The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific
and Cultural Organization

International Atomic
Energy Agency

H4.SMR/1775-44

"8th Workshop on Three-Dimensional Modelling of
Seismic Waves Generation, Propagation and their Inversion"

25 September - 7 October 2006

Geodynamics of Mediterranean

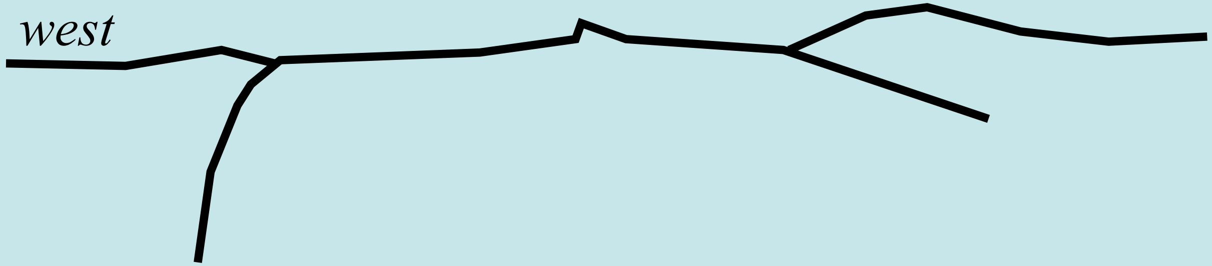
C. Doglioni

Universita' degli Studi di Roma
Roma

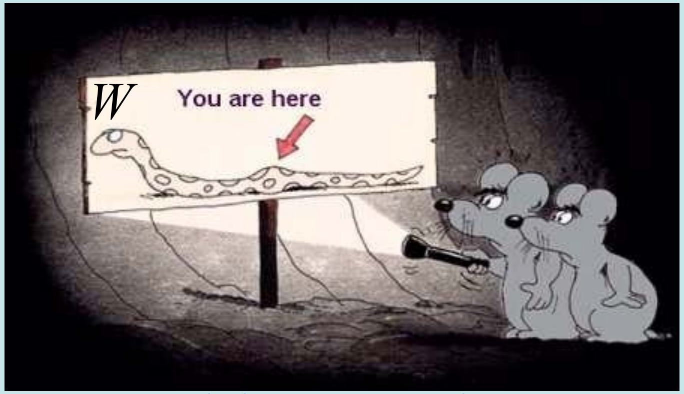
Global Tectonic Asymmetry
&
Applications to the Mediterranean

Imagination rules the world
Napoleon

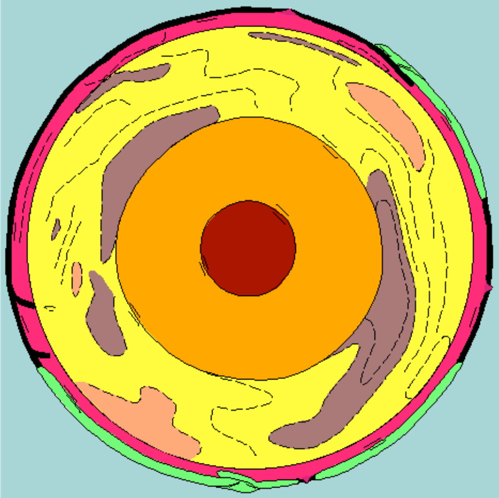
1) Orogens and Rifts show an “E-W” global asymmetry



2) The lithosphere moves along a westerly polarized flow

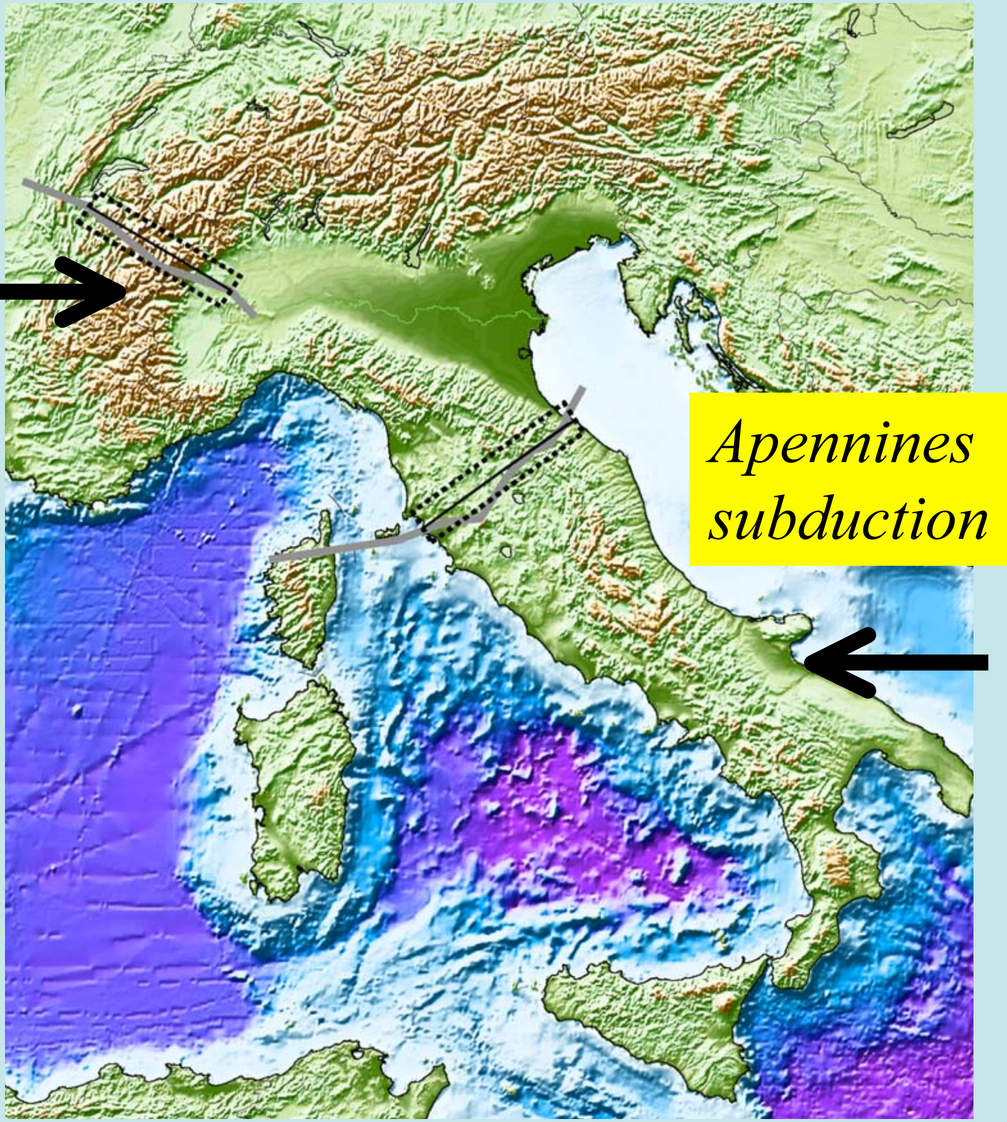


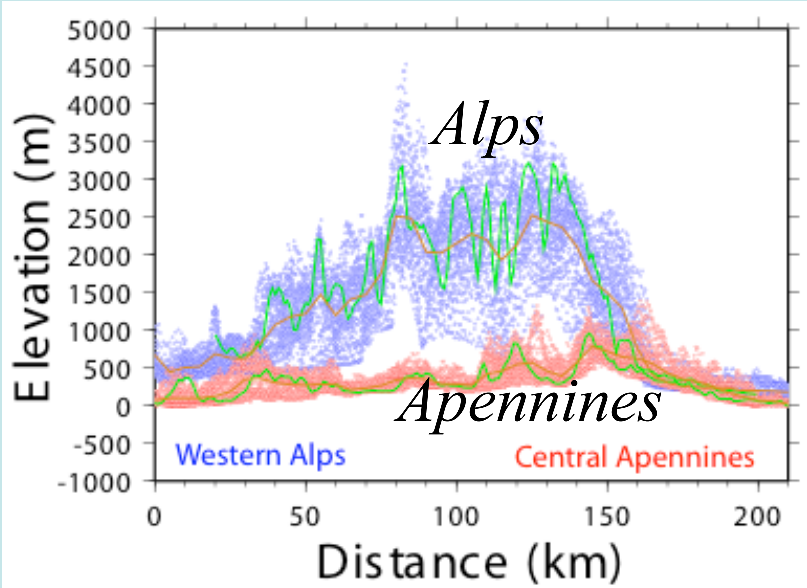
3) Plate tectonics is tuned by Earth’s rotation



TOPOGRAPHY

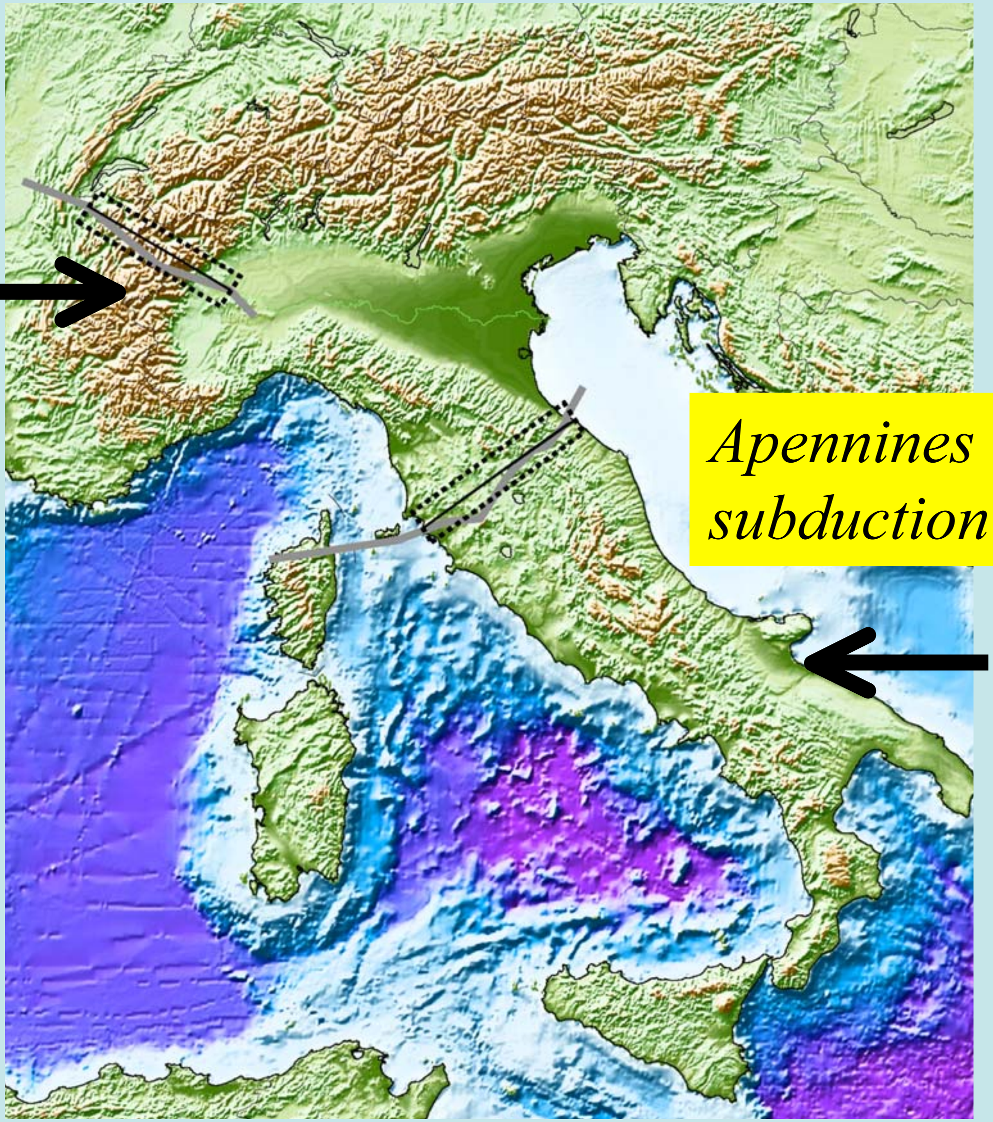
Alpine subduction



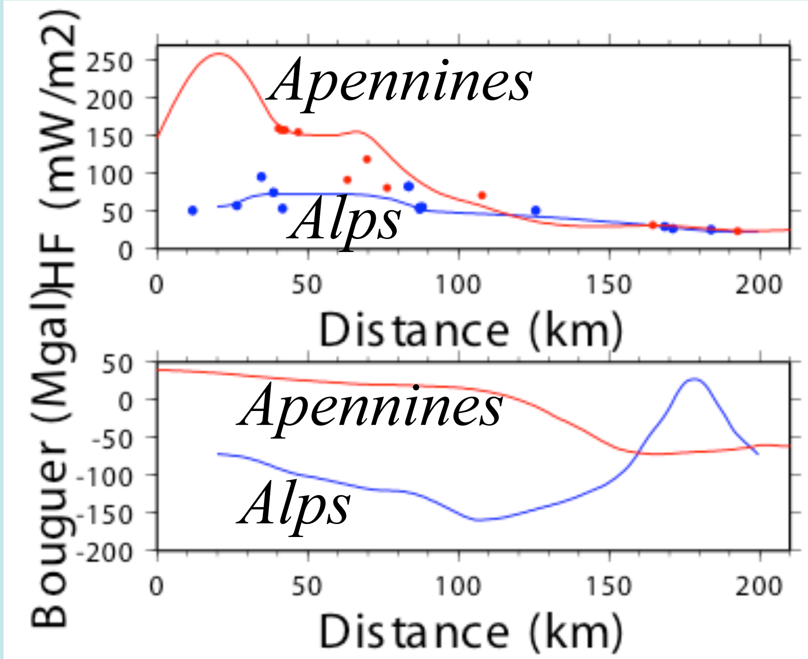


BOUGER ANOMALY & HEAT FLOW

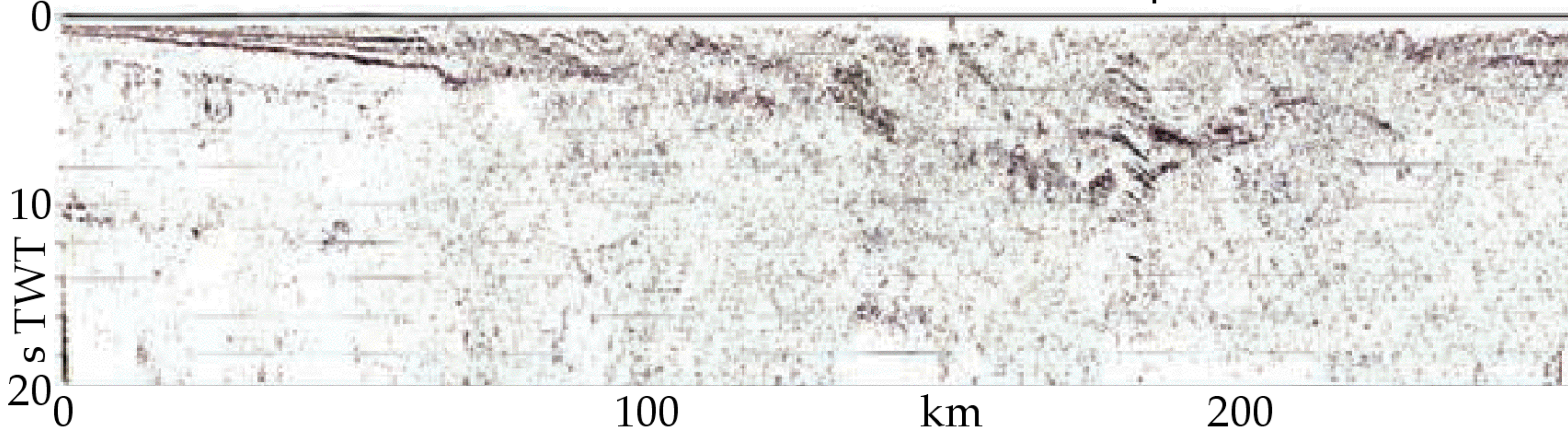
Alpine subduction

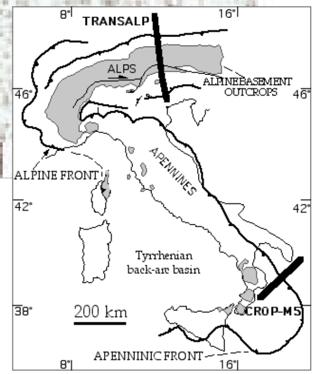


Apennines subduction

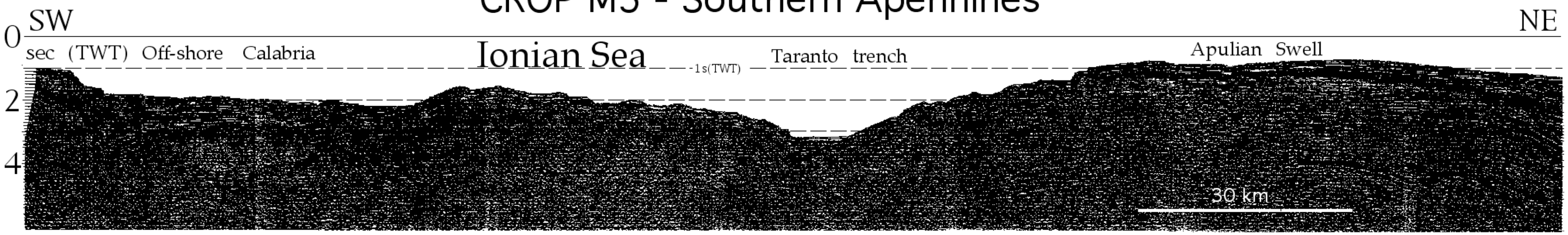


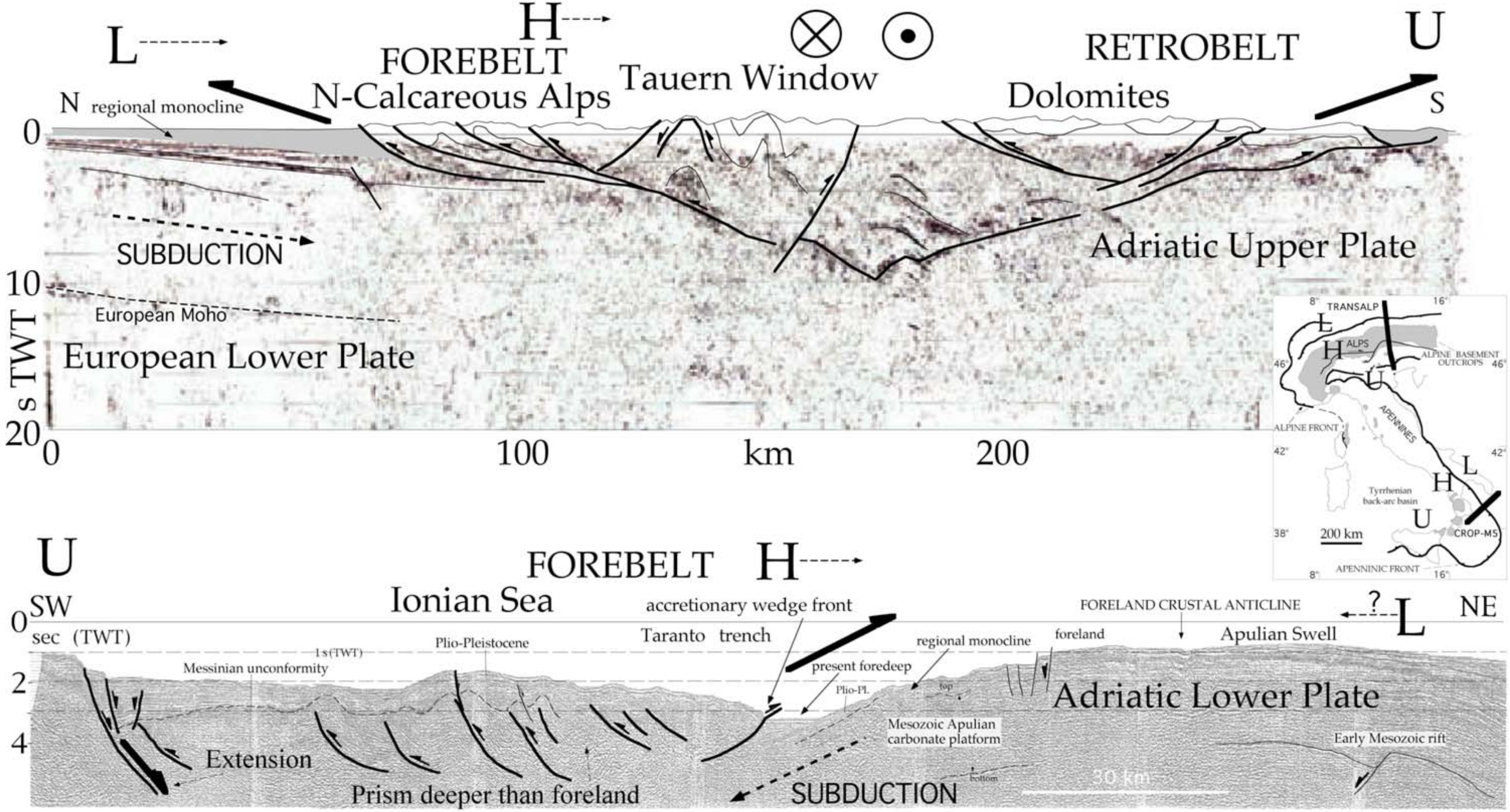
TRANSALP - Eastern Alps





CROP M5 - Southern Apennines

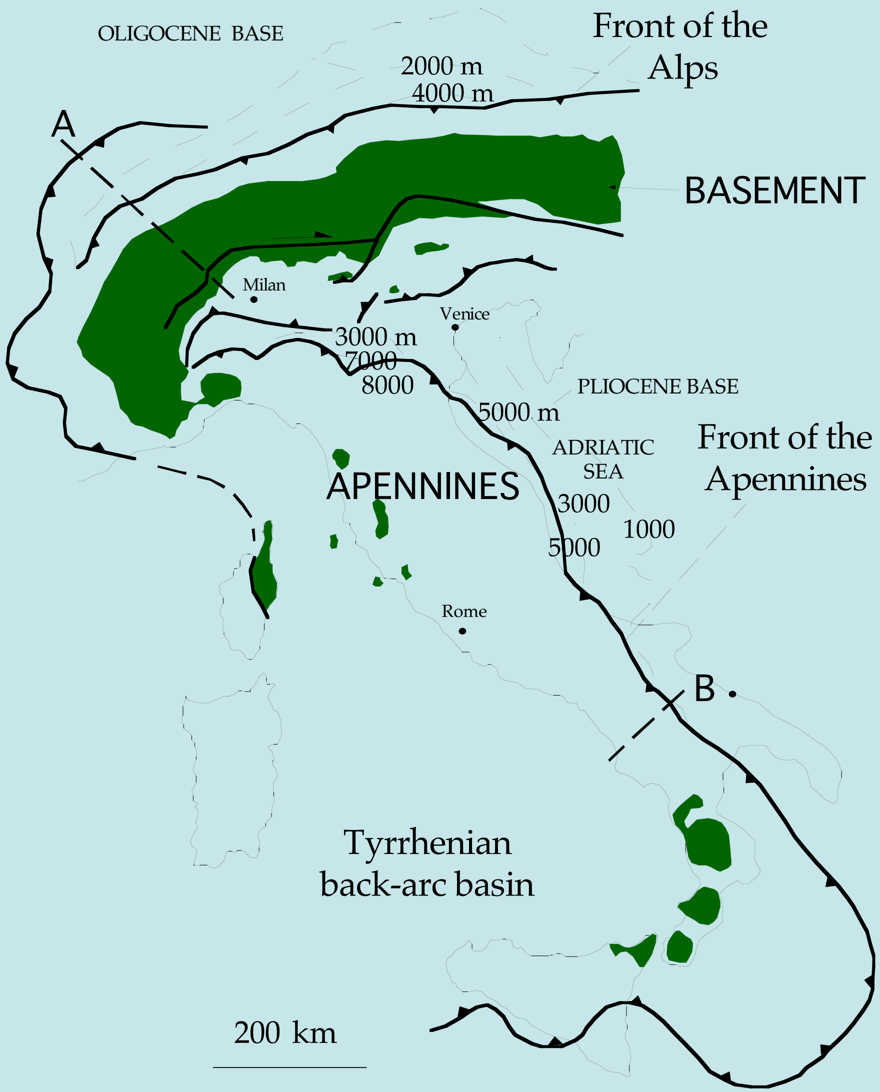



L
H
FOREBELT
N-Calcareous Alps
Tauern Window
RETROBELT
Dolomites
U
N
regional monocline
S
SUBDUCTION
Adriatic Upper Plate
European Moho
European Lower Plate
s TWT
0
10
20
0
100
km
200
TRANSALP
ALPS
ALPINE BASEMENT OUTCROPS
ALPINE FRONT
APENNINES
Tyrrhenian back-arc basin
200 km
CROP-M5
APENNINIC FRONT
U
FOREBELT
H
Ionian Sea
accretionary wedge front
FORELAND CRUSTAL ANTICLINE
?
L
SW
NE
sec (TWT)
Taranto trench
Apulian Swell
Plio-Pleistocene
regional monocline
foreland
Messinian unconformity
present foredeep
Adriatic Lower Plate
Mesozoic Apulian carbonate platform
Extension
Early Mesozoic rift
Prism deeper than foreland
SUBDUCTION
30 km
2
4

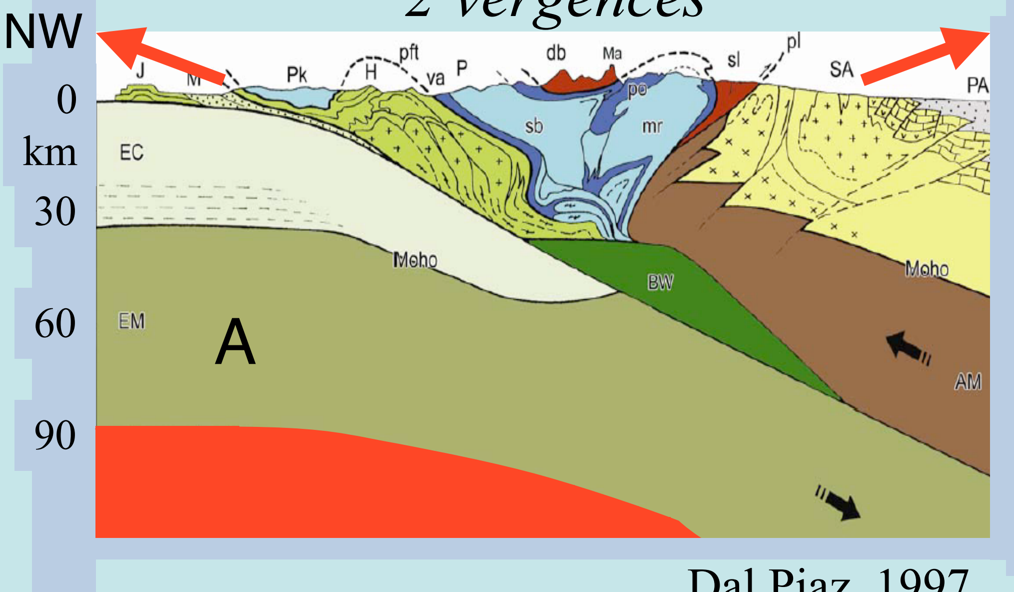
ROCKS


OLIGOCENE BASE
Front of the Alps
2000 m
4000 m
A
BASEMENT
Milan
Venice
3000 m
7000
8000
PLIOCENE BASE
5000 m
ADRIATIC SEA
Front of the Apennines
APENNINES
3000
1000
5000
Rome
B
Tyrrhenian back-arc basin
200 km

VERGENCES & MOHO

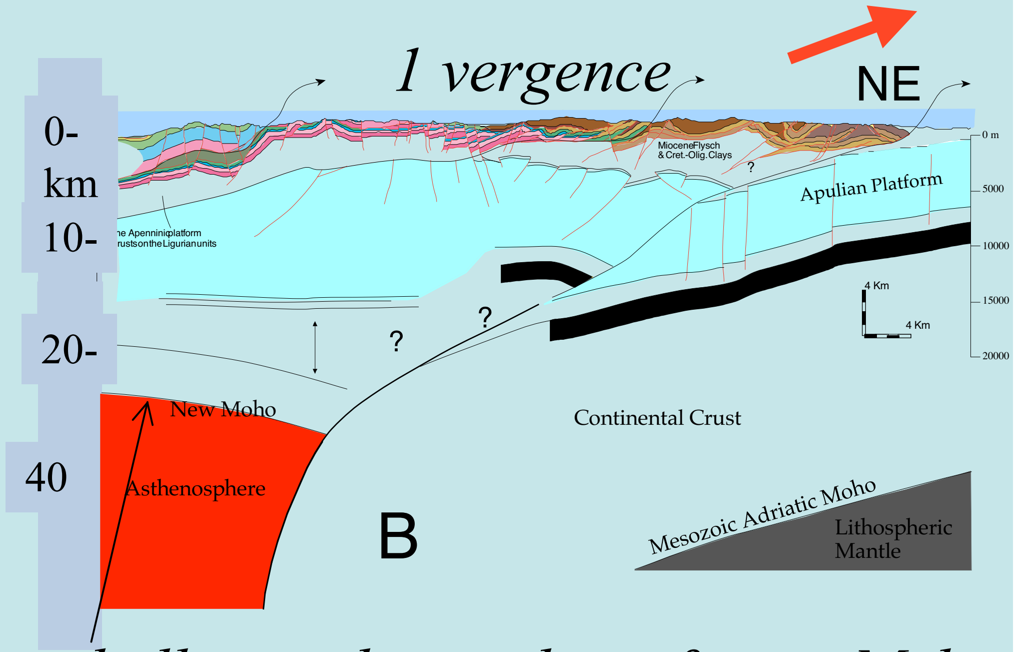


2 vergences



Dal Piaz, 1997

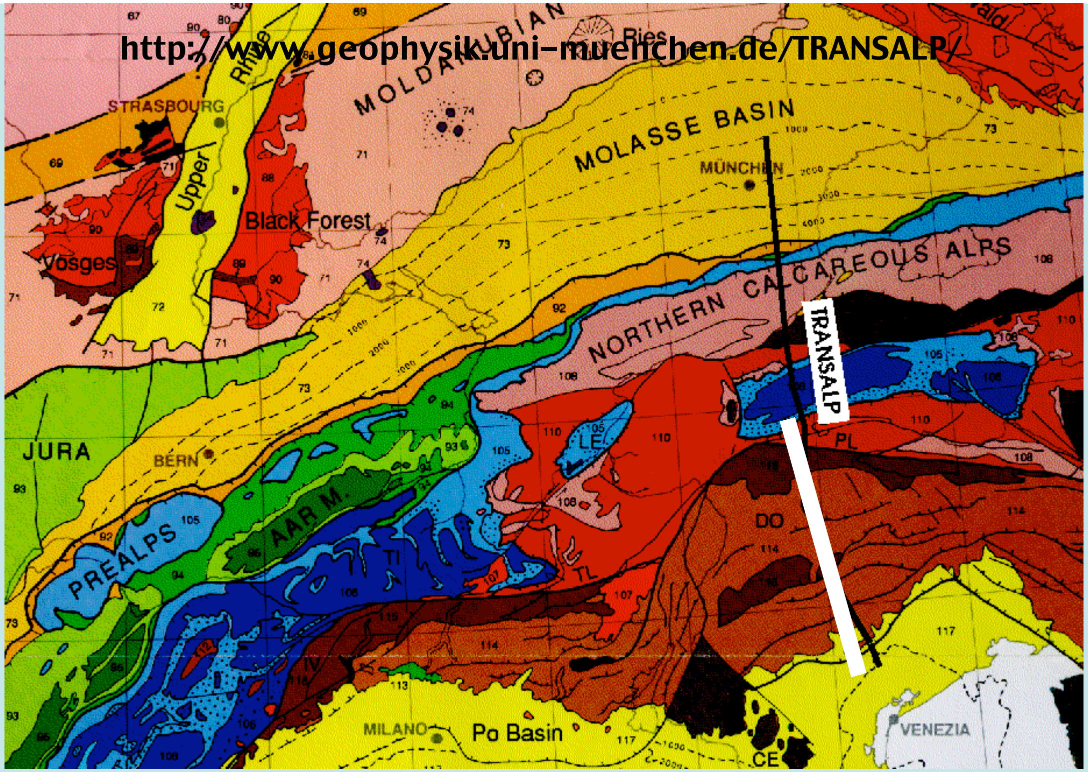
1 vergence

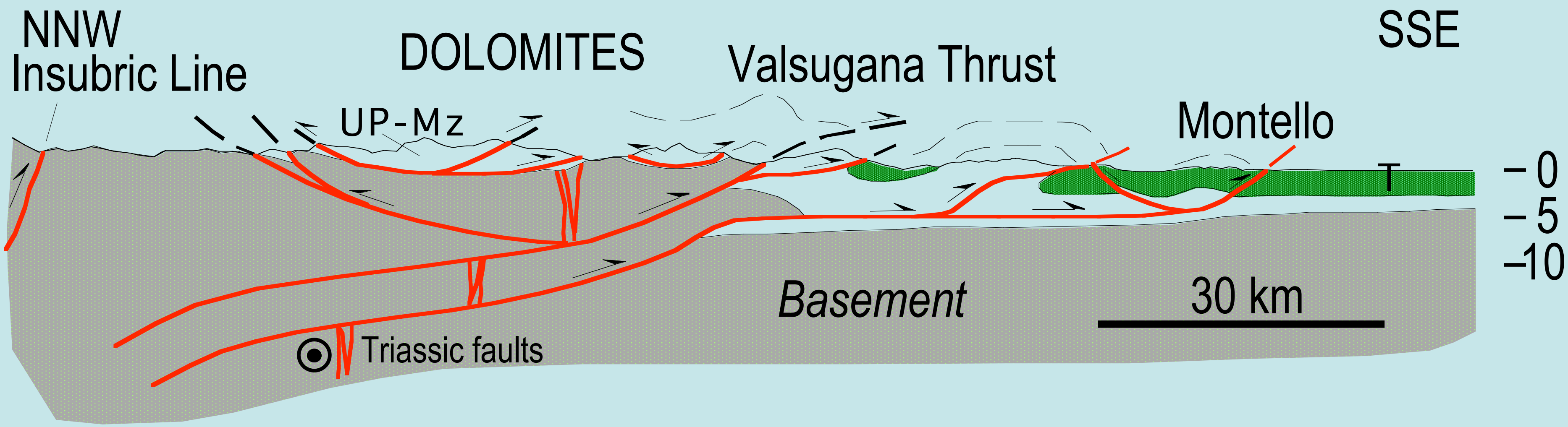


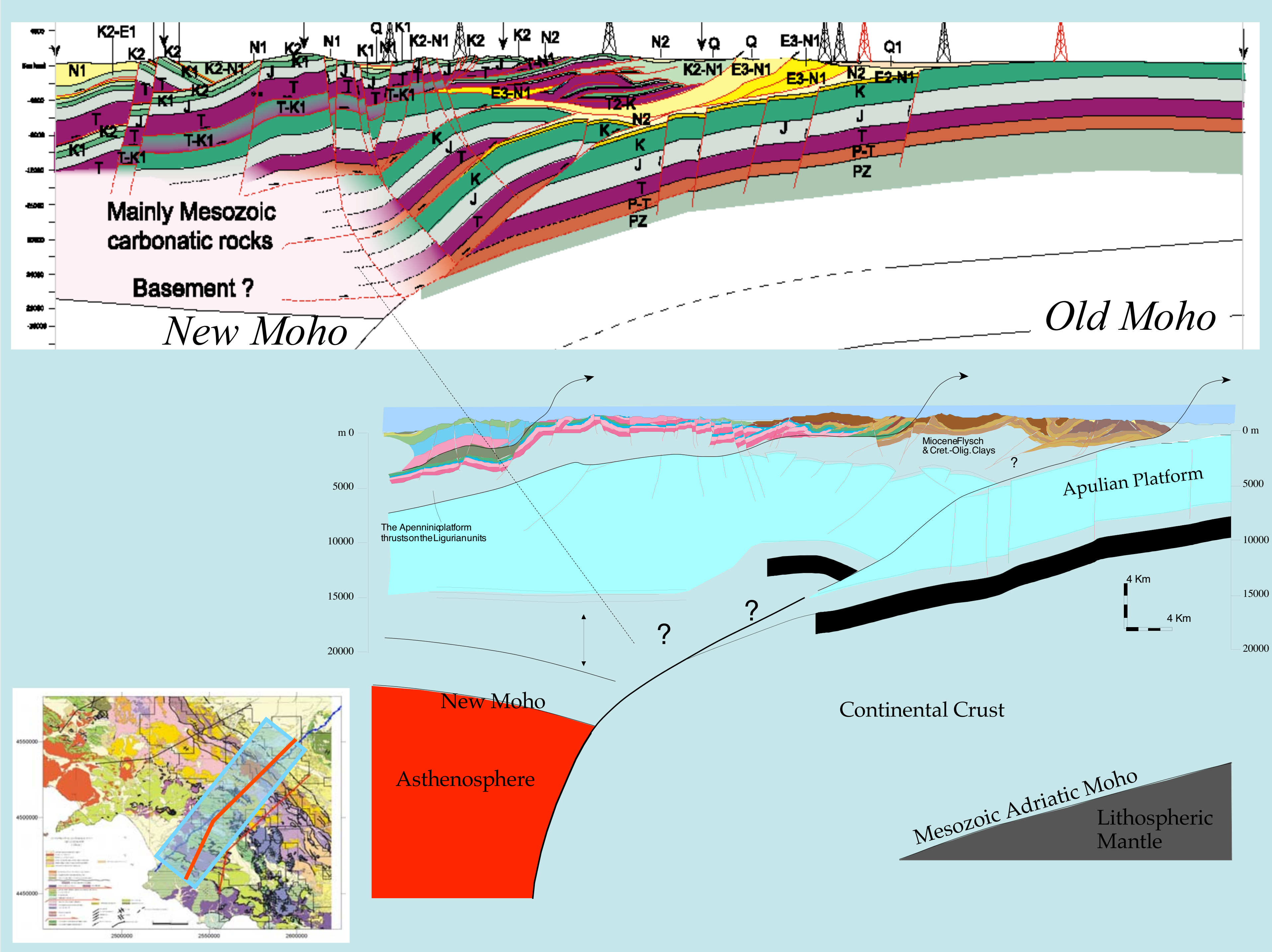
shallow asthenosphere & new Moho

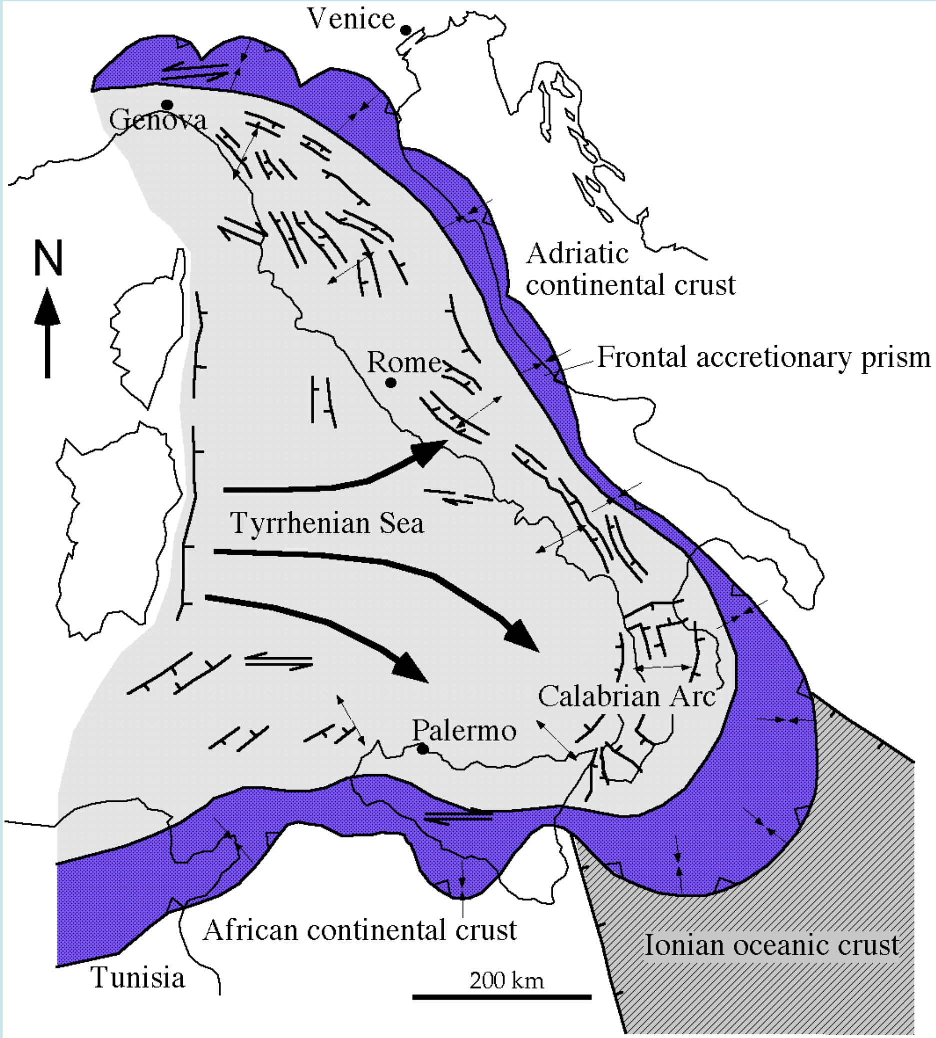
ALPS
Blue schists ophiolites
Age 160 Ma - HP 50 Ma

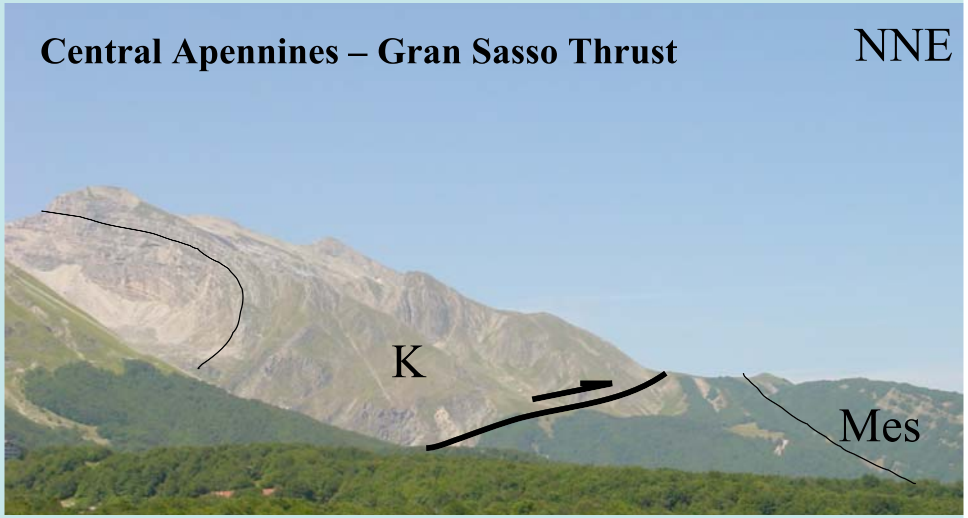
APENNINES
"unmetamorphosed" ophiolites

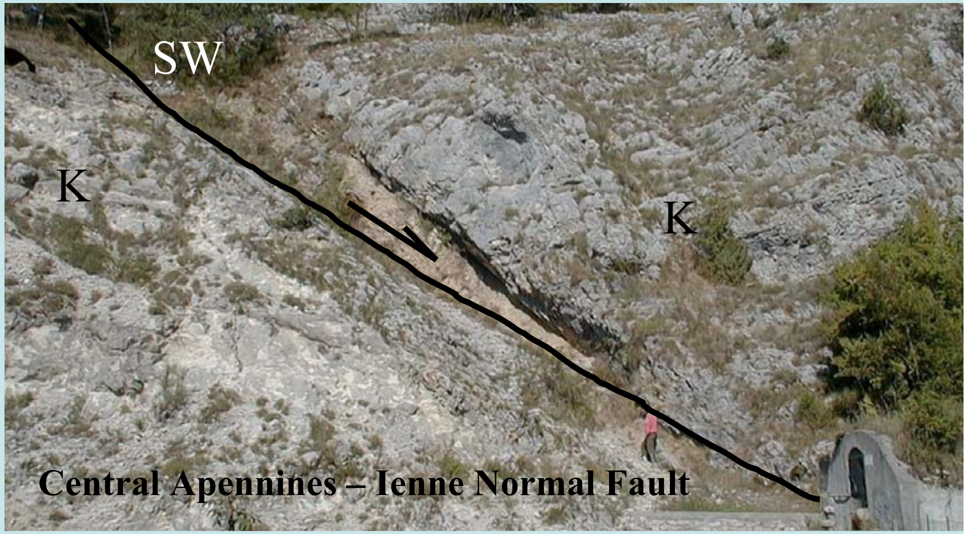

http://www.geophysik.uni-muenchen.de/TRANSALP/
MOLDANUBIAN
Ries
STRASBOURG
Upper Rhine
Black Forest
Vosges
MOLASSE BASIN
MÜNCHEN
NORTHERN CALCAREOUS ALPS
TRANSALP
JURA
BERN
PREALPS
AAR M.
LE
PL
DO
TL
TI
MILANO
Po Basin
VENEZIA
CE


NNW
Insubric Line
DOLOMITES
UP-Mz
Valsugana Thrust
SSE
Montello
T
– 0
– 5
–10
Basement
30 km
Triassic faults

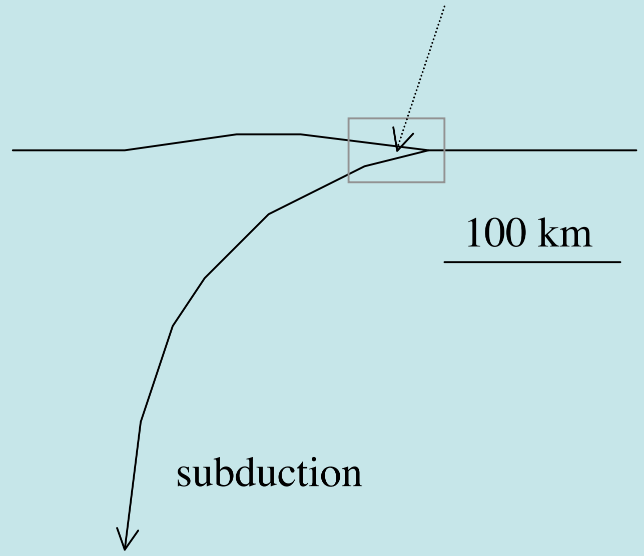

Mainly Mesozoic carbonatic rocks
Basement ?
New Moho
Old Moho
m 0
5000
10000
15000
20000
0 m
MioceneFlysch
& Cret.-Olig. Clays
?
Apulian Platform
The Apenniniqplatform
thrustsontheLigurianunits
4 Km
4 Km
?
?
New Moho
Asthenosphere
Continental Crust
Mesozoic Adriatic Moho
Lithospheric
Mantle

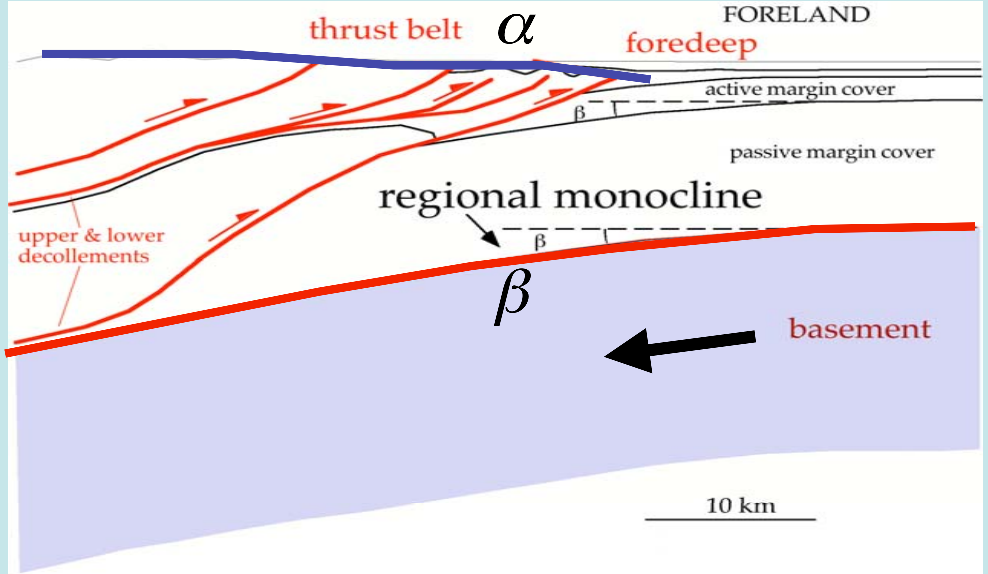

Venice
Genova
N
Adriatic continental crust
Rome
Frontal accretionary prism
Tyrrhenian Sea
Calabrian Arc
Palermo
African continental crust
Ionian oceanic crust
Tunisia
200 km

