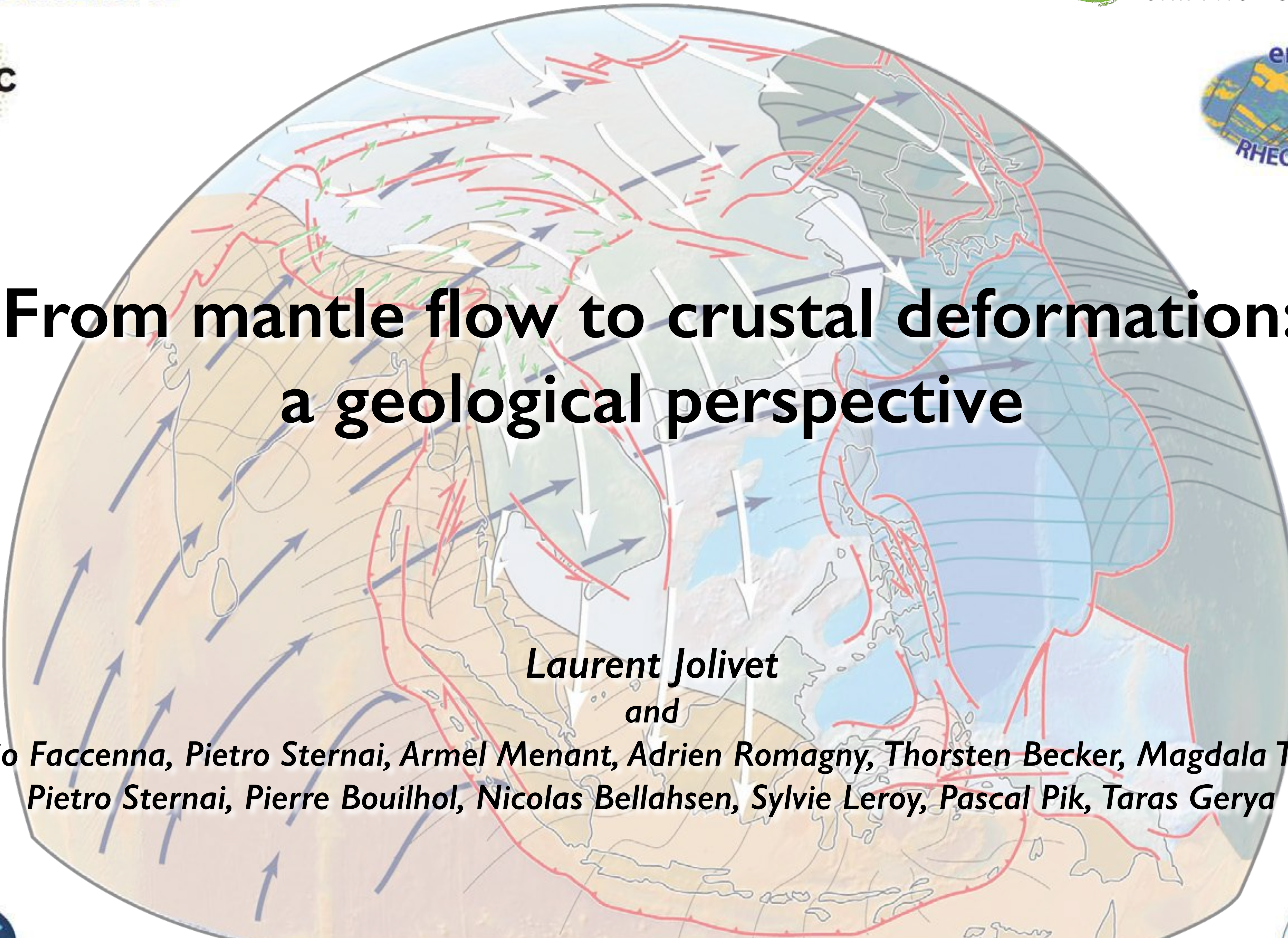
50 Years of Plate Tectonics

25-26 June, 2018, Collège de France, Paris



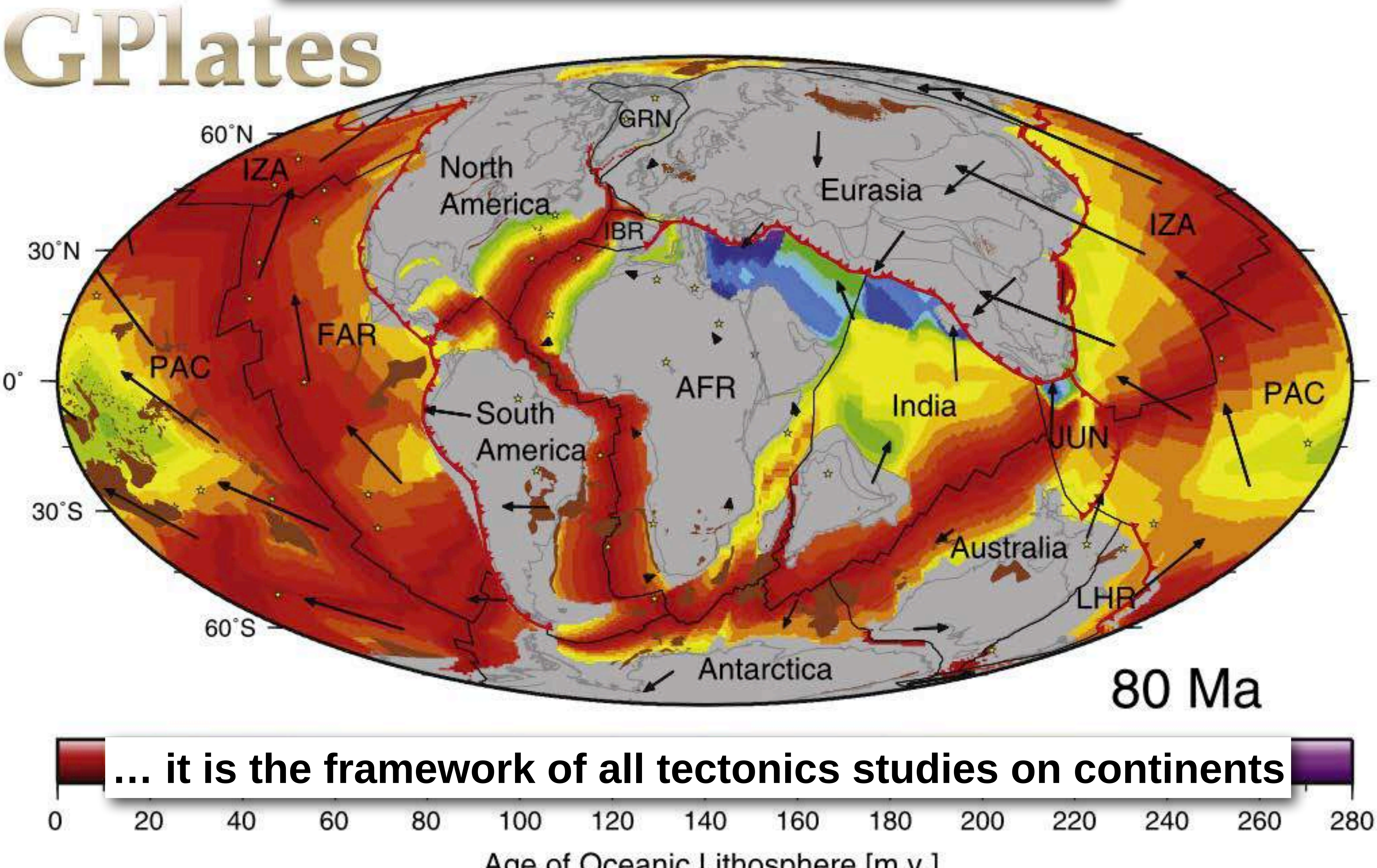
From mantle flow to crustal deformation: a geological perspective

Laurent Jolivet

and

Claudio Faccenna, Pietro Sternai, Armel Menant, Adrien Romagny, Thorsten Becker, Magdala Tesauro, Pietro Sternai, Pierre Bouilhol, Nicolas Bellahsen, Sylvie Leroy, Pascal Pik, Taras Gerya

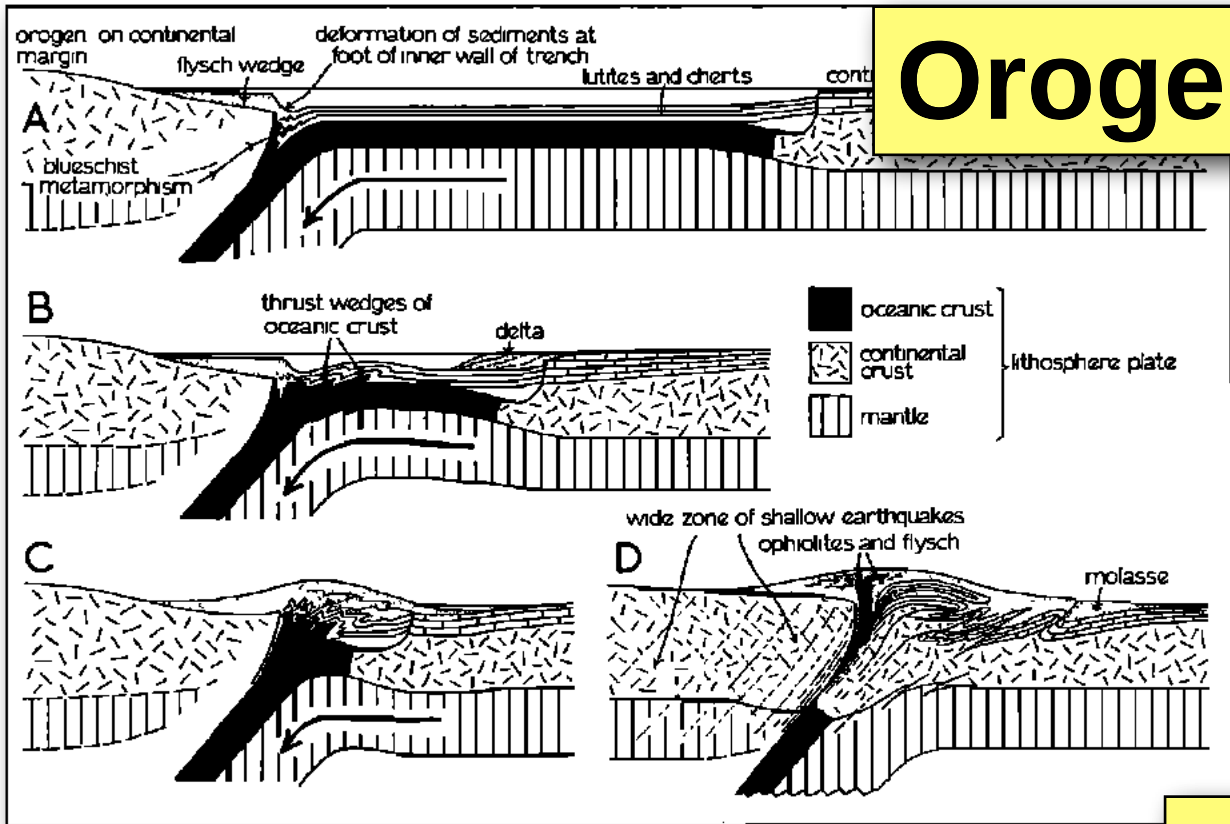
Plate tectonics was born from the oceans



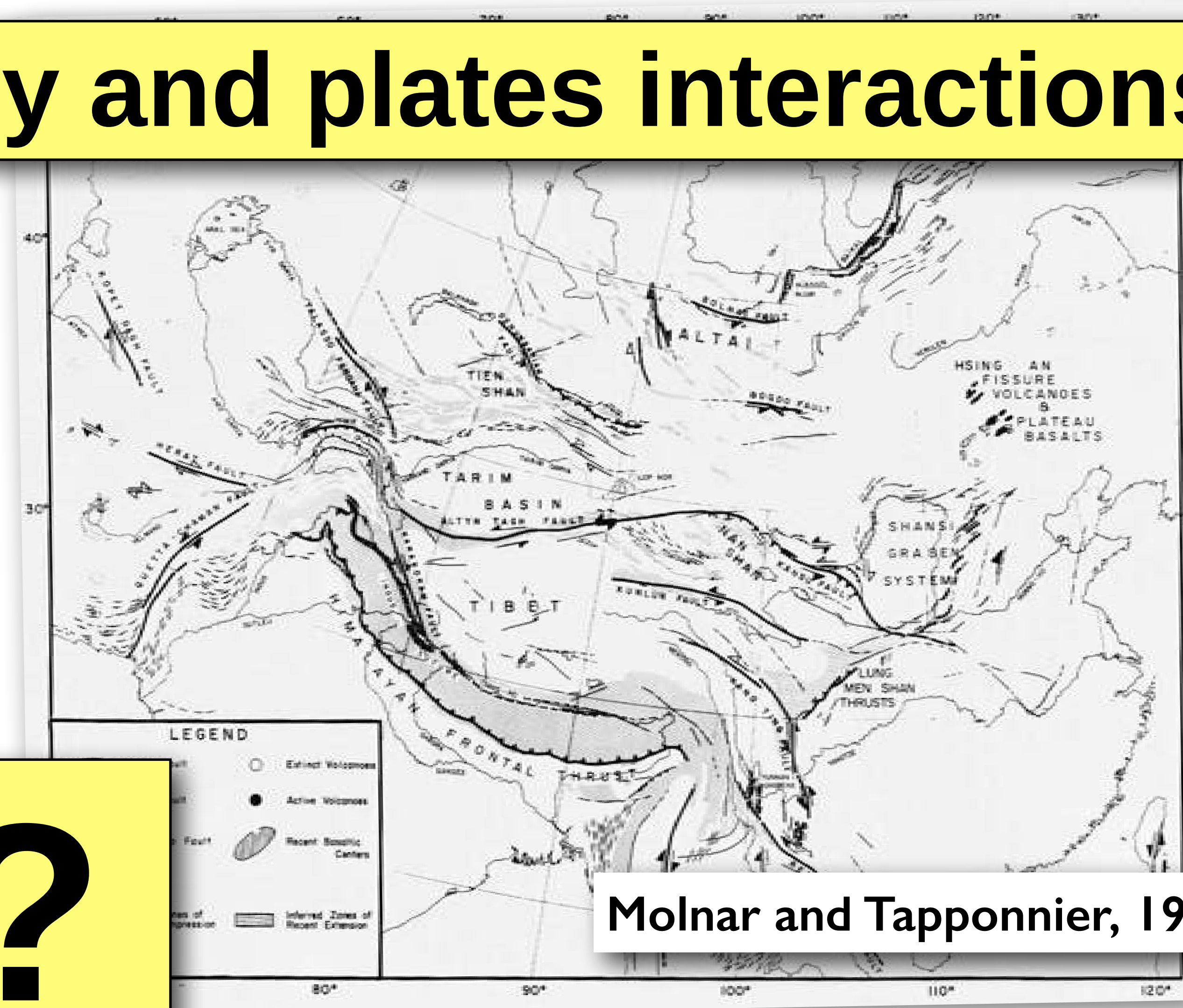
… it is the framework of all tectonics studies on continents

Seton et al., 2012

Orogeny and plates interactions

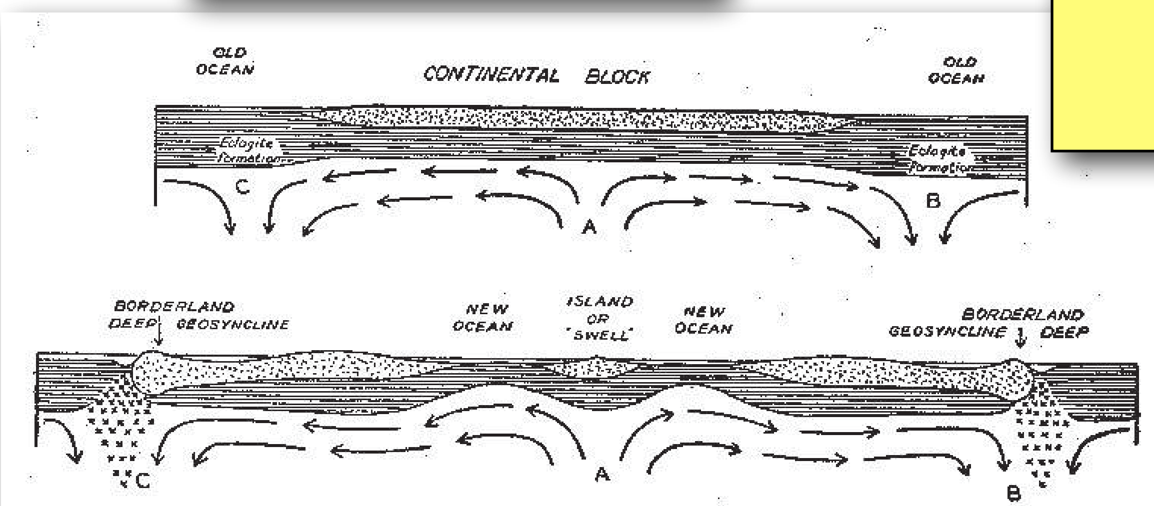


Dewey and Bird, 1970



Molnar and Tapponnier, 1975

?



Figs. 2 and 3.

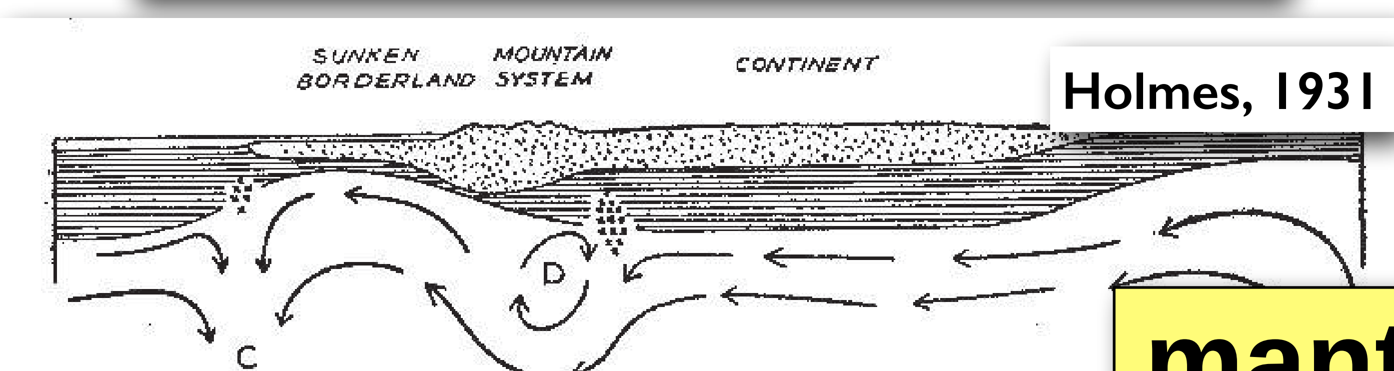
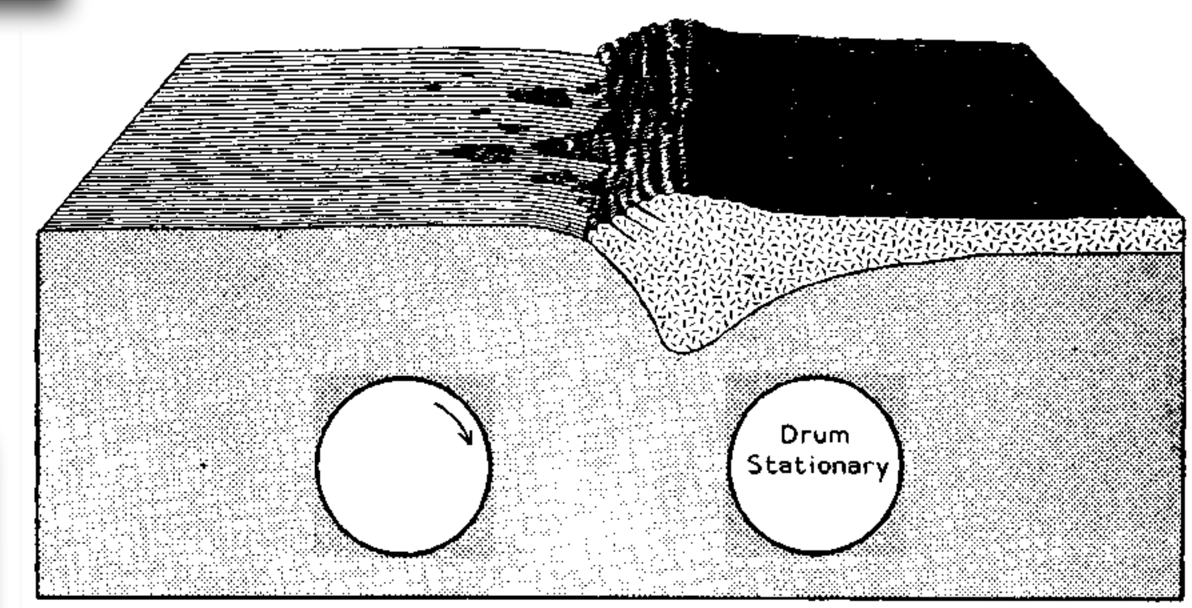


Fig. 4.

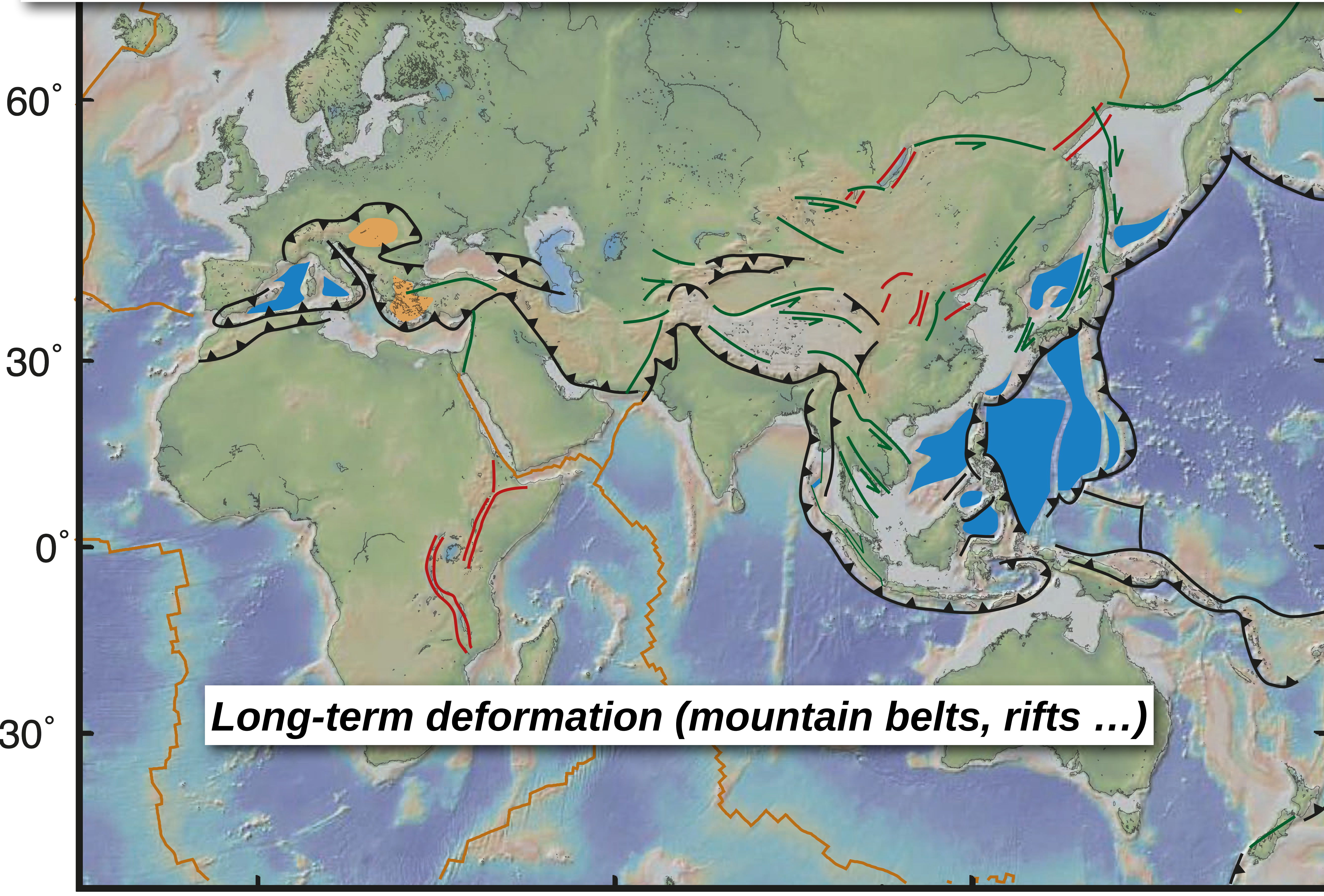
Holmes, 1931



Griggs, 1939

mantle convection

Plate kinematics is the framework for studying crustal deformation



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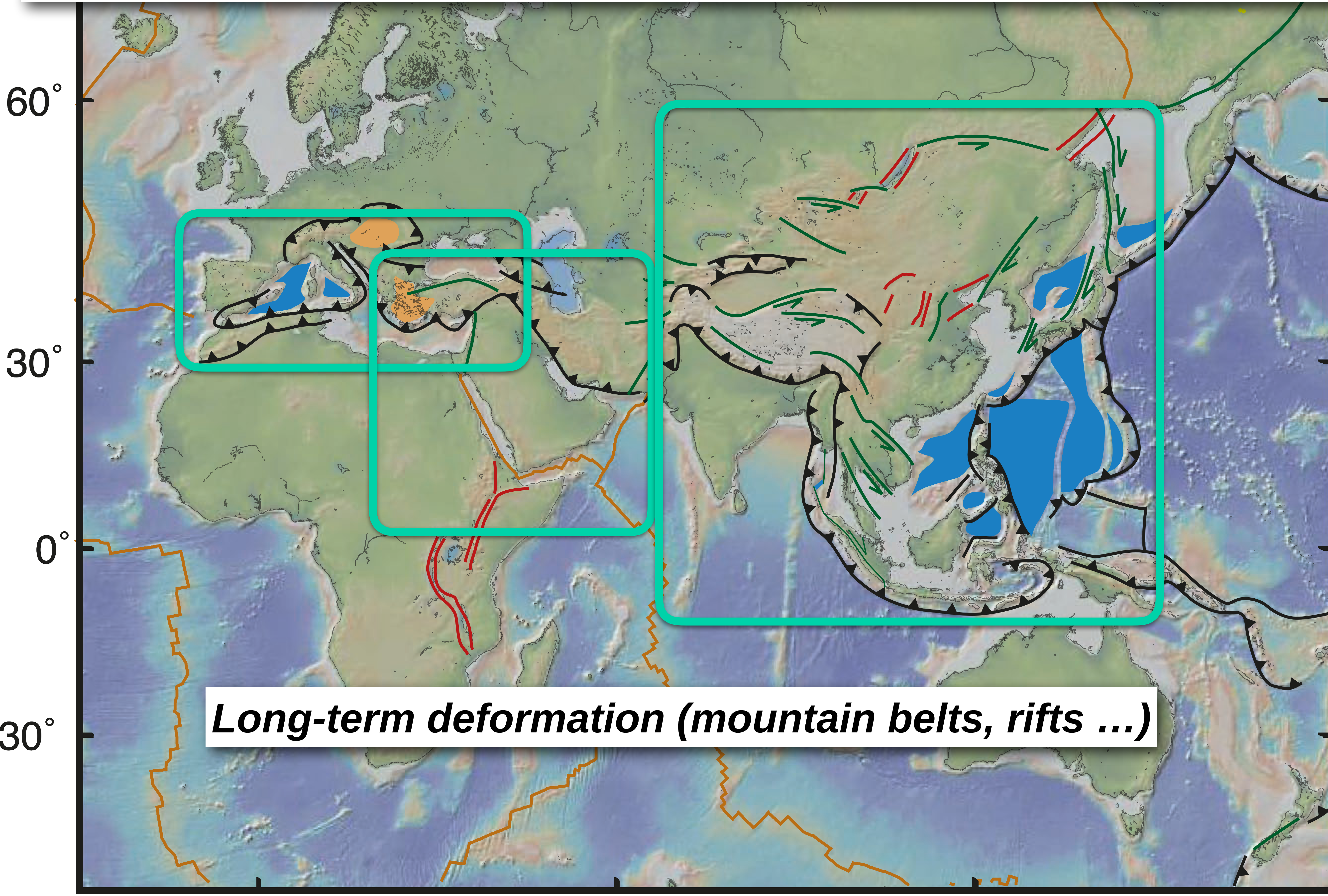
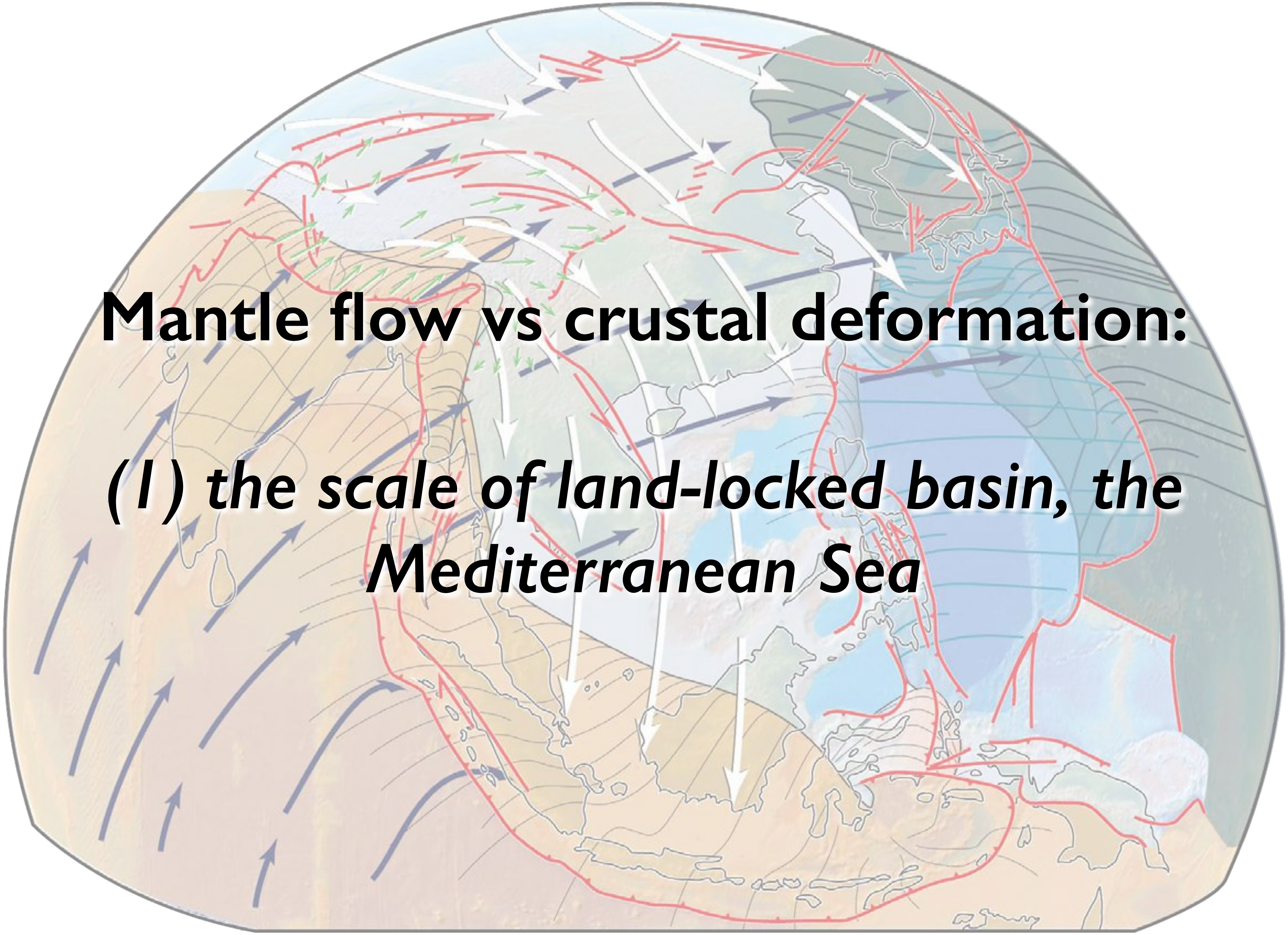
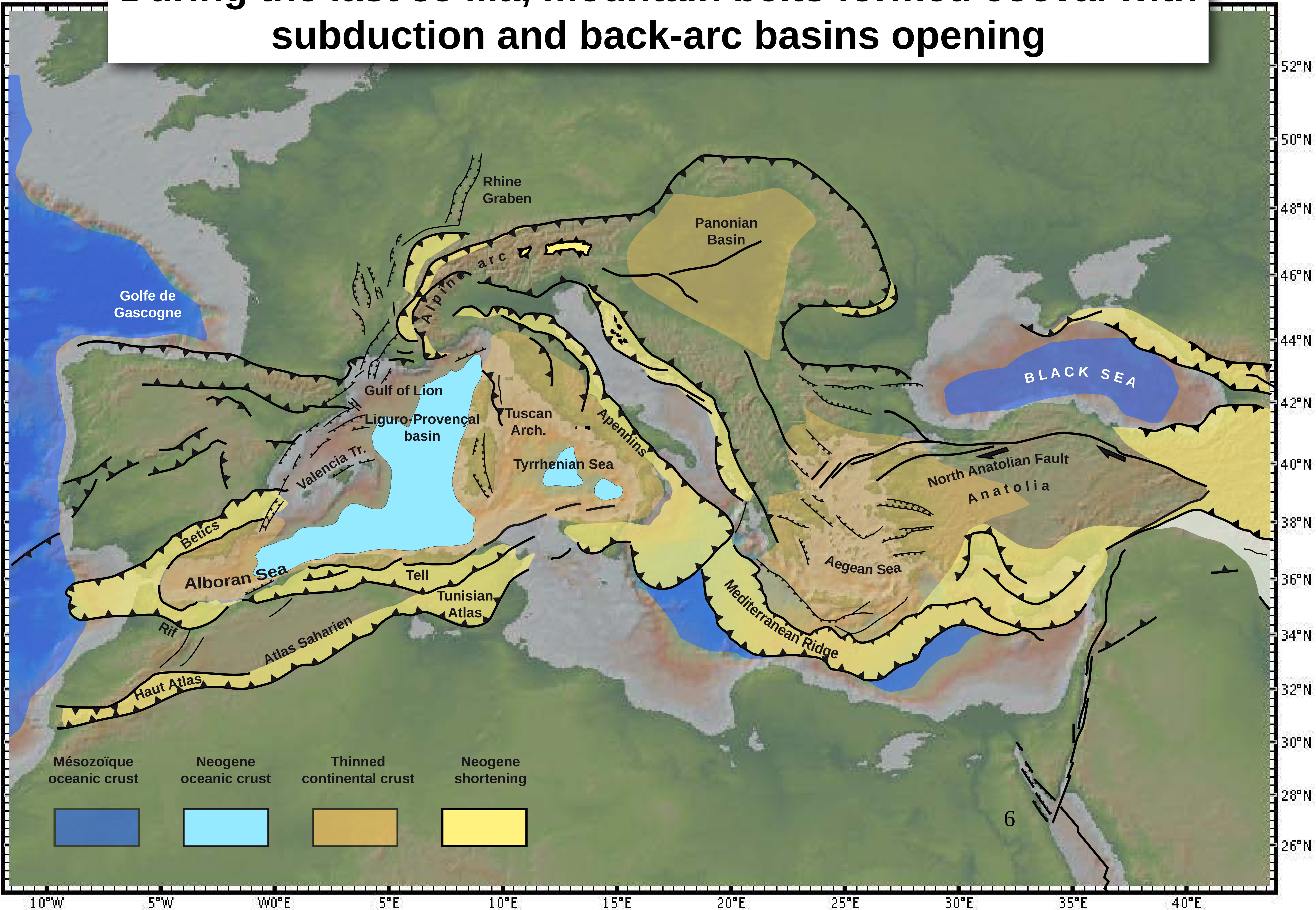




Mantle flow vs crustal deformation:

(1) the scale of land-locked basin, the Mediterranean Sea

During the last 35 Ma, mountain belts formed coeval with subduction and back-arc basins opening



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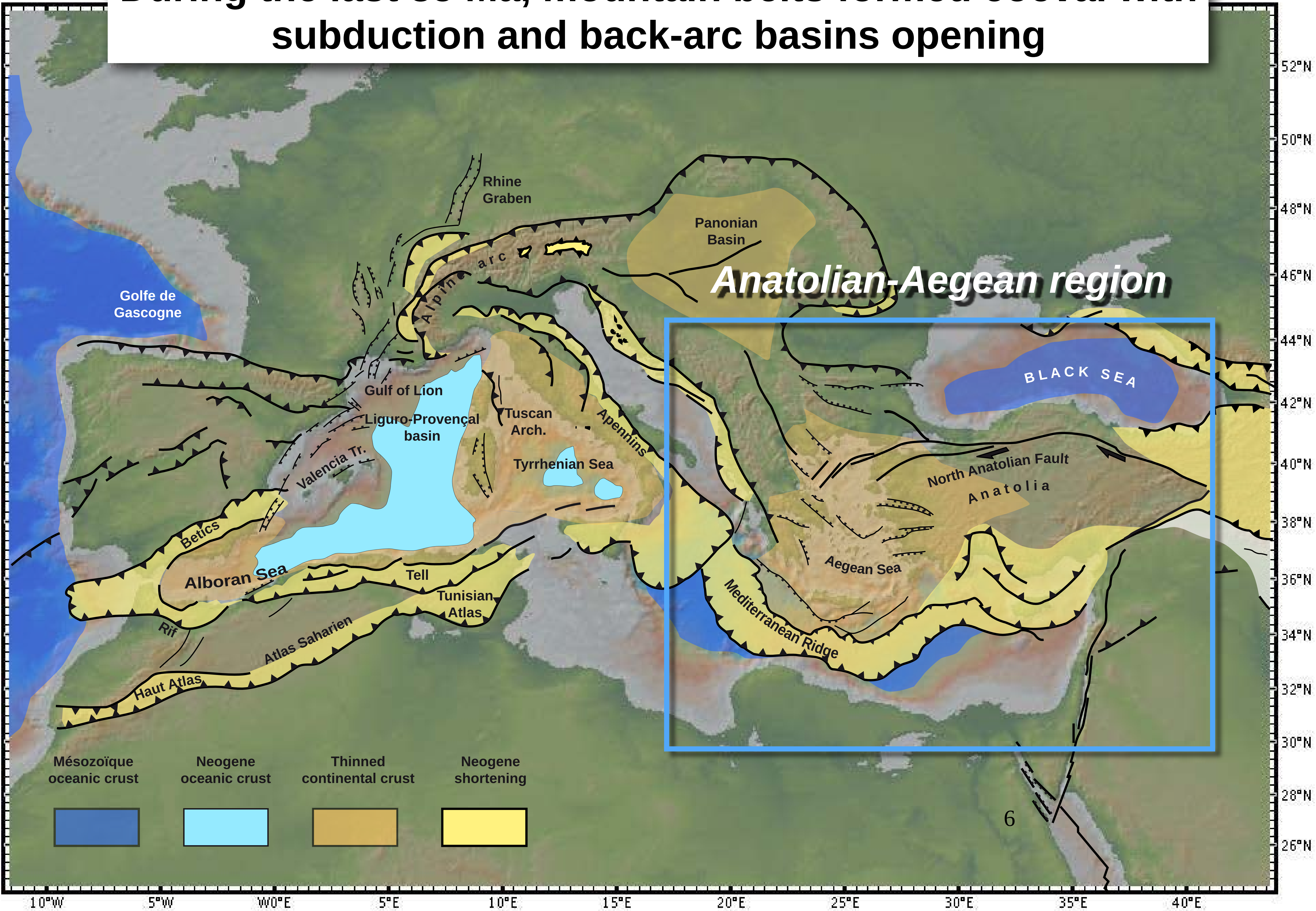
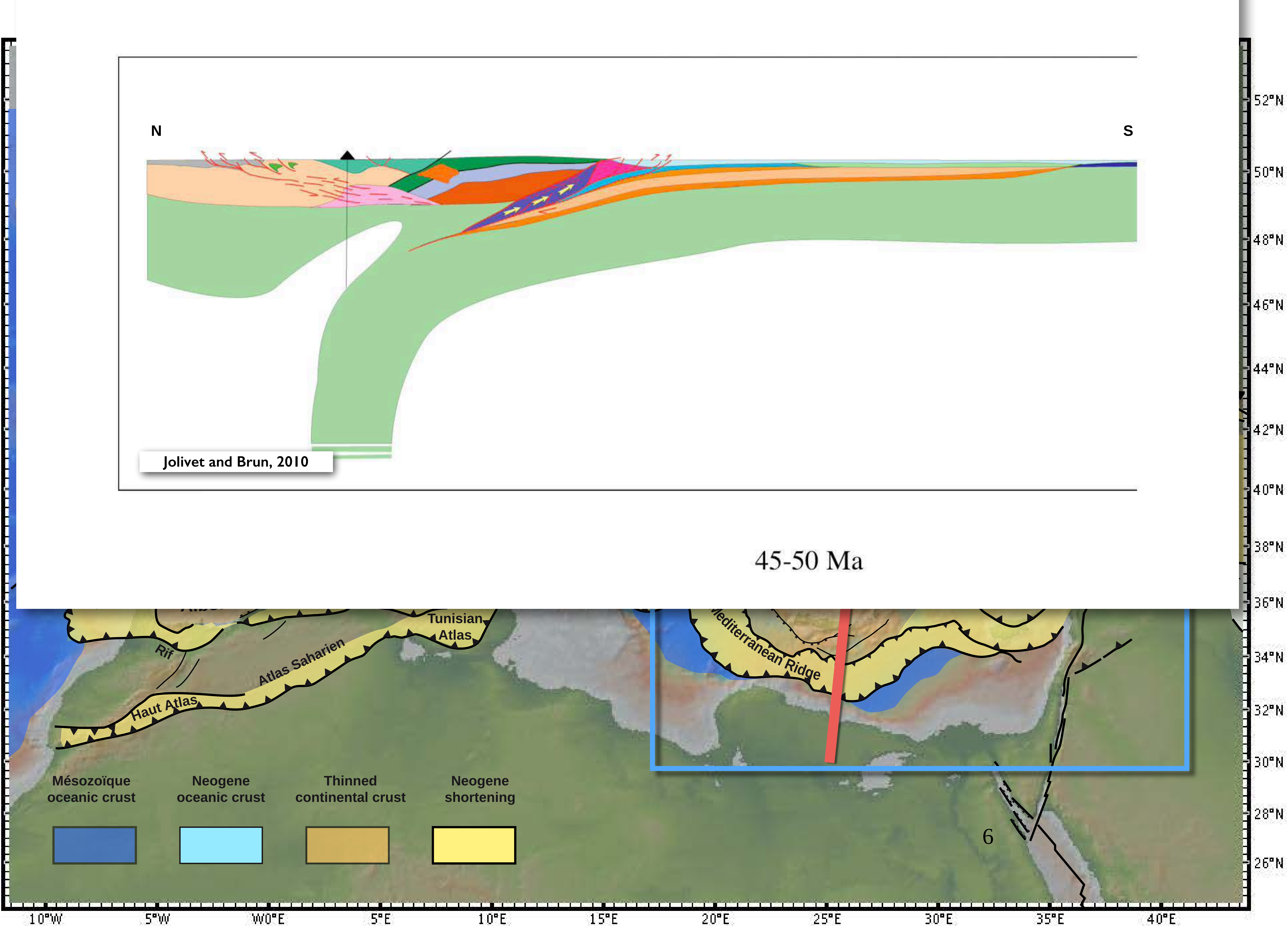
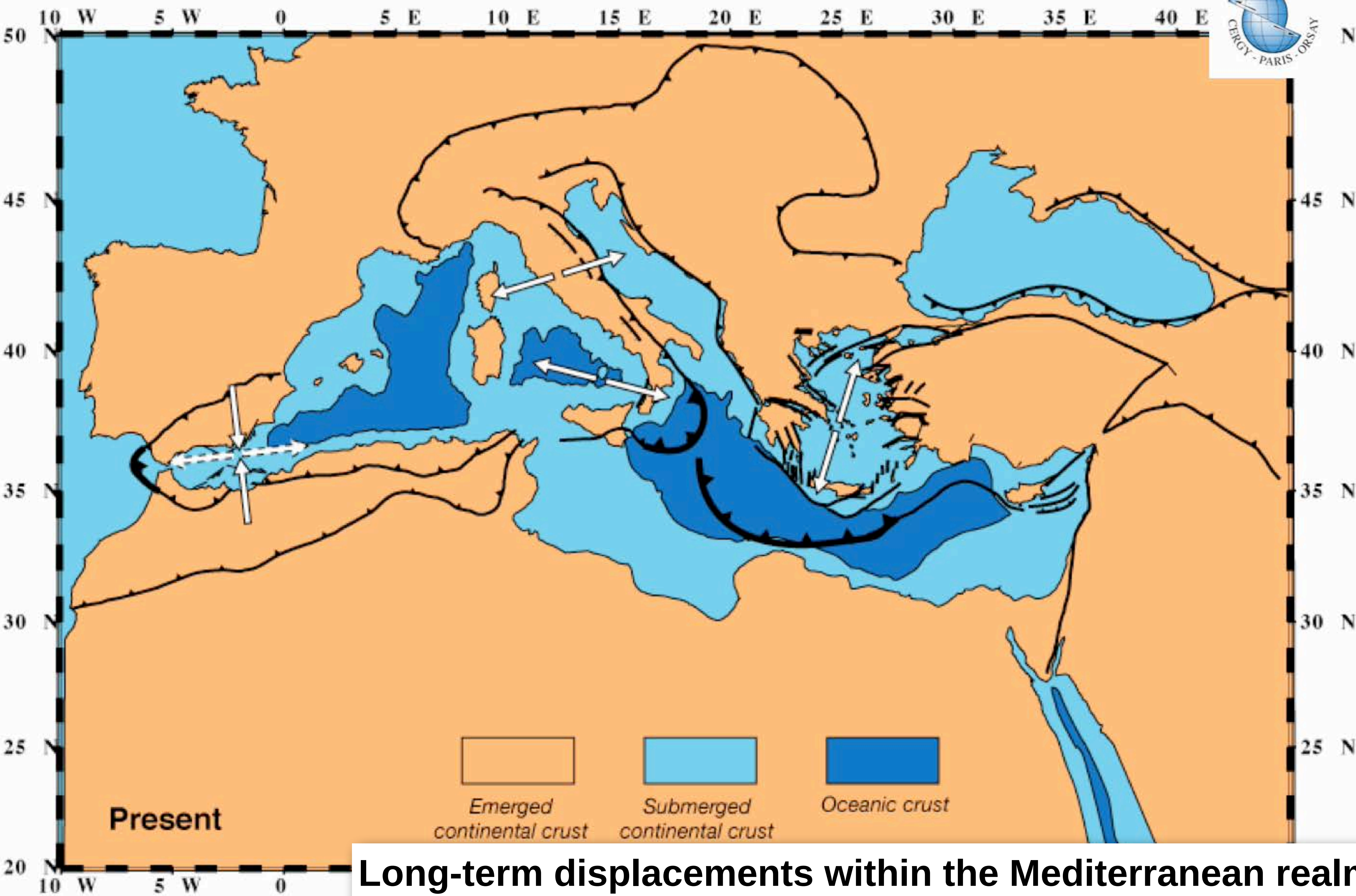



