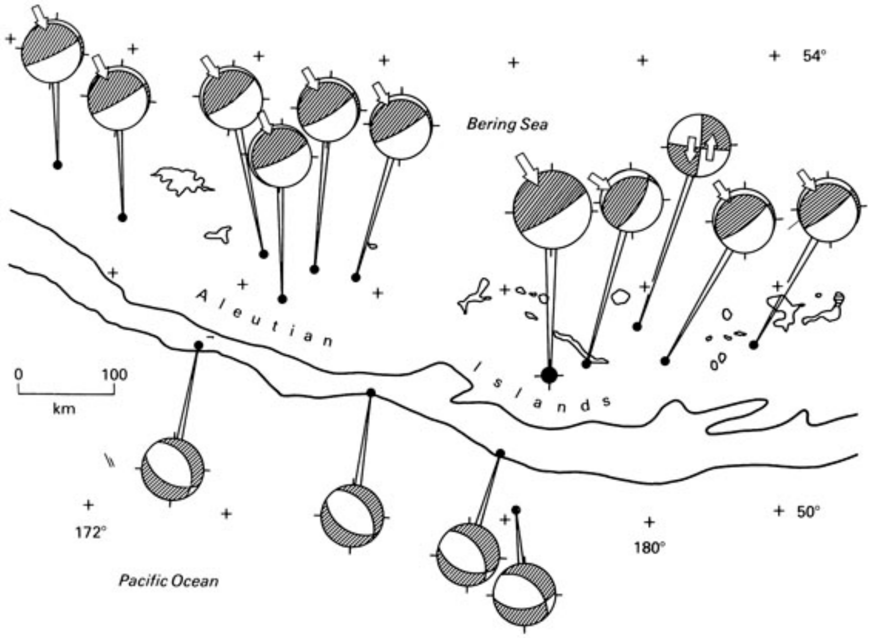
Focal Depths: green < 50 km, yellow = 50 to 250 km, red > 250 km




Bering Sea
Aleutian Islands
0
100
km
54°
172°
180°
50°
Pacific Ocean
Kuril Trench
Axis
Hokkaido Rise
⑤
C1405
④
V2006
③
C1405
②
C1405
①
C1207
0
km
2
0
150
km
NW
SE
145°E
150°E
155°E
180°E
175°W
170°W
165°W
160°W
155°W

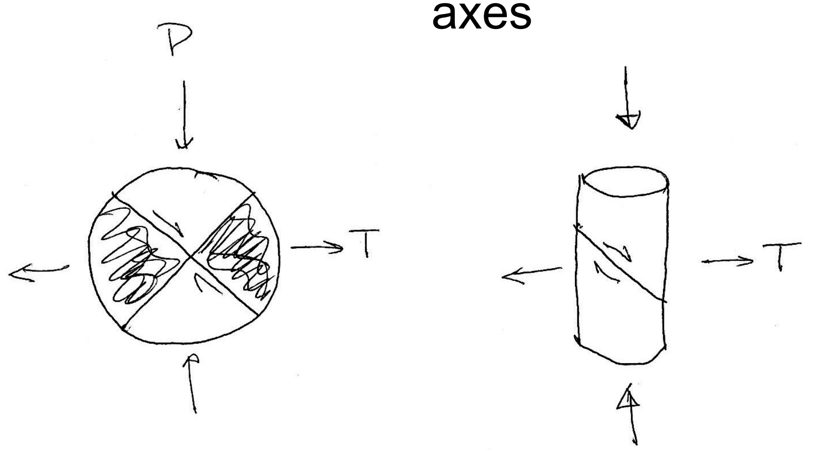
Note: these are cross sections of beach balls



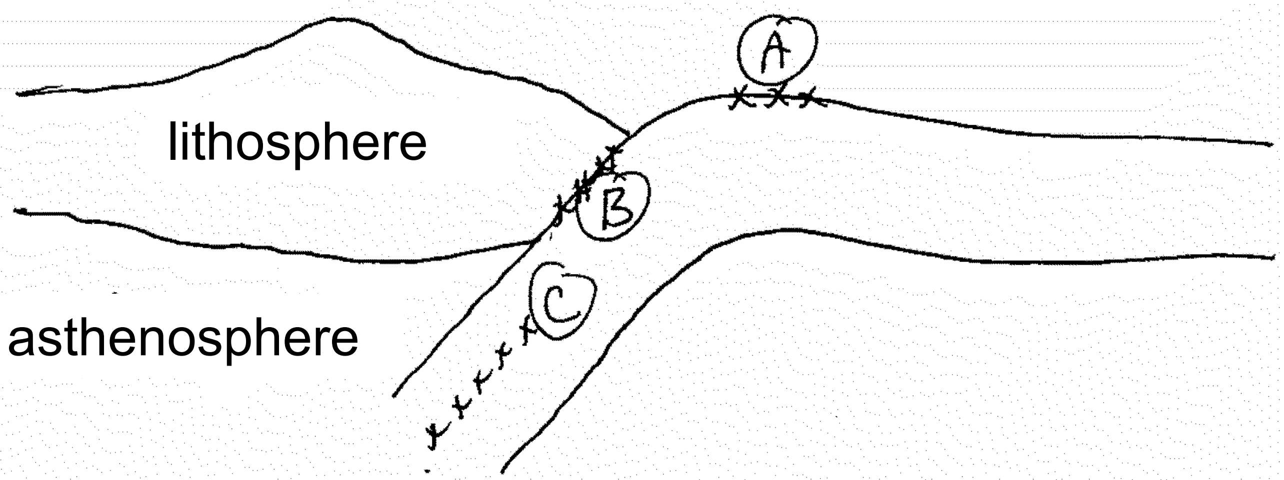


In the deeper earthquakes, the stress axes are oriented parallel or perpendicular to dip

Principal stress axes



Earthquake "Environments"



Ⓐ

- normal faulting caused by bending of slab (shallower than 25 kms)

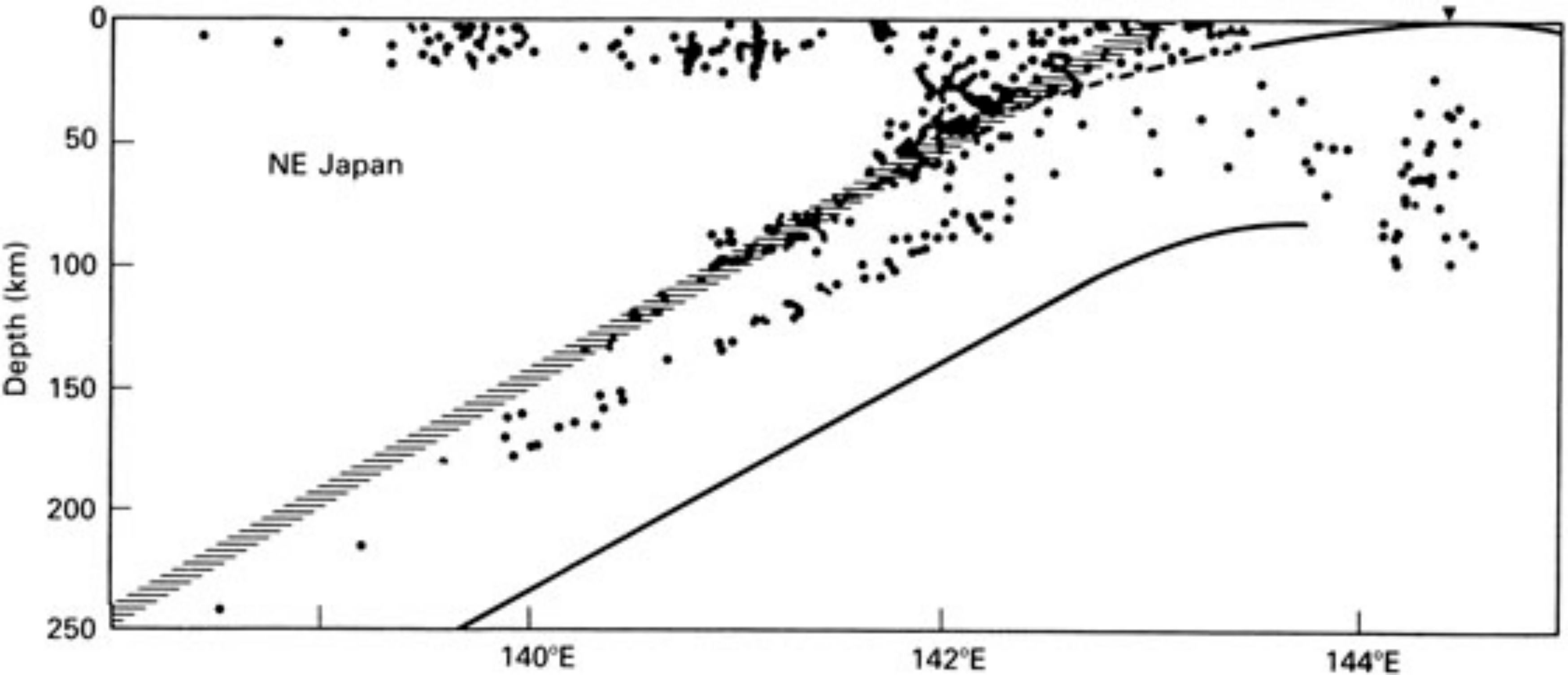
Ⓑ

- thrust faulting caused by slip along interface (shallower than 100 kms)
- thrust faulting caused by unbending of slab

Ⓒ

- caused by internal deformation of slab
- earthquakes occur 30 – 40 kms below top of slab
- principal stress axes are || or ⊥ to dip of descending slab
- attributed to: dehydration of serpentinites (70 to 300 kms)
  or a phase change from olivne to spinel (> 300 kms)

Double Benioff Zone



KK&V Fig 9.12

Upper plane: metamorphic reactions in subducted crust
Lower plane: metamorphic reactions in subducted mantle

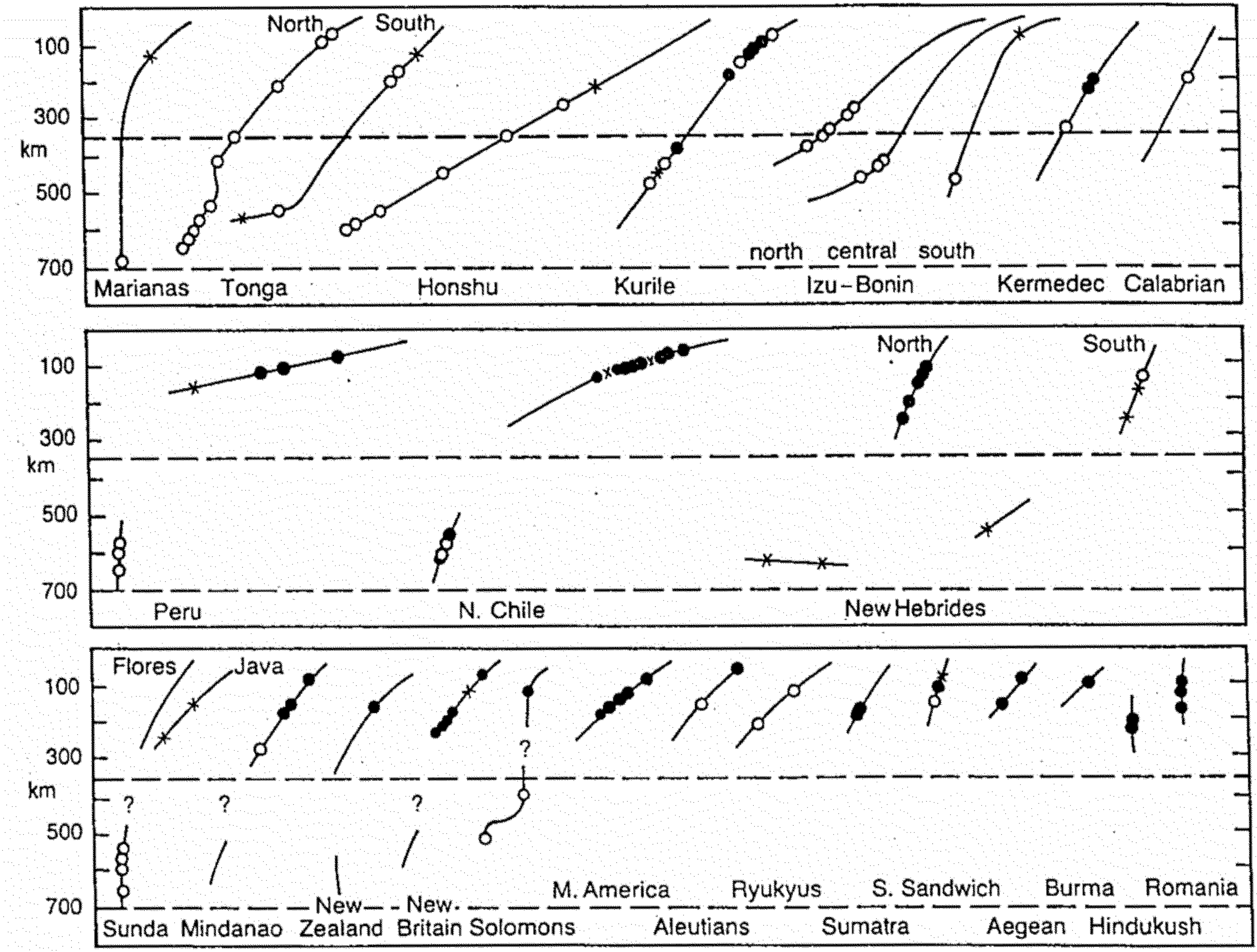


Fig. 8.16 Summary of the distribution of downdip stresses in Benioff zones. Open circles, events with compressional axis parallel to dip of zone; solid circles, events with tensional axis parallel to dip of zone; crosses, neither P- nor T-axis parallel to zone; solid lines, approximate form of seismic zone

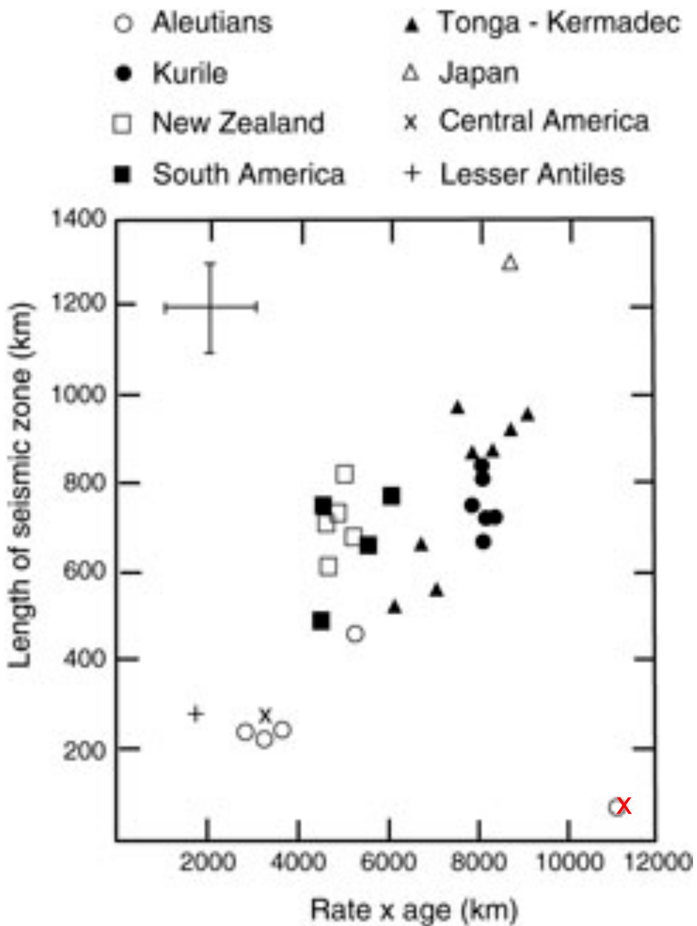
Isacks and Molnar (1971)

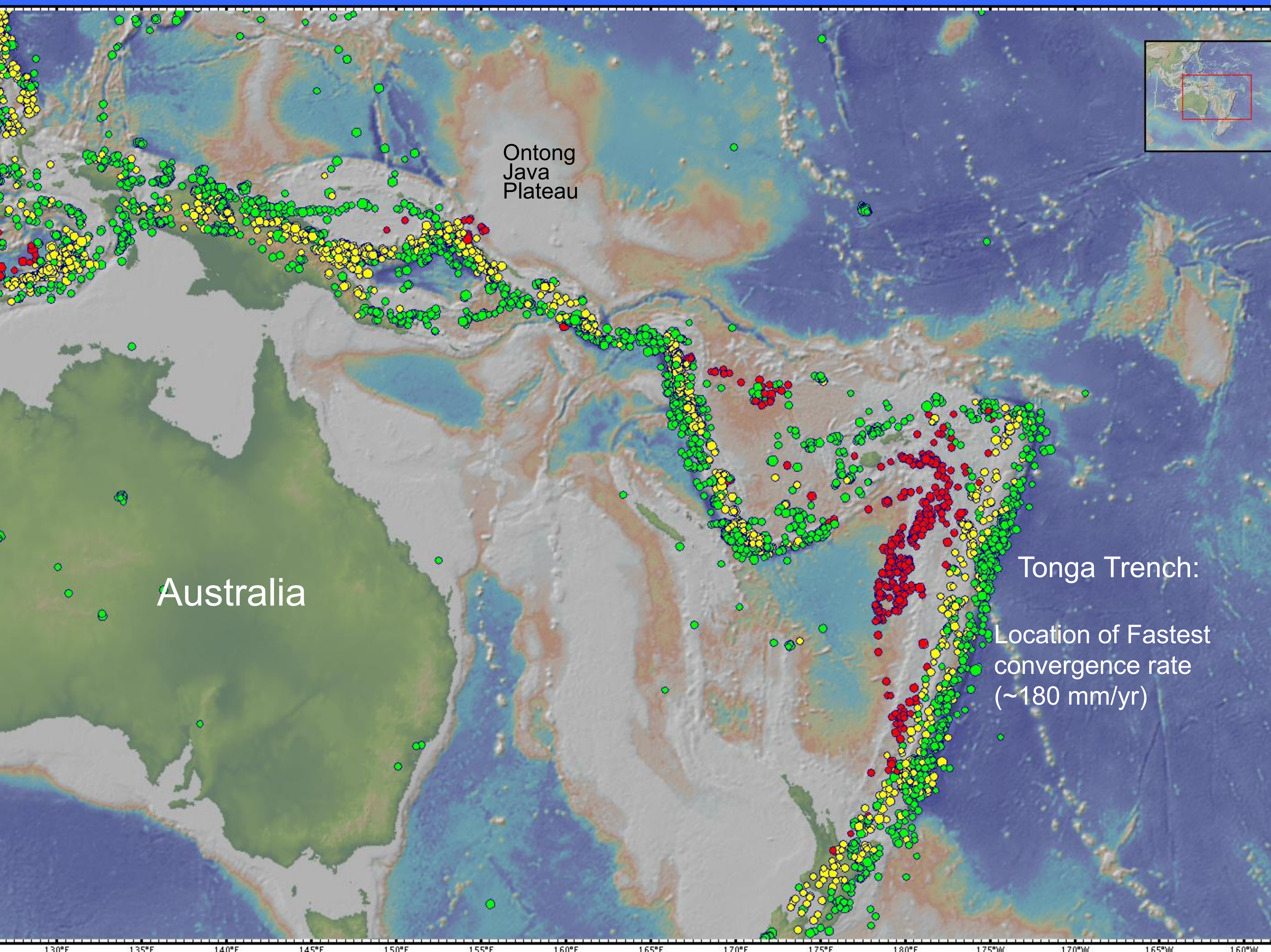
also, KKV fig. 9.15

Length of the Benioff Zone

- Earthquakes can only be generated as long as the slab is cold enough to store elastic energy.
- After a certain amount of time slabs warm up and become "assimilated."
- Young and slowly converging slabs warm up at shallower depths than cold, fast converging slabs.
- Roughly:

