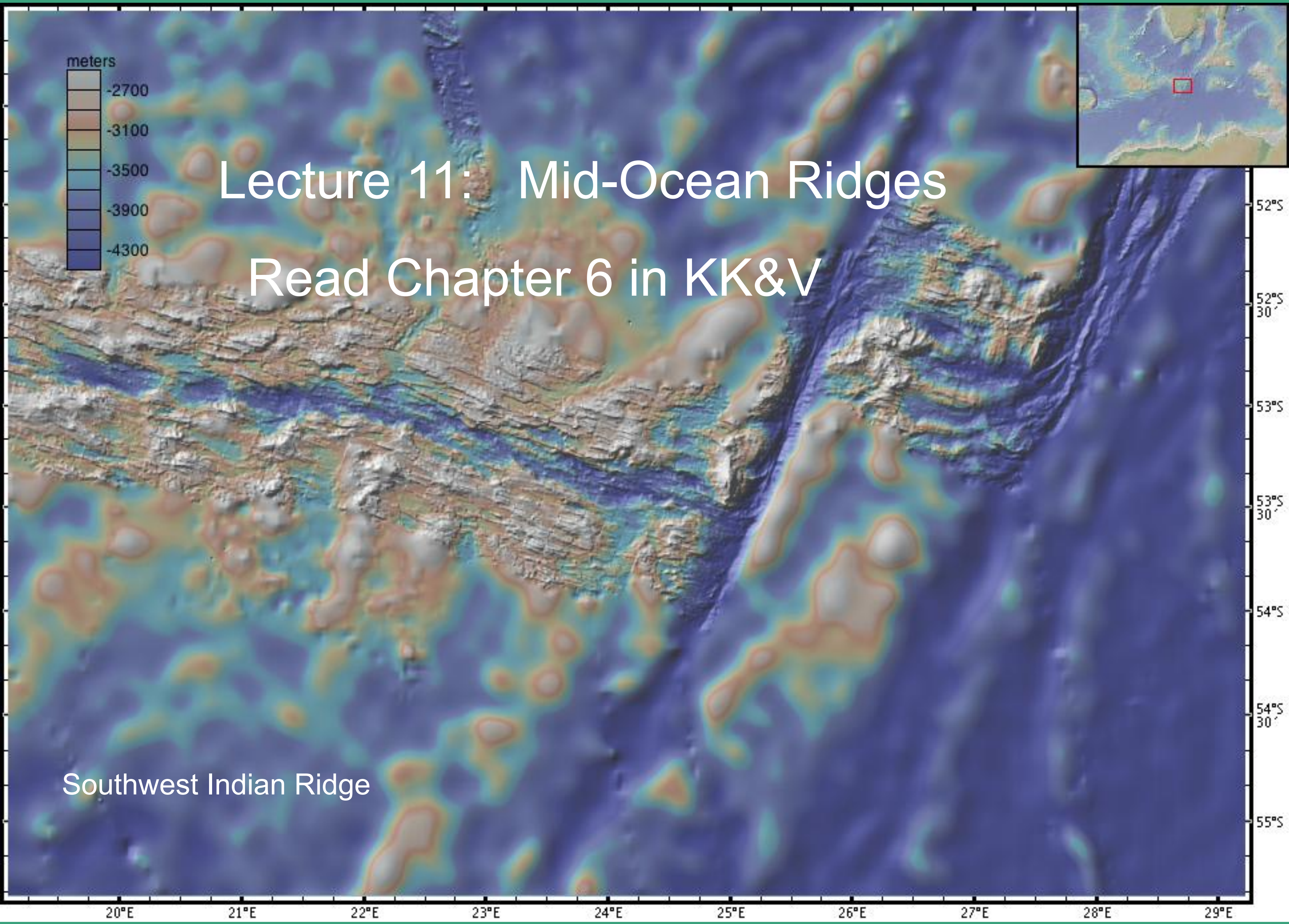
Lecture 11: Mid-Ocean Ridges

Read Chapter 6 in KK&V



Discovery of mid-ocean ridge system (1950s)

Marie Tharp & Bruce Heezen

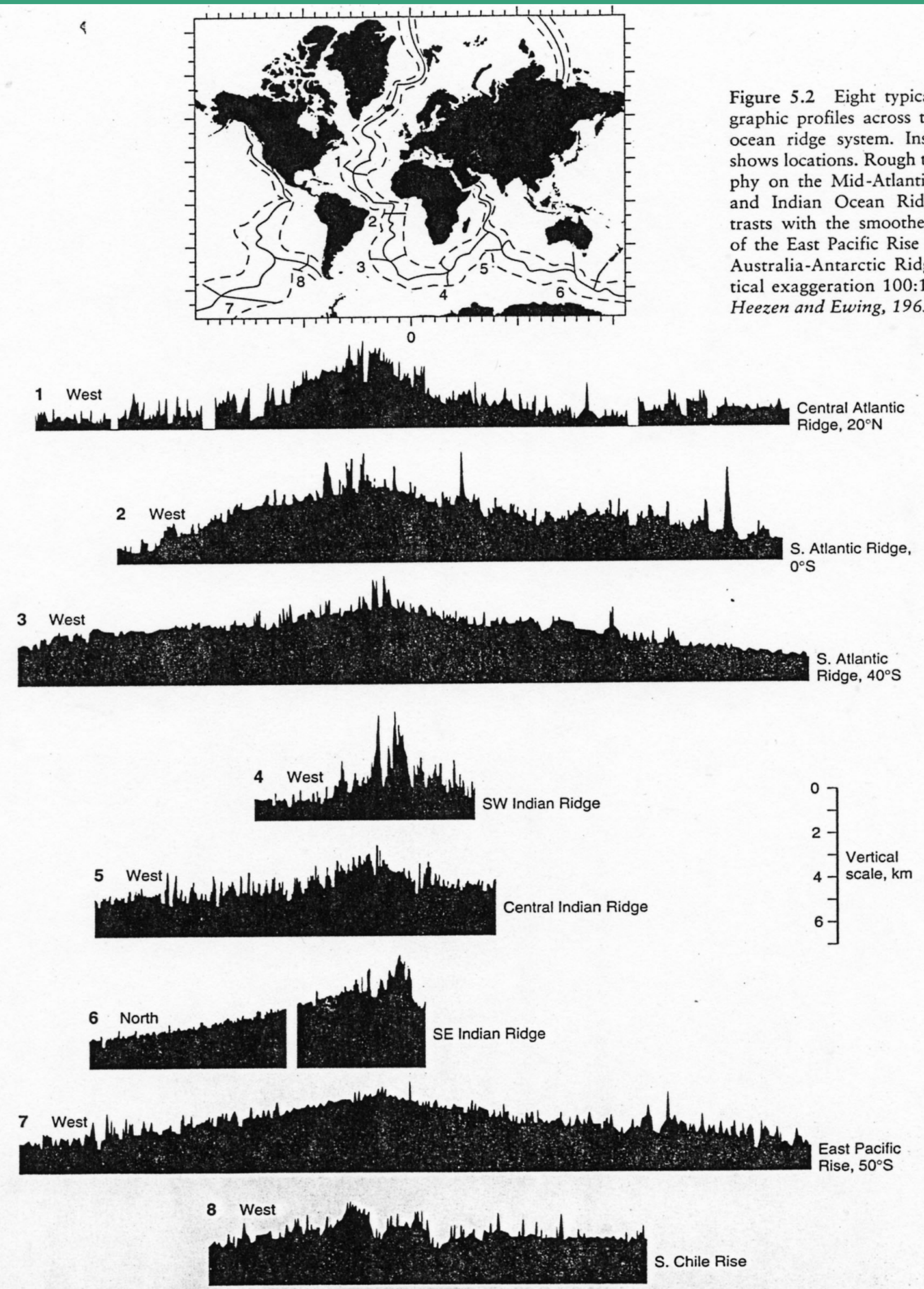
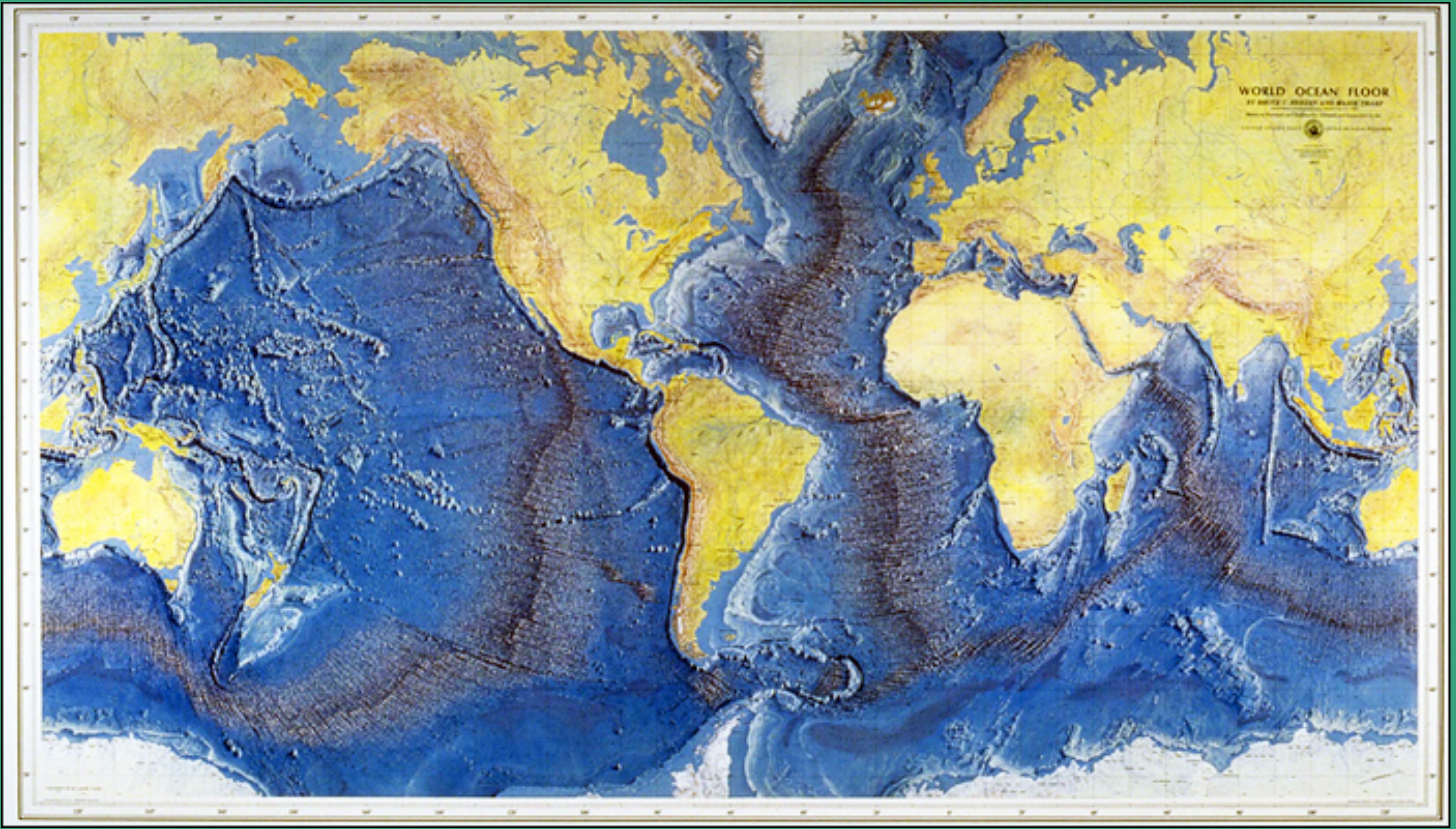
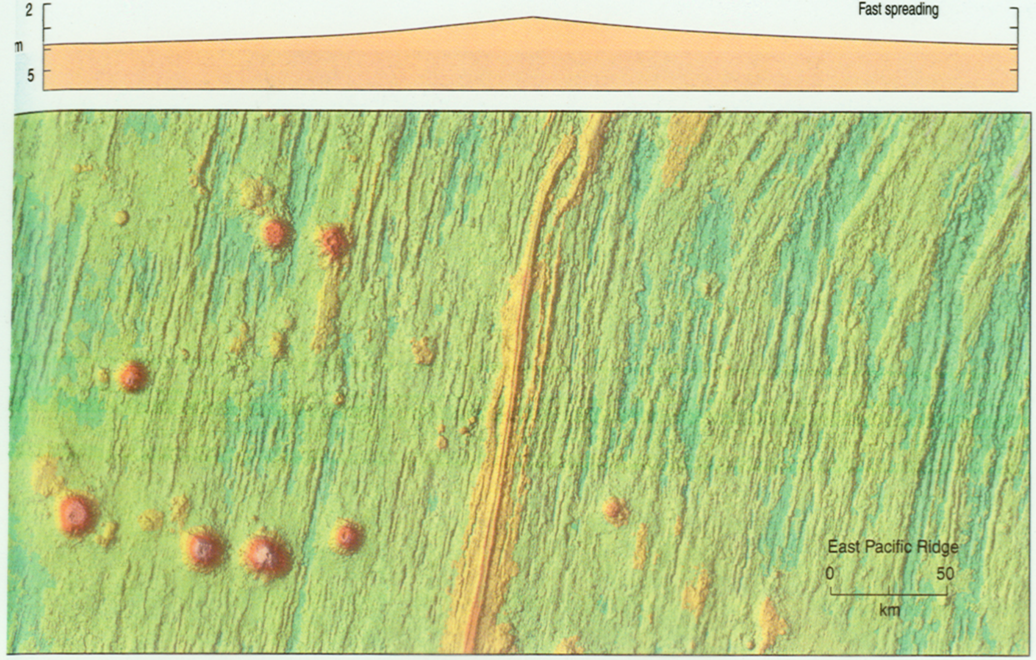
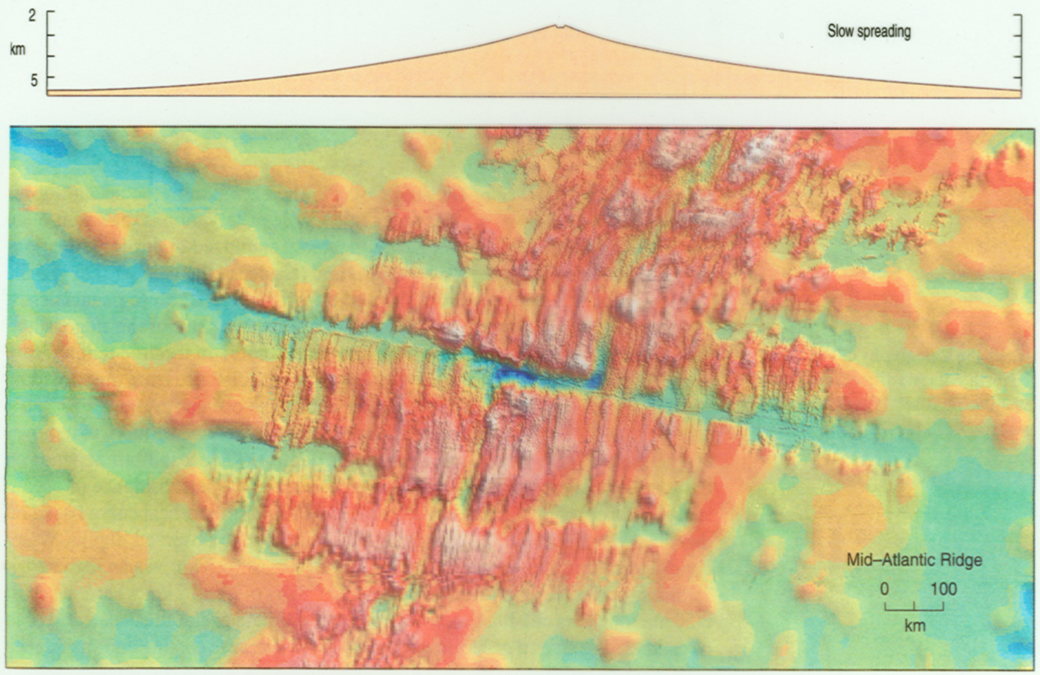


Figure 5.2 Eight typical topographic profiles across the mid-ocean ridge system. Inset map shows locations. Rough topography on the Mid-Atlantic Ridge and Indian Ocean Ridge contrasts with the smoother slopes of the East Pacific Rise and the Australia-Antarctic Ridge. Vertical exaggeration 100:1. *(After Heezen and Ewing, 1963)*


WORLD OCEAN FLOOR

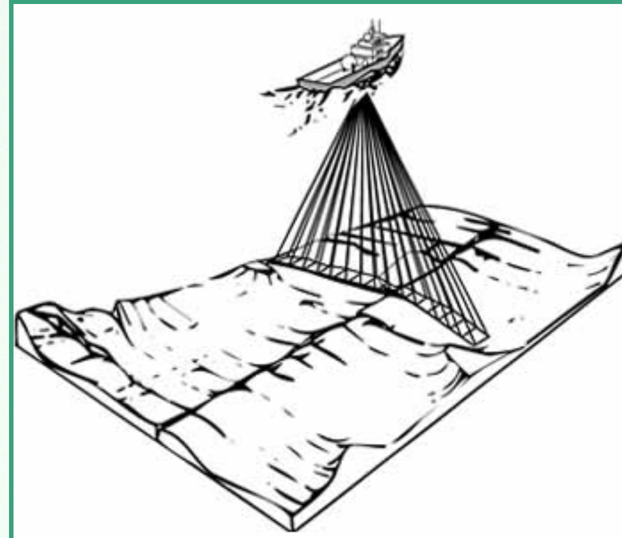


A) Fast-spreading ridges, such as the East Pacific Ridge, usually have gentle slopes and lack a prominent ift valley.



(B) Slow-spreading ridges, such as the Mid-Atlantic Ridge, have steeper flanks and prominent rift valleys. Transform faults offset the ridge in numerous places.

FIGURE 19.3 **Spreading rate** helps control many features of an oceanic ridge. *(Courtesy of Lamont-Doherty Earth Observatory)*



Multi-beam bathymetry;
swath mapping

Map a swath equal to
4 times the water depth

Top:
East Pacific rise
150 mm/yr,
Smooth(ish) topo, axial high

Bottom:
Mid-Atlantic ridge
20 mm/yr,
rough topo, rift valley

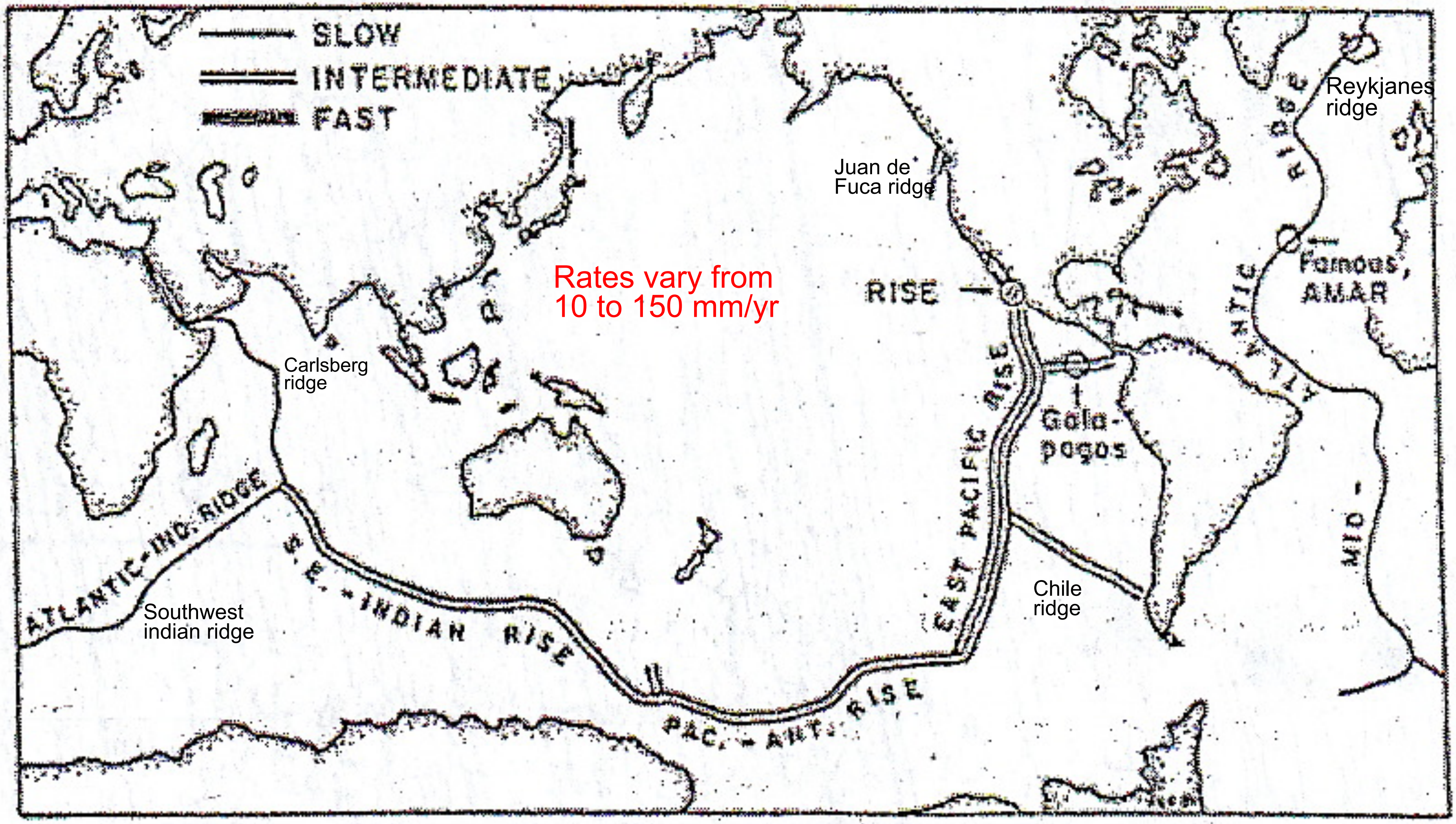


Figure 1 Major seafloor spreading centers shown schematically; transform faults, back-arc spreading centers, and subduction zones omitted. Slow spreading rates, 1.0–5.0 cm/yr; intermediate rates, 5.0–9.0 cm/yr; fast rates, 9.0–18.0 cm/yr. Mid-ocean ridge diving-expeditions indicated.

Characteristics of the Axial Zone

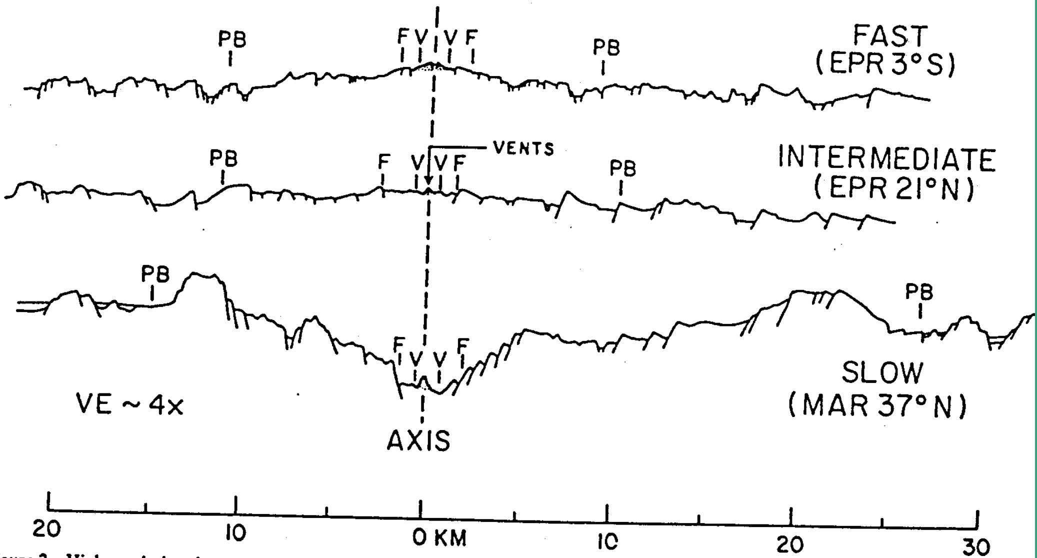


Figure 2 High resolution deep-tow profiles of mid-ocean ridges at fast, intermediate, and slow rates. Neovolcanic zone bracketed by Vs, zone of fissuring by Fs, plate boundary zone (width of active faulting) by PBs. The neovolcanic zone is generally very narrow (~1 km). Active faulting occurs up to 10–30 km off axis. Data from Lonsdale (1977), Normark (1976), Shih (1980), Macdonald et al (1975), and Macdonald & Luyendyk (1977).

Macdonald (1982)

Neovolcanic zone: (Ax - V)

1 – 2 kms wide,
Fresh, glassy lava flows
Central volcanics

Zone of Crustal Fissuring: (V - F)

Adjacent to neovoolcanic zone
Fissures are 1 – 3 m wide
Form bands 1 – 2 kms across
Allows water to penetrate into crust

Active Faulting Zone: (F - PB)

Starts 1 – 4 kms form axis
Individual throws on faults up to 200 m
Some scarps 600 m high

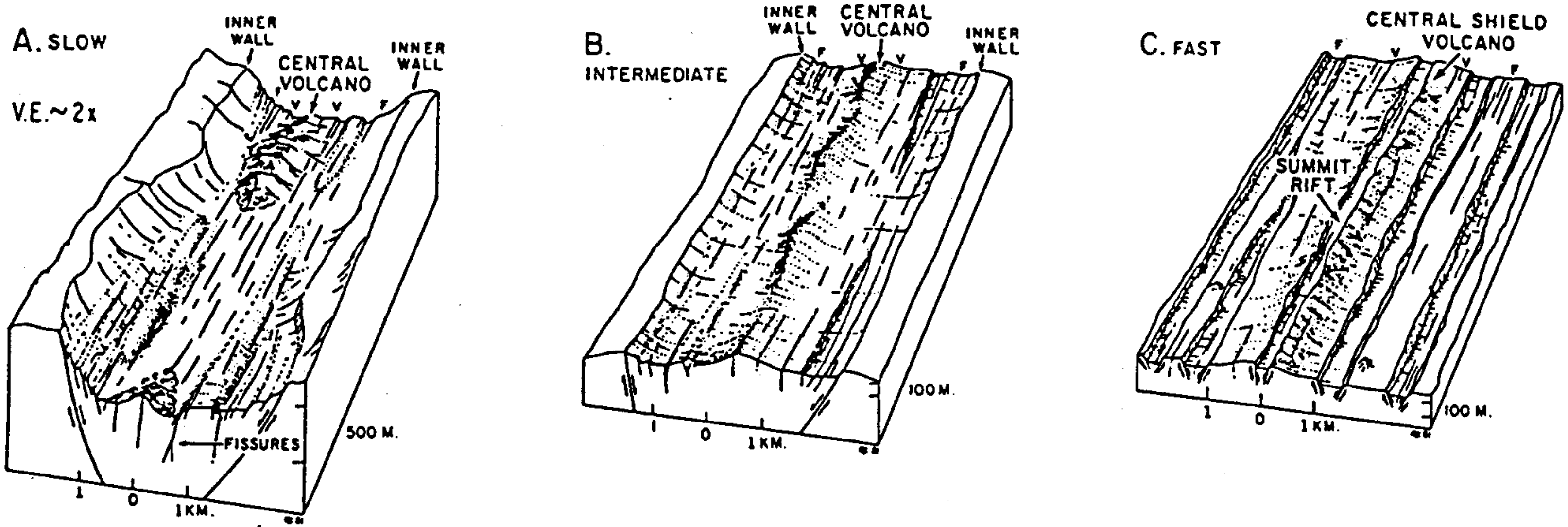
Spreading Rates

	Full rate (mm/yr)	Rift Valley?
<u>Fast:</u> 90-150		
East Pacific Rise (EPR)	80-150	No
fastest at 30^{o}S, slower towards North		
<u>Intermediate:</u> 50-90		
Pacific-Antarctic Ridge	60-100	No
fastest toward North		
slower at South end	~60	Yes
Southeast Indian Ridge	65-80	No
Australian-Antarctic Discordance	75	Yes
Costa Rica Ridge	60	No
Juan de Fuca	60	No
Chile Ridge	60	Yes
<u>Slow:</u> 10-50		
South Atlantic	40	Yes
Central Atlantic	20-25	Yes
North Atlantic	15-20	Yes
Nansen (Arctic)	10-15	Yes
Southwest Indian	15	Yes

Rule: > 65 no rift valley < 55 rift valley 55-65 maybe

Exceptions: Reykjanes Ridge (hot spot), Australia-Antarctica Discordance (cold spot)

More characteristics



MACDONALD

Figure 3 Schematic illustrations of the neovolcanic zone at different spreading rates. The central volcano is highly discontinuous at slow rates (*A*), moderately continuous with *en echelon* offsets at intermediate rates (*B*), and often almost perfectly continuous at fast rates (*C*). At fast rates the volcano resembles a Hawaiian shield volcano with a summit rift. At slow to intermediate rates it is a volcanic construction of pillow lavas. Fissuring of the crust appears to be greatest adjacent to the neovolcanic zone but may occur within it as well. Labels V and F as in Figure 2. (Sketch *A* modified after Moore et al 1974.)

