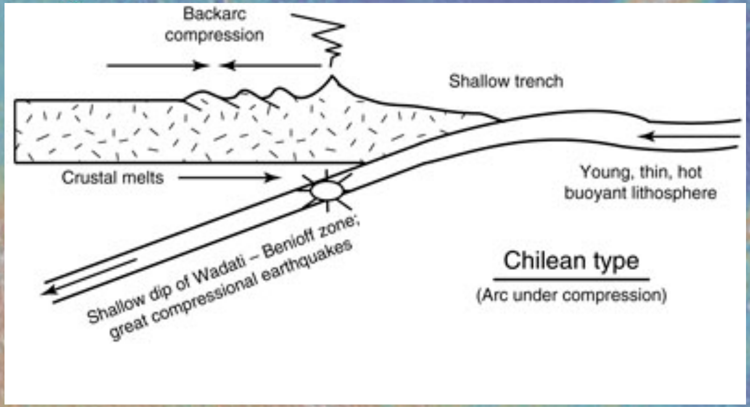
Lecture 12: Orogeny

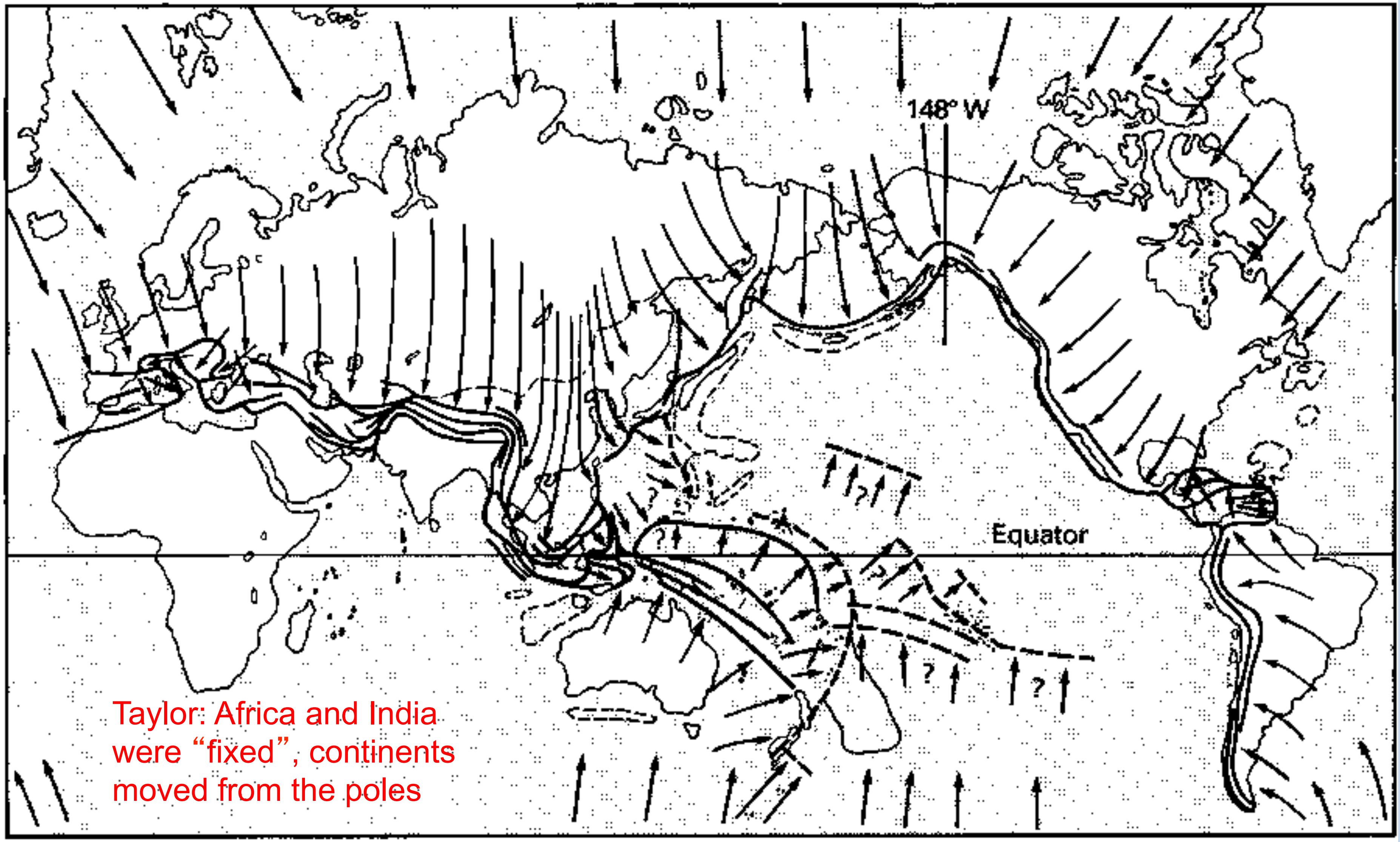
Andean (non-collisional, ocean-continent)
Himalayan (collisional, continent-continent)

Read sections 10.1 to 10.4 in KK&V



Above: *The highest Peak to Peak summit - Aconcagua*

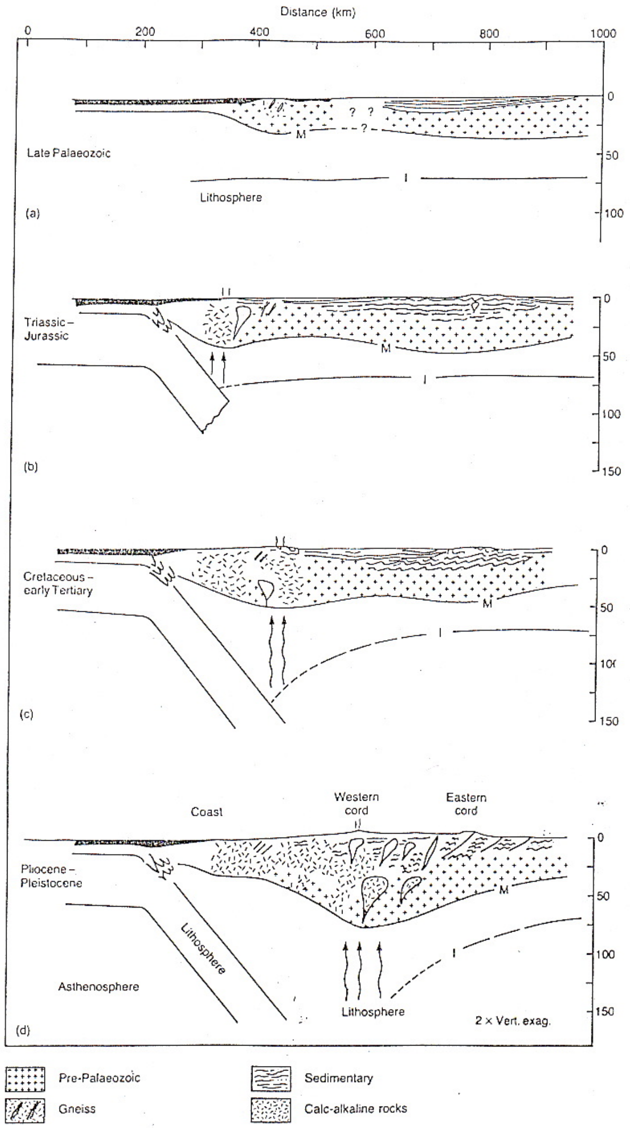
Early explanations for arcuate mountain ranges…



Taylor: Africa and India were “fixed”, continents moved from the poles

Fig. 1.2 Taylor’s mechanism for the formation of Tertiary mountain belts by continental drift (after Taylor, 1910).

Classic Andean Orogeny



Late Paleozoic:

Passive margin

Triassic-Jurassic:

Onset of subduction and
arc magmatism

Cretaceous-early Tertiary

Landward migration of arc

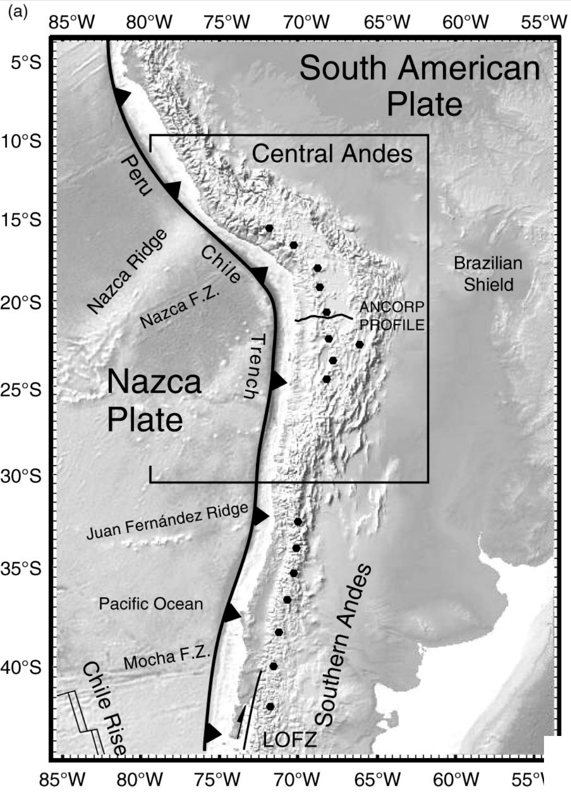
Neogene

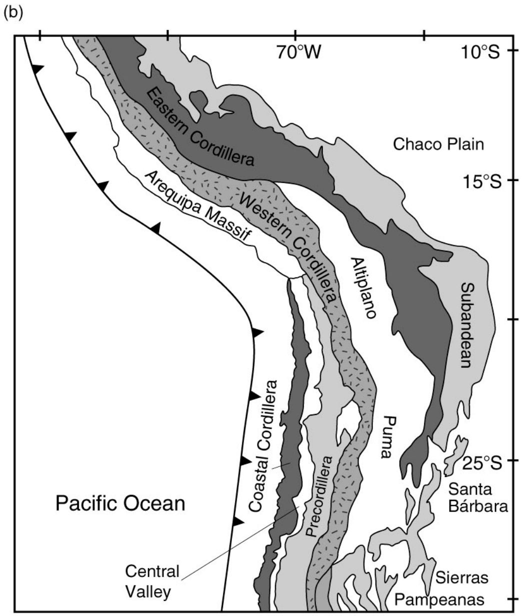
Further migration of arc
Enhanced magmatism
Development of foreland
fold and thrust belts

JAMES (1971)
from K&V

More recent (pre-1970's) view of the formation of the Andes

Actually, a lot less is magmatic than is implied by this figure



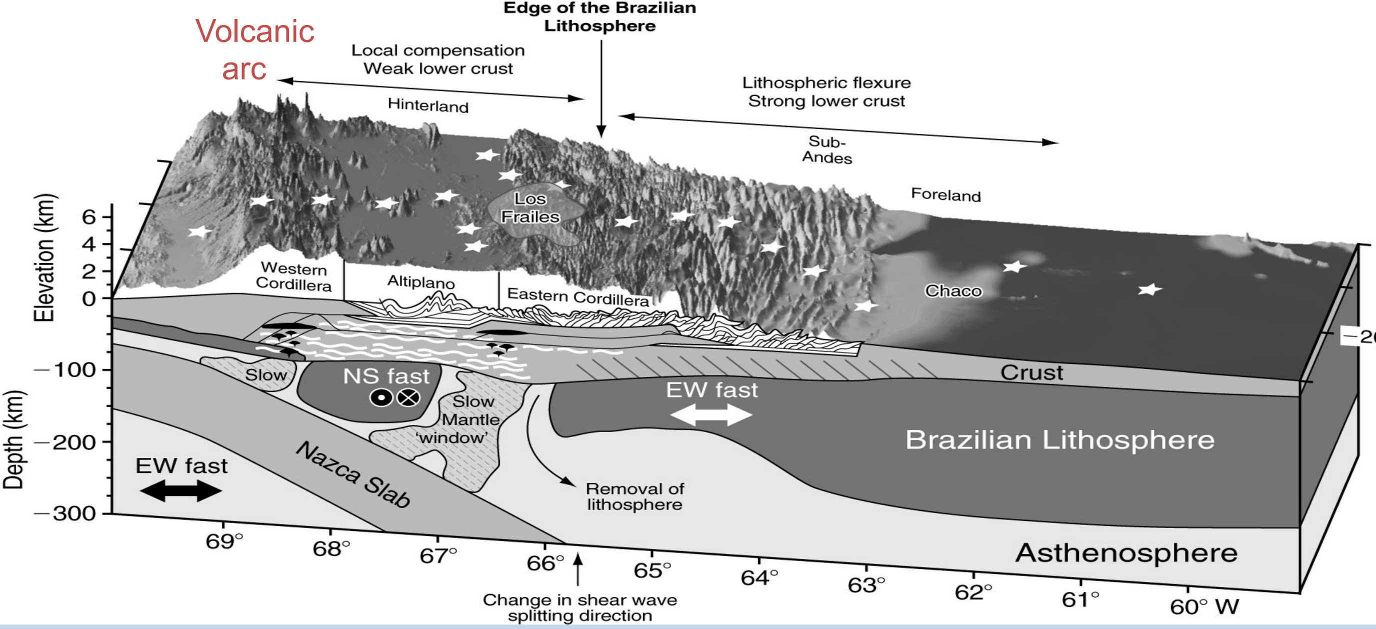


Only parts of the Andean range are magmatic

In the widest parts, the bulk consists of folded and thrusted sedimentary and basement rocks

Western cordillera = volcanic arc
Eastern cordillera = culmination of fold and thrust belt

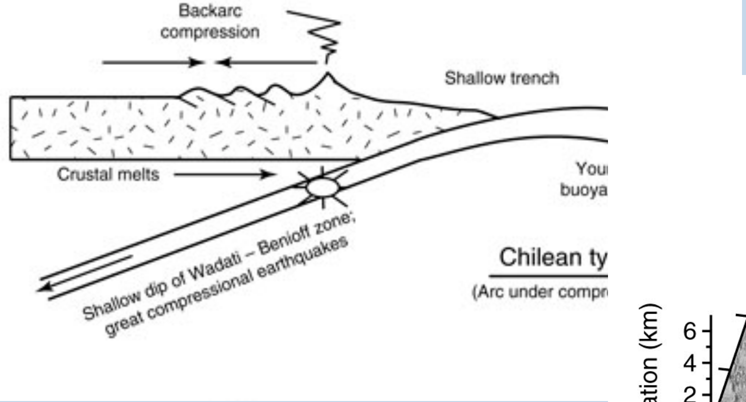
KK&V fig 10.1

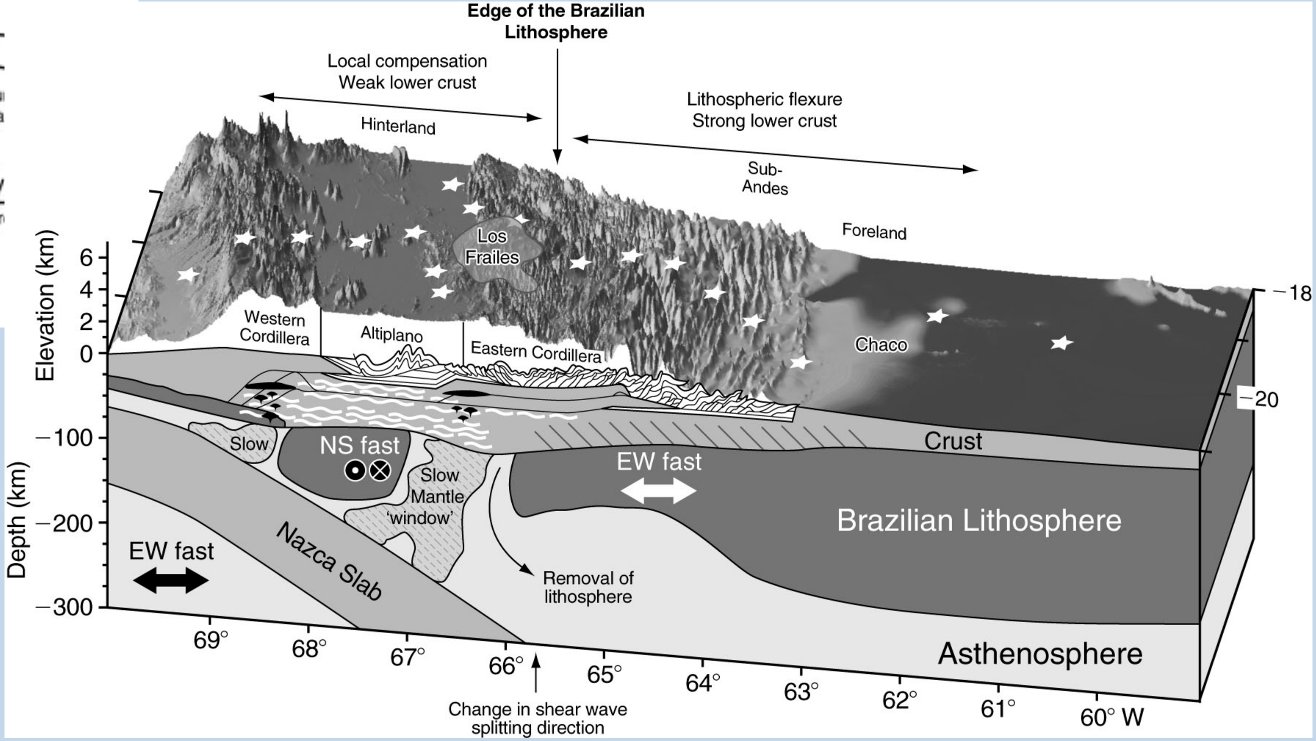


Note: shear waves sometimes travel faster in one direction than in another ("shear wave splitting"; used to infer the sense of shear in the ductile rocks)

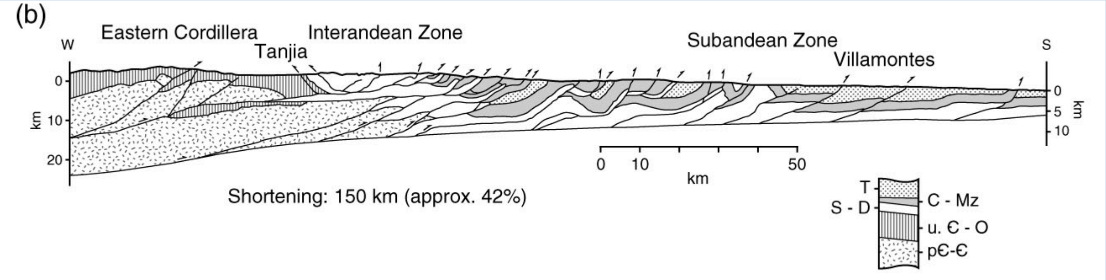
Foreland fold and thrust belts

KK&V fig 10.7





Some similarities to accretionary prisms: sediments are being scrapped off basement, deformation front, long thrust faults



But big differences: often thrusts extend into the basement, and even cut through entire crust; mechanism for crustal shortening

KK&V fig 10.5

The Andean foreland is associated with three different styles of tectonic shortening:
a) thin-skinned, b) thick-skinned and c) basement thrusts that cut through the entire crust.
The latter are found in the Pampean Ranges of the "flat slab" sections – with very destructive earthquakes.

"Flat slab" subduction

Slab Segmentation

Nazca-South America

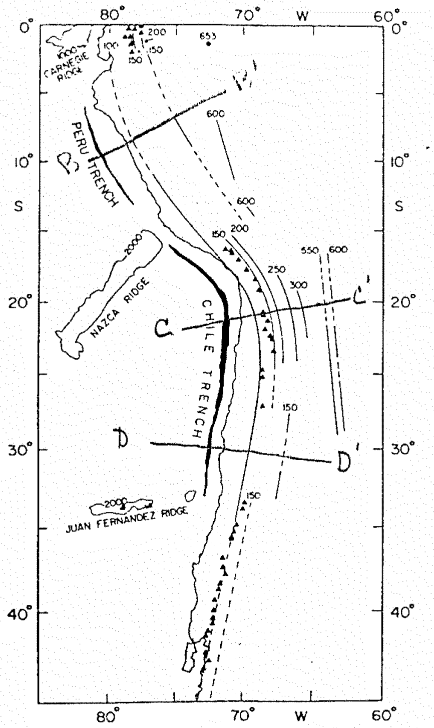


Figure 5. Map showing contours of hypocentral depth to top of inclined seismic zone.

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

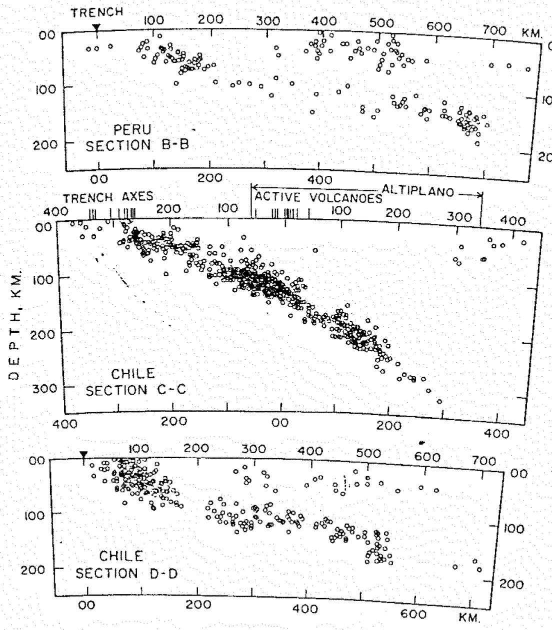
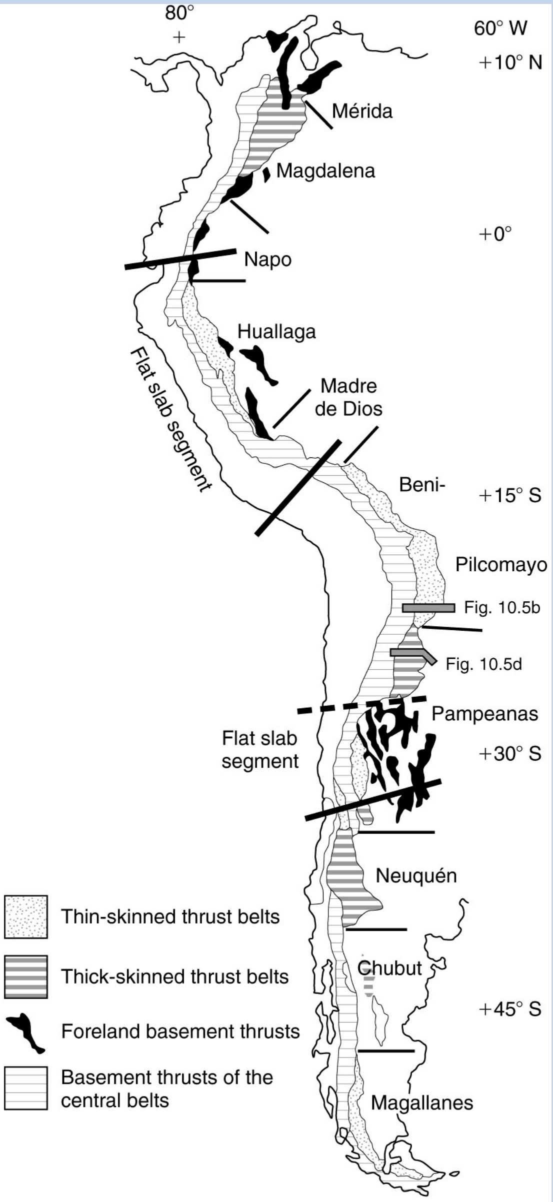


Figure 4. Cross sections showing segments of inclined seismic zone (A, B, C, D, E) and deep seismic zone (F, G, H). See Figure 3 for locations and limits of sections.

(Barazangi & Isacks 1976)

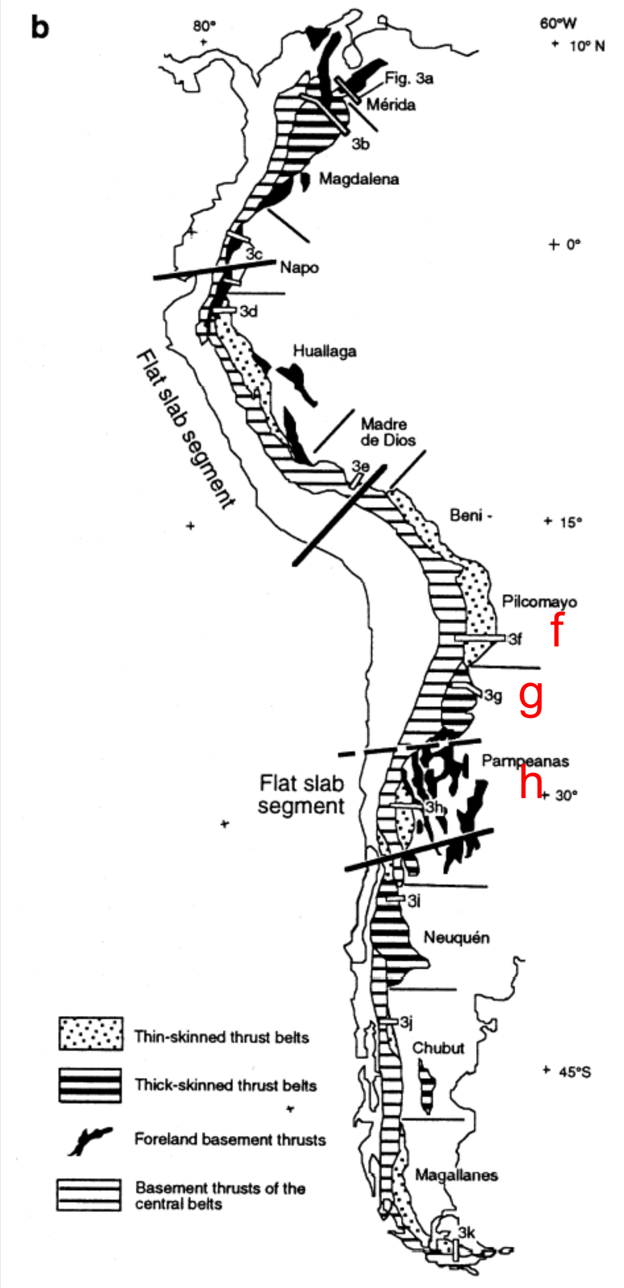


▨	Thin-skinned thrust belts
▤	Thick-skinned thrust belts
■	Foreland basement thrusts
☰	Basement thrusts of the central belts

KK&V Fig 10.4

The style of foreland thrust faulting varies from region to region

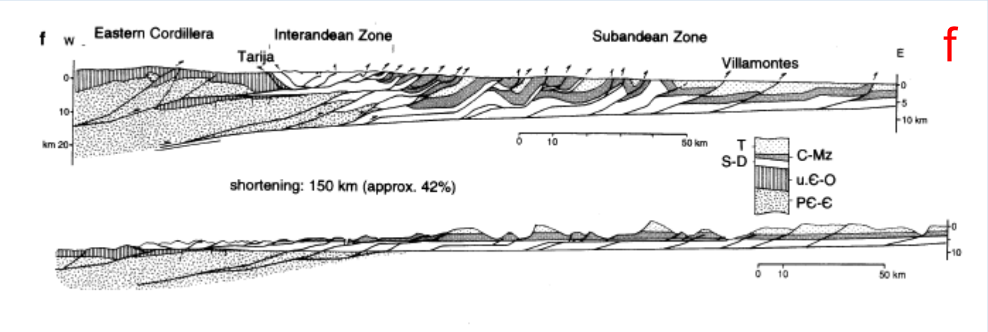
1) Thin-skinned (thrusts start within Paleozoic sediments at depths of 7 -10 km)
2) Thick-skinned (thrusts start within Pre-Cambrian basement at 10 – 20 kms), and
3) Foreland basement thrusts (thrusts cut through entire crust) (in flat slab segments)



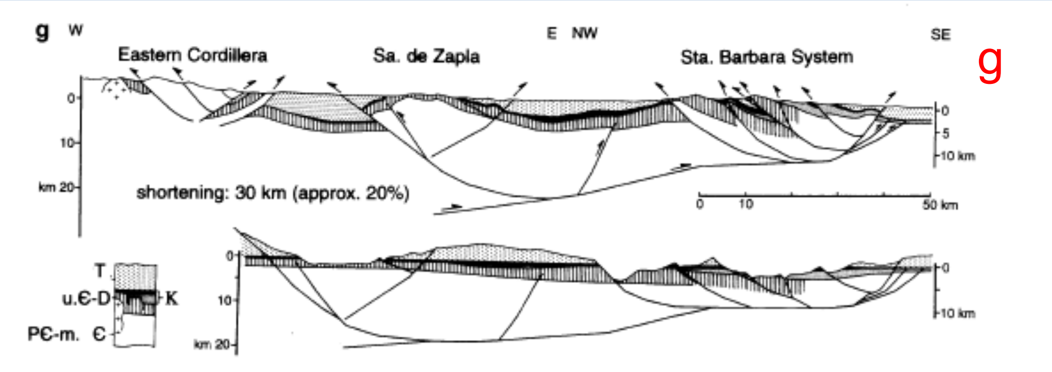
KK&V Fig. 10.4

Thin-skinned

Top: observed cross-section
Bottom: palinspastic reconstruction

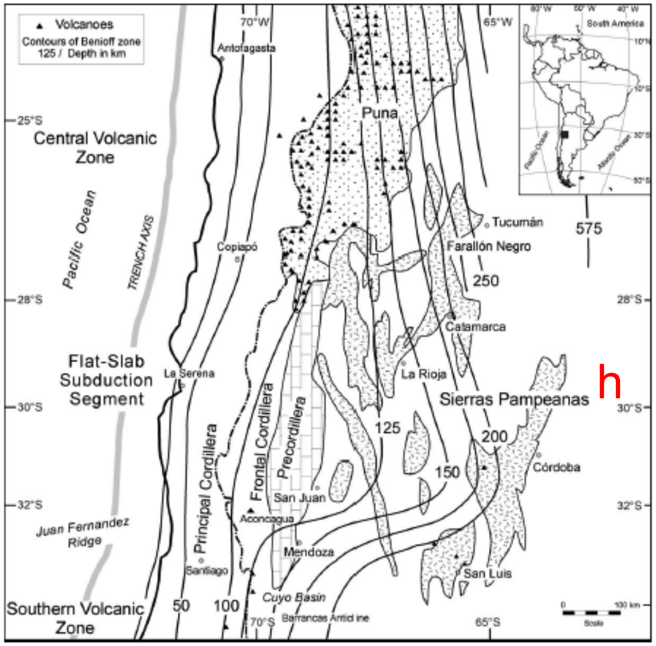


Thick-skinned



KK&V Fig. 10.5

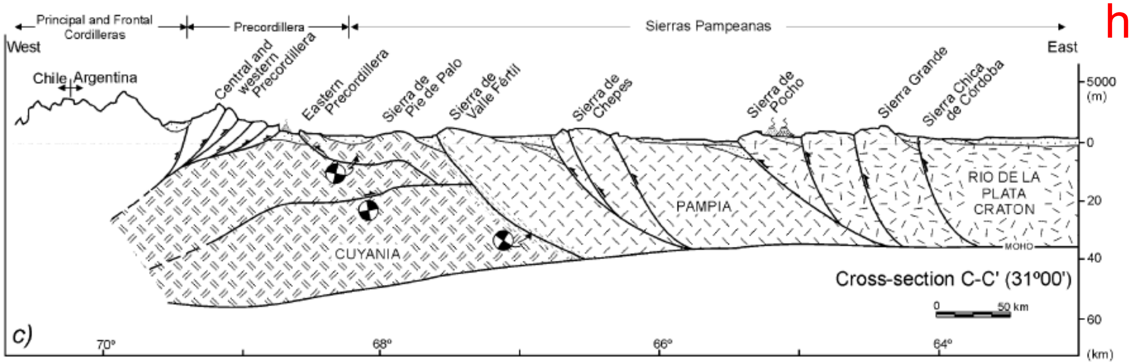
V.A. Ramos et al. / Journal of South American Earth Sciences 15 (2002) 59–78

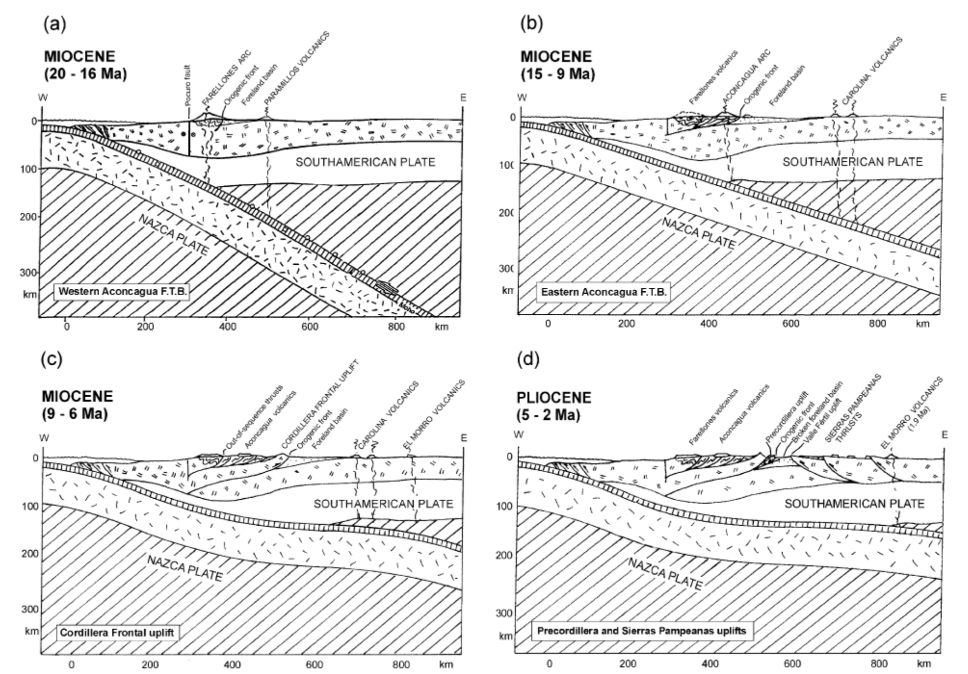


g. 1. Location of the Pampean flat-slab segment in the Central Andes of Argentina and Chile with contours of depth to the oceanic slab (after Cahill and acks (1992)) and outline of the major structural provinces and the basement blocks of the Sierras Pampeanas.

Sierra Pampeanas:

Basement thrusts cutting through entire crust observed in the flat-slab segment east of the Juan Fernandez ridge





Eastward migration of volcanism in Miocene (20 – 6 Ma) as slab shallows, then (since 5 Ma) cessation of volcanism and development of basement thrusts as slab goes flat

Destructive earthquakes

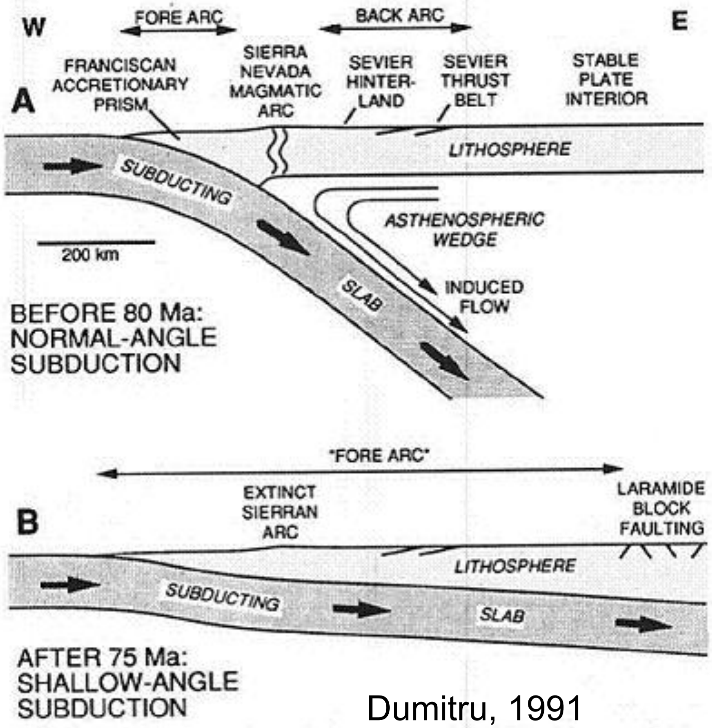
Laramide orogeny: ~75-45 Ma


Laramide structural arches and basement uplifts

(after E. Erslev)

E Humphreys

From Tarbuck, E and Lutgens, F., 1996, Earth, Prentice-Hall



Dumitru, 1991

Style of basement uplift in the Laramides is similar to the style of basement faulting in the Pampean Ranges of western Argentina–hence speculation that the Laramides were also caused by flat slab subduction


Laramide deformation: Precambrian rocks thrust up and over Paleozoic rocks. Near Cody, Wyoming (Courtesy of Prof. Burchfiel).

