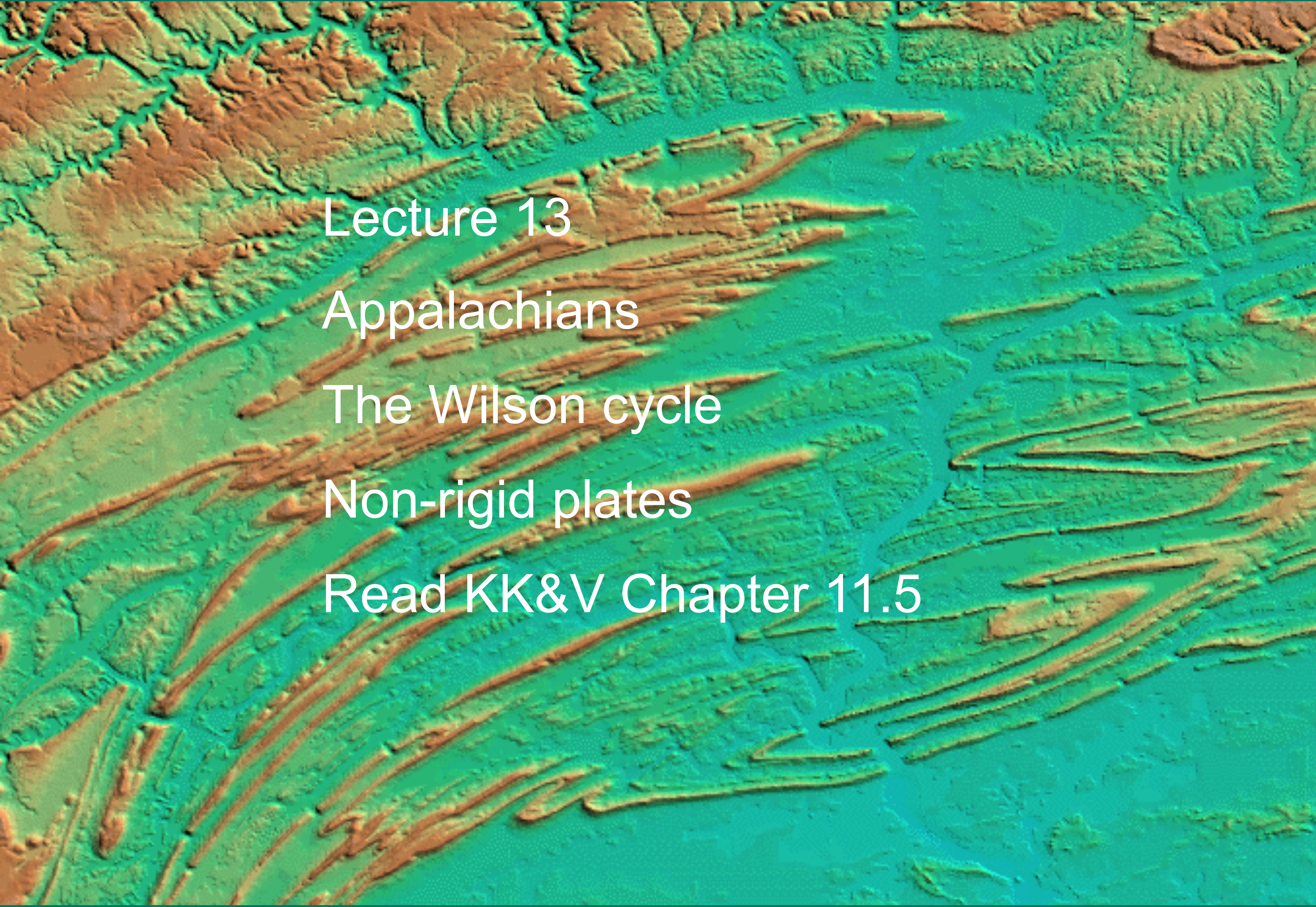


Lecture 13

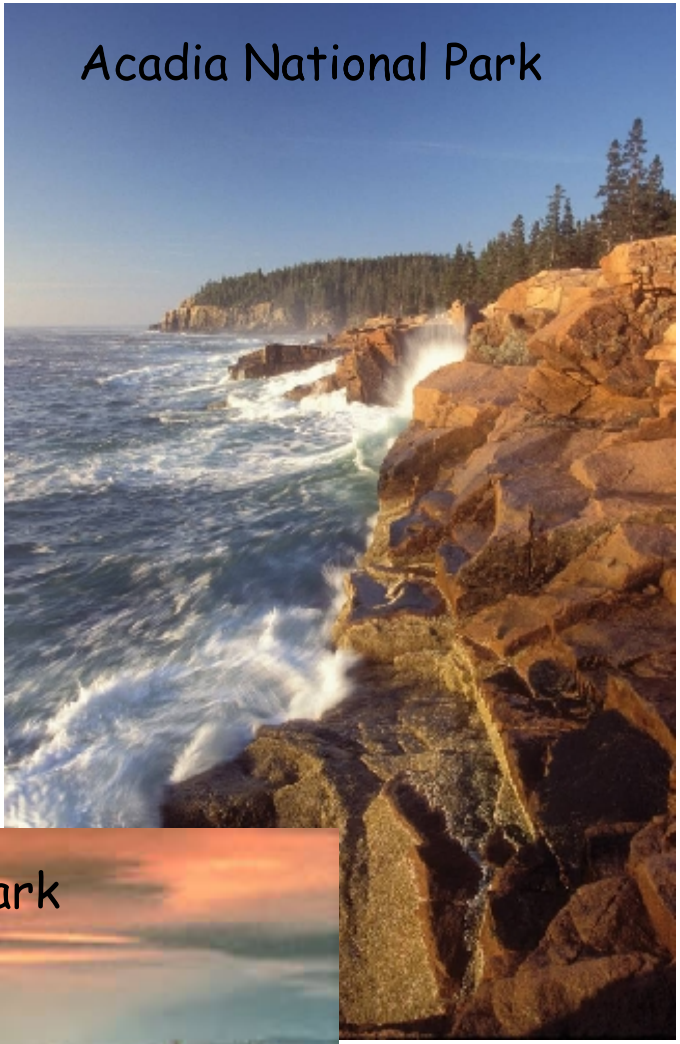
Appalachians

The Wilson cycle

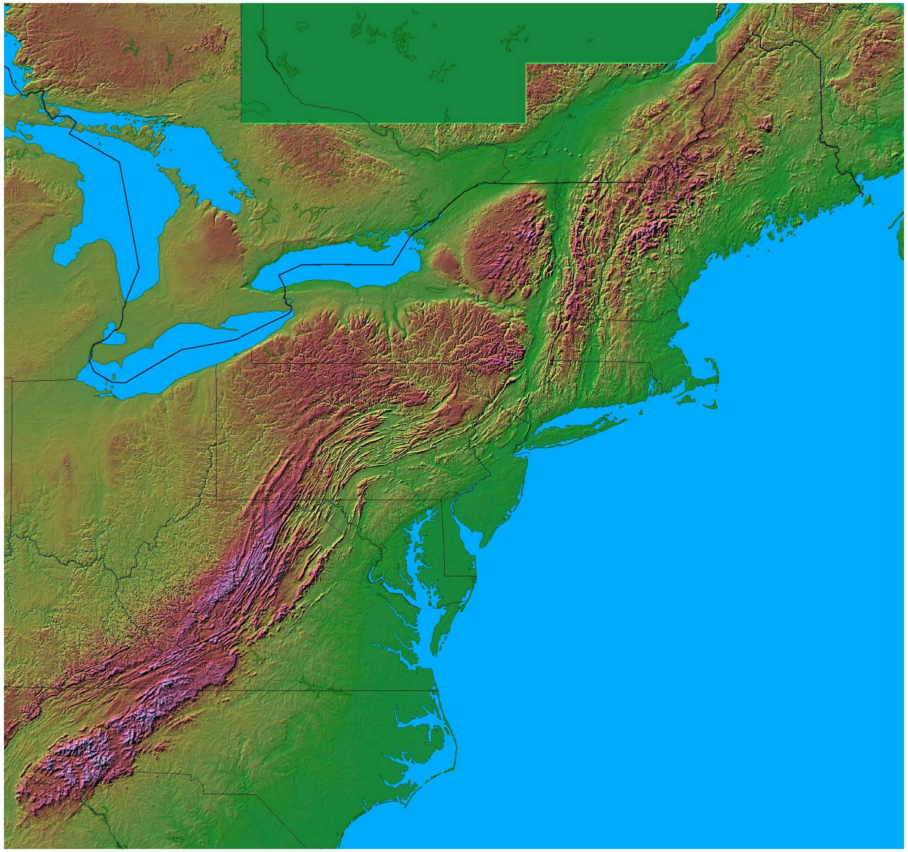
Non-rigid plates

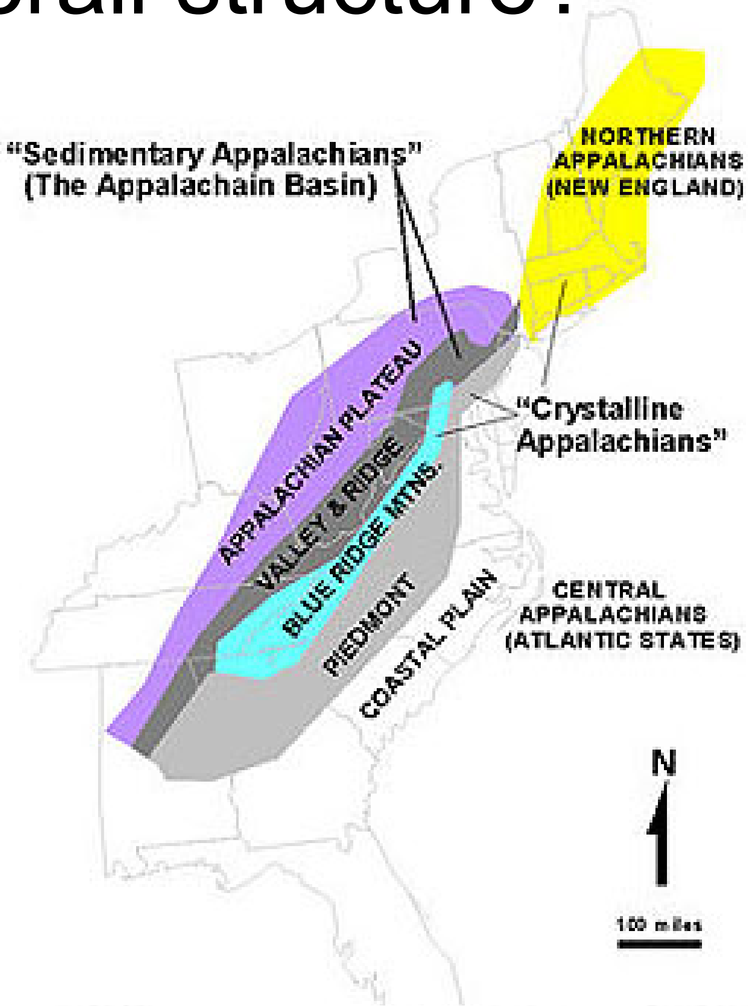
Read KK&V Chapter 11.5

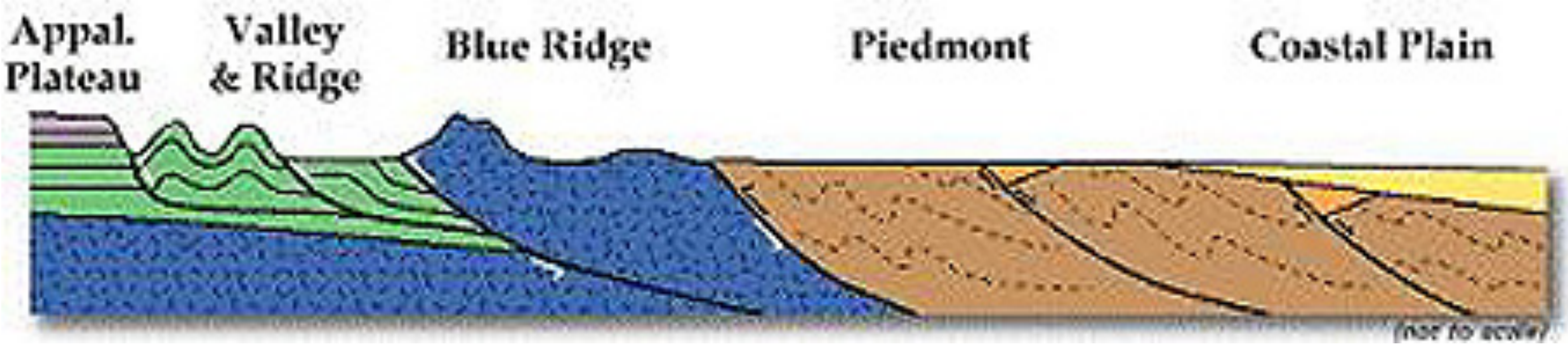
The Appalachian Mountain Belt



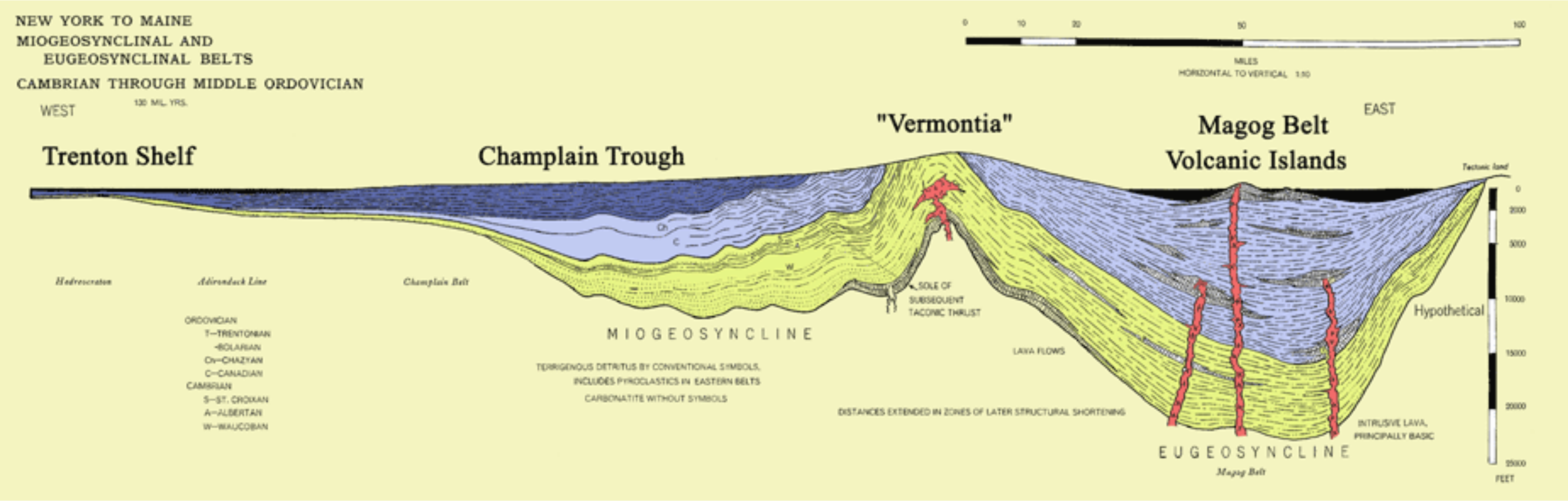
What is the overall structure?







Pre-plate tectonics interpretation



Geosynclinal theory (KK&V Chapter 1.3)

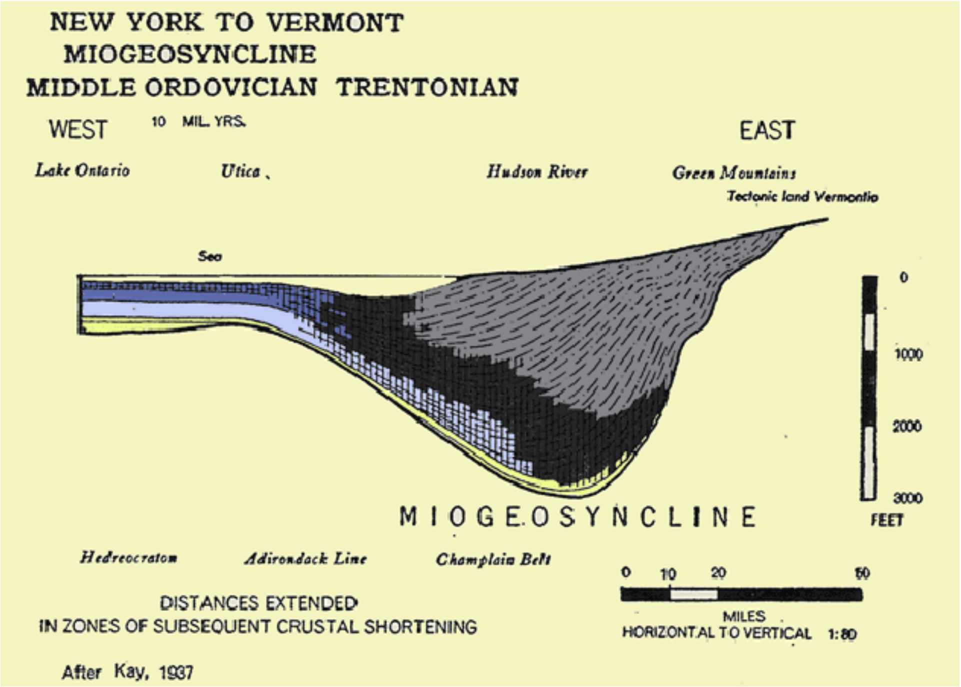
Geologists envisioned elongate, geographically fixed belts of thick sediments which were precursors to mountain belts

Folding and uplift led to mountains

Synclines and anticlines on a giant scale

Miogeosyncline = passive margin sediments
Eugeosynclines = volcanic margin sediments

Marshall Kay (1930's)

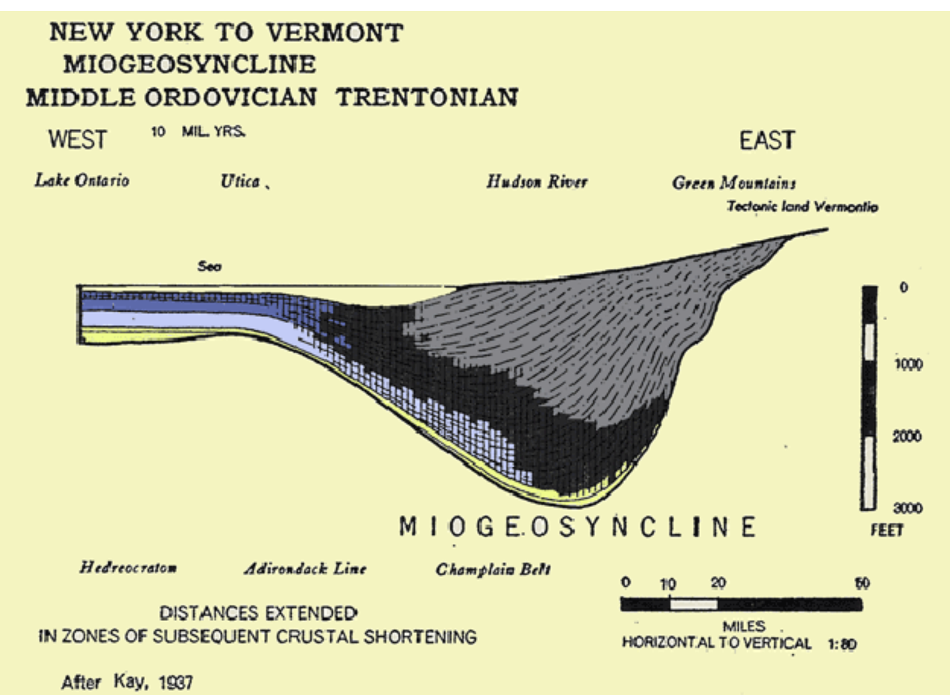


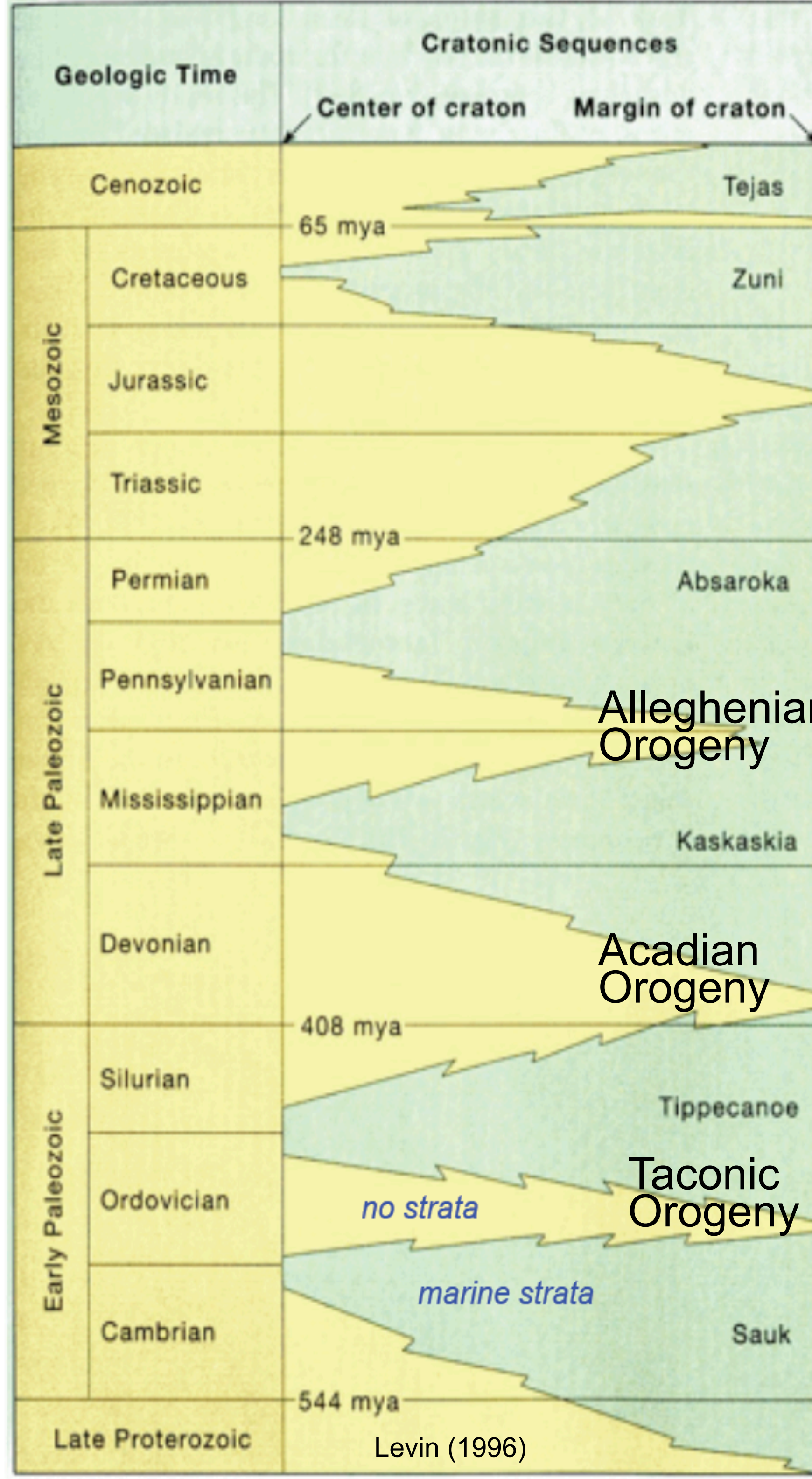
Cratonic Sedimentary Sequences in North America

Thick sequences of (preserved) passive margin sediments with periods of missing sediments

Periods of missing sediments (yellow)correspond to collisions/orogenies

First sediments to be deposited after a hiatus were huge thicknesses of clastics (clastic wedges)





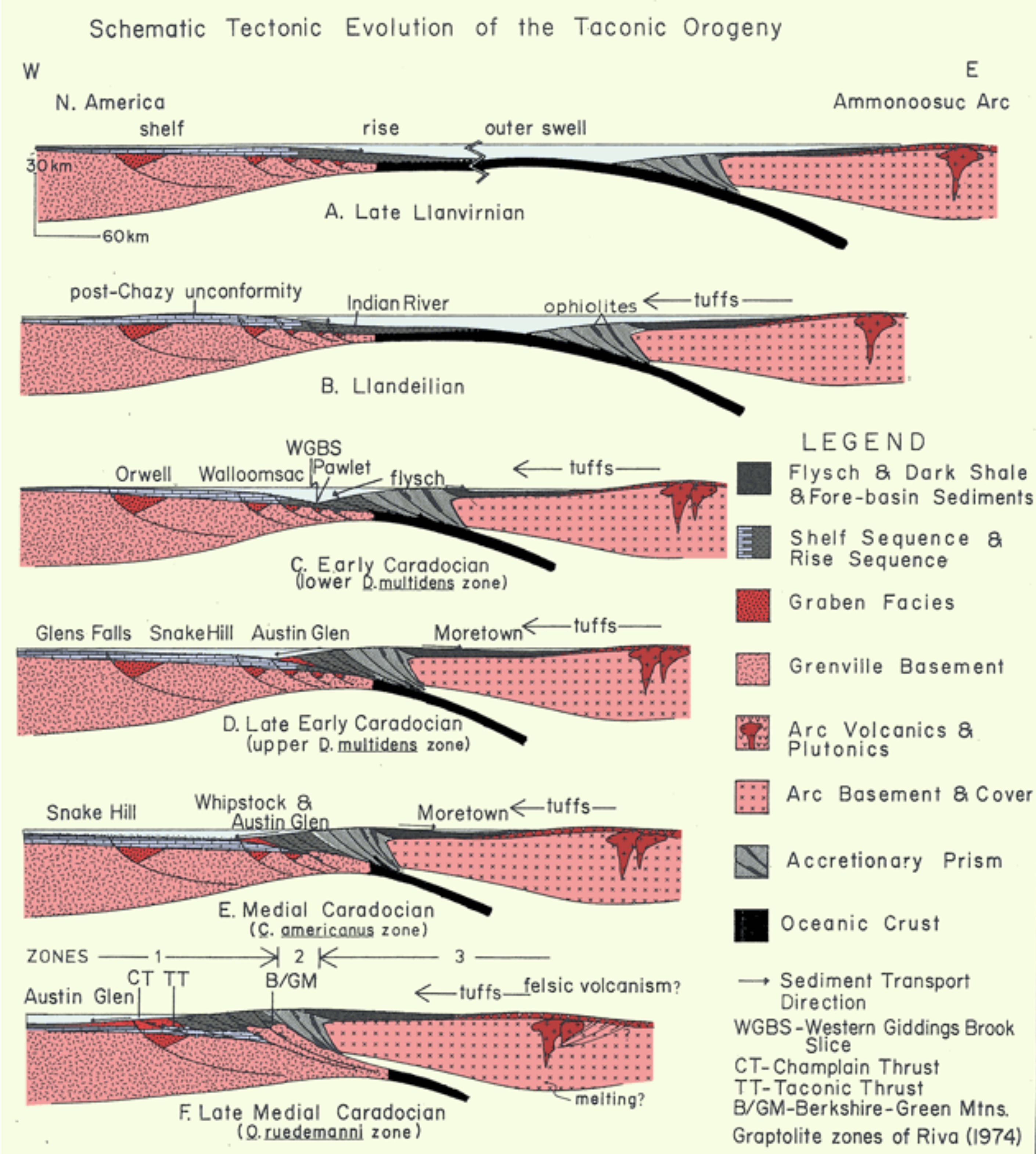


Plate tectonics provided the mechanism

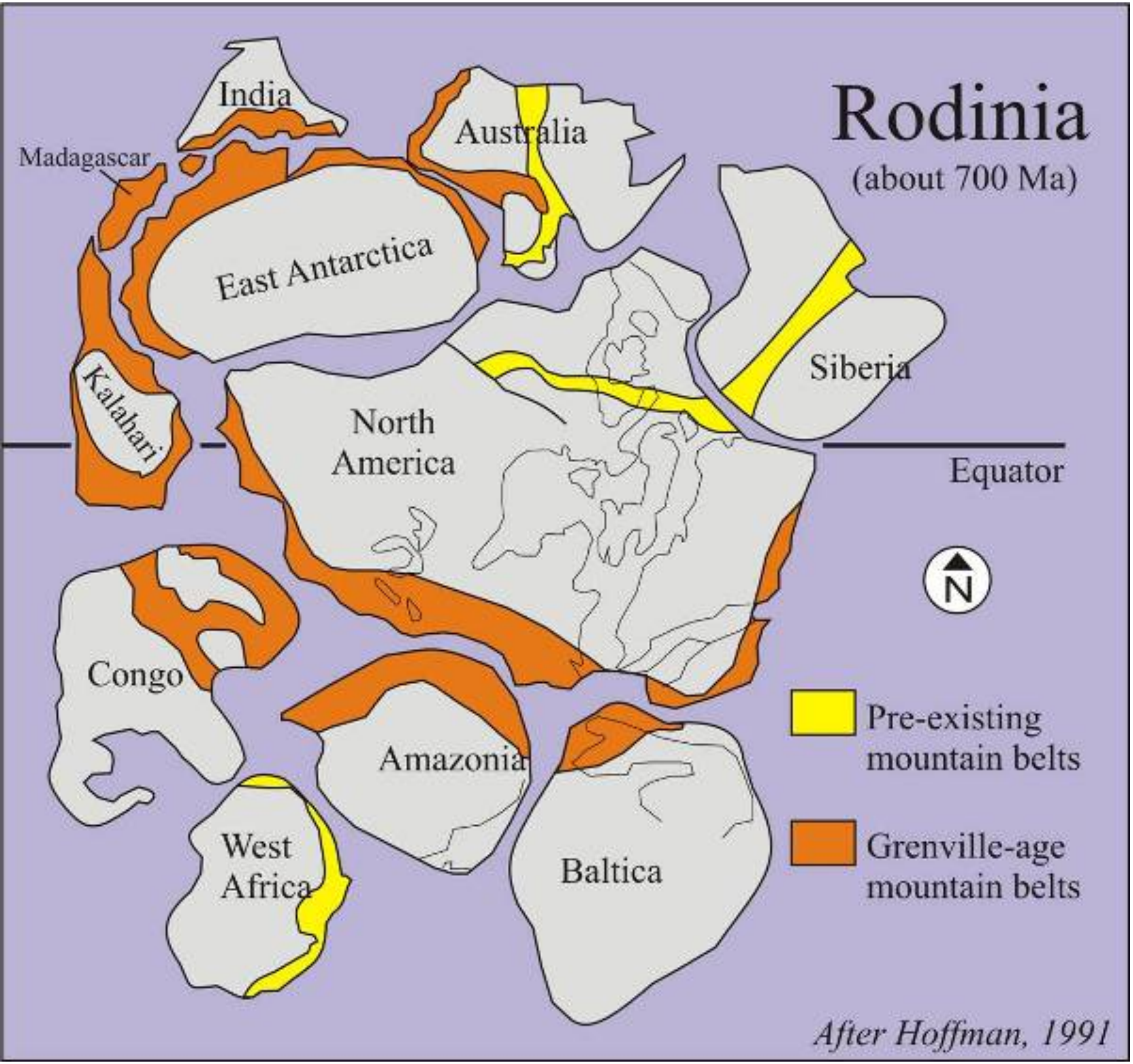
Similar to collision of India and Asia in the Cenozoic:
A continental passive margin collides with a trench

Hiatuses correspond to collisions with arcs, terrains, and continents

Clastic wedges are from erosion of mountain belts following collisions

Rowley and Kidd, 1981

Rodinia



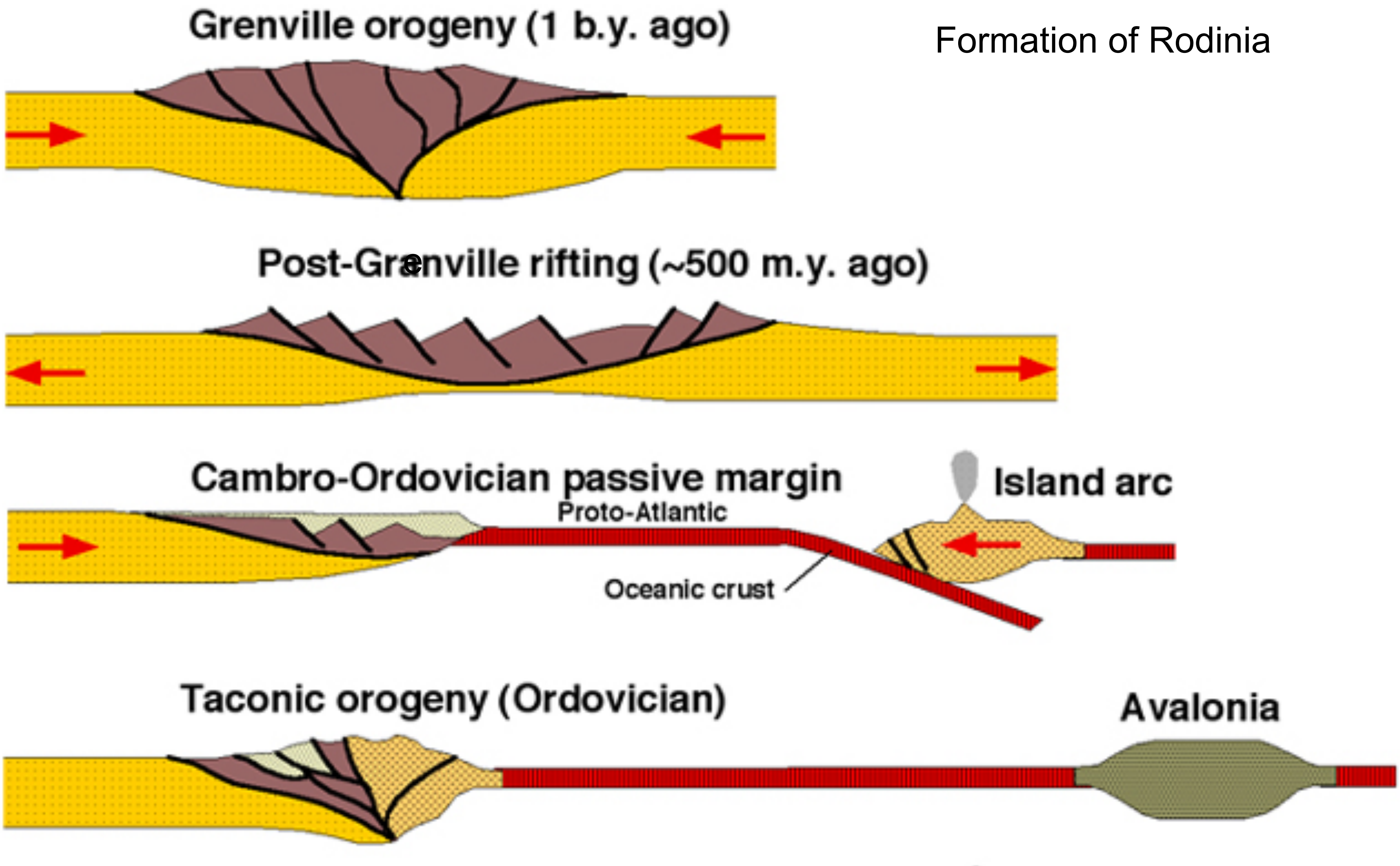
Another important concept: Pangaea was not the only supercontinent. In fact, there have been many. The most recent (prior to Pangaea) was Rodinia around 700 Ma.