Central Volcanoes:

Discontinuous at slow spreading rates
Continuous feature at fast rates

Frequency of eruptions:

Slow: every 5,000 – 10,000 years
Intermediate: every 300 – 600 years
Fast: every 50 years

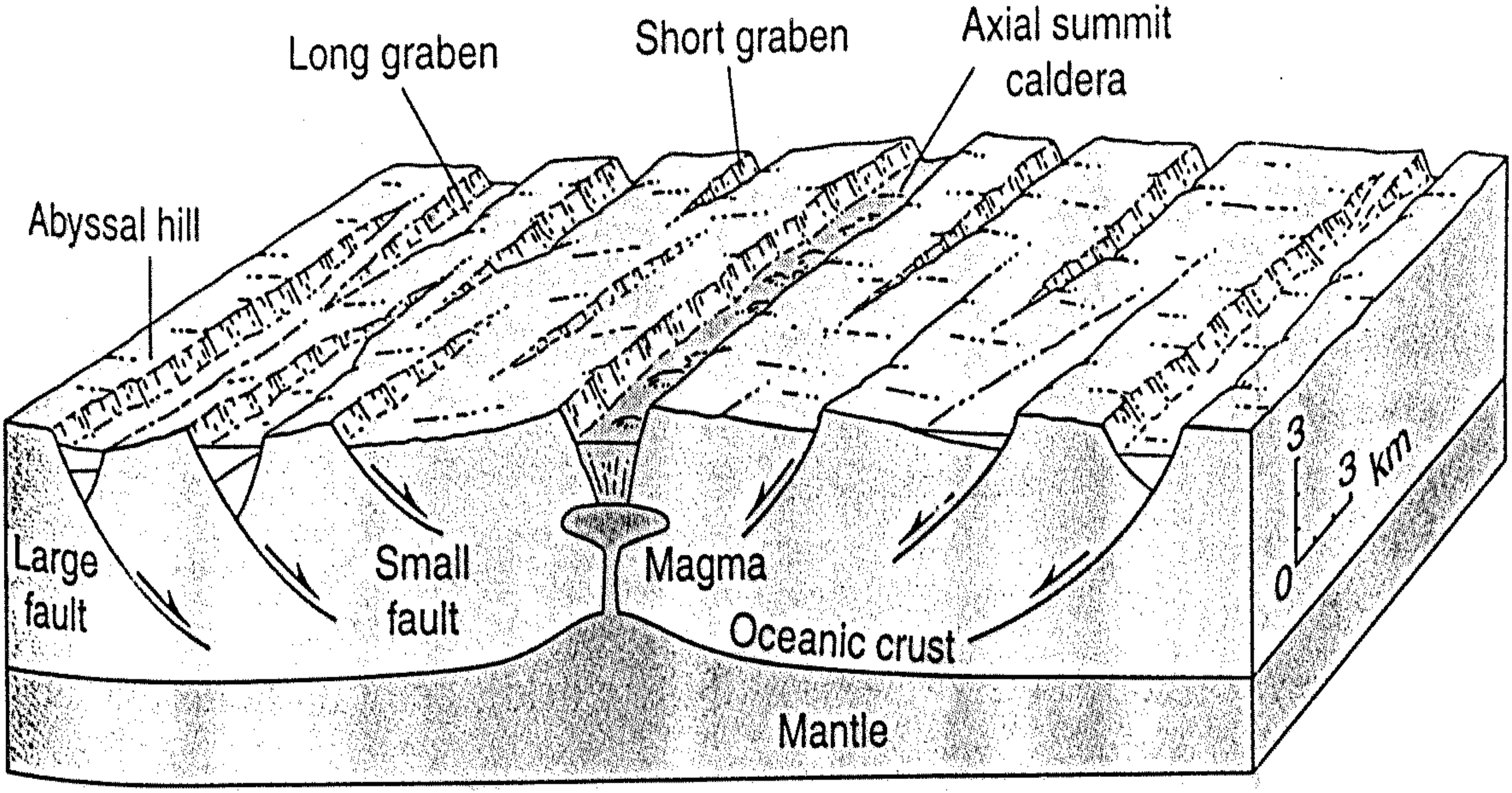
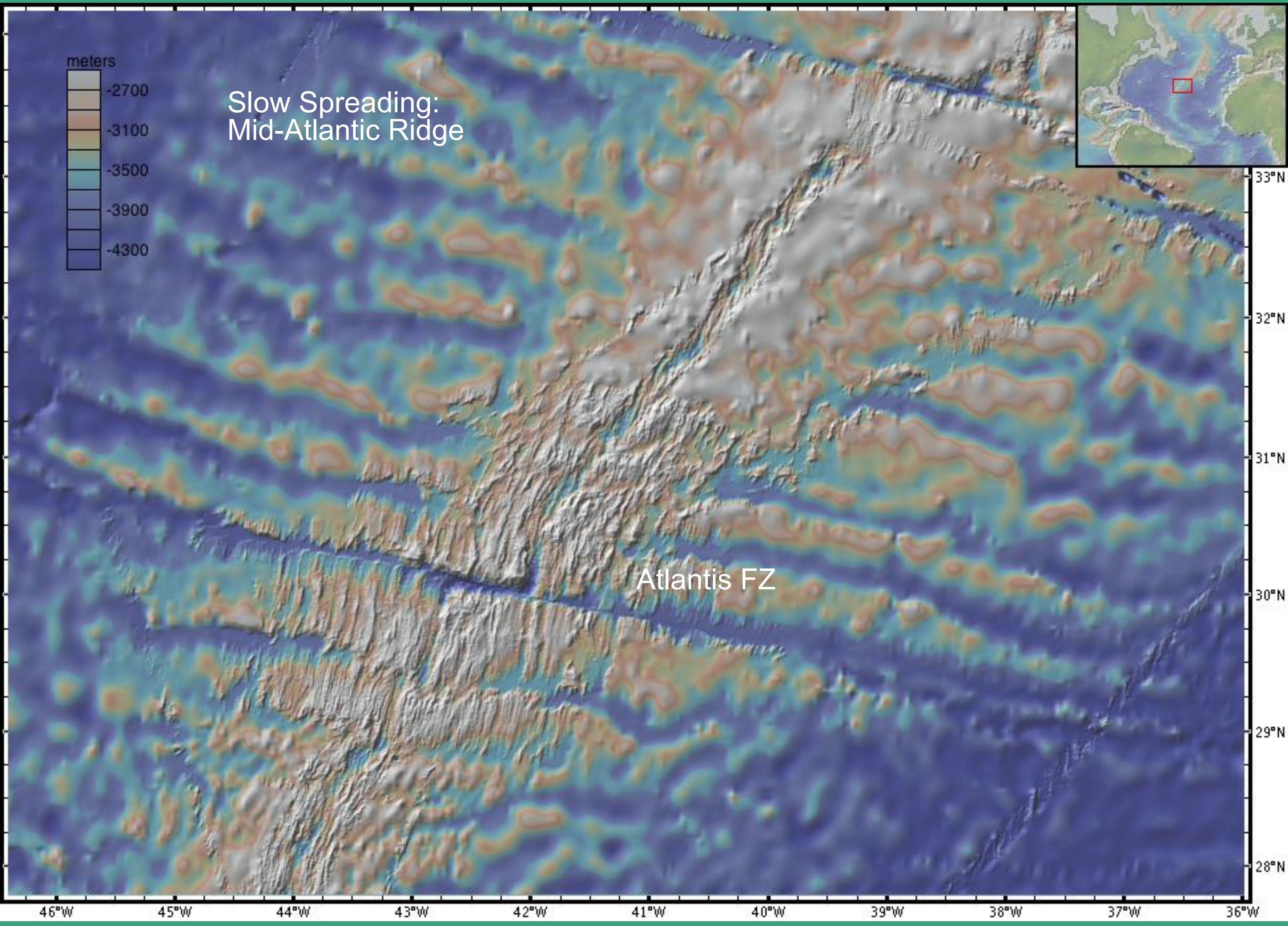
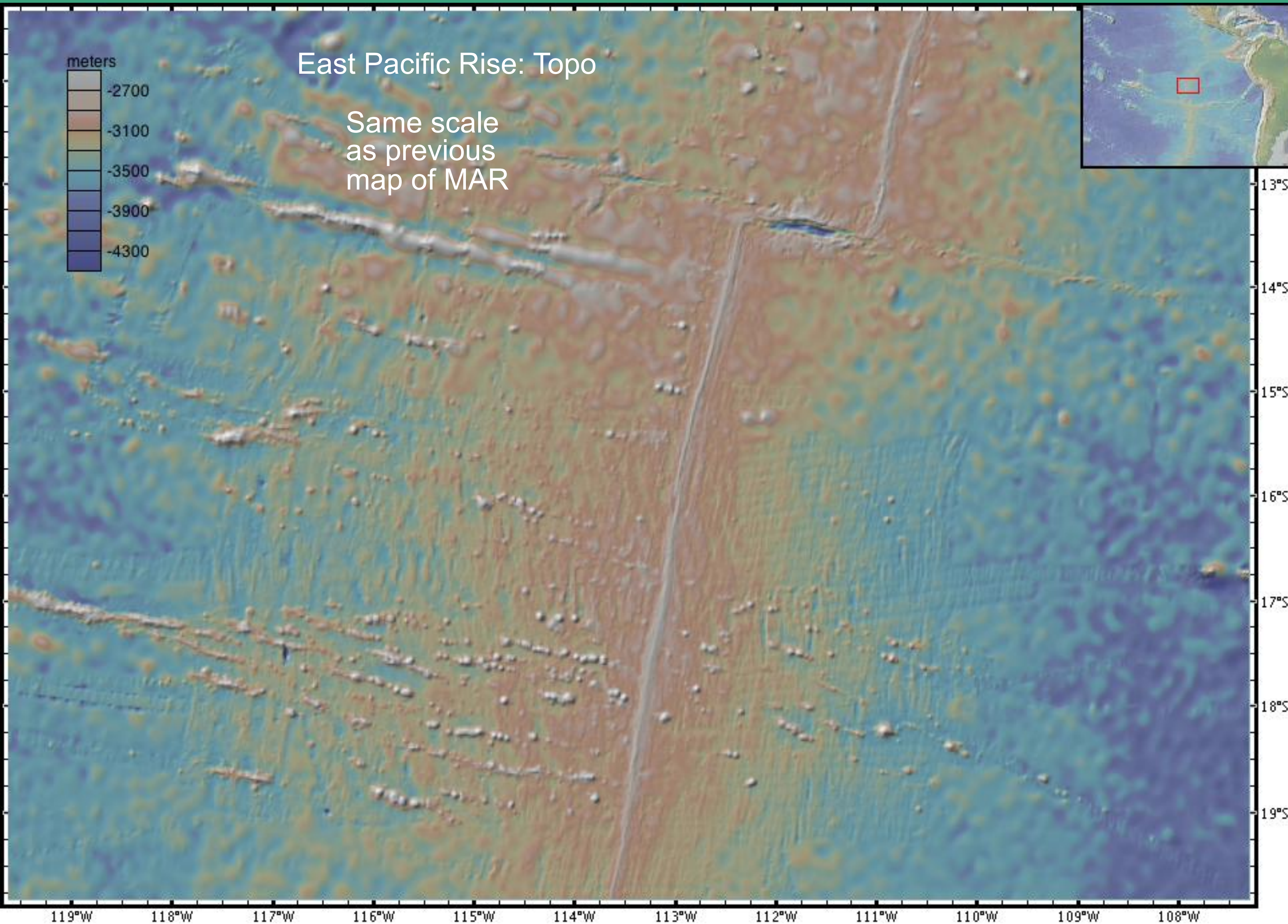
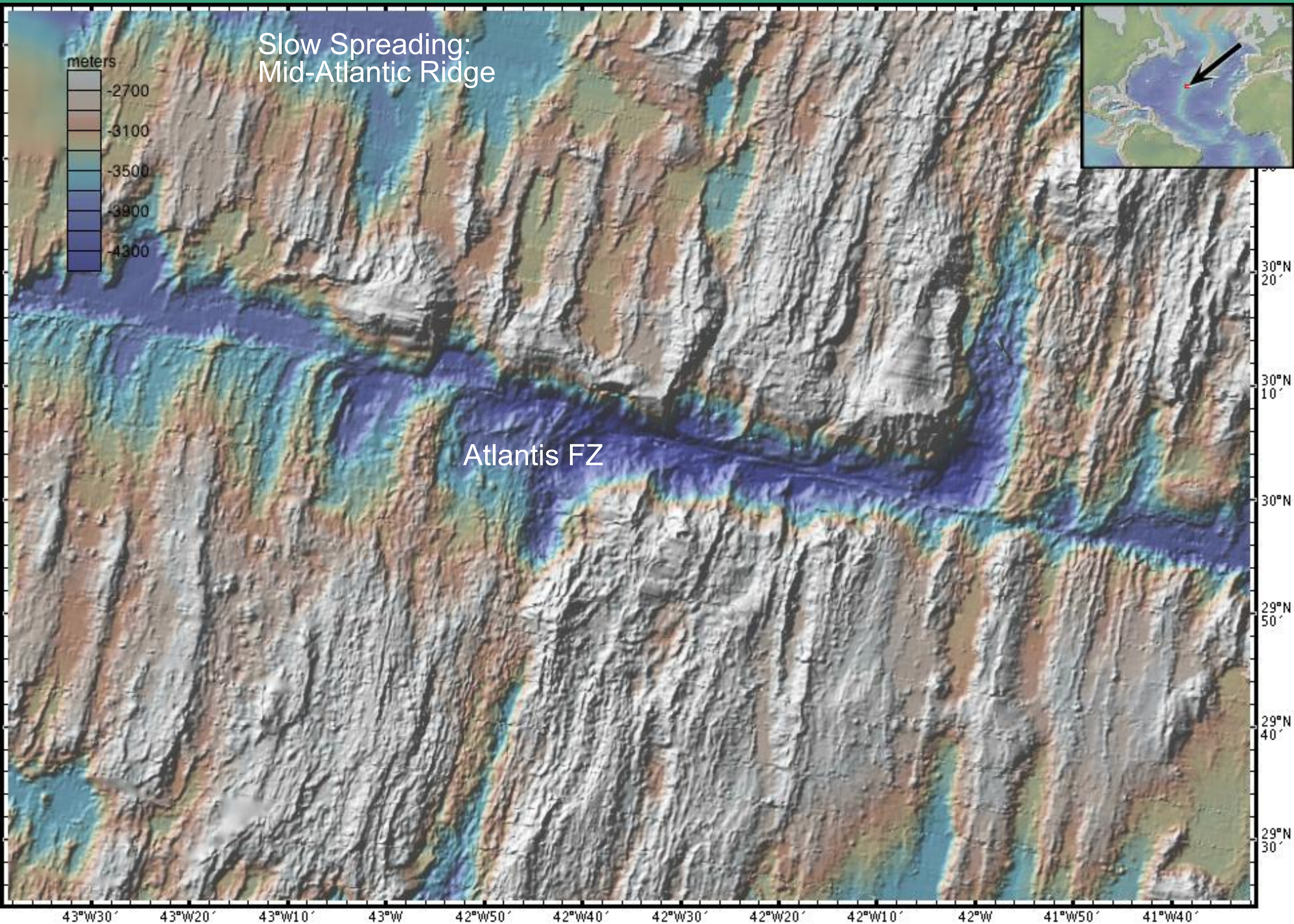


FIGURE 19.28 **Abyssal hills** form at the oceanic ridge by a combination of faulting and volcanic processes. These hills are the dominant landforms on the ocean floor.


meters
-2700
-3100
-3500
-3900
-4300
Slow Spreading:
Mid-Atlantic Ridge
Atlantis FZ
33°N
32°N
31°N
30°N
29°N
28°N
46°W
45°W
44°W
43°W
42°W
41°W
40°W
39°W
38°W
37°W
36°W


East Pacific Rise: Topo
Same scale
as previous
map of MAR
meters
-2700
-3100
-3500
-3900
-4300
13°S
14°S
15°S
16°S
17°S
18°S
19°S
119°W
118°W
117°W
116°W
115°W
114°W
113°W
112°W
111°W
110°W
109°W
108°W

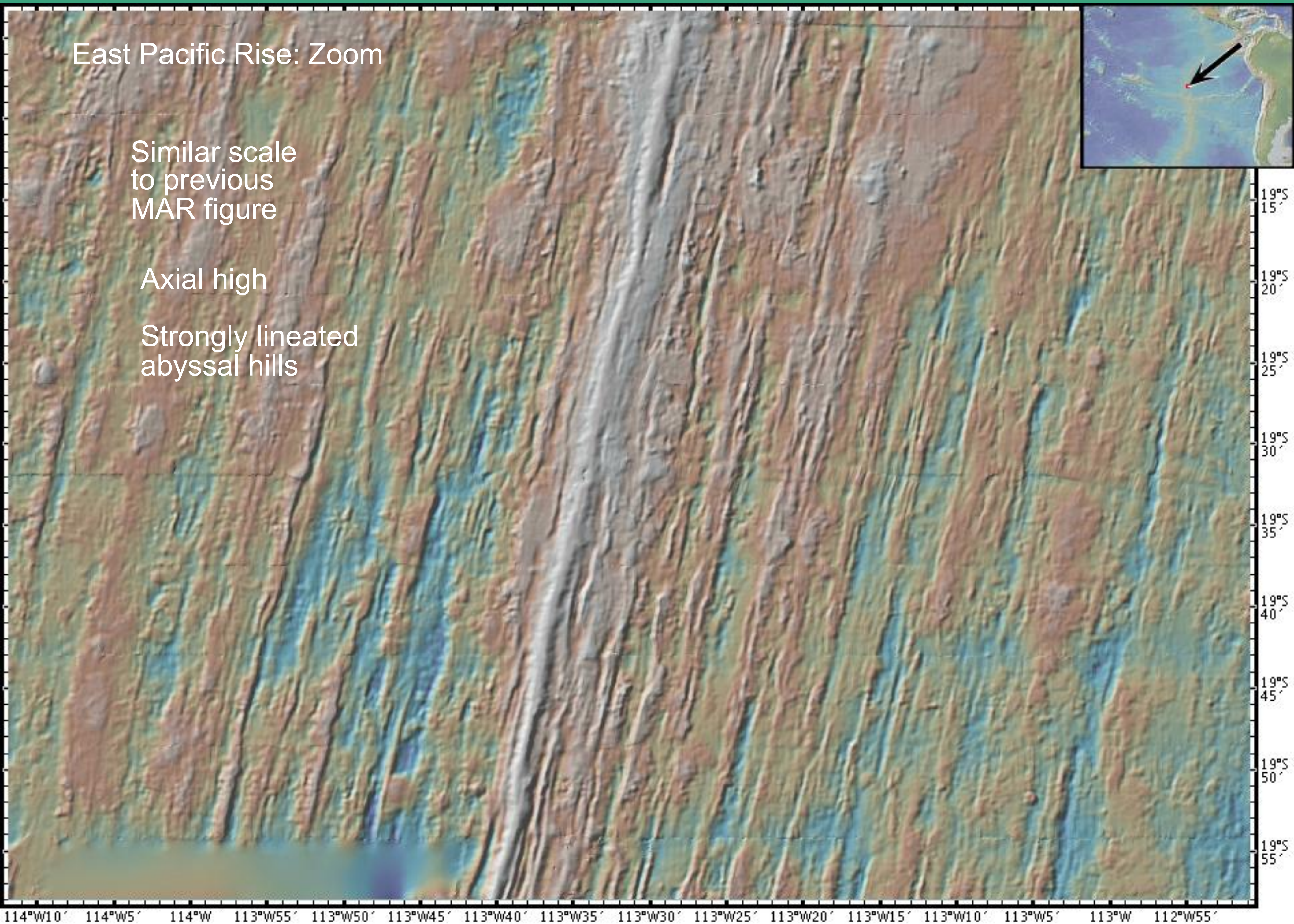

Slow Spreading:
Mid-Atlantic Ridge
meters
-2700
-3100
-3500
-3900
-4300
Atlantis FZ
30°N 20´
30°N 10´
30°N
29°N 50´
29°N 40´
29°N 30´
43°W30´
43°W20´
43°W10´
43°W
42°W50´
42°W40´
42°W30´
42°W20´
42°W10´
42°W
41°W50´
41°W40´

East Pacific Rise: Zoom

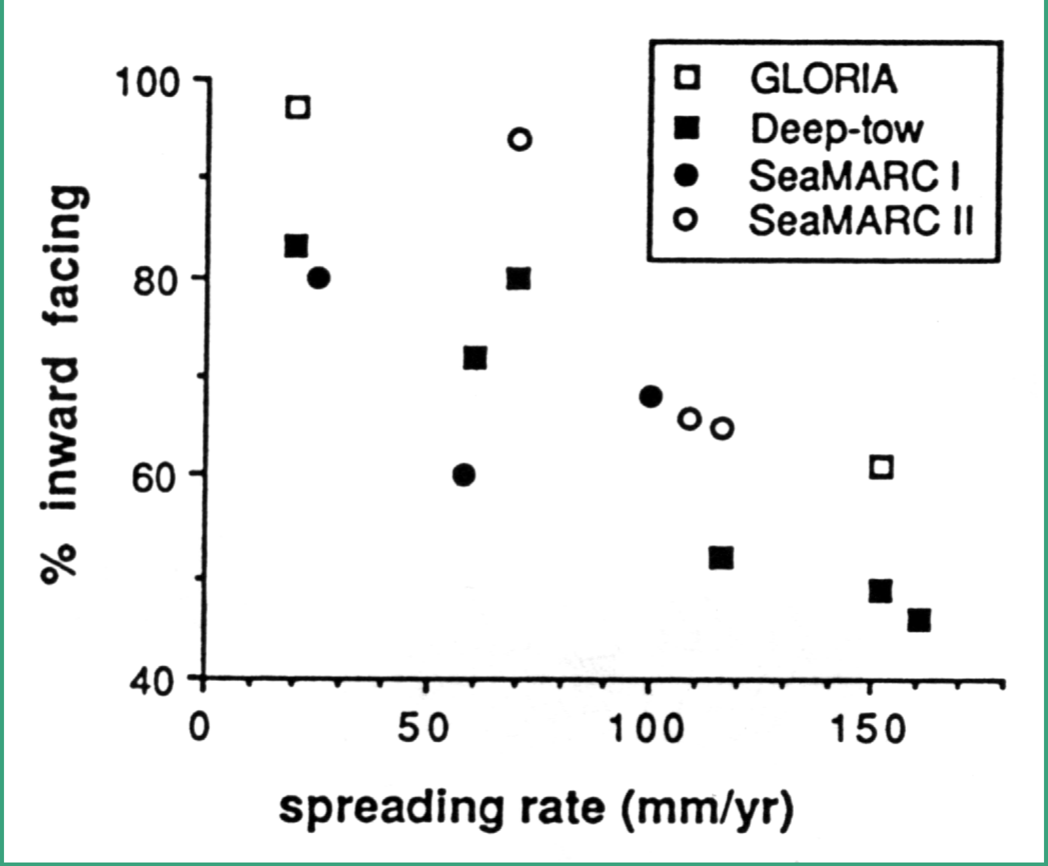
Similar scale
to previous
MAR figure

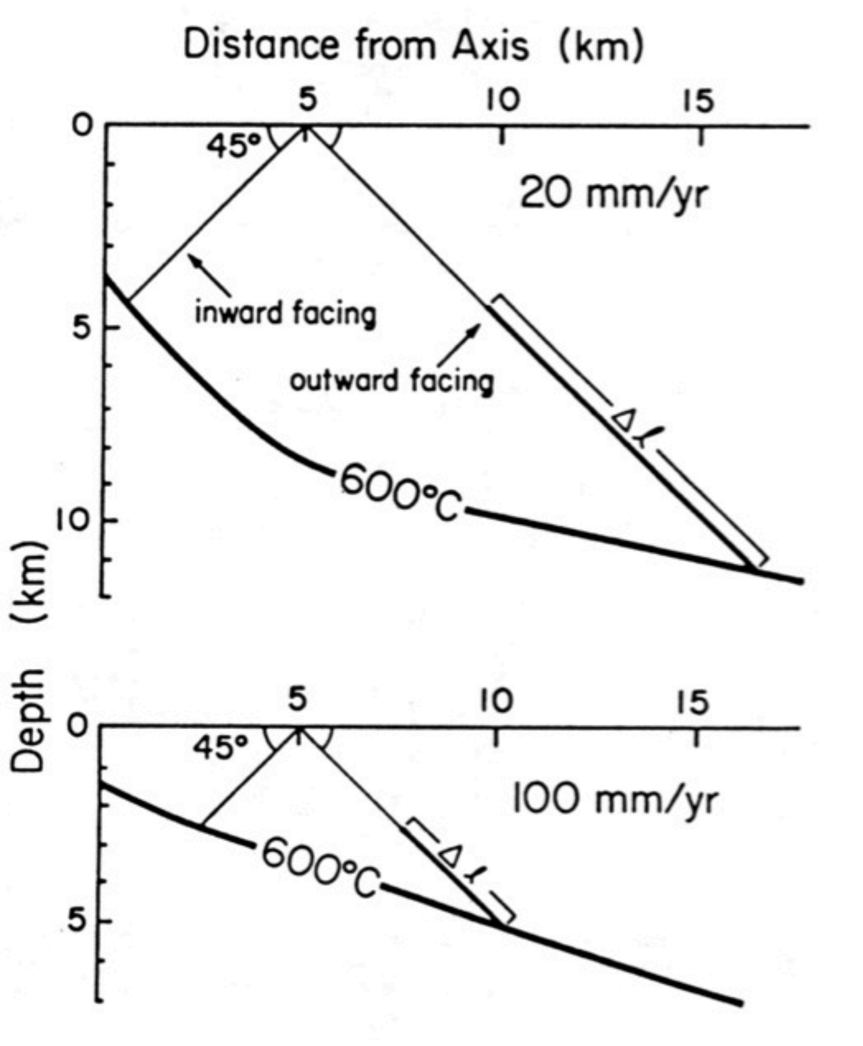
Axial high

Strongly lineated
abyssal hills

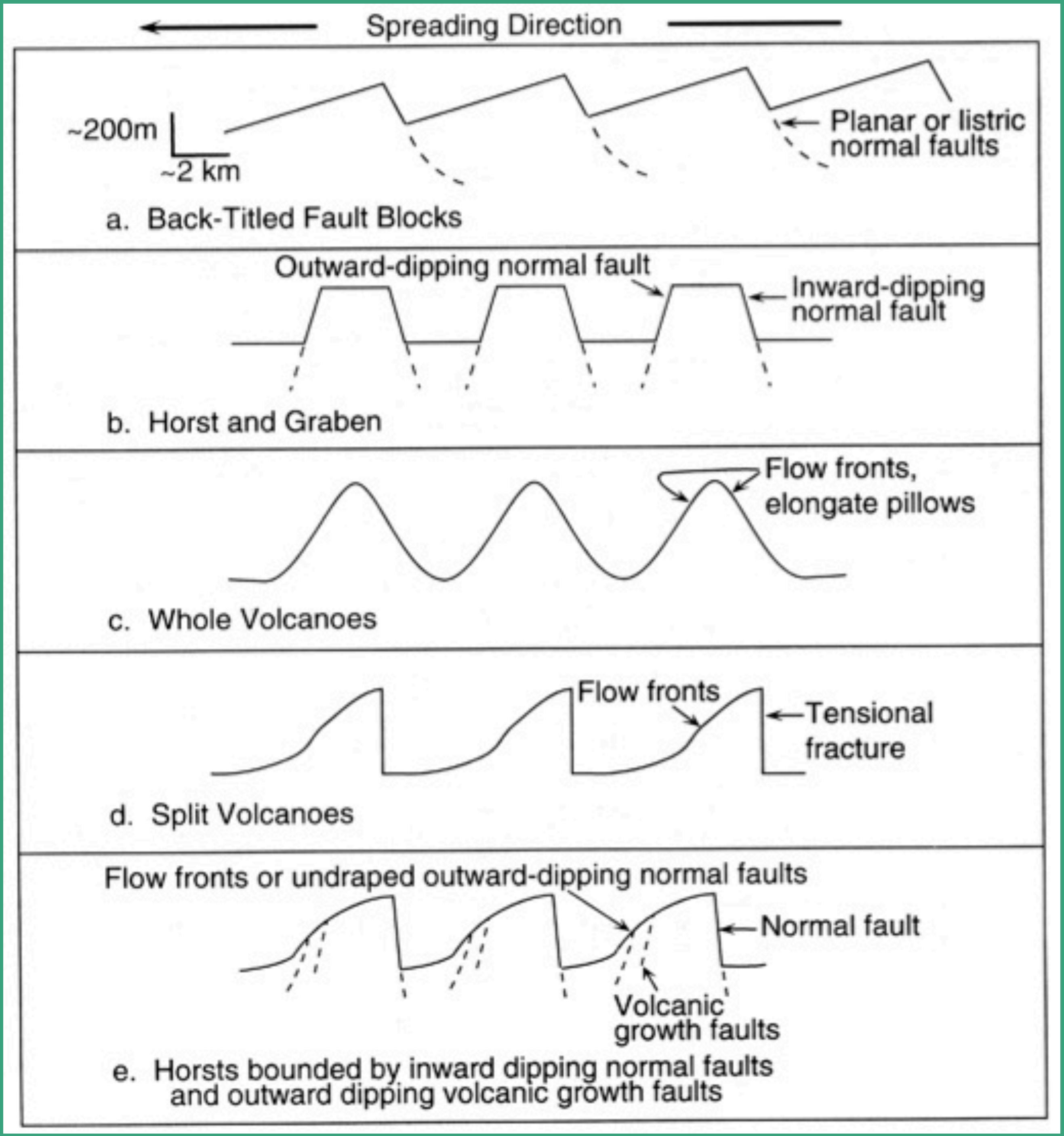


Inward vs outward-dipping faults as a function of spreading rate



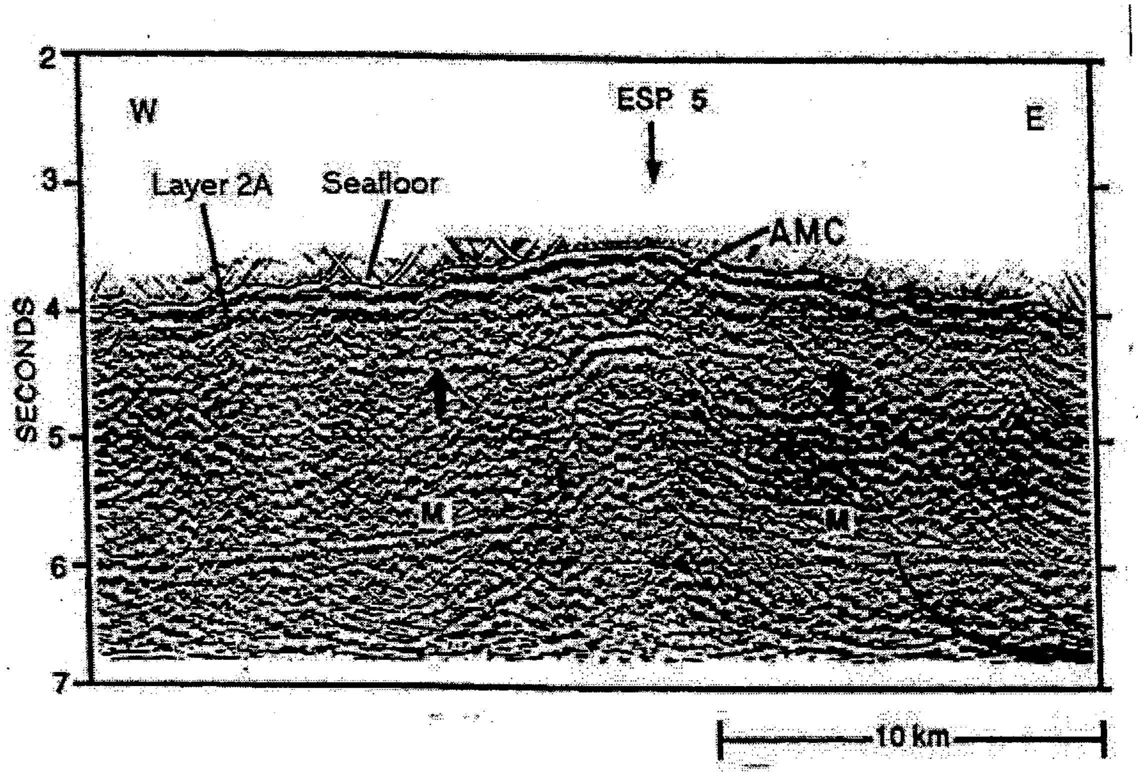


Carbotte and McDonald, 1990



Spreading Direction
~200m
~2 km
Planar or listric normal faults
a. Back-Titled Fault Blocks
Outward-dipping normal fault
Inward-dipping normal fault
b. Horst and Graben
Flow fronts, elongate pillows
c. Whole Volcanoes
Flow fronts
Tensional fracture
d. Split Volcanoes
Flow fronts or undraped outward-dipping normal faults
Normal fault
Volcanic growth faults
e. Horsts bounded by inward dipping normal faults and outward dipping volcanic growth faults