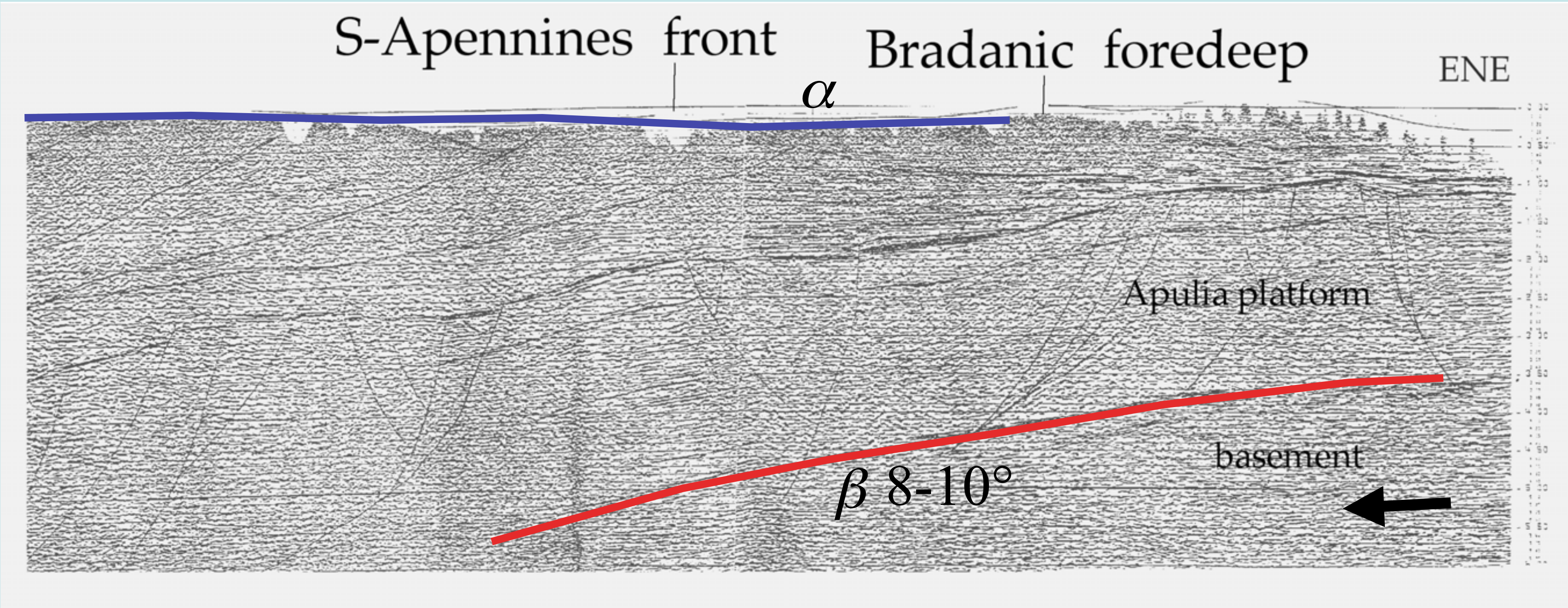

Central Apennines – Gran Sasso Thrust
NNE
K
Mes

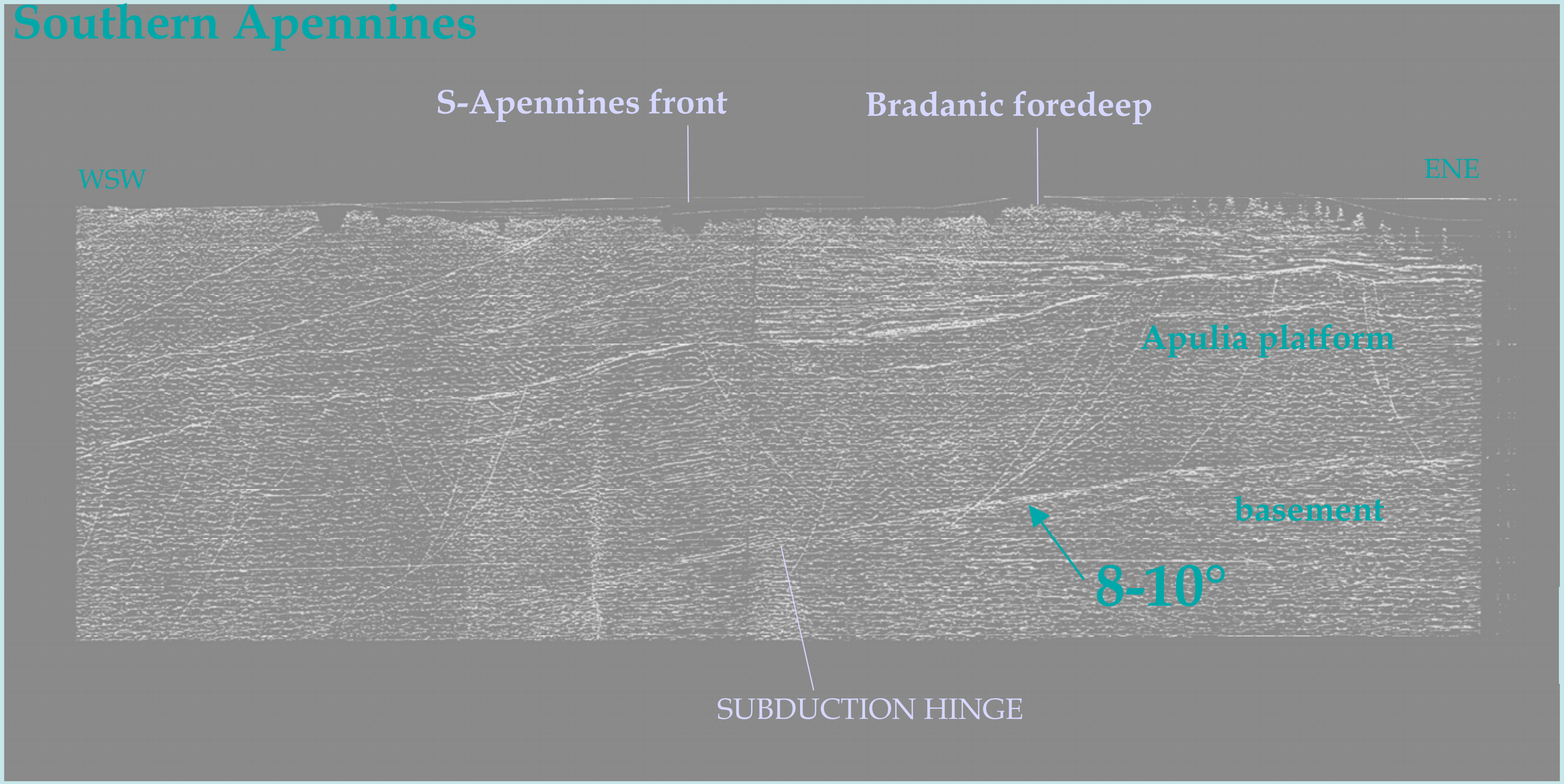

SW
K
K
Central Apennines – Ienne Normal Fault

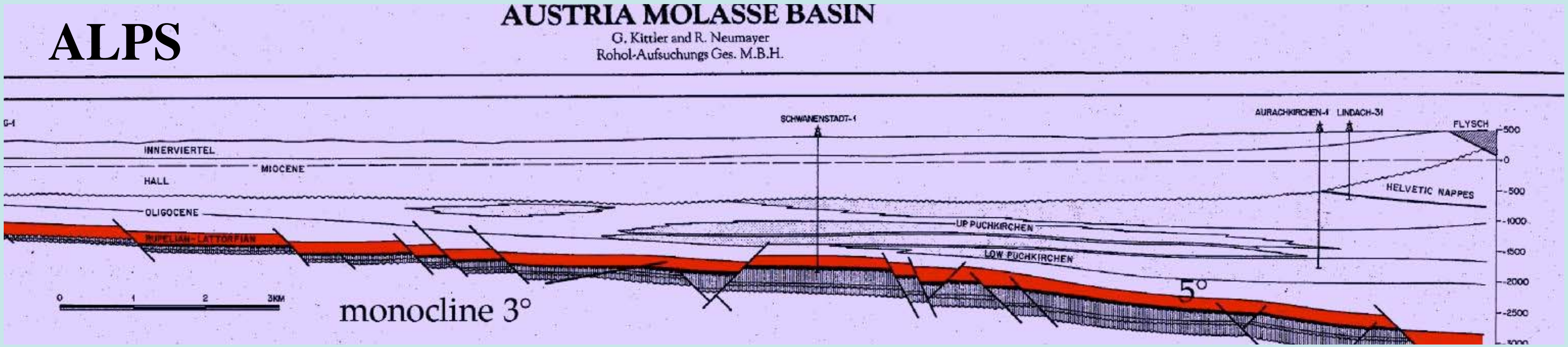
REGIONAL MONOCLINE



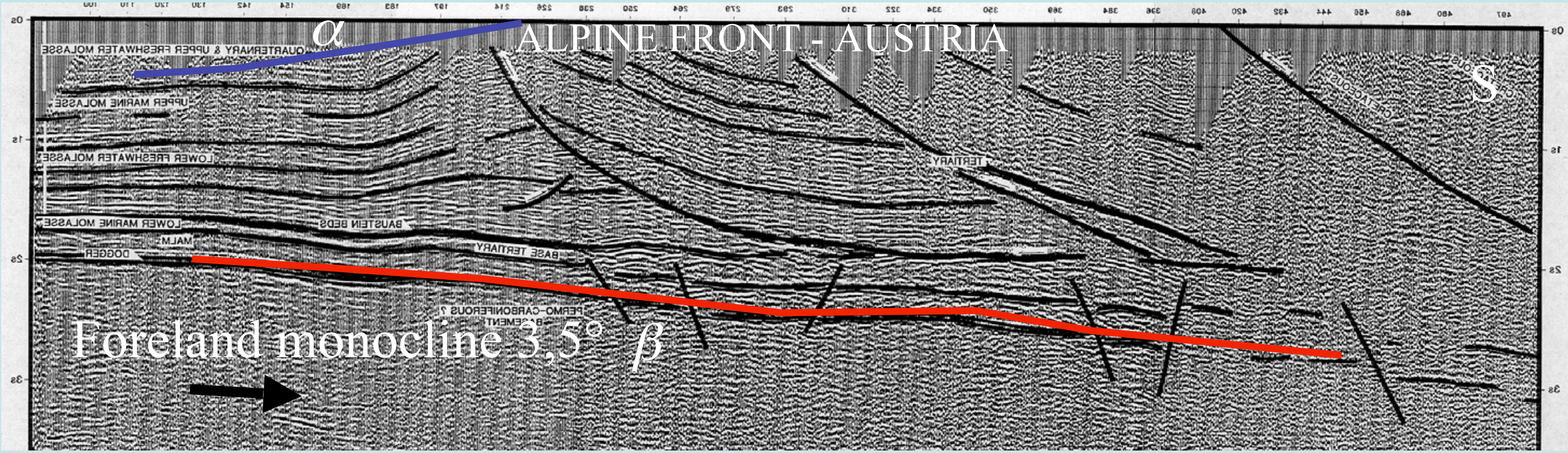




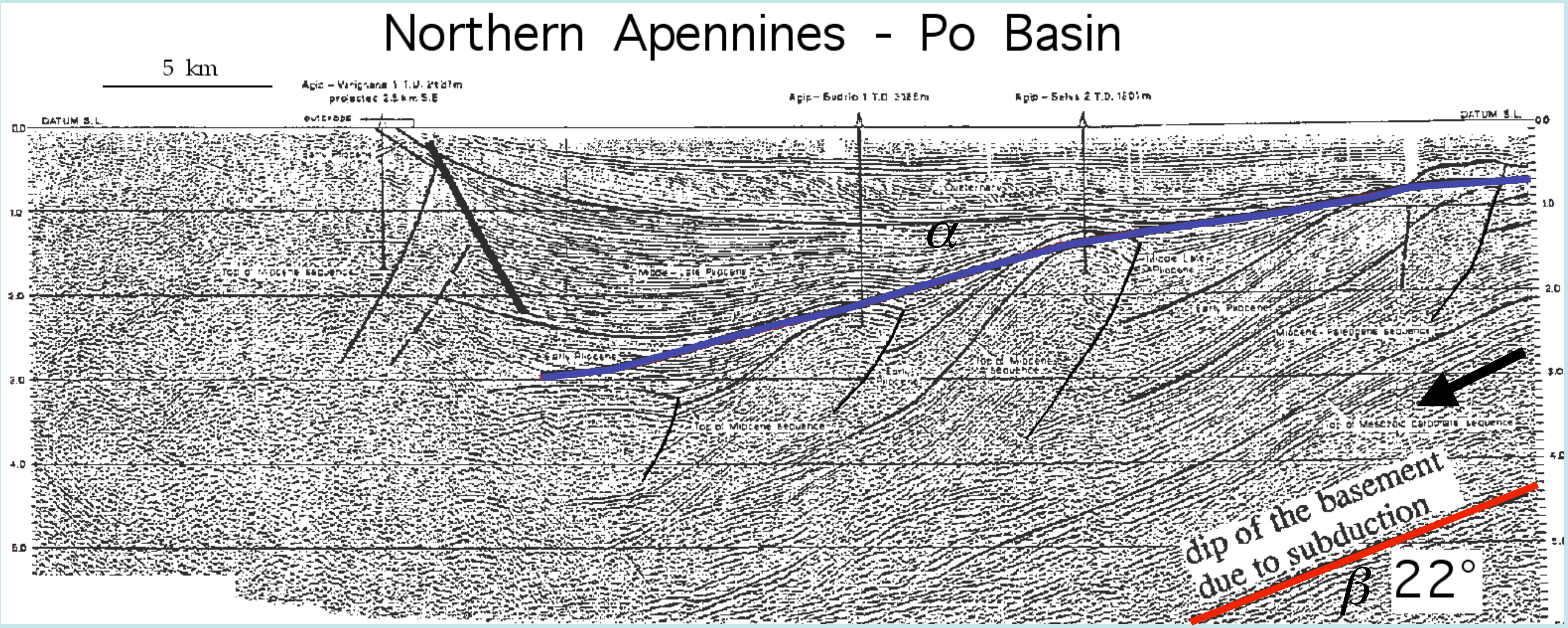




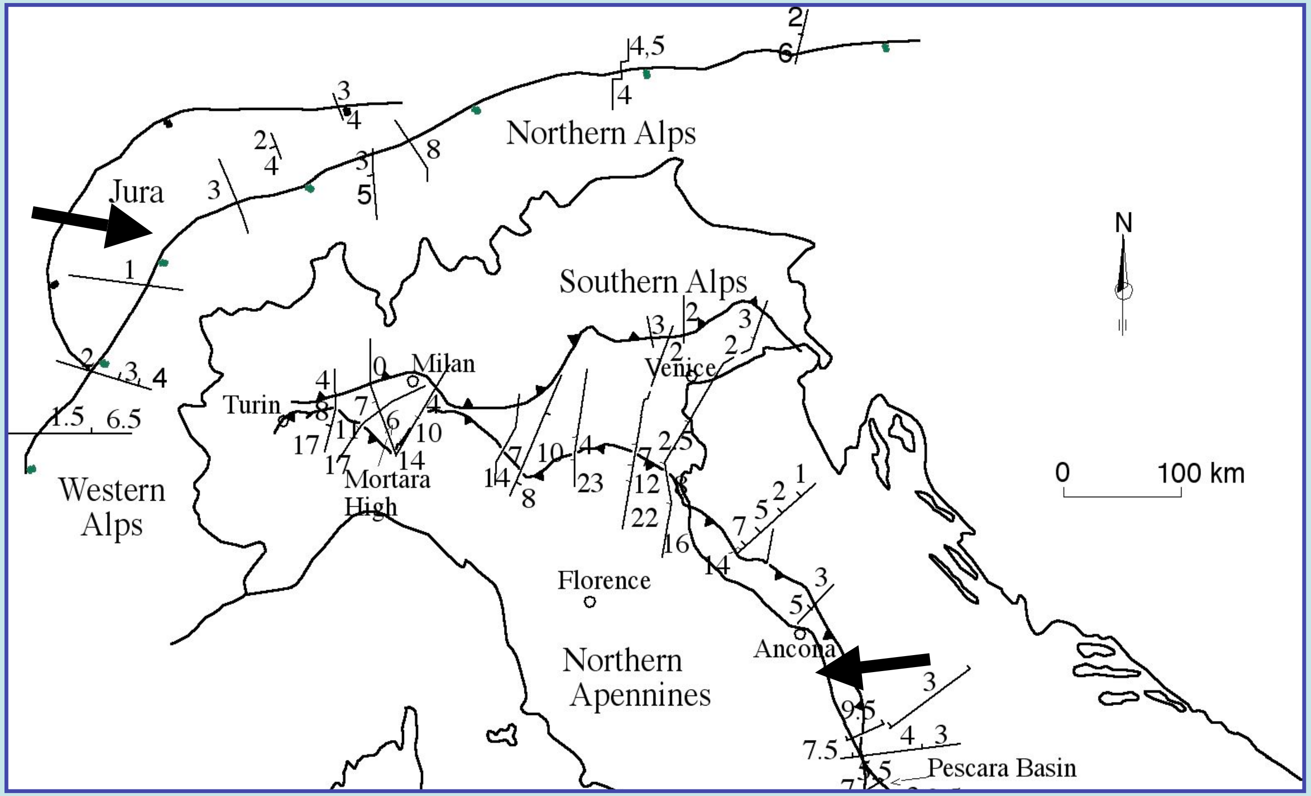
Kittler & Neumayer (1983)



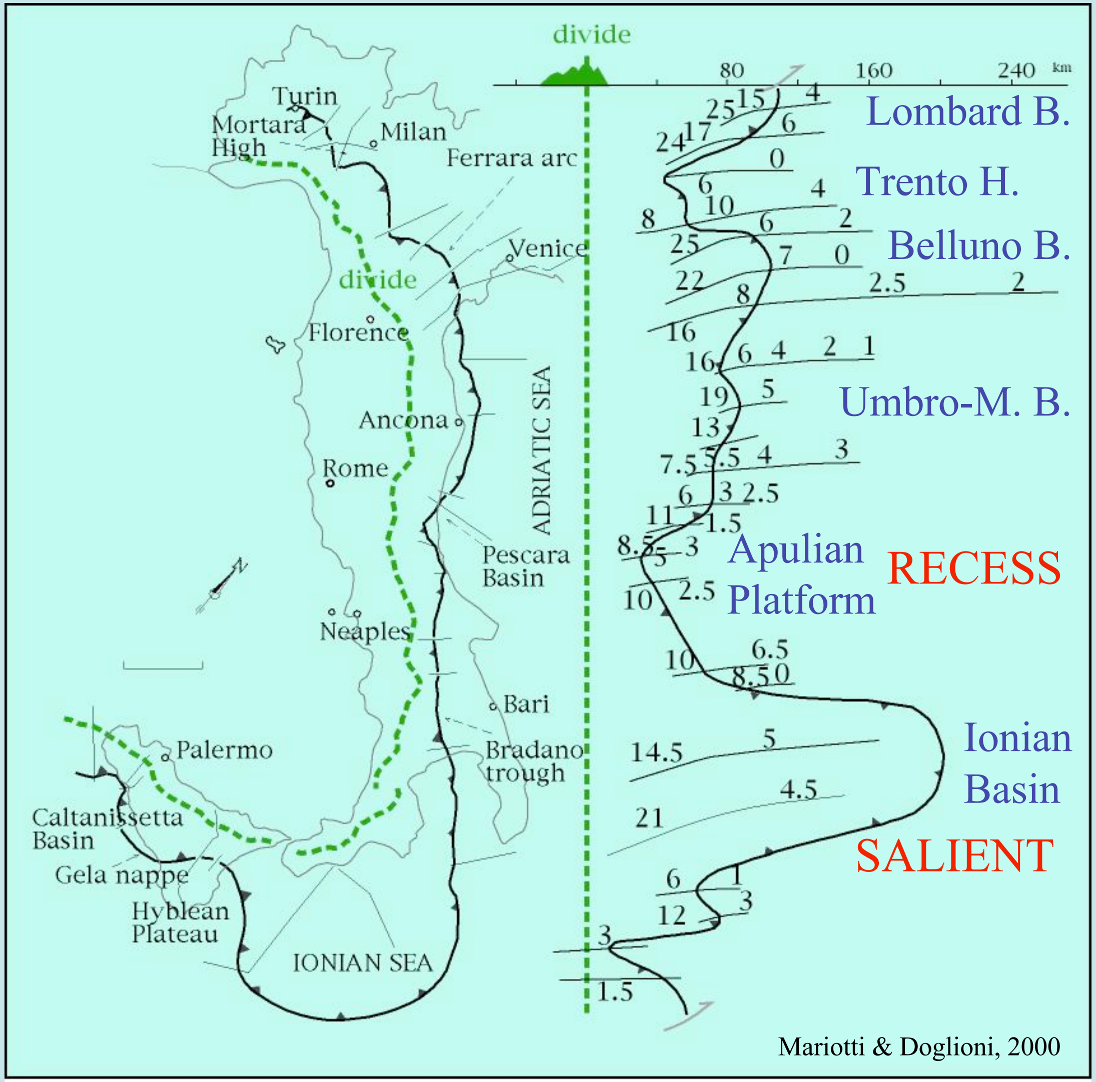
Bachmann & Koch, 1983



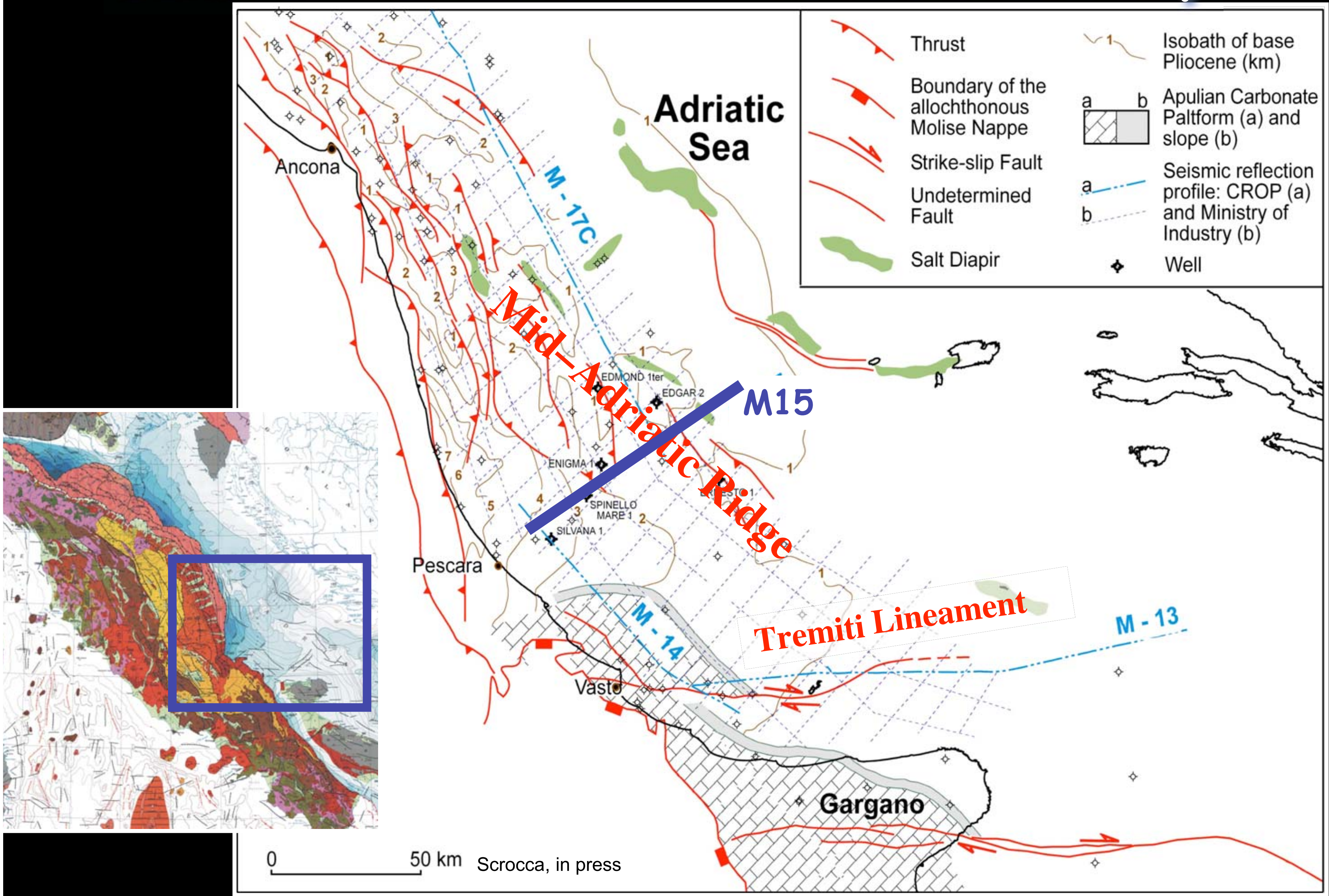
Pieri, 1983

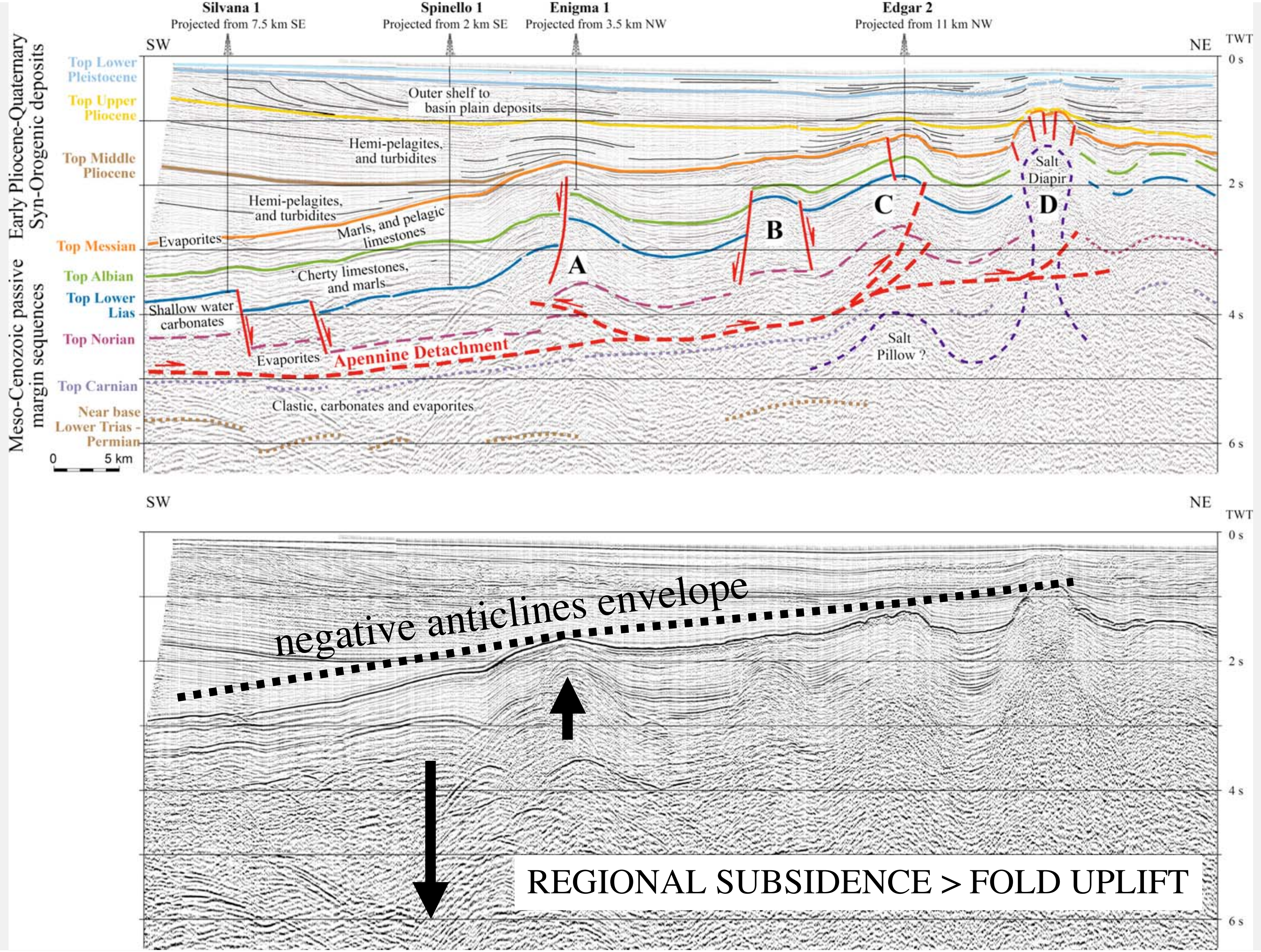


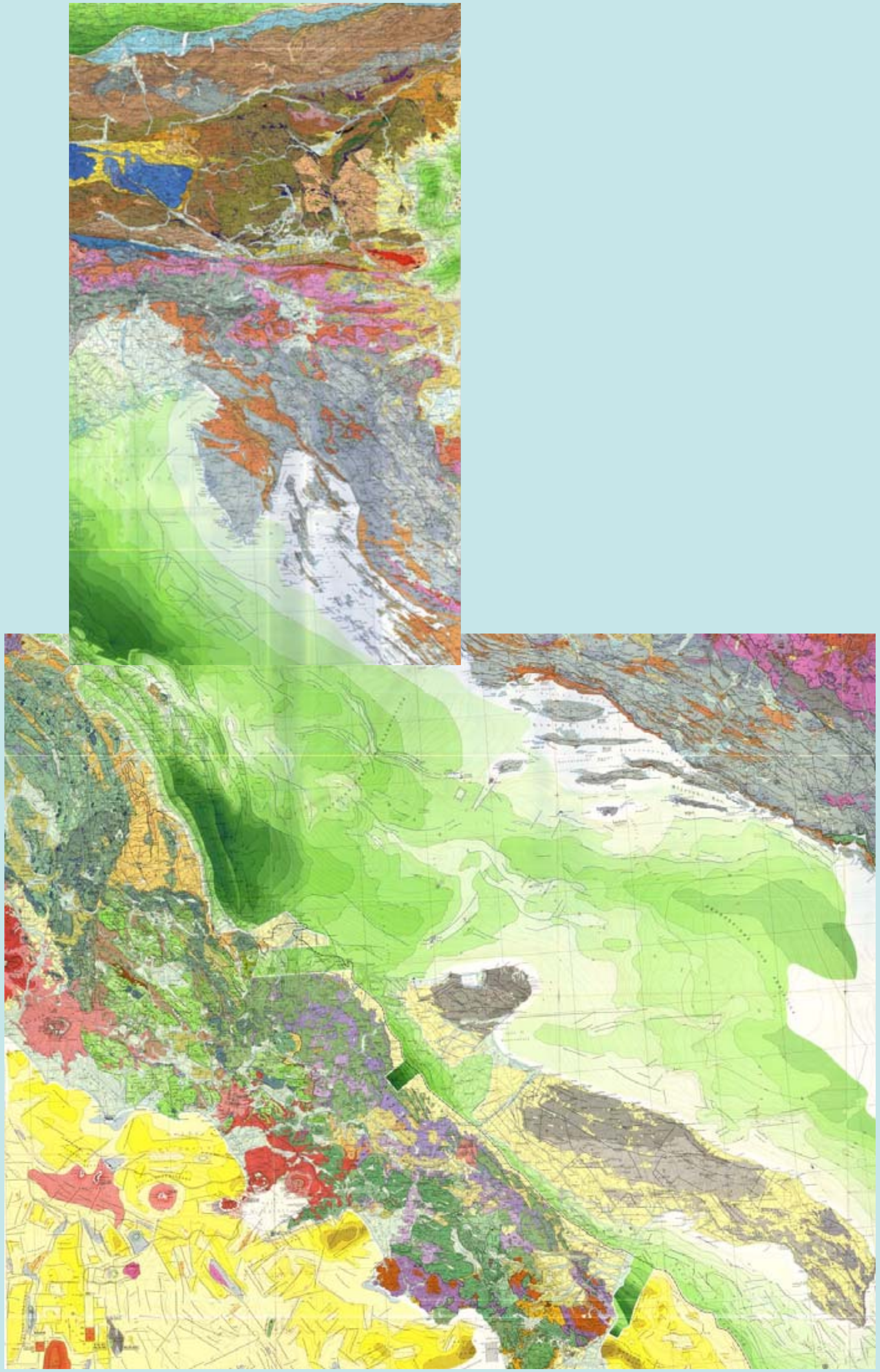
Northern Alps
Jura
Southern Alps
Milan
Turin
Venice
Mortara High
Western Alps
Florence
Northern Apennines
Ancona
Pescara Basin
N
0
100 km


divide
80
160
240 km
Lombard B.
Trento H.
Belluno B.
Umbro-M. B.
Apulian Platform
RECESS
Ionian Basin
SALIENT
Turin
Mortara High
Milan
Ferrara arc
Venice
divide
Florence
Ancona
Rome
ADRIATIC SEA
Pescara Basin
Neaples
Bari
Palermo
Bradano trough
Caltanissetta Basin
Gela nappe
Hyblean Plateau
IONIAN SEA
Mariotti & Doglioni, 2000

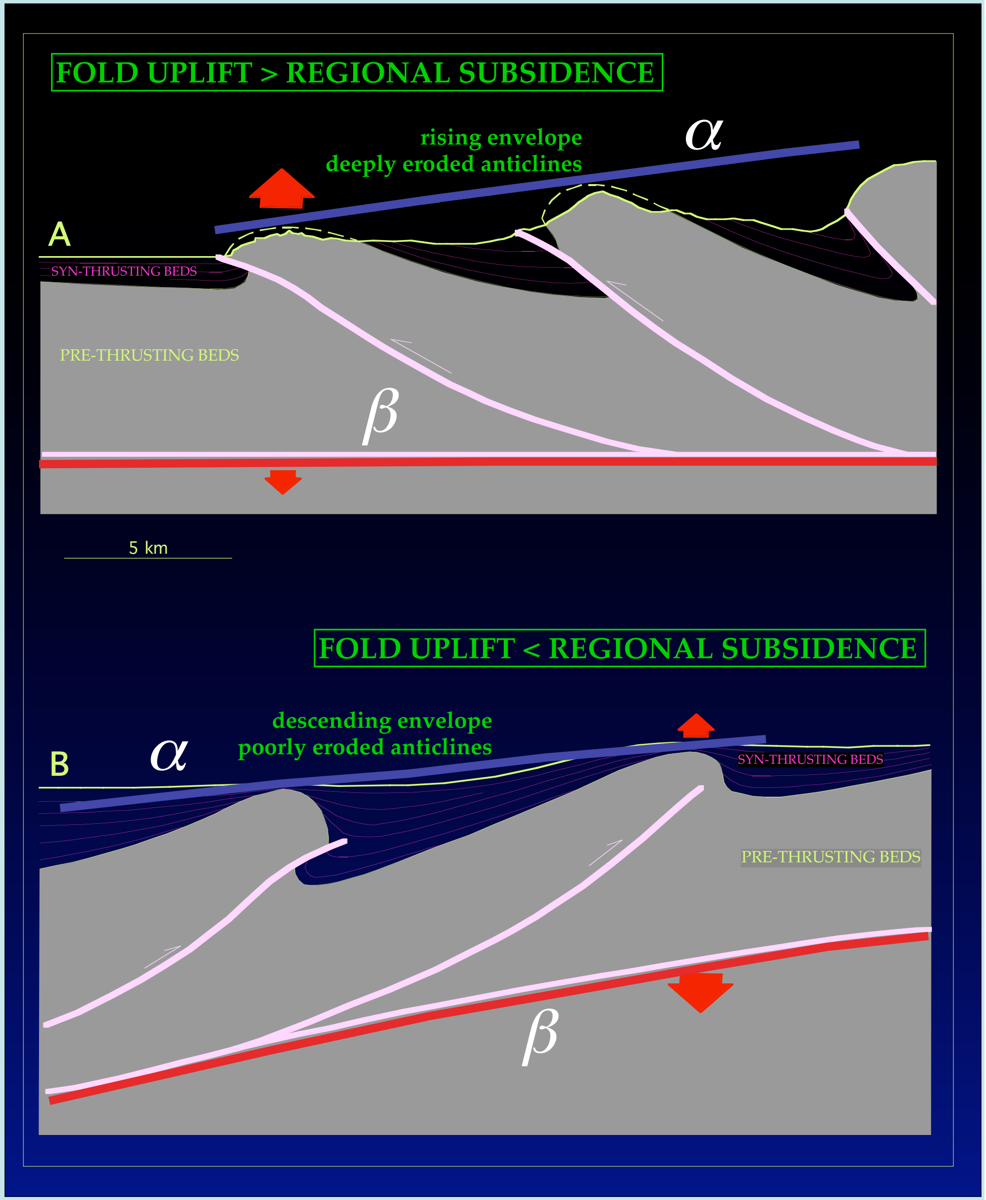
Central Adriatic Sea: Structural Map



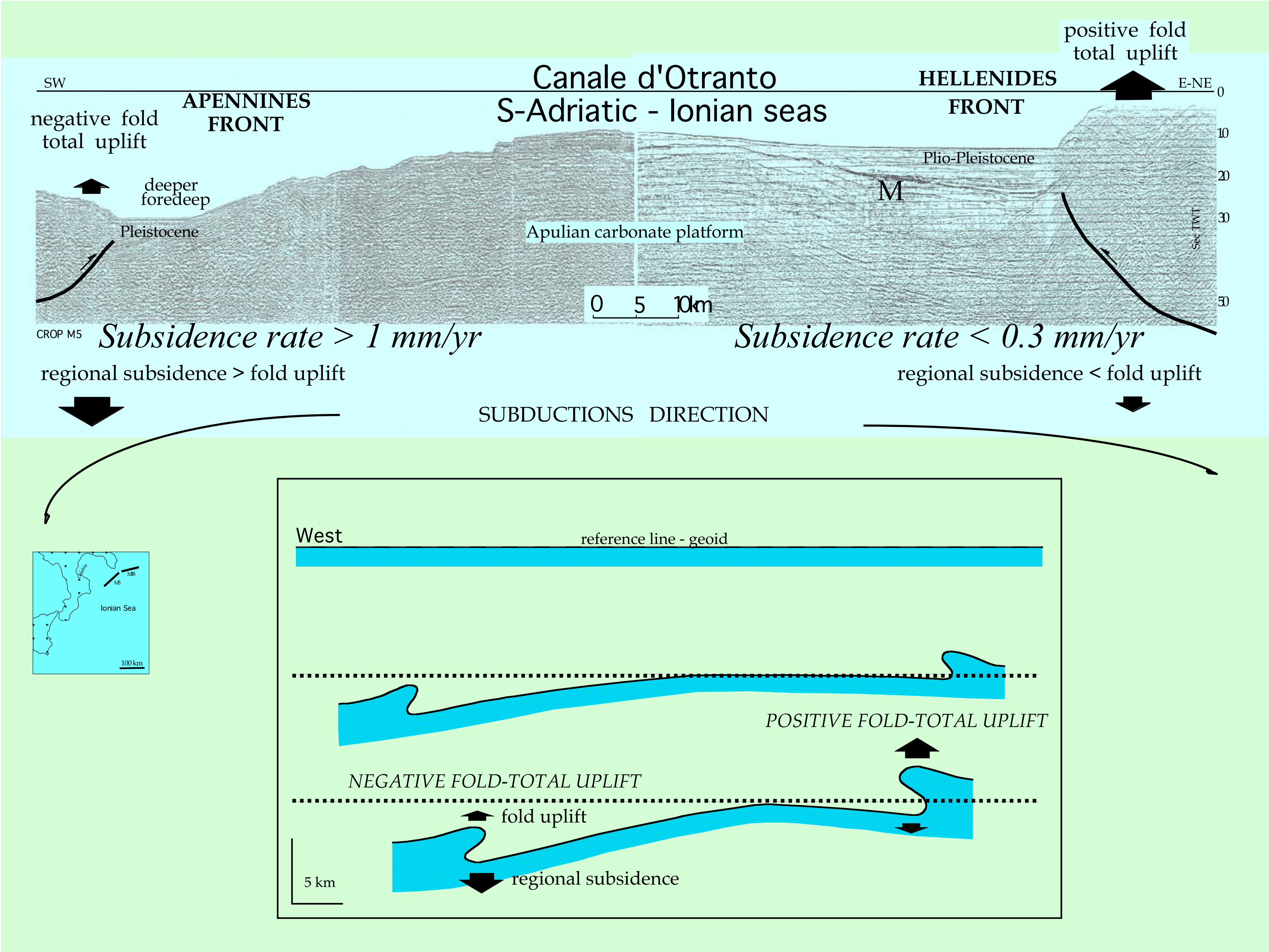

Silvana 1
Projected from 7.5 km SE
Spinello 1
Projected from 2 km SE
Enigma 1
Projected from 3.5 km NW
Edgar 2
Projected from 11 km NW
SW
NE
TWT
Early Pliocene-Quaternary Syn-Orogenic deposits
Meso-Cenozoic passive margin sequences
Top Lower Pleistocene
Top Upper Pliocene
Top Middle Pliocene
Top Messian
Top Albian
Top Lower Lias
Top Norian
Top Carnian
Near base Lower Trias - Permian
Outer shelf to basin plain deposits
Hemi-pelagites, and turbidites
Hemi-pelagites, and turbidites
Marls, and pelagic limestones
Evaporites
Cherty limestones, and marls
Shallow water carbonates
Evaporites
Apennine Detachment
Clastic, carbonates and evaporites
Salt Diapir
Salt Pillow ?
A
B
C
D
0 s
2 s
4 s
6 s
0
5 km
SW
NE
TWT
negative anticlines envelope
REGIONAL SUBSIDENCE > FOLD UPLIFT
0 s
2 s
4 s
6 s



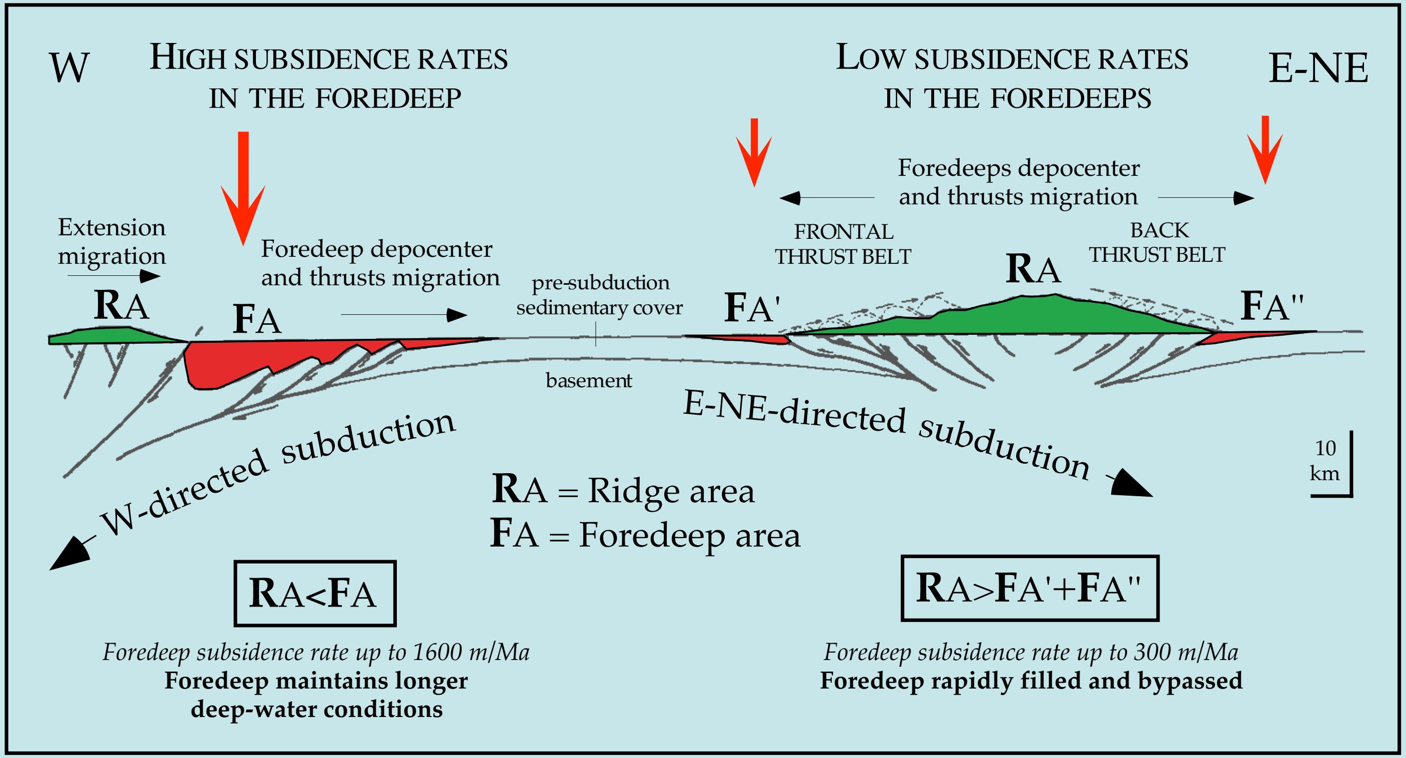
Alps - Dinarides

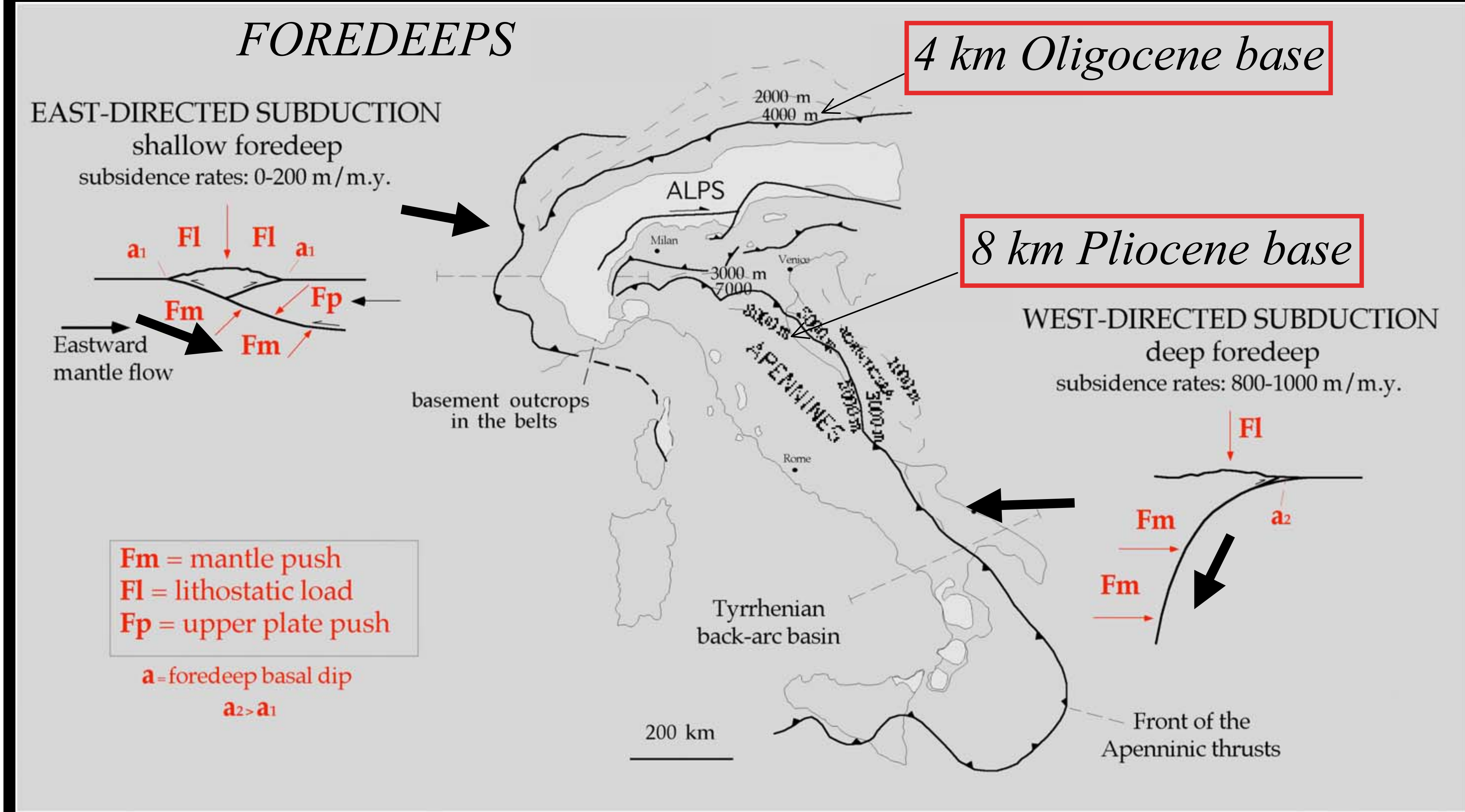


Apennines

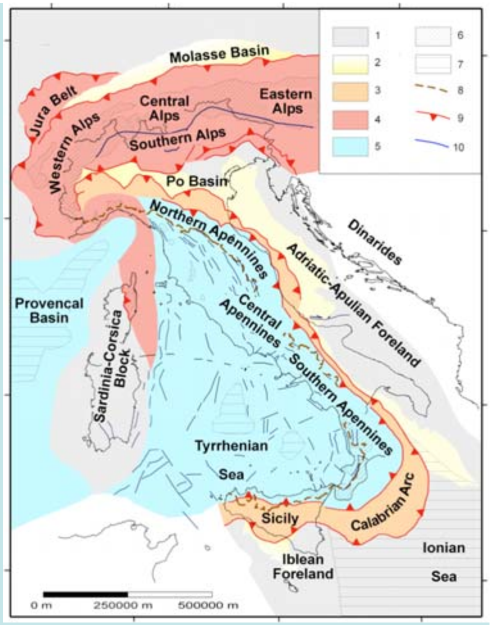


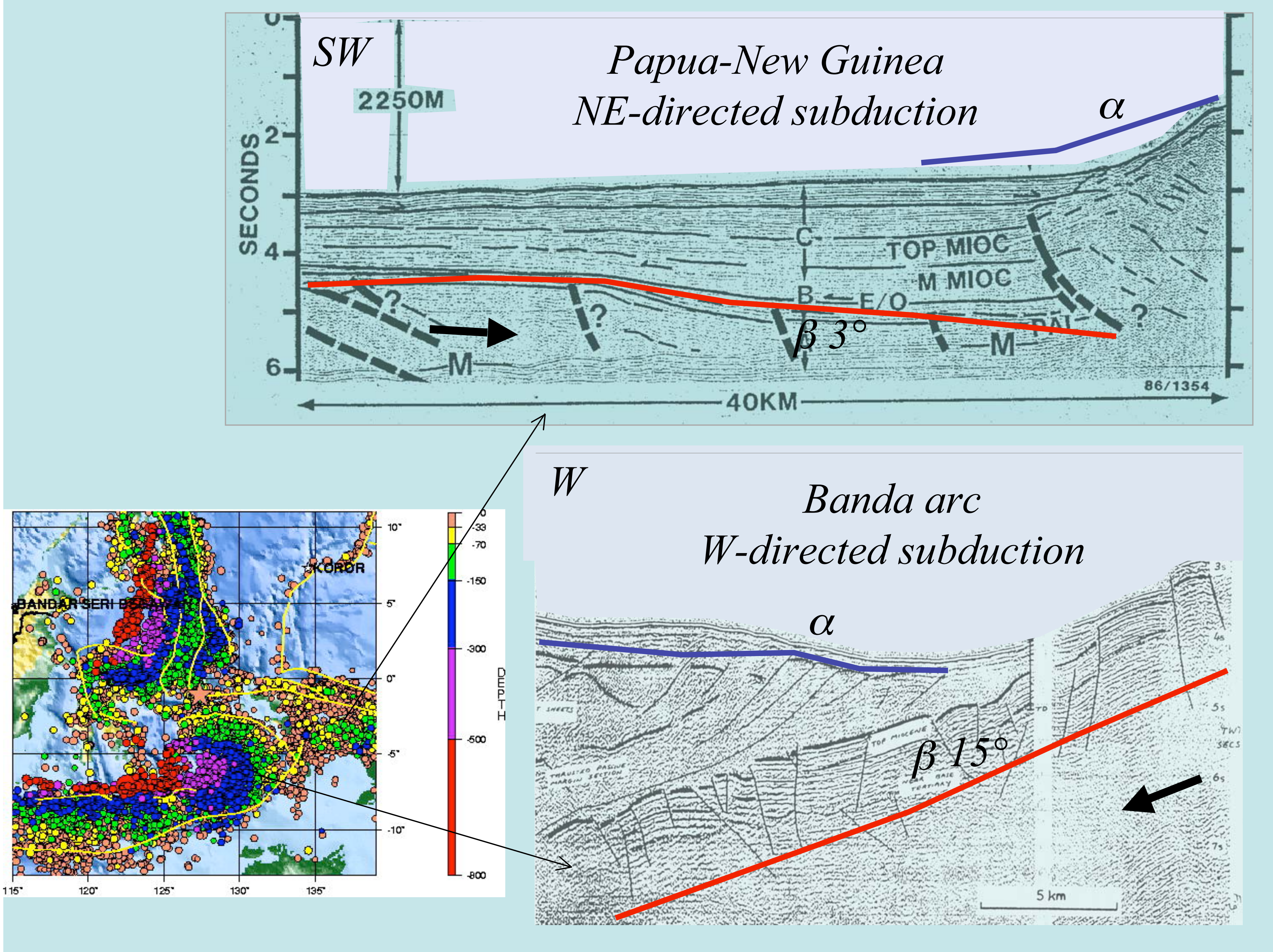
Canale d'Otranto
S-Adriatic - Ionian seas
SW
E-NE
APENNINES
FRONT
HELLENIDES
FRONT
negative fold
total uplift
positive fold
total uplift
deeper
foredeep
Pleistocene
Apulian carbonate platform
Plio-Pleistocene
M
0 5 10 km
0
10
20
30
50
Sec TWT
CROP M5
Subsidence rate > 1 mm/yr
regional subsidence > fold uplift
Subsidence rate < 0.3 mm/yr
regional subsidence < fold uplift
SUBDUCTIONS DIRECTION
M5
Ionian Sea
100 km
West
reference line - geoid
POSITIVE FOLD-TOTAL UPLIFT
NEGATIVE FOLD-TOTAL UPLIFT
fold uplift
regional subsidence
5 km