N
S
Jolivet and Brun, 2010
Tunisian Atlas
Rif
Atlas Saharien
Haut Atlas
Ridge
Mésozoïque oceanic crust
Neogene oceanic crust
Thinned continental crust
Neogene shortening
6
52°N
50°N
48°N
46°N
44°N
42°N
40°N
38°N
36°N
34°N
32°N
30°N
28°N
26°N
10°W
5°W
W0°E
5°E
10°E
15°E
20°E
25°E
30°E
35°E
40°E

45-50 Ma

Reconstructions (Eurasia fixed)



Jolivet *et al.*, 2005

Long-term displacements within the Mediterranean realm are much faster than the Africa-Eurasia convergence

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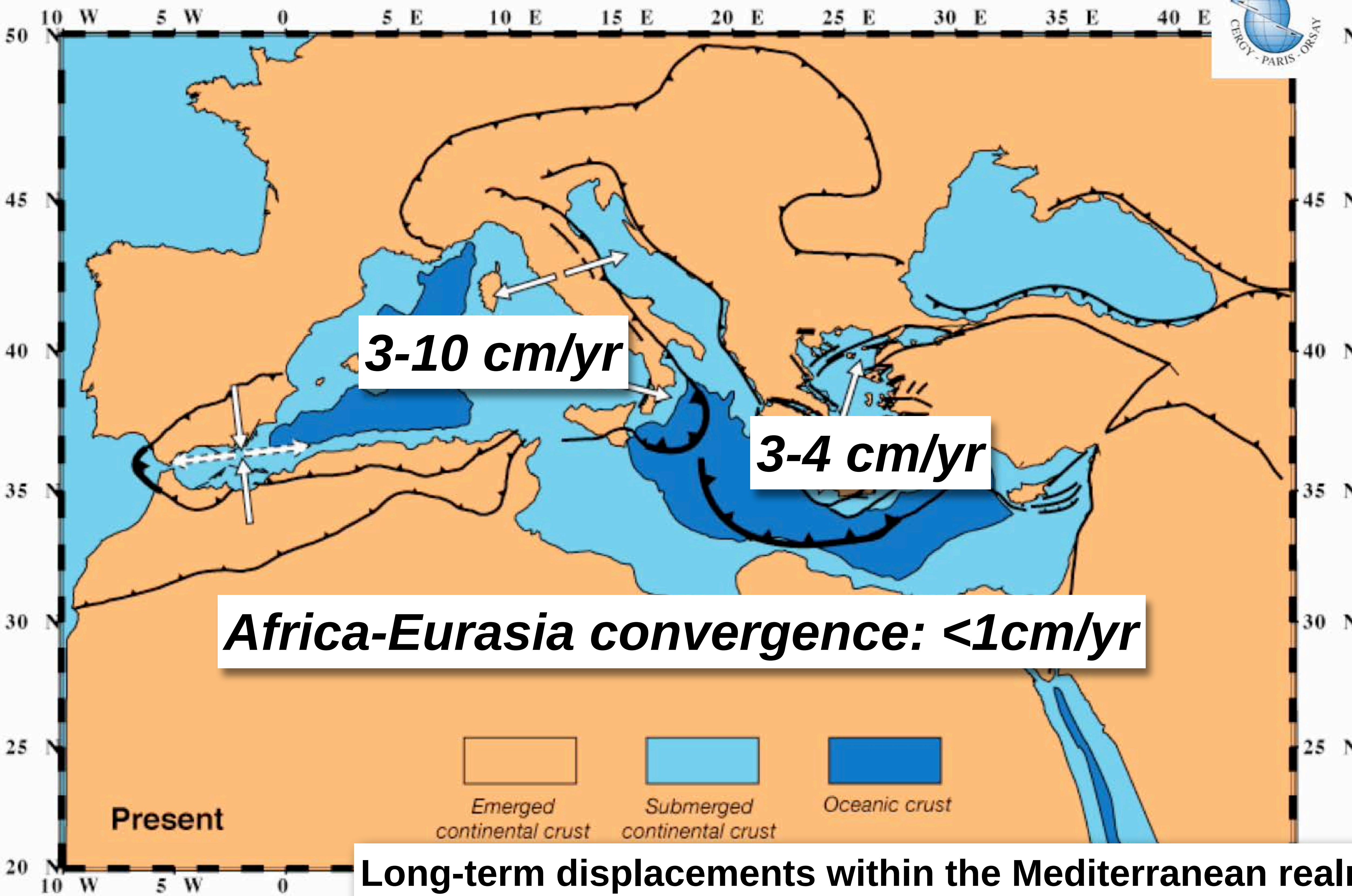

Long-term displacements within the Mediterranean realm are much faster than the Africa-Eurasia convergence

Jolivet *et al.*, 2005

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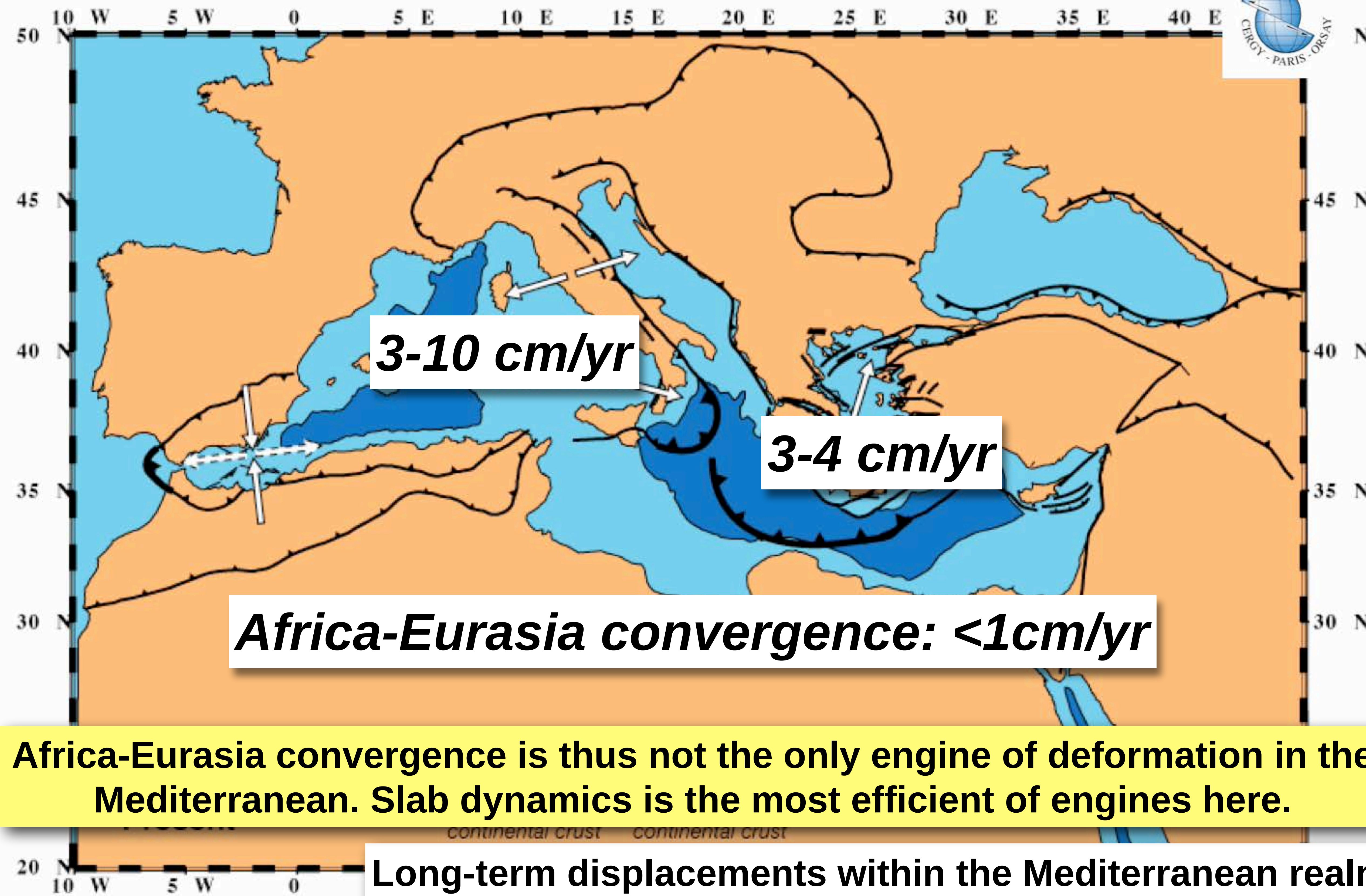
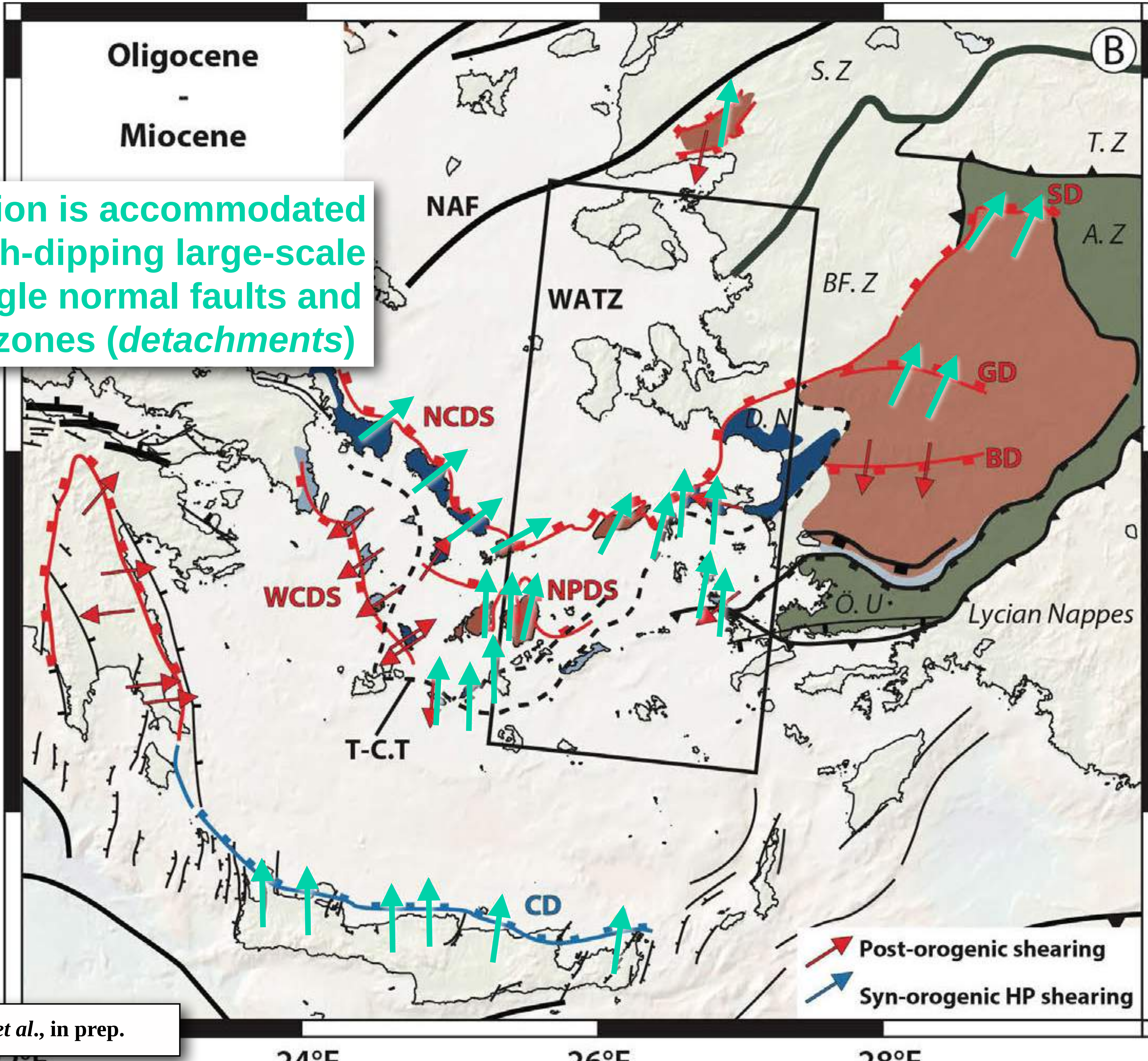


Africa-Eurasia convergence is thus not the only engine of deformation in the Mediterranean. Slab dynamics is the most efficient of engines here.

Long-term displacements within the Mediterranean realm are much faster than the Africa-Eurasia convergence

Jolivet *et al.*, 2005

Extension is accommodated by north-dipping large-scale low-angle normal faults and shear zones (*detachments*)



Roche *et al.*, in prep.

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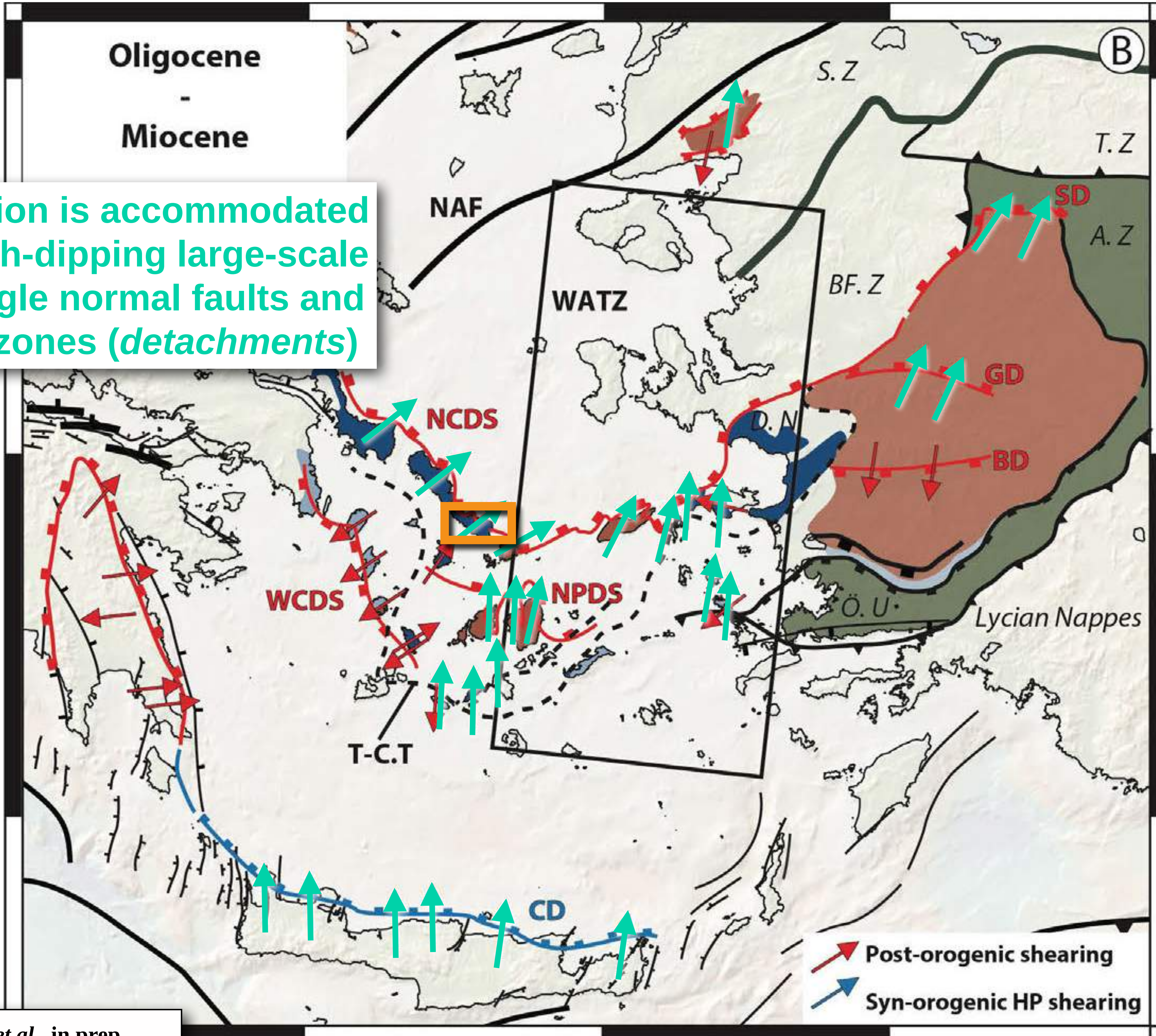

Roche *et al*., in prep.

The North Cycladic Detachment on Tinos Island (Cyclades)

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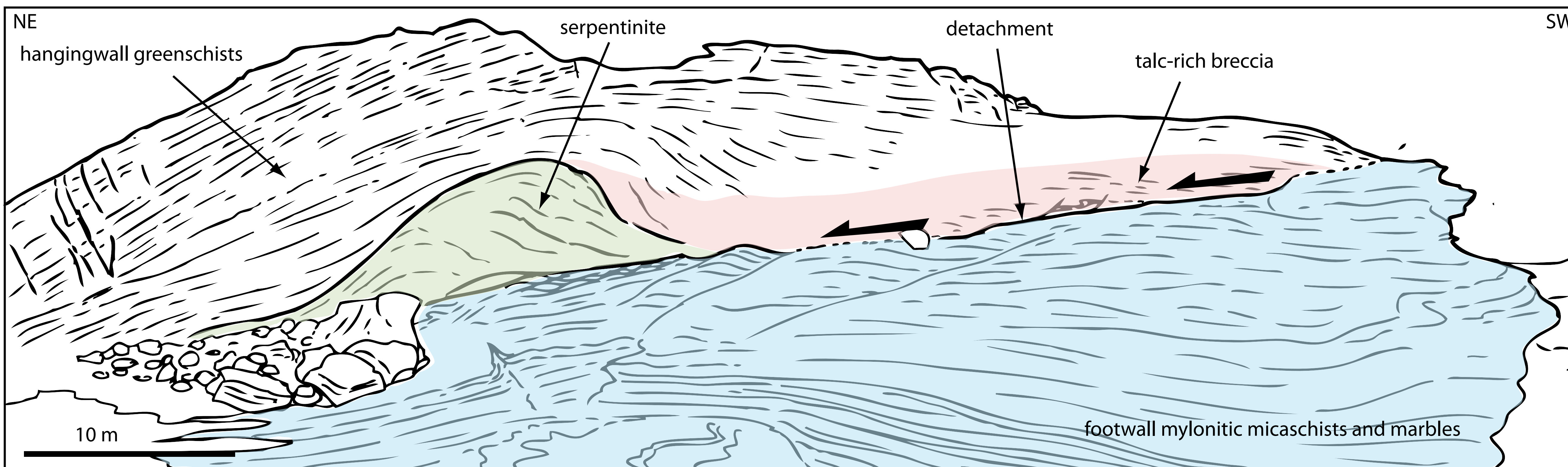

Jolivet et al., 2010

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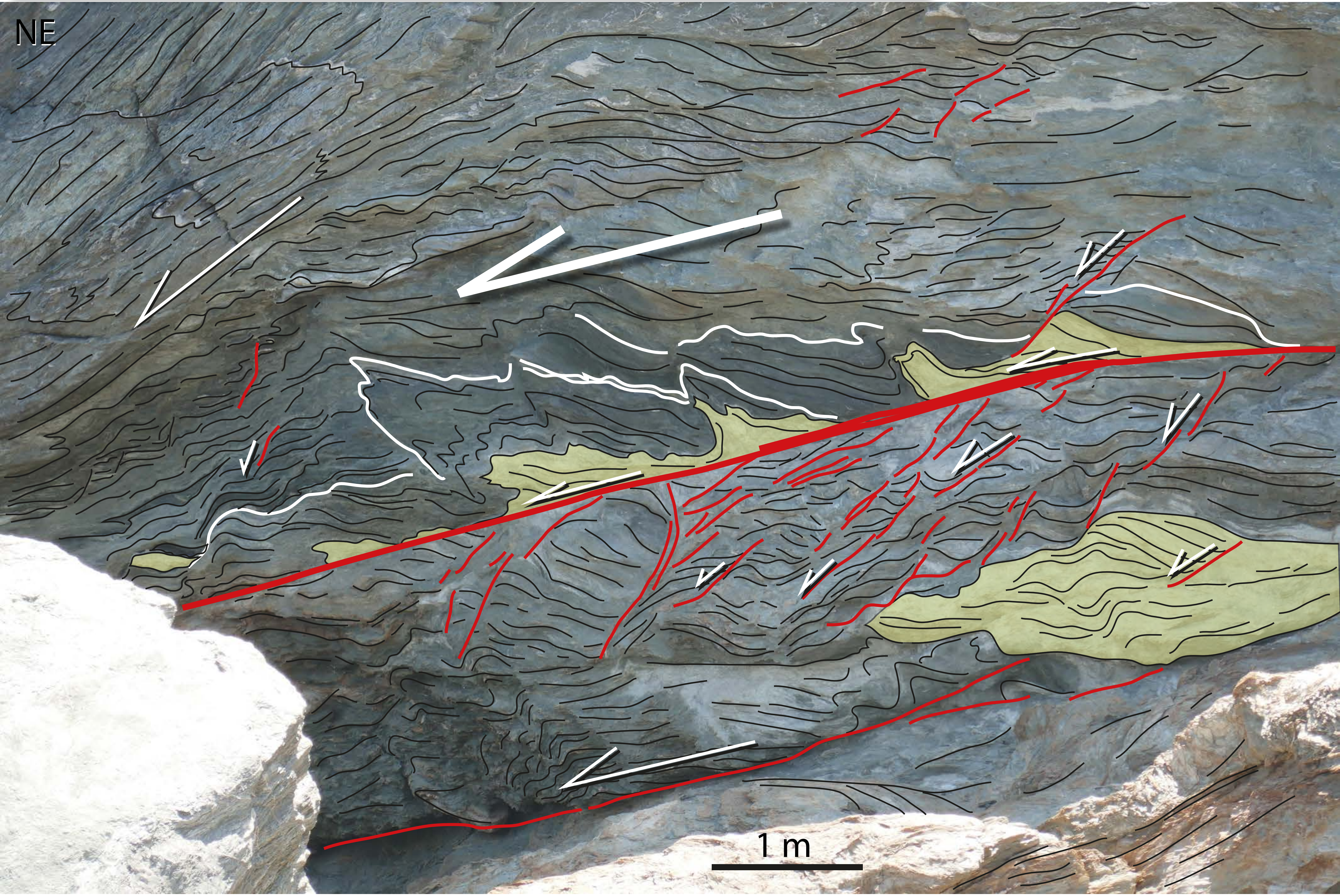
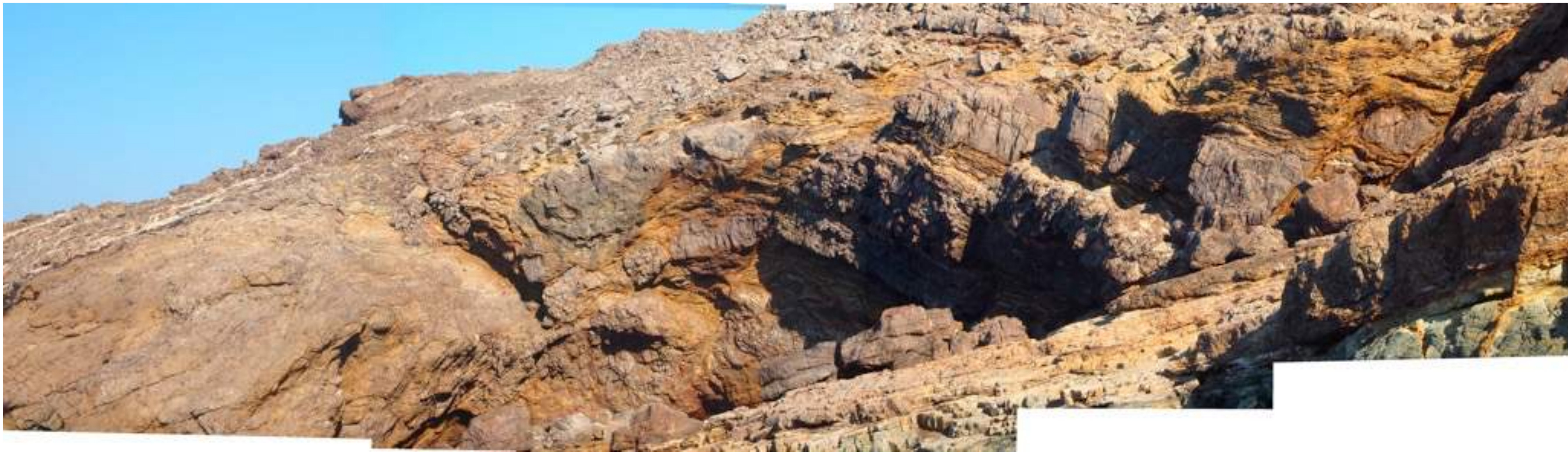


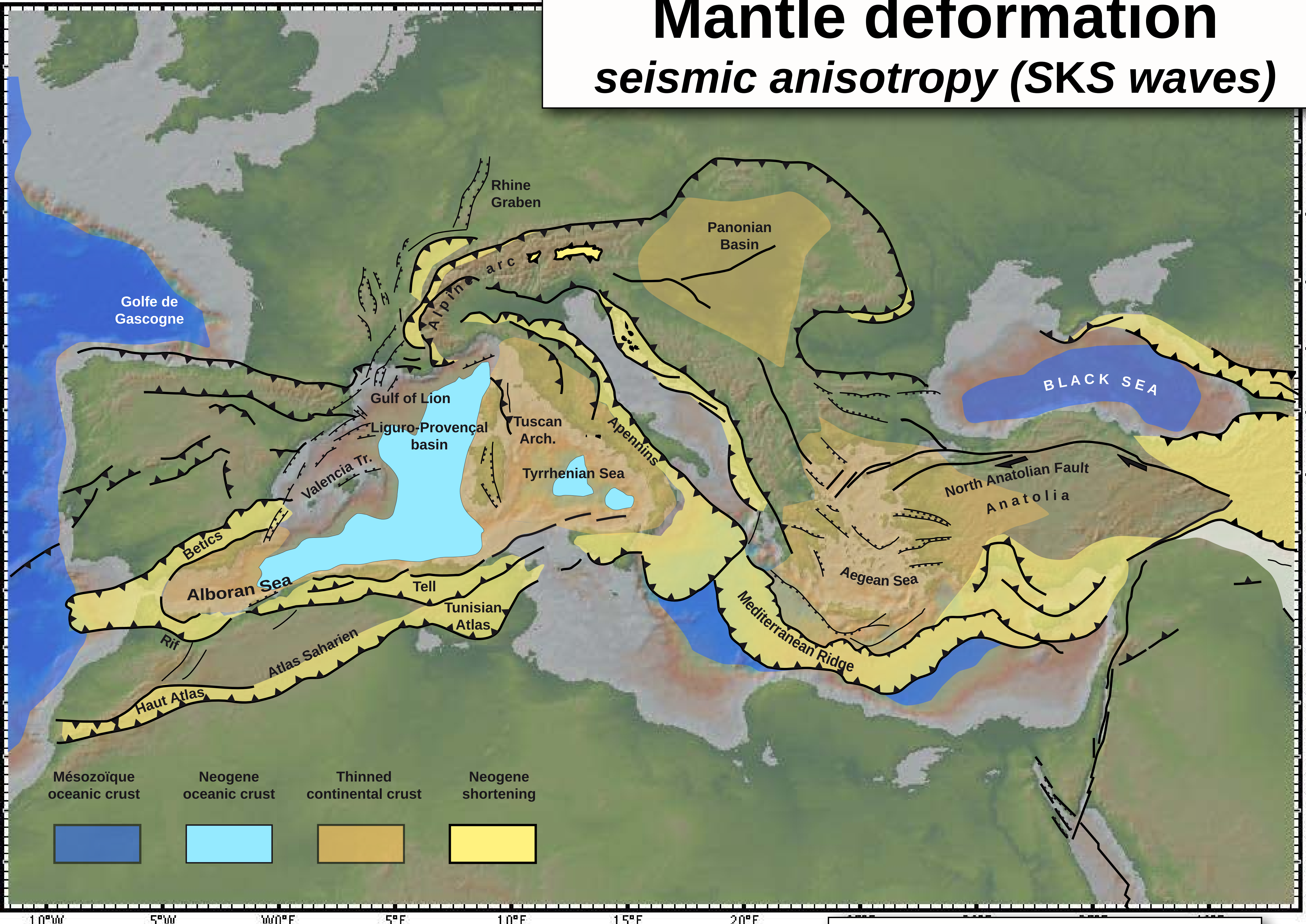
The North Cycladic Detachment on Mykonos Island (Cyclades)



Jolivet et al., 2010; Lecomte et al., 2010

Mantle deformation

seismic anisotropy (SKS waves)



Jolivet et al., 2009; Faccenna et al., 2014

Mantle deformation

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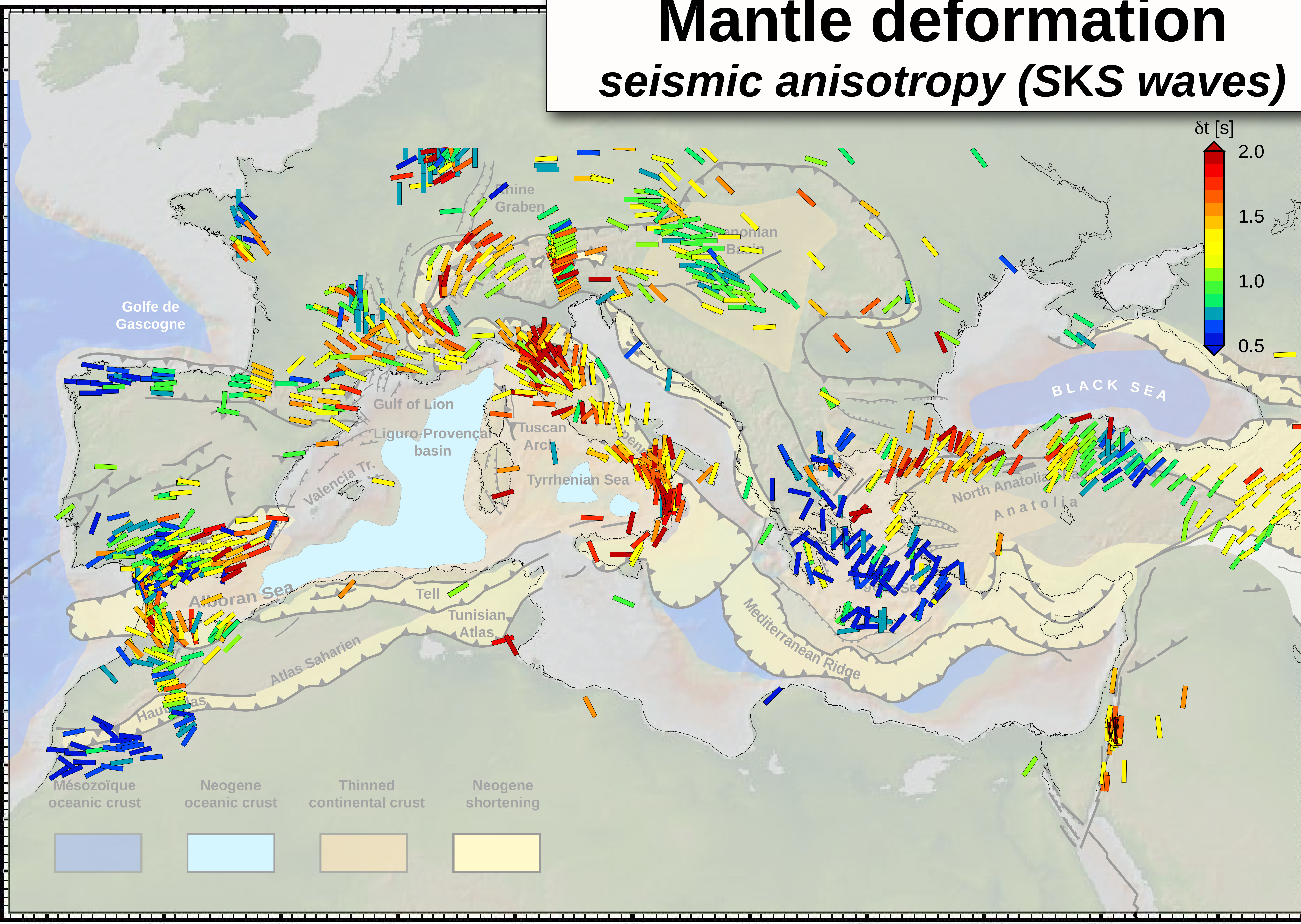

Jolivet et al., 2009; Faccenna et al., 2014

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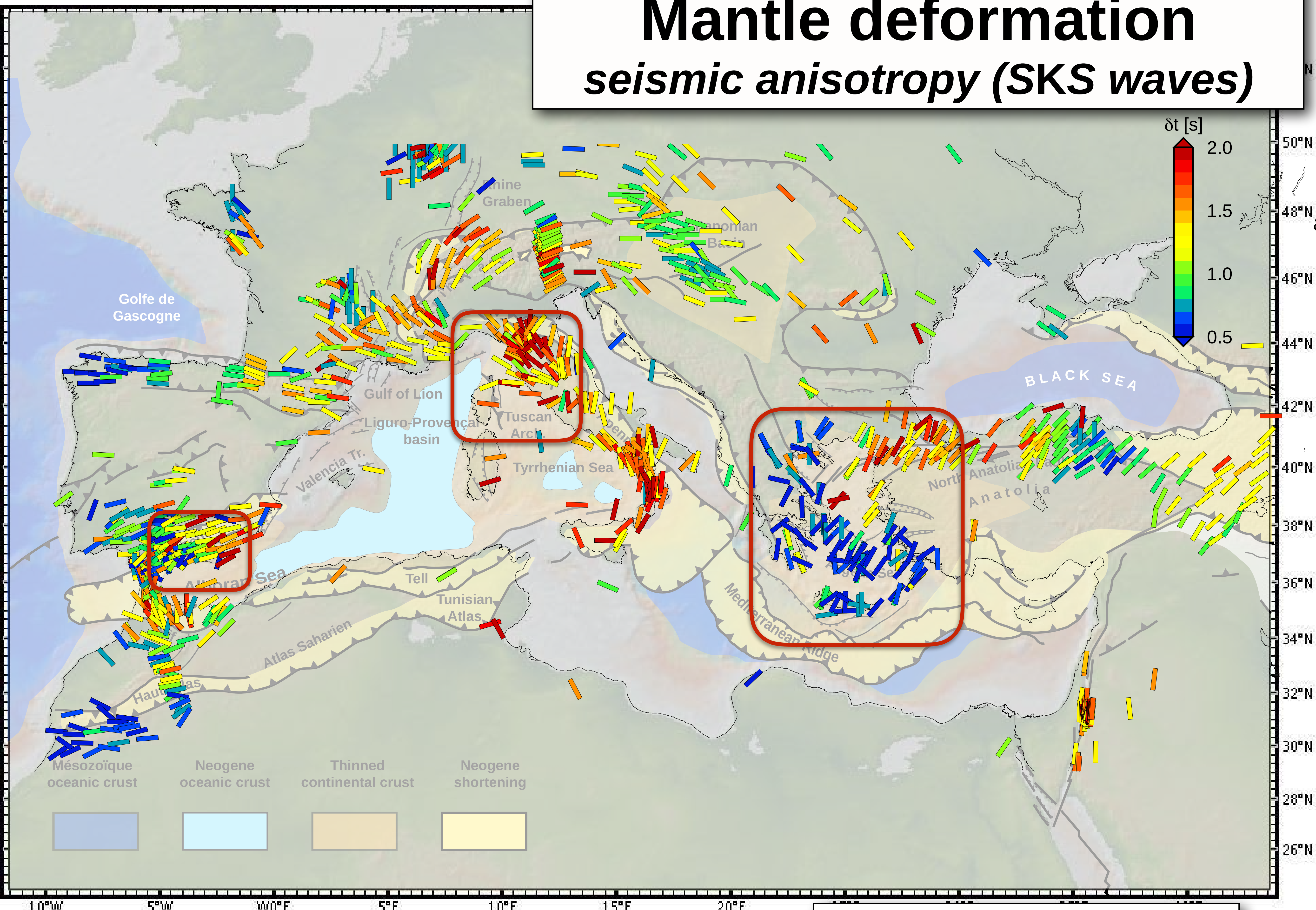