Additional Seismic Constraints



Axial magma chamber (AMC)

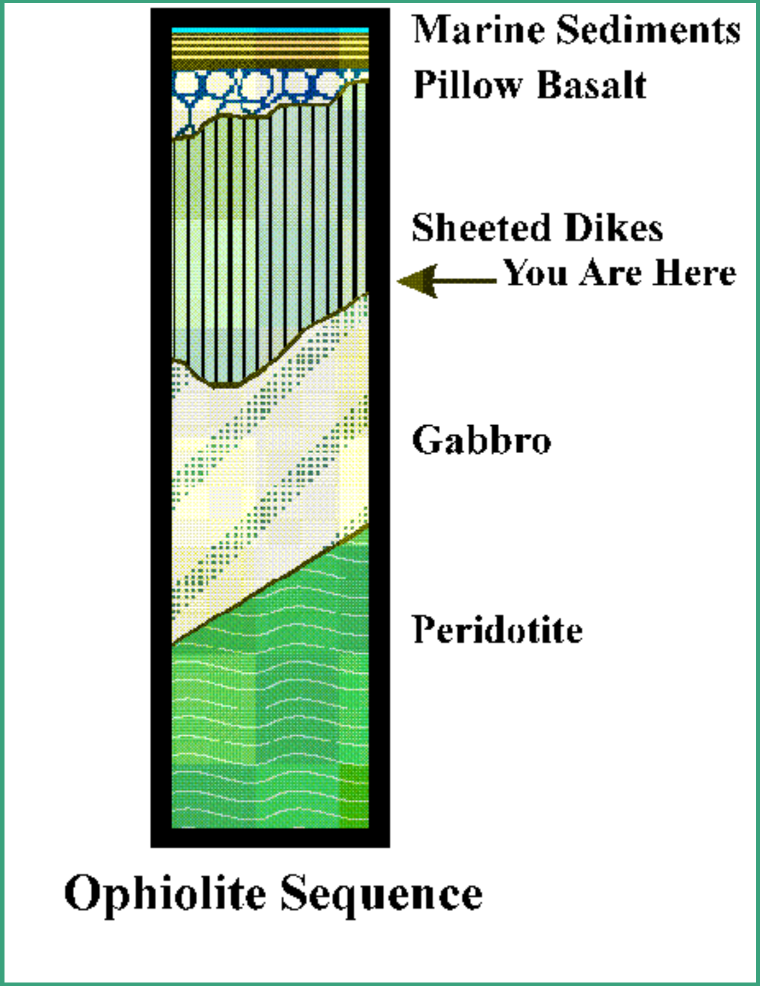
reversed polarity reflection from liquid magma lens
few kms wide
10s meters to a few 100 m thick
"steady state" magma lens at fast spread ridges

Layer 2A thickness variations near ridge

~ equivalent to extrusives (pillow lavas and sheet flows)
at fast spread ridges doubles in thickness of 1-3 km

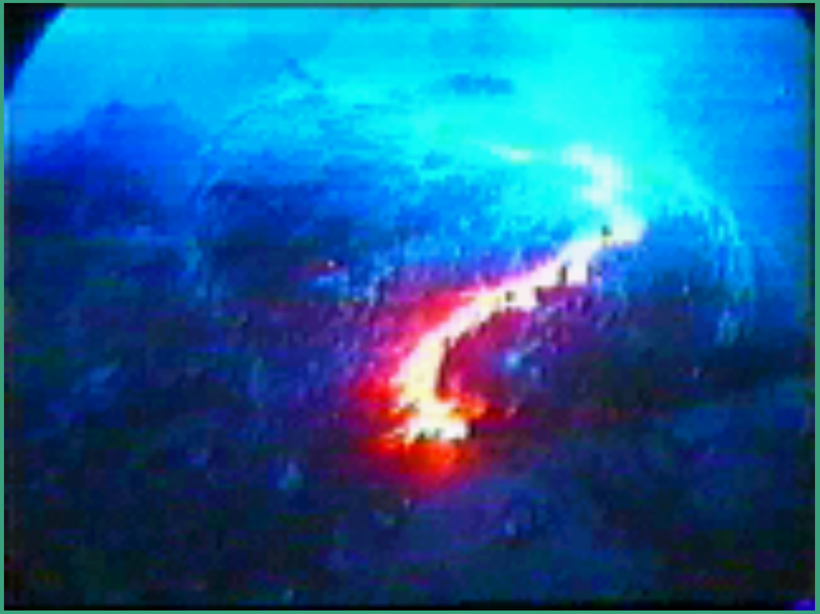
Structure of the oceanic crust

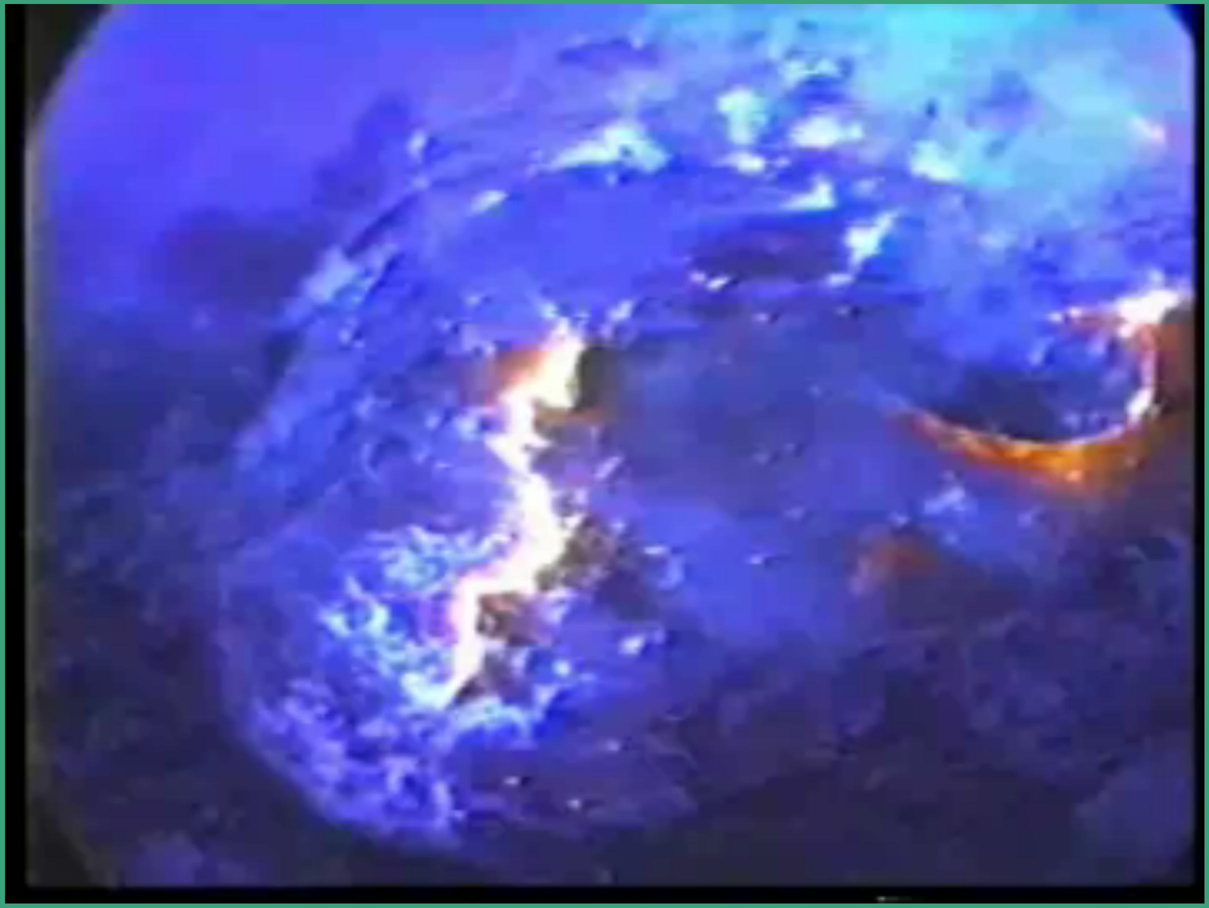
Pillow lavas

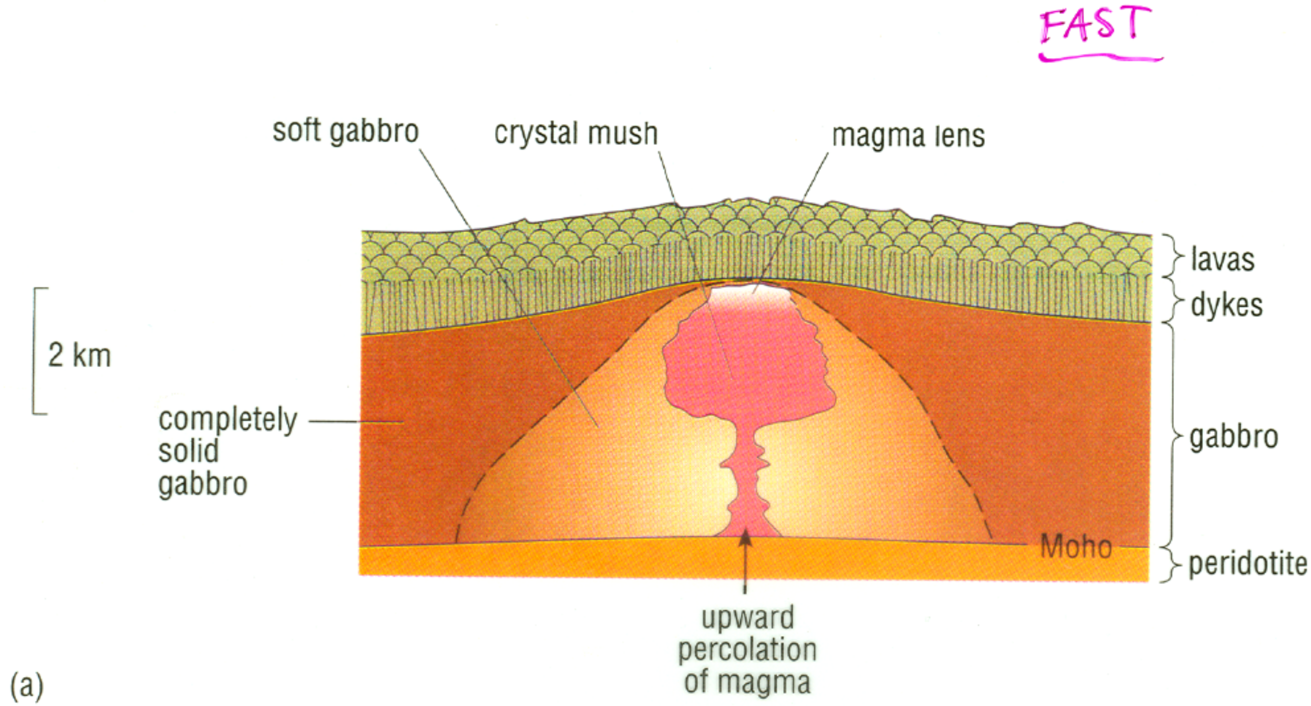


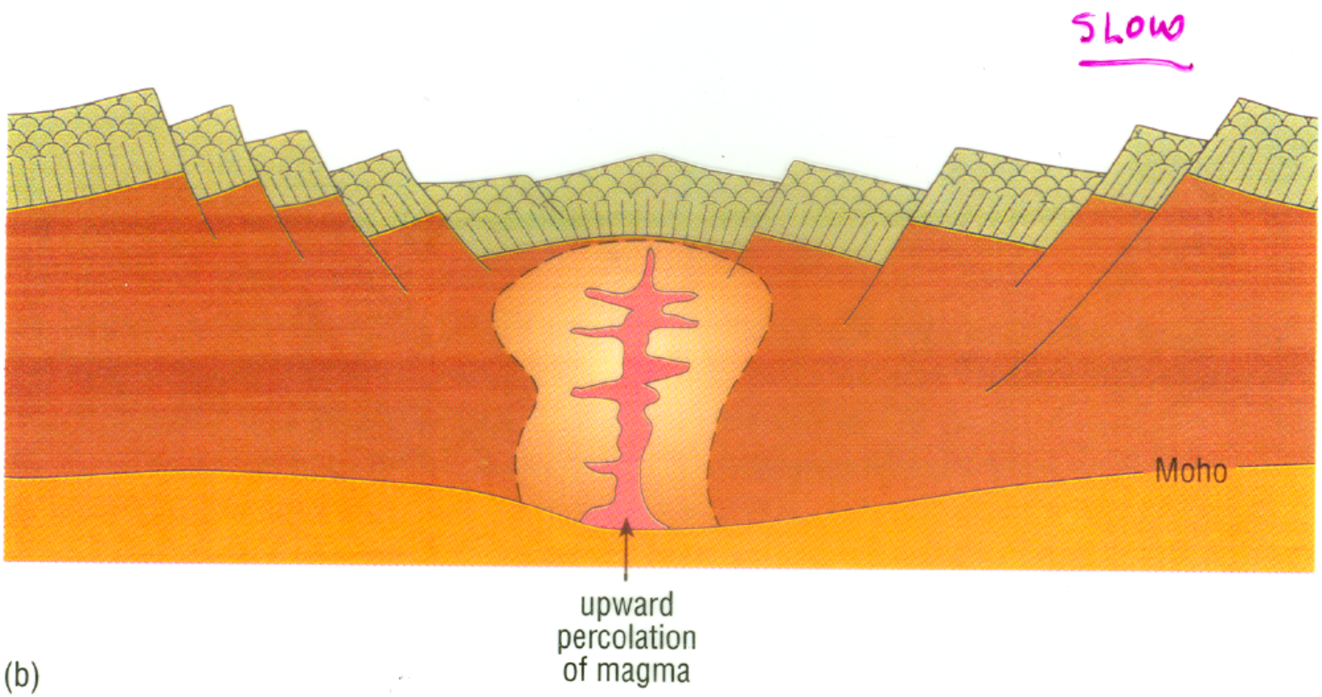
Sheeted dikes

Formation of pillow lavas







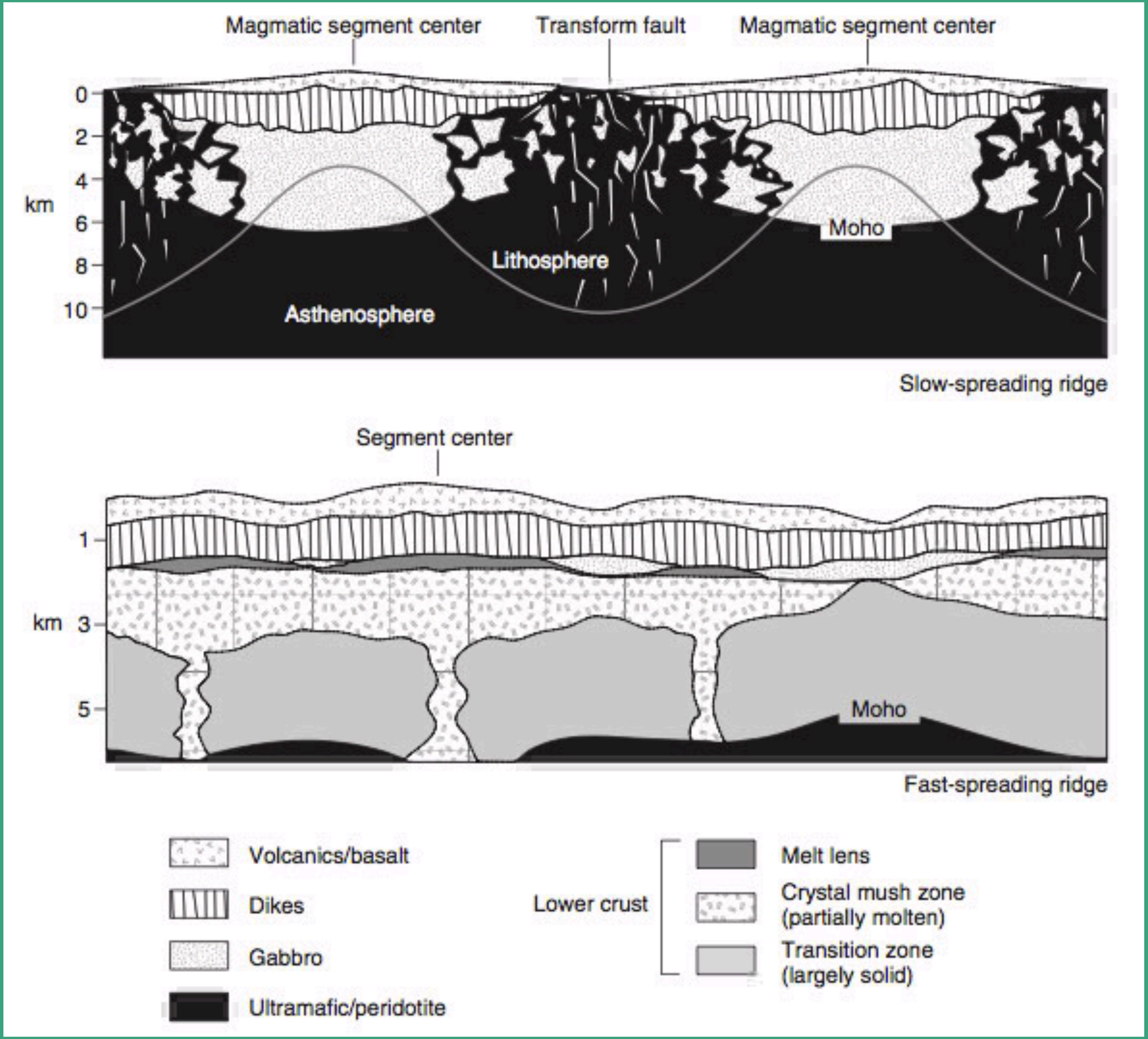


A much larger magma budget at a fast spreading ridge than at a slow spreading ridge

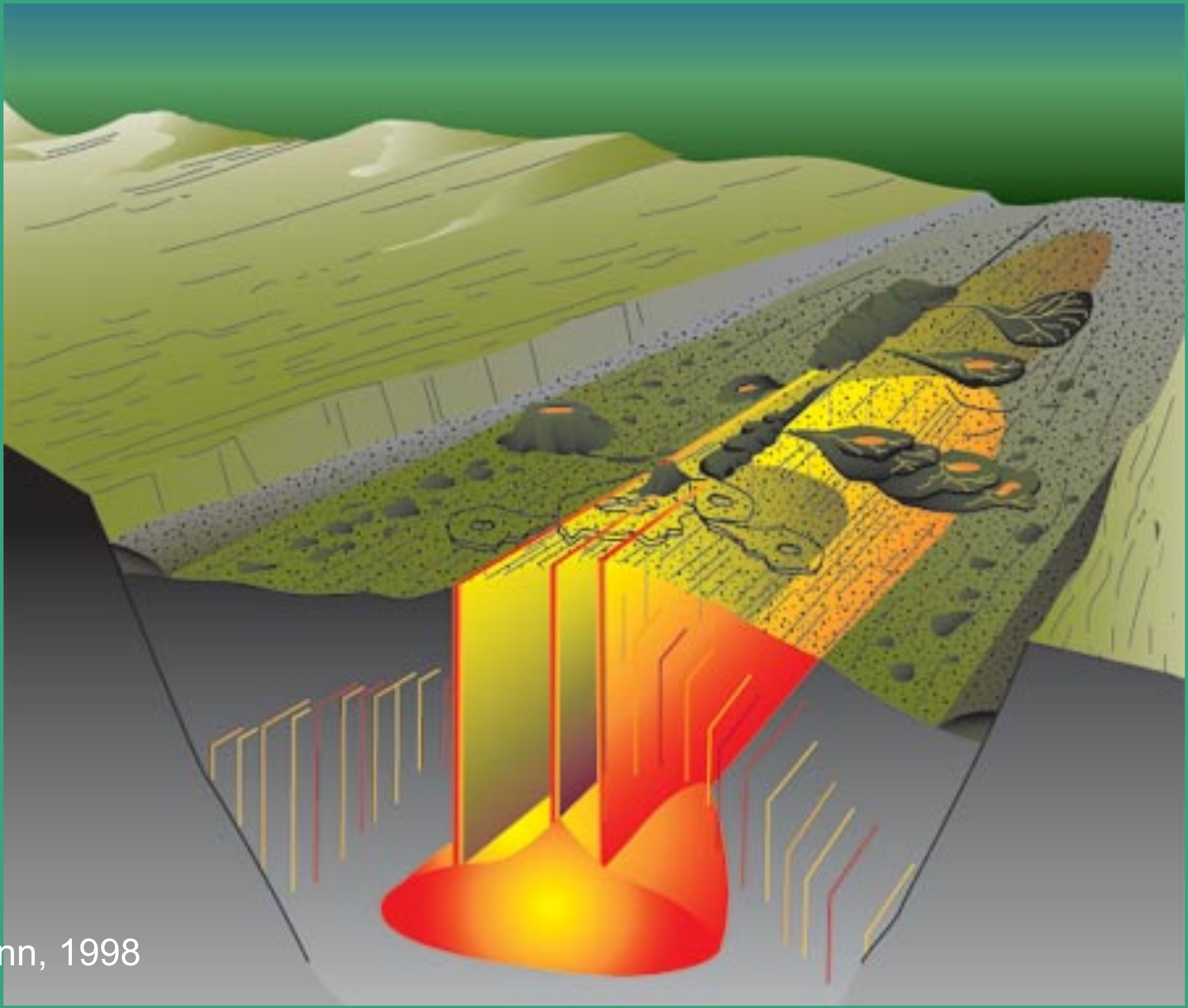
Magma lens > 50% melt
Crystal mush < 10% melt

No magma lens at a slow spreading ridge

Along-axis variations in crustal morphology

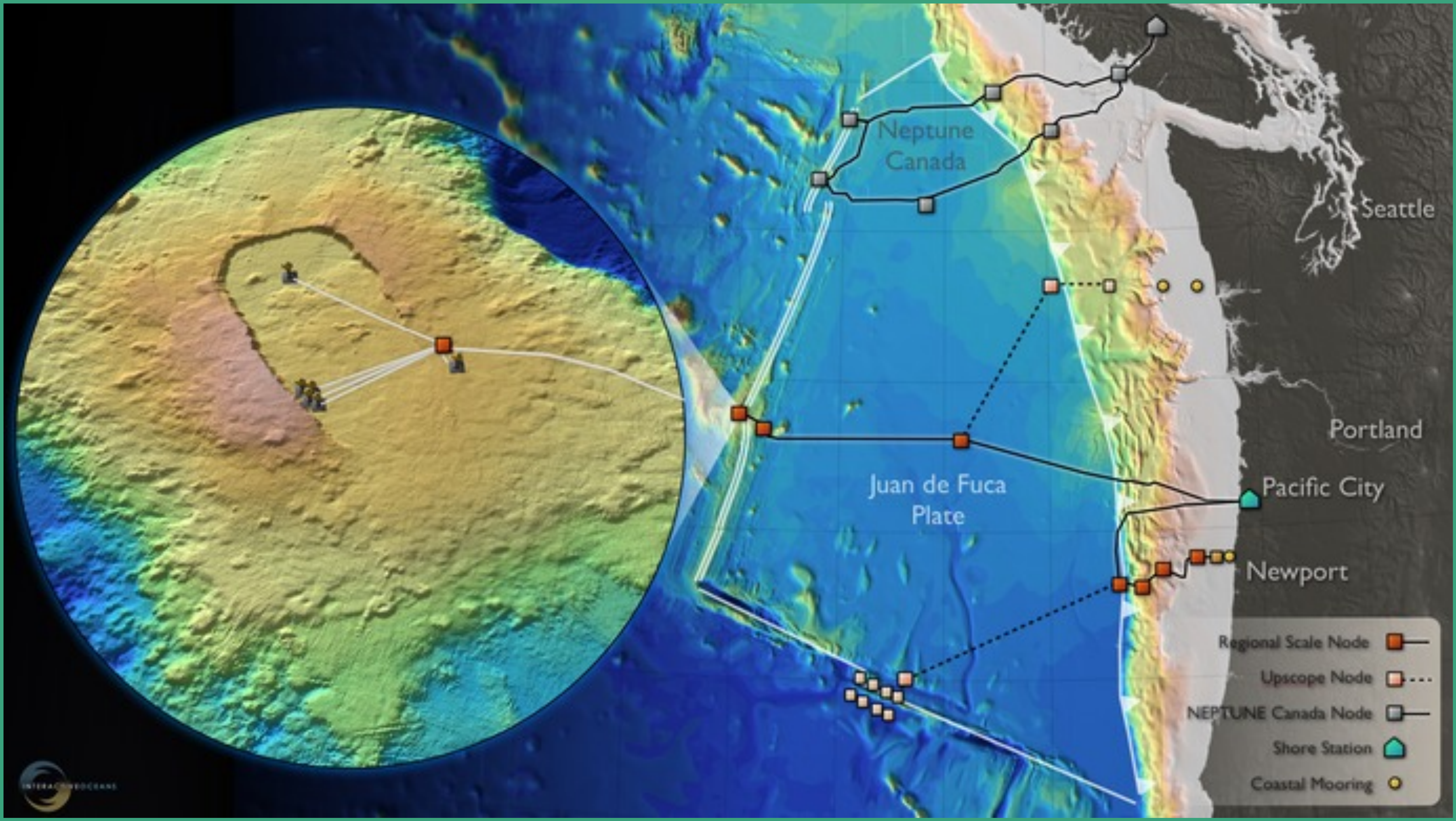


Magma transport along the ridge axis (slow spreading)