In the western US, the “flat slab” event is attributed to the subduction of a hypothetical large, aseismic ridge (perhaps like the Ontong-Java plateau) in the late Cretaceous and early Cenozoic.

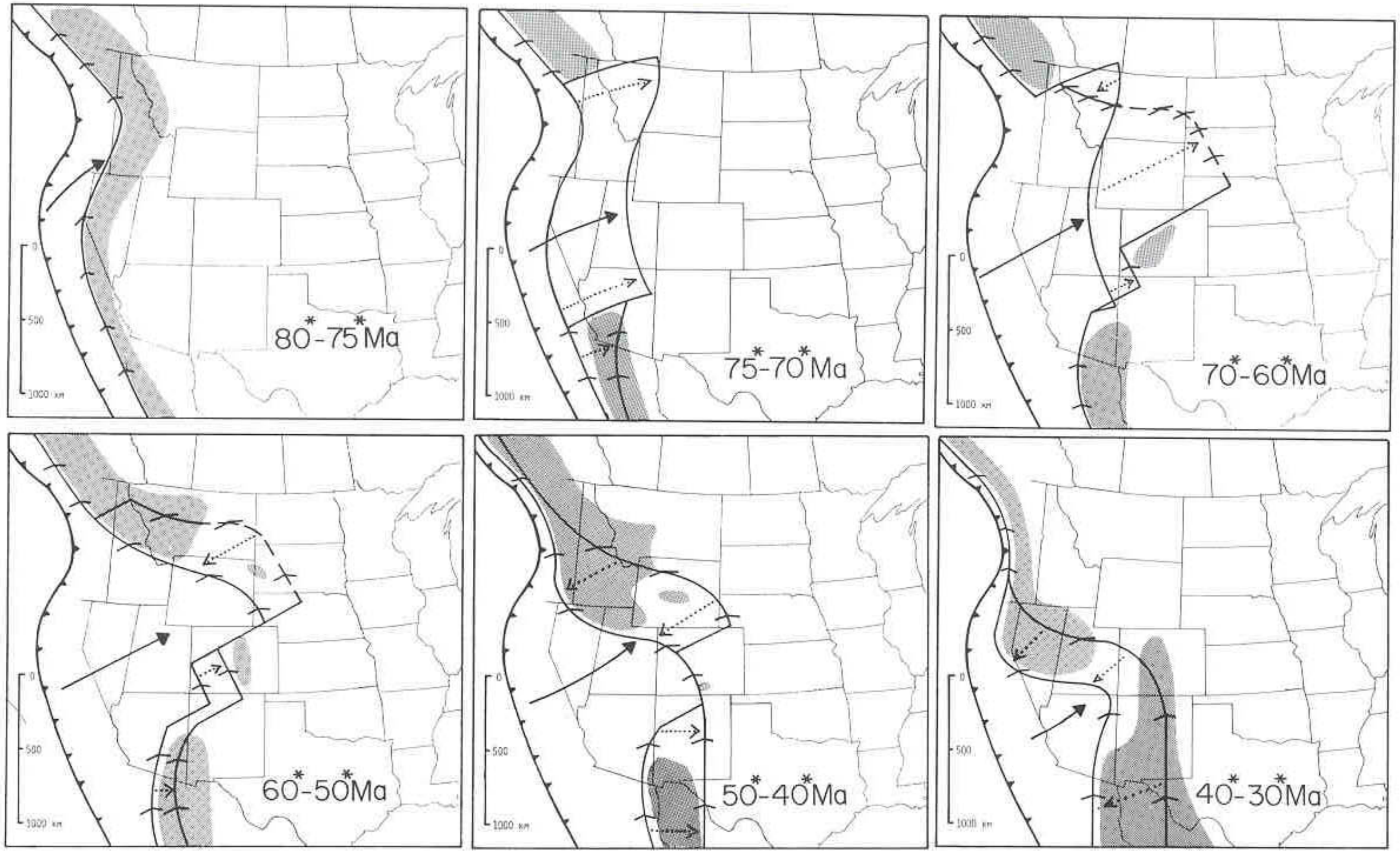
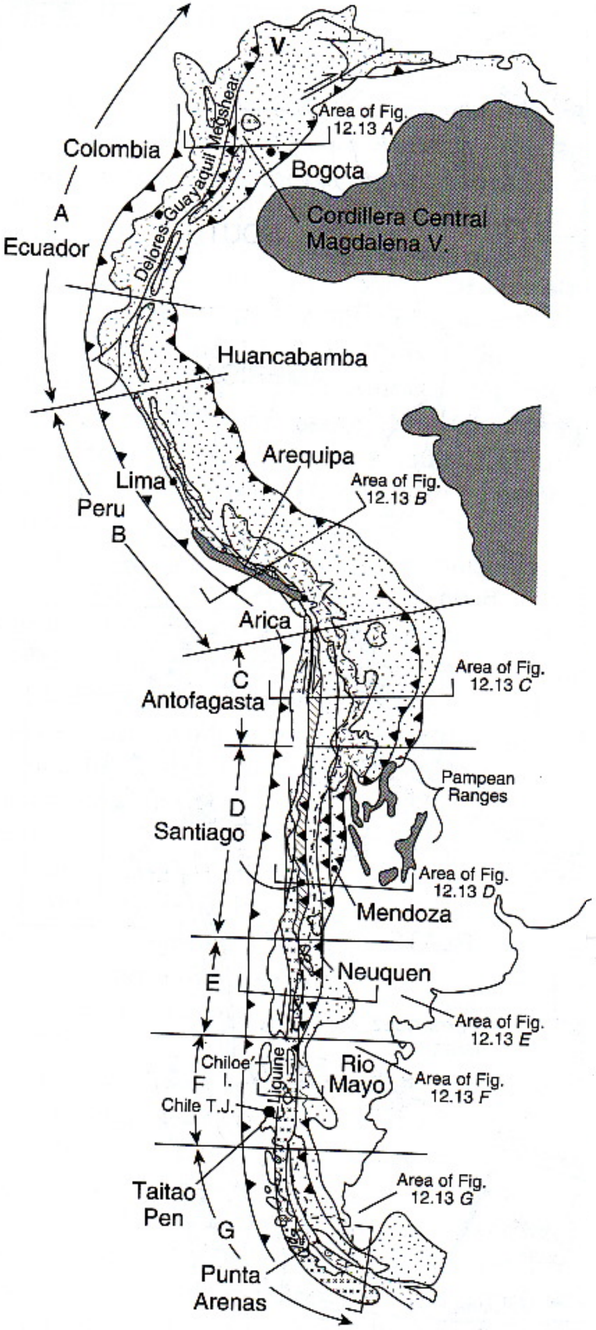


Fig. 5. Hypothesized locations of horizontal subduction beneath North America from late Cretaceous through Oligocene time. Palinspastic base map is from Hamilton [1978]. Solid arrows show velocity of the Farallon plate with respect to North America [Engebretson, 1983]; lengths are equal to 5 m.y. of relative displacement. Shading indicates regions of volcanism from Snyder et al. [1976] and Lipman [1980]. Solid lines without angle symbols at 70 m.y. represent edges of the flat slab, which should not have caused volcanism. Lines with dihedral angle symbols are suggested hingelines at the beginning and end of each period. Dotted arrows show the sense of hingeline migration. (*Note that all dates are based on cooling ages, so that if any significant time is required for intrusion and cooling, the slab may have actually reached the indicated position at an earlier time.)

Bird, 1988

Andean orogeny: present



Great latitudinal complexity

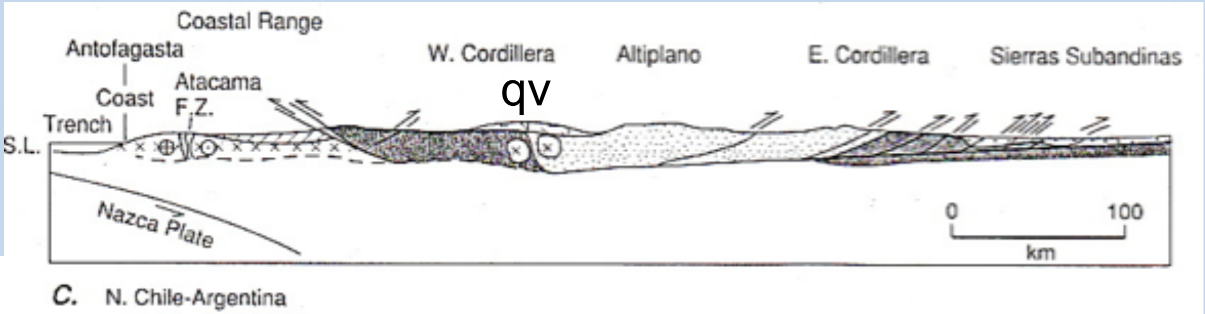
Temporal/spatial patterns of volcanism and magmatism
Fore-arc and Foreland (Back-arc) basins
Thrust faults in fore-arc and foreland
Trench parallel strike slip faults
(e.g. Atacam Fault and Liquine-Ofqui Fault)
Accreted terranes (Ecuador and Columbia)

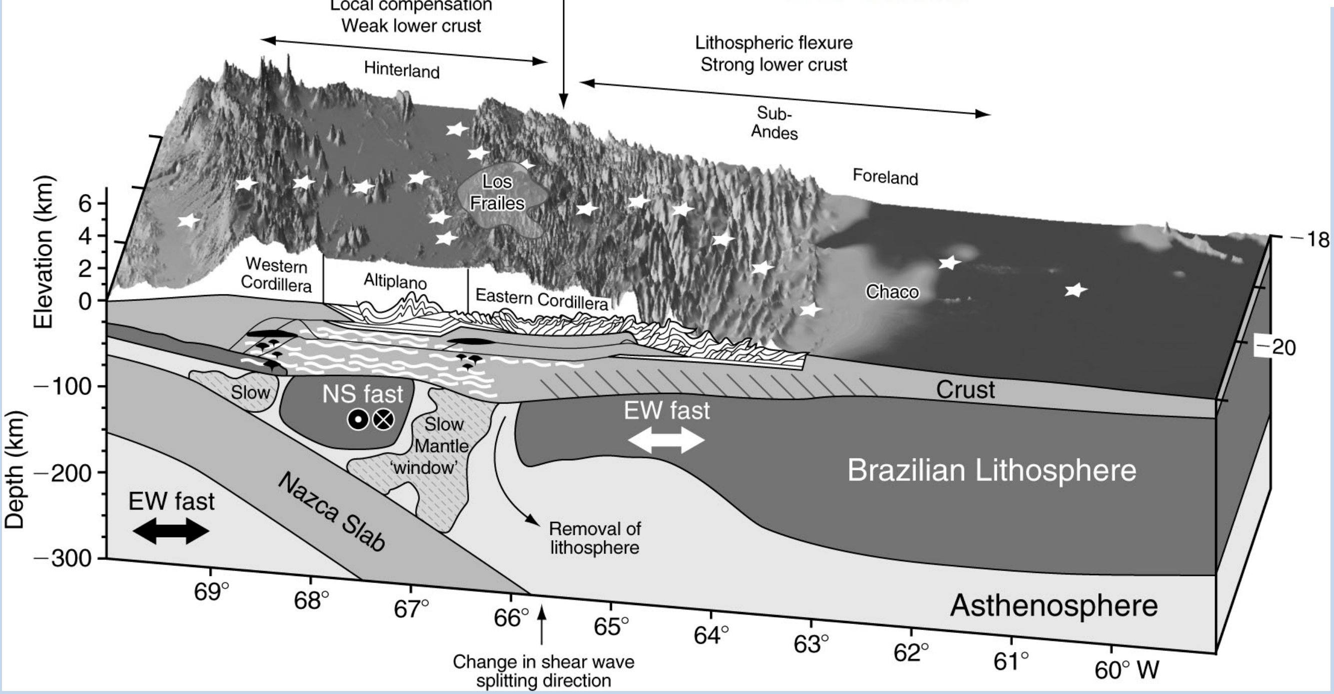
- ▨ Quaternary volcanics
- ■ Precambrian rocks
- ▨ Oceanic rocks
- ▨ Marginal basin rocks
- ▨ Miogeocline associated rift volcanics and sediments
- ▨ Batholith and associated rocks
- ☐ Metamorphic core complex

Figure 12.12 Map of Andes, South America, showing principal tectonic features. *(After Mégard, 1989; Mpodozis and Ramos, 1989)*

Moores and Twiss M&T

Northern Chile



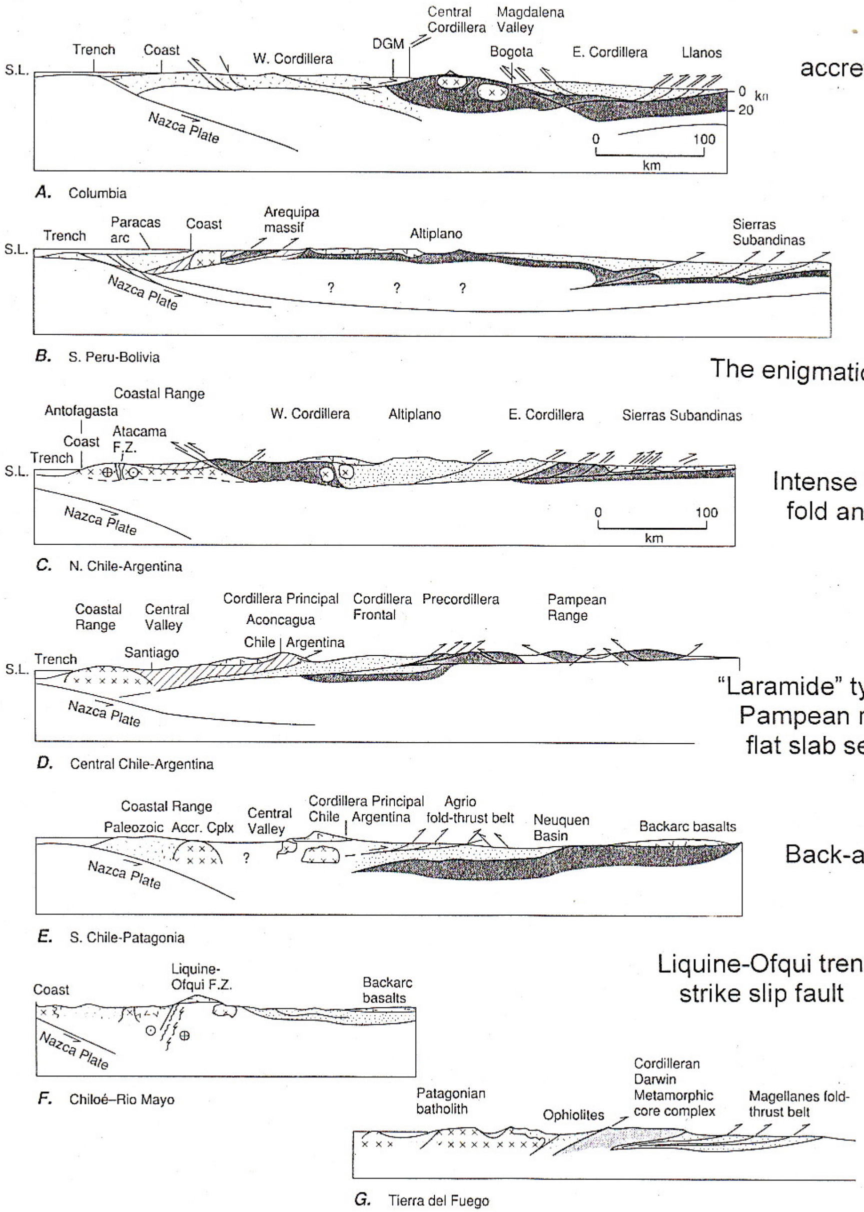


qv = quaternary volcanics (< 2.6 Ma)

Note: Atacama fault: attributed to partitioning of oblique convergence into normal and parallel components

Western cordillera = volcanic arc
Eastern cordillera = culmination of crustal shortening
Altiplano = high plateau separating them

Cross-sections (same key): numbing
but note:



accreted terranes

The enigmatic Altiplano

Intense foreland fold and thrust belt

"Laramide" type uplift of Pampean range in flat slab section

Back-arc basalts

Liquine-Ofqui trench parallel strike slip fault

ophiolites

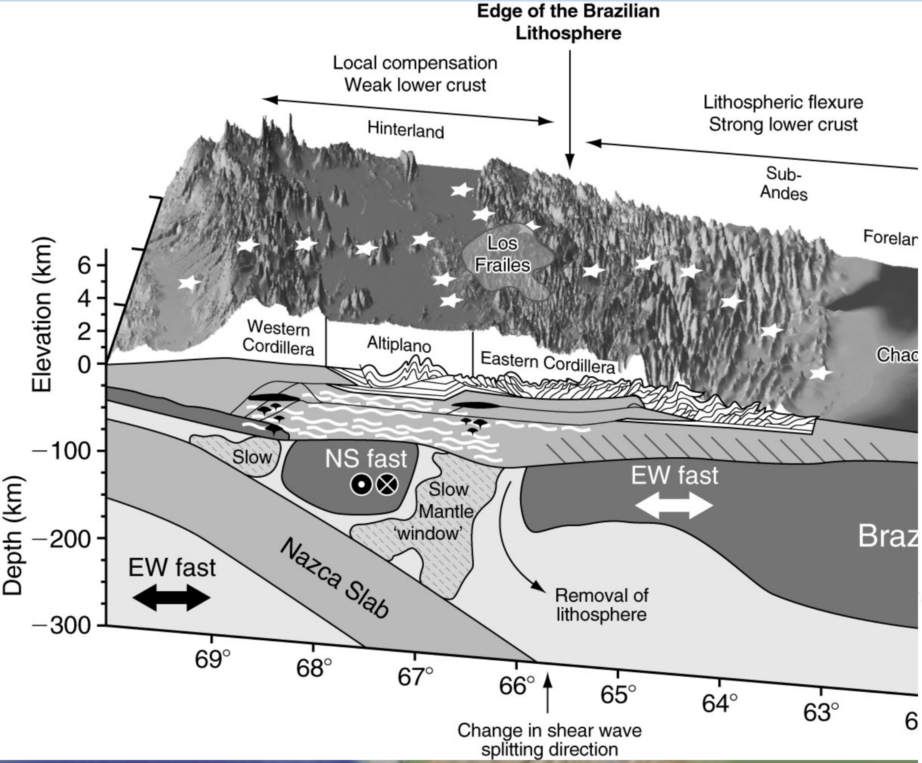
This series of cross-sections illustrates the range of tectonic styles that exist in different parts of the Andes; and at any place they also change through time.

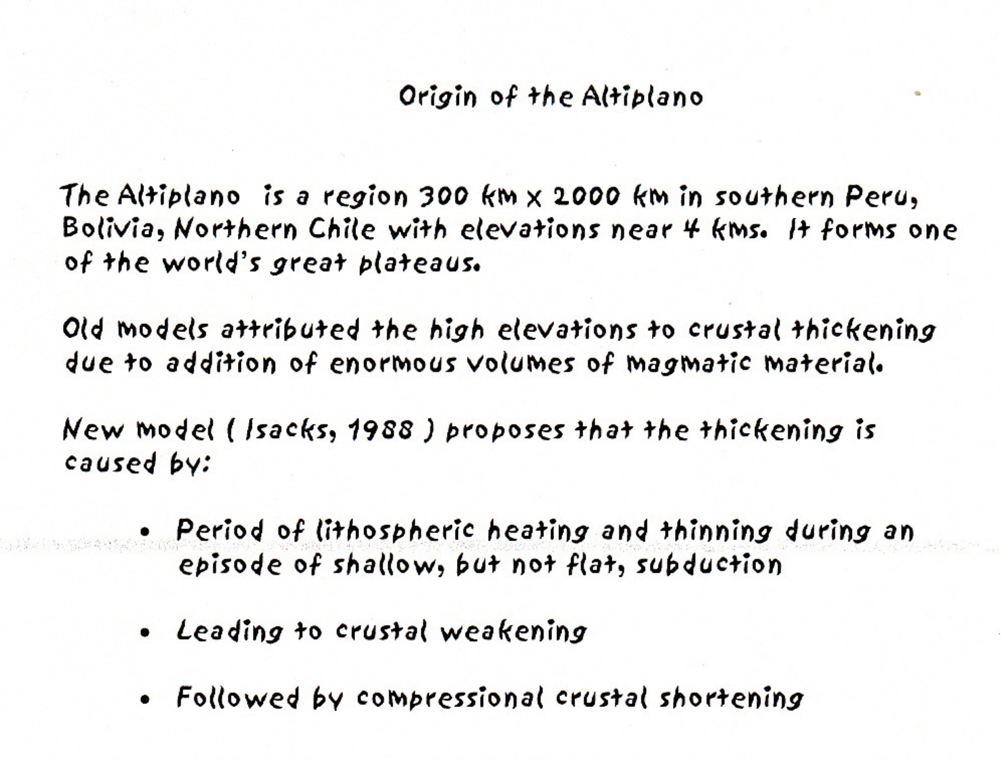
- ░ Quaternary volcanics
- ■ Precambrian rocks
- ░ Oceanic rocks
- ▨ Marginal basin rocks
- ░ Miogeocline associated rift volcanics and sediments
- ▦ Batholith and associated rocks
- ☐ Metamorphic core complex

Figure 12.12 Map of Andes, South America, showing principal tectonic features. *(After Mégard, 1989; Mpodozis and Ramos, 1989)*

For example, along section E the Andes are built on top of a rift basin (Neuquen) that formed at the time of South America - Africa rifting at 130 Ma.

Moores and Twiss





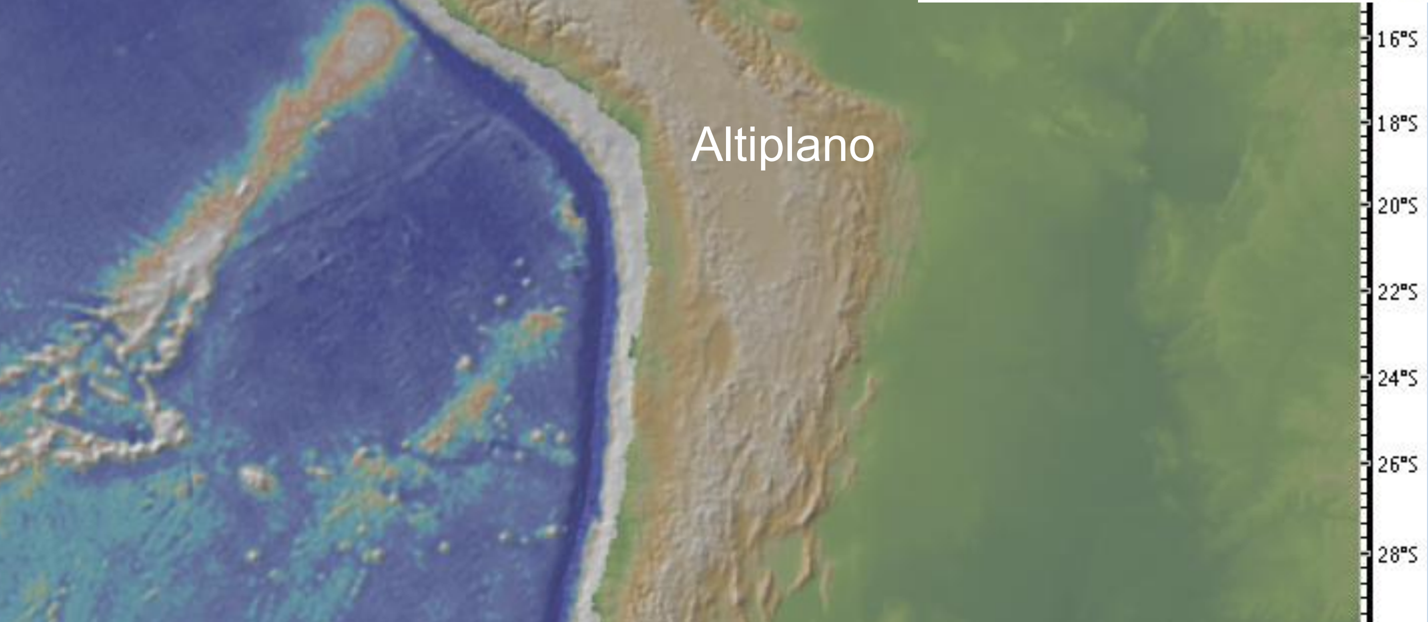
Origin of the Altiplano

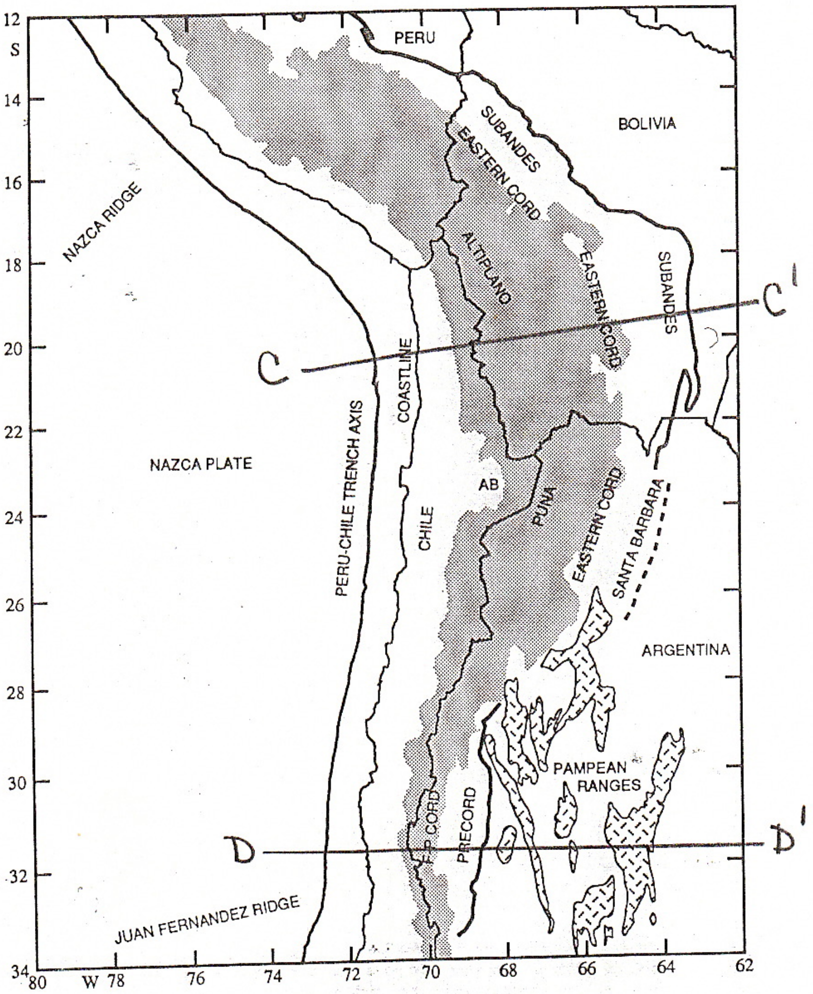
The Altiplano is a region 300 km x 2000 km in southern Peru, Bolivia, Northern Chile with elevations near 4 kms. It forms one of the world's great plateaus.

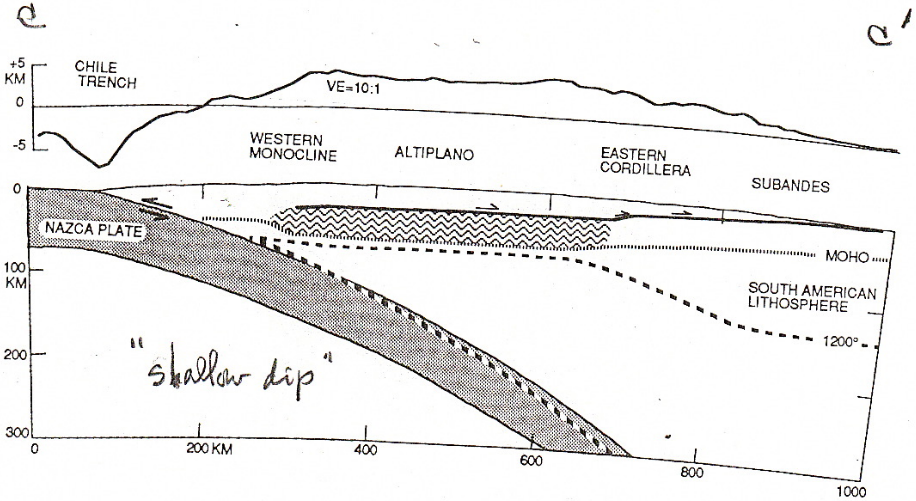
Old models attributed the high elevations to crustal thickening due to addition of enormous volumes of magmatic material.

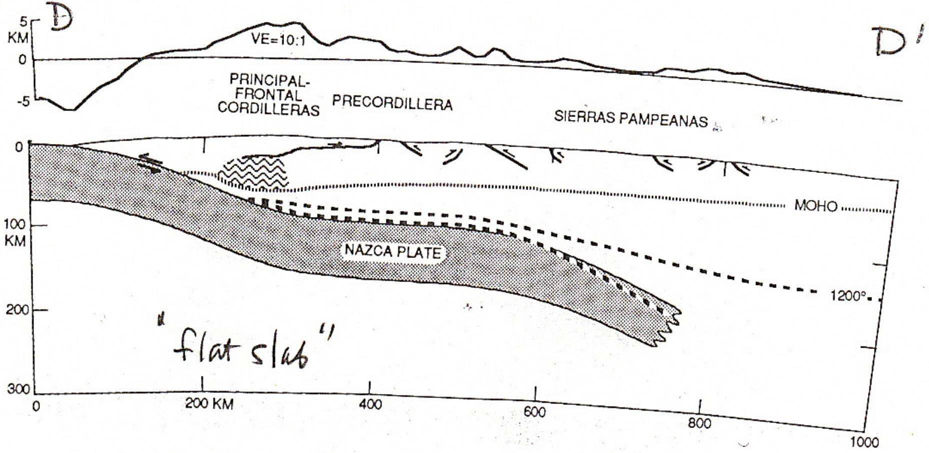
New model (Isacks, 1988) proposes that the thickening is caused by:

- Period of lithospheric heating and thinning during an episode of shallow, but not flat, subduction
- Leading to crustal weakening
- Followed by compressional crustal shortening









Note that the Altiplano occurs in the “shallow dip” segment, top.
Not to be confused with the ”flat slab” segment, below

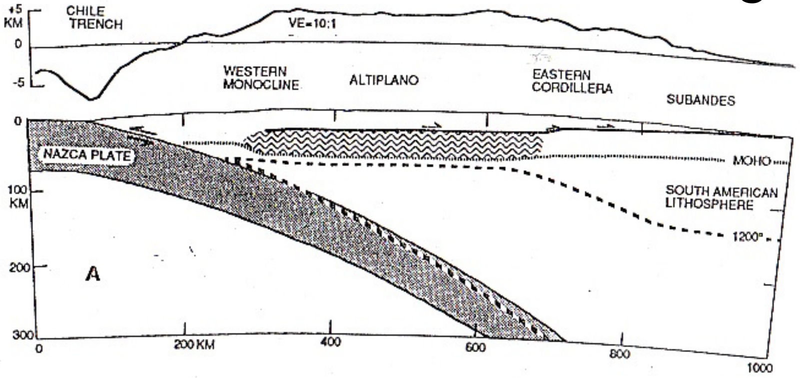
Isacks (1988)

Crustal thickening model for the Origin of the Altiplano

Present day

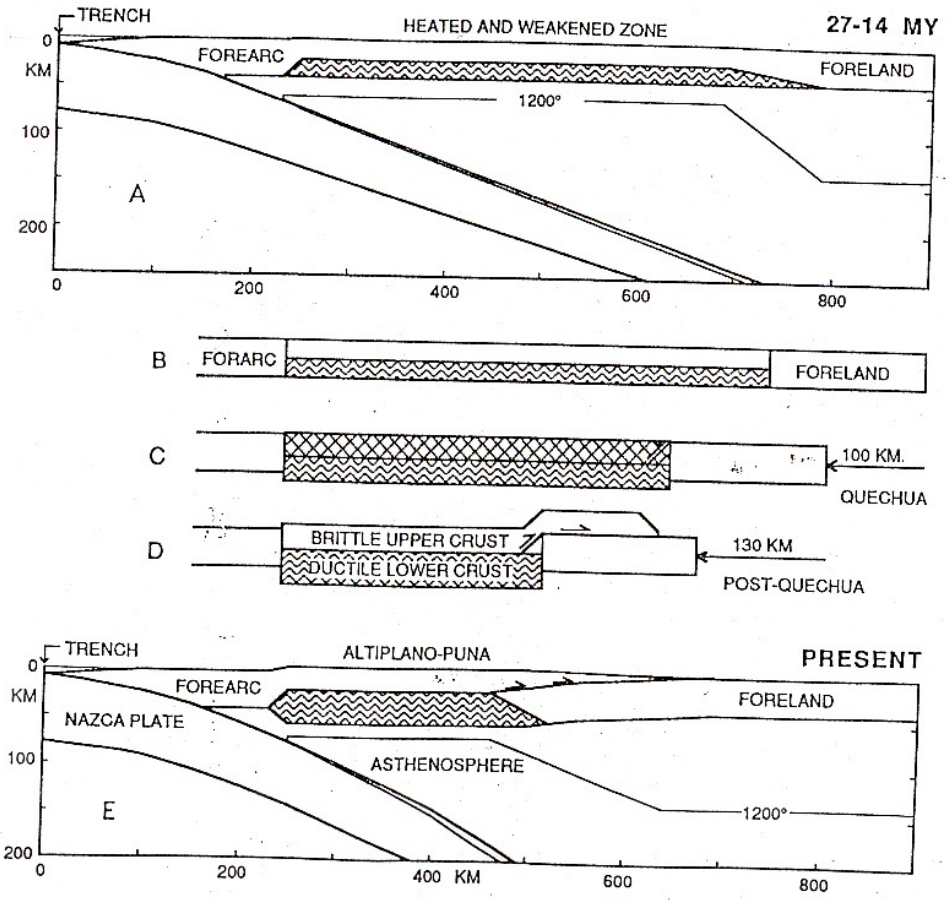
C

C’

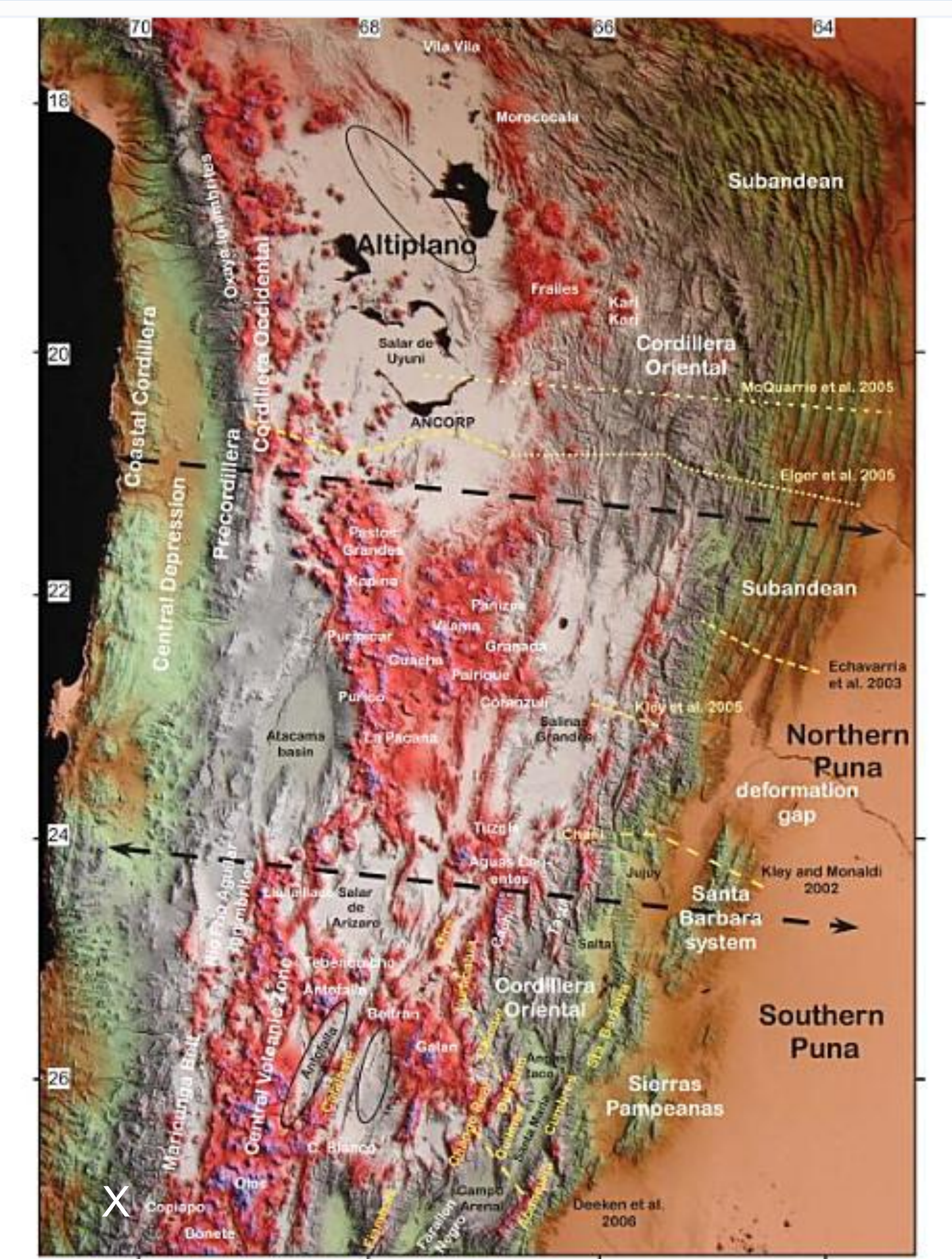


High elevation of the Altiplano is due to crustal shortening (300+ km) and thickening following a period of shallow (but not flat) subduction, during which the crust was heated and weakened.