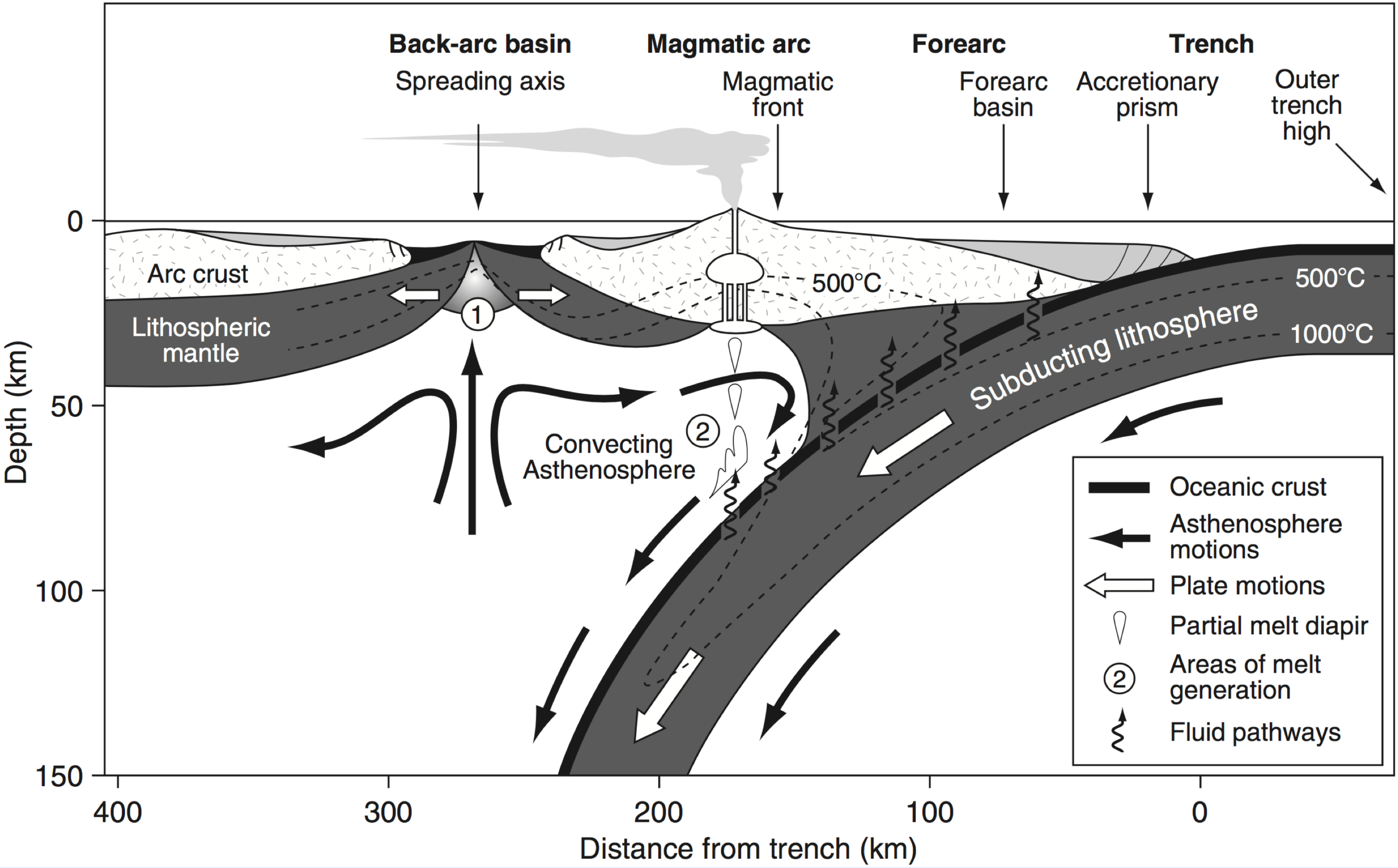
Length of Benioff Zone = Convergence Rate(mm/yr) x Age(Ma)/10



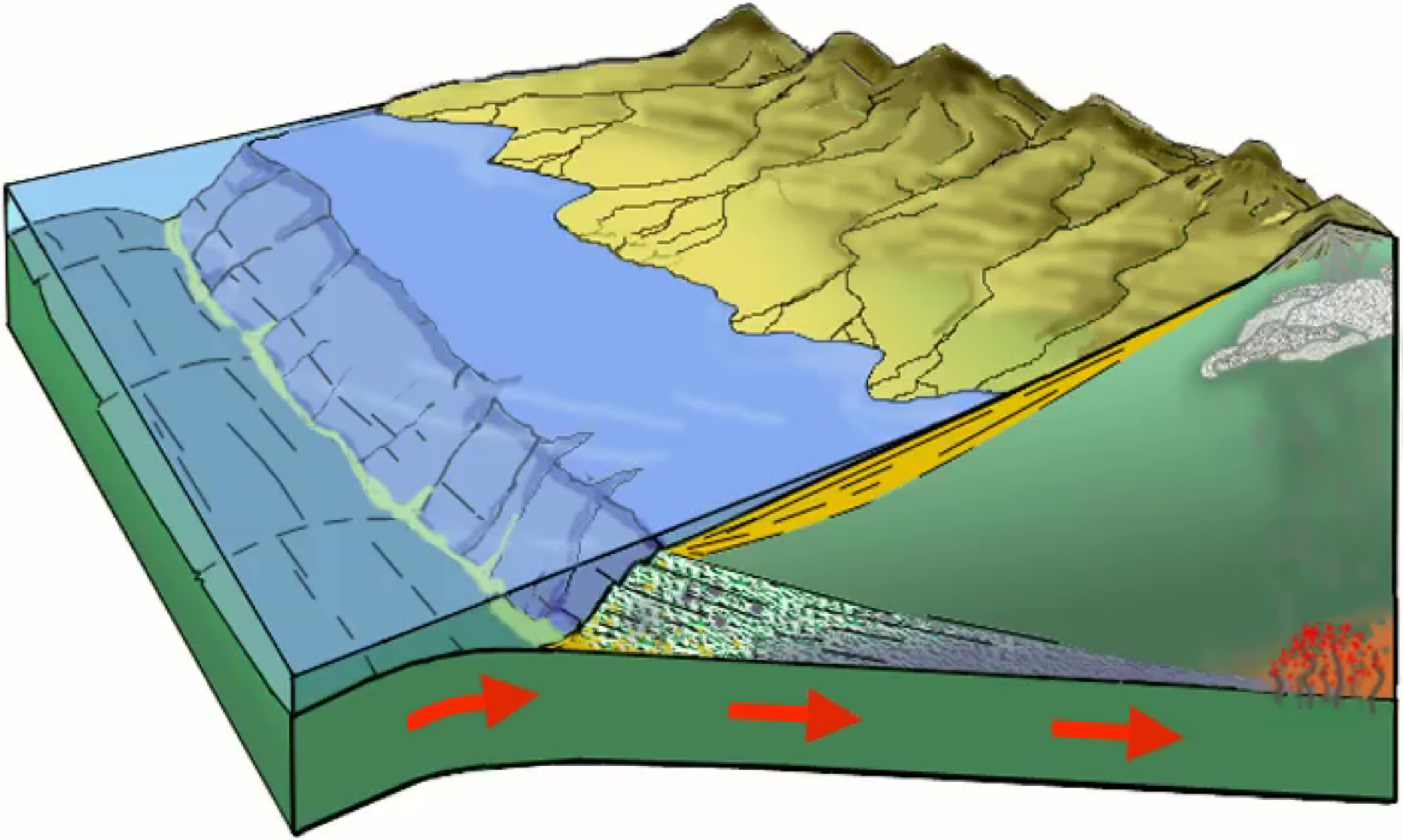


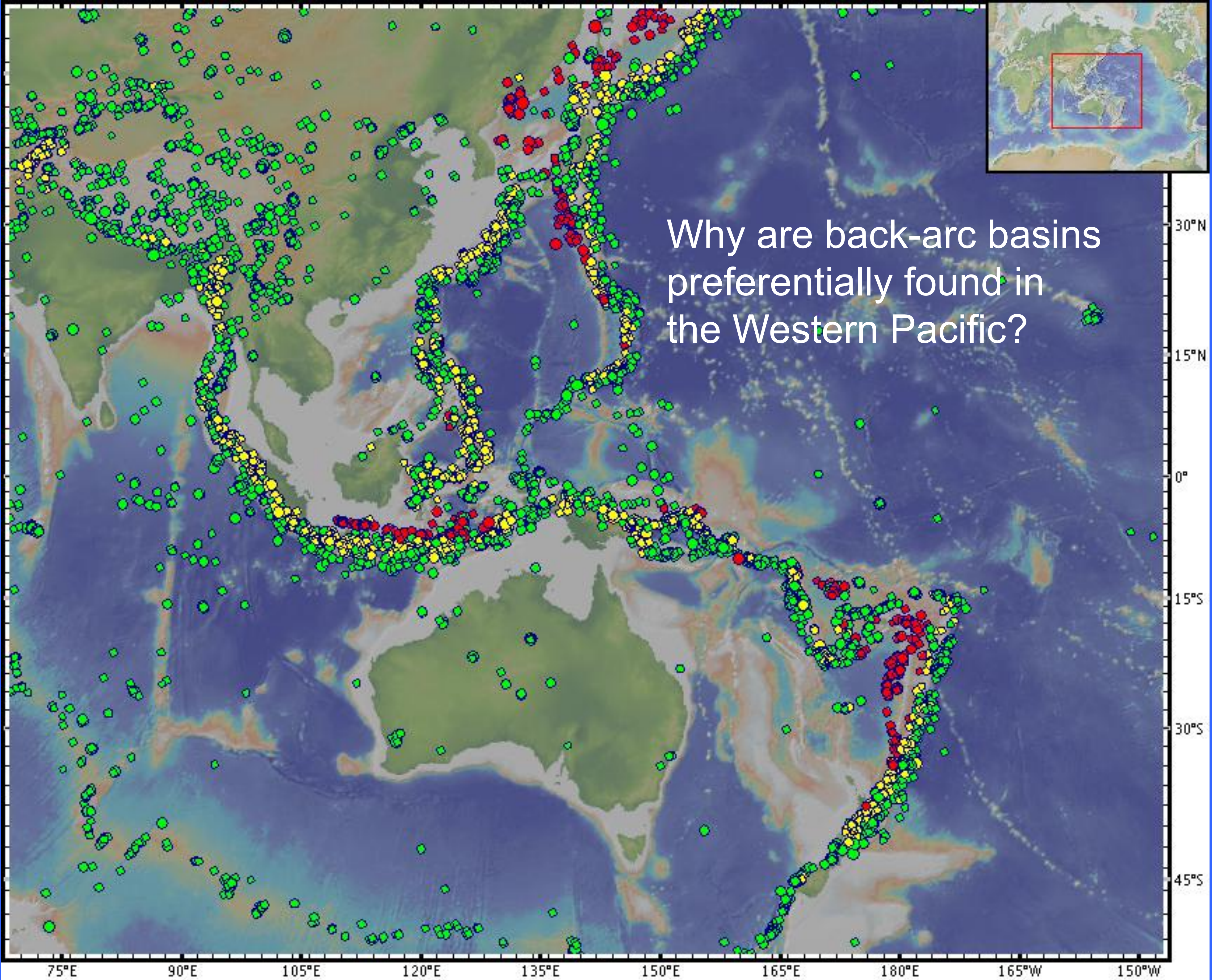
Tonga Trench:

Location of Fastest convergence rate (~180 mm/yr)

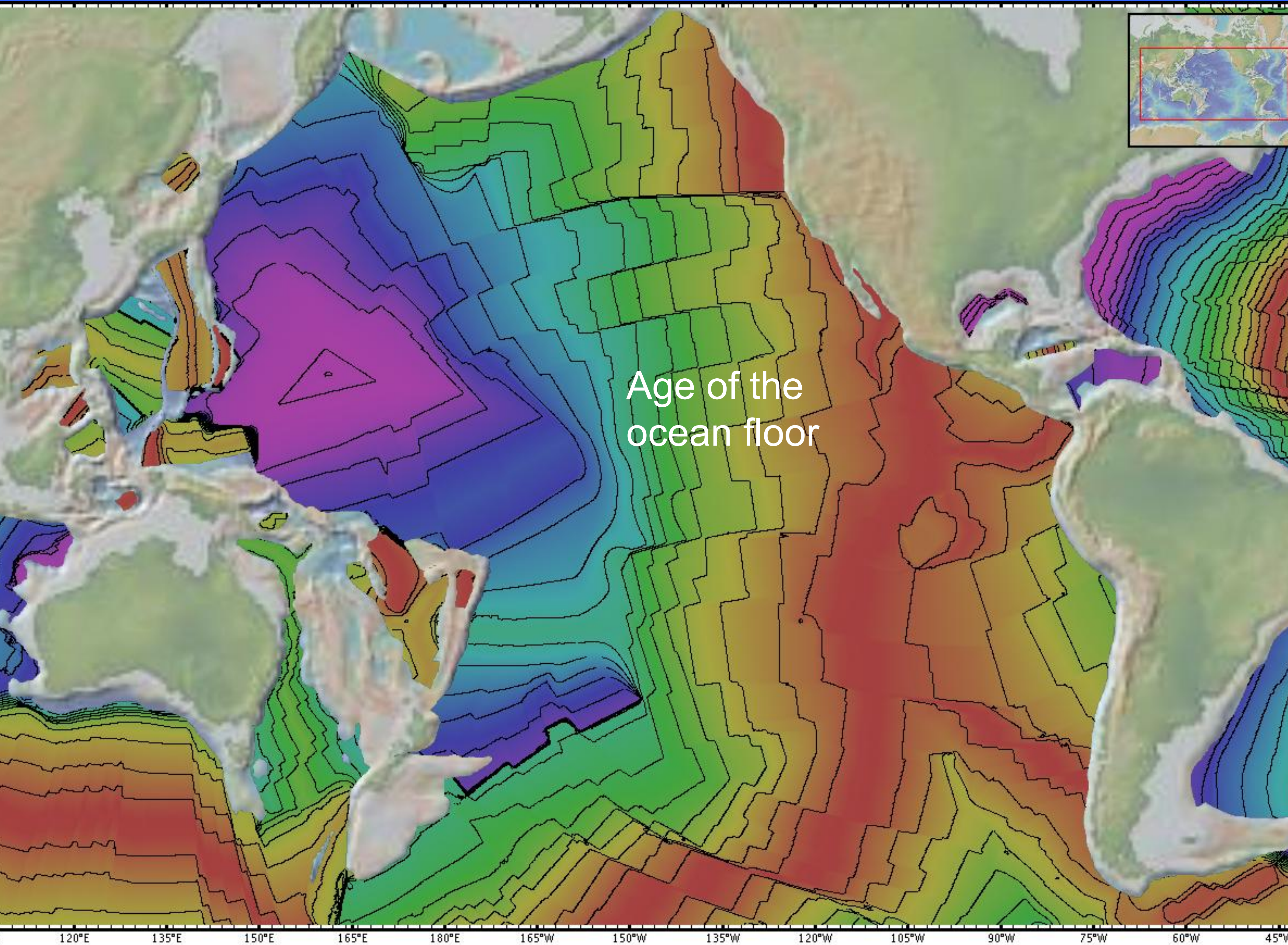

Back-arc basin
Spreading axis
Magmatic arc
Magmatic front
Forearc
Forearc basin
Trench
Accretionary prism
Outer trench high
Arc crust
Lithospheric mantle
500°C
500°C
1000°C
Subducting lithosphere
Convecting Asthenosphere
1
2
Oceanic crust
Asthenosphere motions
Plate motions
Partial melt diapir
2
Areas of melt generation
Fluid pathways
Depth (km)
0
50
100
150
400
300
200
100
0
Distance from trench (km)

KK&V Fig 9.3





Why are back-arc basins preferentially found in the Western Pacific?


Age of the ocean floor

Differences in tectonic style: age of the slab and "roll-back"

One idea …

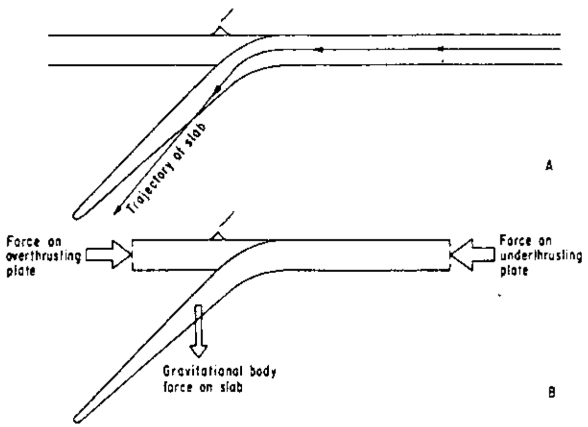


Fig. 2. Cross-section of island arcs. A. Expected trajectory of slab relative to an inert asthenosphere. Note that position of slab migrates seaward (following Elsasser [33]. B. Forces acting on the two plates and the downgoing slab.

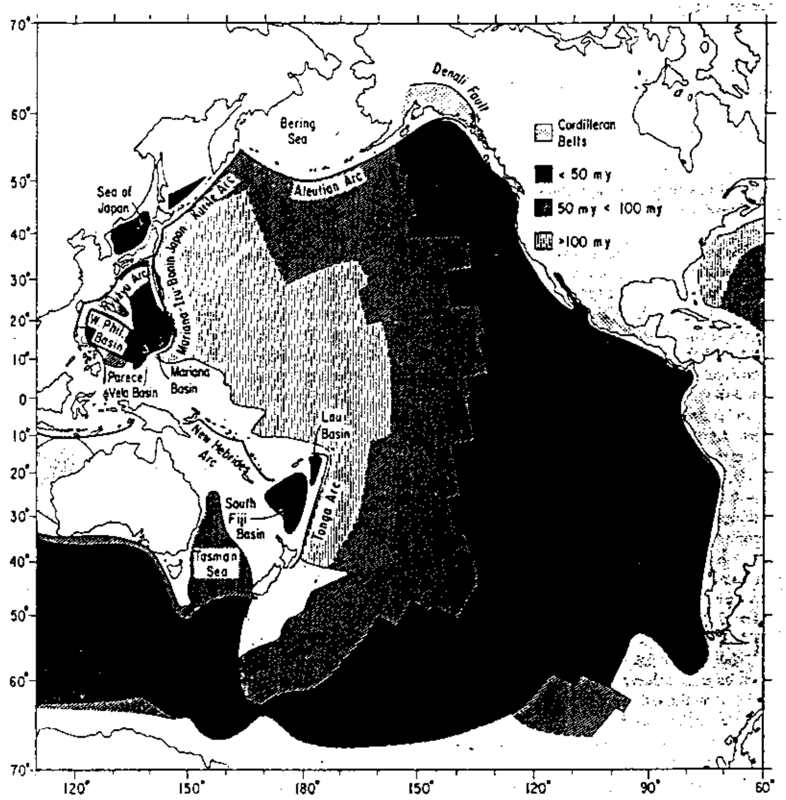


Fig. 1. Map of the Pacific showing ages of the ocean floor and Cordilleran-type belts. Note active Cordilleran-type belts in the eastern Pacific and younger ocean floor in the interarc basins of the western Pacific.

- Descending slab acts as an anchor, unable to move its position laterally, except …..
- Slab moves seaward as it sinks due to gravity (roll-back)
- Older, colder slabs sink faster and move seaward faster, hence…..
- Extensional tectonics are found where there is old subducting crust

Molnar and Atwater (1978)

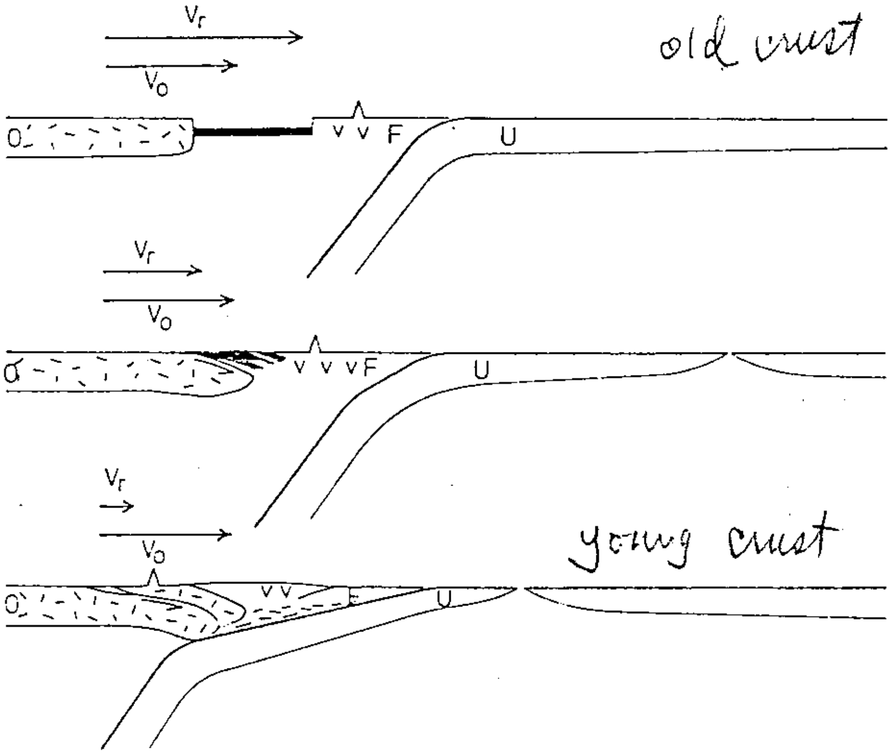
Importance of relative motion of overriding plate

Consider: V_o = seaward motion of overriding plate relative to mantle

V_r = rollback velocity

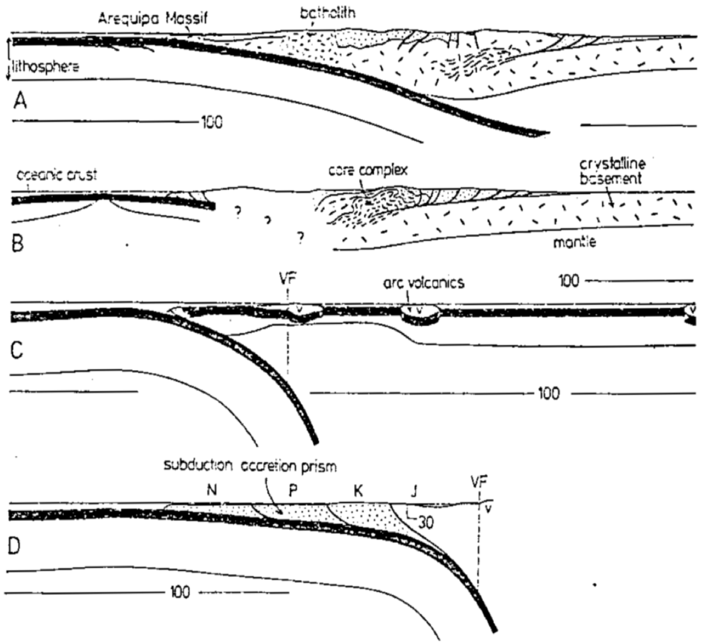
Then if $V_o > V_r$ compressive tectonics

if $V_r > V_o$ extensional tectonics



Dewey (1980)

Classification of tectonic characteristics at Subduction Zones



Compressive
(Peru/Chile)

Neutral
(Cascadia)

Extensional
(Marianas)

Neutral with
Lots of sediments
(Alaska)

Figure 2. True scale sections across the Pacific margin (scale in kilometres). A. Central Peru. B. Western Canada. C. Marianas. D. Alaska (age of subduction-accretion prism: J – Jurassic, K – Cretaceous, P – Paleogene, N – Neogene).