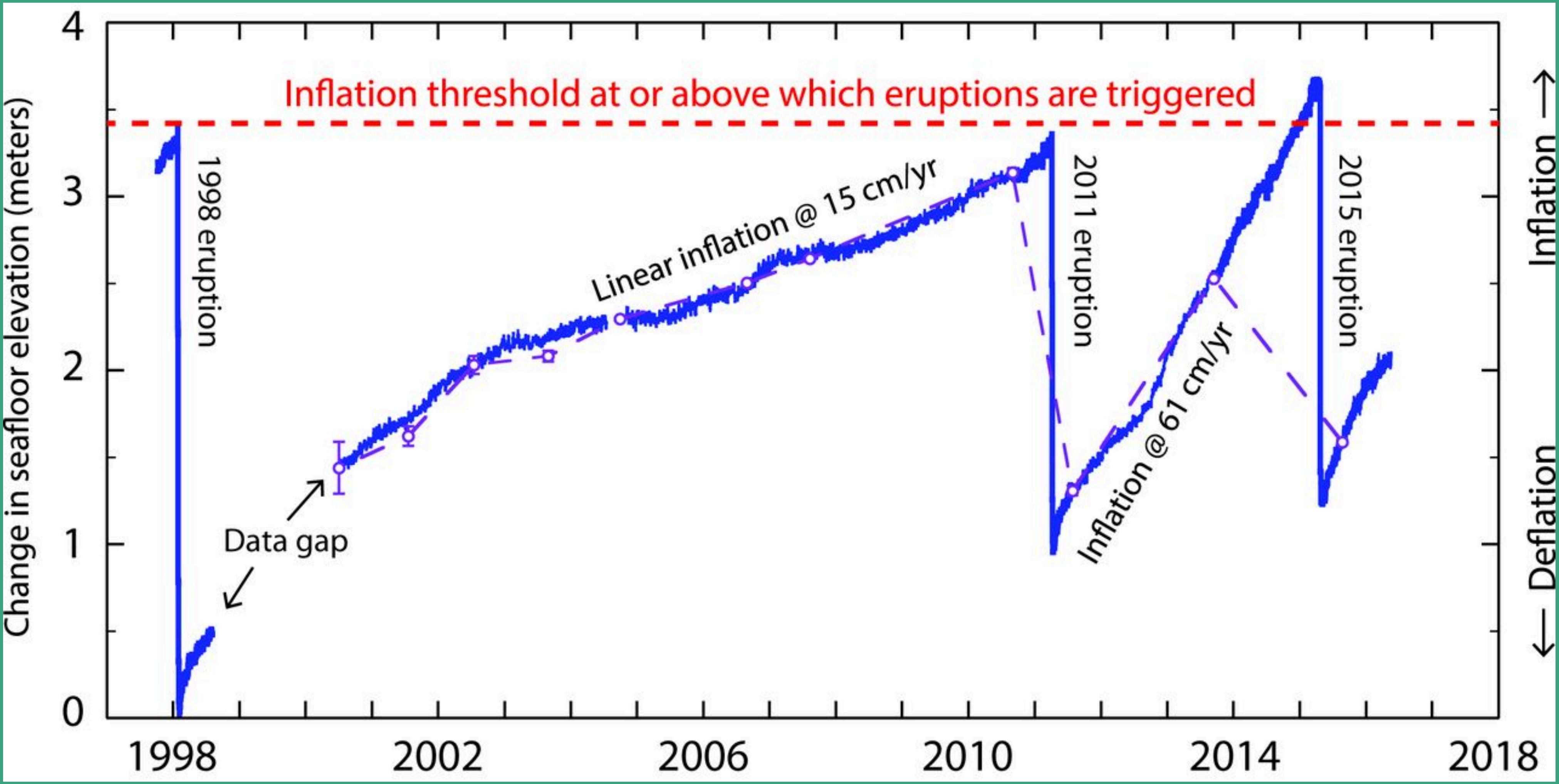


Smith and Cann, 1998

Example: Axial Seamount (Juan de Fuca Ridge)

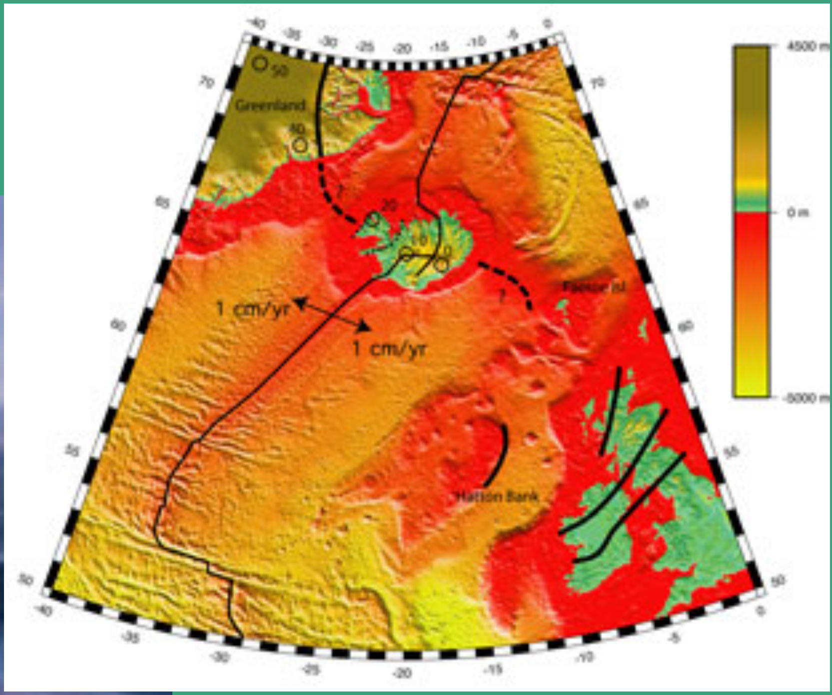


Example: Axial Seamount (Juan de Fuca Ridge)



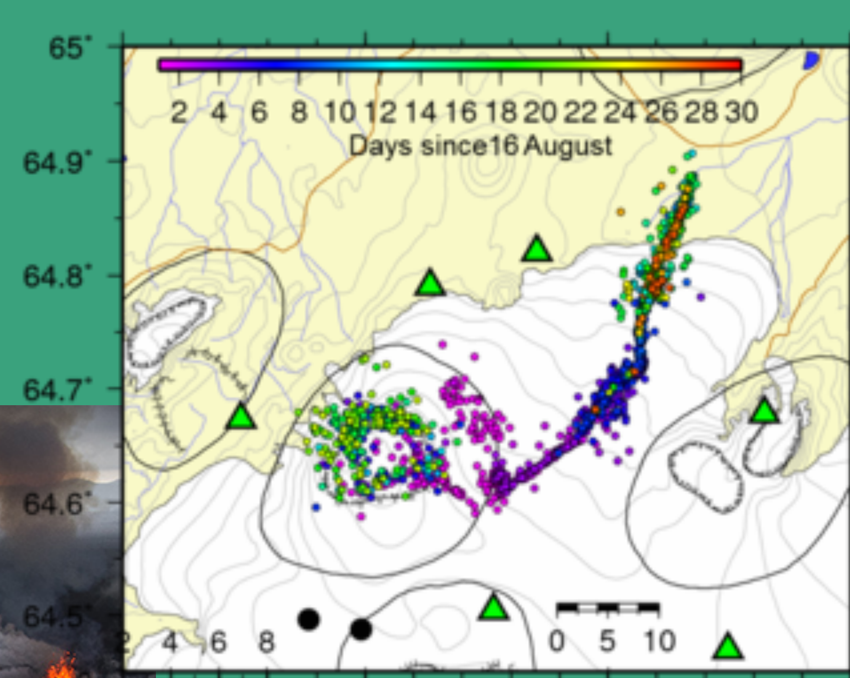
Nooner and Chadwick, 2016

Iceland: on-land spreading center

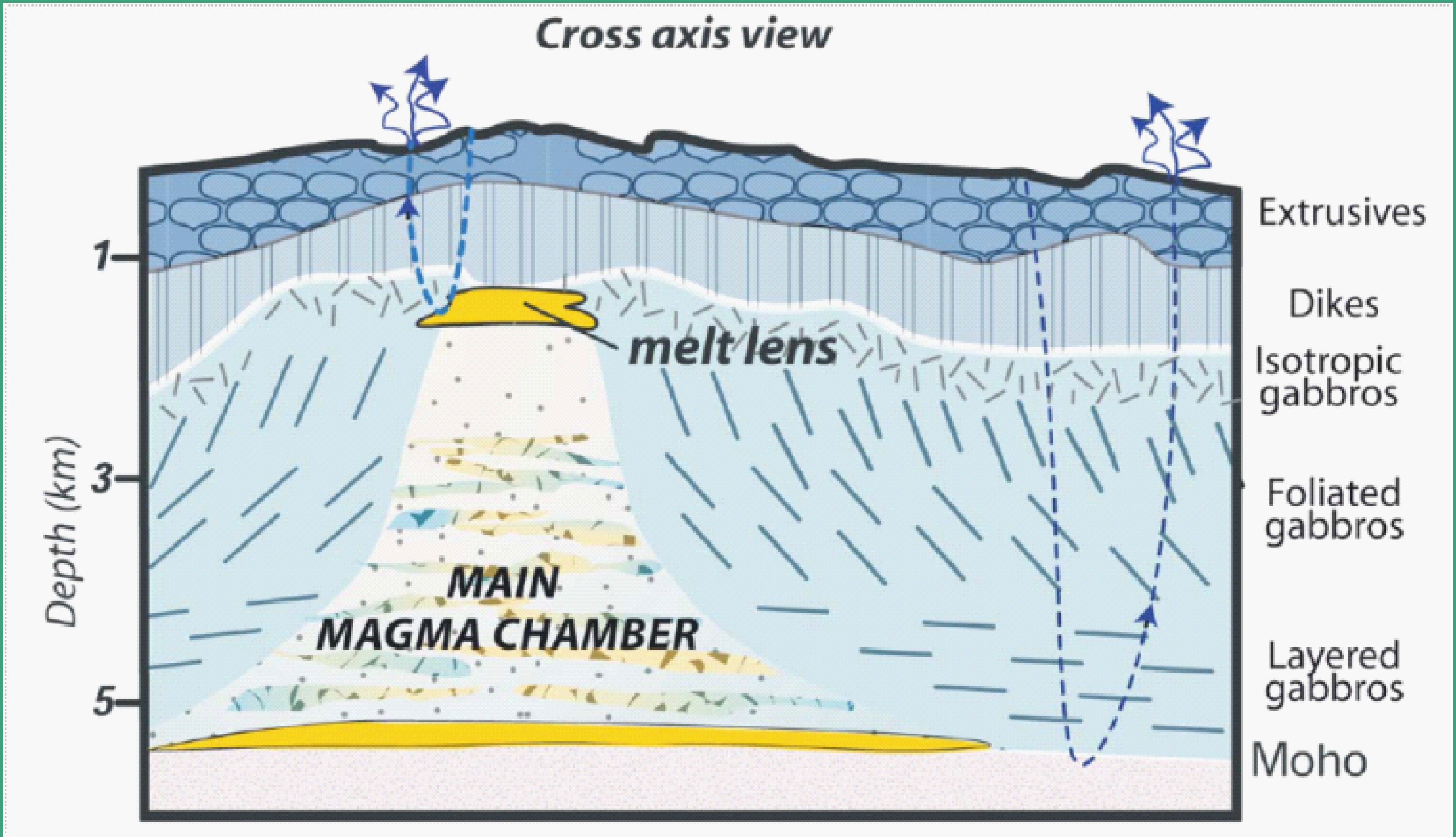


Magmatic rifting episode of 1977 (Krafla)

Iceland: on-land spreading center

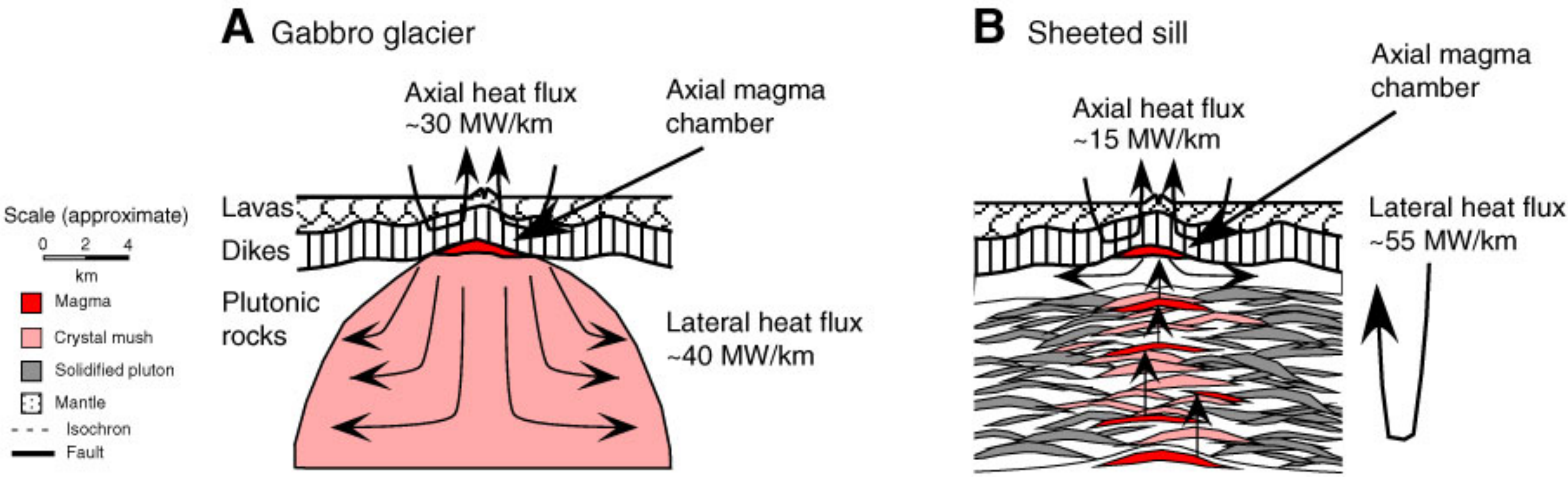


Magmatic rifting episode of 2014 (Bardarbunga)



In contrast, magma supply to the ridge axis is nearly continuous along-strike at high spreading rates

Models of the lower crust at fast-spreading ridges



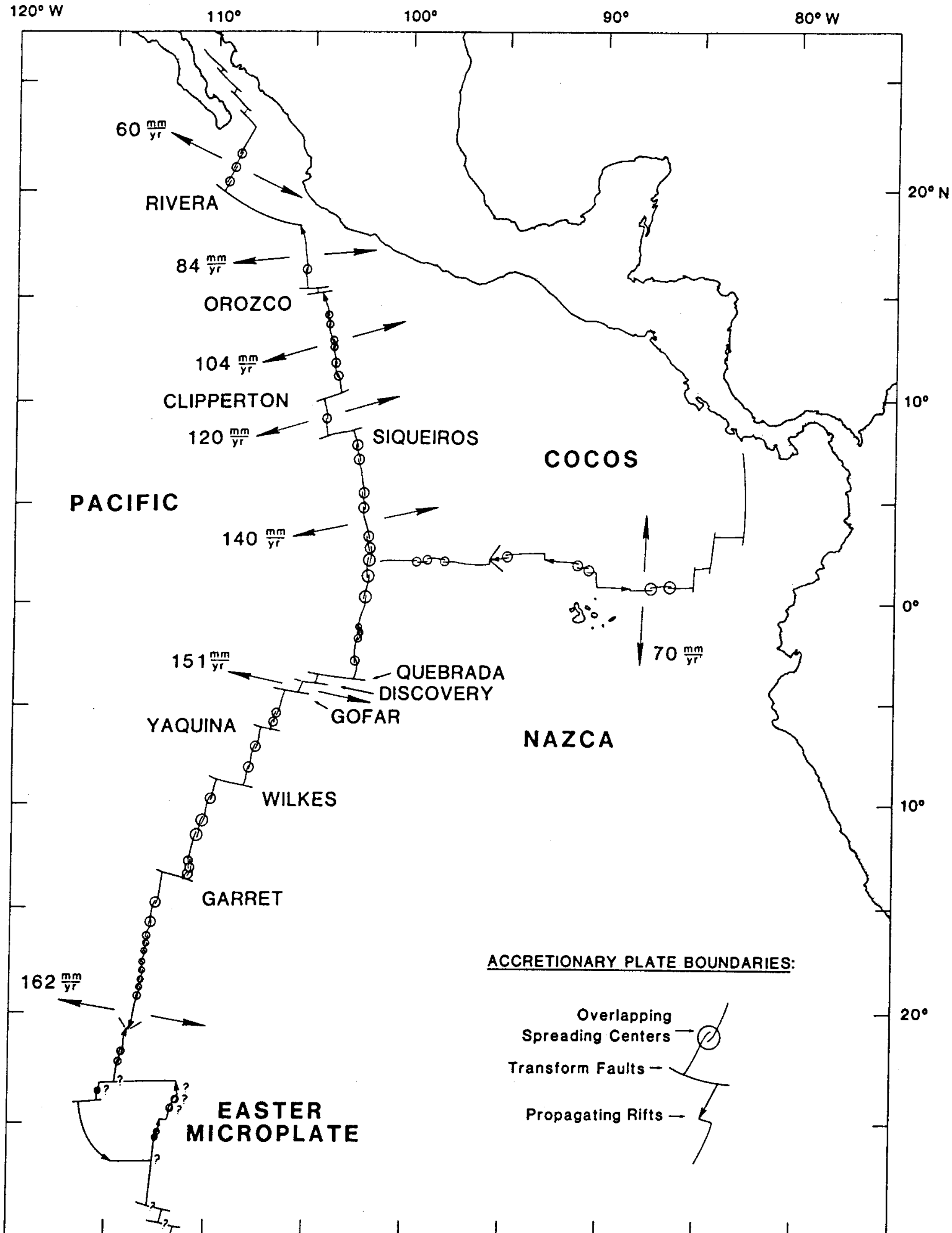
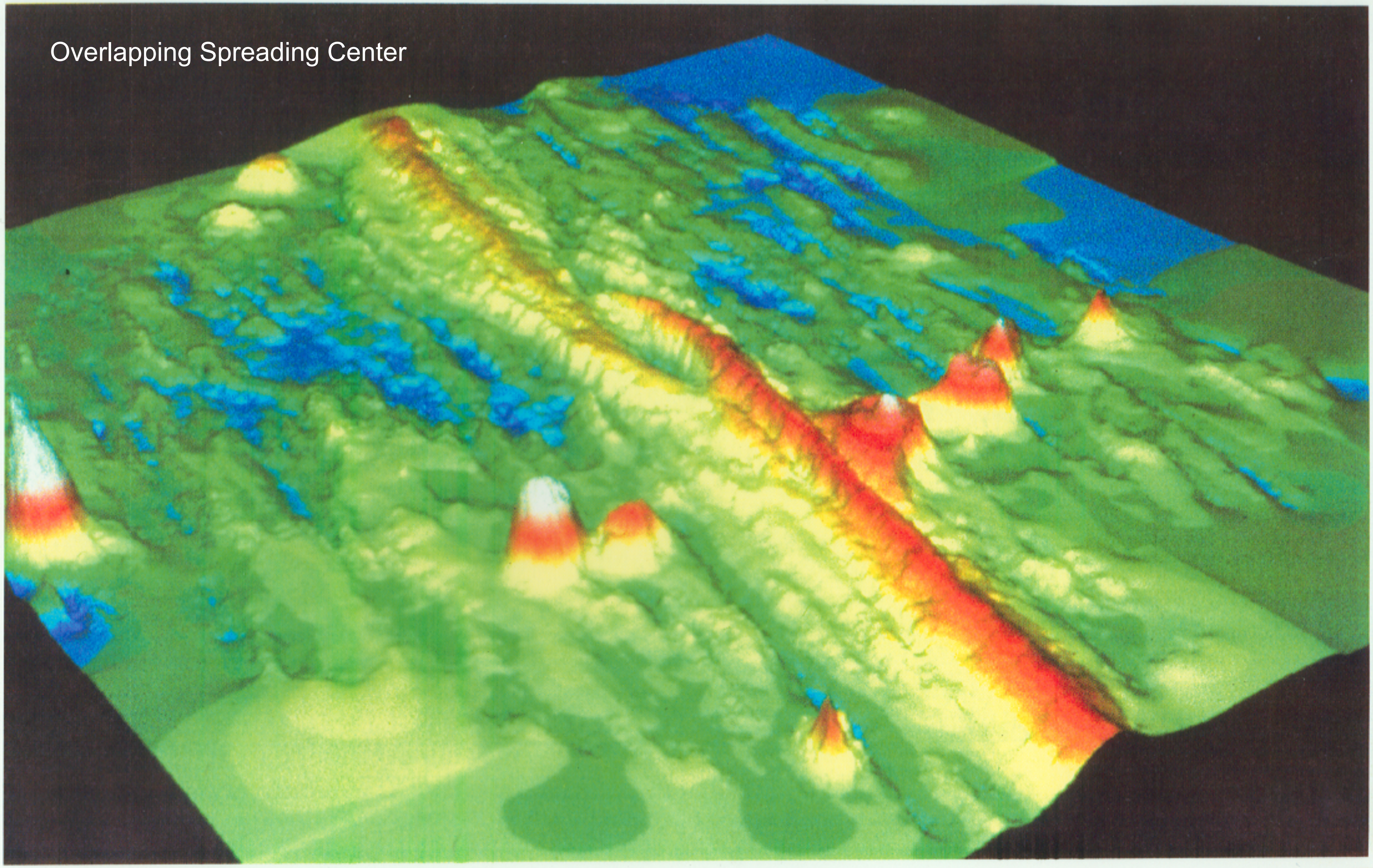


Figure 1. Tectonic chart of the EPR showing spreading centers, transform faults, propagating rifts, and overlapping spreading centers based primarily on Sea Beam coverage. Very small ridge-axis discontinuities (0- to 1-km offsets) are not illustrated. Full spreading rates are as shown.

Ridge axis is not perfectly continuous…



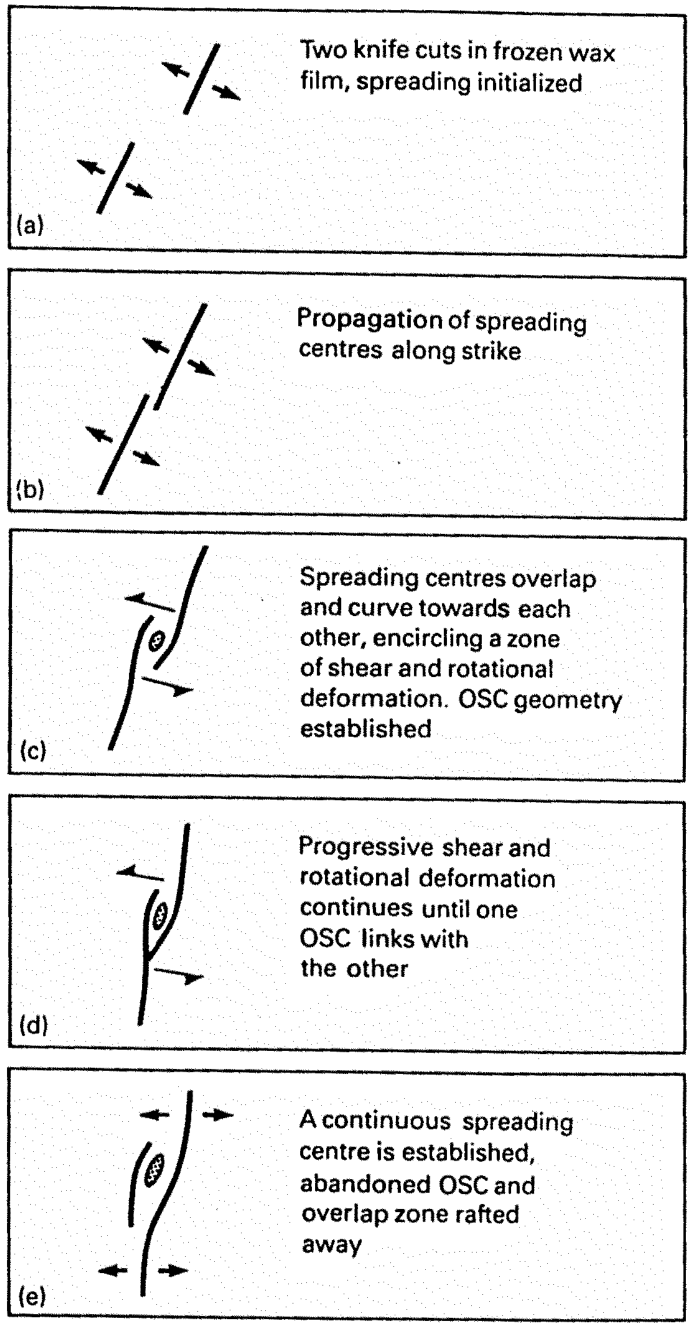
Separate ridge segments with different topo heights

Development of overlapping Spreading Centers

OSCs are ephemeral features.

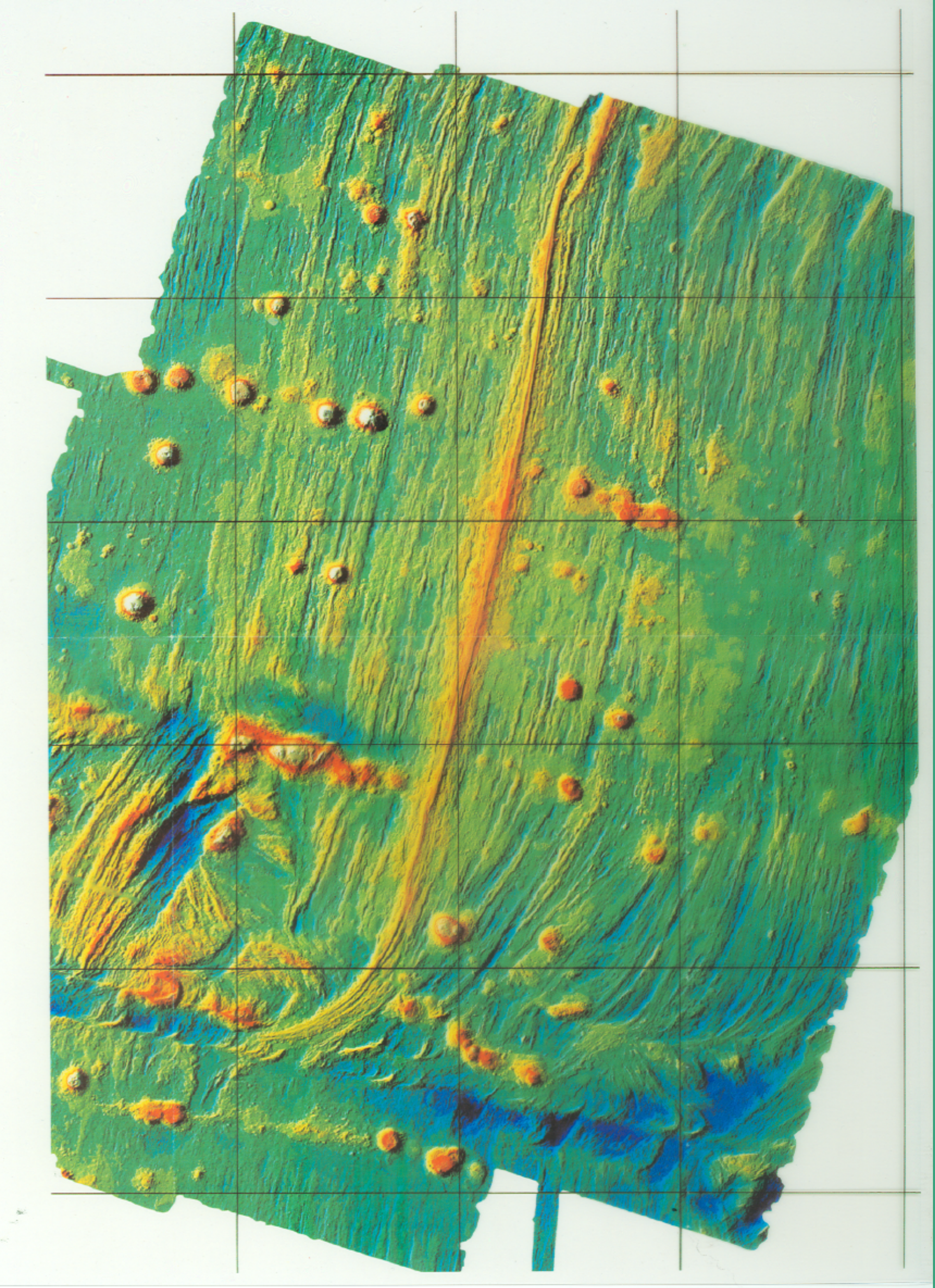
They migrate up and down ridge, die and re-form.