Model



Isacks (1988)

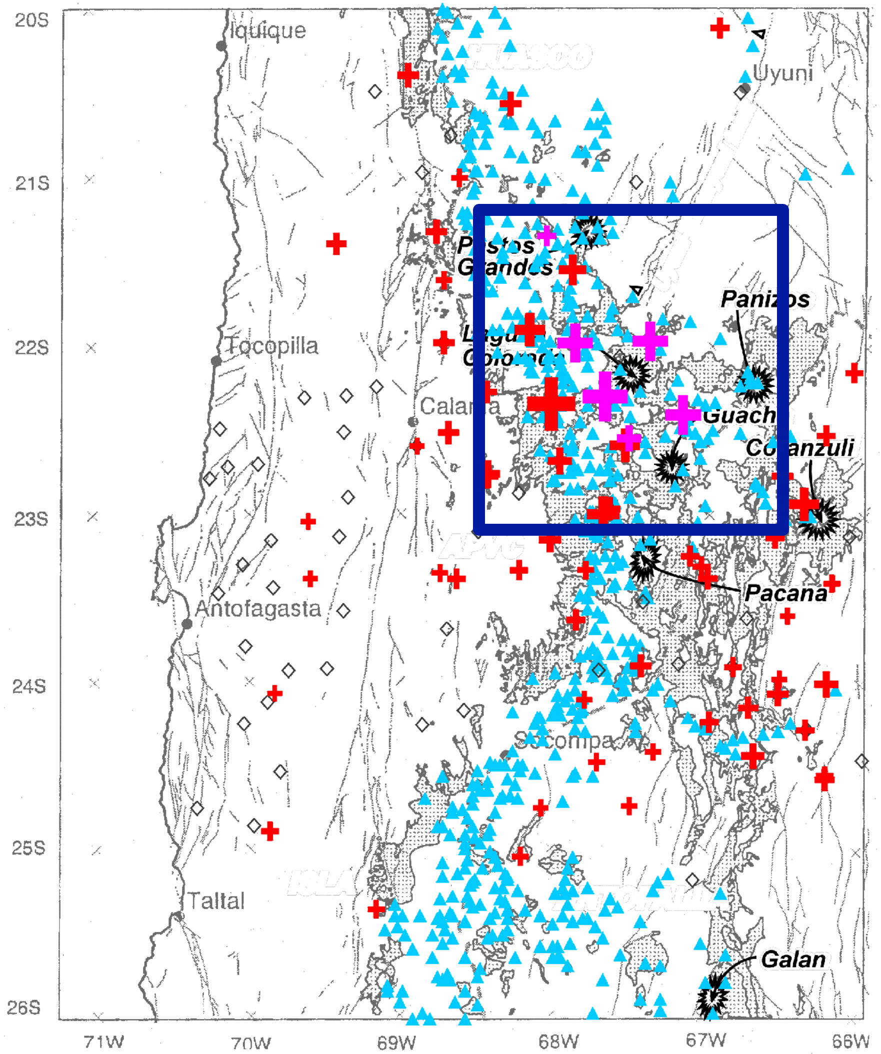


Half of the world’s lithium is in Bolivia

X = Chilean miners (Copiapo)

Kay and Colra (2009) GSA Memoir 204

Altiplano-Puna, South America



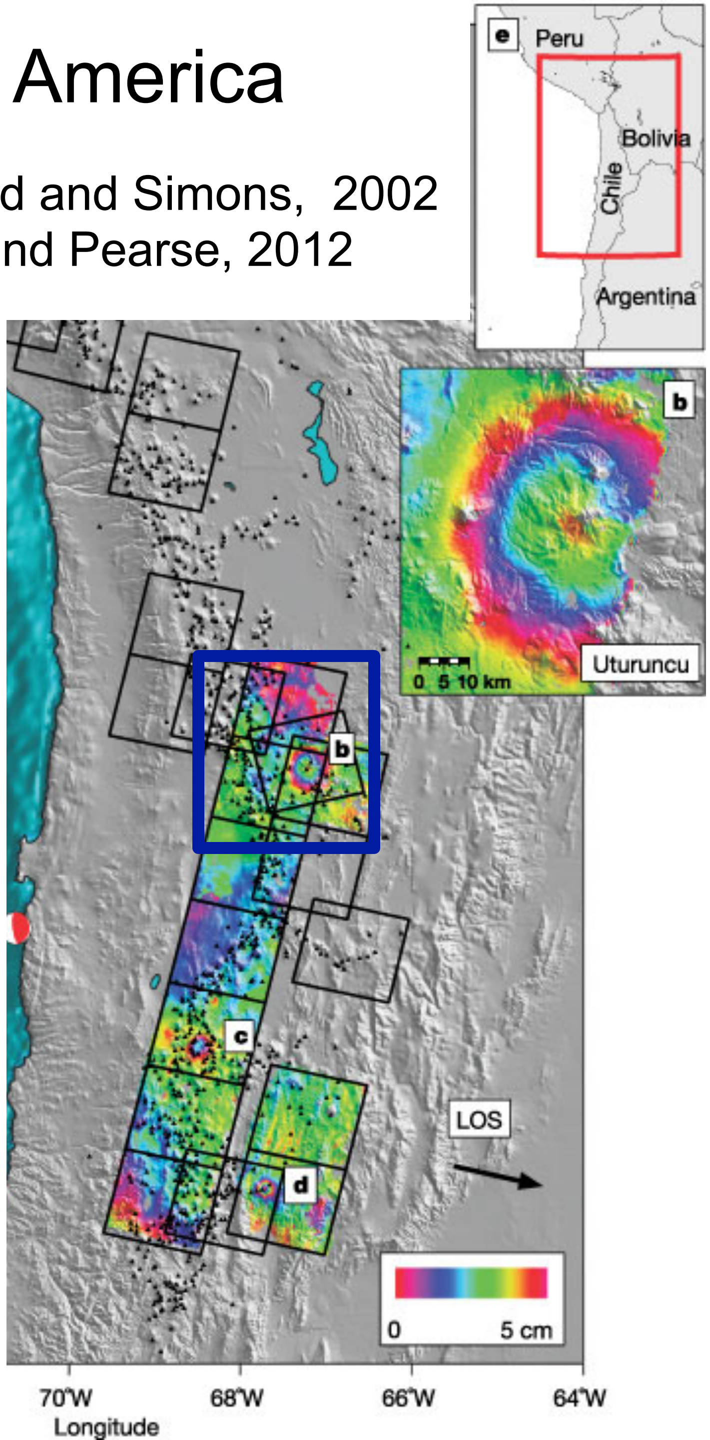
+ Ps/P= 5%

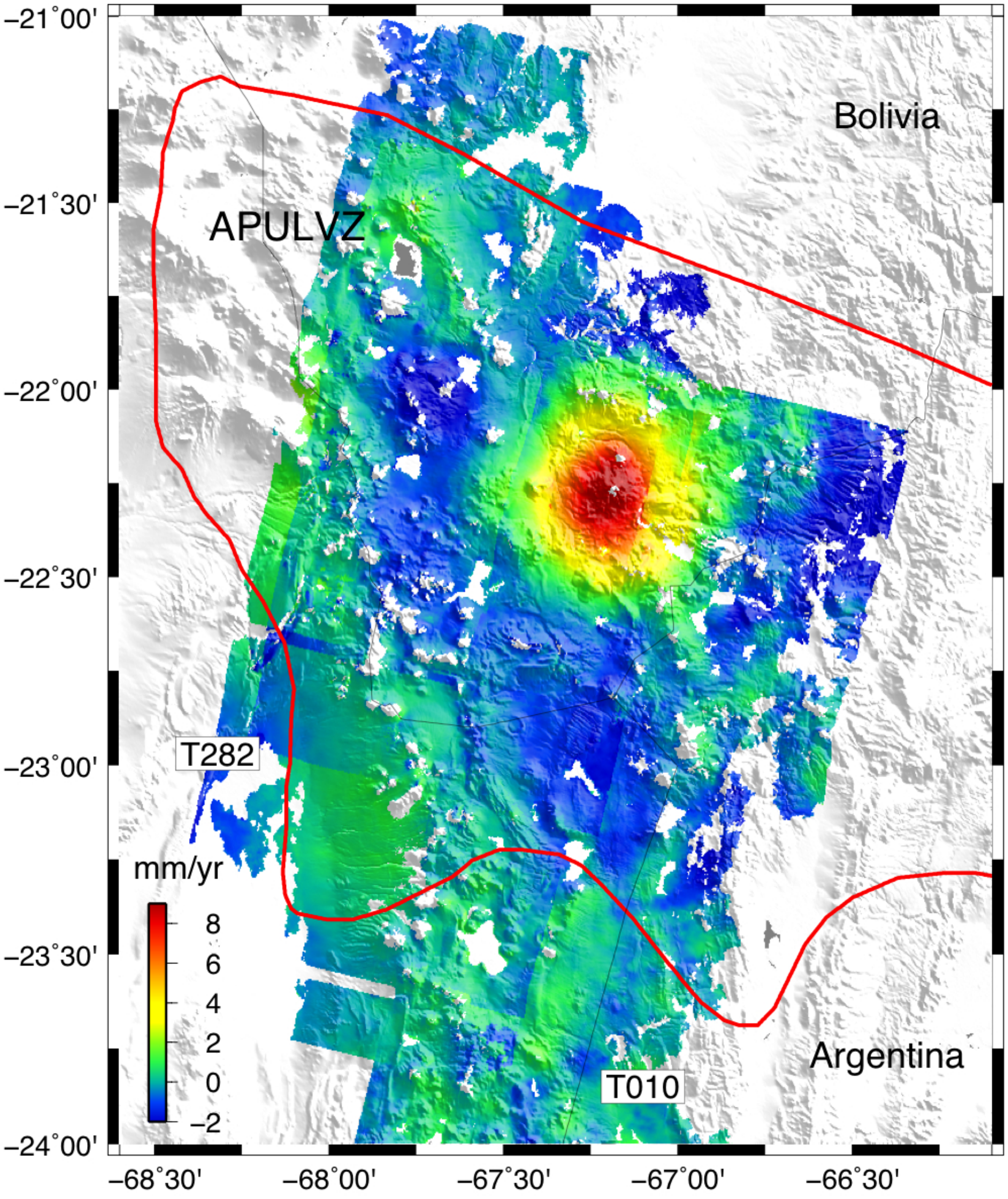
✚ Ps/P= 50 %

Extremely low seismic velocities at depth of ~19 km

Yuan et al., 2000

Pritchard and Simons, 2002
Fialko and Pearse, 2012

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Bolivia
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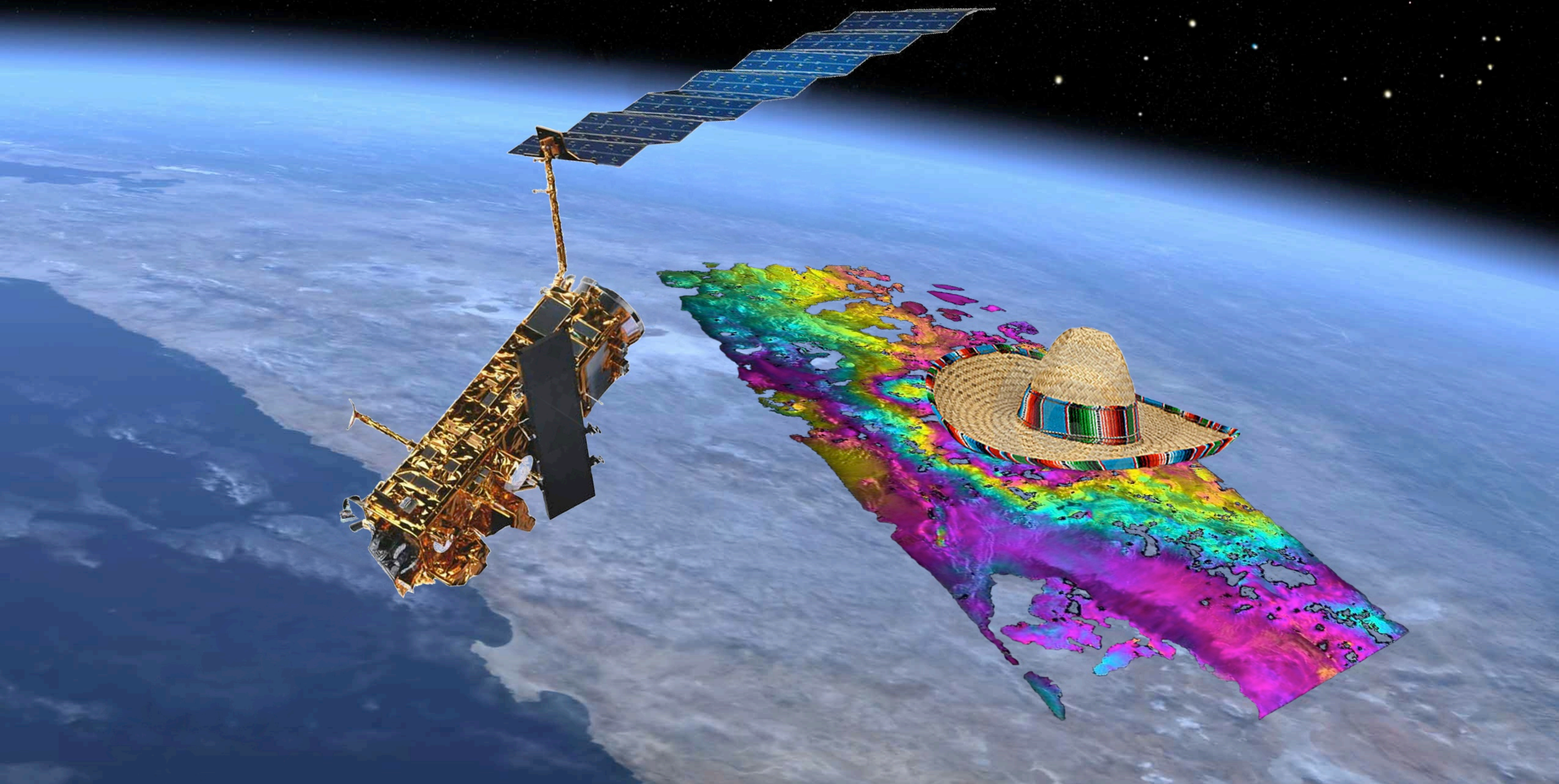
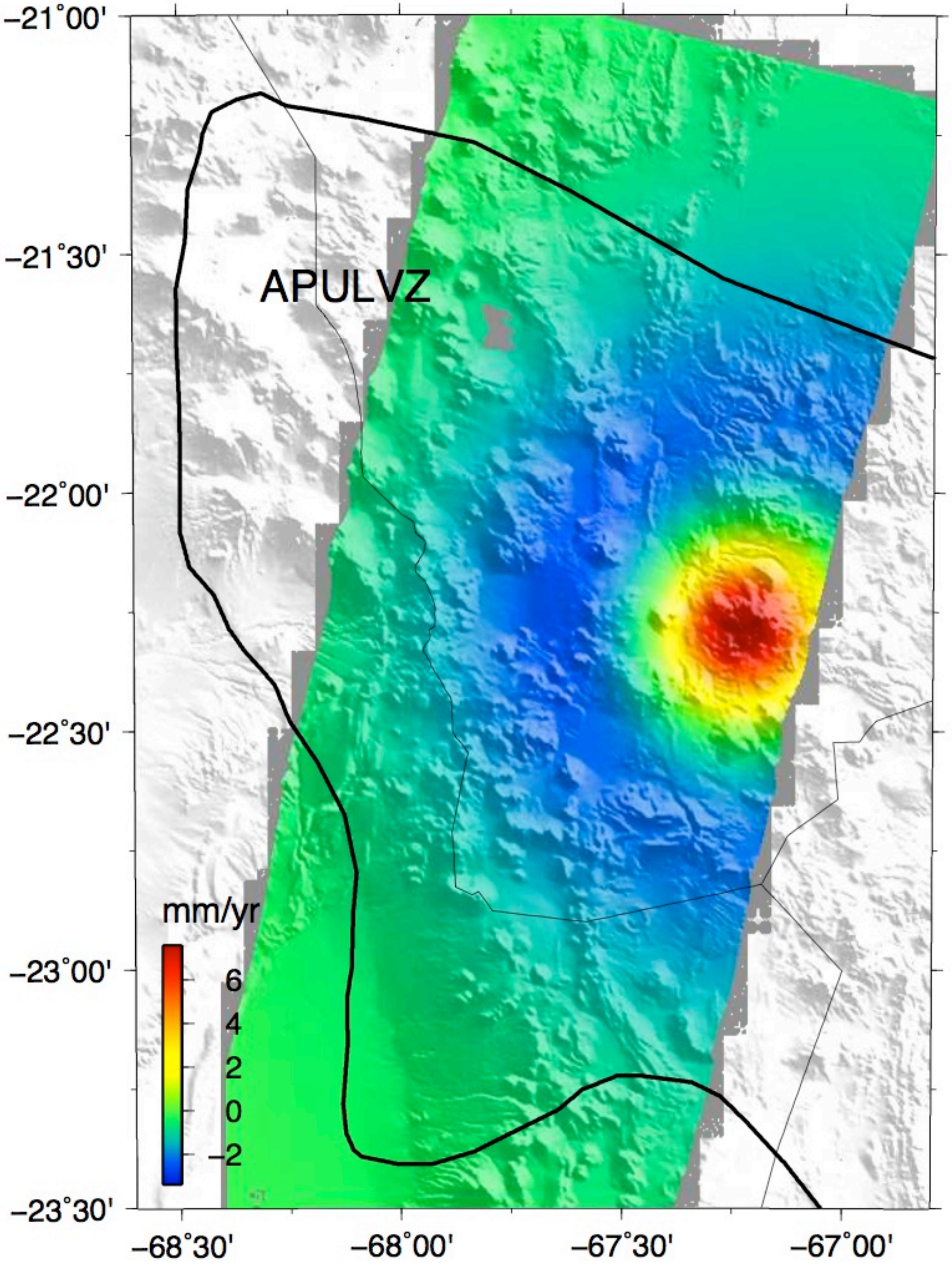
“Sombrero” uplift





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-21°30'
-22°00'
-22°30'
-23°00'
-23°30'
APULVZ
mm/yr
6
4
2
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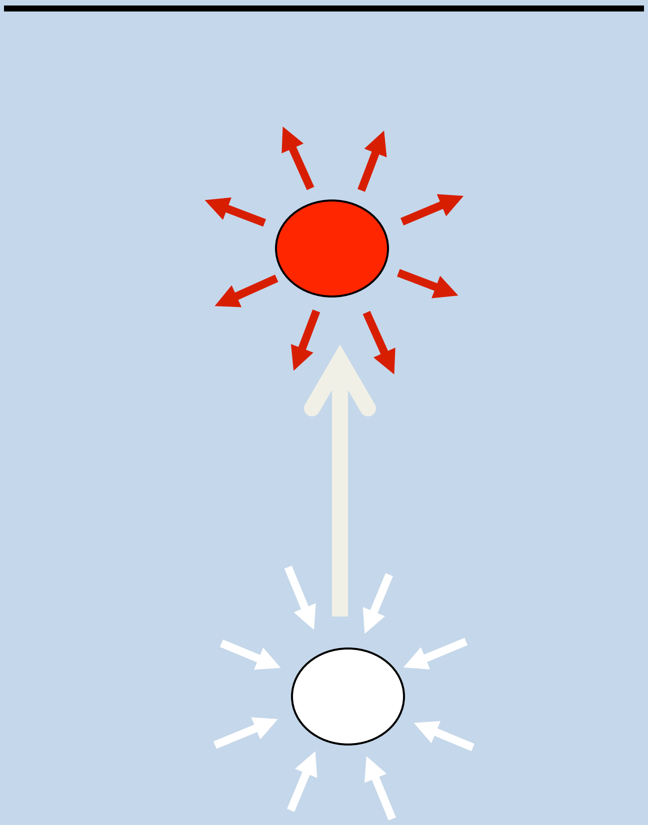
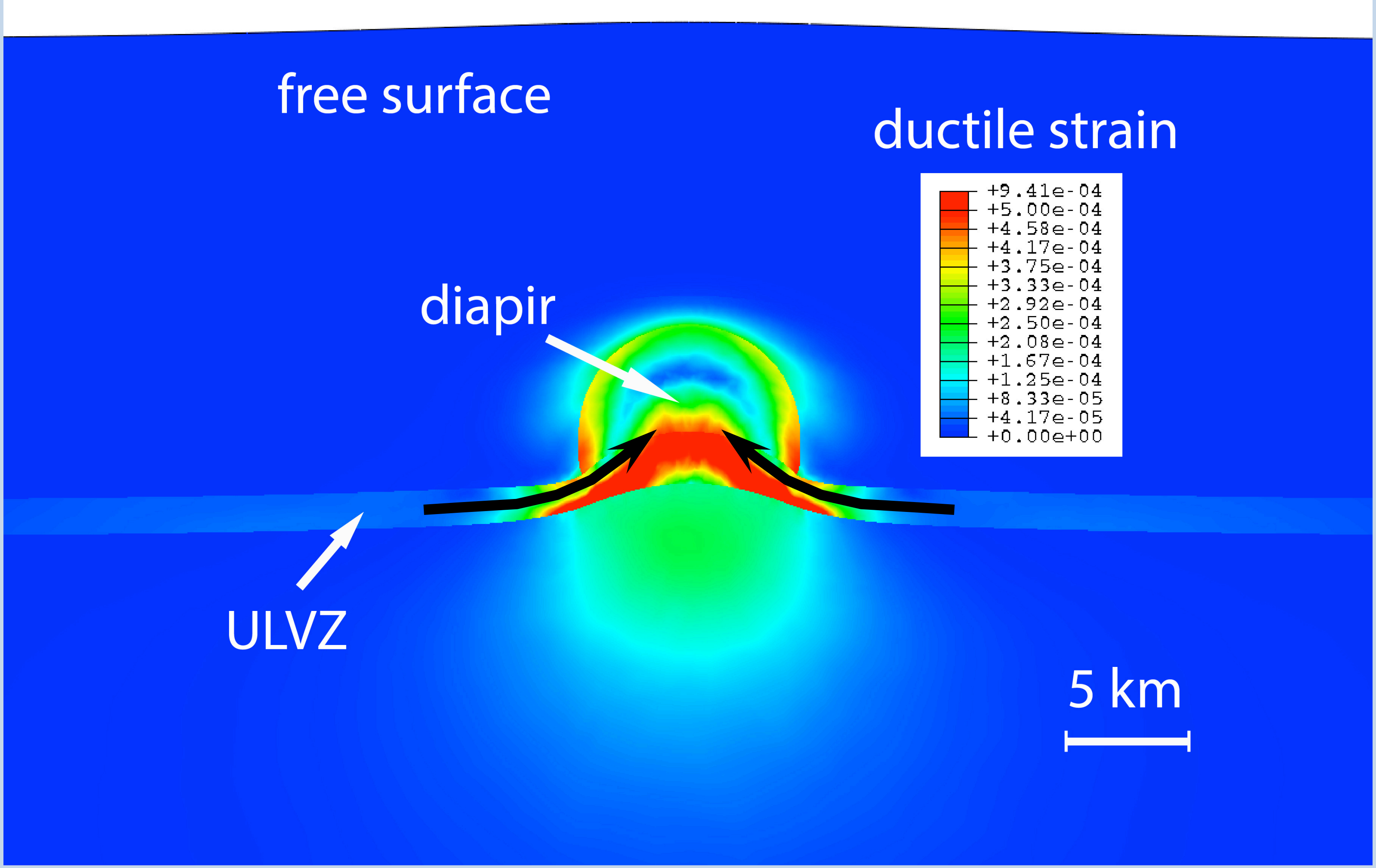
-2
-68°30'
-68°00'
-67°30'
-67°00'

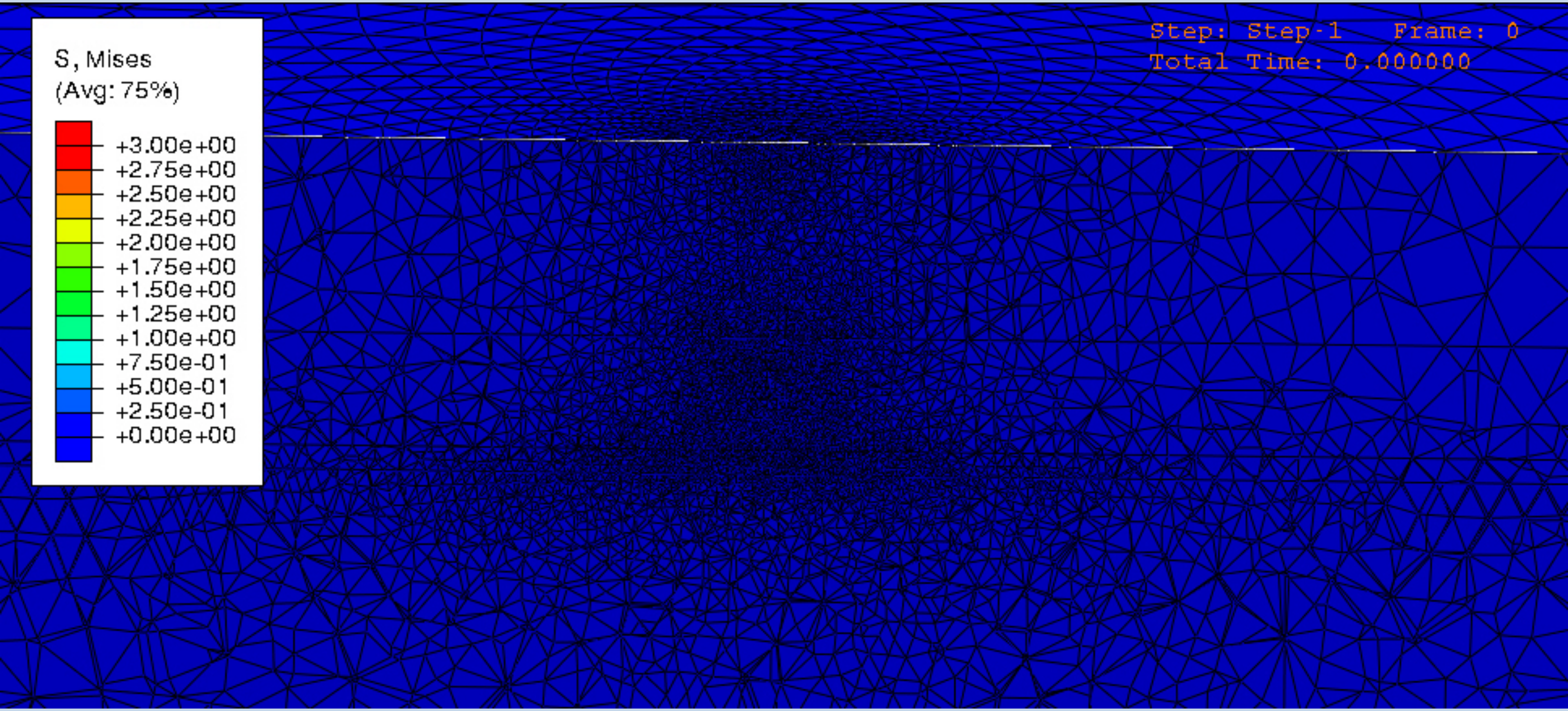
“Mogi dipole”



Model: buoyant diapir on top of AP Magma Body



t=40 yrs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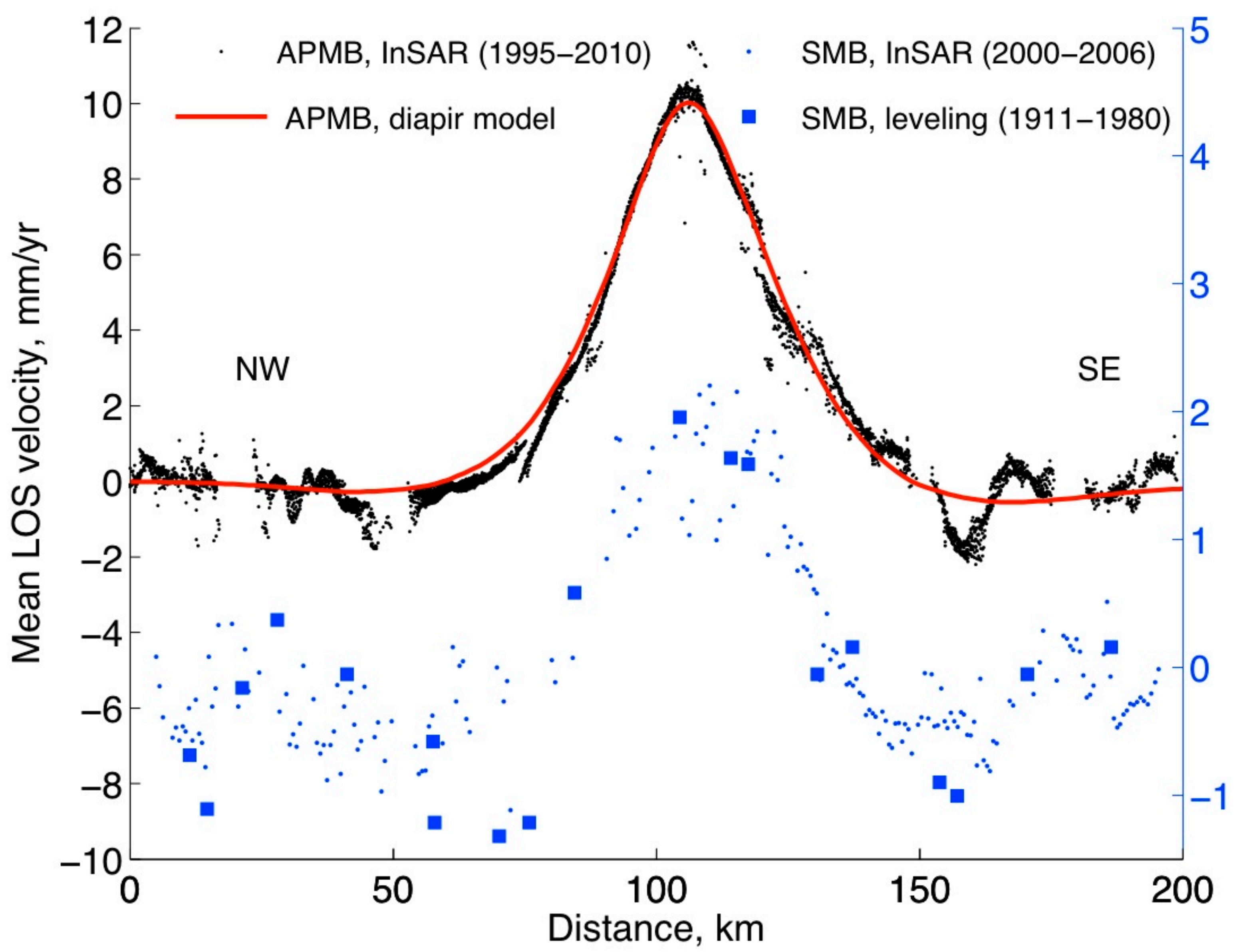
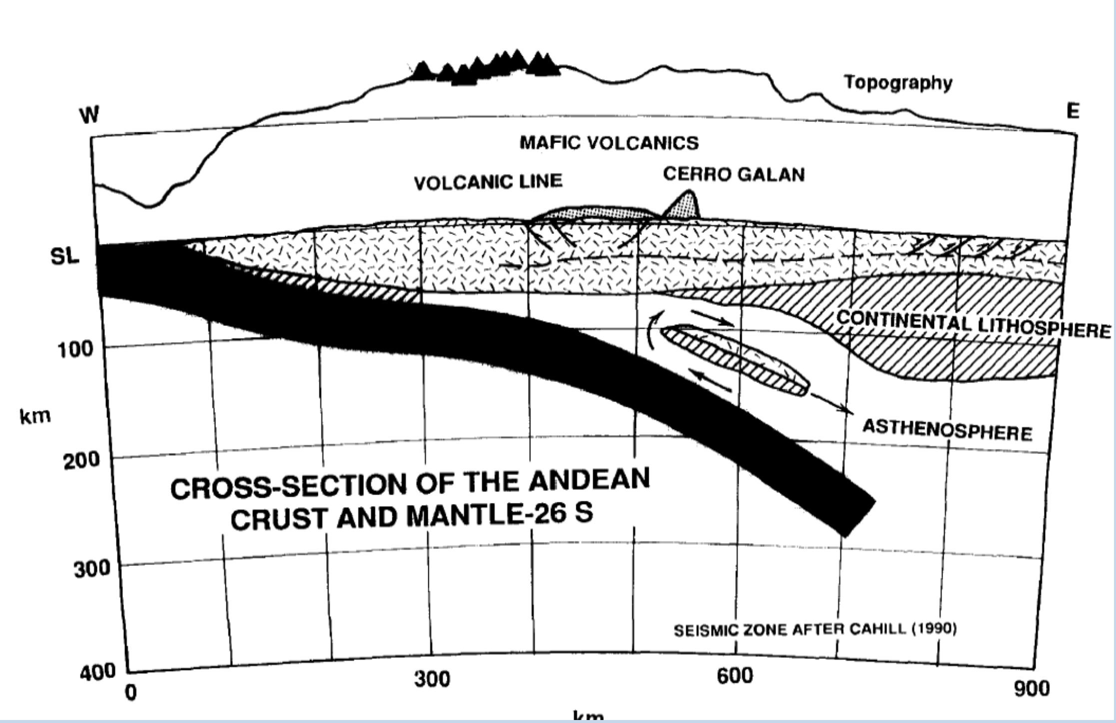

APMB, InSAR (1995–2010)
SMB, InSAR (2000–2006)
APMB, diapir model
SMB, leveling (1911–1980)
NW
SE
Mean LOS velocity, mm/yr
Distance, km
12
10
8
6
4
2
0
−2
−4
−6
−8
−10
0
50
100
150
200
5
4
3
2
1
0
−1

Largest active magma bodies in the continental crust

- Discovered by seismic studies
- Similar emplacement depth (~20 km)
- Geodetically detected uplift
- Similar uplift rates (millimeters/yr)
- Different tectonic settings



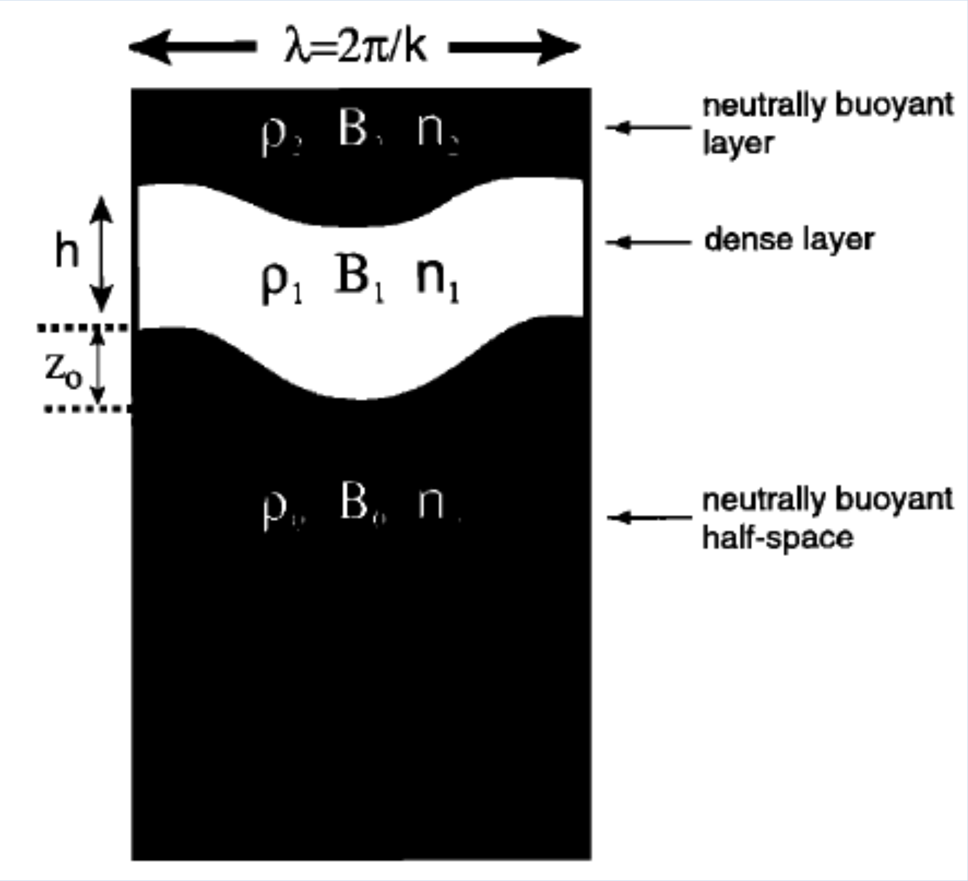
But wait!
Two ways to get uplift:

1) Crustal thickening
2) Delamination: the foundering of dense lithosphere into less dense asthenosphere

Although lithospheric mantle in general is less dense than the underlying asthenosphere, in cases where there has been a lot of crustal shortening and thickening there may be phase changes in the lower crust and upper mantle that makes this region negatively buoyant. If this material is replaced by less dense material, get isostatic uplift

Leads to volcanic magmas with distinct compositions

Kay and Kay (1993)



And yet one more idea:

A slight twist:
Convective instability of lower crust

Jull and Kellemen (2001) showed that there is actually a broad range of compositions and conditions in the lower crust where thickened crustal material will be negatively buoyant relative to the underlying mantle and form "blobs" of material that "drip" off of the base of the crust.