Compressive

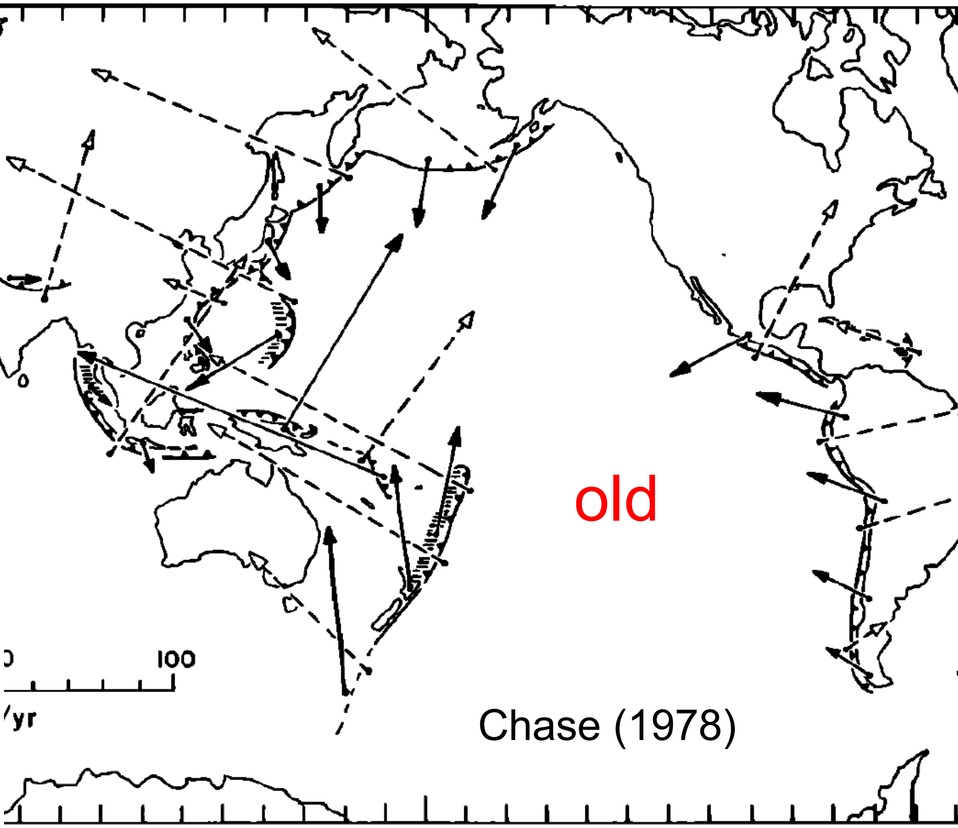
- Shallow, flat Beniff zones
- Back-arc thrusting
- Lies on continental margins
- Many large earthquakes in overriding plates

Extensional

- Steep Benioff zones
- Back-arc basins with plate accretion
- Intra-oceanic
- Few earthquakes in overriding plate

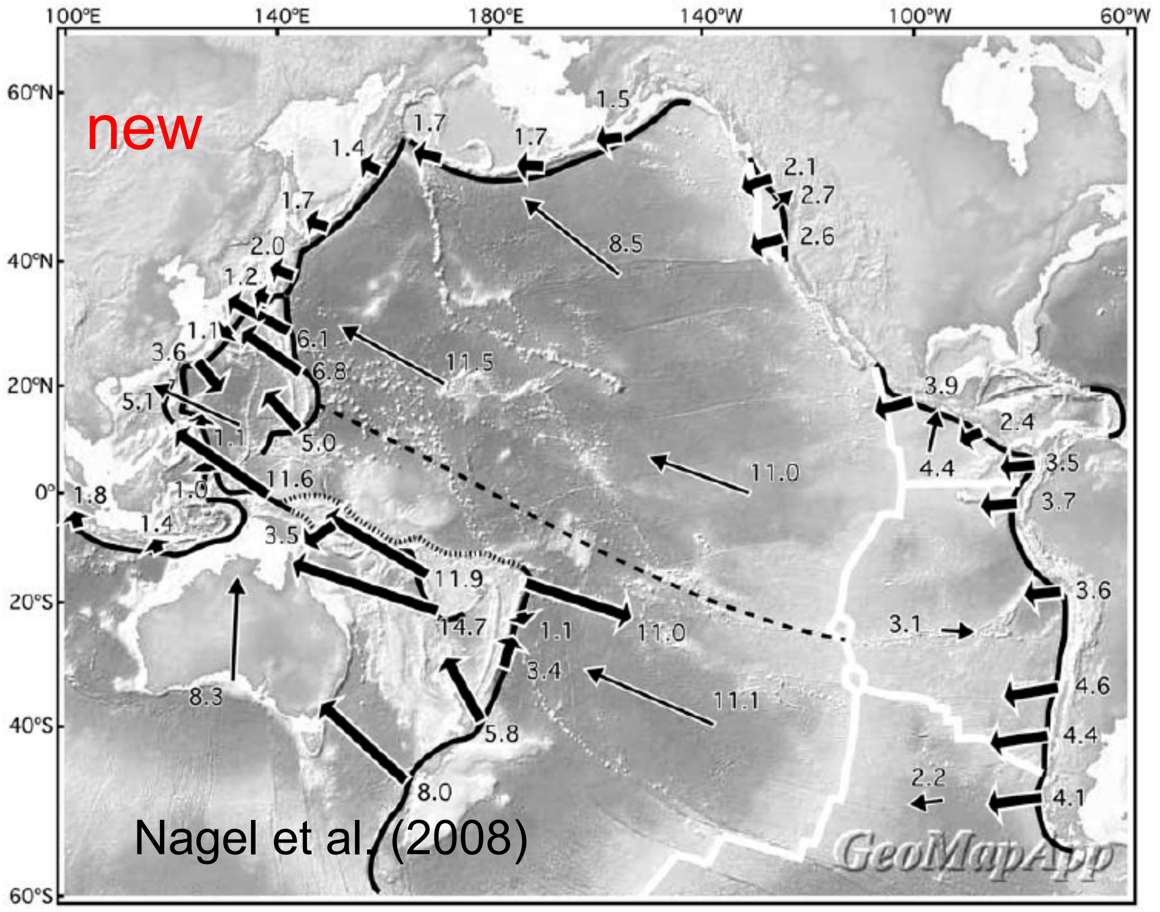
Dewey (1980)

Well, the initial hypothesis (right) did not stand the comparison with the data



old

Chase (1978)

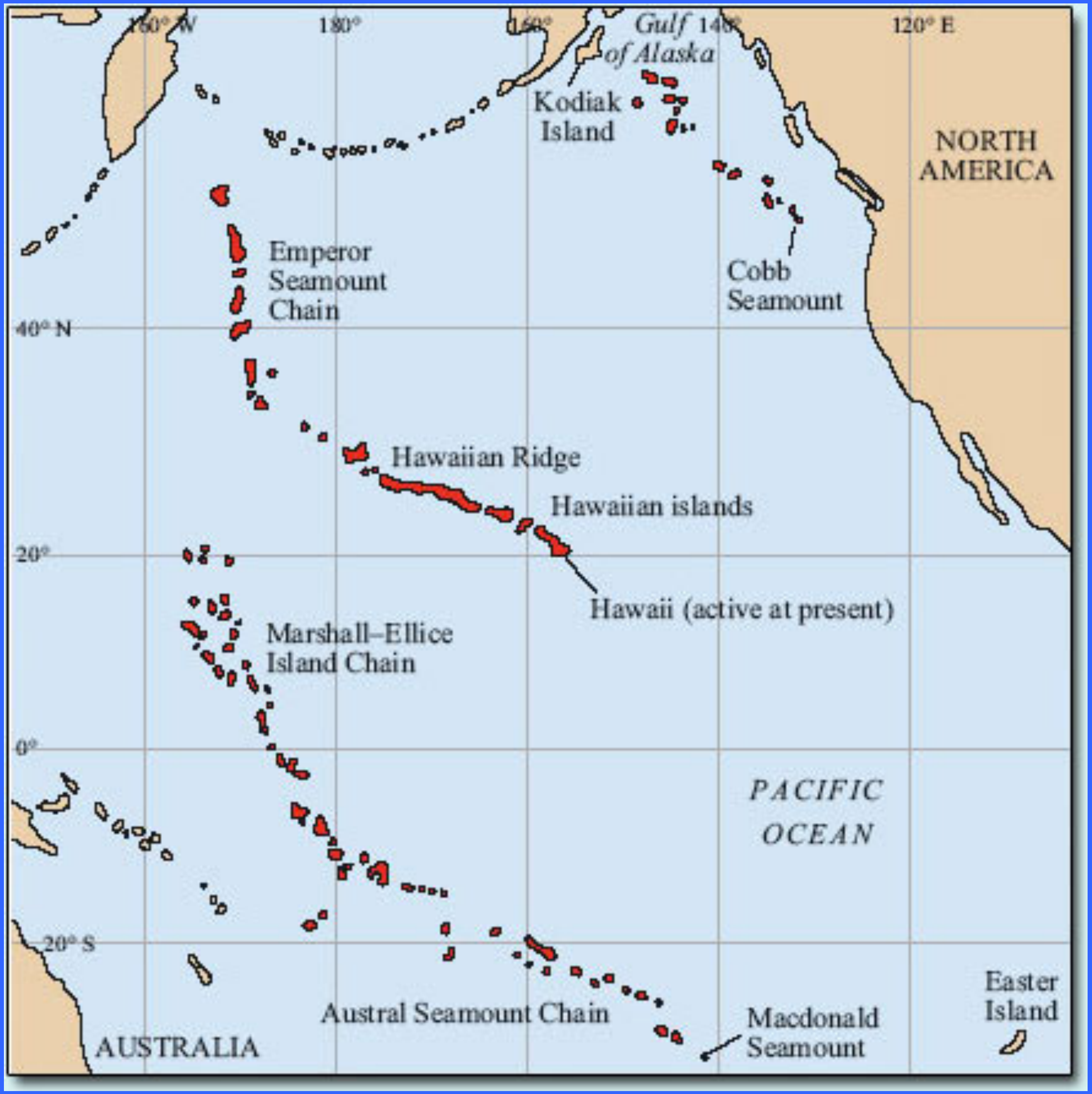


new

Nagel et al. (2008)

Heavy black arrows = overriding plate w.r.t. mantle

Newer data (left) show that this is not true; Northeast Asia and Japan move slowly away from trench; the trenches which are retreating have young crust (compare to Dewey, 1980)

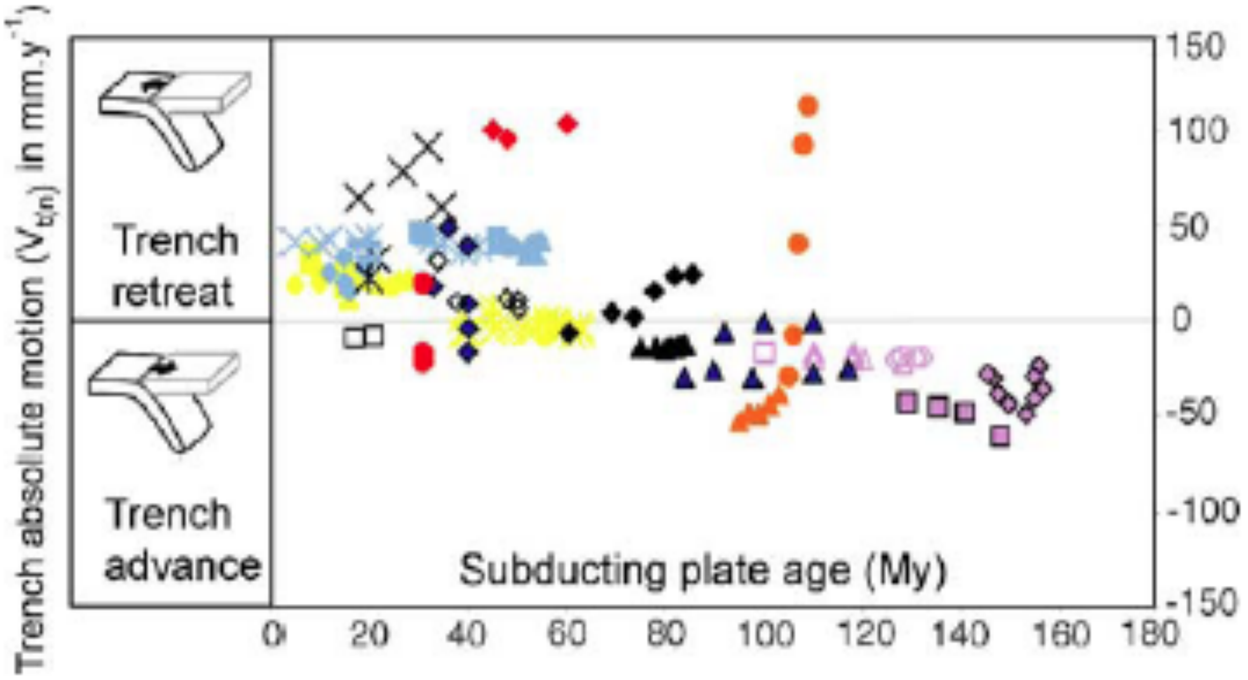


Motion with respect to the mantle a.k.a. Absolute plate motions

Volcanic chains like Hawaii form by motion of the Pacific plate over magma plumes embedded in the mantle

Islands and seamounts get progressively older off to NW

Several chains of volcanic features show similar progression; constrain motion of plate w.r.t. deep mantle



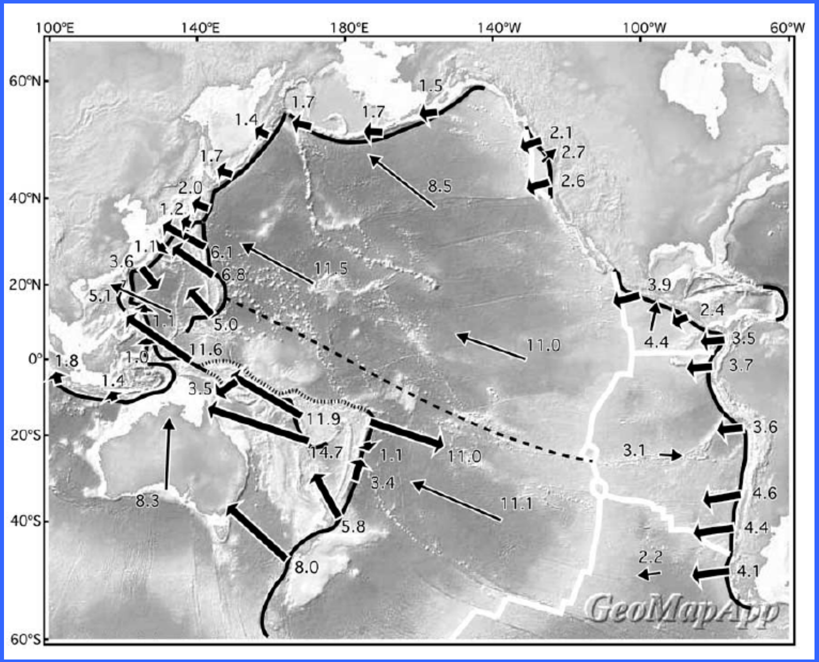
So Molnar and Atwater were wrong.

Correlation of slab rollback (trench retreat) with age of subducting slab is opposite:

in general, young slabs are retreating, old slabs are advancing.

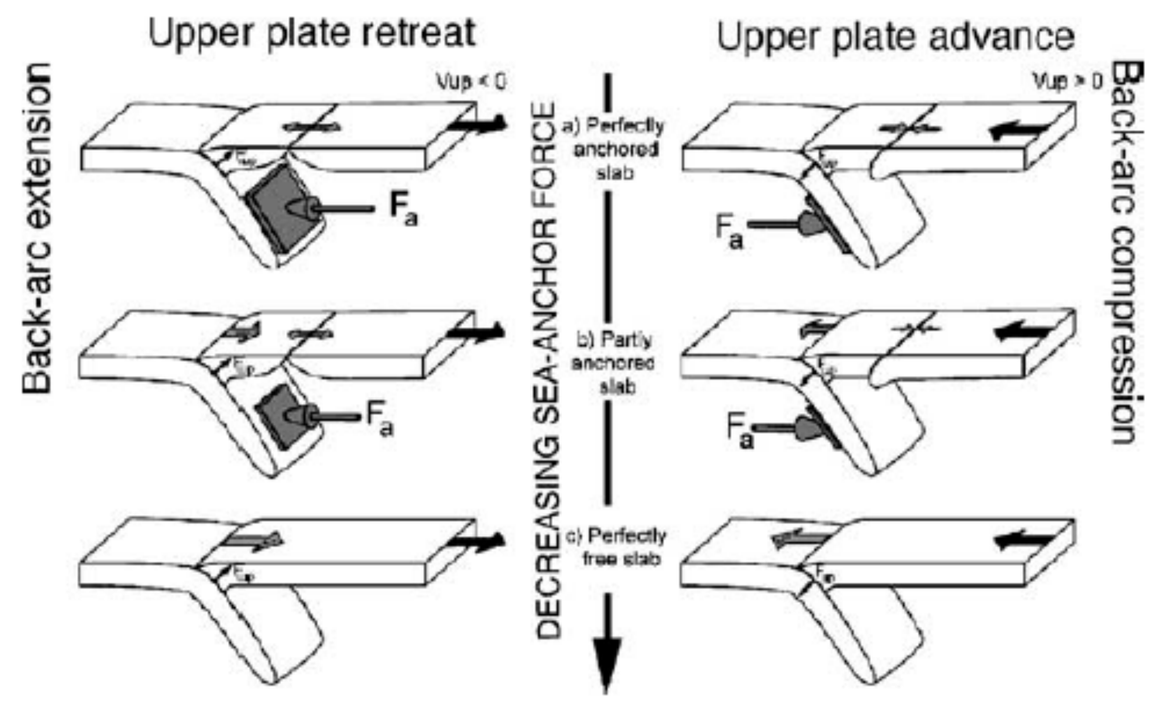
Heuret and Lallemand (2005)

Also, slab retreat does not correlate with back-arc extension



Nagel et al. (2008)

Heavy black arrows =
absolute motion of upper plate
if no back-arc basin, then =
absolute motion of slab

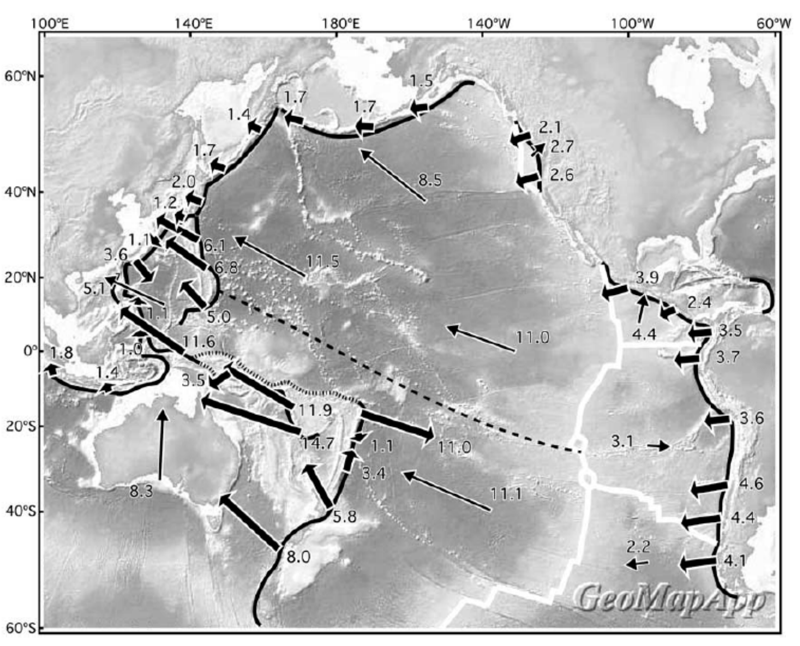


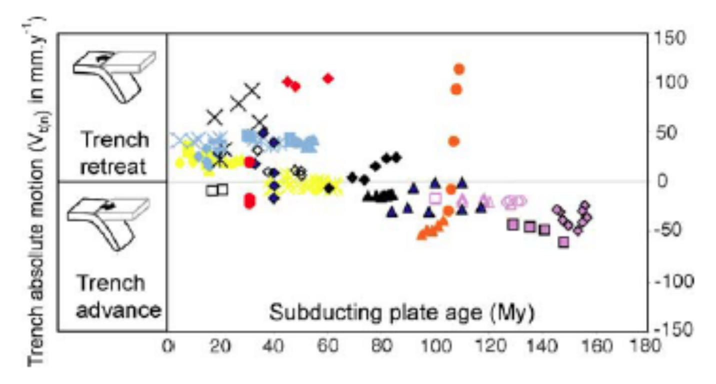
Instead, a global correlation exists between upper plate absolute motion and back-arc deformation

i.e., get back-arc extension when upper plate retreats and vice-versa

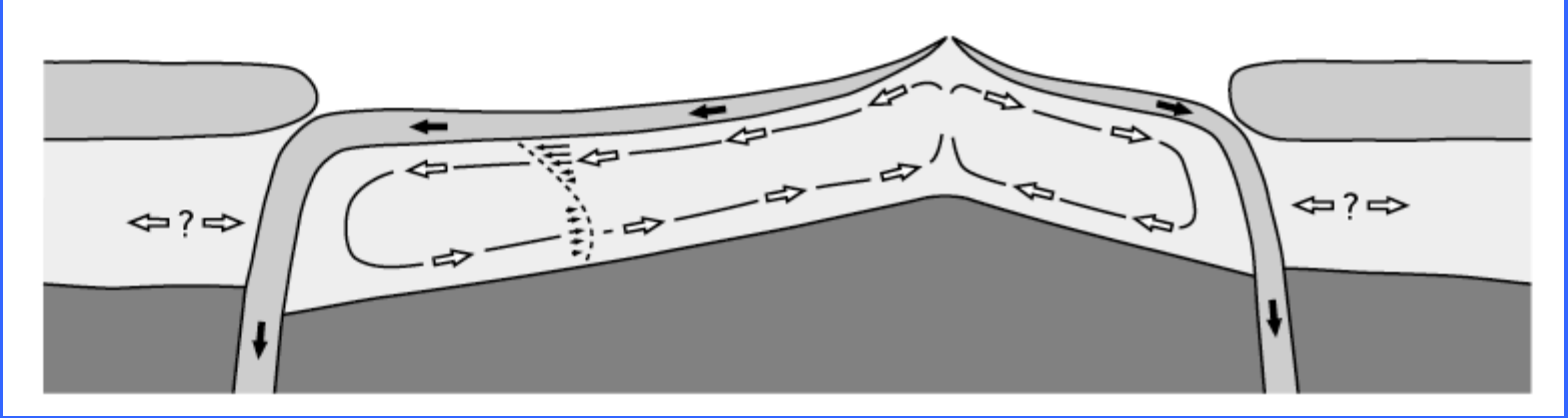
Amount of "deformation" reflects how well slab is anchored in mantle

Perfectly anchored slab
versus perfectly free





Nagel et al. (2008)



Nagel et al. (2008)

New model: slab is either anchored or pushed by mantle flow (sinking due to gravity is minor)

Net outflux of asthenospheric material from Pacific, causes basin to shrink

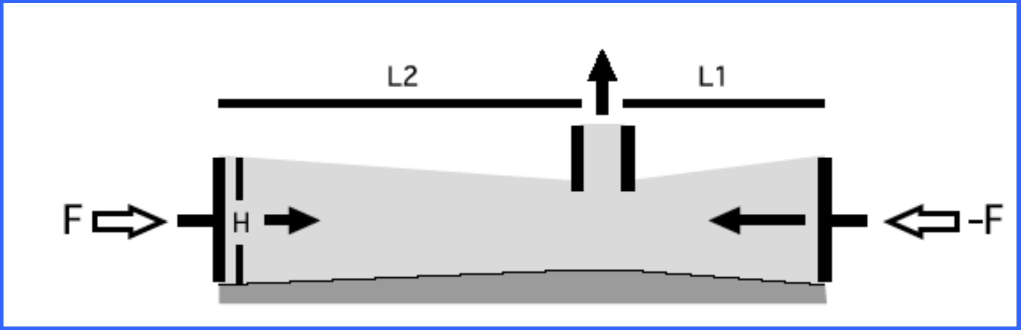
So why is eastern Pacific retreating faster than western Pacific?