Reflect segmentation of ridge at a scale smaller than FZs



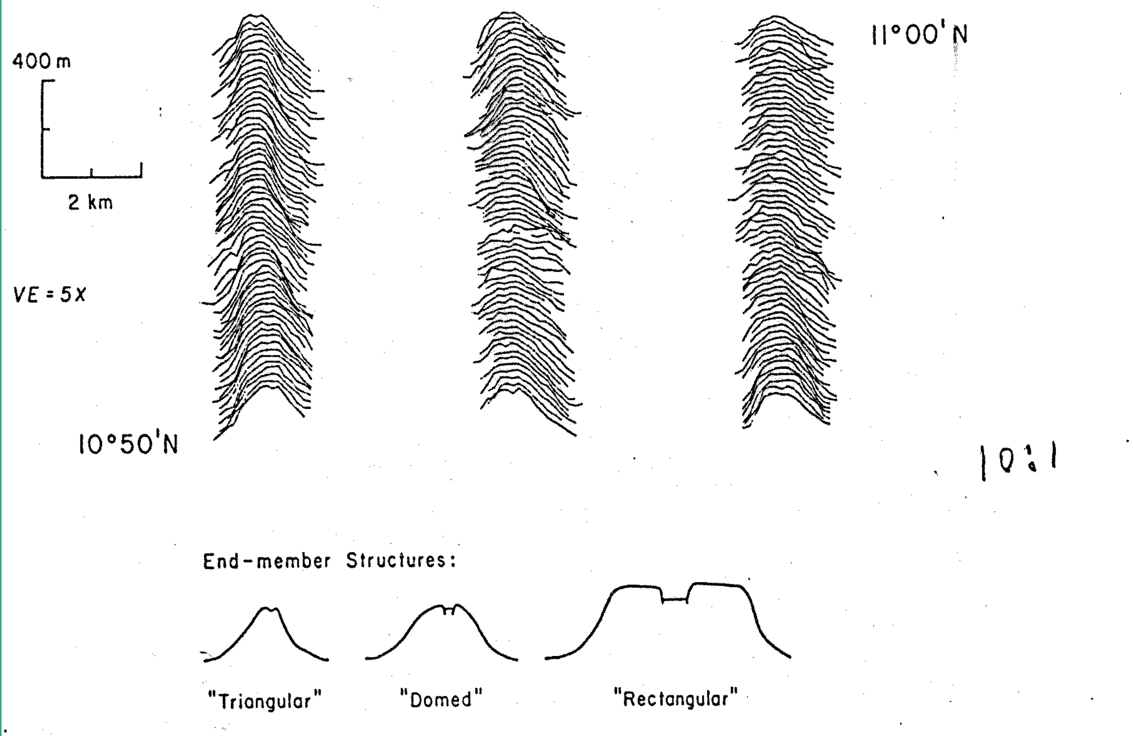
East Pacific Rise
7°S

What do you see?



Cross sectional shape of the axial high

Macdonald et al.: East Pacific Rise From Siqueiros to Orozco Fracture Zones

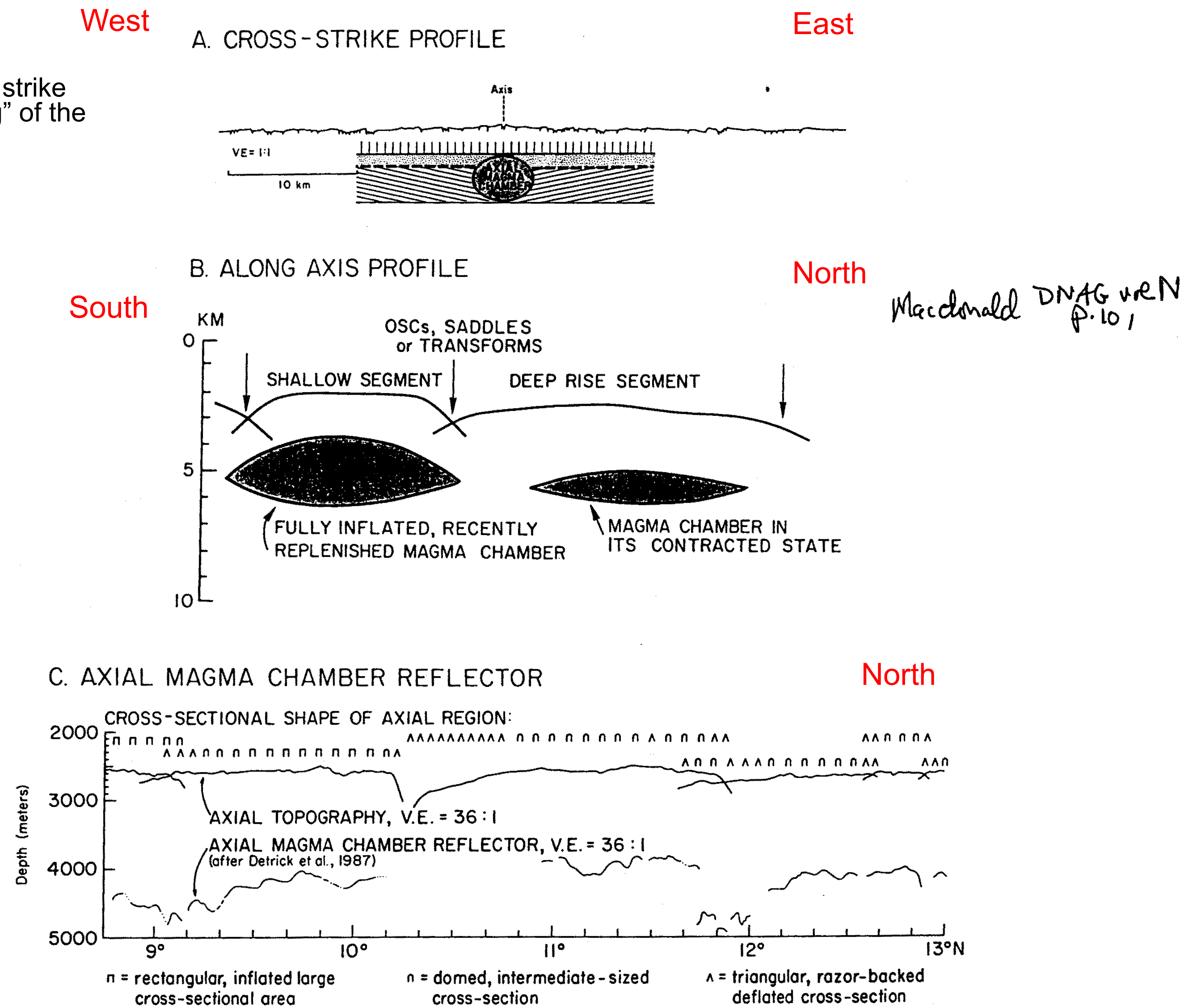


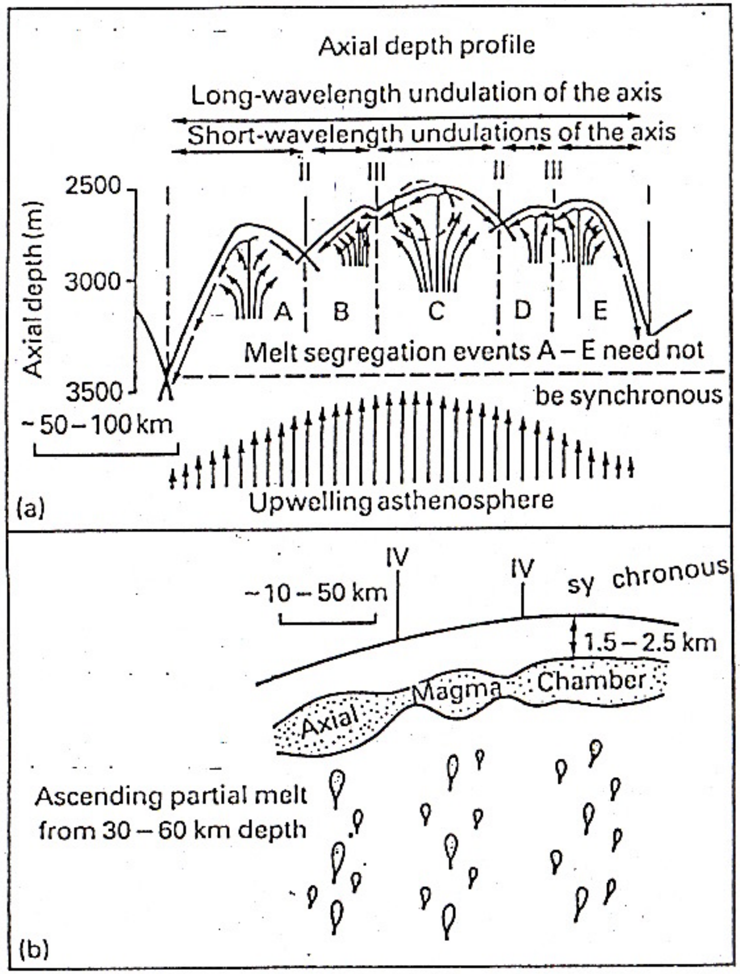
This variation in cross-sectional shape of the axial high is a sensitive indicator of the local magma supply

The narrower cross-sections (e.g. triangular) indicates a reduction in magma and are found near discontinutities.

The broader cross-sections (e.g. rectangular) indicates a greater magma supply and are found near the center of segments.

Variations along strike reflect “plumbing” of the magma system





Ridge Segmentation

1) Spreading leads to asthenospheric upwelling

2) Decompression melting leads to melt segregation (A-E)

3) Upwelling is enhanced beneath shallowest portion

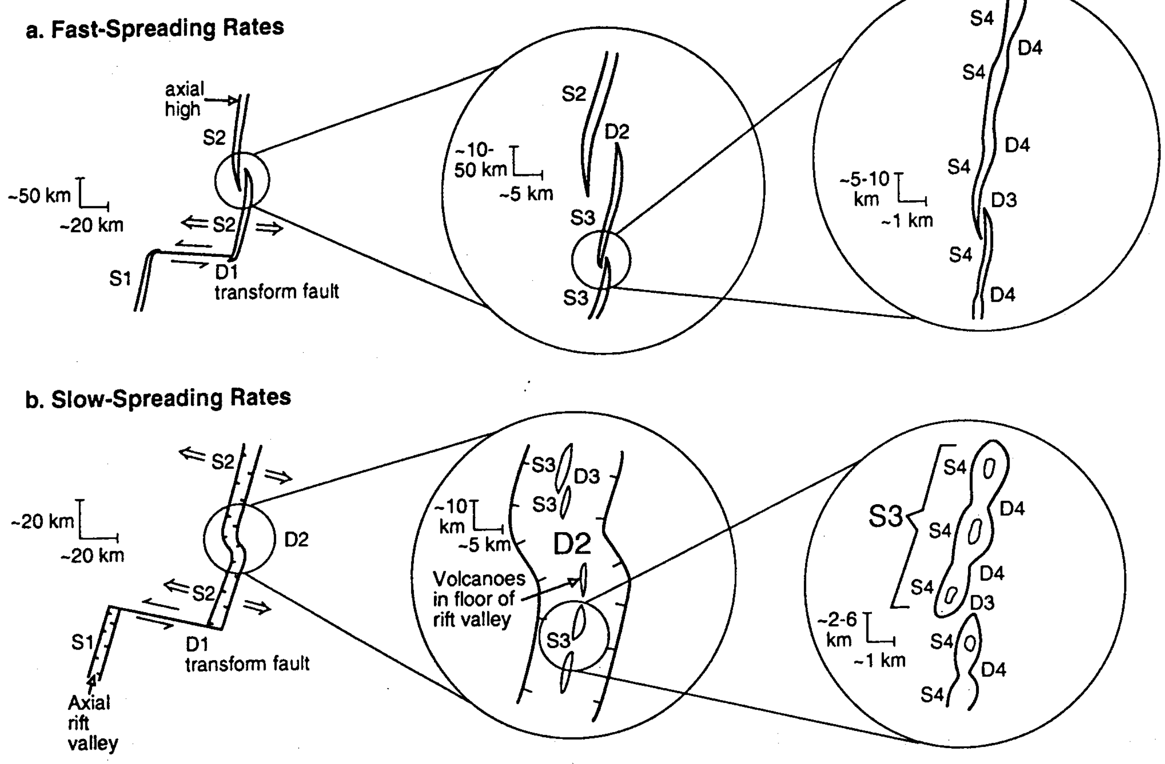
4) “Deviations” in axis reflect places where distal ends of flow meet

I = transform faults
II = overlapping spreading centers
III = small OSCs
IV = deviations in axial linearity

Note that (b) is a zoom on a small part of (a) (the circled region in segment c)

Ridge Segmentation

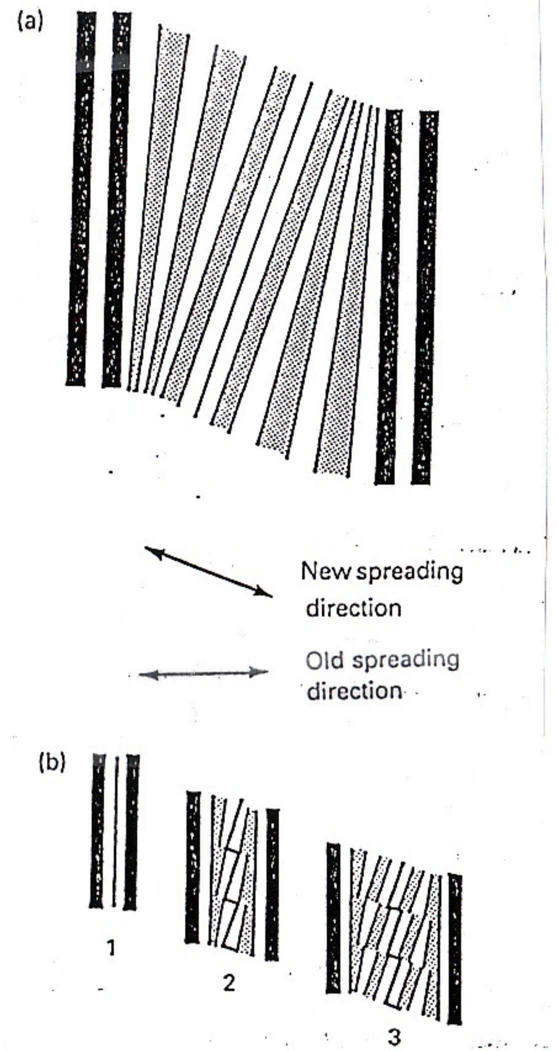
K. C. MACDONALD ET AL.



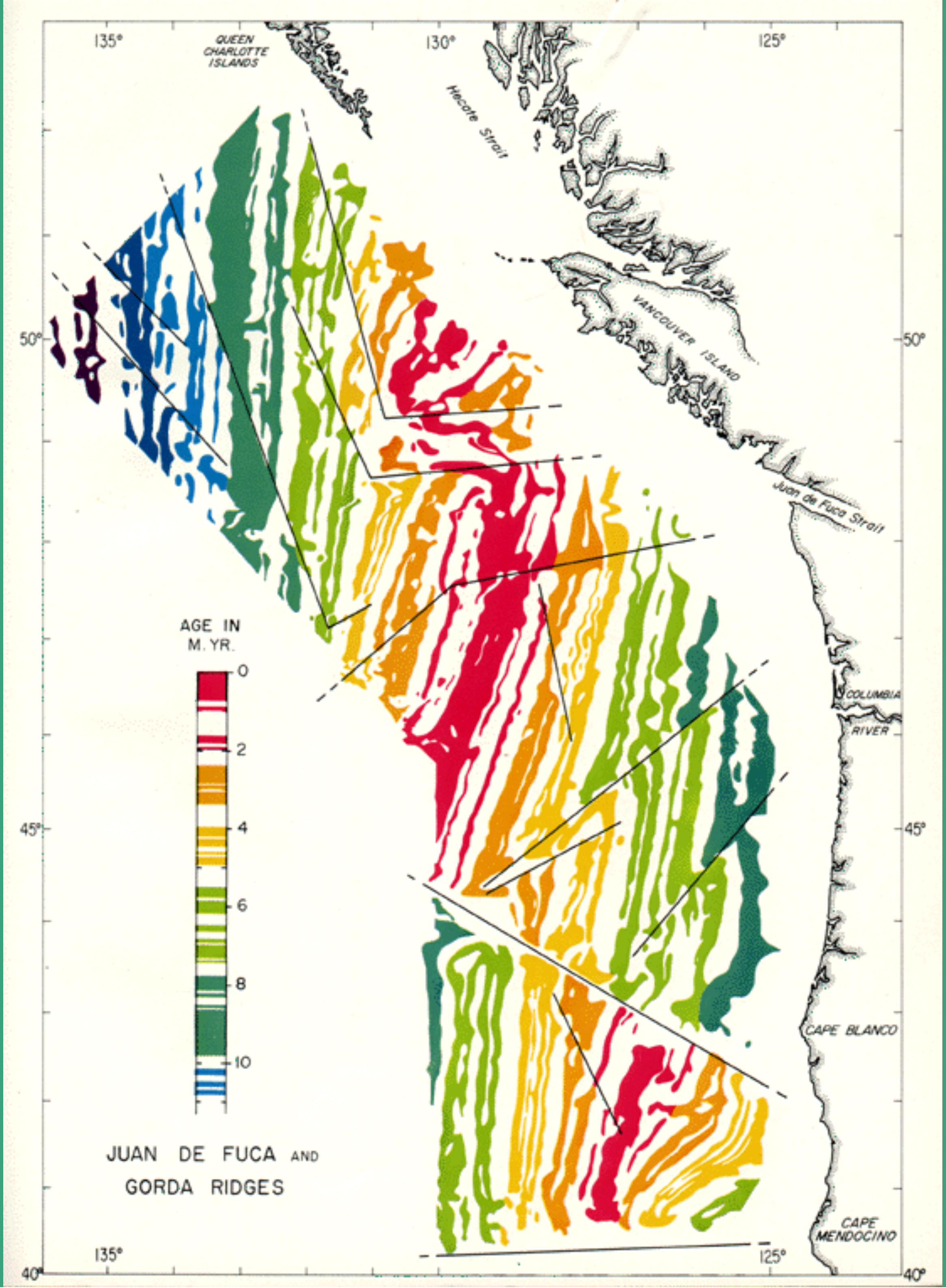
Order	Fast	Slow
1st	Transform Fault	Transform Fault
2nd	Over-lapping Spreading Center	Oblique Shear Zone
3rd	Small OSCs	Inter-volcano gaps
4th	Deviations from axial linearity (Devals)	Intra-volcano gaps
0th	Micro plate	

How do ridges adjust to changes in spreading direction?

(Hey at al., 1988)



Original idea (Menard and Atwater, 1968): Smooth, continuous rotations of individual ridge segments. Axis gradually rotates as ridge segments spread asymmetrically, with different rates at opposite ends. Expect fan-like patterns of anomalies



Analysis of the magnetic anomaly pattern on the Juan de Fuca ridge led Hey (1977) to propose that ridge segments adjust by a process called ridge propagation in which spreading centers with the new spreading direction gradually replaced spreading centers with the old direction.

They key to this idea was the recognition that offsets of the anomalies that were originally attributed to strike slip faults actually marked the boundaries between lithosphere created at the old and new ridge segments. These boundaries are called pseudo-faults.

Propagating rifts:

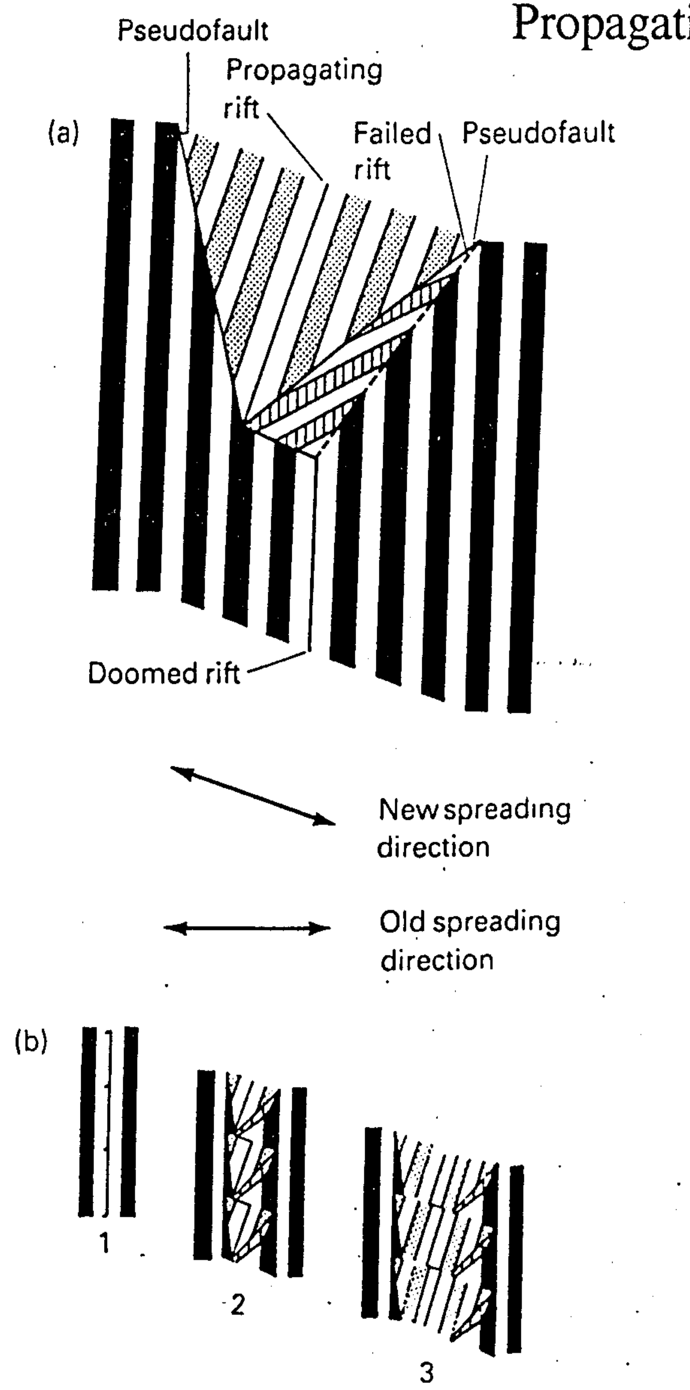


Fig. 6.17 (a) Ridge adjustment by rift propagation; (b) evolution of a stepped ridge following propagation (after Hey *et al.*, 1988, *Journal of Geophysical Research* 93, with permission from the American Geophysical Union).

A "doomed rift," orthogonal to the old spreading direction, is progressively replaced by a new "propagating rift" which is orthogonal to the new spreading direction. Boundaries between new and old lithosphere are called "pseudo-faults." The pseudo-faults form a V-shaped wake.

Between the "failed rift" and "pseudo-fault" on the right-hand plate is a zone of "transferred lithosphere" (hatchured) containing crust "transferred" from the plate on the left to the plate on the right at the tip of the propagator.

Unlike the original "rotation" model, the boundary between new and old material is abrupt.

Propagators probably originate at discontinuities on the ridge such as overlapping spreading centers.

Kearey and Vine (1990)

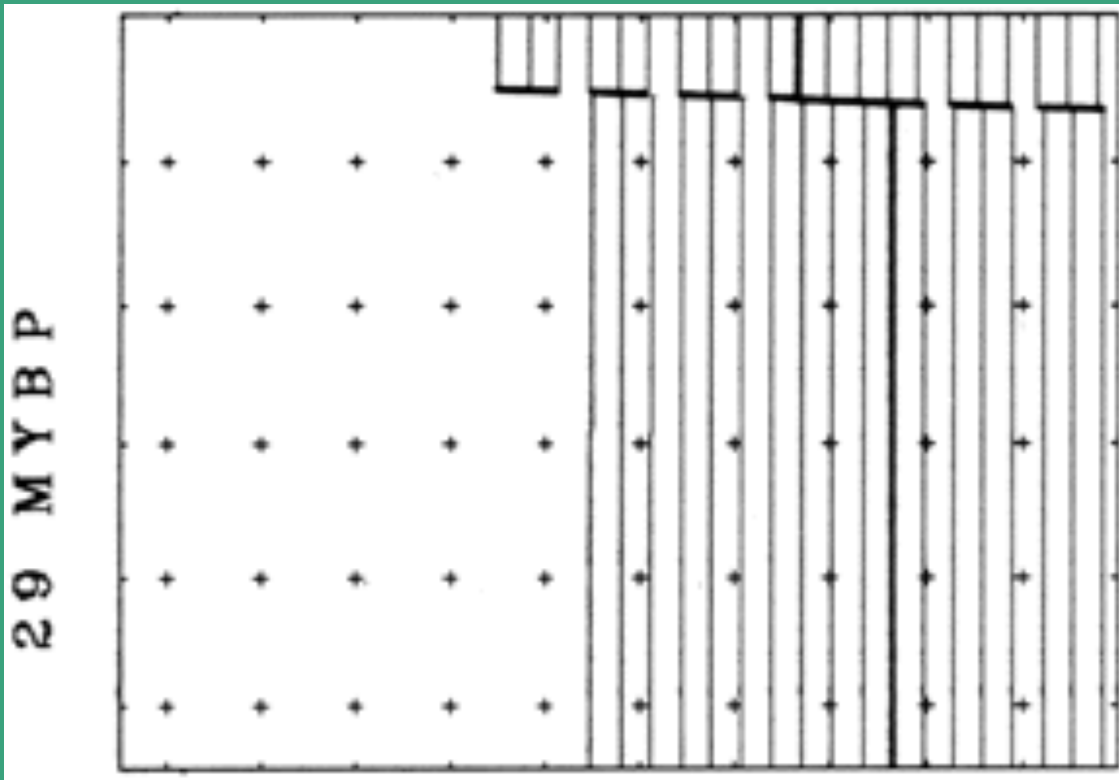
The left PF is also called the Outer pseudo-fault

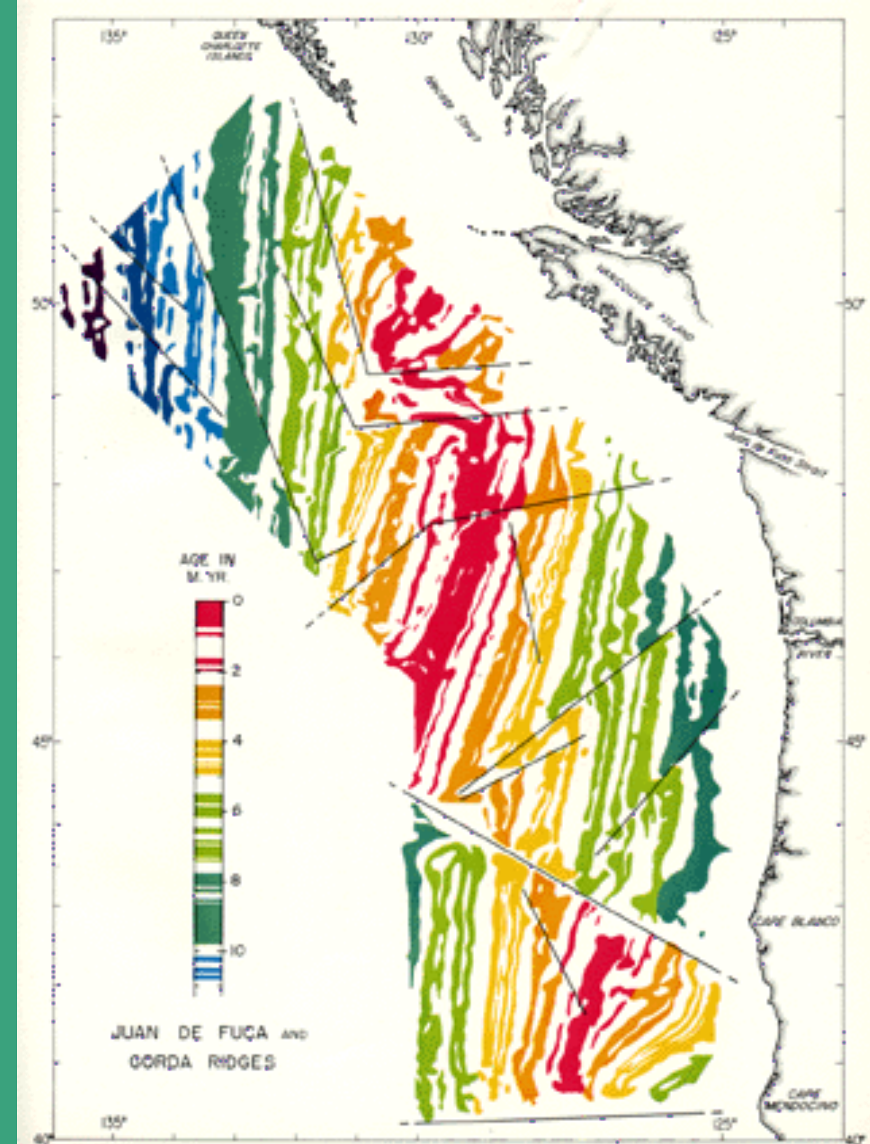
The right one is the Inner pseudo= fault.

Note: The way in which failed rift is labeled is misleading.