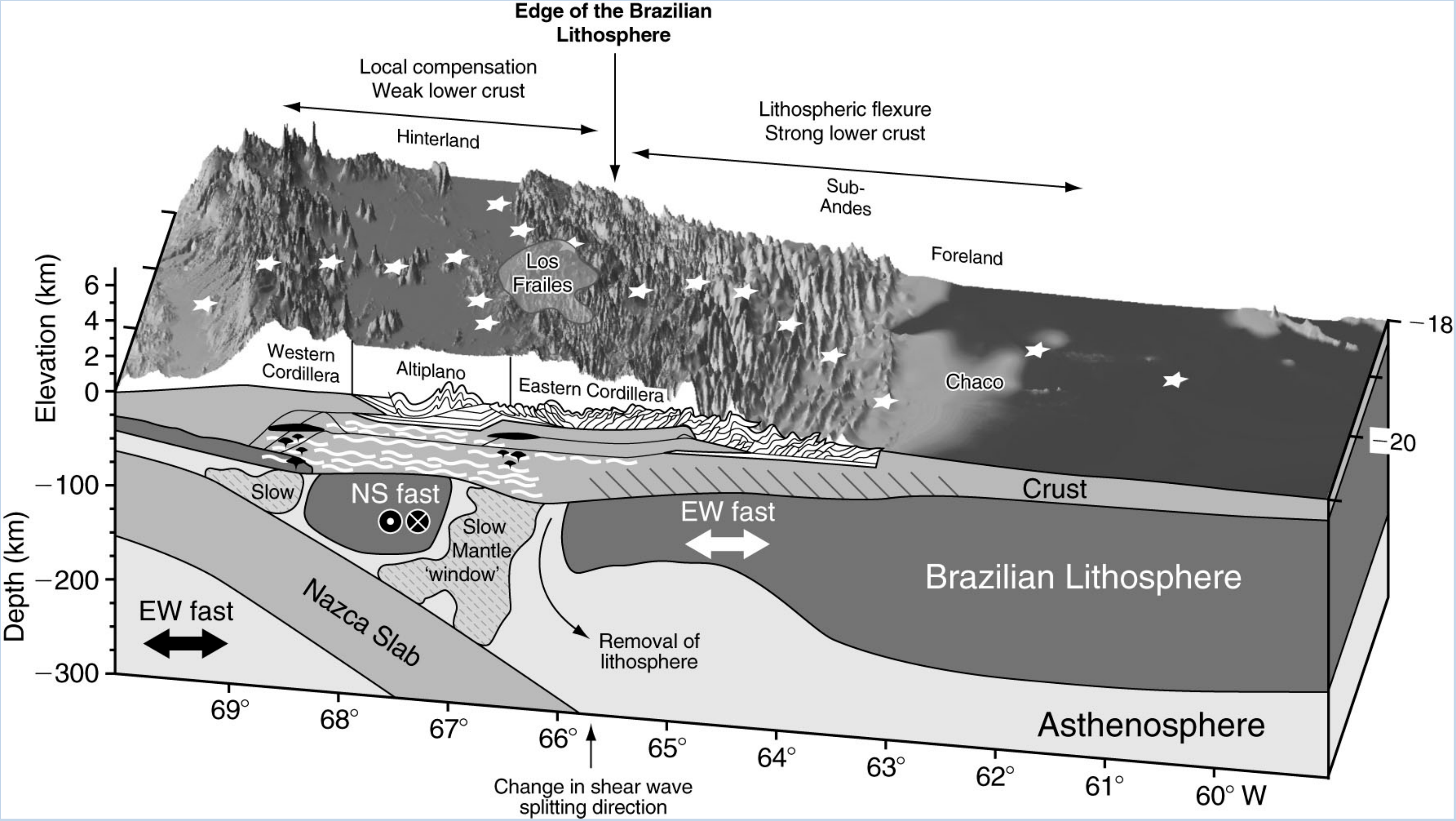
Not to be confused with "delamination" where the lower crust "peels off."

A lithospheric drip can be envisioned as honey dripping off a spoon, where an initial lithospheric blob is followed by a long tail of material.

When a small, high-density mass is embedded near the base of the crust and the area is warmed up, the high-density piece will be heavier than the area around it and it will start sinking. As it drops, material in the lithosphere starts flowing into the newly created conduit.

ScienceDaily

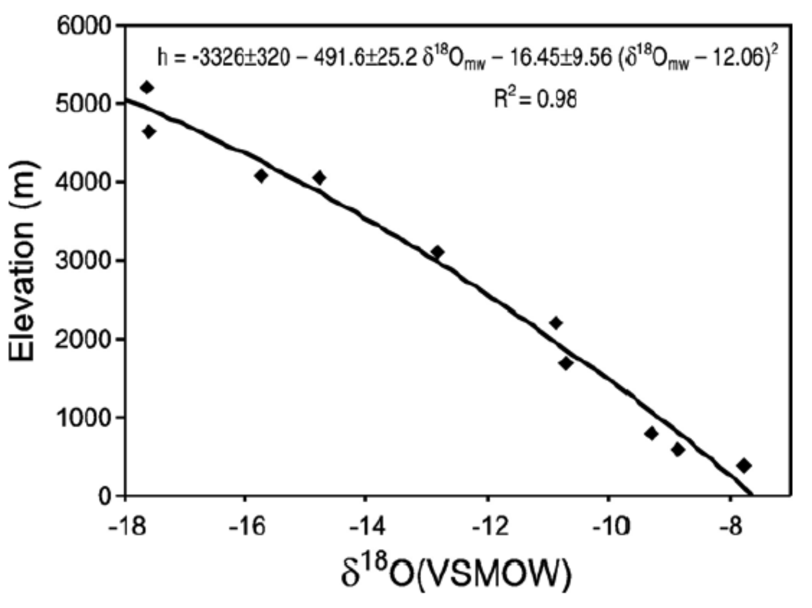
The model in KK&V has both: crustal shortening along long, flat thrusts (a la Isacks) and removal of lower crust by delamination/drips



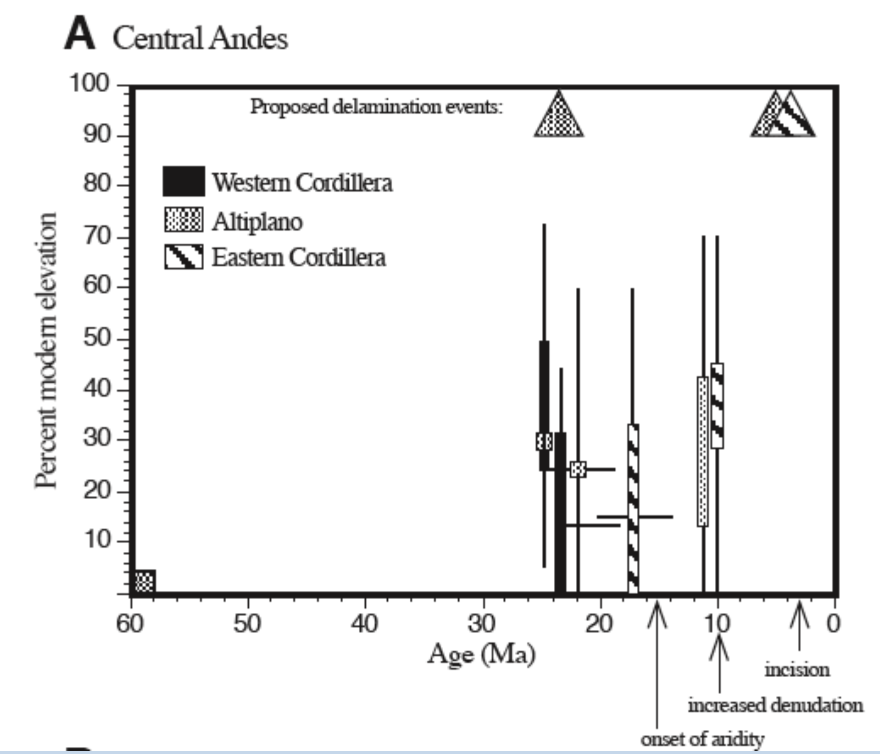
The timing of Andean uplift would enable us to discriminate between the orogenic process.

Hard to constrain: clues from marine/coastal facies, climate history, drainage development

Altiplano at about half its present elevation at 10 Ma; so when did it go up?



Garzione and Molnar (2006)



Gregory-Wodzicki (2000)

Newer method: Oxygen isotope paleo-altimetry from carbonates (above)

See systematic decrease in delta O^{18} with altitude in modern day lake deposits of precipitated carbonates; determine a regional (northern Altiplano) relationship

Find a systematic pattern in ancient lake deposits that indicate a change in altitude in one place over time.

Stable Isotopes of Oxygen:

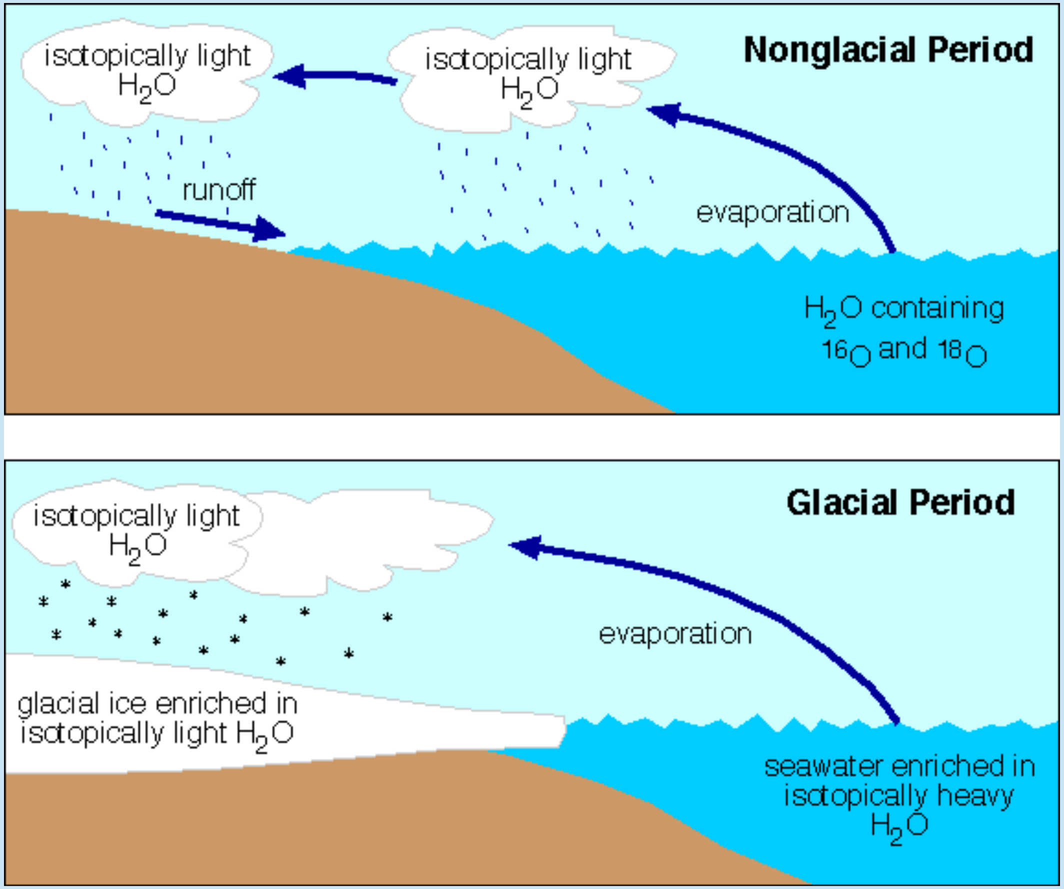
$^{16}O = 99.76\%$

$^{18}O = 00.20\%$

The ratio varies as the environment changes:

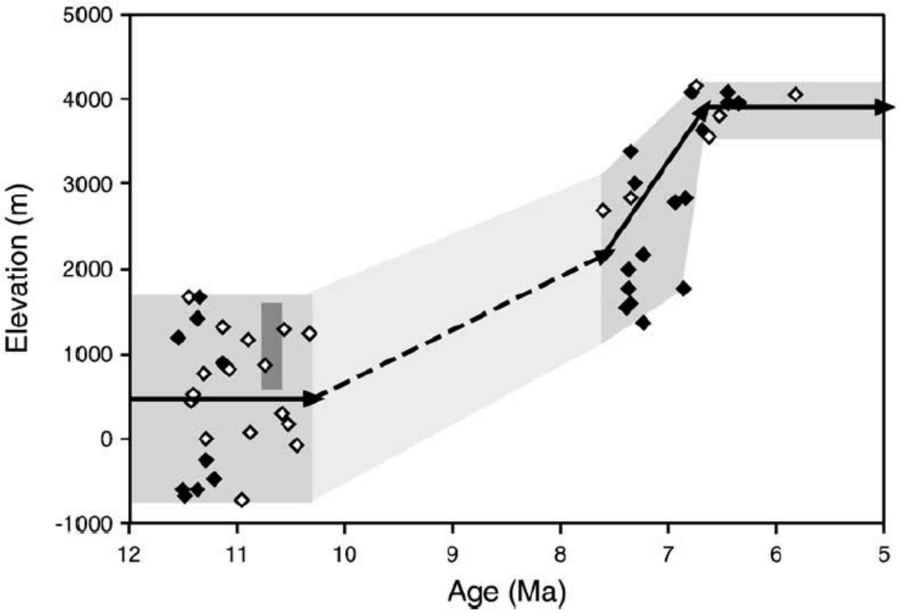
When the climate is colder, the "light" oxygen goes into ice

fractionation



The oxygen isotope ratio is a "proxy" for temperature

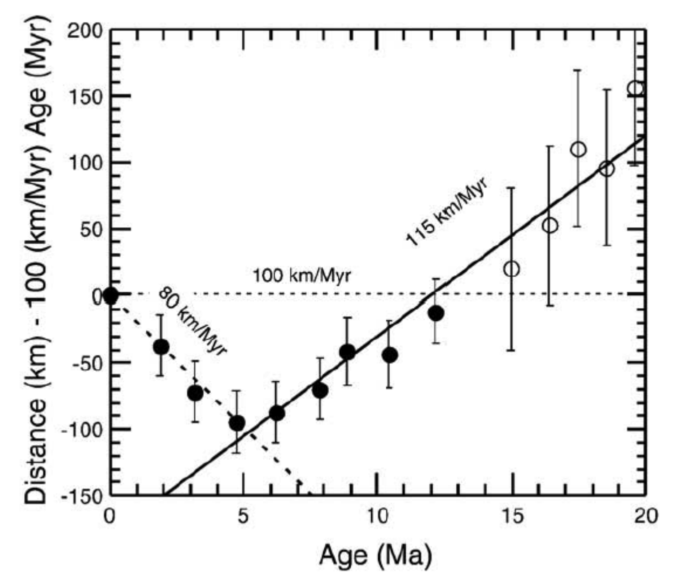
Measure ratio with a mass spectrometer



Observations based on delta O^{18} paleoaltimetry:

uplift (2.5 to 3.5 km) of the Altiplano was sudden, between 10 and 7 Ma

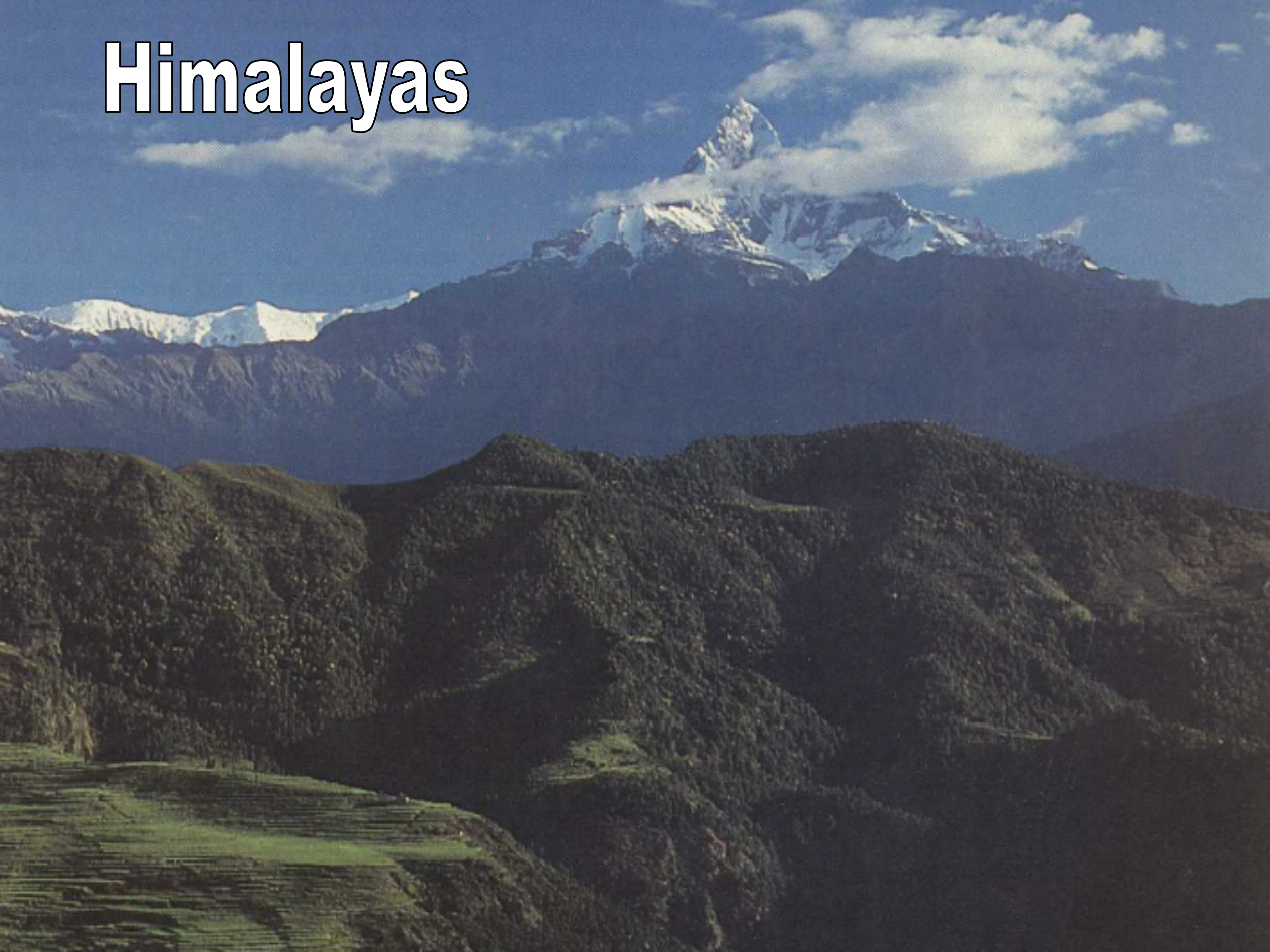
This is too fast for Isacks's crustal thickening. Requires that uplift is due to delamination (i.e. removal of dense lower crust and upper mantle);



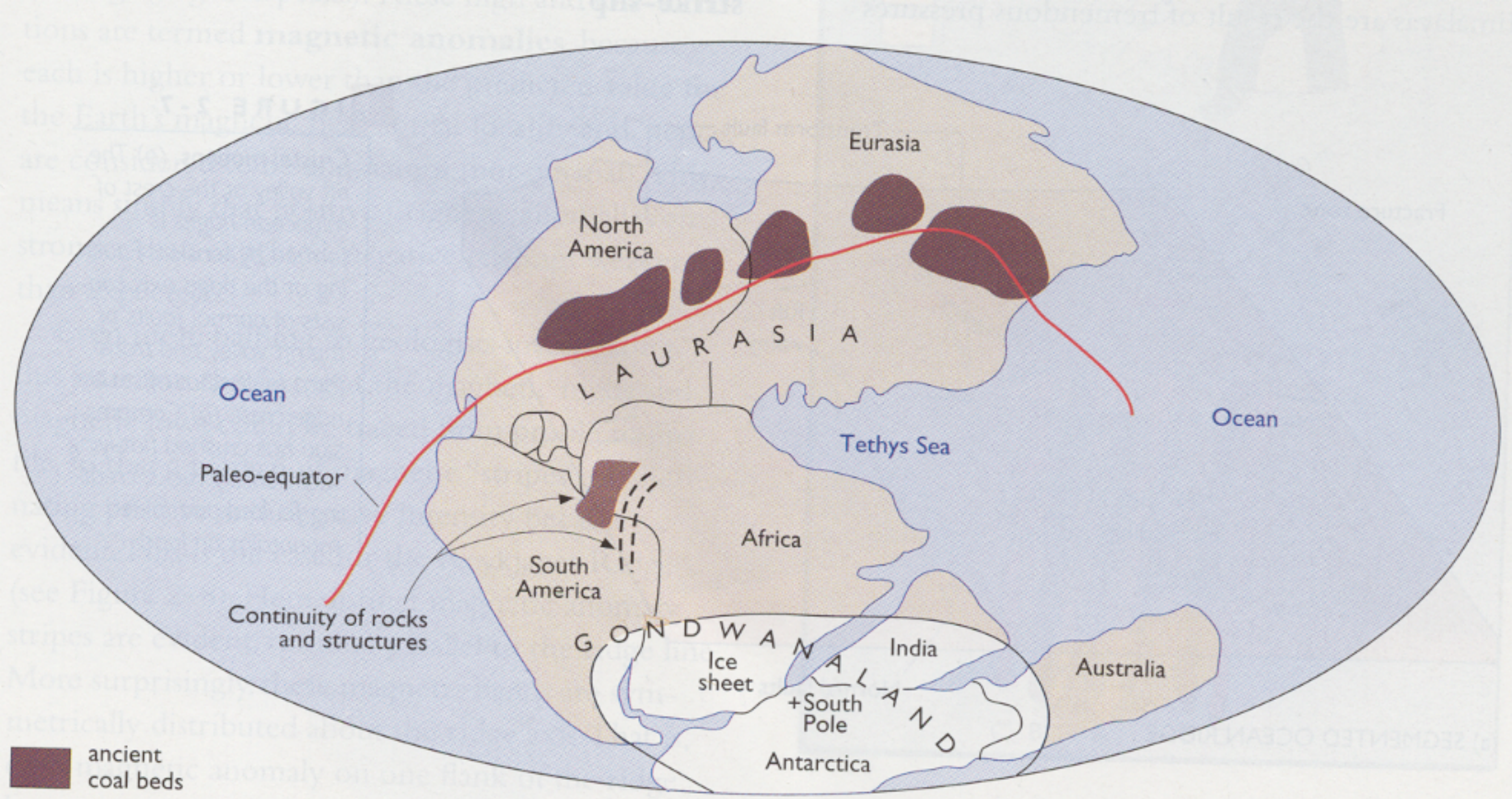
Garzione et al. (2006)

Another way to date uplift:
See decrease in convergence rate between Nazca and So. Amer at same time (from the plate circuit). The authors interpret this as being due to an increase in the force per unit length applied by highlands on the plate boundary which they attribute to uplift of the Andes.

Himalayas

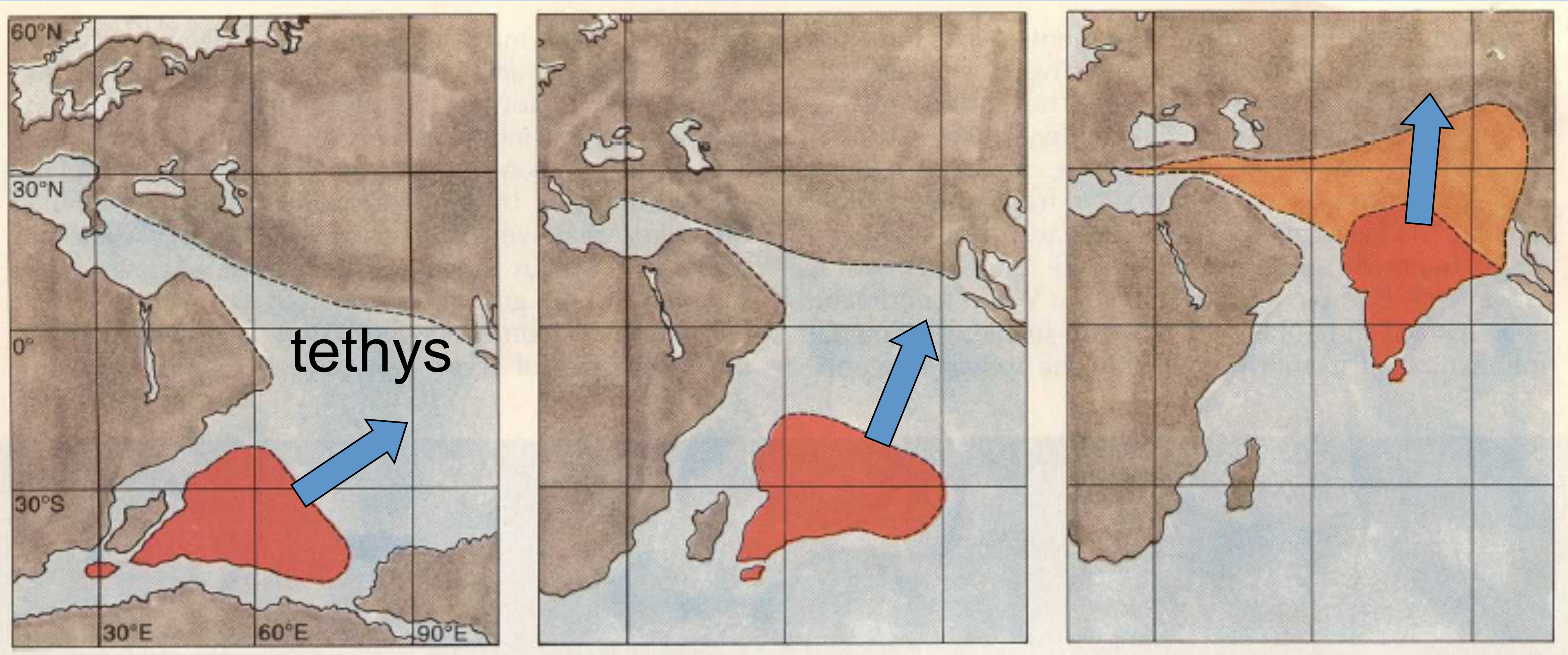


Tethys –goddess of the sea



The vast ocean that preceded the breakup of Pangaea and Gondwanaland

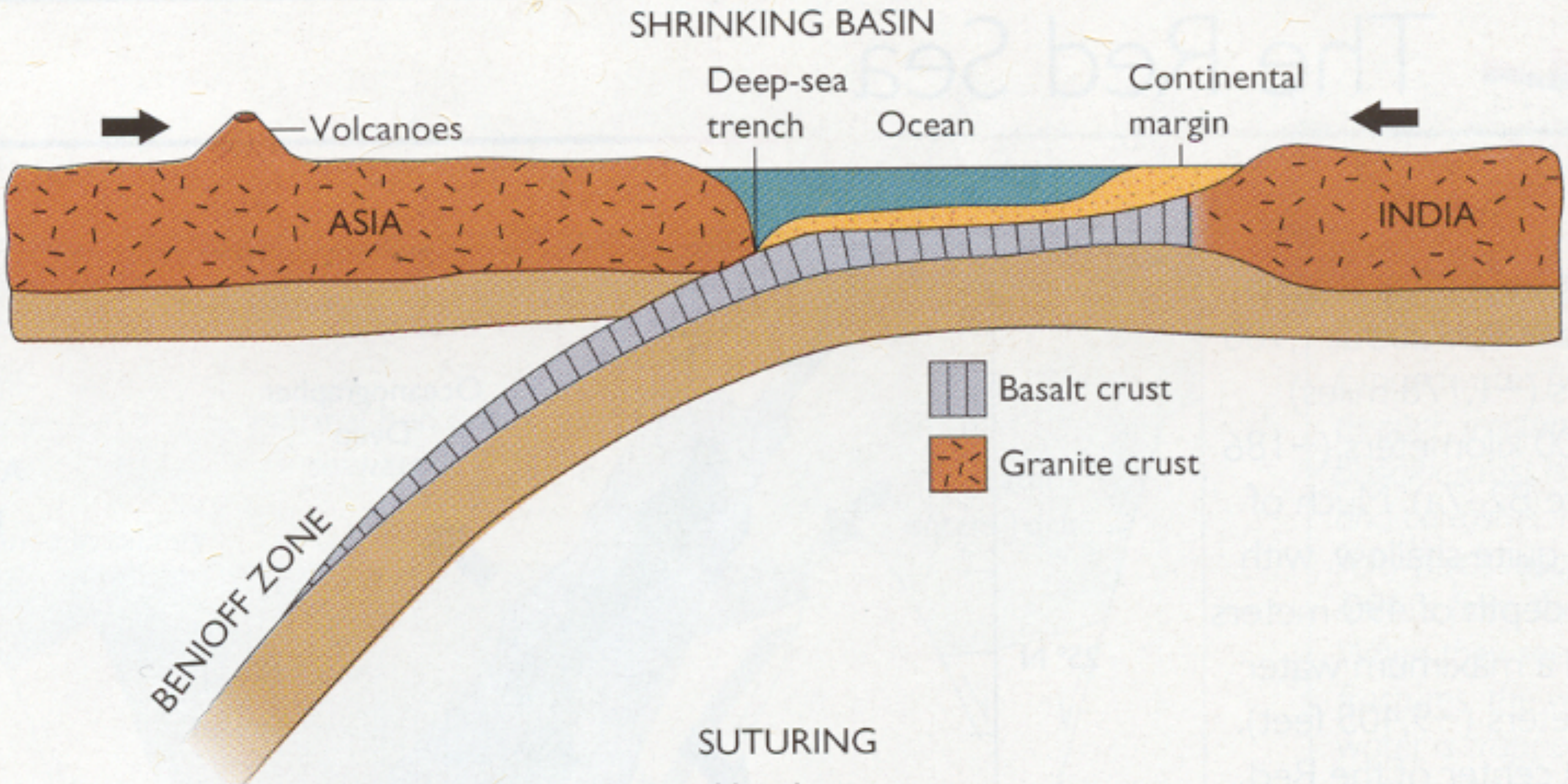
Motion of India with respect to Eurasia

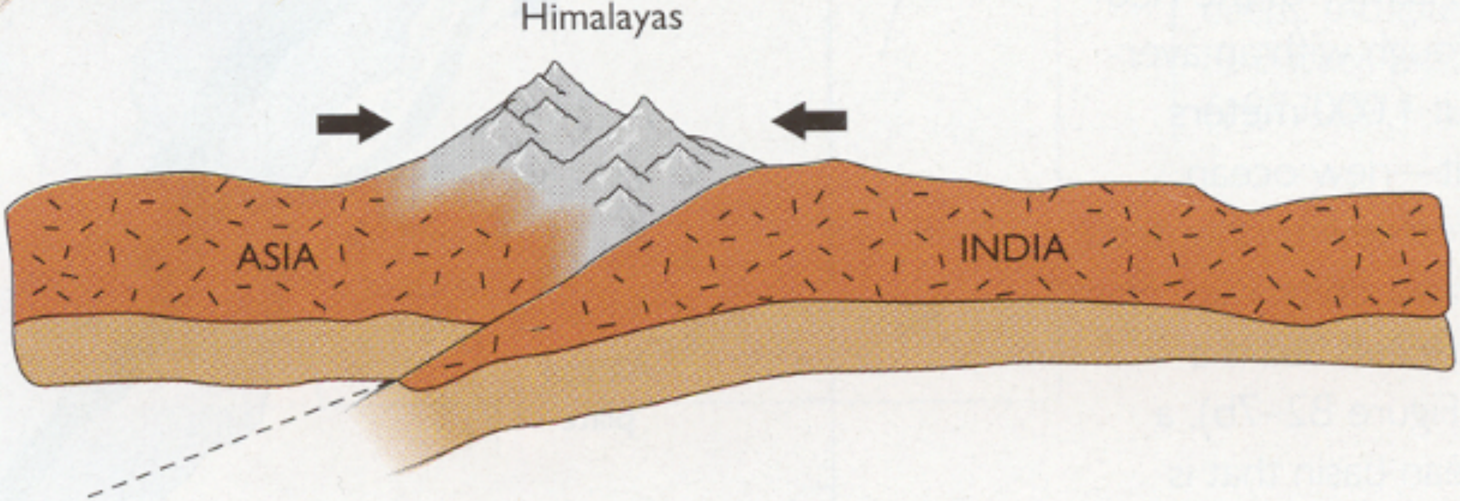


120 my

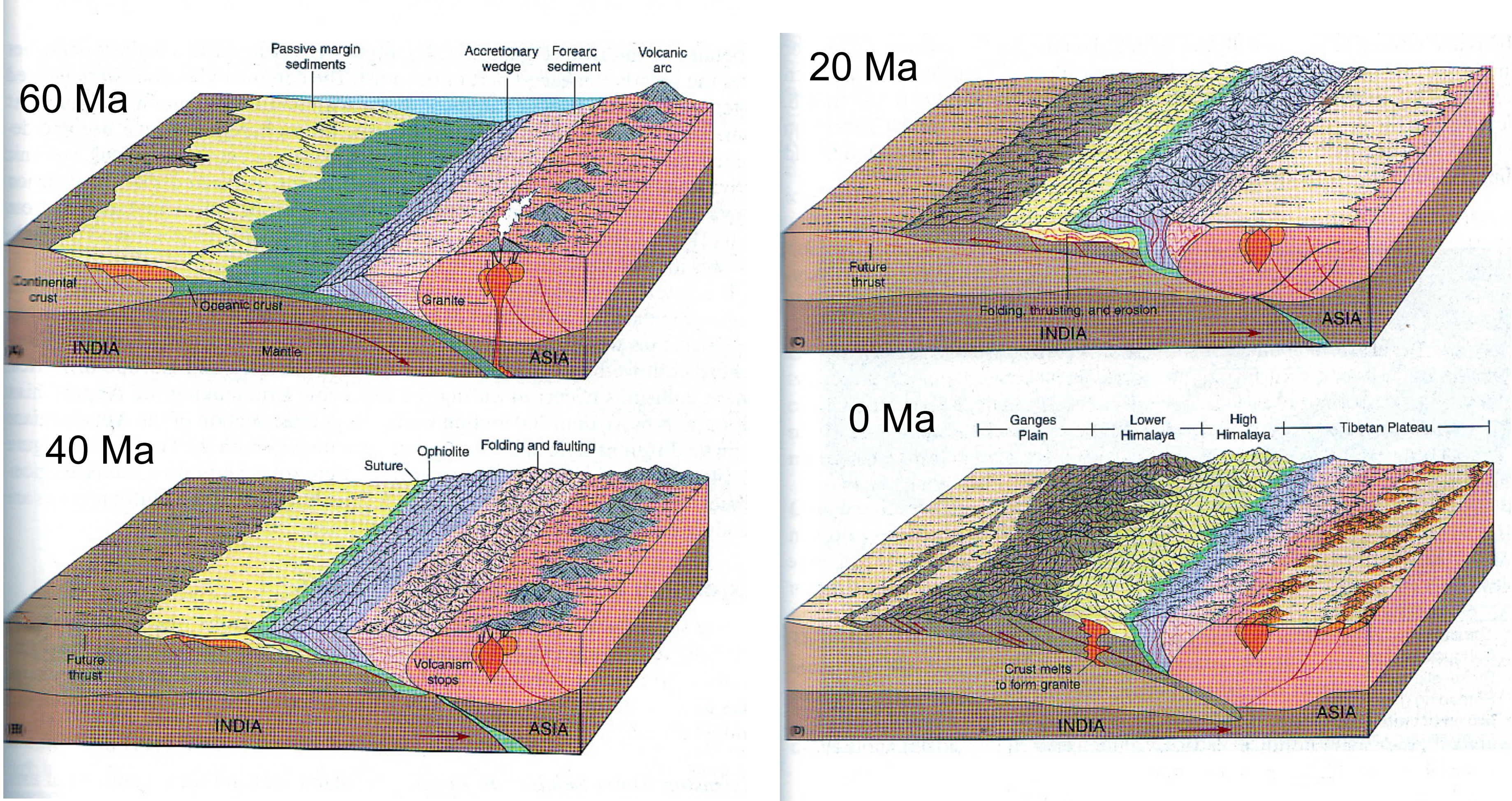
80 my

40 my


SHRINKING BASIN
Deep-sea trench
Continental margin
Volcanoes
Ocean
ASIA
INDIA
Basalt crust
Granite crust
BENIOFF ZONE