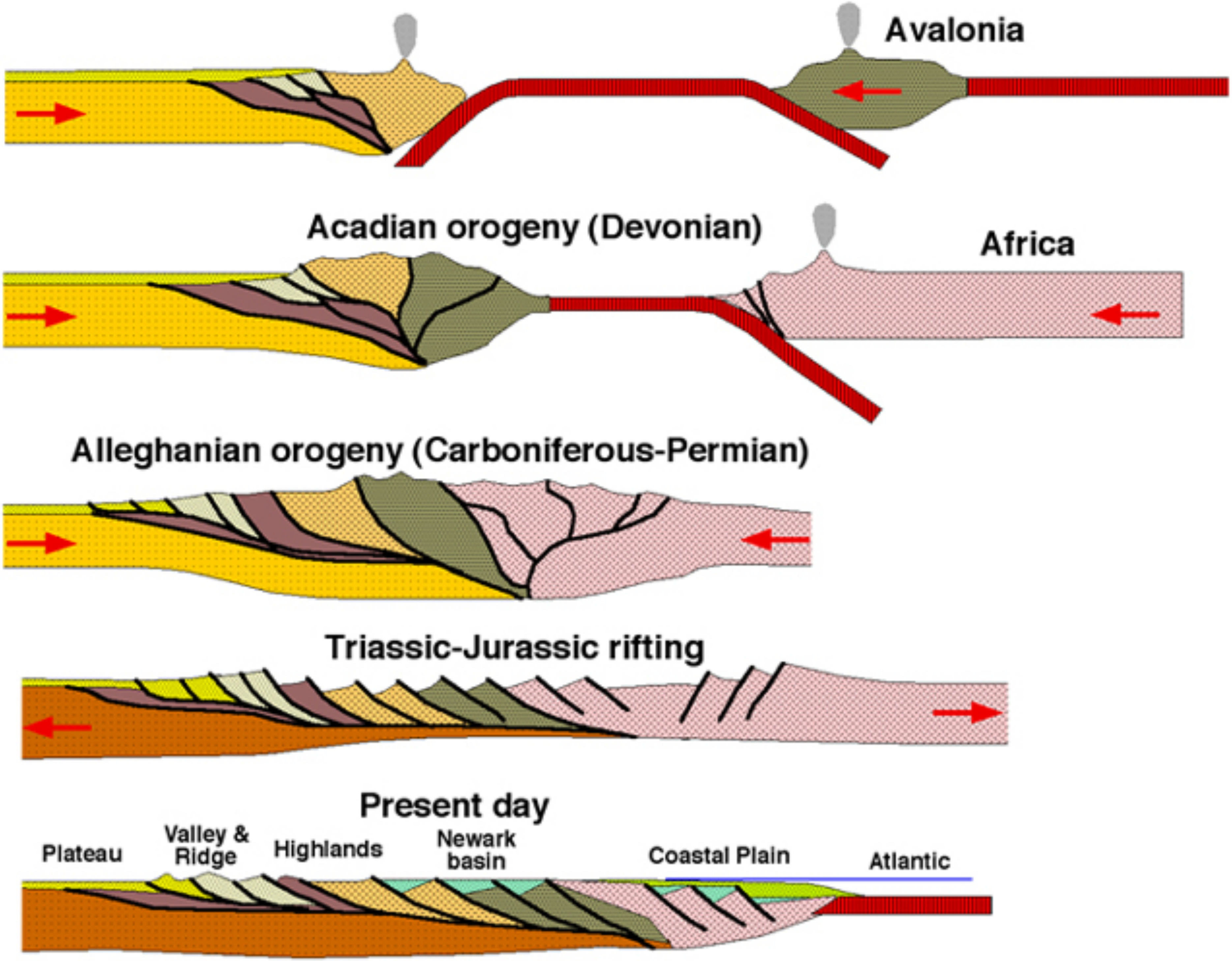
It formed when many large continental pieces coalesced during the time of the Grenville orogeny

This led J. Tuzo Wilson to propose a regular cycle of opening and closing of oceans …

Wilson Cycle

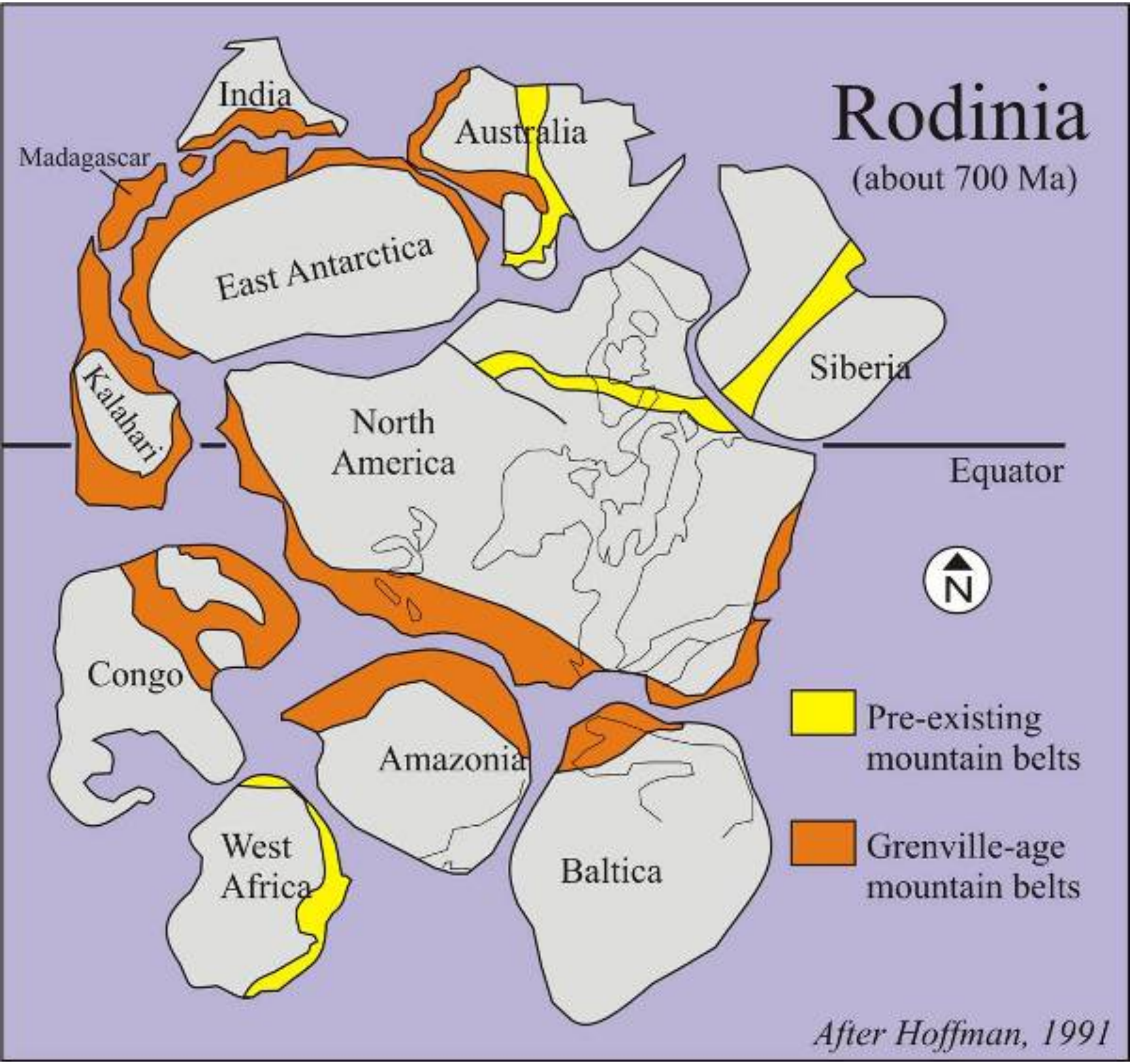
Formation of Rodinia





Avalonia
Acadian orogeny (Devonian)
Africa
Alleghanian orogeny (Carboniferous-Permian)
Triassic-Jurassic rifting
Present day
Plateau
Valley & Ridge
Highlands
Newark basin
Coastal Plain
Atlantic

Rodinia



Tectonic background

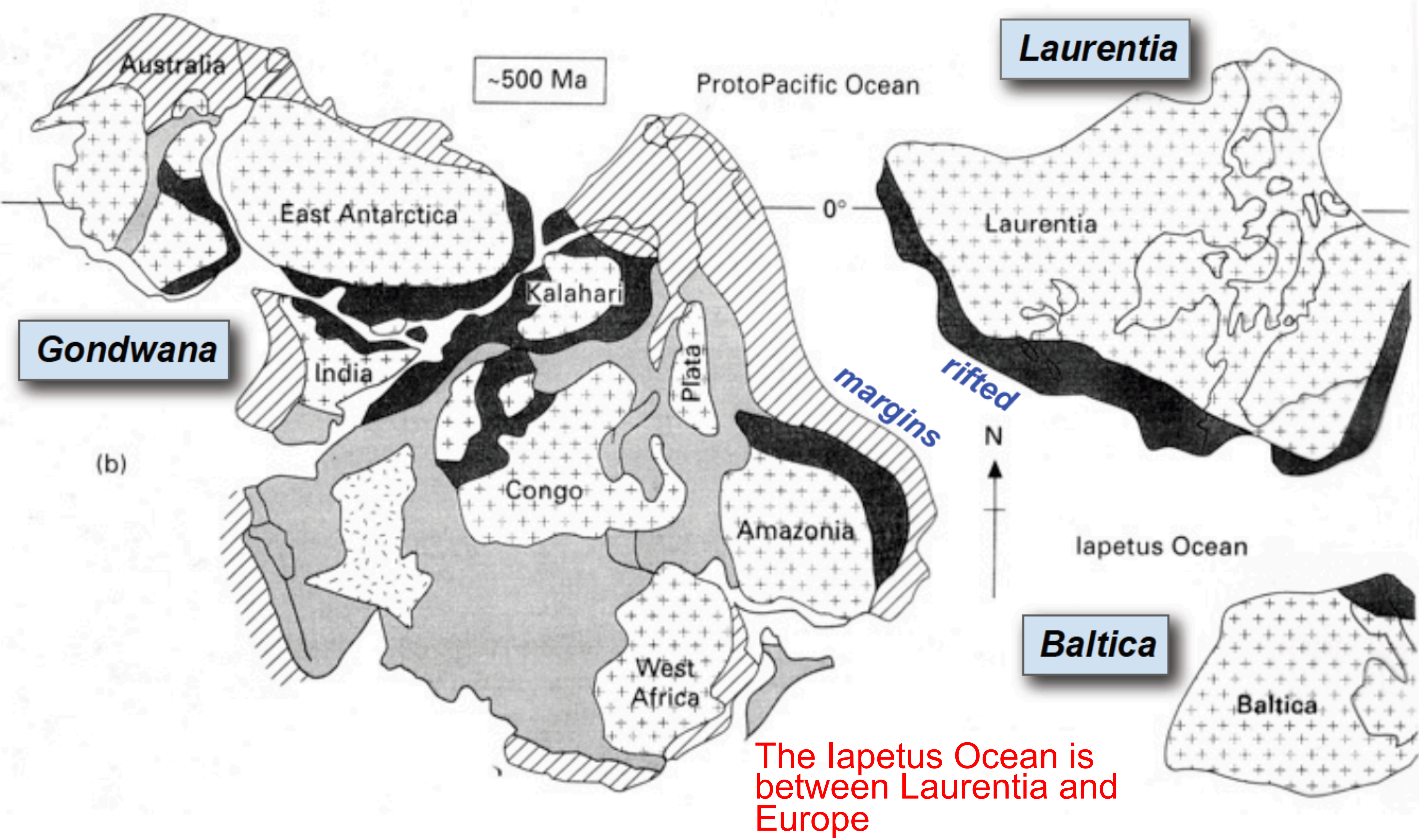
The Grenville orogeny in eastern Laurentia (ancestral North America) about 1 b.y. ago resulted from assembly of the supercontinent Rodinia which contained ancestral cores of today's continents.

Note East Antarctica and Australia are joined to the western North America

SWEAT hypothesis (SouthWest US and East AnT)

Rodinia Breakup

Rodinia separated into several major continents including ***Gondwana***, ***Laurentia*** (second incarnation), and ***Baltica*** (northwestern Europe)



Keary & Vine, 1996

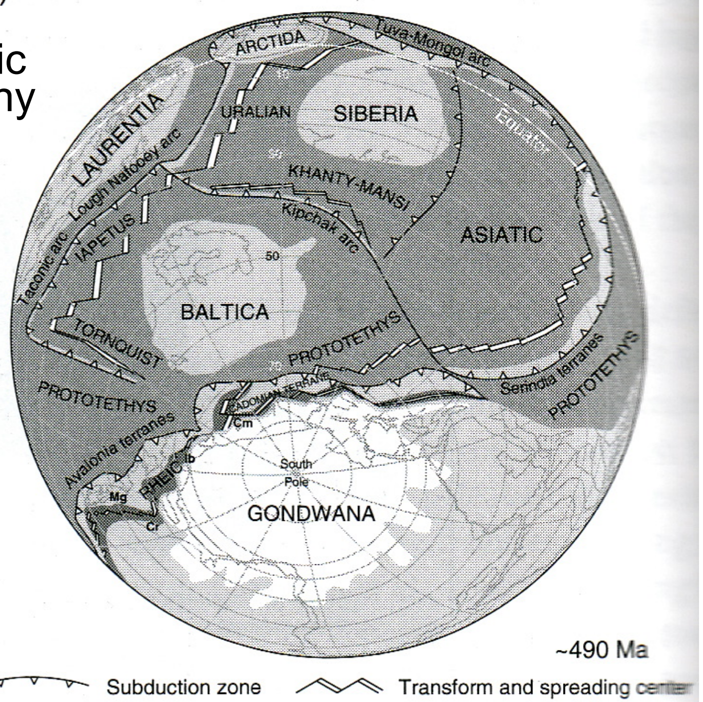
Between 480 and 420, one or more arcs, a large “terrain” (Avalonia) and a chunk of Europe (Baltica) collide with Laurentia. Iapetus closes.

The Rheic Ocean lies between Laurentia and Africa (Gondwana)

These various collisions formed the Appalachian Mountains

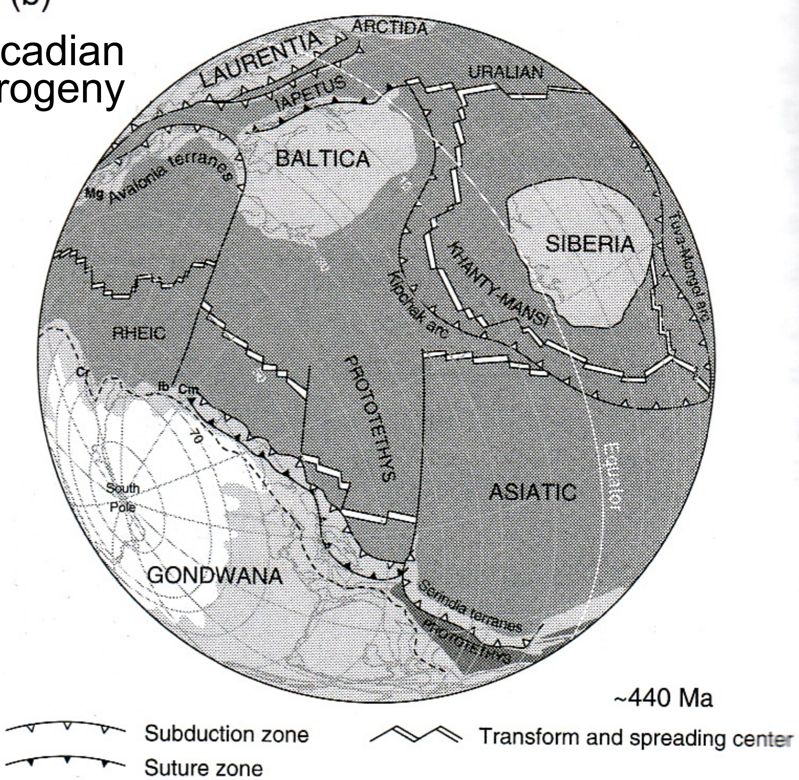
(a)

Taconic orogeny

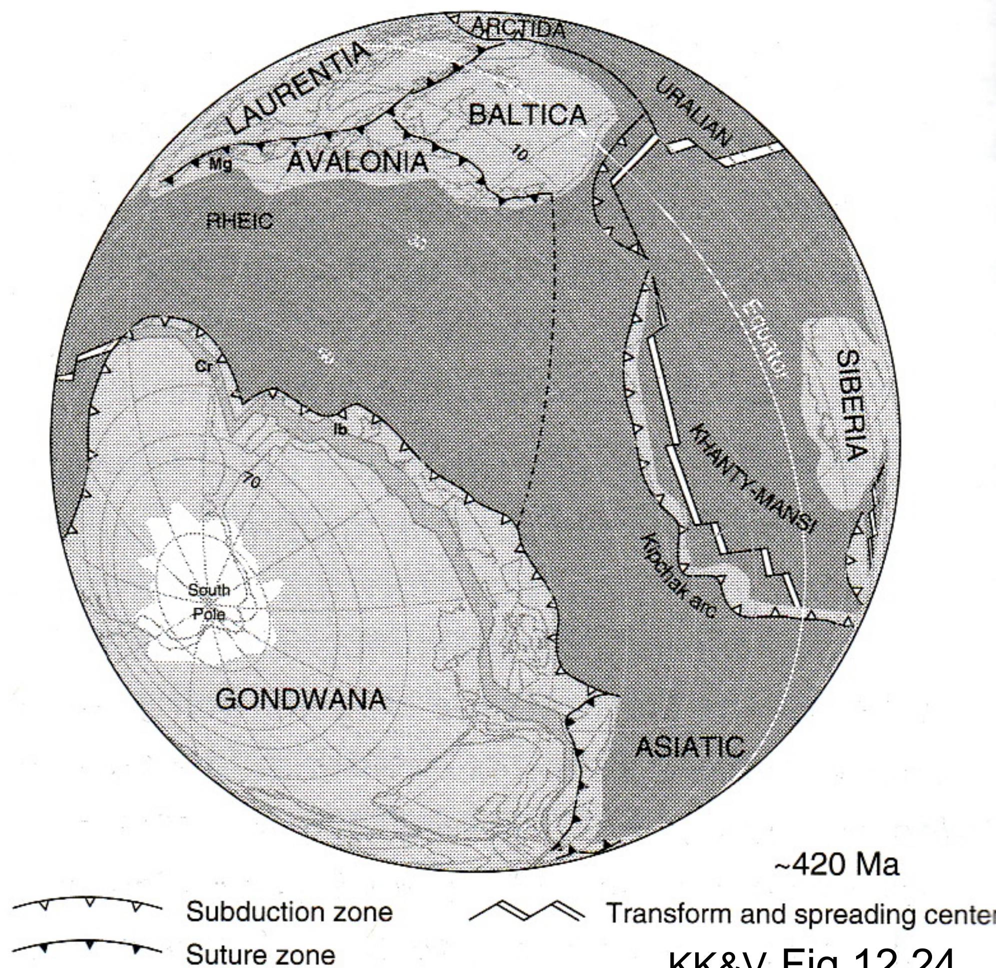


(b)

Acadian orogeny



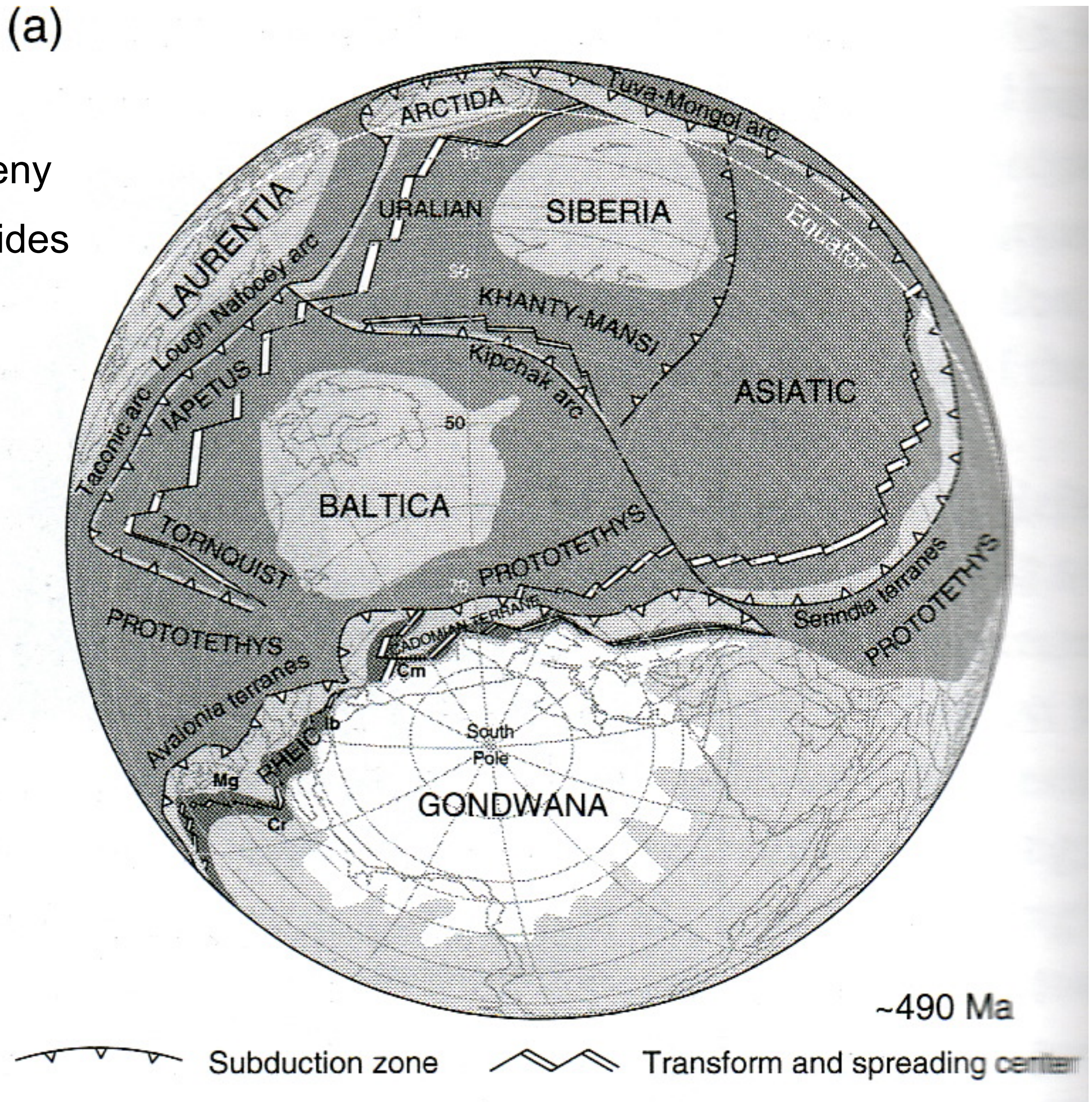
(c)



KK&V Fig 12.24

Taconic Orogeny

Island arc collides with Laurentia



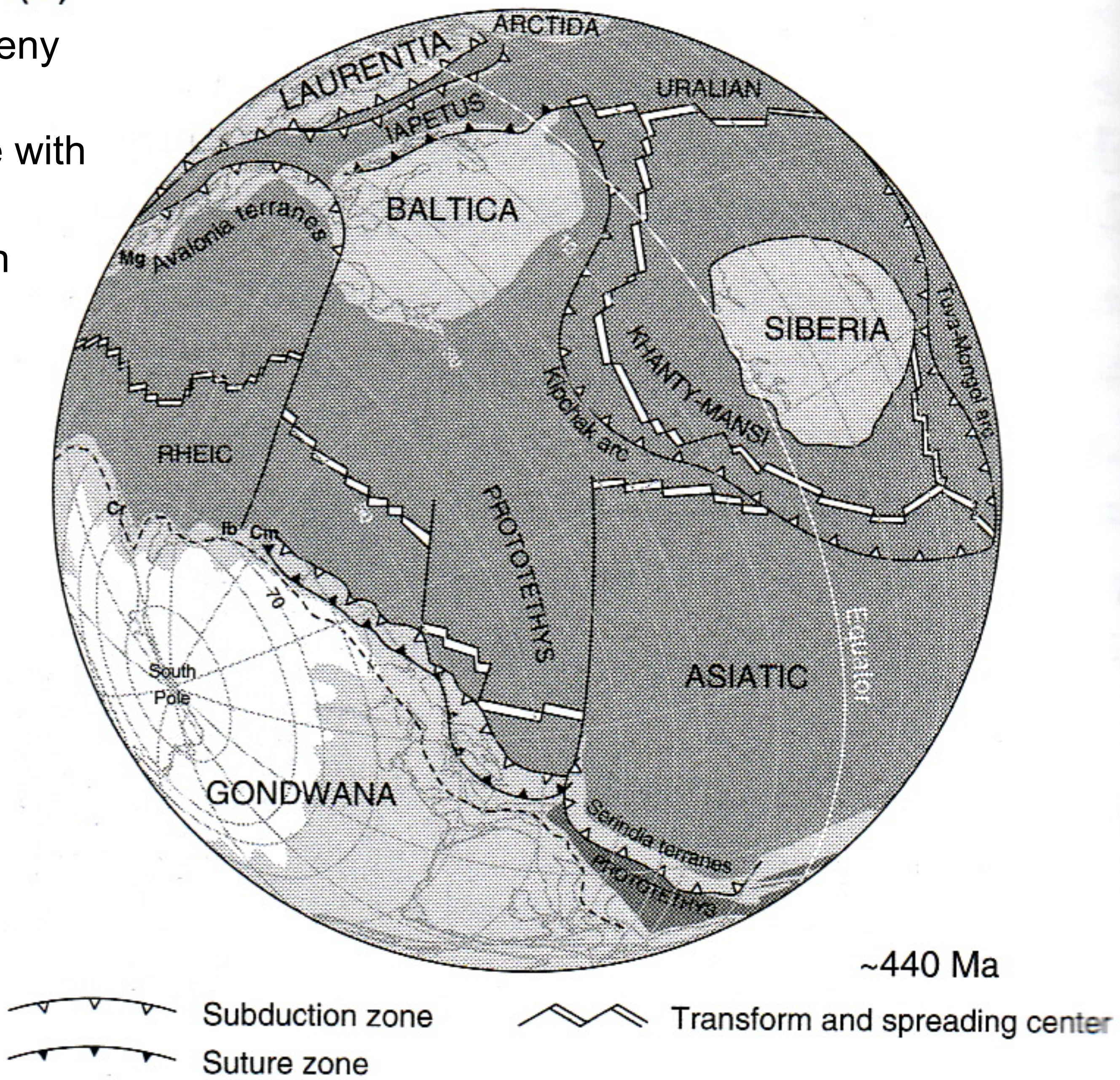
KK&V Fig 12.24

Acadian Orogeny

Avalonia and Baltica coillide with Laurentia

Iapetus Ocean closes

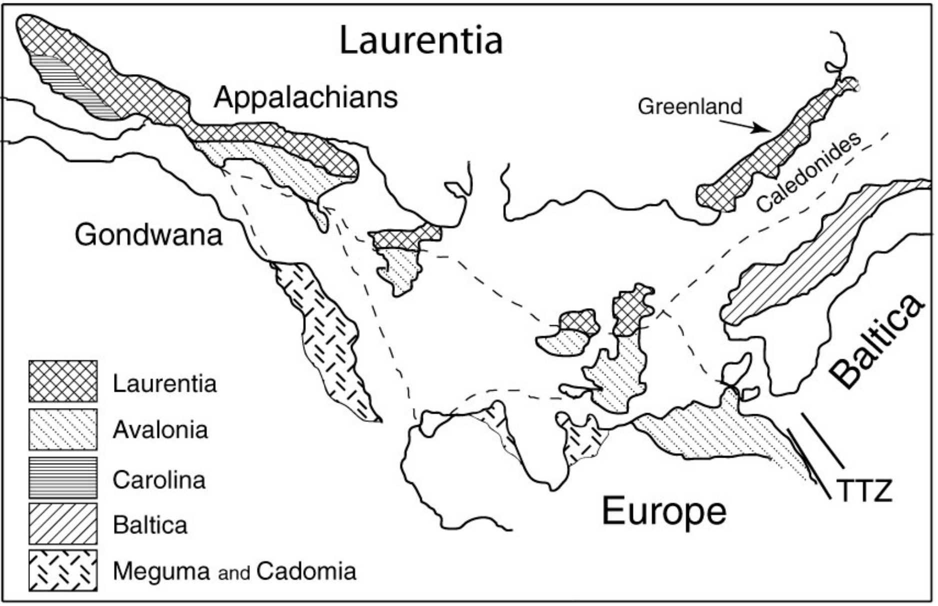
(b)