Asthenospheric flow is dominantly horizontal; material is gradually removed from asthenosphere as it accretes to lithosphere and slab is subducted into lower mantle.

This outflux from the asthenosphere leads to a continuous pressure drop in the oceanic domain and associated flow from the outside world toward the ocean.

This flow causes slabs to retreat and the oceans to shrink.

Asymmetric Basin Model to explain fast retreating trench in Eastern Pacific

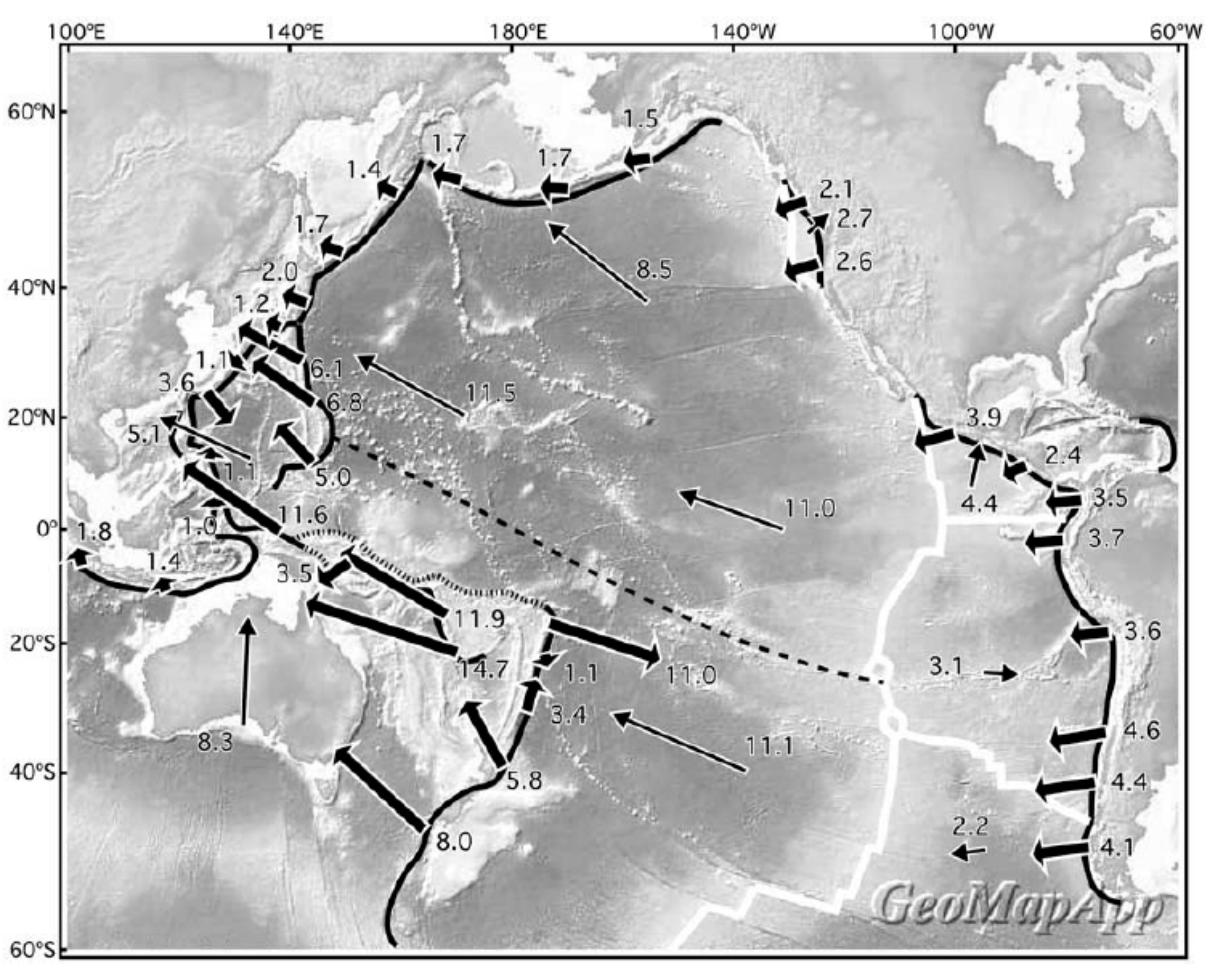


Nagel et al. (2008)

When the ocean basin is asymmetrical, the slab of the shorter plate retreats faster as a result of asymmetric accretion

Hence Eastern Pacific is retreating (shrinking) faster than western Pacific

So, changed question from “why are so many BABs in Western Pacific?” to “why aren’t there BABs in eastern Pacific?”



Slab Segmentation

Nazca-South America

BB' and DD' are segments with "flat slabs"

- Slab subducts horizontally for several hundred kms
- No volcanoes
- Due to subduction of buoyant features such as the Nazc ridge

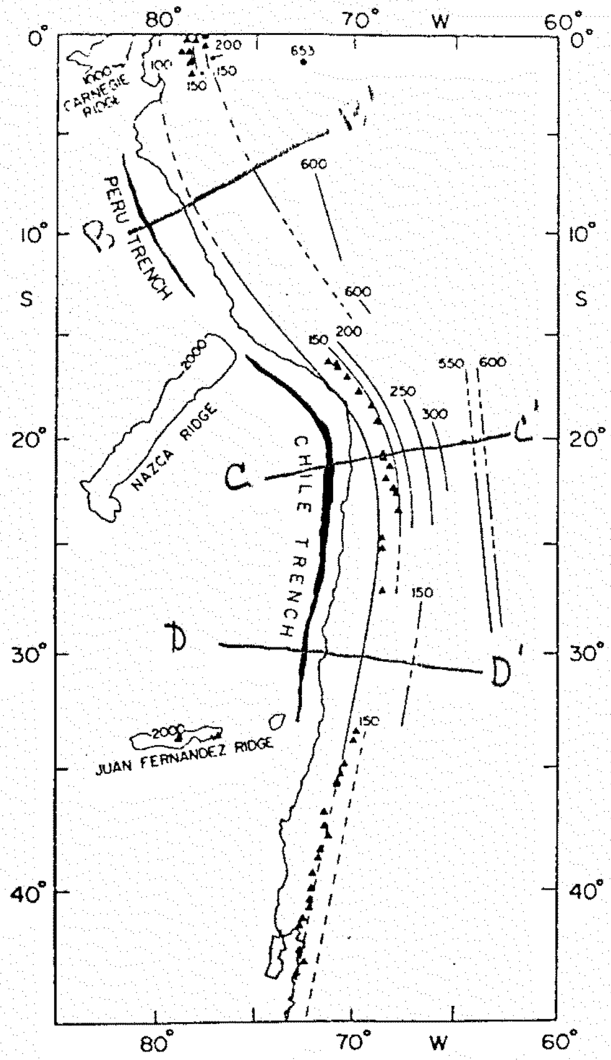


Figure 5. Map showing contours of hypocentral depth to top of inclined seismic zone.

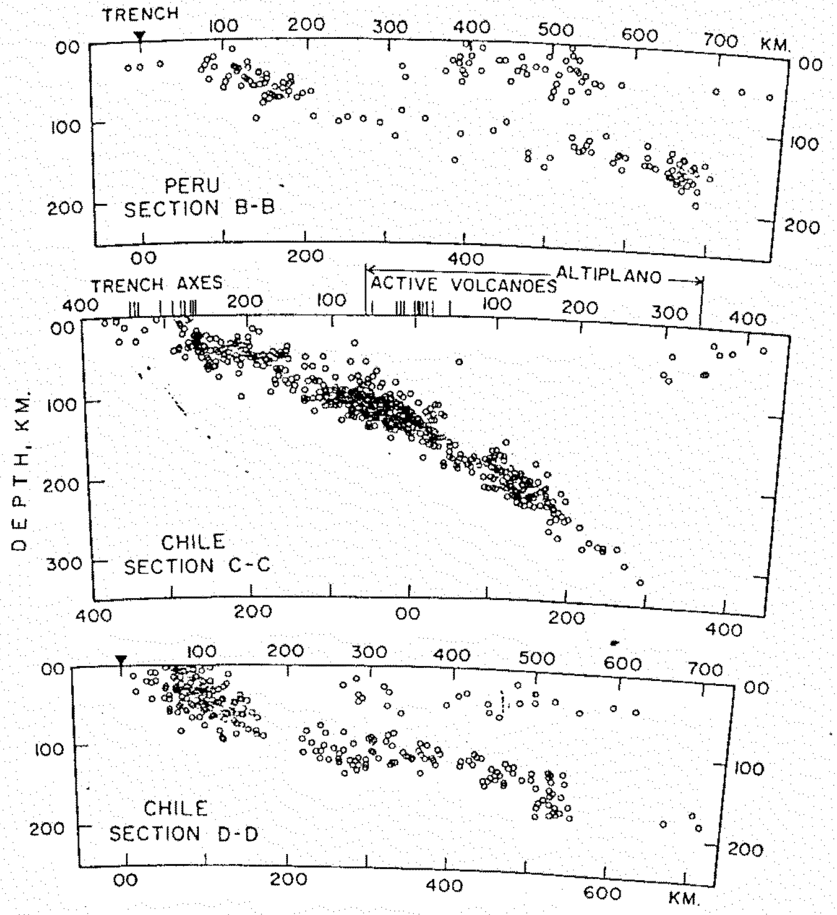
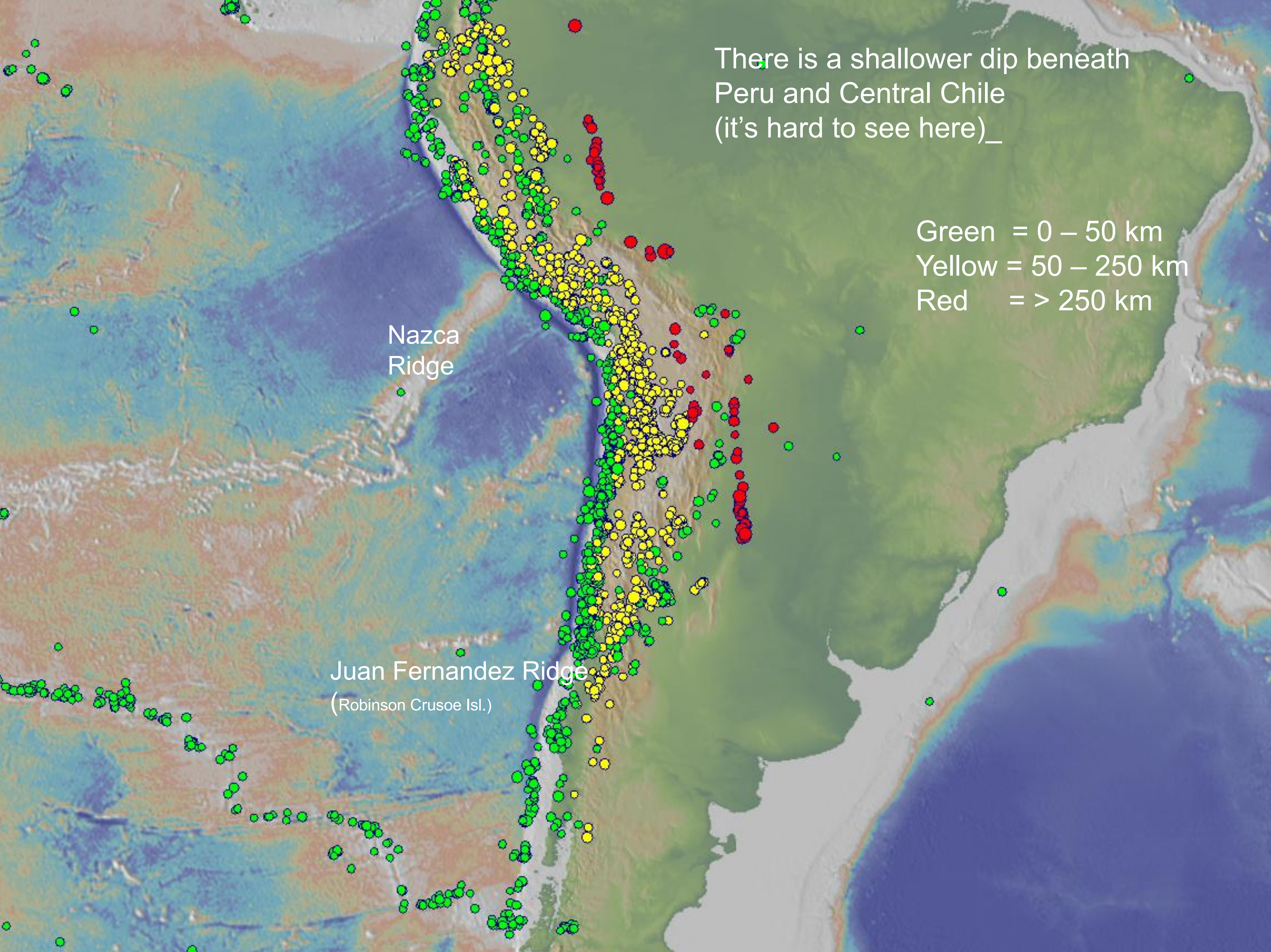


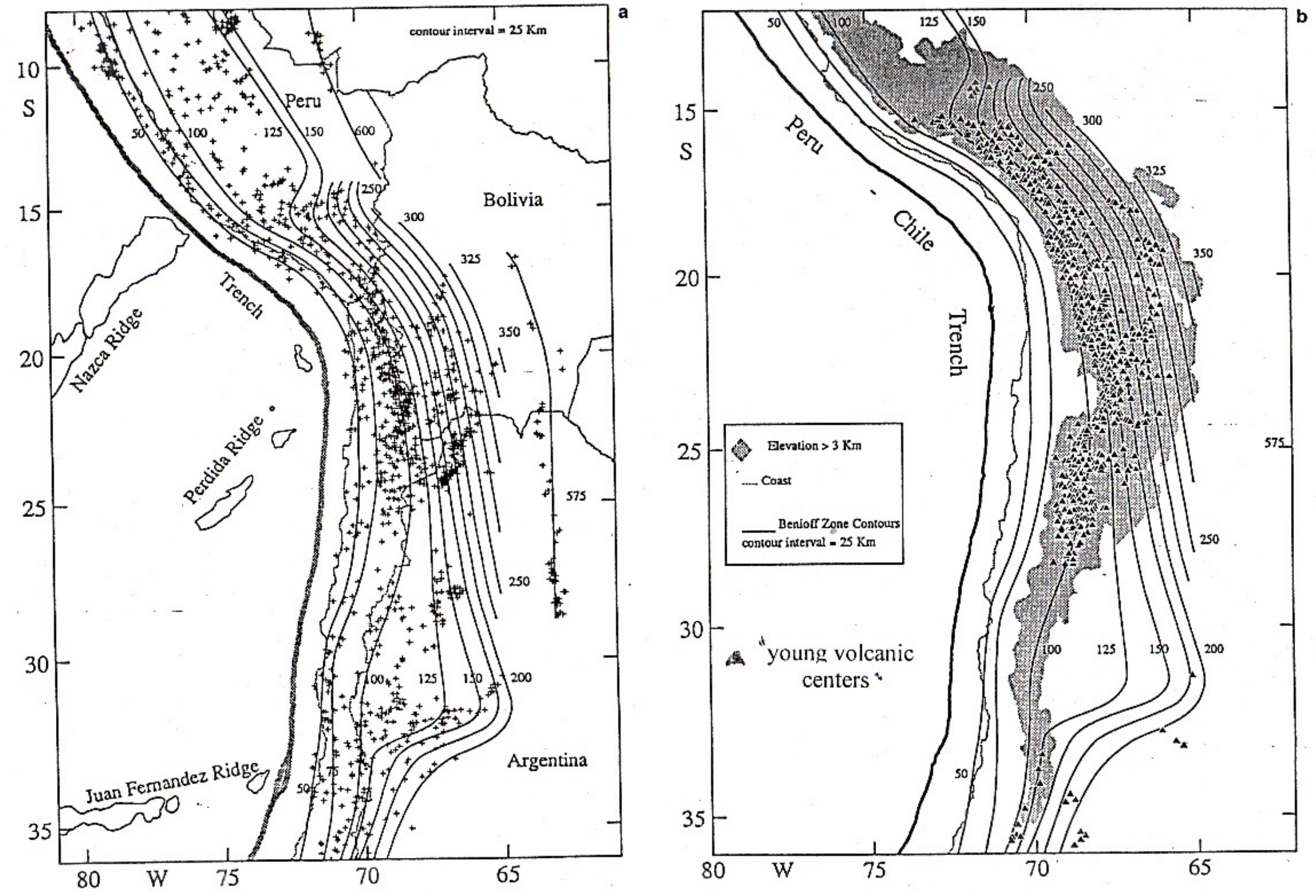
Figure 4. Cross sections showing segments of inclined seismic zone (A, B, C, D, E) and deep seismic zone (F, G, H). See Figure 3 for locations and limits of sections.