SUTURING
Himalayas
ASIA
INDIA

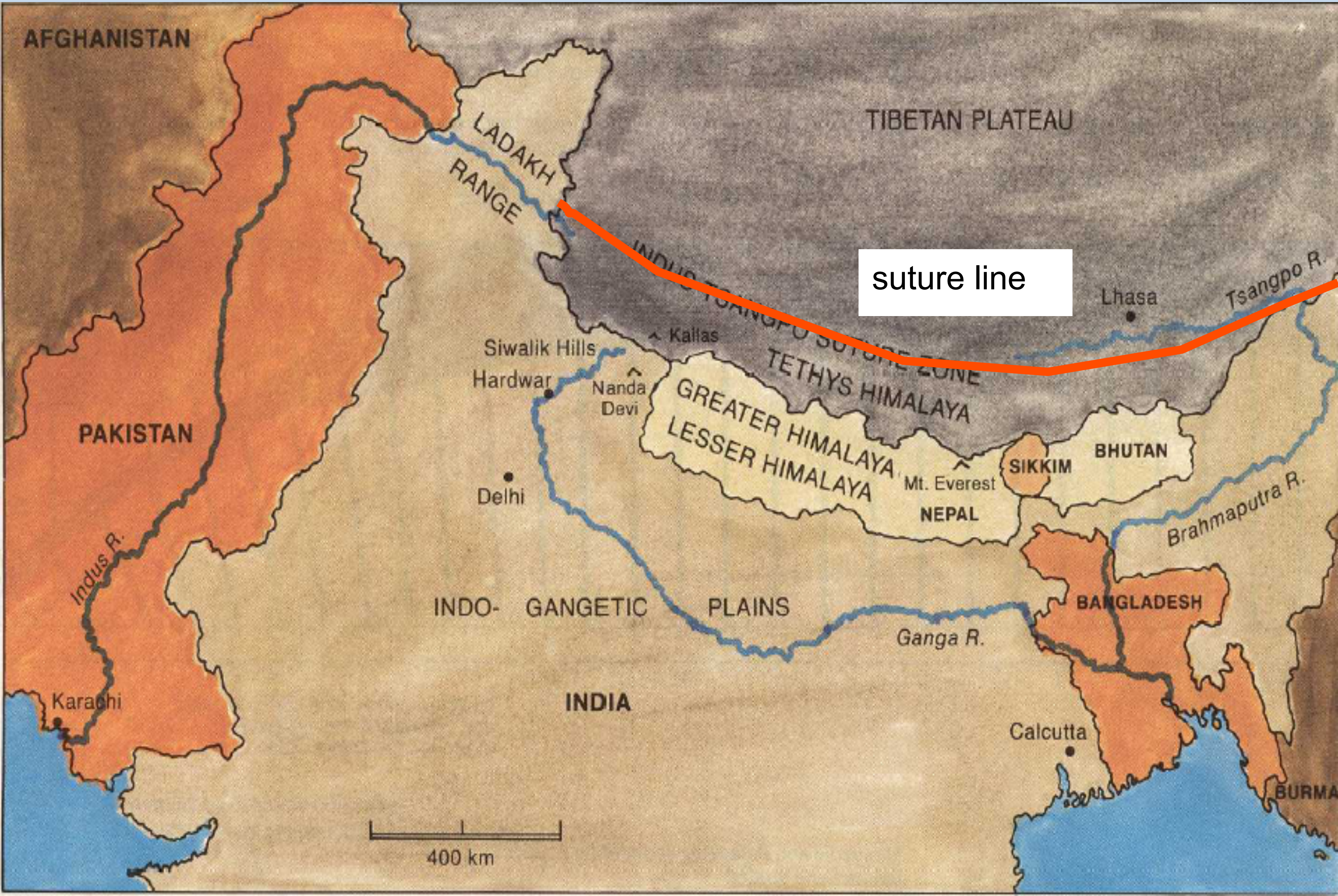
Four stages in the India-Eurasia collision



Yellow = Paleozoic and Mesozoic passive margin sediments (India)
Green = deep sea basin oceanic crust/sediments (Tethys)
Blue = accretionary wedge sediments (Asia)
Pink = fore-arc basin sediments
Dark red = volcanic arc
Brown = Indian continental crust
Tan = recently deposited sediments; products of recent rapid erosion

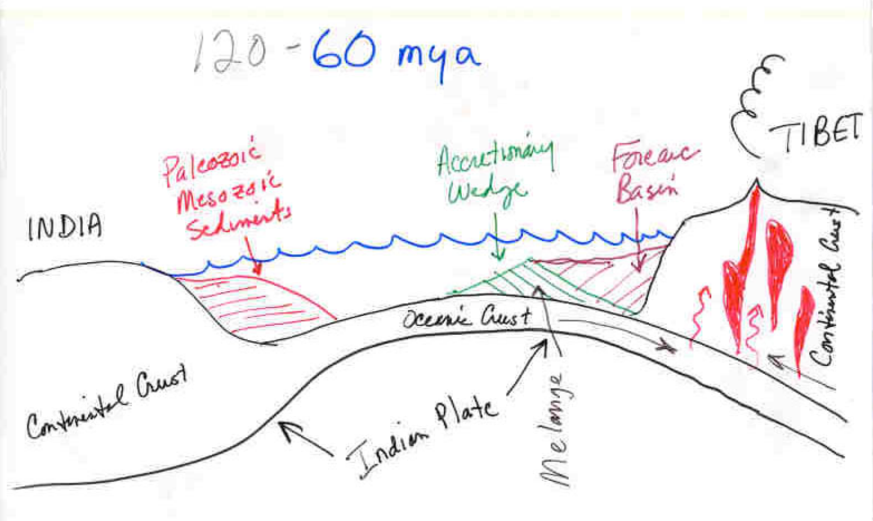
Top of Everest = Ordovician limestones

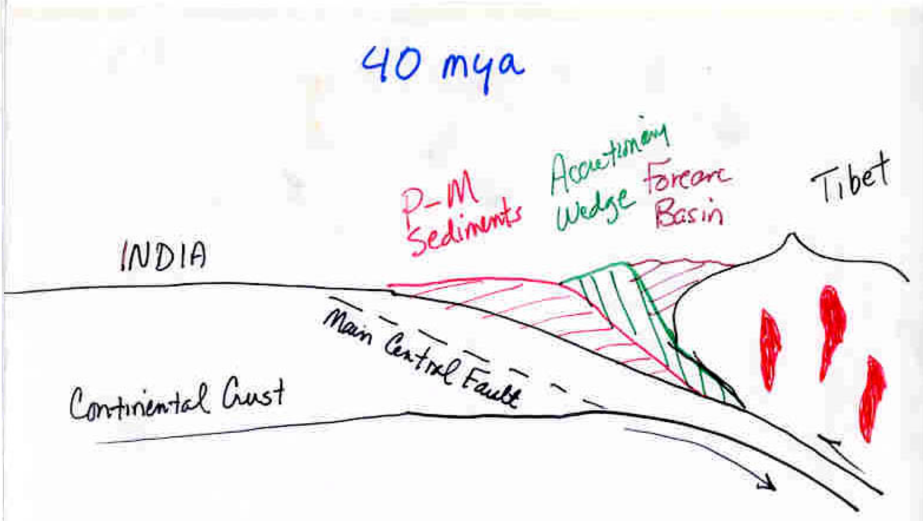
Hamblin & Christiansen

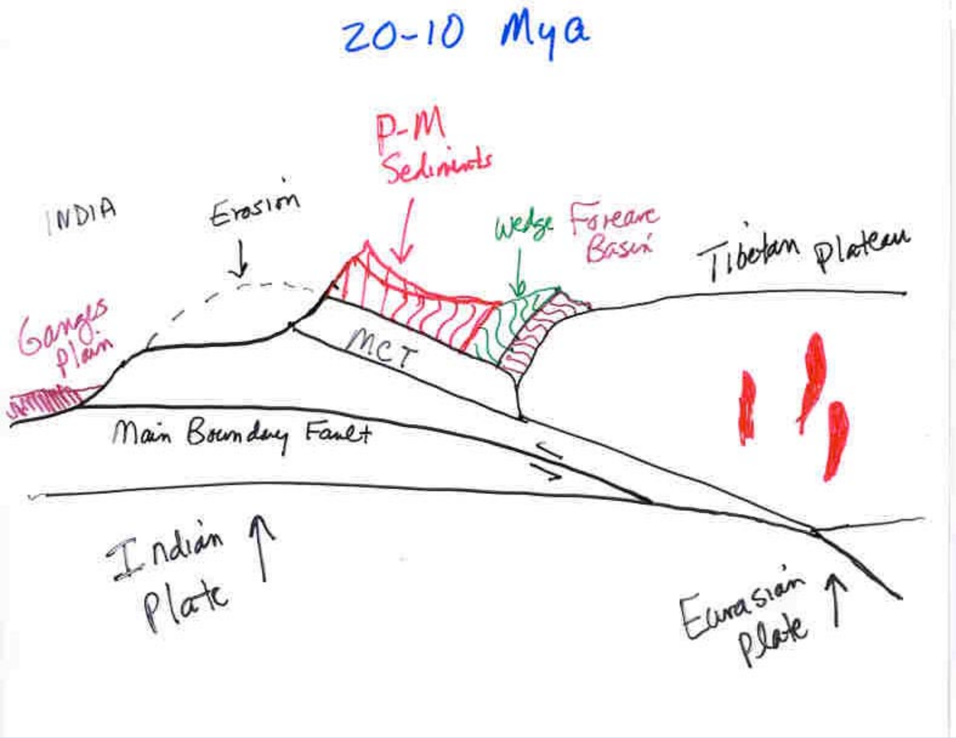


suture line

AFGHANISTAN
TIBETAN PLATEAU
LADAKH RANGE
INDUS-TSANGPO SUTURE ZONE
Kailas
Lhasa
Tsangpo R.
TETHYS HIMALAYA
GREATER HIMALAYA
LESSER HIMALAYA
Siwalik Hills
Hardwar
Nanda Devi
Mt. Everest
SIKKIM
BHUTAN
NEPAL
PAKISTAN
Delhi
Brahmaputra R.
Indus R.
BANGLADESH
INDO- GANGETIC PLAINS
Ganga R.
Karachi
INDIA
Calcutta
BURMA
400 km







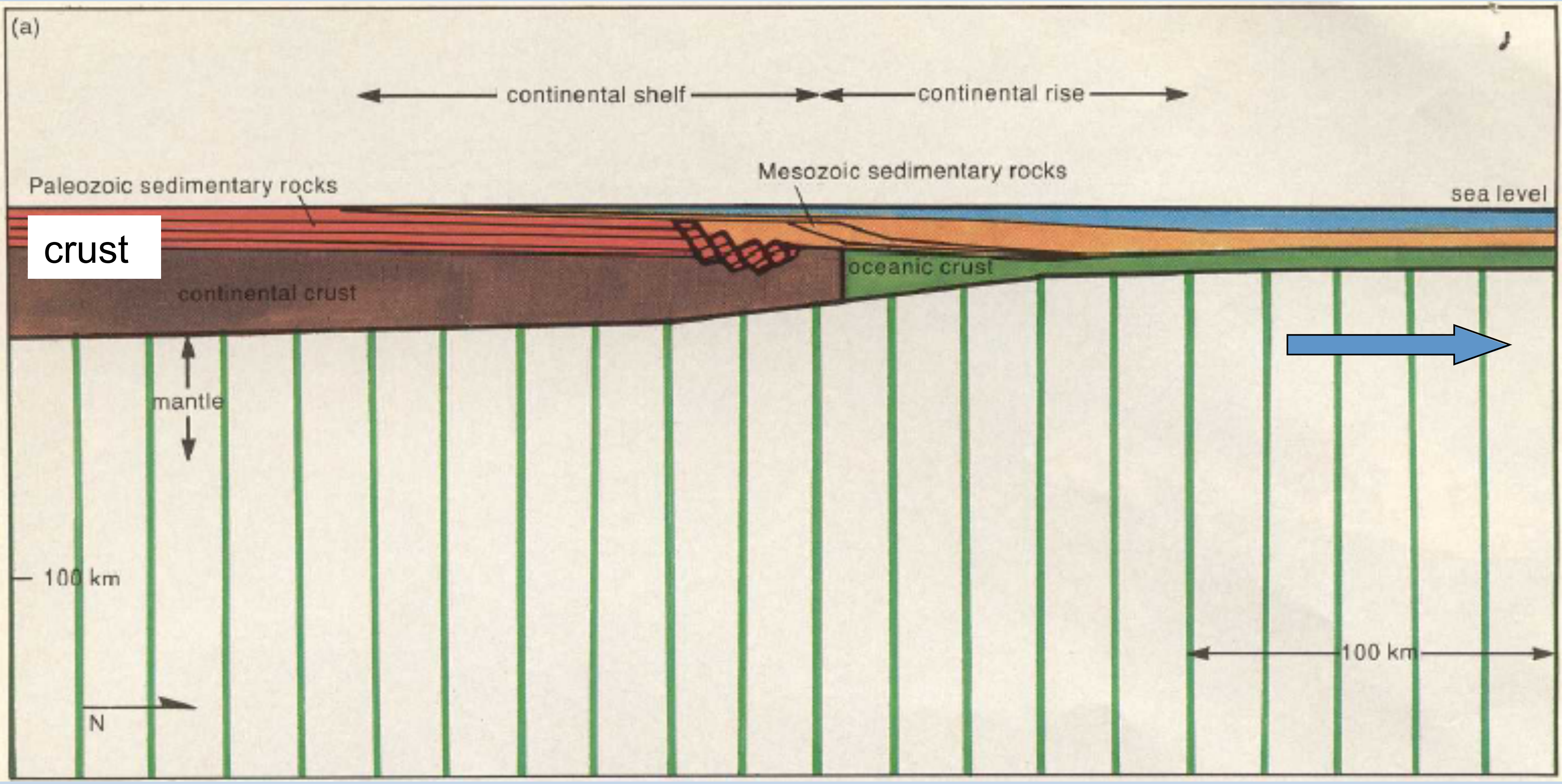
Two huge thrust faults cut through the Indian plate:

Main Central Fault (MCT) (~40 Ma)
Main Boundary Fault (MBF) (~20 Ma)

Mark Williams snobear.colorado.edu/Markw/mark.html

80 my ago

Indian continent passive continental margin Tethys ocean

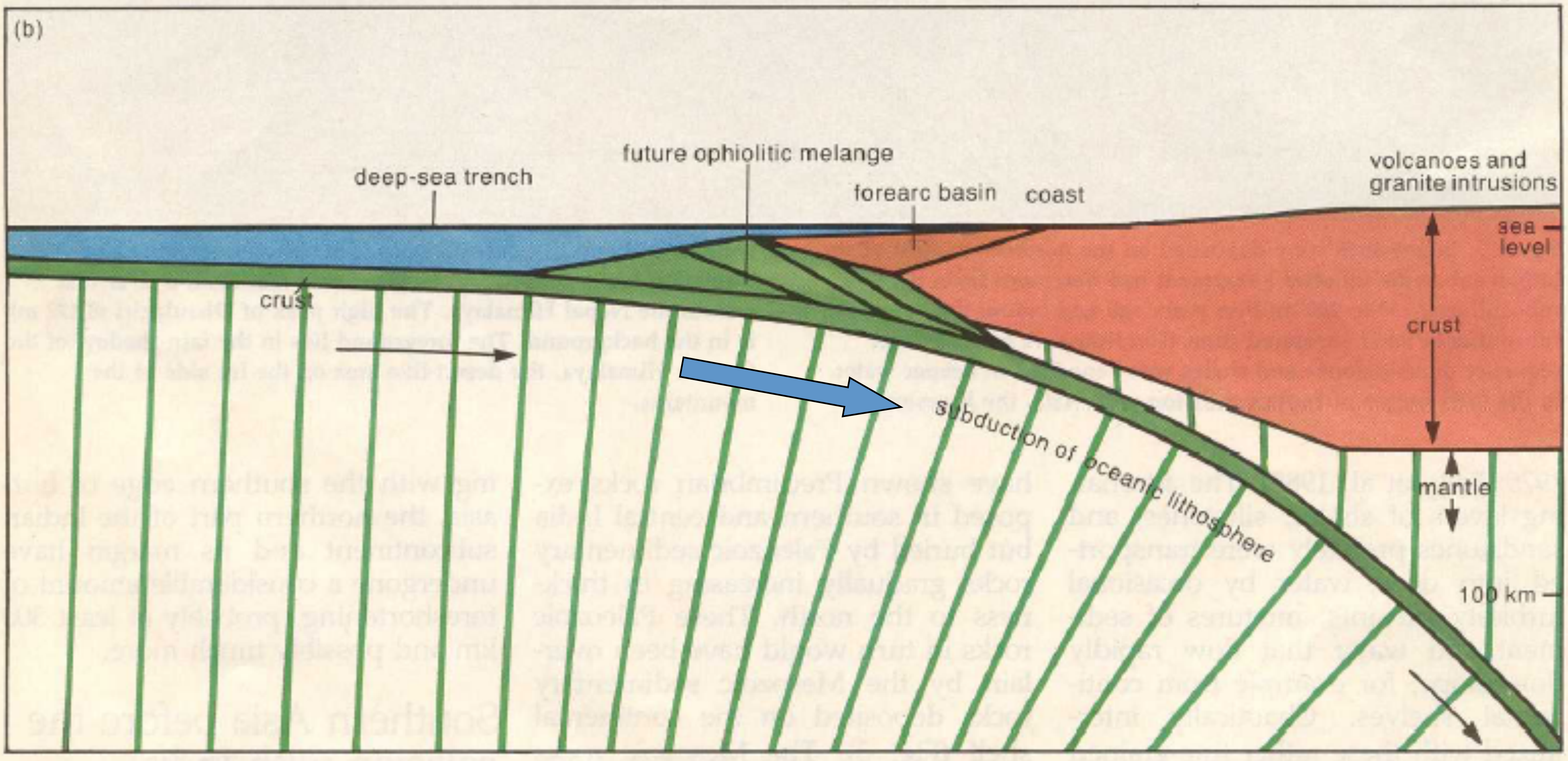


60 my ago

Tethys ocean

convergent margin

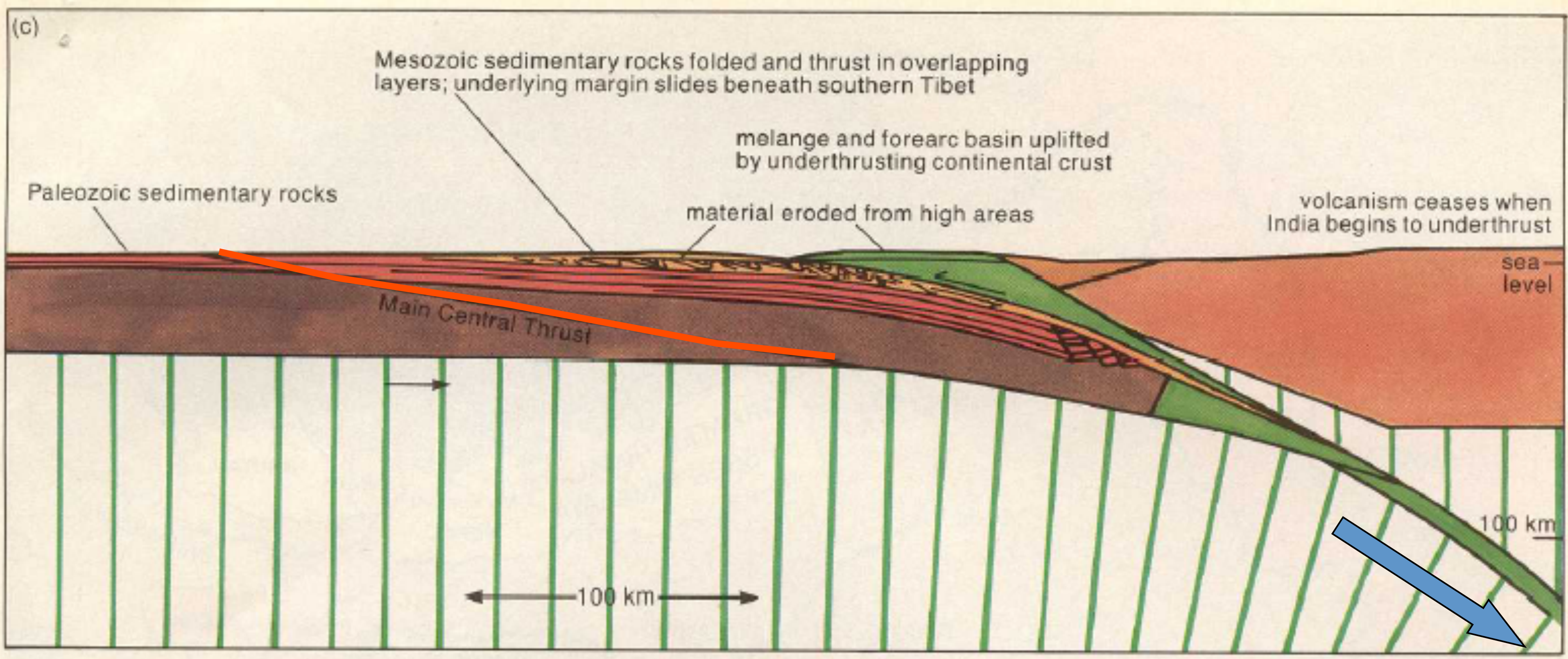
Eurasian continent



initial formation of an accretionary prism

40 my ago

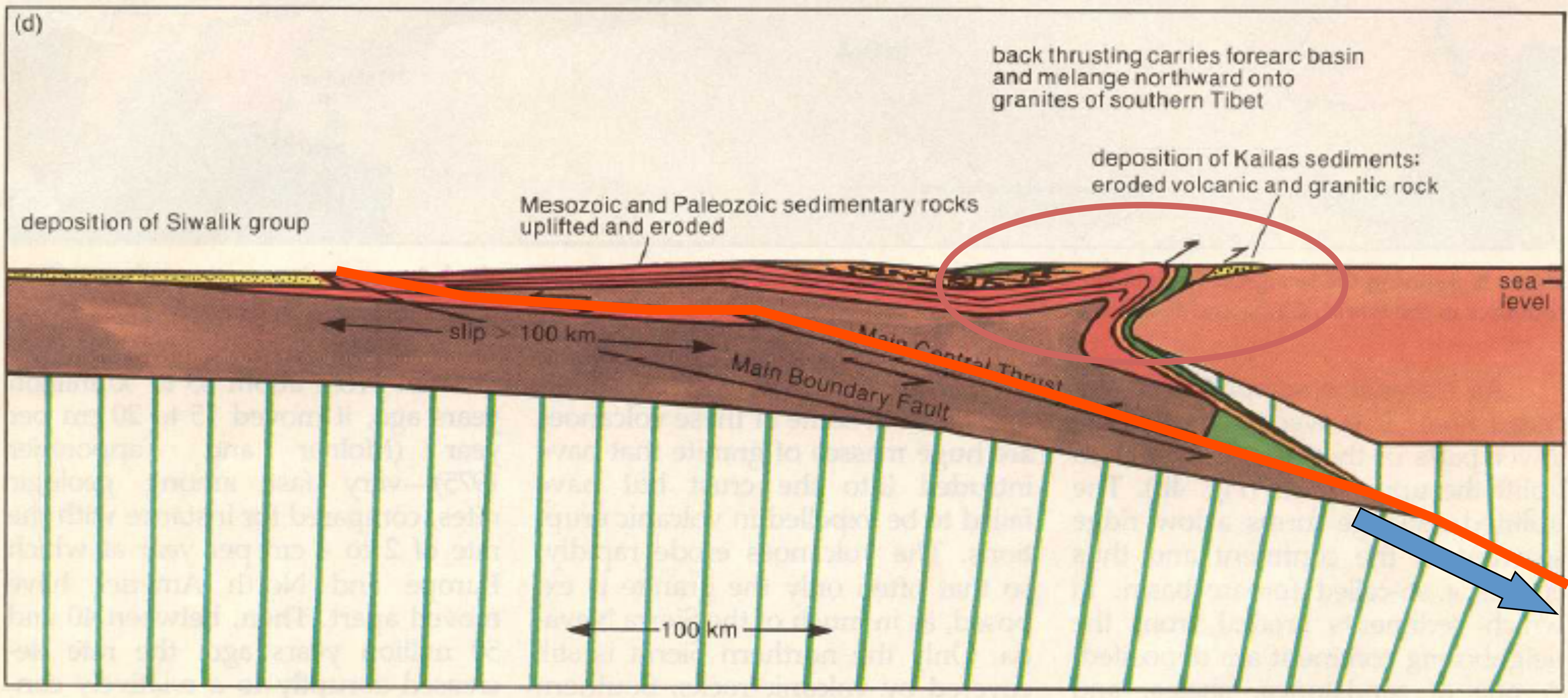
Collision of India with Eurasia



the formation of a huge thrust cutting entirely through the Indian crust:
the Main Central Thrust

20 my ago

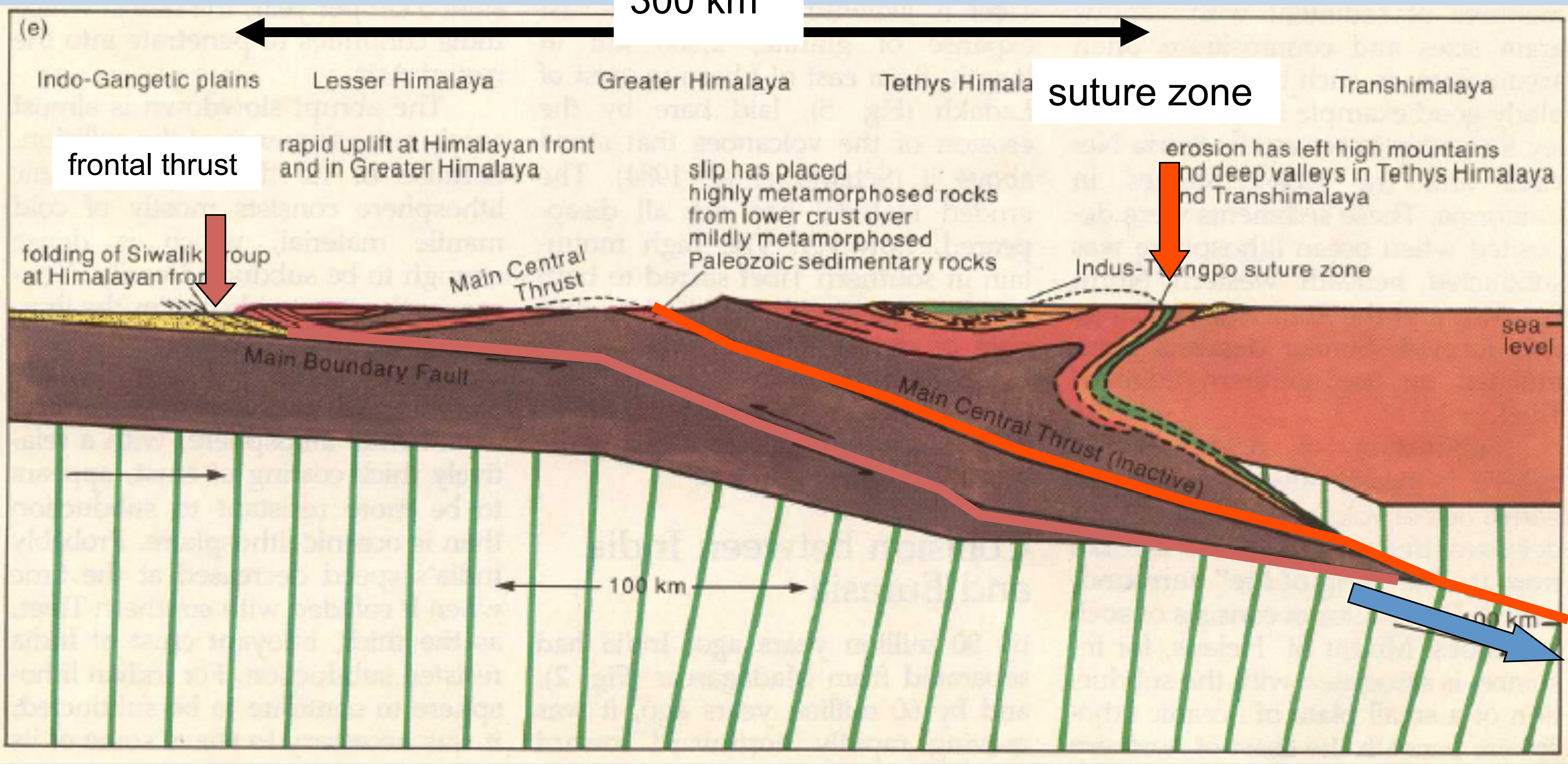
all that is left of the Tethys ocean



The Main Central thrust brings the northern edge of India up and onto the intact part of India father south

Second giant thrust: Main Boundary Fault

today



Lesser Himalaya

Greater Himalaya

Tethys Himalaya

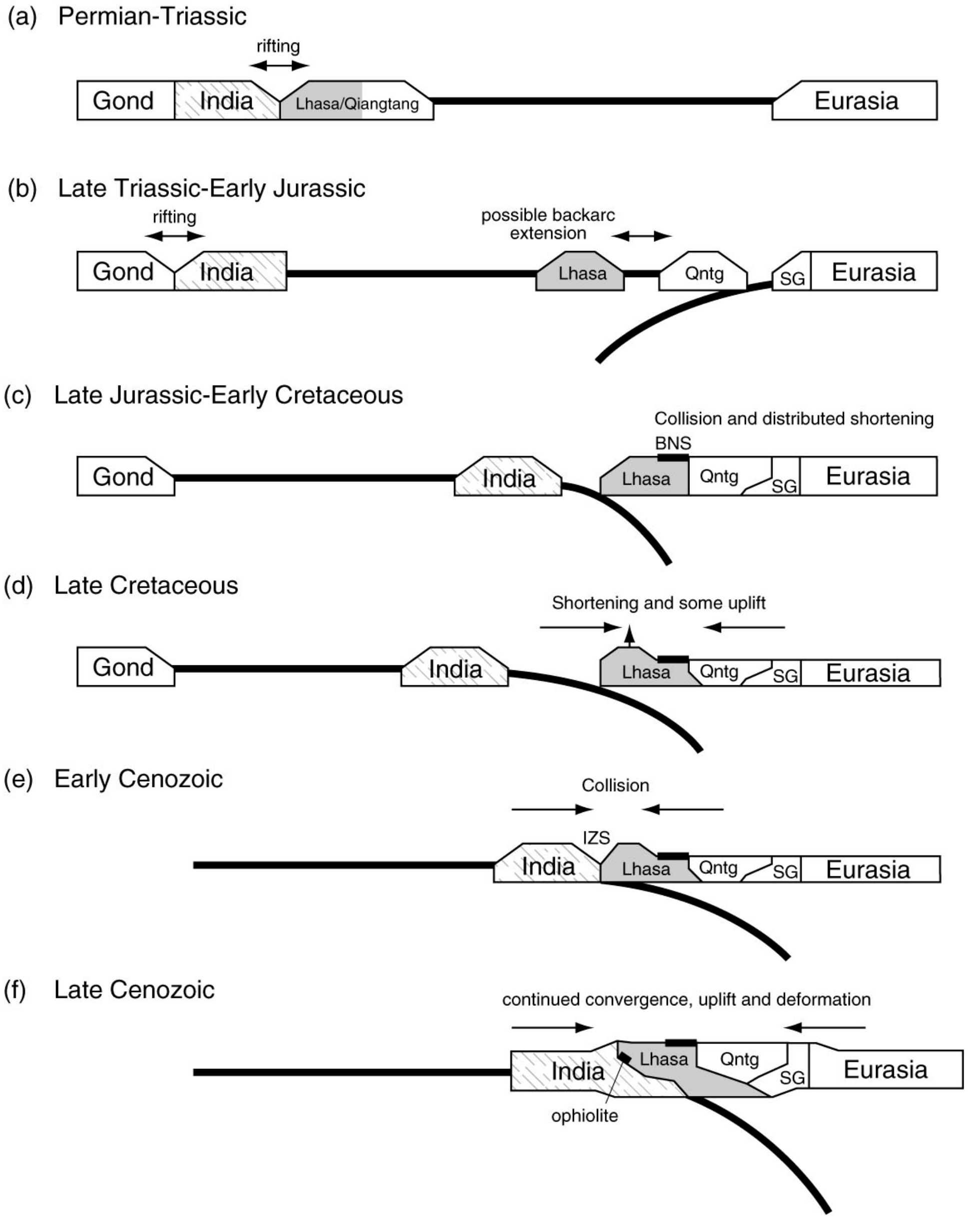
Trans-Himalaya

300 km

suture zone

frontal thrust

Two slivers of the former edge of India now rest upon India, greatly thickening today’s crust and the entire lithosphere



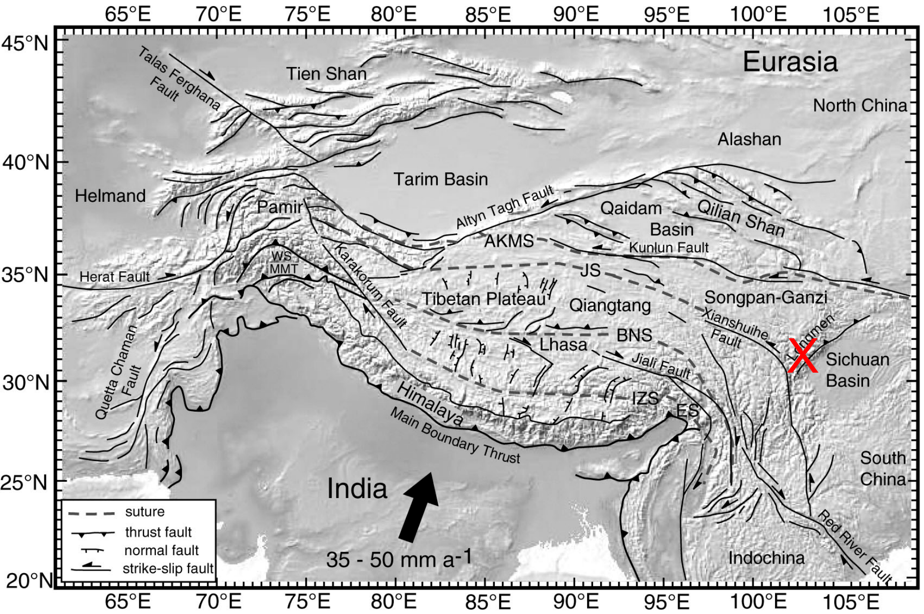
India-Tibet collision was preceded by collisions of several micro-continents and island arcs