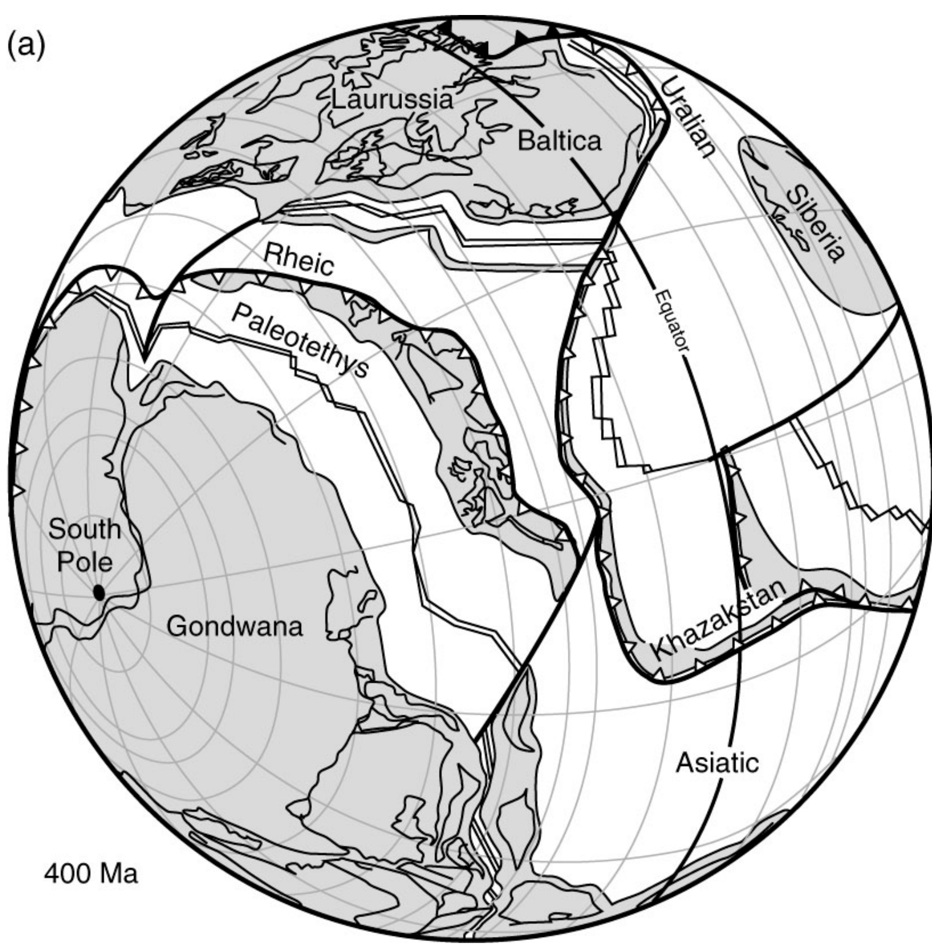


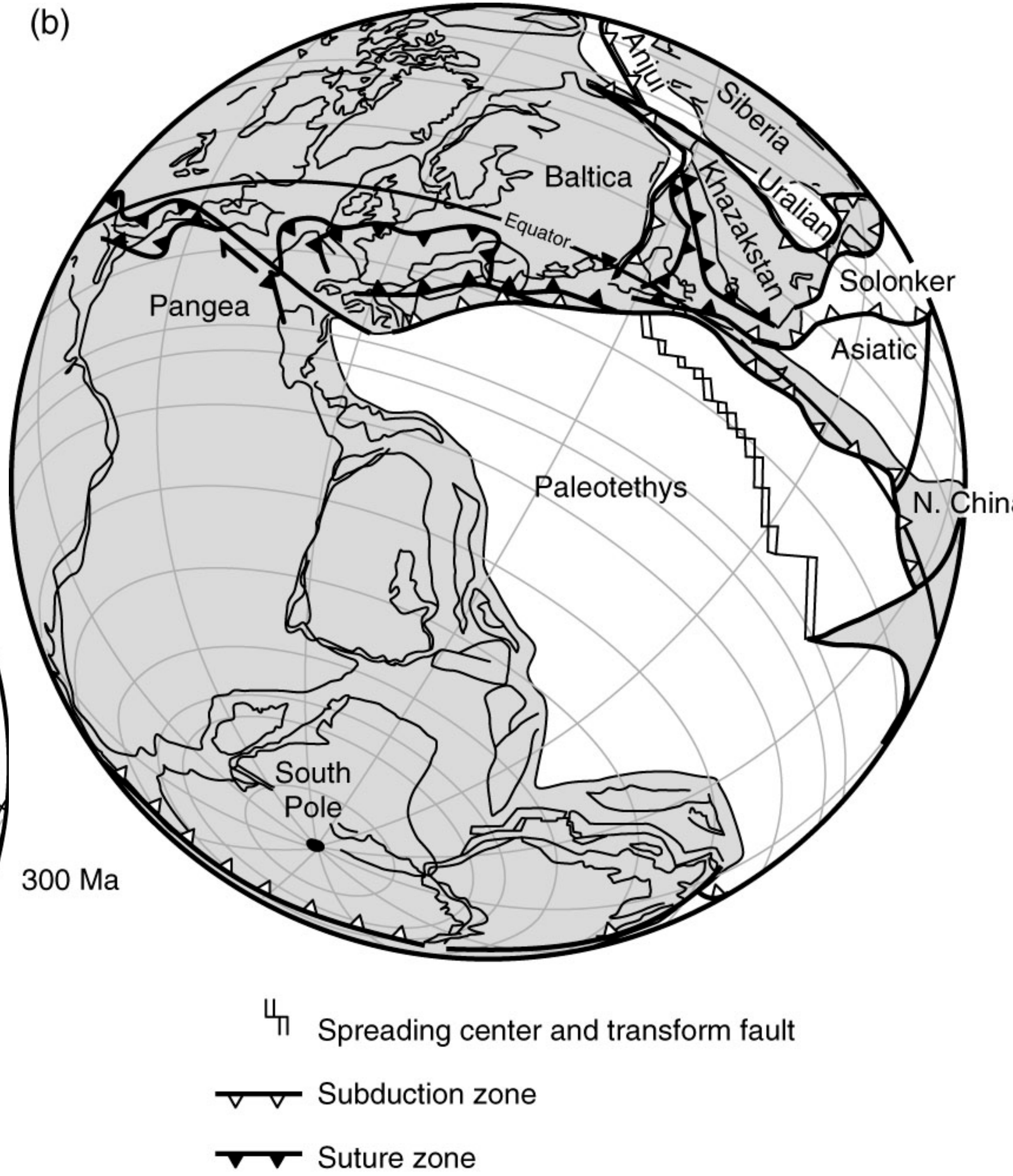
KK&V Fig 12.24

Alleghenian Orogeny:
Africa collides with
Laurentia

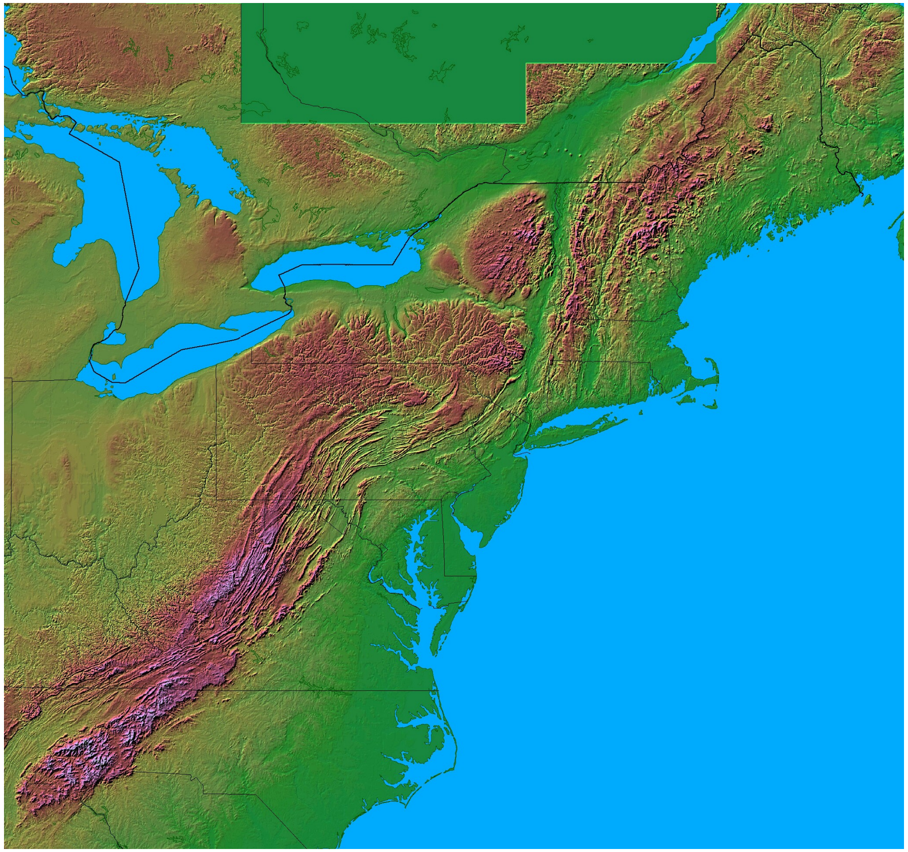
And by 300
Ma you have
Pangea

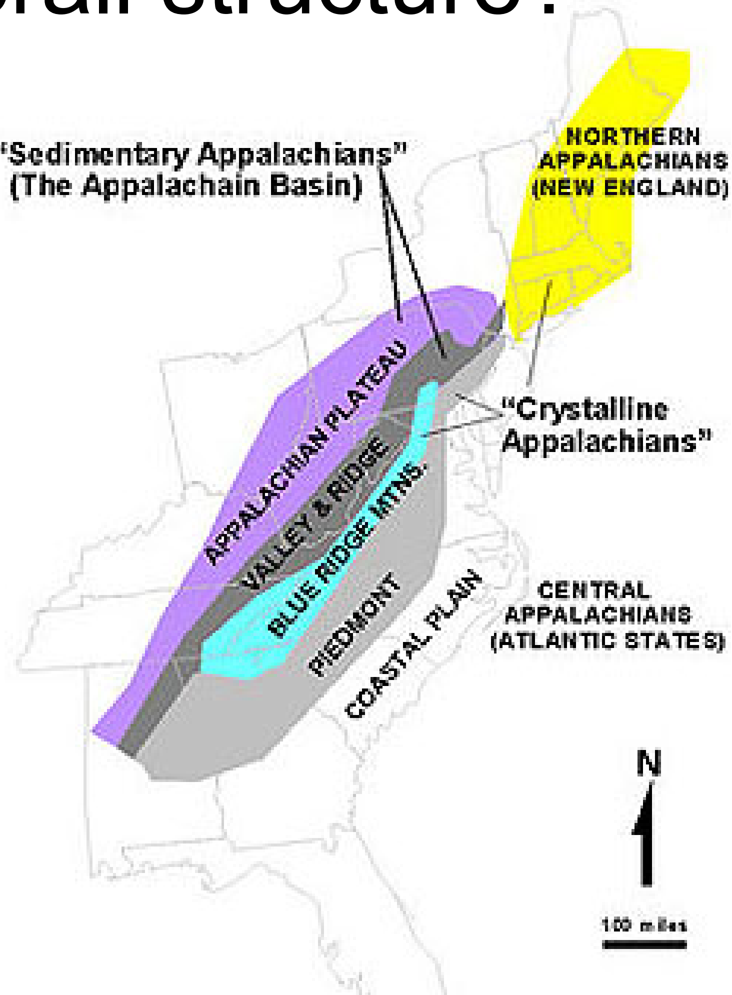


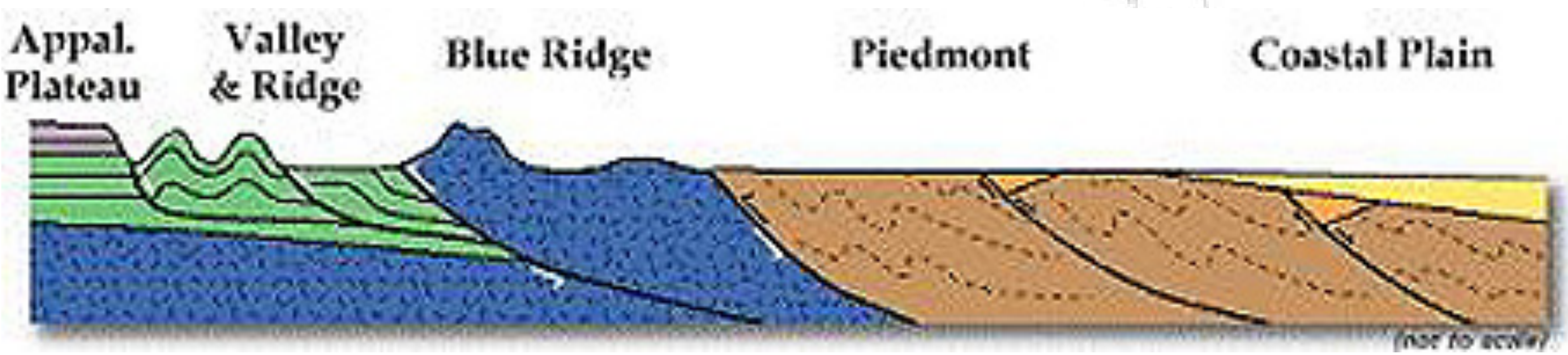




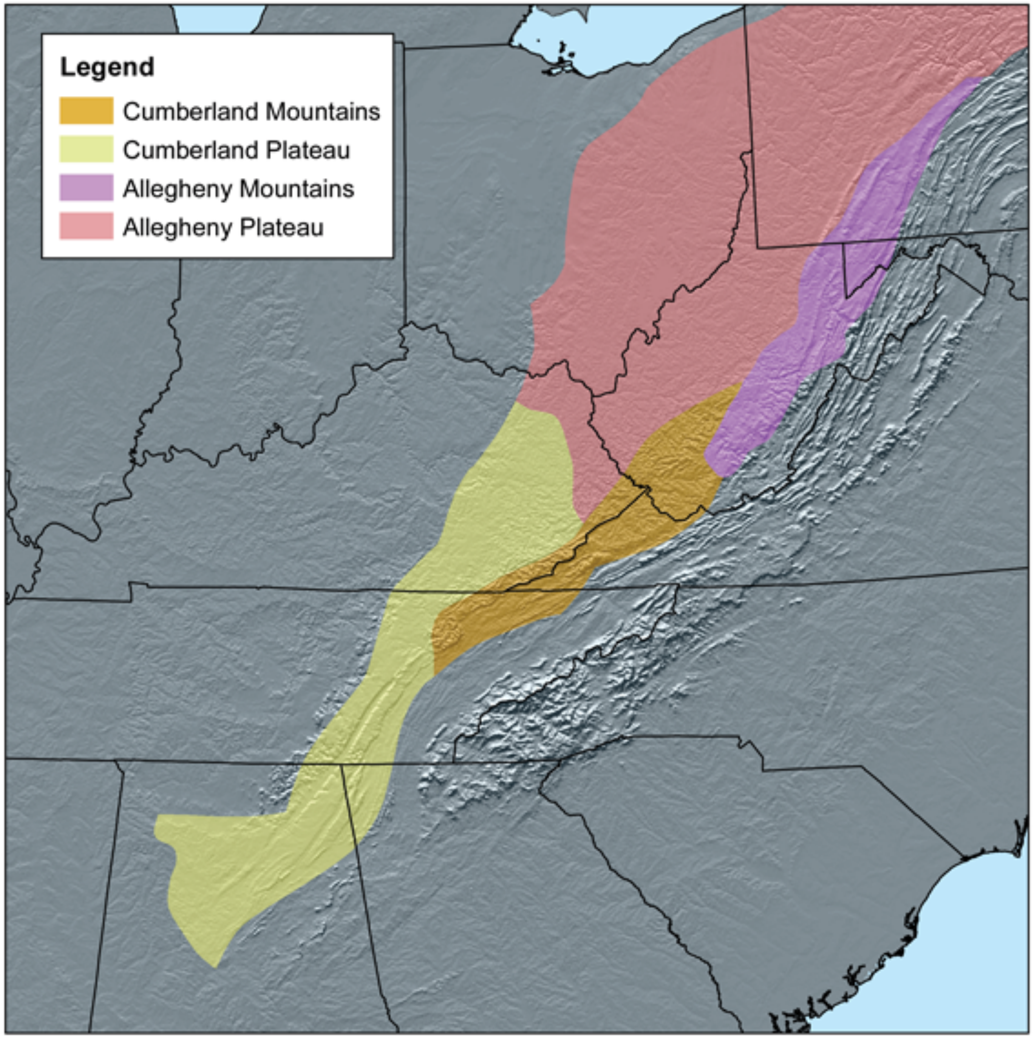
What is the overall structure?





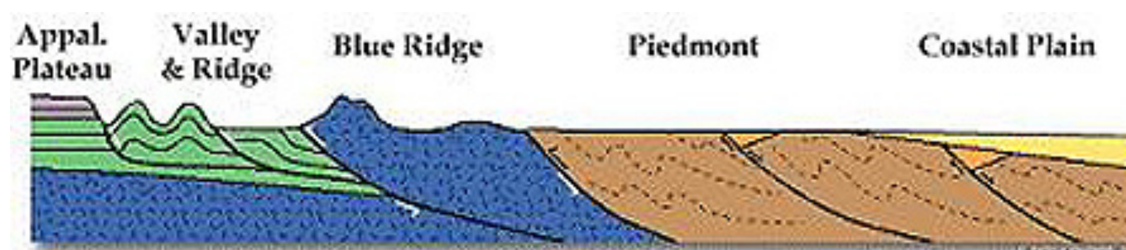


The Appalachian Plateaus

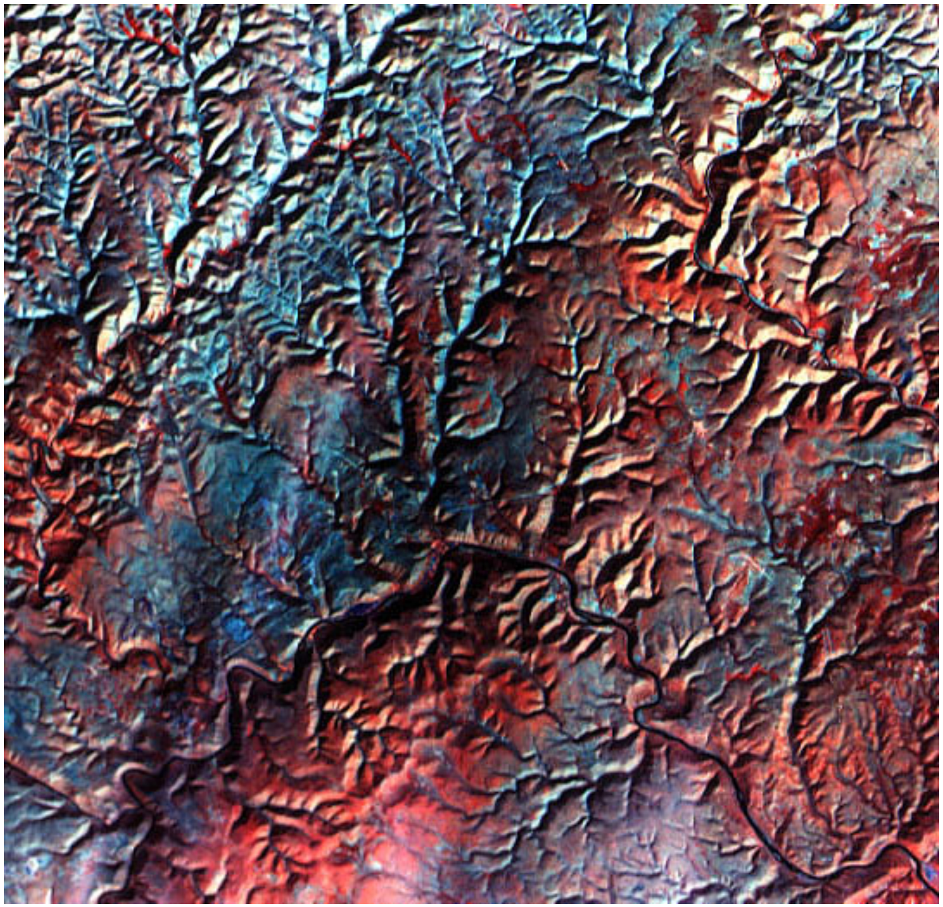


From commons/wikimedia.org

- Mainly flat lying sediments
  - Gently deformed into a broad syncline about 220 miles wide
  - Middle to late Paleozoic sediments (sandstone, shales, coal, limestones)
  - Some clastic deposits derived from mountains to the east
    How can we tell the direction to the mountains?

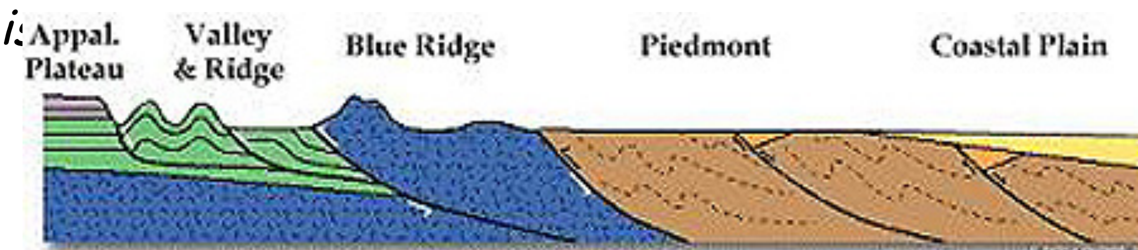


The Appalachian Plateaus

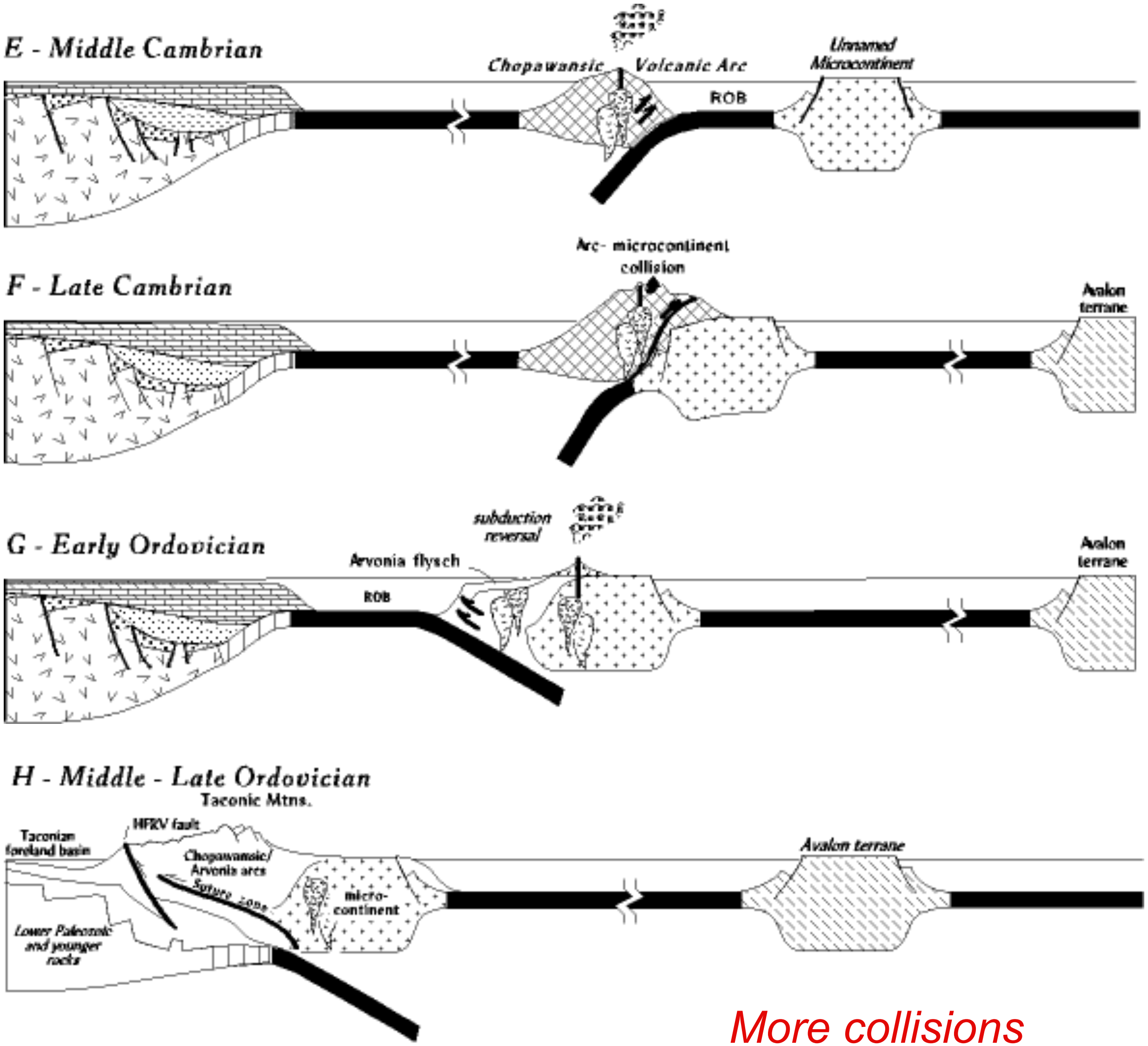


Landsat image (from NASA) of plateau in Pennsylvania. Note the pattern of rivers here. How does this indicate that the rocks are horizontal?

Typical limestone exposures in New York (photo by J.S. Abers)



The Ordovician Taconic Orogeny



The changes in the Ordovician limestones on the passive margin reflect an approaching volcanic arc.

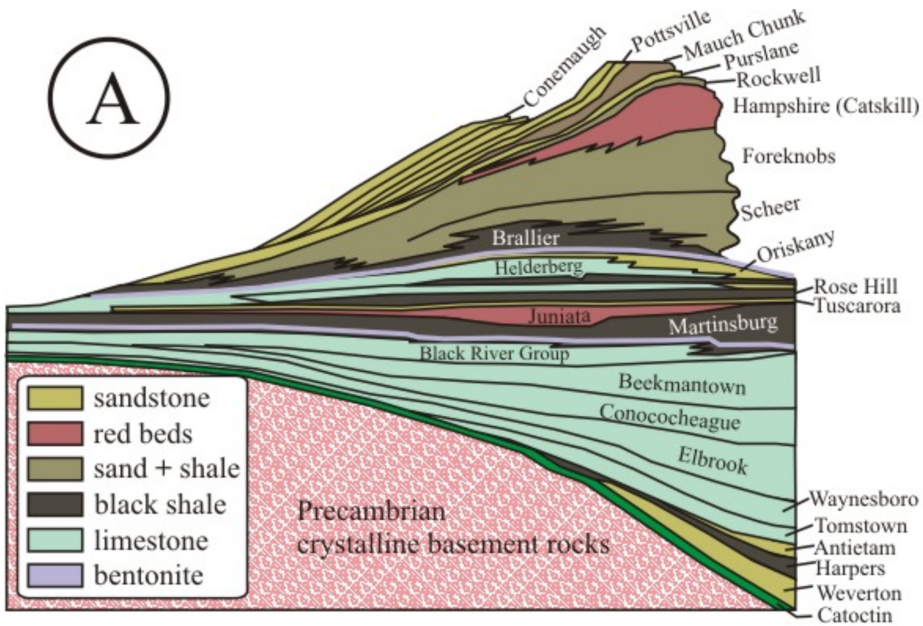
This explains the present juxtaposition of carbonates and volcanic rocks of the same age.

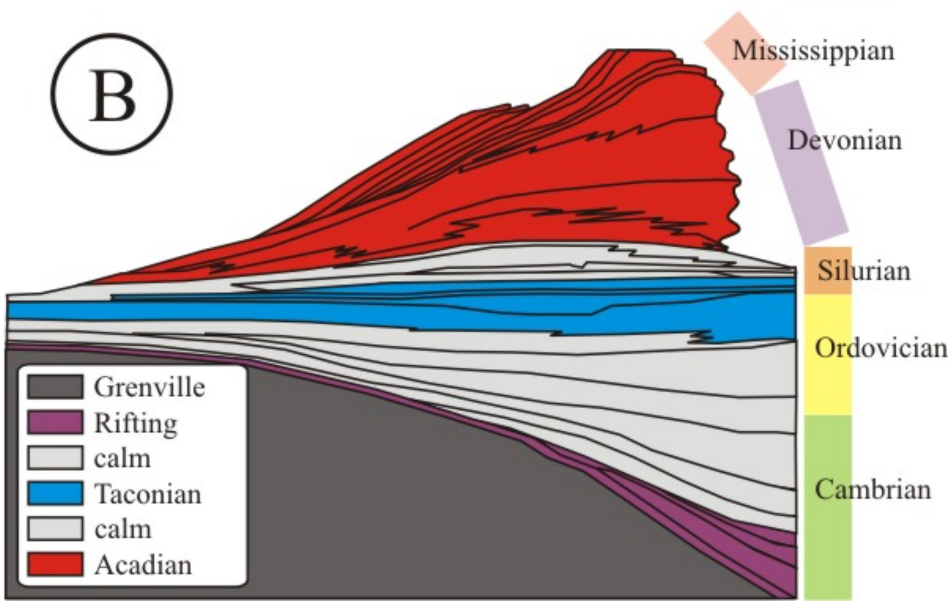
The volcanic arc is an example of an exotic terrane - rocks of very different origin that are tectonically transported and collide with the continent.

More collisions on the horizon

Images: http://cmres.jmu.edu

What is the signature of a collision?





The collision of the Taconic terrane in the Ordovician is only one of three collisions along the east coast in the Paleozoic.

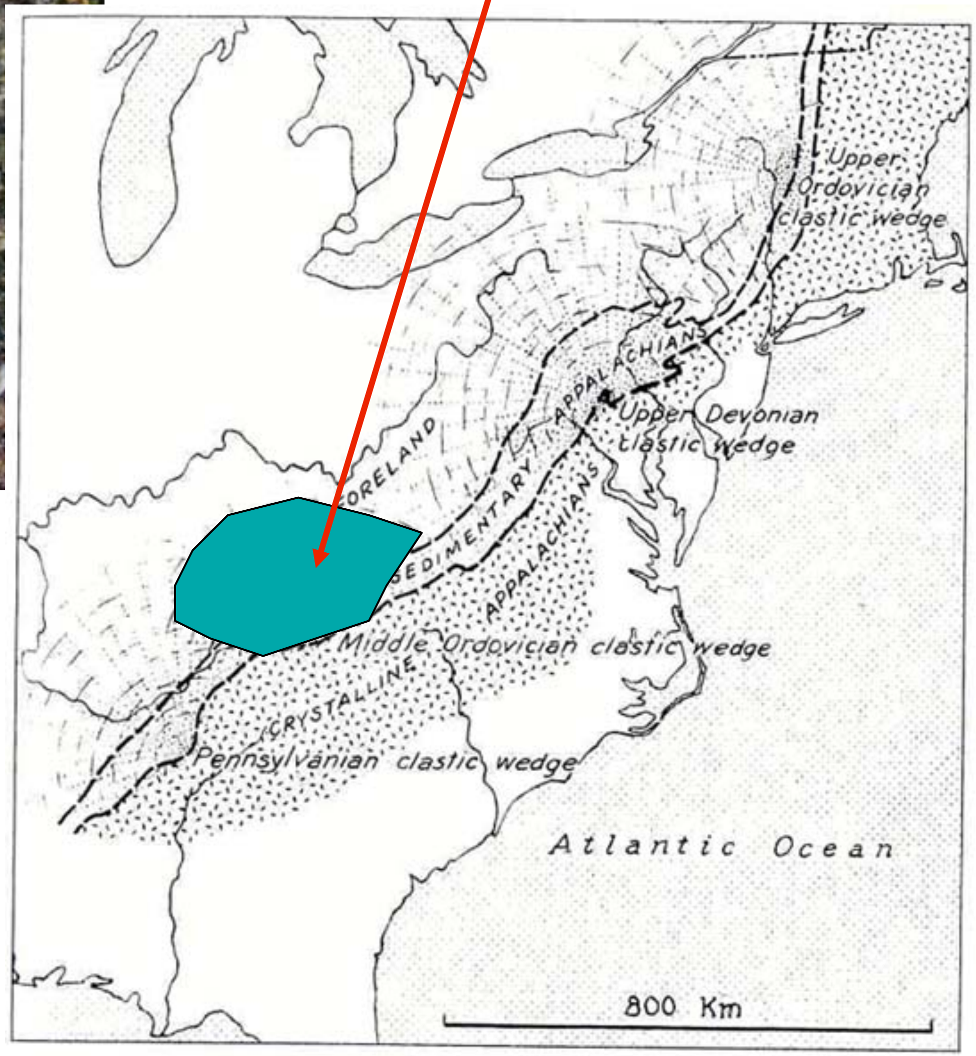
In each case:
> collision marked by clastic wedge
> later sedimentation returns to carbonates, quartz sandstones as the mountain range is eroded (calm period prior to the next collision)

Note that these clastic wedges are all thicker to the east, the direction in which the mountains lie. What type of sedimentary structures in the clastic wedge might tell us the direction of the source?

Figures from Callan Bentley

What type of sediment after collision?

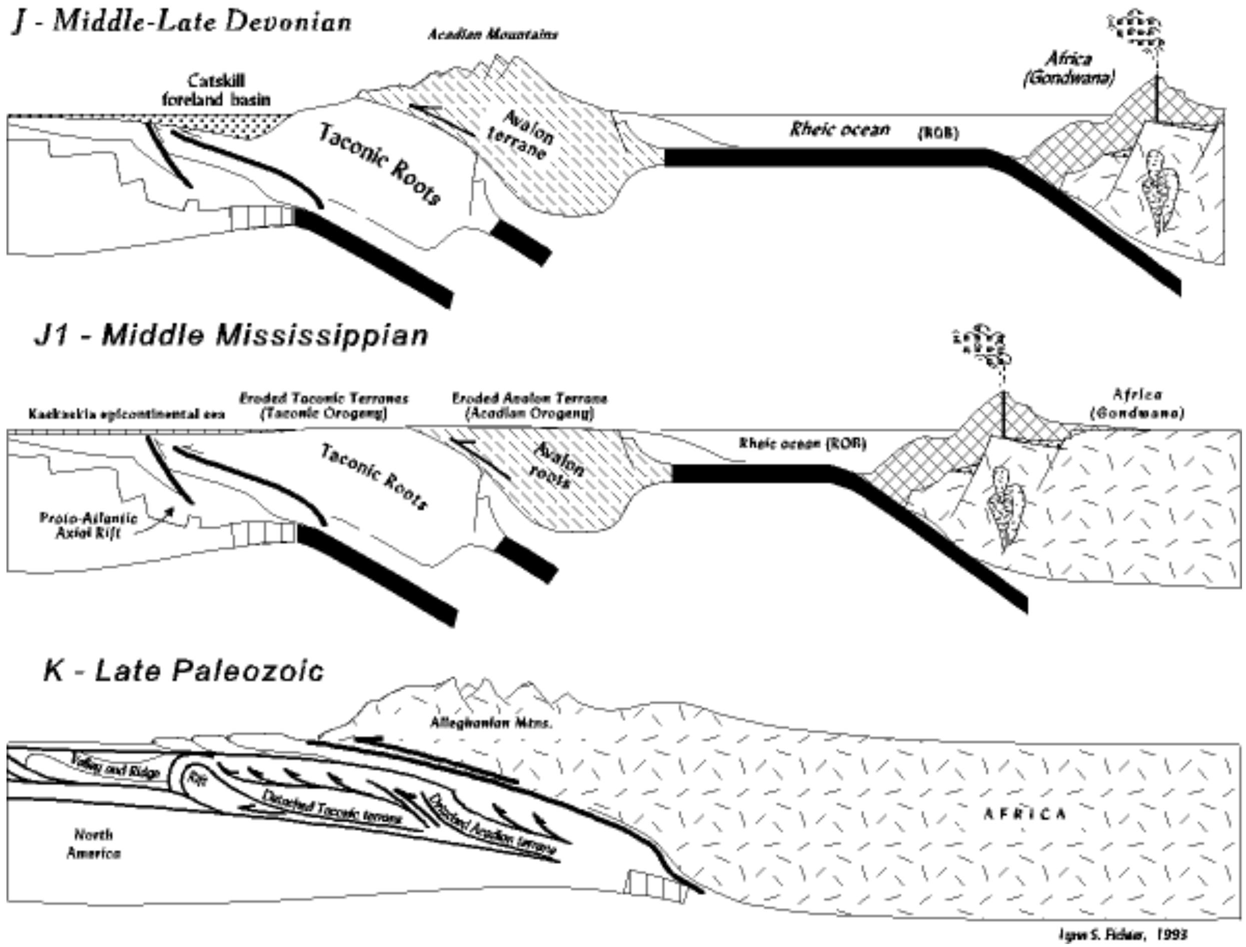
Middle Ordovician
clastic wedge



Immature clastic sediments (e.g. the conglomerate above) shed into the basin. These sediments form large clastic wedges (note that the ages of these are slightly different along the mountain range).

Figures from Callan Bentley

Here We Go Again!



The Avalon terrane collides in the middle to late Devonian (Acadian orogeny).

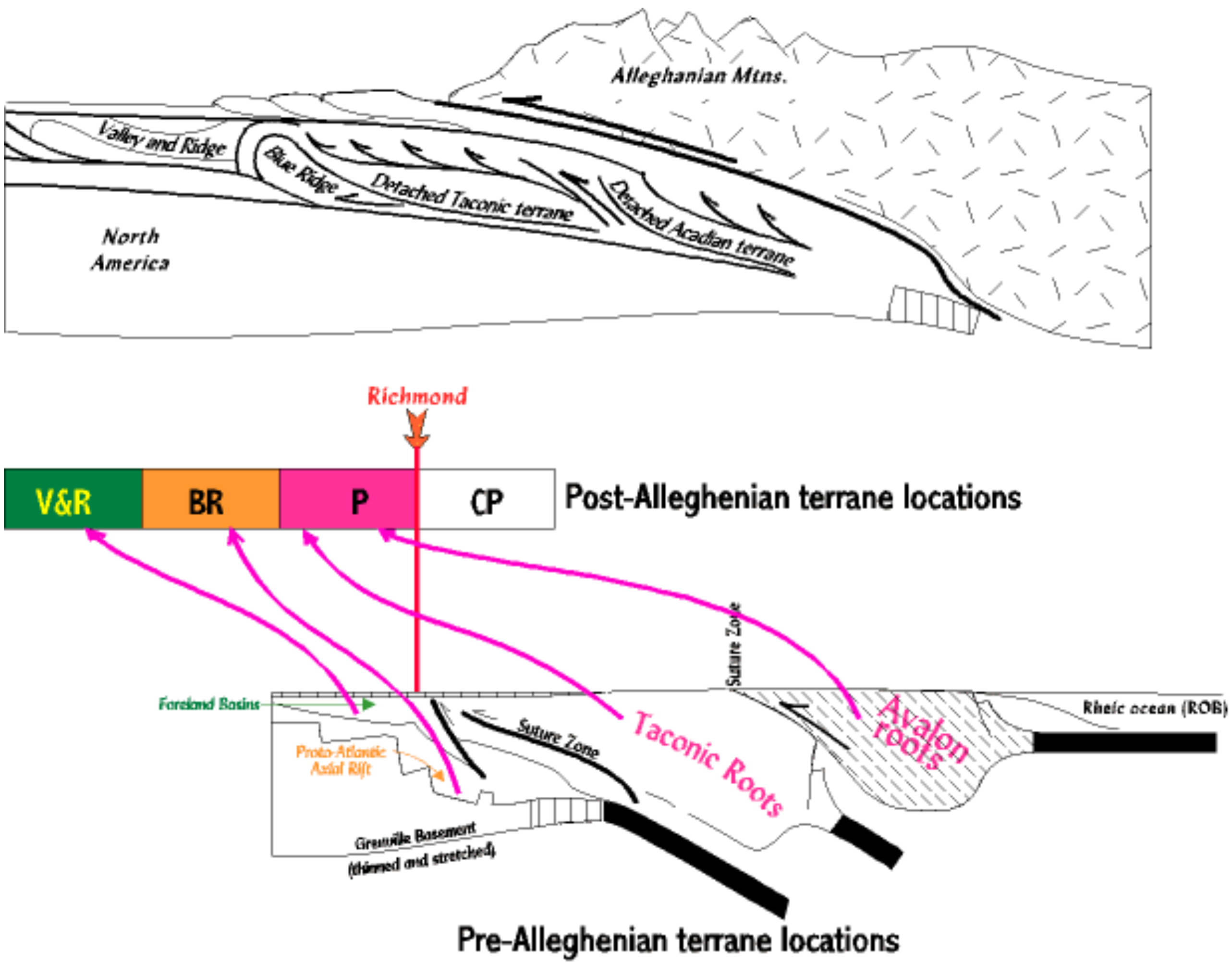
Mountains are eroded by the Mississippian.