Jolivet et al., 2009; Faccenna et al., 2014

Mantle deformation

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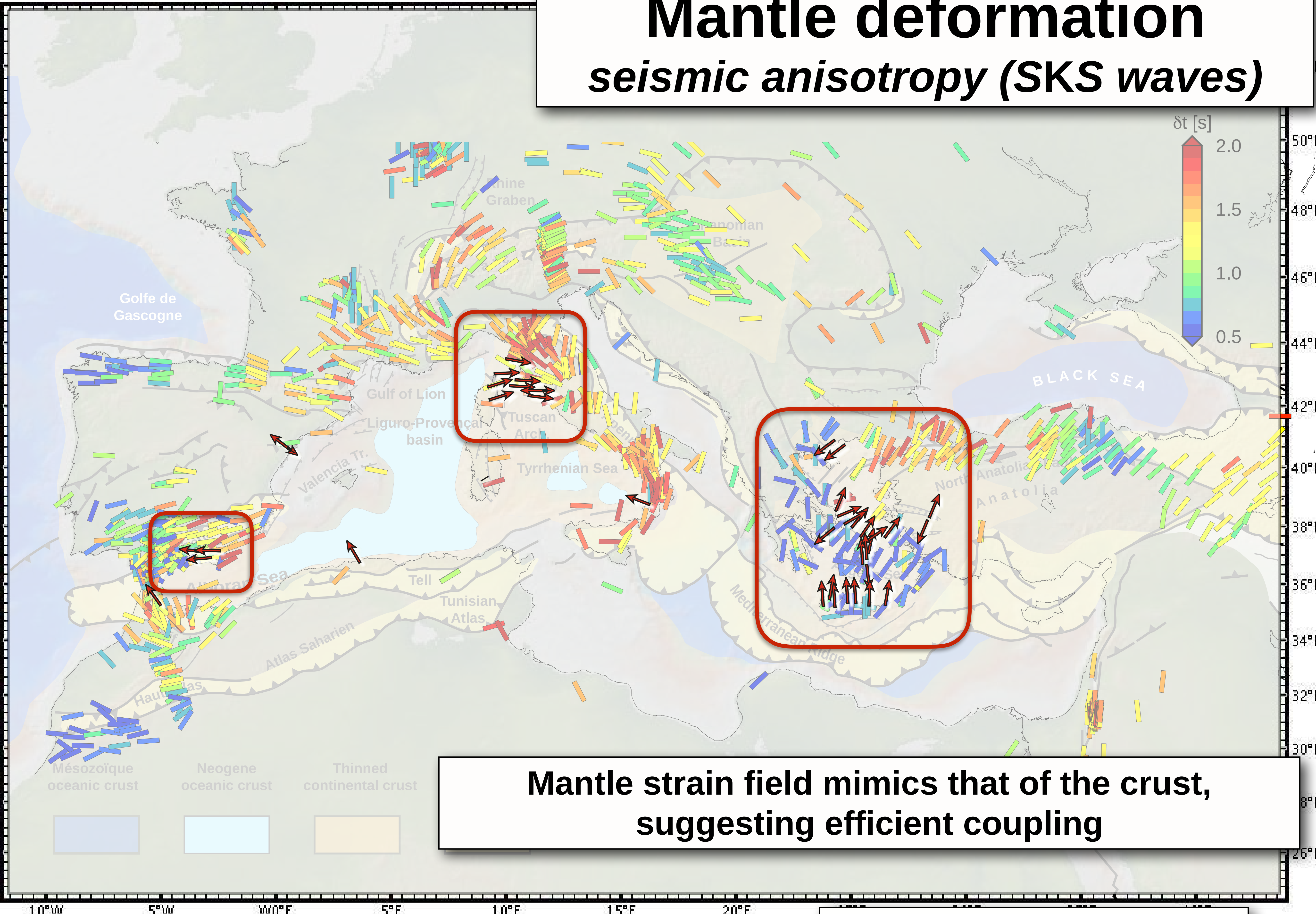
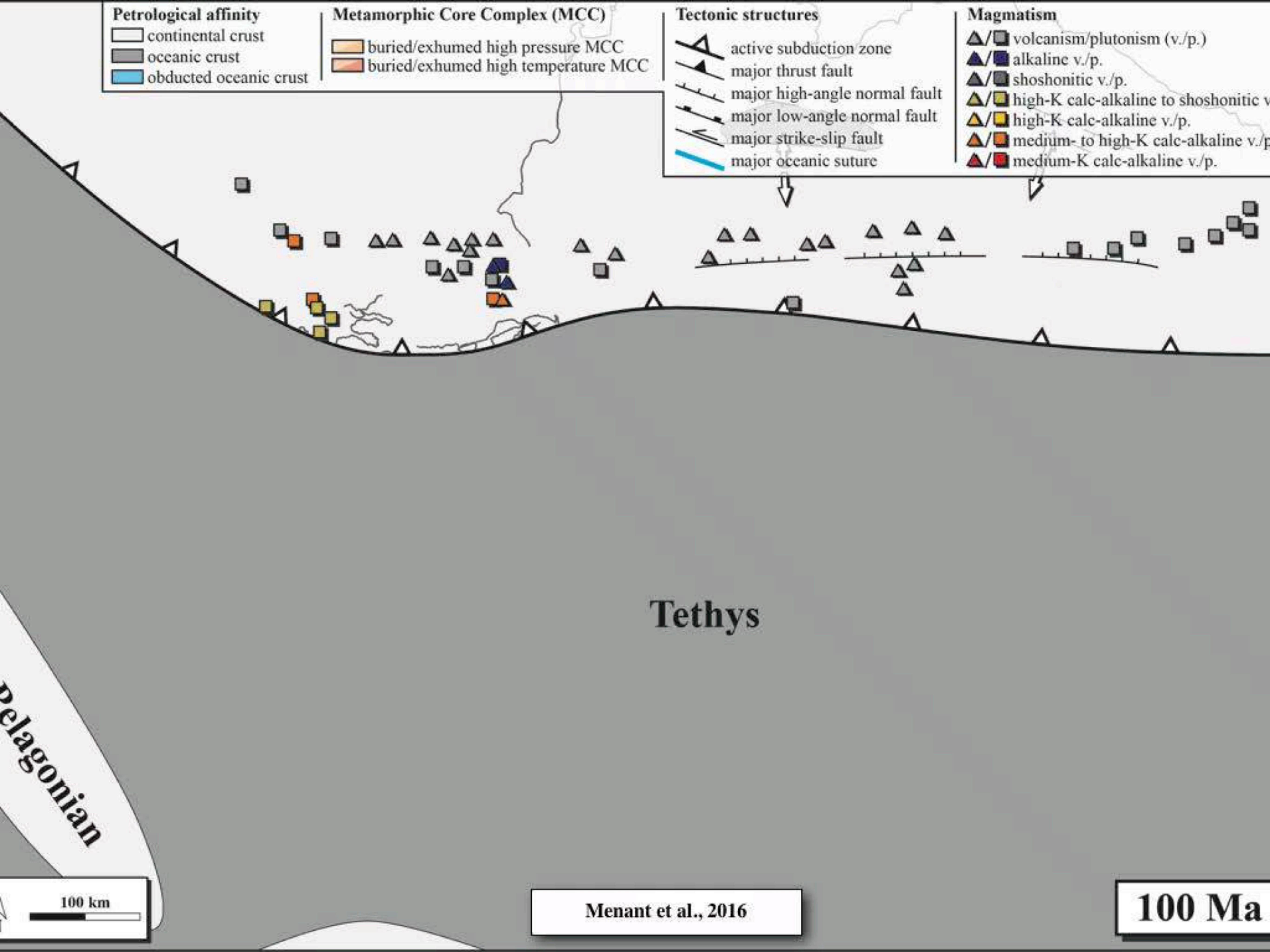
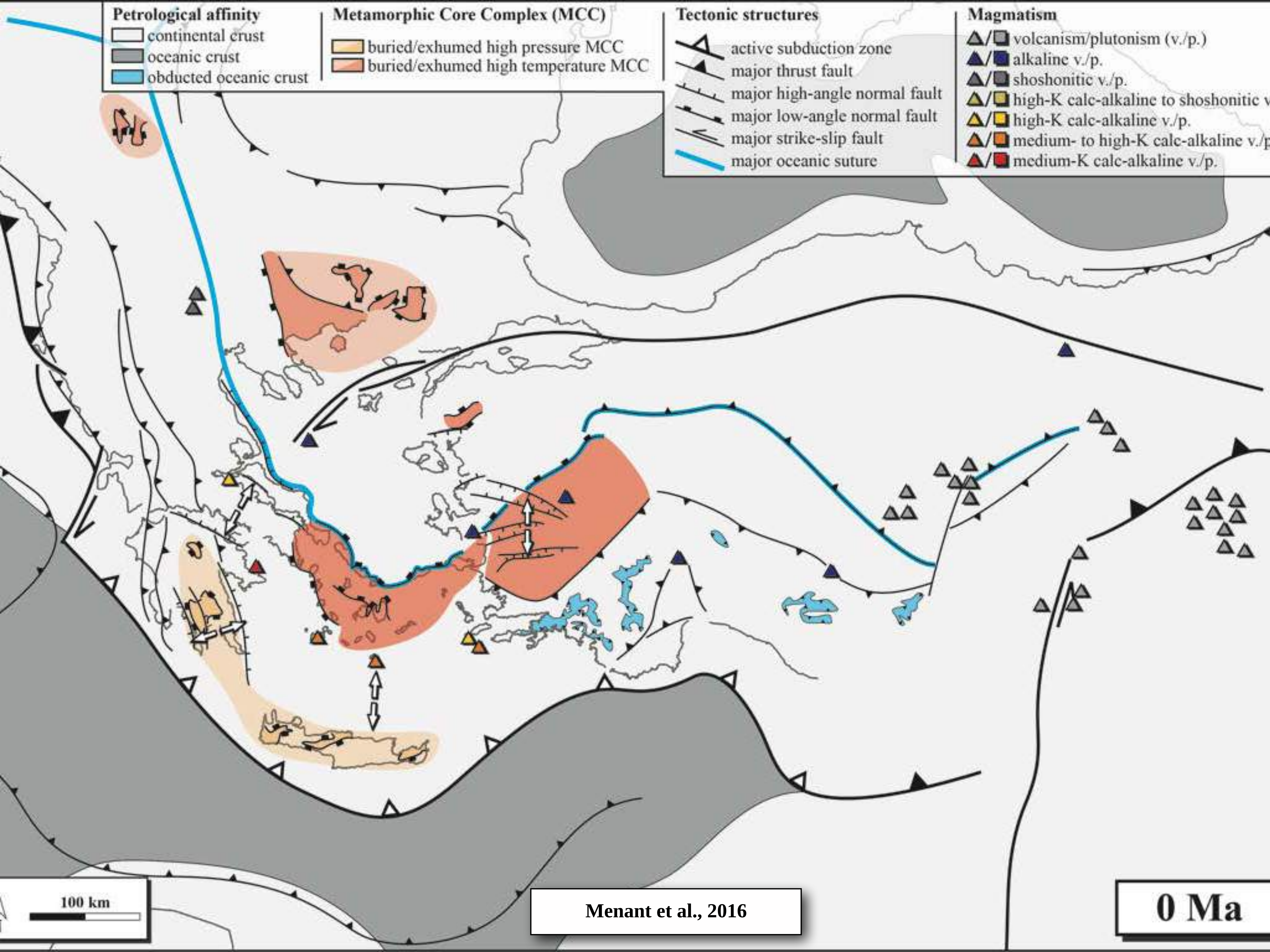


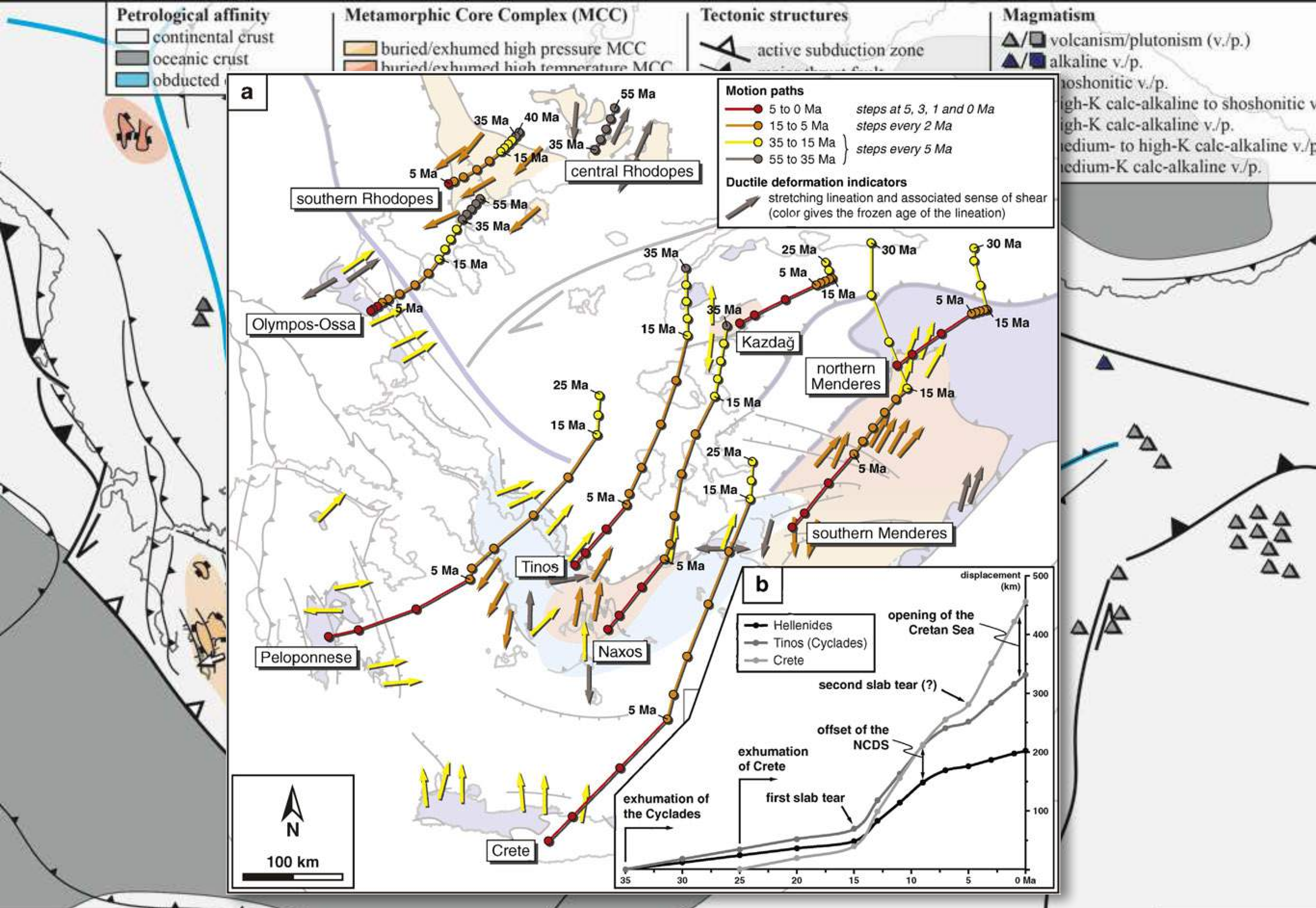
Mantle strain field mimics that of the crust, suggesting efficient coupling

Jolivet et al., 2009; Faccenna et al., 2014

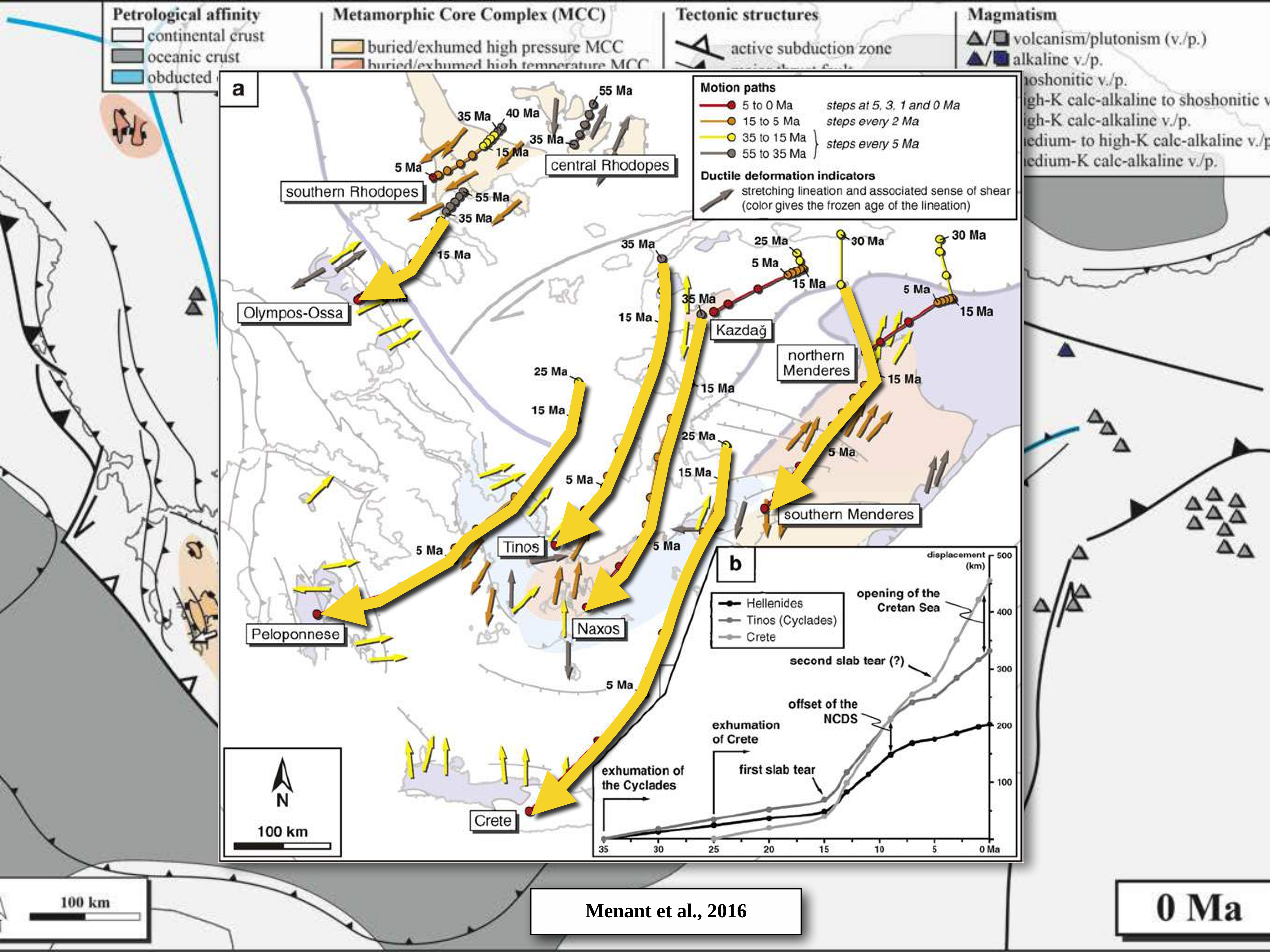

Petrological affinity
continental crust
oceanic crust
obducted oceanic crust
Metamorphic Core Complex (MCC)
buried/exhumed high pressure MCC
buried/exhumed high temperature MCC
Tectonic structures
active subduction zone
major thrust fault
major high-angle normal fault
major low-angle normal fault
major strike-slip fault
major oceanic suture
Magmatism
volcanism/plutonism (v./p.)
alkaline v./p.
shoshonitic v./p.
high-K calc-alkaline to shoshonitic v
high-K calc-alkaline v./p.
medium- to high-K calc-alkaline v./p
medium-K calc-alkaline v./p.
Tethys
Pelagonian
100 km
Menant et al., 2016
100 Ma



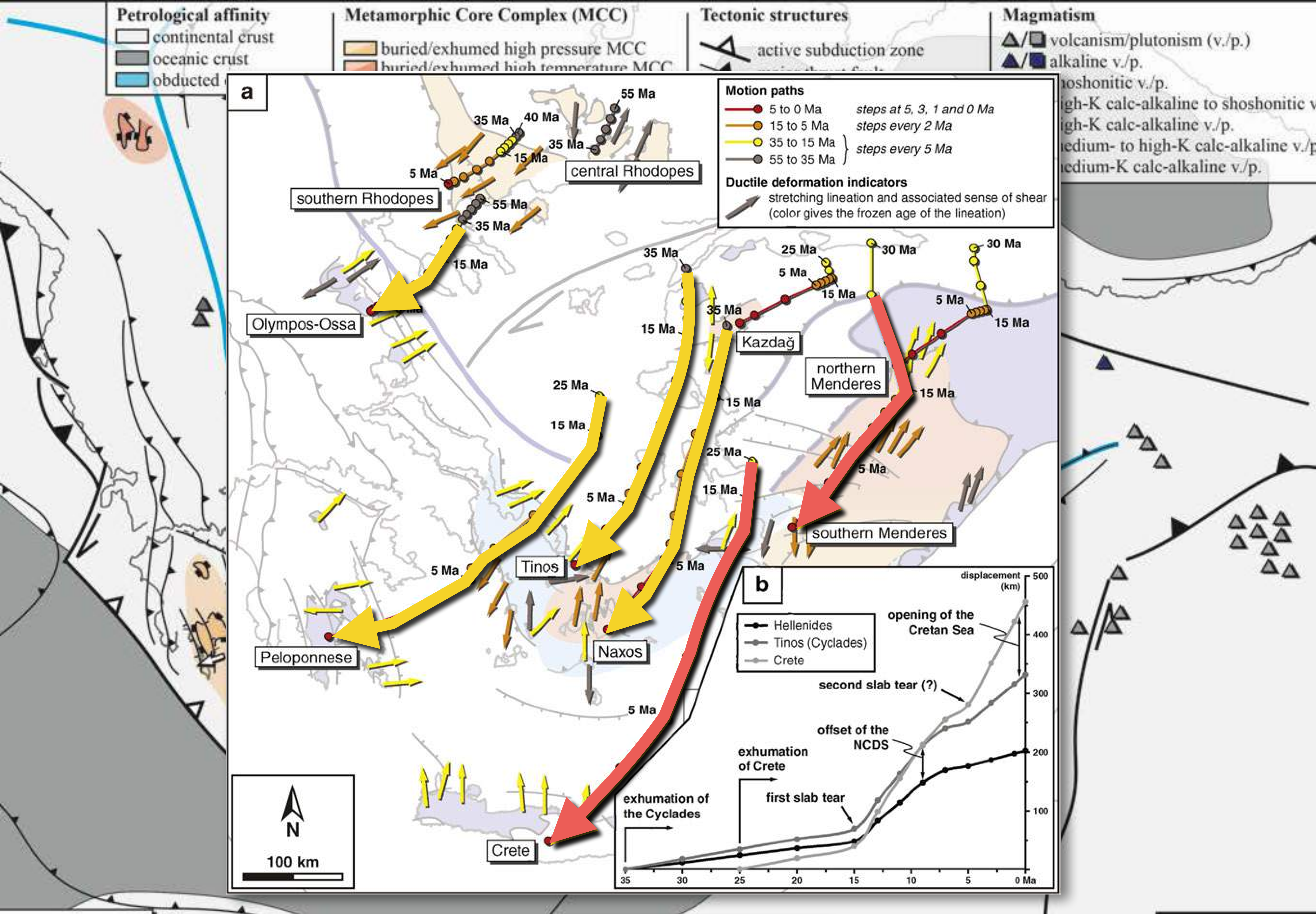
Menant et al., 2016



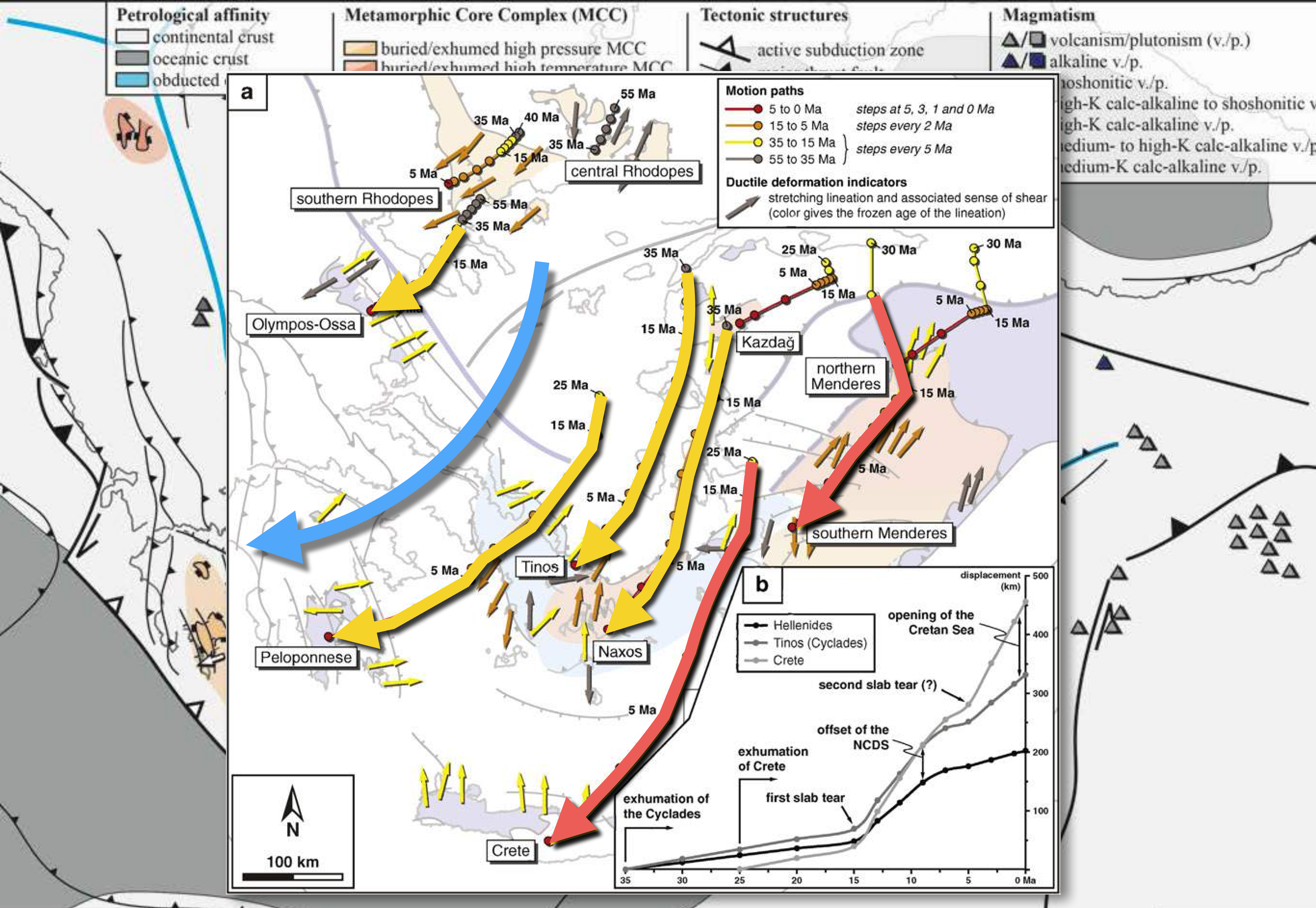
Menant et al., 2016



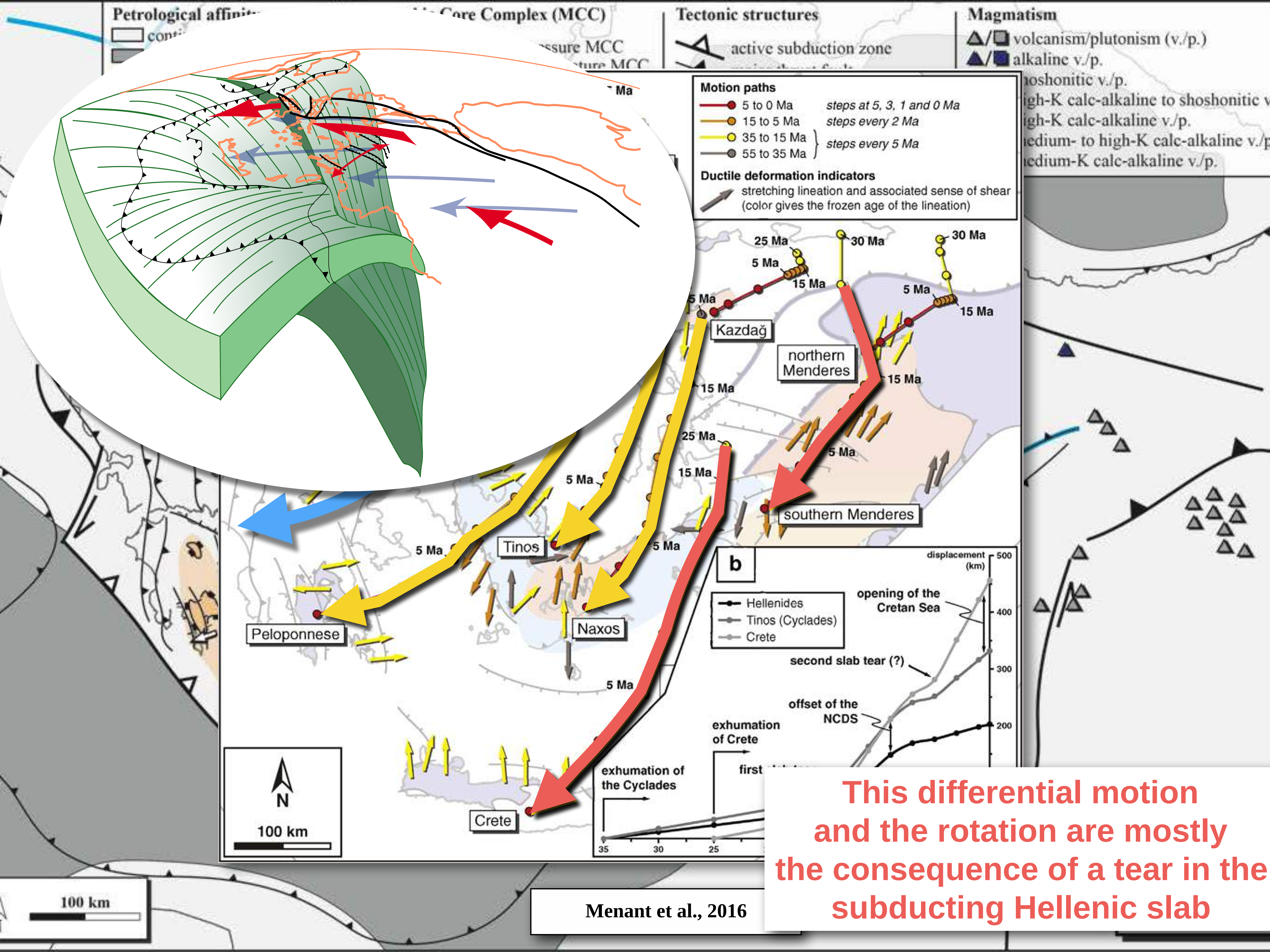
Menant et al., 2016



Menant et al., 2016

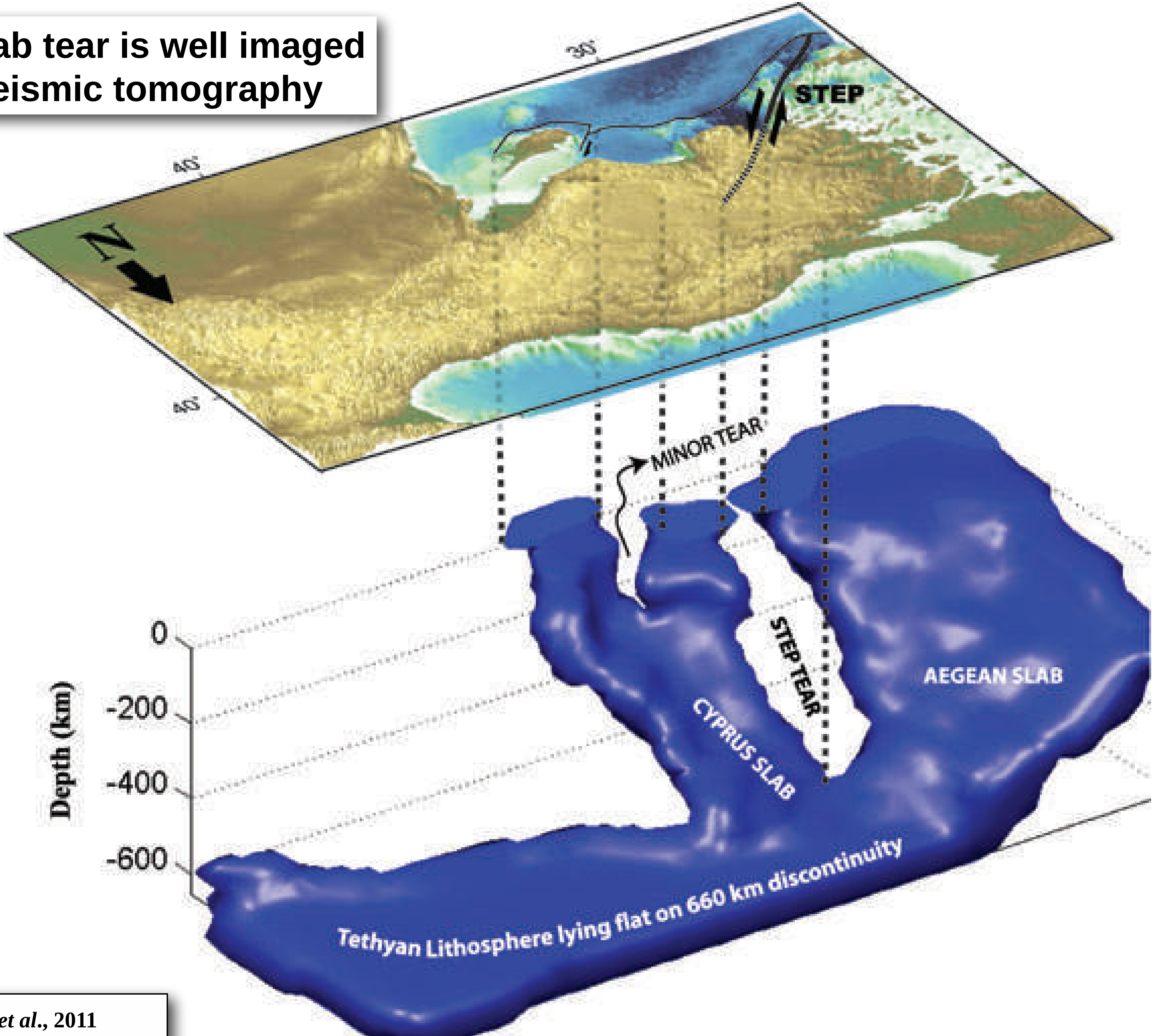


Menant et al., 2016



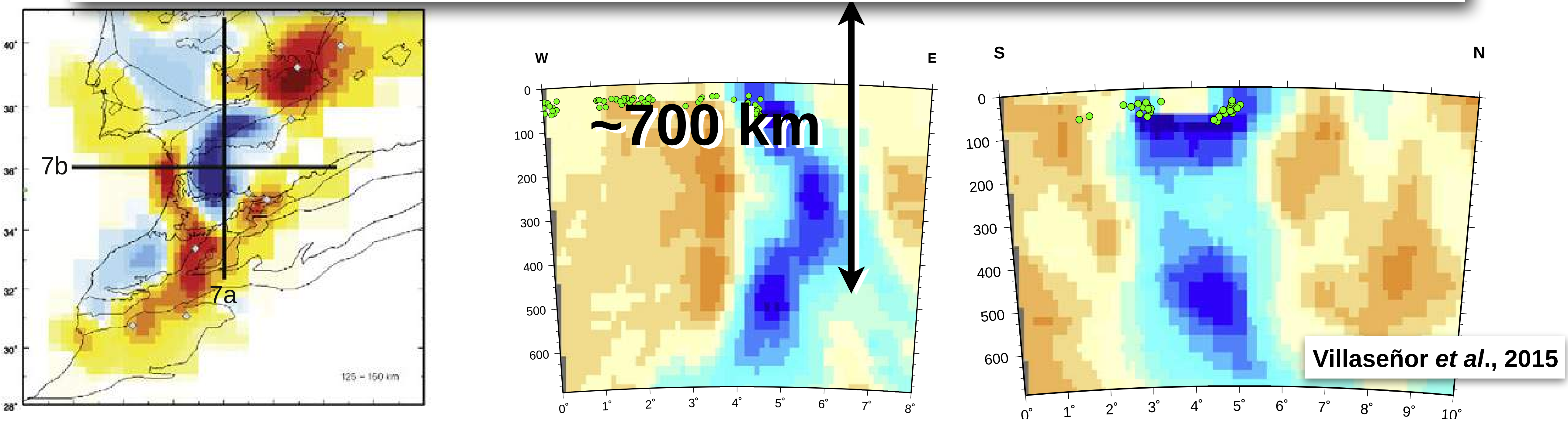
Menant et al., 2016

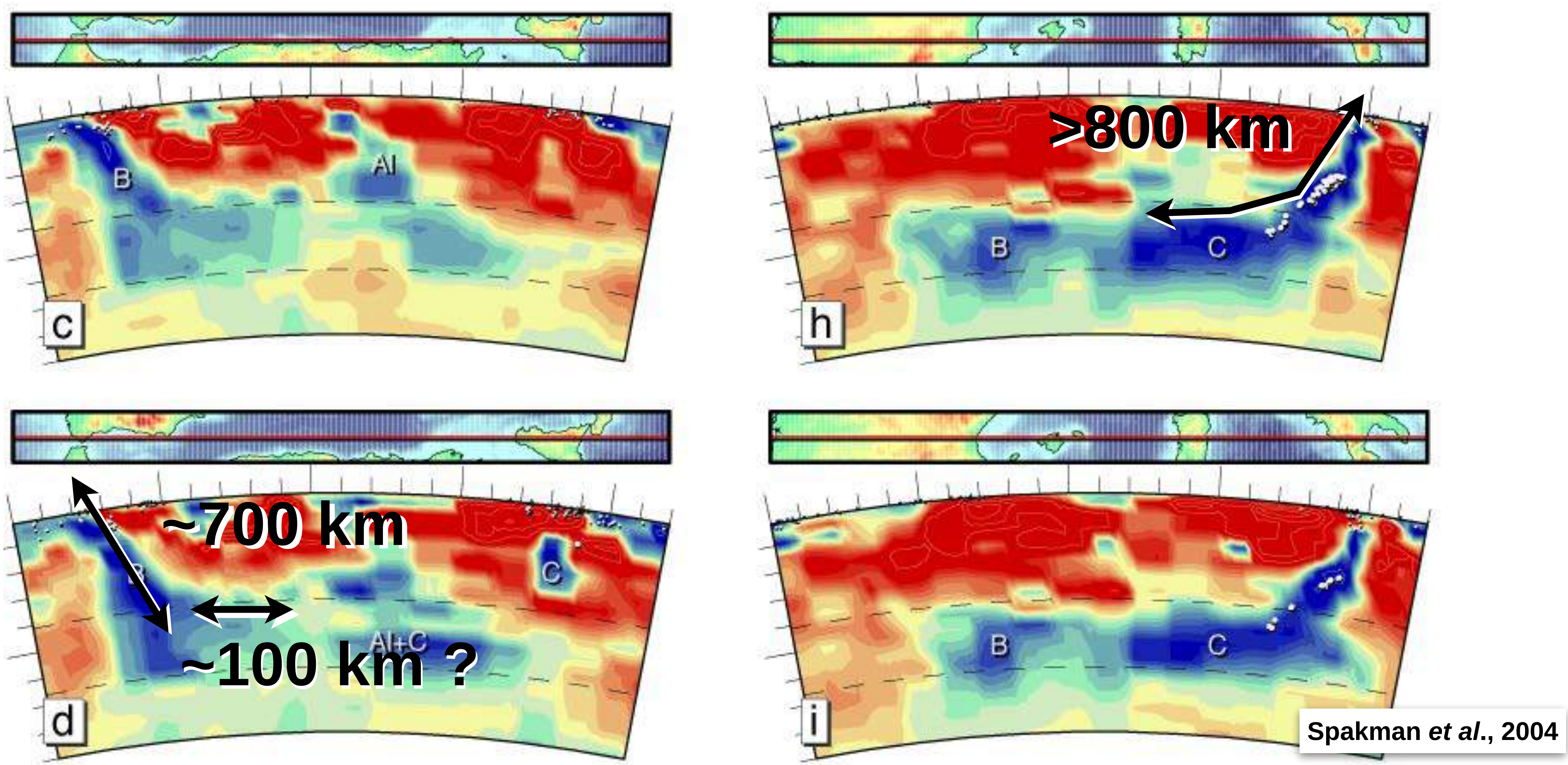
This slab tear is well imaged by seismic tomography



Biryol *et al.*, 2011

The geometry of the subducting lithosphere is well known nowadays





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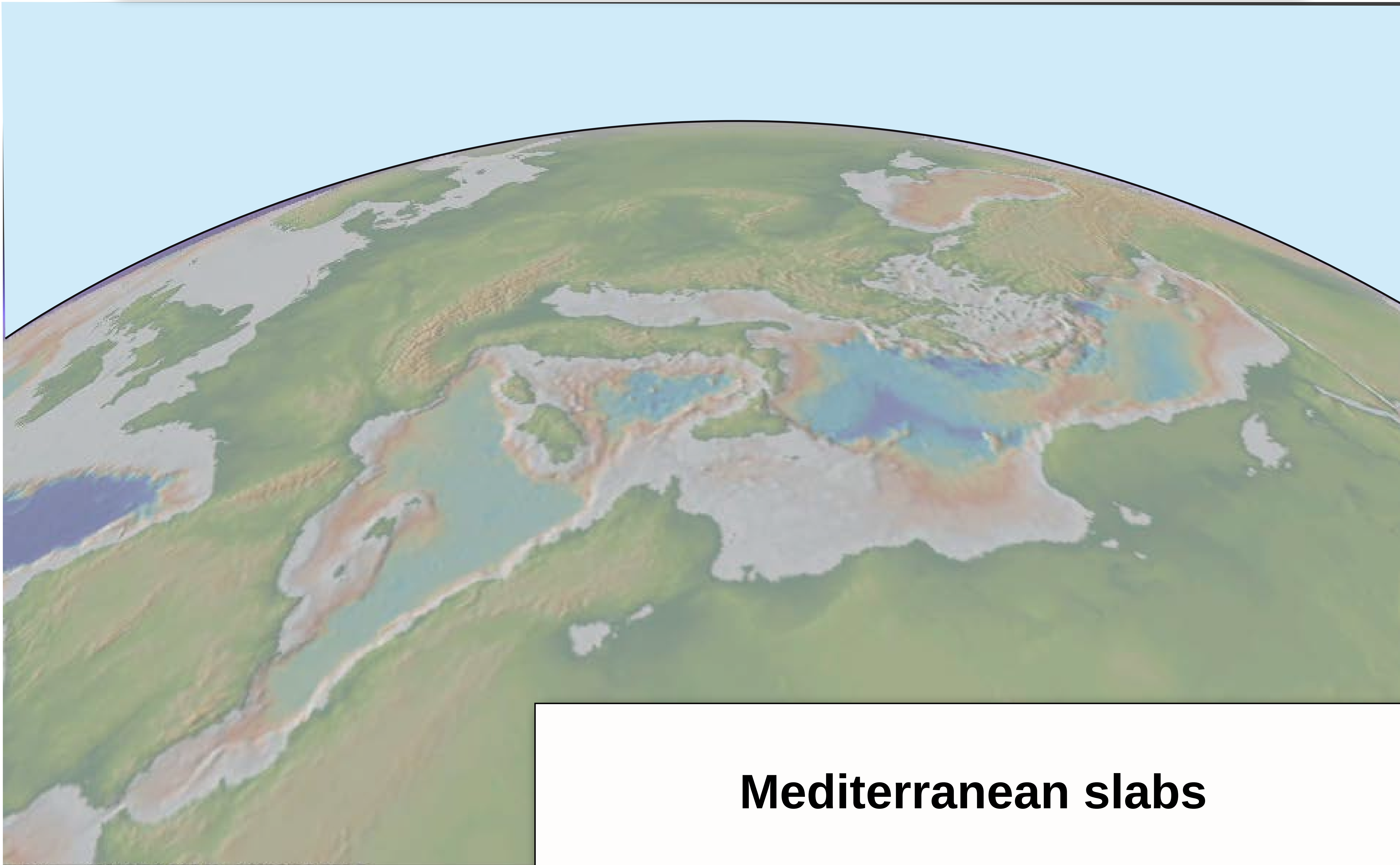

Mediterranean slabs

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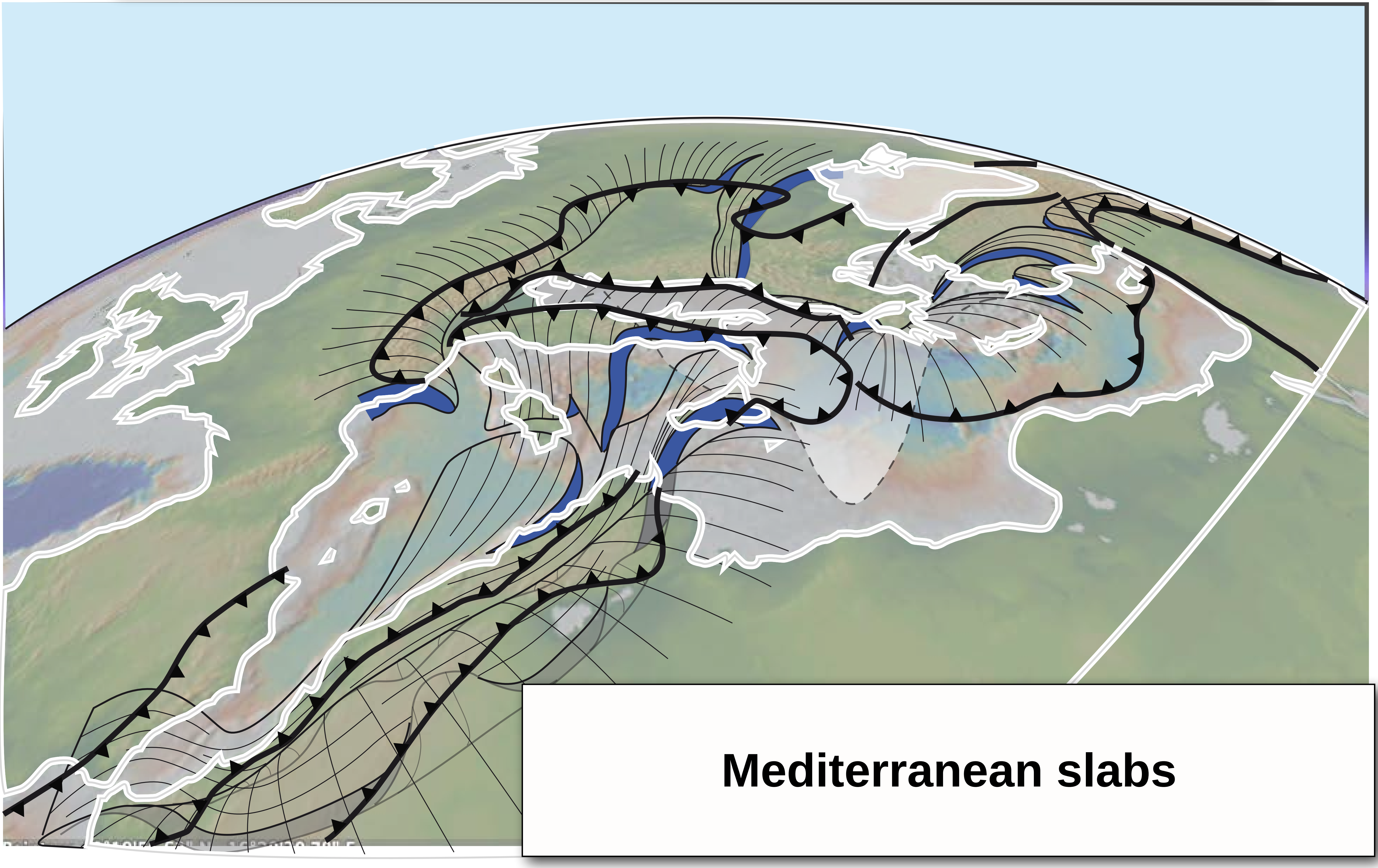