Accretion of these terranes marked by series of suture zones in Tibet and China

Indus-Zangbo suture zone (IZS) marks India-Tibet collision

Himalayan orogen is built on collage of exotic material

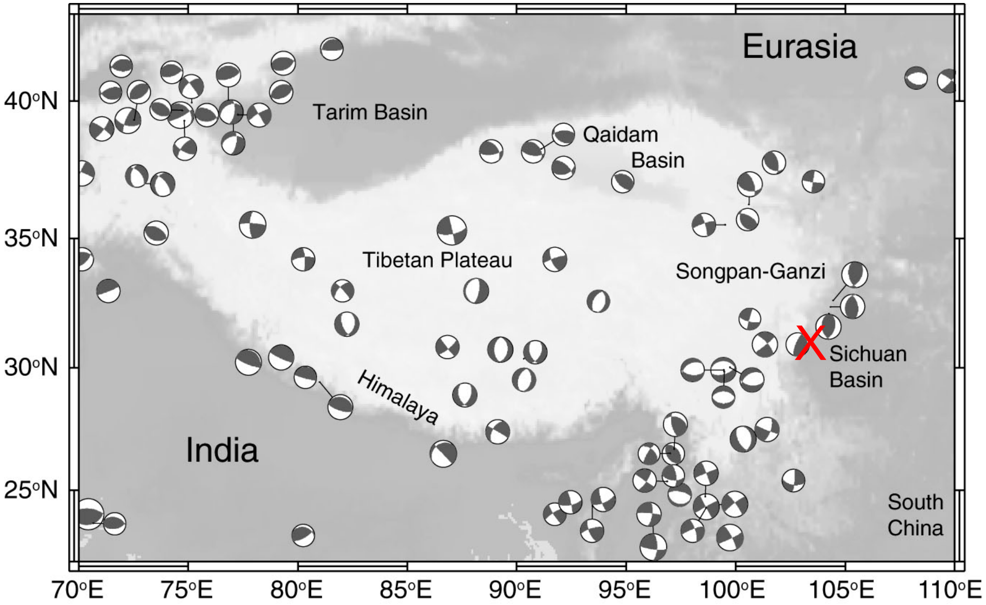
KK&V Fig 10.15



Earthquake focal mechanisms show

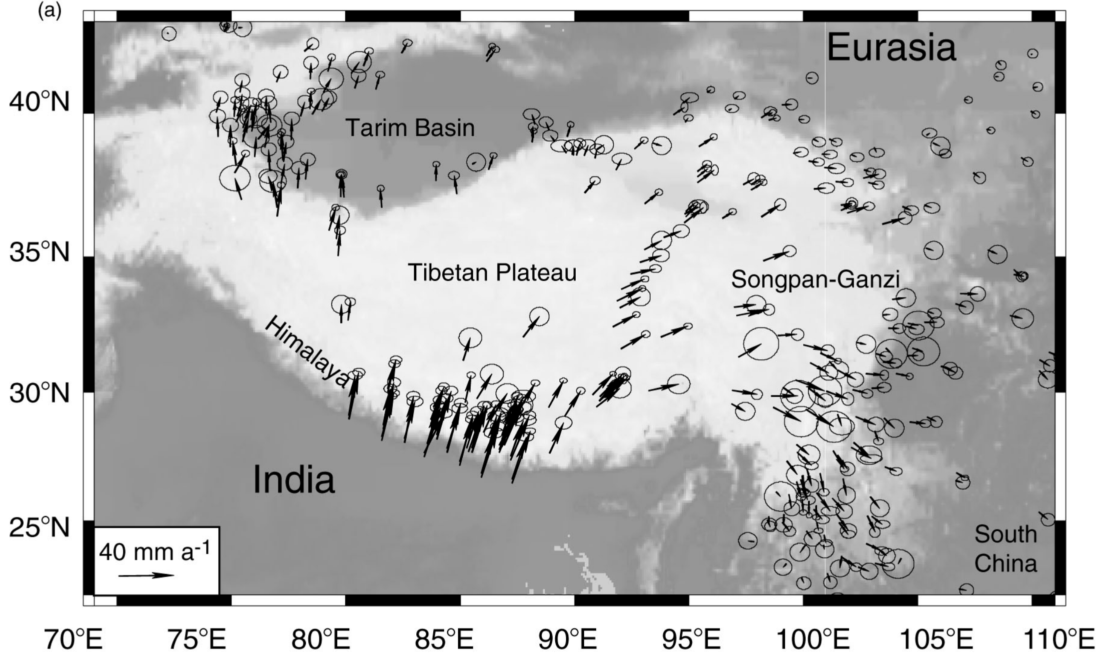
1) Thrust faulting on south, east and north side of Tibet plateau and within the Himalaya
2) North of Himalaya, in Tibet, normal faulting and east-west extension dominate
3) Strike slip faulting dominates 1500 km north of Himalaya and extending eastward into Indo-China

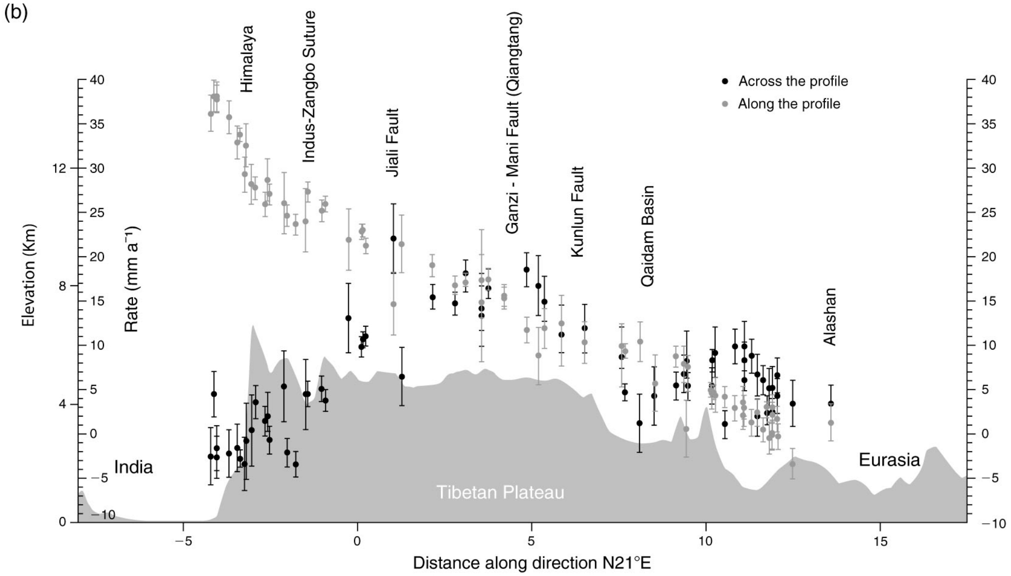
India is converging on Eurasia at 35-50 mm/yr and has been for the last 40 million years since the collision first started. There has been ~2000 km of convergence since collision started



X = 2008 Sichuan quake, mag. 7.9, thrust fault

KK&V Figs 10.13 and 10.17





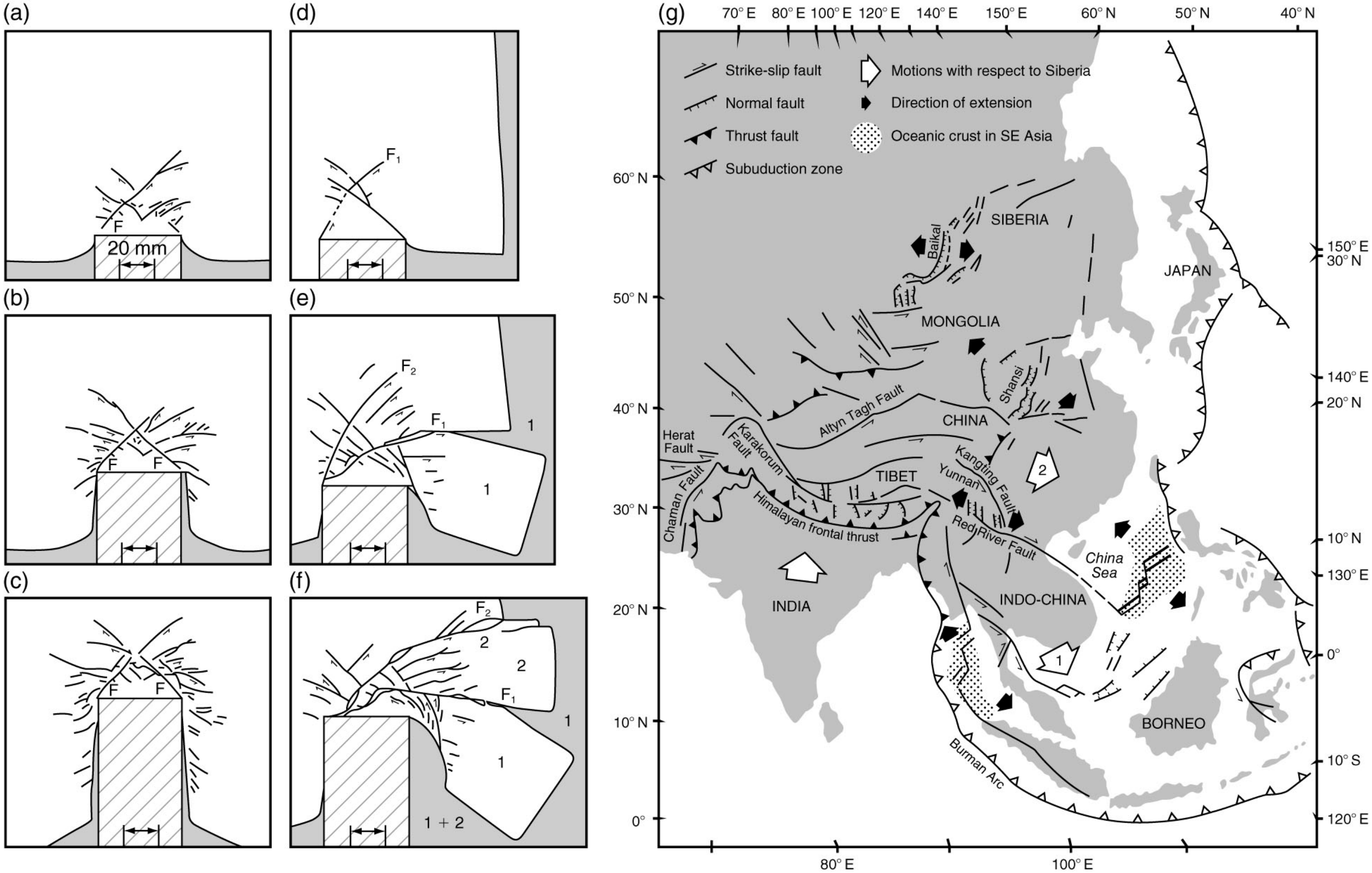
GPS and other measurements show that currently deformation within the Tibetan Plateau and its margin absorb more than 90% of relative motion between India and Eurasia

Internal shortening accounts for more than 1/3 of total convergence

Additional shortening north of Tibetan plateau

Tibetan plateau is also extruding eastward relative to India and Asia

Slices of crust move laterally out of the way; lateral escape

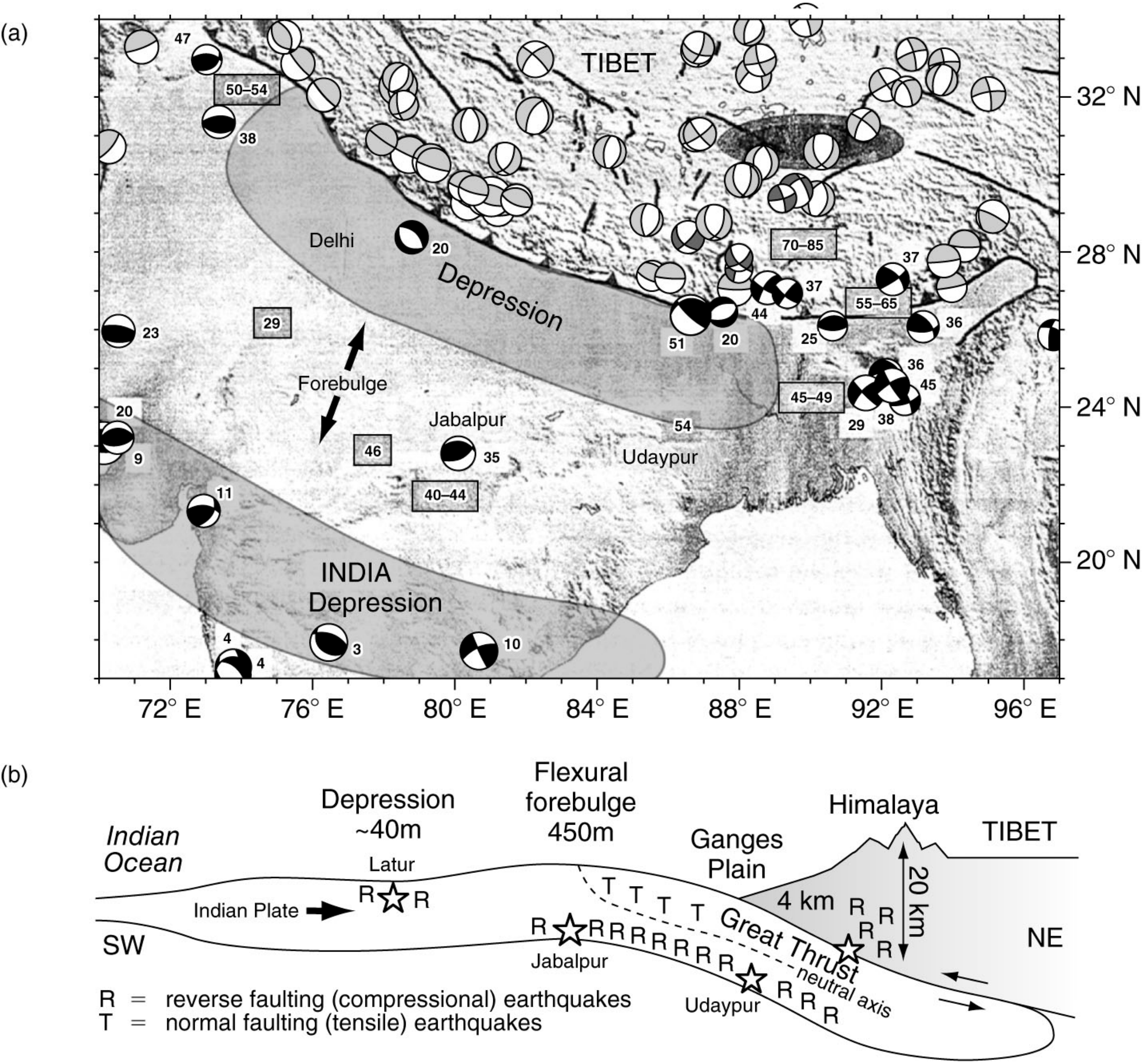


KK&V Fig 10.22

"Indenter tectonics" (Tapponnier and Molnar, 1976): India acts as a rigid block (indenter) that presses into and deforms a softer block (Asia)

Lateral extrusion of parts of Asia may accommodate about 1/3 of the convergence between India and Eurasia

Also called "escape tectonics"



Indian plate flexes and slides beneath the Himalaya

Seismic tomography shows a broad and deep zone of cold material in upper mantle beneath suture zone

This is interpreted as broken off pieces of Indian continental crust

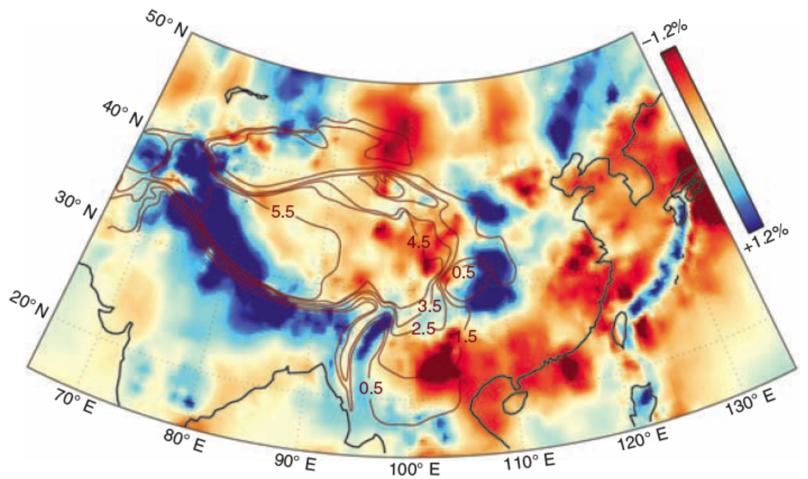
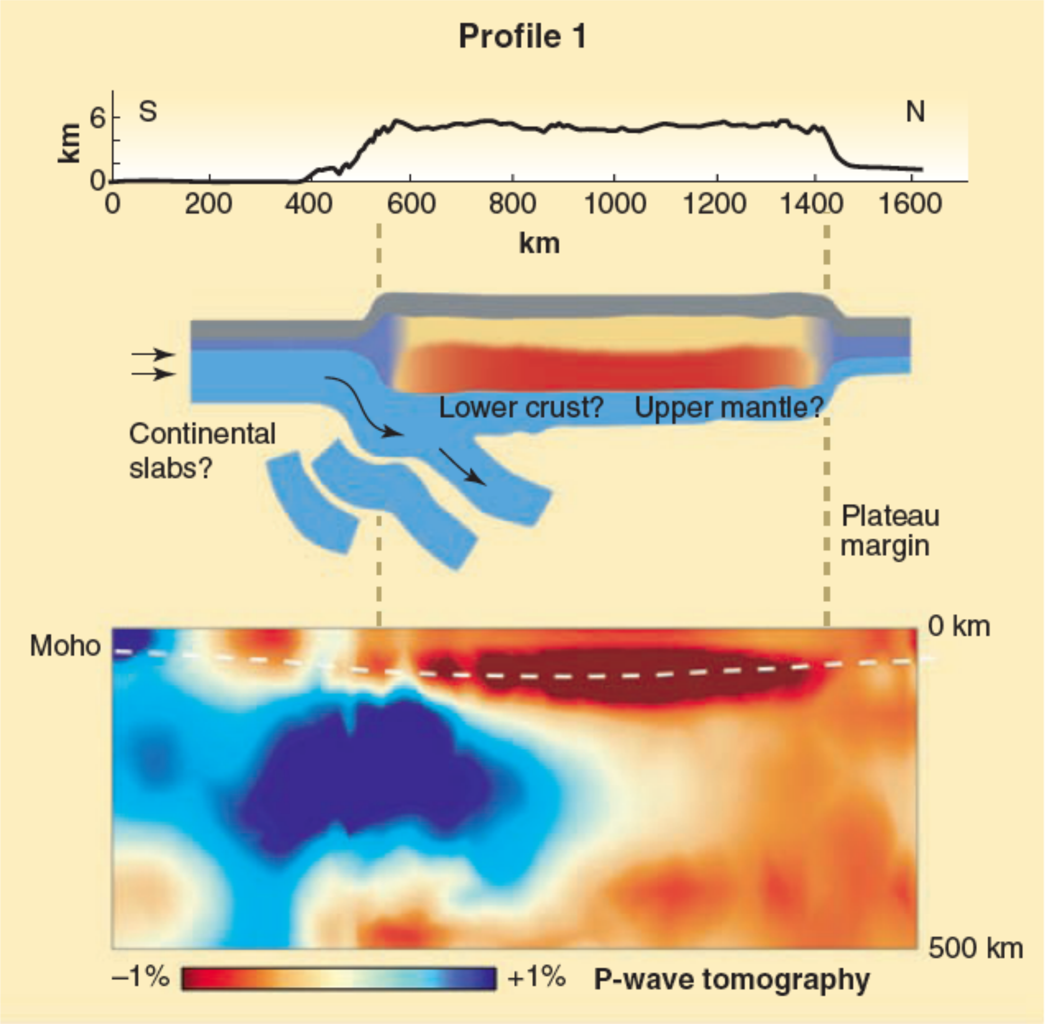
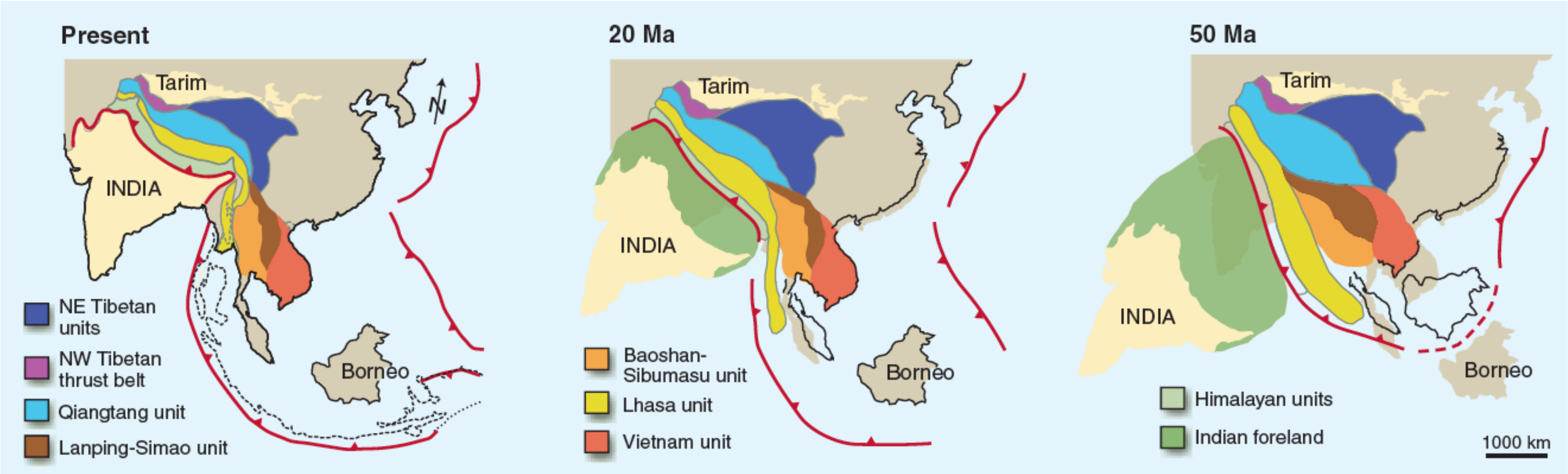


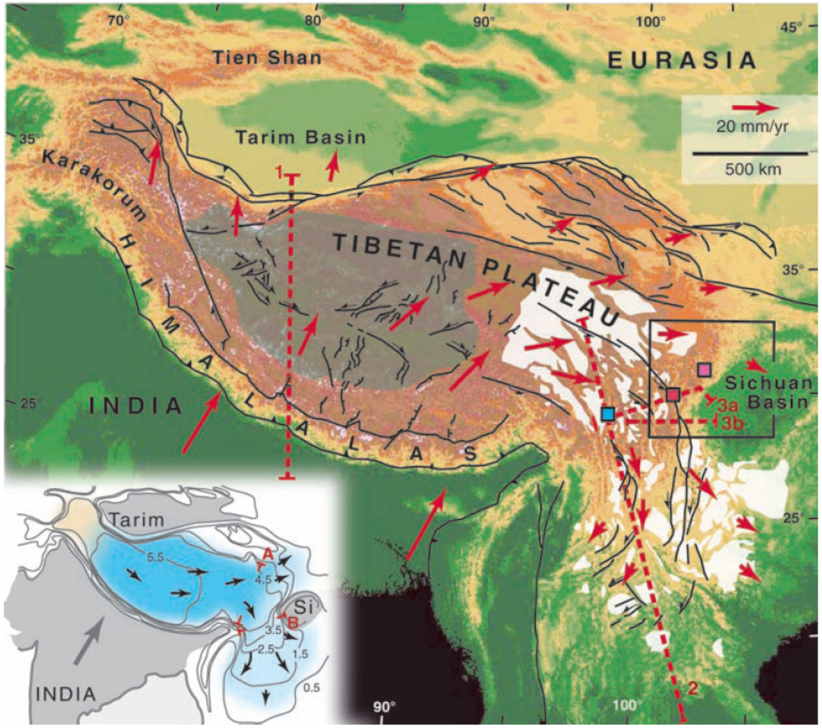
Fig. 4. Lateral variation in *P*-wave speed, at 200-km depth, relative to a laterally homogeneous reference Earth model. This image is part of a global model obtained



India continues to move northward, leaving pieces of crust behind in the mantle

Royden et al. (2008)





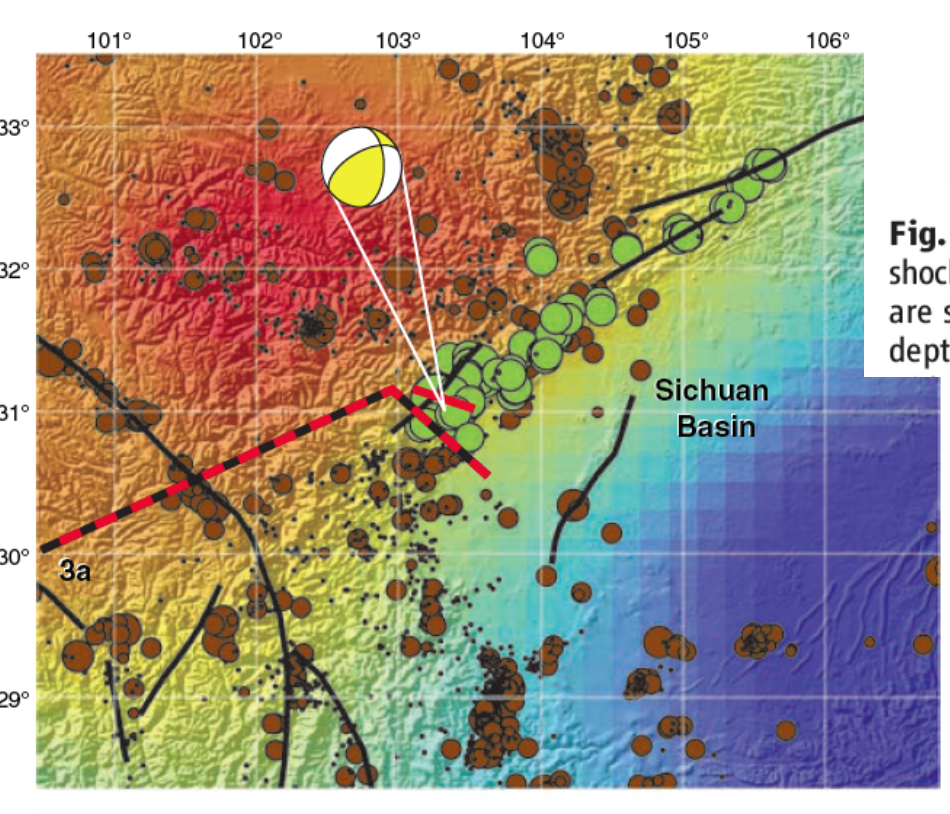
Summary of extruded terrains

Left:
Red arrows = GPS velocities
Blue = direction of deep crustal flow

Note: Sichuan basin

Royden et al. (2008)

2008 Sichuan EQ located on thrust fault involved in eastward extrusion of Tibet



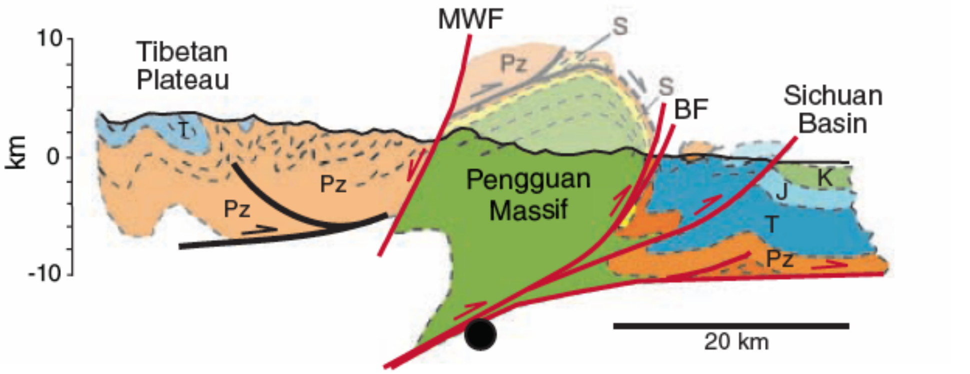
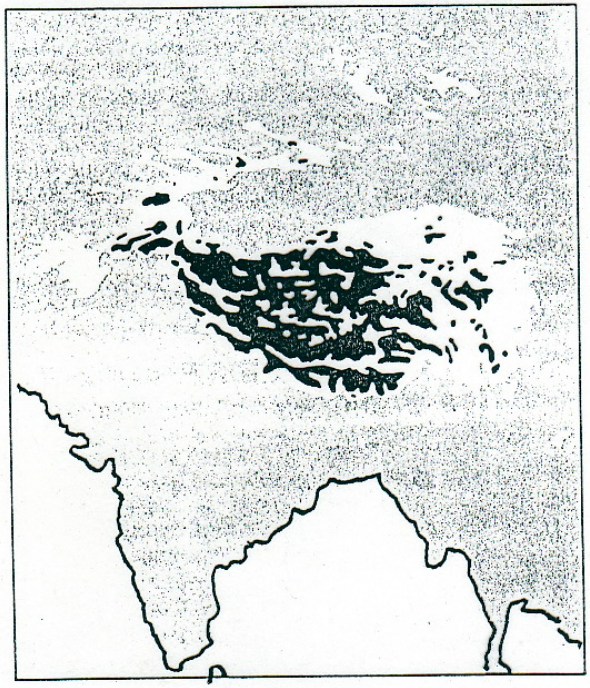


Fig. 6. (**Top**) Epicenters of 12 May 2008 Wenchuan earthquake and aftershocks (green circles), with focal mechanism for the main event (*48*). Events are superimposed on map of lateral variation in *P*-wave speed at 100-km depth relative to a laterally homogeneous reference Earth model (*47*),

Royden et al. (2008)

Uplift of Tibet



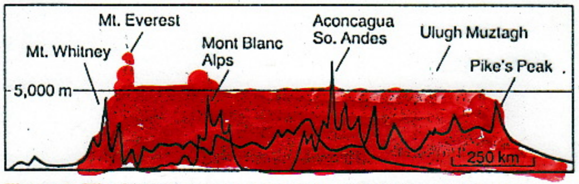
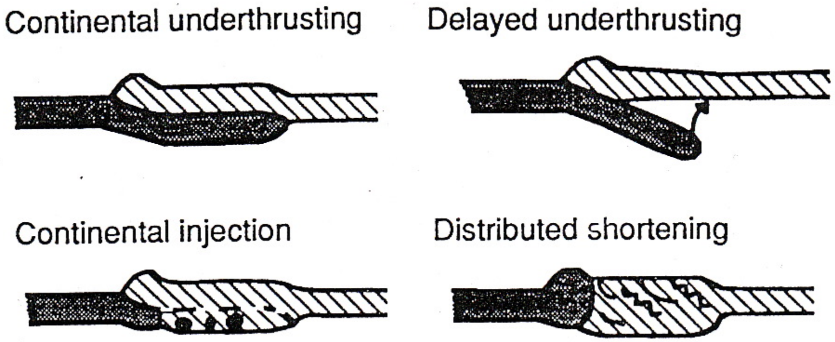


Figure 2. The brown area on this topographic map of Asia shows elevations higher than 5,000 m; the tan area shows elevations between 2,500 and 5,000 m. A similar map for any other continent would be almost entirely gray and tan, with only specks of brown here and there, because the elevation of 5,000 m is reached only by isolated peaks on the North and South American, African, and Antarctic continents, and nowhere in Europe, as shown in the profiles below the map.

Elevation in excess of 5000 m over an area the size of France
Dwarfs all other plateaus

Molnar (1989) American Scientist, v. 77, p. 350-360

Origin of the Tibetan Plateau: Rejected Models



1) Continental Underthrusting:
    classic: flat slab subduction
    but: no evidence for cold Indian lithosphere
        beneath Tibet
    instead: have low S-wave velocities
    also: would give a gradual northward propagation of
        Tibetan uplift, which isn't seen

2) Delayed Underthrusting
    has subducted slab rising abruptly around 5 Ma
    but: requires unusually fluid mantle above slab

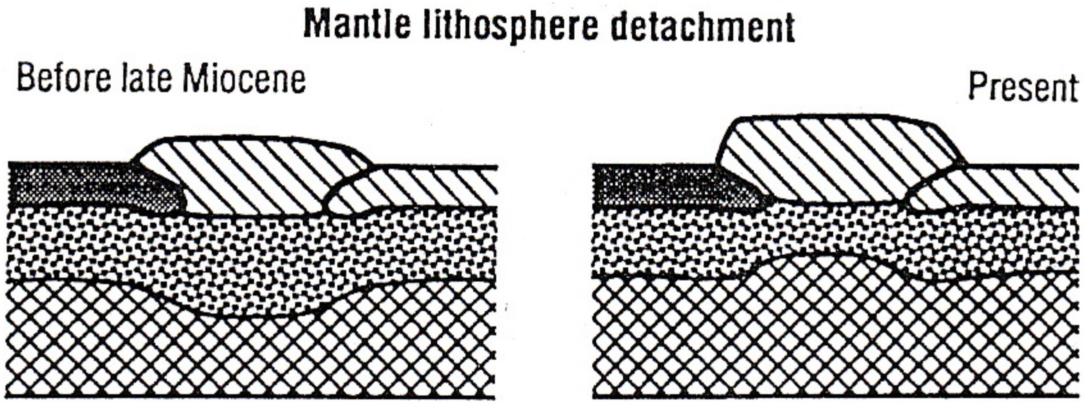
3) Continental injection:
    Tibetan lower crust behaves as a low viscosity fluid
    and pieces of India are assimilated into it
    but: uplift occurs in distinct episodes

4) Distributed shortening
    50 % shortening of Tibet by folding and thrusting
        produces thickening and uplift
    but: little evidence for this magnitude of shortening

Harrison et al. (1992)

Origin of the Tibetan Plateau:

Preferred Model of Harrison et al (1992):



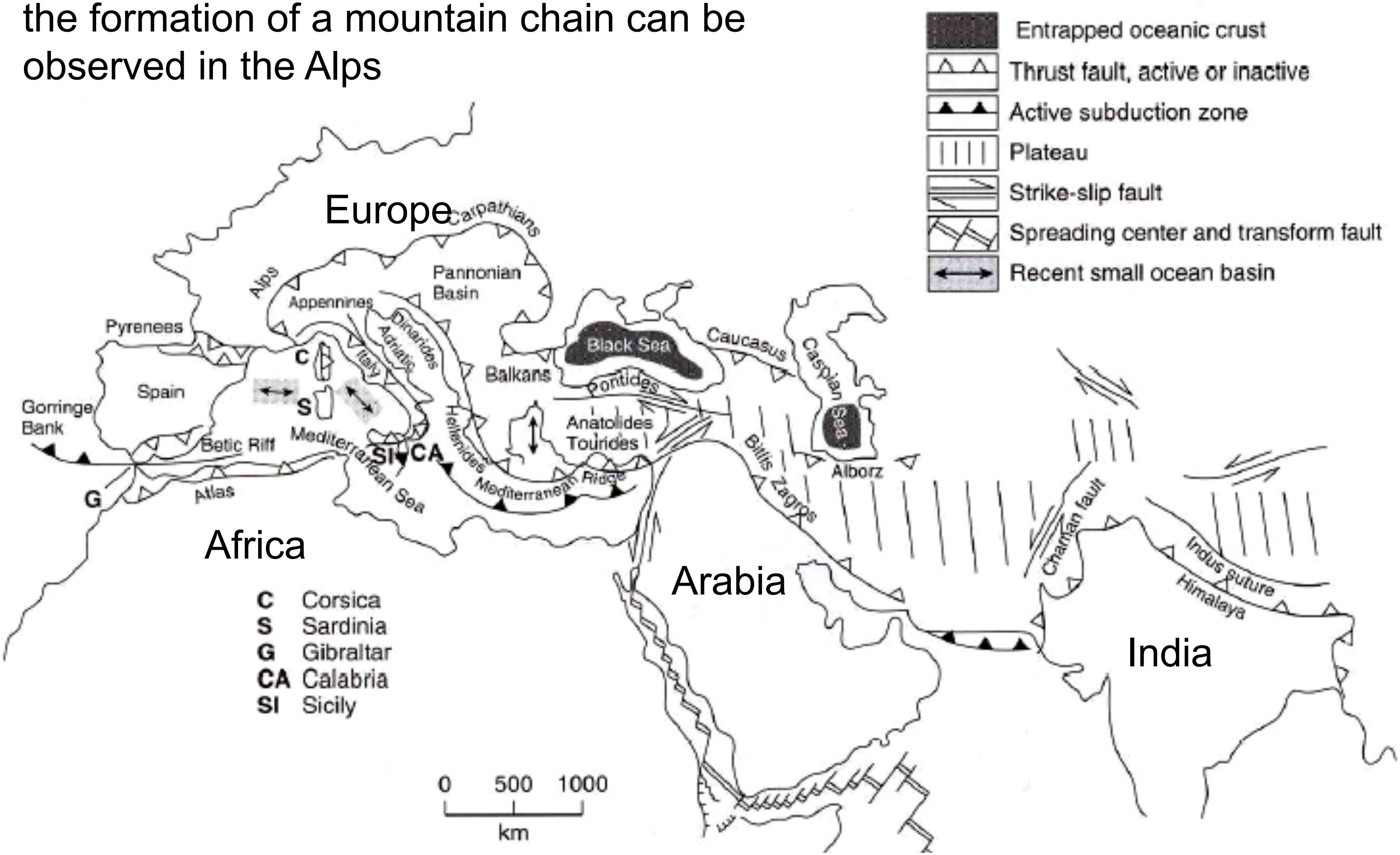
Lithospheric delamination

Lateral thermal gradients lead to convective instability
beneath Tibet leading to detachment of the mantle lithosphere
The mantle is displaced by less dense and hotter asthenosphere