Africa collides during the latest part of the Paleozoic (Alleghenian orogeny)

The Alleghenian mountains were likely comparable to the Himalayas. Note the reverse faulting taking place beneath the African plate.

Images: http://cmres.jmu.edu

Everyone Shift to the West



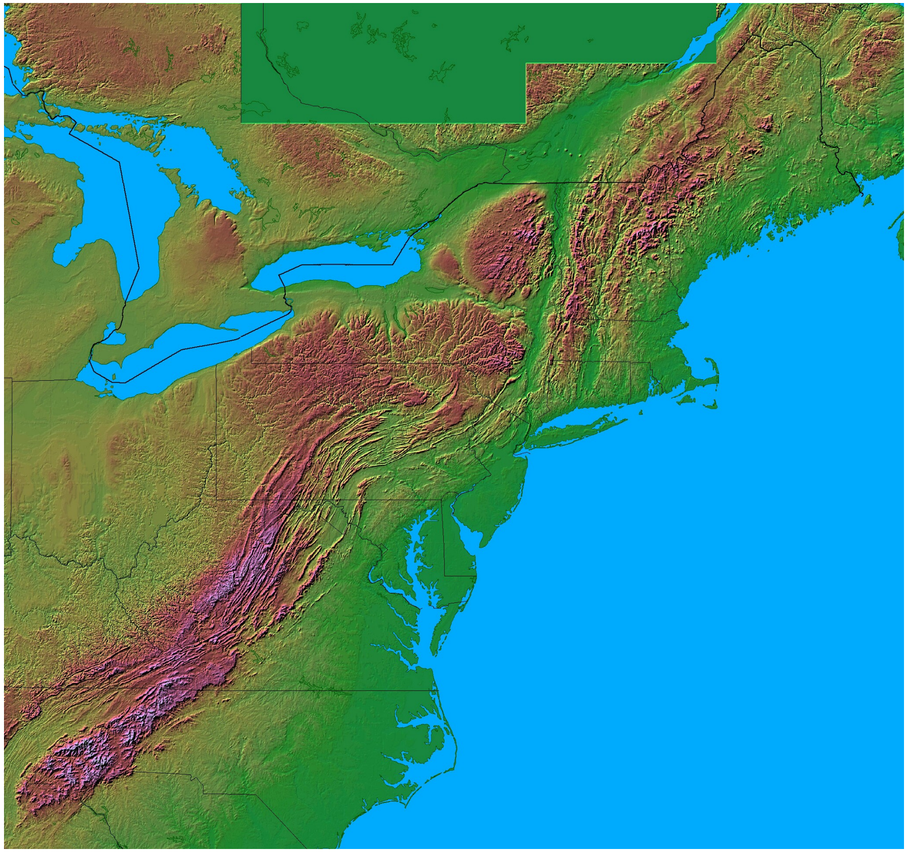
As the African plate slid, it caused many of the underlying terranes to also detach and move westward (some by 100 km or more)

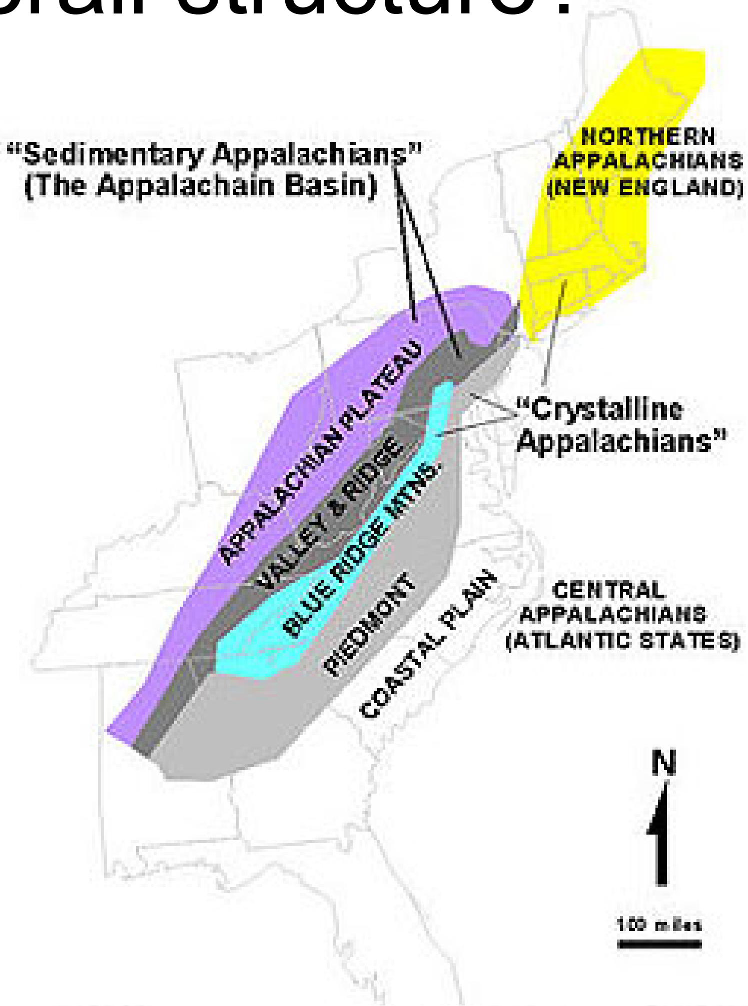
The low angle reverse faults along which much of this displacement occurred are called thrust faults. Weak sedimentary units (e.g. shales) are often where the sliding occurs.

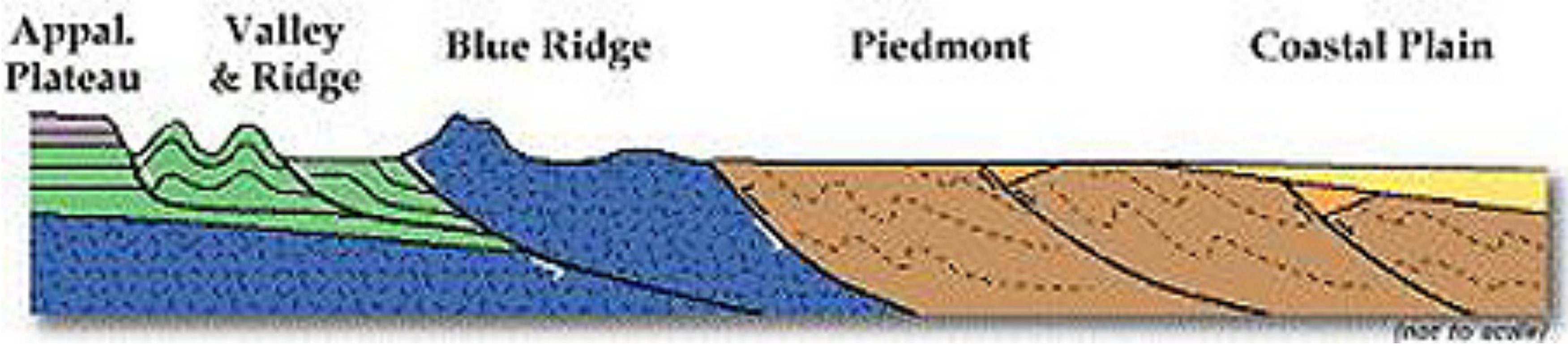
This slide shows where the major tectonic elements come from

Images: http://cmres.jmu.edu

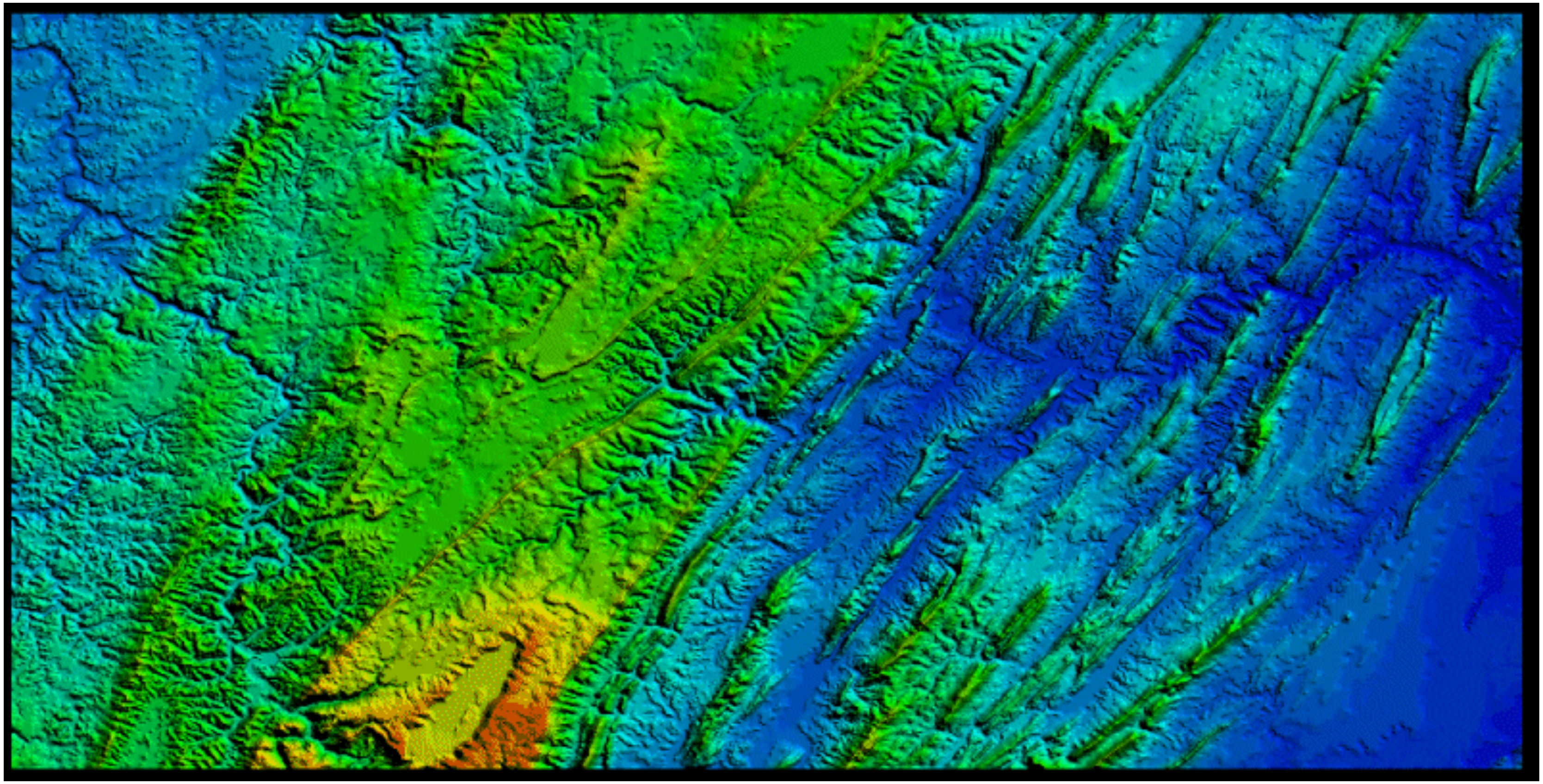
What is the overall structure?







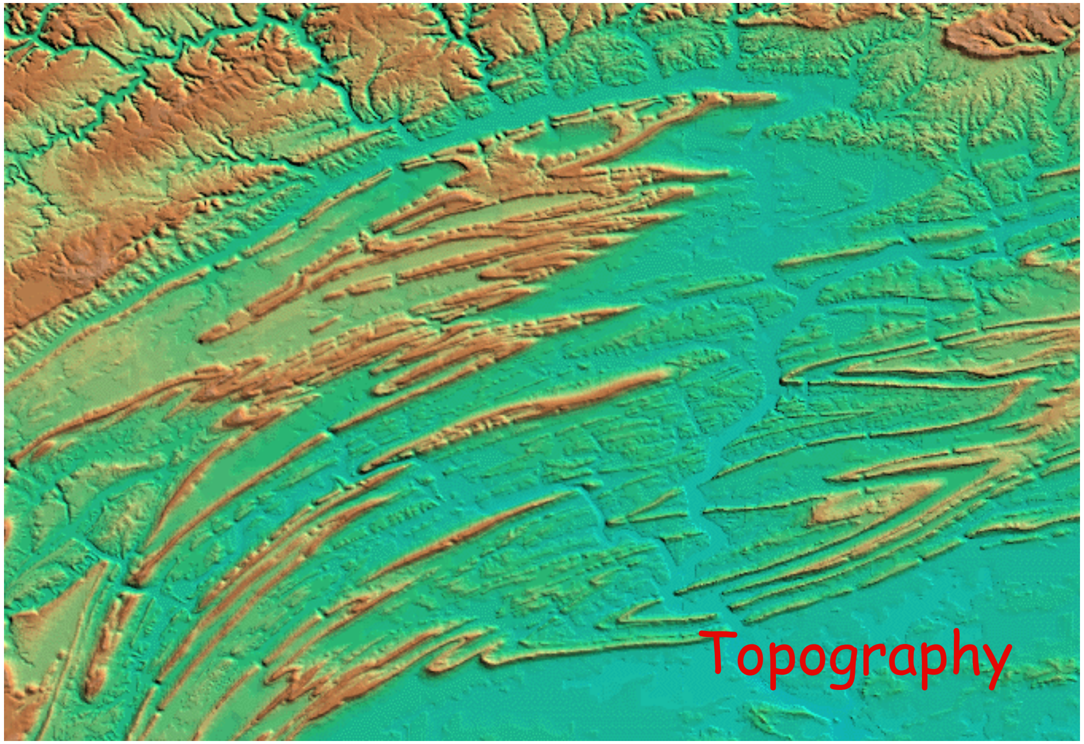
The Allegheny Front

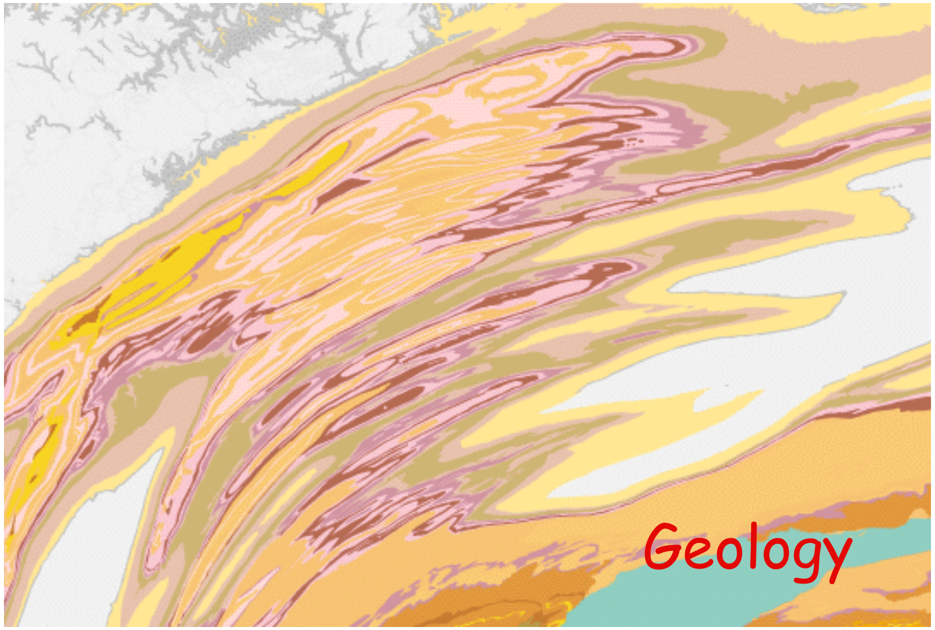


Allegheny Plateau - almost flat lying sediments

Valley and Rige - underlain by thrust faulted and folded sedimentary rocks

Images: http://cmres.jmu.edu



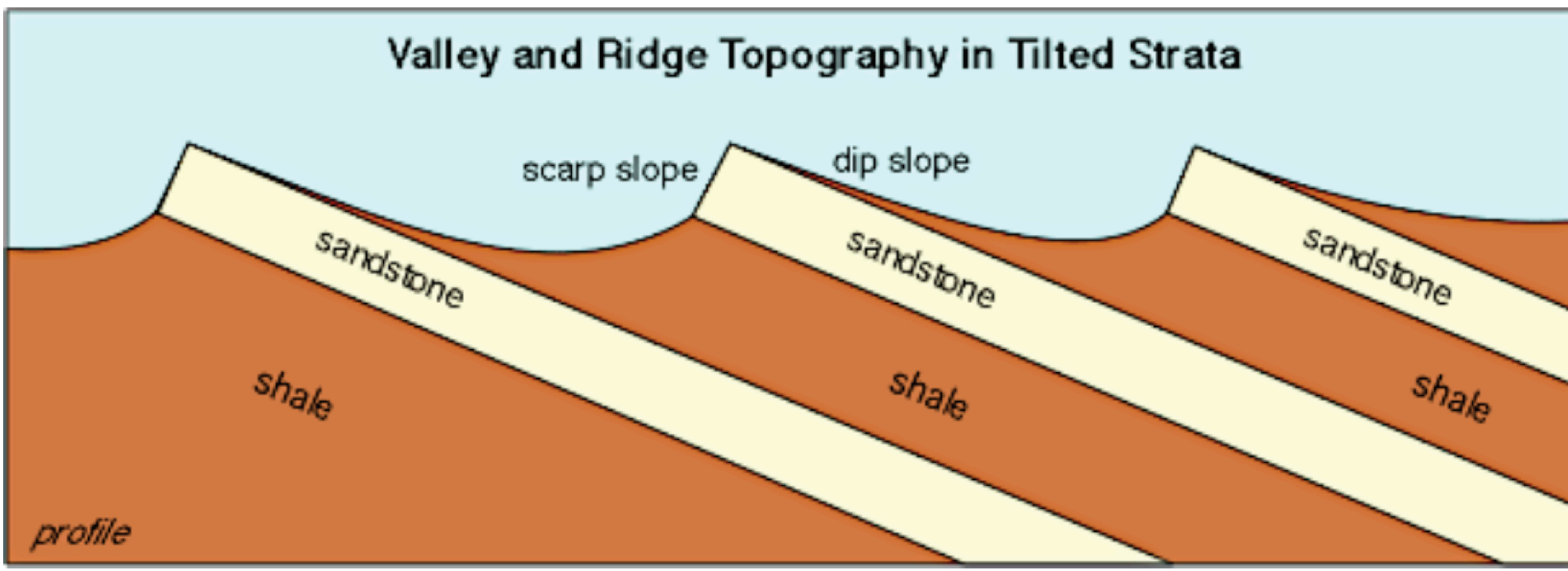


- Topography often reflects the geology
  - Ridge forming units
    - Sandstones
  - Valley floors
    - Limestones
    - Shales
- Rivers and streams also affected by geology

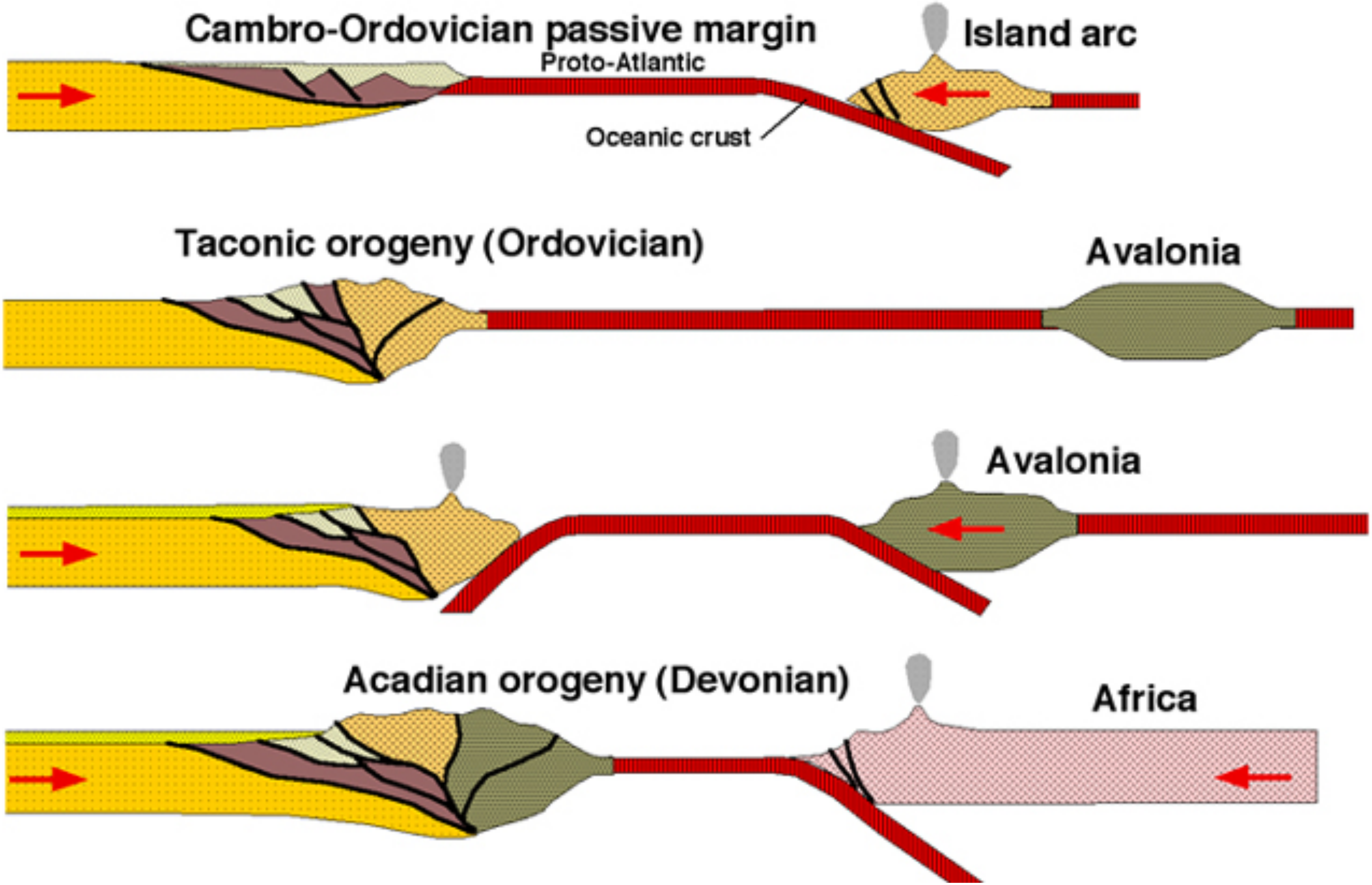
Valley and Ridge

Ridges are upheld by resistant strata - sandstone & conglomerate

Valleys are underlain by easily weathered strata - shale & limestone

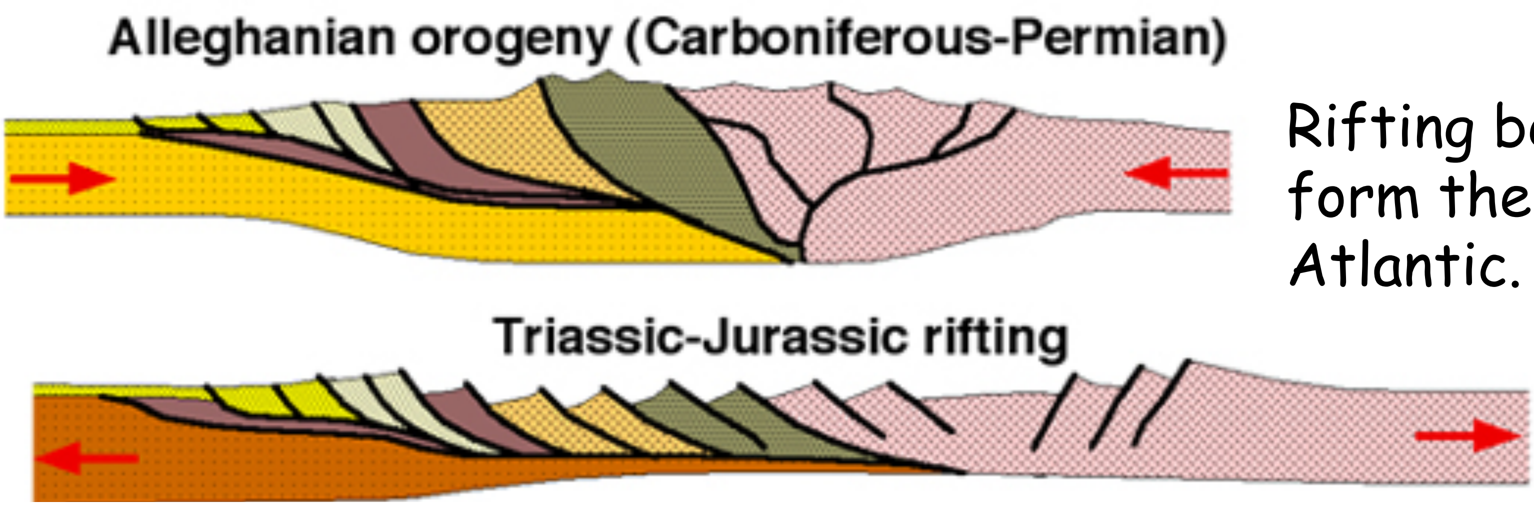


The Ocean Closes



Multiple collisions, volcanic arc, terrane, and then Africa

Rifting of Pangea



Rifting begins again to form the present Atlantic.

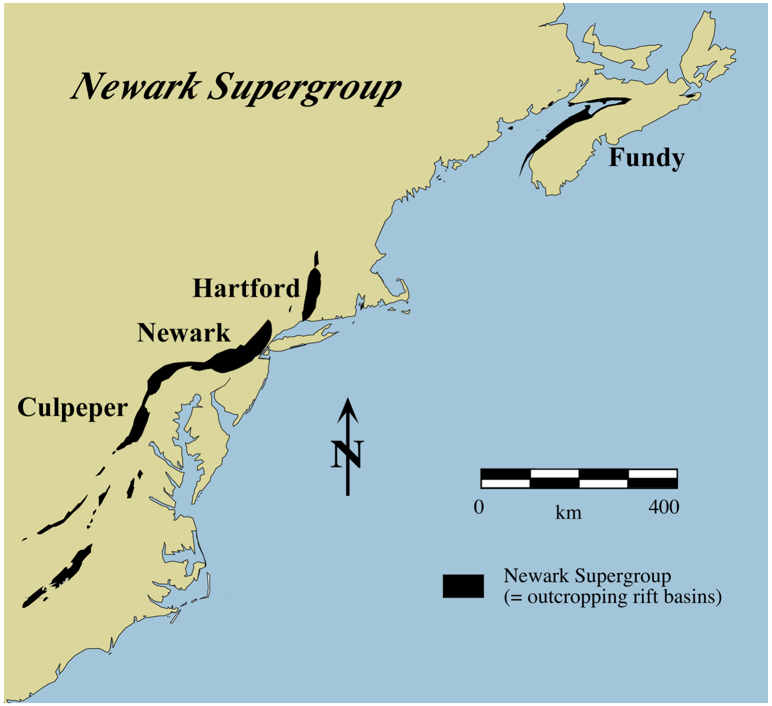
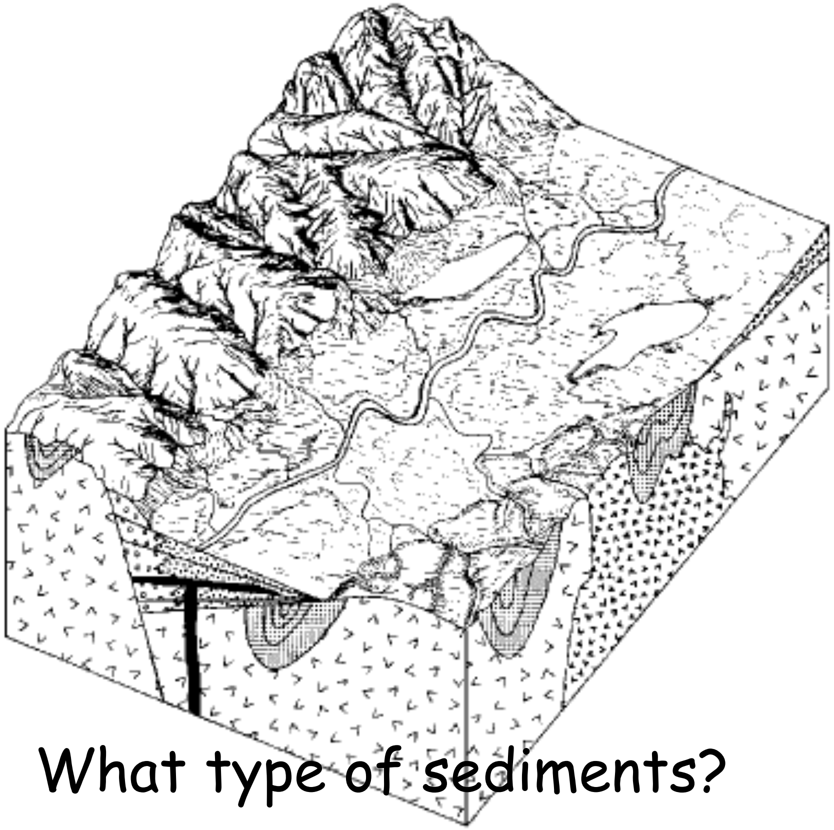
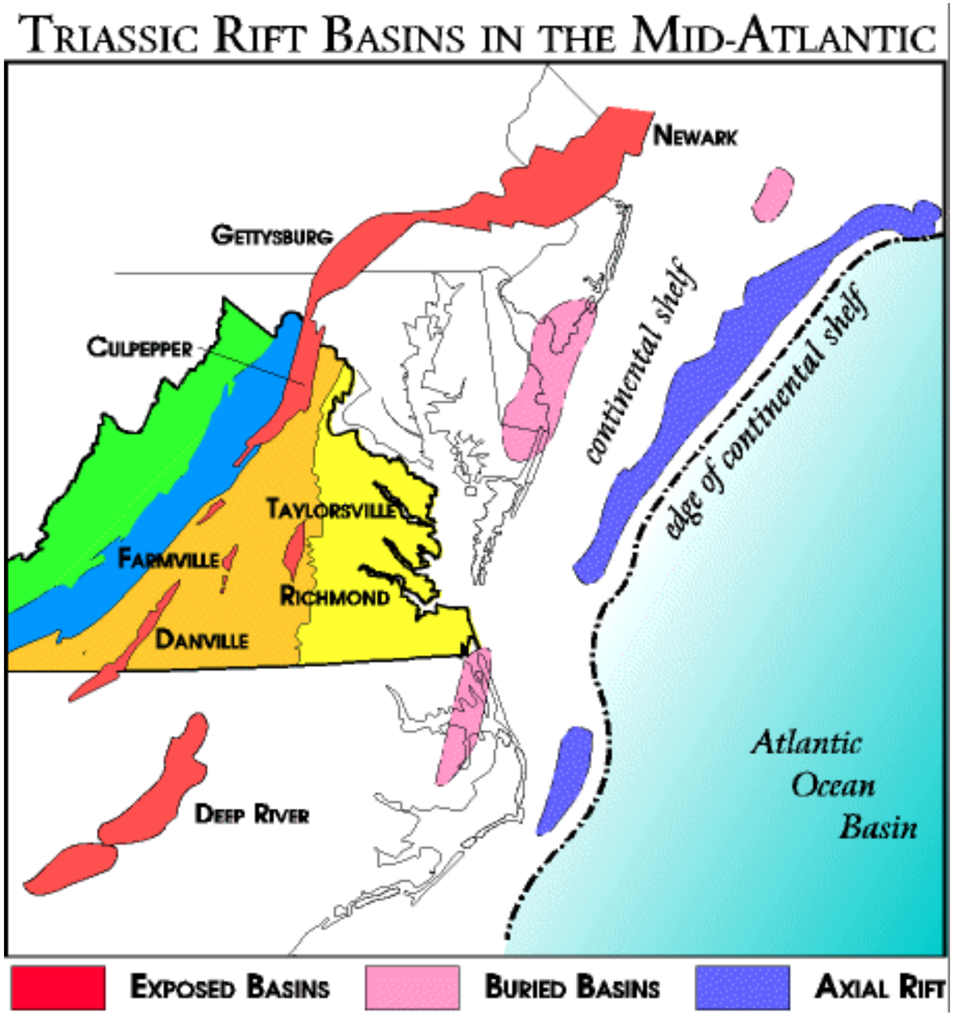


Image from P. Olsen



What type of sediments?

Rifting of Pangea - Another Wilson Cycle

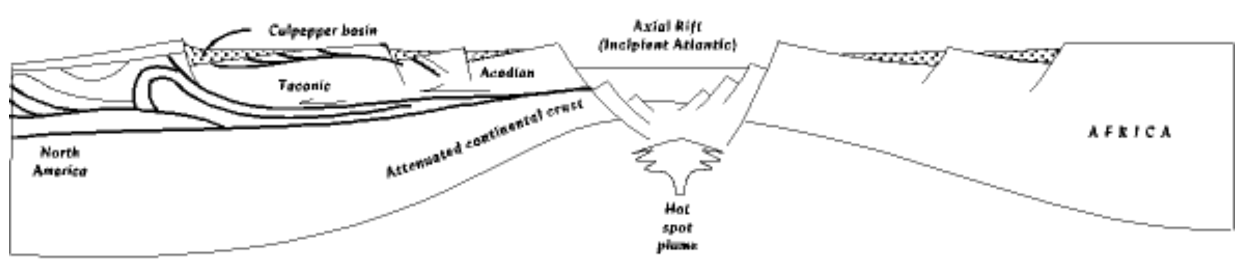


The supercontinent Pangea rifted apart in the Triassic, with seafloor spreading in the Jurassic to form the modern Atlantic Ocean.

The rifting is associated with volcanism (200 Ma), thick deposits of red sediments (e.g. the Newark Basin).