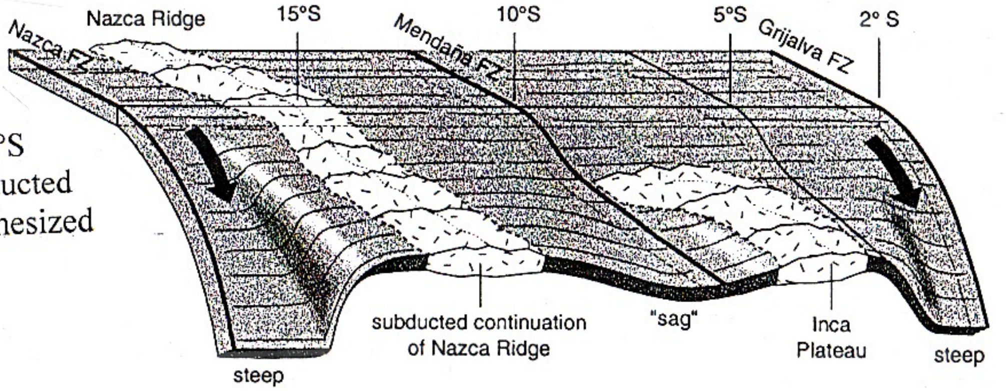
Barazangi & Isacks 1976)



There is a shallower dip beneath
Peru and Central Chile
(it’s hard to see here)_

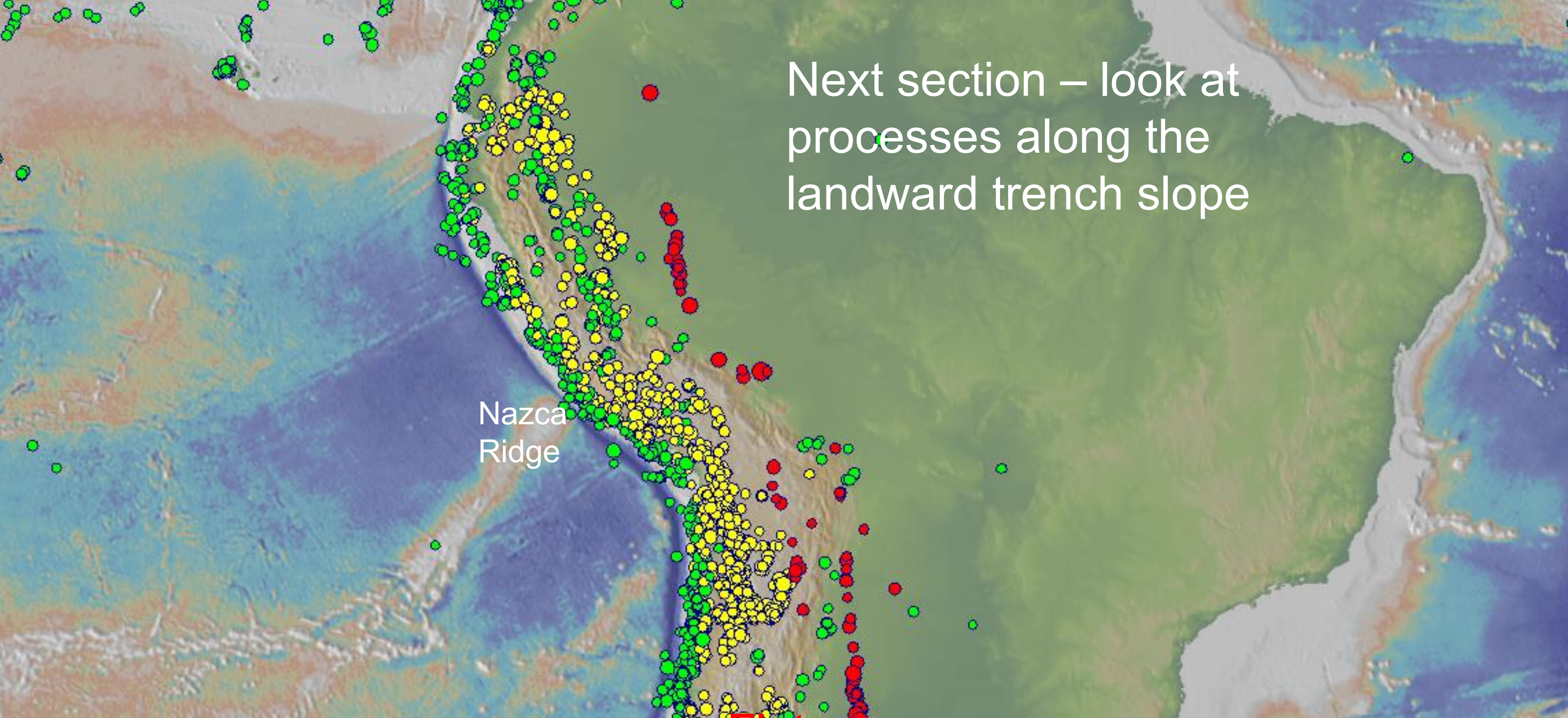
Green = 0 – 50 km
Yellow = 50 – 250 km
Red   = > 250 km



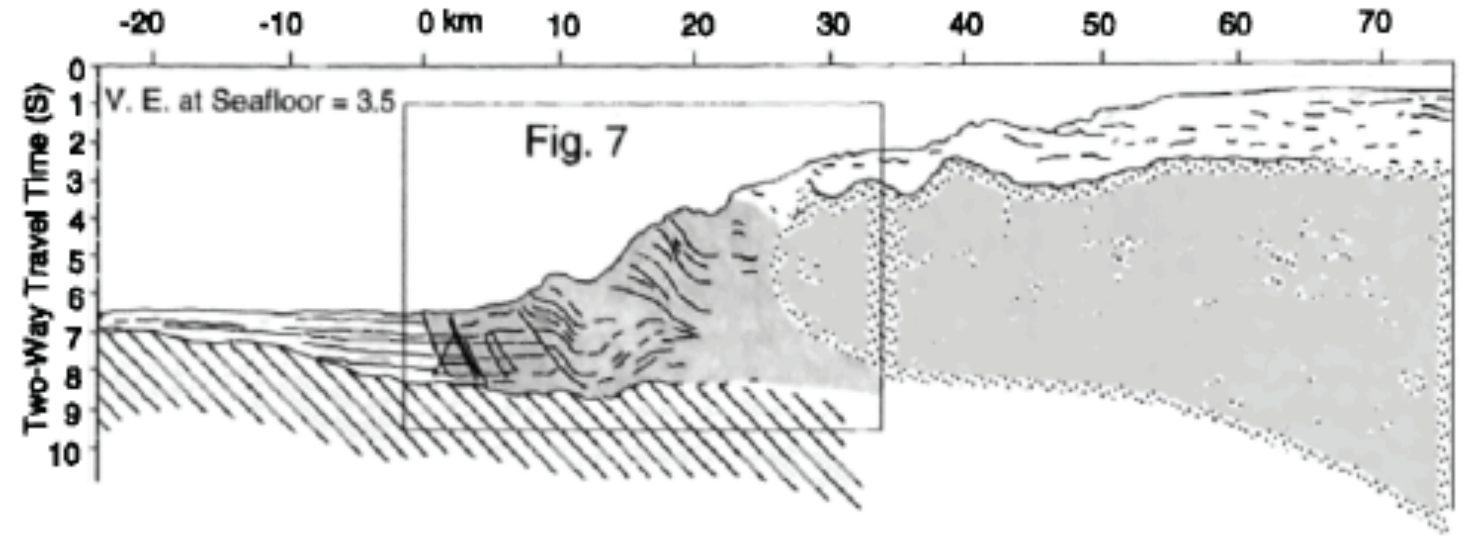


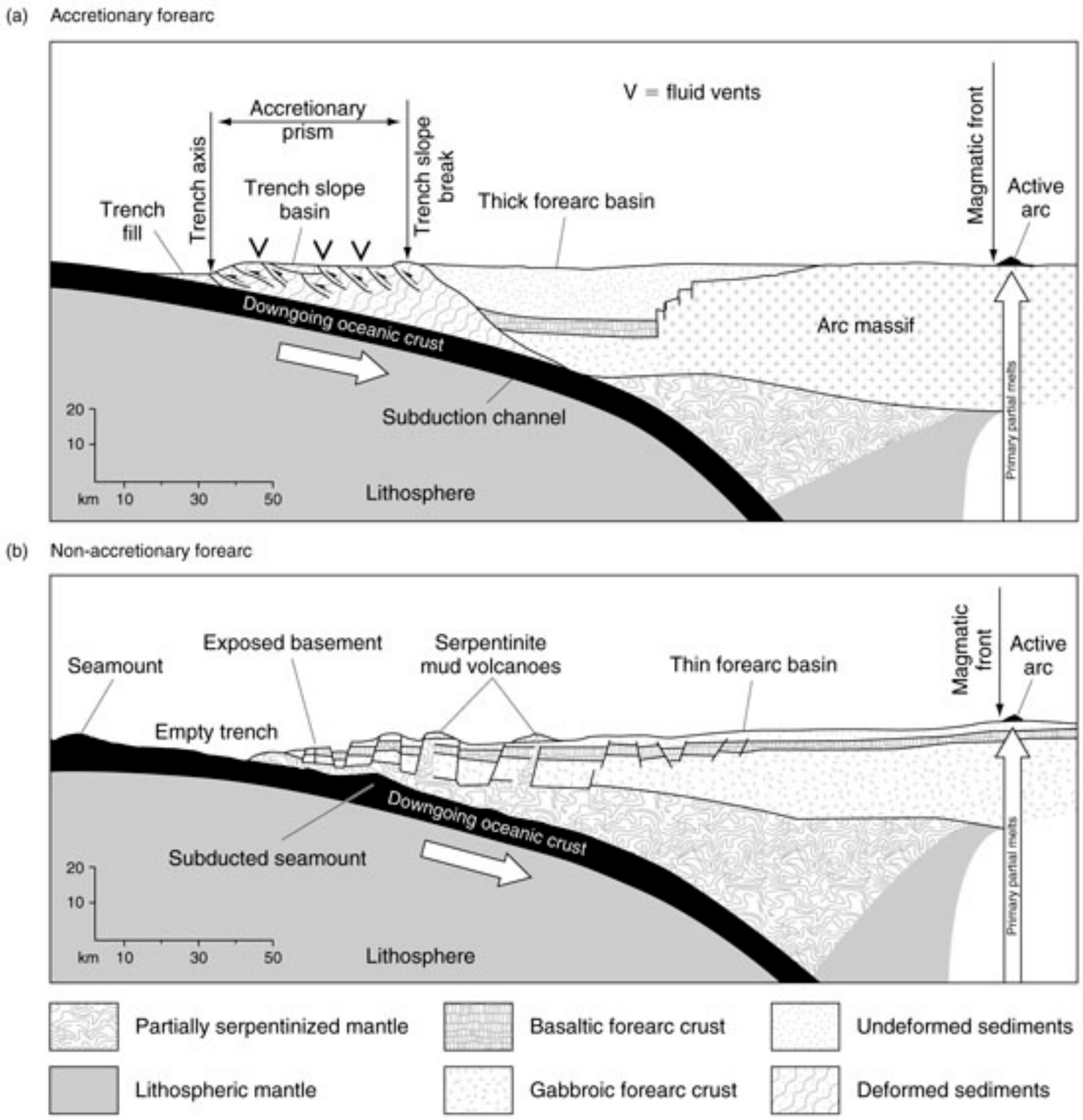
Shape of slab 5°S to 18°S
Note placement of subducted
Nazca ridge and hypothesized
"Incan Plateau"

Gutscher et al. (1999)



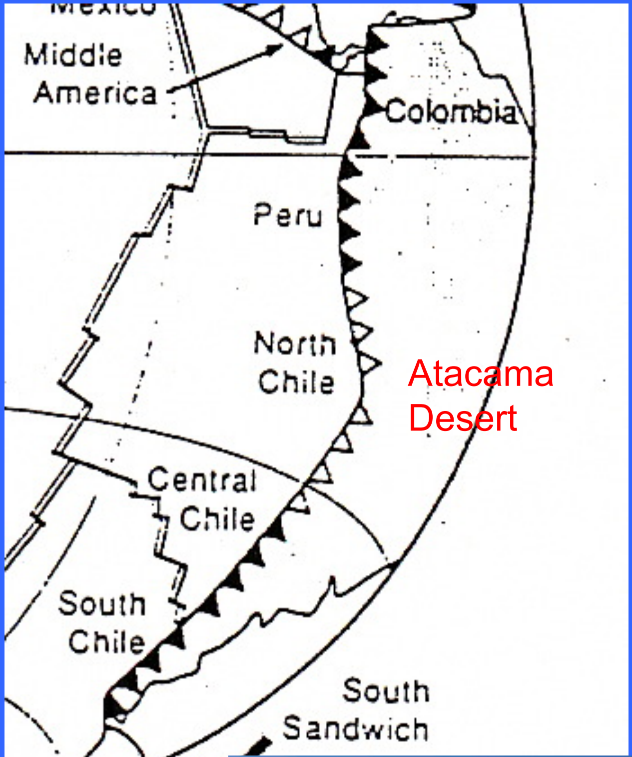
Next section – look at processes along the landward trench slope





(e.g. amount of sediment in trench reflects rainfall/erosion in adjacent mountains)

Accretionary versus non-accretionary environments

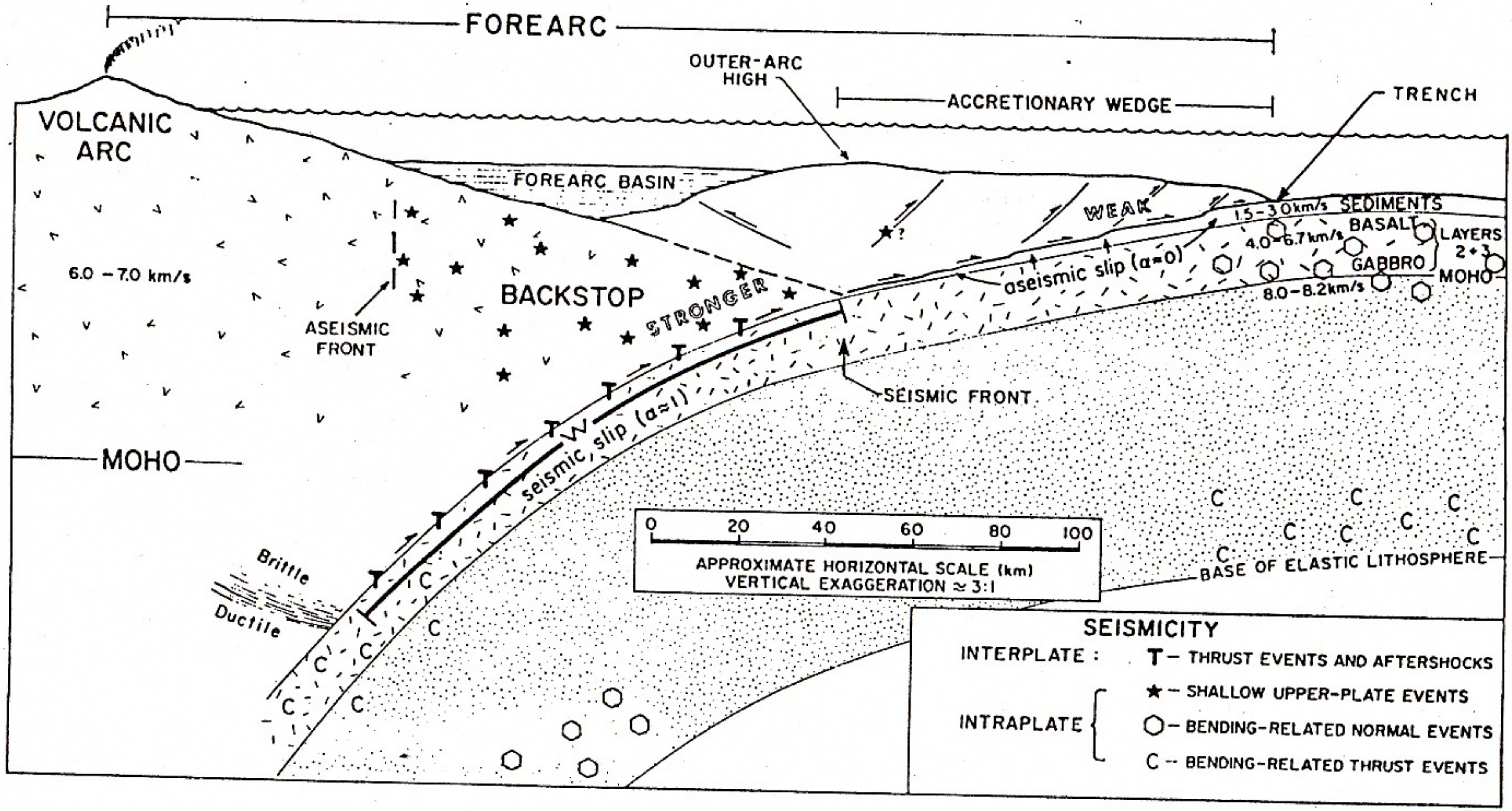


ALMA= Atacama Large Millimeter Array

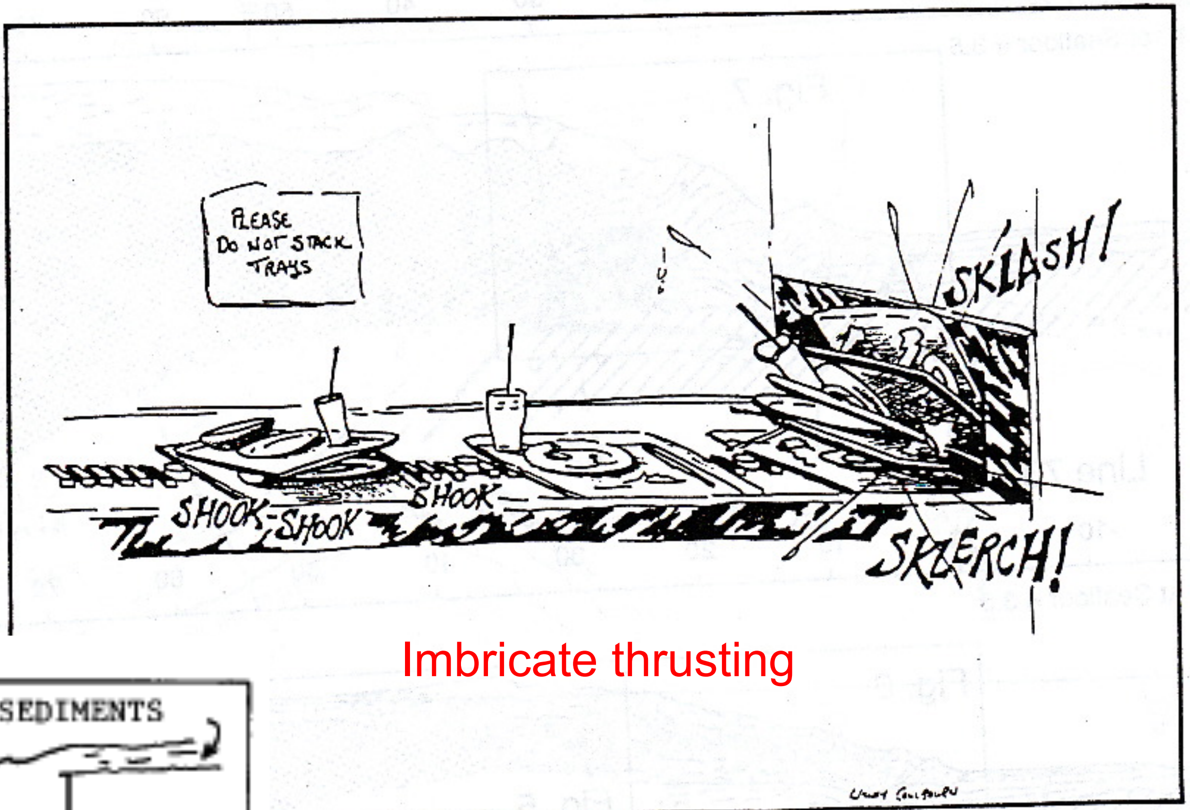
Filled barbs = accretionary
Open barbs = non-accretionary

Other non-accretionary = ocean-ocean trenches

Classic accretionary structures



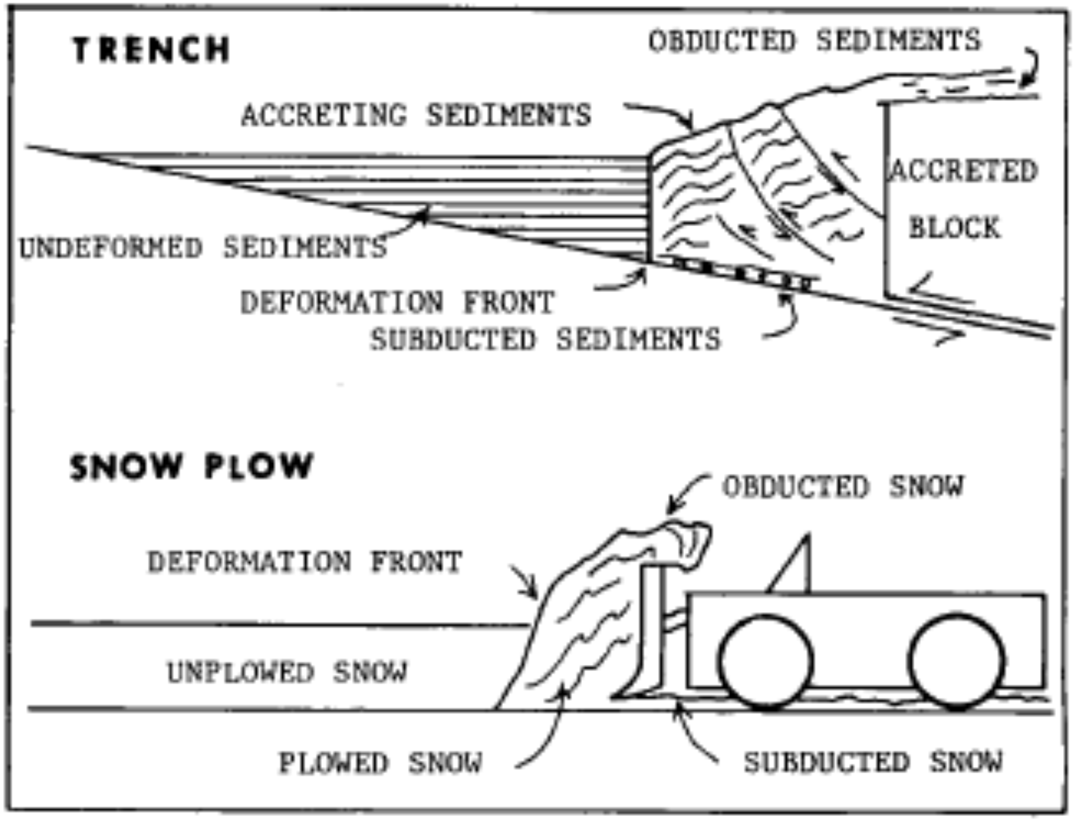
Analogs



nics in the University of Hawaii cafeteria. Conveyor belt carries trays toward restrictive
do not always pass tranquilly through to the dishwasher. Once a tray jams against the
e injected at the bottom of the stack. Intertray paper cups and plates are dewatered and
tion and overflow onto floor ceases only when the kitchen worker presses STOP button.