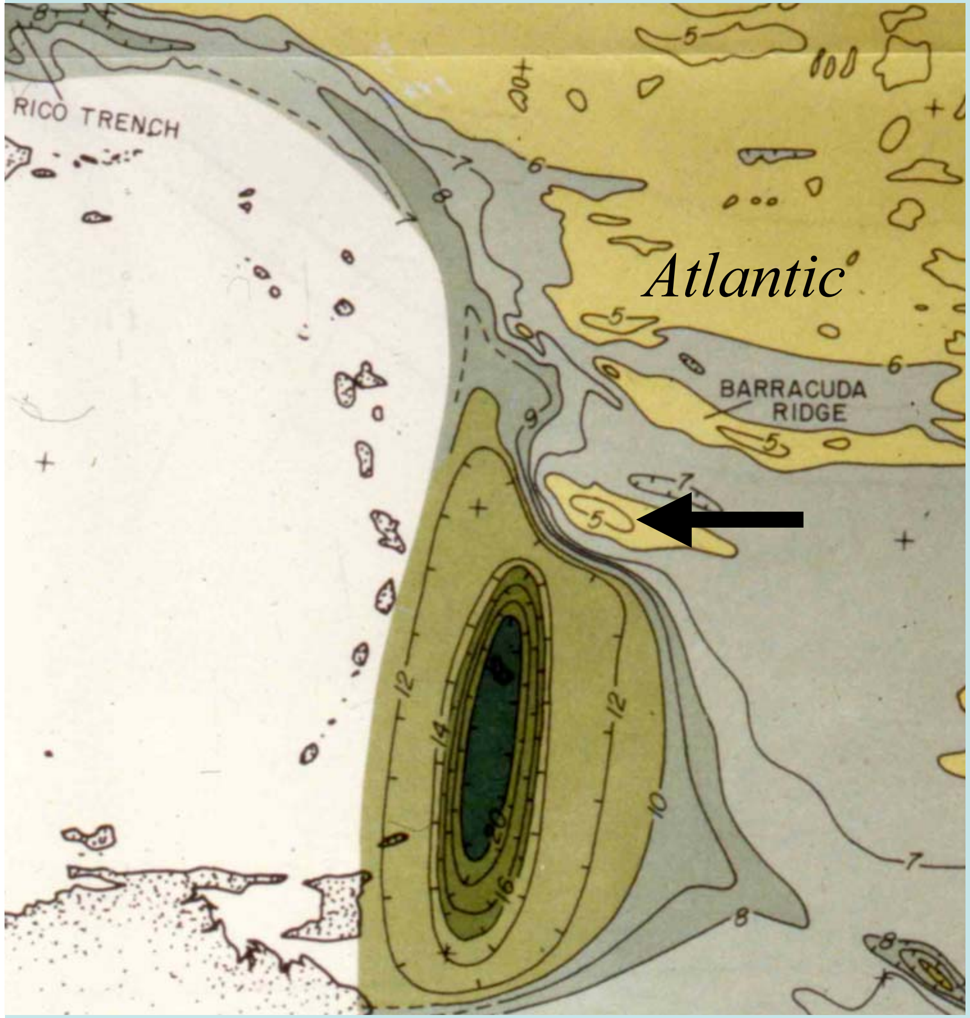

W
HIGH SUBSIDENCE RATES
IN THE FOREDEEP
LOW SUBSIDENCE RATES
IN THE FOREDEEPS
E-NE
Foredeeps depocenter
and thrusts migration
Extension
migration
Foredeep depocenter
and thrusts migration
FRONTAL
THRUST BELT
BACK
THRUST BELT
RA
FA
RA
FA'
FA''
pre-subduction
sedimentary cover
basement
W-directed subduction
E-NE-directed subduction
10
km
RA = Ridge area
FA = Foredeep area
RA<FA
RA>FA'+FA''
Foredeep subsidence rate up to 1600 m/Ma
Foredeep maintains longer
deep-water conditions
Foredeep subsidence rate up to 300 m/Ma
Foredeep rapidly filled and bypassed

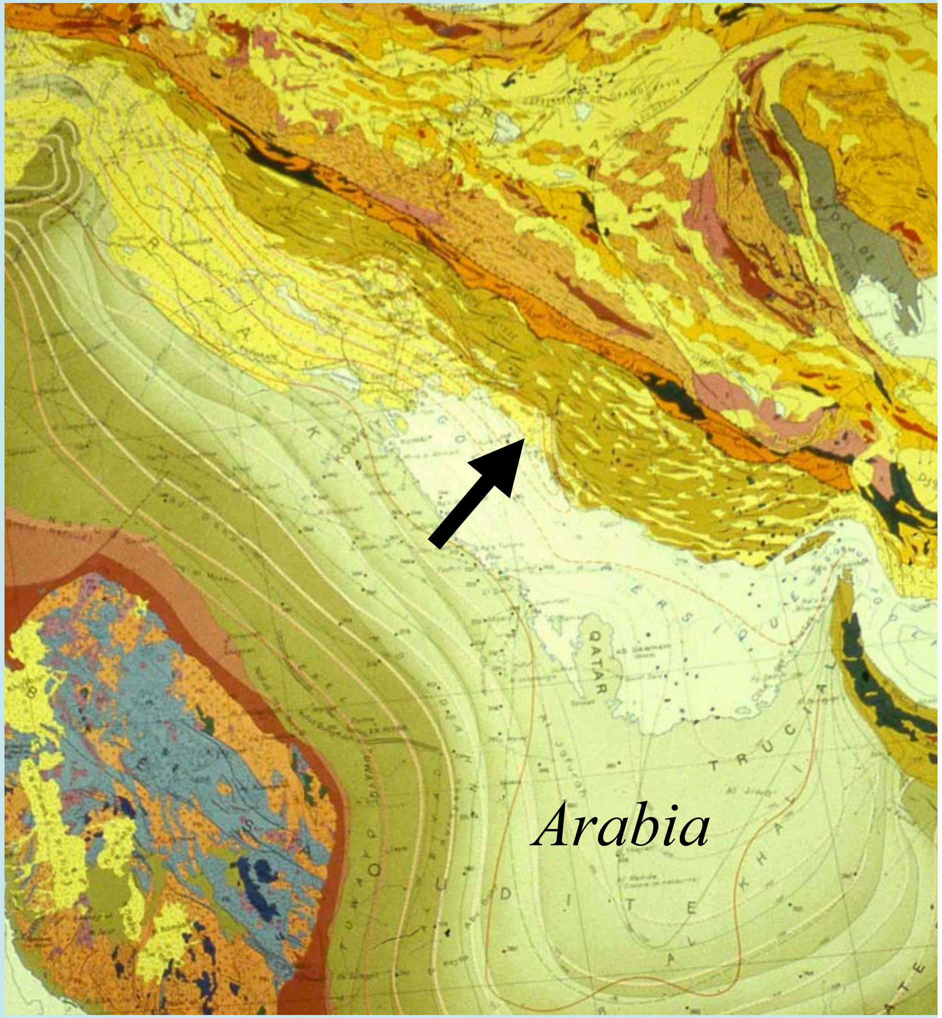

FOREDEEPS
4 km Oligocene base
8 km Pliocene base
EAST-DIRECTED SUBDUCTION
shallow foredeep
subsidence rates: 0-200 m/m.y.
Fl
Fl
a1
a1
Fm
Fp
Fm
Eastward
mantle flow
2000 m
4000 m
ALPS
Milan
Venice
3000 m
7000
APENNINES
Rome
basement outcrops
in the belts
WEST-DIRECTED SUBDUCTION
deep foredeep
subsidence rates: 800-1000 m/m.y.
Fl
Fm
a2
Fm
Fm = mantle push
Fl = lithostatic load
Fp = upper plate push
a = foredeep basal dip
a2 > a1
Tyrrhenian
back-arc basin
200 km
Front of the
Apenninic thrusts

ALPS	*APENNINES*
- double vergence	- single vergence
- high topography	- low topography
- shallow foredeep	- deep foredeep
- deep rocks involved	- shallow rocks involved
- shallow foreland monocline dip	- steep foreland monocline dip
- thickened crust under the belt	- thinned crust under the belt
- thickened lithosphere	- shallow hangingwall asthenosphere
- no backarc basin	- widespread hangingwall extension & well developed backarc basin



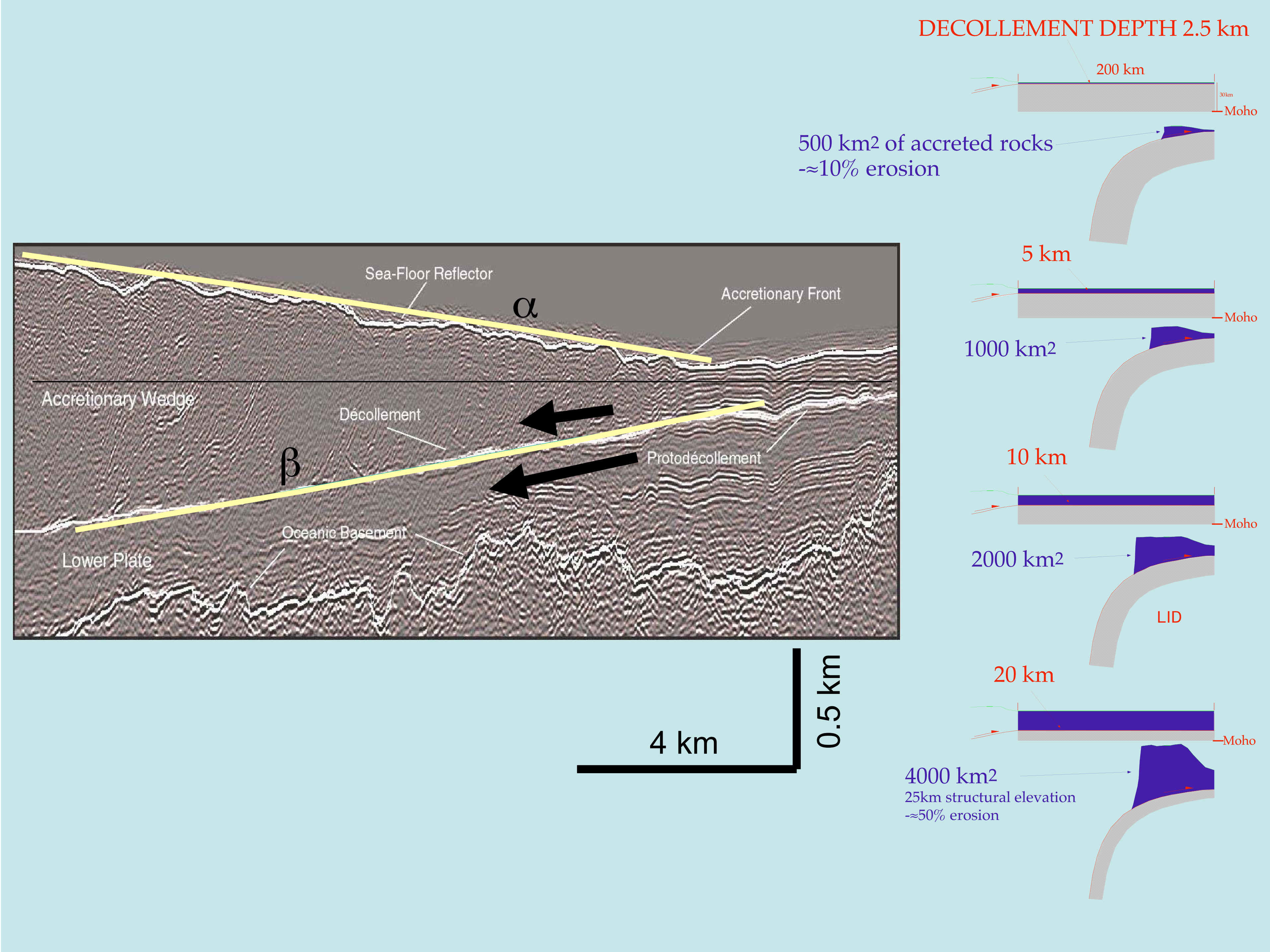

SW
Papua-New Guinea
NE-directed subduction
α
2250M
SECONDS
TOP MIOC
M MIOC
β 3°
M
40KM
86/1354
W
Banda arc
W-directed subduction
α
β 15°
5 km
KOROR
DEPTH
0
-33
-70
-150
-300
-500
-800
115°
120°
125°
130°
135°
10°
5°
0°
-5°
-10°

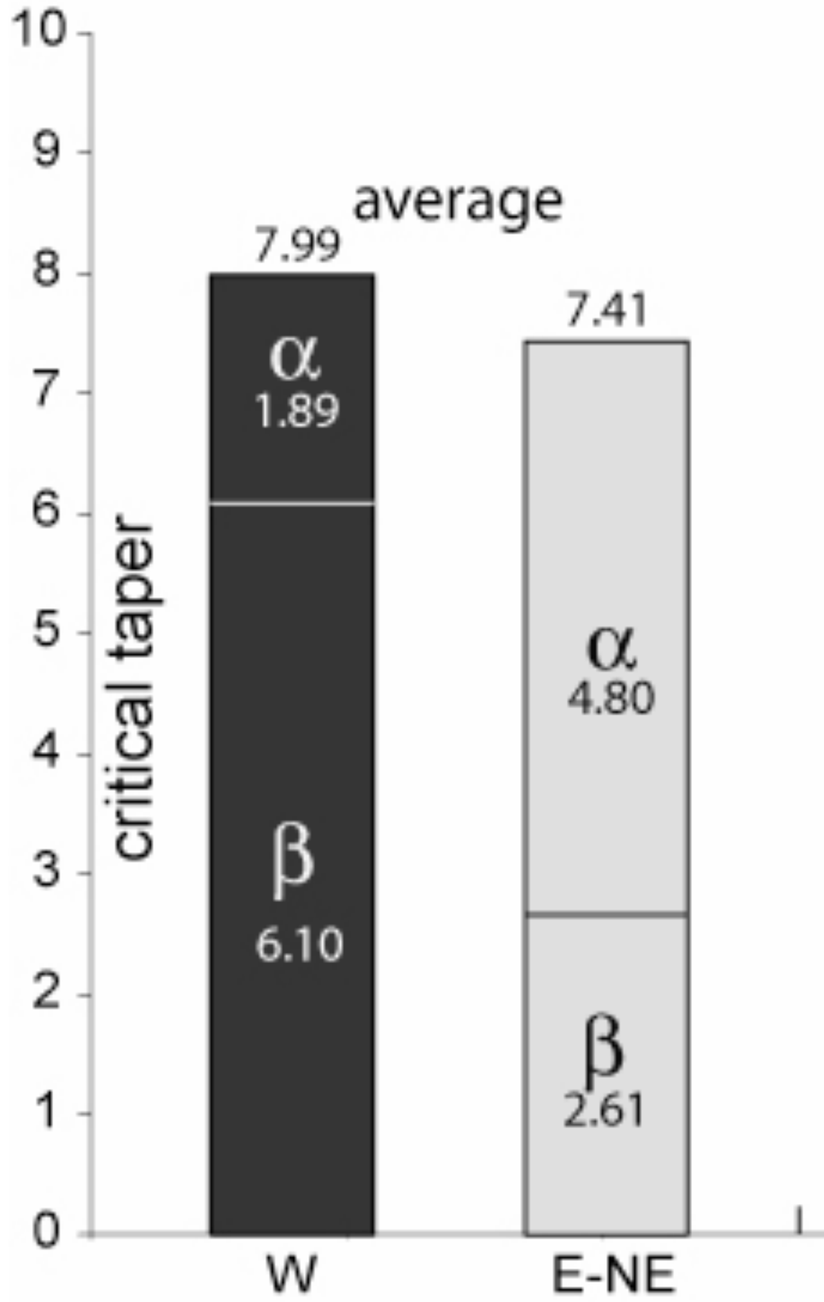




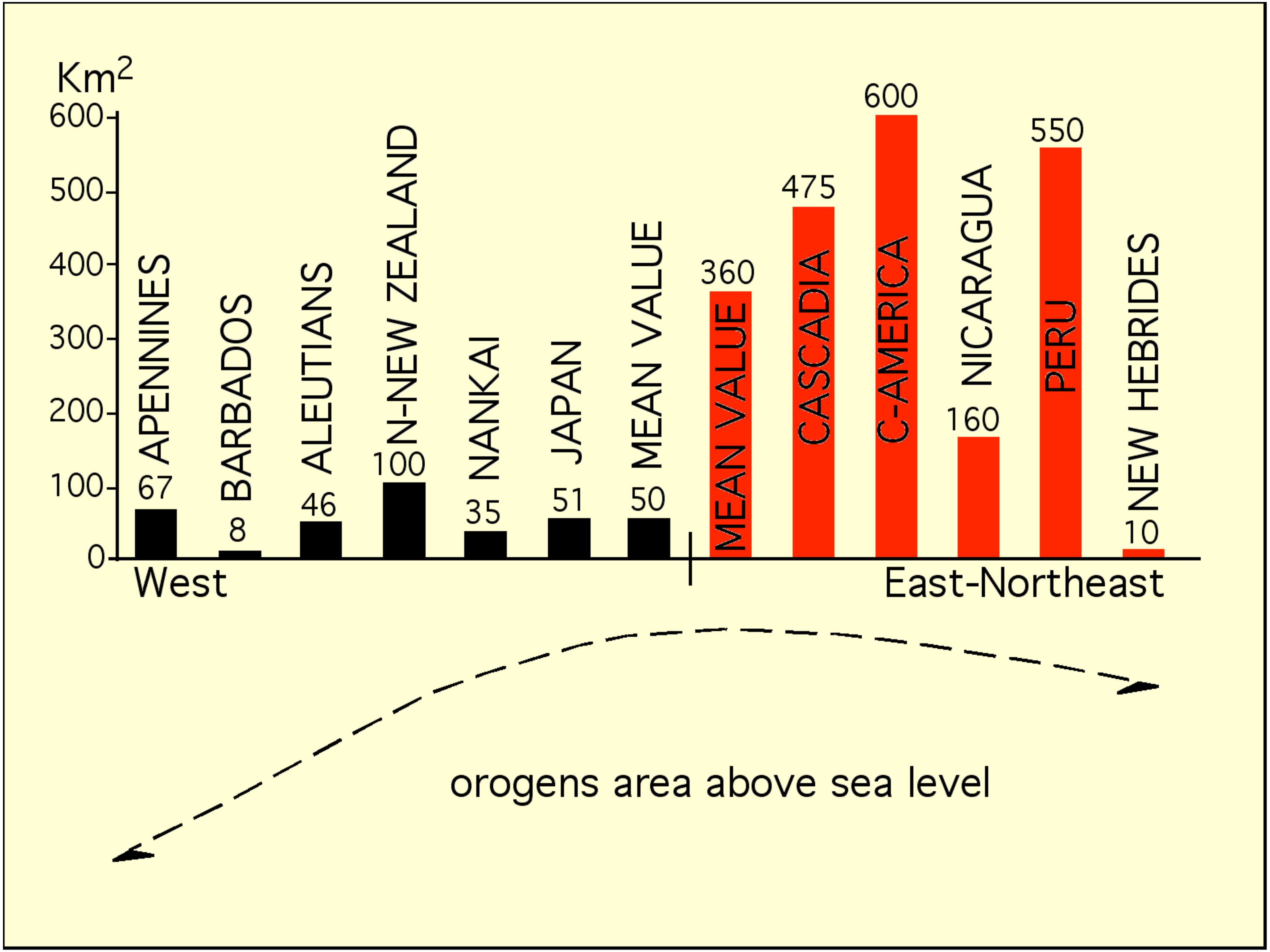
Barbados W-subduction

Zagros NE-subduction

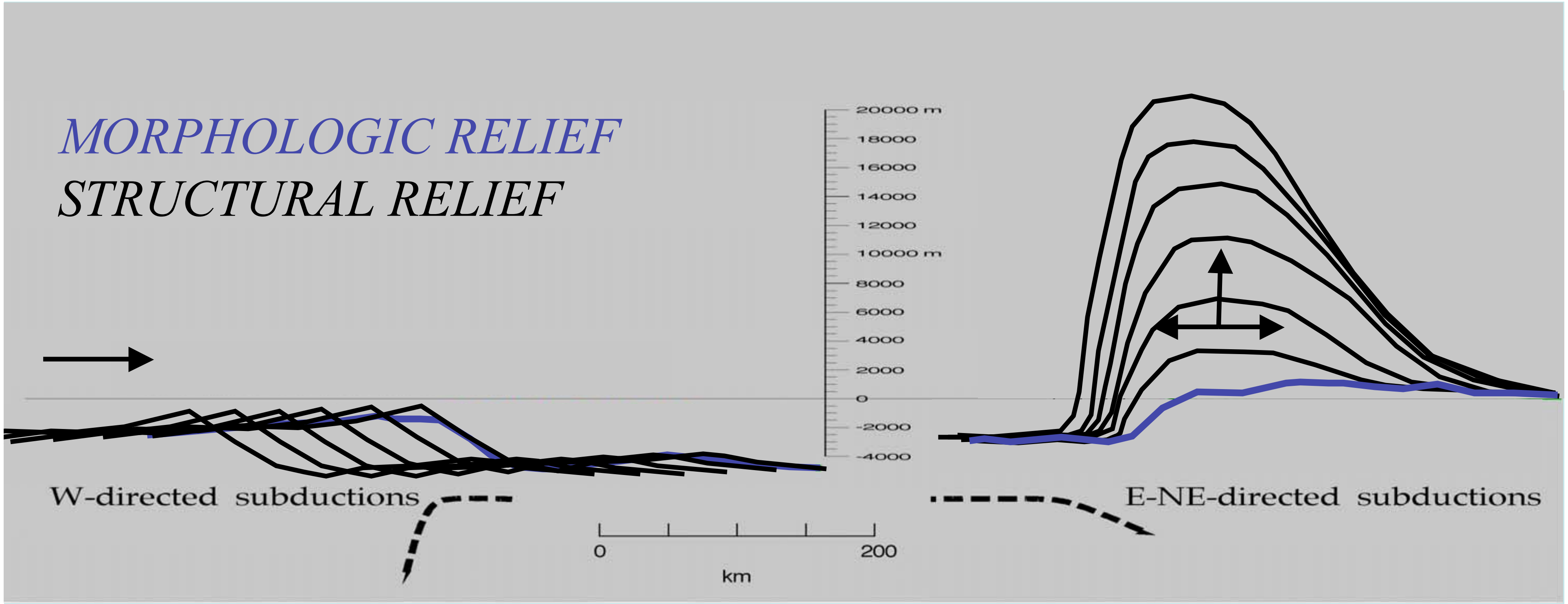

DECOLLEMENT DEPTH 2.5 km
200 km
Moho
500 km2 of accreted rocks
-≈10% erosion
5 km
Moho
1000 km2
10 km
Moho
2000 km2
LID
20 km
Moho
4000 km2
25km structural elevation
-≈50% erosion
Sea-Floor Reflector
Accretionary Front
α
Accretionary Wedge
Décollement
β
Protodécollement
Oceanic Basement
Lower Plate
4 km
0.5 km



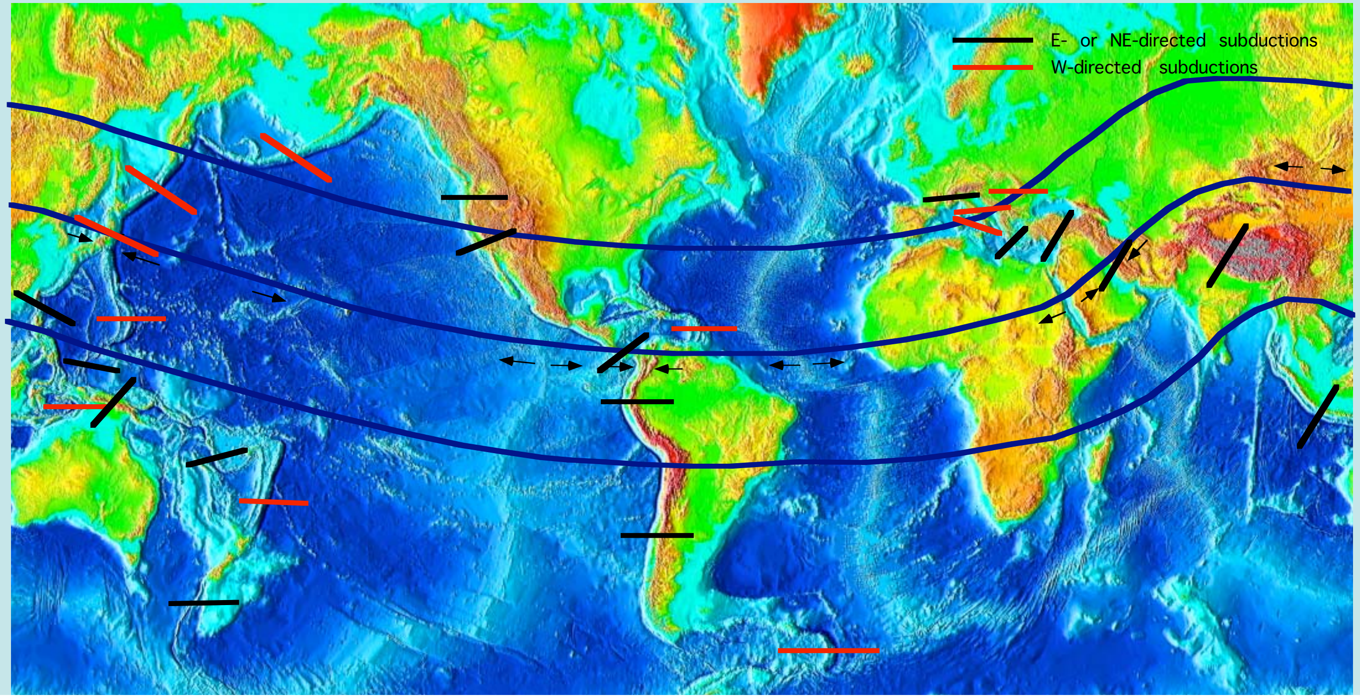
Lenci & Doglioni, 2006



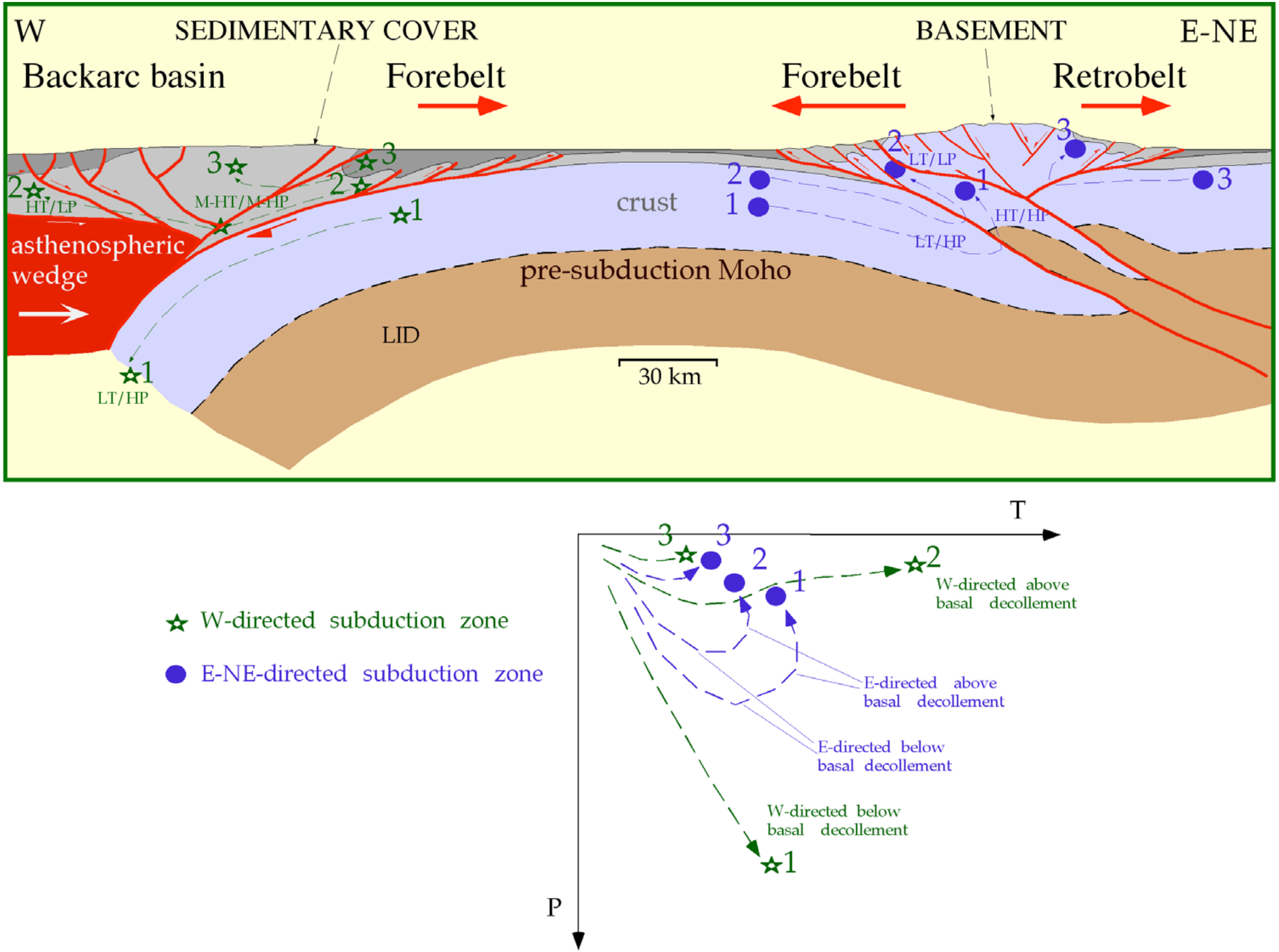
Km2
600
500
400
300
200
100
0
APENNINES
67
BARBADOS
8
ALEUTIANS
46
N-NEW ZEALAND
100
NANKAI
35
JAPAN
51
MEAN VALUE
50
MEAN VALUE
360
CASCADIA
475
C-AMERICA
600
NICARAGUA
160
PERU
550
NEW HEBRIDES
10
West
East-Northeast
orogens area above sea level



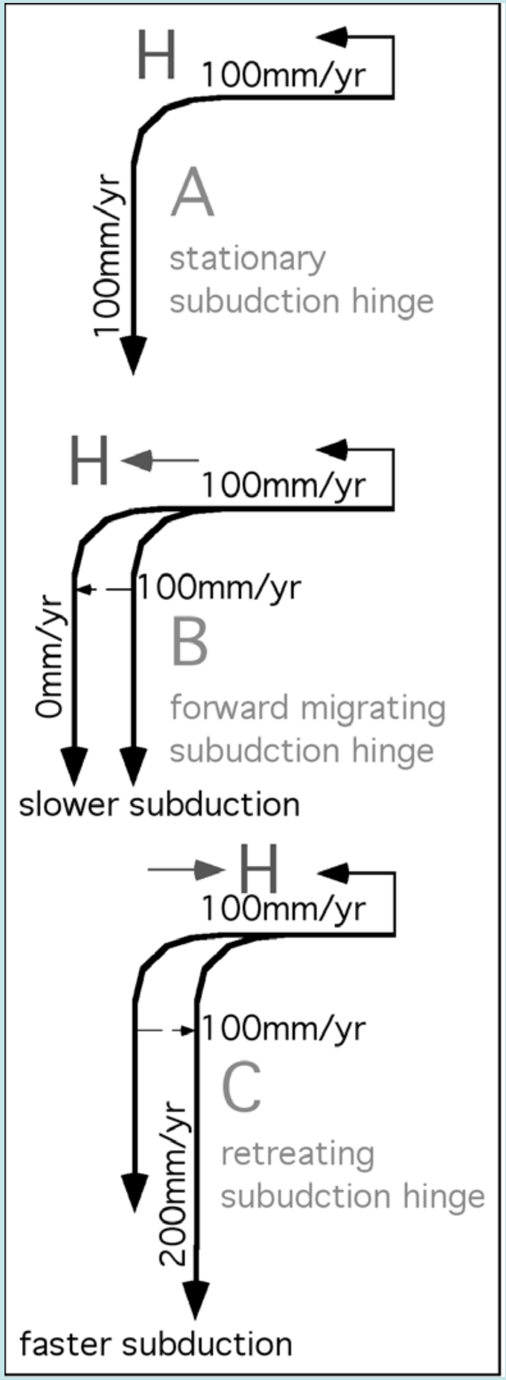
MORPHOLOGIC RELIEF
STRUCTURAL RELIEF
20000 m
18000
16000
14000
12000
10000 m
8000
6000
4000
2000
0
-2000
-4000
W-directed subductions
E-NE-directed subductions
0
200
km

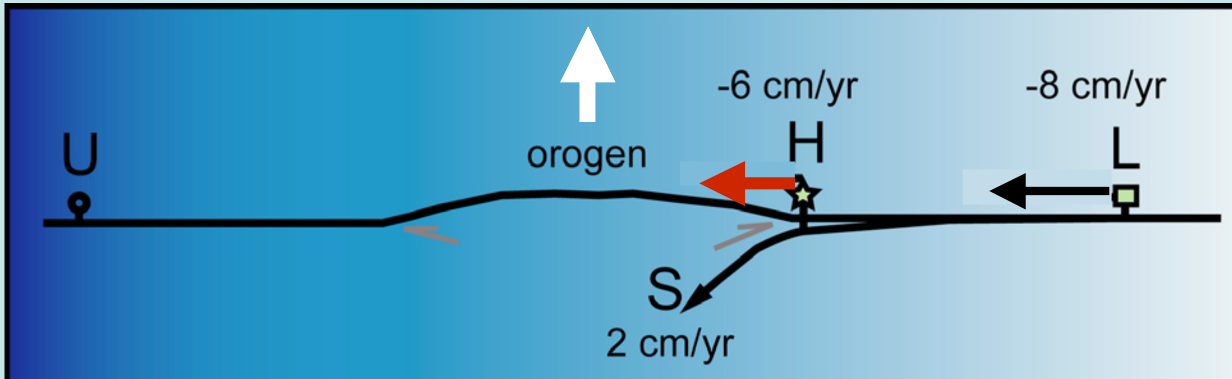


E- or NE-directed subductions
W-directed subductions



W
SEDIMENTARY COVER
BASEMENT
E-NE
Backarc basin
Forebelt
Forebelt
Retrobelt
asthenospheric wedge
crust
pre-subduction Moho
LID
30 km
HT/LP
M-HT/M-HP
LT/HP
LT/LP
HT/HP
LT/HP
T
P
W-directed subduction zone
E-NE-directed subduction zone
W-directed above basal decollement
E-directed above basal decollement
E-directed below basal decollement
W-directed below basal decollement


H
100mm/yr
100mm/yr
A
stationary
subudction hinge
H
100mm/yr
100mm/yr
0mm/yr
B
forward migrating
subudction hinge
slower subduction
H
100mm/yr
100mm/yr
200mm/yr
C
retreating
subudction hinge
faster subduction



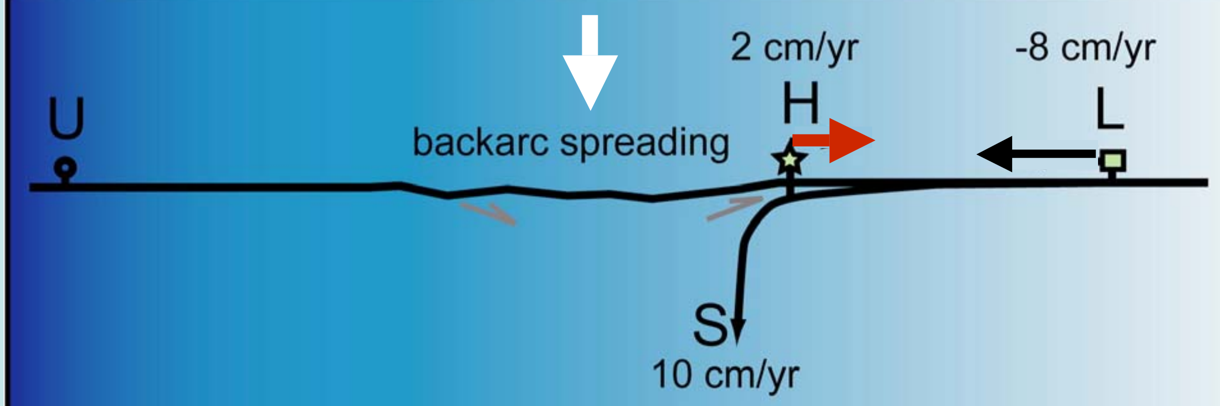
hinge retreat H relative to L (HL) = -2 cm/yr

U+L = -8 cm

U+H = -6 cm

S = 2 cm

UL(8)>HL(2) = orogen



hinge retreat H relative to L (HL) = -10 cm/yr

U+L = -8 cm

U+H = 2 cm

S = 10 cm

UL(8)<HL(10) = backarc

U=upper plate (fixed)
H=subduction hinge
L=lower plate
S=subduction rate

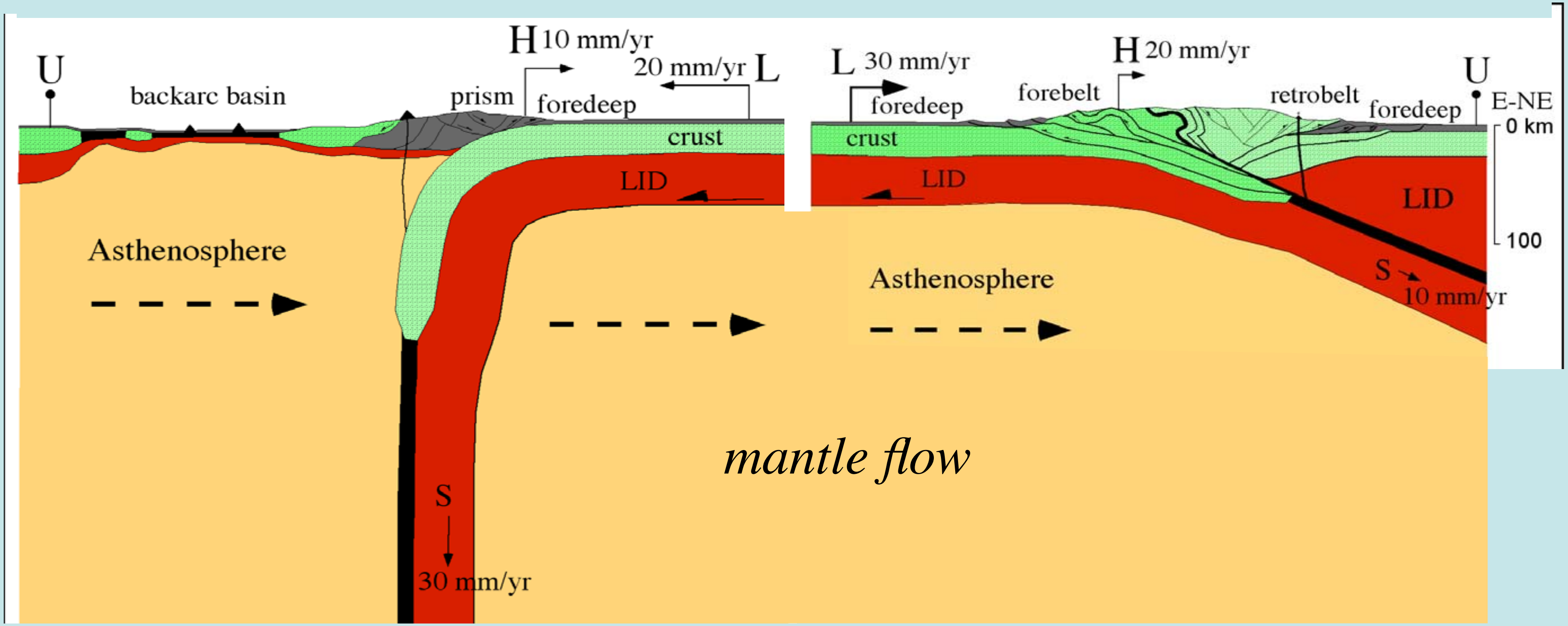
Subduction<Convergence

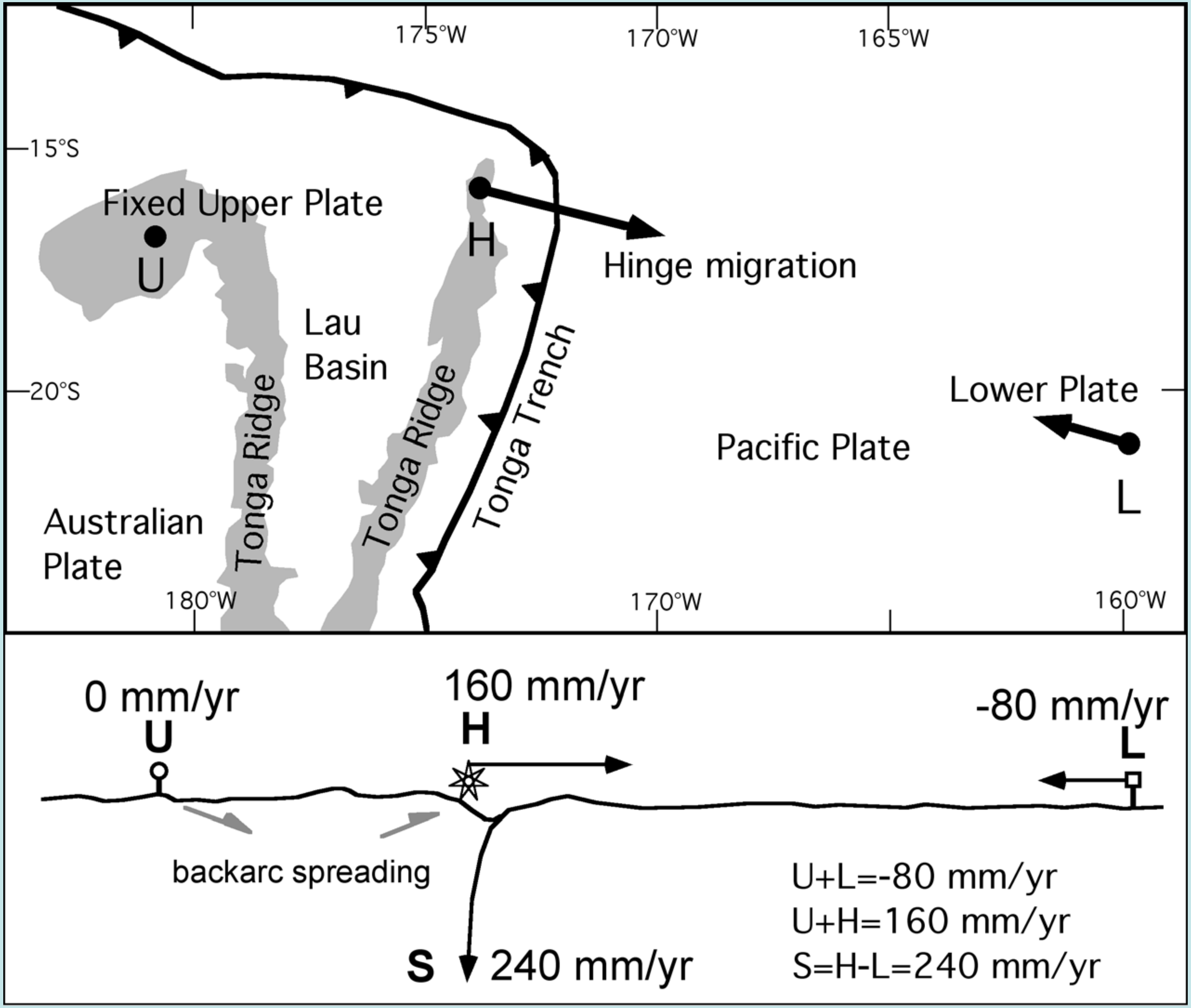
S=H-L

Subduction>Convergence

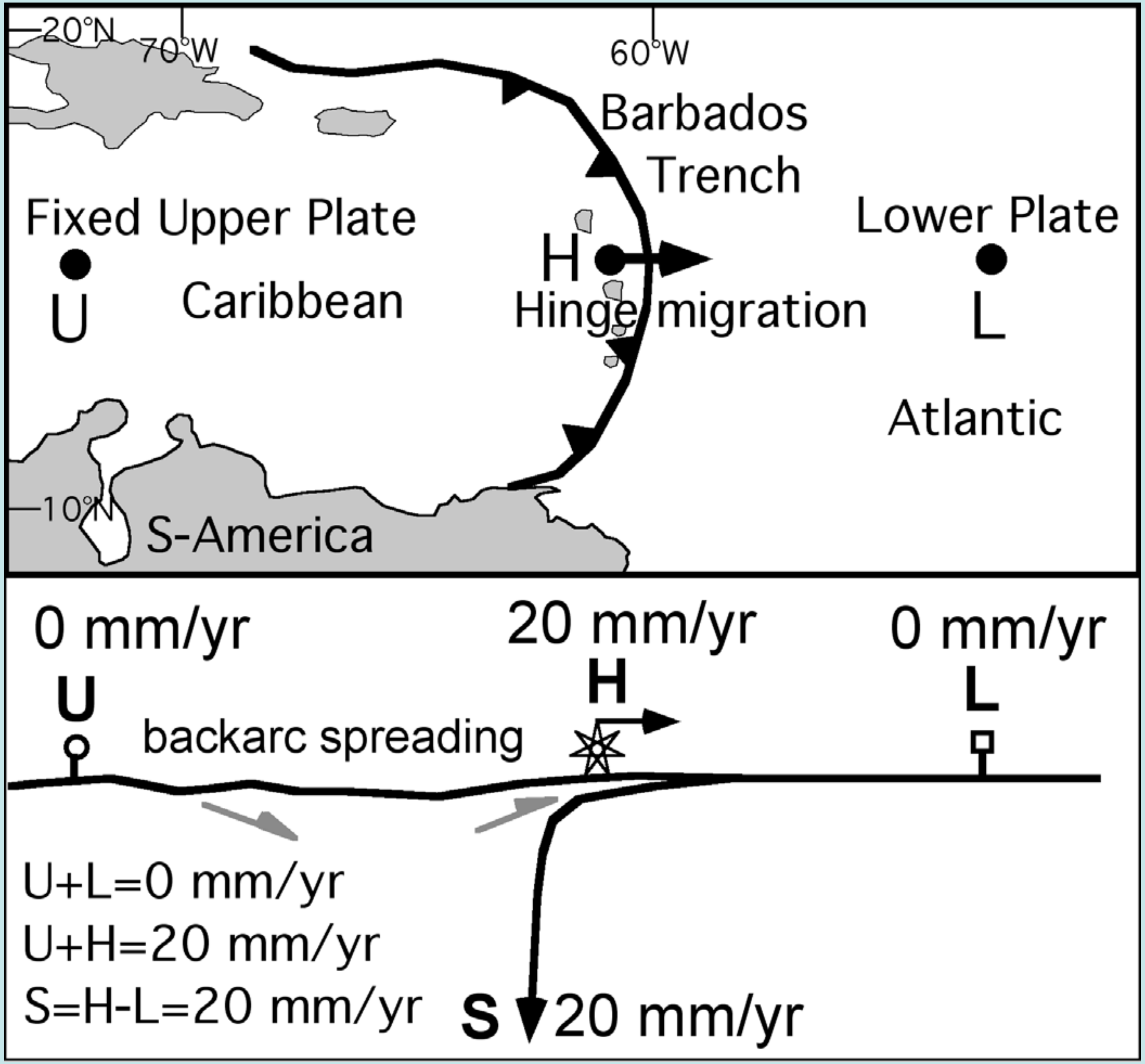
Apenninic type

Alpine type

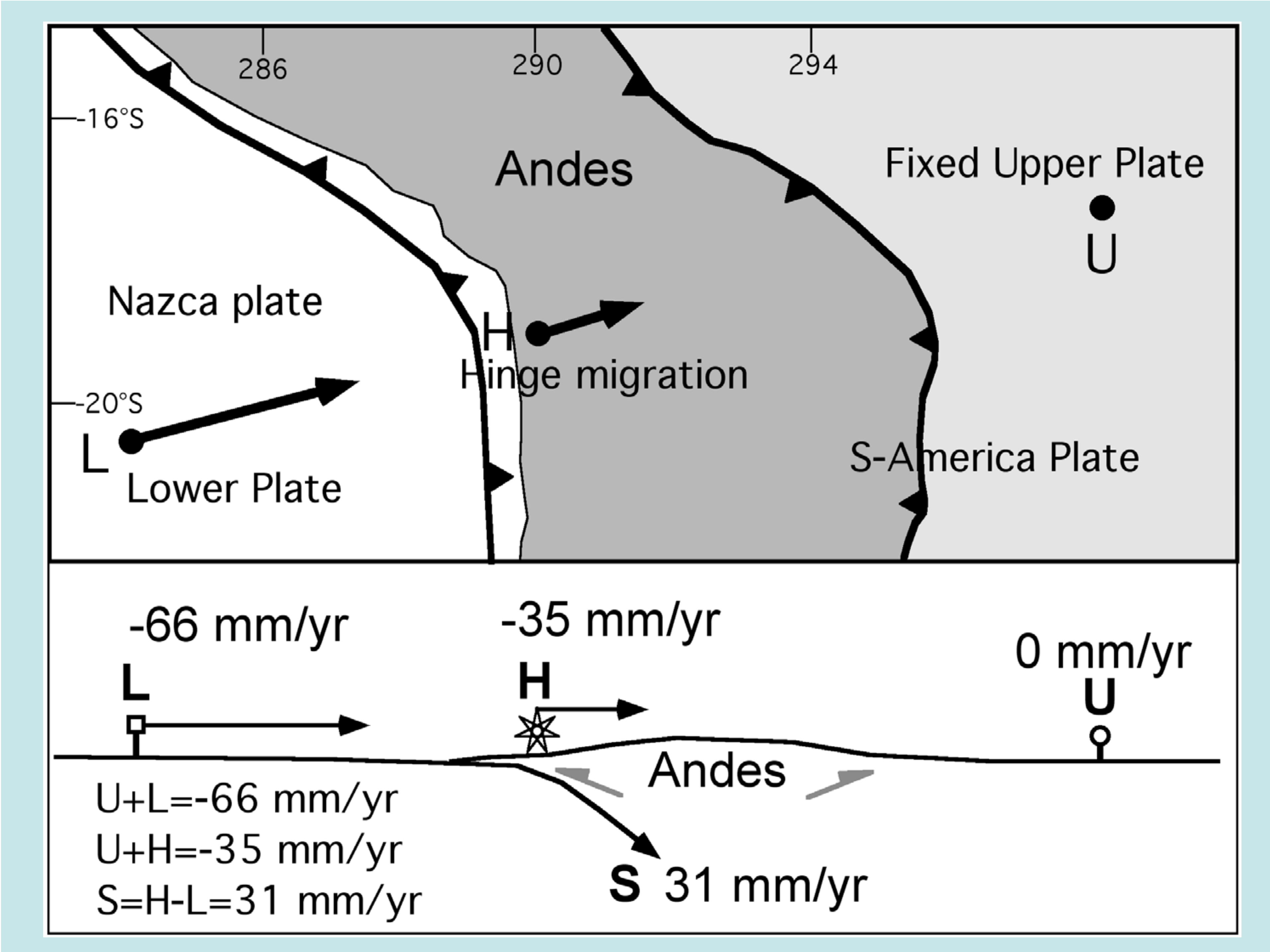




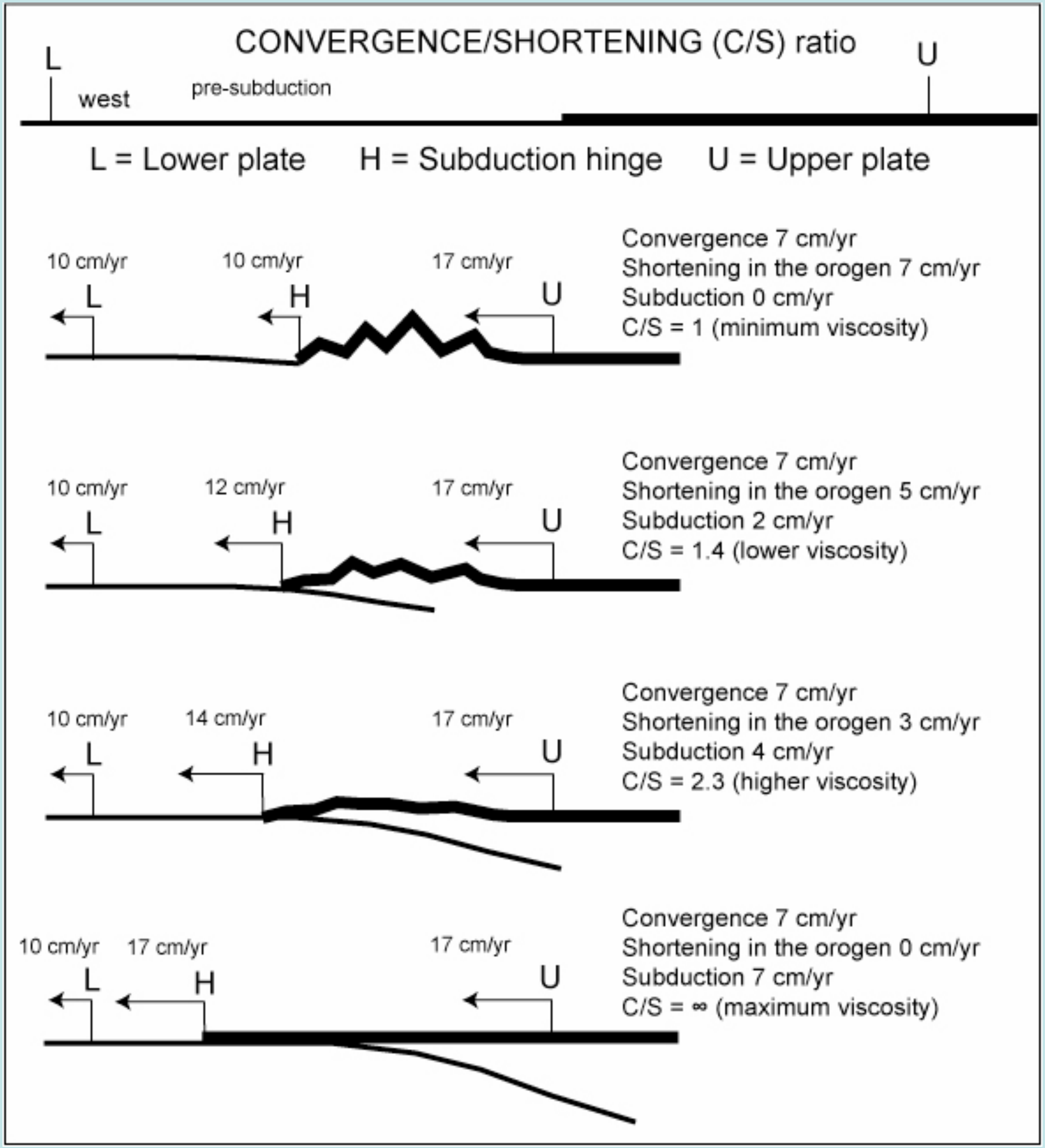
175°W
170°W
165°W
15°S
20°S
Fixed Upper Plate
U
H
Hinge migration
Lau
Basin
Tonga Ridge
Tonga Ridge
Tonga Trench
Lower Plate
Pacific Plate
L
Australian
Plate
180°W
170°W
160°W
0 mm/yr
U
160 mm/yr
H
-80 mm/yr
L
backarc spreading
U+L=-80 mm/yr
U+H=160 mm/yr
S=H-L=240 mm/yr
S
240 mm/yr