Or lithospheric drips

The Alps: Mont Blanc

Another example of the closure of a sea and the formation of a mountain chain can be observed in the Alps



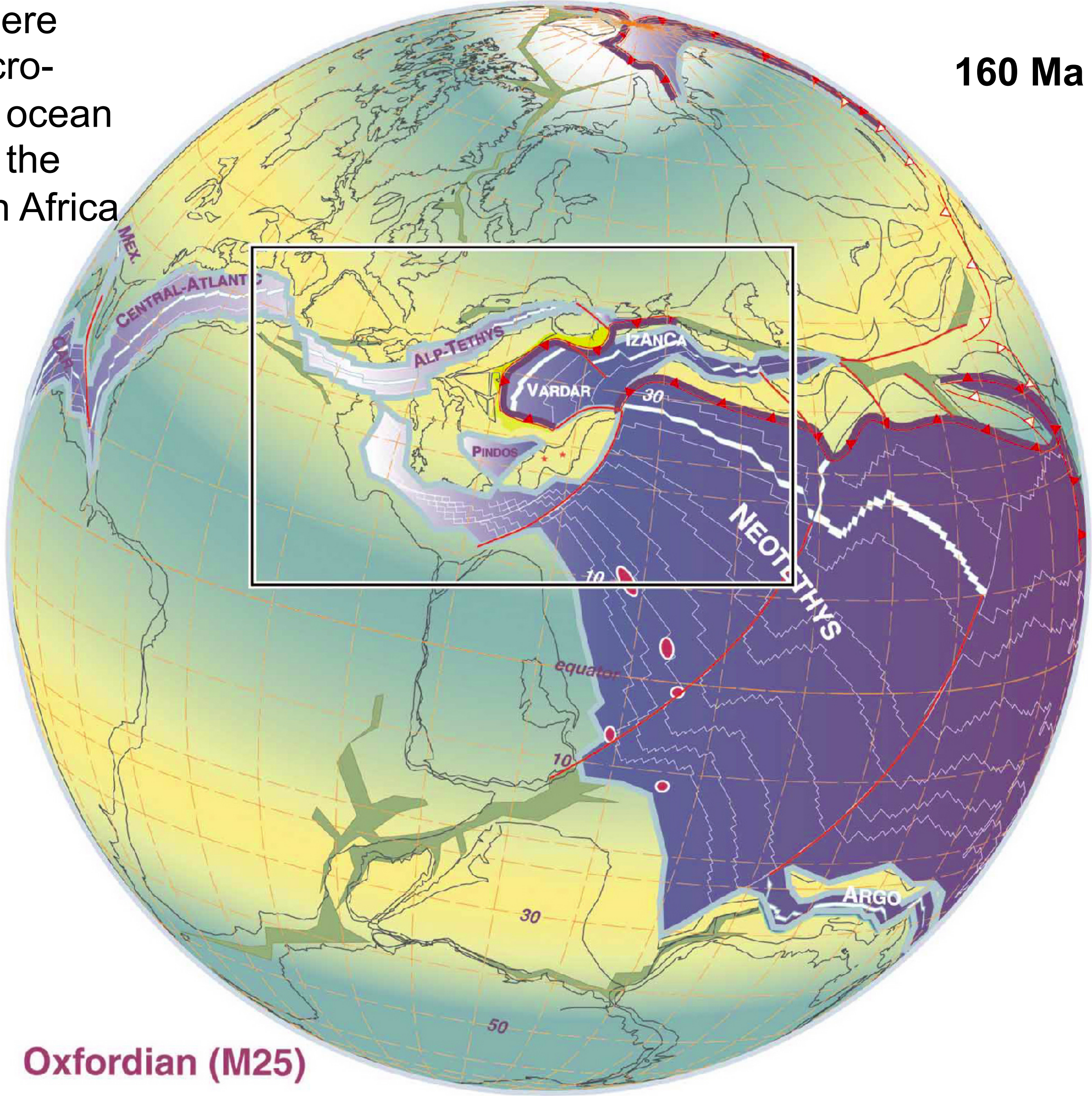
However, here not all of the seaway has disappeared. Last pieces of Tethys: Black Sea, Southern Caspian Sea, African margin north of Libya

Here, will discuss just a few points – where there are similarities to other concepts we have discussed in the last two lectures:

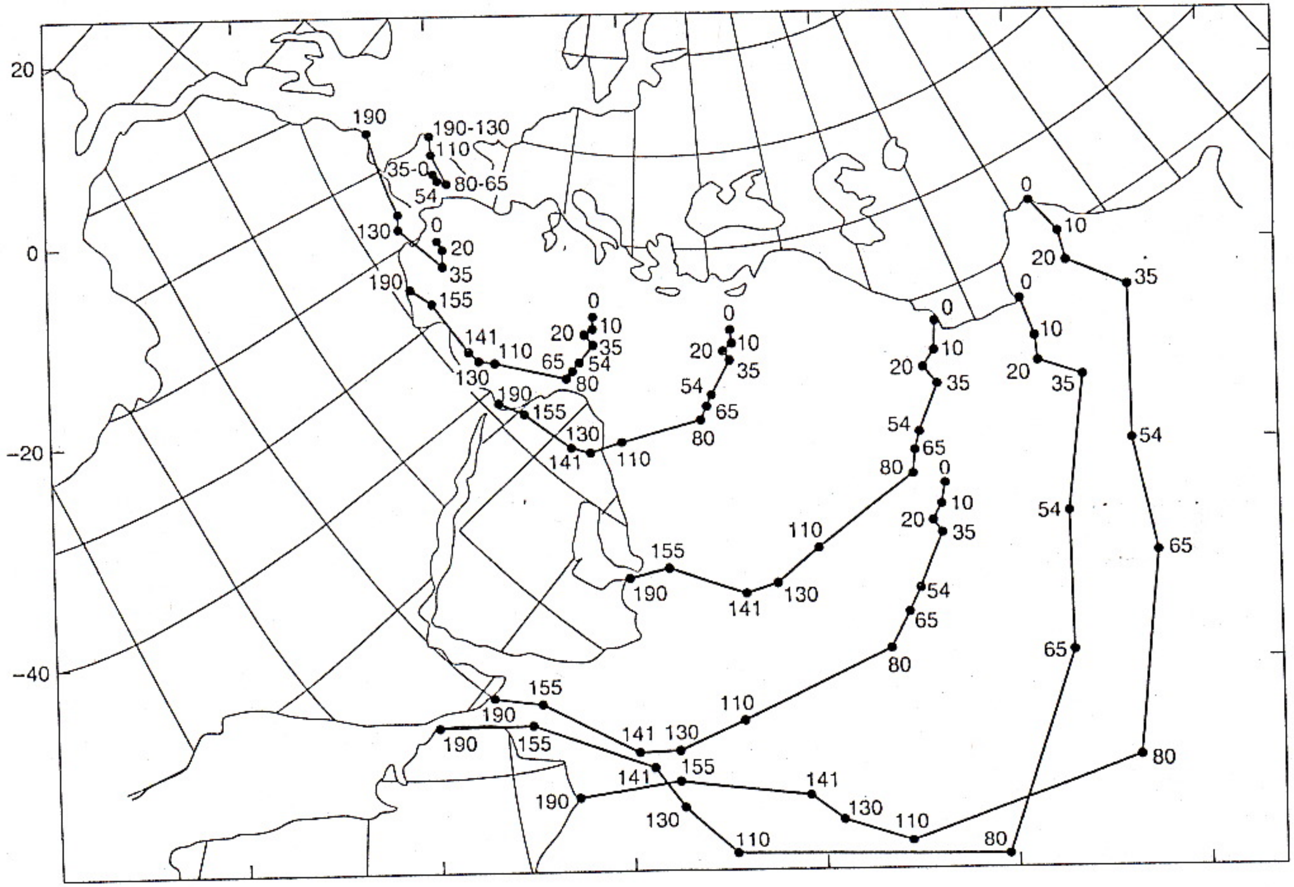
1) Classic Indenter model
2) Back arc basins driven by roll-back

As with India, There were several micro-plates and small ocean basins caught in the collision between Africa and Eurasia

160 Ma

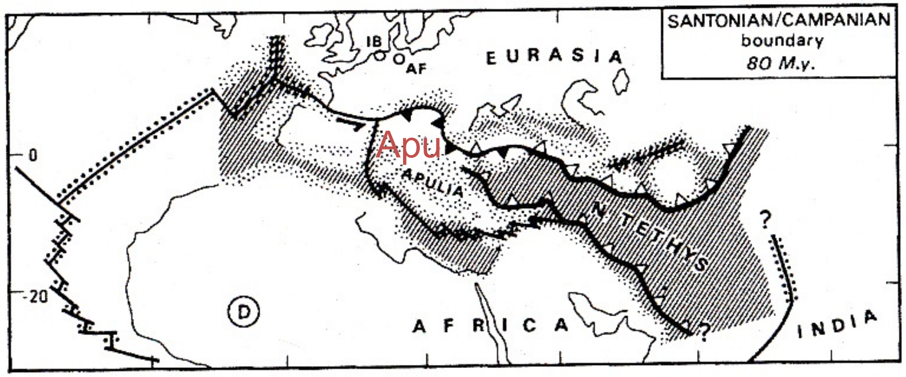


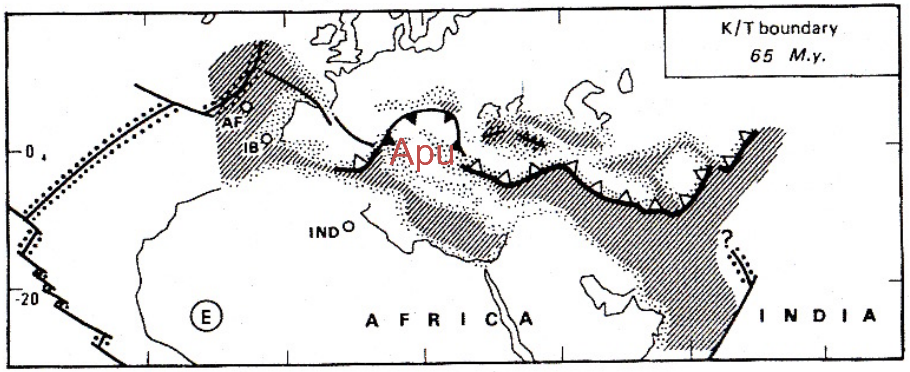
Oxfordian (M25)

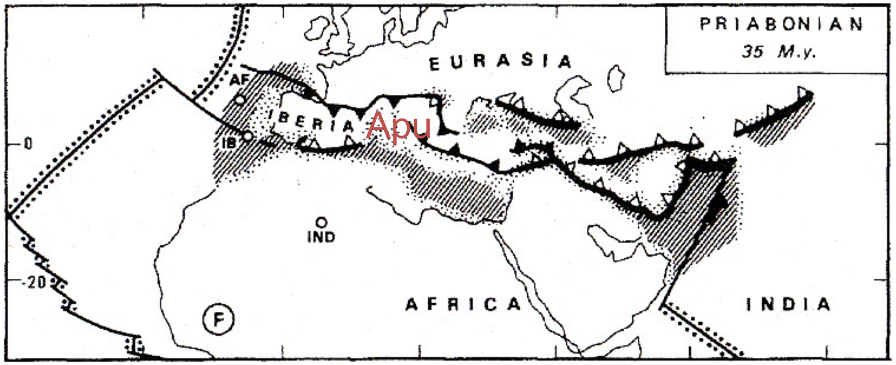


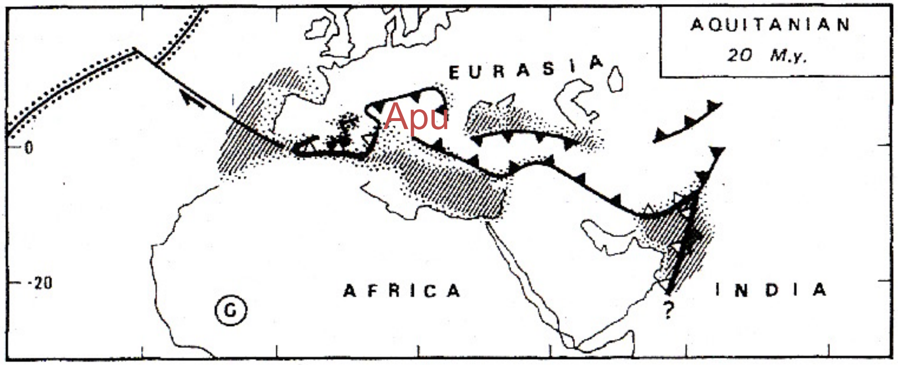
Big difference: the motion of Africa relative to Eurasia
is much slower than India

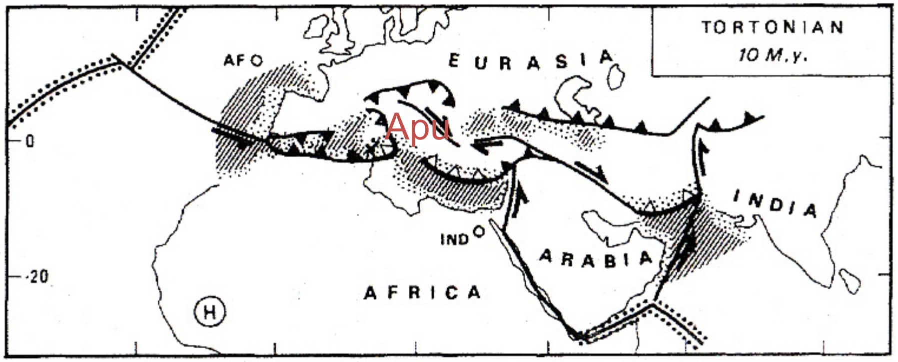
Reconstructions of Mediterranean Region since the Late Cretaceous











Some events:

- Collision of Apulia with Eurasia at 80 Ma
- Iberia is transferred to Eurasia around 30 Ma
- Back-arc extension in western Med and Aegean Sea since 20 Ma
- “Extrusion” of Carpathians and Turkey

Apulia (Apu) = microplate consisting of northeastern Italy and Adriatic sea

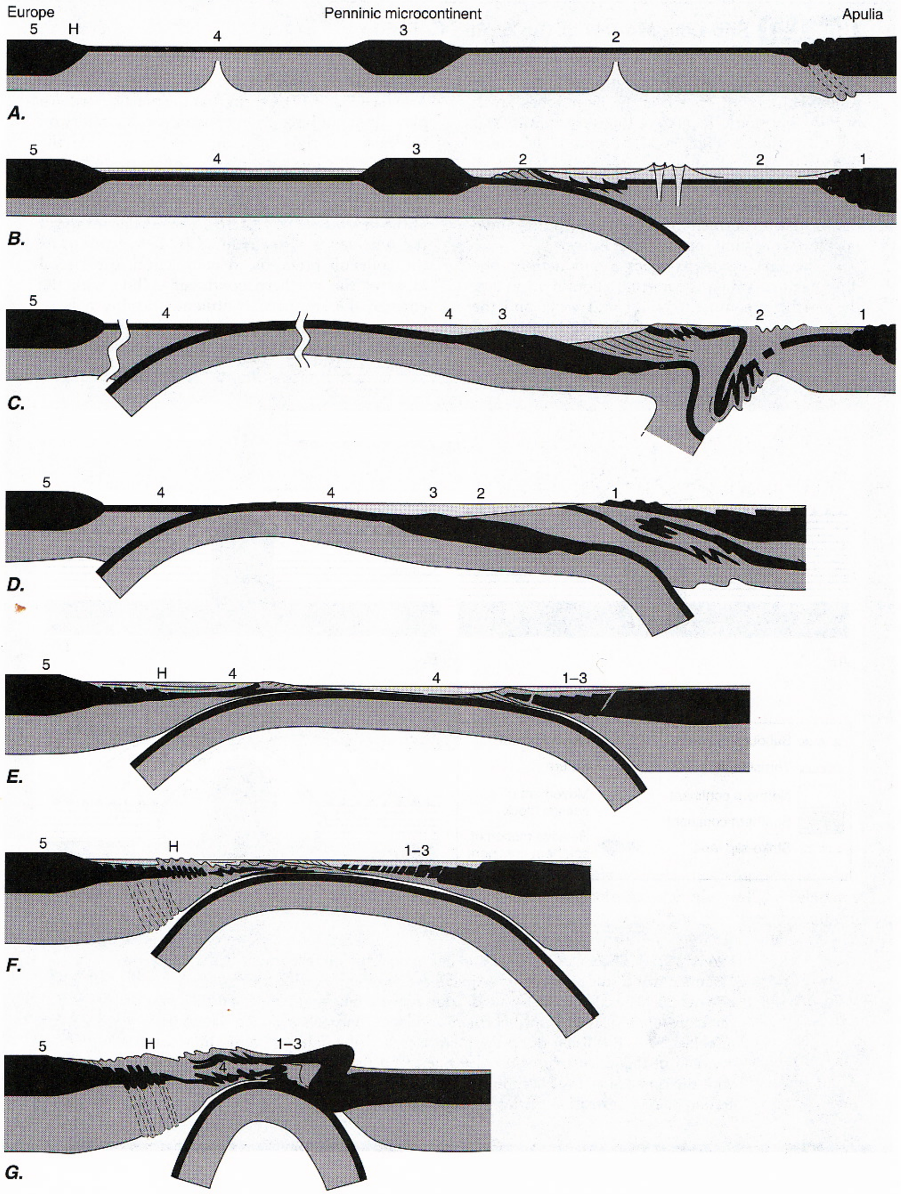
Dercourt et al. (1986)

Europe Africa

130 Ma

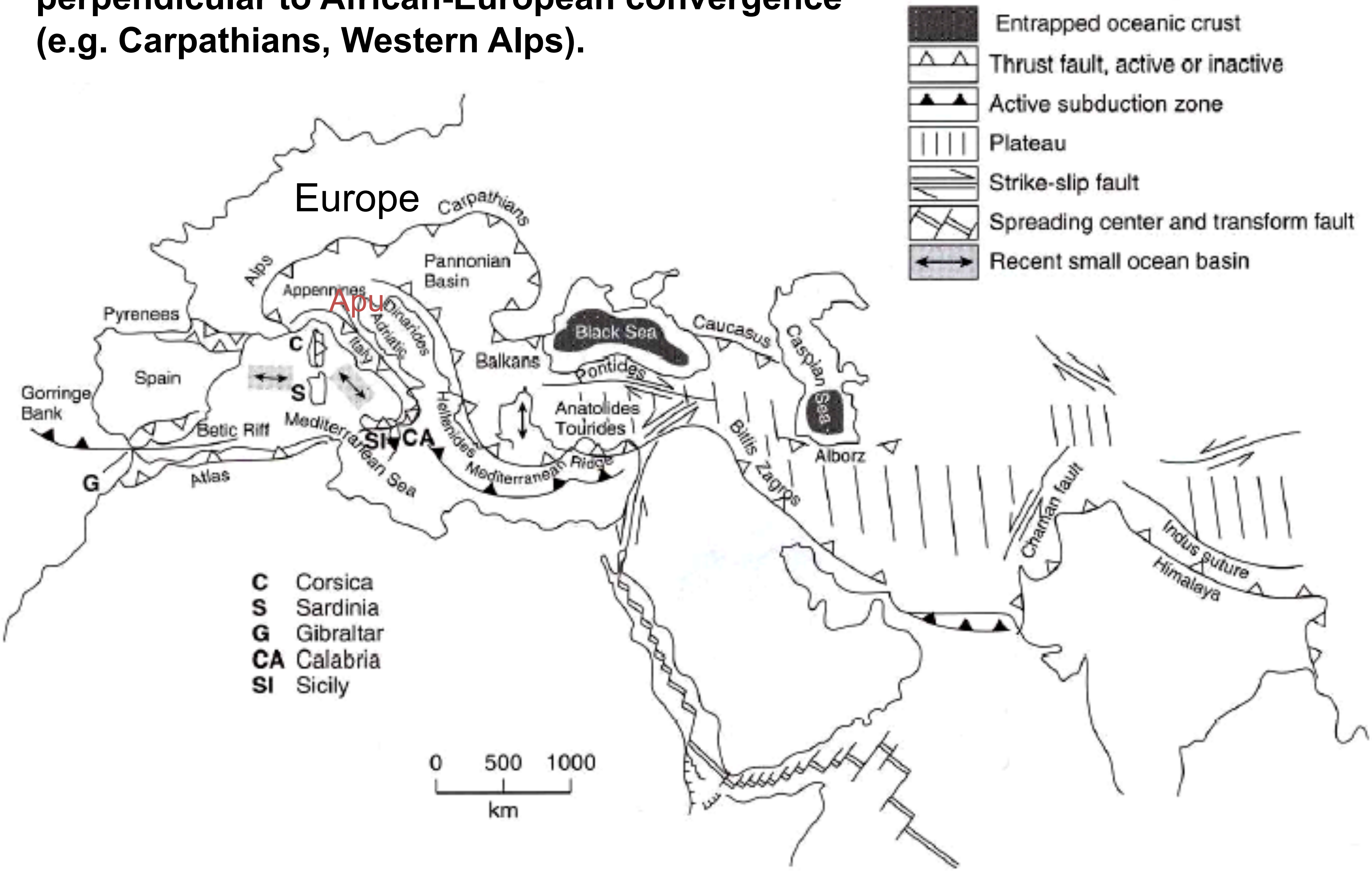
90 Ma

5 – 0 Ma



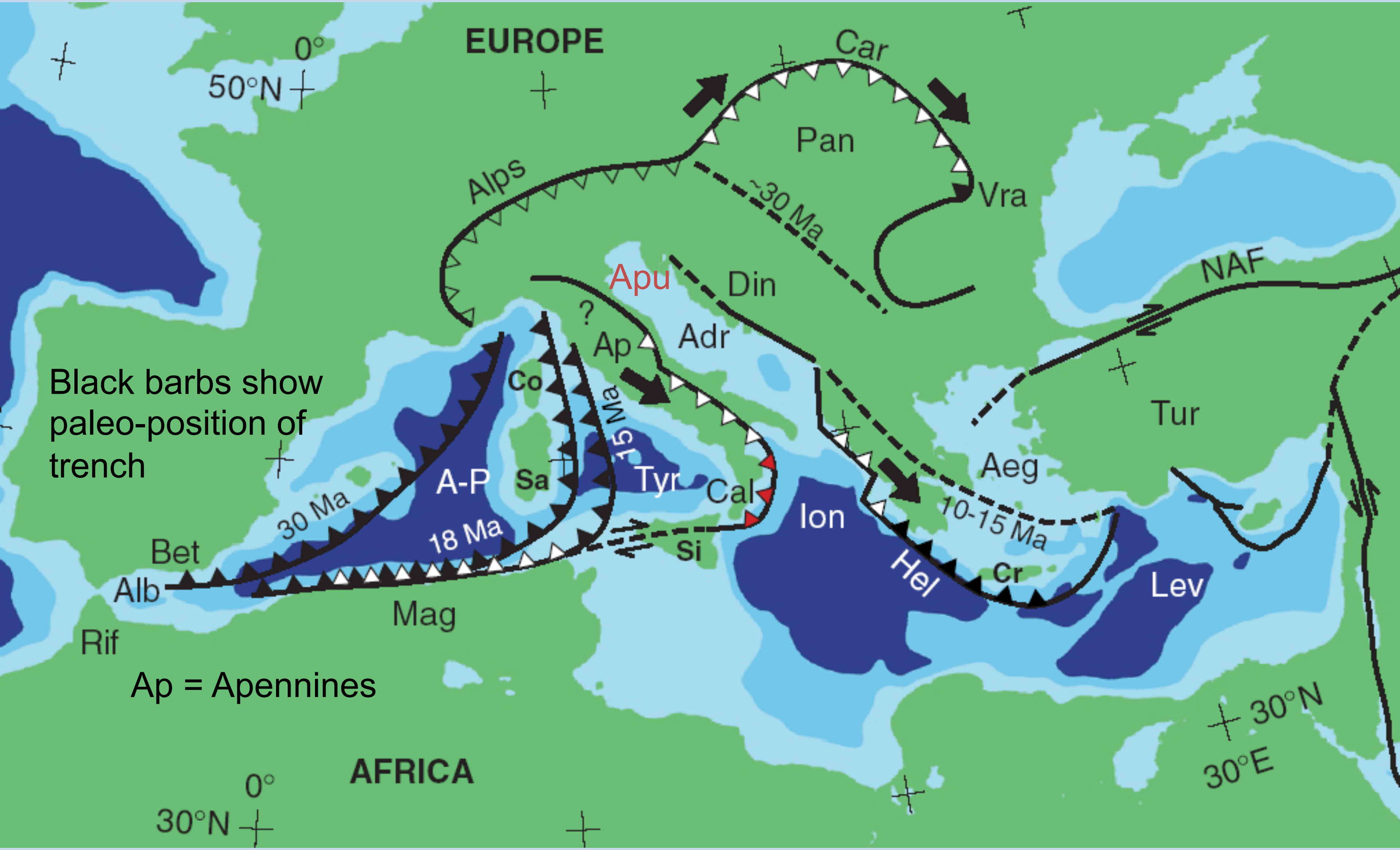
Like the India-Eurasia collision, the collision of Africa and Europe was preceded by the accretion of mirco-continents and island arcs

Some Arcs seem to indicate shortening perpendicular to African-European convergence (e.g. Carpathians, Western Alps).



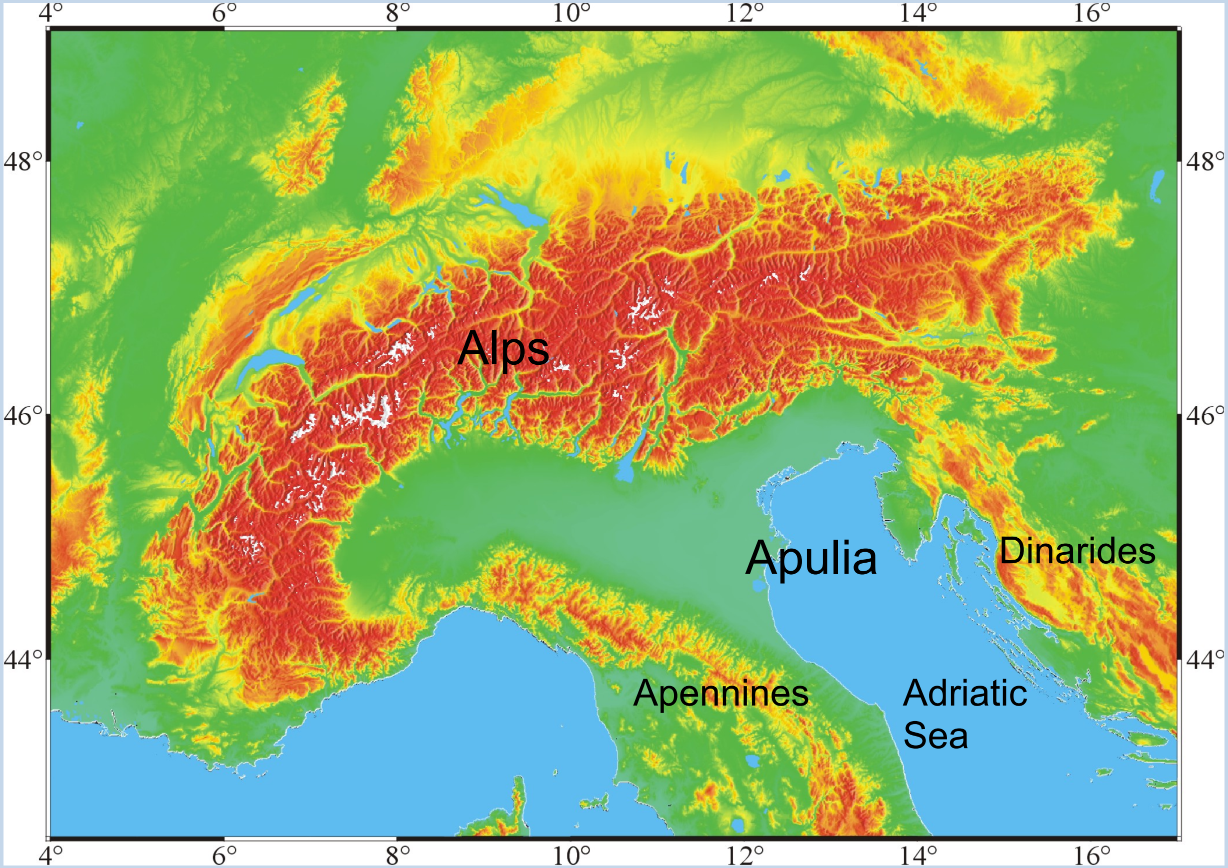
Apulia (Apu) – another example of indenter tectonics

Tyrrhean Sea (Tyr), Aegean Sea (Aeg)= back arc basins due to roll-back



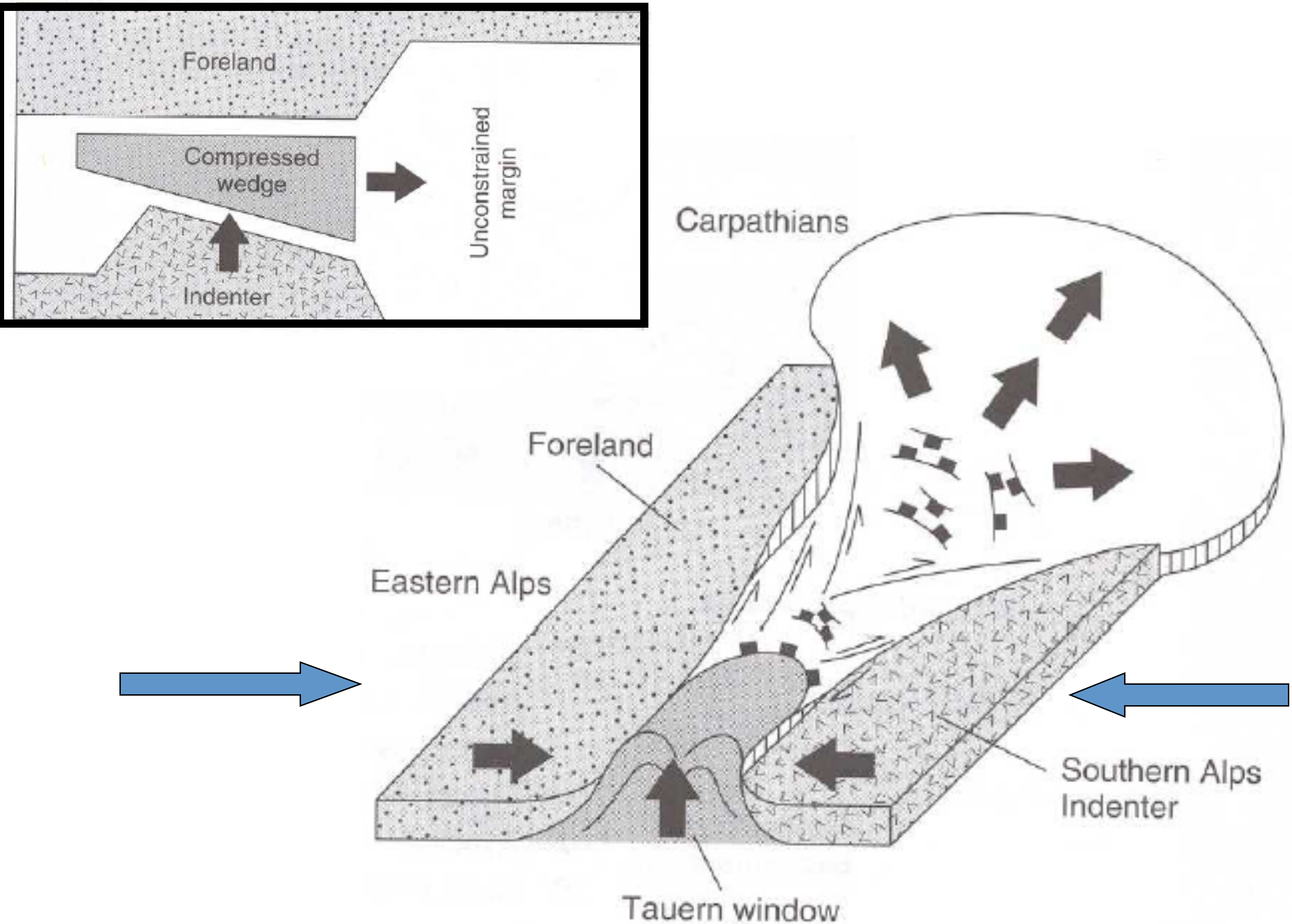
Black barbs show paleo-position of trench

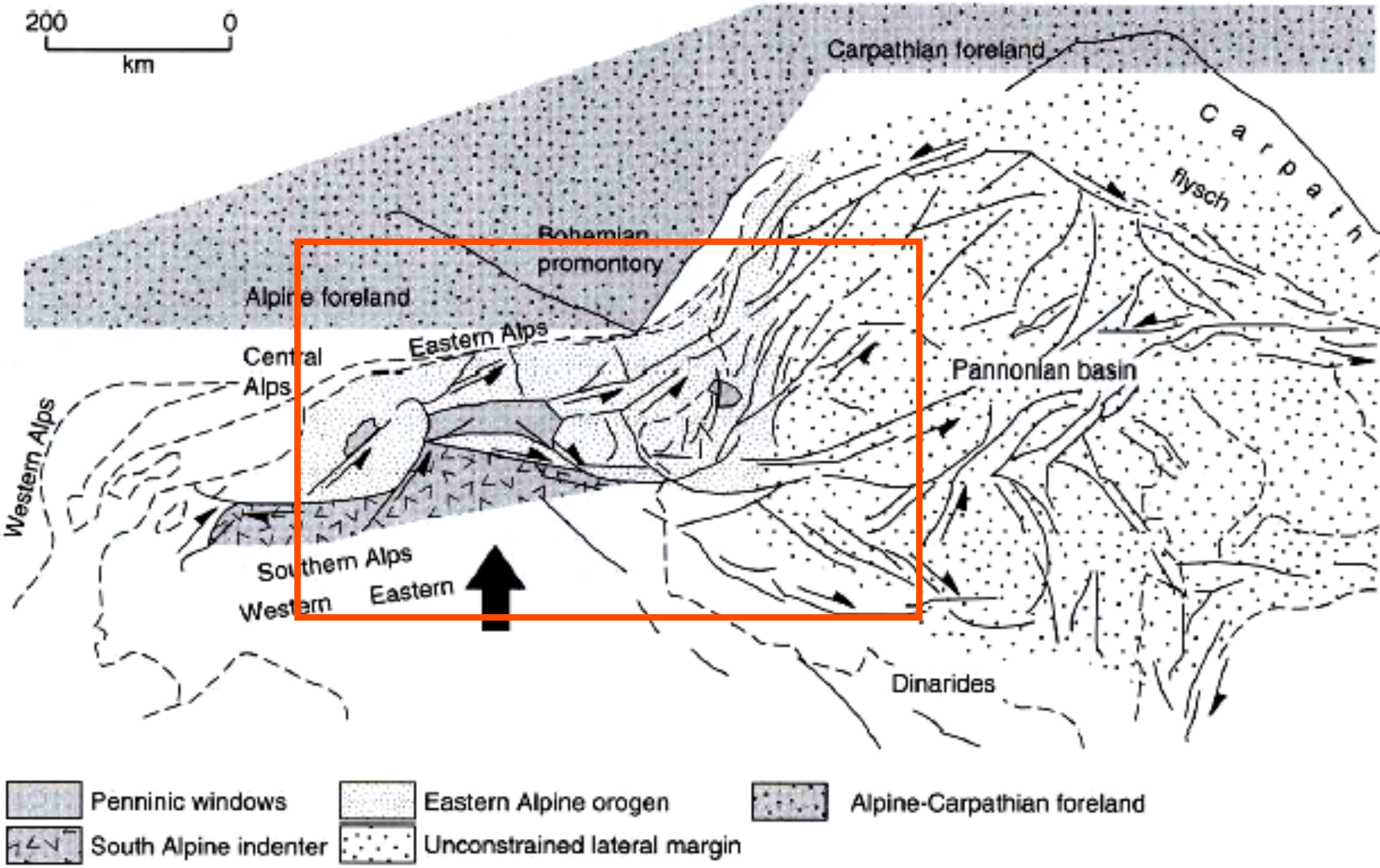
Ap = Apennines



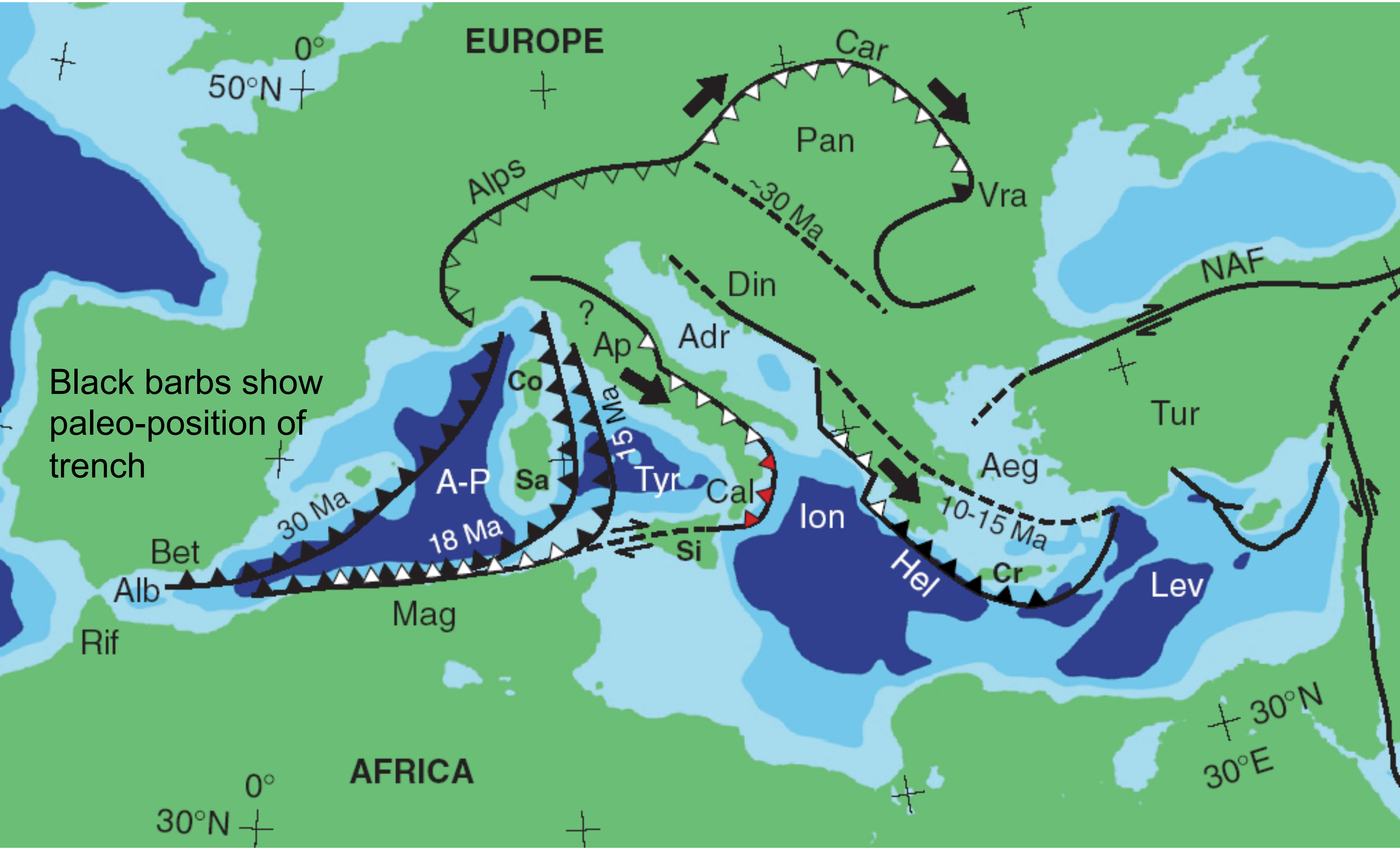
“Apulia,” the indenter, is the block east of the Apennines and west of the Dinarides (the northeastern part of Italy and Adriatic Sea).