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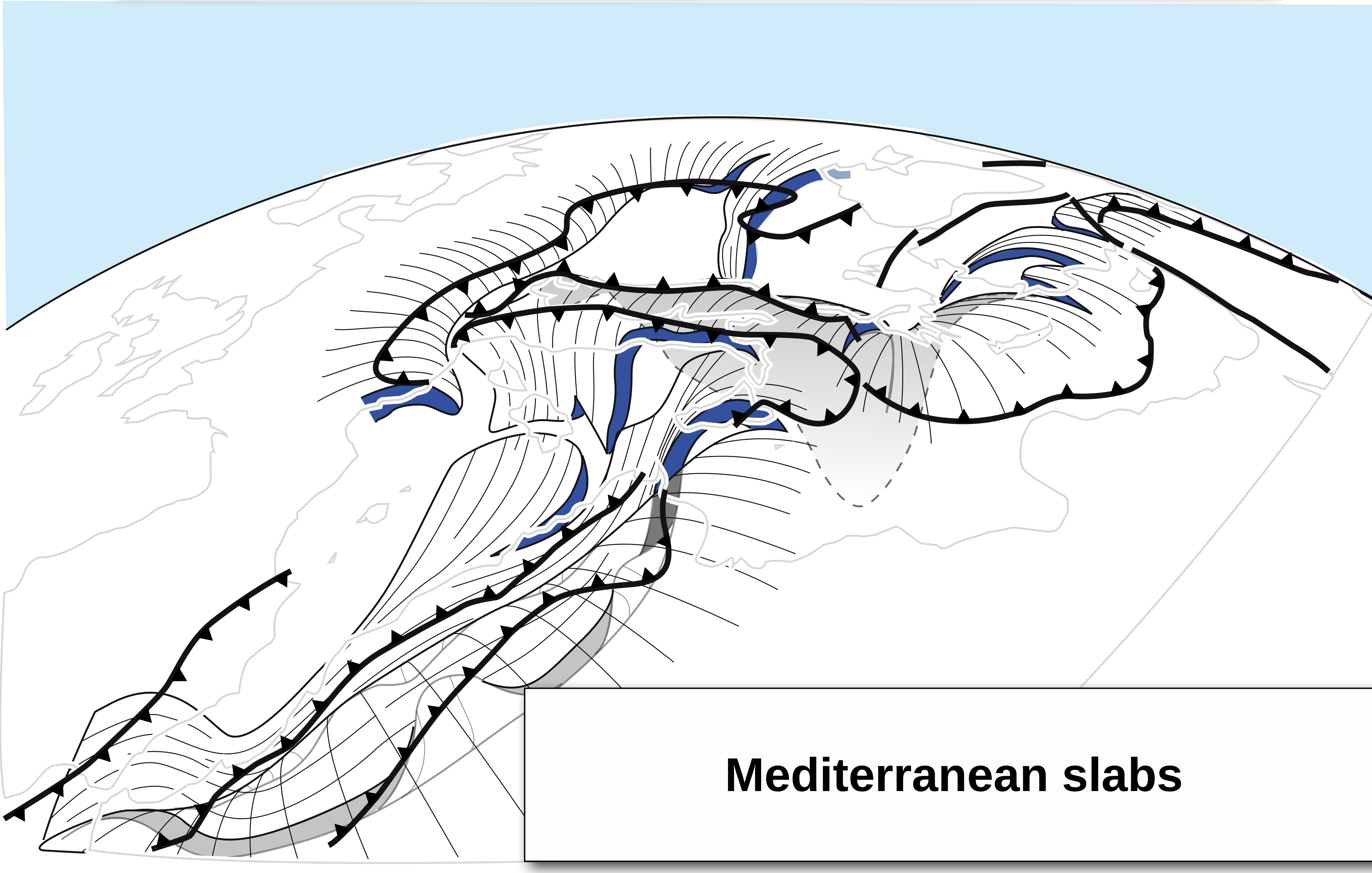
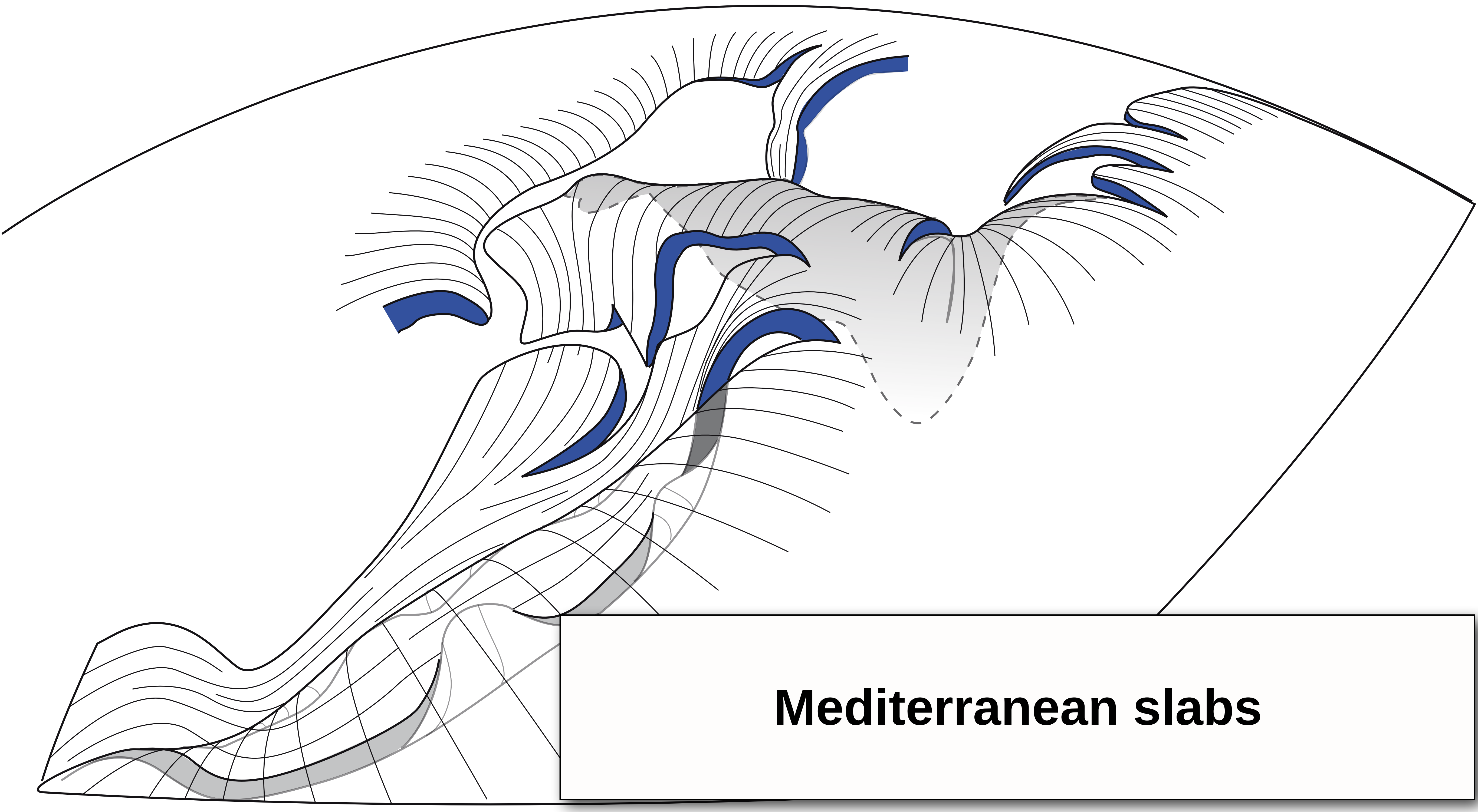


Mediterranean slabs

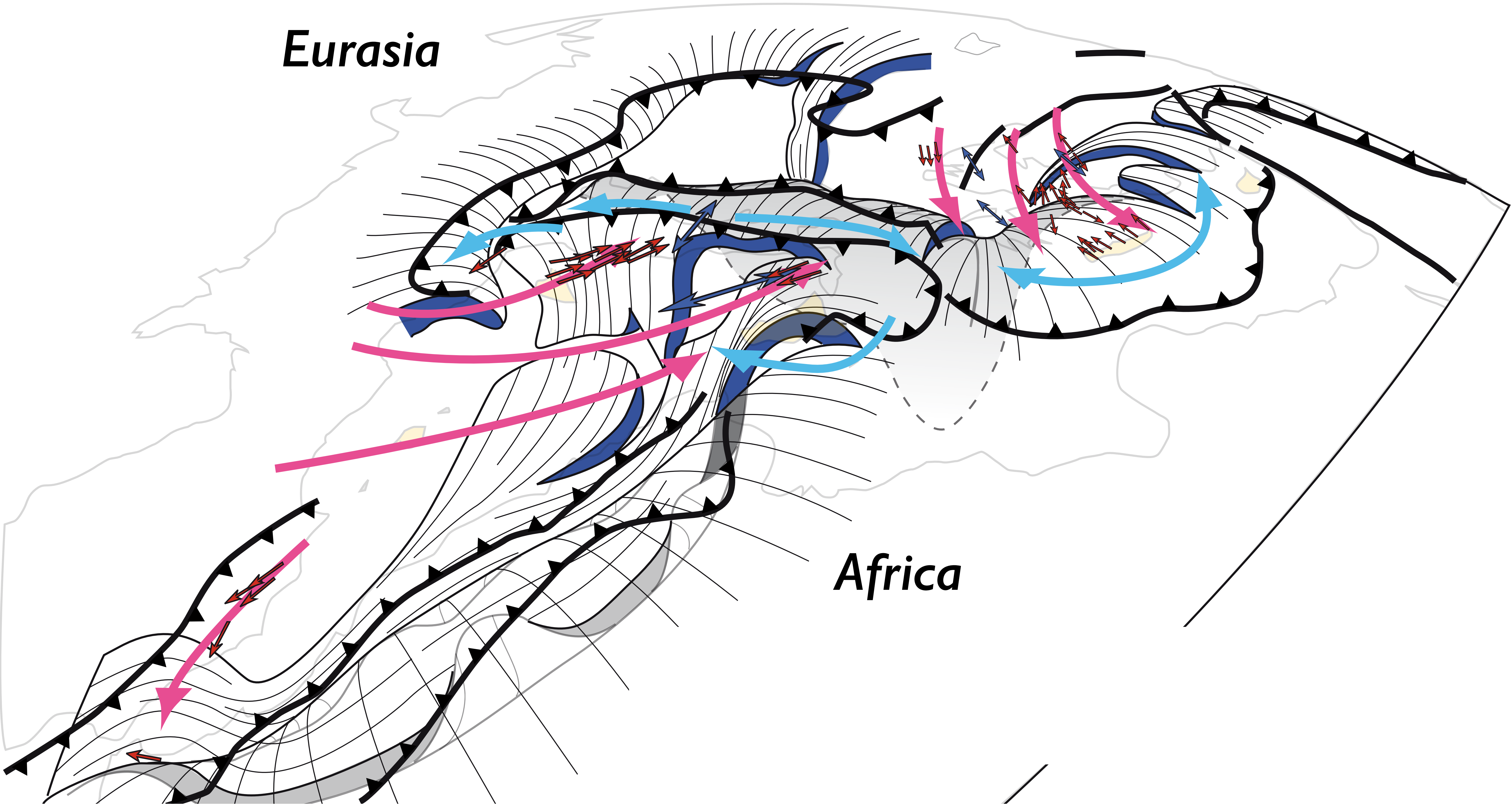
The geometry of the subducting lithosphere is well known nowadays

A complex geometry inherited from 35 Ma of slab retreat



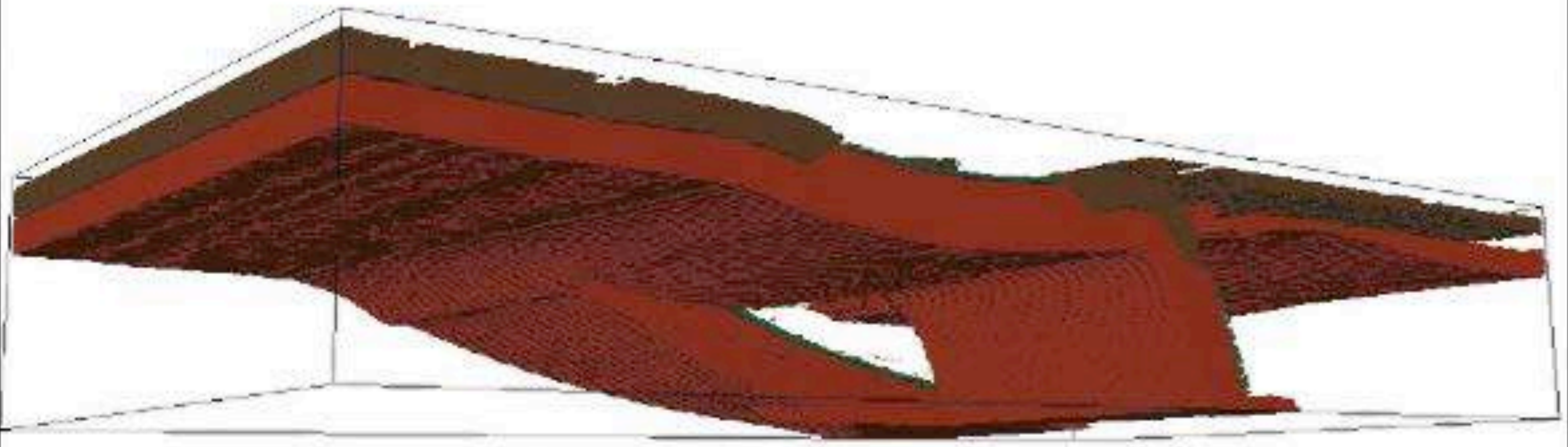
Mediterranean slabs

In this interpretation, slab retreat causes asthenospheric flow, which in turns controls back-arc extension above



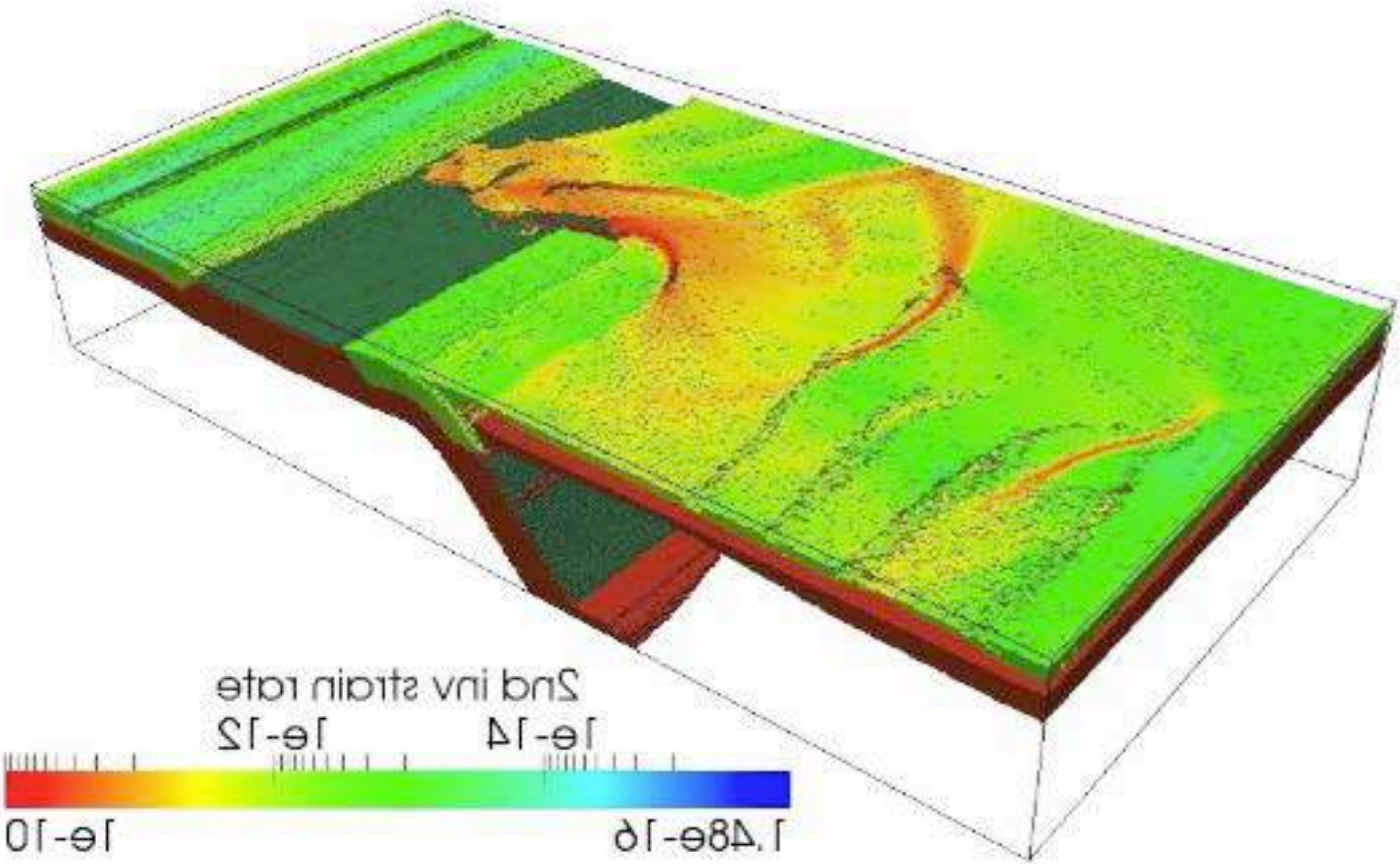
Jolivet, Faccenna & Piromallo, 2009.

Modelling the effects of a slab tear:



Sternai et al., 2014

Modelling the effects of a slab tear:



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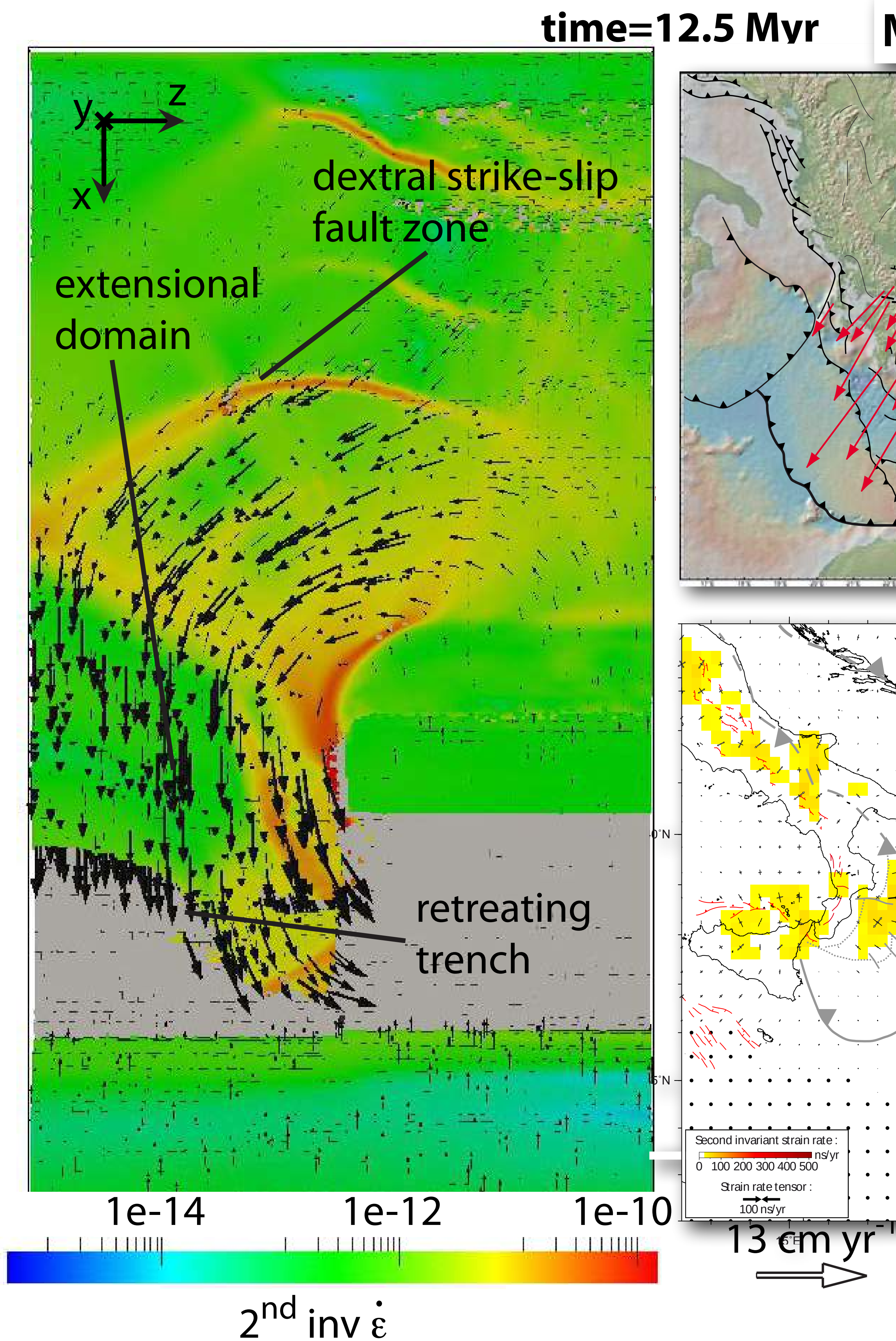
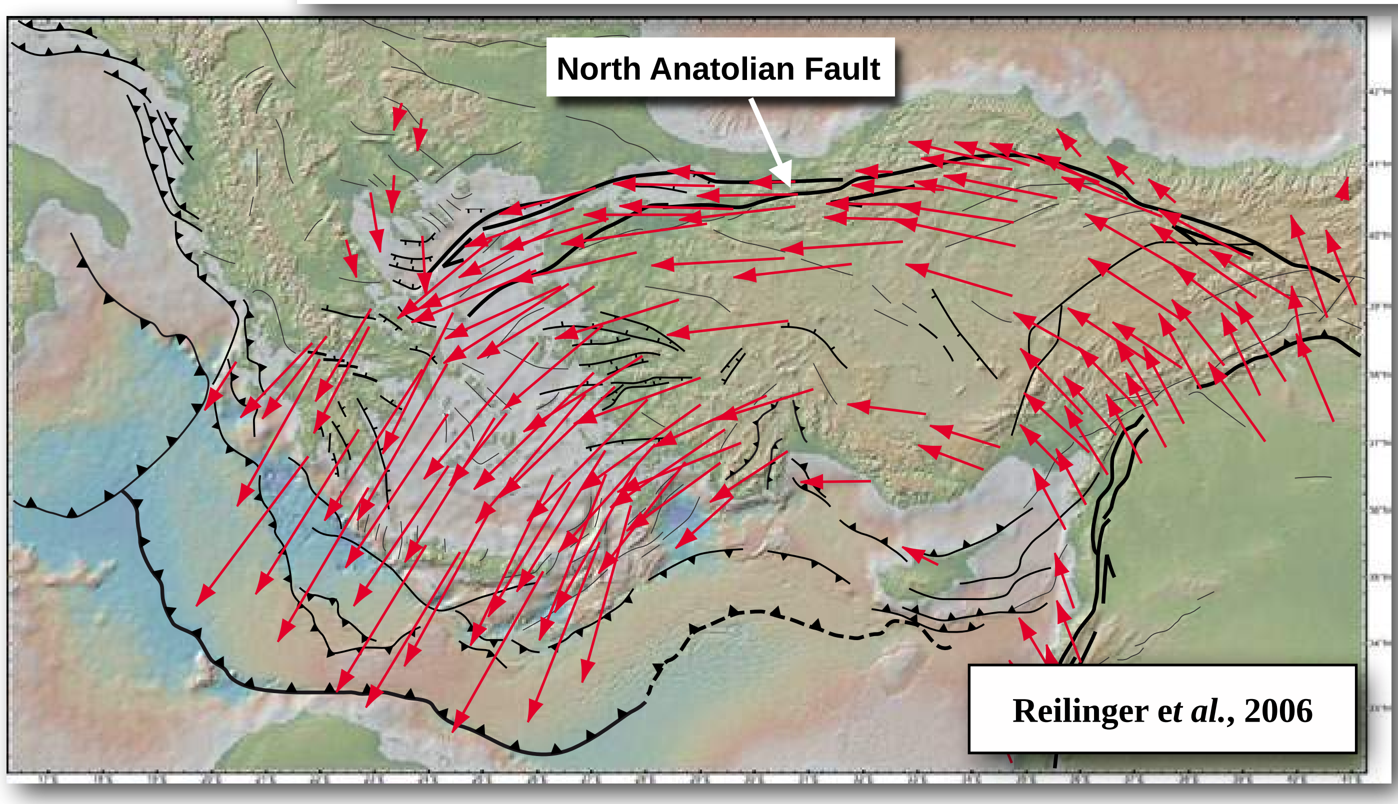
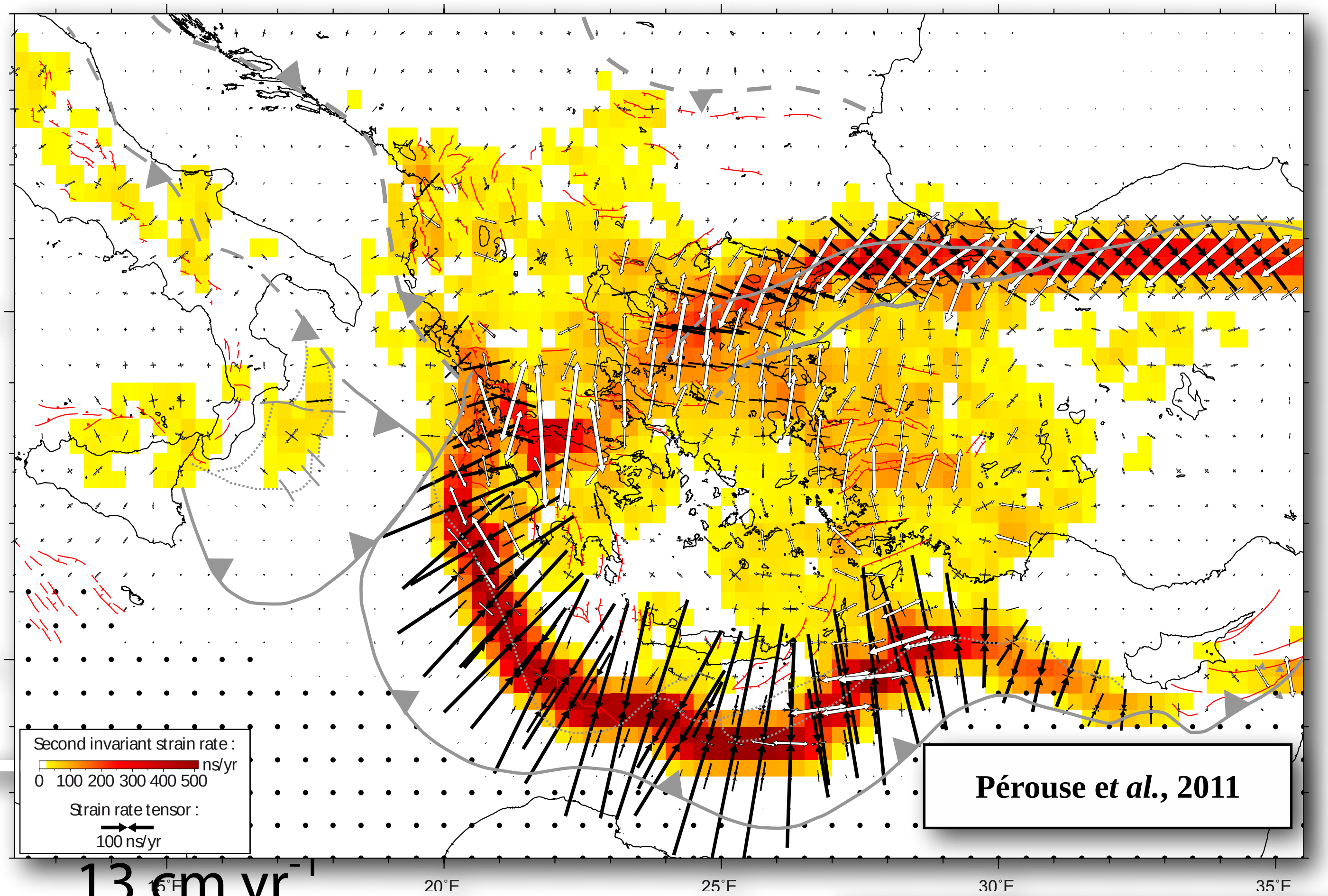
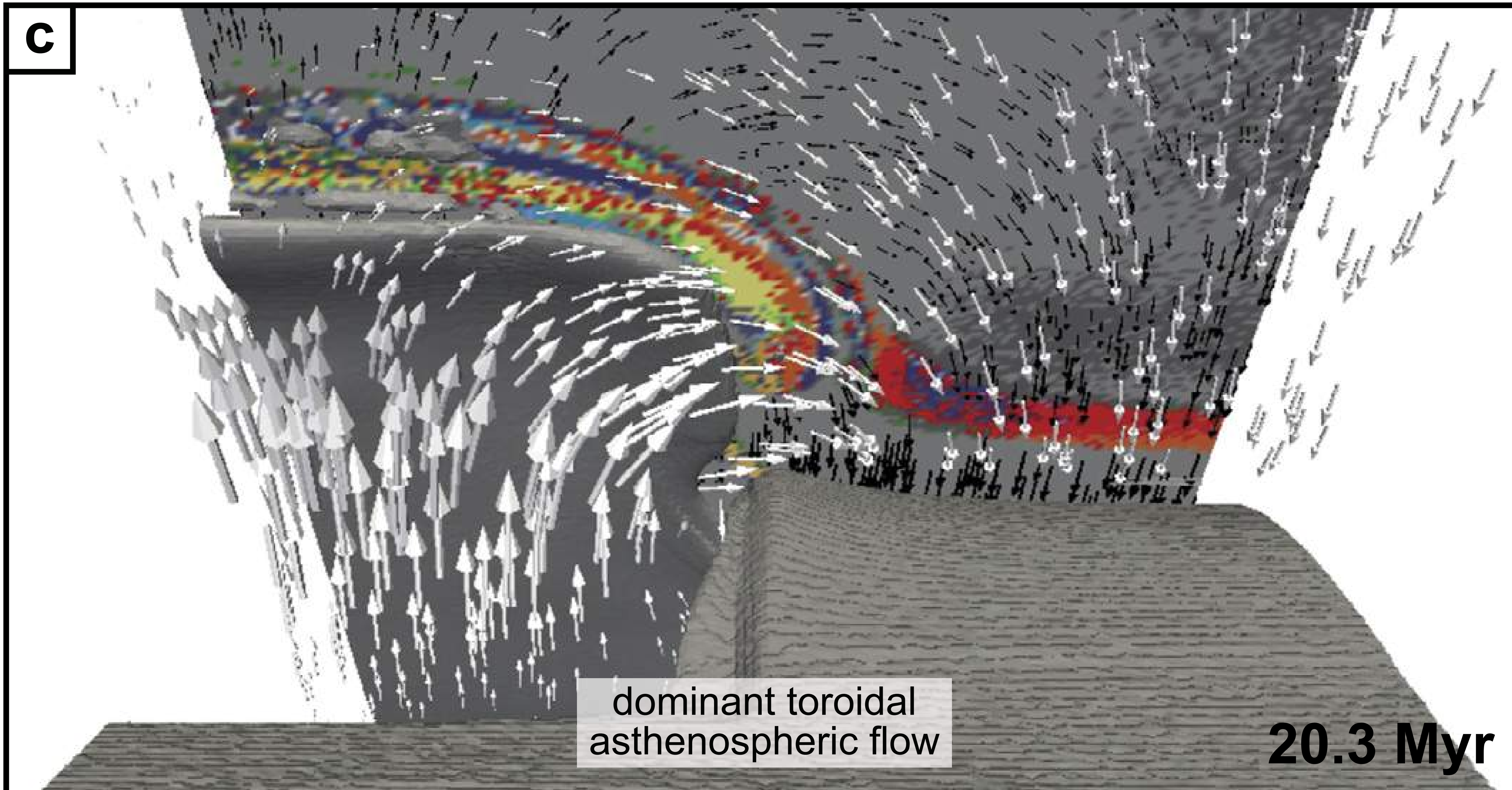






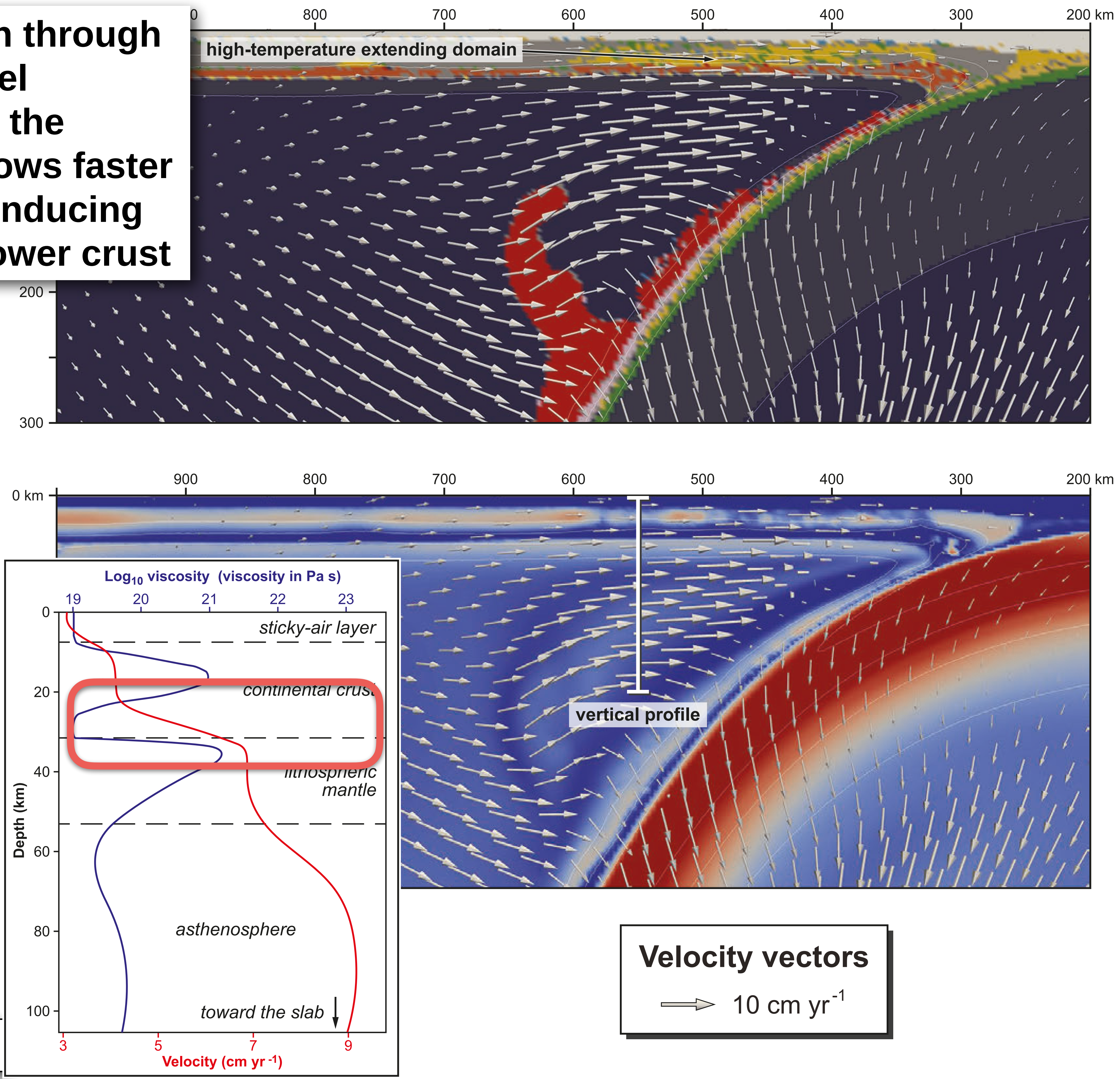
Sternai et al., 2014

In this new model, arrows show the asthenospheric flow and colours show melts (magmas)



Menant *et al.*, 2016

A vertical section through this model shows that the asthenosphere flows faster than the crust, inducing shearing of the lower crust