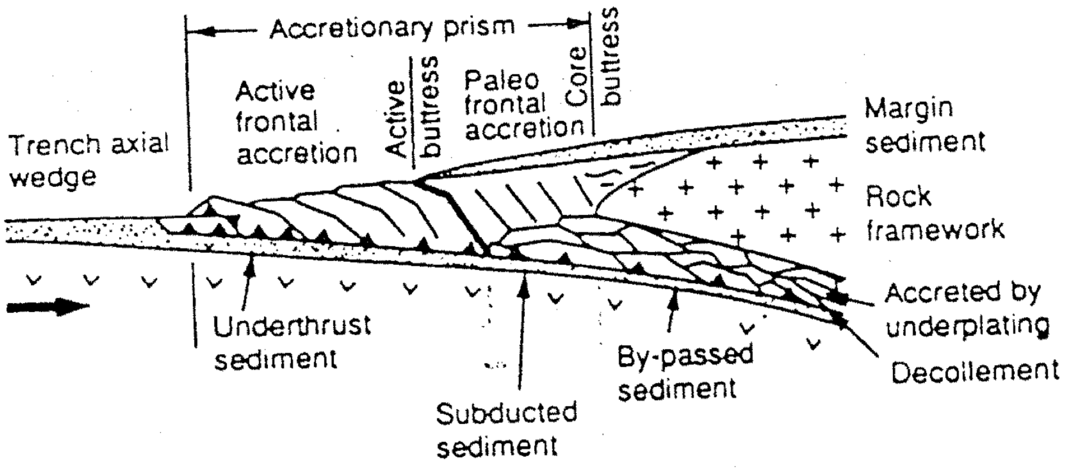
Imbricate thrusting

Coulbourn, 1981



Helwig and Hall, 1974

ACCRETIONARY AND SEDIMENT SUBDUCTION PROCESSES



VON HUENE & SCHOLL (1991)

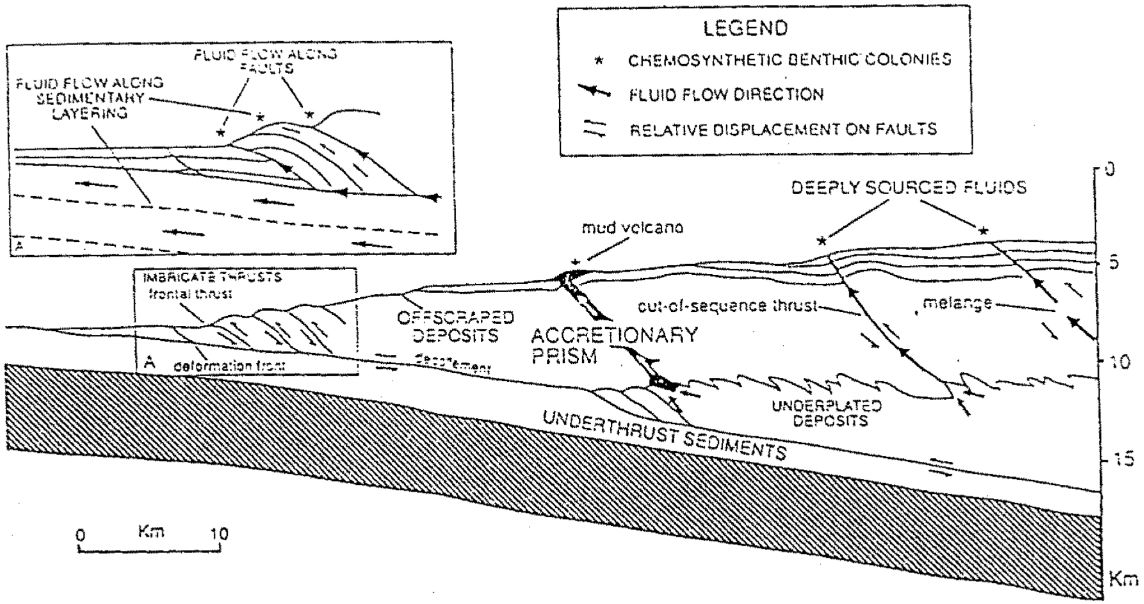


Figure 1. Schematic cross section of an accretionary prism showing major tectonic elements and features controlling fluid emplacement and expulsion.

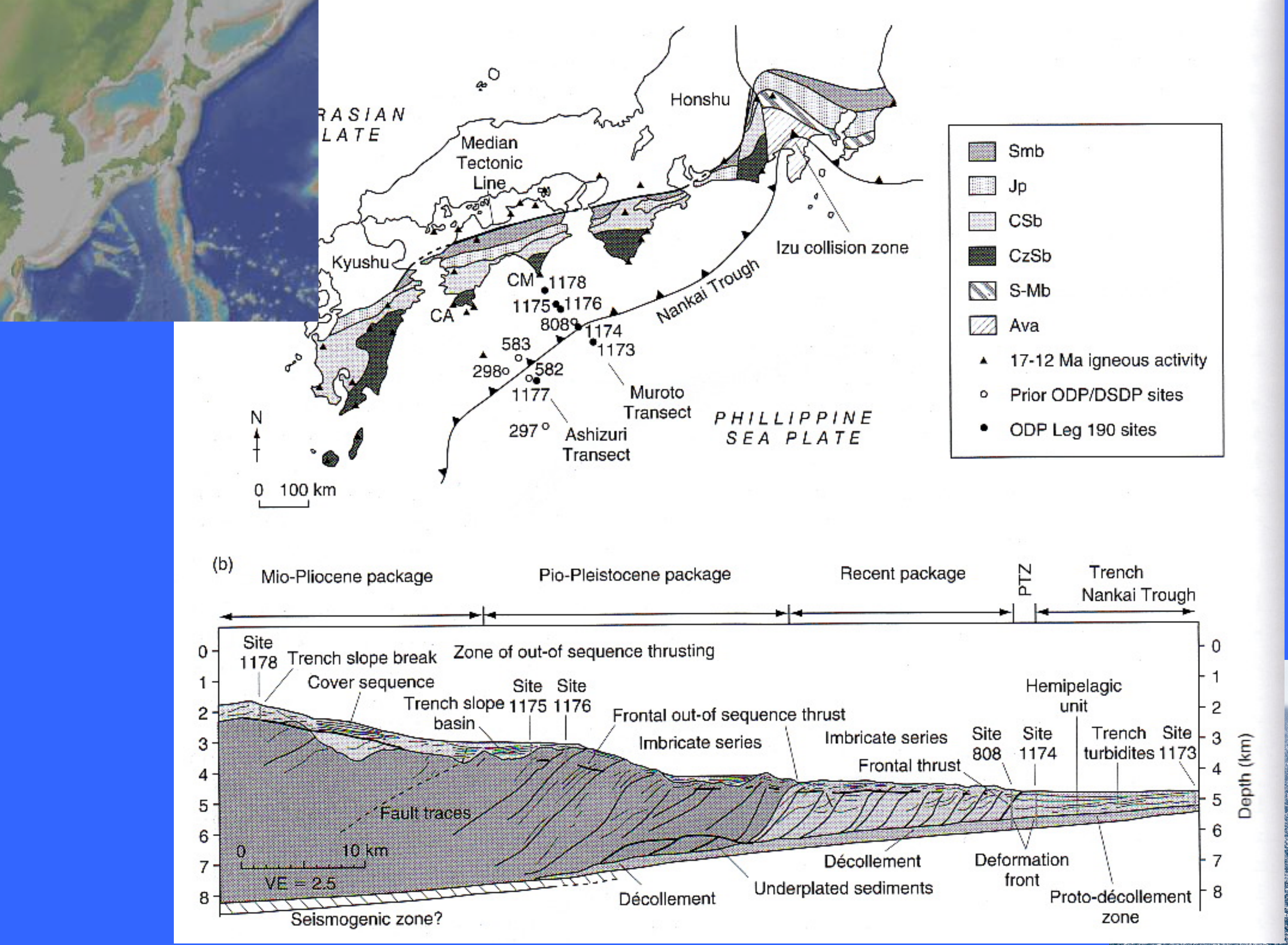
MOORE & VROLIJK (1992)

The **decollement** is the boundary between undeformed sediments that are being subducted and the scraped off, accreted material

The style of faulting in the accretionary prism is called imbricate thrusting;

The imbricate thrust faults form passageways for fluid flow through the prism

Nankei Trough: classic accretionary prism

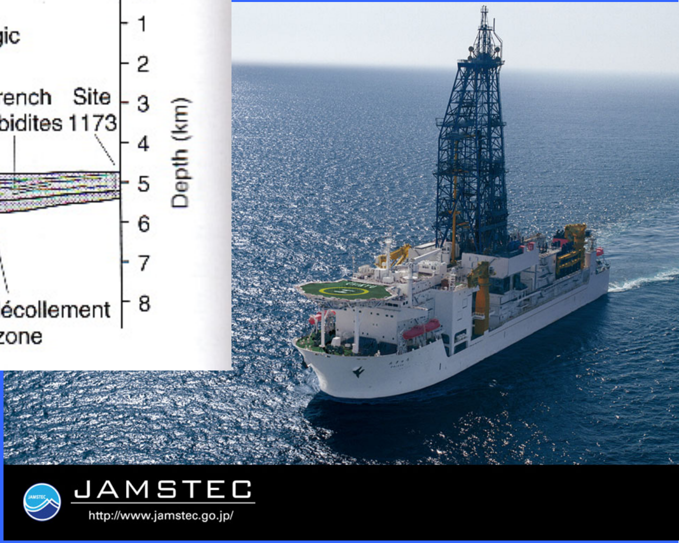


KK&V Fig 9.20

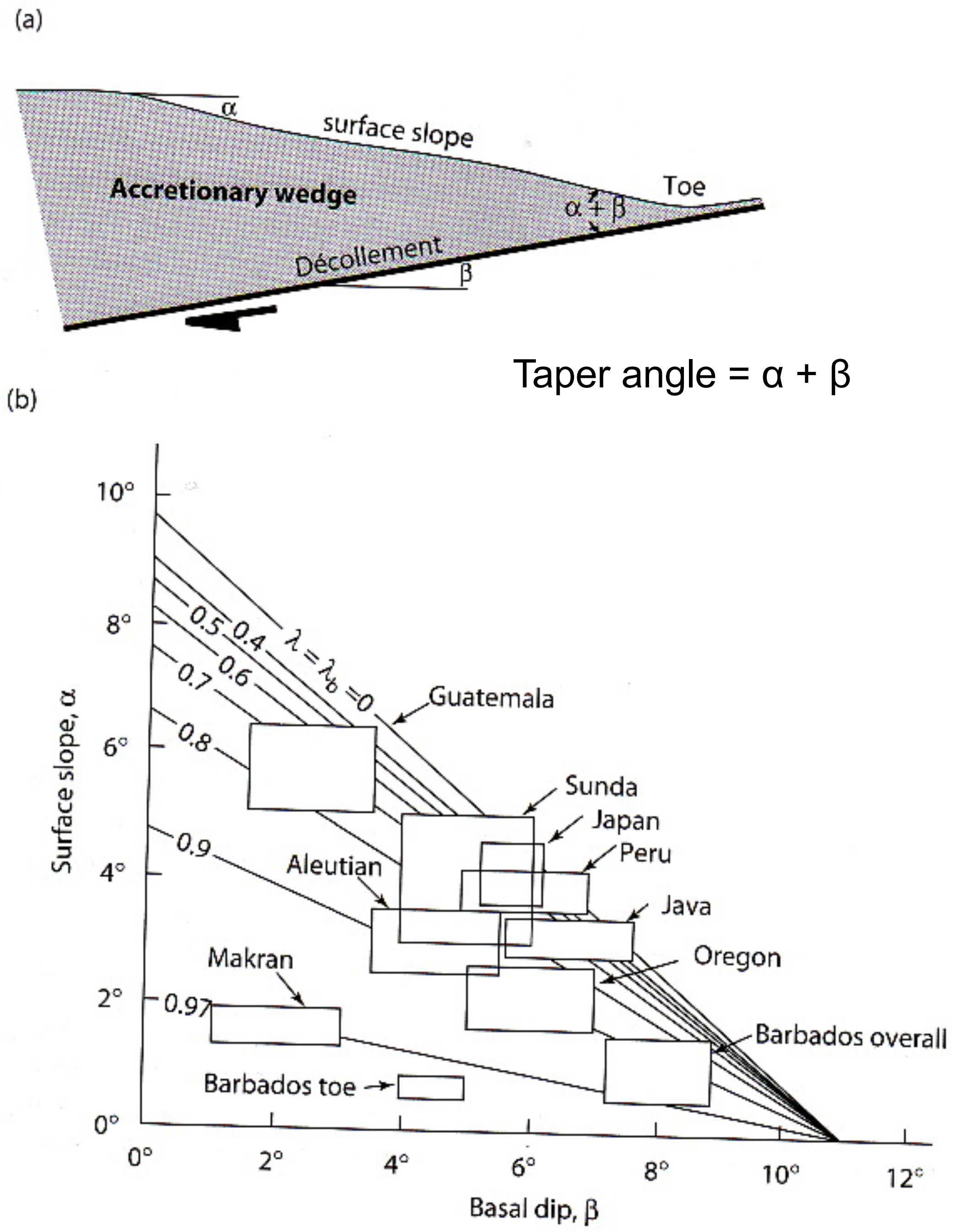
Major seismic hazard; very destructive earthquake here in 1944

Ambitious drilling program

Chikyu (Earth)



Riser drilling
Japan Current



Taper angle = α + β

Accreting prisms are tapered wedges

Upper surface slope (α) is related to
(1)the resistance to sliding on the decollement and
(2) the strength of the rock

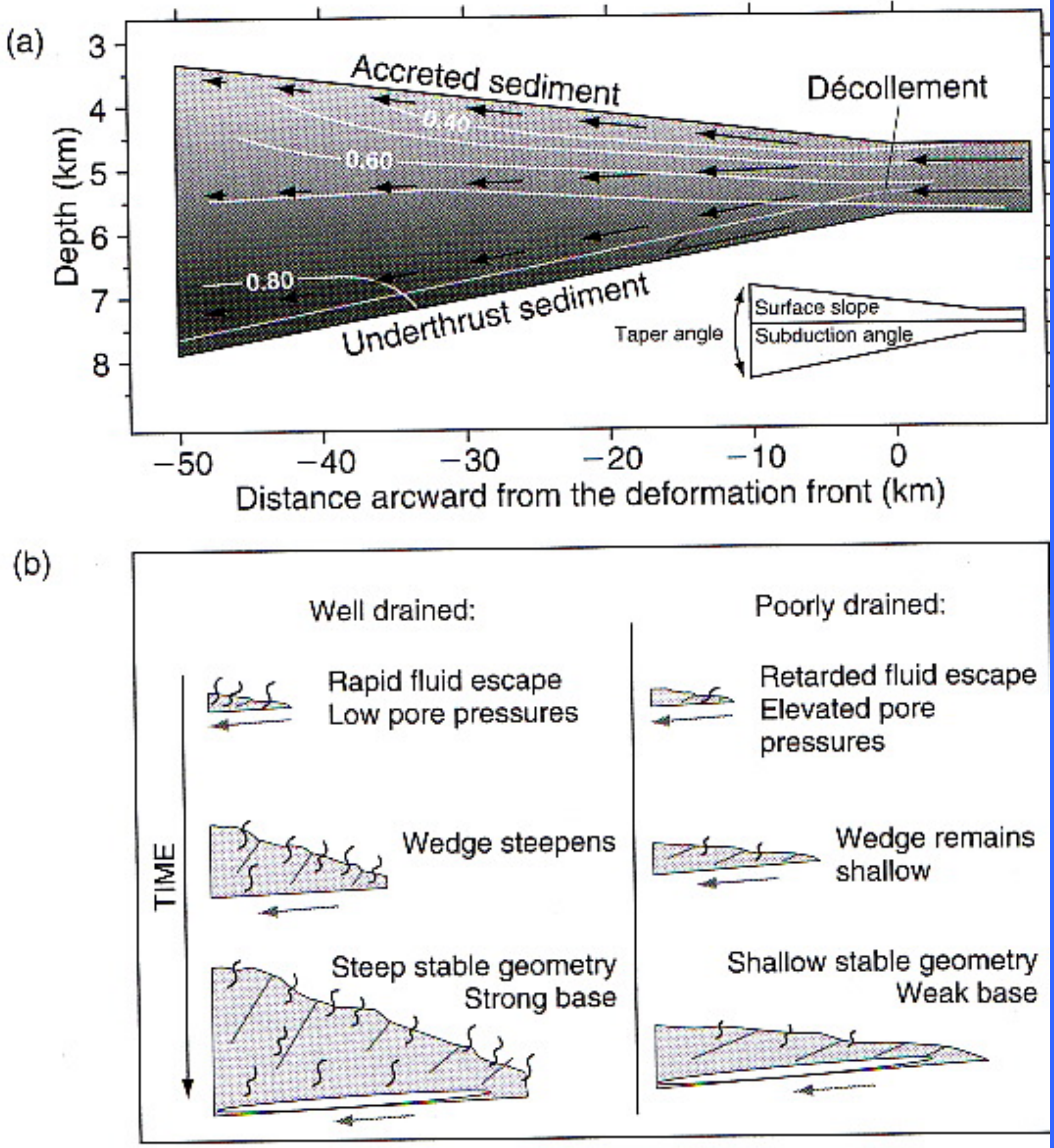
These are related to:
- pore fluid pressure (λ)
- dip of the basal decollement (β)
- weight of the overlying rock

Tectonic shortening steepens the surface, but if it becomes oversteepened then have mechanical adjustments

Result: develop a steady state shape

Lower figure: theoretical tapers for various pore fluid pressures

KK&V fig 9.21



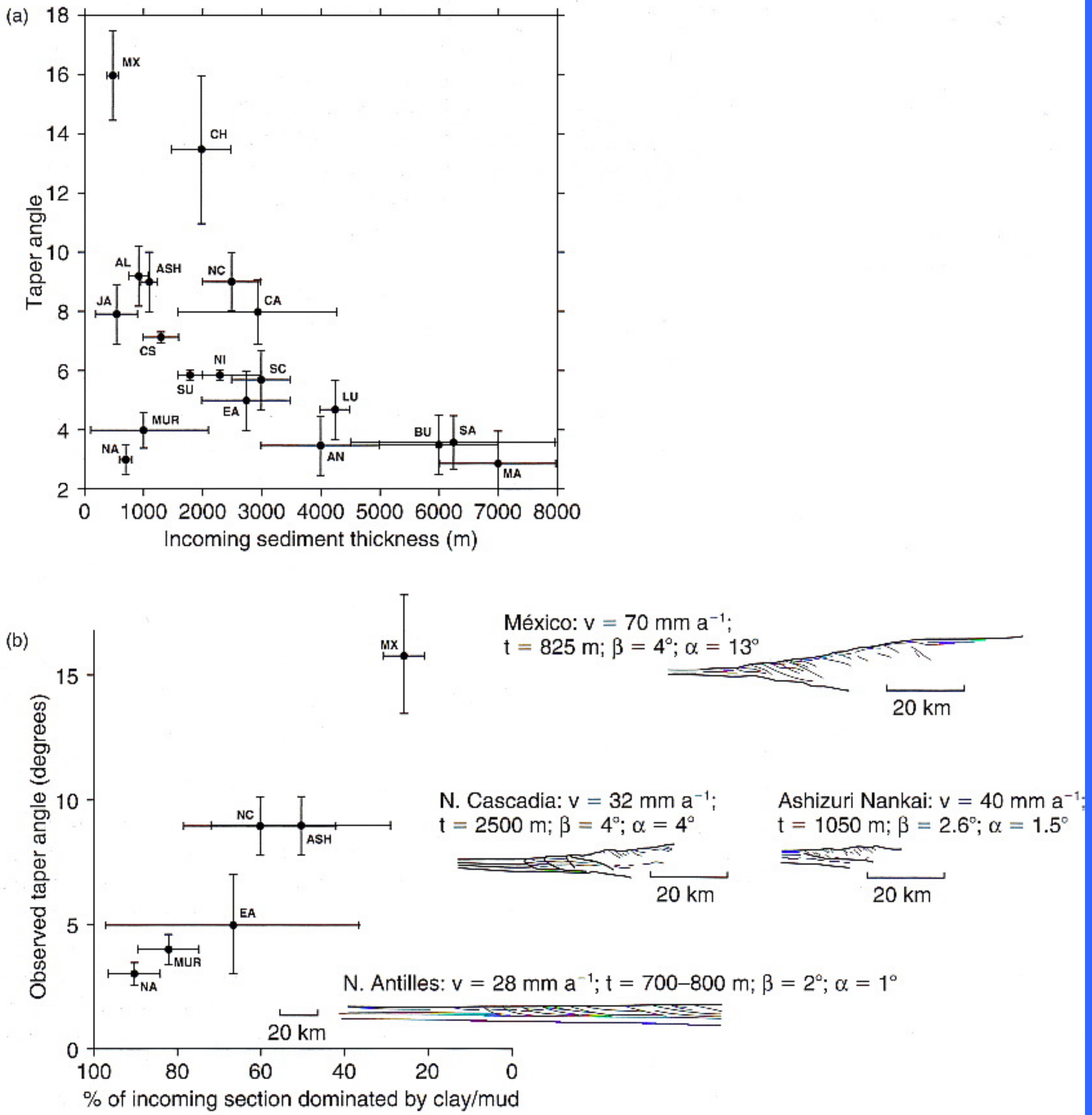
Numerical model of fluid flow within an accretionary prism (contours are pore fluid pres.)