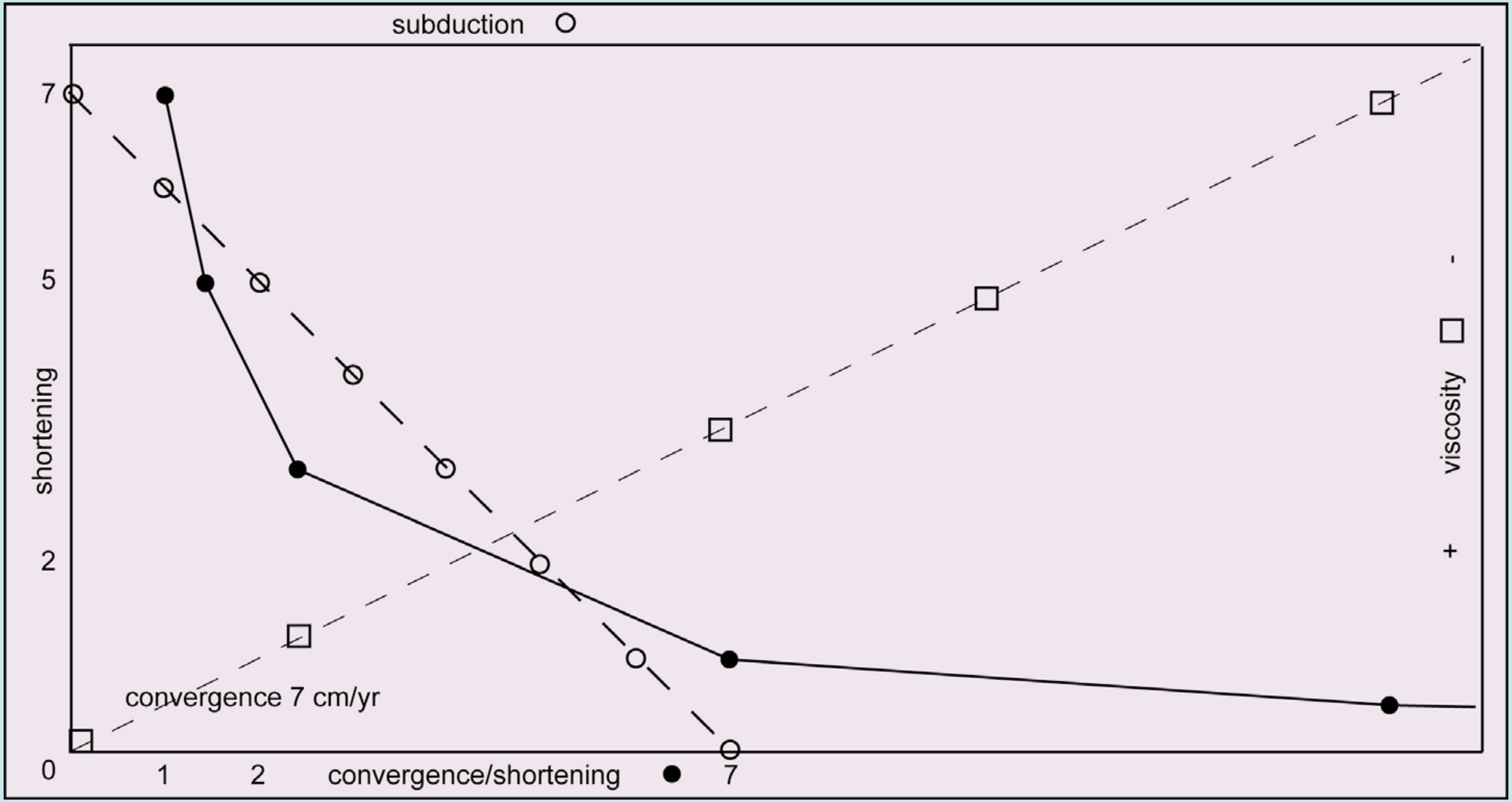


20°N
70°W
60°W
Barbados
Trench
Fixed Upper Plate
Lower Plate
H
U
L
Caribbean
Hinge migration
Atlantic
10°N
S-America
0 mm/yr
20 mm/yr
0 mm/yr
U
H
L
backarc spreading
U+L=0 mm/yr
U+H=20 mm/yr
S=H-L=20 mm/yr
S
20 mm/yr

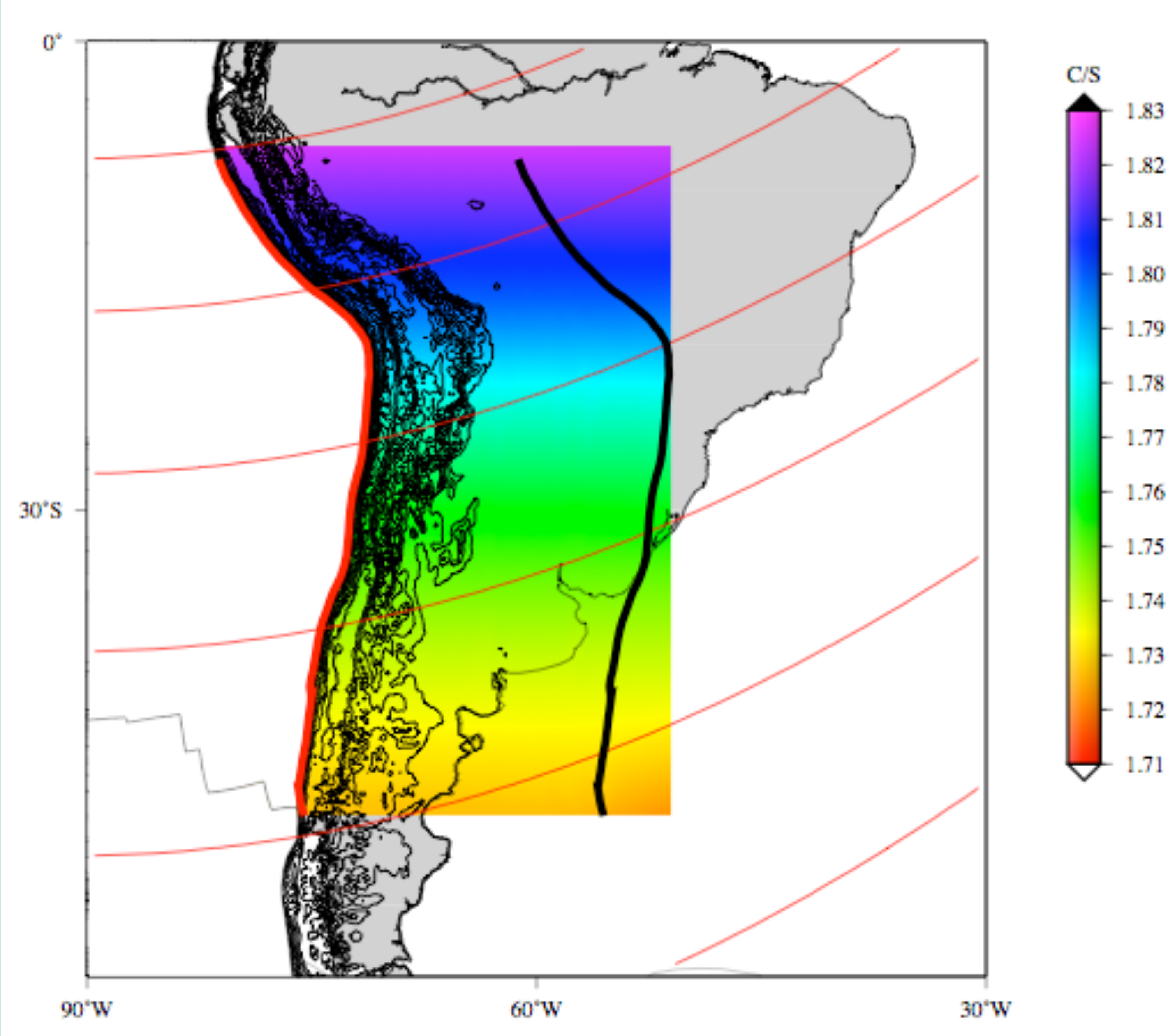


286
290
294
-16°S
-20°S
Andes
Fixed Upper Plate
U
Nazca plate
H
Hinge migration
L
Lower Plate
S-America Plate
-66 mm/yr
-35 mm/yr
0 mm/yr
L
H
U
Andes
U+L=-66 mm/yr
U+H=-35 mm/yr
S=H-L=31 mm/yr
S 31 mm/yr

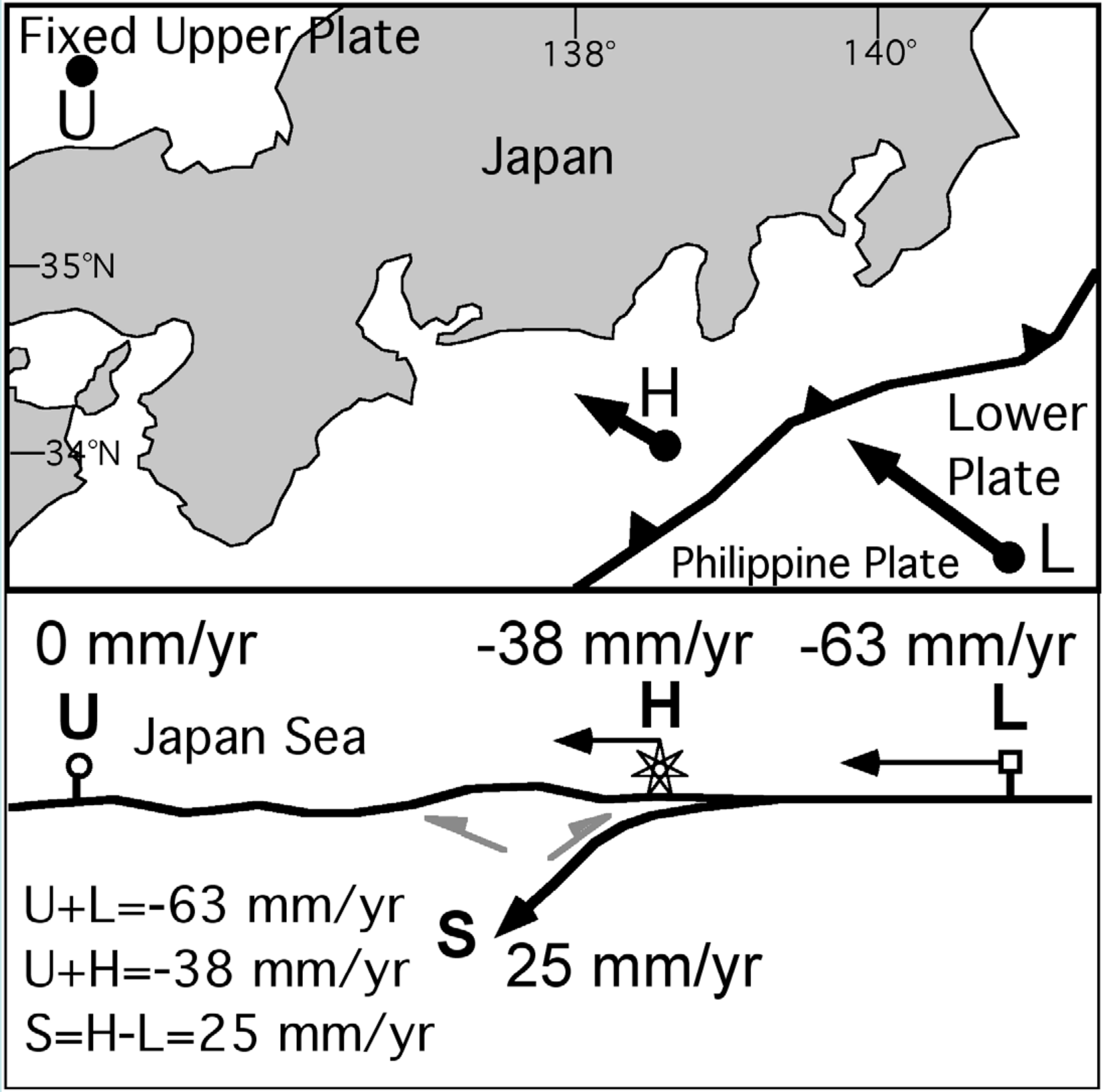

CONVERGENCE/SHORTENING (C/S) ratio
L
U
west
pre-subduction
L = Lower plate
H = Subduction hinge
U = Upper plate
10 cm/yr
10 cm/yr
17 cm/yr
L
H
U
Convergence 7 cm/yr
Shortening in the orogen 7 cm/yr
Subduction 0 cm/yr
C/S = 1 (minimum viscosity)
10 cm/yr
12 cm/yr
17 cm/yr
L
H
U
Convergence 7 cm/yr
Shortening in the orogen 5 cm/yr
Subduction 2 cm/yr
C/S = 1.4 (lower viscosity)
10 cm/yr
14 cm/yr
17 cm/yr
L
H
U
Convergence 7 cm/yr
Shortening in the orogen 3 cm/yr
Subduction 4 cm/yr
C/S = 2.3 (higher viscosity)
10 cm/yr
17 cm/yr
17 cm/yr
L
H
U
Convergence 7 cm/yr
Shortening in the orogen 0 cm/yr
Subduction 7 cm/yr
C/S = ∞ (maximum viscosity)



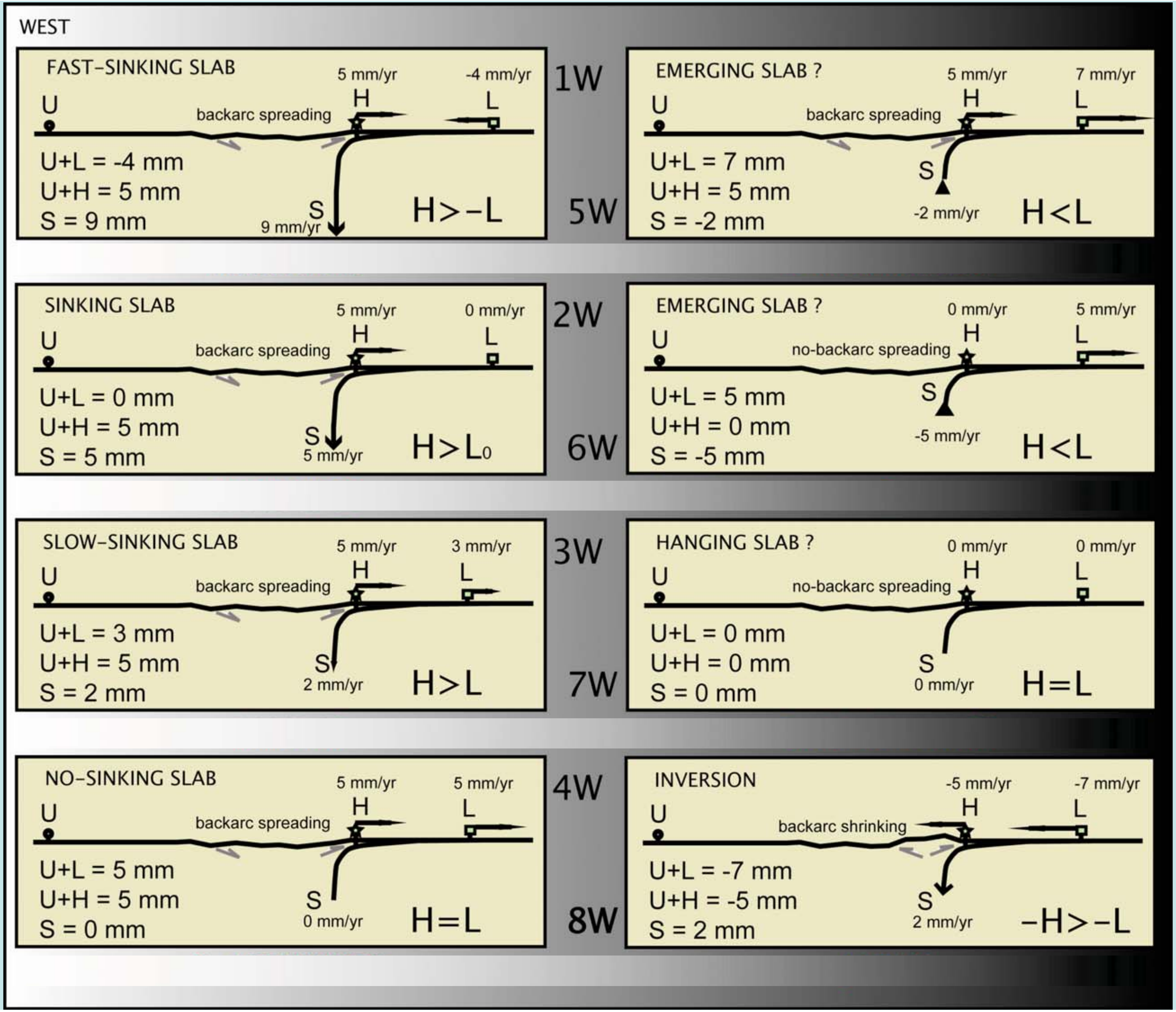
subduction
7
5
2
0
shortening
1
2
convergence/shortening
7
convergence 7 cm/yr
viscosity
-
+

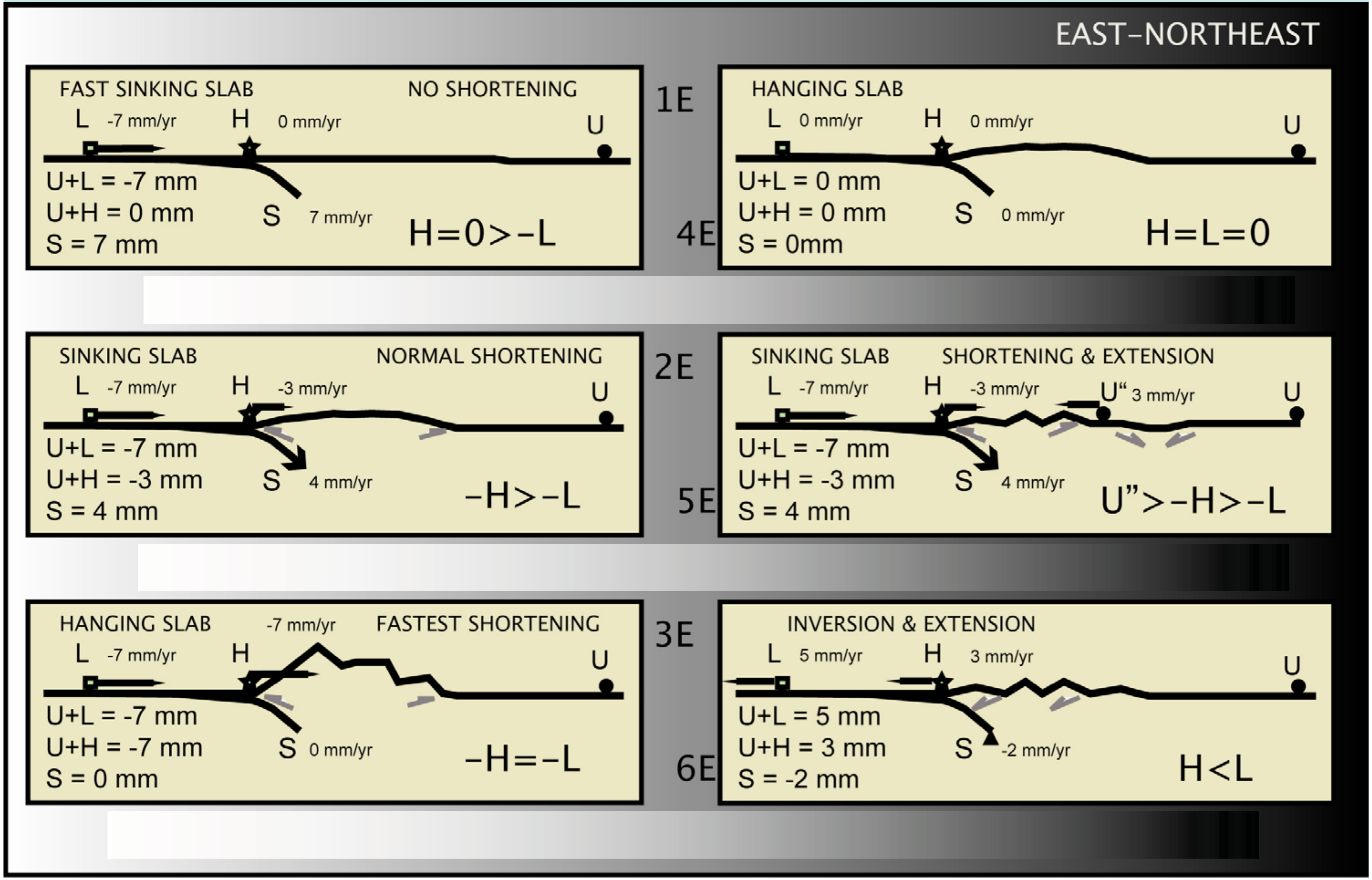


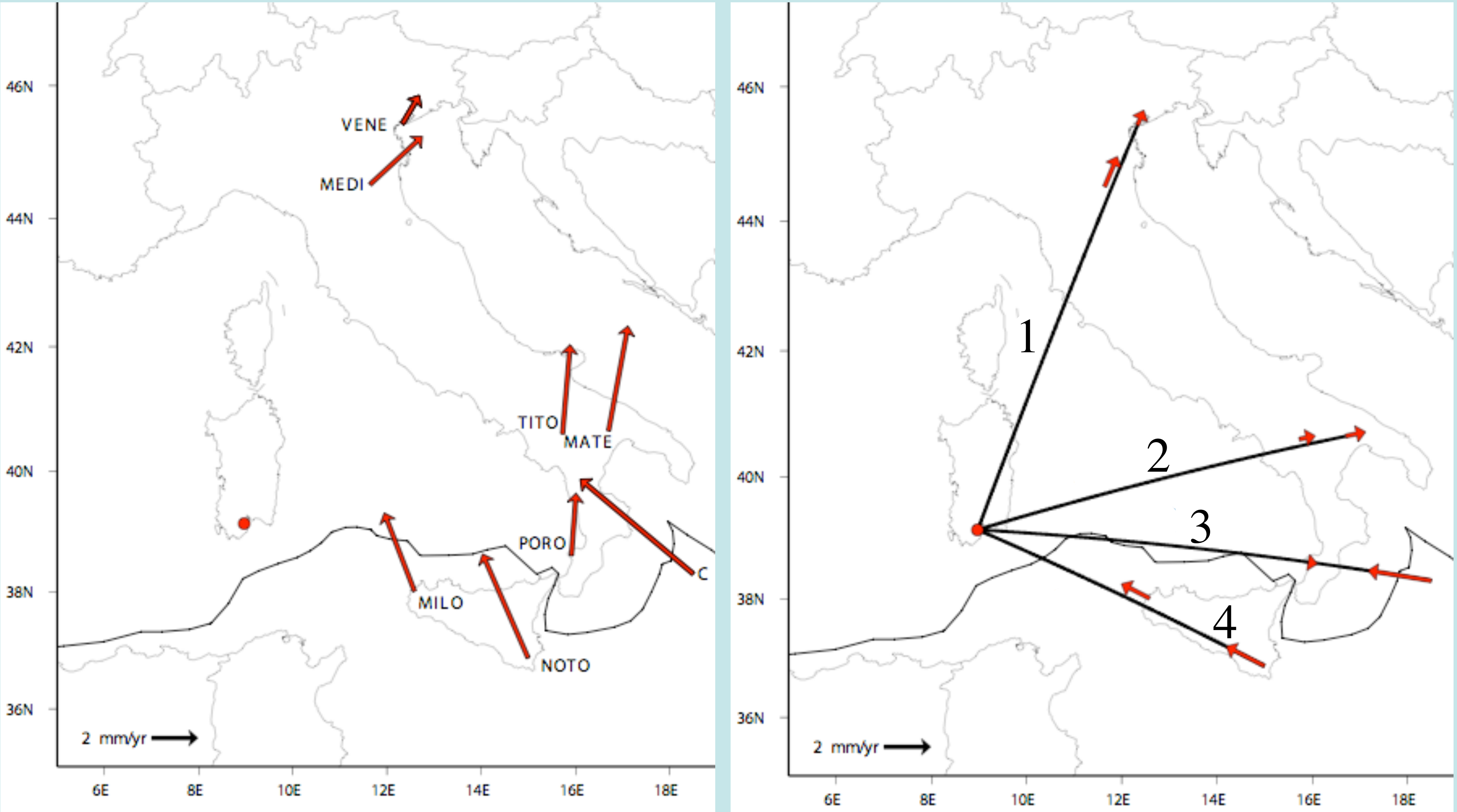
Higher convergence/shortening ratio, higher lithosphere viscosity

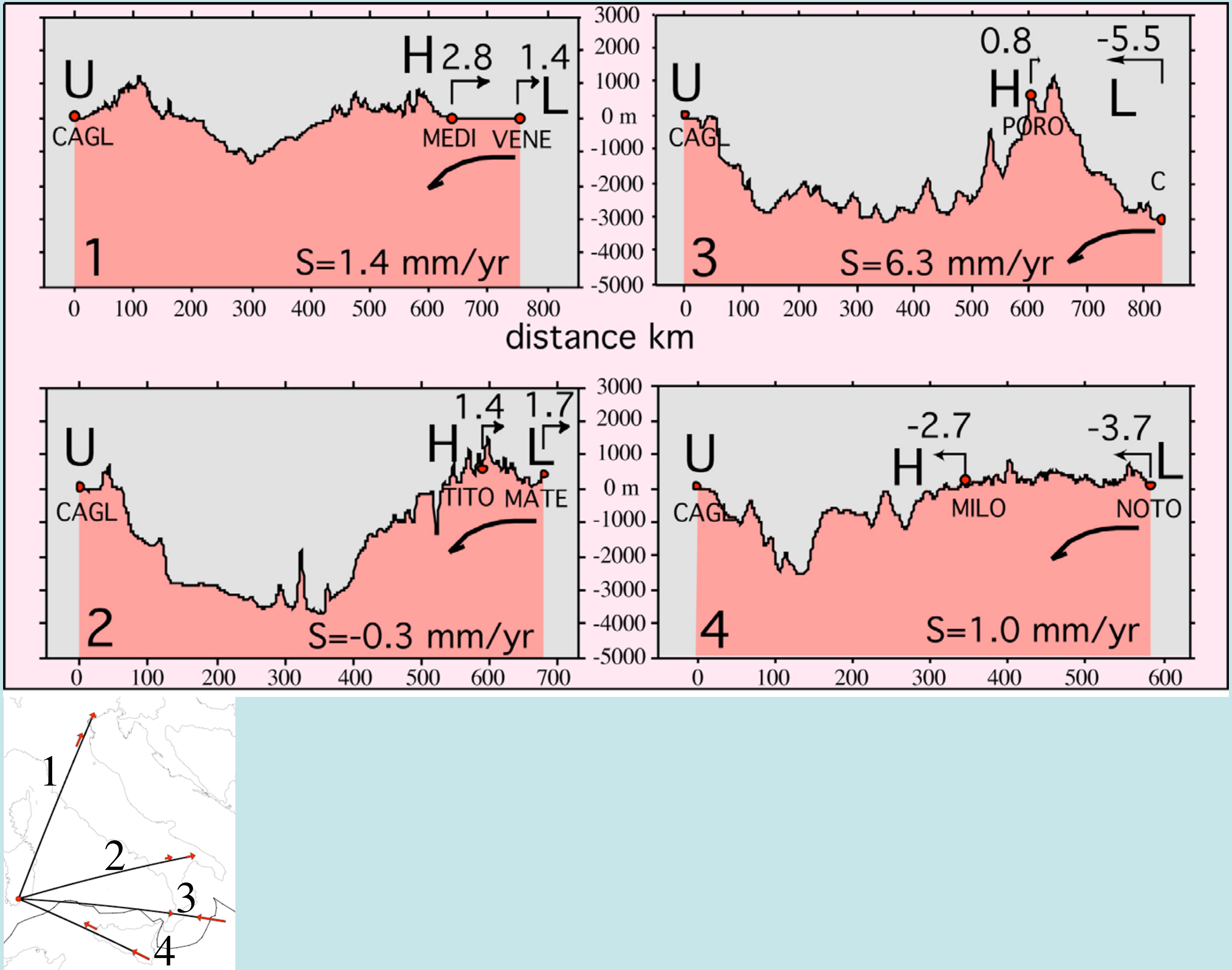


Fixed Upper Plate
U
138°
140°
Japan
35°N
34°N
H
Lower
Plate
Philippine Plate
L
0 mm/yr
-38 mm/yr
-63 mm/yr
U
H
L
Japan Sea
U+L=-63 mm/yr
U+H=-38 mm/yr
S=H-L=25 mm/yr
S
25 mm/yr


WEST
1W
5W
2W
6W
3W
7W
4W
8W
FAST-SINKING SLAB
5 mm/yr
-4 mm/yr
U
H
L
backarc spreading
U+L = -4 mm
U+H = 5 mm
S = 9 mm
S
9 mm/yr
H>-L
EMERGING SLAB ?
5 mm/yr
7 mm/yr
U
H
L
backarc spreading
U+L = 7 mm
U+H = 5 mm
S = -2 mm
S
-2 mm/yr
H<L
SINKING SLAB
5 mm/yr
0 mm/yr
U
H
L
backarc spreading
U+L = 0 mm
U+H = 5 mm
S = 5 mm
S
5 mm/yr
H>L0
EMERGING SLAB ?
0 mm/yr
5 mm/yr
U
H
L
no-backarc spreading
U+L = 5 mm
U+H = 0 mm
S = -5 mm
S
-5 mm/yr
H<L
SLOW-SINKING SLAB
5 mm/yr
3 mm/yr
U
H
L
backarc spreading
U+L = 3 mm
U+H = 5 mm
S = 2 mm
S
2 mm/yr
H>L
HANGING SLAB ?
0 mm/yr
0 mm/yr
U
H
L
no-backarc spreading
U+L = 0 mm
U+H = 0 mm
S = 0 mm
S
0 mm/yr
H=L
NO-SINKING SLAB
5 mm/yr
5 mm/yr
U
H
L
backarc spreading
U+L = 5 mm
U+H = 5 mm
S = 0 mm
S
0 mm/yr
H=L
INVERSION
-5 mm/yr
-7 mm/yr
U
H
L
backarc shrinking
U+L = -7 mm
U+H = -5 mm
S = 2 mm
S
2 mm/yr
-H>-L


EAST–NORTHEAST
1E
4E
2E
5E
3E
6E
FAST SINKING SLAB
NO SHORTENING
L -7 mm/yr
H 0 mm/yr
U
U+L = -7 mm
U+H = 0 mm
S = 7 mm
S 7 mm/yr
H=0>-L
HANGING SLAB
L 0 mm/yr
H 0 mm/yr
U
U+L = 0 mm
U+H = 0 mm
S = 0mm
S 0 mm/yr
H=L=0
SINKING SLAB
NORMAL SHORTENING
L -7 mm/yr
H -3 mm/yr
U
U+L = -7 mm
U+H = -3 mm
S = 4 mm
S 4 mm/yr
-H>-L
SINKING SLAB
SHORTENING & EXTENSION
L -7 mm/yr
H -3 mm/yr
U“ 3 mm/yr
U
U+L = -7 mm
U+H = -3 mm
S = 4 mm
S 4 mm/yr
U”>-H>-L
HANGING SLAB
-7 mm/yr
FASTEST SHORTENING
L -7 mm/yr
H
U
U+L = -7 mm
U+H = -7 mm
S = 0 mm
S 0 mm/yr
-H=-L
INVERSION & EXTENSION
L 5 mm/yr
H 3 mm/yr
U
U+L = 5 mm
U+H = 3 mm
S = -2 mm
S -2 mm/yr
H<L


VENE
MEDI
TITO
MATE
PORO
C
MILO
NOTO
46N
44N
42N
40N
38N
36N
2 mm/yr
6E
8E
10E
12E
14E
16E
18E
1
2
3
4

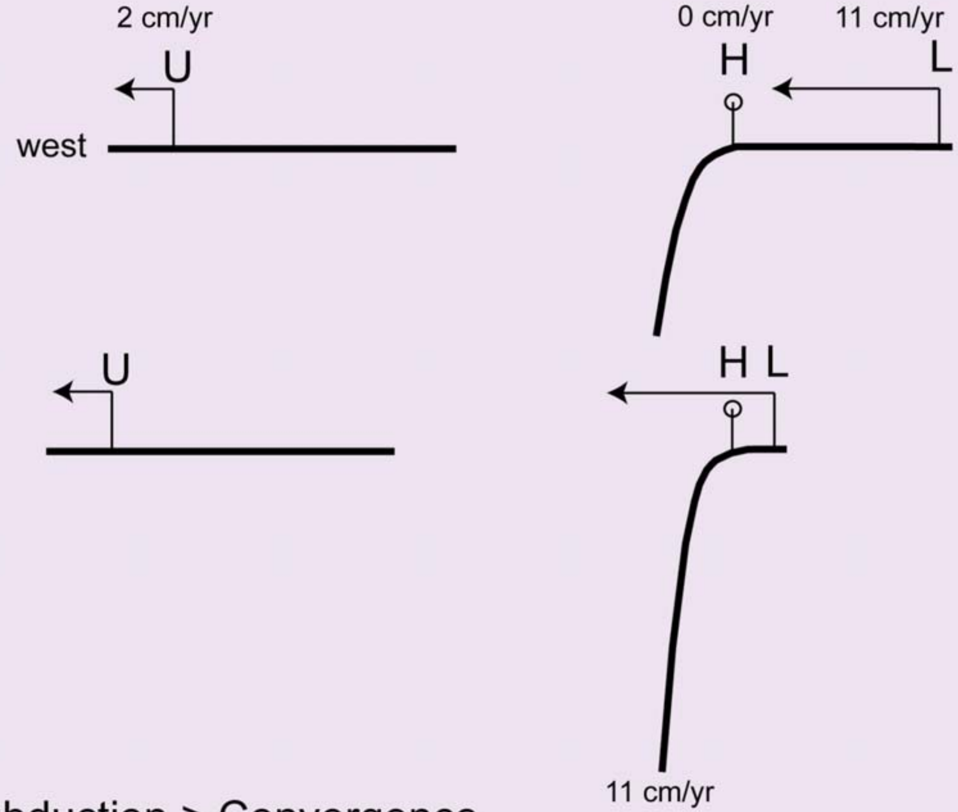


U
H 2.8
1.4 L
CAGL
MEDI
VENE
1
S=1.4 mm/yr
distance km
U
0.8
H
-5.5
L
CAGL
PORO
C
3
S=6.3 mm/yr
U
H
1.4
1.7
L
CAGL
TITO
MATE
2
S=-0.3 mm/yr
U
-2.7
H
-3.7
L
CAGL
MILO
NOTO
4
S=1.0 mm/yr
3000
2000
1000
0 m
-1000
-2000
-3000
-4000
-5000
0
100
200
300
400
500
600
700
800
1
2
3
4

PLATE MOTIONS RELATIVE TO THE MANTLE

L = Lower plate
H = Subduction hinge
U = Upper plate

Convergence 9 cm/yr
Shortening in the prism 11 cm/yr
Subduction 11 cm/yr
Backarc spreading 2 cm/yr



Subduction > Convergence
Hinge fixed with the mantle
Hinge diverging east relative to upper plate

PLATE MOTIONS RELATIVE TO THE MANTLE

L = Foreland plate
H = Subduction hinge
U = Upper plate

Convergence 7 cm/yr
Shortening in the orogen 5 cm/yr
Subduction 2 cm/yr

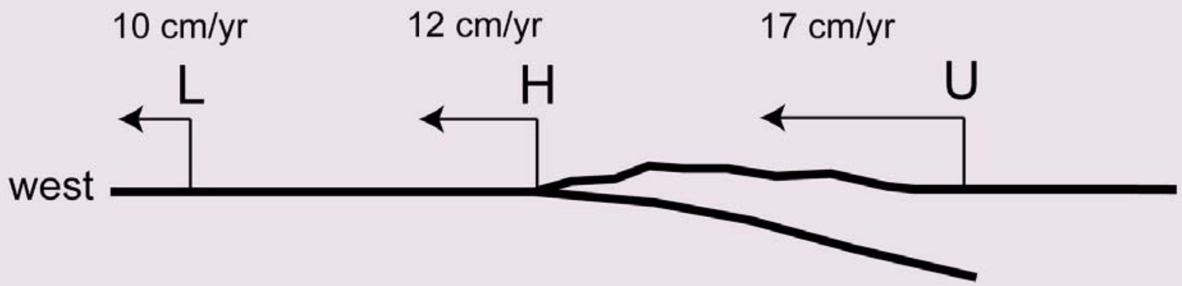
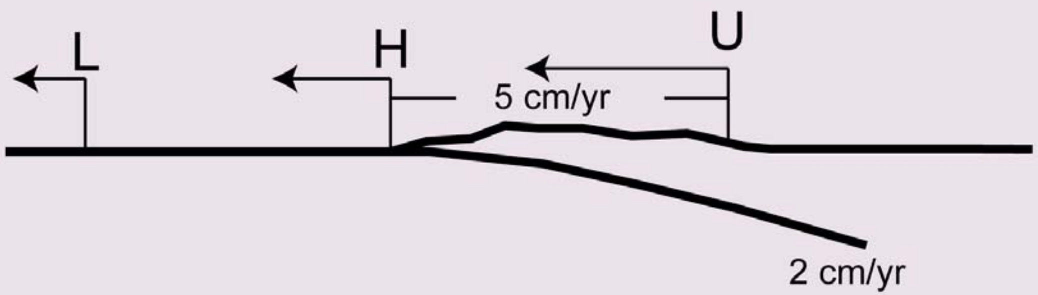
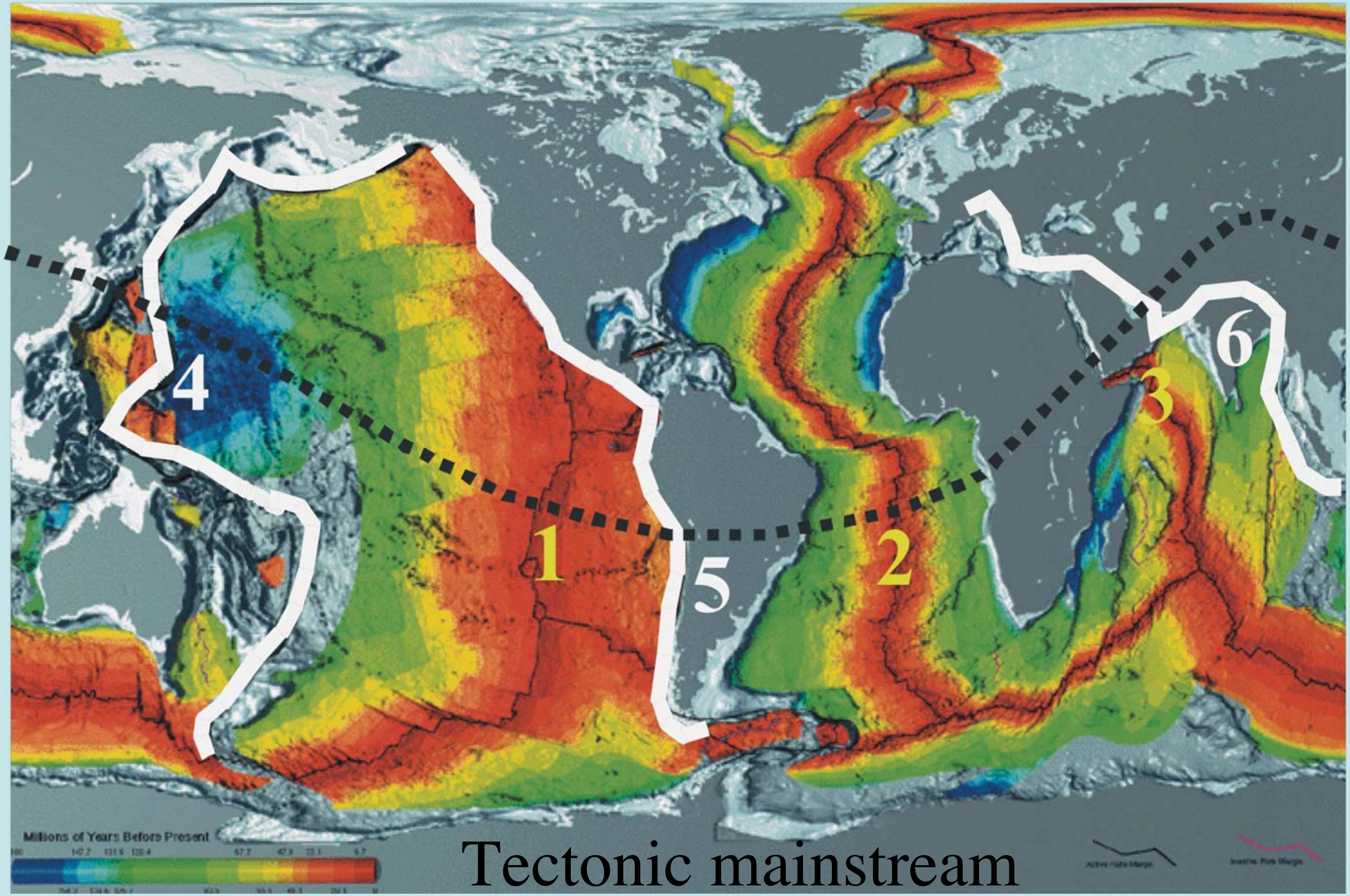


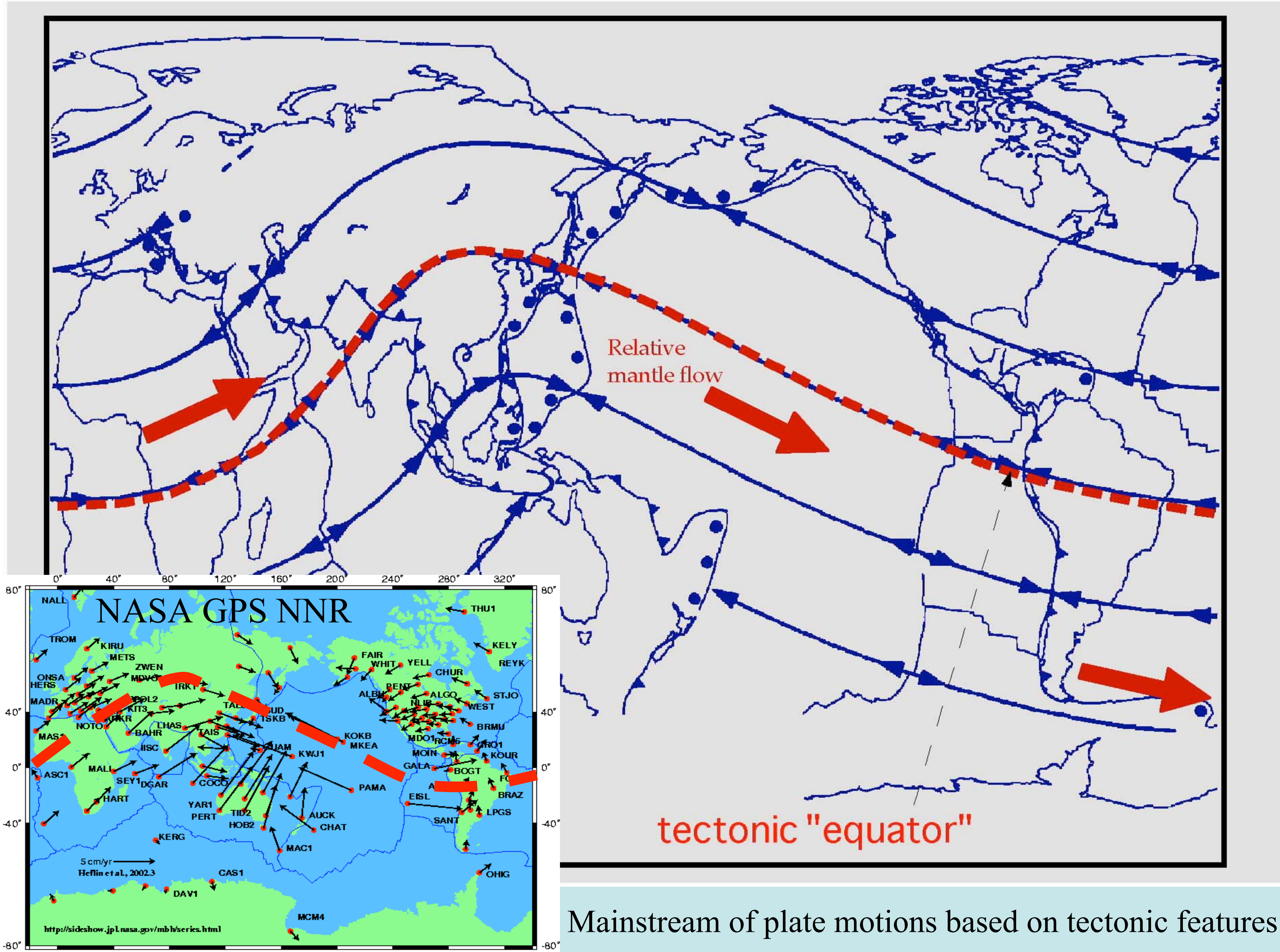
Plate motions not controlled by subduction rate



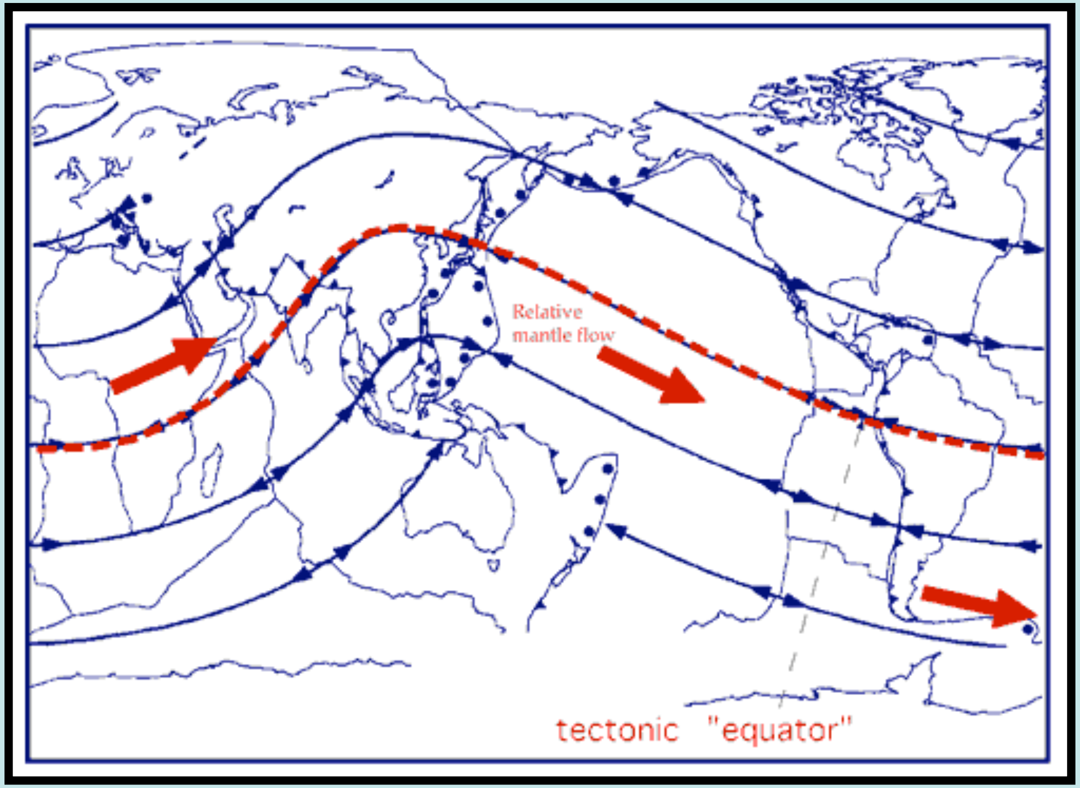
Subduction < Convergence
Hinge retreating west relative to mantle
Hinge converging east relative to upper plate

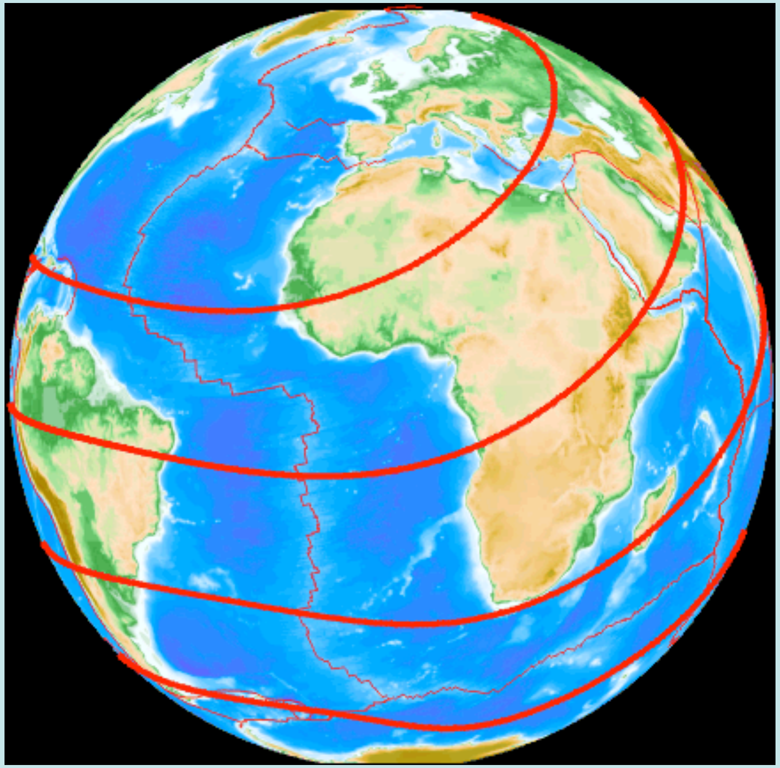


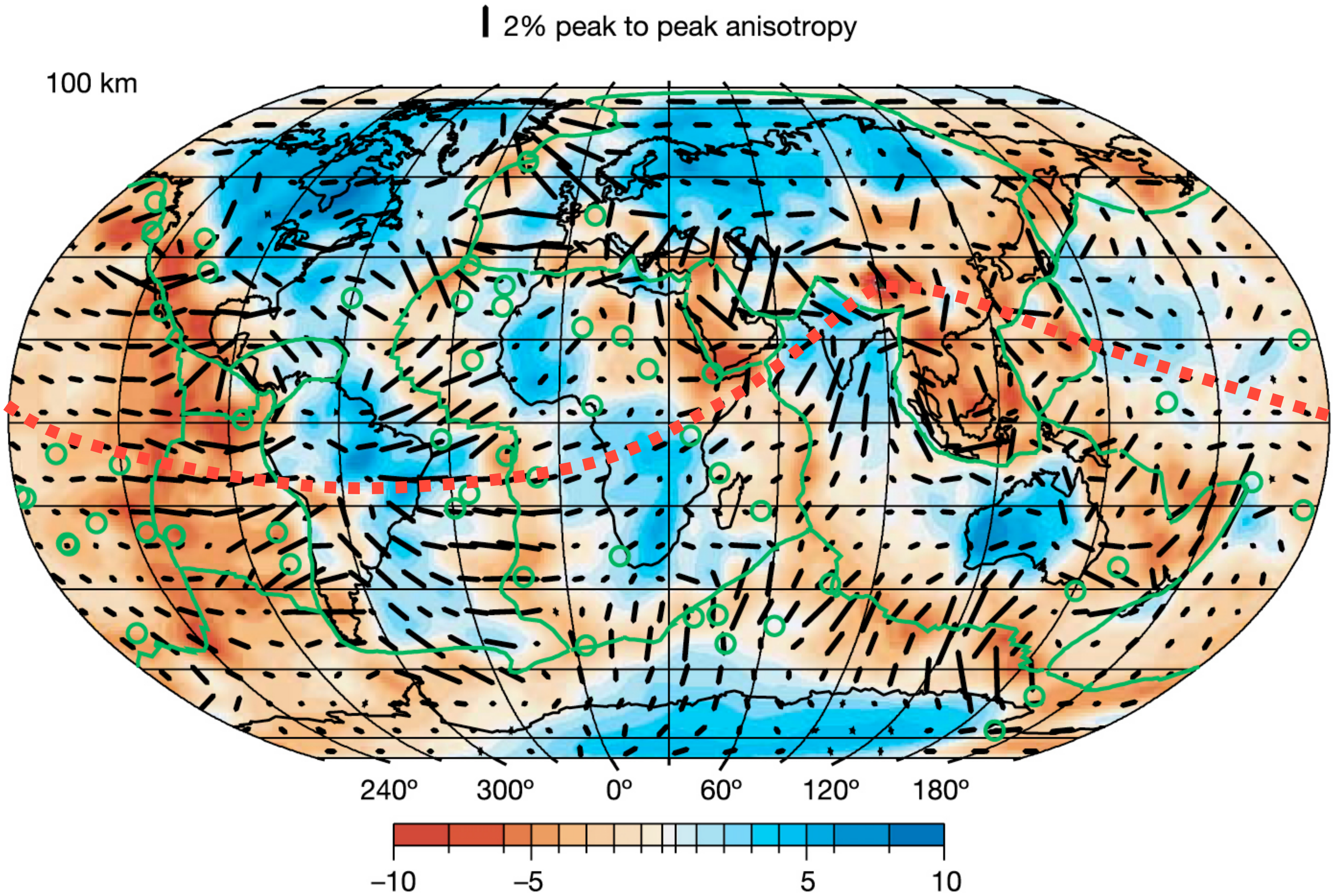
1= East Pacific Rise
2= Atlantic Rift
3= Red Sea Indian Ocean Rift
4= West Pacific Subduction
5= Andean Subduction
6= Zagros-Himalayas Subduction