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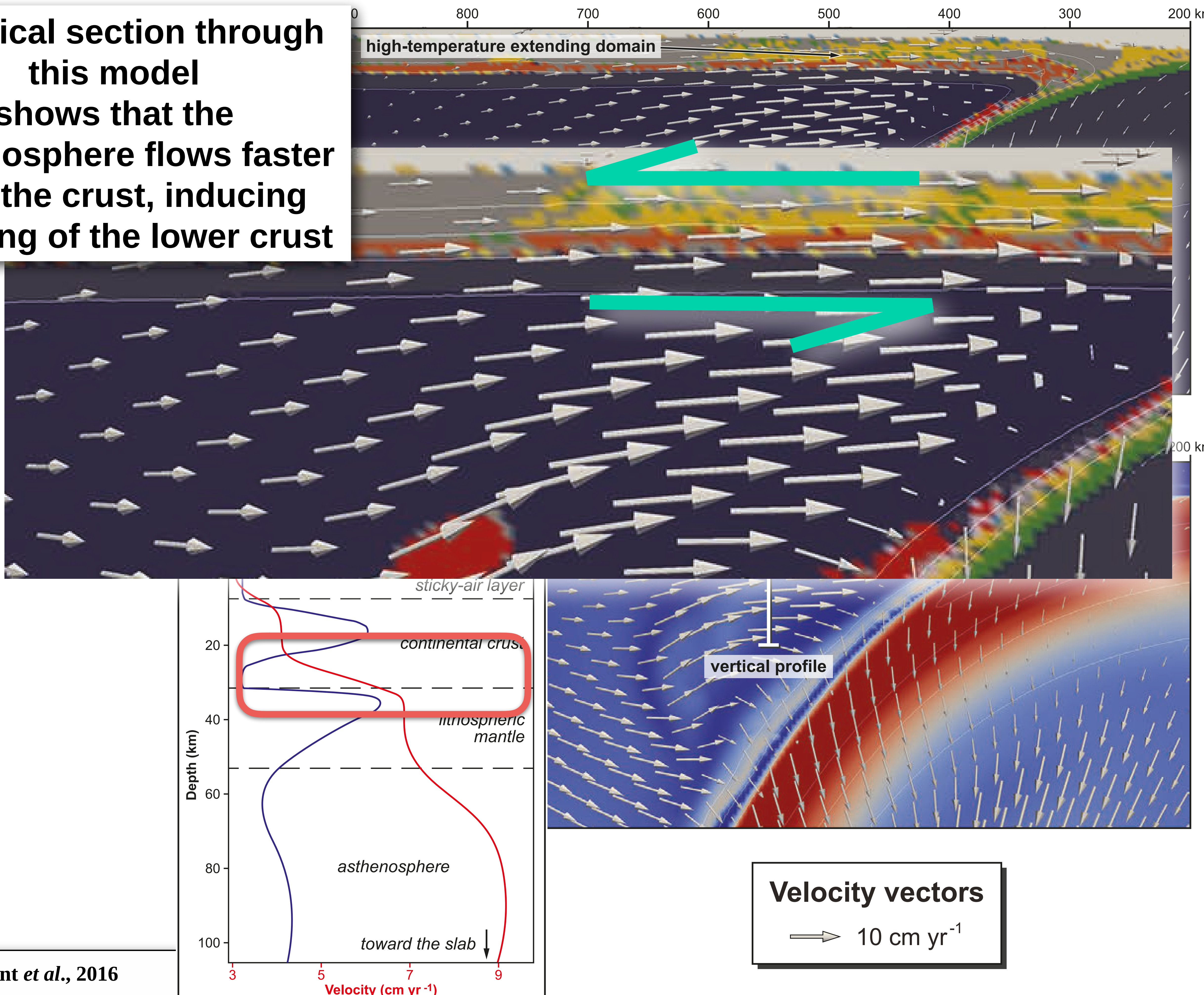
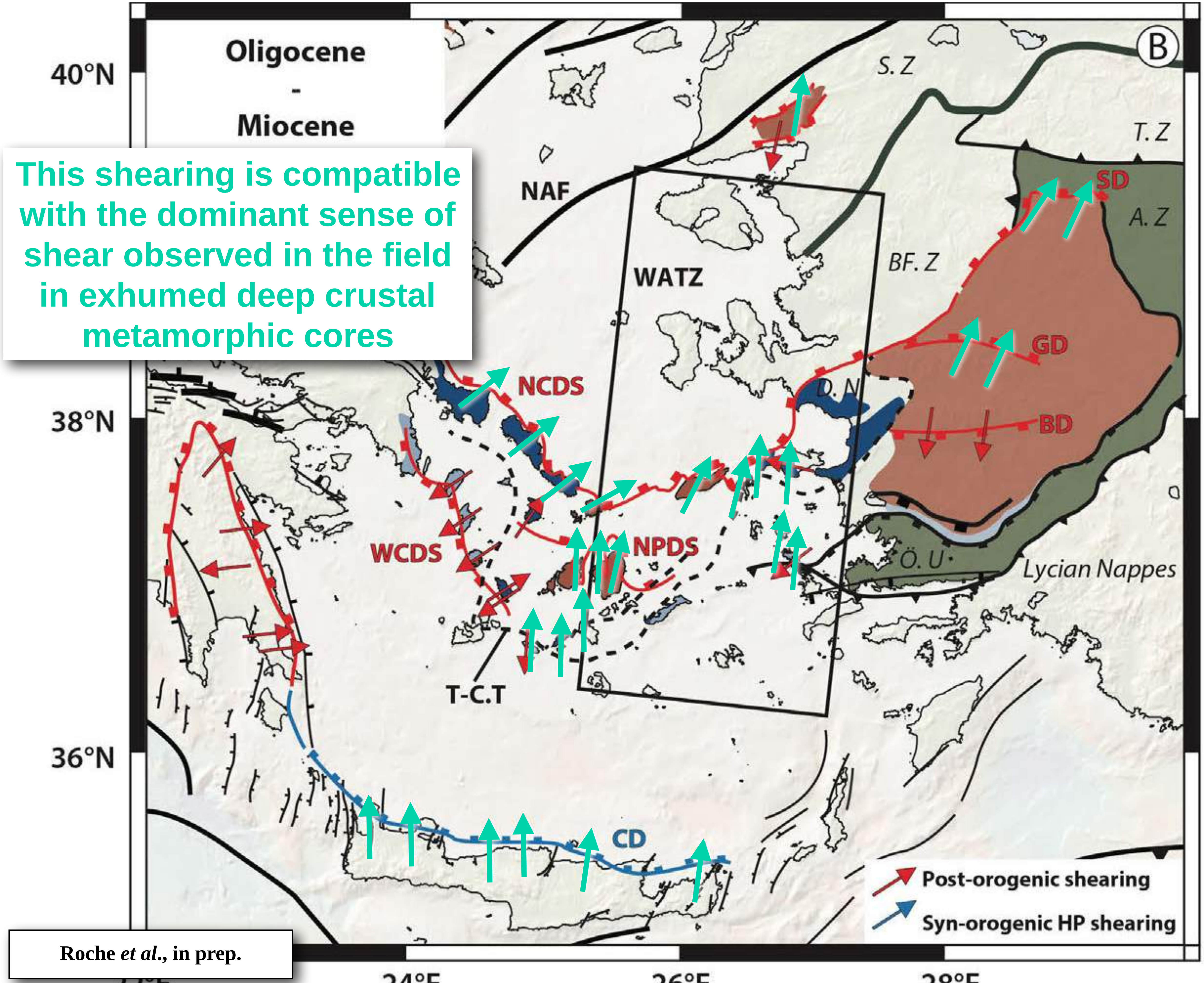
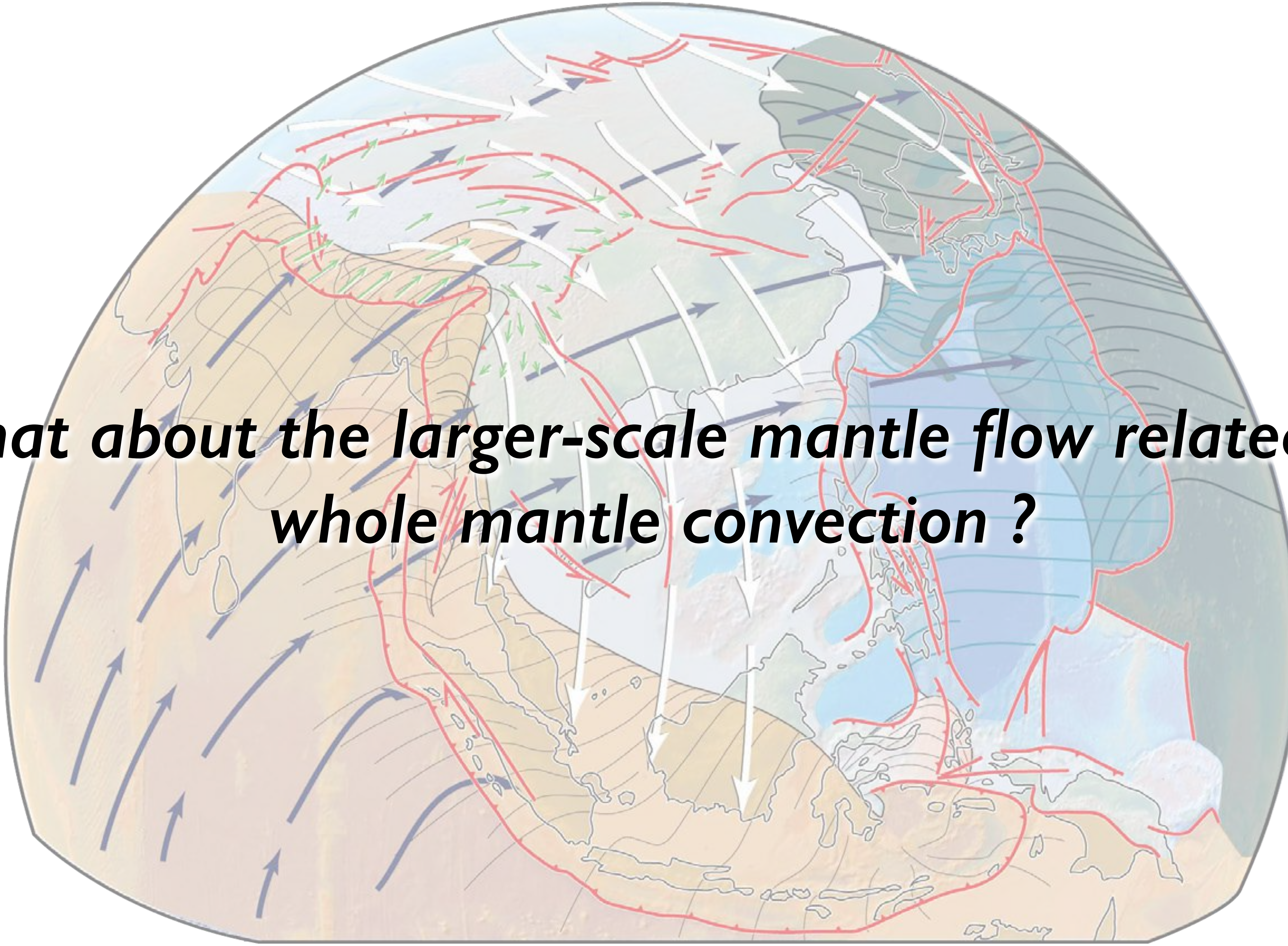
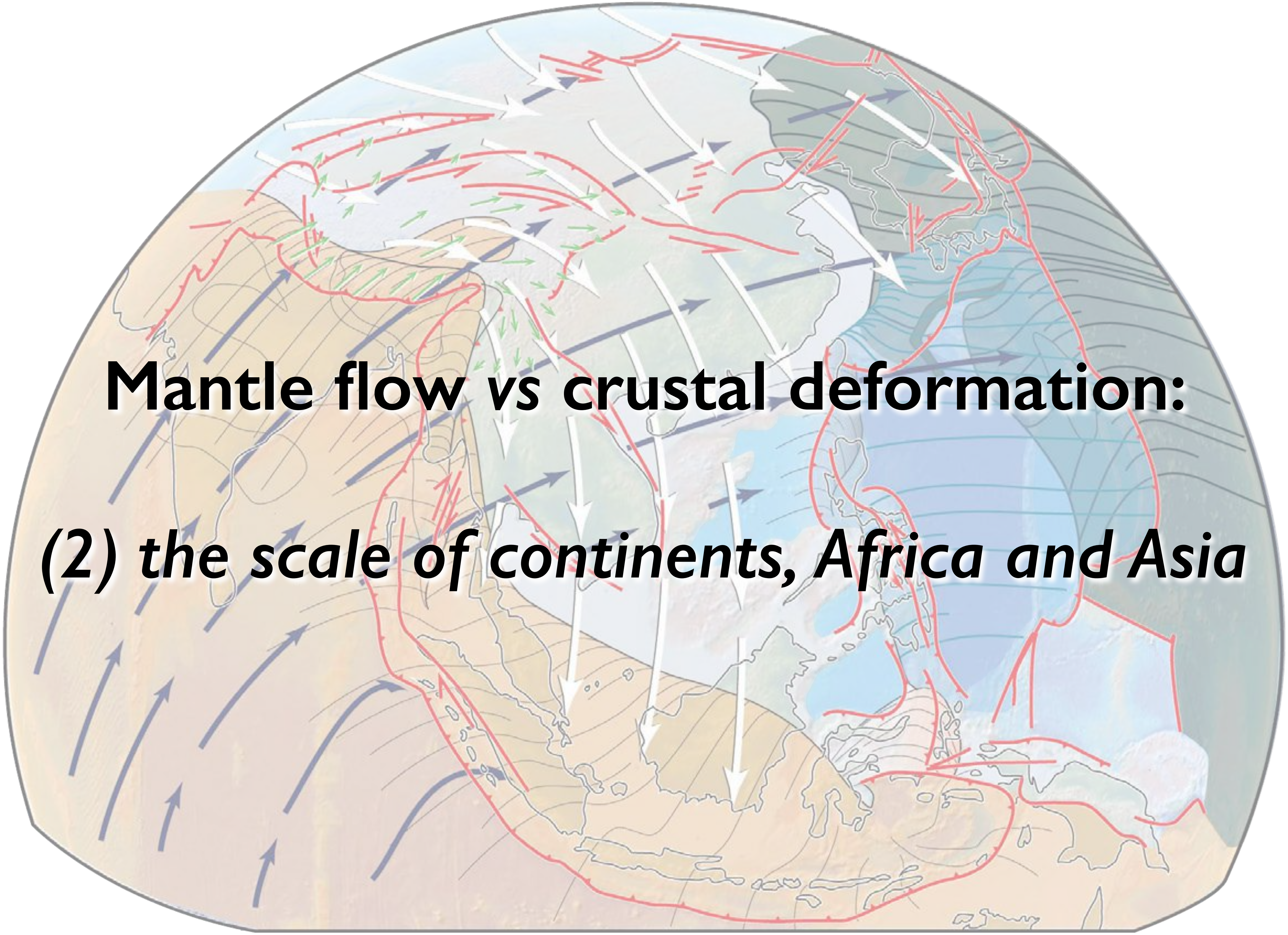


Menant *et al.*, 2016


Oligocene
-
Miocene
This shearing is compatible with the dominant sense of shear observed in the field in exhumed deep crustal metamorphic cores
40°N
38°N
36°N
24°E
26°E
28°E
B
S. Z
T. Z
SD
A. Z
BF. Z
NAF
WATZ
GD
BD
D. N
NCDS
WCDS
NPDS
Ö. U
Lycian Nappes
T-C.T
CD
Post-orogenic shearing
Syn-orogenic HP shearing
Roche et al., in prep.

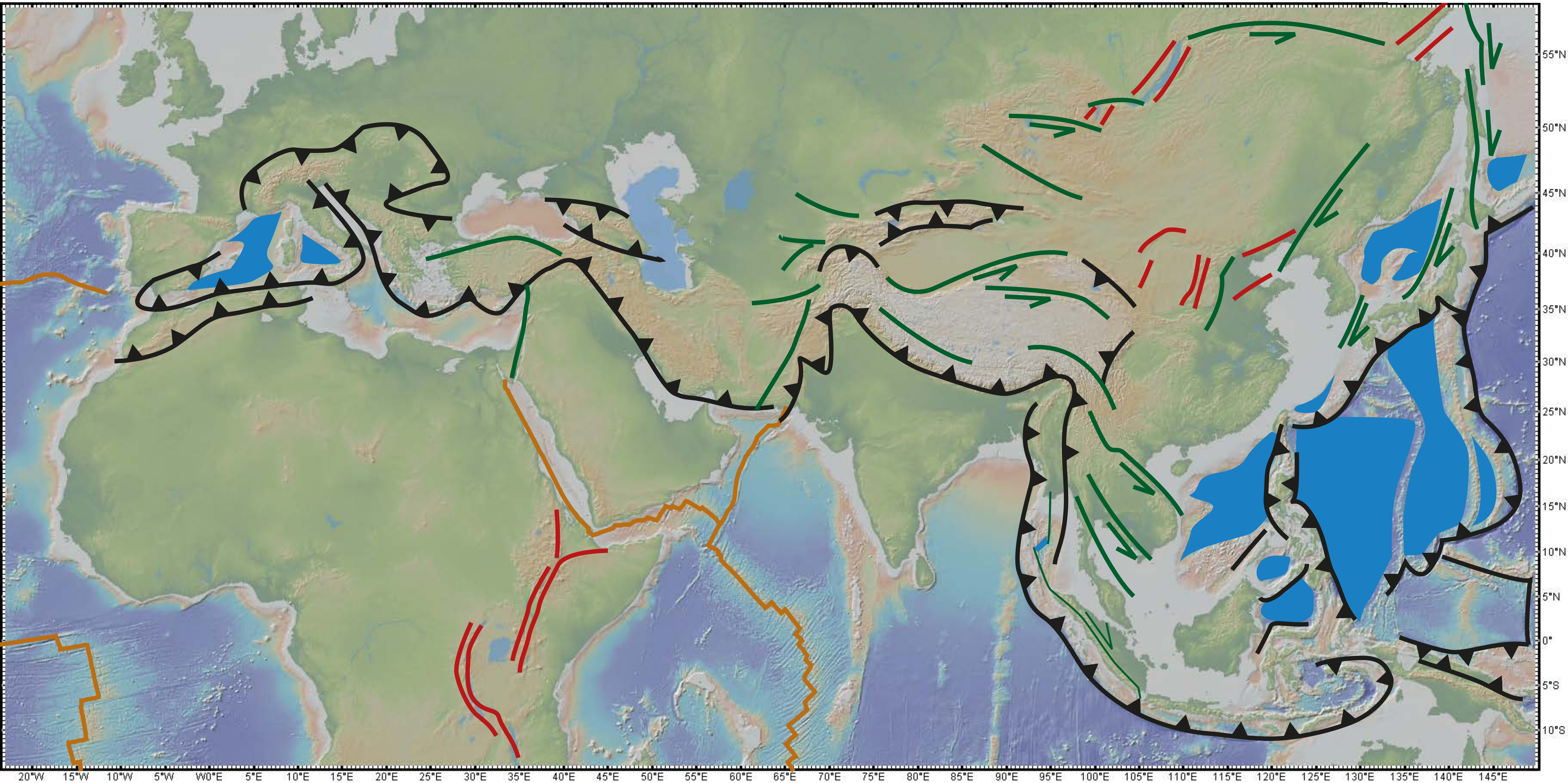


What about the larger-scale mantle flow related to whole mantle convection ?



Mantle flow *vs* crustal deformation:

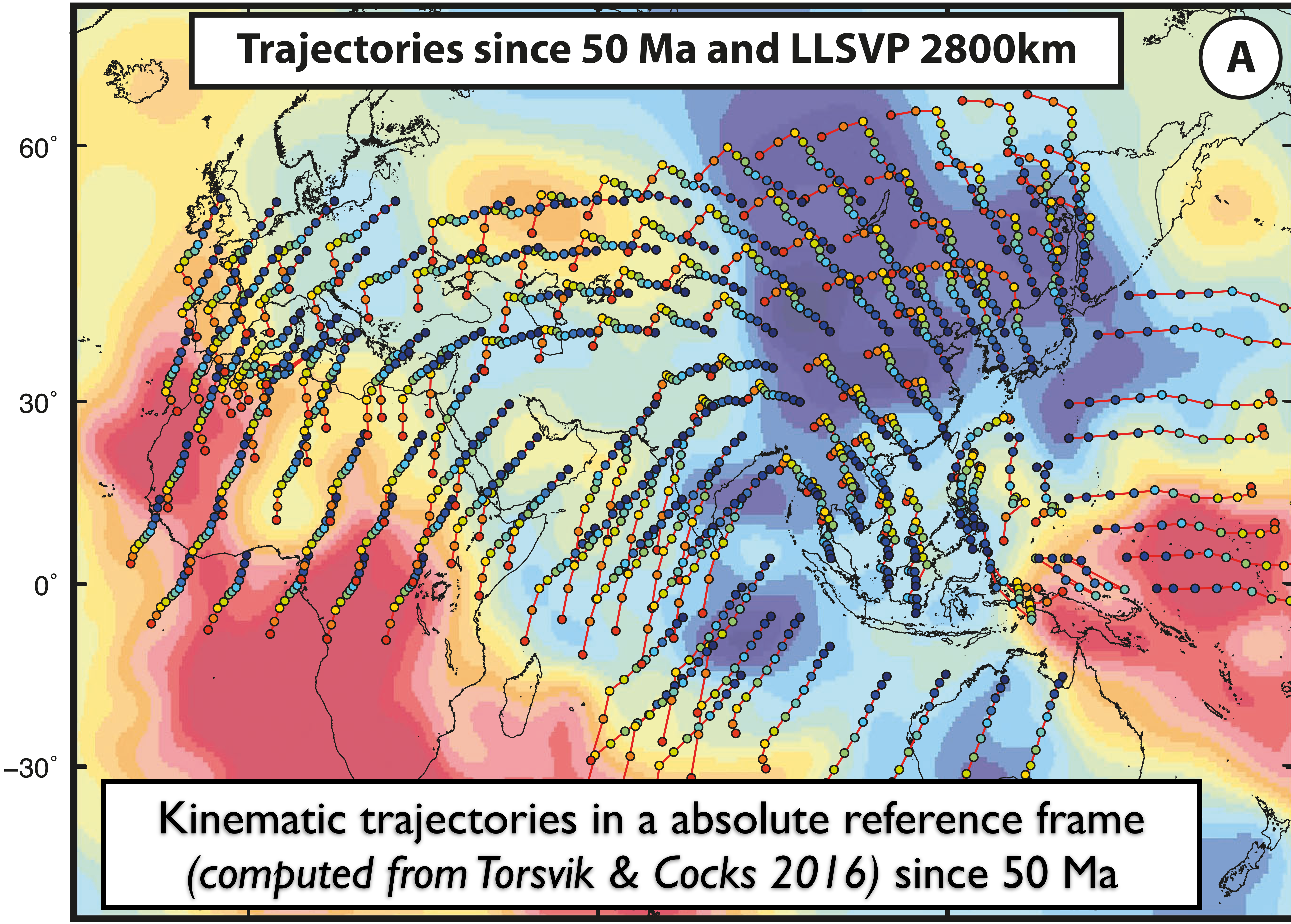
(2) the scale of continents, Africa and Asia



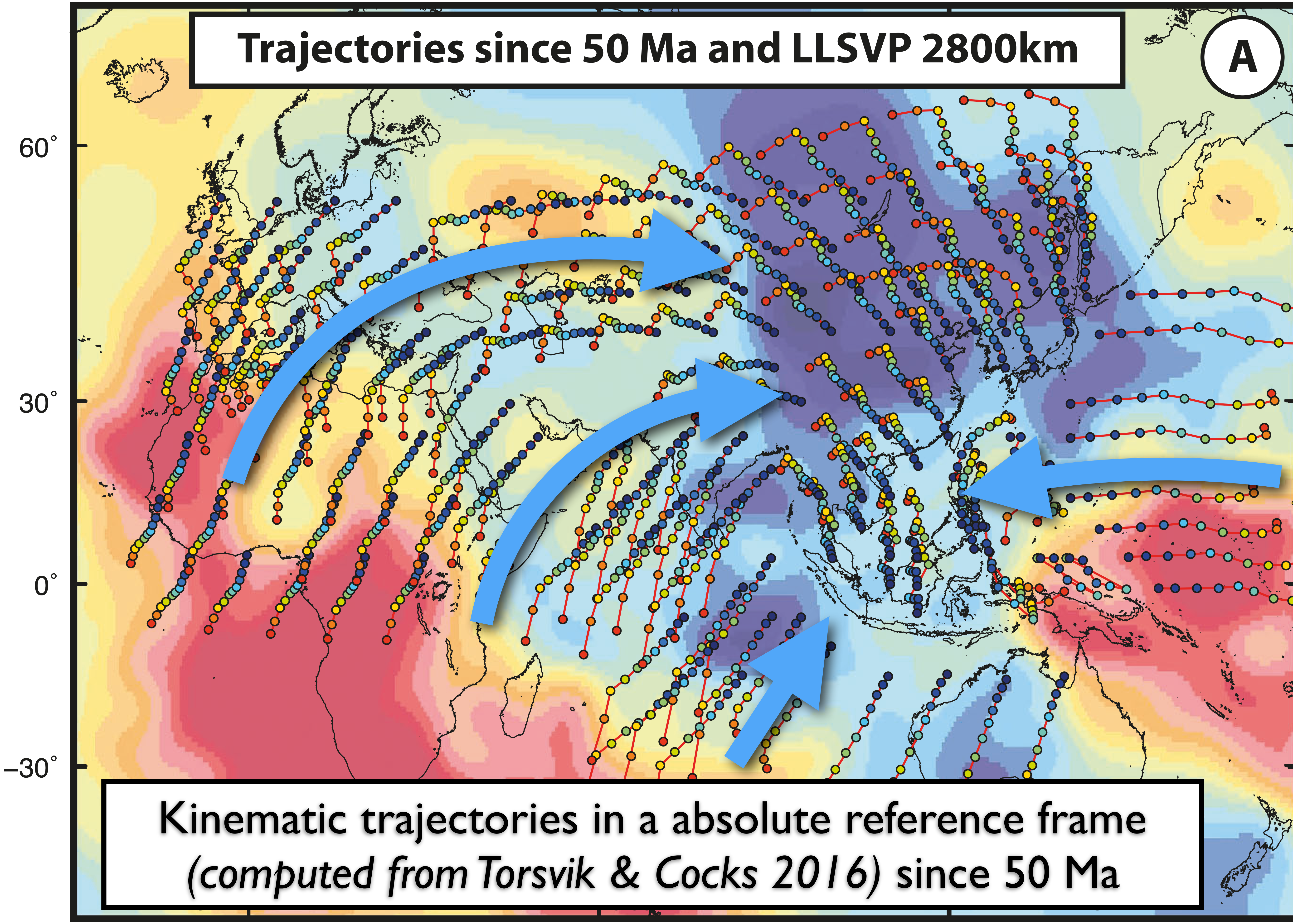
major thrust fronts

major strike-slip faults

major rifts



tomography from Becker and Boschi, 2002



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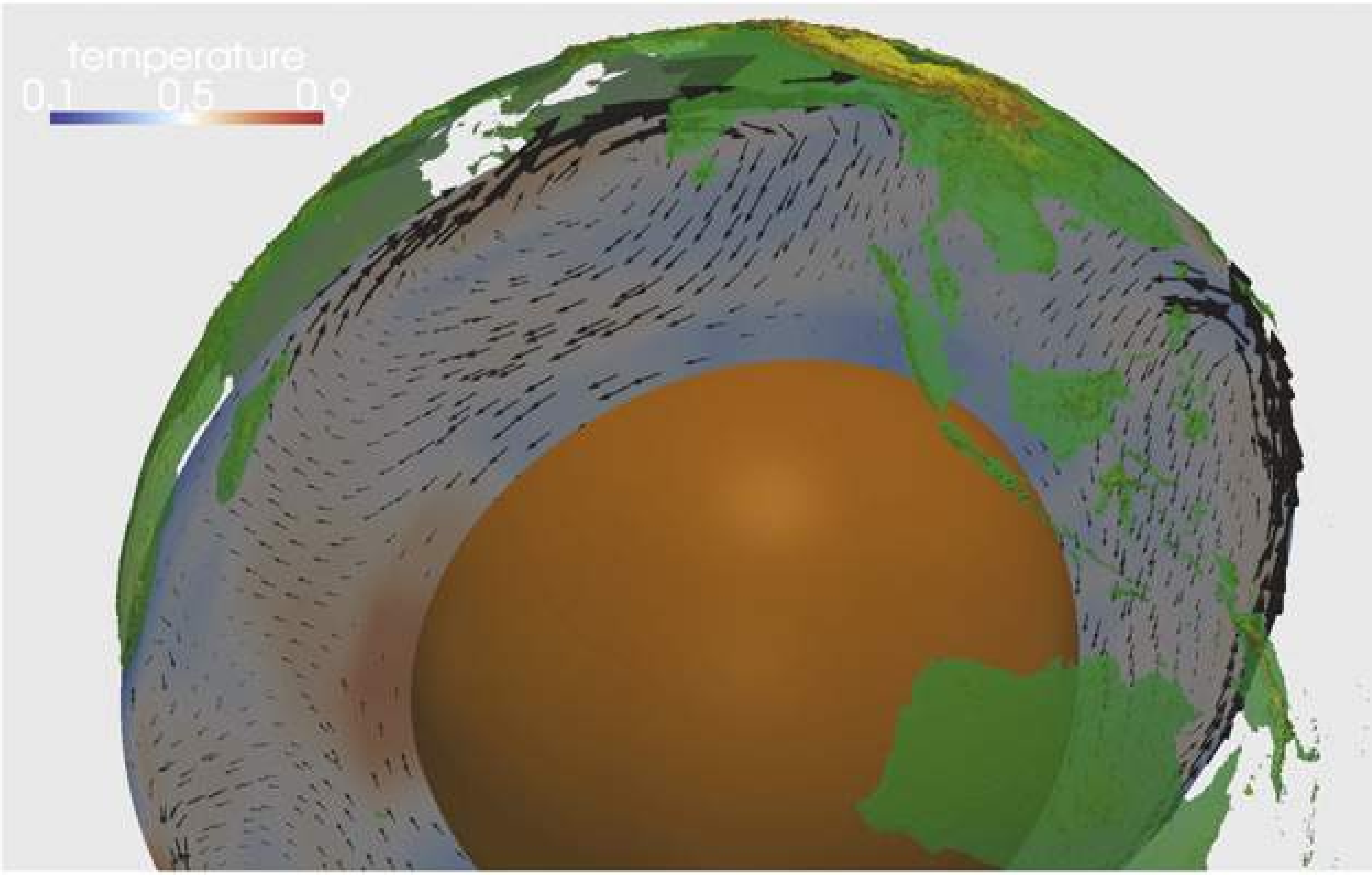
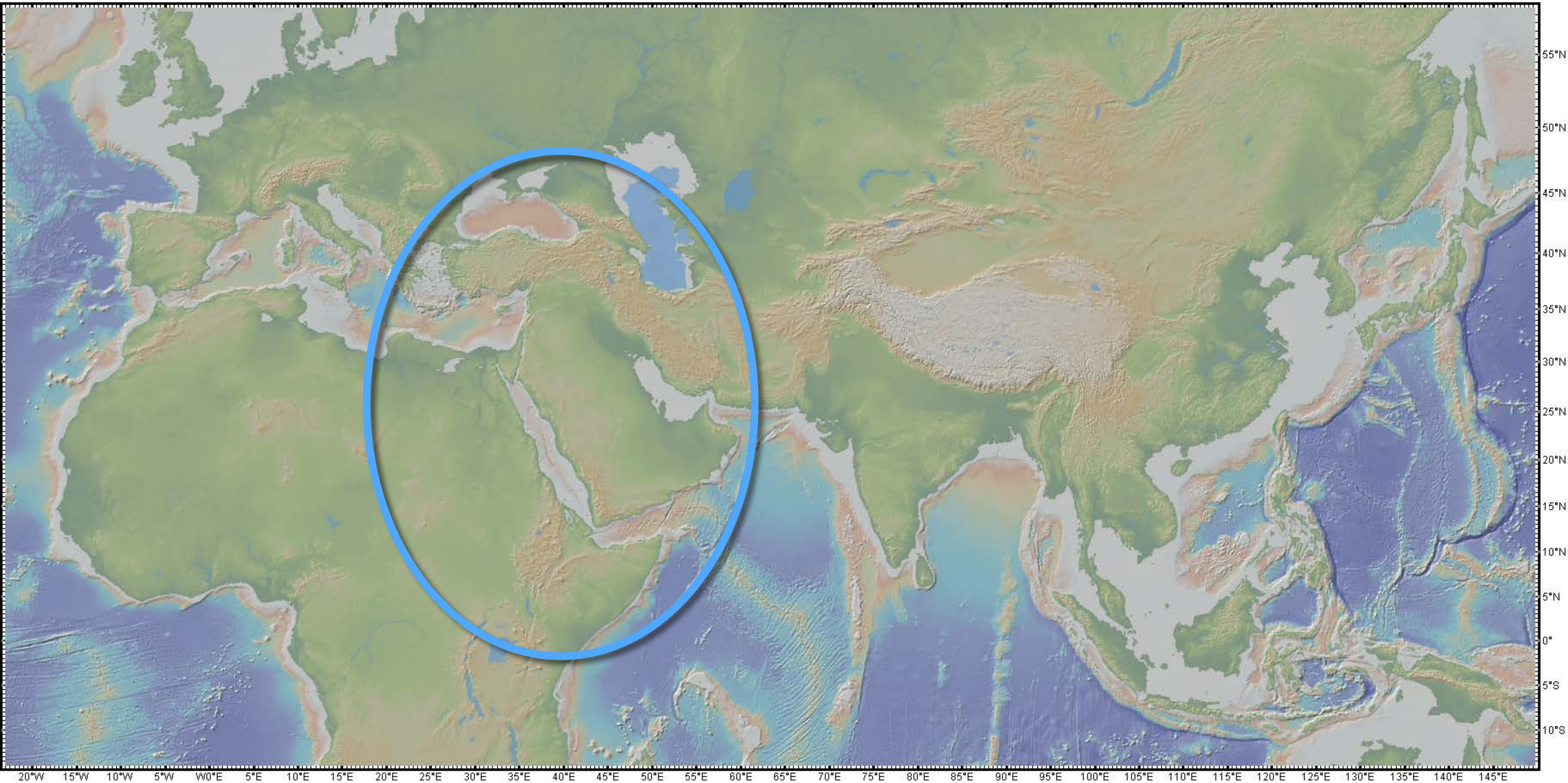


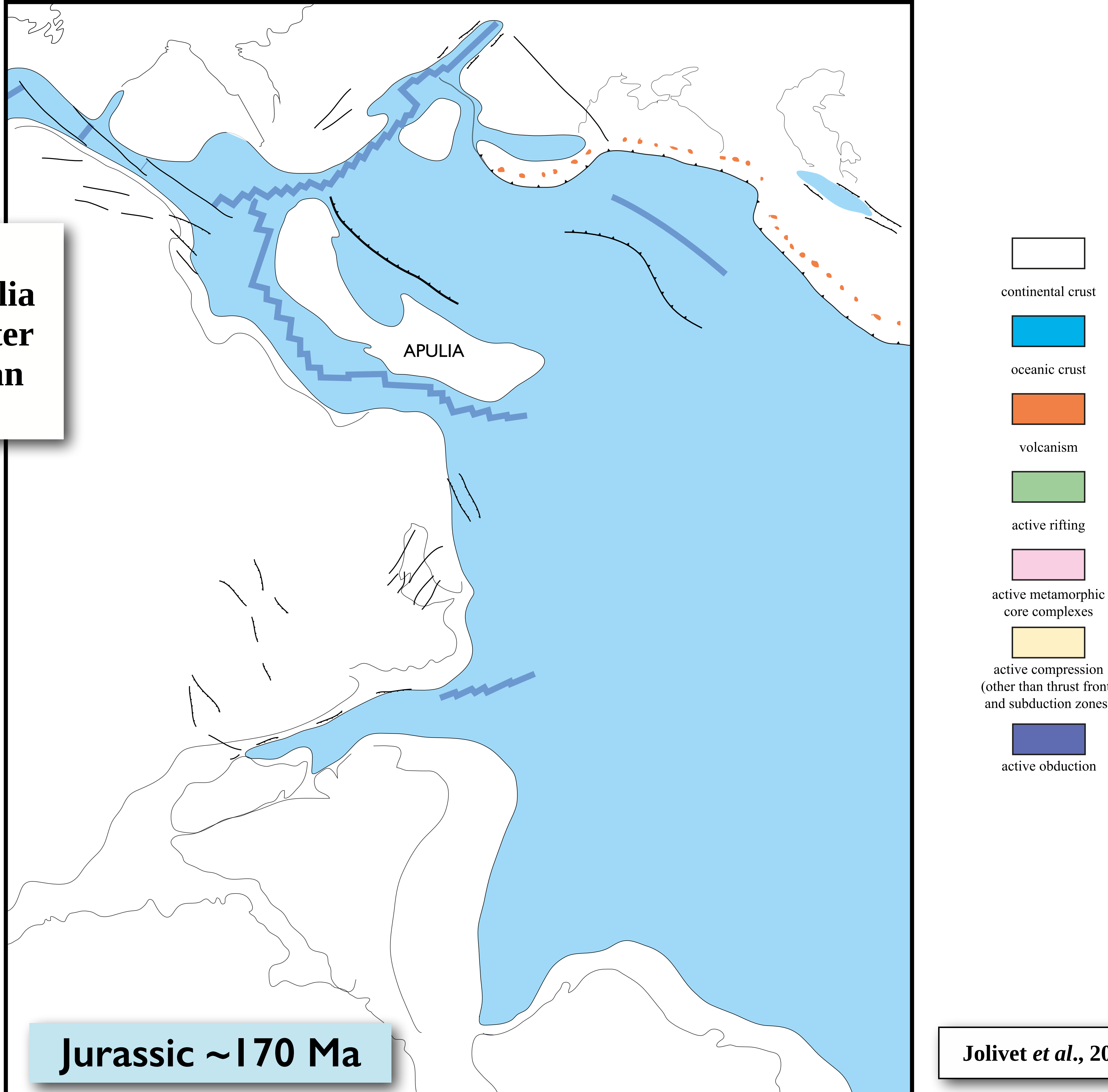
India is carried by a large-scale convection scale encompassing the whole mantle, animated by a large plume and the Tethyan subduction zones: the « conveyor belt »

Becker & Faccenna, 2011

The Afar triple junction: Red Sea, Gulf of Aden and East African Rift



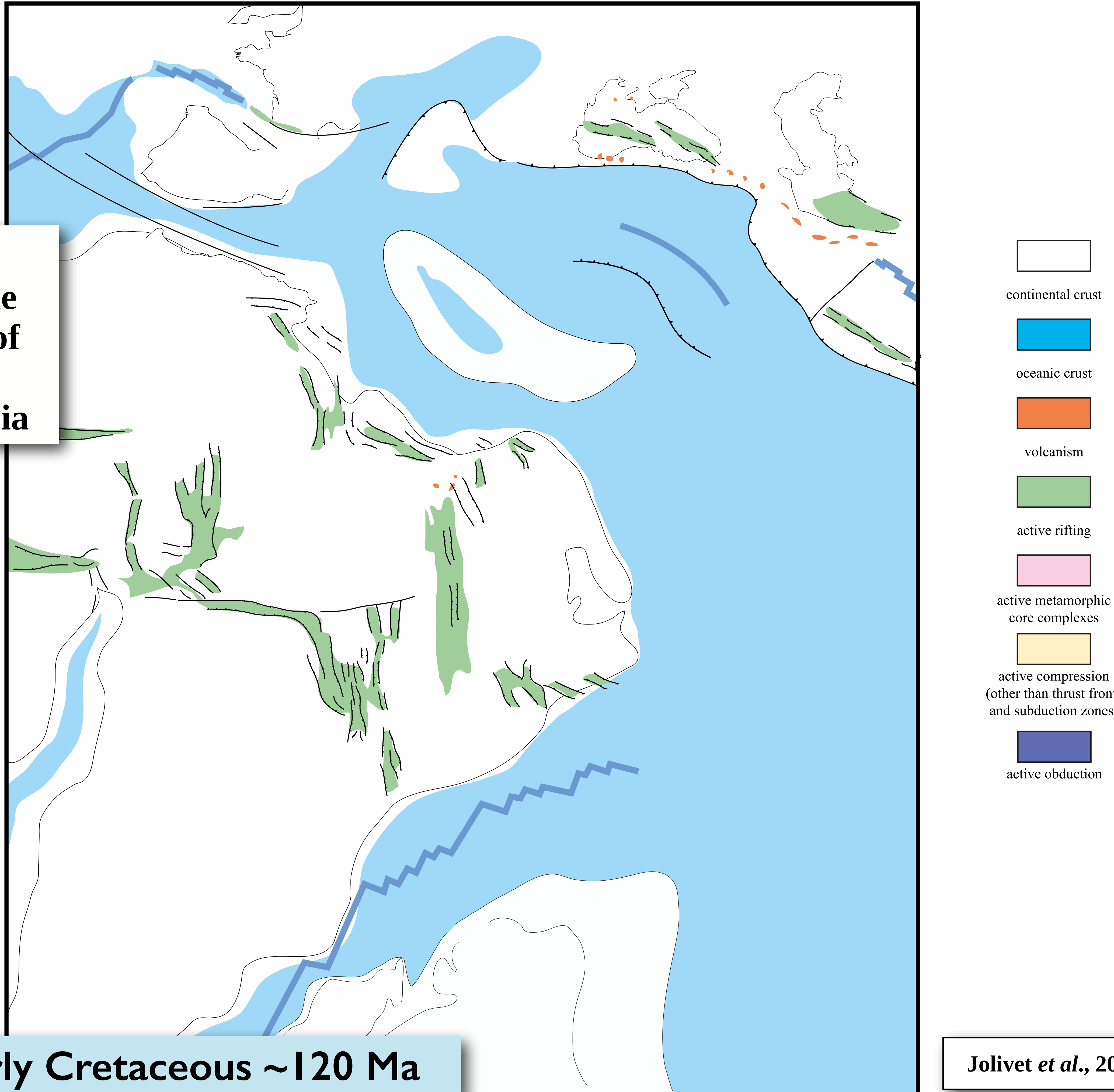
Rifting, then drifting of Apulia that moves faster northward than Africa



Jurassic ~170 Ma

Jolivet *et al.*, 2016

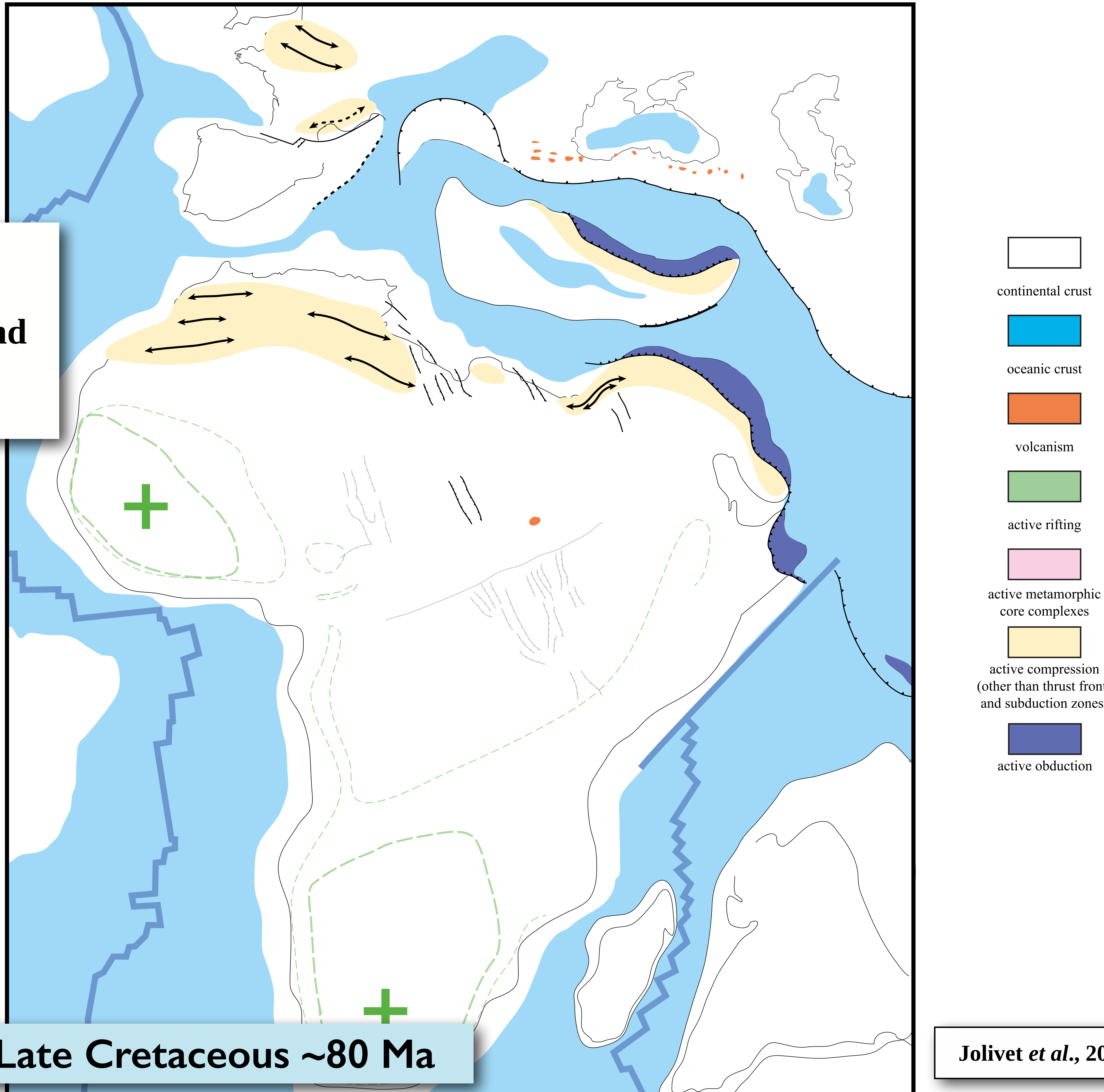
Generalized extension in the northern half of Africa and southern Eurasia



Early Cretaceous ~120 Ma

Jolivet *et al.*, 2016

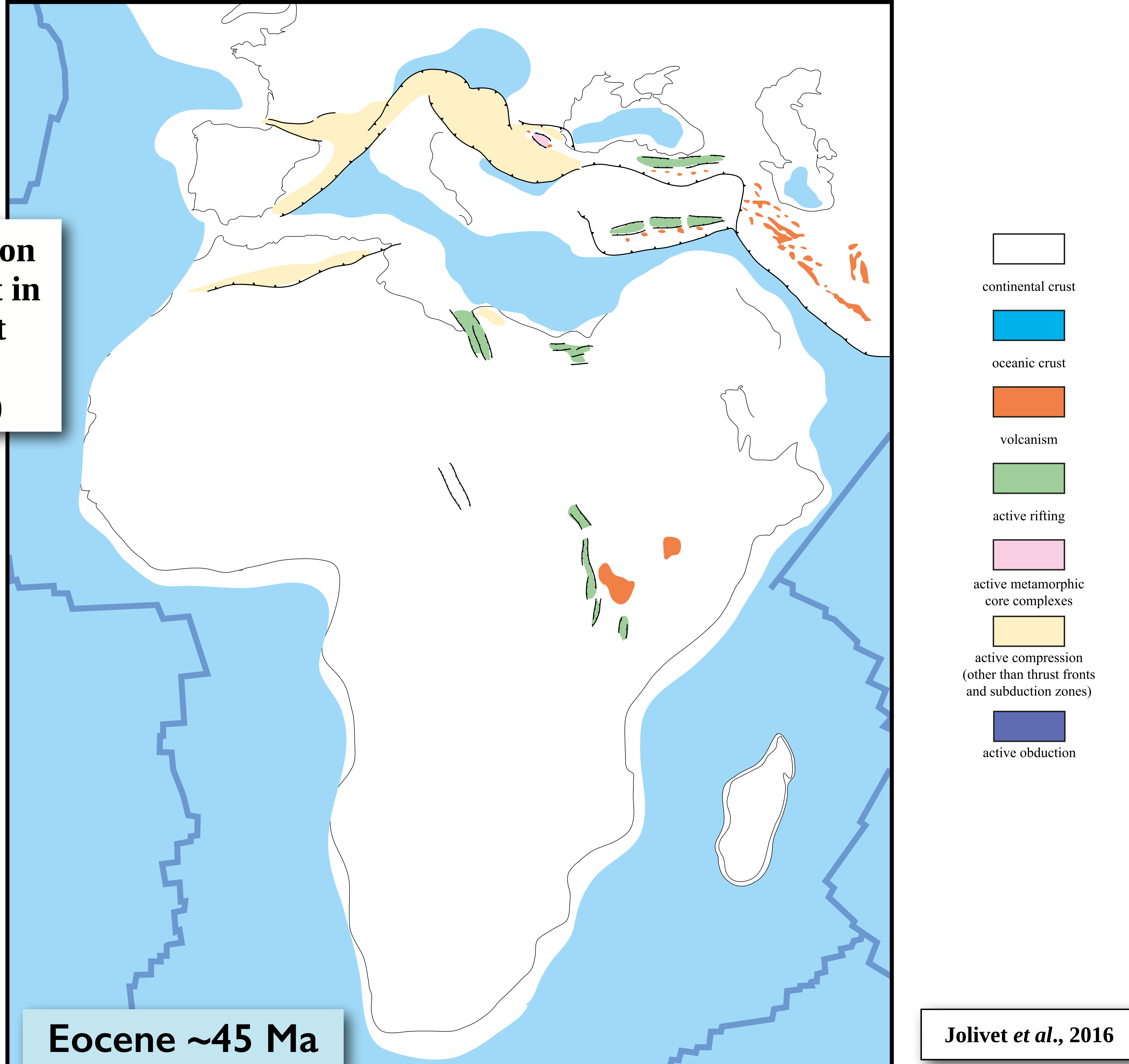
Generalized compression and obduction



Late Cretaceous ~80 Ma

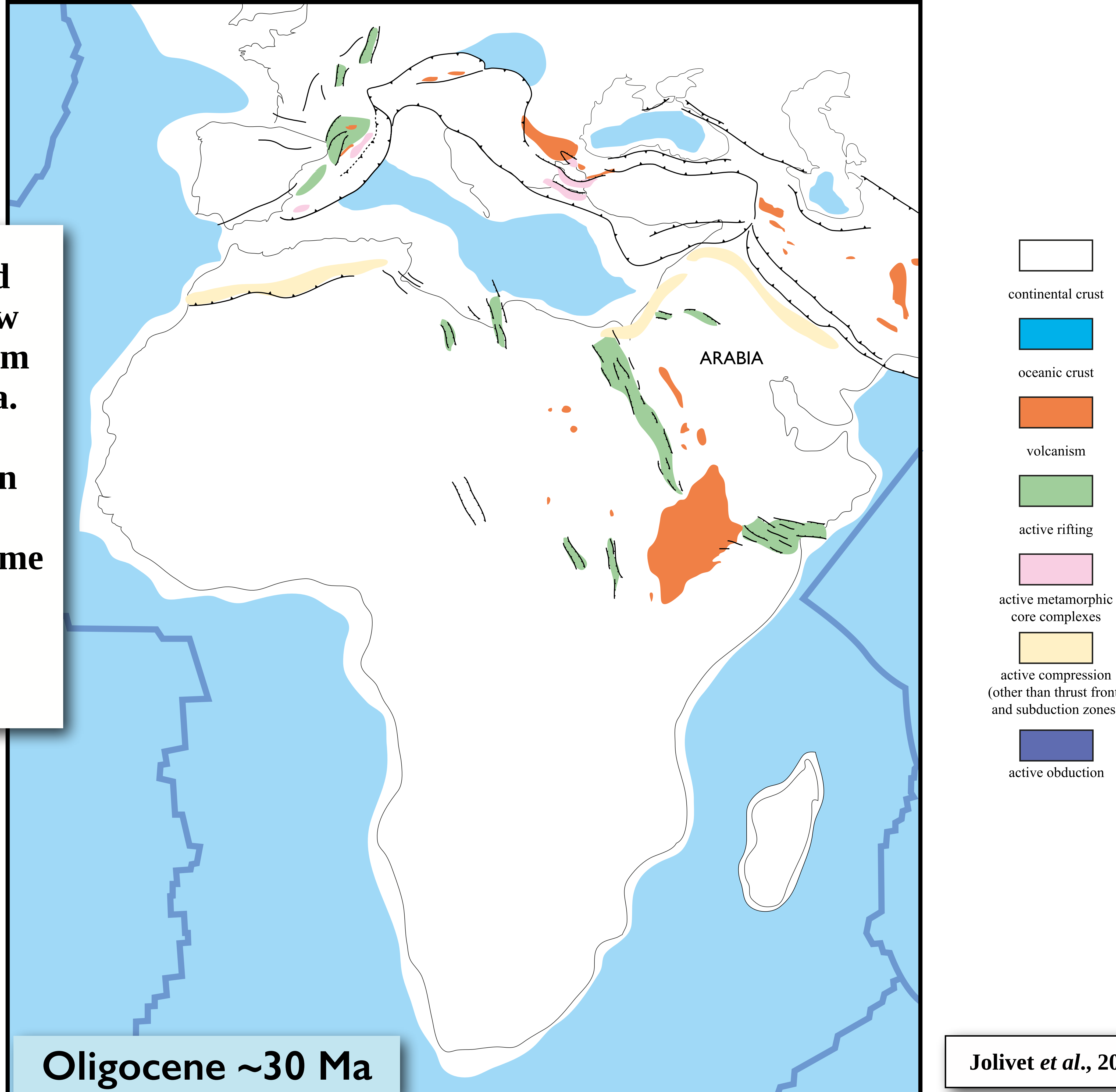
Jolivet *et al.*, 2016

Back to extension in Africa except in the northwest (first Atlas compression)