Relationship between pore fluid pressure and taper angle

Low pore fluid pressure is related to steep wedges

High pore fluid pressure to shallow wedges

KK&V fig 9.22



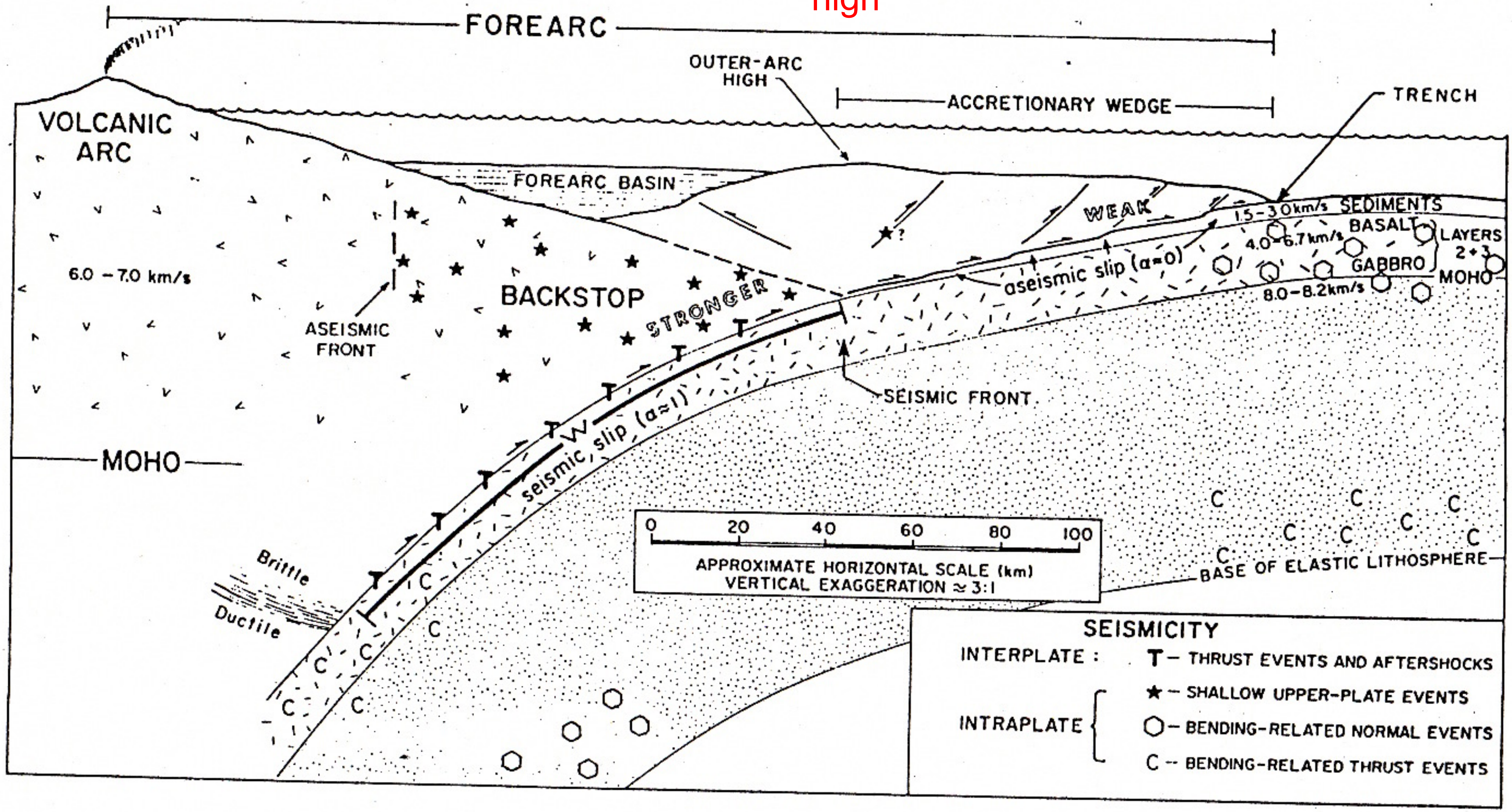
Taper angle of active accretionary prisms plotted as a function of sediment thickness (top) and lithology (bottom)

(top) Thick sedimentary sections give rise to large prisms that sustain high pore fluid pressures and low taper angles

(bottom) Low permeability sediments (high clay/mud) also have high pore pressures hence low taper

KK&V fig. 9.23

Outer arc high



Accretionary prisms grow over time

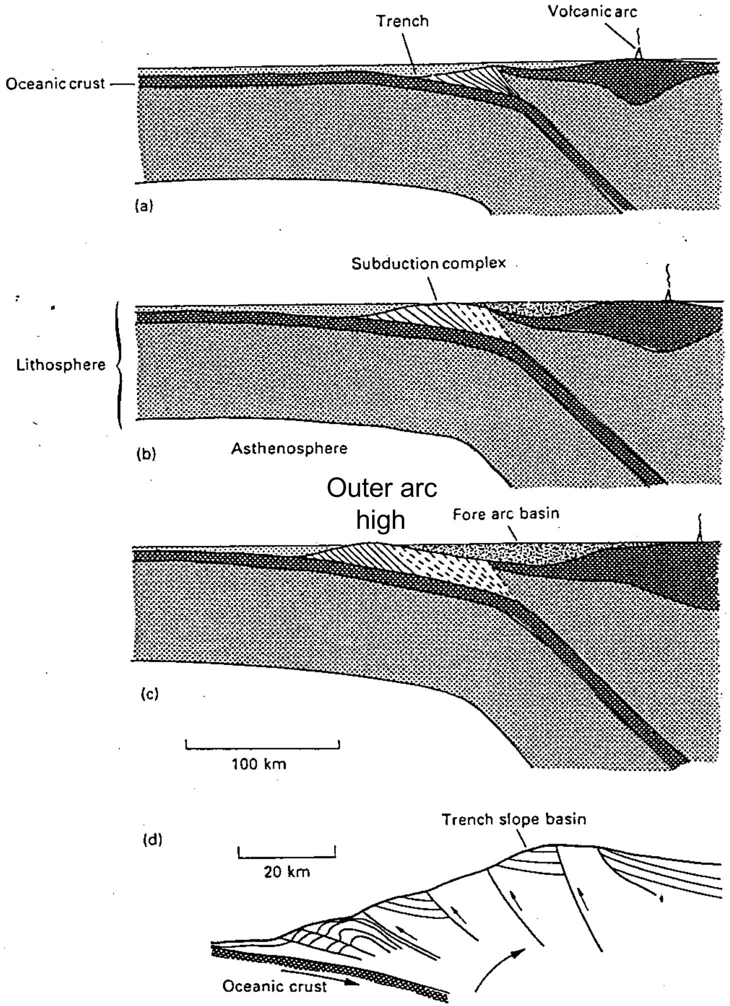
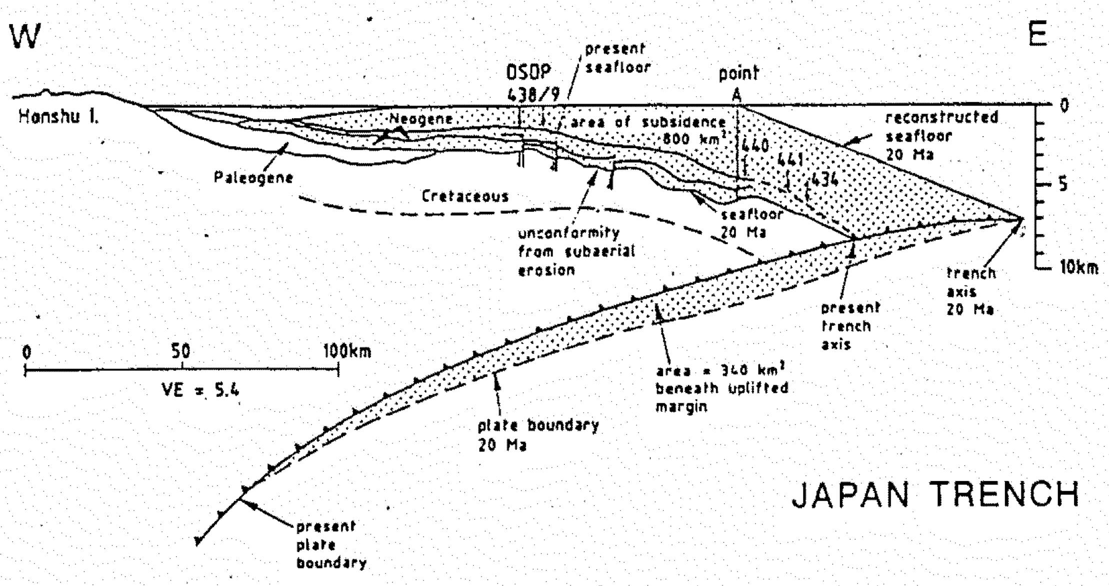


Fig. 8.26 (a–c) Idealized sequence of the evolution of an accretionary prism (redrawn from Dickinson, 1977, with permission from the American Geophysical Union): (a) incipient stage; (b) forearc basin; (c) full forearc basin. Solid lines in subduction complex, active thrusts; broken lines, inactive thrusts. (d) Schematic, vertically exaggerated section of an accretionary wedge (redrawn from Cowan & Silling, 1978, with permission from the American Geophysical Union).

Kearey & Vine (1996)

SUBDUCTION EROSION!

NOT ALL LANDWARD TRENCH SLOPES ARE GROWING!



Drilling shows that 20 Ma ago lower slope was very shallow

Some process is removing lower slope material from underneath

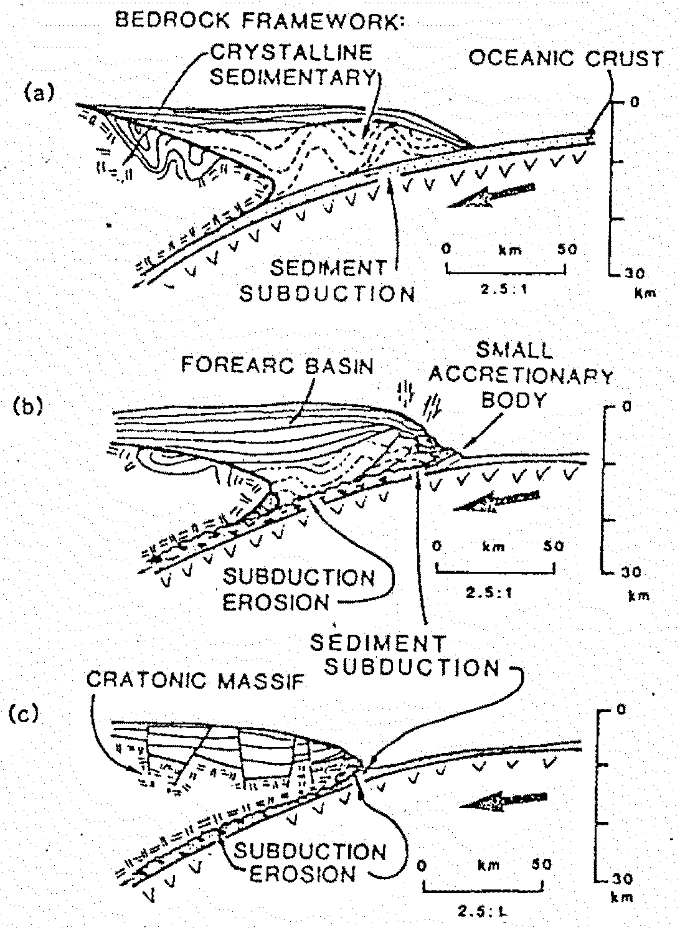
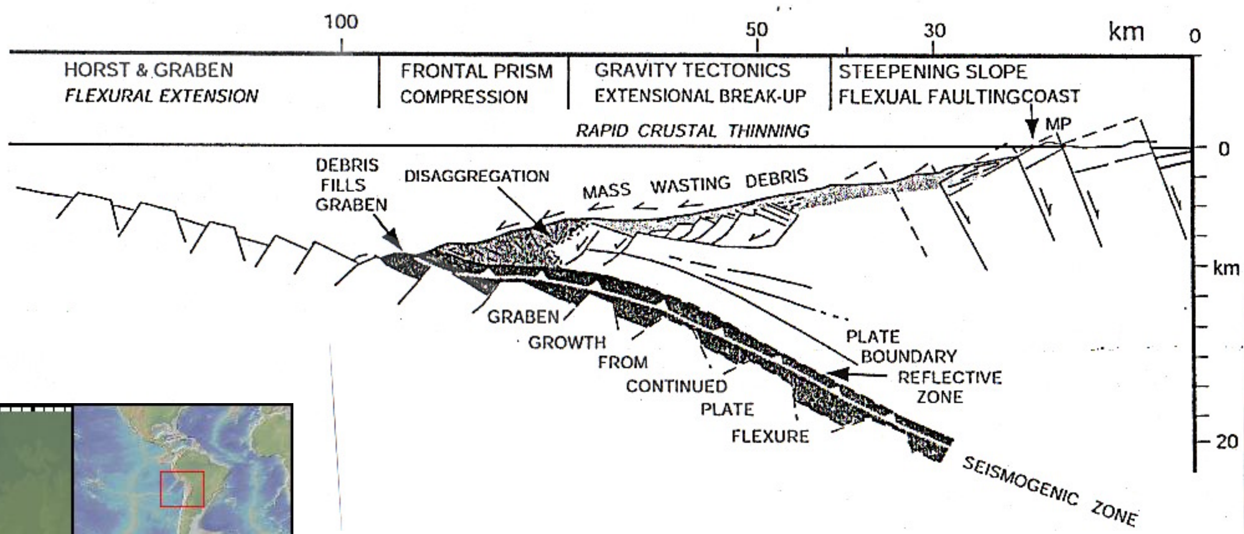


Figure 2. Conceptual models of sediment subduction and subduction erosion. (a) Tectonic consumption of oceanic deposits beneath bedrock framework of an ocean margin. (b) Subduction of oceanic deposits and subduction erosion of margin's bedrock framework, and *temporary* outgrowth of small wedge of accreted oceanic beds at base of margin. (c) Advanced stage of subduction erosion, which has exposed igneous and metamorphic framework of a cratonic massif at inner wall of a deep-sea trench.

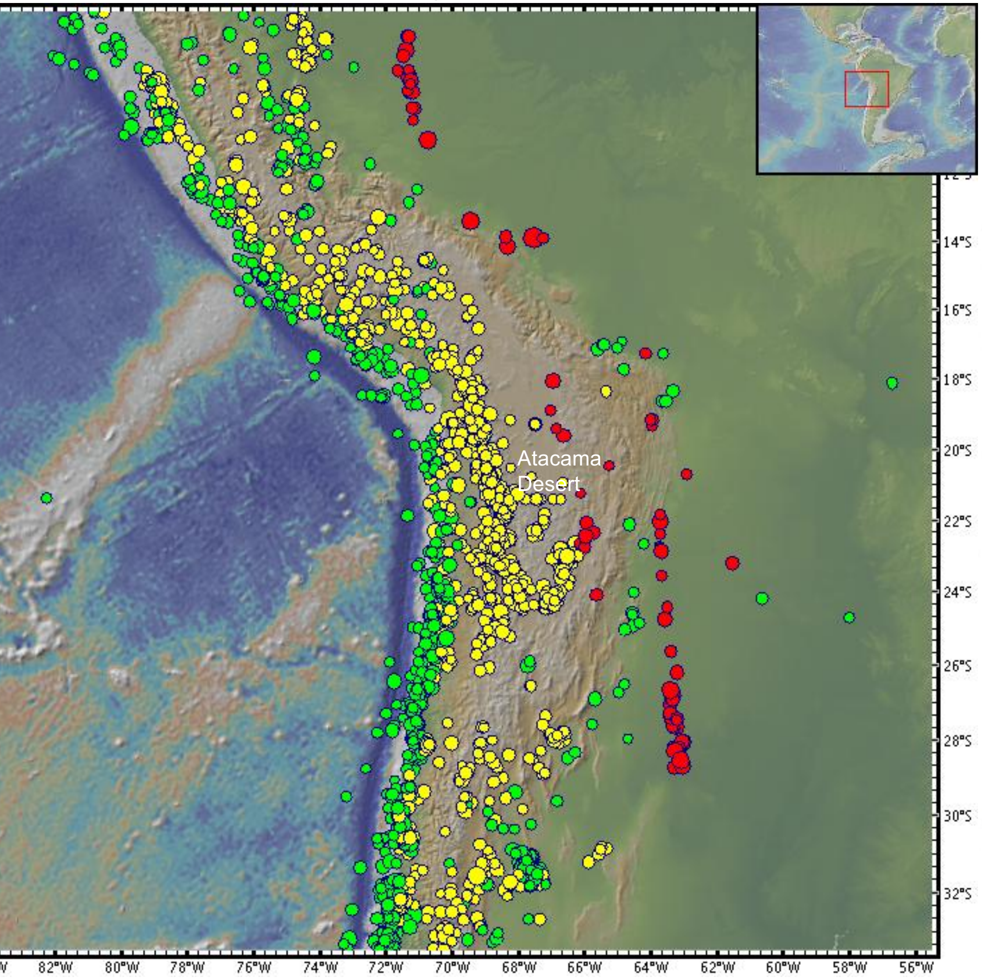
Von Huene & Scholl (1991)

SCHOLL et al (1980)

Subduction erosion by interaction with horst and graben topography



Chile Trench



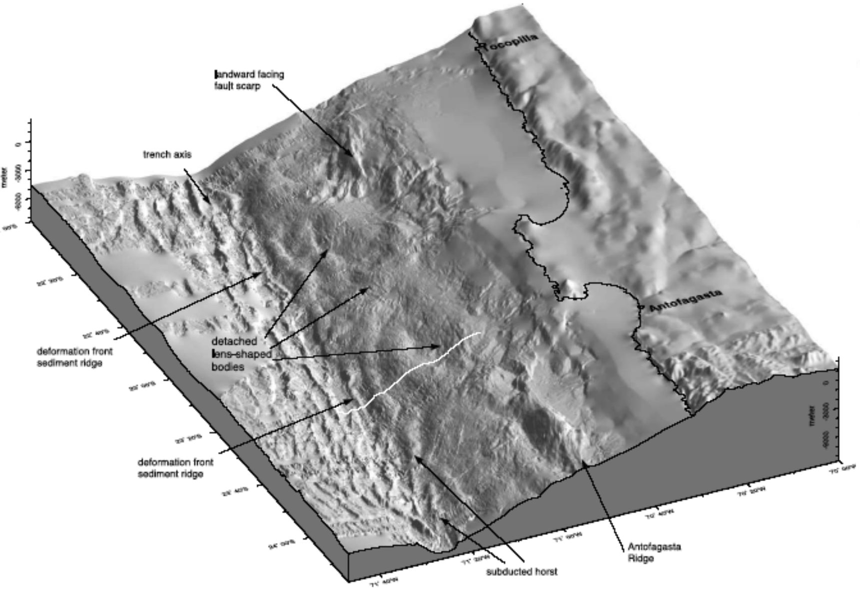
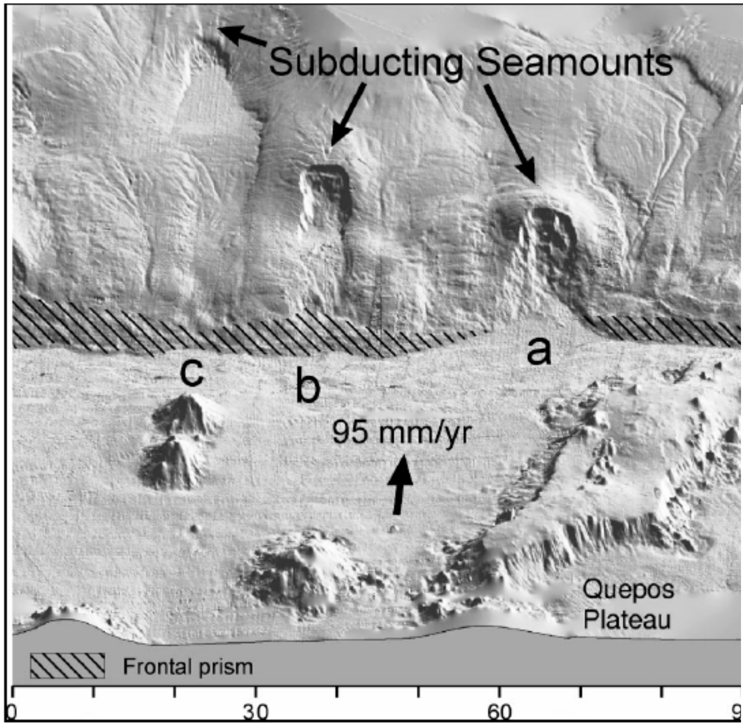
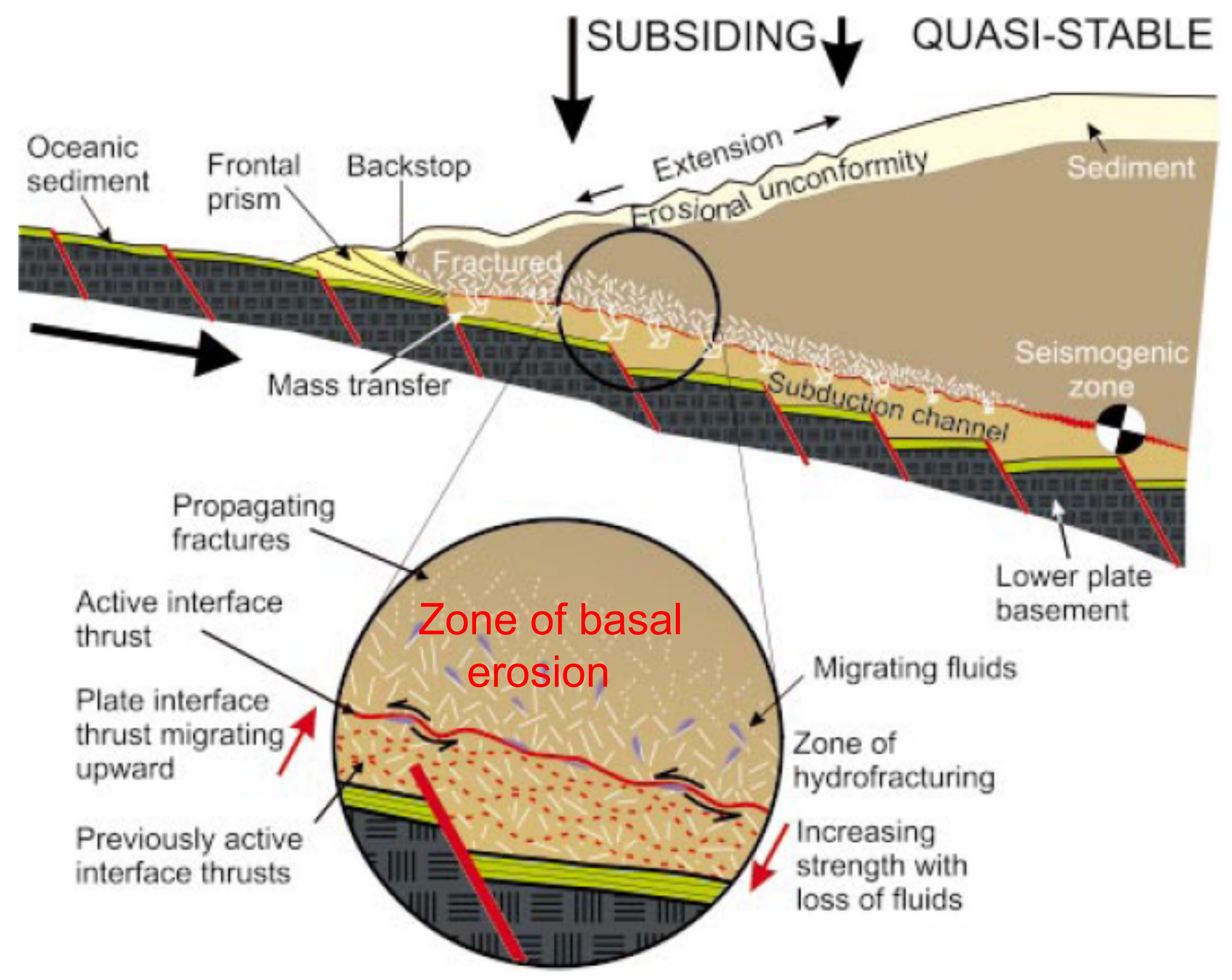