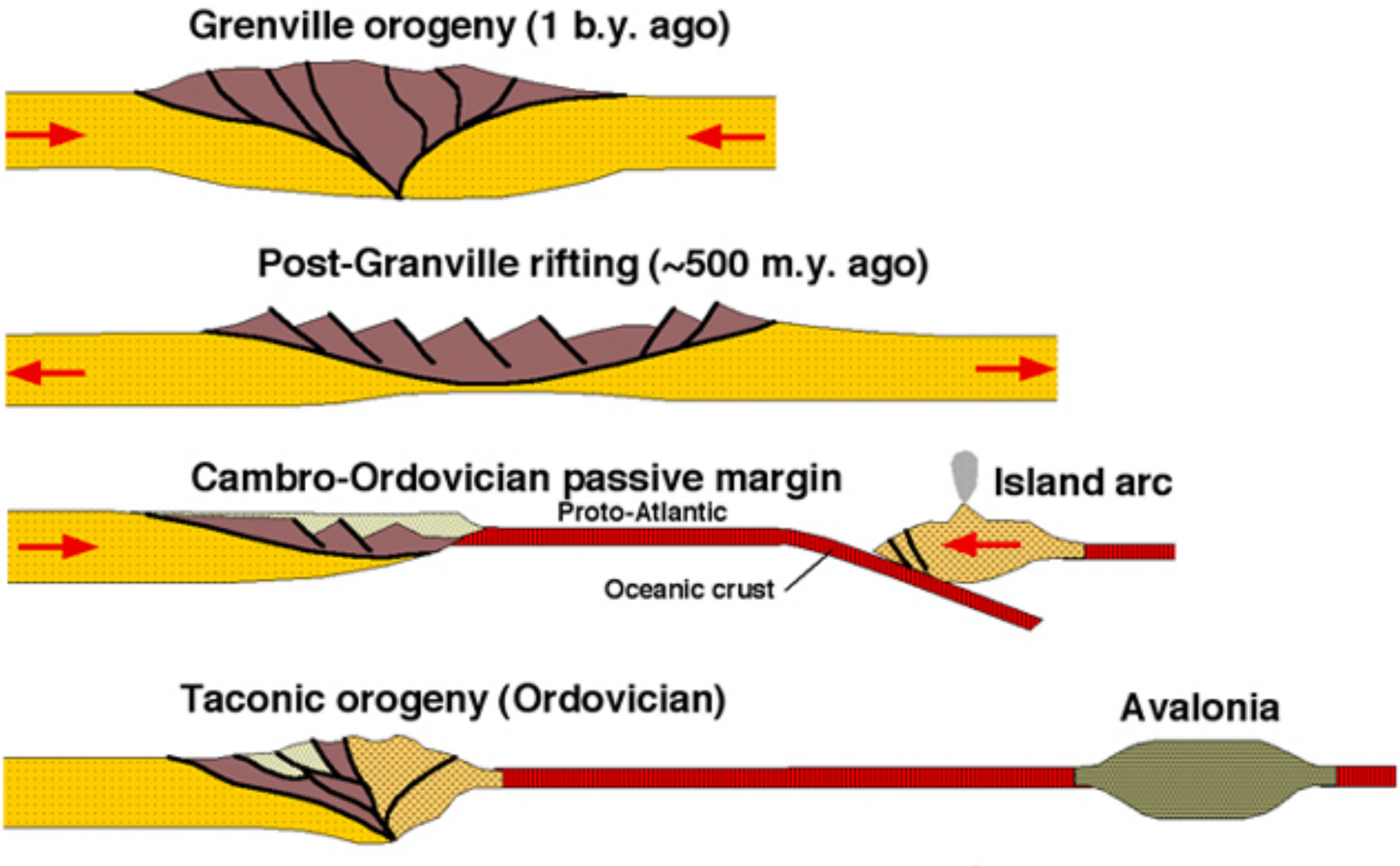
Would you expect any terranes that are younger than the Jurassic to be found along the east coast?

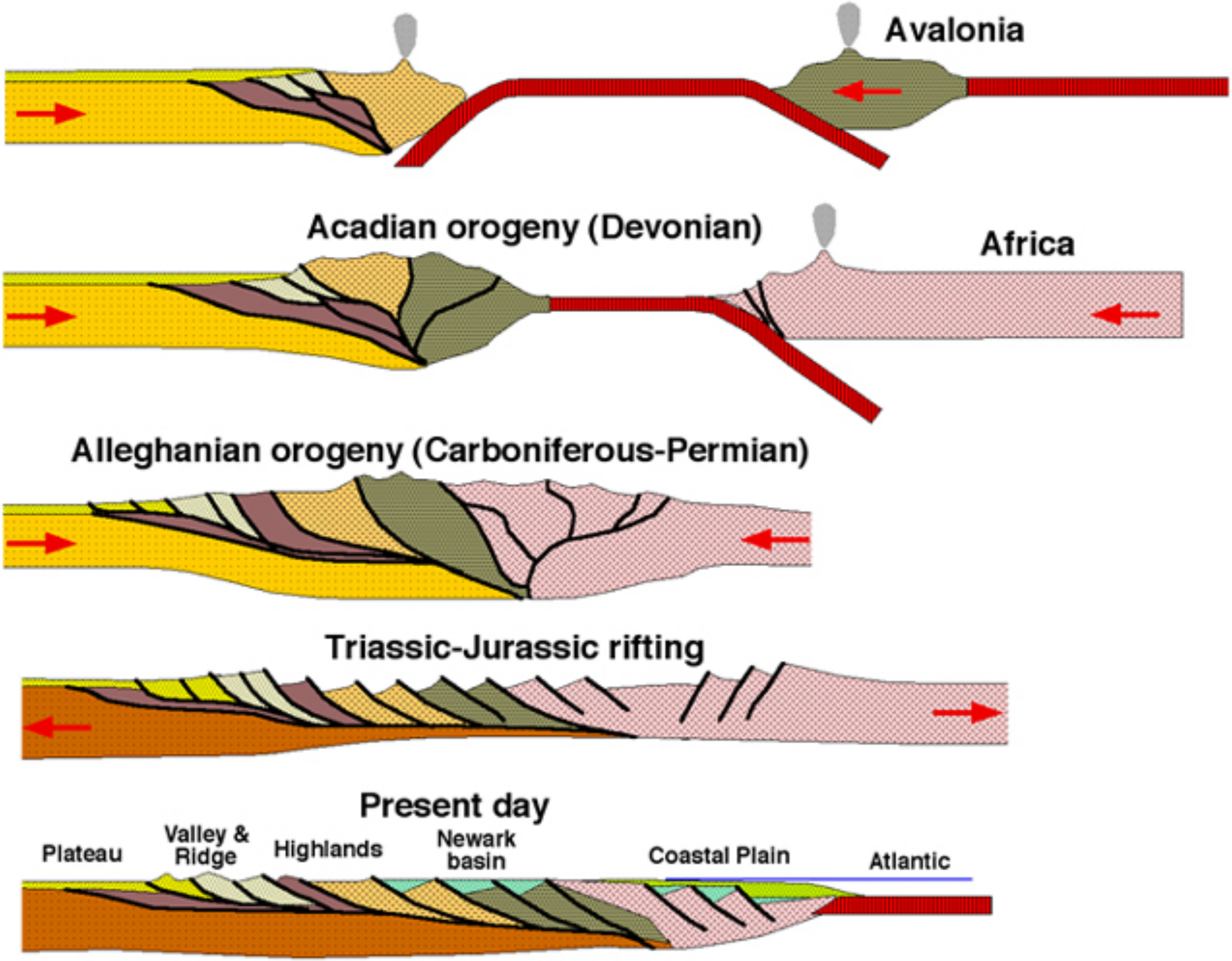
L - Triassic-Lower Jurassic



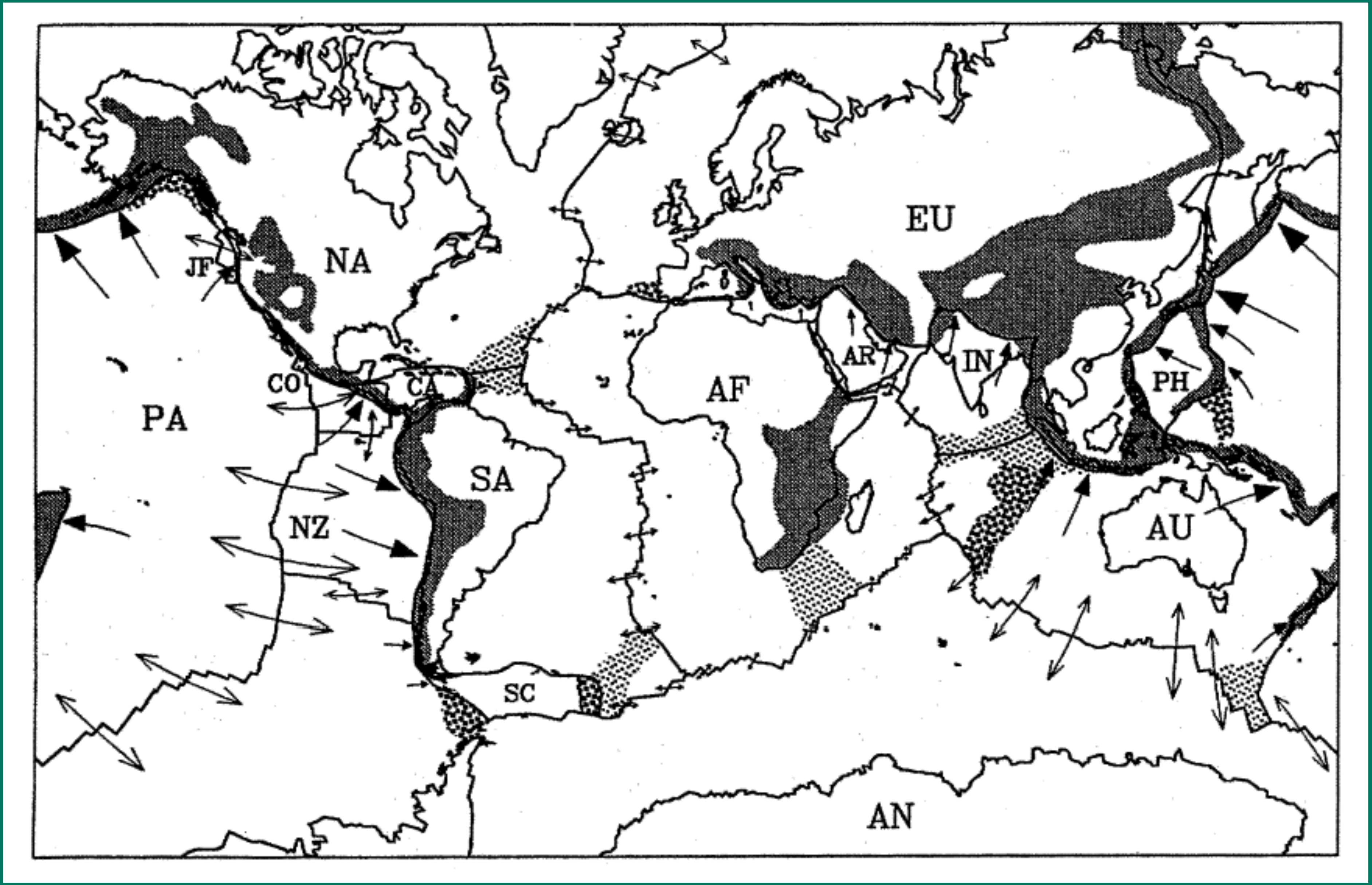
Images: http://cmres.jmu.edu

Wilson Cycle




Avalonia
Acadian orogeny (Devonian)
Africa
Alleghanian orogeny (Carboniferous-Permian)
Triassic-Jurassic rifting
Present day
Plateau
Valley & Ridge
Highlands
Newark basin
Coastal Plain
Atlantic

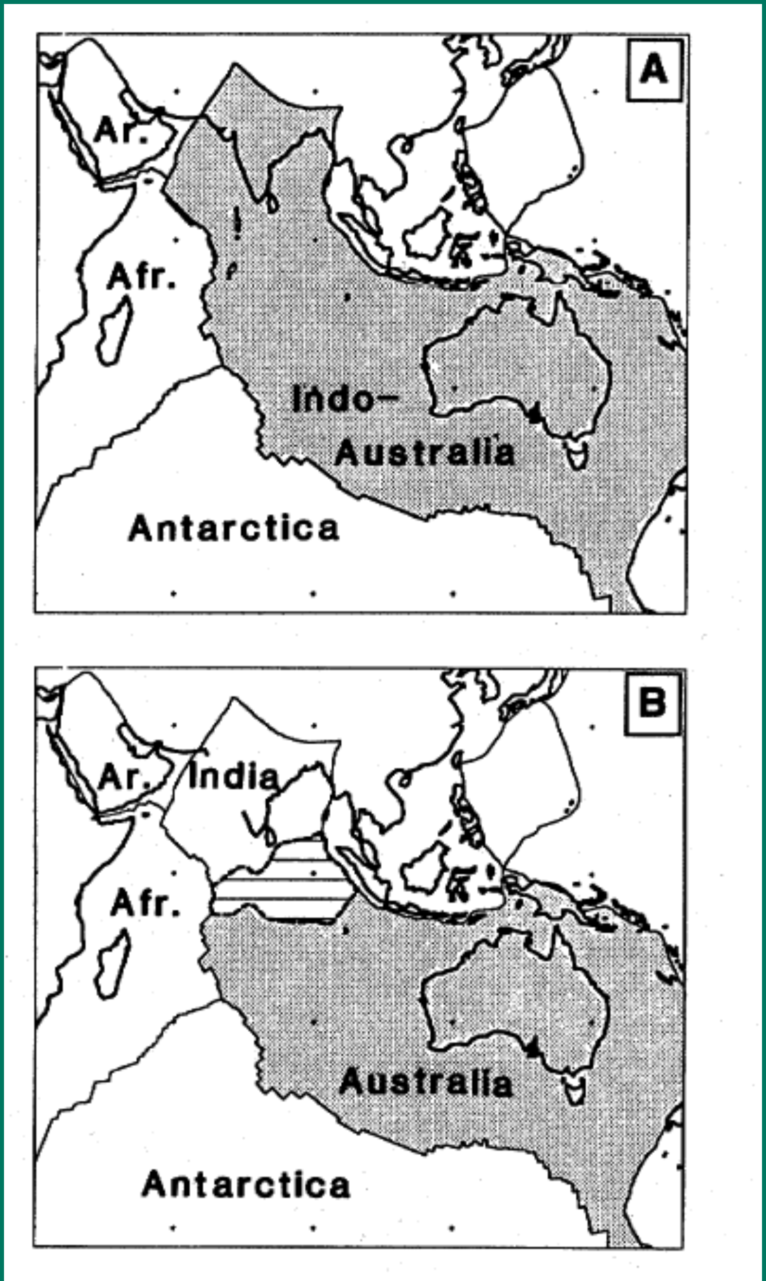
How rigid are plates? How much do oceanic plates deform?



Diffuse plate boundaries

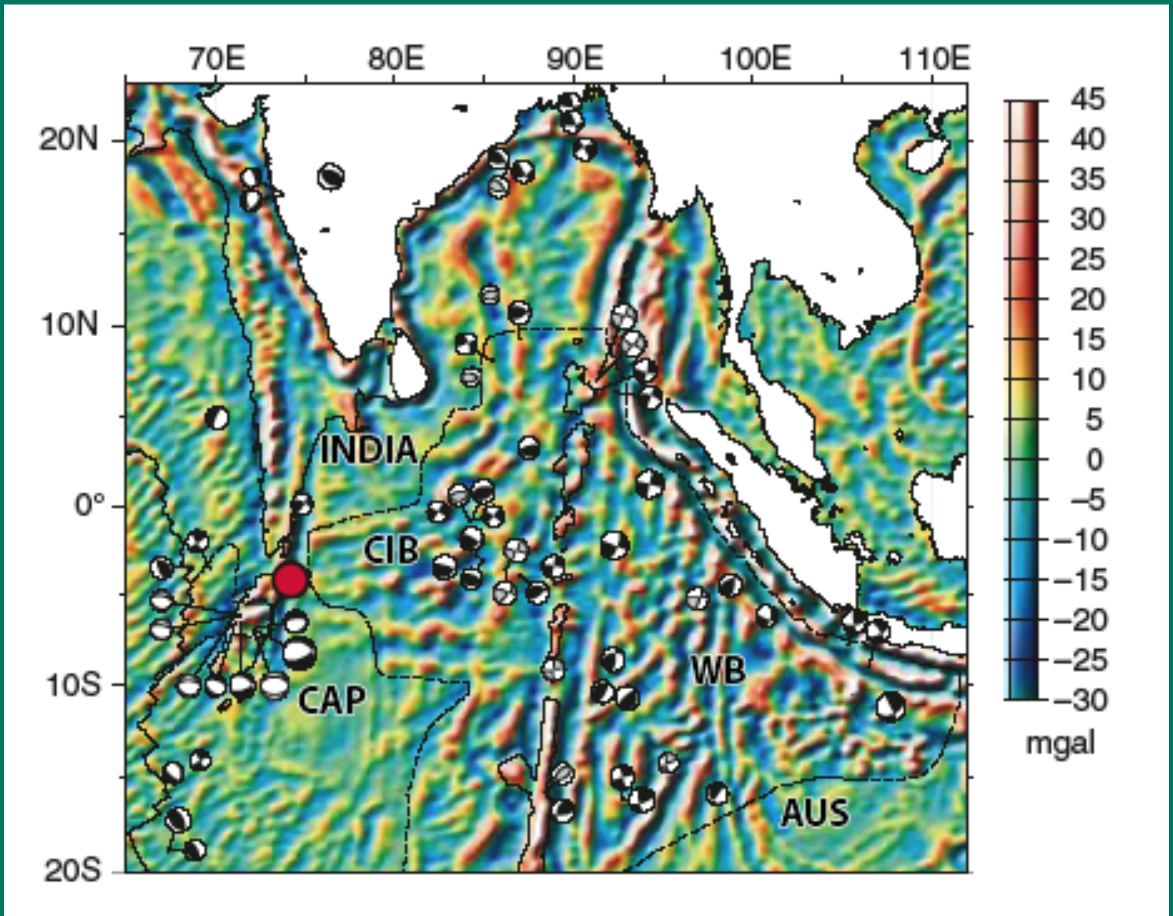
Dark = continental
Lighter = oceanic

Gordon and Stein (1992)

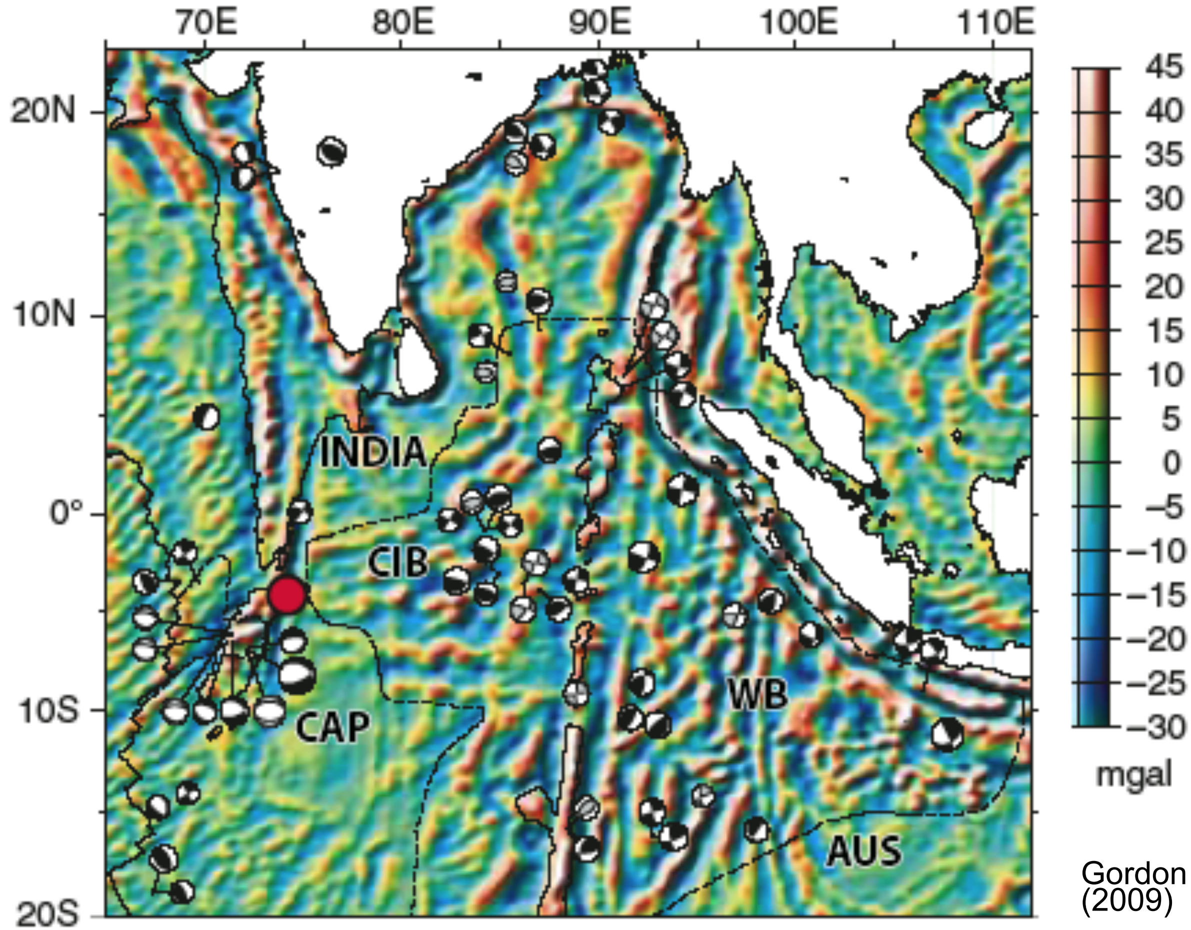


Classic example of a diffuse plate boundary

Zone of deformation running across Indian plate from Central Indian ridge to Java-Sumatra trench



Satellite gravity field



Gordon (2009)

Characterized by:

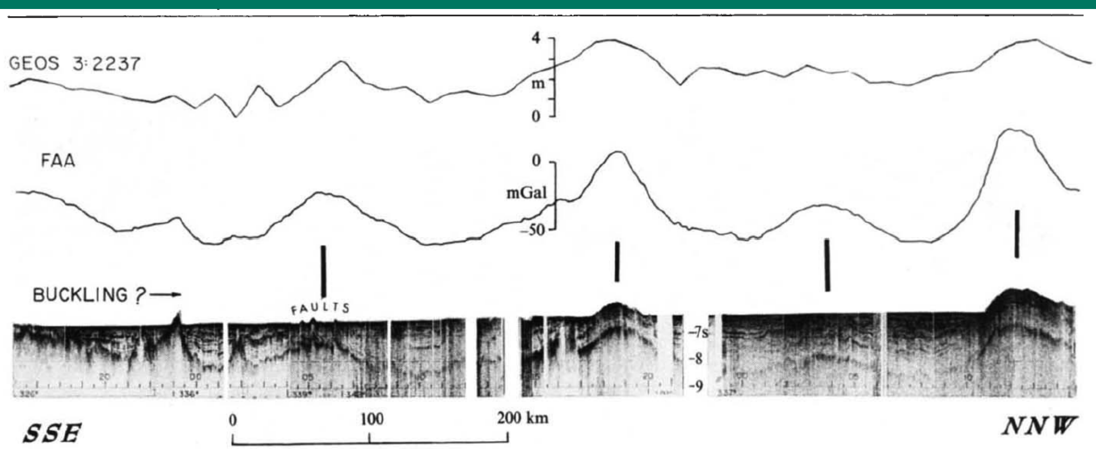
a) Zone of intraplate seismicity in Indian Ocean

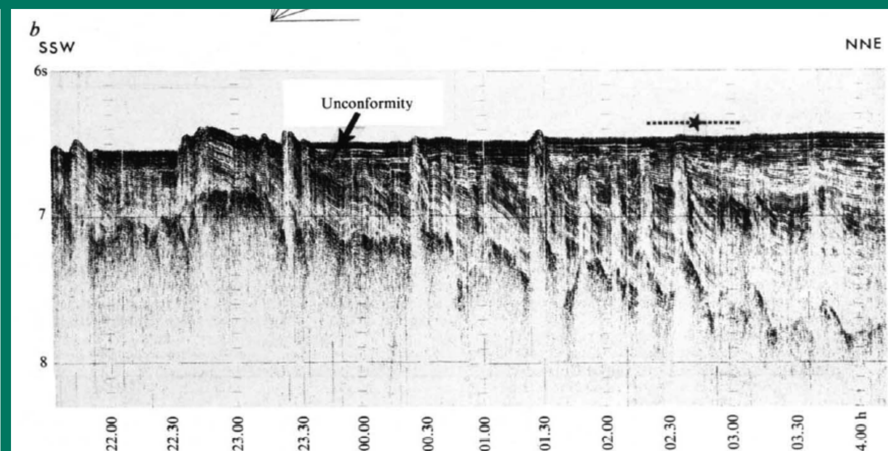
b) Large E-W striking gravity lineaments caused by convergence between Australia and India

c) Seismic reflection profiles reveal shortening

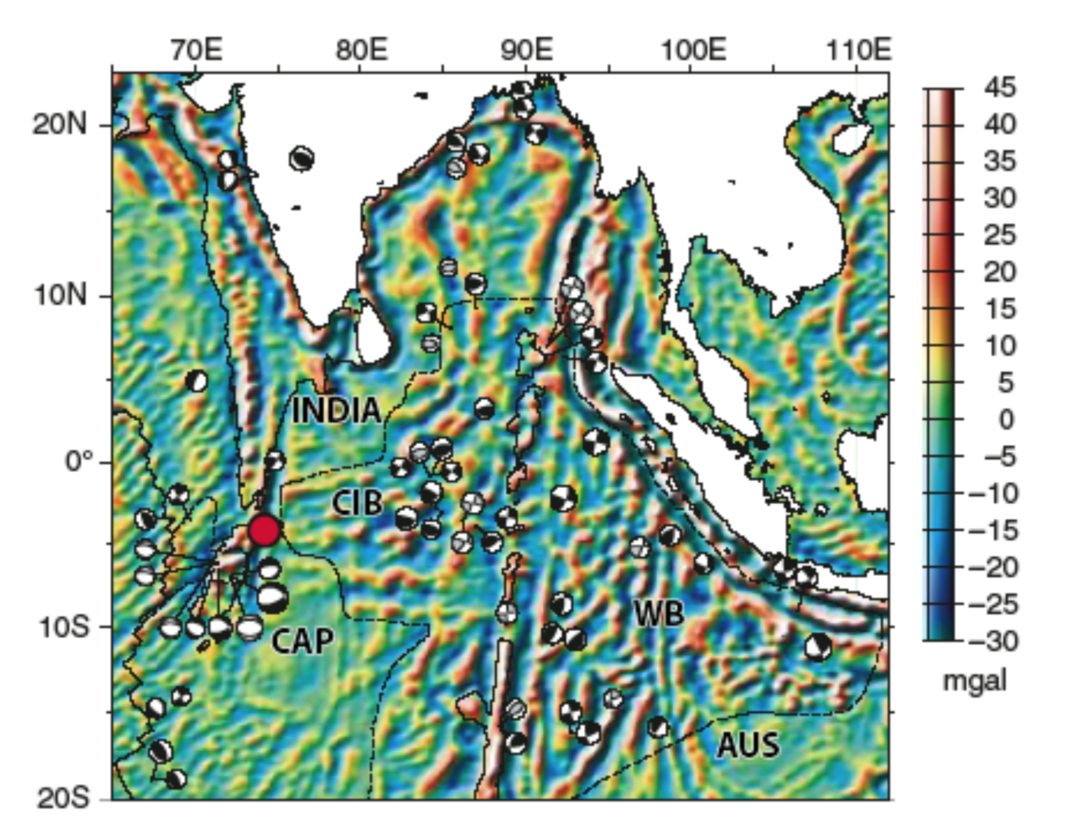
d) Plate reconstructions indicate over 100 km of shortening

EQ focal mechanisms show a mixture of compression, strike slip faulting and extension.

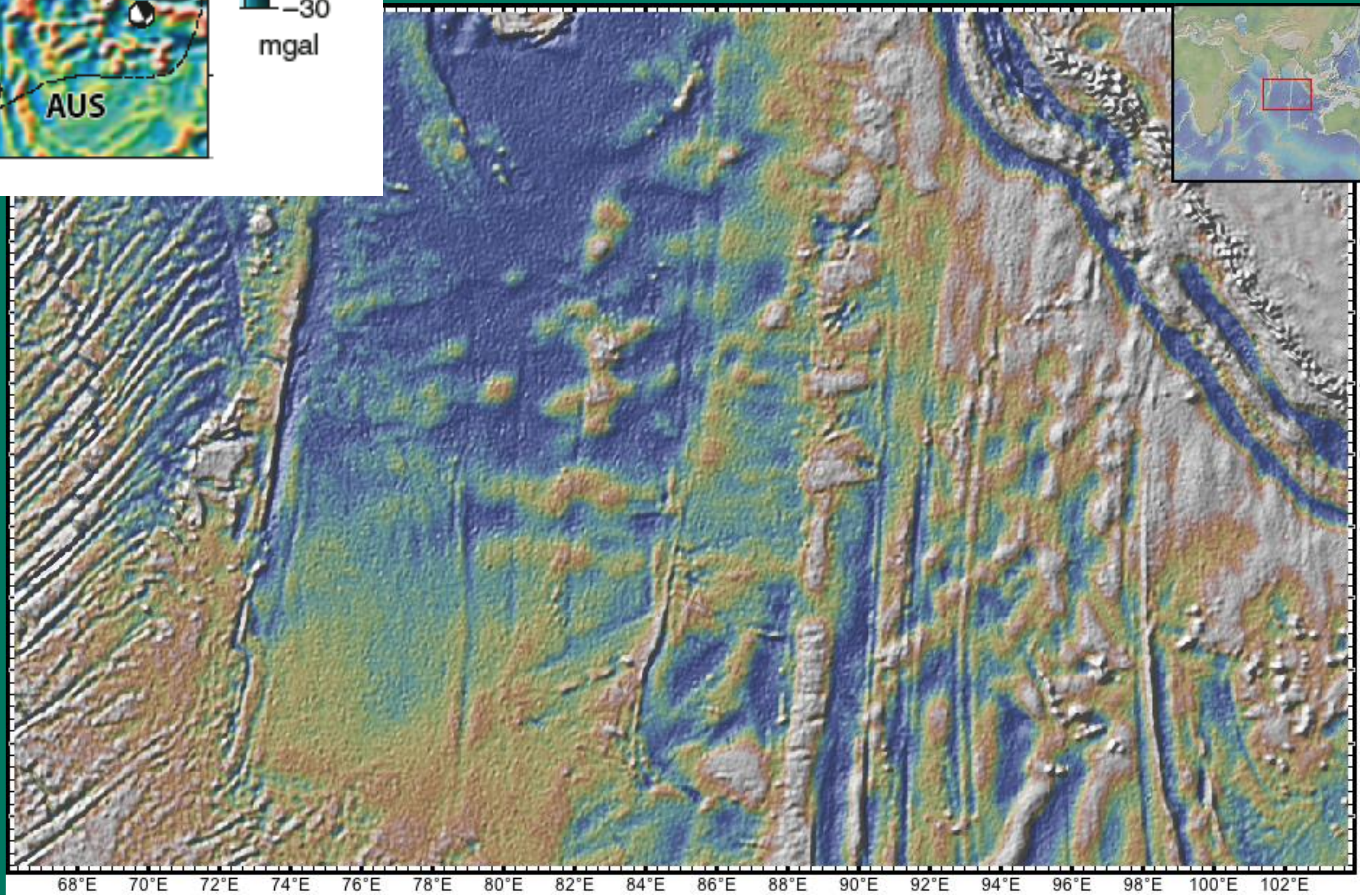


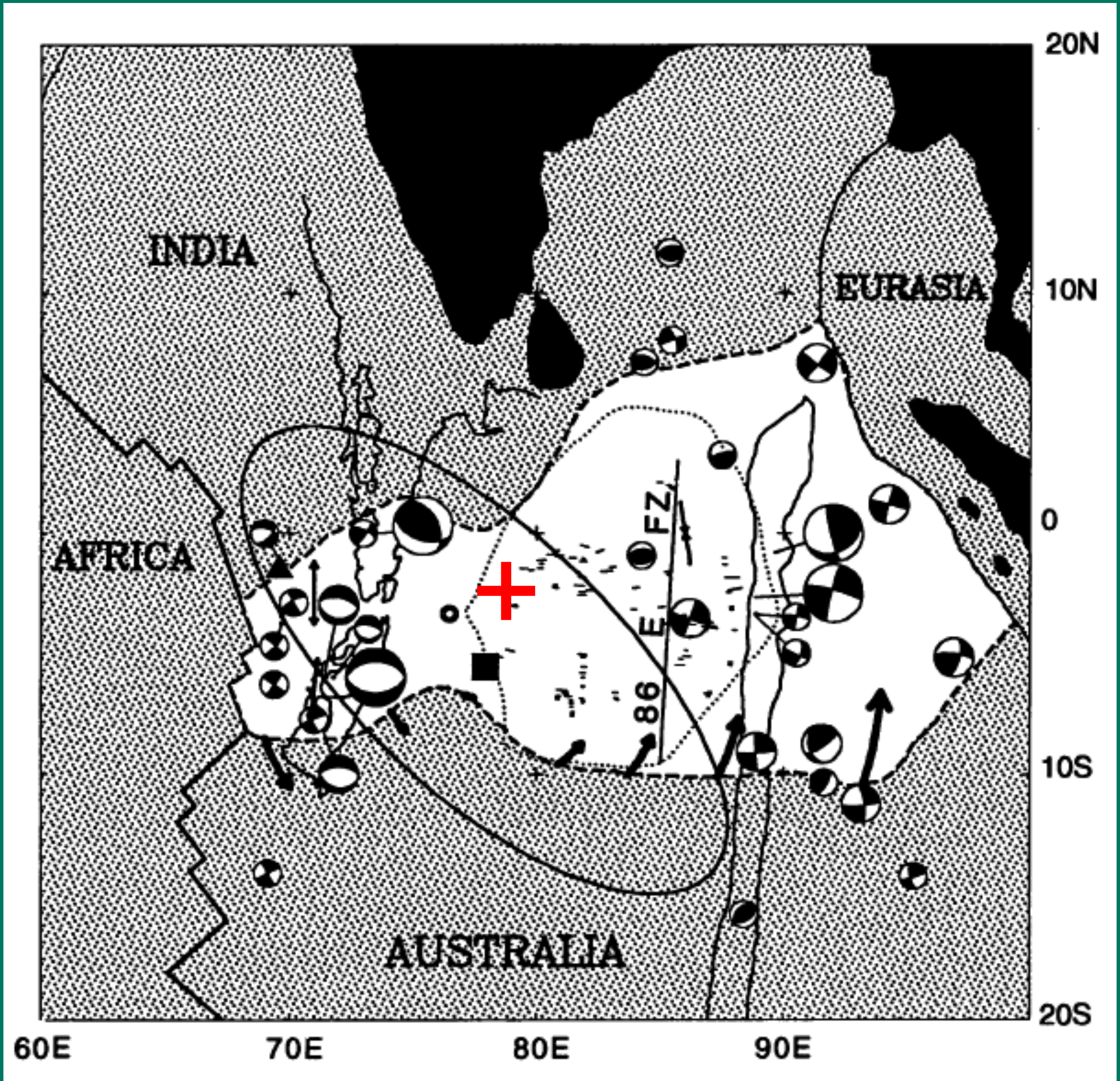


Weissel et al. (1980)



The gravity field looks particularly complex because the East-West striking gravity lineaments caused by compression are superimposed on gravity anomalies over the North-South striking fracture zones