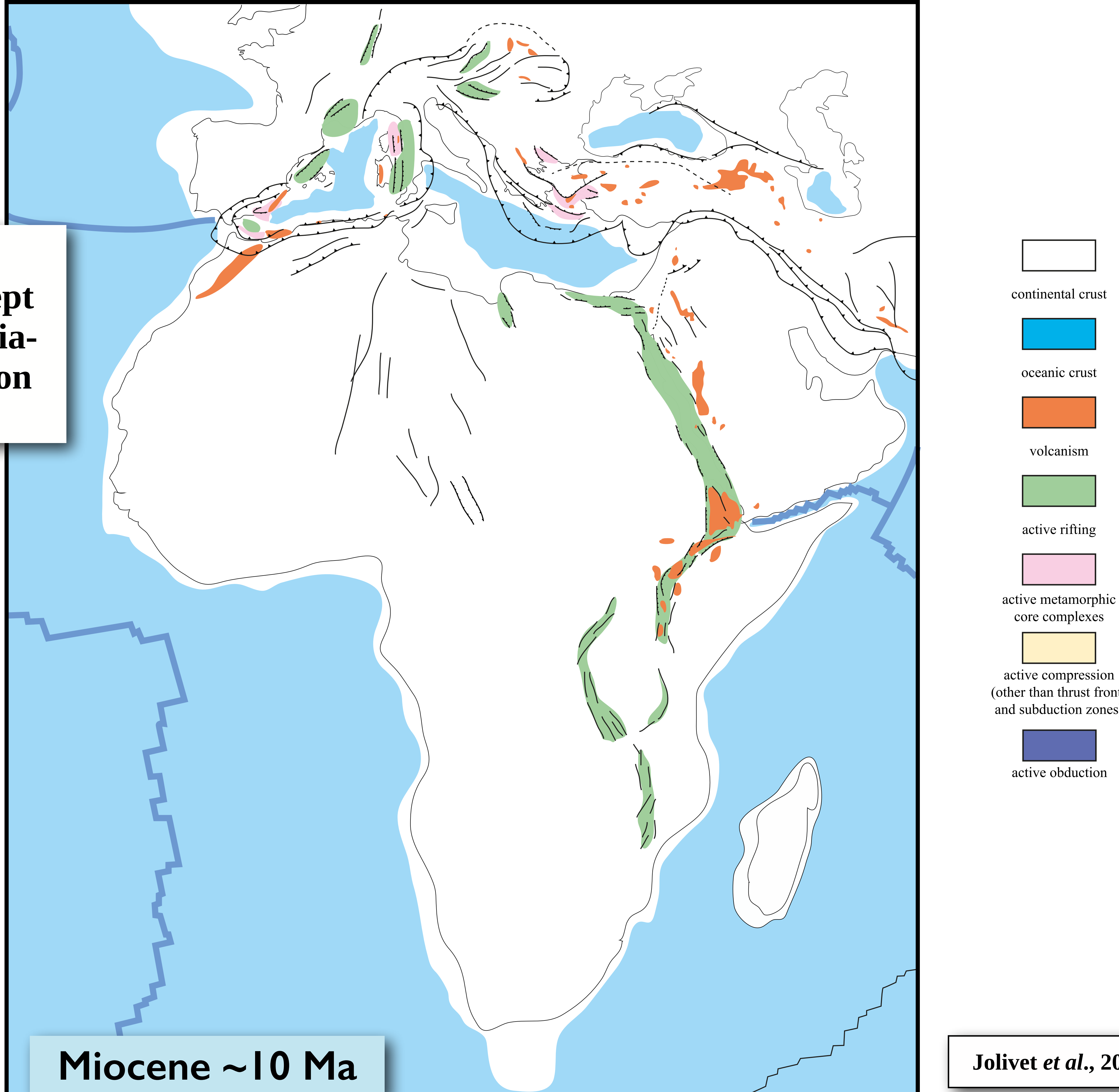
Jolivet *et al.*, 2016

Extension and rifting of a new block away from Africa: Arabia. In the Mediterranean region, the subduction regime becomes everywhere extensional



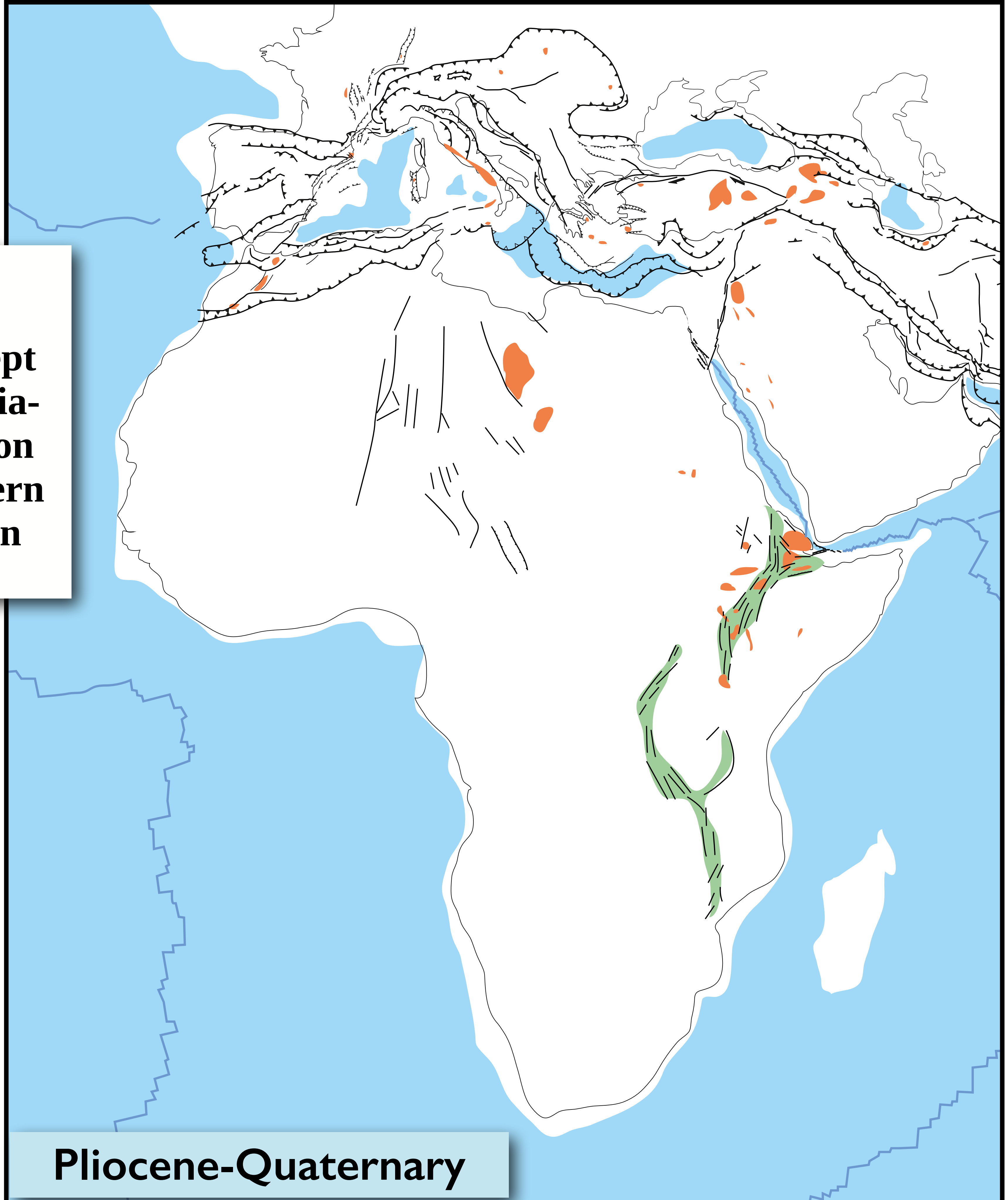
Jolivet *et al.*, 2016

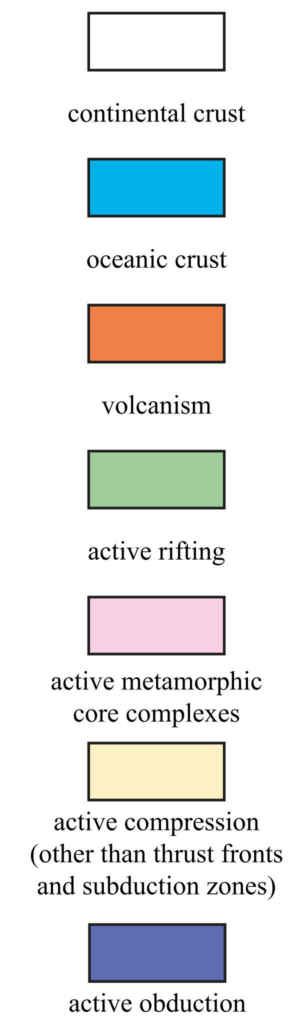
Generalized extension, except along the Arabia-Eurasia collision zone



Jolivet *et al.*, 2016

Generalized extension, except along the Arabia-Eurasia collision zone and Western Mediterranean

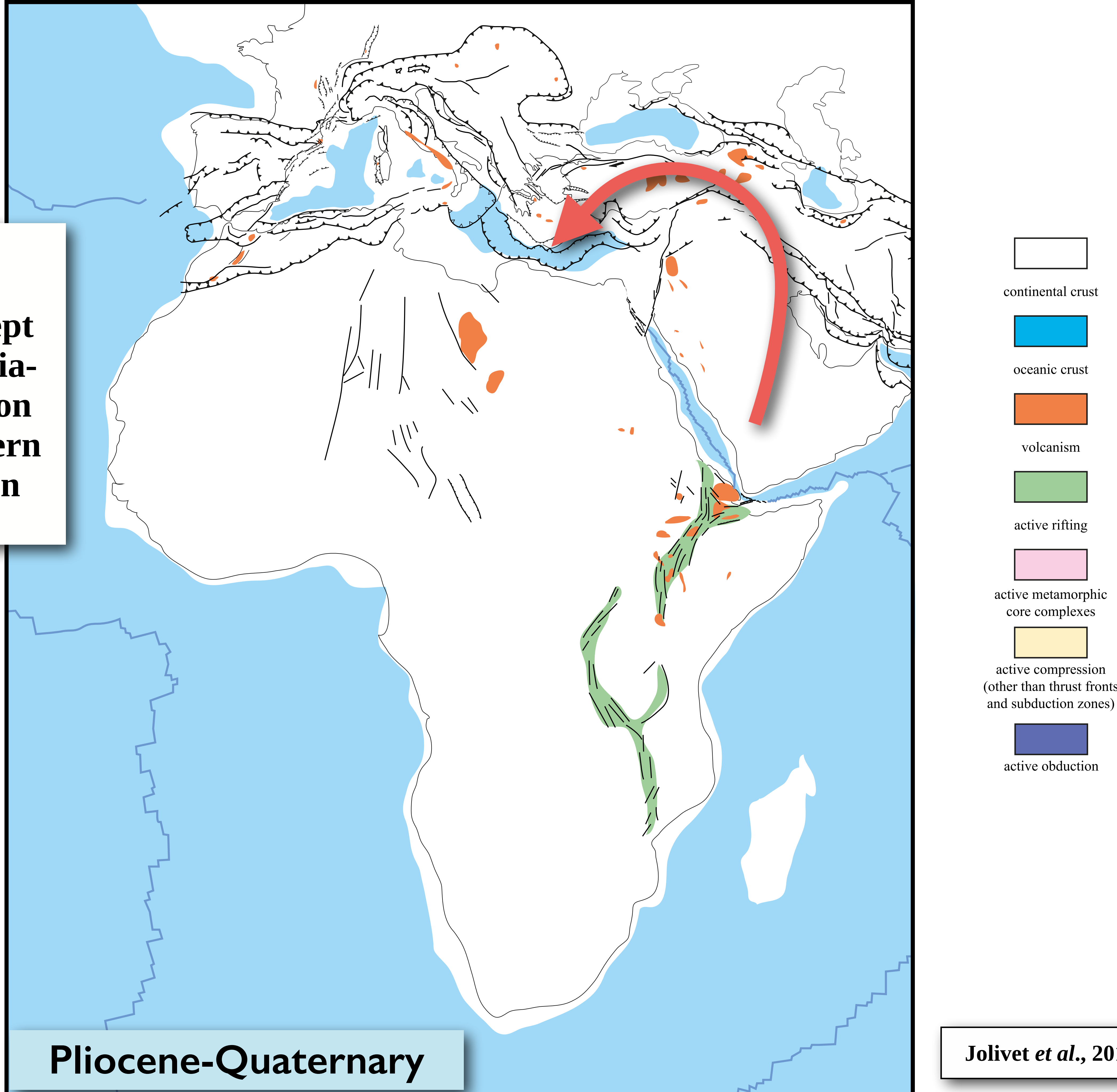




Pliocene-Quaternary

Jolivet *et al.*, 2016

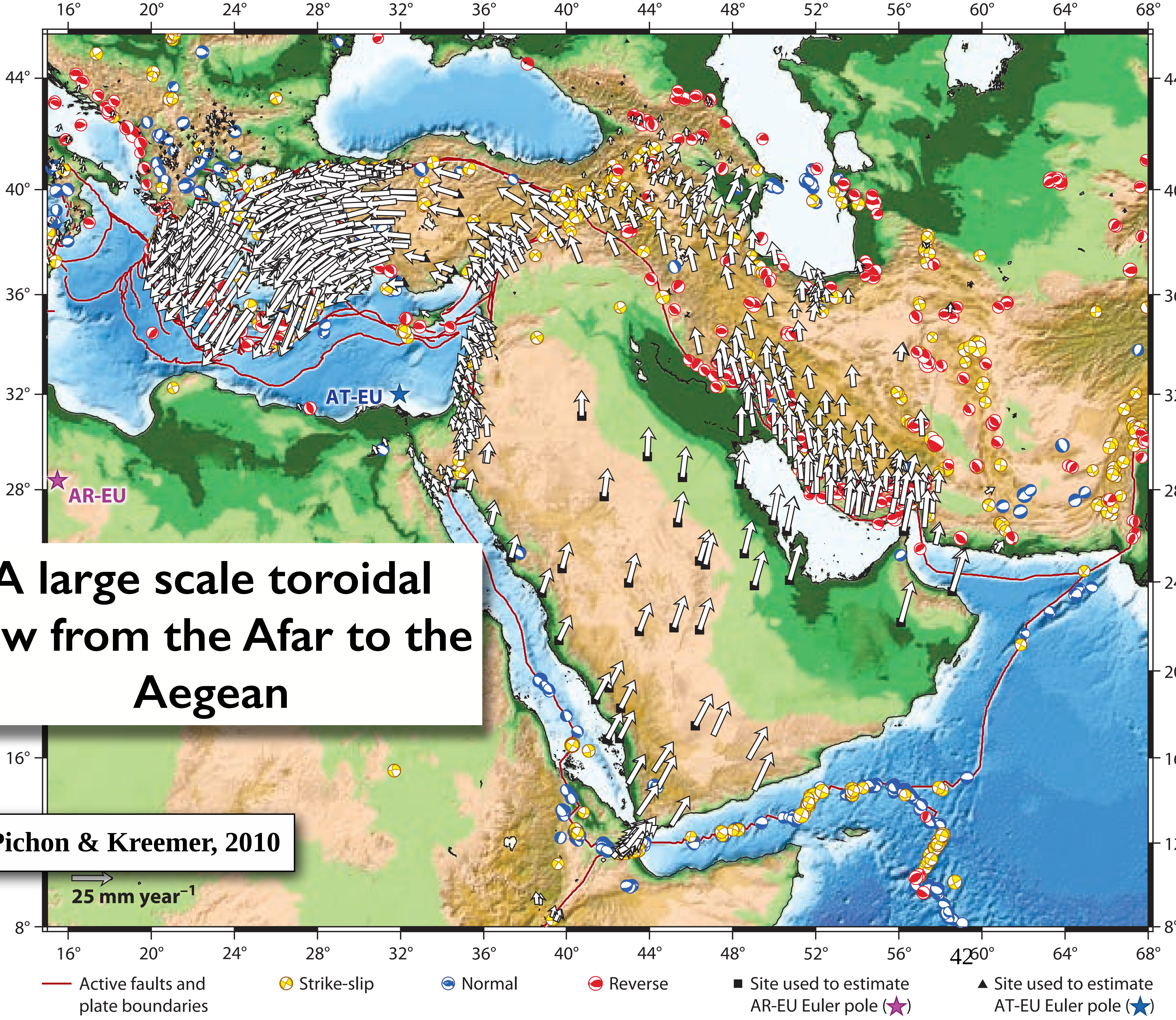
Generalized extension, except along the Arabia-Eurasia collision zone and Western Mediterranean



Pliocene-Quaternary

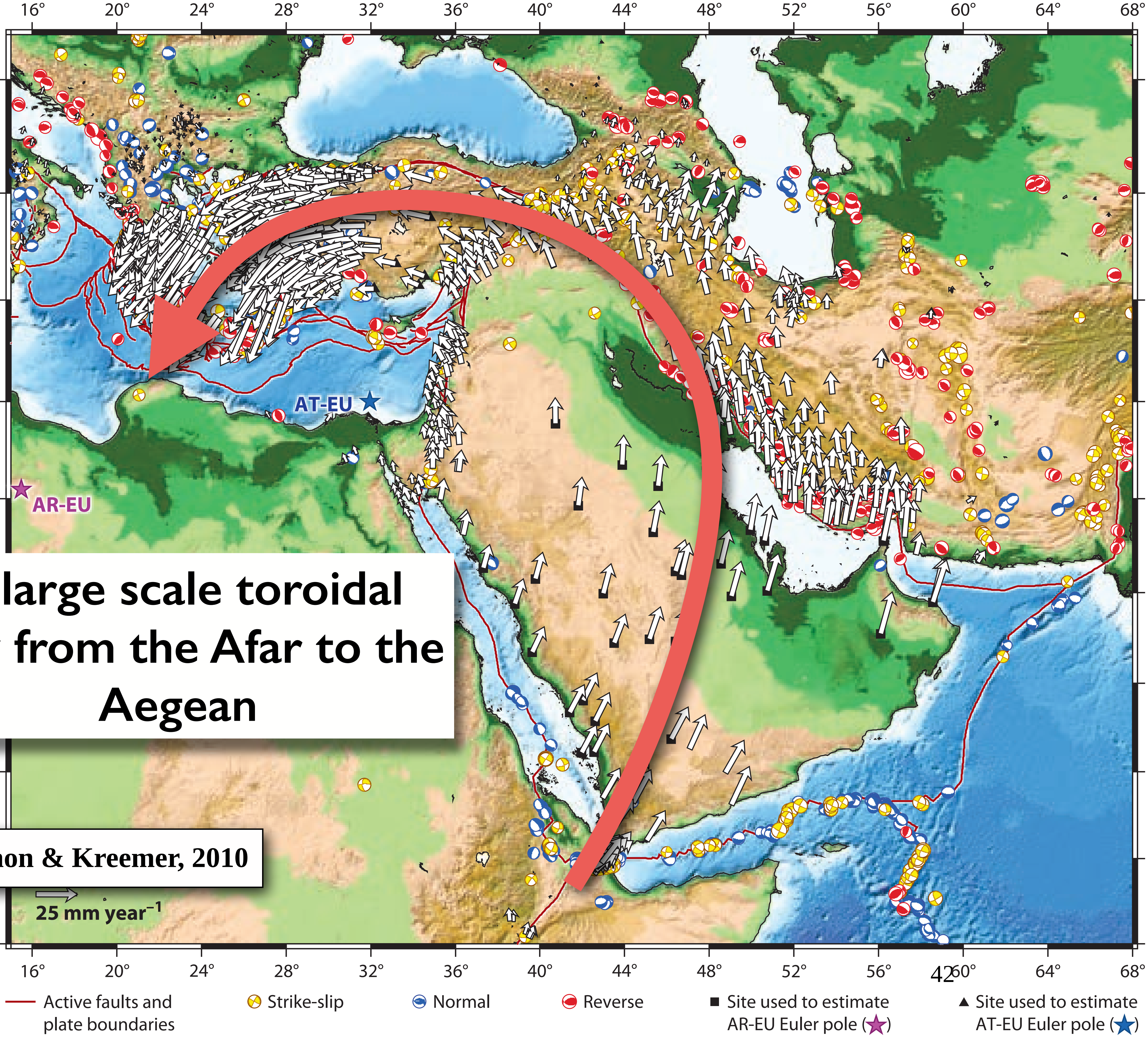
Jolivet *et al.*, 2016

A large scale toroidal flow from the Afar to the Aegean

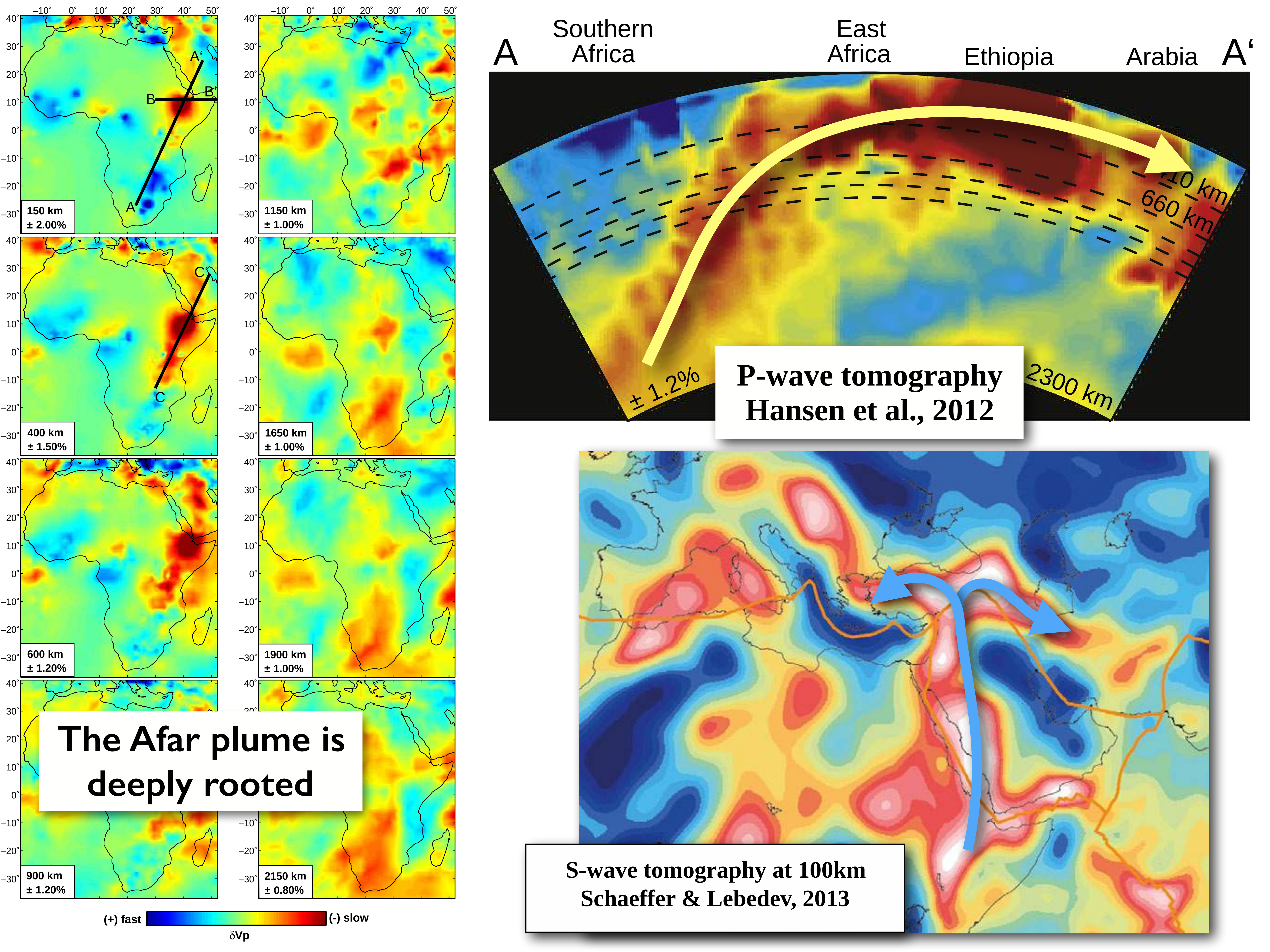


Le Pichon & Kreemer, 2010

A large scale toroidal flow from the Afar to the Aegean

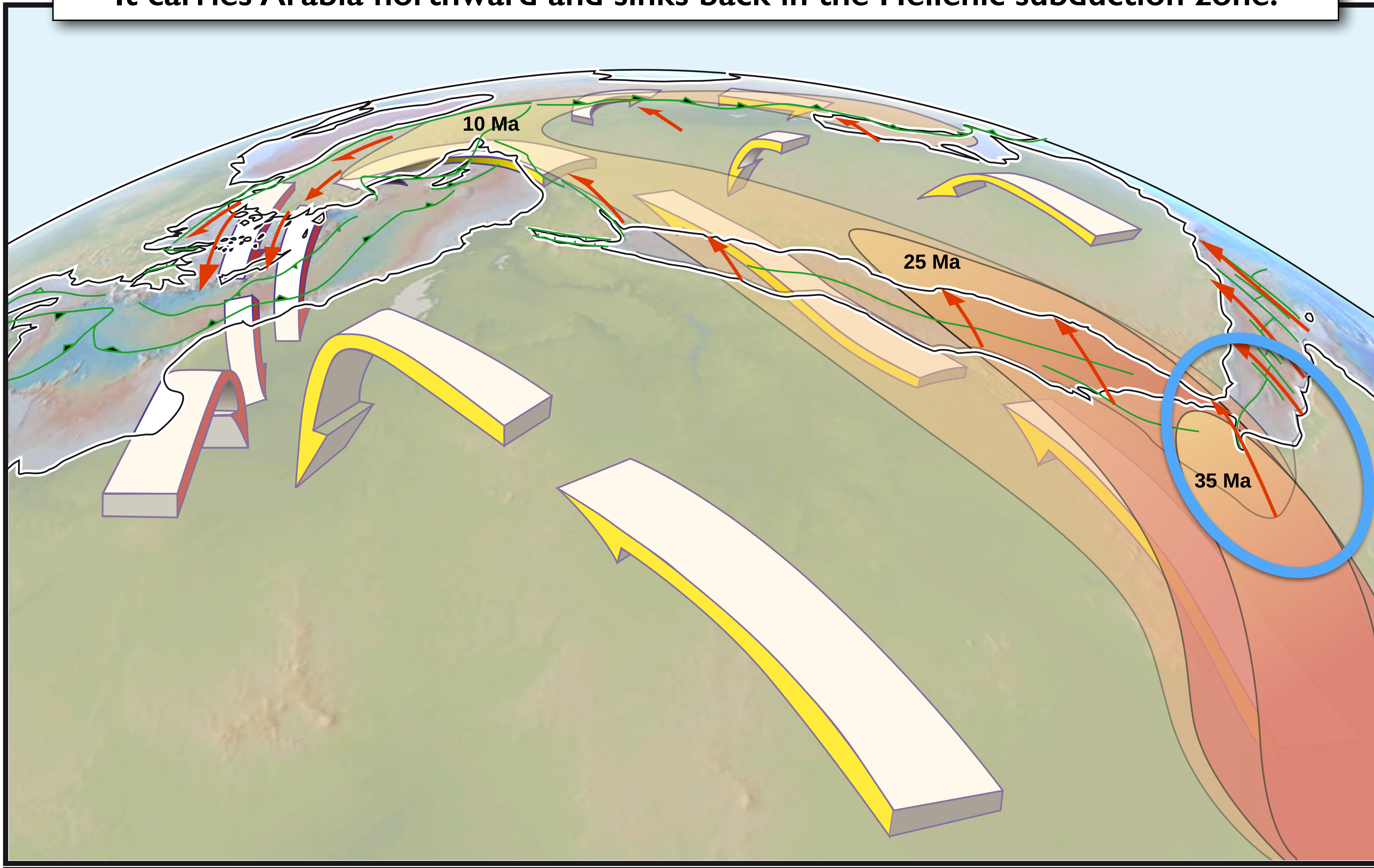


Le Pichon & Kreemer, 2010

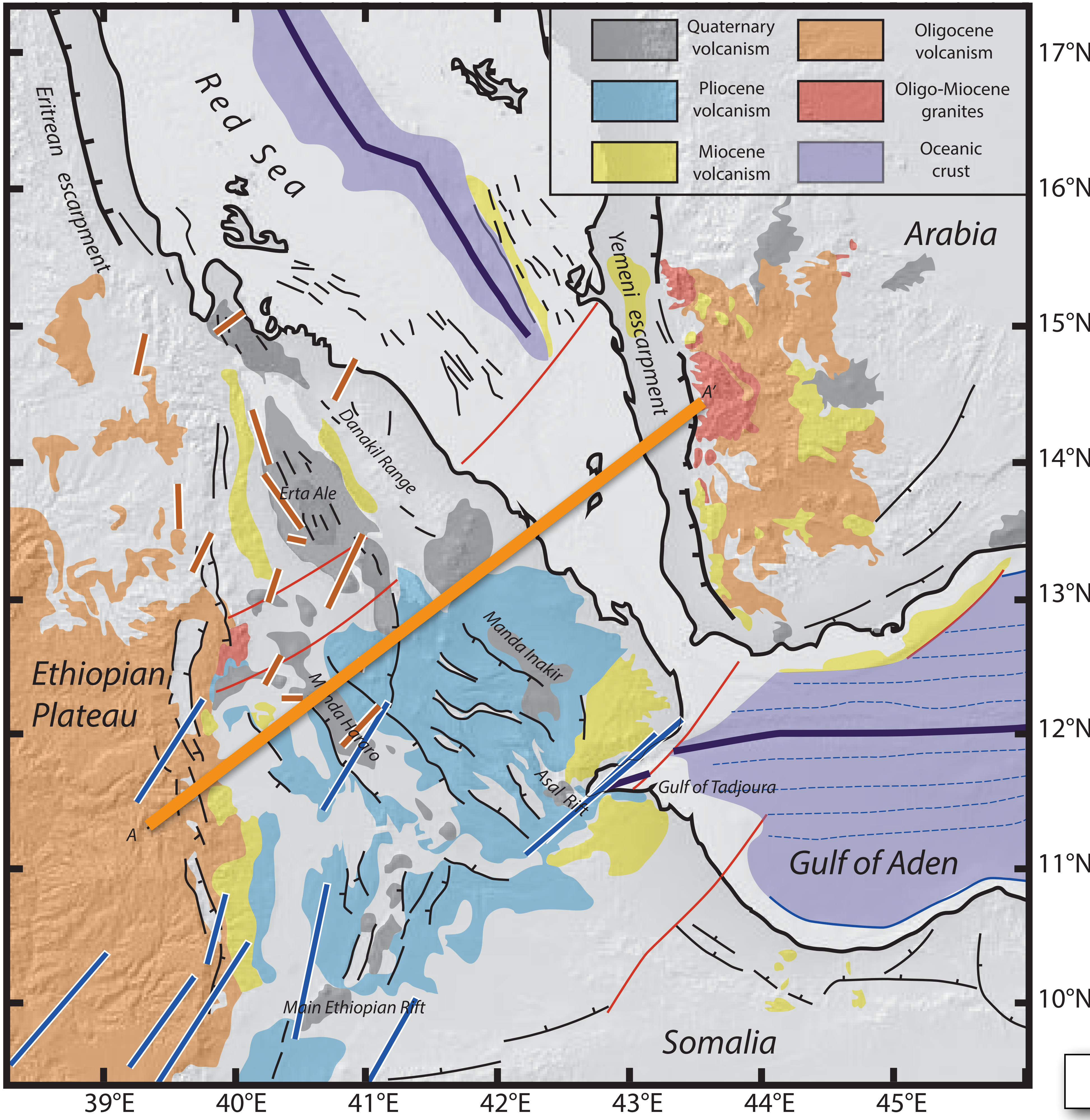


The Afar plume is deeply rooted
150 km ± 2.00%
400 km ± 1.50%
600 km ± 1.20%
900 km ± 1.20%
1150 km ± 1.00%
1650 km ± 1.00%
1900 km ± 1.00%
2150 km ± 0.80%
A
A'
B
B'
C
C'
(+) fast
(-) slow
δVp
A
Southern Africa
East Africa
Ethiopia
Arabia
A'
410 km
660 km
± 1.2%
2300 km
P-wave tomography
Hansen et al., 2012
S-wave tomography at 100km
Schaeffer & Lebedev, 2013

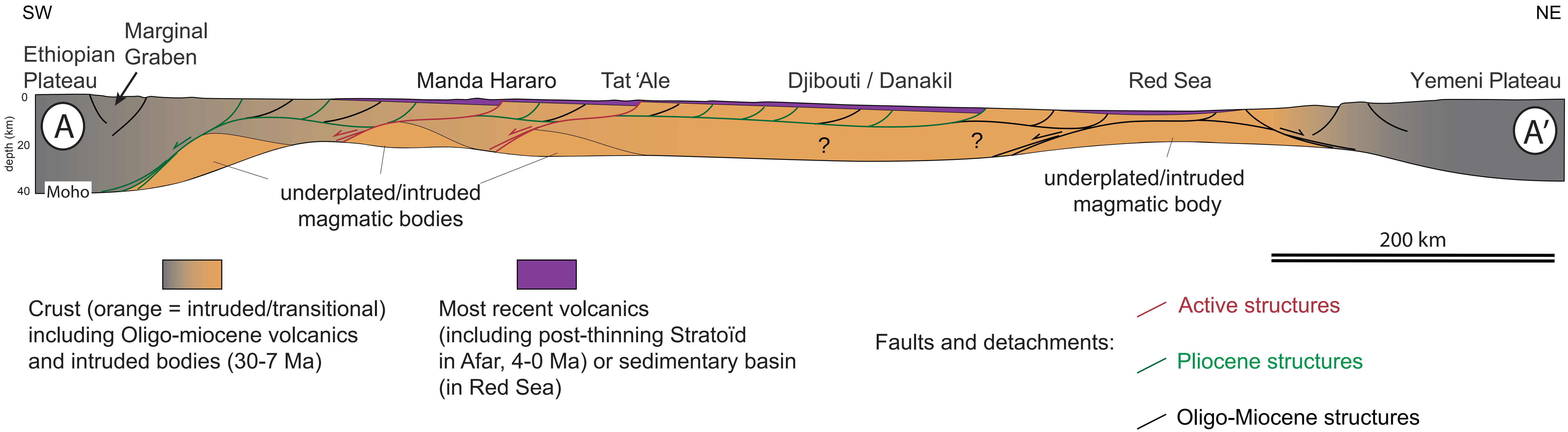
Asthenospheric flow related to plume is faster than the motion of Africa. It carries Arabia northward and sinks back in the Hellenic subduction zone.



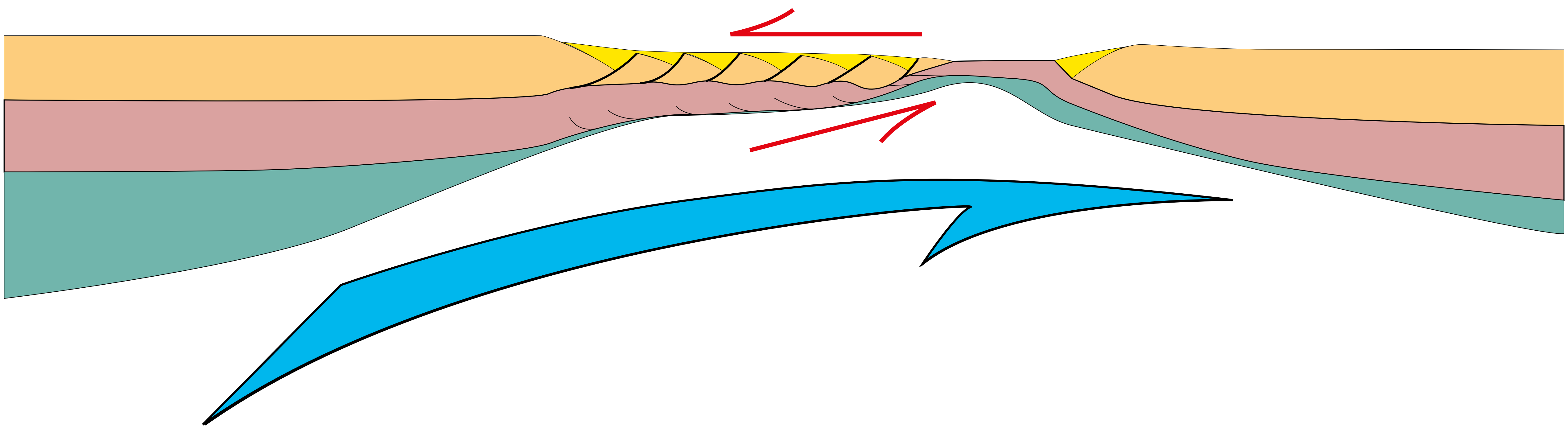
Faccenna et al., 2013



Stab *et al.*, 2015



Rifting, plume migration and asthenospheric flow

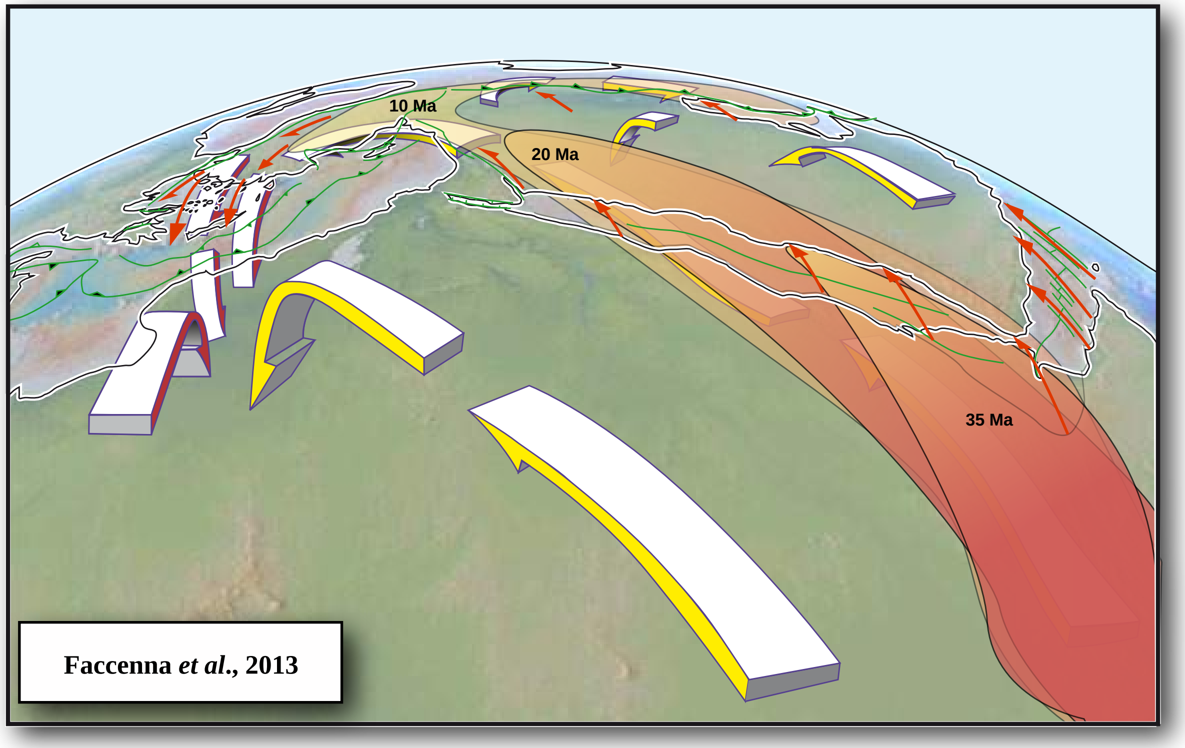


Basal shear by the asthenospheric flow induces asymmetrical deformation in the crust.