Mainstream of plate motions based on tectonic features


Relative
mantle flow
tectonic "equator"





Debayle et al., 2005, Nature

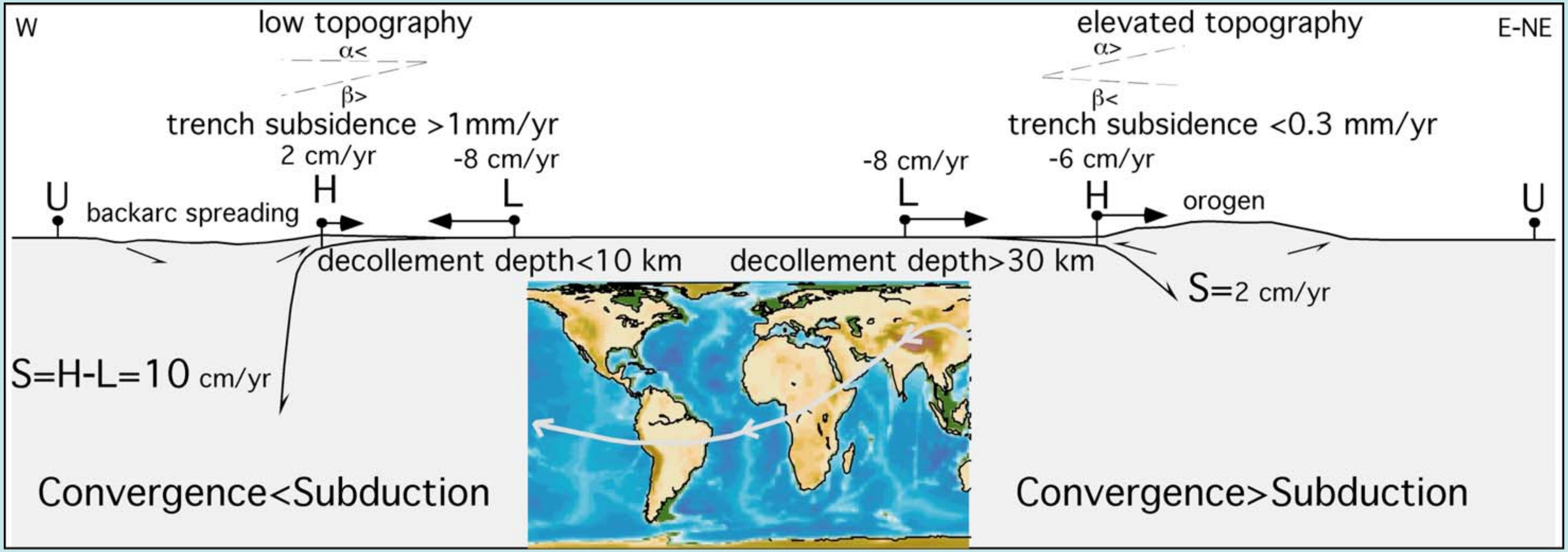
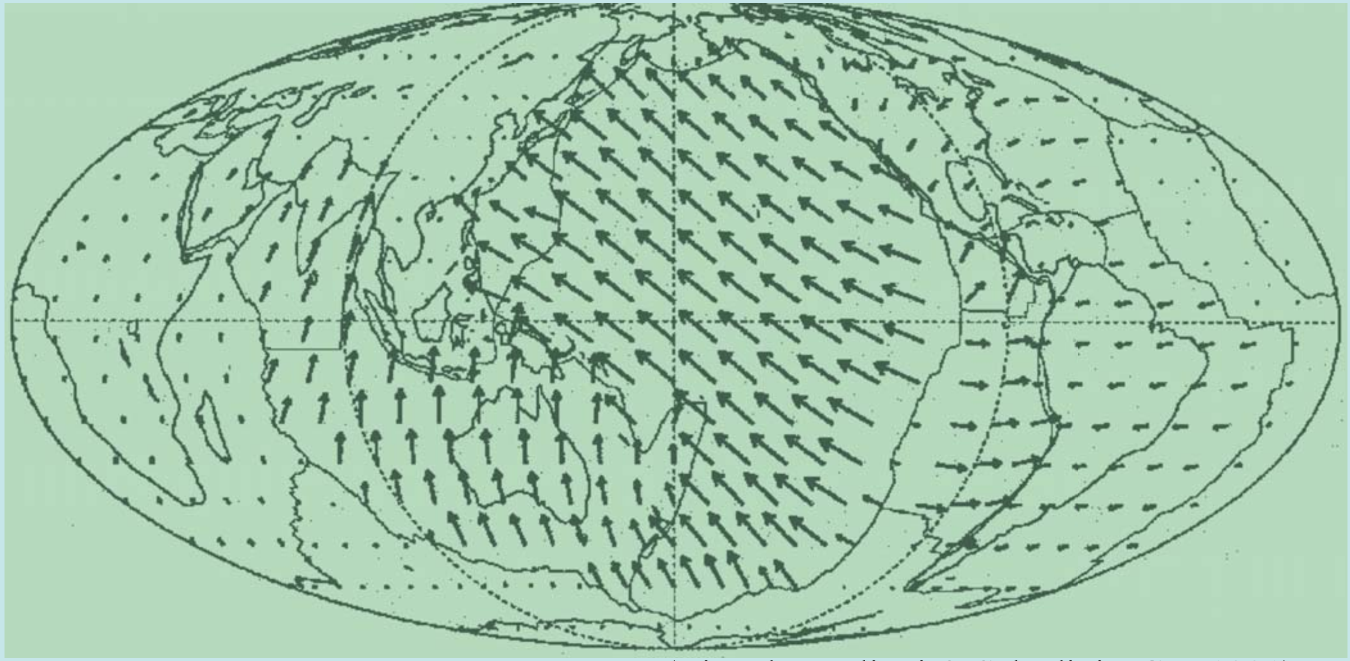
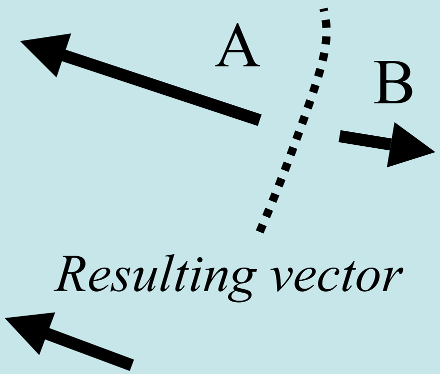
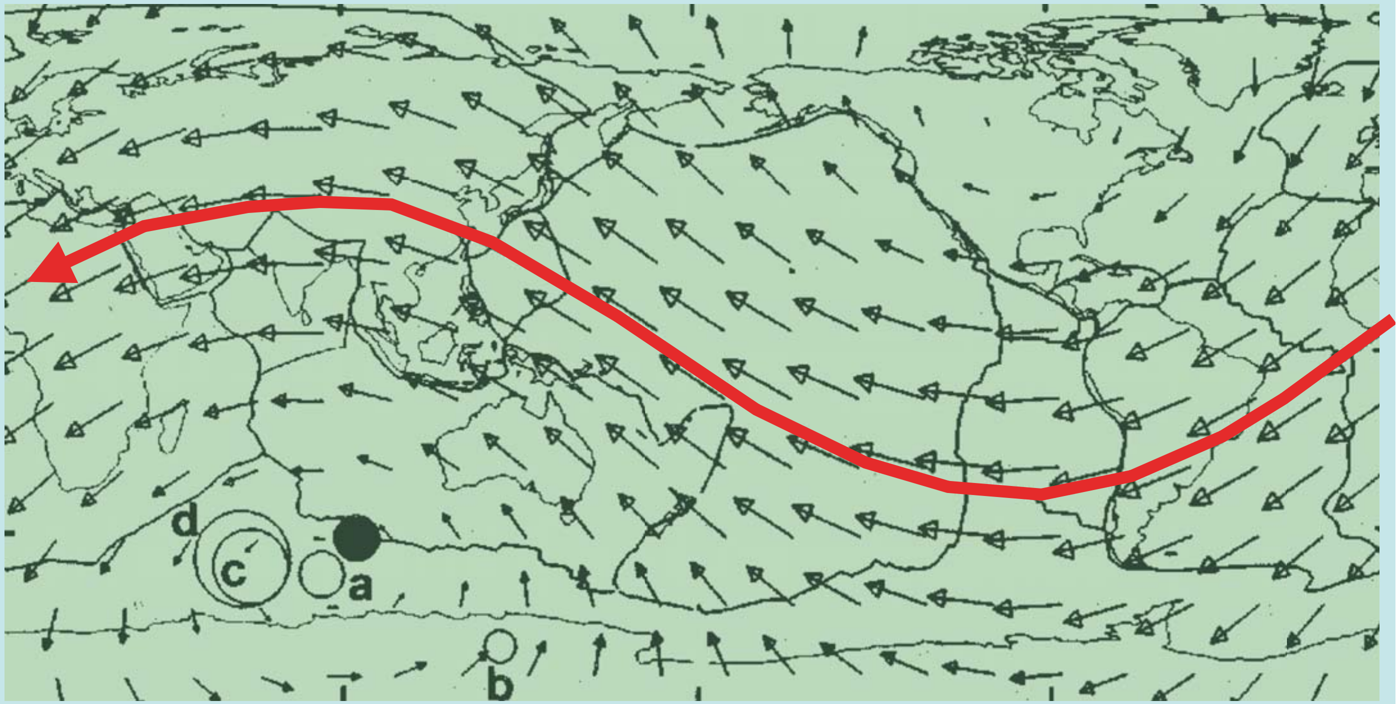

W
low topography
α<
β>
trench subsidence >1mm/yr
2 cm/yr
-8 cm/yr
elevated topography
α>
β<
trench subsidence <0.3 mm/yr
-8 cm/yr
-6 cm/yr
E-NE
U
backarc spreading
H
L
L
H
orogen
U
decollement depth<10 km
decollement depth>30 km
S=2 cm/yr
S=H-L=10 cm/yr
Convergence<Subduction
Convergence>Subduction

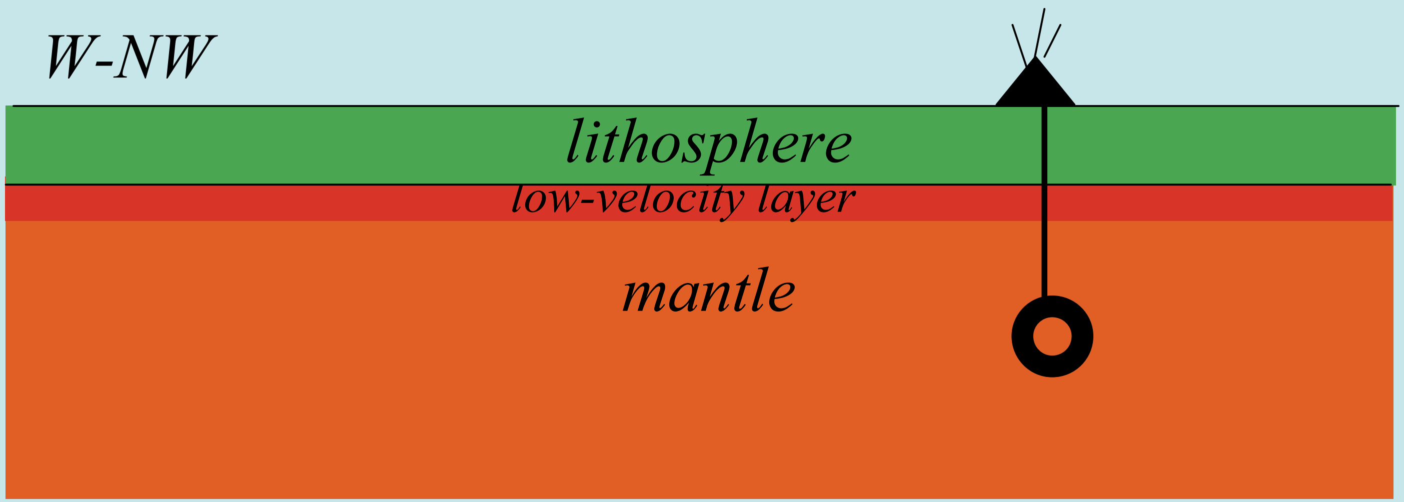
Plate motions based on the Hotspot Reference Frame
(O'Connell, Gable & Hager, 1991)



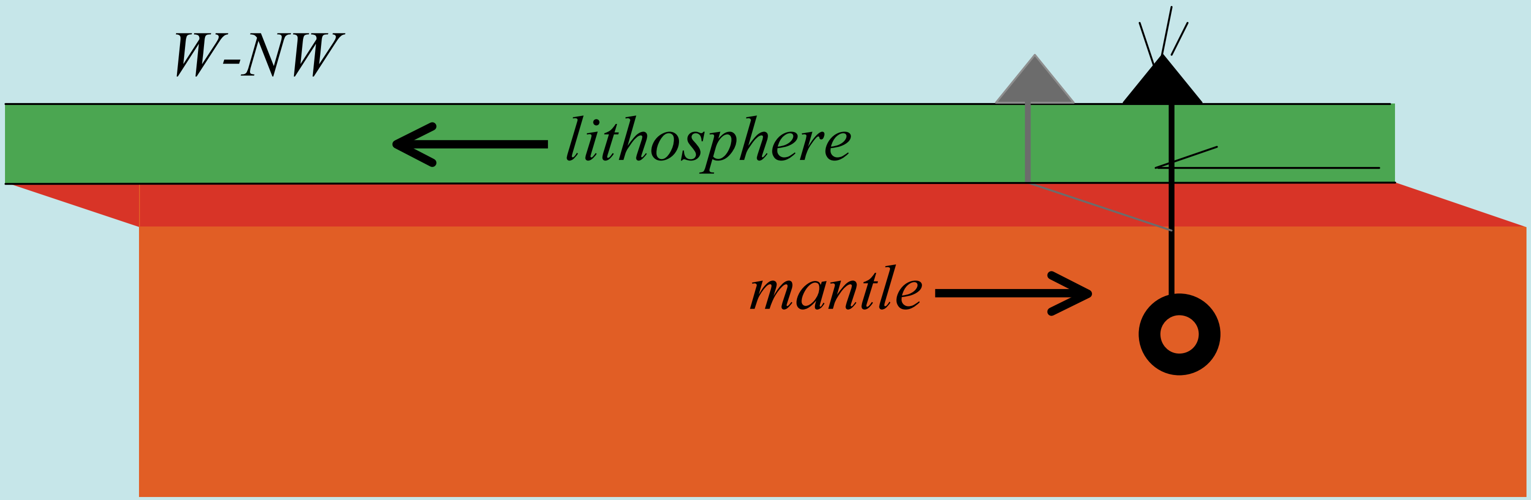
(Ricard, Doglioni & Sabadini, JGR, 1991)





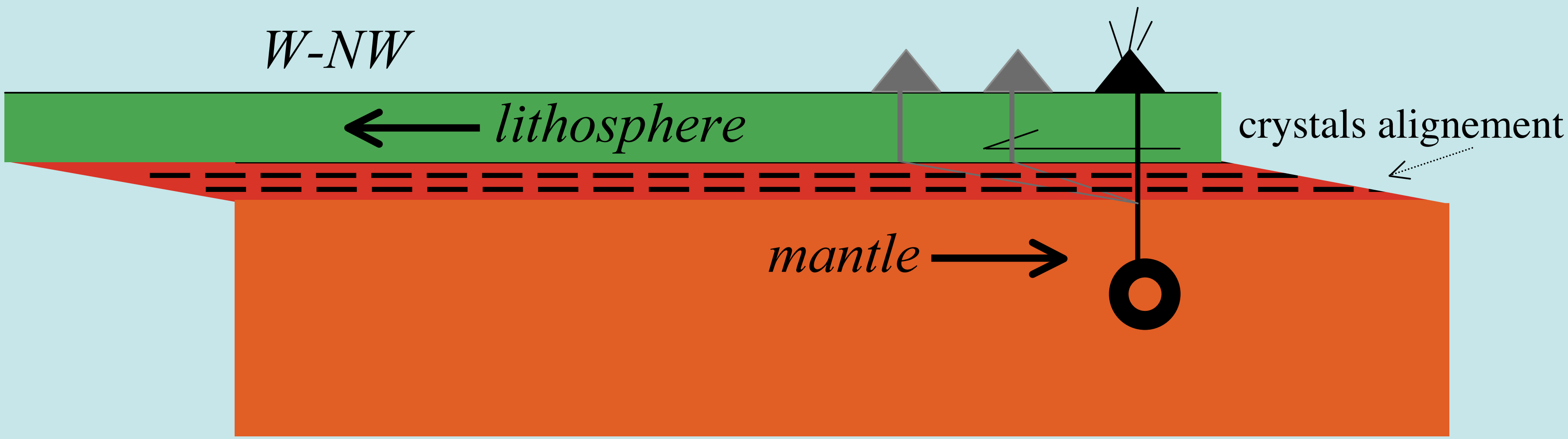

W-NW
lithosphere
low-velocity layer
mantle

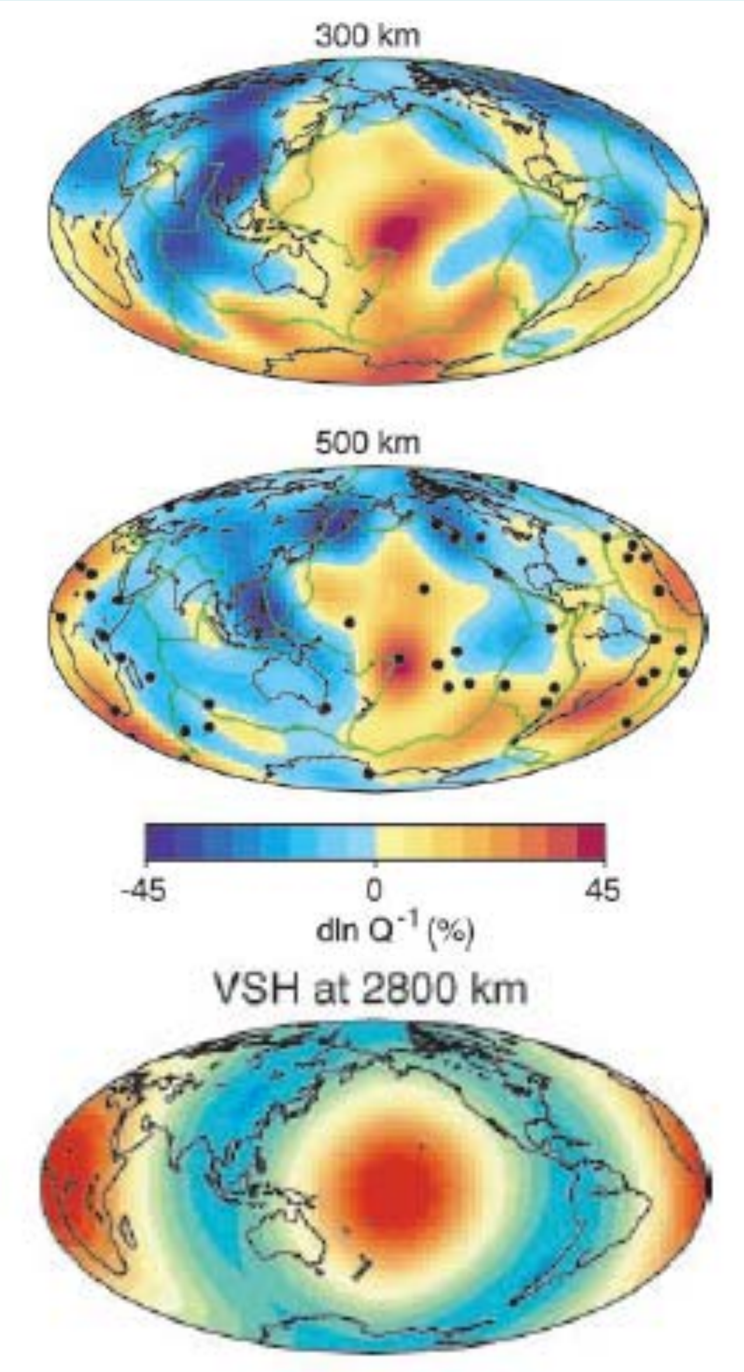
"Westward" drift of the lithosphere

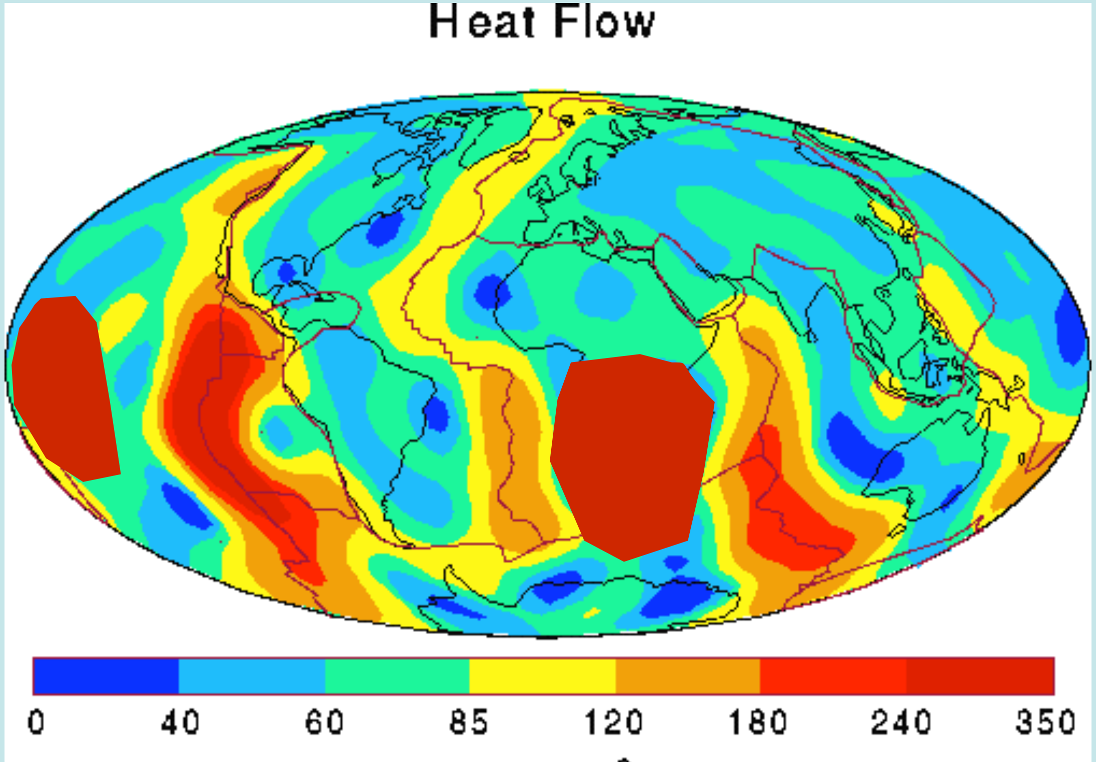


“Westward” drift of the lithosphere

(or “eastward” mantle flow)

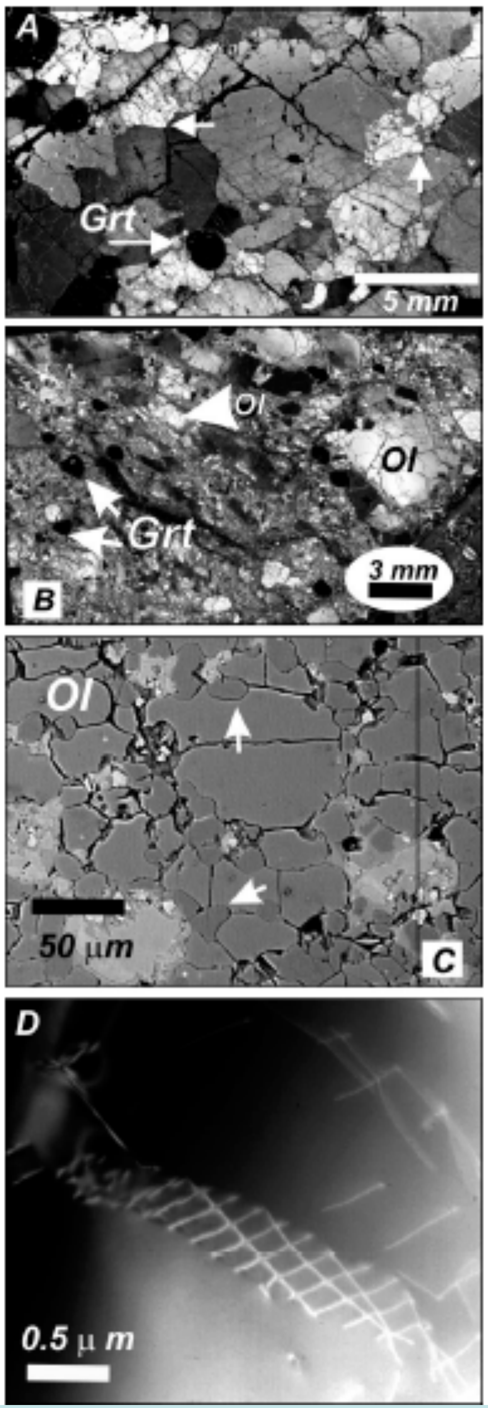


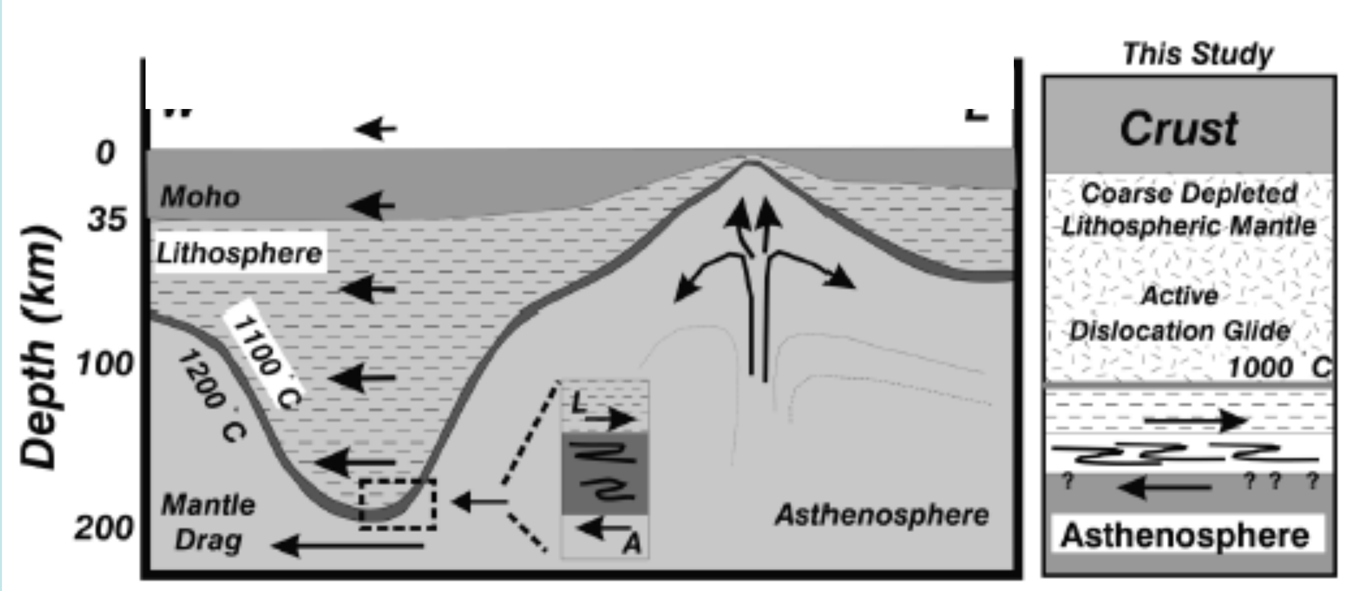




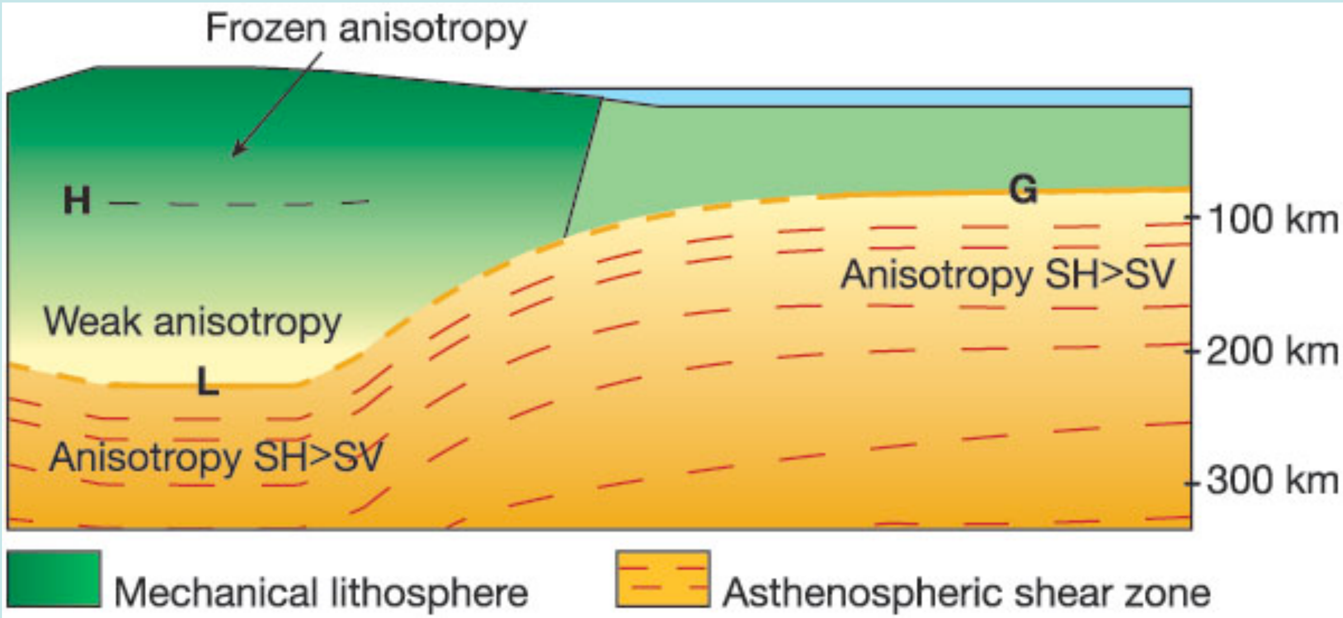
Pollack, 1996

Romanowicz & Gung, 2002

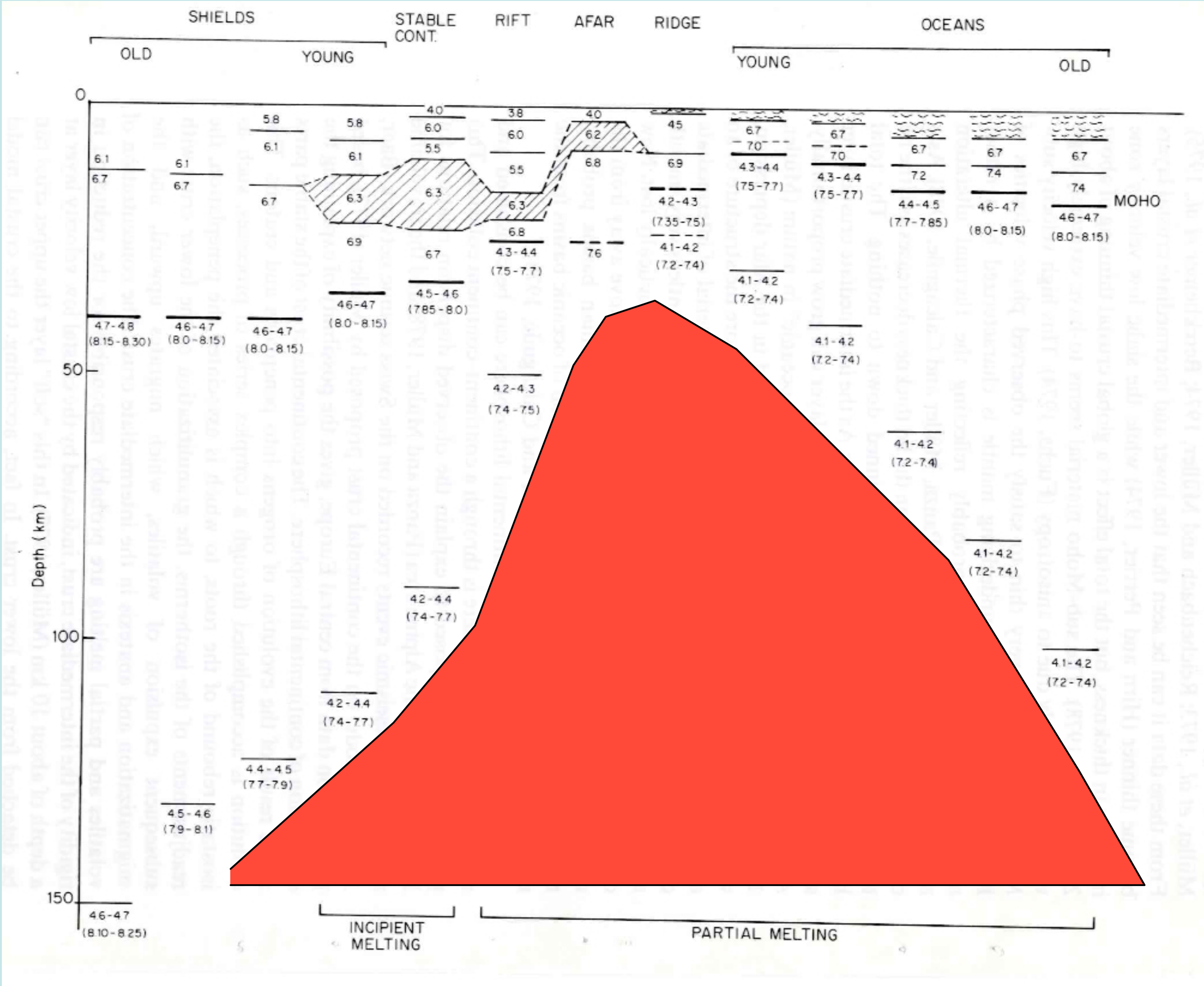




Kennedy et al., Geology 2002

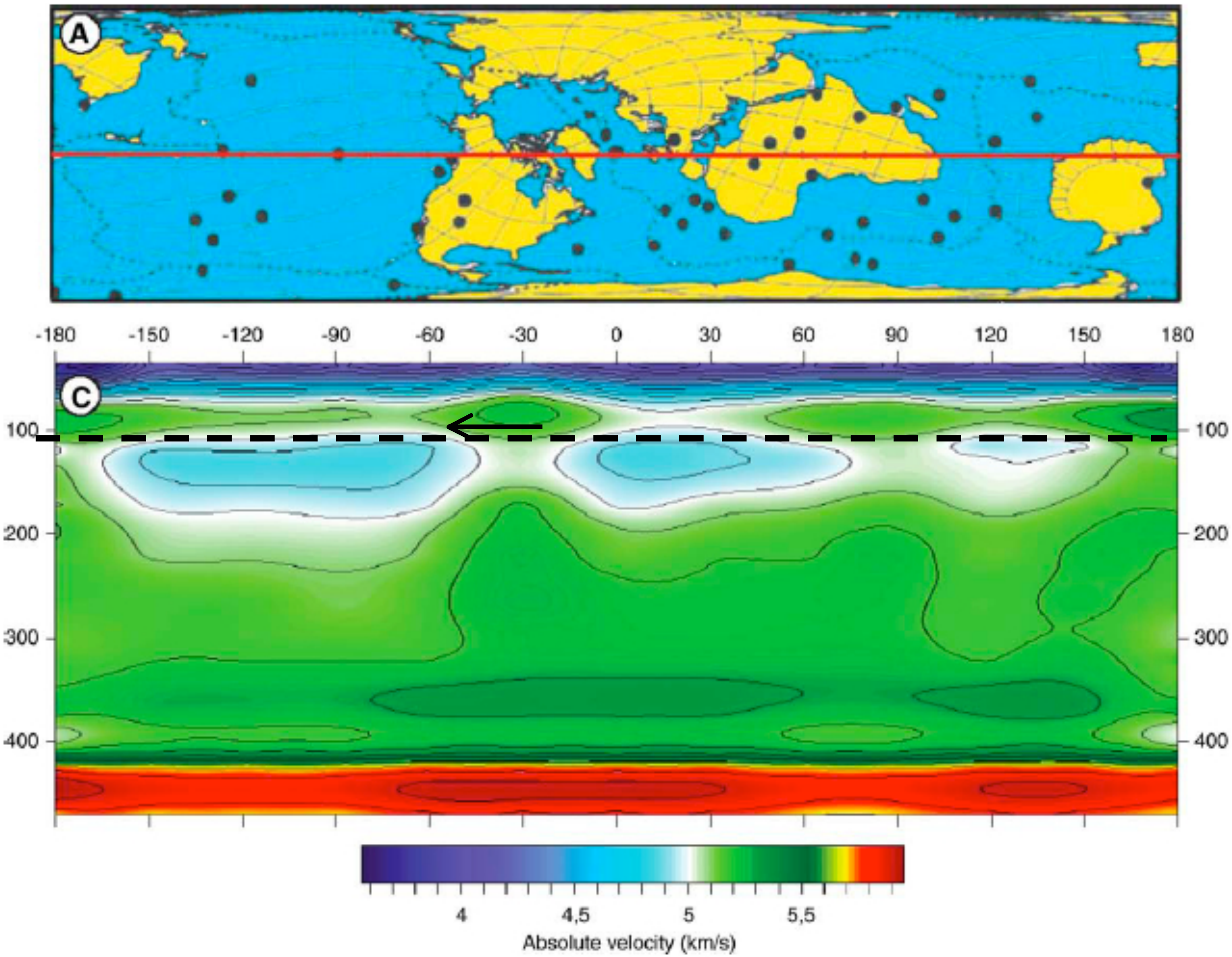


Gung et al., Nature 2003

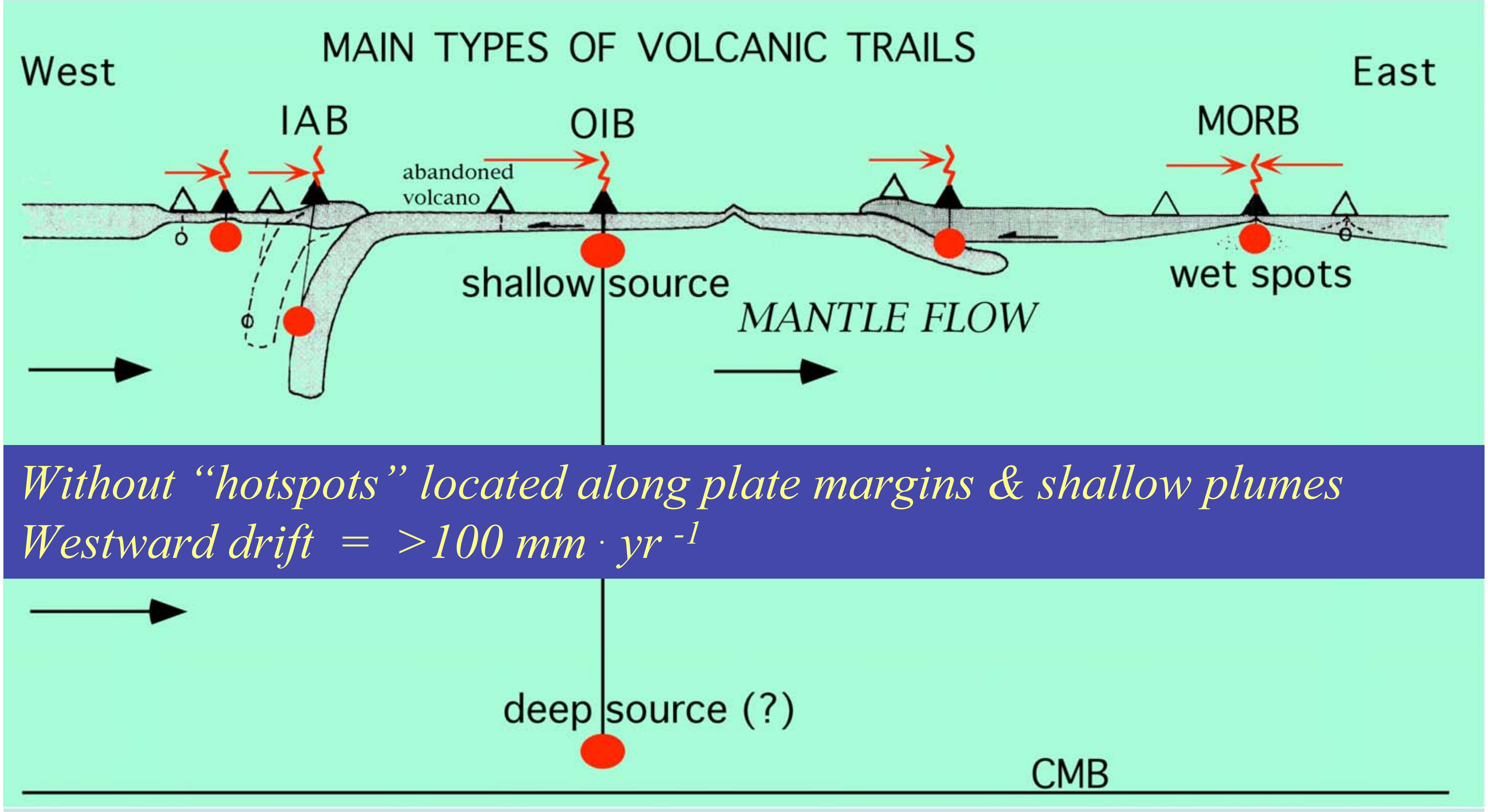


SHIELDS
OLD
YOUNG
STABLE CONT.
RIFT
AFAR
RIDGE
OCEANS
YOUNG
OLD
MOHO
Depth (km)
0
50
100
150
INCIPIENT MELTING
PARTIAL MELTING

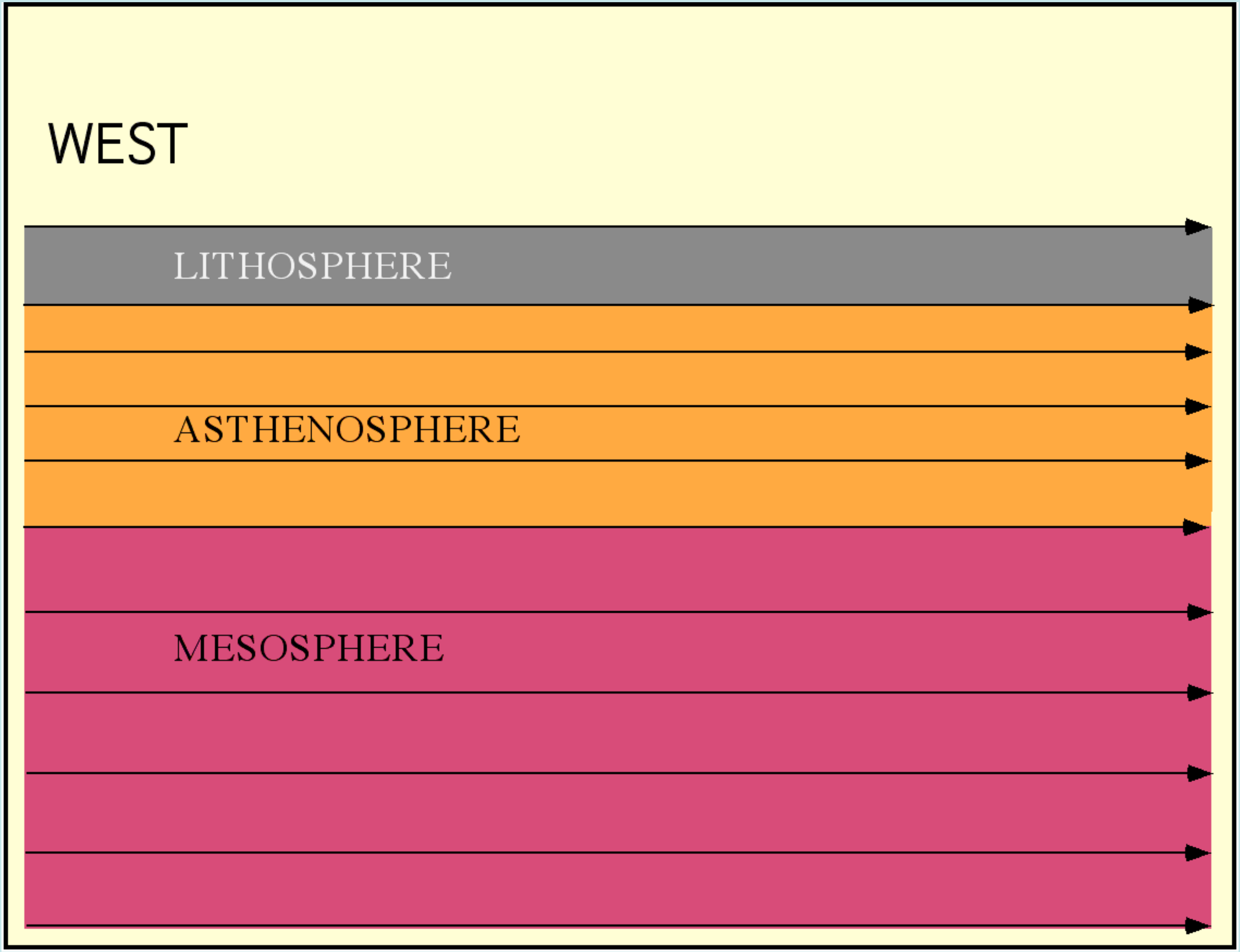
Panza, 1980

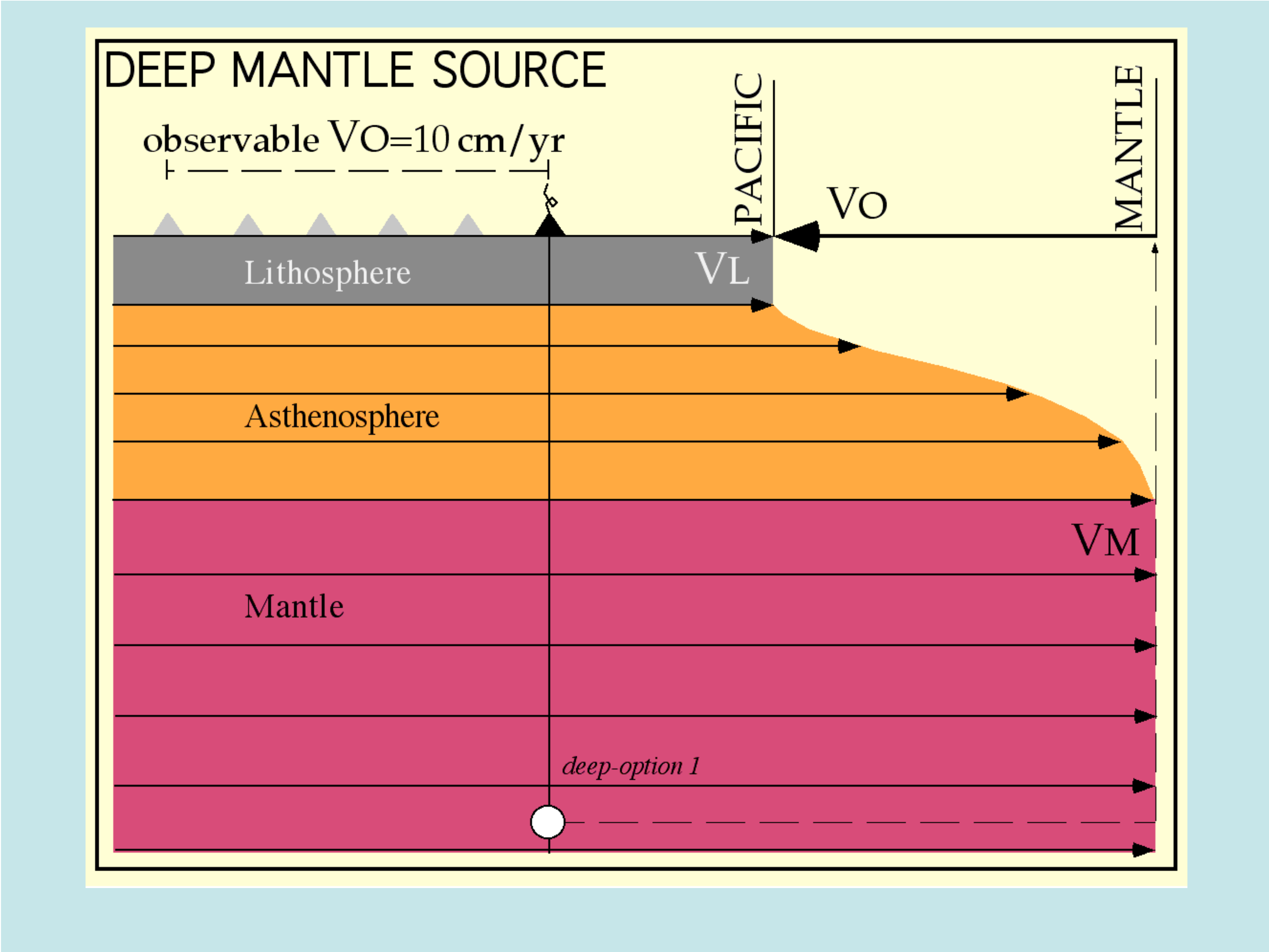

A
C
-180
-150
-120
-90
-60
-30
0
30
60
90
120
150
180
100
200
300
400
4
4,5
5
5,5
Absolute velocity (km/s)