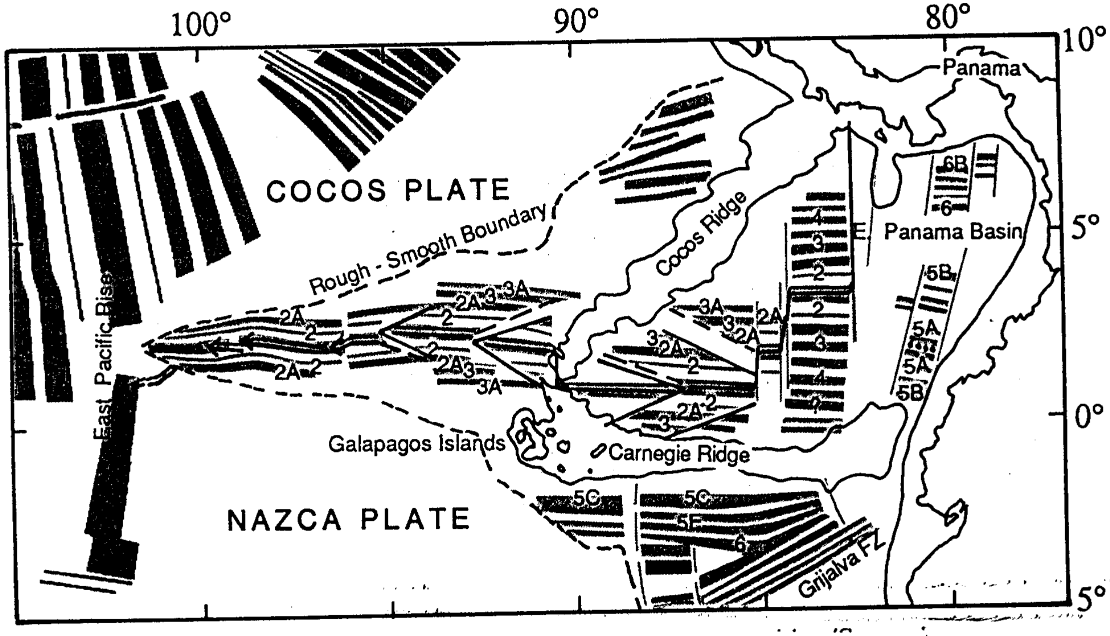
Look closely at the arrows

It is to the right of the pseudo-fault





Each frame is a reconstruction of a predicted isochron-pattern "snapshot" from a16 mm computer graphic movie depicting plate tectonic and propagating rift evolution in the Juan de Fuca area. The reconstructions are at 1-million year intervals beginning at 29 million years before present with isochrons at 2-million year intervals. These images are from Hey and Wilson (1982).



Atwater (1989)

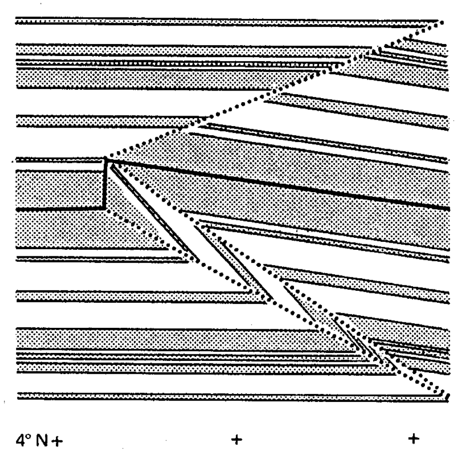
Galapagos ridge

Here the propagators move away from the hot spot (the Galapagos Islands)

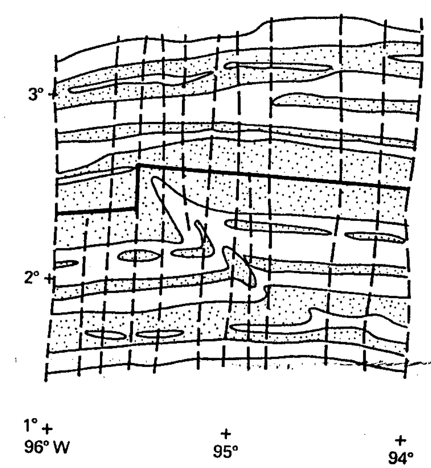
Propagators on the Galapagos ridge move away from the Galapagos Hotspot.

They might have been triggered by minor changes in plate motion or perhaps by changes in magma supply.

(a)



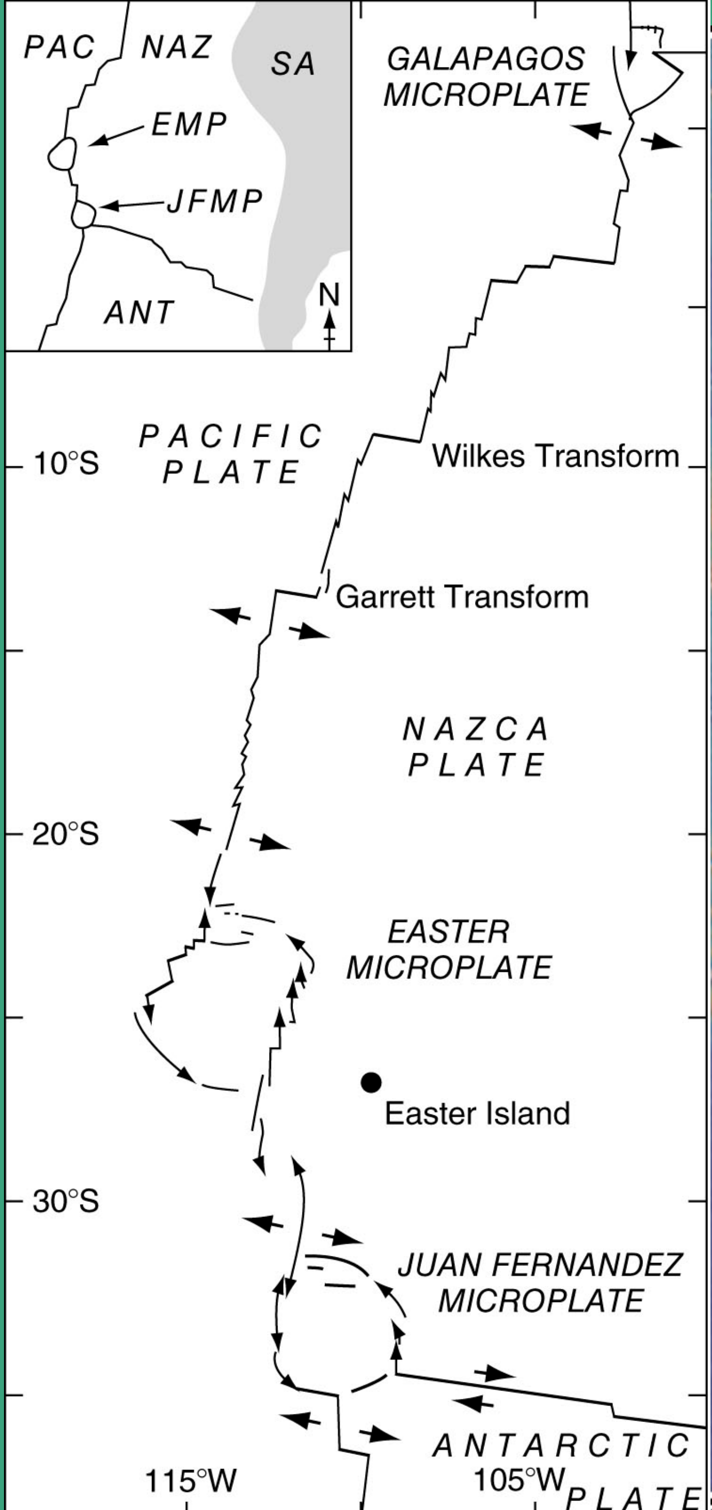
(b)

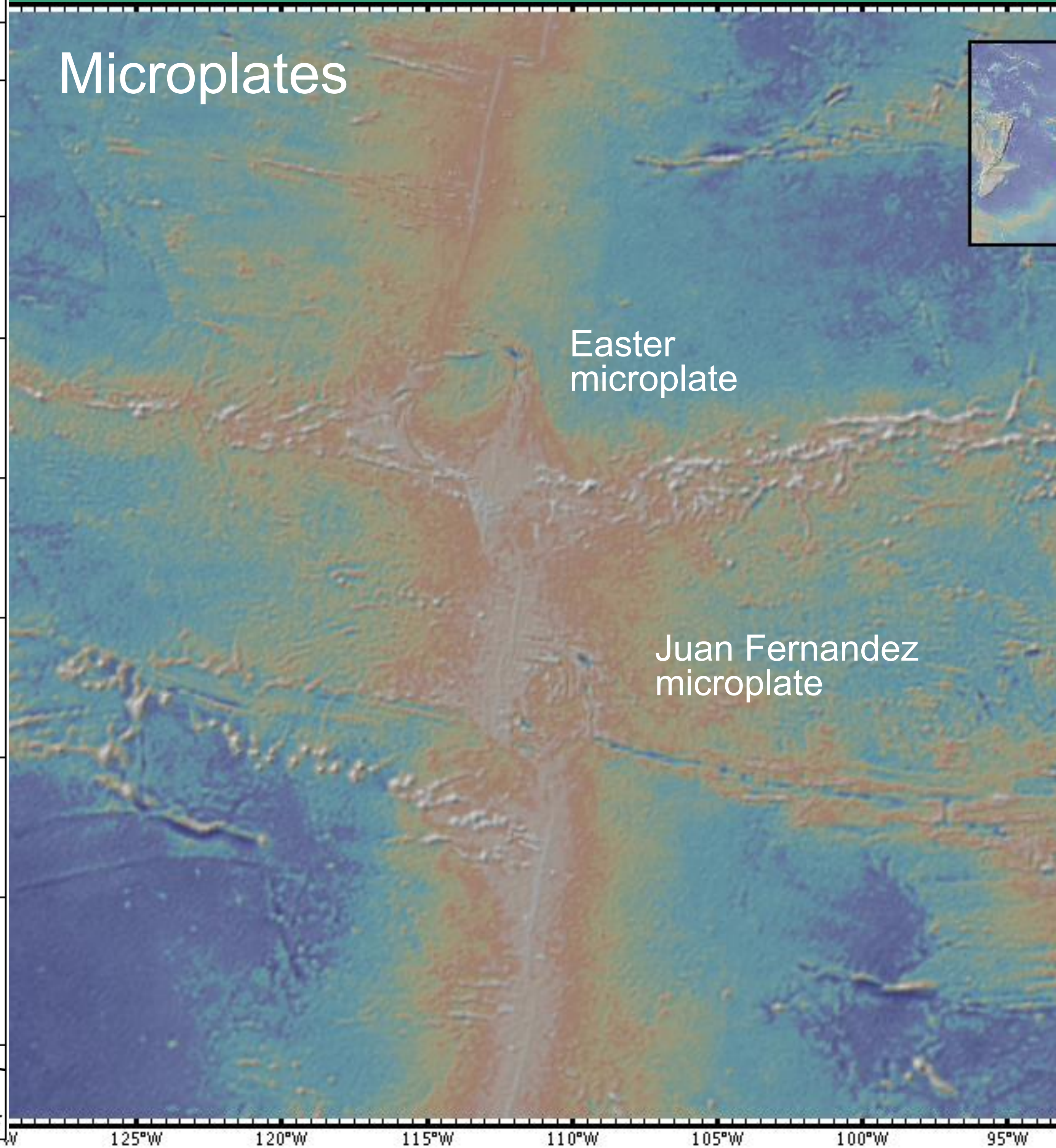


Hey at al. (1980) as shown in Kearey and Vine (1990)

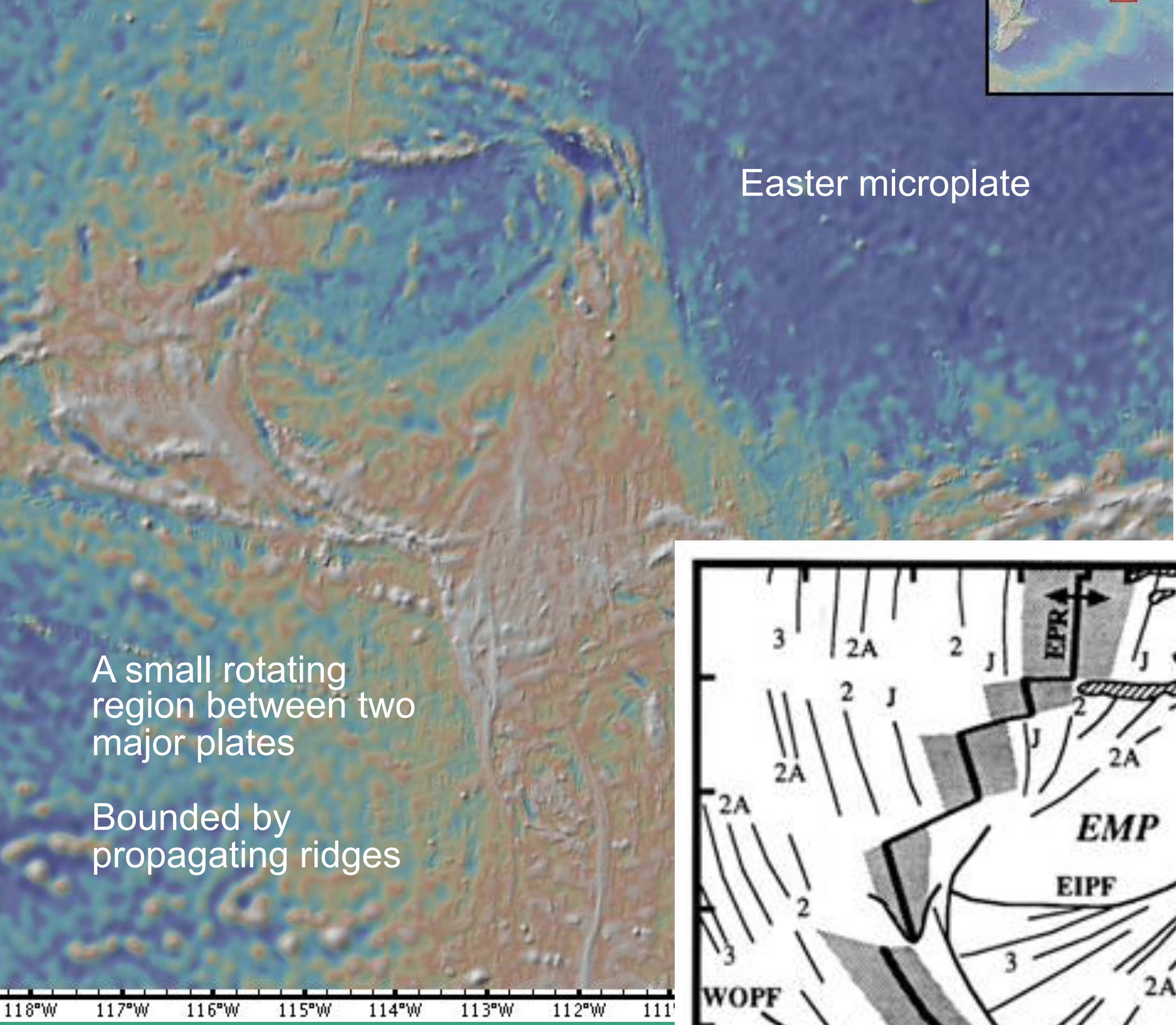
Fig. 6.17 (a) Predicted magnetic lineation pattern resulting from ridge propagation; (b) observed magnetic anomalies near 96°W west of the Galapagos Islands (redrawn from Hey *et al.*, 1980, *Journal of Geophysical Research*, 85, with permission from the American Geophysical Union).

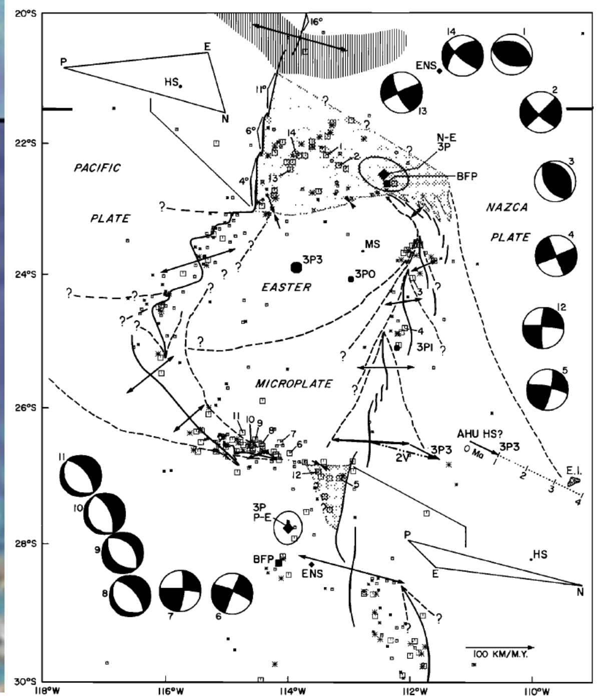
Microplates





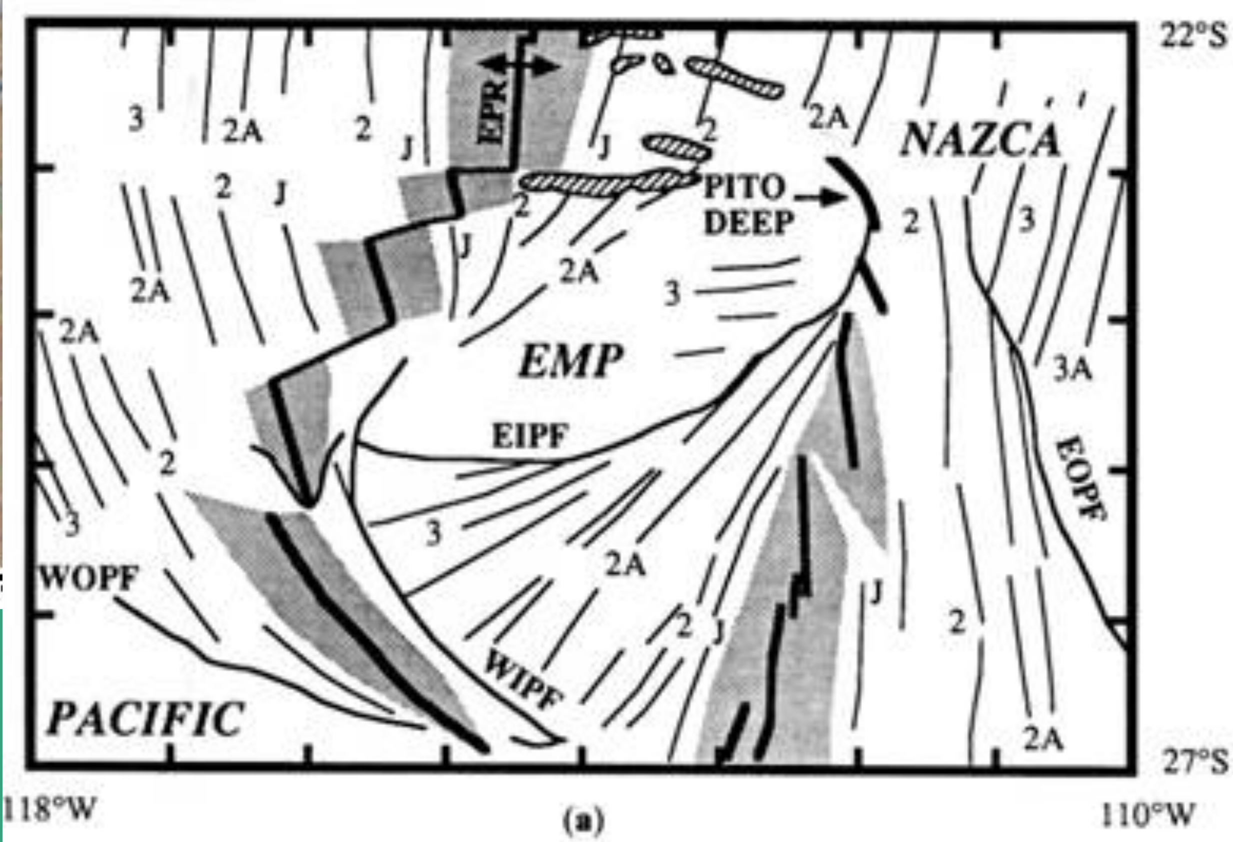
Easter microplate





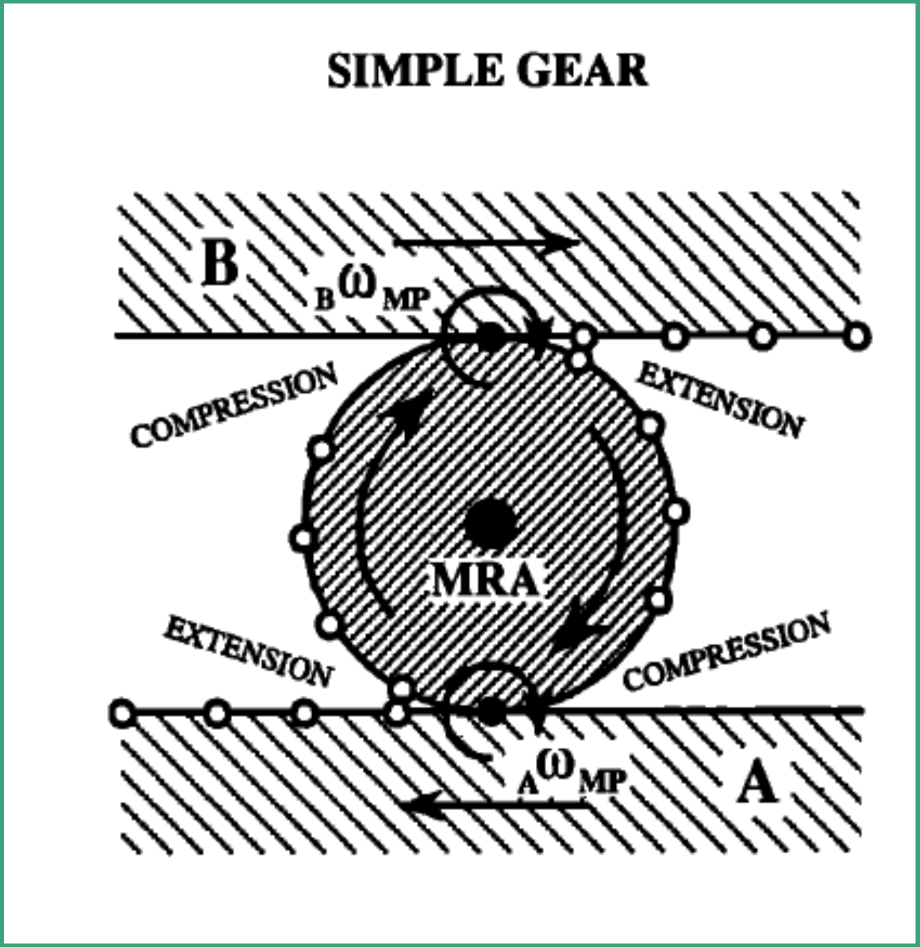
A small rotating region between two major plates