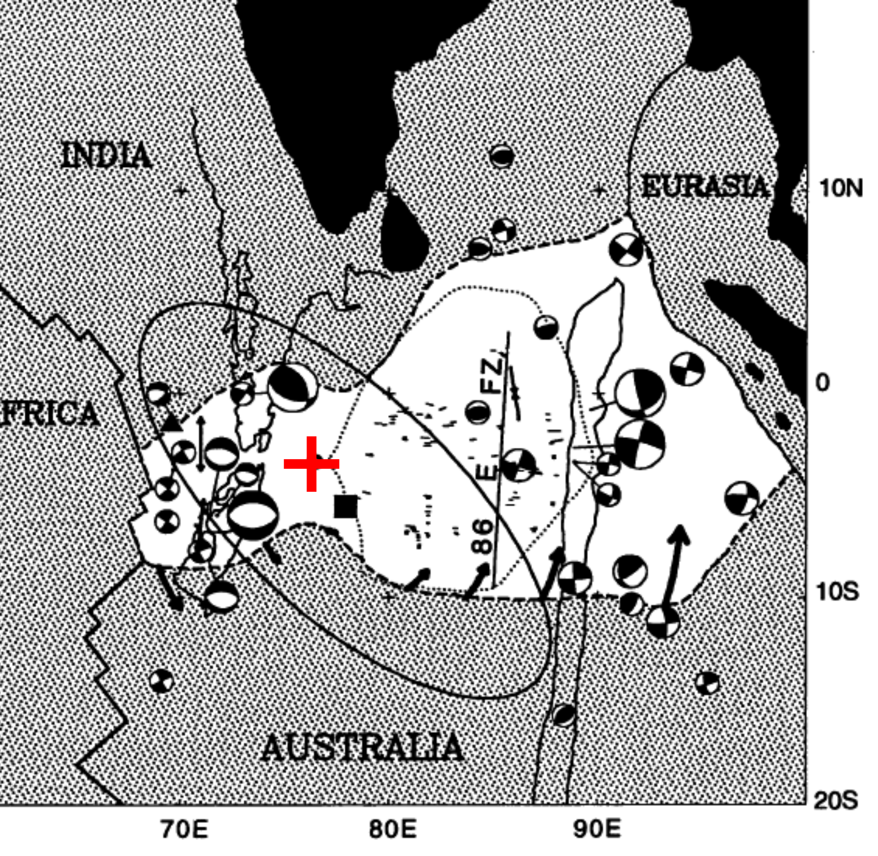


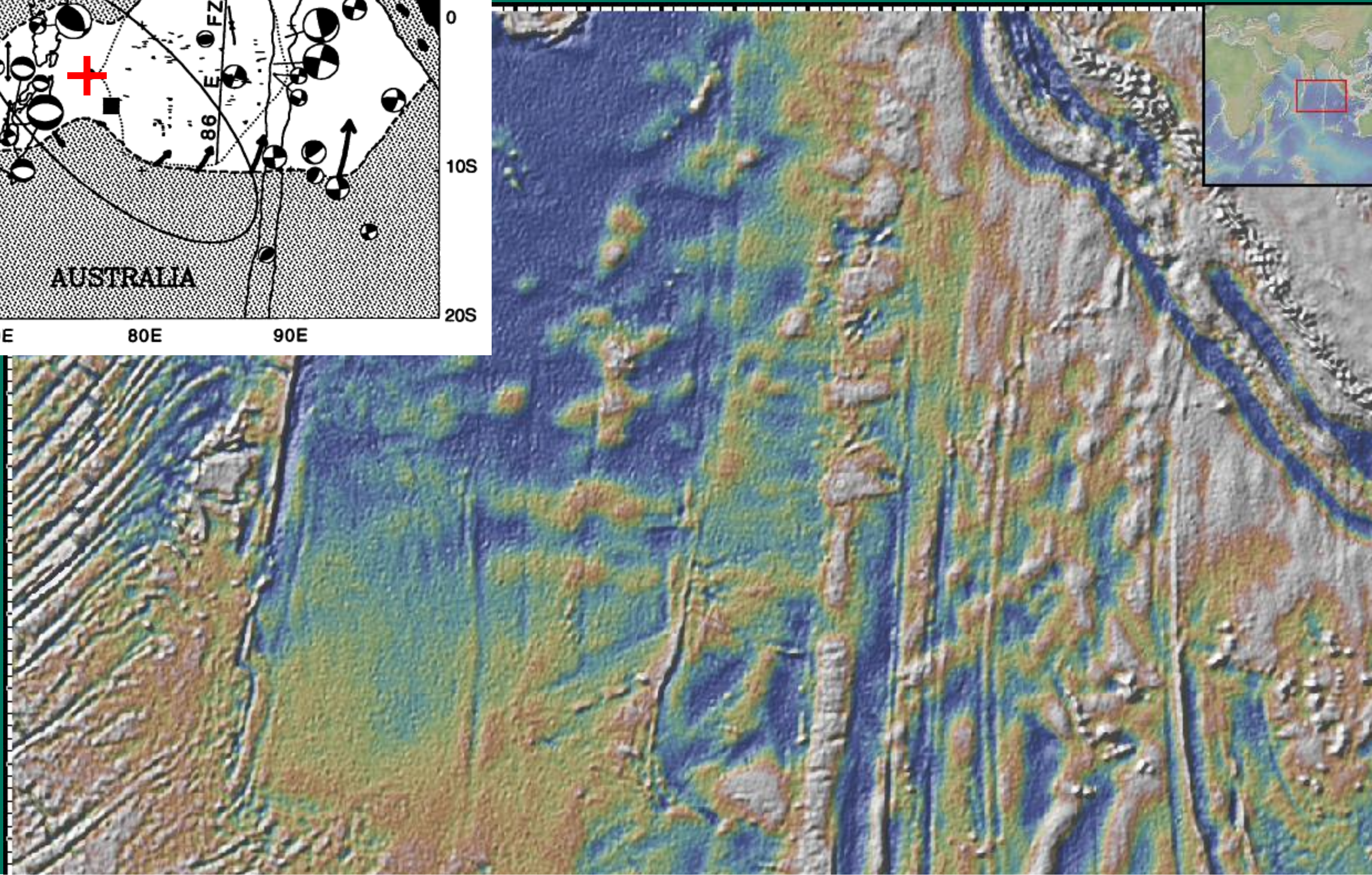
What do focal mechanisms tell us about the type of deformation across the diffuse plate boundary?

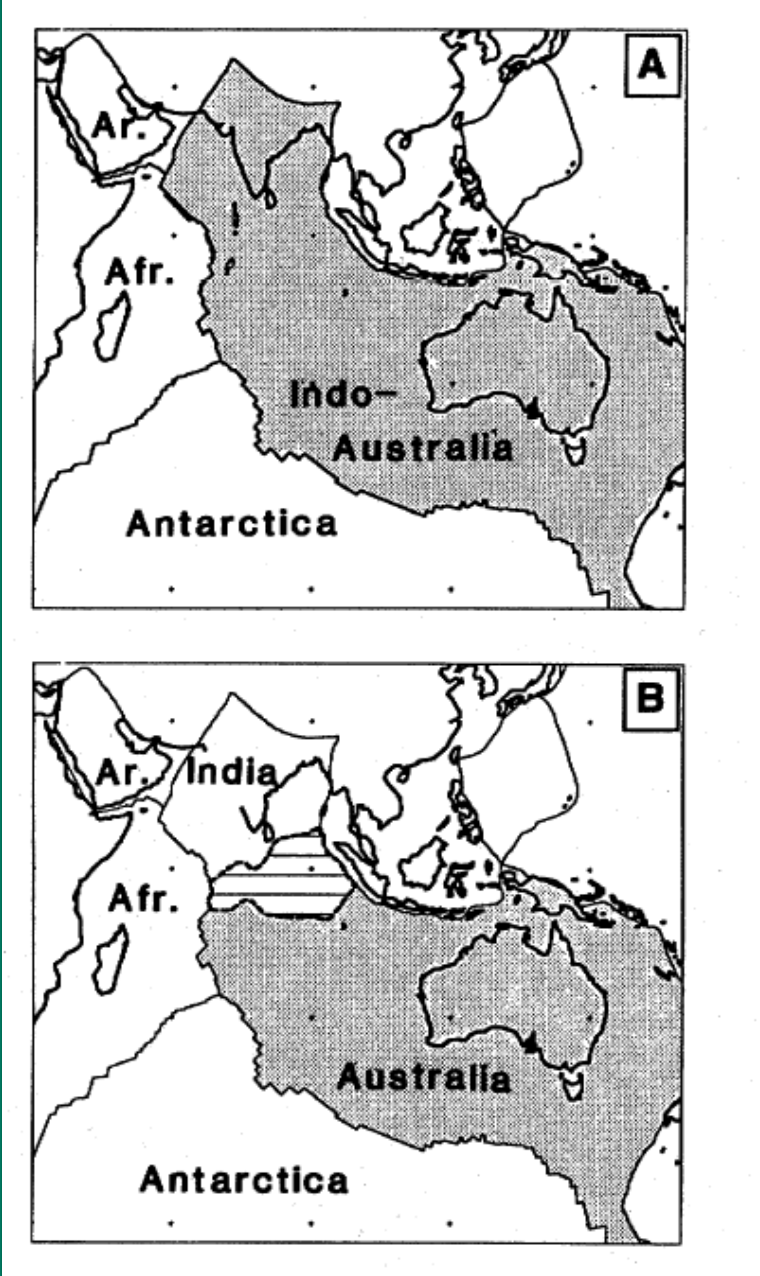
Is it all compression?

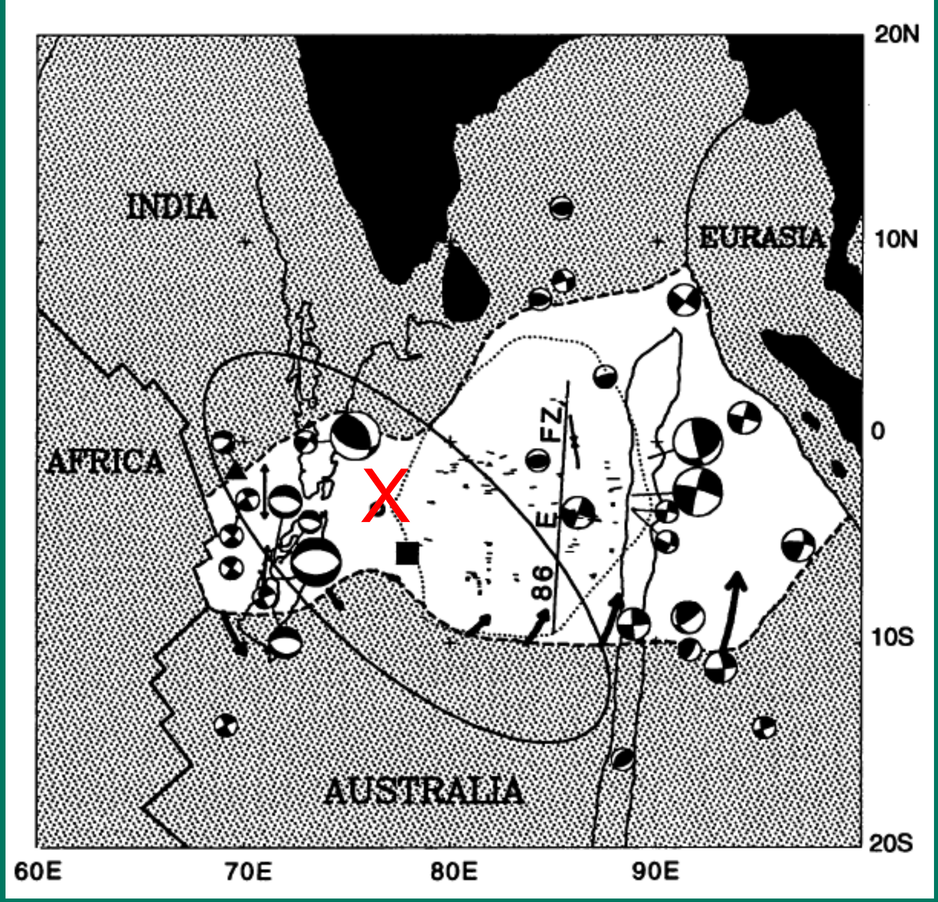
+ marks India-Australia Euler pole

The strike slip faulting in the eastern part is probably due to reactivation of old N-S striking fracture zones







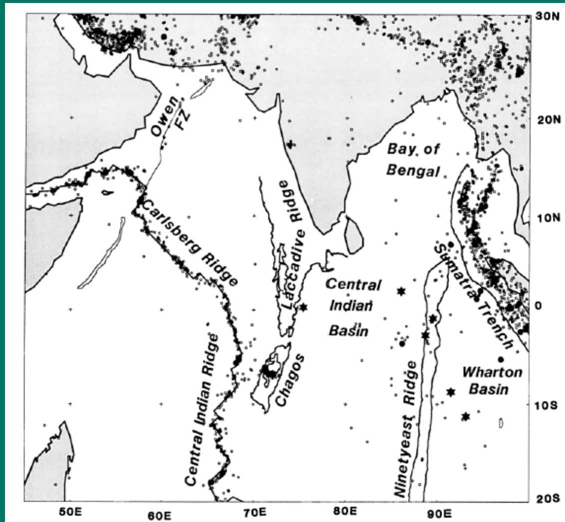


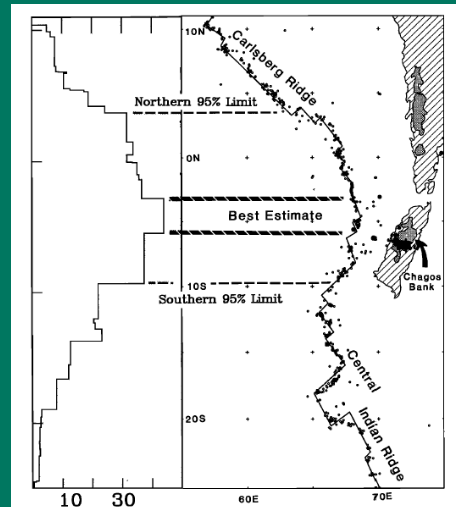
Outside of the diffuse plate boundary (white region), the plates are behaving rigidly

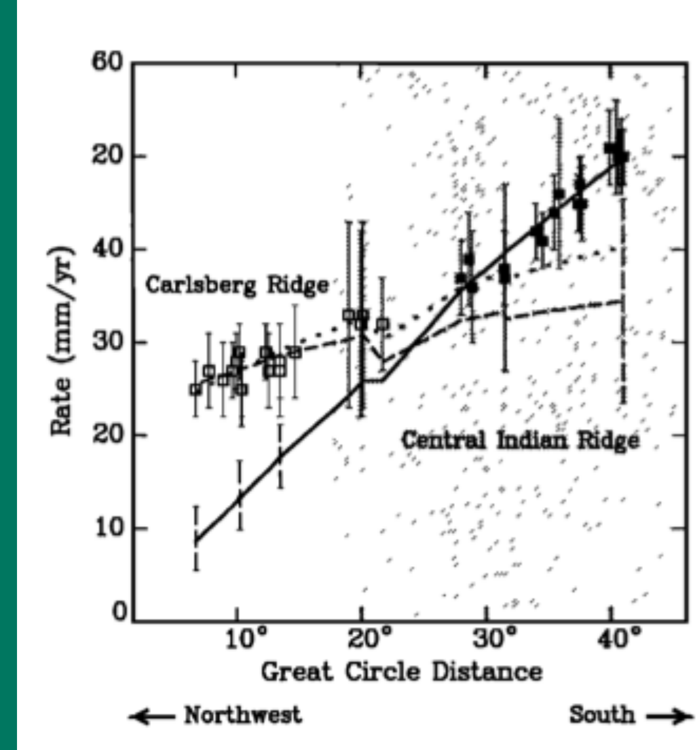
Motion between the Indian and Australian plate is constrained by an Euler pole (X) which is located within the deformation zone; compression on east side, extension on west side

The Euler pole was determined by detailed surveys of magnetic anomalies and FZs along the Central Indian ridge and Carlsberg ridge: observe slightly different spreading rates

Gordon and Stein (1992)



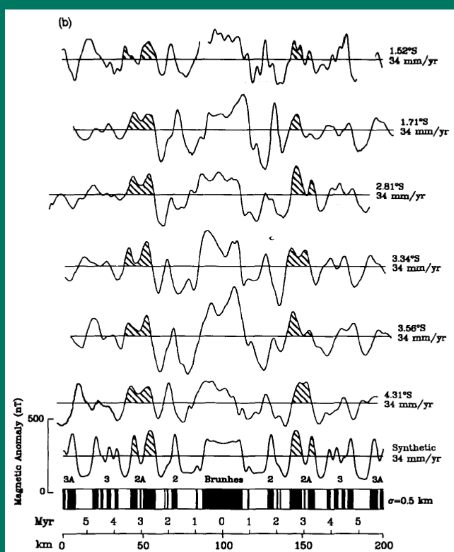


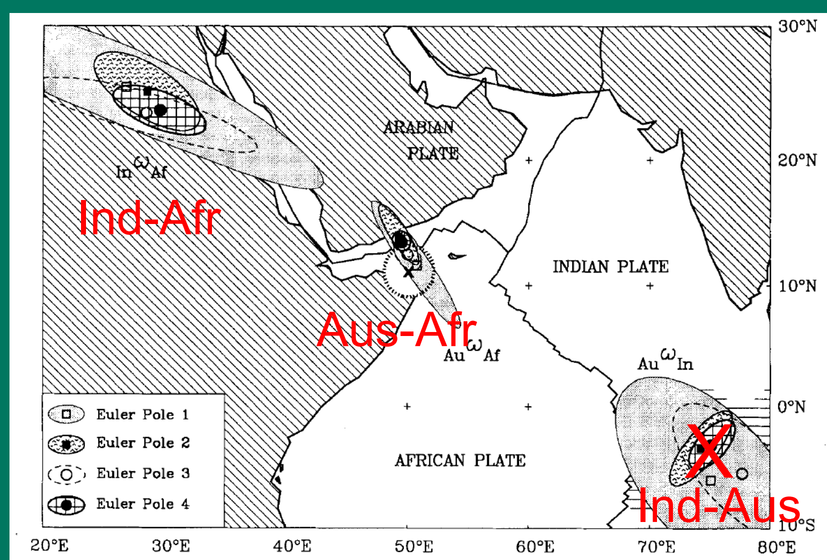


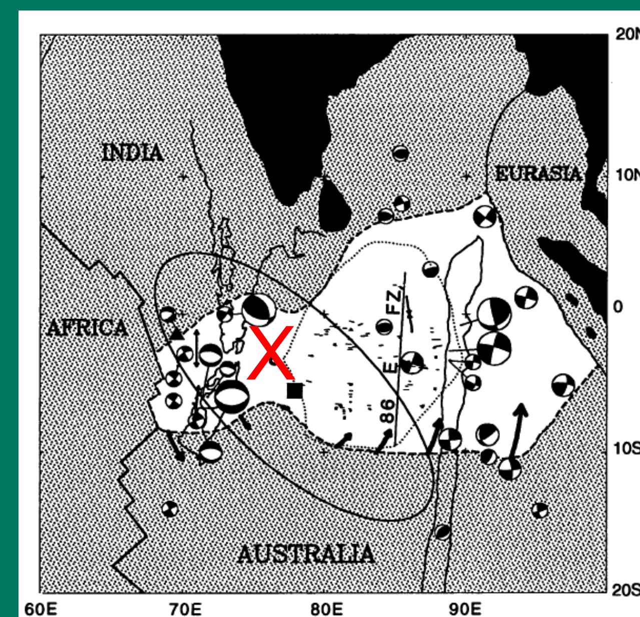
Indian-Australian deformation:

A textbook example of how to determine Euler poles using spreading rates, FZ azimuths, and vector summation

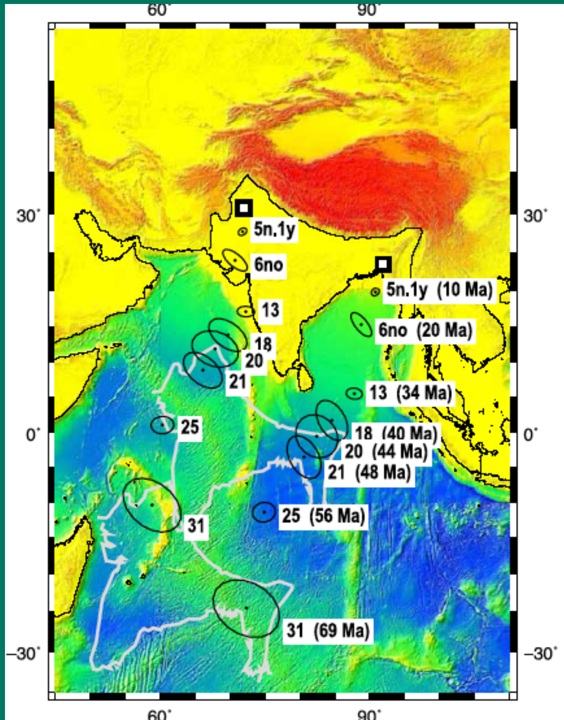
Ind-Afr – Aus-Afr = Ind-Aus

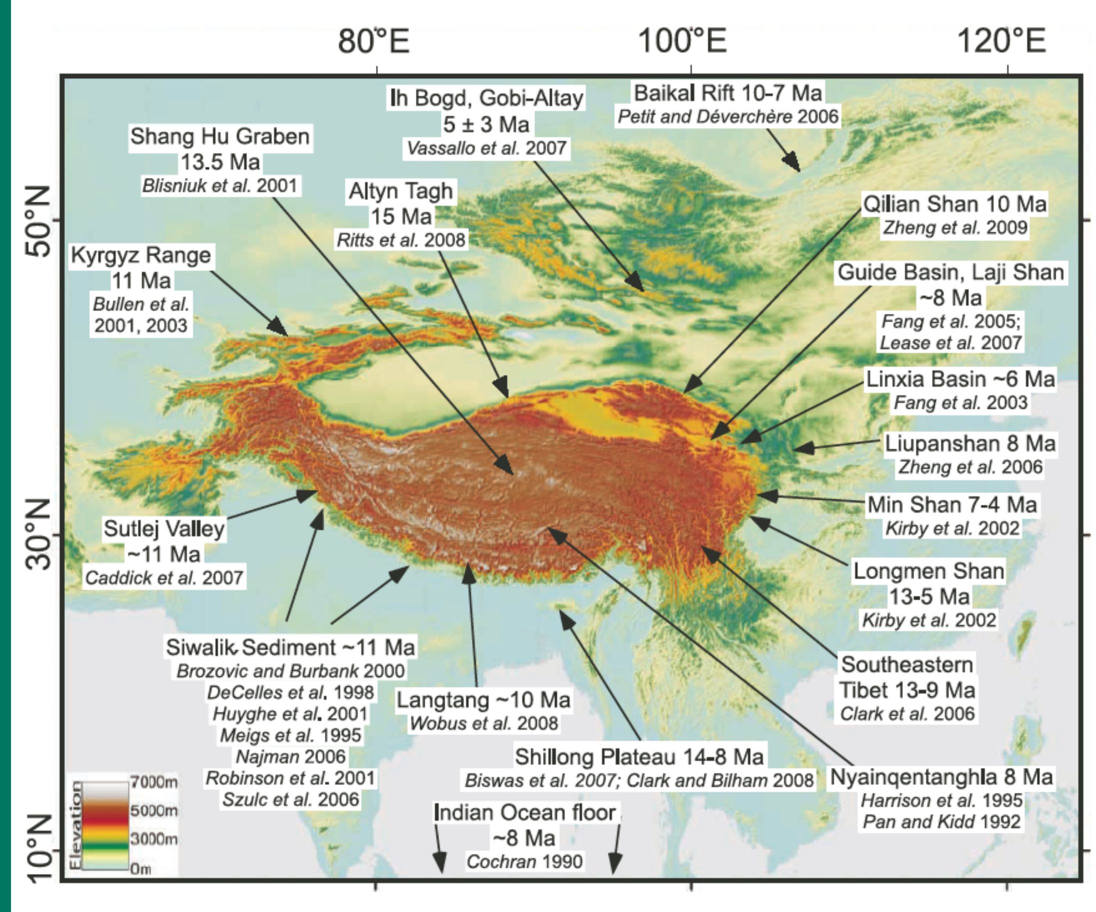




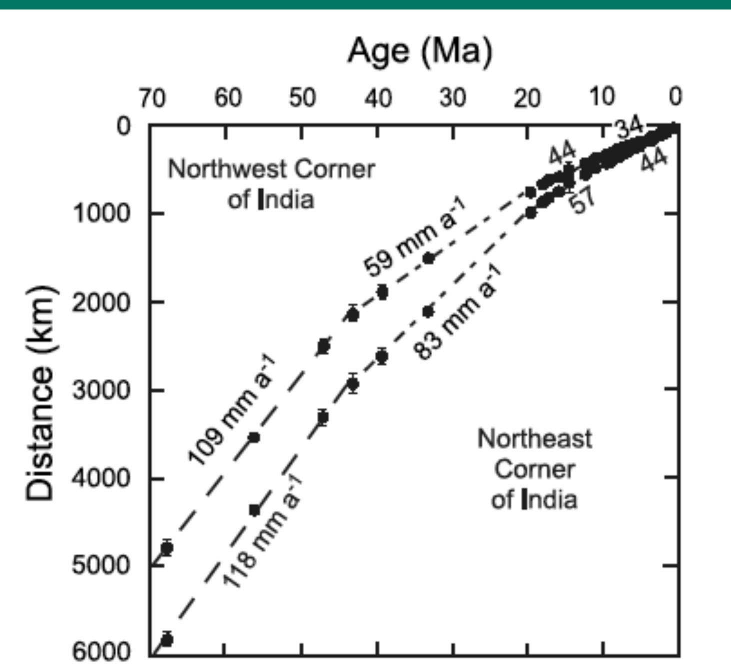


Gordon et al. (1990); DeMets et al. (1994)





Age of uplift in Tibet



Molnar and Stock (2009)

When did it start and why?

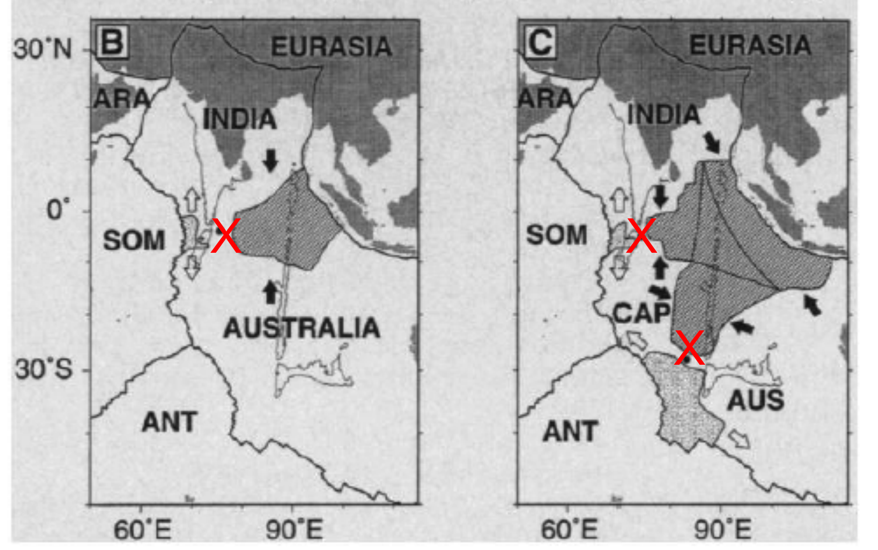
Compression started between 20 and 15 Ma.

Lithospheric folding (large gravity rolls) started at 8 Ma, with rate of deformation (convergence between Ind and Aus) tripling at that time

Perhaps related to an outward push from latest episode of uplift in Tibet (top)

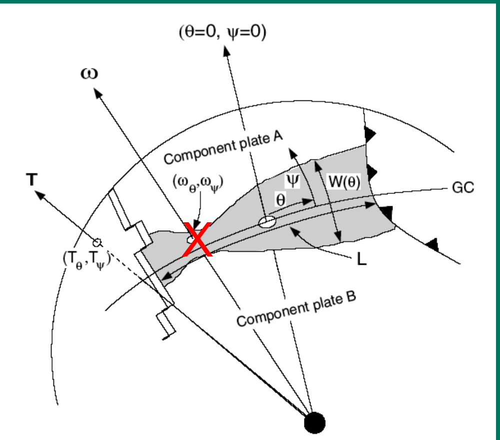
The uplift is relate to slowing of Convergence rate between India and Eurasia around 10-15 Ma

As if: India slowed down, Aus didn’t want to …



Royer and Gordon (1997) found another diffuse plate boundary within Australian plate;

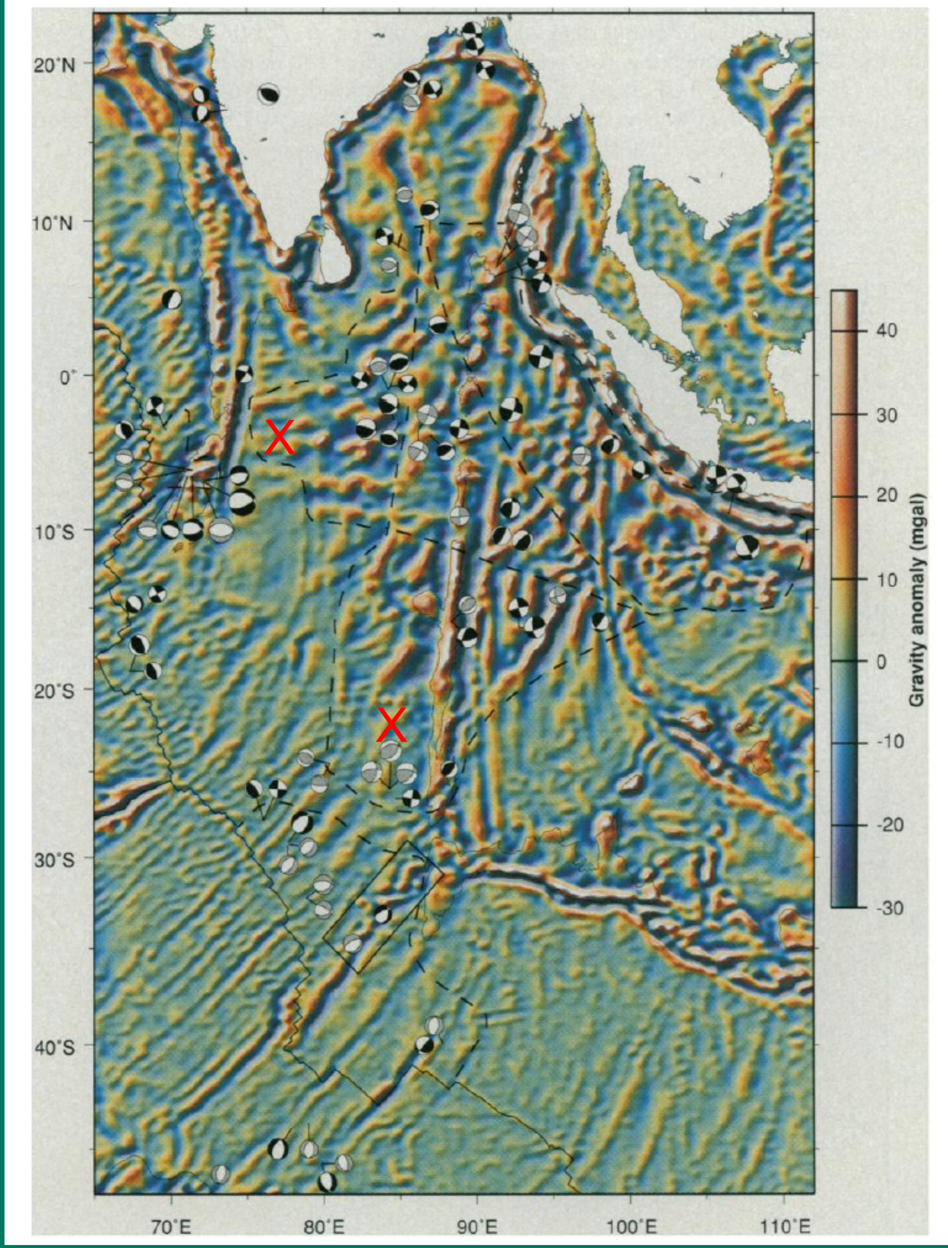
South of original boundary
Called the rigid area the Capricorn plate



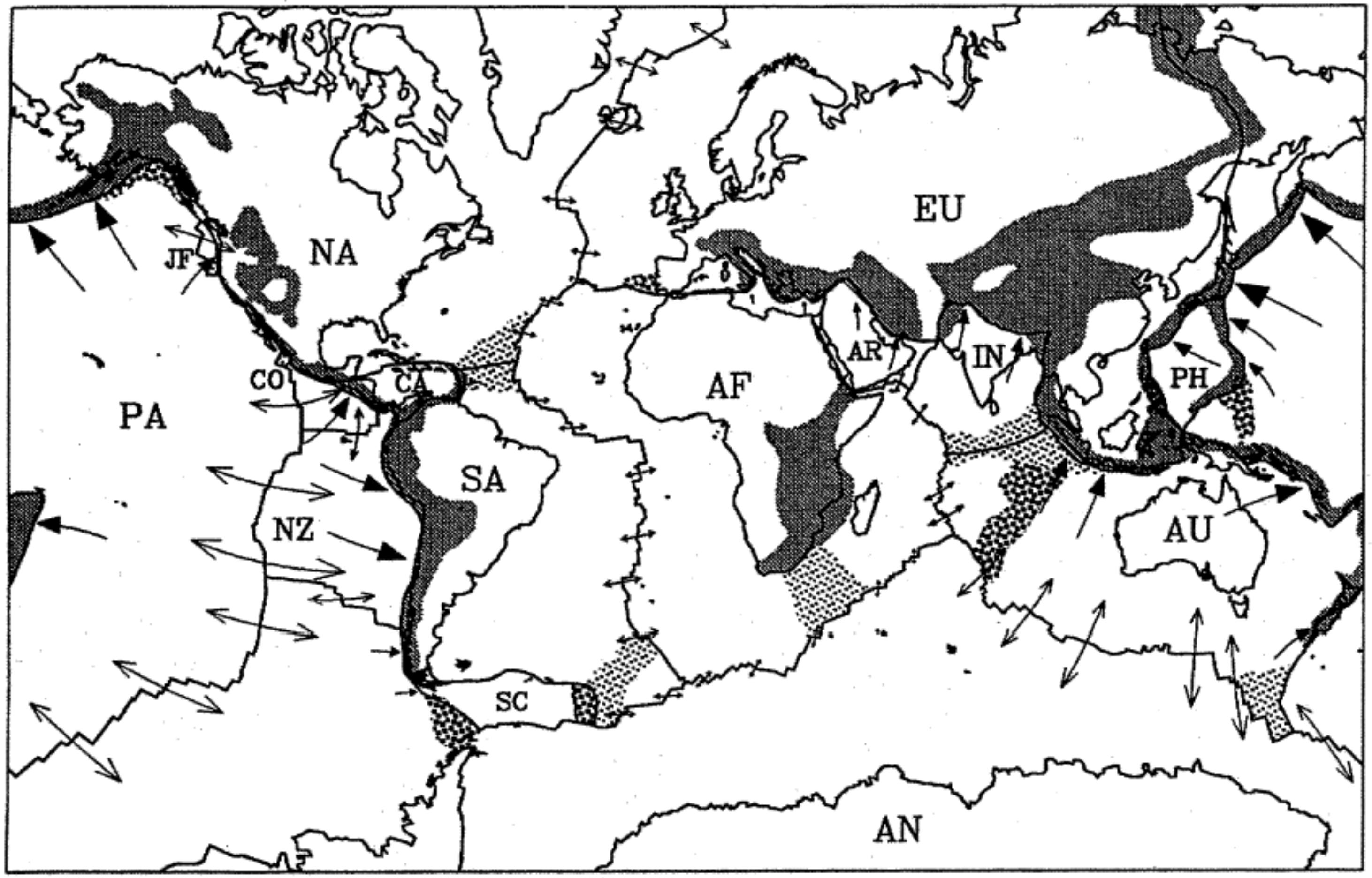
Found that Euler pole (X) also was in the diffuse boundary zone
Showed there was a geodynamic preference for the rotation pole to be along boundary