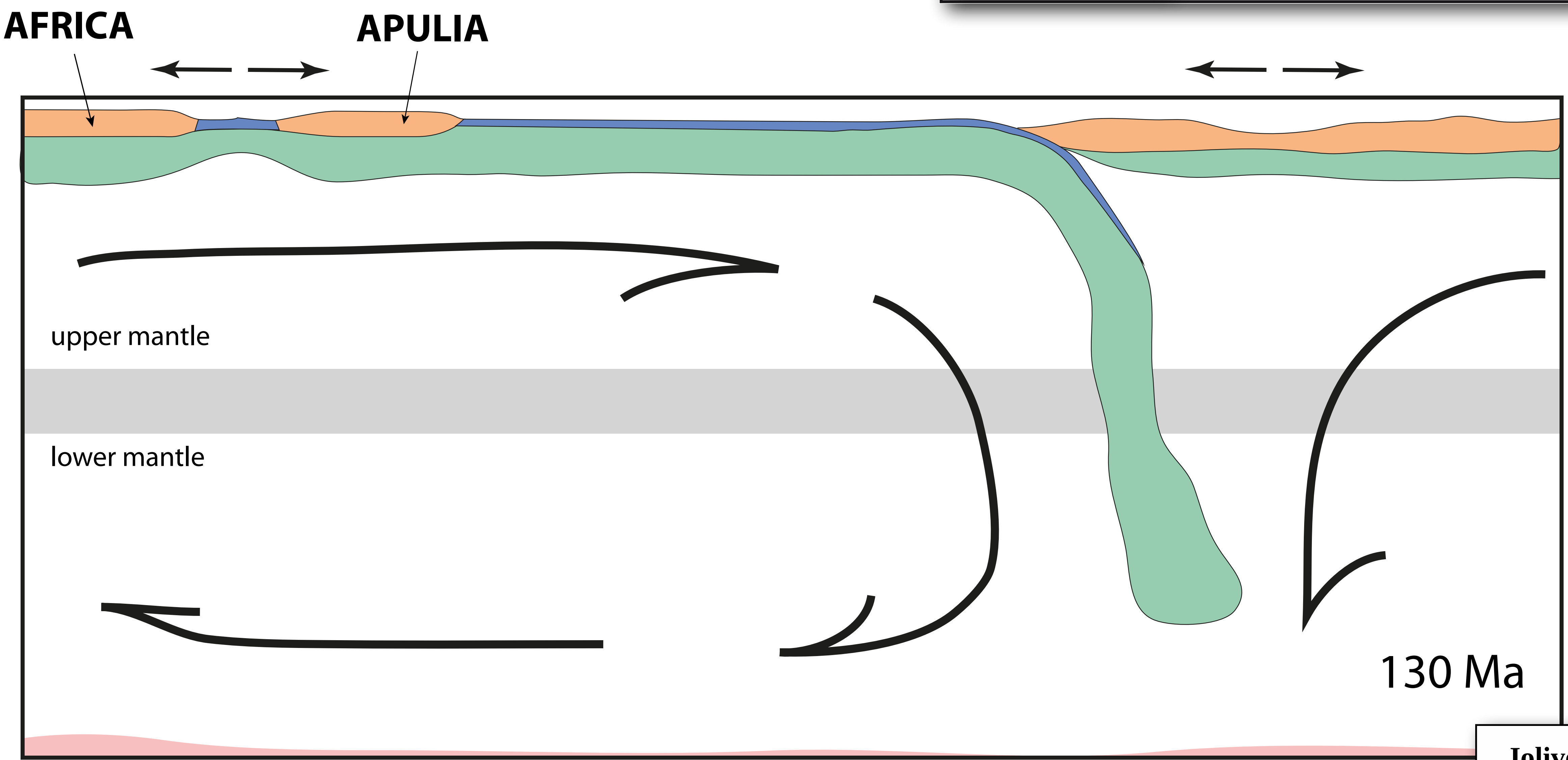
Jolivet *et al*., submitted

A possible scenario at the scale of the mantle:

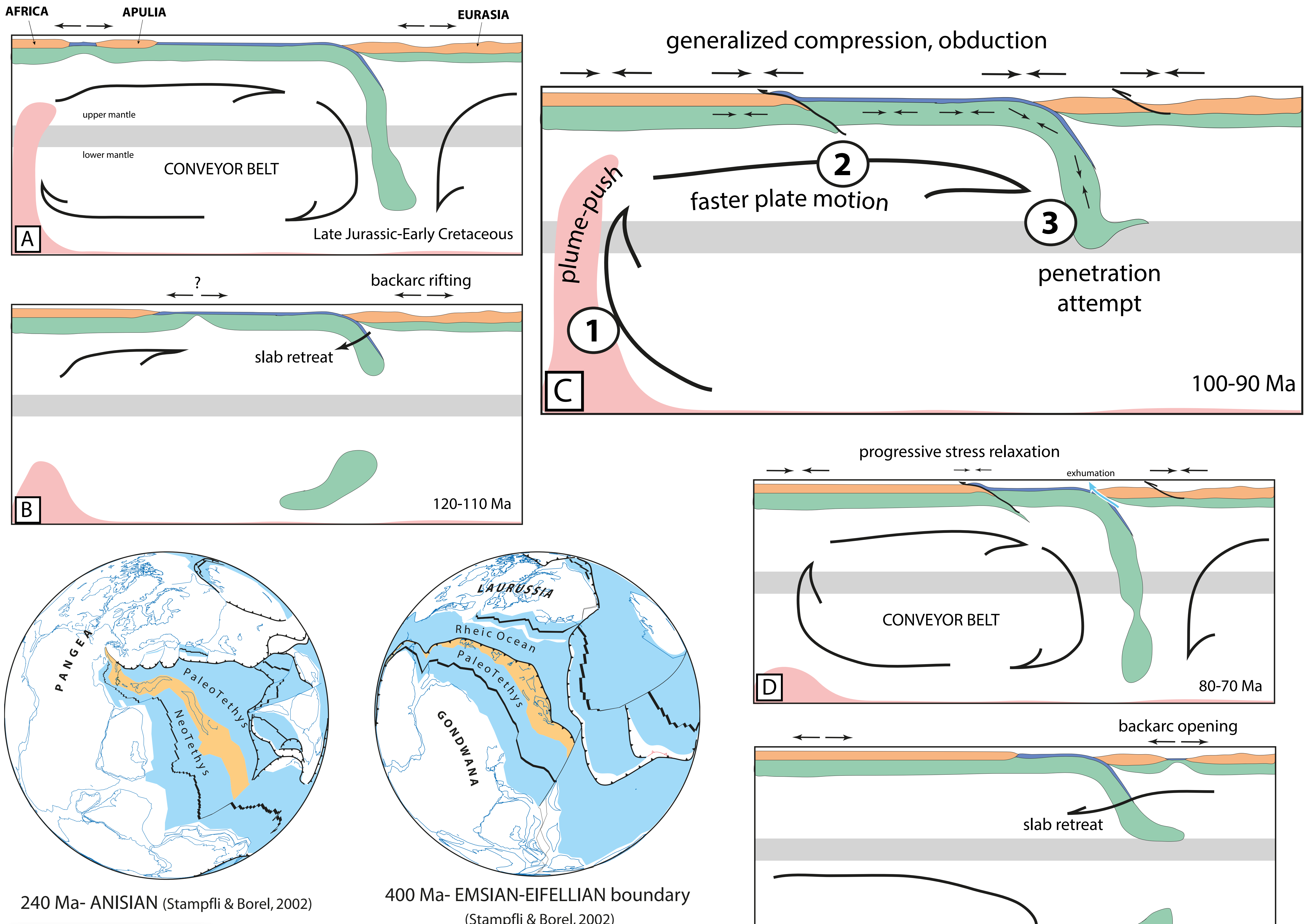
Long-term behaviour: mantle convection drags pieces of Africa toward the north, Apulia and then Arabia



Faccenna *et al.*, 2013

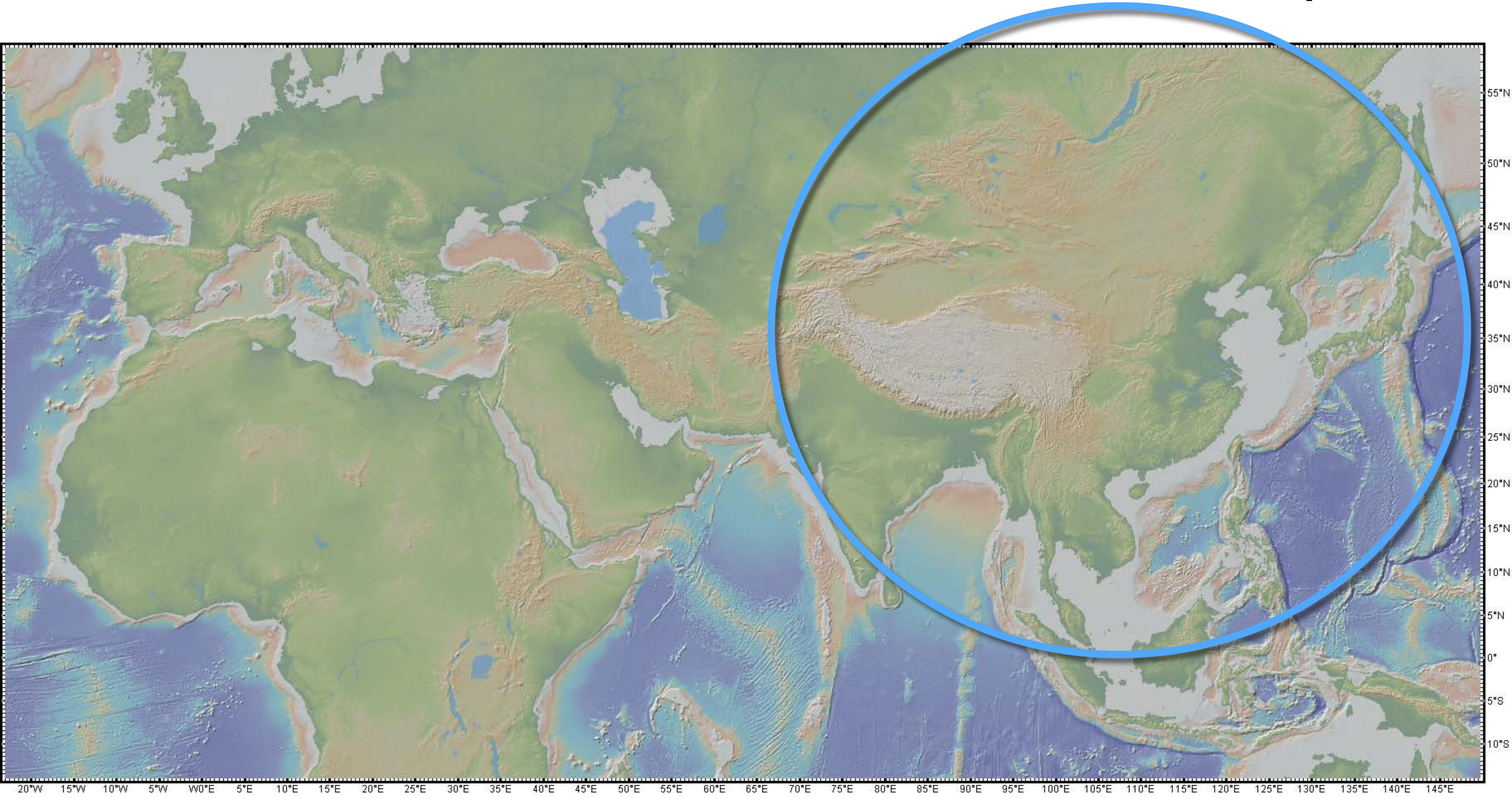


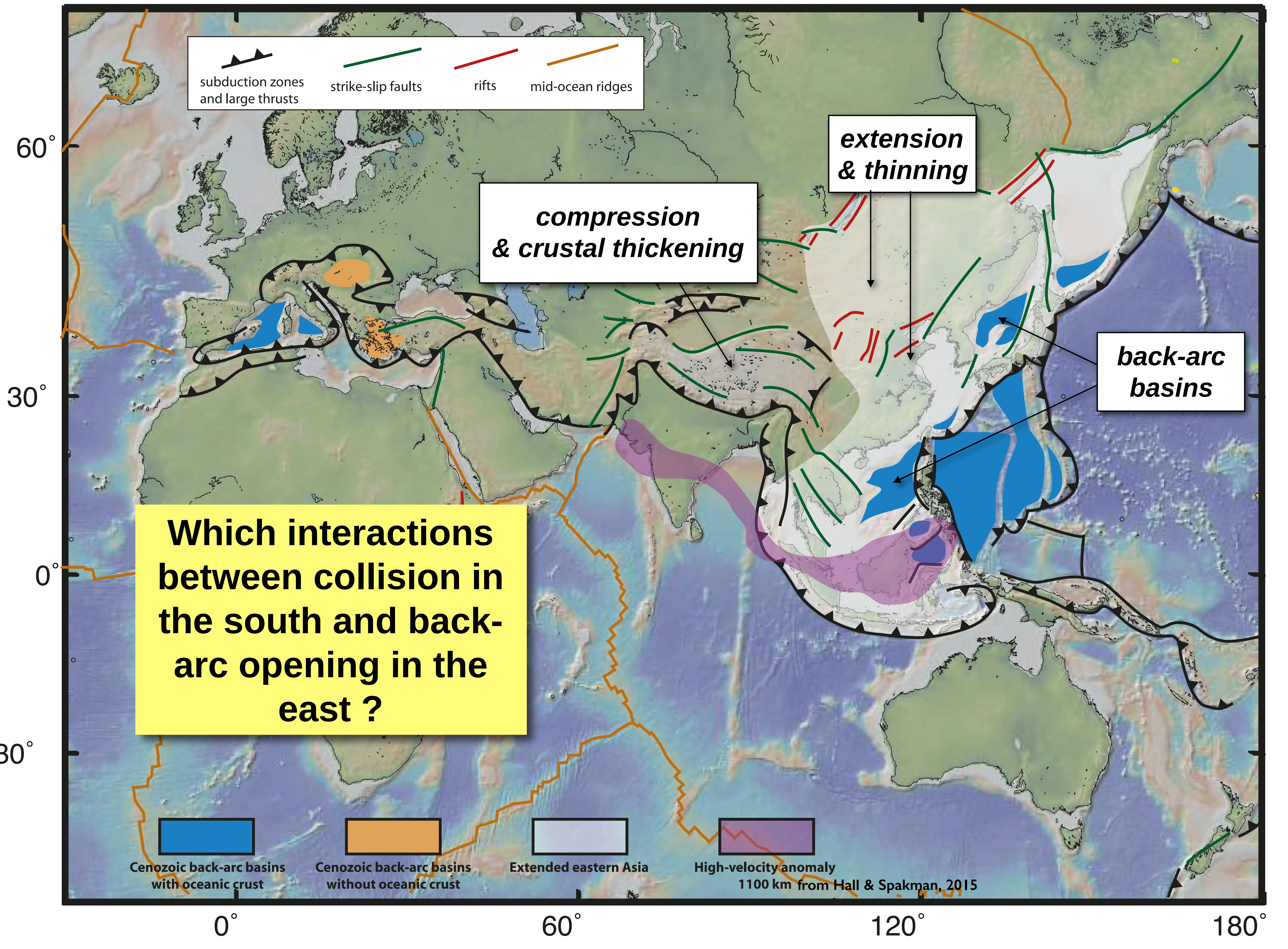
Jolivet *et al.*, 2016



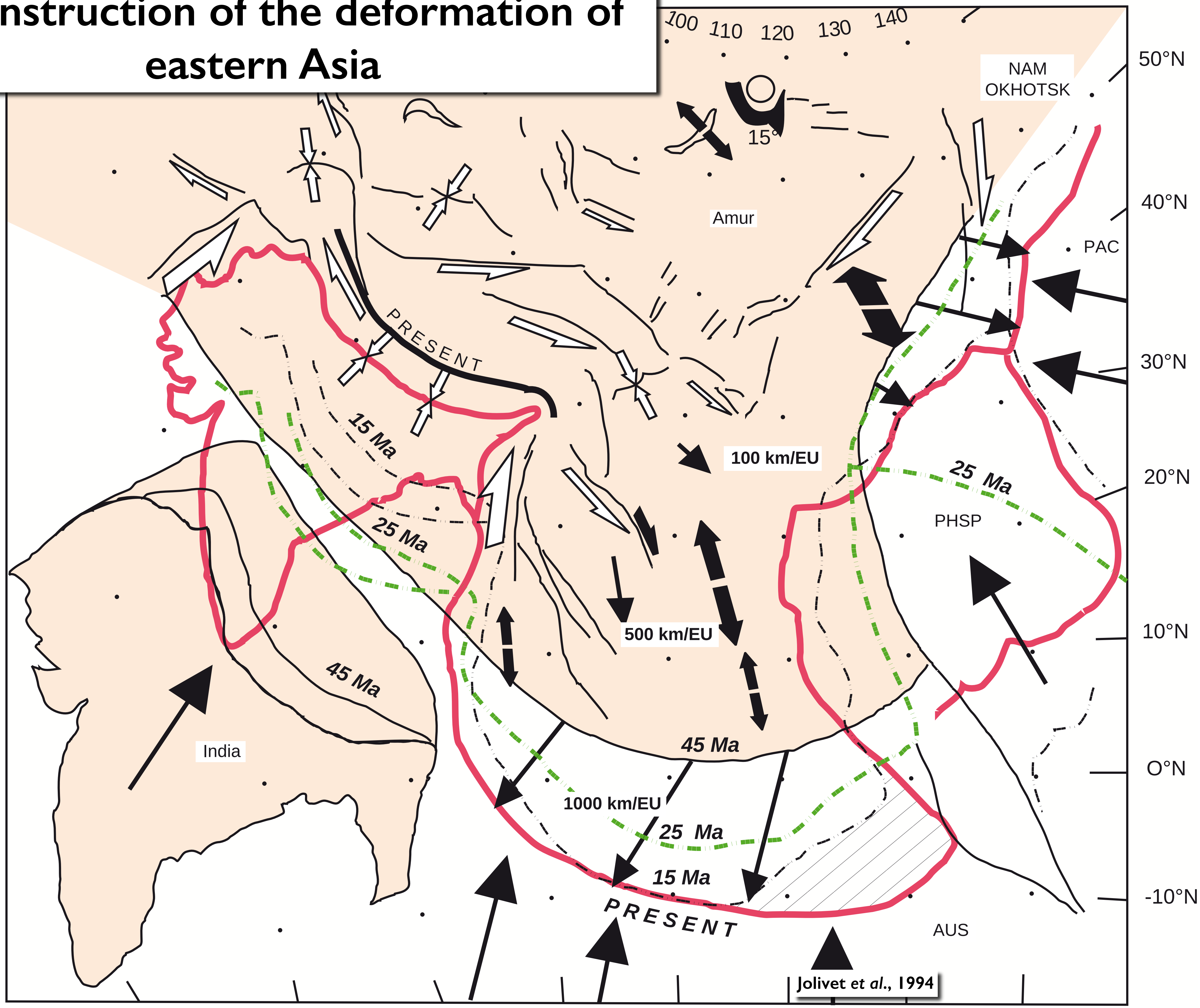
Jolivet *et al.*, 2016

The deformation of East Asia is a consequence of the collision with India and of the subduction of the Pacific and Indian oceanic lithospheres



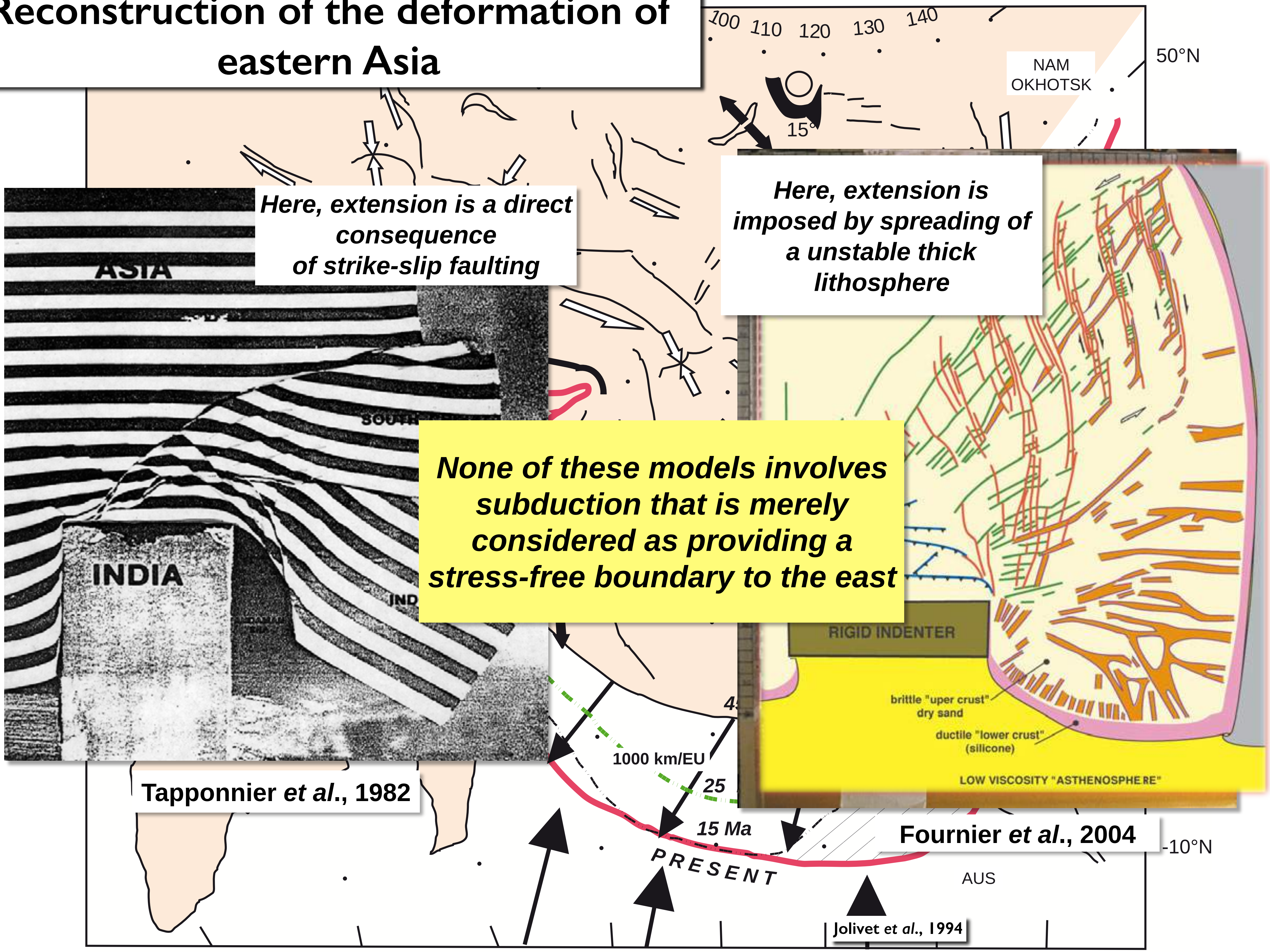

subduction zones and large thrusts
strike-slip faults
rifts
mid-ocean ridges
compression & crustal thickening
extension & thinning
back-arc basins
Which interactions between collision in the south and back-arc opening in the east ?
Cenozoic back-arc basins with oceanic crust
Cenozoic back-arc basins without oceanic crust
Extended eastern Asia
High-velocity anomaly 1100 km
from Hall & Spakman, 2015
60°
30°
0°
30°
0°
60°
120°
180°

Reconstruction of the deformation of eastern Asia



Jolivet *et al.*, 1994

Reconstruction of the deformation of eastern Asia



Here, extension is a direct consequence of strike-slip faulting

Tapponnier *et al.*, 1982

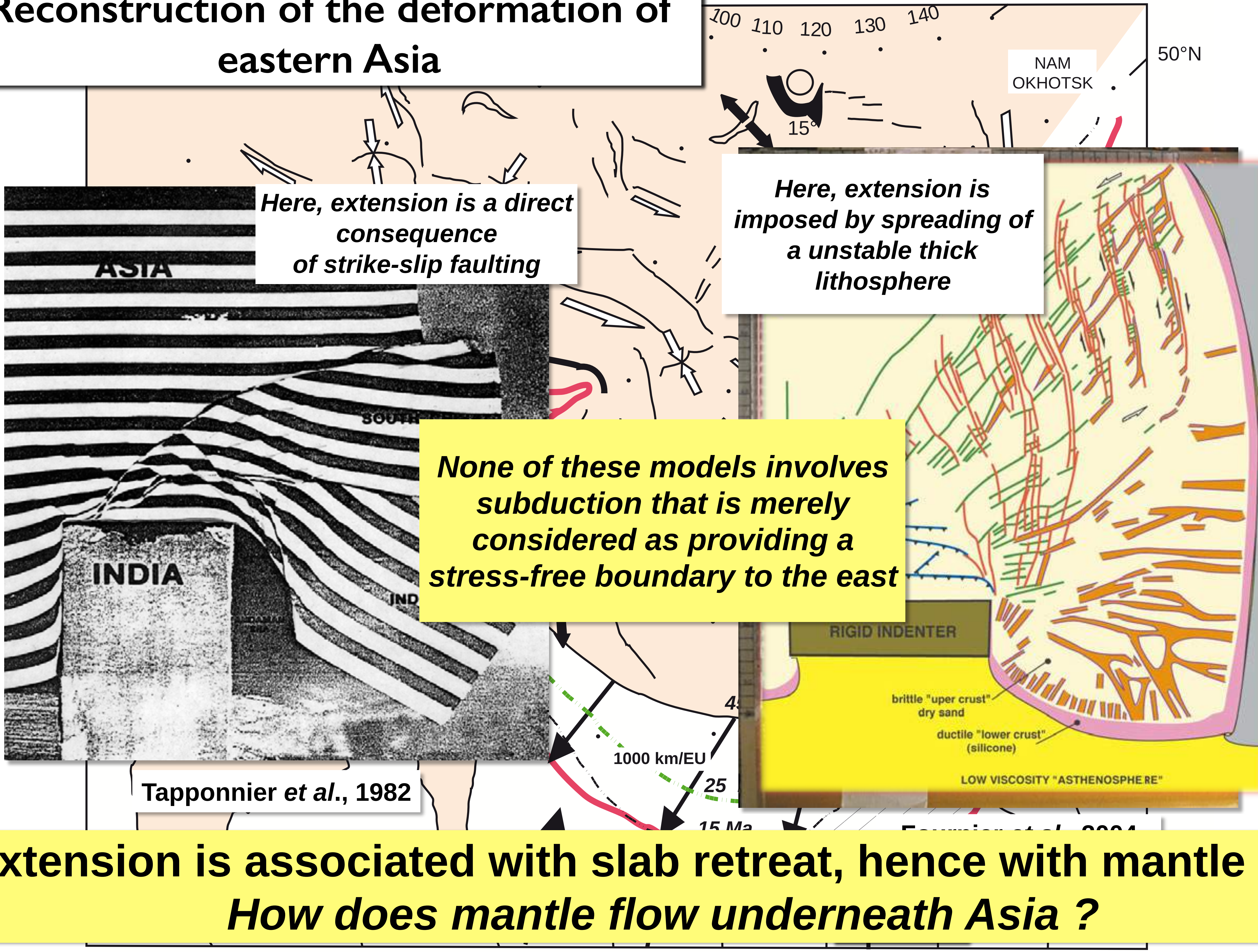
Here, extension is imposed by spreading of a unstable thick lithosphere

Fournier *et al.*, 2004

None of these models involves subduction that is merely considered as providing a stress-free boundary to the east

Jolivet *et al.*, 1994

Reconstruction of the deformation of eastern Asia



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Here, extension is imposed by spreading of a unstable thick lithosphere

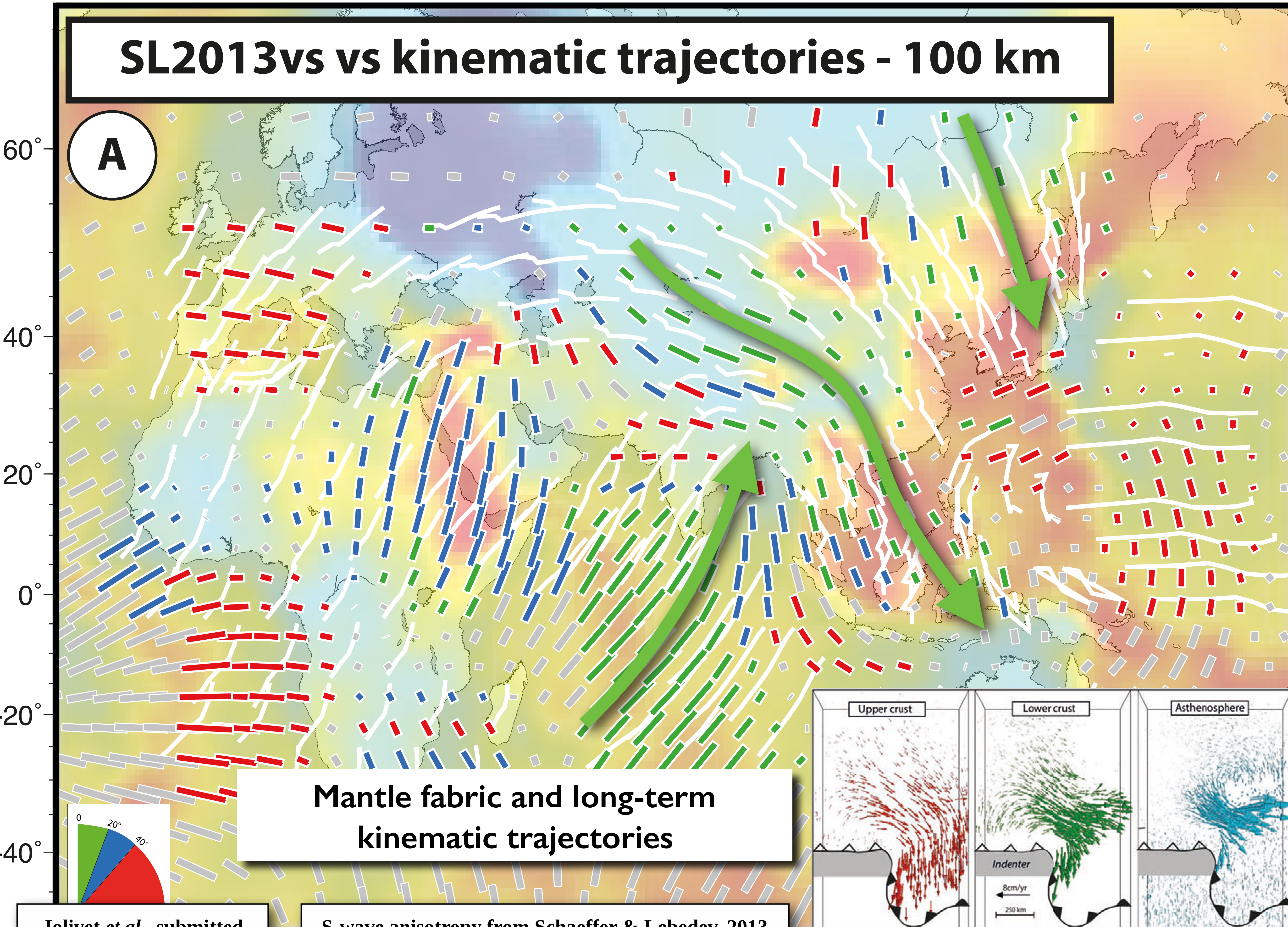
Fournier *et al.*, 2004

None of these models involves subduction that is merely considered as providing a stress-free boundary to the east

Extension is associated with slab retreat, hence with mantle flow.

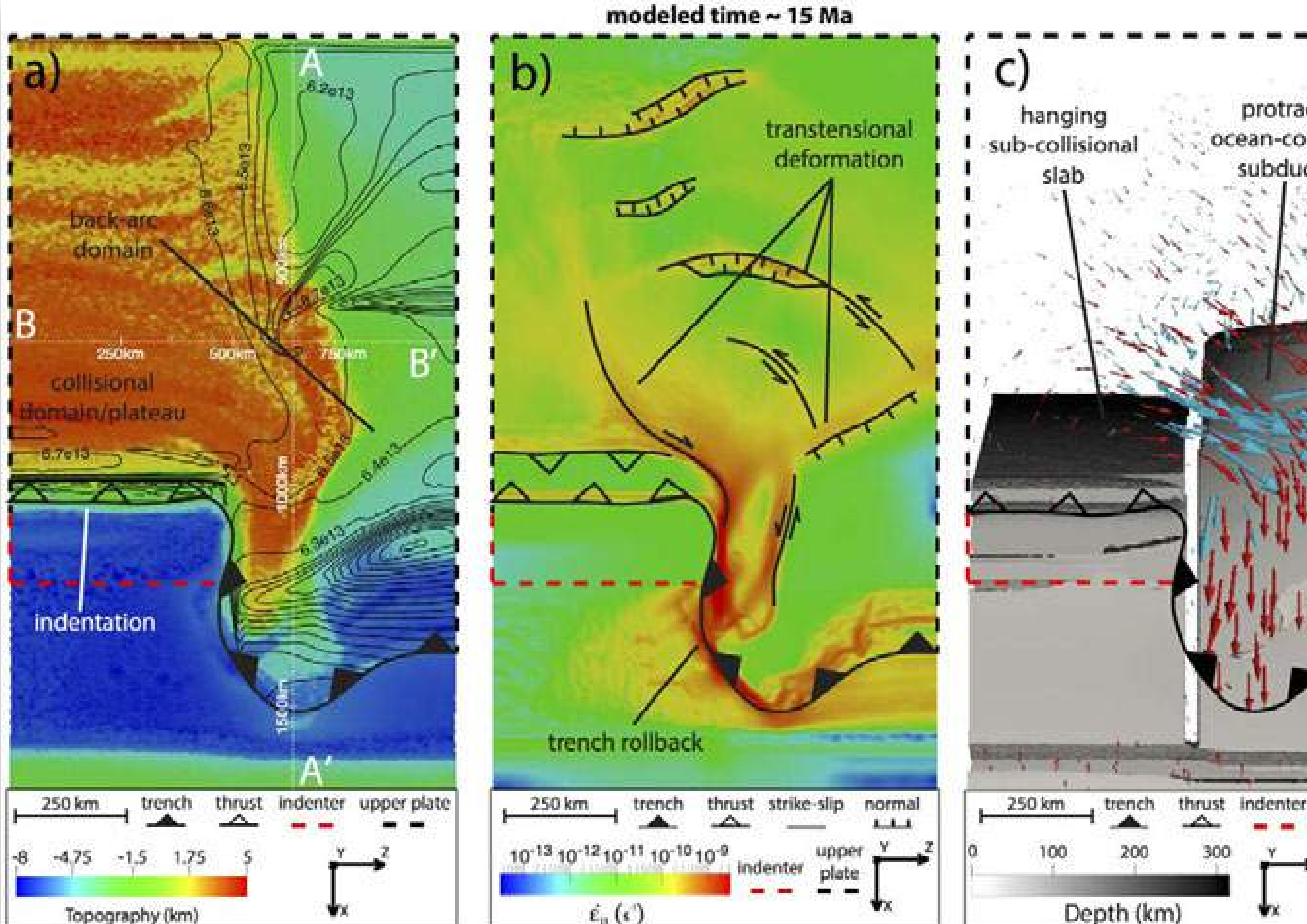
How does mantle flow underneath Asia ?

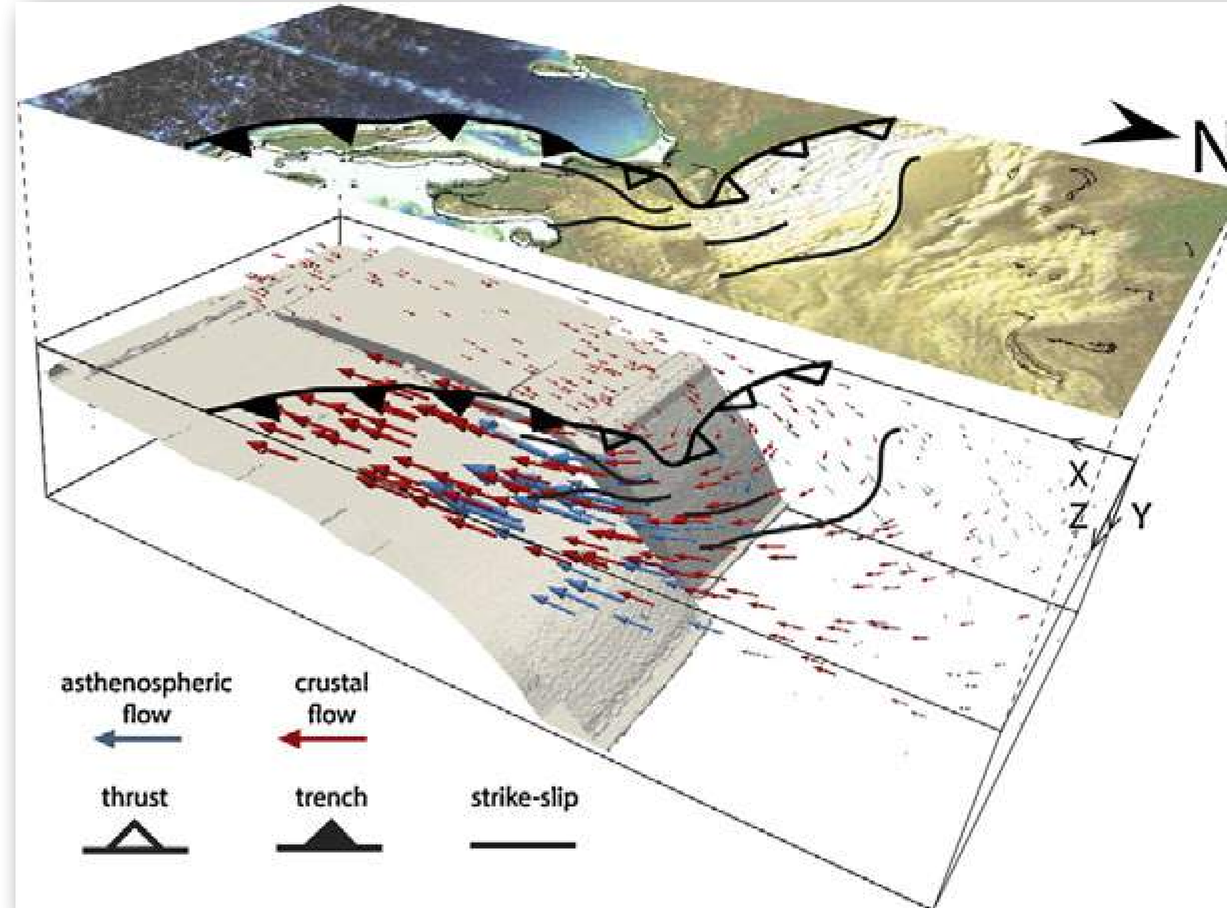
Jolivet *et al.*, 1994



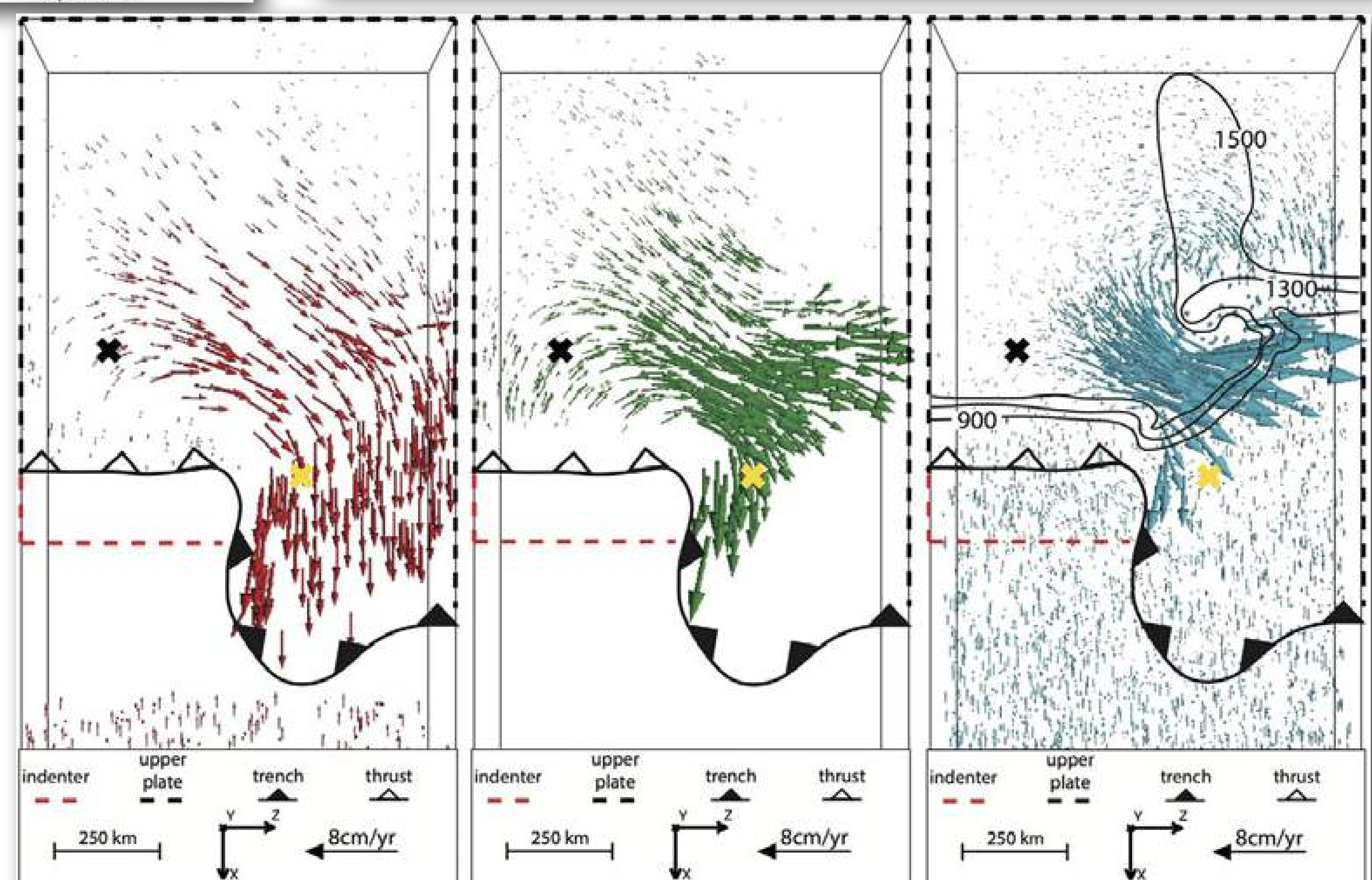
Jolivet *et al.*, submitted

S-wave anisotropy from Schaeffer & Lebedev, 2013

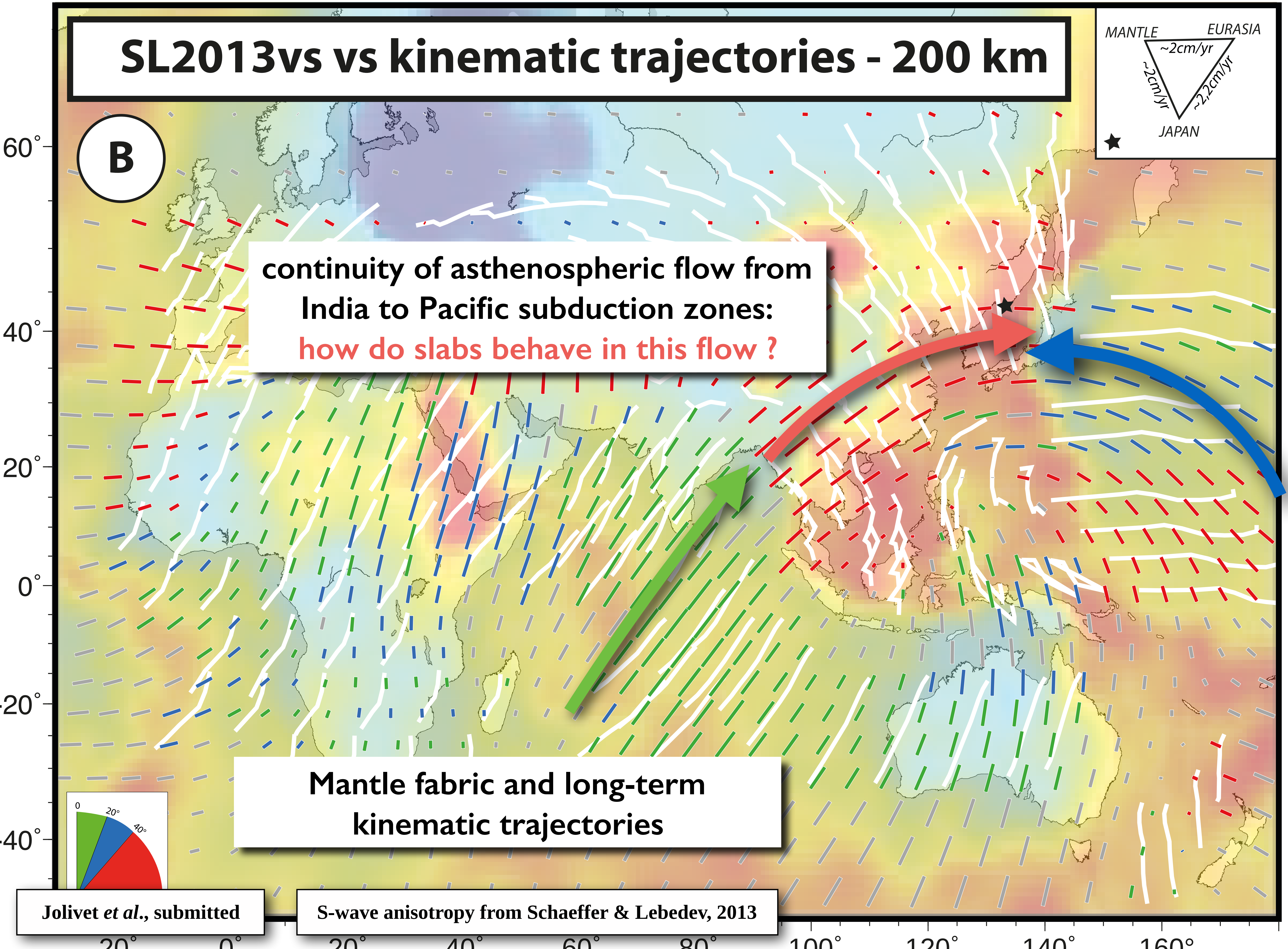




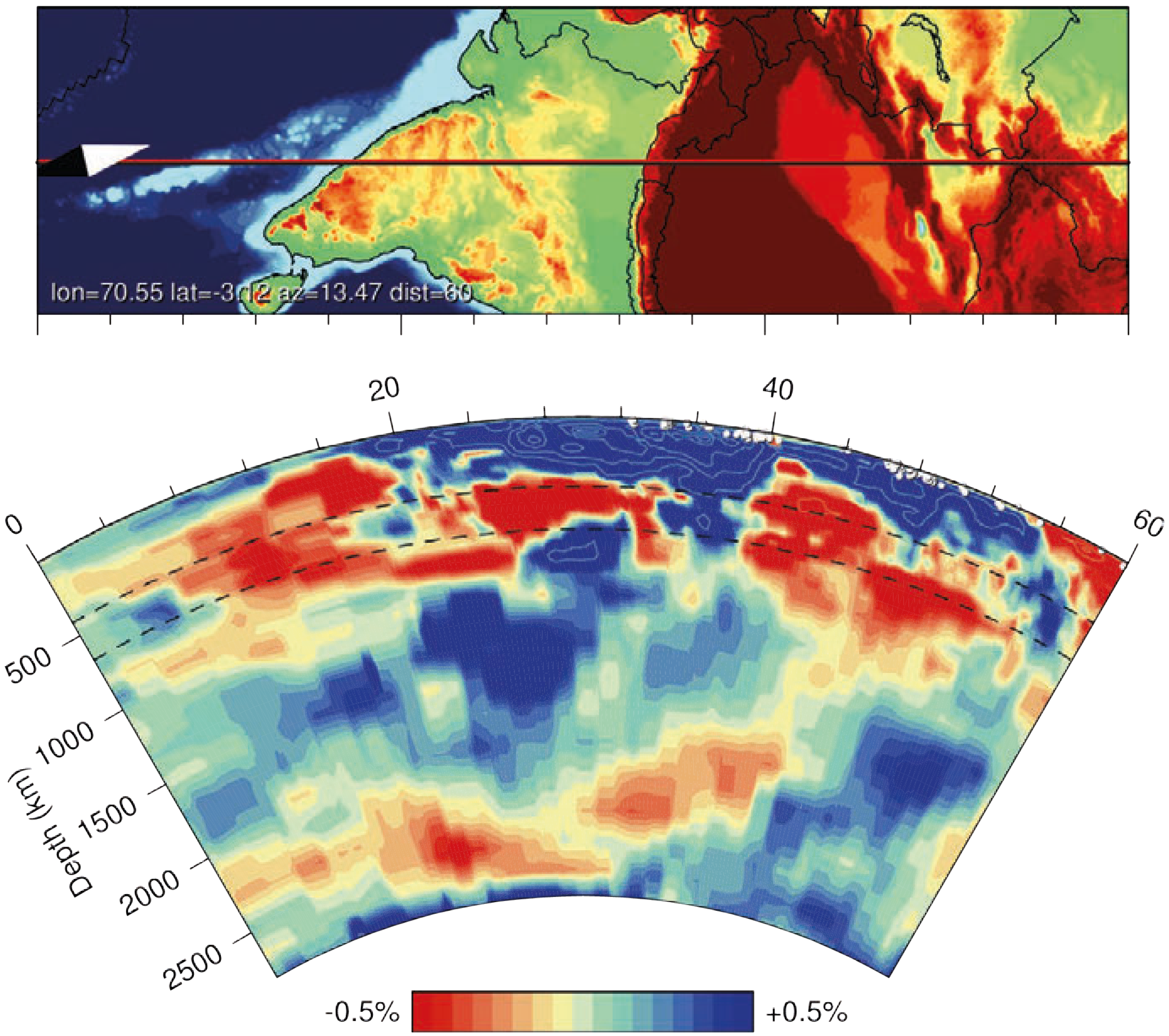
Mantle fabric at 100 km is very similar to the flow obtained in this model showing the deformation of the upper plate east of the collision zone, above the Sunda retreating subduction zone