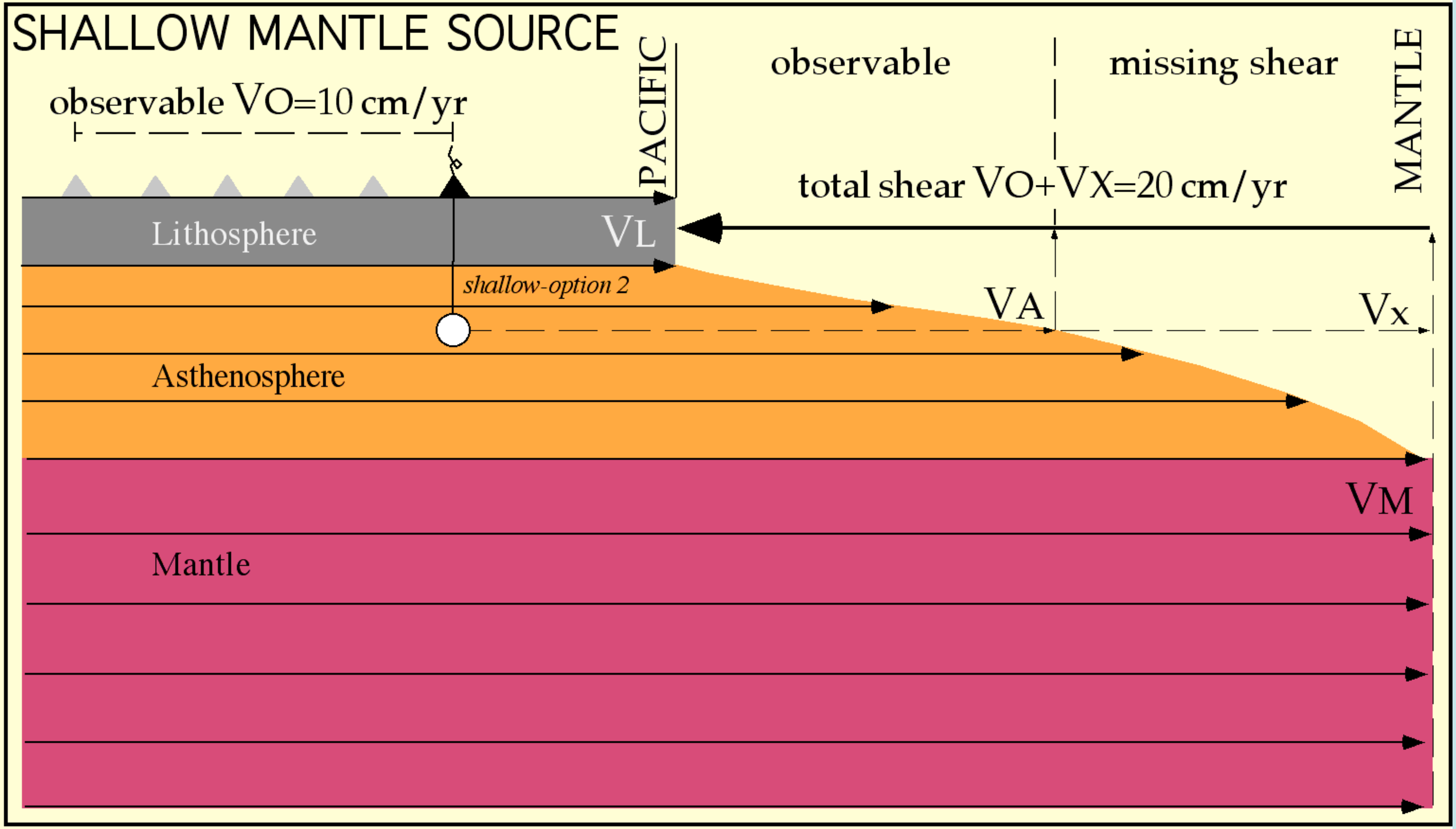
- *Different depths of the magmatic sources*
- *Most of them in the asthenosphere or in the lithospheric mantle*
- *Most of them along moving and mantle-detached plate margins*

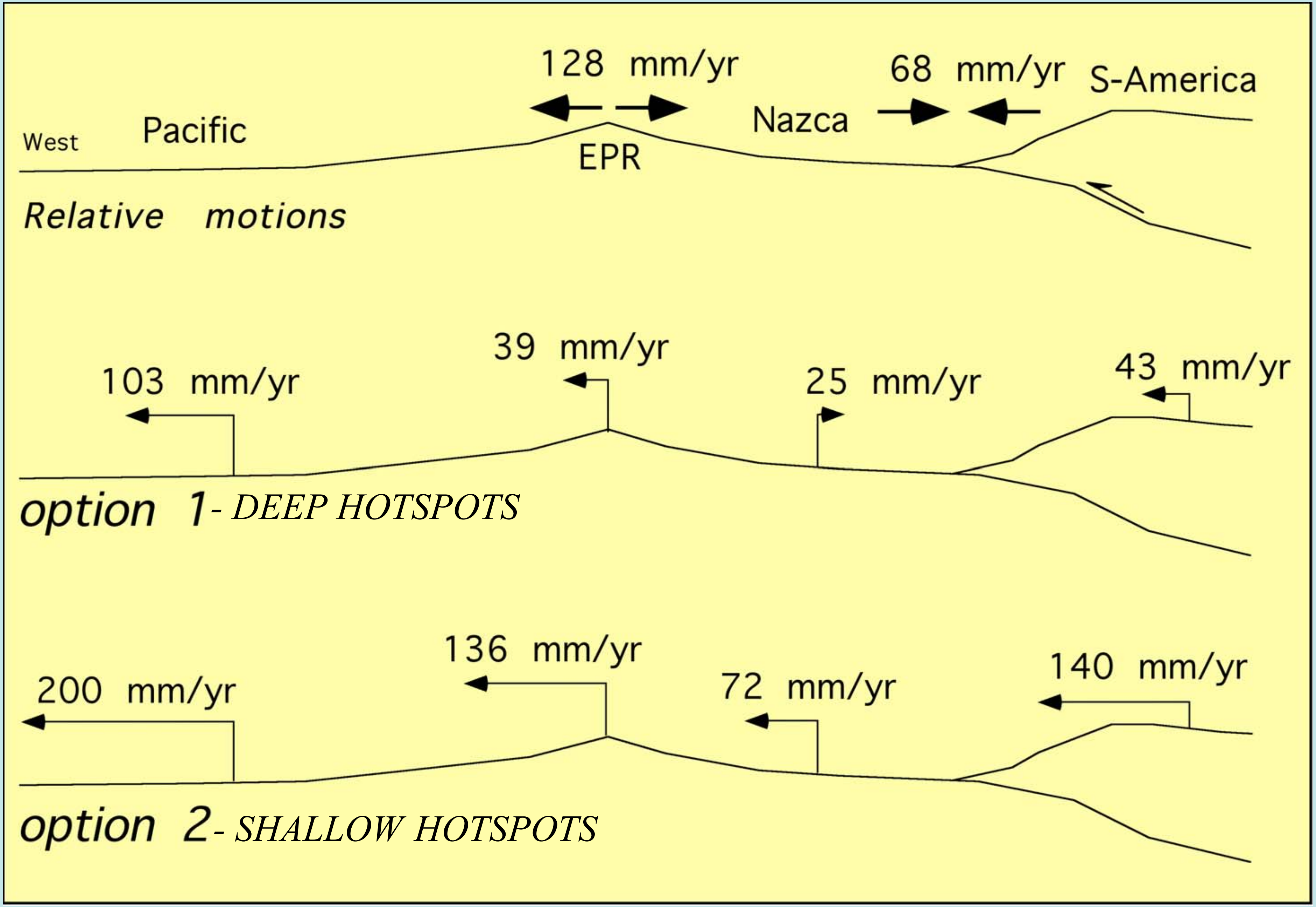


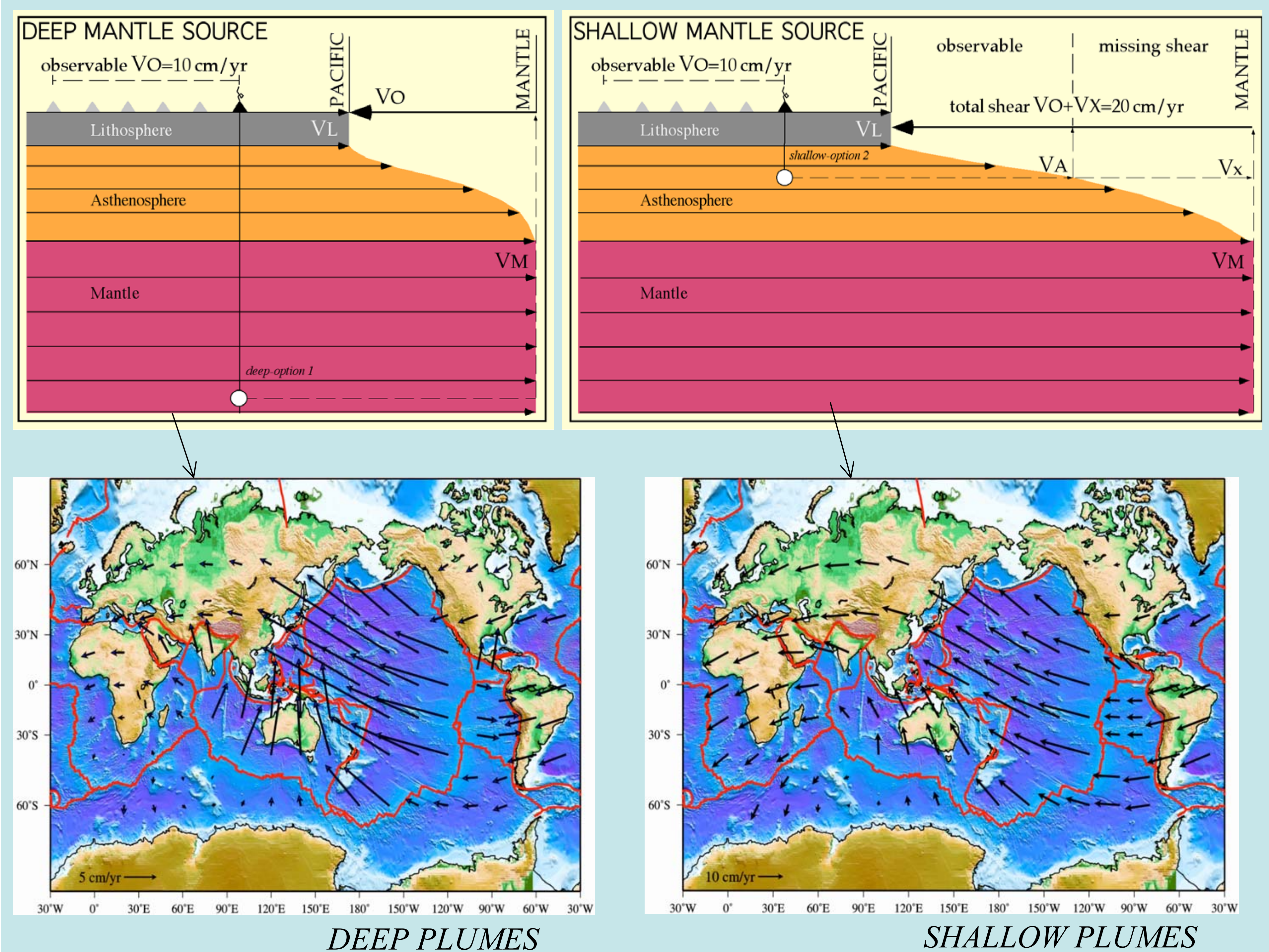
Without "hotspots" located along plate margins & shallow plumes
Westward drift = >100 mm · yr $^{-1}$


WEST
LITHOSPHERE
ASTHENOSPHERE
MESOSPHERE

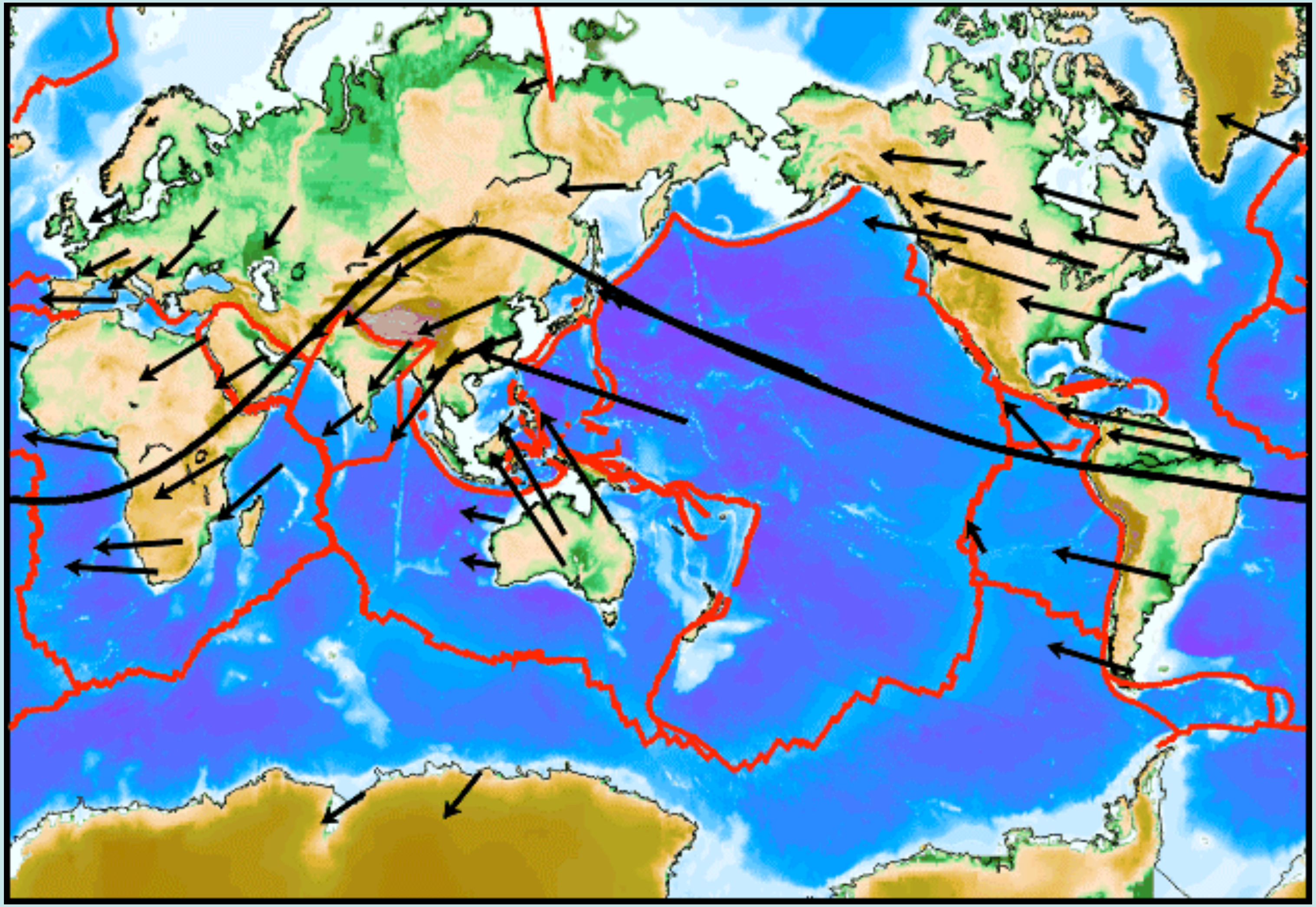

DEEP MANTLE SOURCE
observable VO=10 cm/yr
PACIFIC
VO
MANTLE
Lithosphere
VL
Asthenosphere
VM
Mantle
deep-option 1


SHALLOW MANTLE SOURCE
observable VO=10 cm/yr
PACIFIC
observable
missing shear
MANTLE
total shear VO+VX=20 cm/yr
Lithosphere
VL
shallow-option 2
VA
Vx
Asthenosphere
VM
Mantle


128 mm/yr
68 mm/yr
S-America
Nazca
West
Pacific
EPR
Relative motions
39 mm/yr
103 mm/yr
25 mm/yr
43 mm/yr
option 1- DEEP HOTSPOTS
136 mm/yr
200 mm/yr
72 mm/yr
140 mm/yr
option 2- SHALLOW HOTSPOTS

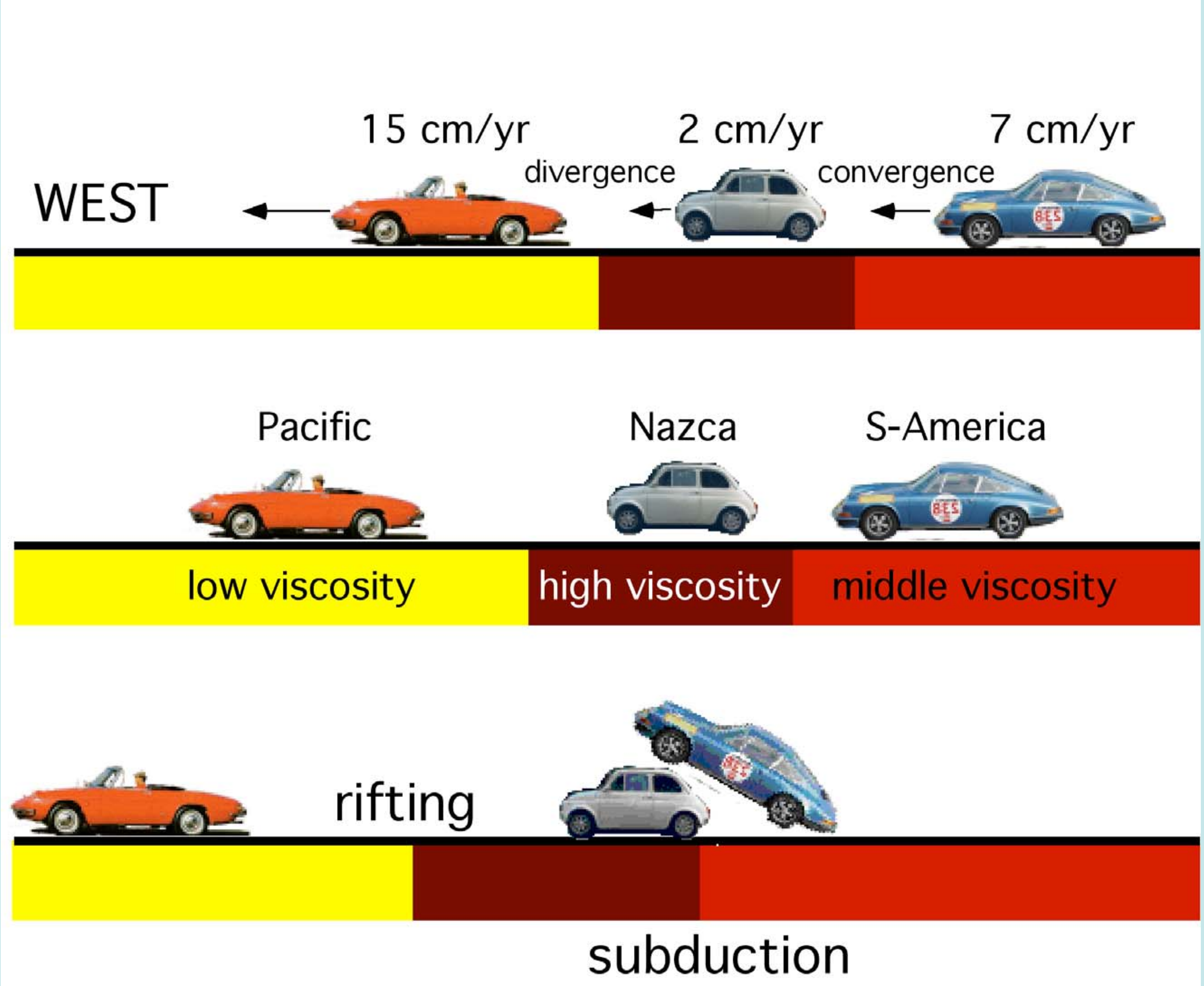

DEEP MANTLE SOURCE
observable VO=10 cm/yr
PACIFIC
VO
MANTLE
Lithosphere
VL
Asthenosphere
VM
Mantle
deep-option 1
SHALLOW MANTLE SOURCE
observable VO=10 cm/yr
PACIFIC
observable
missing shear
MANTLE
total shear VO+VX=20 cm/yr
Lithosphere
VL
shallow-option 2
VA
VX
Asthenosphere
VM
Mantle
60°N
30°N
0°
30°S
60°S
5 cm/yr
30°W 0° 30°E 60°E 90°E 120°E 150°E 180° 150°W 120°W 90°W 60°W 30°W
10 cm/yr
DEEP PLUMES
SHALLOW PLUMES

Tectonic "equator"



The sub-lithospheric mantle should move "E-ward"

Cuffaro, 2006


15 cm/yr
2 cm/yr
7 cm/yr
divergence
convergence
WEST
Pacific
Nazca
S-America
low viscosity
high viscosity
middle viscosity
rifting
subduction

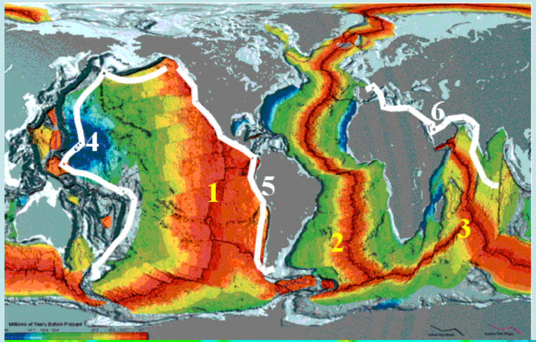
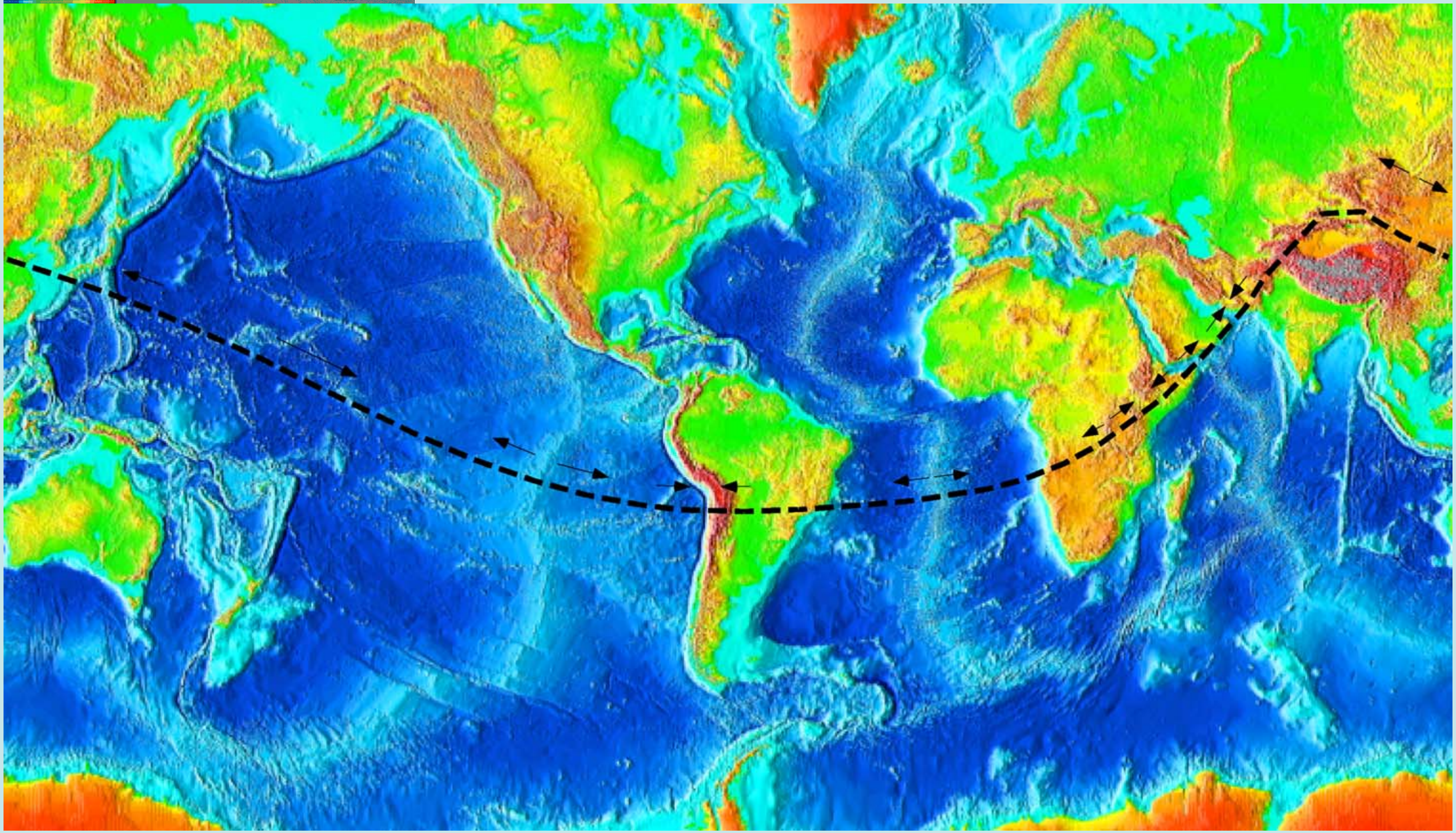


Plate motions are not random during the last 100 Ma, but along a sinusoidal flow: TECTONIC MAINSTREAM



analytical definition of the *tectonic mainstream*

"The line approximating all the Eulerian equators of the crossed plates"

A 3rd order Fourier series in geographic coordinates (φ,λ), may describe the *tectonic mainstream*

after

the estimation of the Eulerian equators of crossed plates

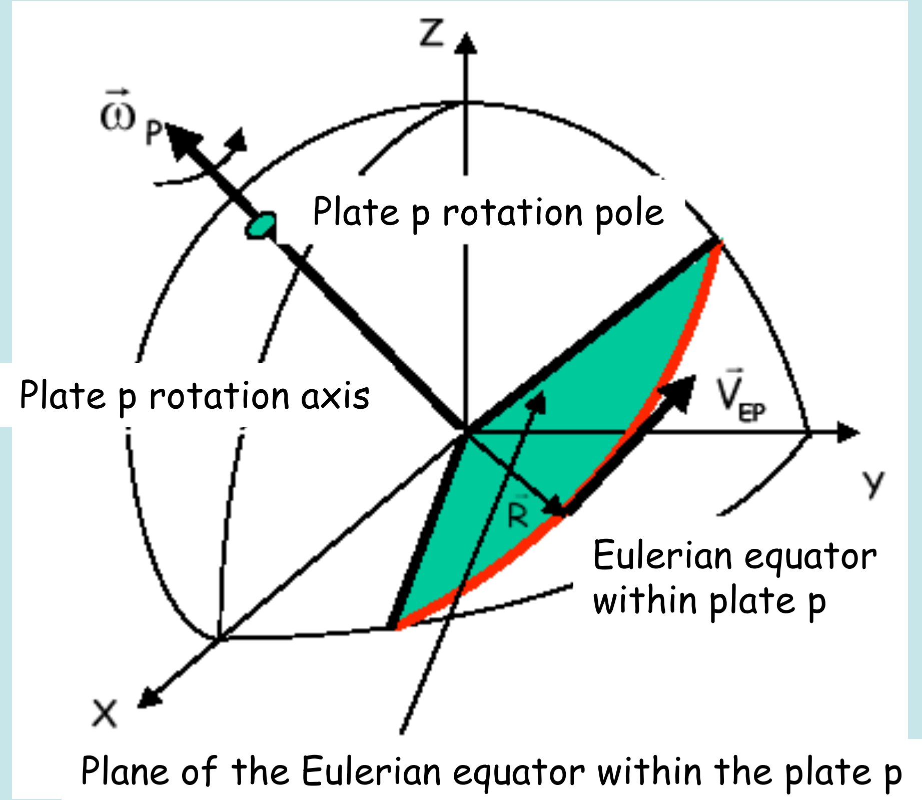
$$\varphi = \frac{a_0}{2} + \sum_{i=1}^{3}\left[a_i \cos(i\lambda) + b_i \sin(i\lambda)\right]$$

analytical representation of the *tectonic mainstream*

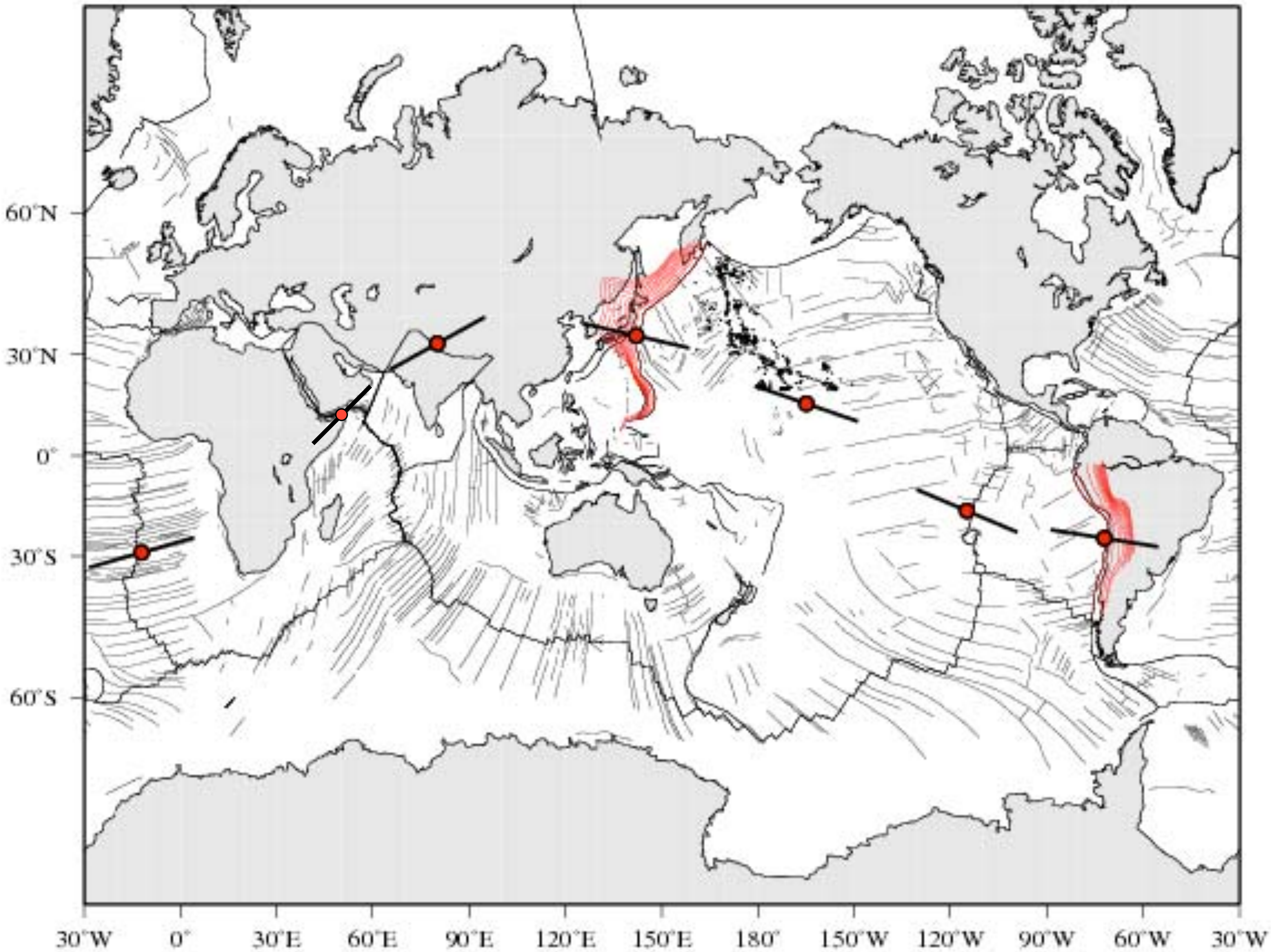
Modeling the "absolute" plate motions

assumptions

- Spherical approximation
- "Absolute" plate motions modeled as 3D rotations (deformations neglected)
- Eulerian equator "image" of the *tectonic mainstream* within each crossed plate



$$\omega_{Xp} \cos\varphi \cos\lambda + \omega_{Yp} \cos\varphi \operatorname{sen}\lambda + \omega_{Zp} \operatorname{sen}\varphi = 0$$


60°N
30°N
0°
30°S
60°S
30°W
0°
30°E
60°E
90°E
120°E
150°E
180°
150°W
120°W
90°W
60°W
30°W

Tectonic mainstream representations

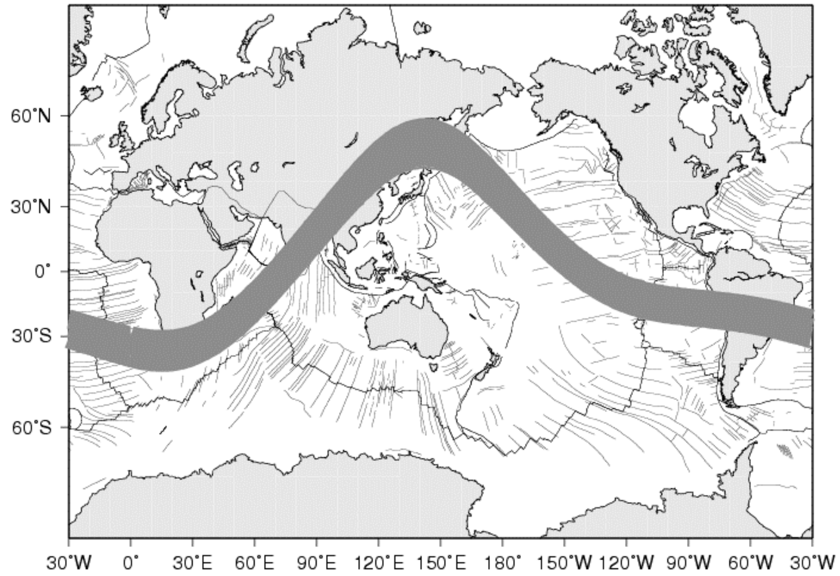
latitude confidence intervals (1 sigma)

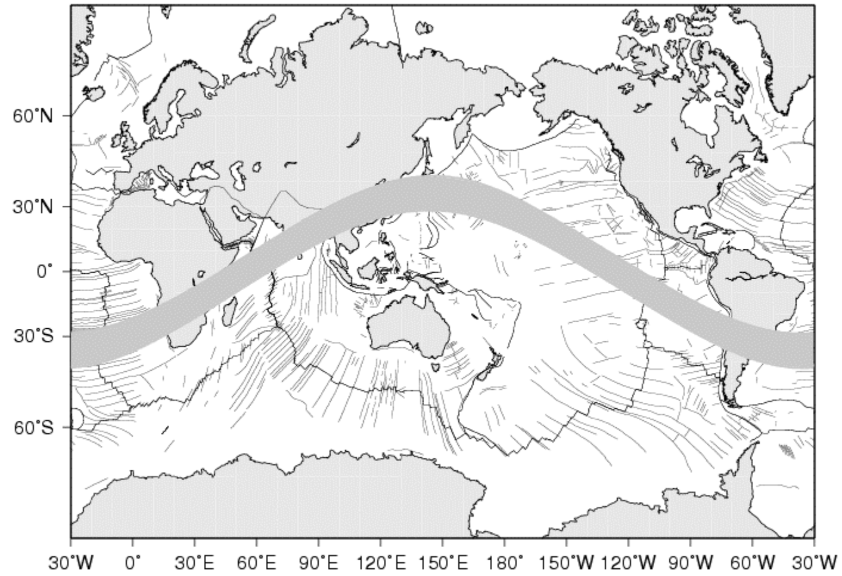
deep mantle

± 7.3°

mid asthenosphere

± 6.8°



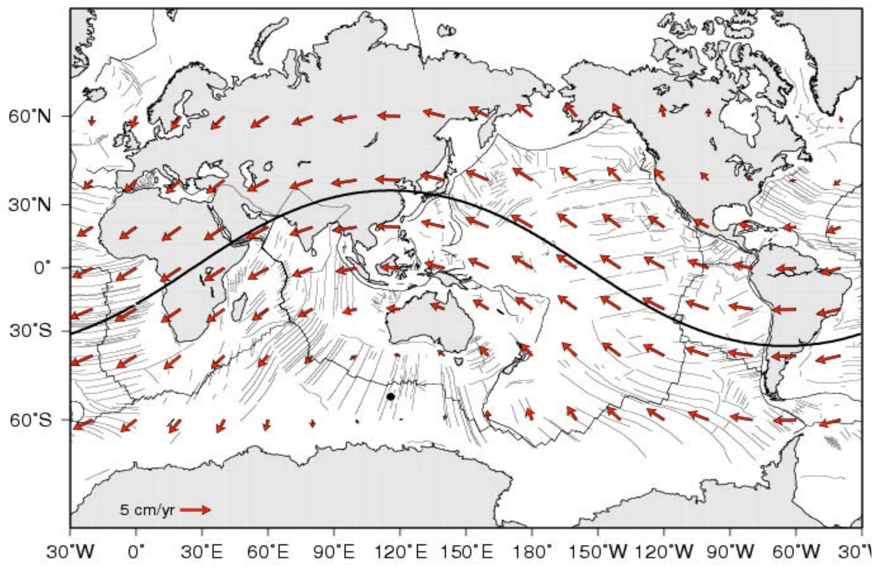


Global lithospheric net rotation

tangential velocities and equators

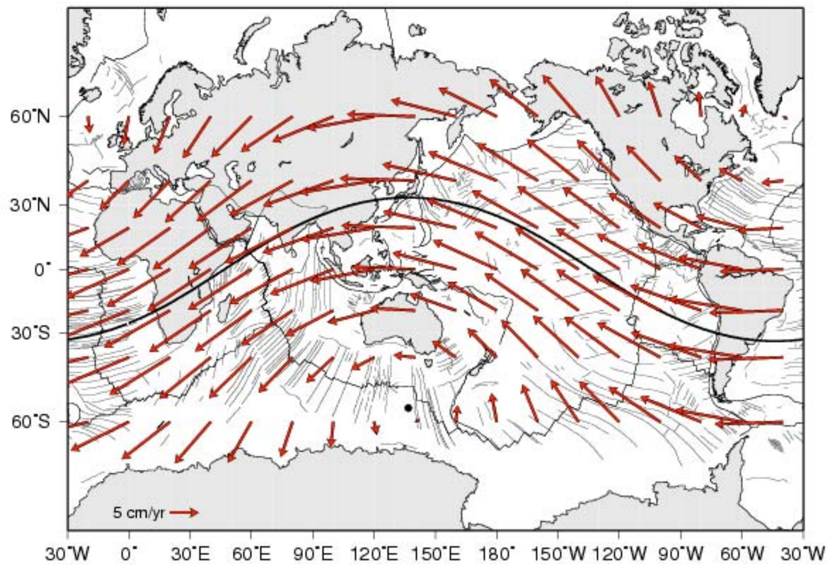
deep mantle

max velocity 4.1 cm/yr



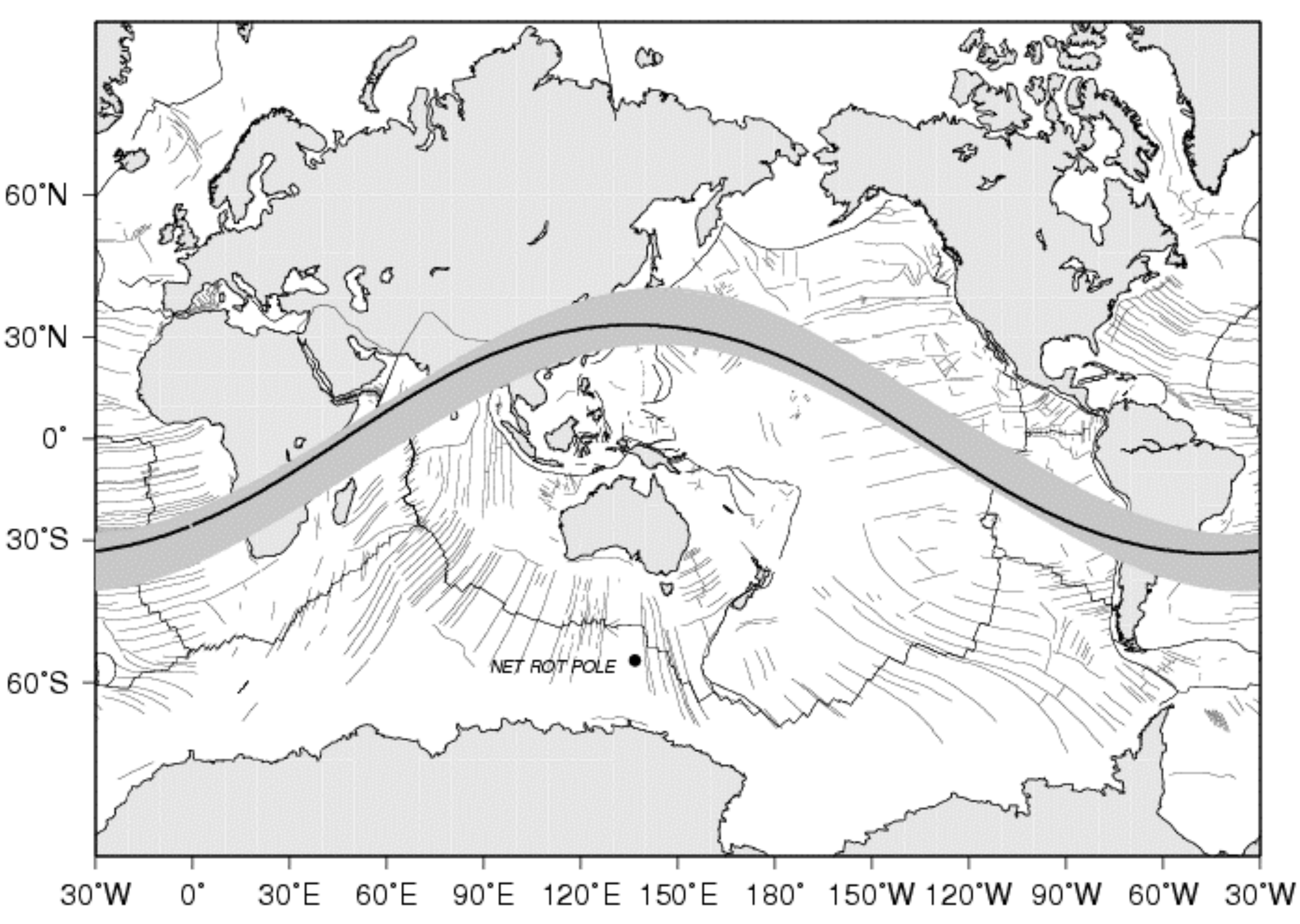
mid asthenosphere

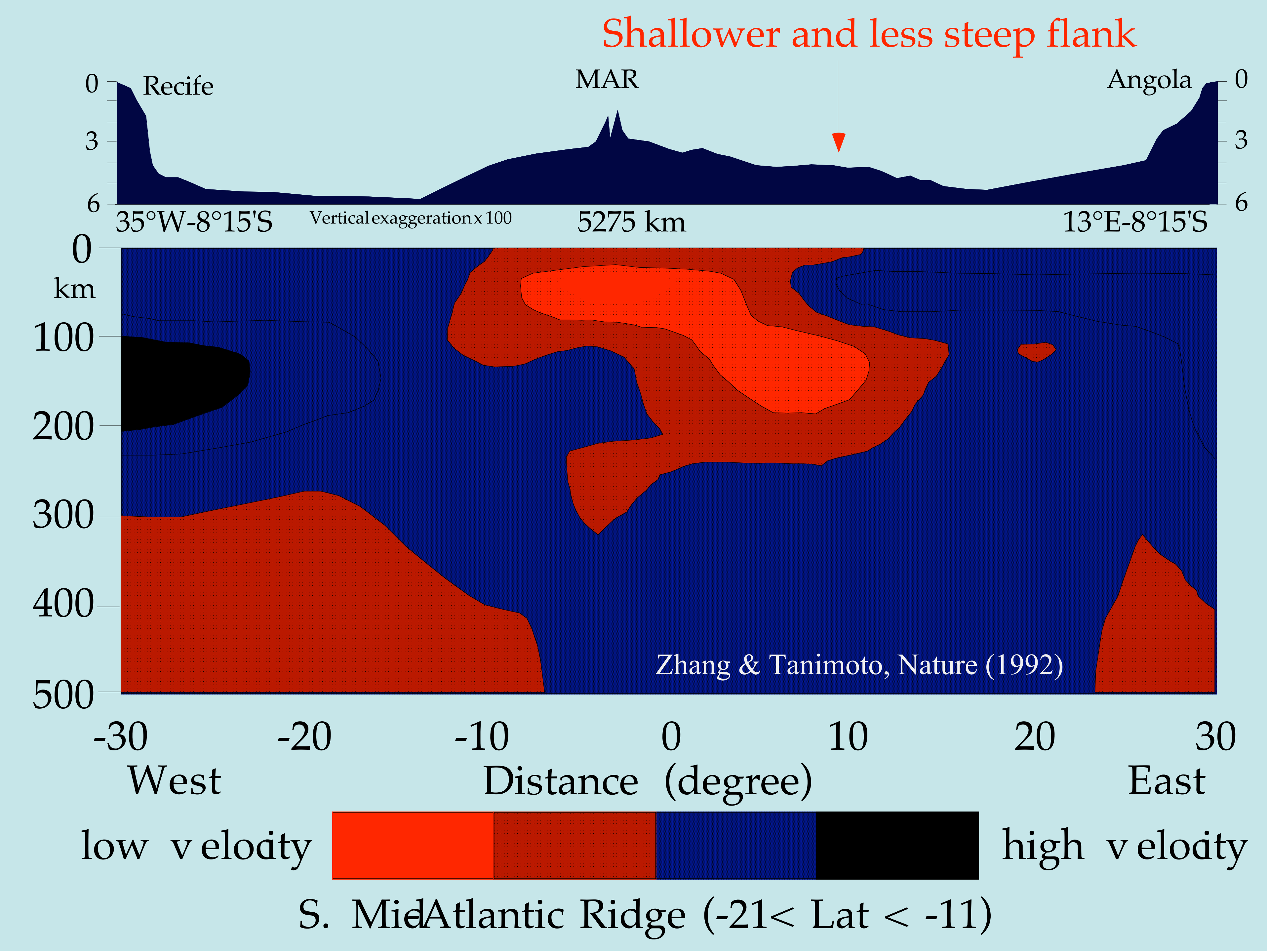
max velocity 13.4 cm/yr



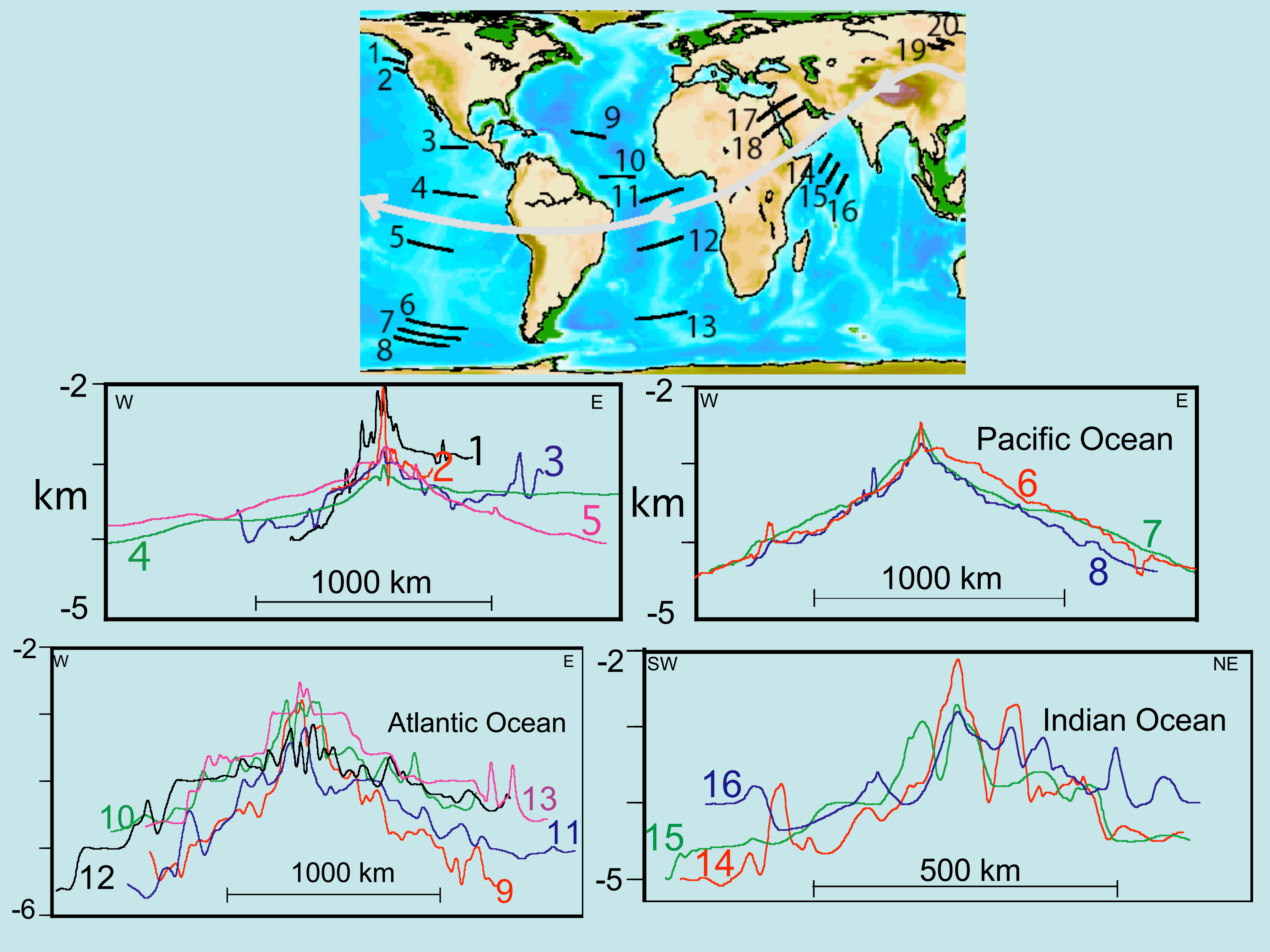
Global lithospheric flow

mid astenosphere net rotation equator lies within the *tectonic mainstream* latitude band



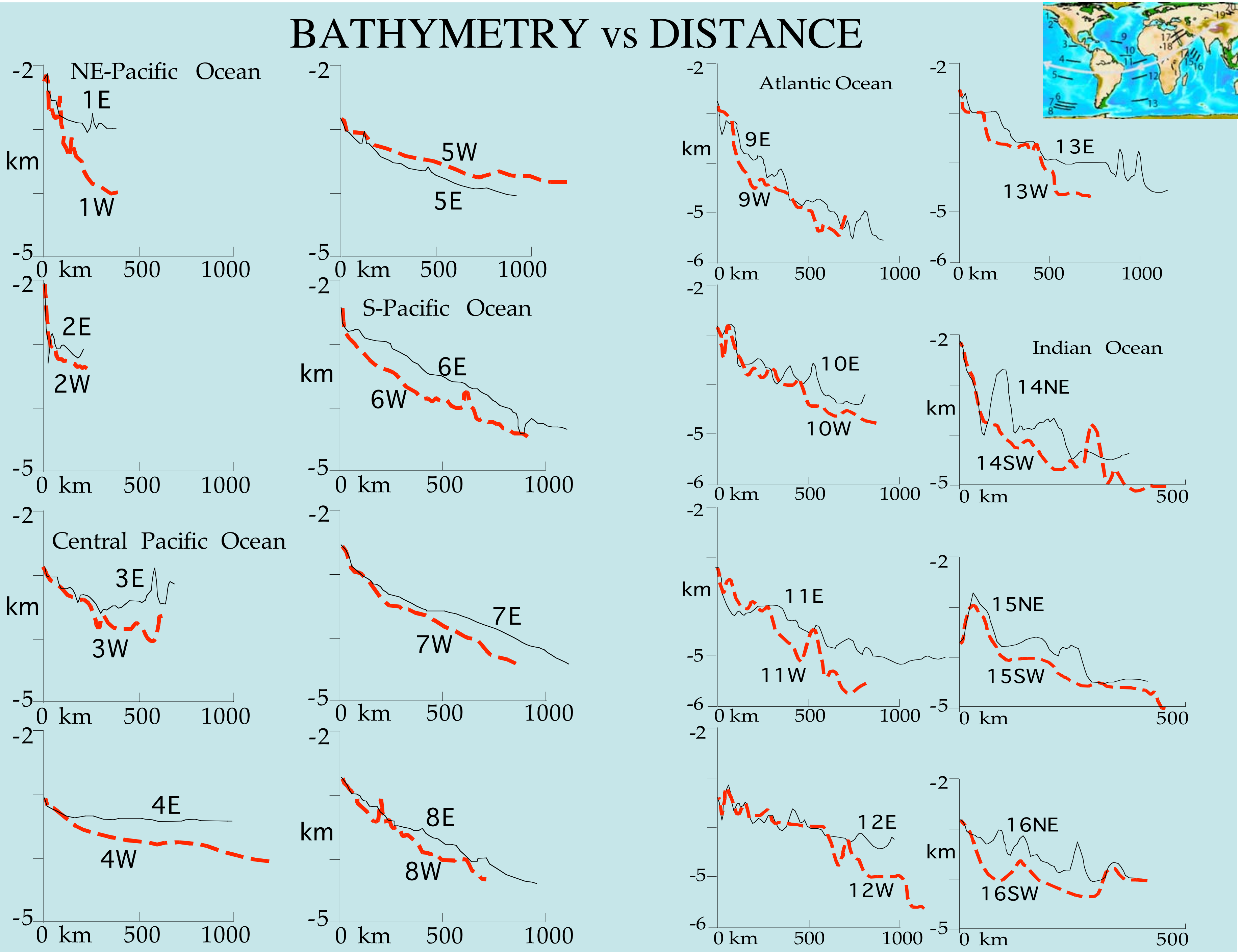


Shallower and less steep flank
Recife
MAR
Angola
0
3
6
35°W-8°15'S
Vertical exaggeration x 100
5275 km
13°E-8°15'S
0
km
100
200
300
400
500
Zhang & Tanimoto, Nature (1992)
-30
-20
-10
0
10
20
30
West
Distance (degree)
East
low velocity
high velocity
S. Mid-Atlantic Ridge (-21< Lat < -11)