Refer to the smaller areas as component plates

Zatman et al. (2005)



Royer and Gordon (1997)



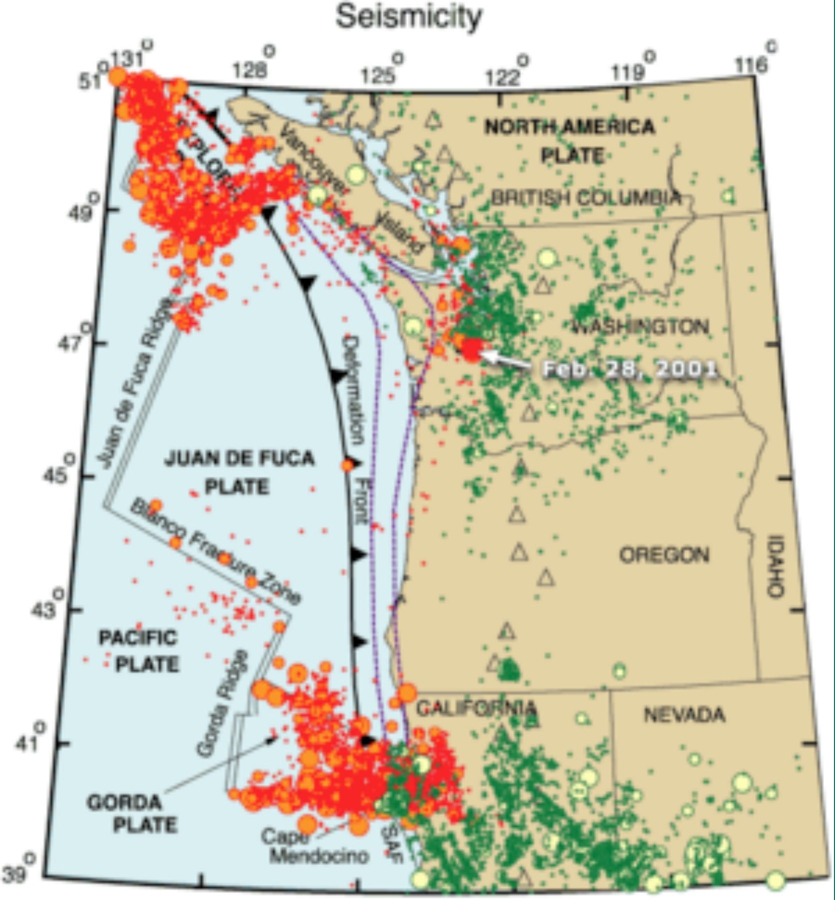
Diffuse plate boundaries

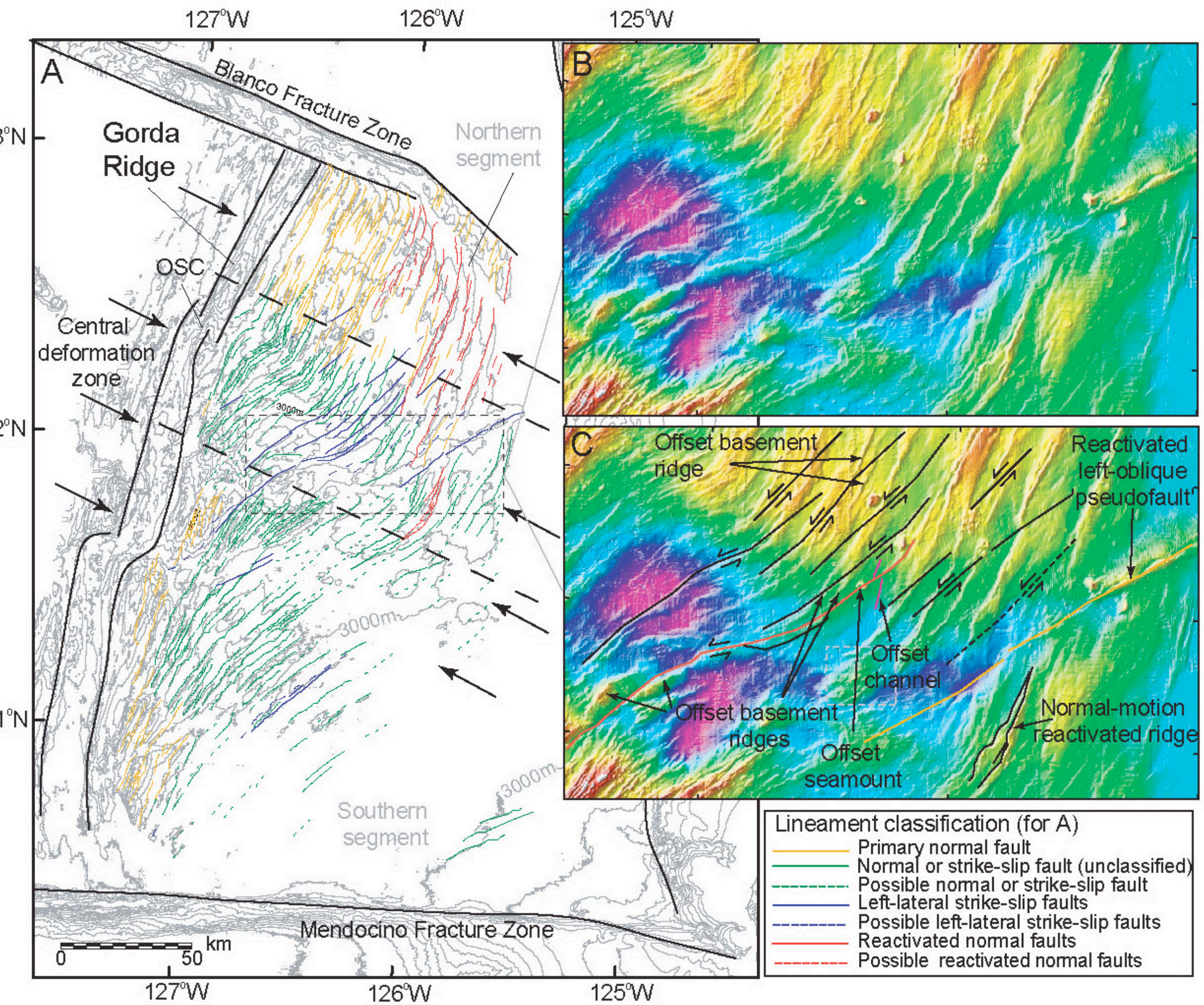
Dark = continental
Lighter = oceanic

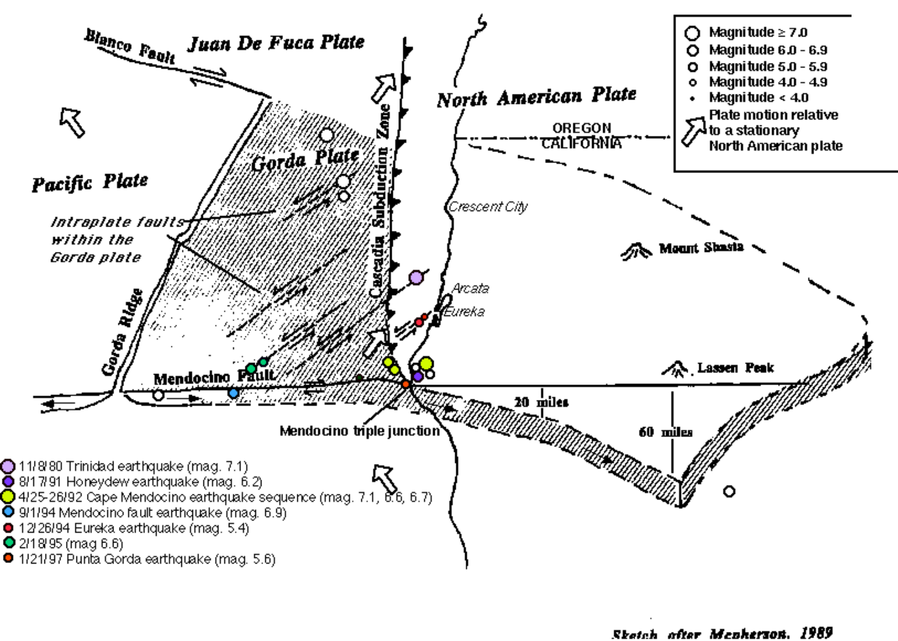
If you throw in continental areas which are deforming then:

areas of ongoing deformation = 15% of Earth's surface

Gordon and Stein (1992)







Oregon State University
Moment Tensor Database

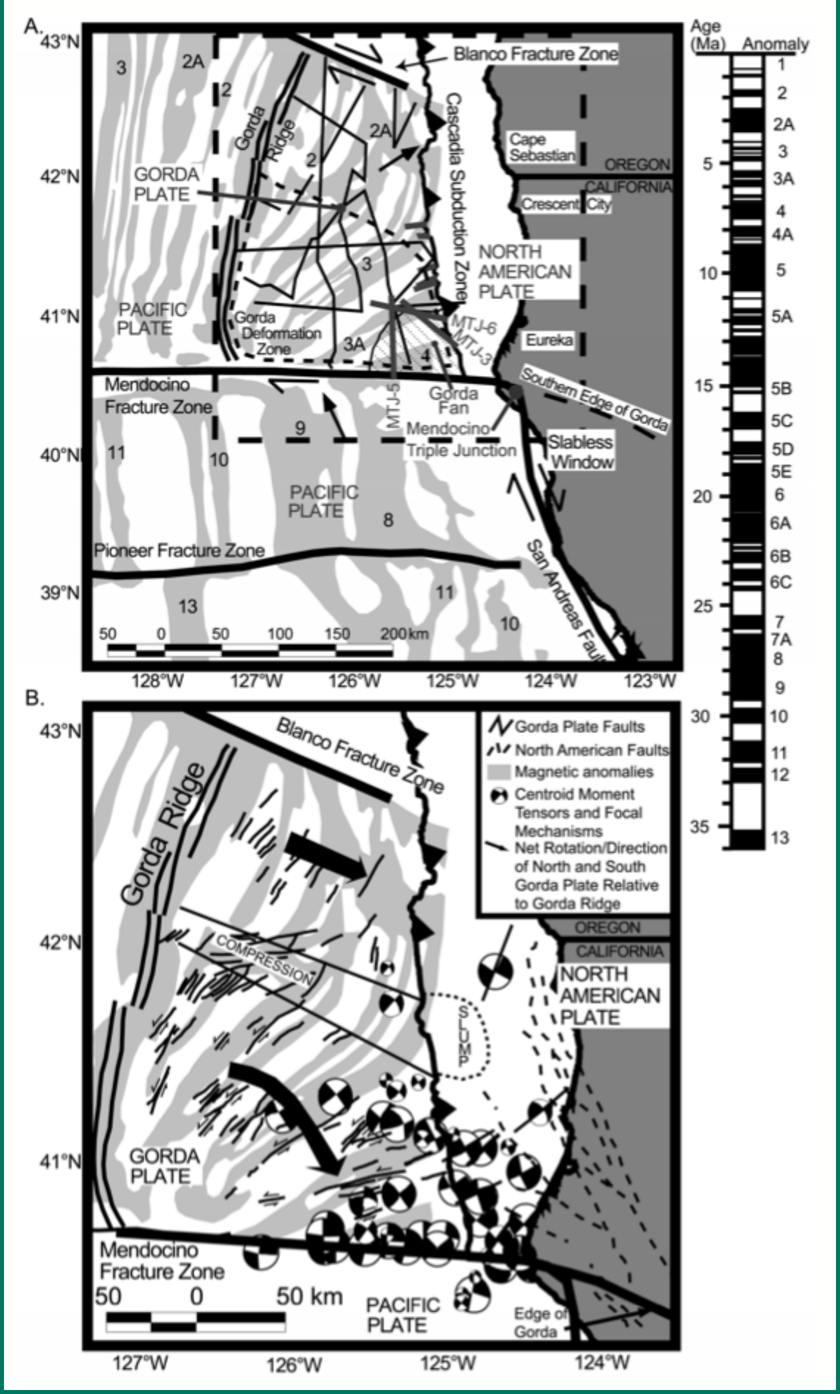
Gorda plate: deforming zone on southern part of Juan de Fuca plate

Reason Atwater used Blanco transform to estimate motion of triple junction

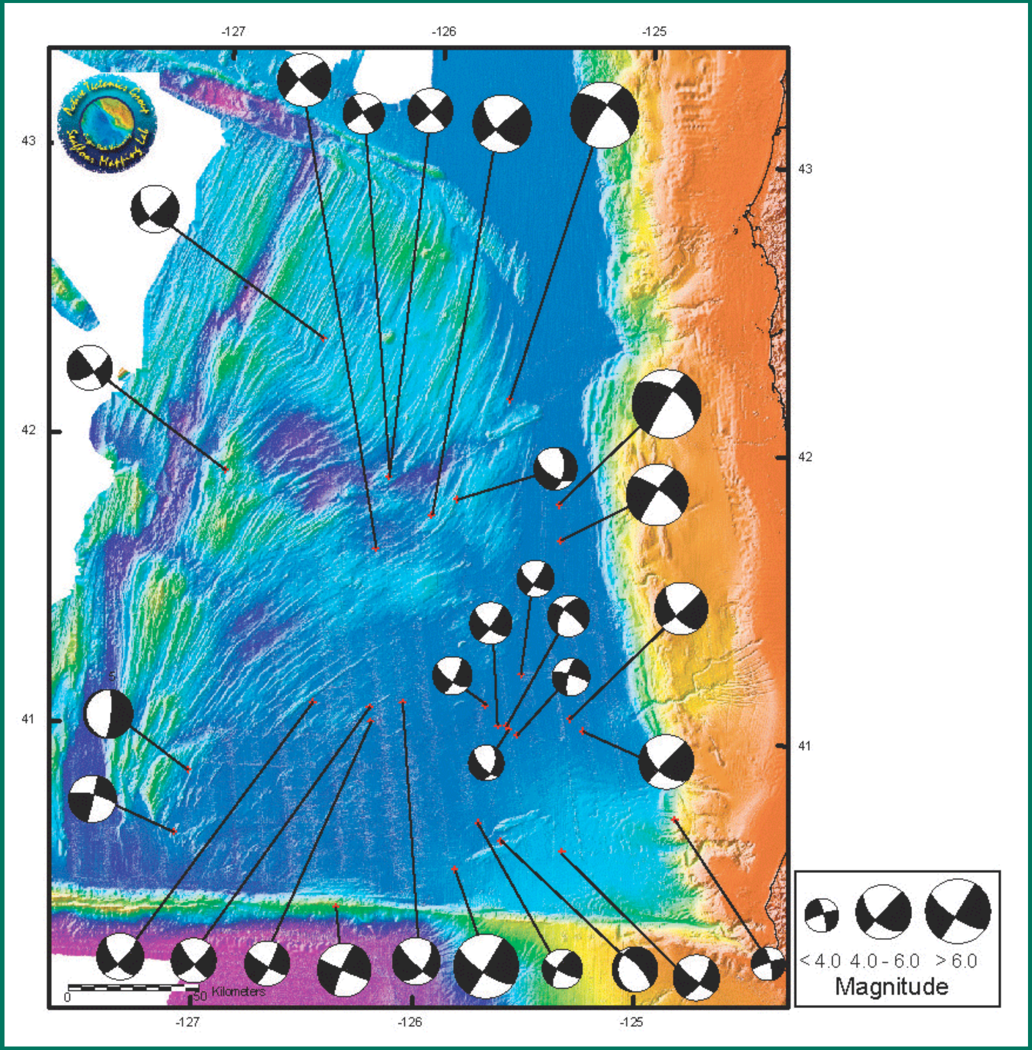
Cause is debatable:

One idea: Southeast of the triple junction, a slab window is generated by removal of the subducting Gorda plate.

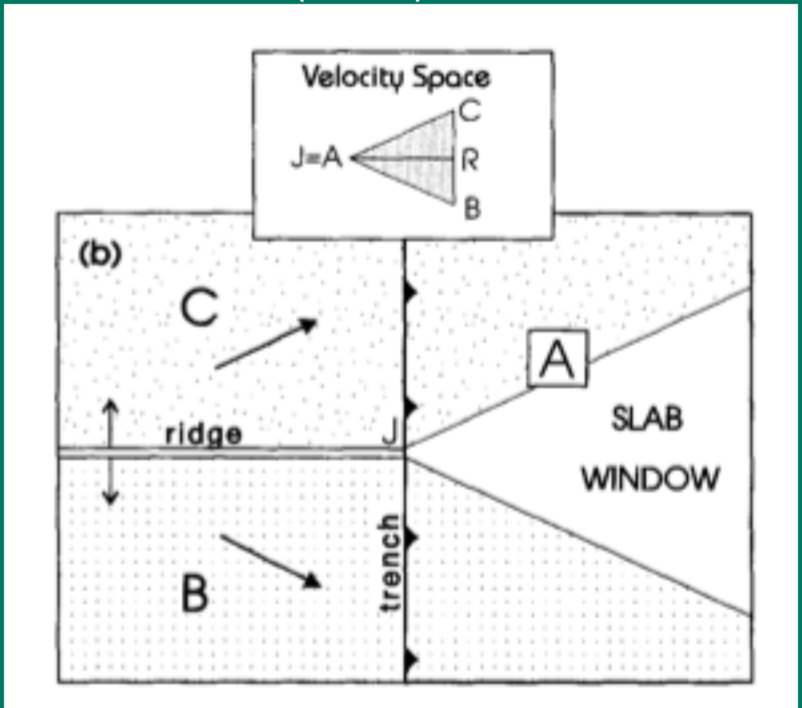
Southwest of the triple junction, the Pacific plate acts as a rigid barrier forcing southern Gorda crust to rotate clockwise, fragment, and flow into the slabless window.



Gulick et al. (2001)



Thorkelson (1996)

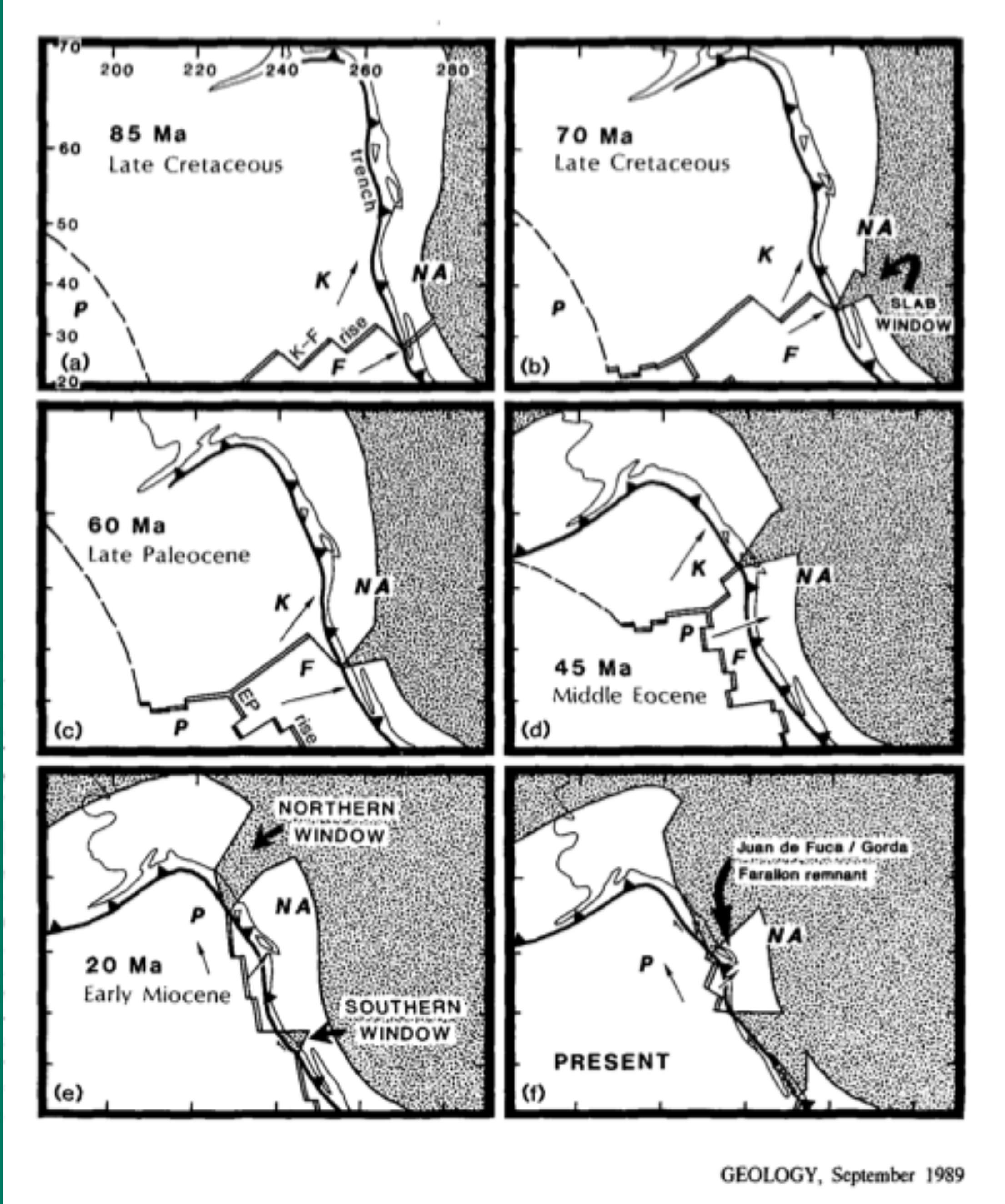


Slab window = region beneath an active margin where there is no underlying subducted crust that was generated at the seafloor

Slab windows can form when spreading ridges subduct depending on the plate geometry.

The gradual subduction of the Pacific-Farallon and Farallon-Kula ridges led to the formation of large slab windows beneath western North America

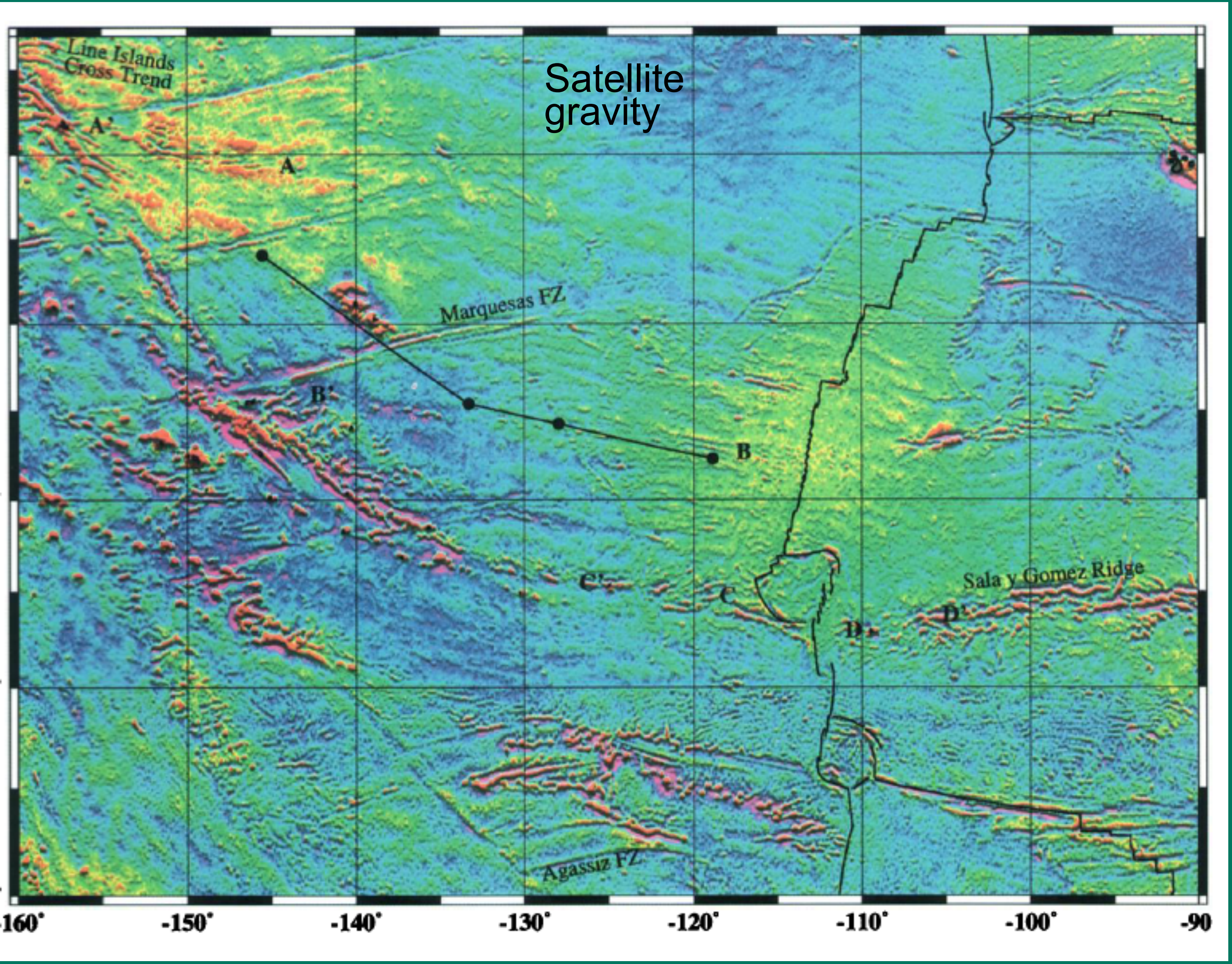
Slab windows are in grey



GEOLOGY, September 1989

Thorkelson (1989)

Gravity rolls – a more subtle type of deformation



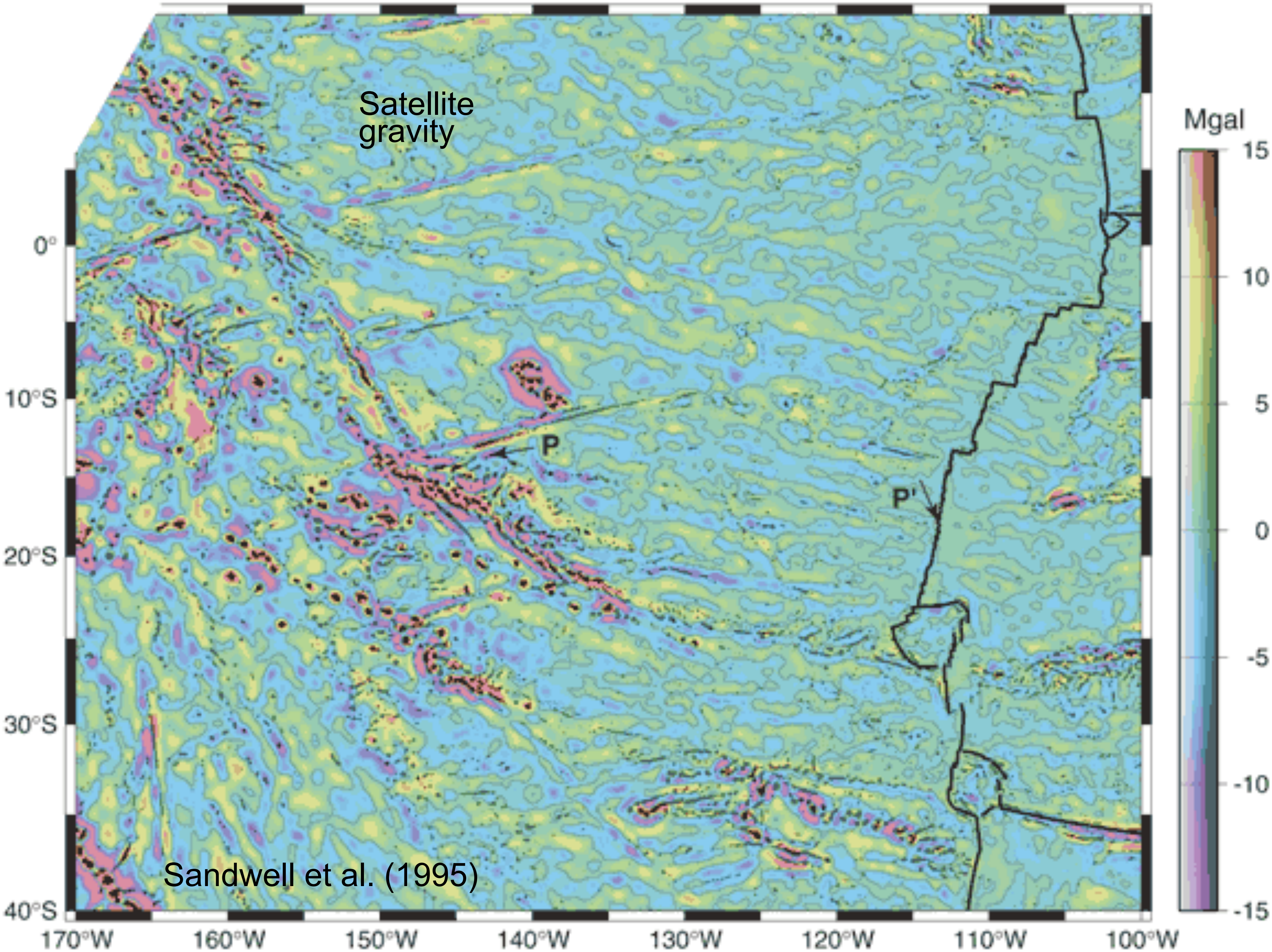
Linear gravity anomalies,
Perpendicular to ridge axis,
10 – 20 mgal amplitude,
300 - 500 km wavelength,
1000's of km long
Associated with volcanic lineaments

Discovered in 1986 when satellite radar altimetry (gravity) data were first collected

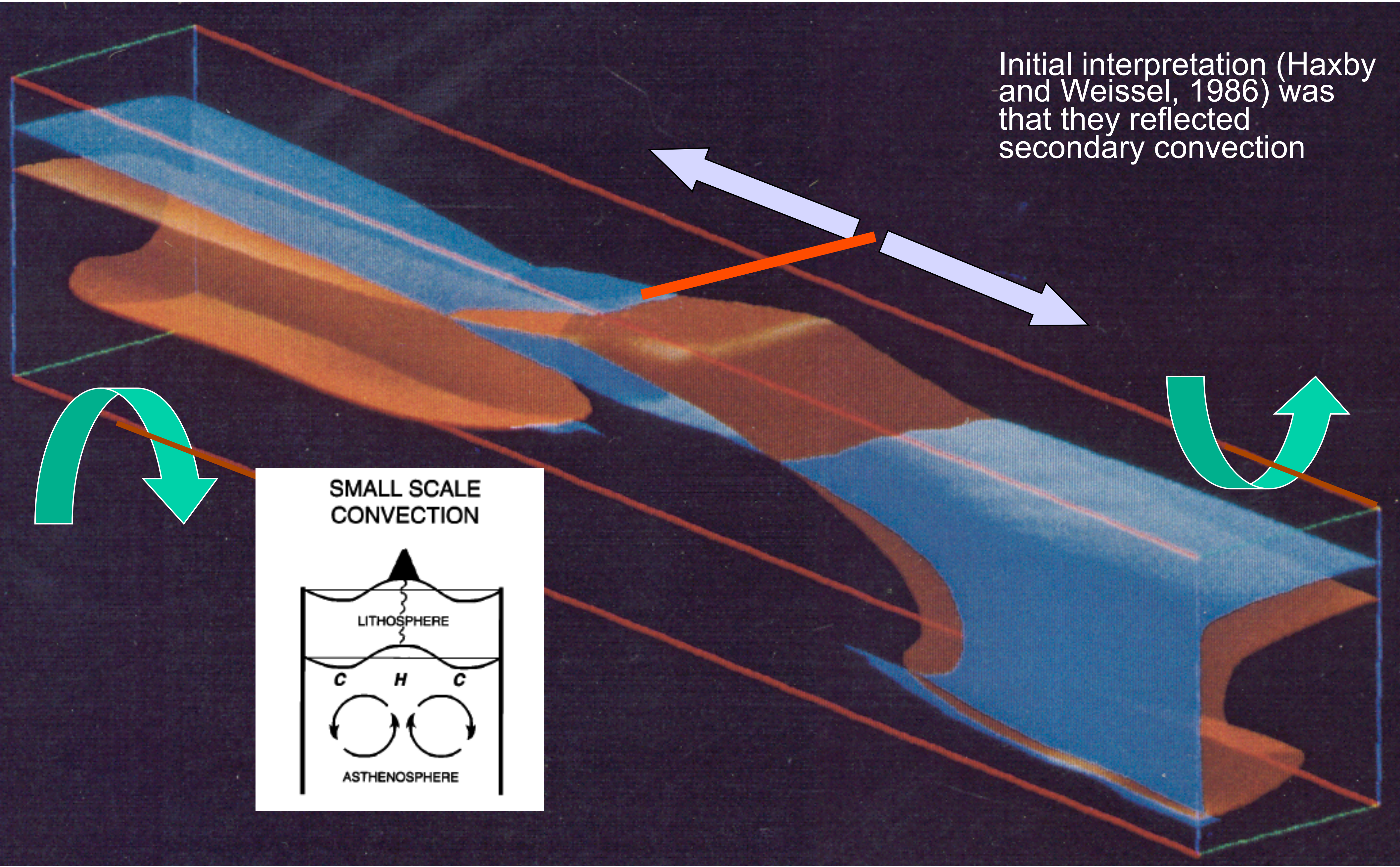
Begin to develop about 2-3 Ma off axis, fully developed by 6 Ma