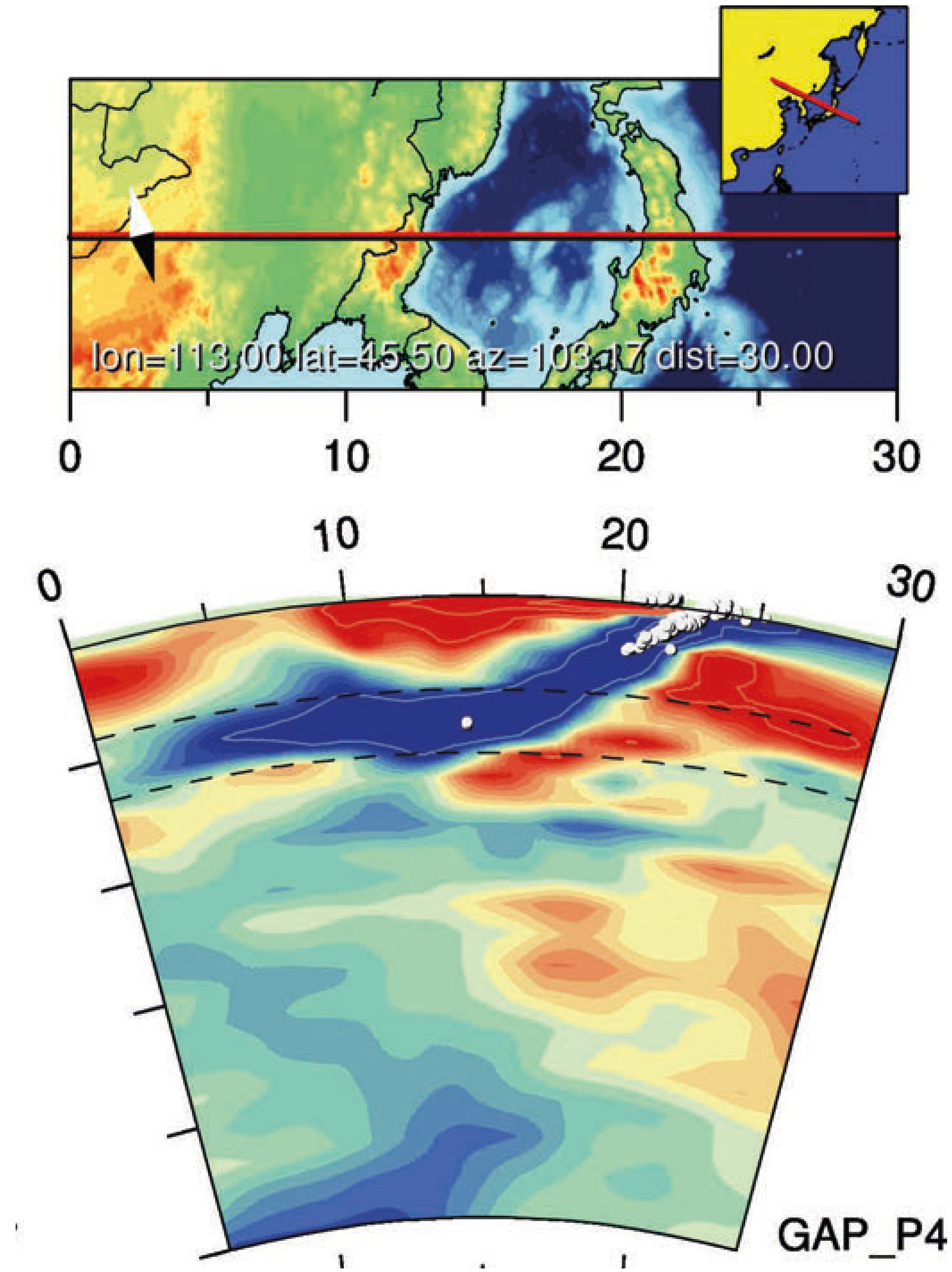


Sternai *et al.*, 2016


SL2013vs vs kinematic trajectories - 200 km
B
MANTLE
EURASIA
~2cm/yr
~2cm/yr
~2,2cm/yr
JAPAN
continuity of asthenospheric flow from India to Pacific subduction zones:
how do slabs behave in this flow ?
Mantle fabric and long-term kinematic trajectories
Jolivet et al., submitted
S-wave anisotropy from Schaeffer & Lebedev, 2013
60°
40°
20°
0°
-20°
-40°
-20°
0°
20°
40°
60°
80°
100°
120°
140°
160°
0
20°
40°

Slab geometries

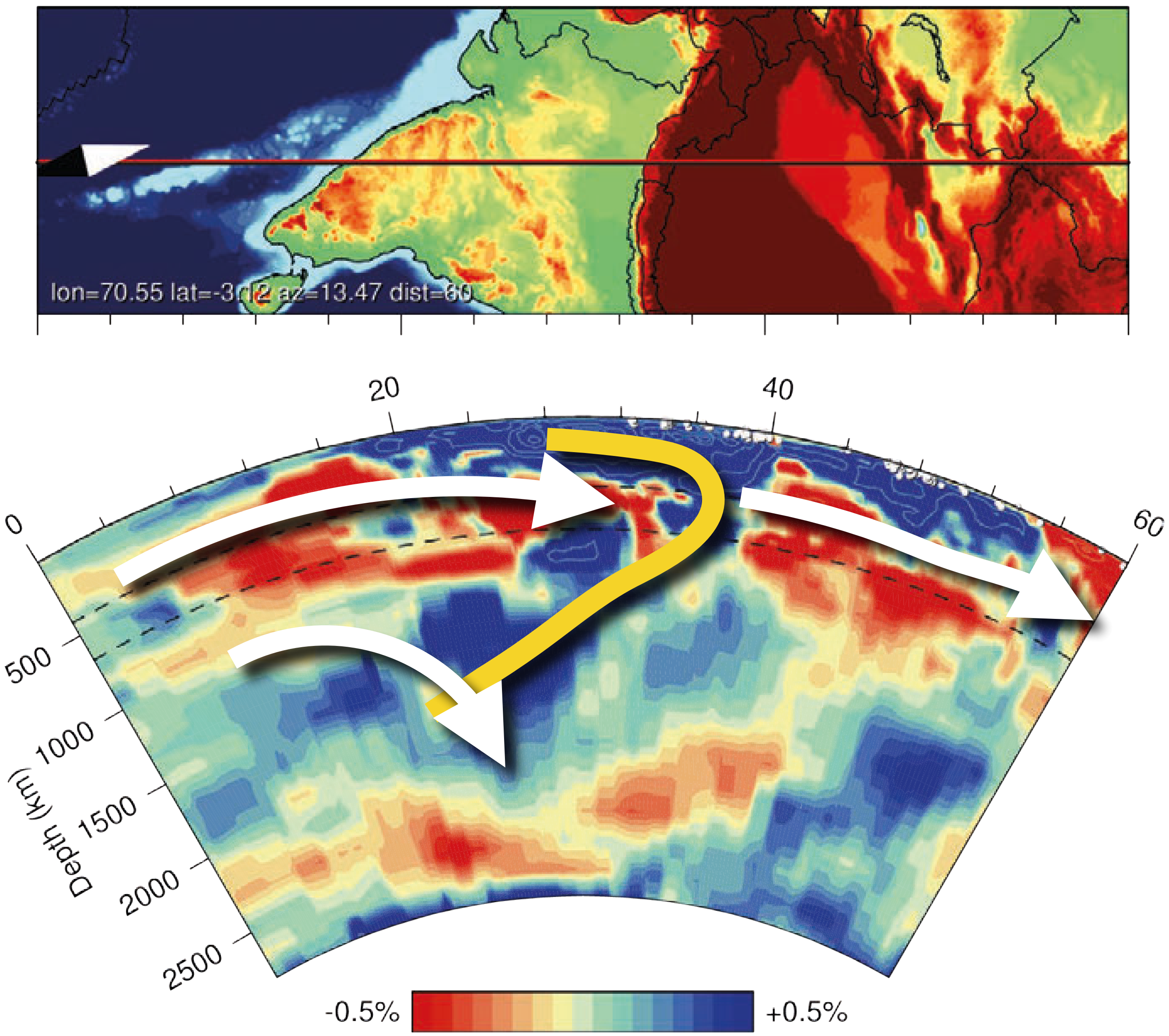




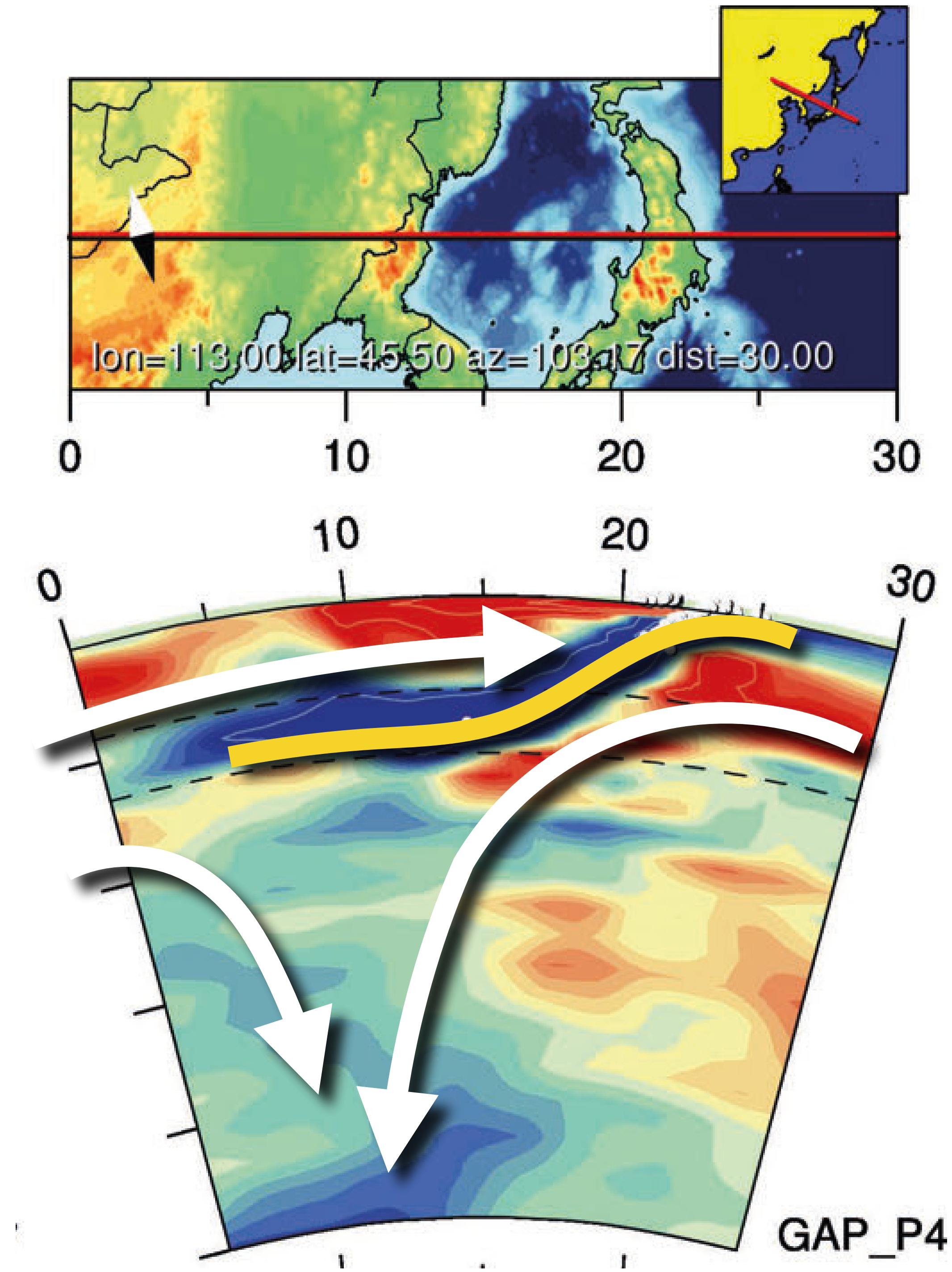
Spakman *et al.*, 2004

from Obayashi *et al.*, 2013. Courtesy of W. Spakman

Slab geometries



Himalayan slab: overhanging



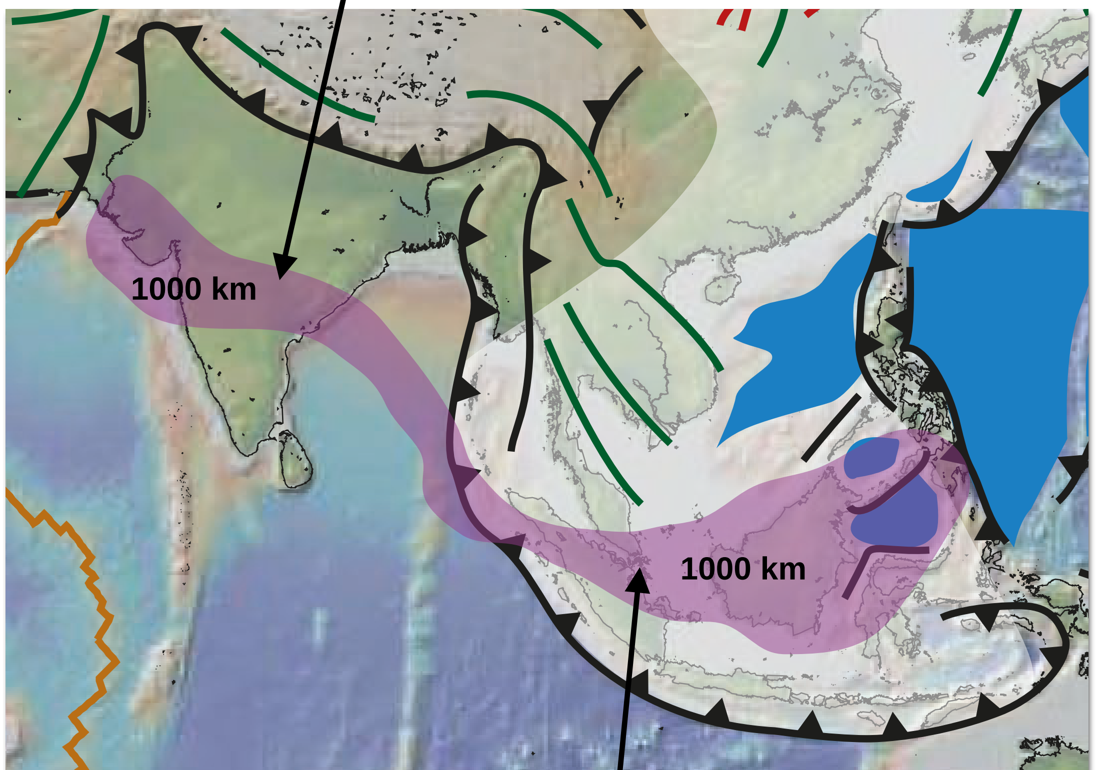
Japan slab: concave-up

Spakman *et al*., 2004

from Obayashi *et al*., 2013. Courtesy of W. Spakman

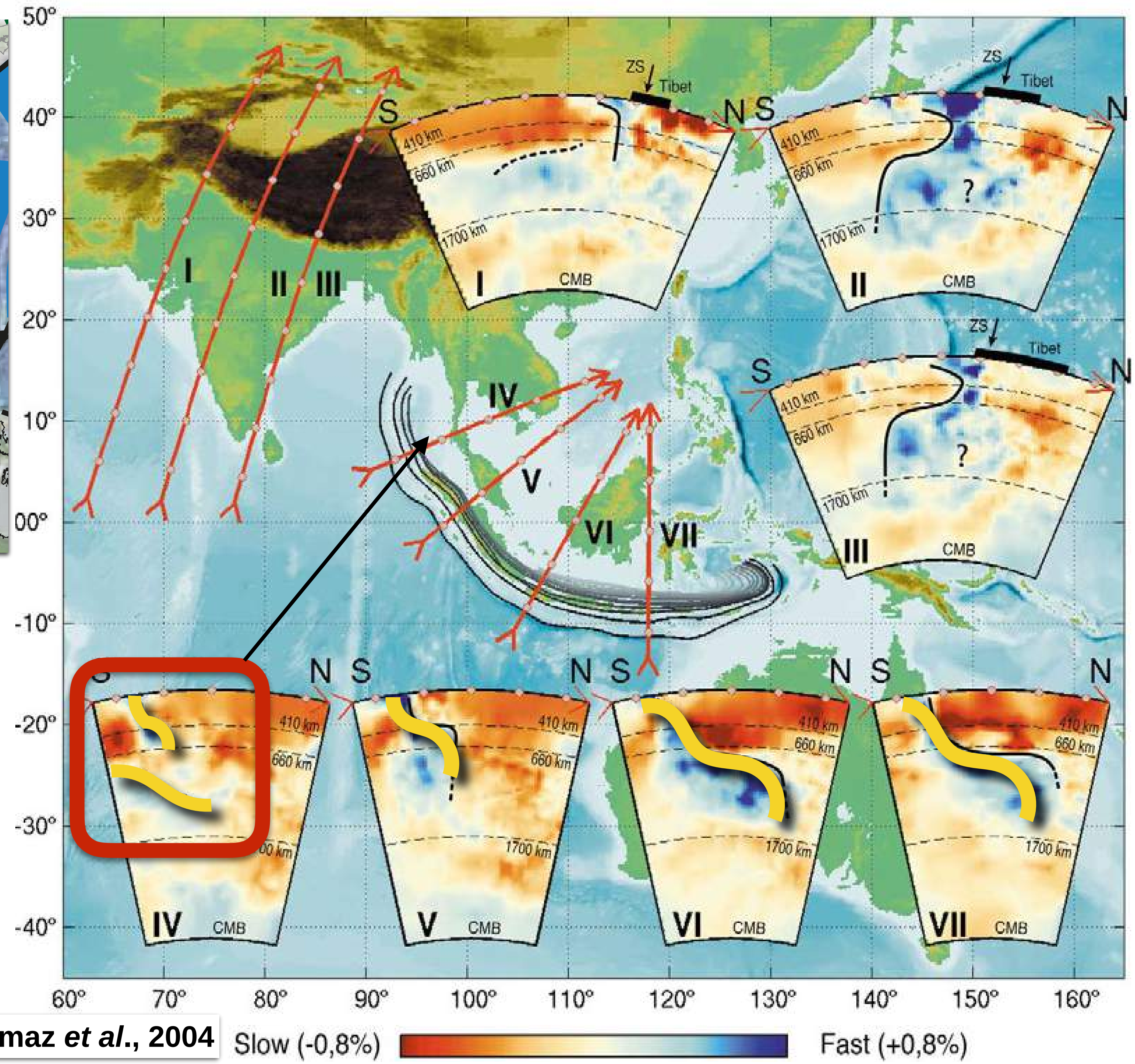
Slab geometries

Himalayan slab: overhanging

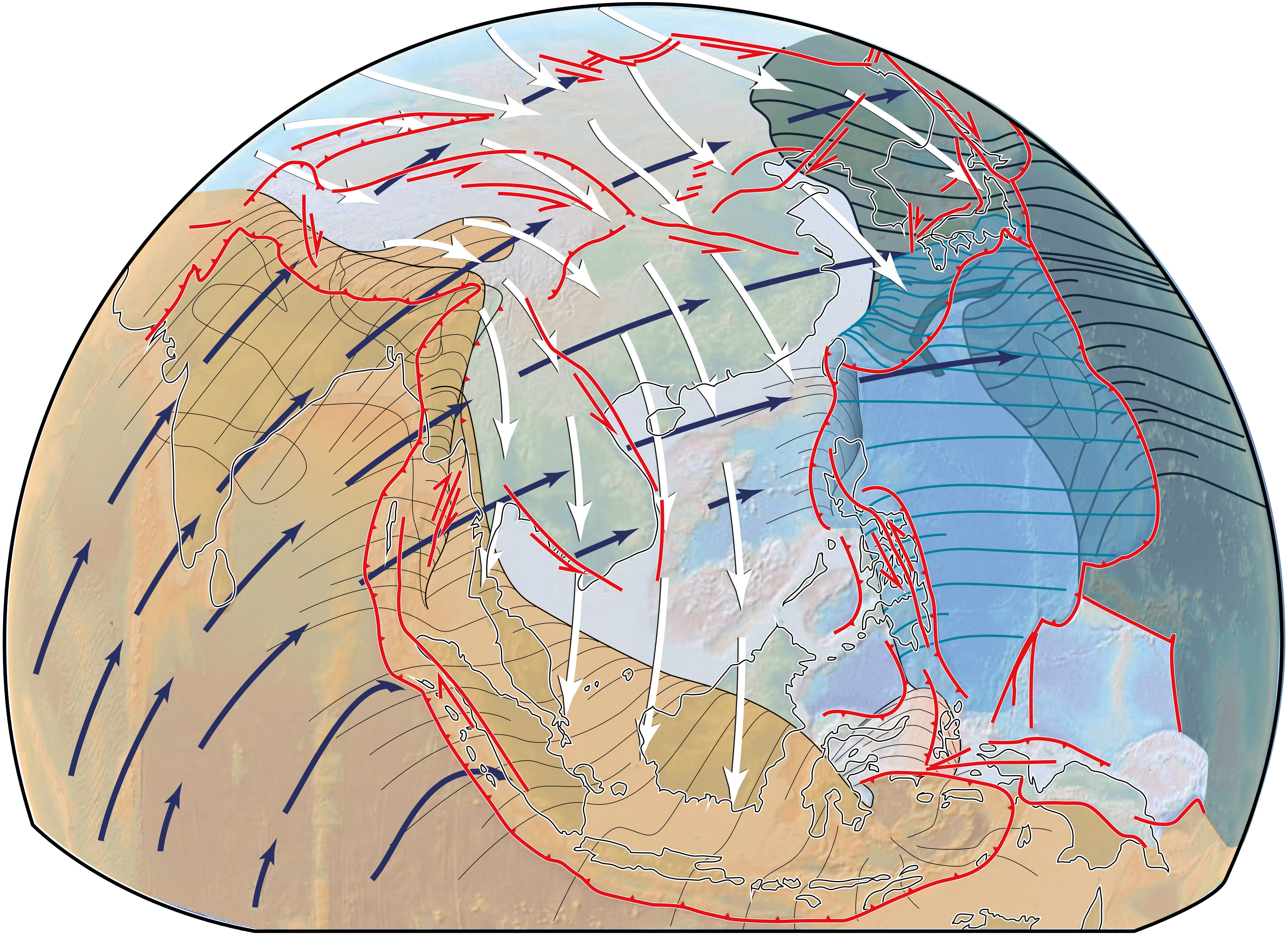


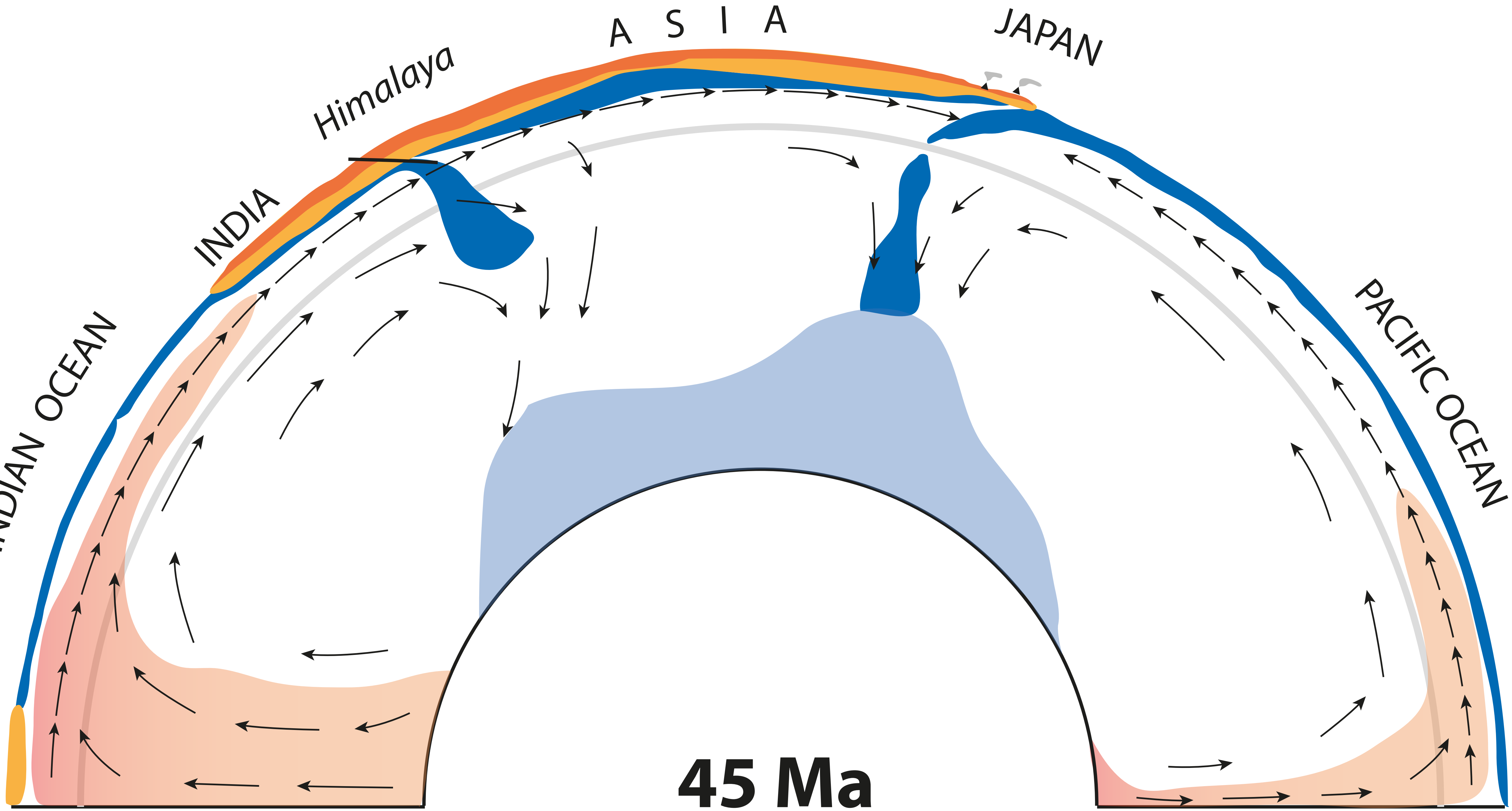
high-velocity anomaly from Hall *et al.*, 2015

Sunda slab: concave-up

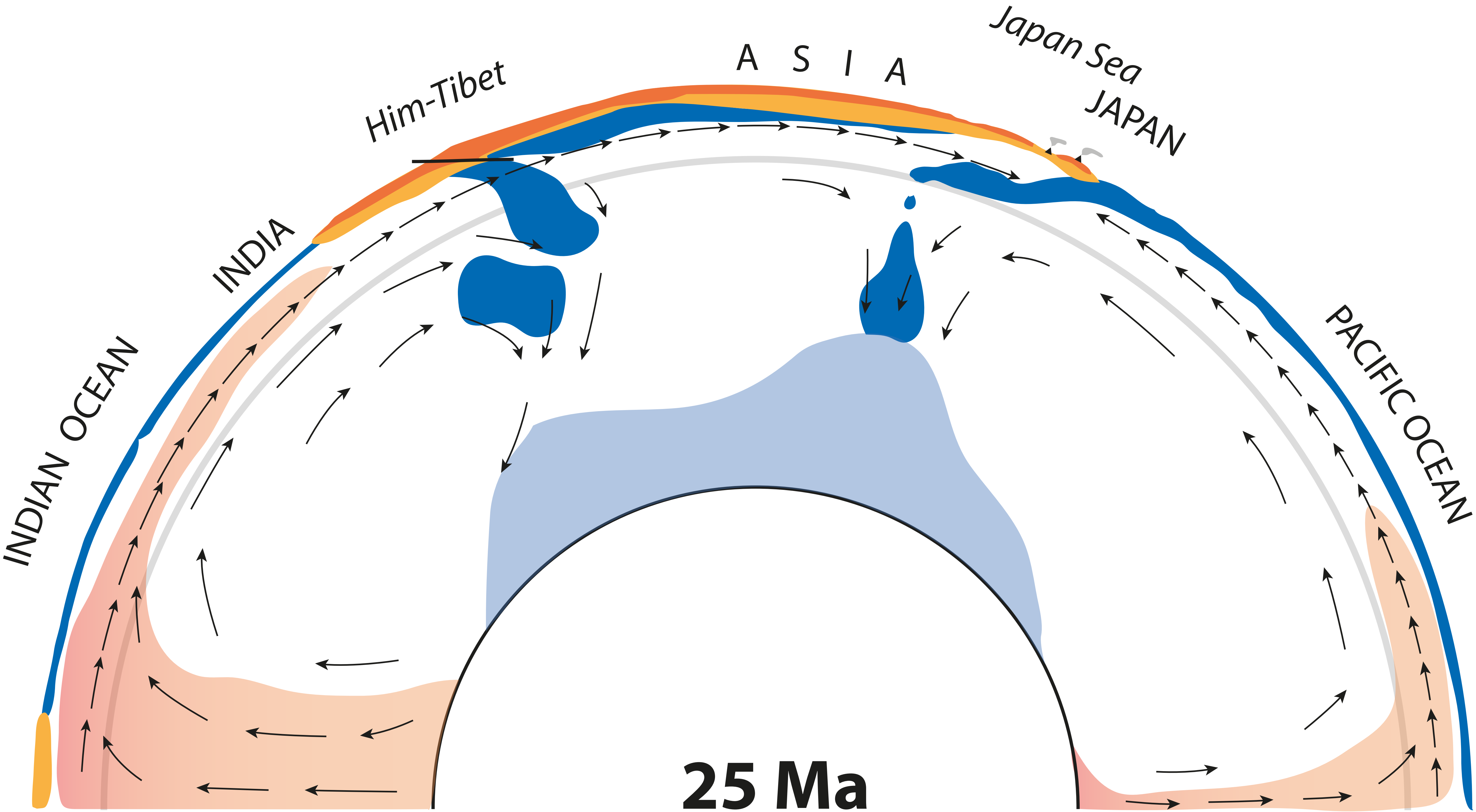


Replumaz *et al.*, 2004

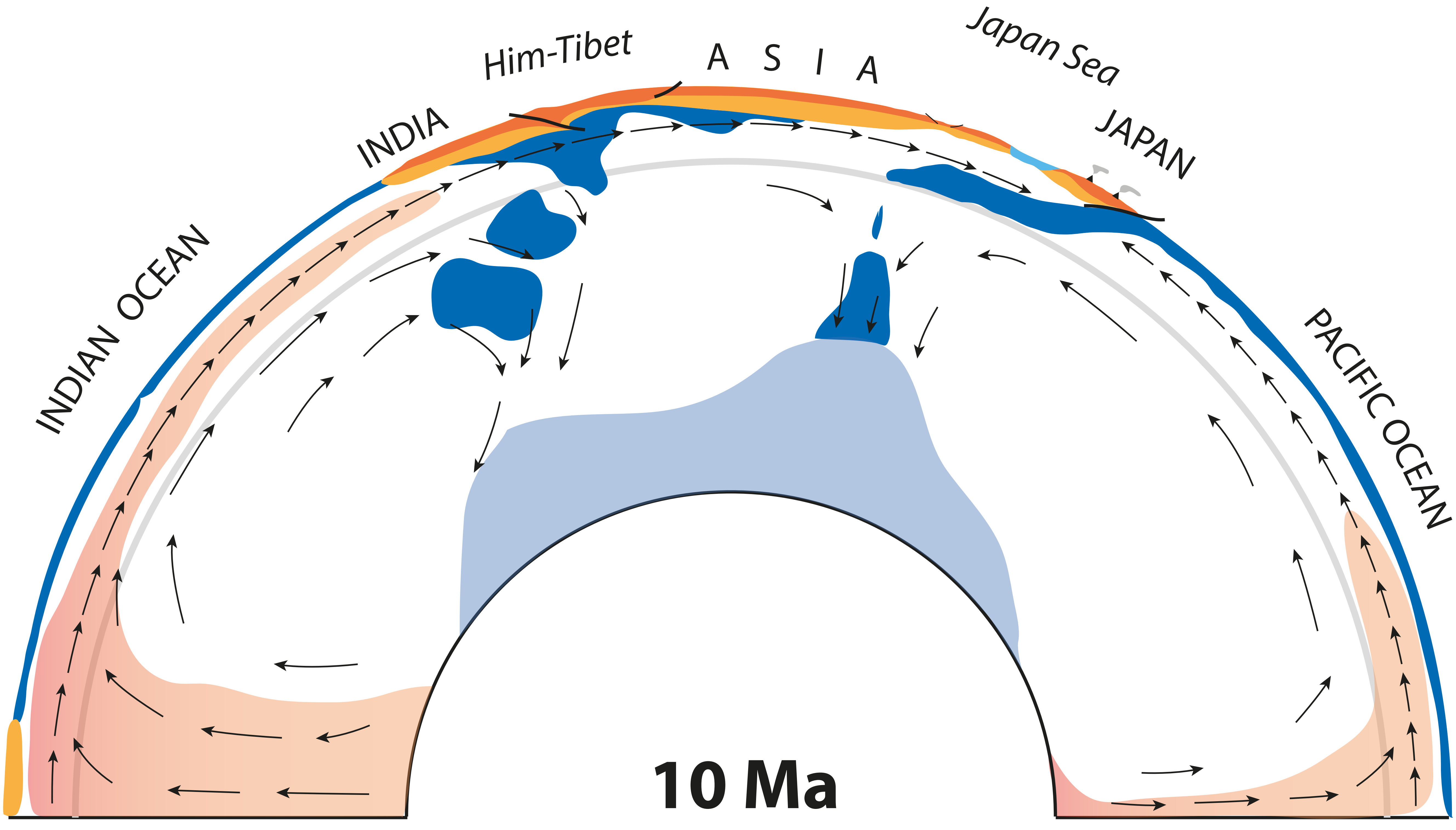




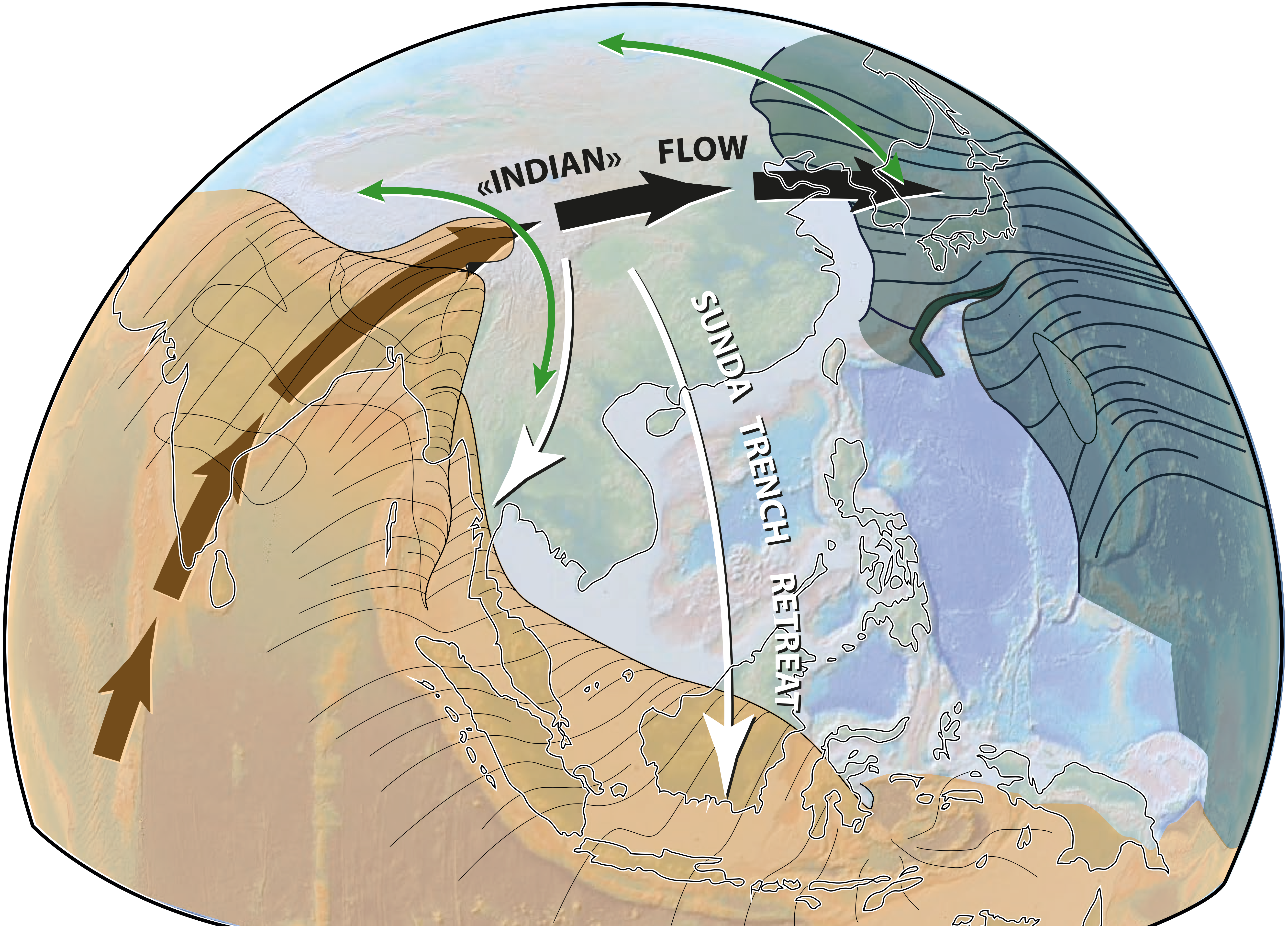
INDIAN OCEAN
INDIA
Himalaya
A S I A
JAPAN
PACIFIC OCEAN
45 Ma



Japan Sea
A S I A
Him-Tibet
JAPAN
INDIA
INDIAN OCEAN
PACIFIC OCEAN
25 Ma



Him-Tibet
A S I A
Japan Sea
INDIA
JAPAN
INDIAN OCEAN
PACIFIC OCEAN
10 Ma


«INDIAN» FLOW
SUNDA TRENCH RETREAT

50 Years of Plate Tectonics