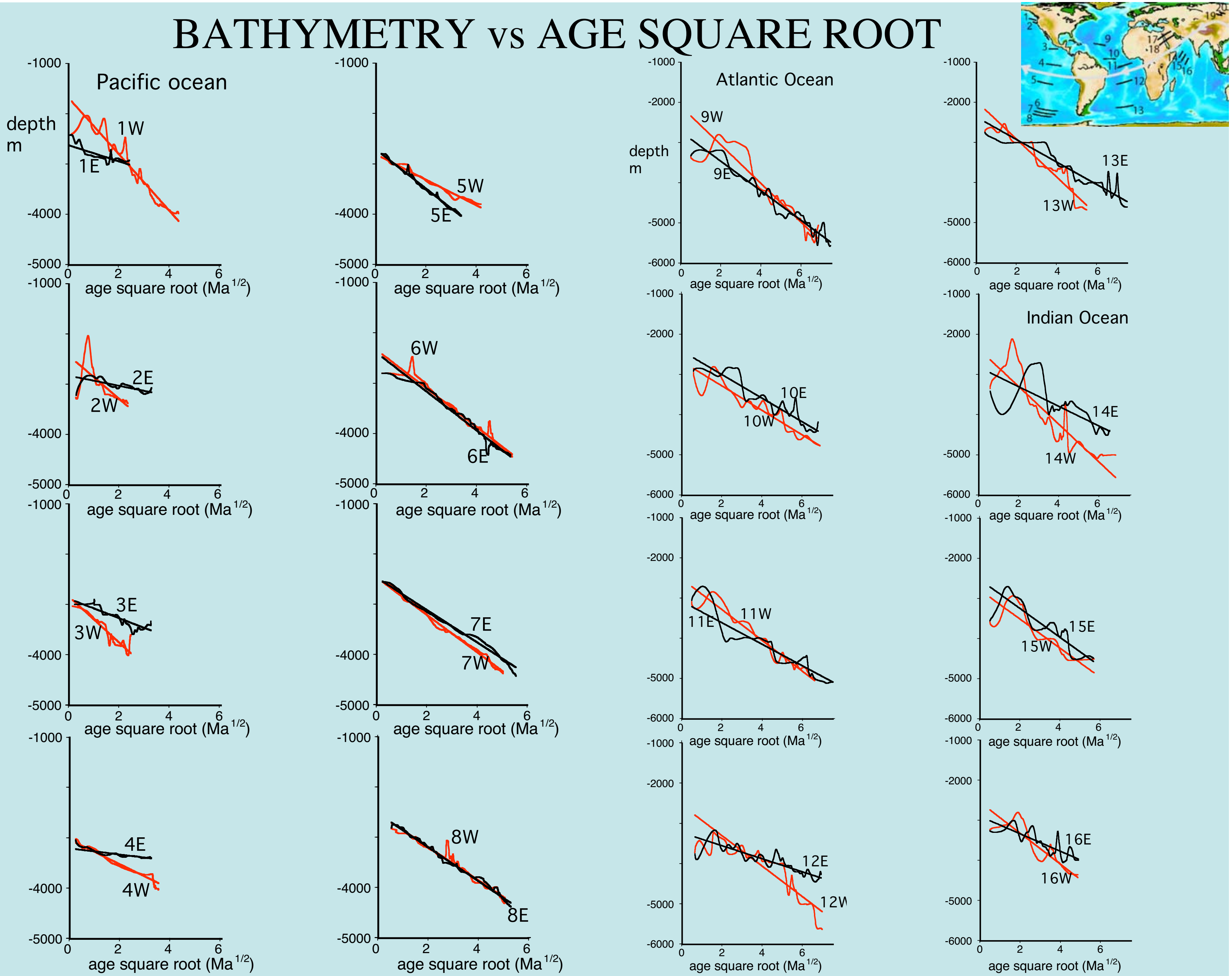


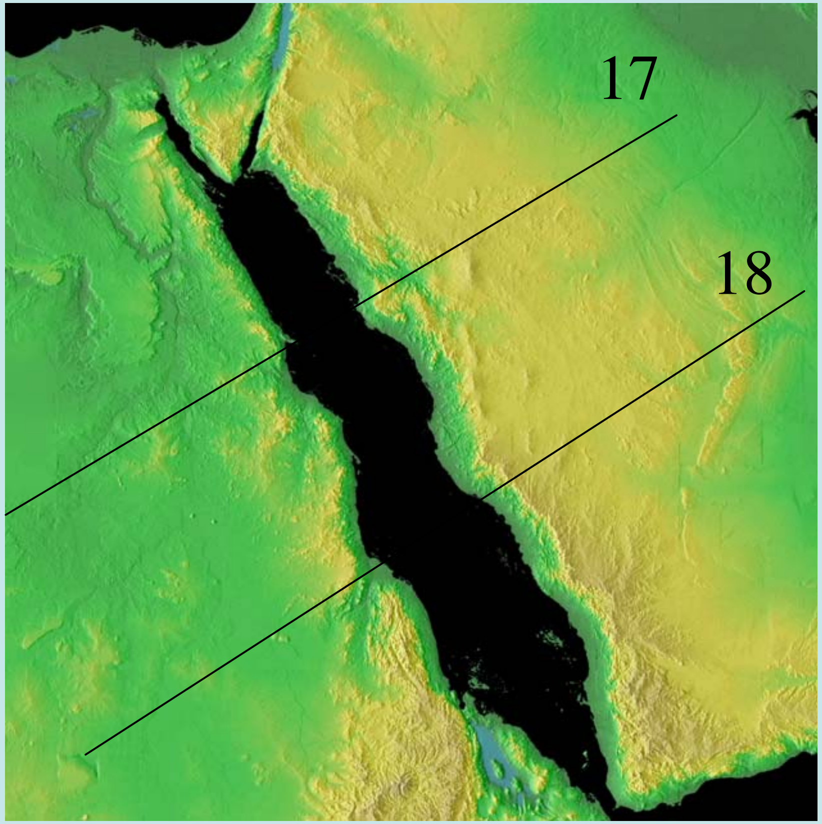
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
-2
km
-5
W
E
1000 km
Pacific Ocean
Atlantic Ocean
-6
Indian Ocean
SW
NE
500 km

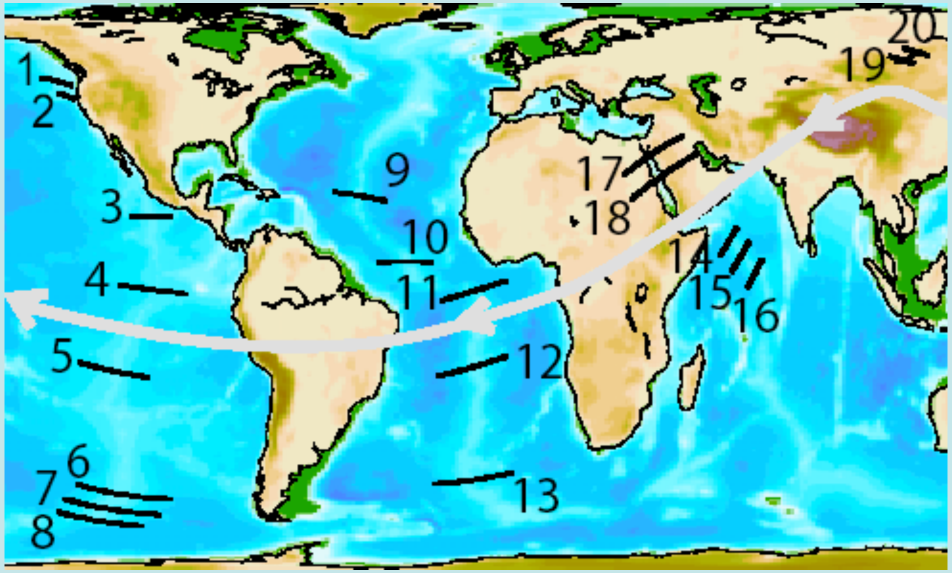
BATHYMETRY vs DISTANCE

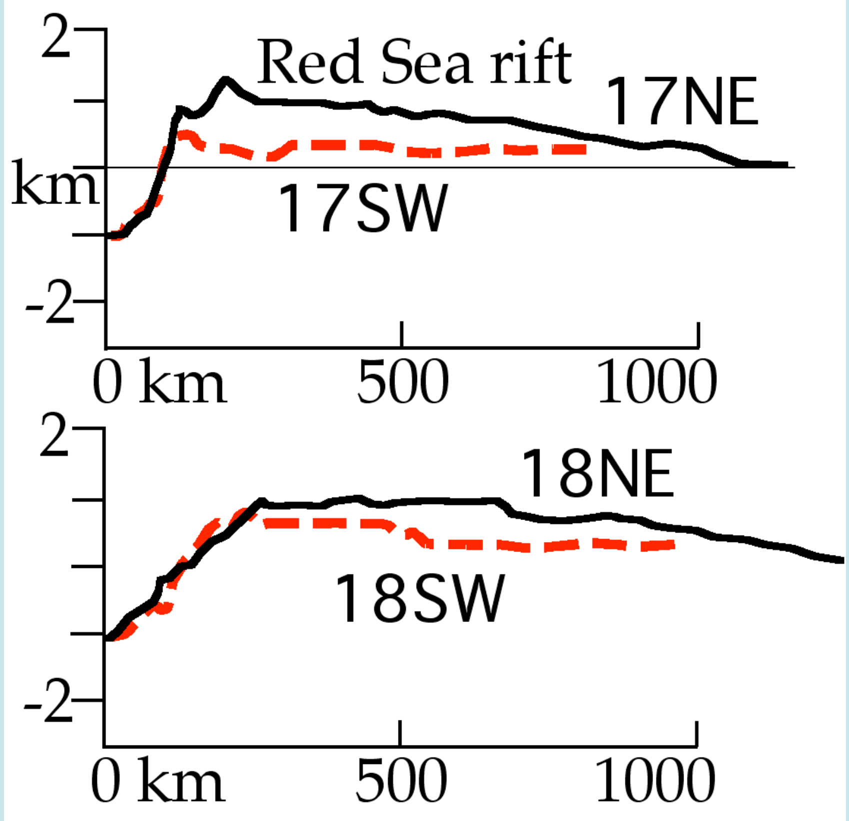


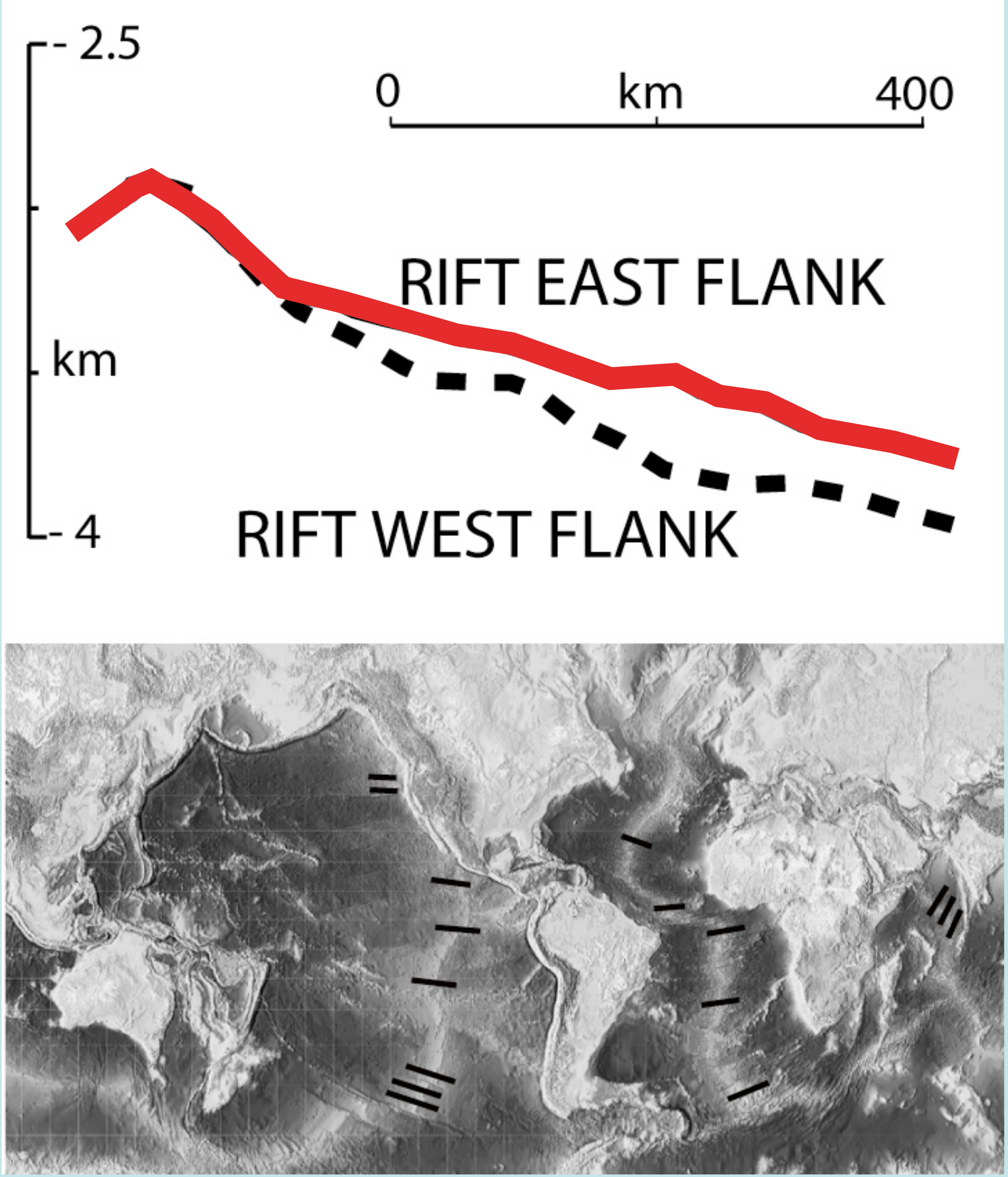
BATHYMETRY vs AGE SQUARE ROOT

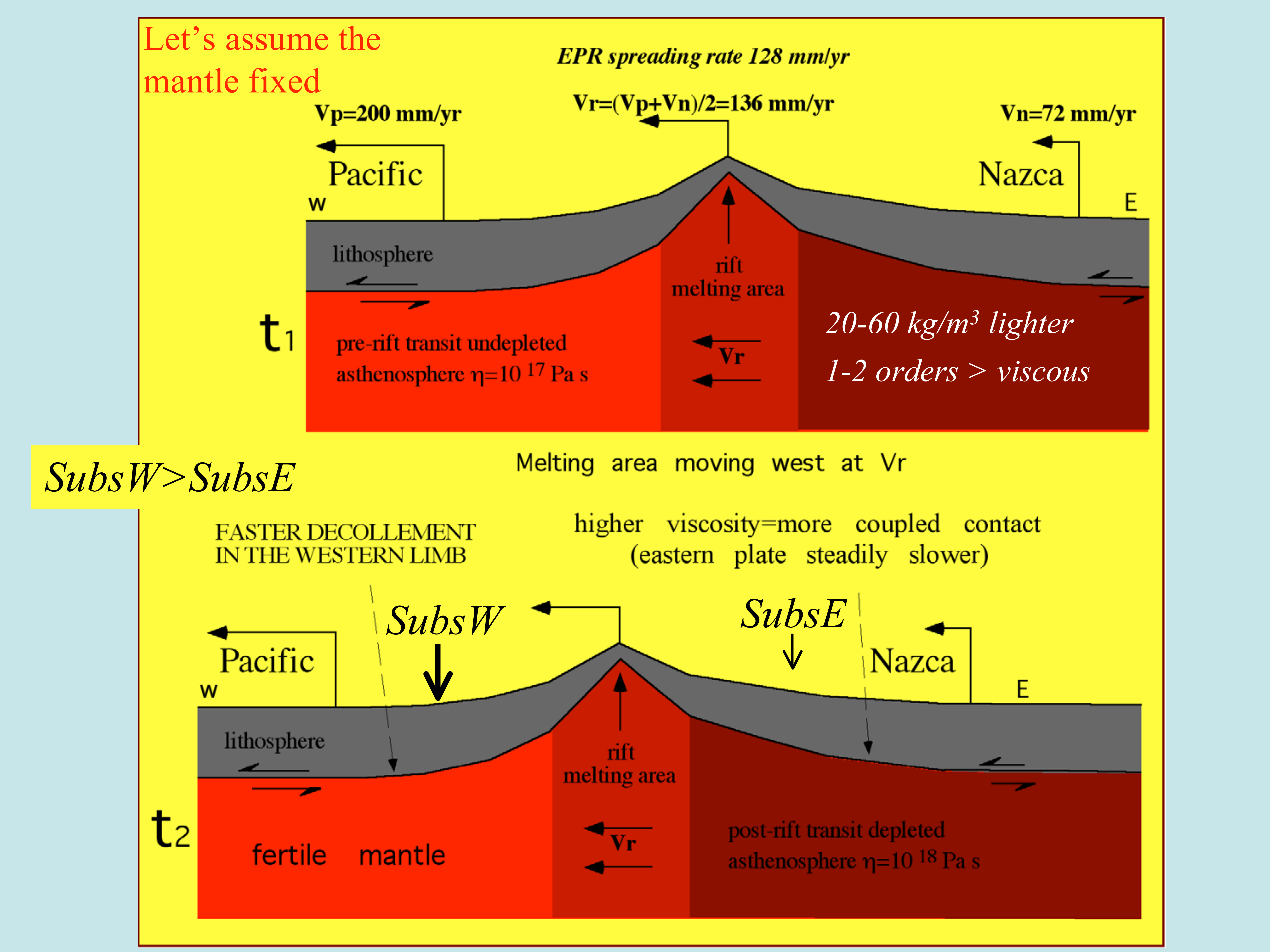


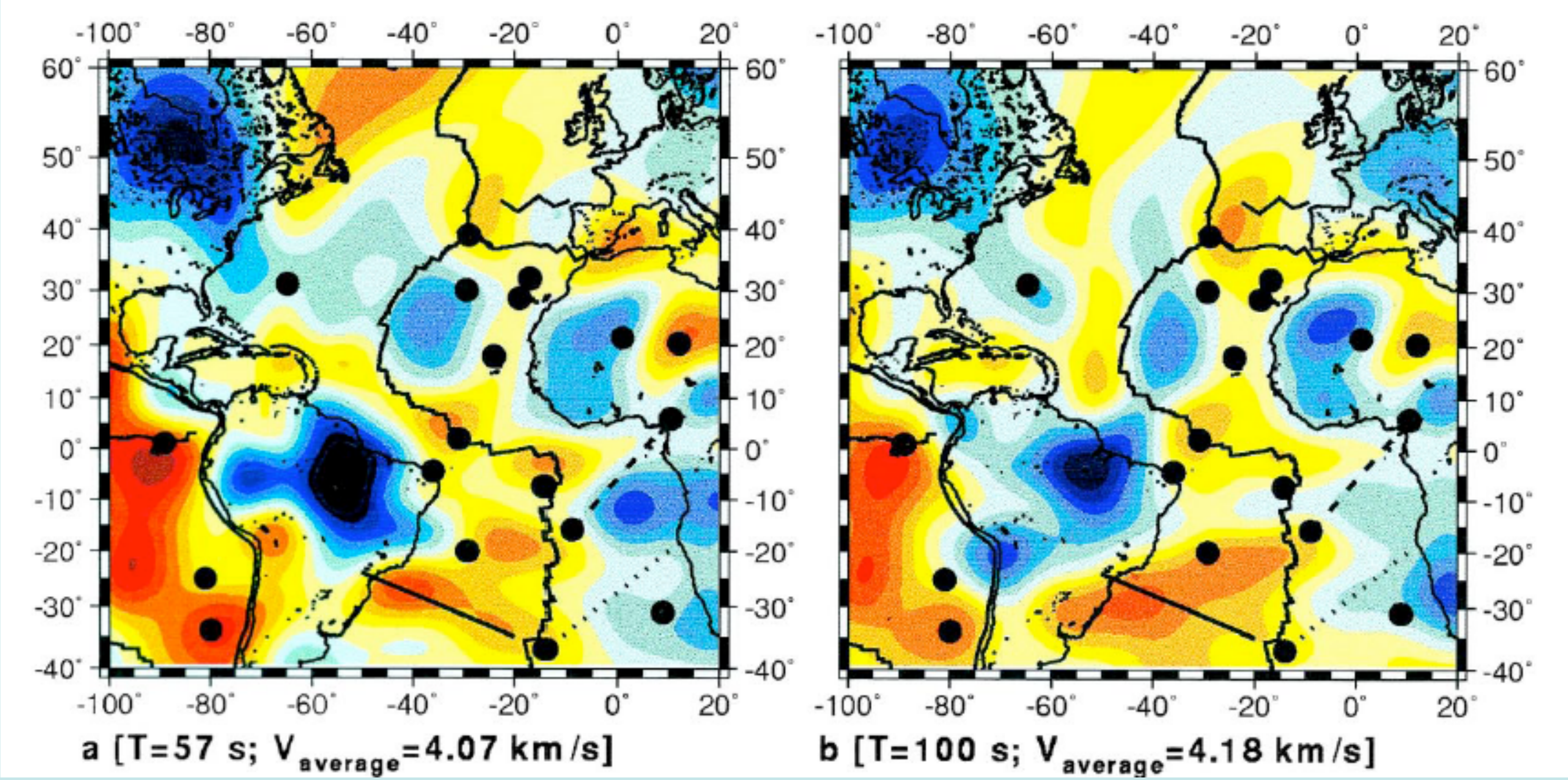

17
18


1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20

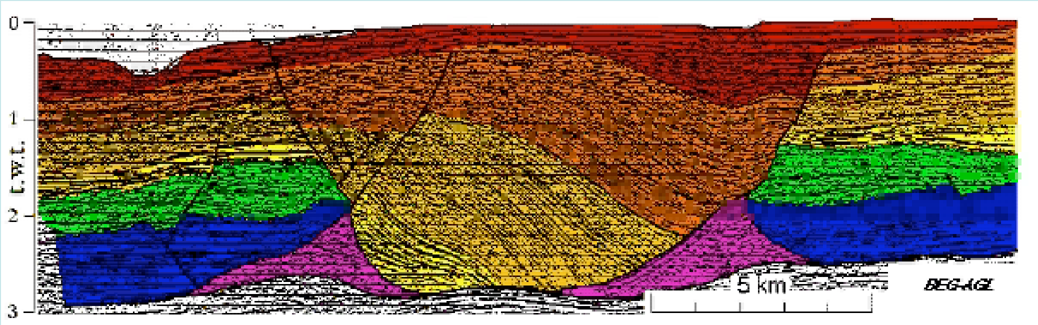

Red Sea rift
17NE
17SW
km
2
-2
0 km
500
1000
18NE
18SW
2
-2
0 km
500
1000


- 2.5
0
km
400
RIFT EAST FLANK
km
- 4
RIFT WEST FLANK


Let's assume the mantle fixed
EPR spreading rate 128 mm/yr
Vp=200 mm/yr
Vr=(Vp+Vn)/2=136 mm/yr
Vn=72 mm/yr
Pacific
Nazca
W
E
lithosphere
rift melting area
t1
pre-rift transit undepleted asthenosphere η=10 17 Pa s
Vr
20-60 kg/m3 lighter
1-2 orders > viscous
SubsW>SubsE
Melting area moving west at Vr
FASTER DECOLLEMENT IN THE WESTERN LIMB
higher viscosity=more coupled contact (eastern plate steadily slower)
SubsW
SubsE
Pacific
Nazca
W
E
lithosphere
rift melting area
t2
fertile mantle
Vr
post-rift transit depleted asthenosphere η=10 18 Pa s

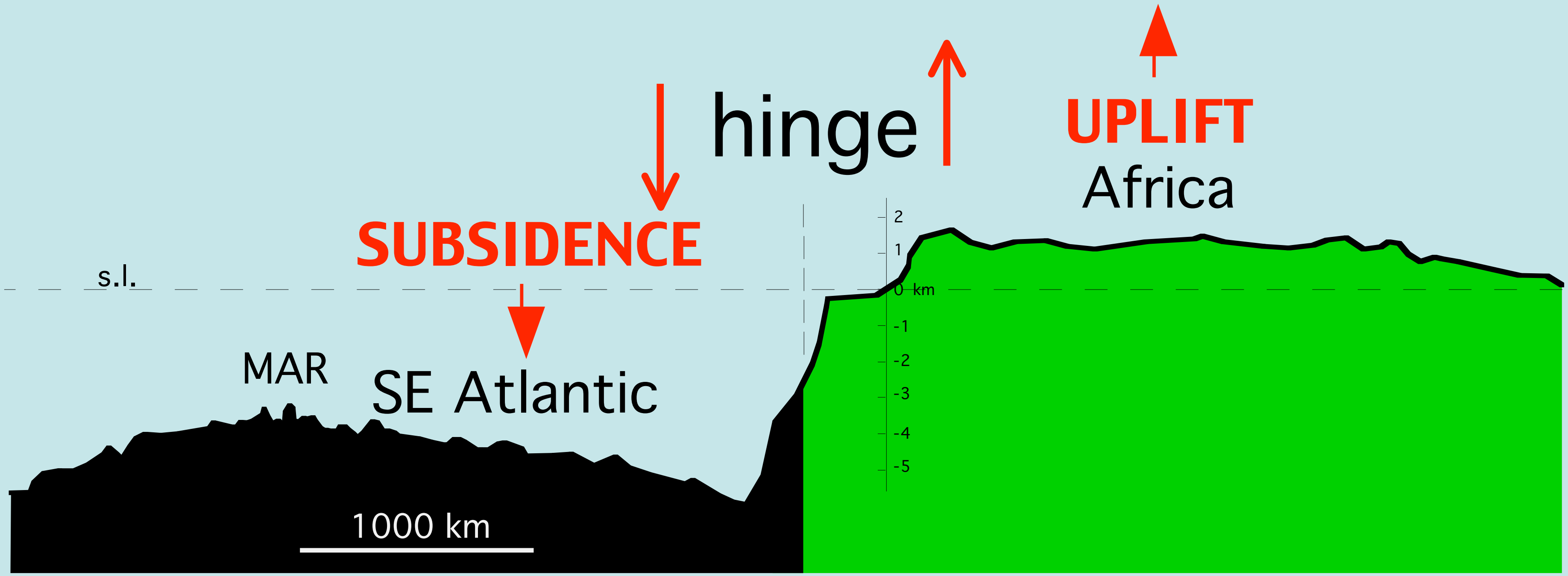


Silveira et al., 1998, PEPI

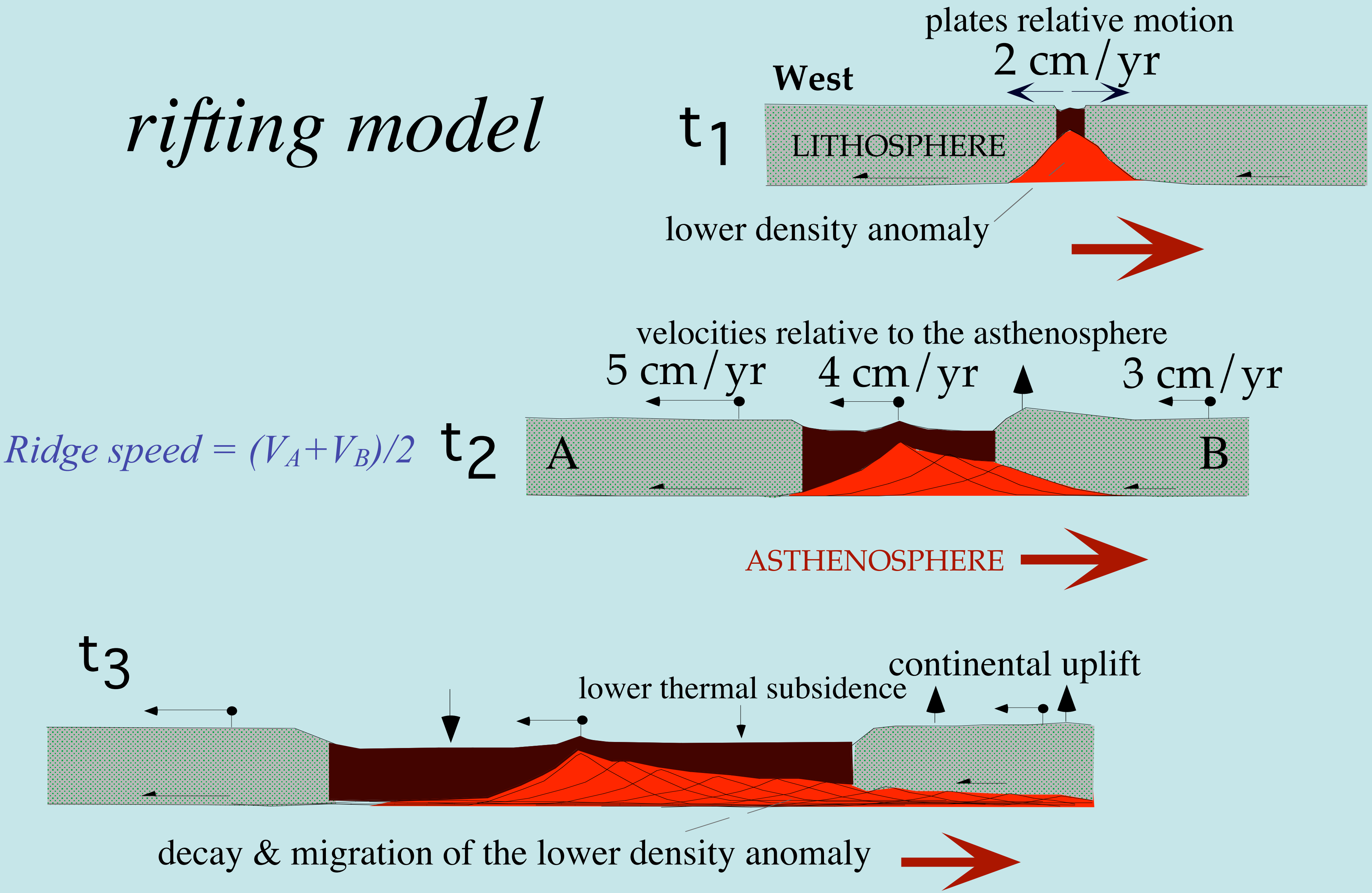


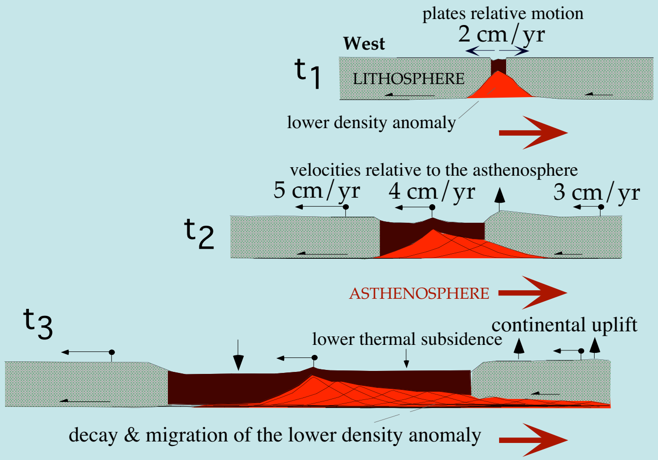
- Different isostatic answer due to lateral variation in composition and temperature of the lithosphere

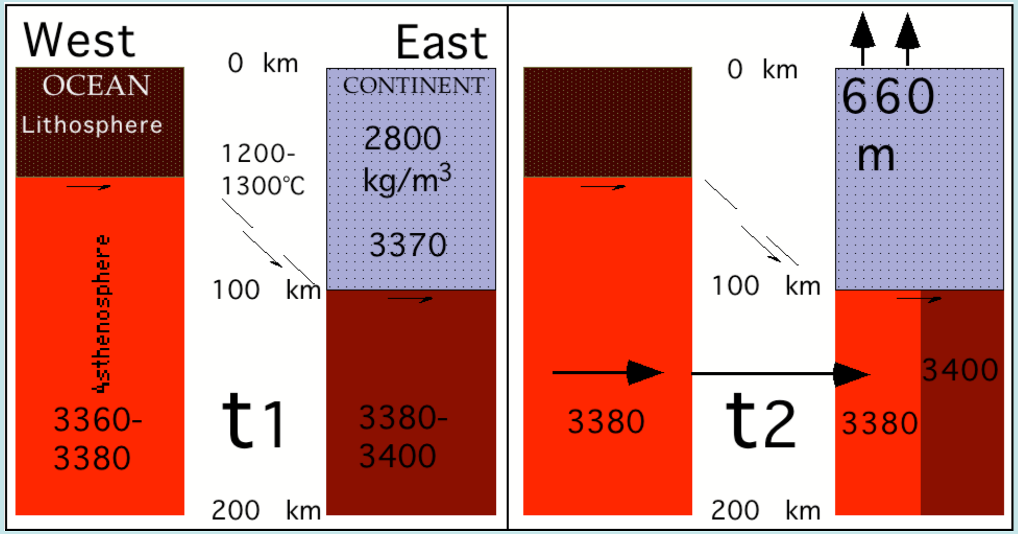
- Coherent system: no independent mantle plume confined underneath the continent

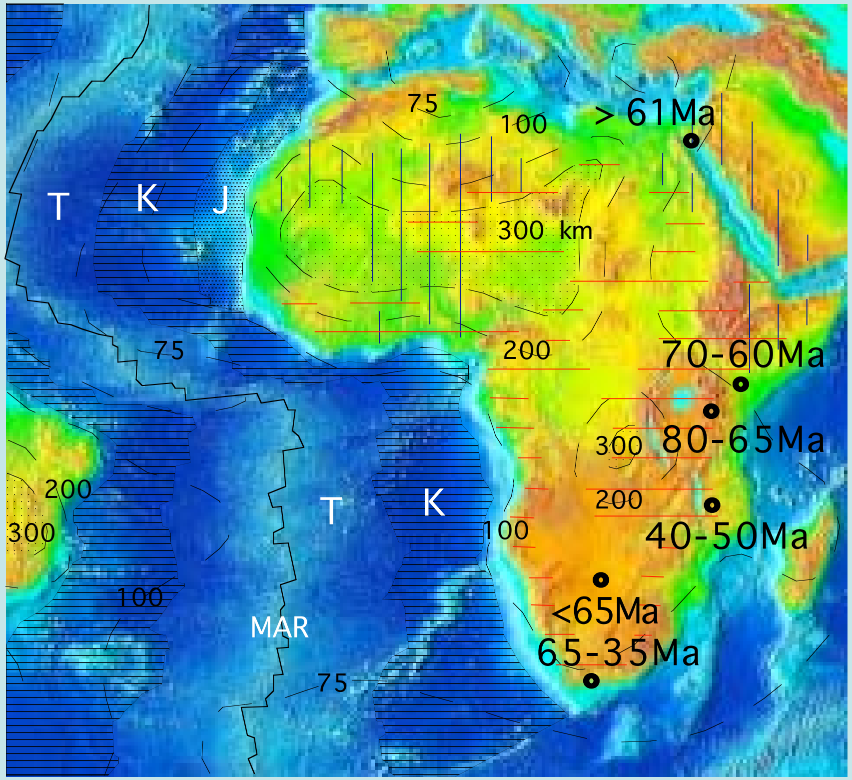


rifting model



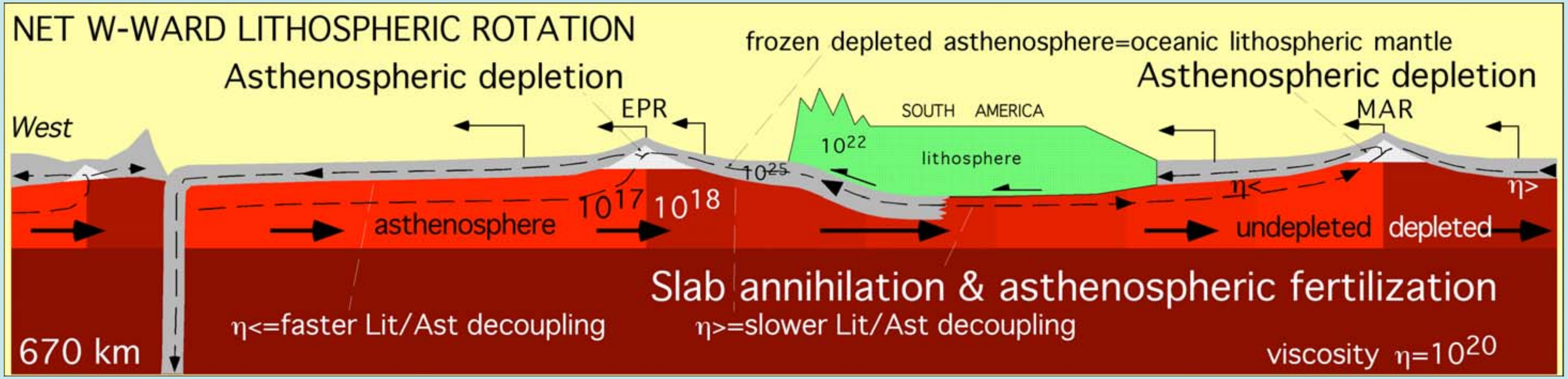

plates relative motion
2 cm/yr
West
t1
LITHOSPHERE
lower density anomaly
velocities relative to the asthenosphere
5 cm/yr
4 cm/yr
3 cm/yr
t2
ASTHENOSPHERE
t3
continental uplift
lower thermal subsidence
decay & migration of the lower density anomaly


West
East
0 km
OCEAN
Lithosphere
CONTINENT
2800
kg/m3
1200-
1300°C
3370
100 km
Asthenosphere
3360-
3380
t1
3380-
3400
200 km
0 km
660
m
100 km
3380
t2
3400
3380
200 km


75
100
> 61Ma
T
K
J
300 km
75
200
70-60Ma
300
80-65Ma
200
300
T
K
200
100
40-50Ma
100
<65Ma
MAR
65-35Ma
75

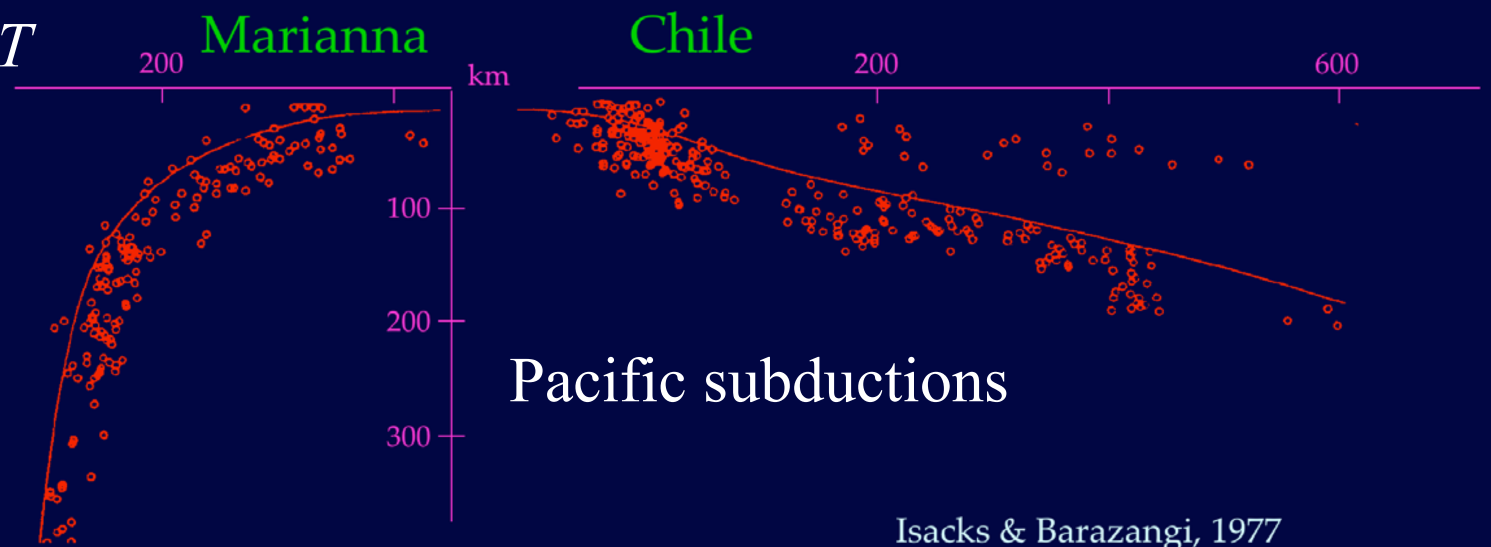
...and Europe?

Geological Map of Western Europe
(Modified after Kirkaldy, 1967)
Quaternary Drift
Tertiary
Cretaceous
Jurassic
Triassic and Permian
Coal Measures
Lower Carboniferous to Cambrian
Crystalline Rocks of Pre-Cambrian and Later age
Tertiary Volcanic Rocks
FAEROES (Igneous)
SHETLANDS
ORKNEYS
HEBRIDES
HIGHLANDS
MIDLAND VALLEY
Southern Uplands
ANTRIM
CENTRAL PLAIN
Carboniferous
CORK
WALES
EAST ANGLIA
LONDON Basin
HANTS Basin
Weald
Jurassic
CORNUBIA
CHANNEL ISLANDS
NORTH SEA
ATLANTIC OCEAN
NORWAY
SWEDEN
GULF OF BOTHNIA
Oslo
Stockholm
GOTTLAND
ESTHONIA
BALTIC SEA
DENMARK
ZUIDER ZEE
HOLLAND
Osnabruck
Hanover
NORTH GERMAN PLAIN
RUHR
HARZ
BELGIUM
RHENISH SCHIEFER-GEBIRGE
HESSE
ARDENNES
BOHEMIAN MASSIF
CARPATHIANS
BRITTANY
PARIS BASIN
Cretac. & Tertiary
VOSGES
RHINE VALLEY
BLACK FOREST
FRANCONIAN JURA
MOLASSE BASIN
EASTERN ALPS
HUNGARY
BAY OF BISCAY
AQUITAINE BASIN
MASSIF CENTRAL
CAUSSE
RHONE VALLEY
JURA Mountains
WESTERN ALPS
CANTABRIAN MTS
PYRENEES
MESETA
APENNINES
ADRIATIC
DINARIC ALPS
GREECE
CORSICA
SARDINIA
BALEARICS
SICILY
MEDITERRANEAN SEA
Ian West, 2001



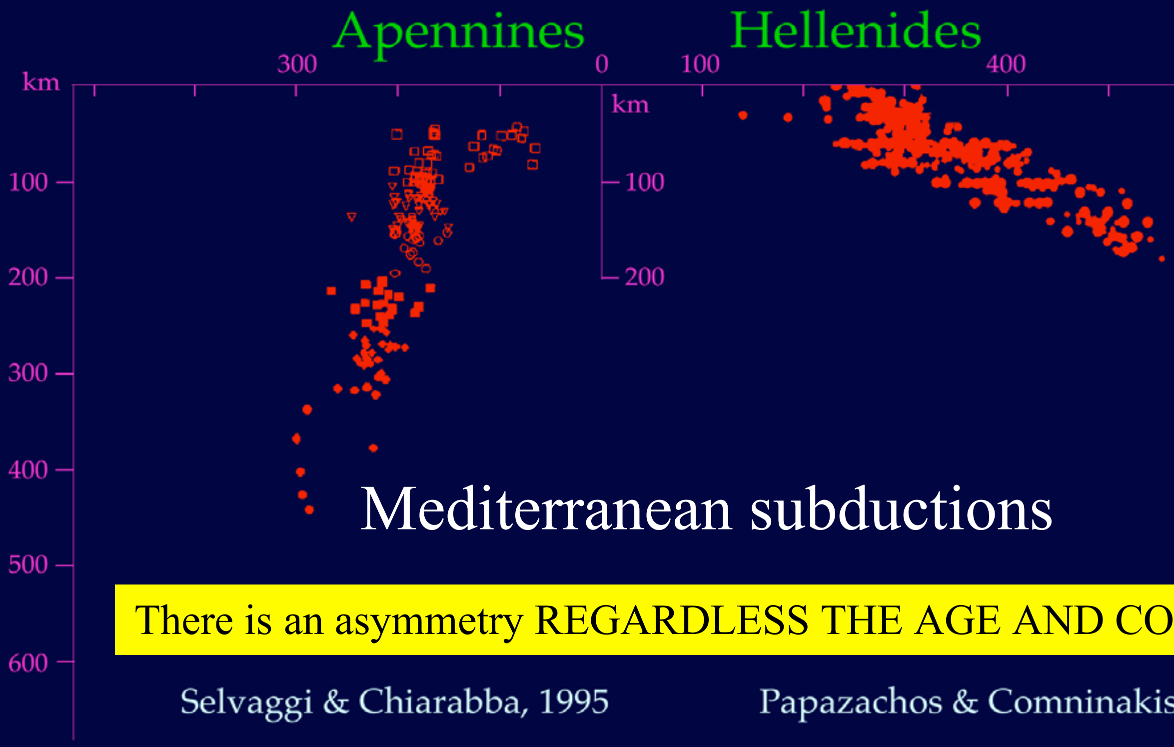
NET W-WARD LITHOSPHERIC ROTATION
frozen depleted asthenosphere=oceanic lithospheric mantle
Asthenospheric depletion
Asthenospheric depletion
EPR
MAR
West
SOUTH AMERICA
10^22
lithosphere
10^25
10^17
10^18
η<
η>
asthenosphere
undepleted
depleted
Slab annihilation & asthenospheric fertilization
η<=faster Lit/Ast decoupling
η>=slower Lit/Ast decoupling
670 km
viscosity η=10^20

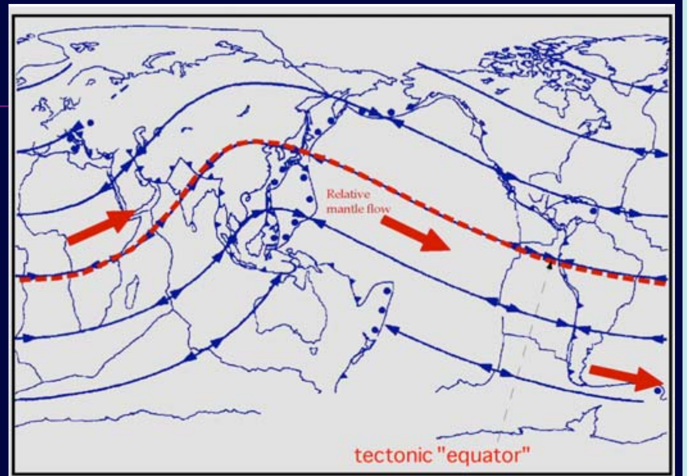
WEST



Pacific subductions

Isacks & Barazangi, 1977

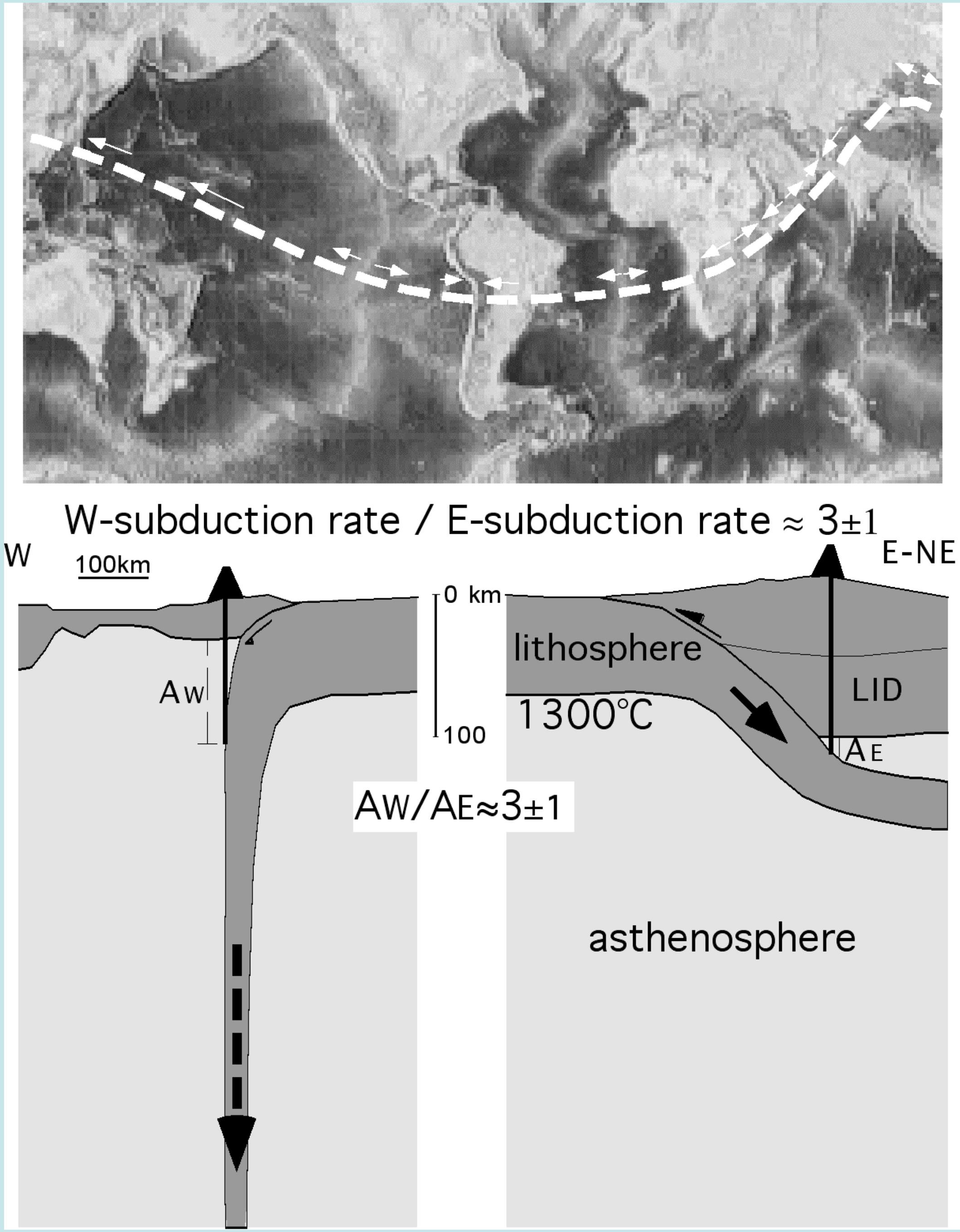




Mediterranean subductions

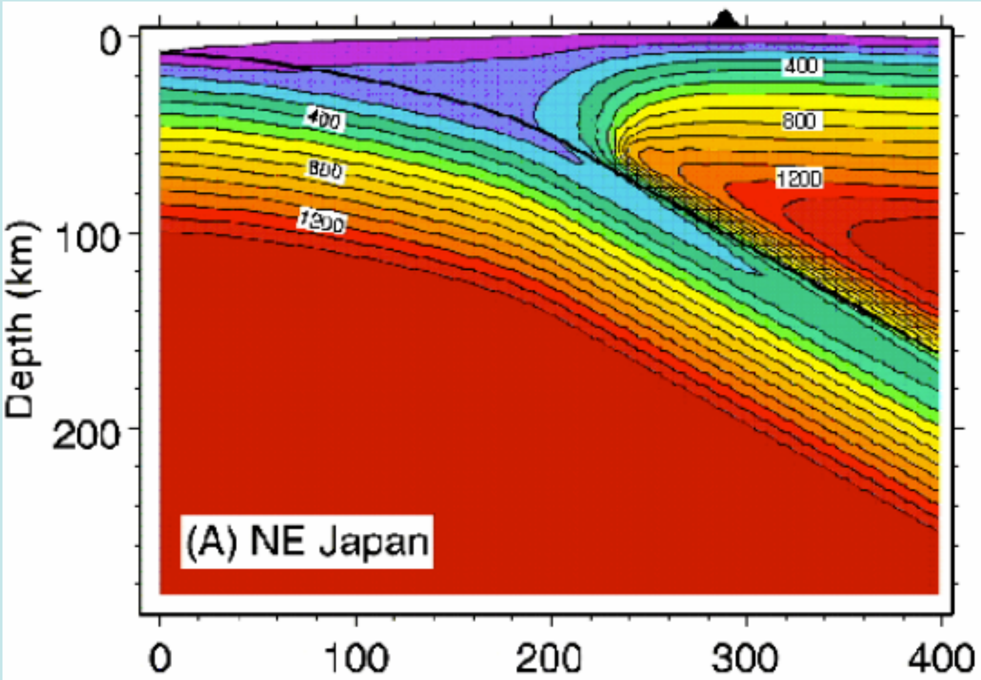
There is an asymmetry REGARDLESS THE AGE AND COMPOSITION of the lithosphere

Selvaggi & Chiarabba, 1995   Papazachos & Comninakis, 1977

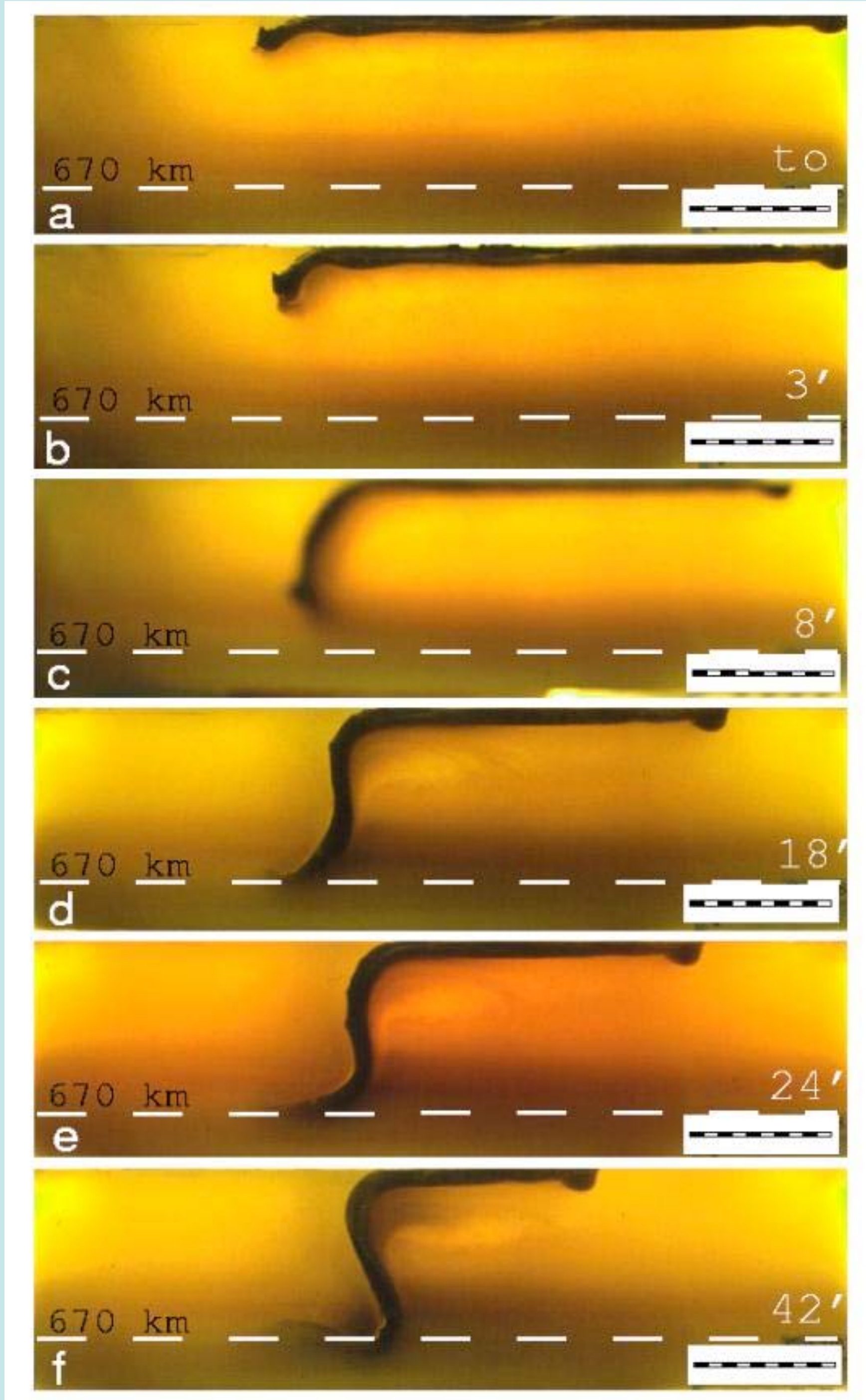

W-subduction rate / E-subduction rate ≈ 3±1
W
100km
0 km
100
E-NE
lithosphere
1300°C
LID
AE
AW
AW/AE≈3±1
asthenosphere

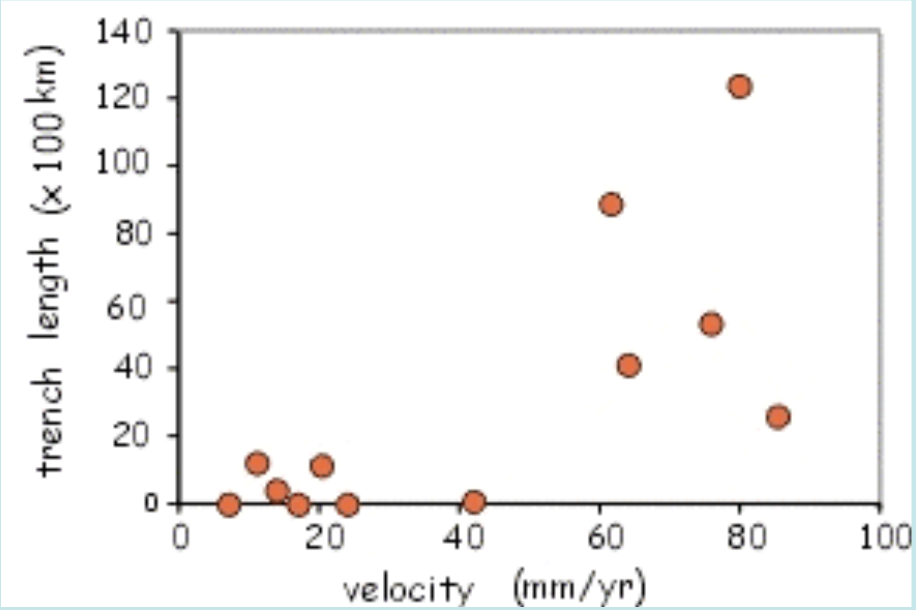
WHERE IS THE SLAB PULL?