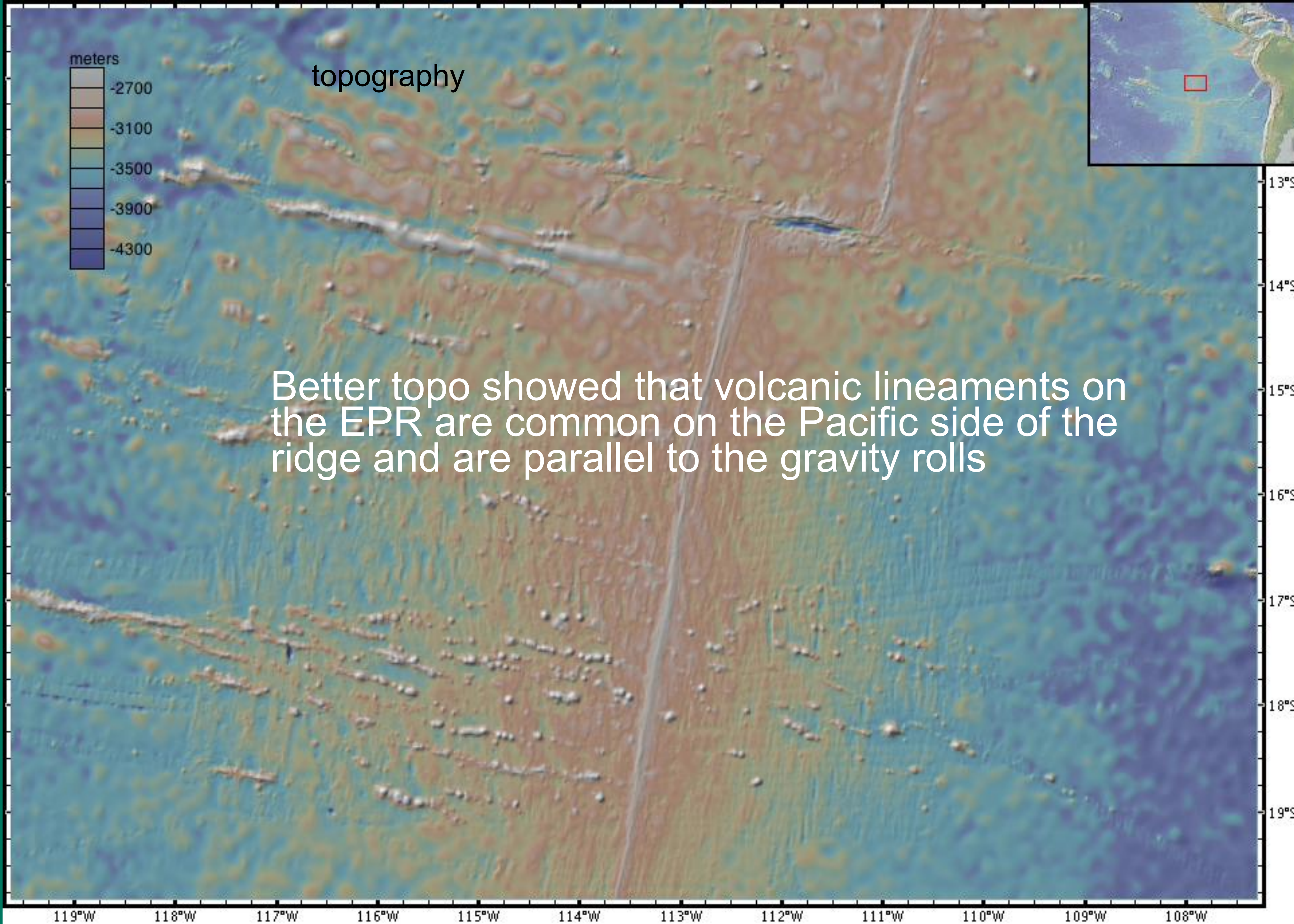
Better developed on Pacific plate than on Nazca plate

PUKAPUKA SEAMOUNT CHAIN

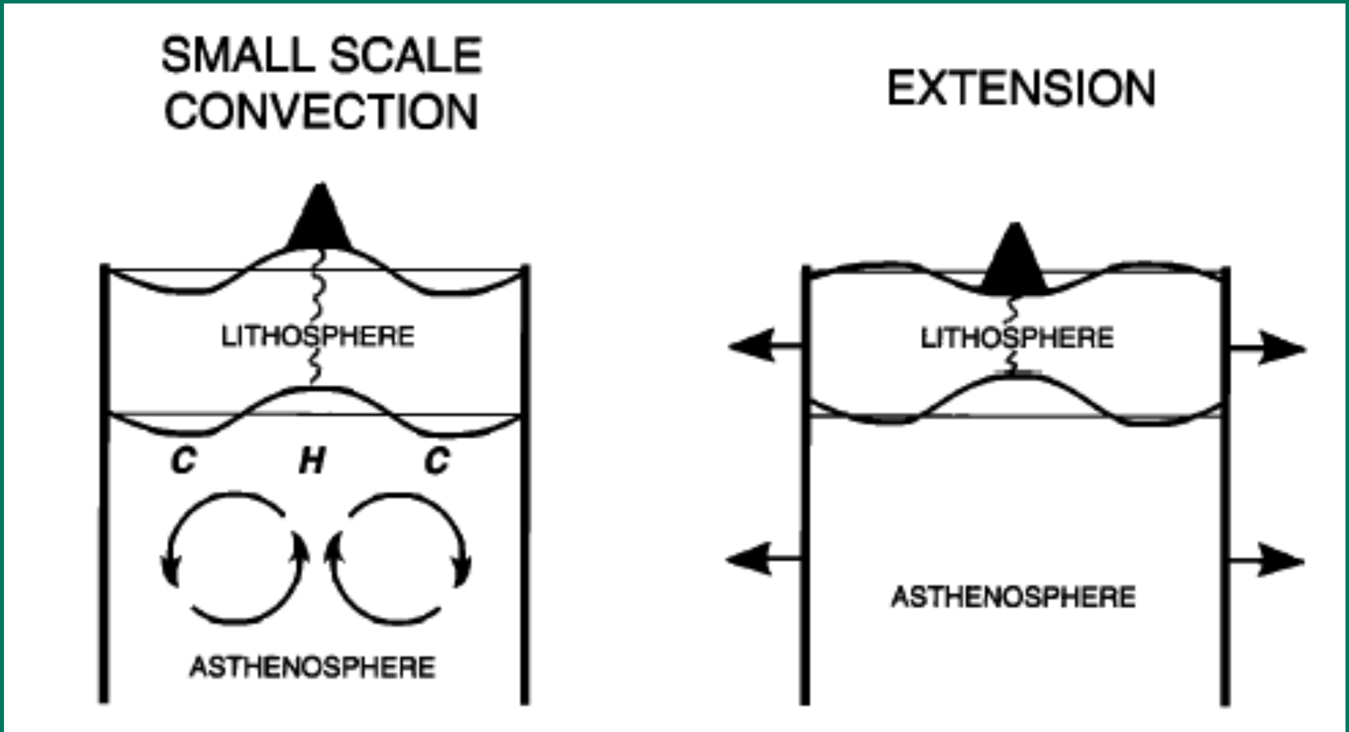


Mantle convection can both **drive** the plates, but also be **induced** by shear at the base of the lithosphere. Here the passive spreading of the the mid-ocean ridge produces a convective roll in the underlying asthenosphere.





Better topo showed that volcanic lineaments on the EPR are common on the Pacific side of the ridge and are parallel to the gravity rolls



Sandwell et al. (1995) pointed out that it is important to look at the relationship between the volcanic lineaments and the gravity rolls

If the volcanic lineaments are in the trough, the rolls may reflect extension in the plate

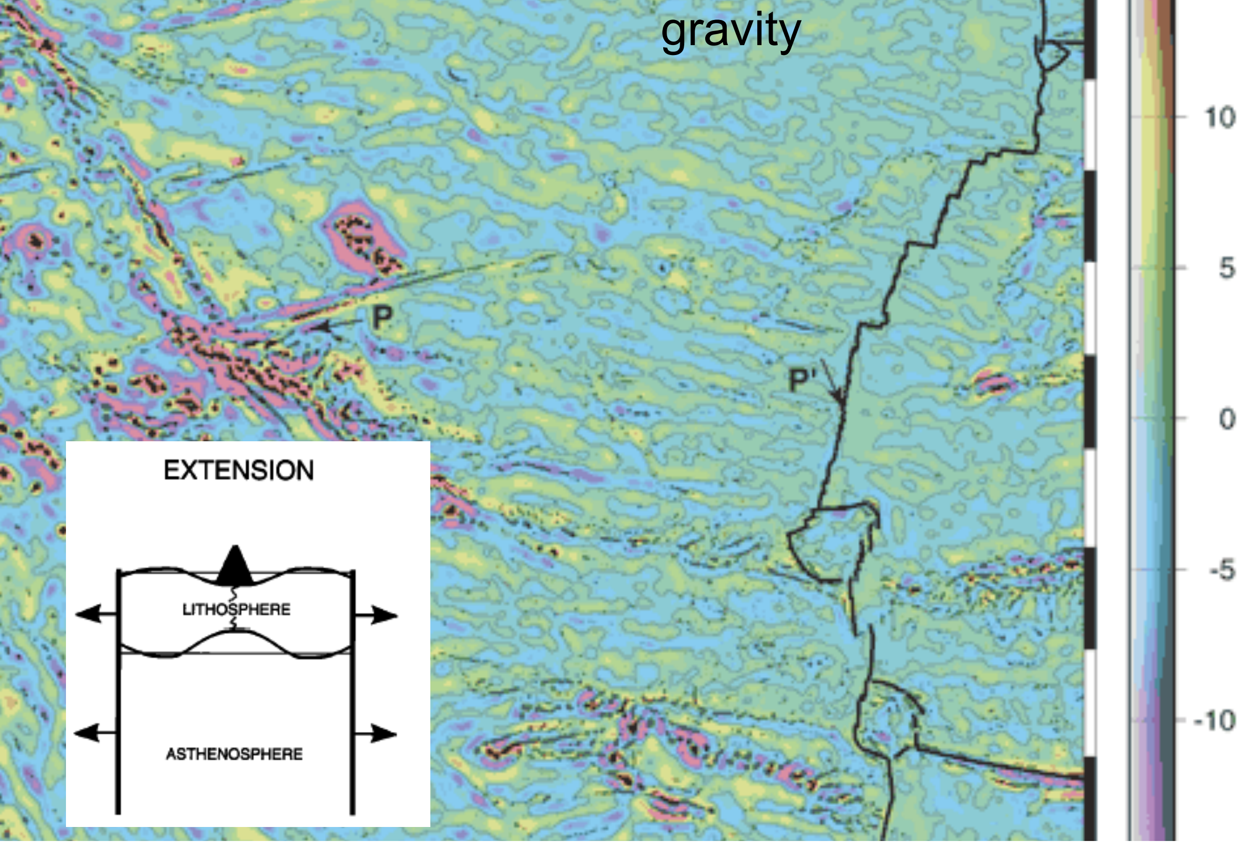
"Boudinage extension" model

Example of boudinage

Layers of harder rock break into chunks when deformed

From French word for sausage

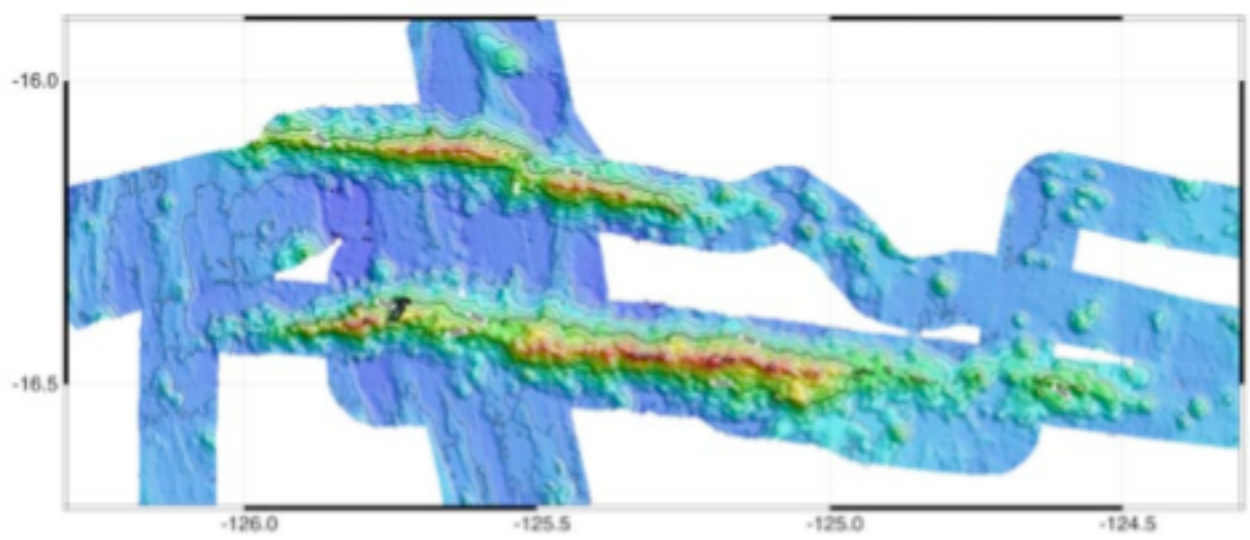
Sandwell et al. (1995)

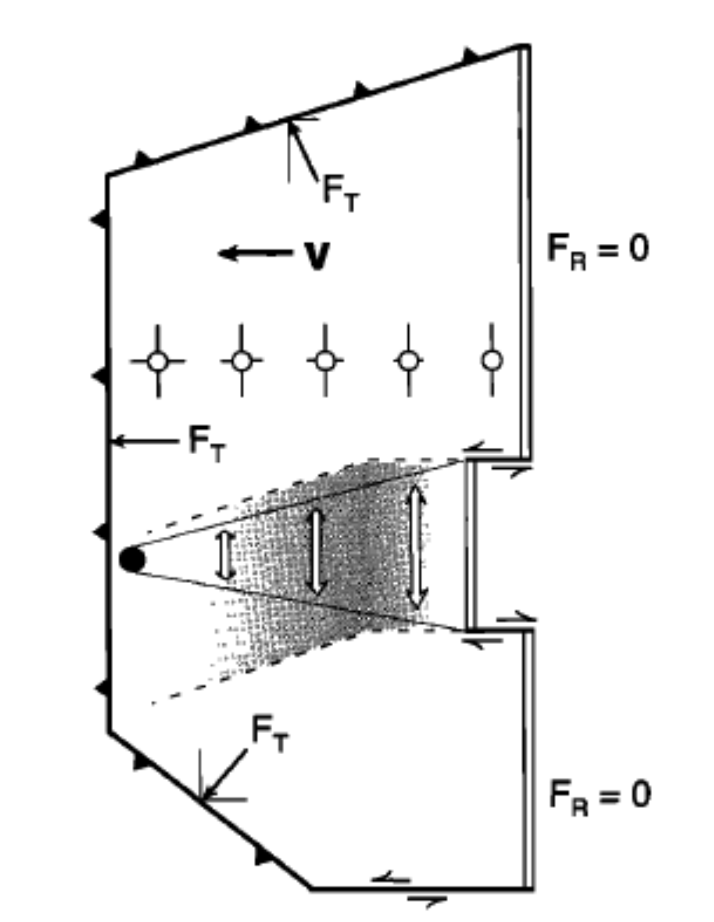


Sandwell et al. (1995) showed that the Puka-Puka volcanic lineament (P-P') ran along a gravity trough

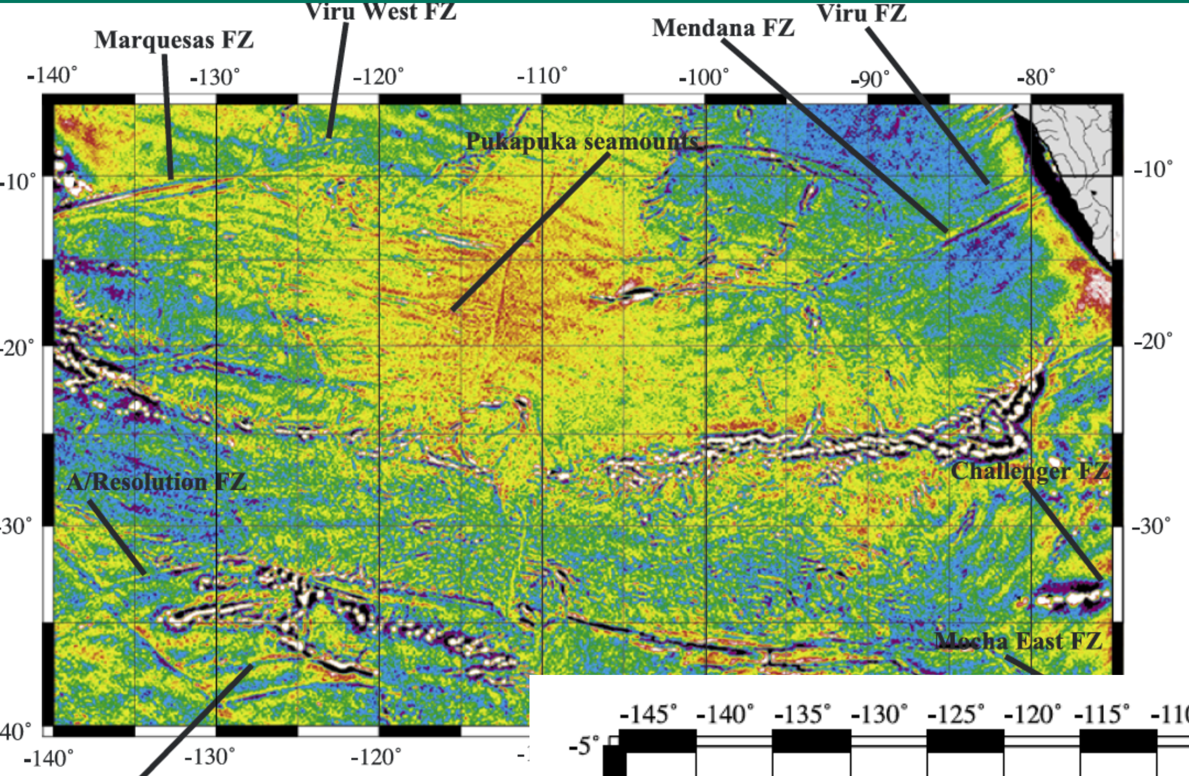
Proposed that the Pacific plate was being stretched by slab pull Therefore, supported extension of the plate;

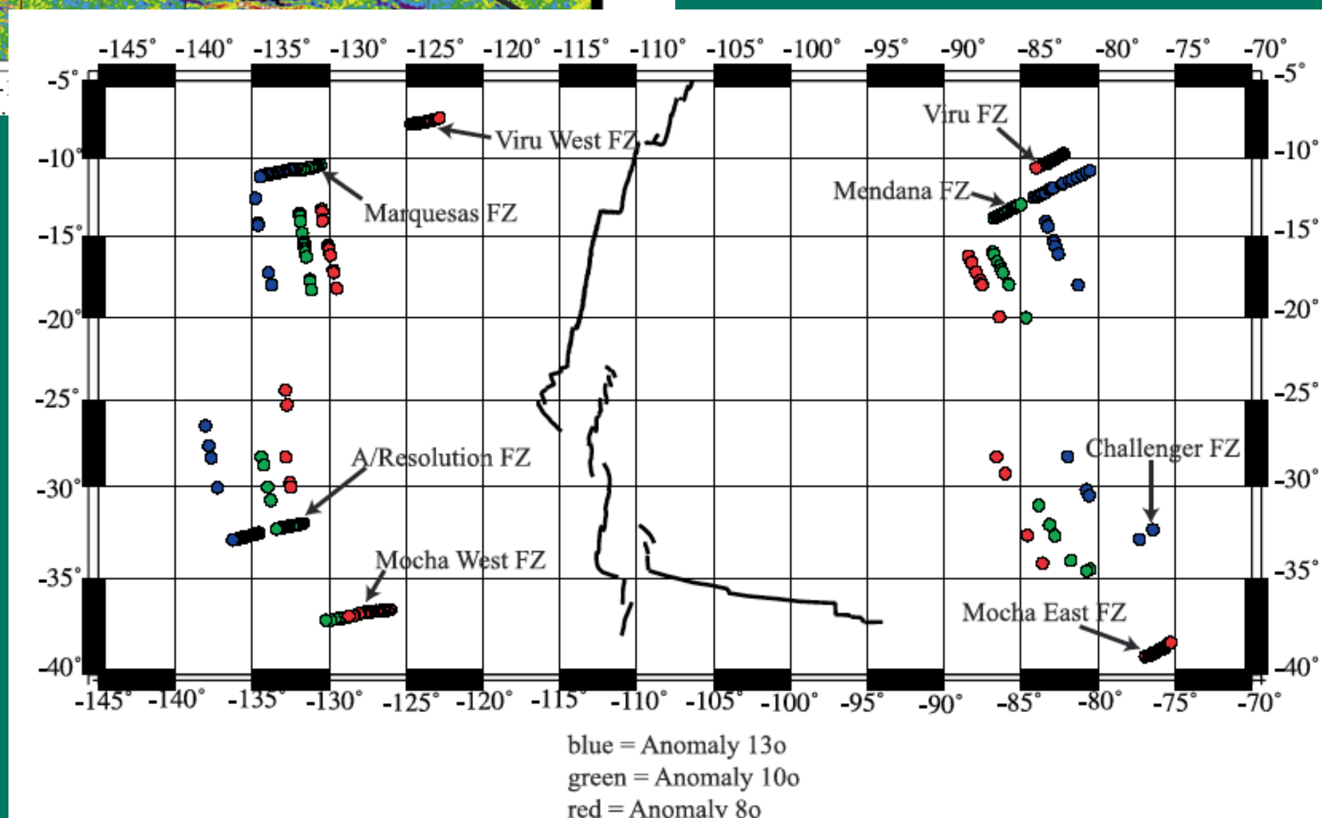
Potential problem: model required 10% stretch





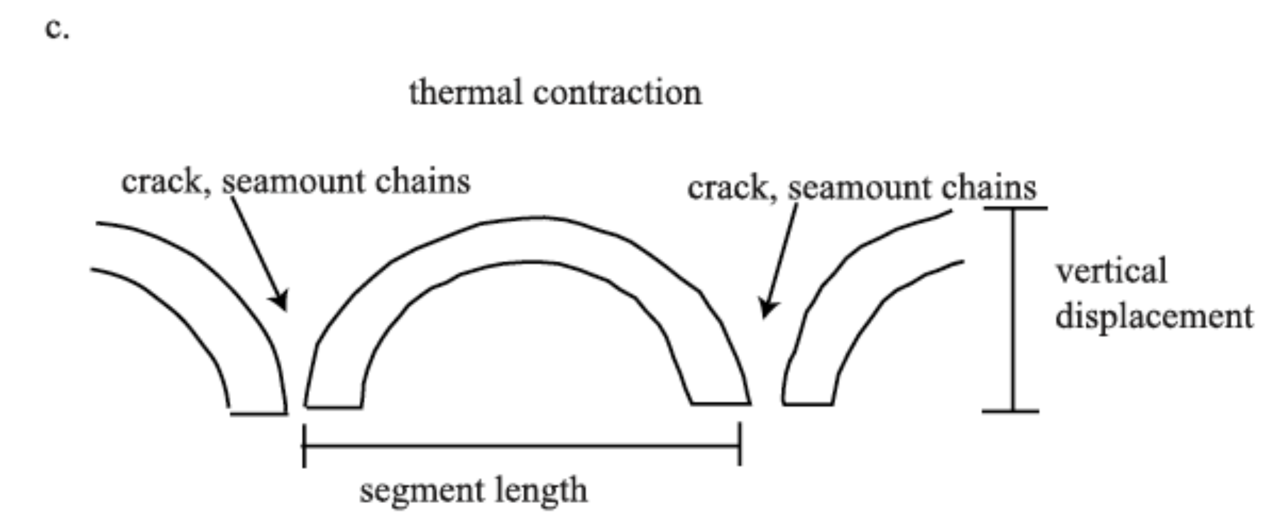
Winterer and Sandwell





Gans et al. (2003) measured the distance between conjugate FZs on the Nazca and Pacific plate

They found that they were roughly the same distance apart and supported less than 0.5% stretching of the Pacific plate



Gans proposed that the gravity rolls are due to warps and cracks caused by uneven thermal contraction

Due to bending stresses caused by vertical variations in cooling rate

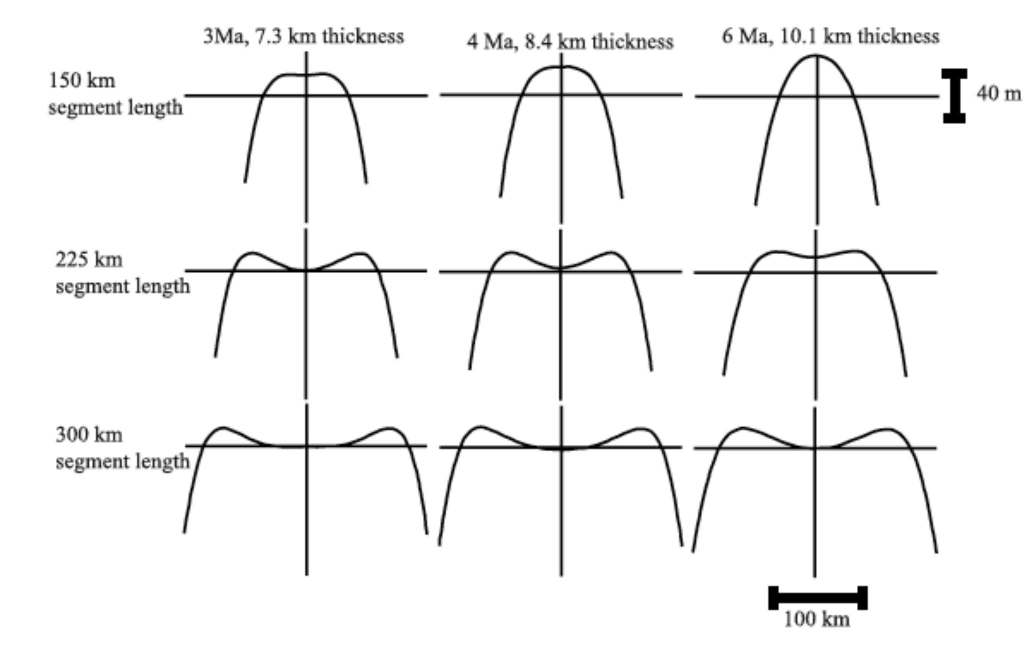
Below models based on simple theory

Gravity lows are areas of weakness subject to brittle failure in the form of cracks that penetrate lithosphere

If plate cracks, then contraction of the lithosphere occurs when plate cools

Lithosphere cools faster at bottom than at top so contracts faster

This causes thermal stresses which produce a bending force which bends the plate convex upward between the cracks



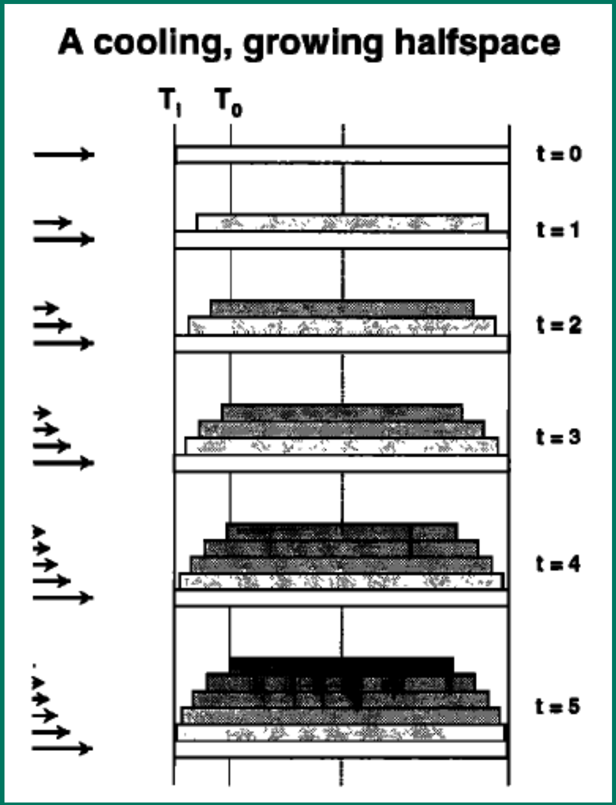
But, their model did not explain crack spacing and underestimated the amplitude

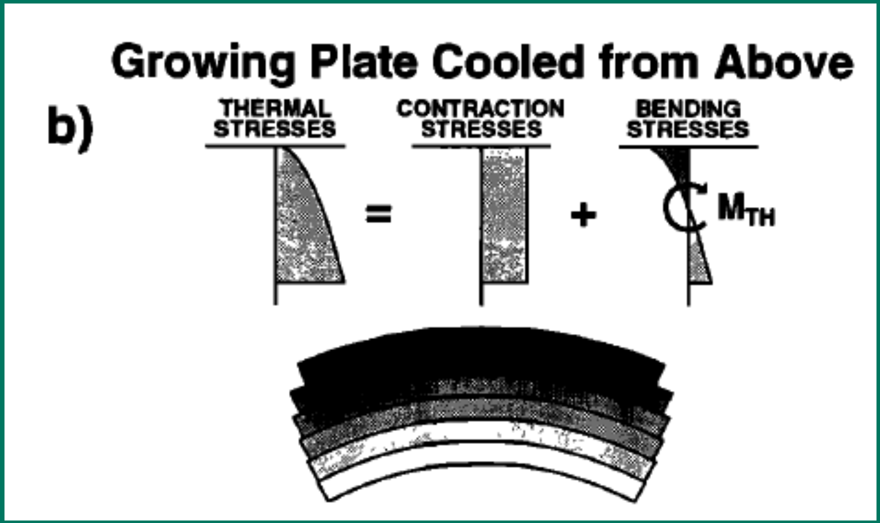
This might not be intuitive but consider this:

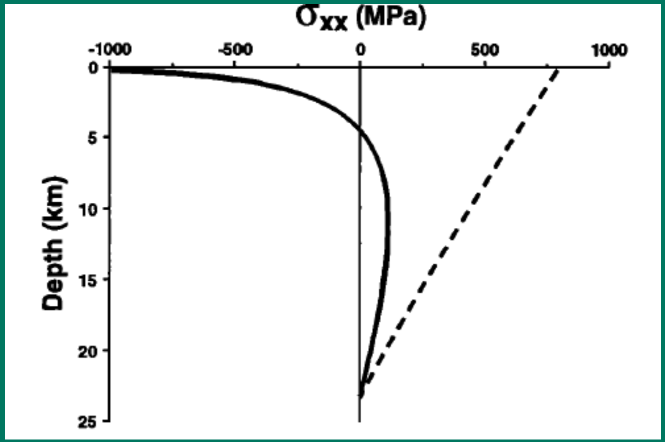
The bottom of the lithosphere is cooling faster than the top because the top has already cooled. The bottom is hotter and, just as with the sq. rt. of T, the hotter part cools at a faster rate.

From Wessel (1992): Make a layer, the top is in compression from the bottom which is cooling faster. Then add a layer below it. This layer then puts the bottom of the layer above it under compression as it cools. Bottom layers want to contract but are held back by upper cooler layers. If relieve depth-average contraction, we are left with a plate that is under compression at surface and tension at depth

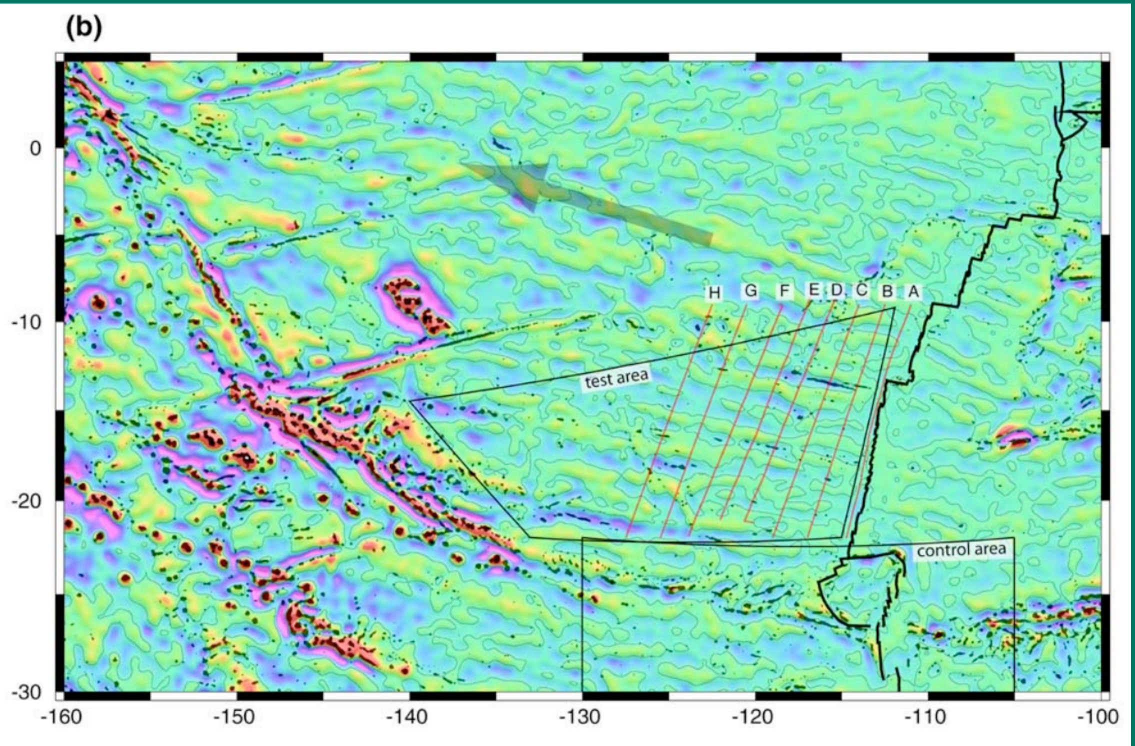
Same as tempered glass. Which puts outside of glass under compression so that a scratch doesn't cause it to break.

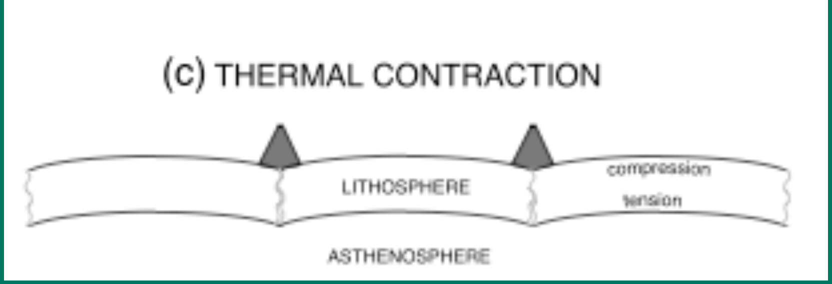






Wessel (1992)





Sandwell and Fialko (2004)

Did a more rigorous modeling of same effect

Got an amplitude 1.6 times greater than Gans , which matched observations