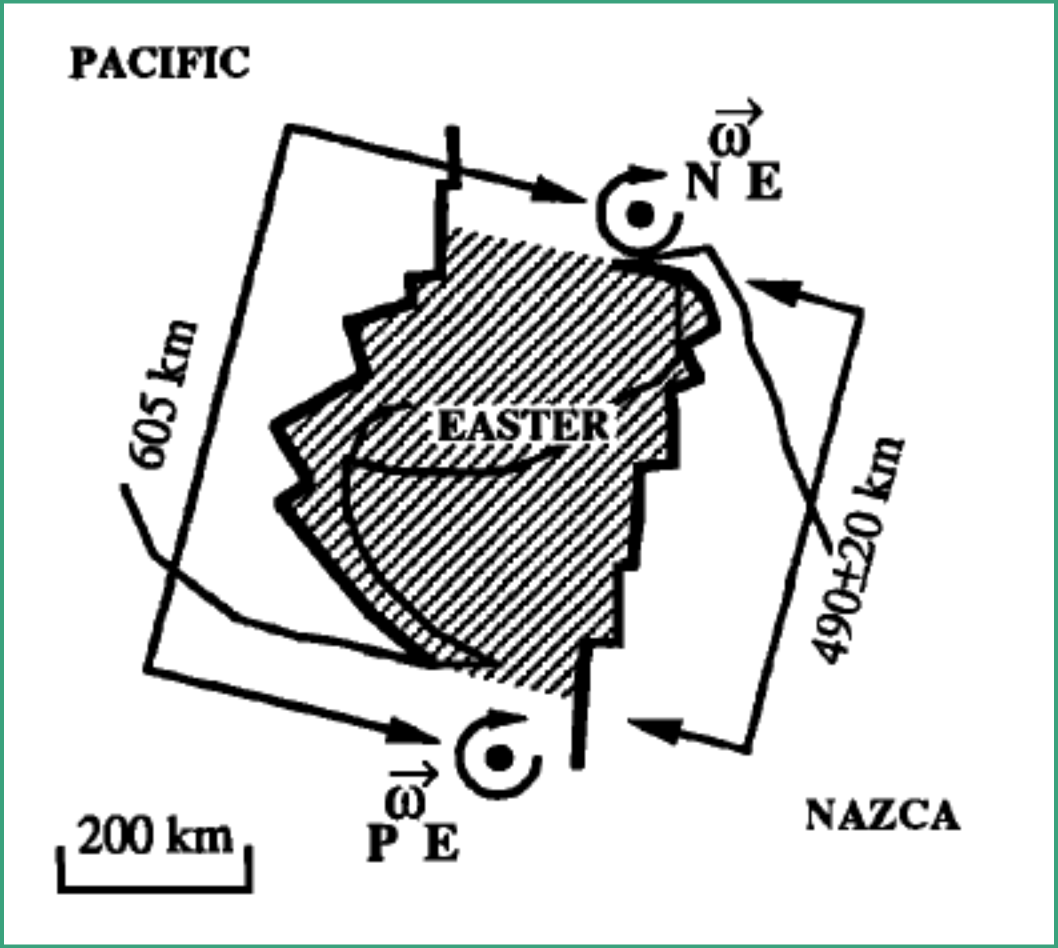
Bounded by propagating ridges



OPF = outer pseudo-fault
IPF = inner pseudo-fault
E/W = east/west

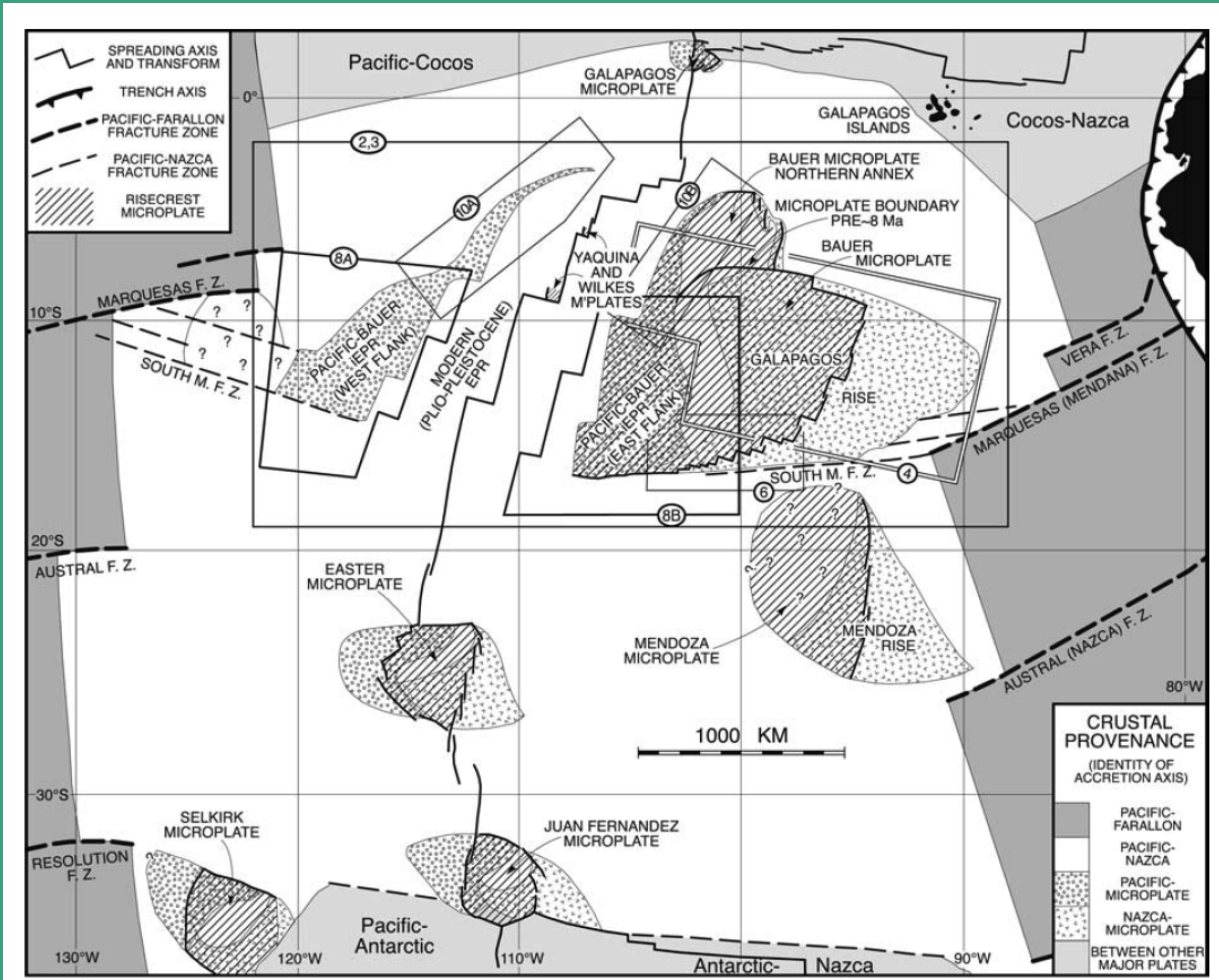
Edge driven microplate kinematics





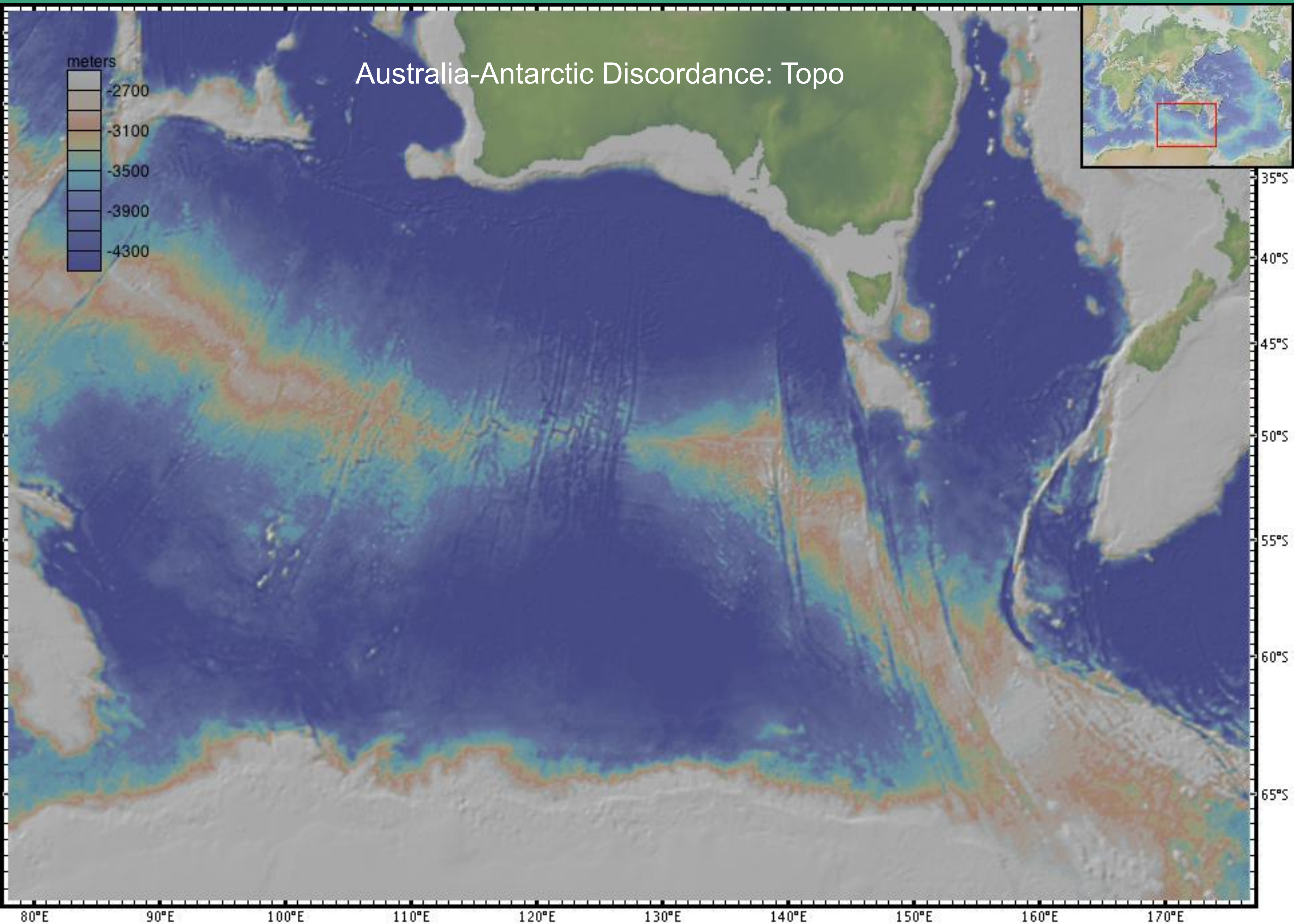
Schouten et al. (1993)

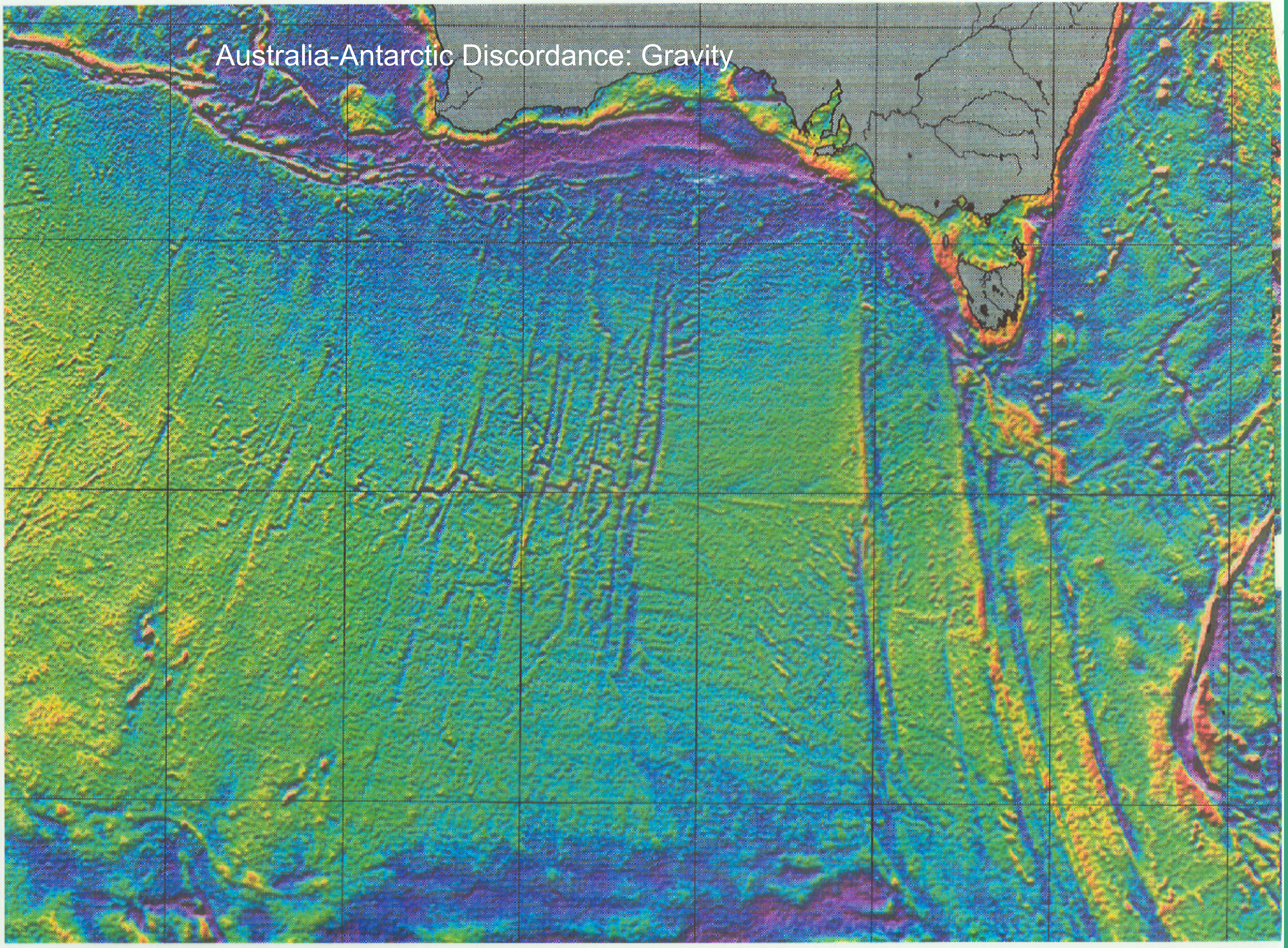
MRA = microplate rotation axis



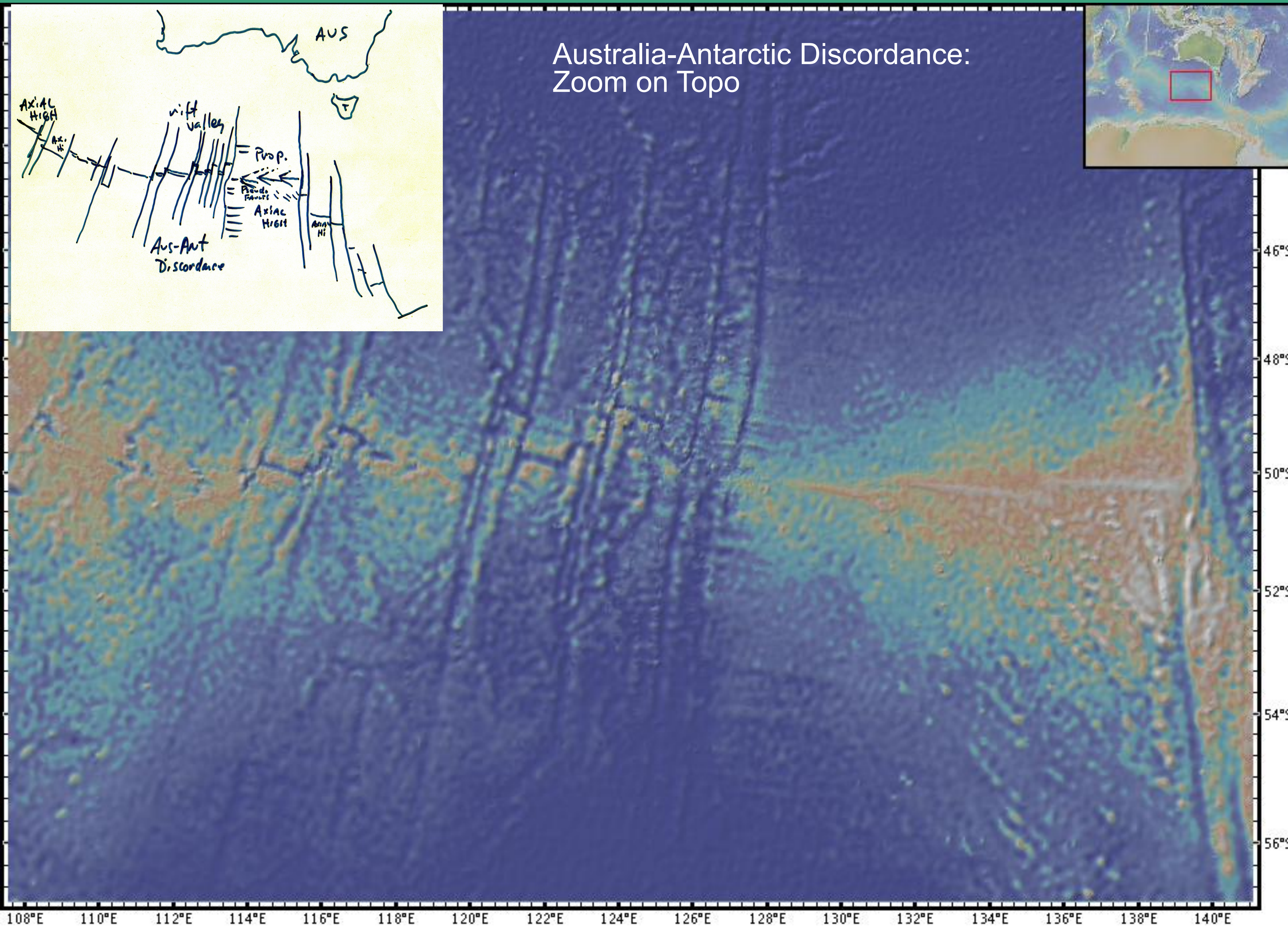
(Eakins and Lonsdale, 2003)

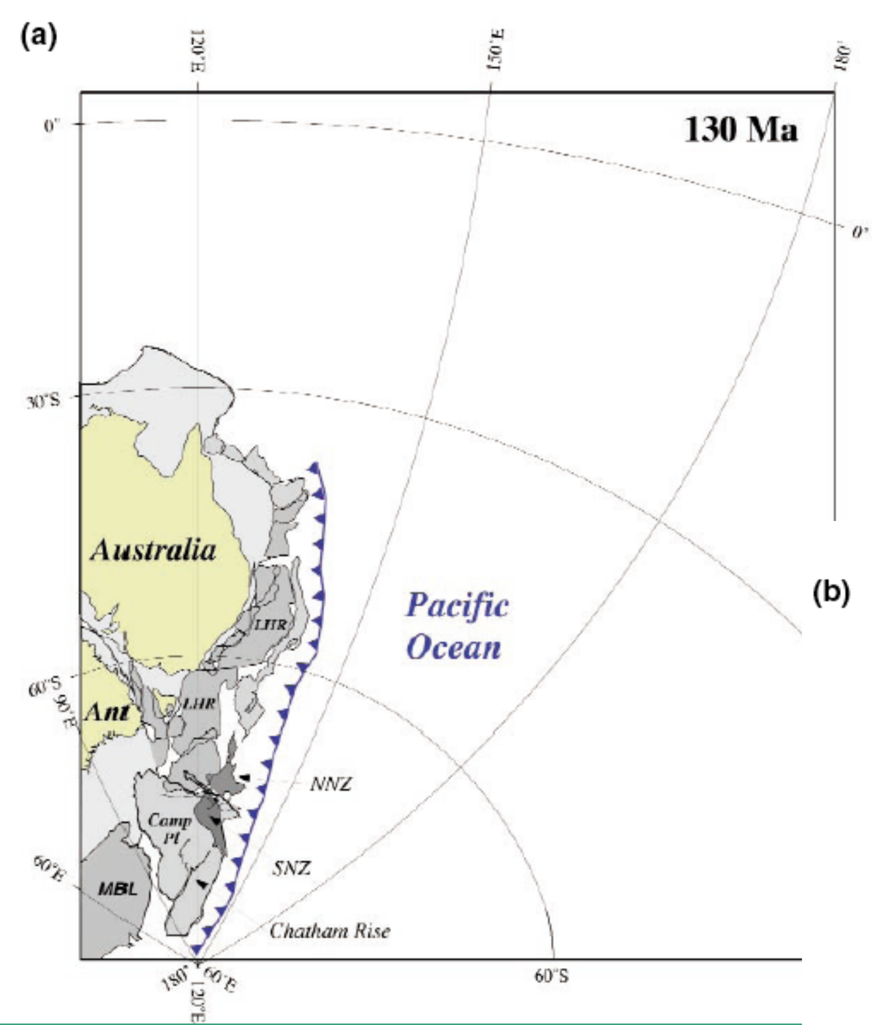
There are many fossil microplates found on the ridge flanks


Australia-Antarctic Discordance: Topo
meters
-2700
-3100
-3500
-3900
-4300
35°S
40°S
45°S
50°S
55°S
60°S
65°S
80°E
90°E
100°E
110°E
120°E
130°E
140°E
150°E
160°E
170°E


Australia-Antarctic Discordance: Gravity

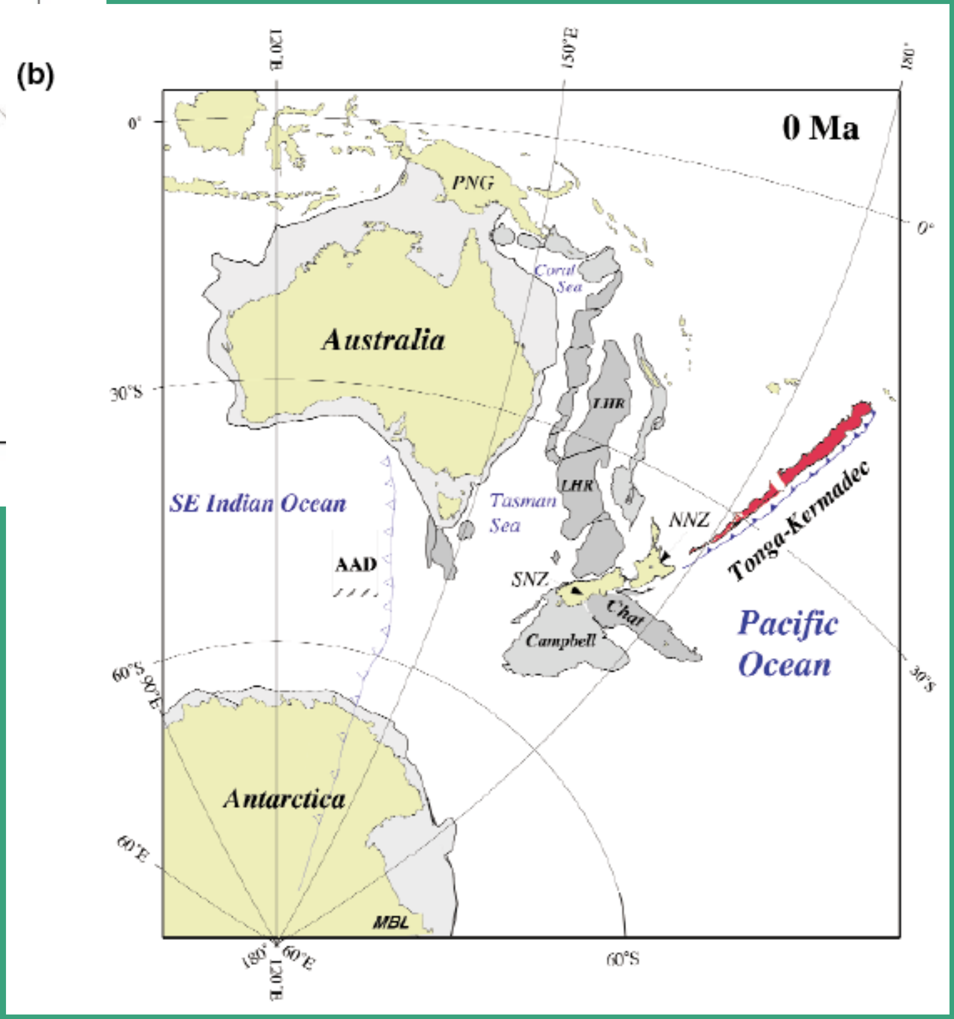
Australia-Antarctic Discordance:
Zoom on Topo





Explanation #1:

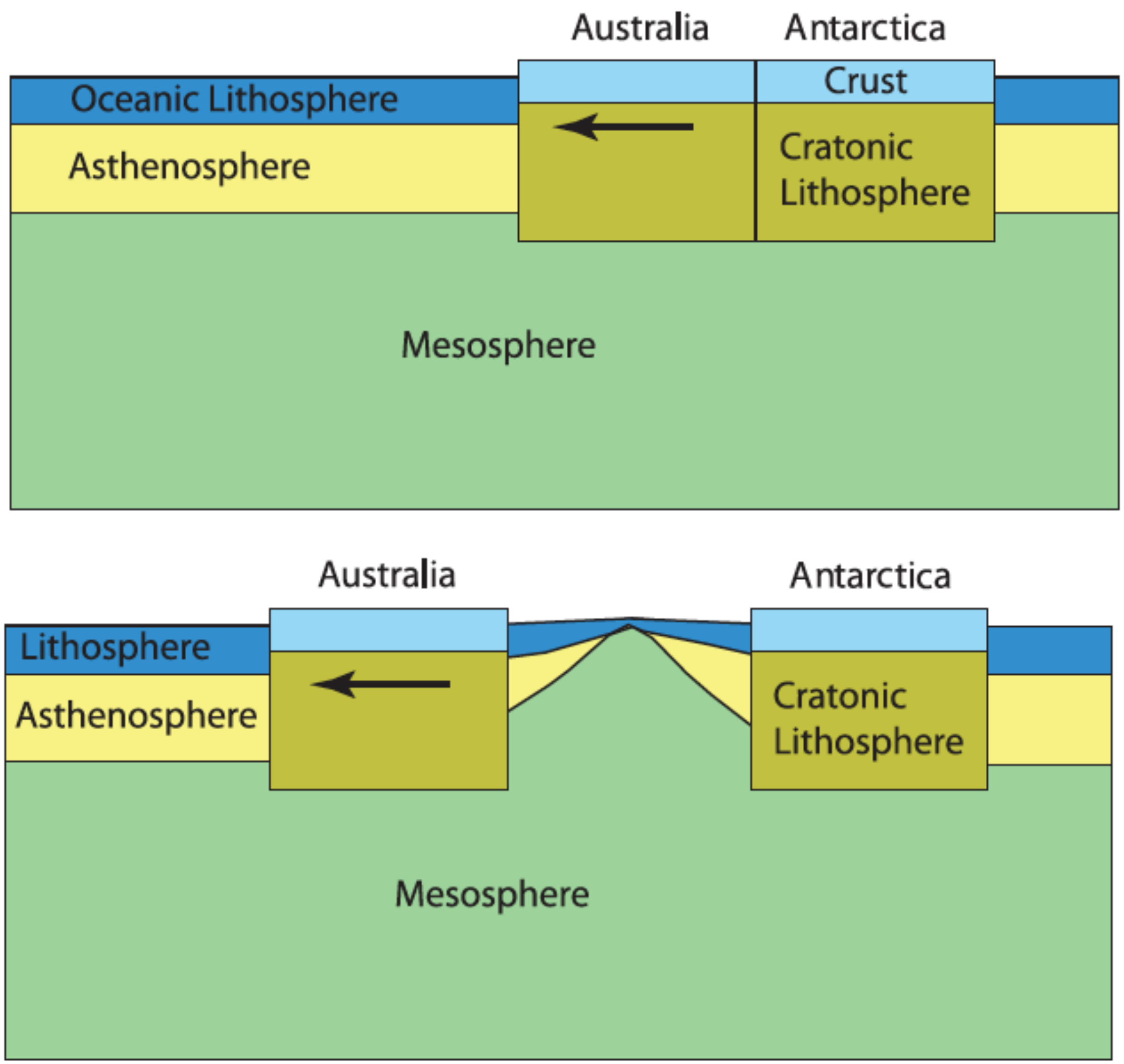
Remnants of a cold subducted slab from period of westward directed subduction 130 to 80 Ma cool the mantle beneath the AAD.

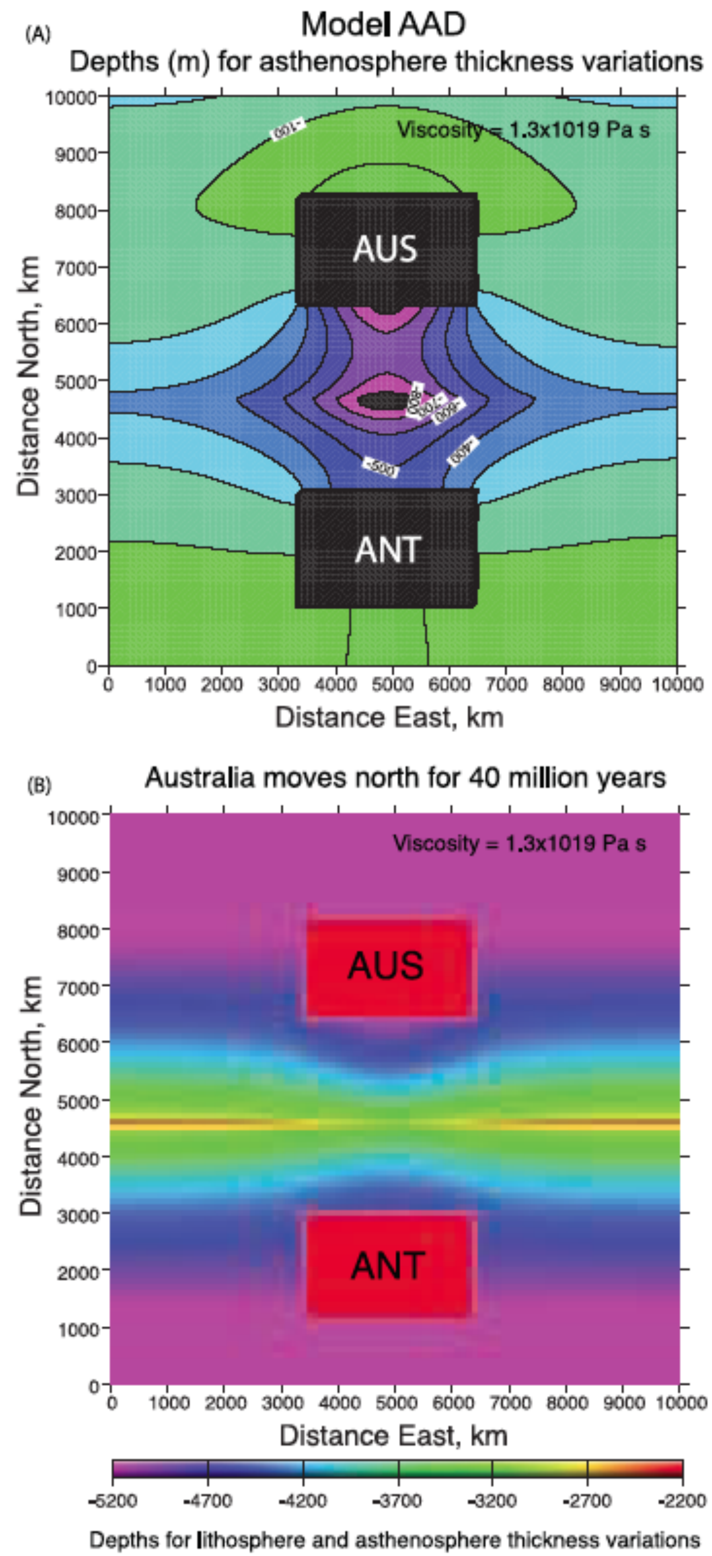


Gurnis and Müller (2003)

Explanation #2:

Asthenosphere is starved because of restriction of asthenospheric flow due to nearby thick continental roots and moderately fast spreading

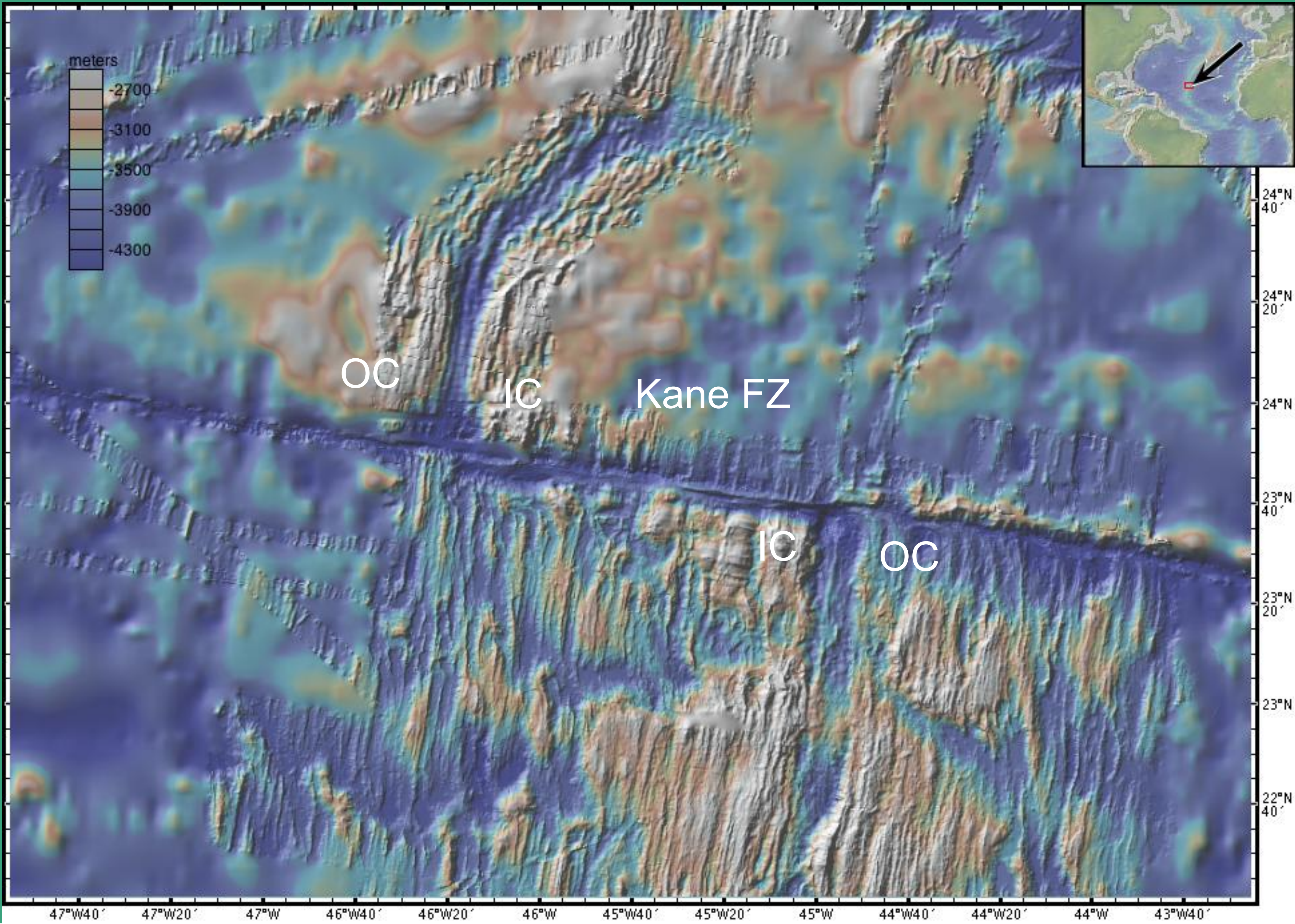




Buck et al. (2009)