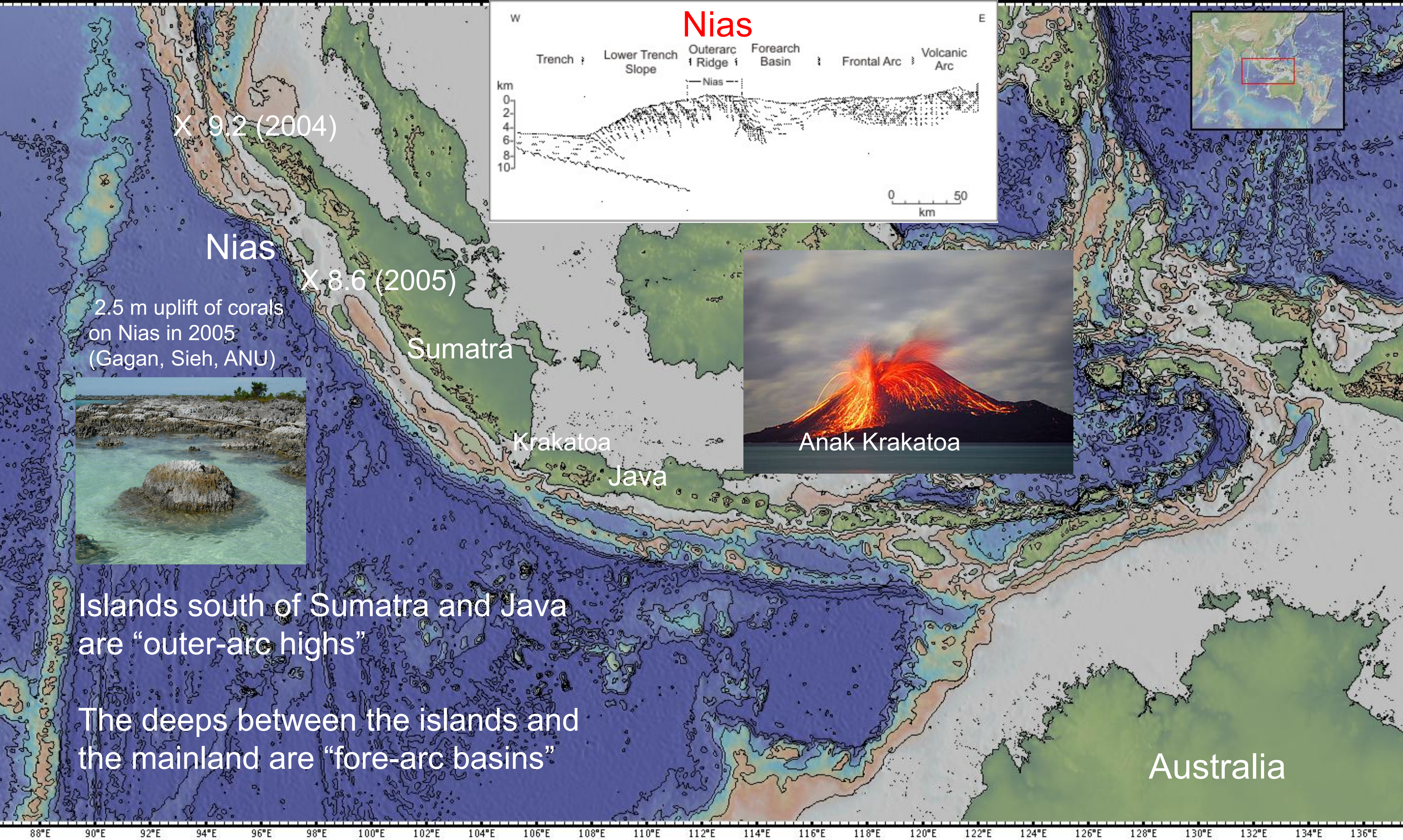
Figure 3b. Shaded relief perpspective diagram. Horst and graben morphology continues beneath the lower slope after subduction of the ocean crust. One of several large landward facing scarps is annotated.





Subduction-erosion model. Dashed pattern along plate interface indicates most severe fracturing. Mass transfer from upper to lower plate occurs as dislodged fragments are dragged into subduction channel. Active plate interface migrates upward and dotted lines in subduction channel represent previously active thrusts.

Von Huene and Ranero, Geology, 2004



2.5 m uplift of corals on Nias in 2005 (Gagan, Sieh, ANU)

Islands south of Sumatra and Java are “outer-arc highs”

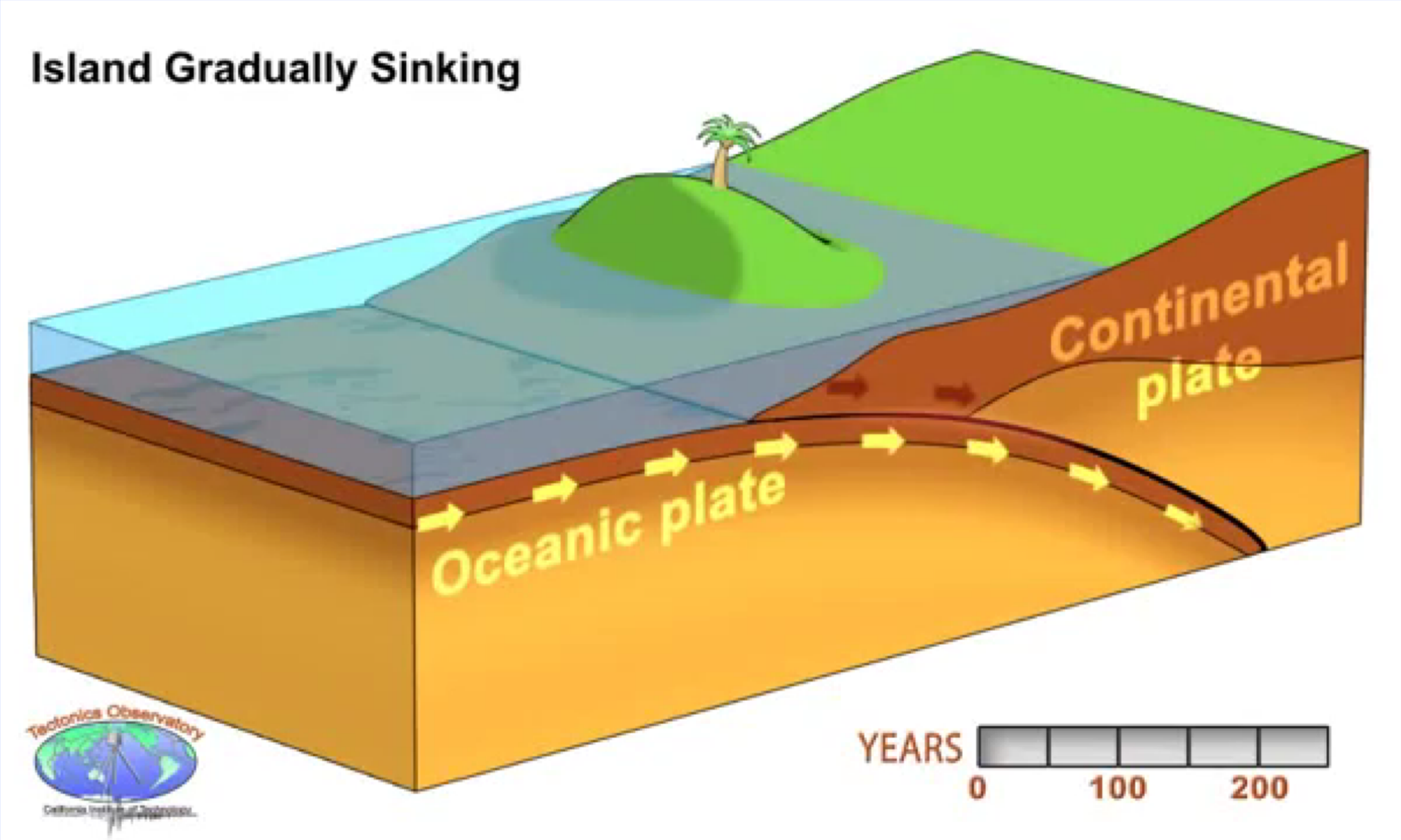
The deeps between the islands and the mainland are “fore-arc basins”

Indonesian Arc: Sumatra-Java trench

Another example: Barbados

Movie title: Krakatoa, East of Java

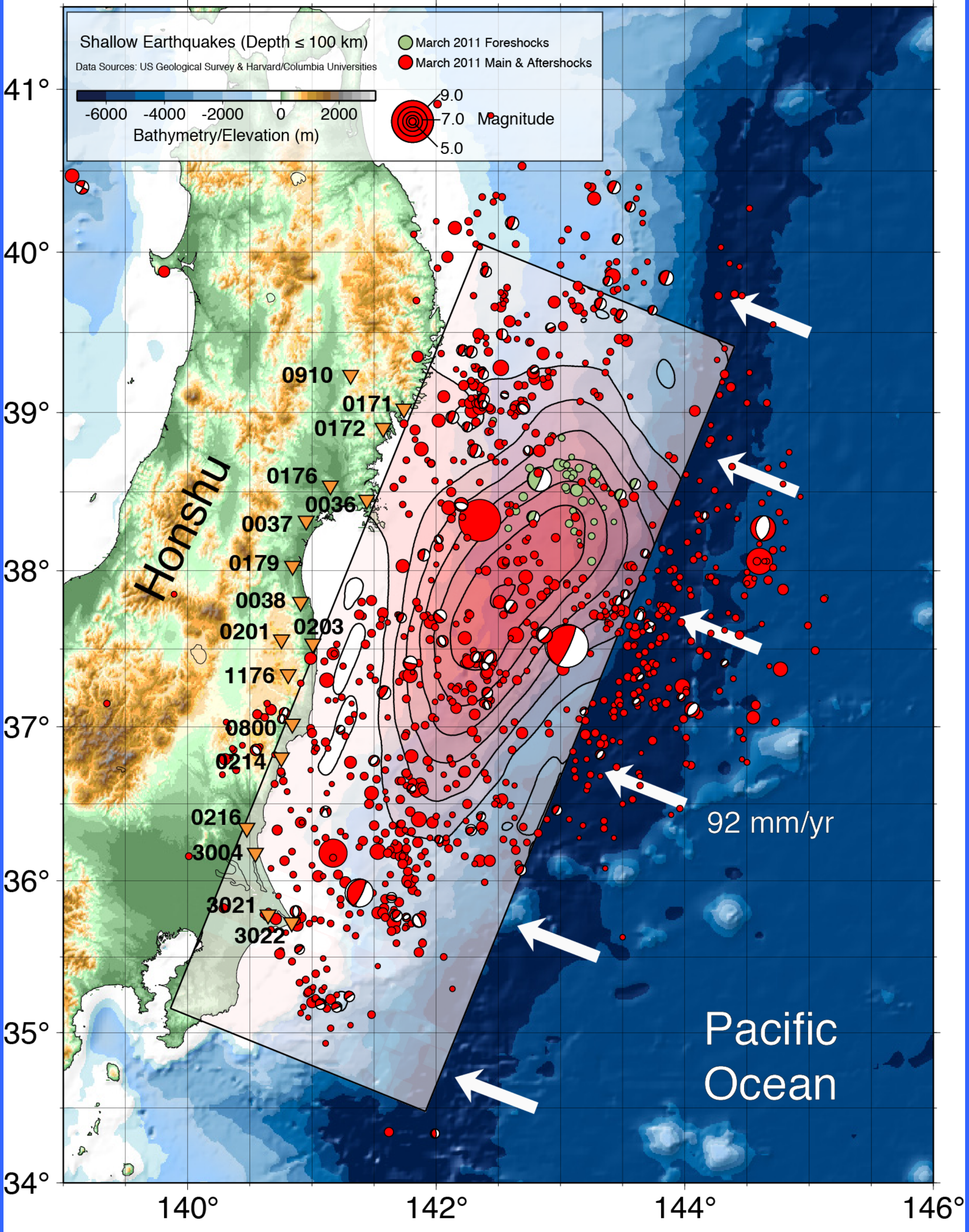
Earthquake cycle on a megathrust



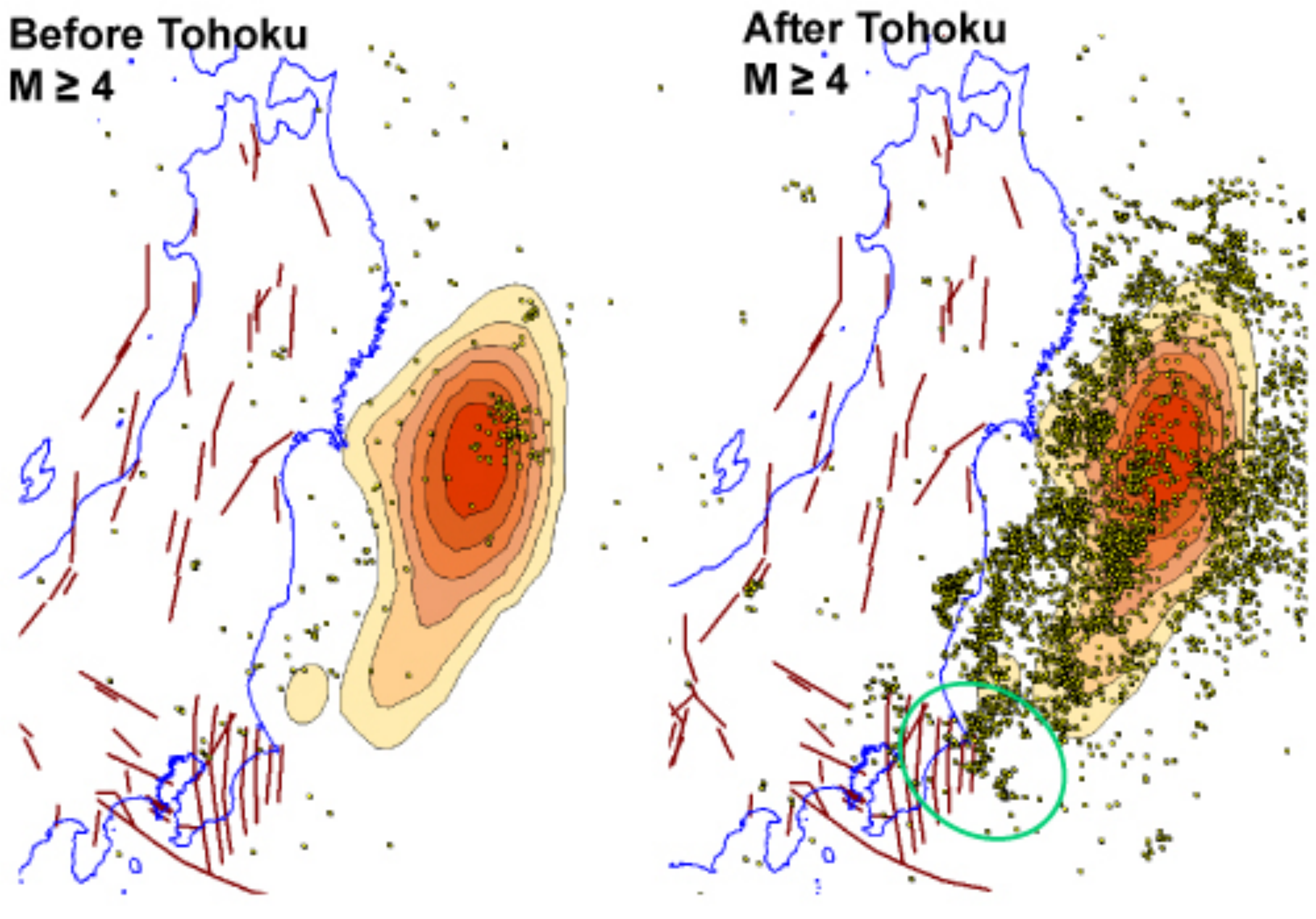
2004 M9 Sumatra Earthquake

2011 M9 Tohoku Japan Earthquake

2011 M9 Tohoku Japan Earthquake


Shallow Earthquakes (Depth ≤ 100 km)
Data Sources: US Geological Survey & Harvard/Columbia Universities
-6000 -4000 -2000 0 2000
Bathymetry/Elevation (m)
March 2011 Foreshocks
March 2011 Main & Aftershocks
9.0
7.0
5.0
Magnitude
Honshu
0910
0171
0172
0176
0036
0037
0179
0038
0201
0203
1176
0800
0214
0216
3004
3021
3022
92 mm/yr
Pacific Ocean
41°
40°
39°
38°
37°
36°
35°
34°
140°
142°
144°
146°

2011 M9 Tohoku Japan Earthquake



Important Terms

- Outer swell/outer bulge
- Accretionary prism
- Trench axial wedge
- Outer-arc high/fore-arc high
- Fore-arc basin
- Backstop
- Imbricate thrusts
- Off-scraped sediments
- Underthrust sediments
- Decollement
- Underplated sediments

Accreting versus non-accreting (erosional) trenches

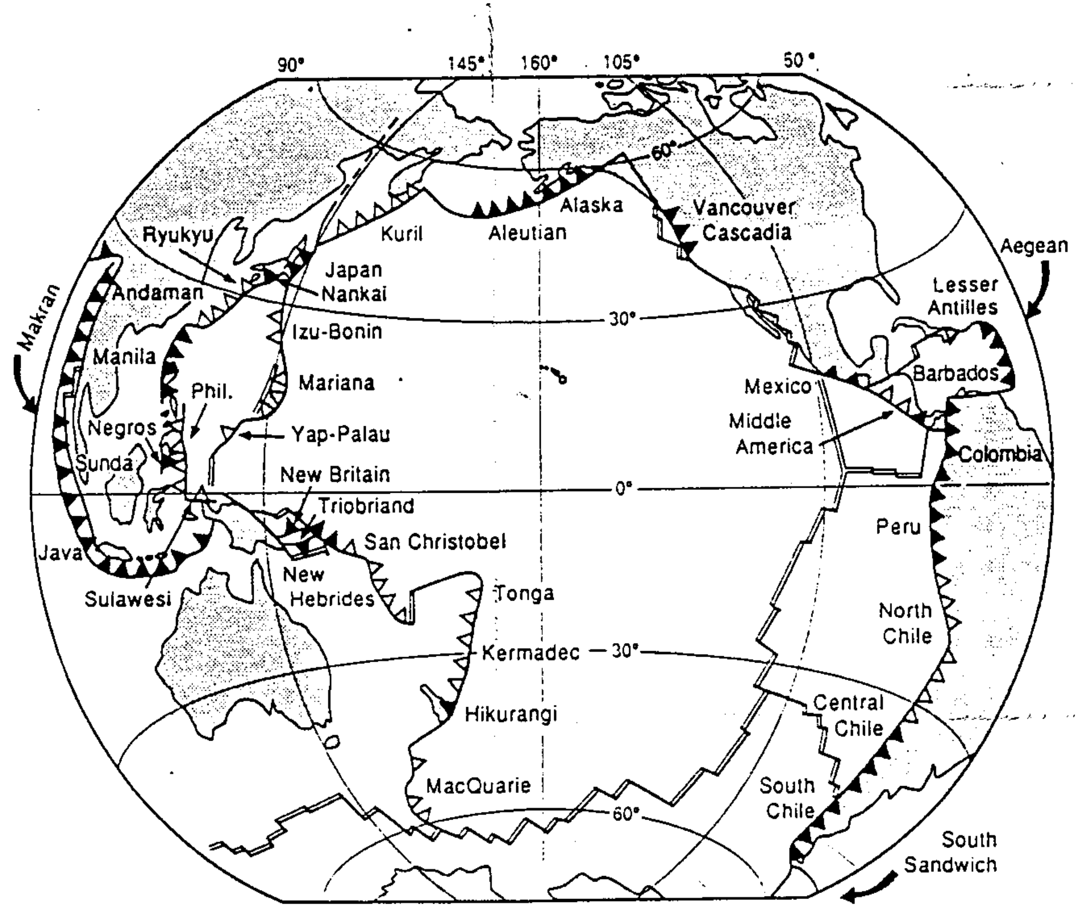


Figure 5. Trenches (barbed lines) and convergent margins of the Pacific, Caribbean, and eastern Indian Ocean regions. Not shown, but indicated, are the short trench systems of the Makran region of the Gulf of Oman, northwestern Indian Ocean, the South Sandwich Trench connecting South America and Antarctica, and the Aegean region of the Mediterranean. Filled barbs are type 1 or accreting trenches, open barbs are type 2 trenches at which effectively no accretionary prism forms (see Table 2).

Von Huene and Scholl (1991)