It first collided with Europe about 80 Ma


Foreland
Compressed wedge
Unconstrained margin
Indenter
Carpathians
Foreland
Eastern Alps
Southern Alps Indenter
Tauern window

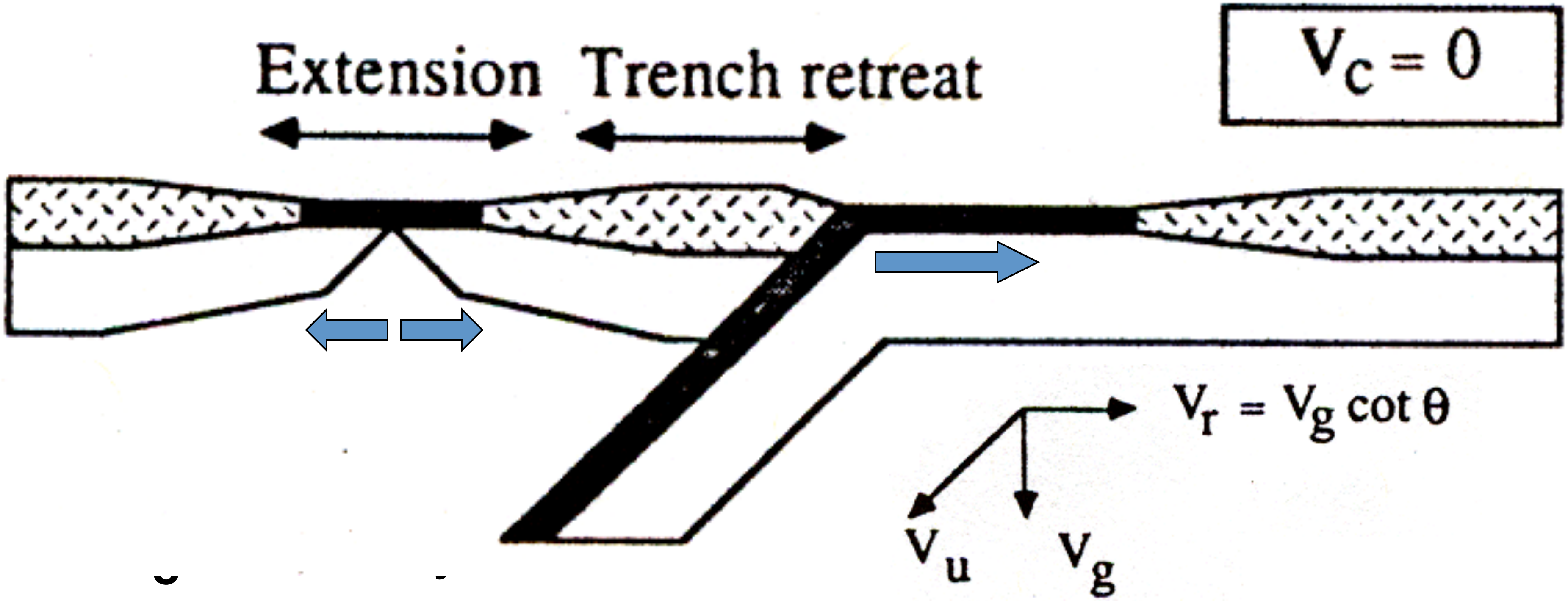

200
0
km
Carpathian foreland
Carpathians
flysch
Bohemian promontory
Alpine foreland
Eastern Alps
Central Alps
Western Alps
Pannonian basin
flysch
Southern Alps
Western
Eastern
Dinarides
Penninic windows
Eastern Alpine orogen
Alpine-Carpathian foreland
South Alpine indenter
Unconstrained lateral margin

You might not expect it here, but there is actually a lot of extension during the collision: back-arc basins



Black barbs show paleo-position of trench

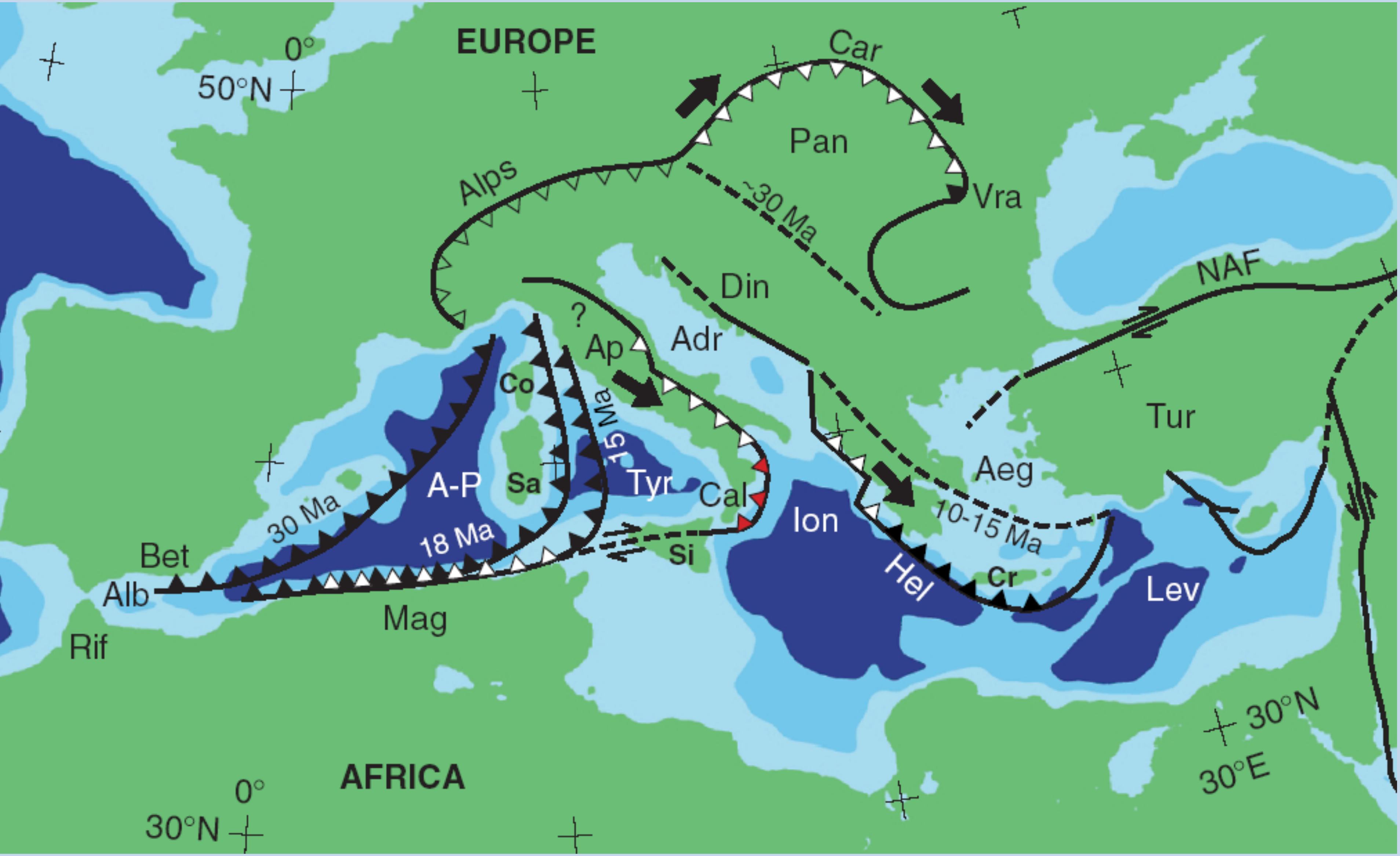
In the case of no convergence, the amount of trench retreat must be balanced by extension in the back-arc



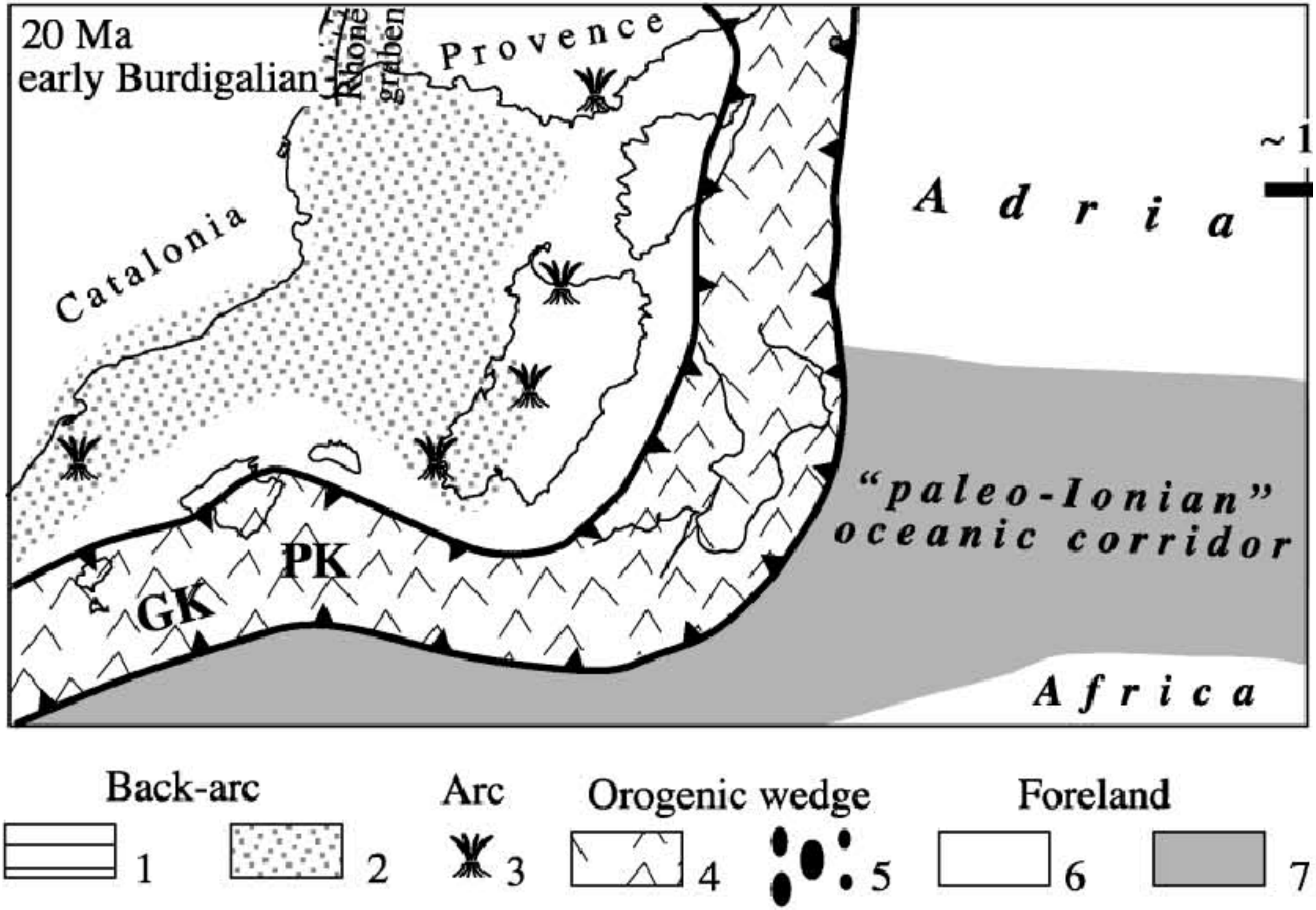
V_c = velocity of convergence

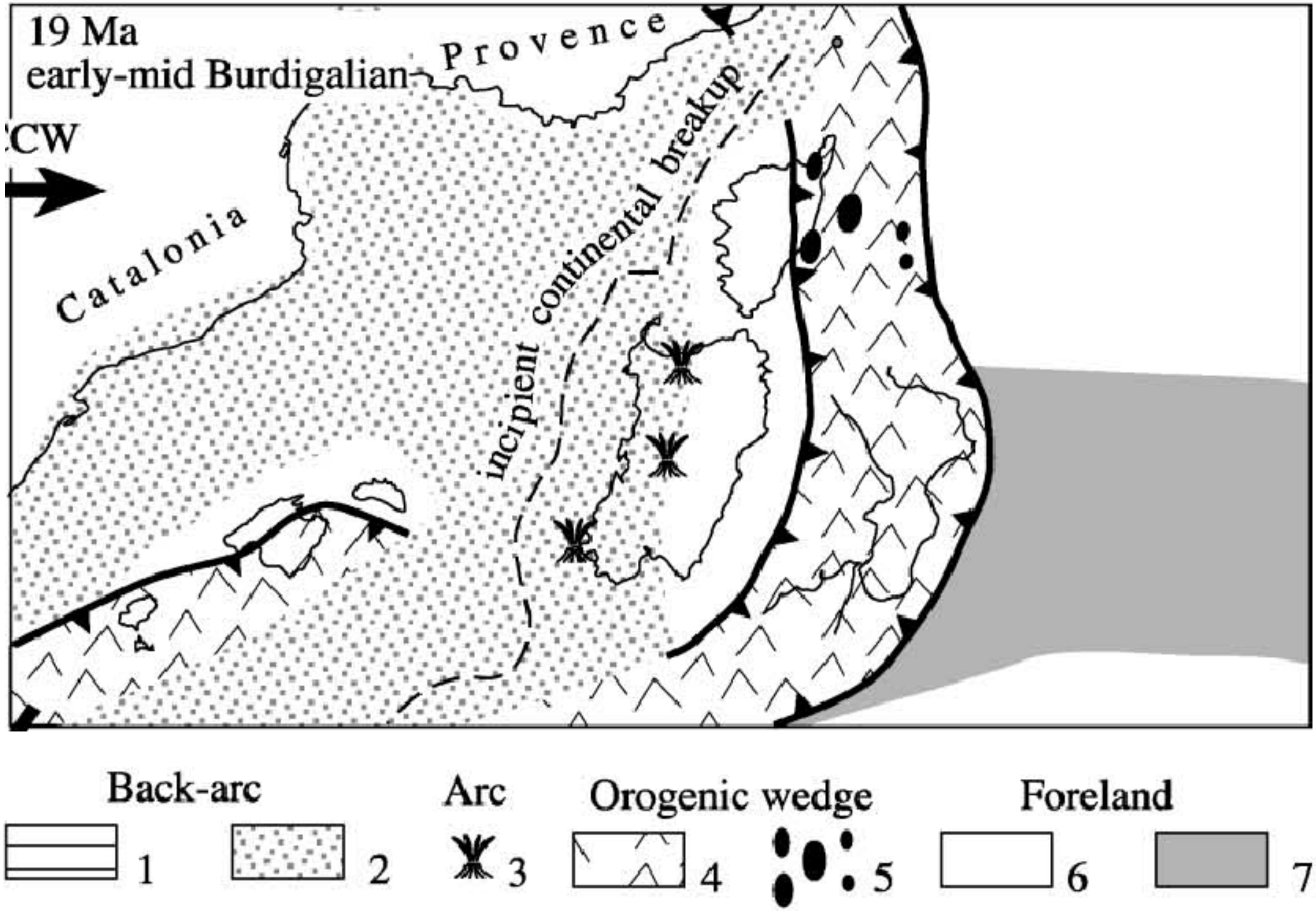
V_r = velocity of the trench retreat

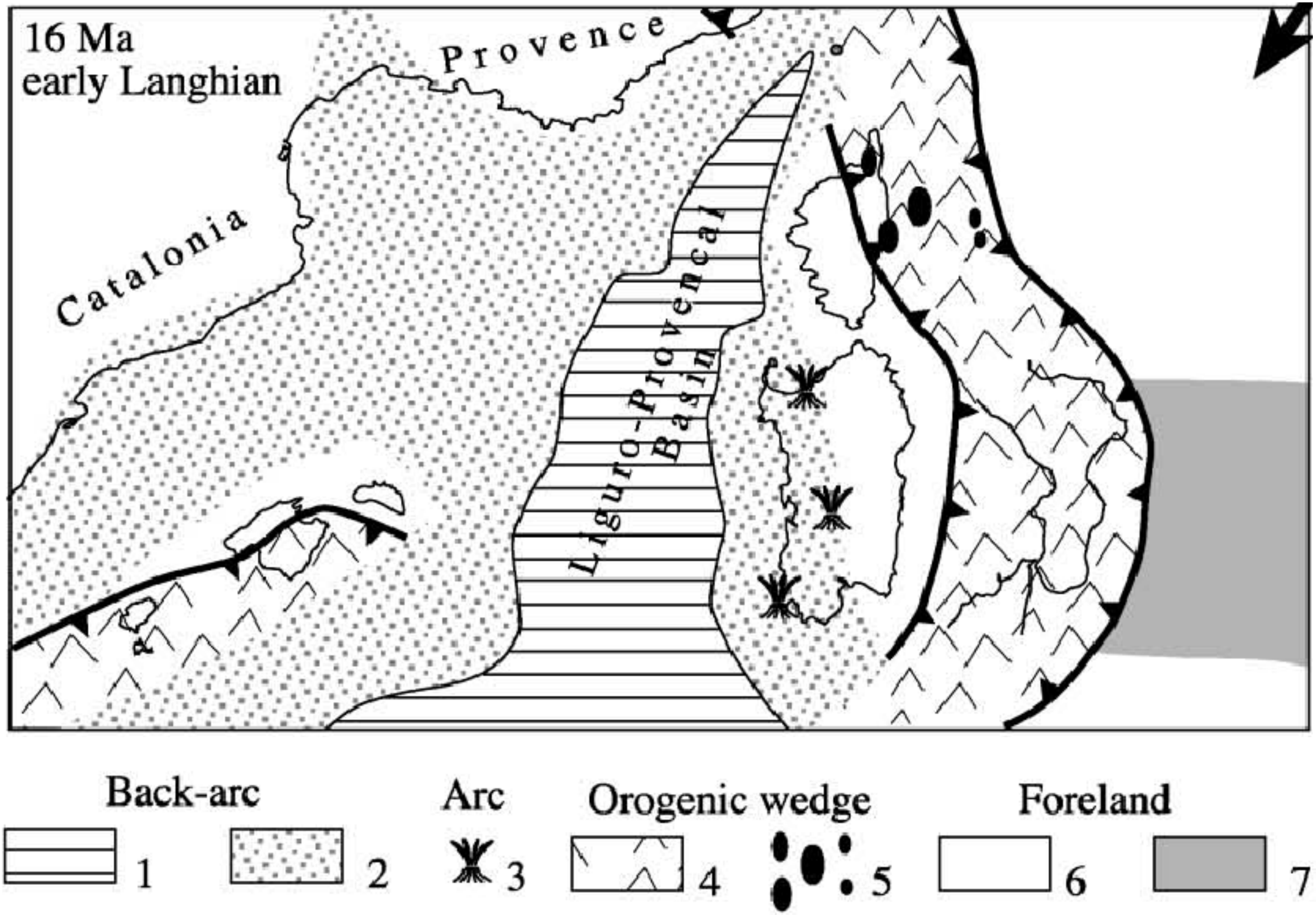
30 Ma Sardinia (Sa), Corsica (Co) and the west side of Italy were next to eastern Spain and the Tyrrhenian Sea (Tyr) was closed

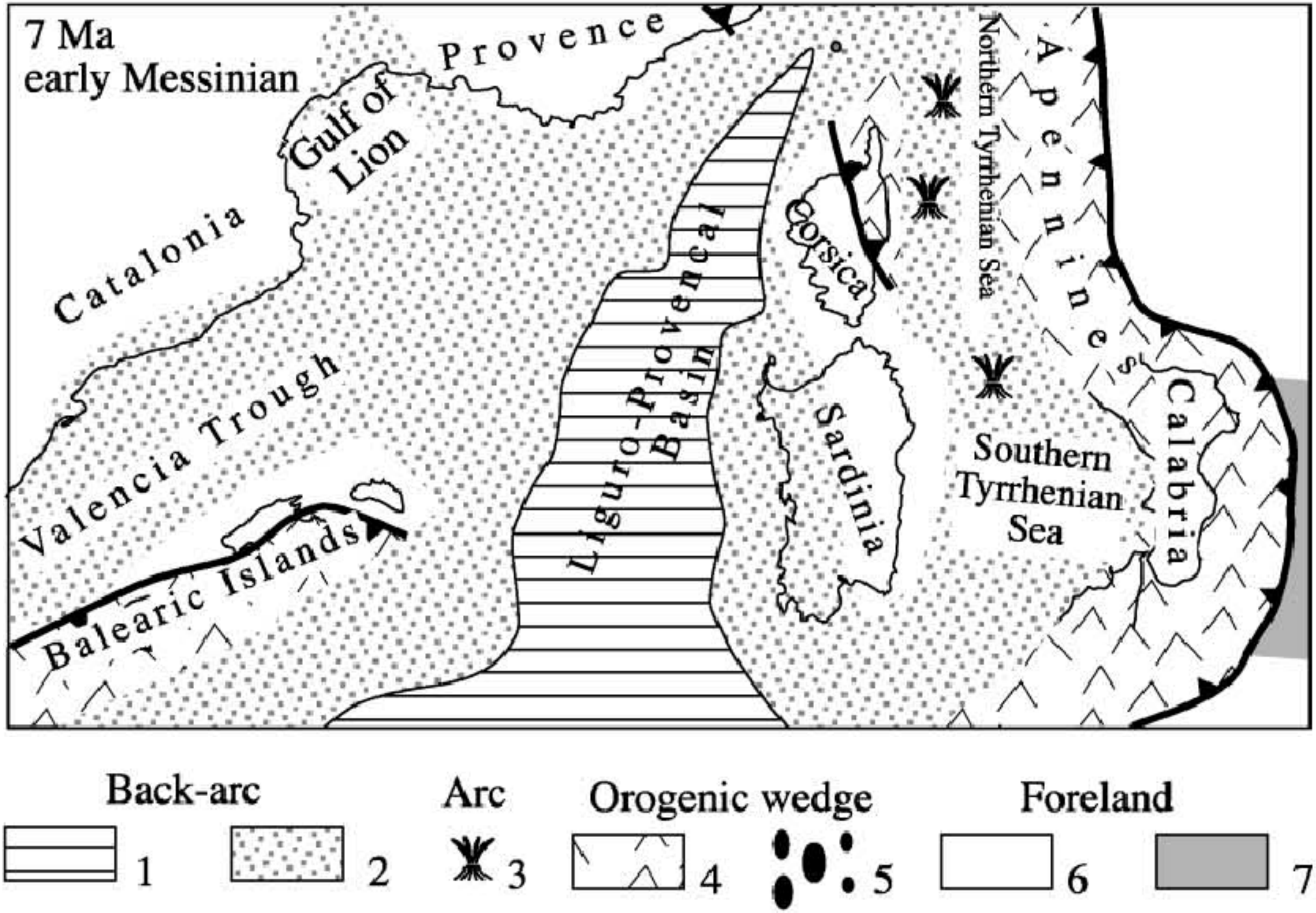


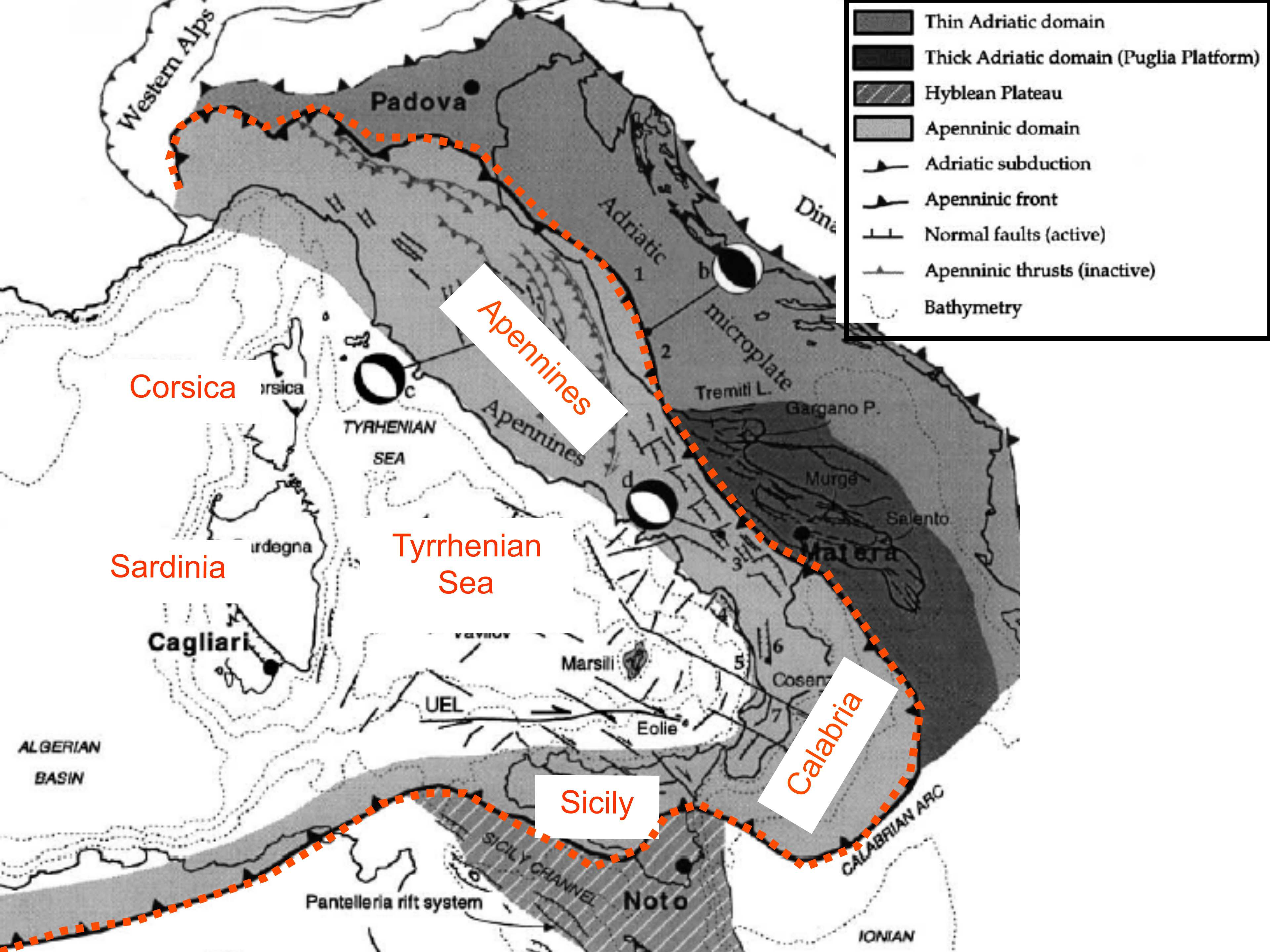
Wortel and Spakman, 2000


20 Ma
early Burdigalian
Rhone graben
Provence
Catalonia
Adria
~1
"paleo-Ionian" oceanic corridor
Africa
PK
GK
Back-arc
Arc
Orogenic wedge
Foreland
1
2
3
4
5
6
7

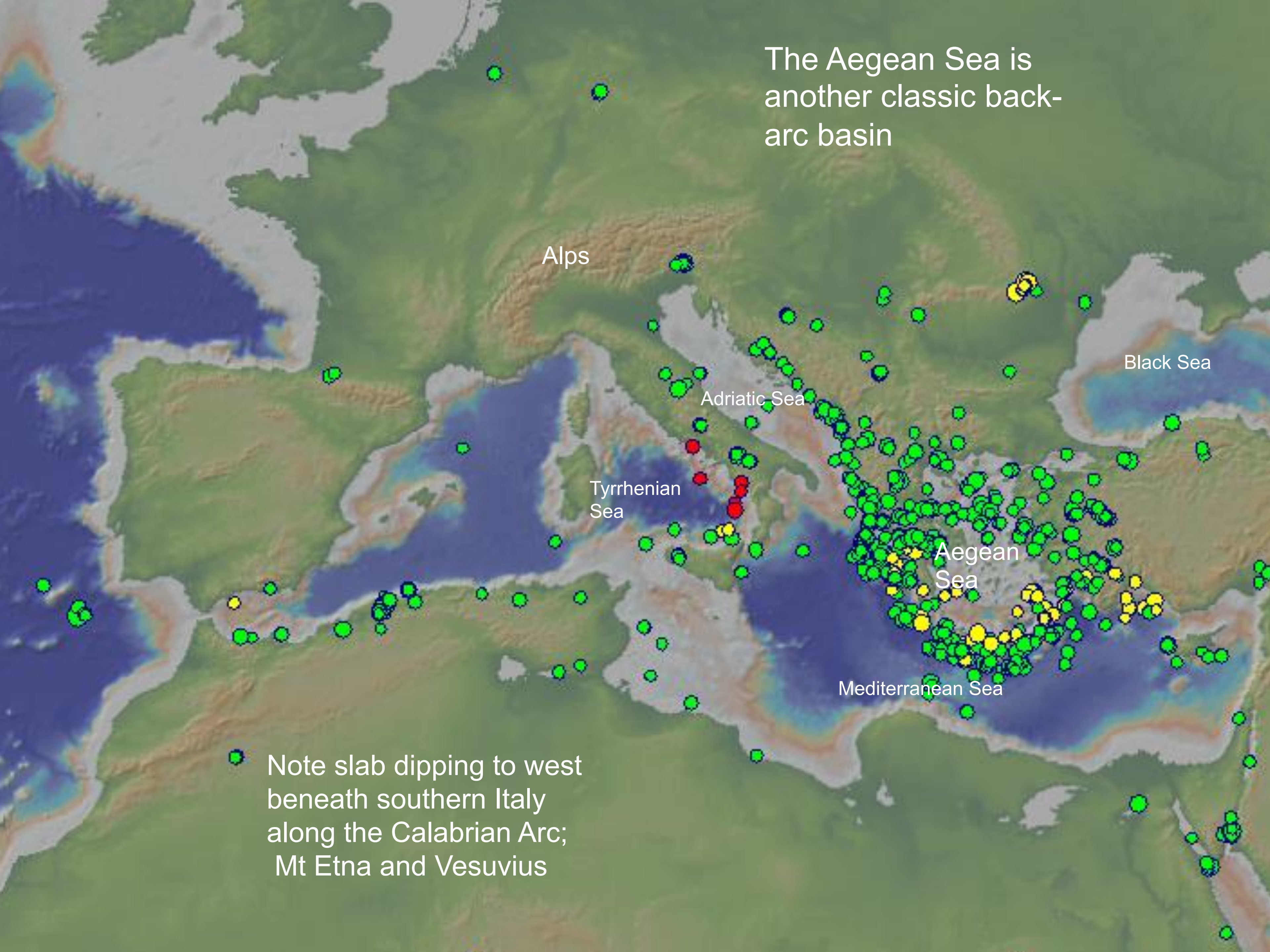

19 Ma
early-mid Burdigalian
Provence
CW
Catalonia
incipient continental breakup
Back-arc
Arc
Orogenic wedge
Foreland
1
2
3
4
5
6
7


16 Ma
early Langhian
Provence
Catalonia
Liguro-Provençal Basin
Back-arc
Arc
Orogenic wedge
Foreland
1
2
3
4
5
6
7


7 Ma
early Messinian
Provence
Gulf of Lion
Catalonia
Valencia Trough
Balearic Islands
Liguro-Provençal Basin
Corsica
Sardinia
Northern Tyrrhenian Sea
Apennines
Southern Tyrrhenian Sea
Calabria
Back-arc
1
2
Arc
3
Orogenic wedge
4
5
Foreland
6
7


Thin Adriatic domain
Thick Adriatic domain (Puglia Platform)
Hyblean Plateau
Apenninic domain
Adriatic subduction
Apenninic front
Normal faults (active)
Apenninic thrusts (inactive)
Bathymetry
Western Alps
Padova
Dina
Adriatic
microplate
b
1
2
Tremiti I.
Gargano P.
Murge
Salento
Matera
Apennines
Apennines
Corsica
rsica
c
TYRHENIAN
SEA
d
3
4
5
6
7
Tyrrhenian
Sea
Sardinia
rdegna
Cagliari
Vavilov
Marsili
Cosen
UEL
Eolie
Calabria
CALABRIAN ARC
Sicily
SICILY CHANNEL
Pantelleria rift system
Noto
ALGERIAN
BASIN
IONIAN

The Aegean Sea is another classic back-arc basin



Note slab dipping to west beneath southern Italy along the Calabrian Arc; Mt Etna and Vesuvius

Bottom line

- During the collision of plates, continents plow deep into the interior of an opposing plate edge, with incoming continental lithosphere subducting to depths as great as 200 km.

- In the process the crust and lithosphere thickens by piling up on the incoming plate slices of this same plate torn off by major thrust faults.

- Material caught in the vice during this suturing process often expels itself sideways (Indenter tectonics).

- In places where the convergence is very slow, the arcs are drawn outward by slab rollback.

- The primary difference between the Himalayas and the Alps is that convergence continued for more than 1000 km after the initial collision of India with Asia, while convergence did not continue between Europe and Africa.