A Tectonic Puzzle at Slow Spreading Centers: Inside Corner Highs

Kane FZ, Mid-Atlantic Ridge



Origin of Inside Corner highs

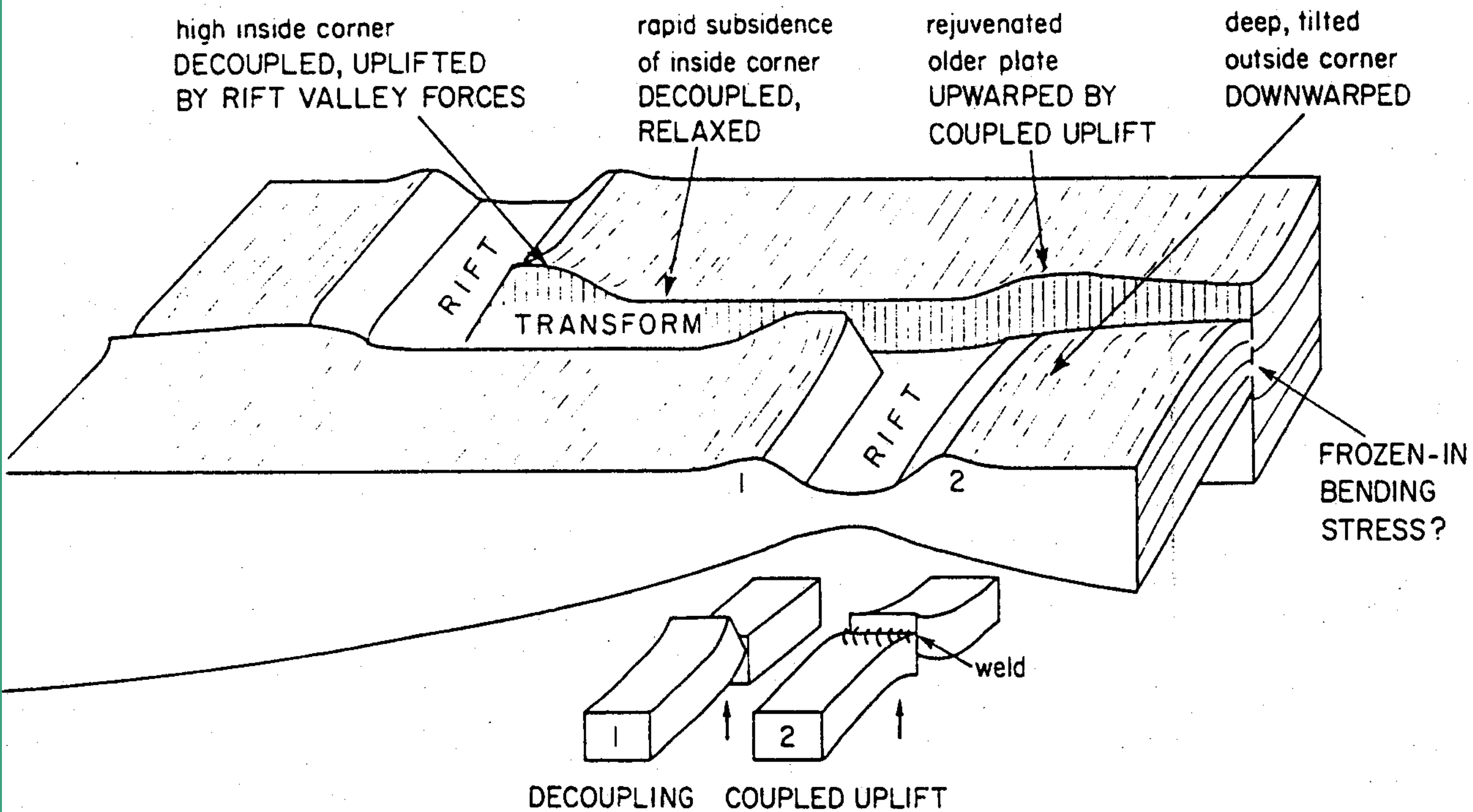
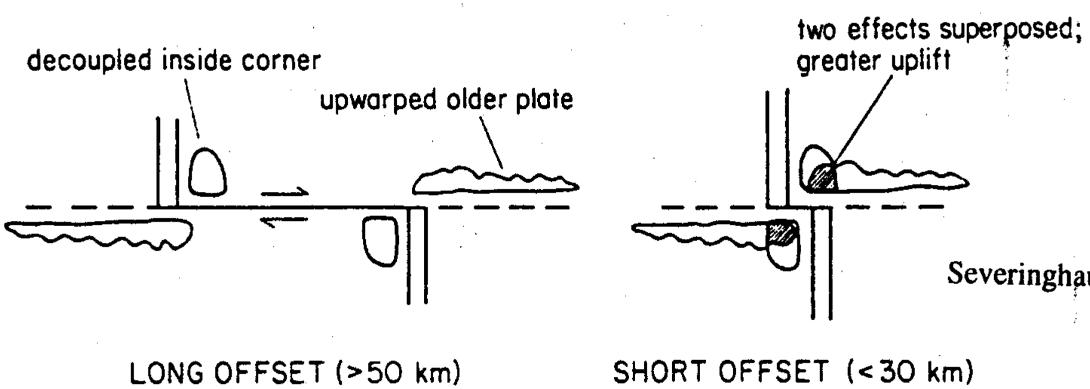


Fig. 8. Summary of the proposed mechanisms for the origin of high inside corners. Observations shown in lower case letters, and their interpretation in terms of the model shown in upper case letters. Transform faulting breaks the lithosphere along a near-vertical fault, permitting differential vertical movement. Vertical movements are a result of the forces that create the rift valley. Decoupling and coupled uplift result from the presence and absence, respectively, of lithospheric failure due to transform faulting. Heavy arrows symbolize the uplift force creating the rift valley walls.



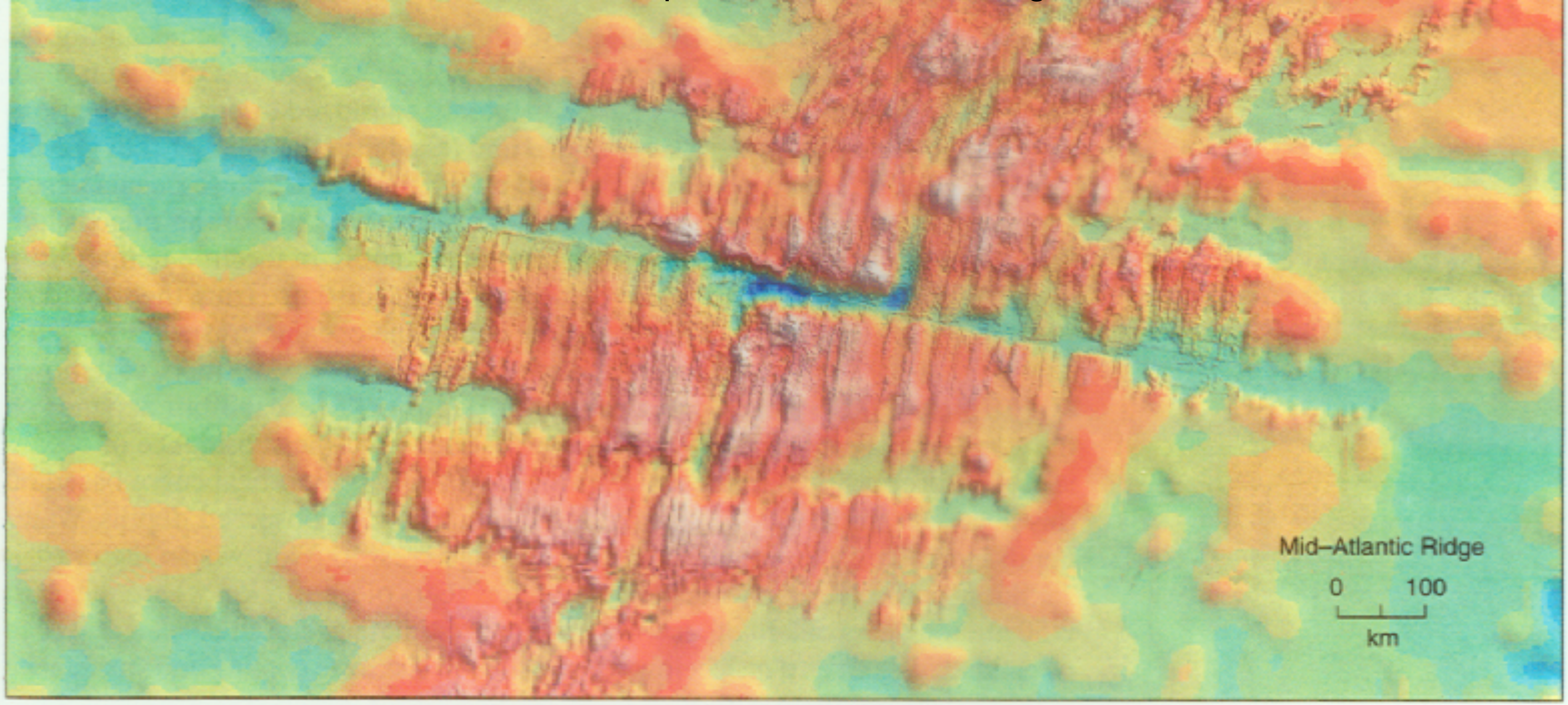
Severinghaus and Macdonald (1988)

Original hypothesis;

there is some merit to it, but considered outdated

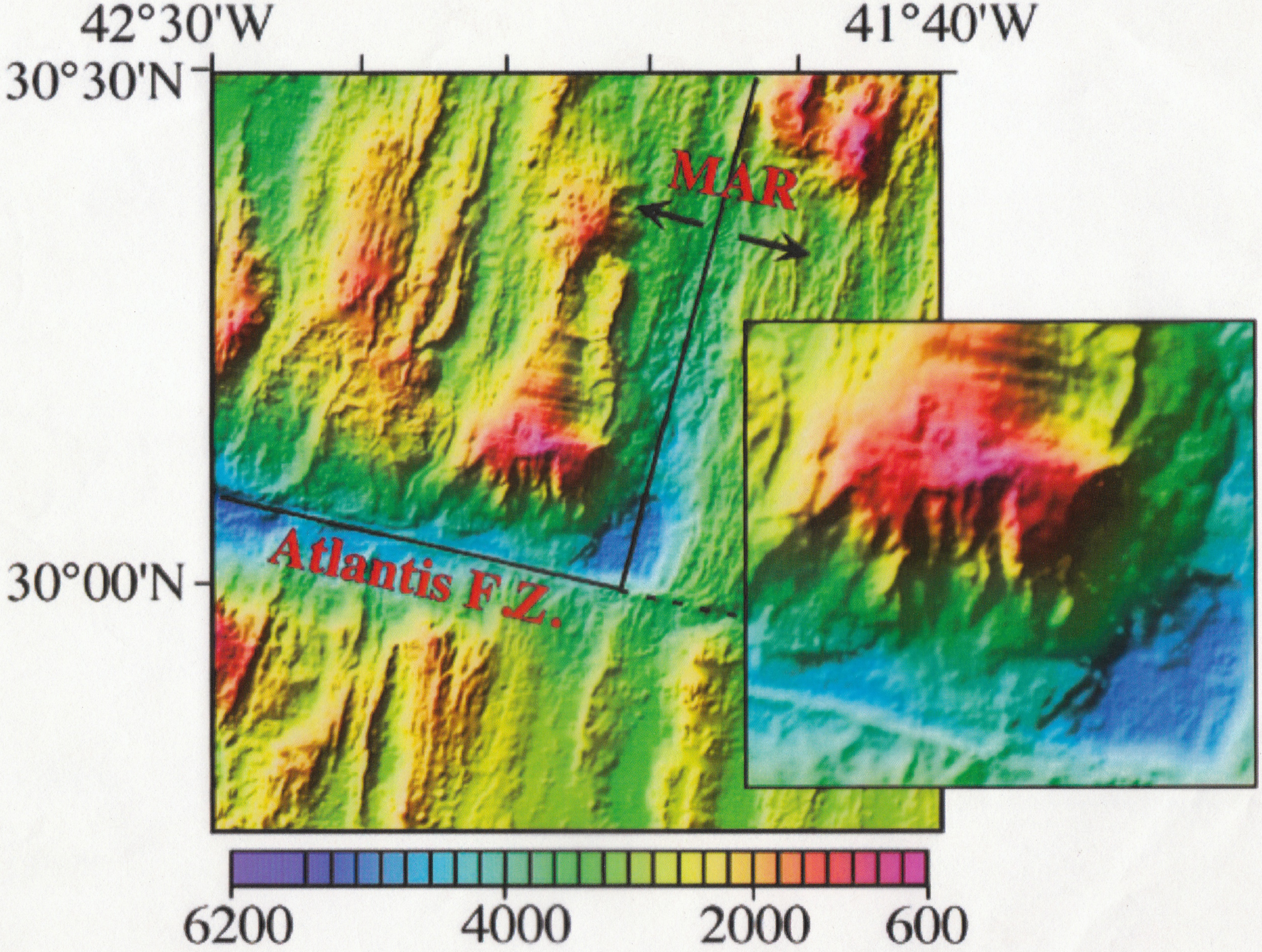
it does not explain more recent observations

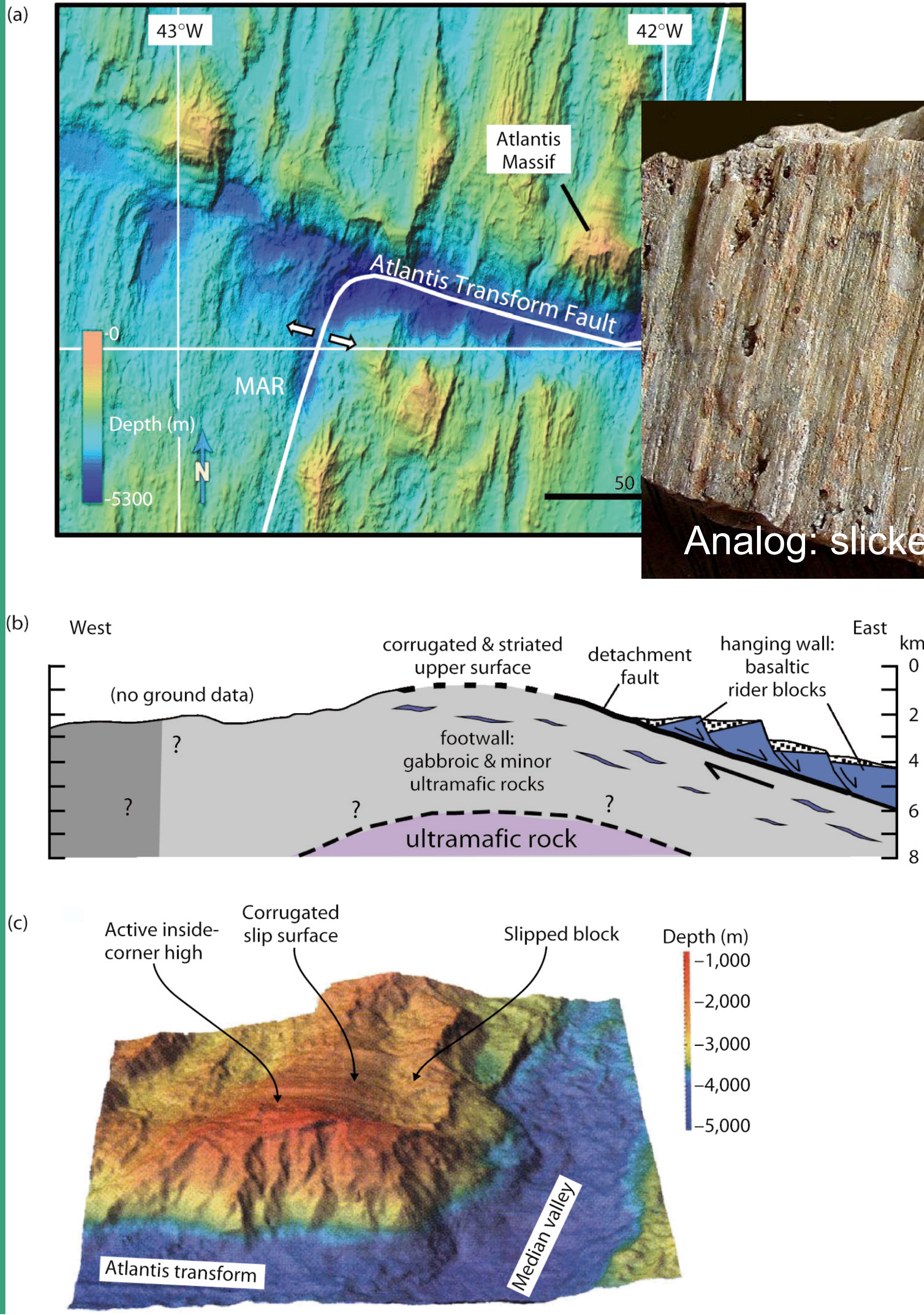
The Atlantis Transform: A classic example of Inside Corner Highs

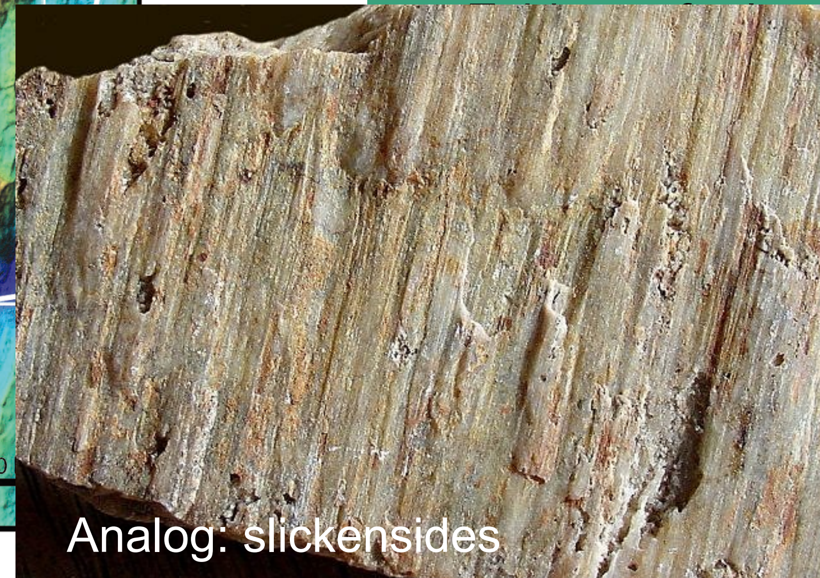


(B) Slow-spreading ridges, such as the Mid-Atlantic Ridge, have steeper flanks and prominent rift valleys. Transform faults offset the ridge in numerous places.

FIGURE 19.3 **Spreading rate** helps control many features of an oceanic ridge. *(Courtesy of Lamont-Doherty Earth Observatory)*


42°30'W
41°40'W
30°30'N
30°00'N
MAR
Atlantis F.Z.
6200
4000
2000
600





angle
ng at
enters

Corrugated surfaces with exposures of serpentinites and gabbros

“mega-mullions”

KK&V plate 6.1

Detachment Faulting in the Basin and Range

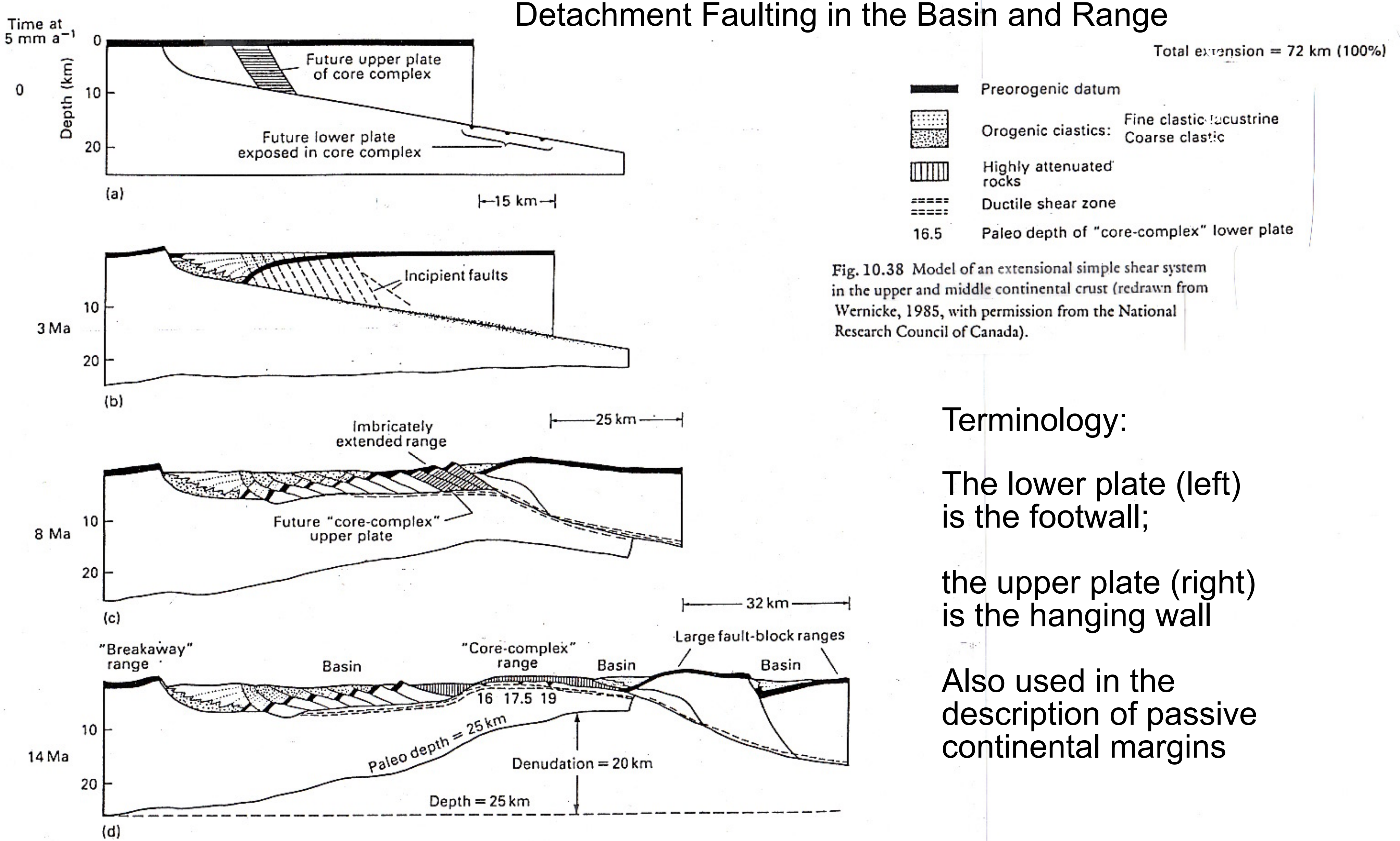


Fig. 10.38 Model of an extensional simple shear system in the upper and middle continental crust (redrawn from Wernicke, 1985, with permission from the National Research Council of Canada).

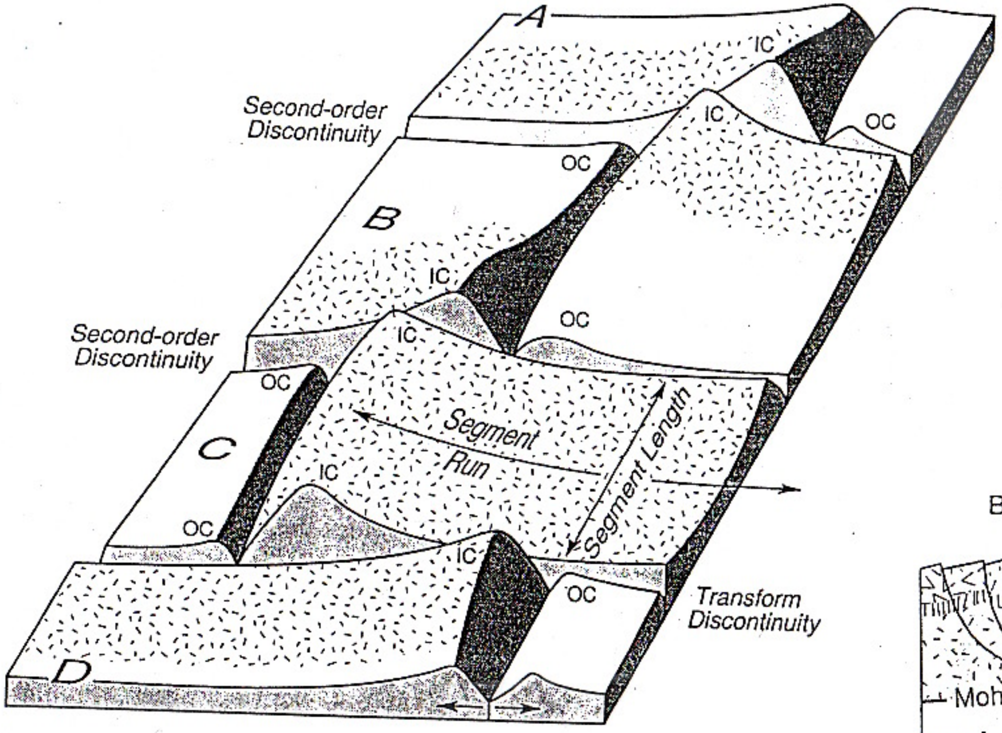
Terminology:

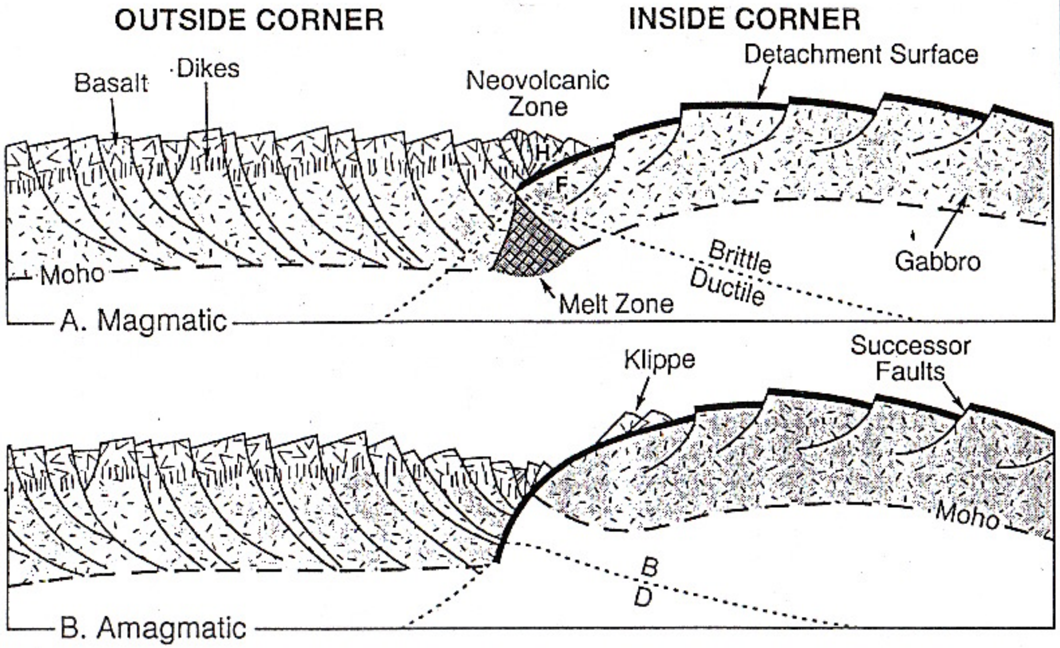
The lower plate (left) is the footwall;

the upper plate (right) is the hanging wall

Also used in the description of passive continental margins

New view of slow-spreading





Tucholke and Lin (1994)

An asymmetrical model for slow spreading ridges

Combines growing awareness of prevalence of detachment faulting in oceanic environments with observations of abundant ultramafics on ICH.

Model:

- Slow spreading is dominated by long periods of amagmatic extension during which there is extensive detachment faulting
- The inside corner is the footwall side
- The outside corner is the hanging wall
- The outside corner has a normal upper crustal sequence
- The inside corner is dominated by exumed lower crustal and upper mantle rocks

Homework 4