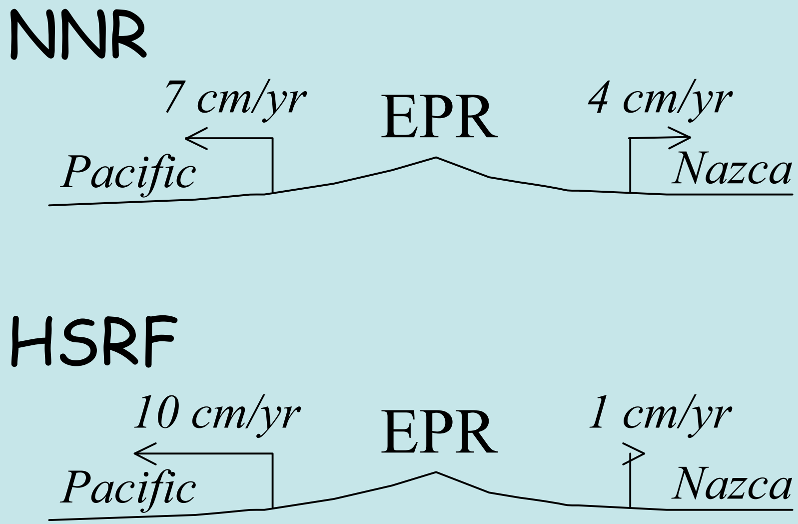
Is the slab a priori heavier, or it becomes denser due to phase transitions induced by the drag of the mantle?



$$\text{Slab pull} = 10^{13}\ \text{N m}^{-1}$$







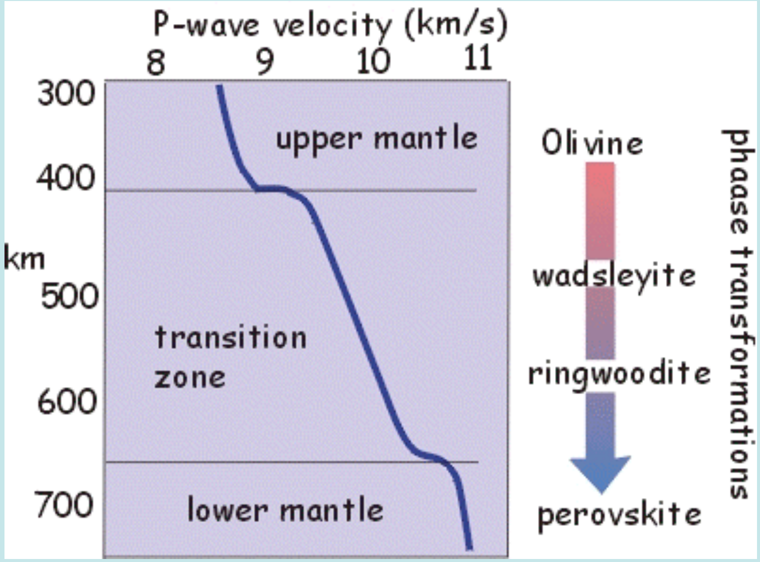
The observations that plates with large slabs are faster (e.g. Forsyth & Uyeda, 1975) is a circular reasoning:

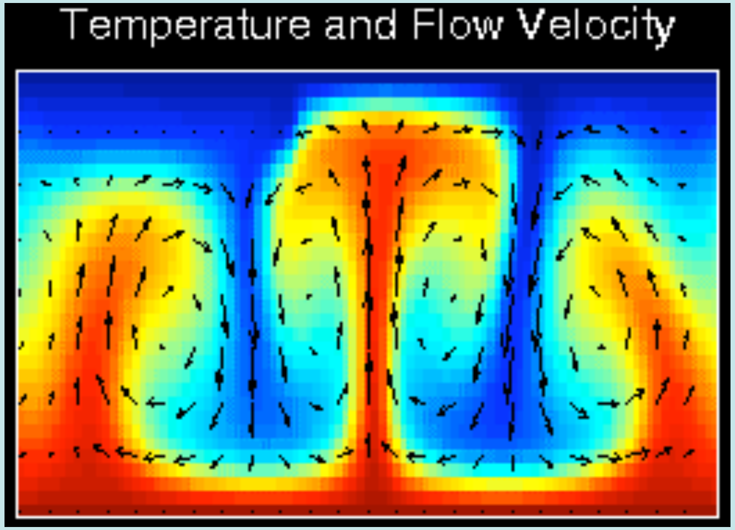
1) they could have longer subduction zones because they are faster, not necessarily vice-versa;

2) but are they faster relative to what?

3) Nazca has fast convergence rates in a not net rotation frame, which is an artifact, but it is much slower relative to the mantle

Assumptions:
Comments



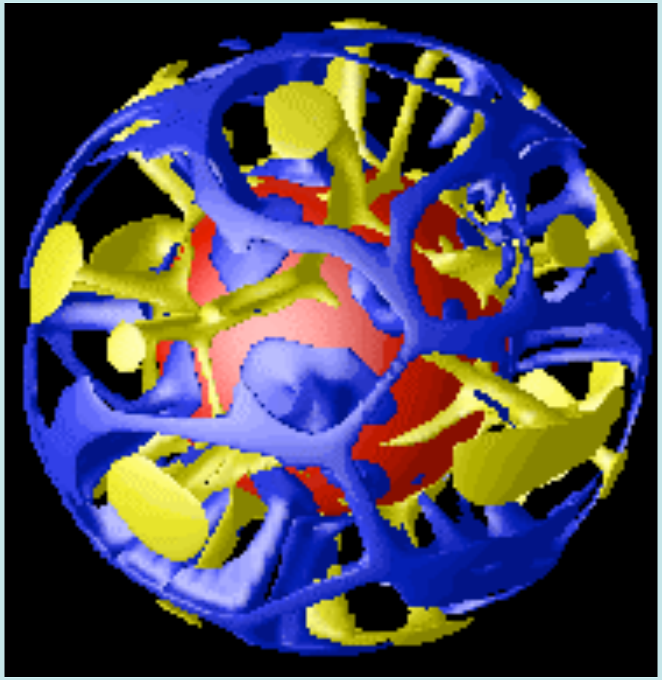


The Mantle is compositionally homogeneous:
Very unlikely, all Earth is intensely stratified by density from the topmost atmosphere down to the core;
If the mantle was homogeneous and movements are only driven by thermal contrast, why the LID does not detach in the middle of a plate?

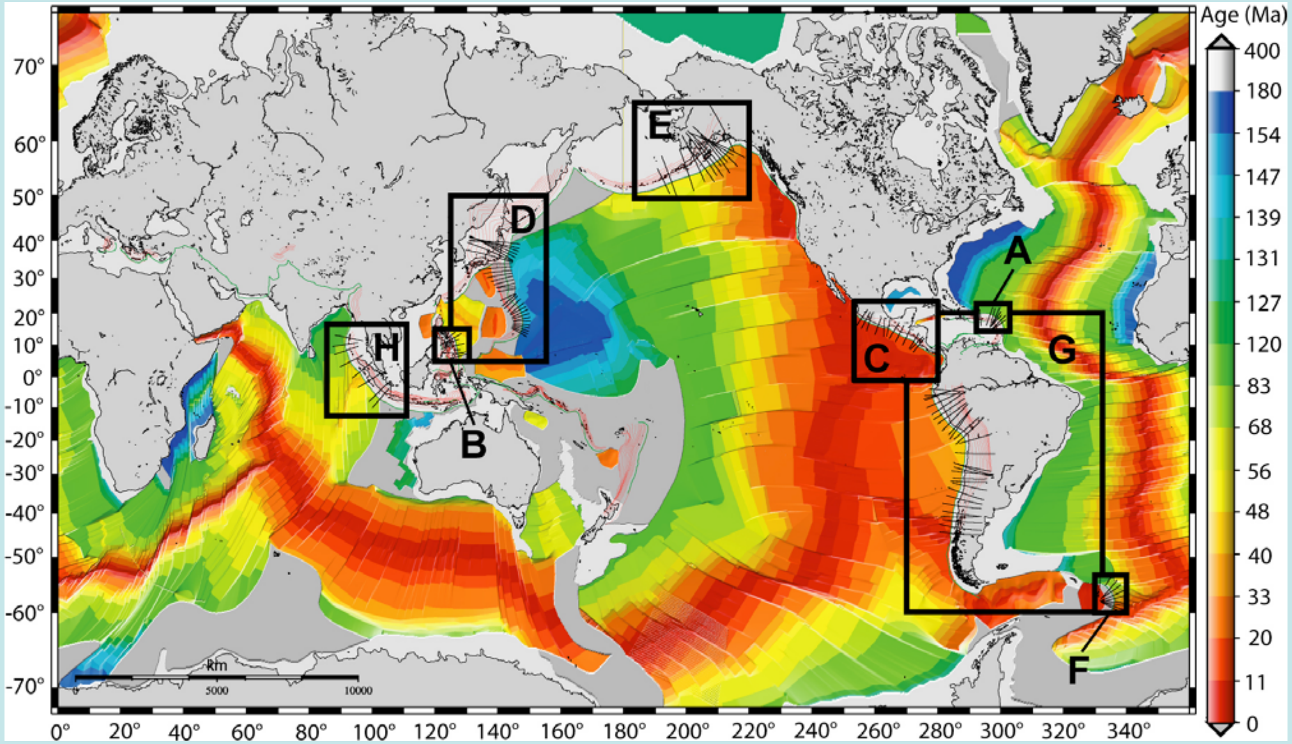
Uprising mantle is laterally accompanied by down-welling:
Atlantic, E-Africa and Indian rifts have not intervening subductions; there are also several cases of paired subduction zones without rifts in between

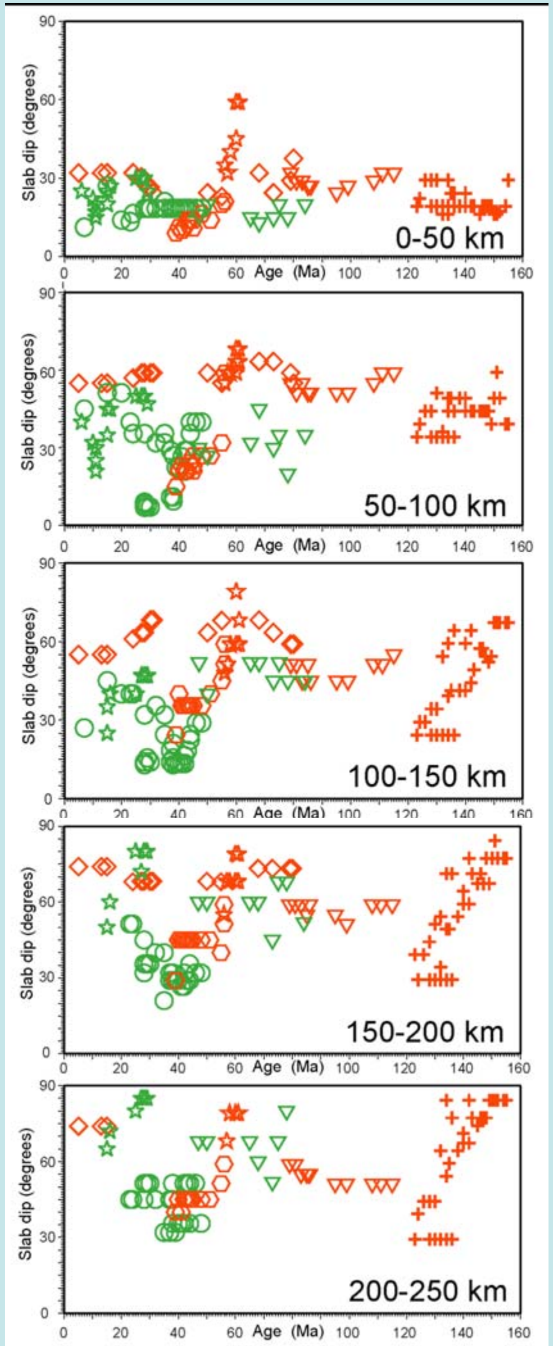
Uprising and down-welling mantle currents are stationary:
Plate margins rather move

Poligonal shapes of cells:
Plate margins can be very linear e.g., the Atlantic ridge



Tackley et al., 2003

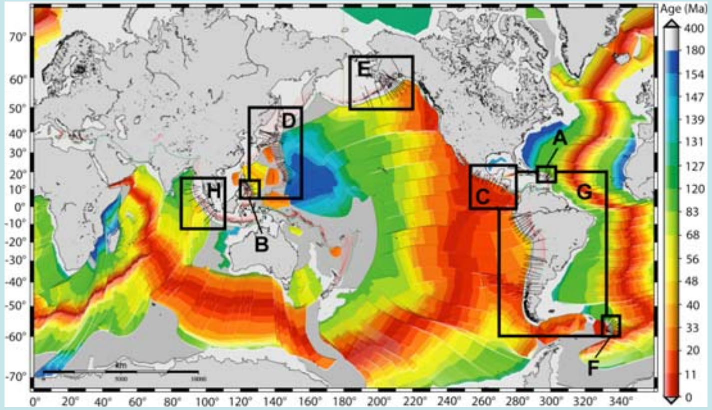




○ South America
☆ Central America
▽ W-Indonesia
⬡ E-Aleutians
◇ Sandwich arc
▽ Caribbeans
☆ Philippines
+ Marianas - Japan

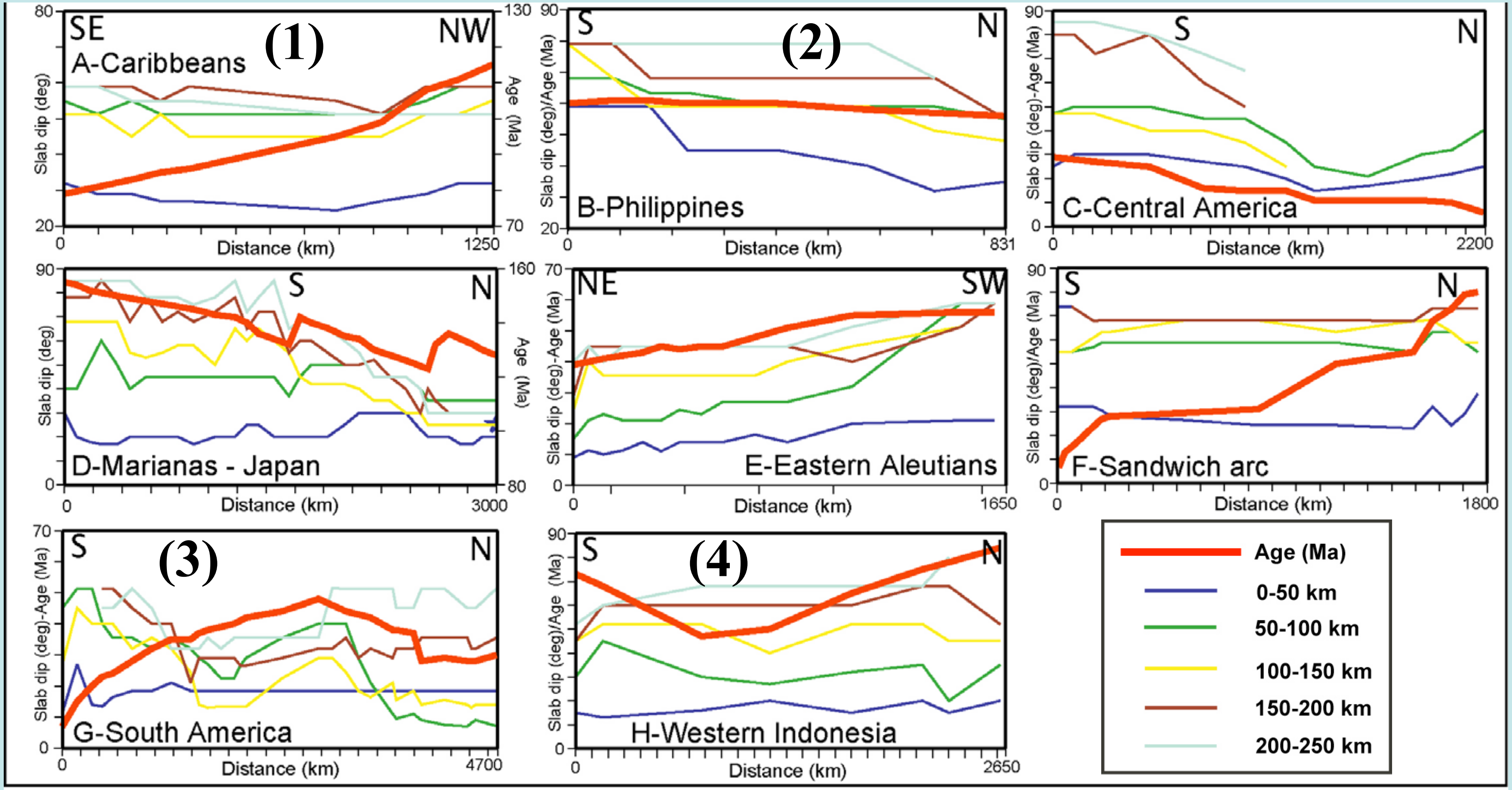
Slab dip Vs. Lithosphere age

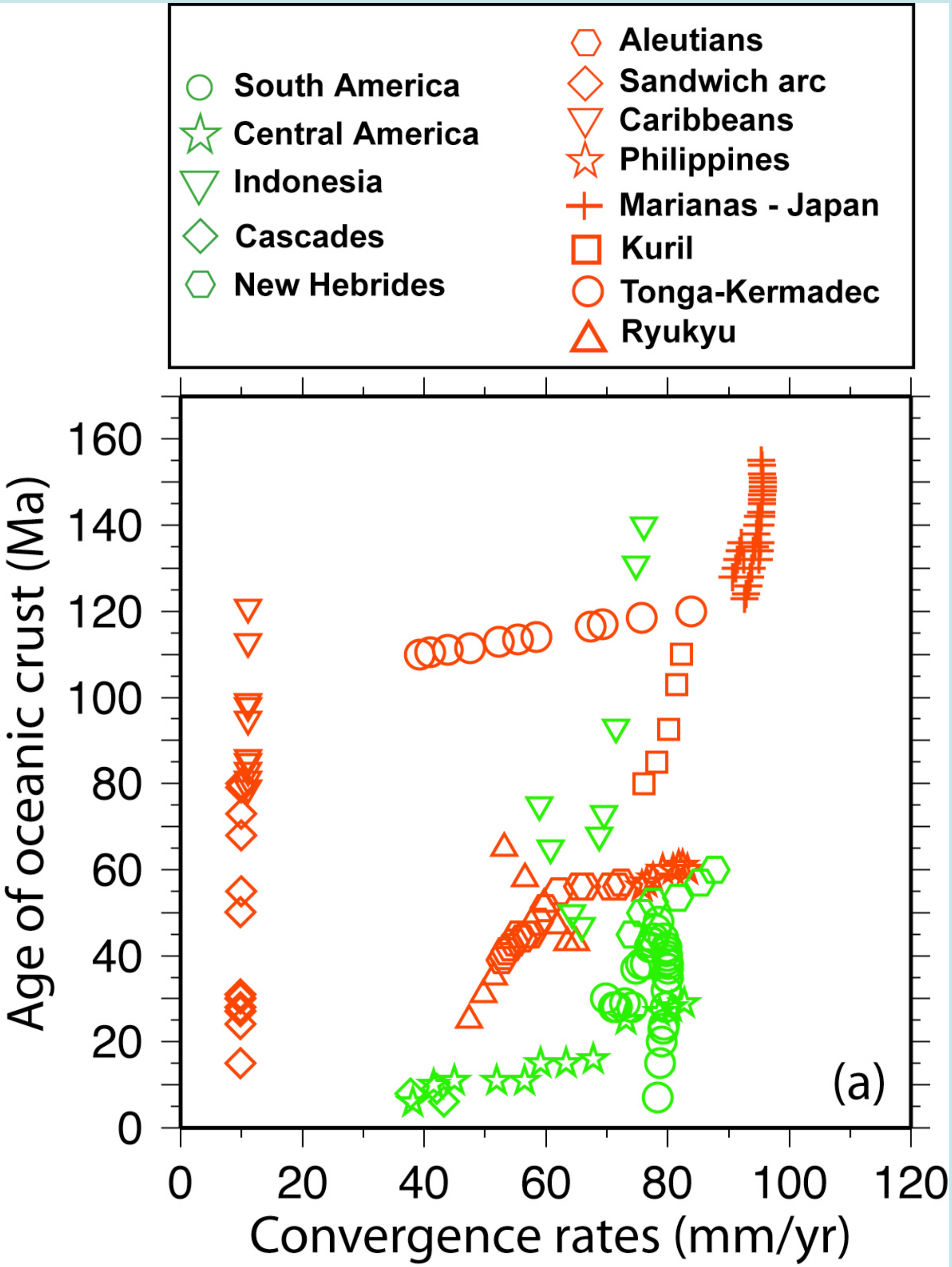
Same dip for variable ages = no correlation

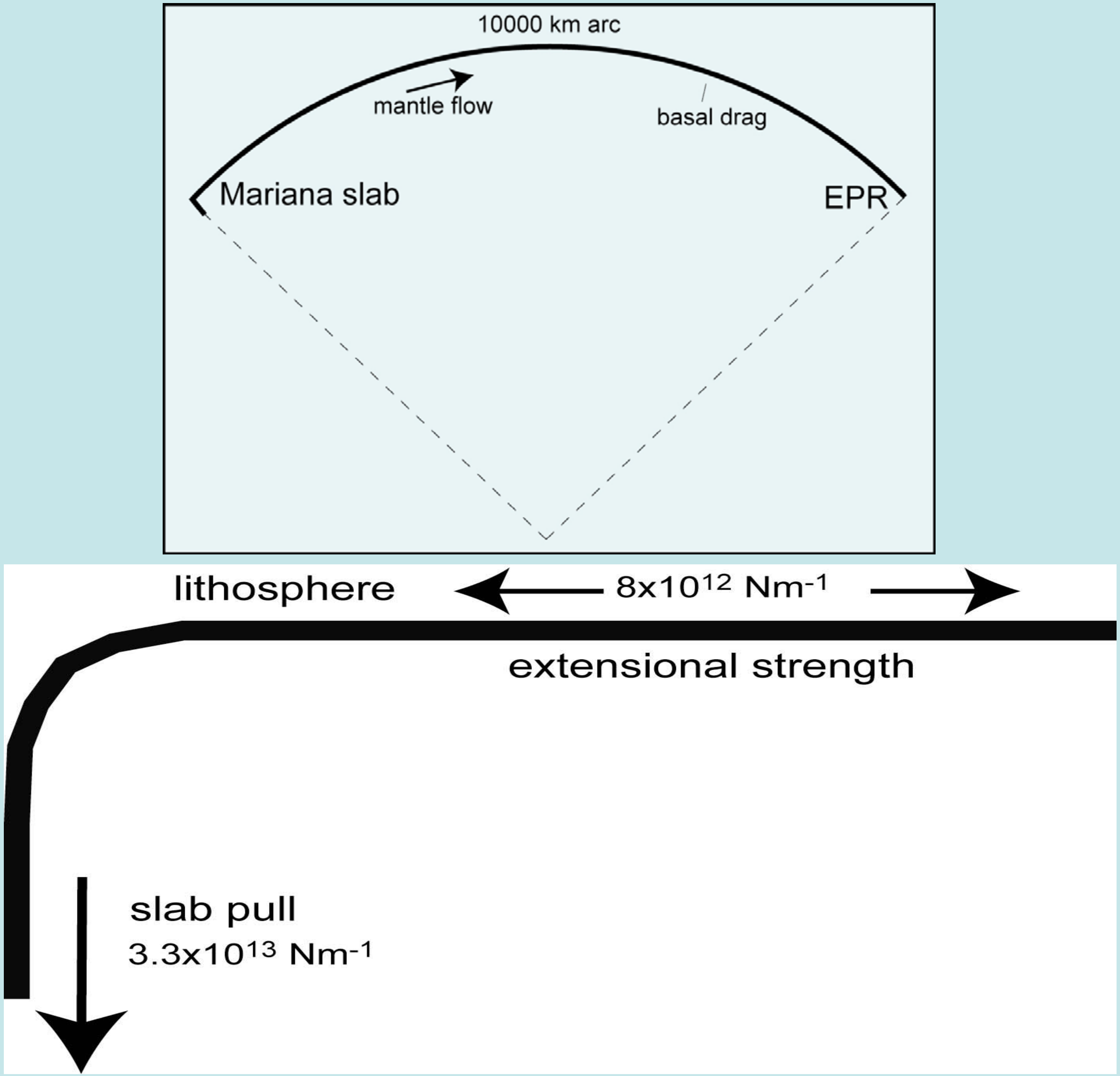


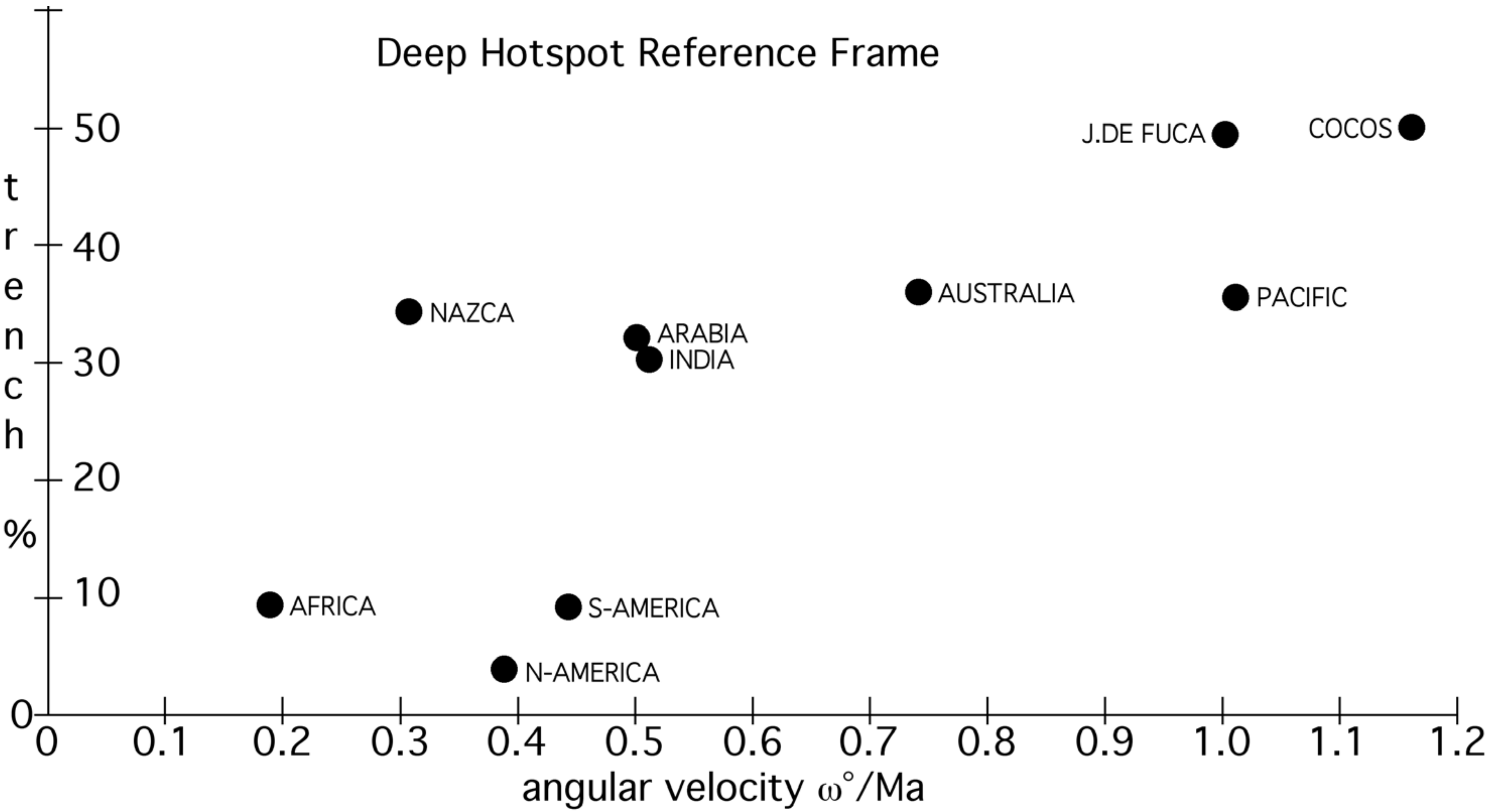
- *Age increases but dip remains constant* **(1)**
- *Dip decreases but age remains constant* **(2)**
- *Dip decreases and age increases* **(3)**
- *Dip increases and age decreases* **(4)**

= *No correlation*

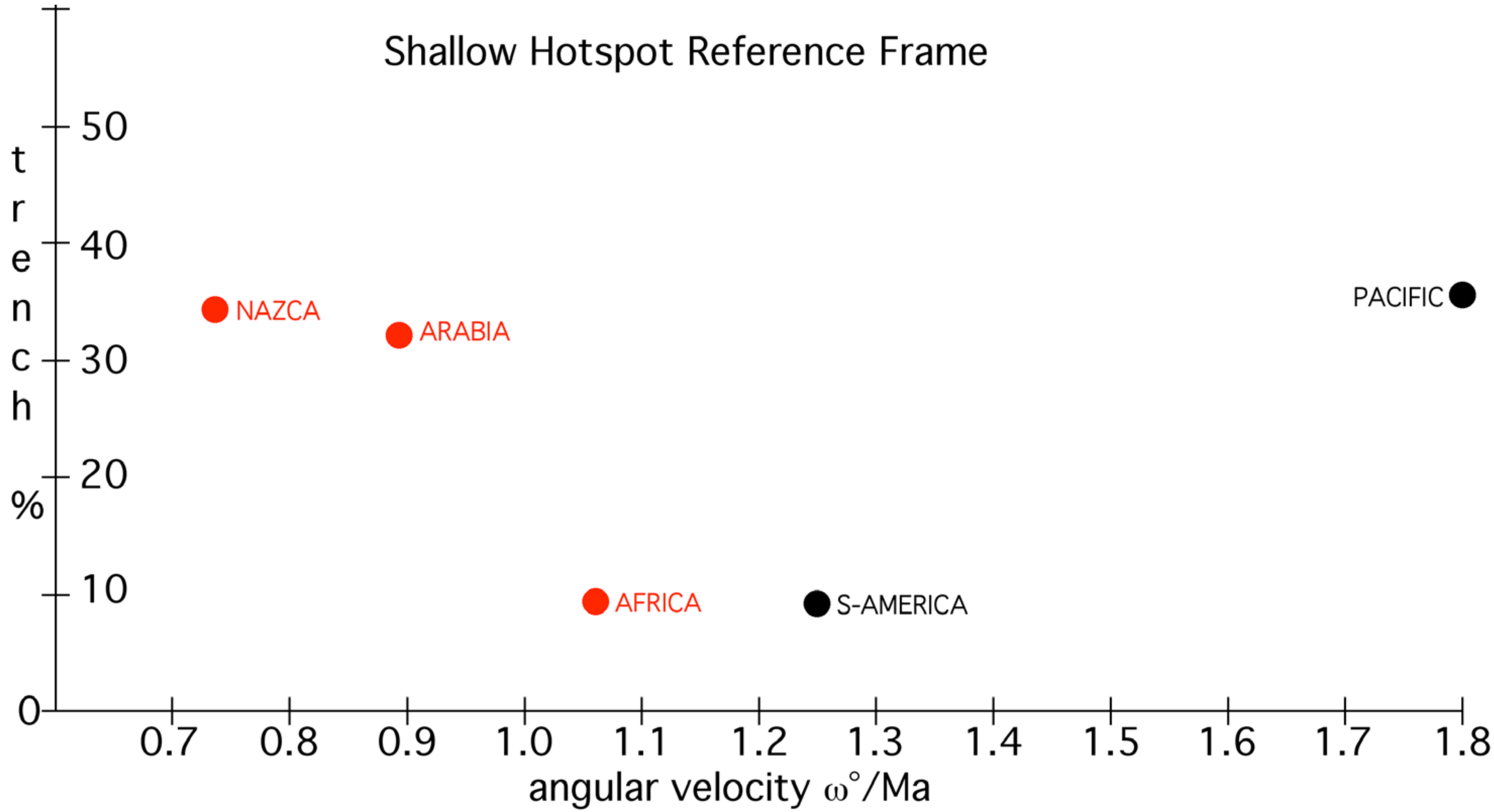


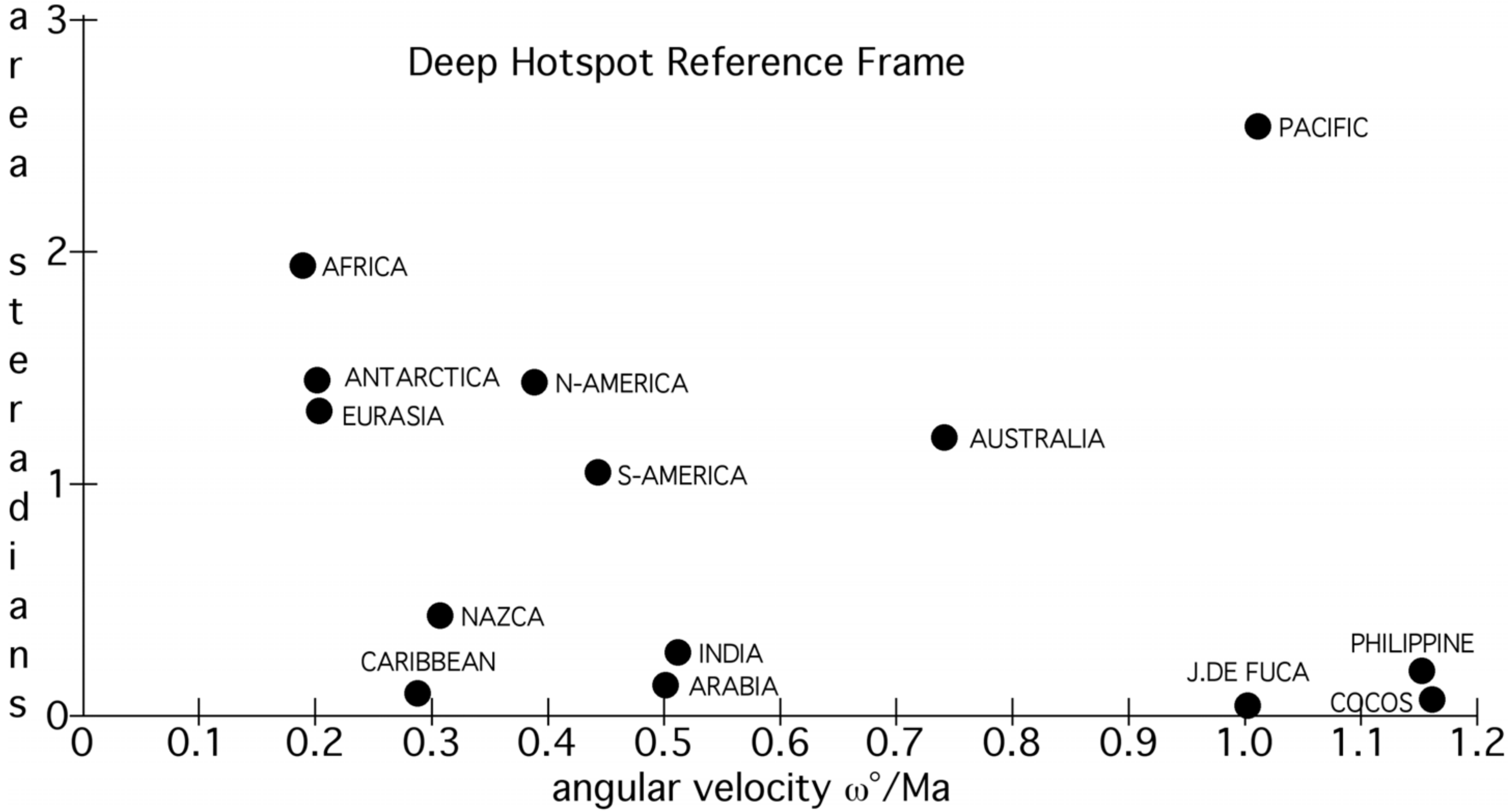

South America
Central America
Indonesia
Cascades
New Hebrides
Aleutians
Sandwich arc
Caribbeans
Philippines
Marianas - Japan
Kuril
Tonga-Kermadec
Ryukyu
Age of oceanic crust (Ma)
0
20
40
60
80
100
120
140
160
Convergence rates (mm/yr)
0
20
40
60
80
100
120
(a)

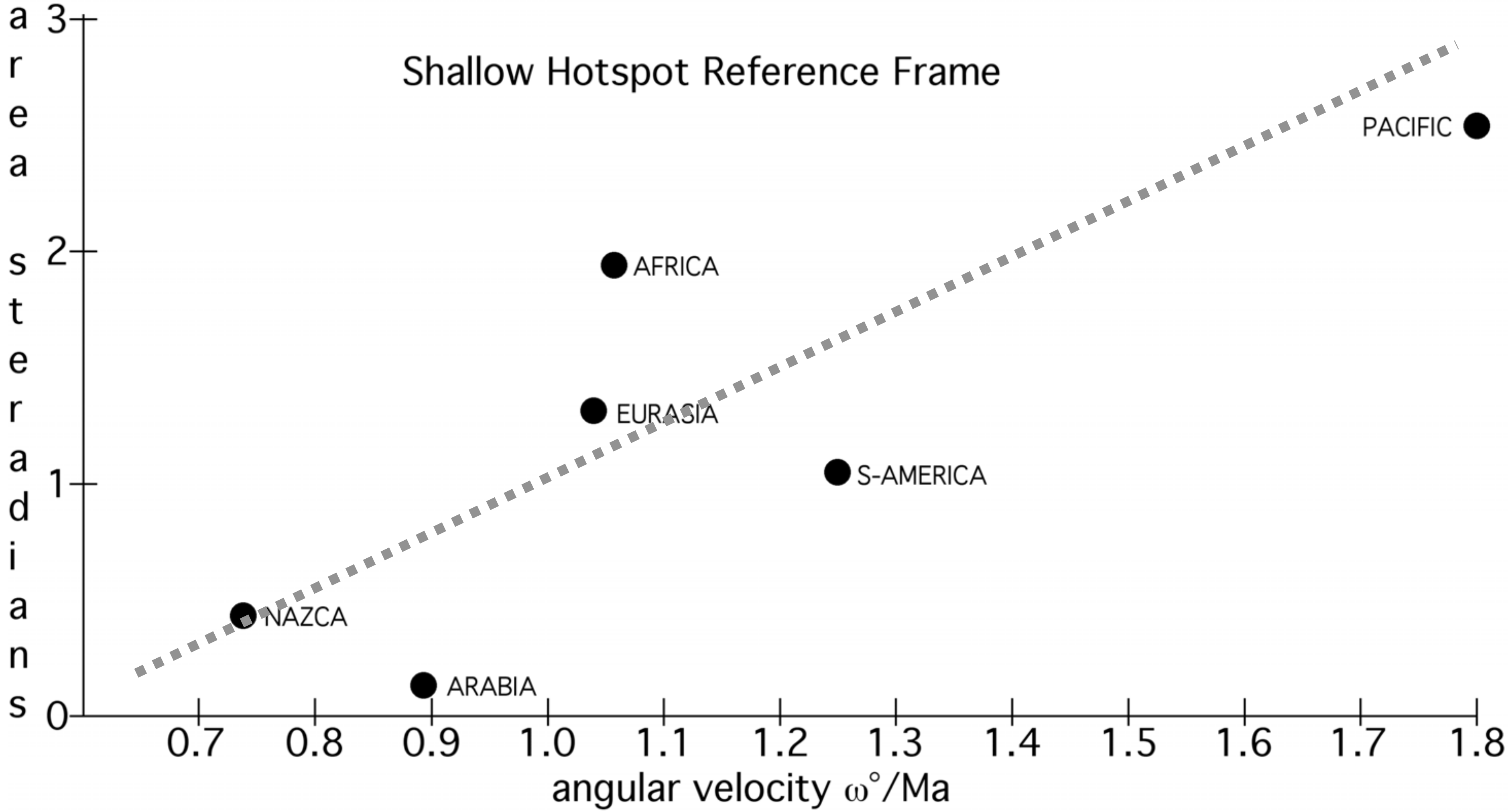

10000 km arc
mantle flow
basal drag
Mariana slab
EPR
lithosphere
8x10^12 Nm^-1
extensional strength
slab pull
3.3x10^13 Nm^-1



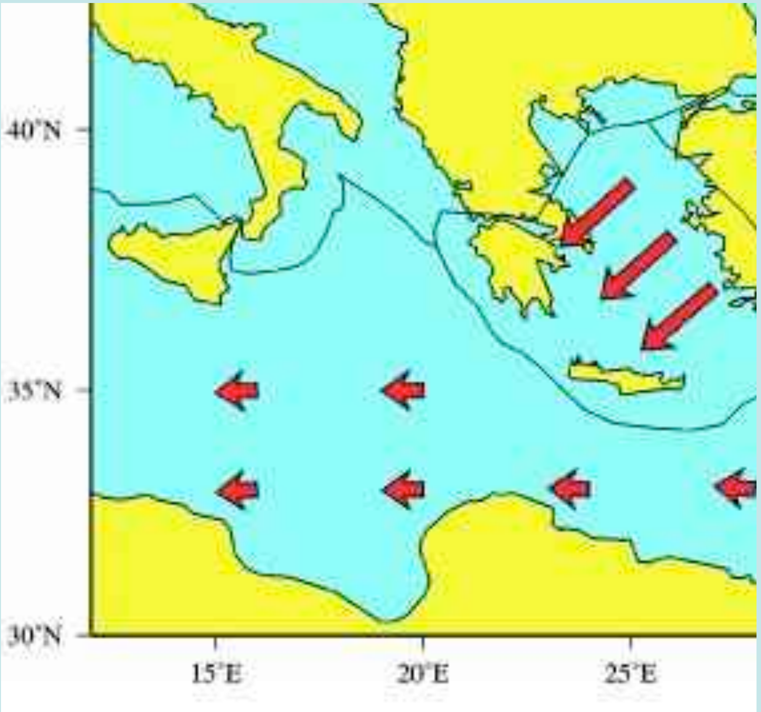
Deep Hotspot Reference Frame
t r e n c h %
50
40
30
20
10
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
angular velocity ω°/Ma
J.DE FUCA
COCOS
NAZCA
ARABIA
INDIA
AUSTRALIA
PACIFIC
AFRICA
S-AMERICA
N-AMERICA


Shallow Hotspot Reference Frame
trench %
50
40
30
20
10
0
NAZCA
ARABIA
PACIFIC
AFRICA
S-AMERICA
0.7
0.8
0.9
1.0
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
angular velocity ω°/Ma


Deep Hotspot Reference Frame
area steradians
angular velocity ω°/Ma
0
1
2
3
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
PACIFIC
AFRICA
ANTARCTICA
N-AMERICA
EURASIA
AUSTRALIA
S-AMERICA
NAZCA
INDIA
CARIBBEAN
ARABIA
PHILIPPINE
J.DE FUCA
COCOS

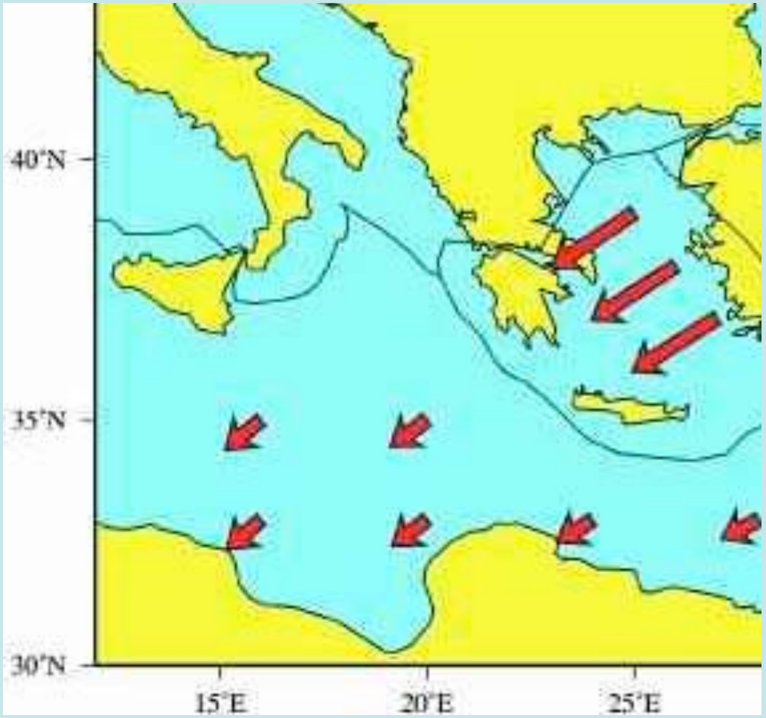

Shallow Hotspot Reference Frame
area steradians
3
2
1
0
PACIFIC
AFRICA
EURASIA
S-AMERICA
NAZCA
ARABIA
0.7
0.8
0.9
1.0
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
angular velocity ω°/Ma

Deep HRF



50 mm/yr

Shallow HRF



100 mm/yr

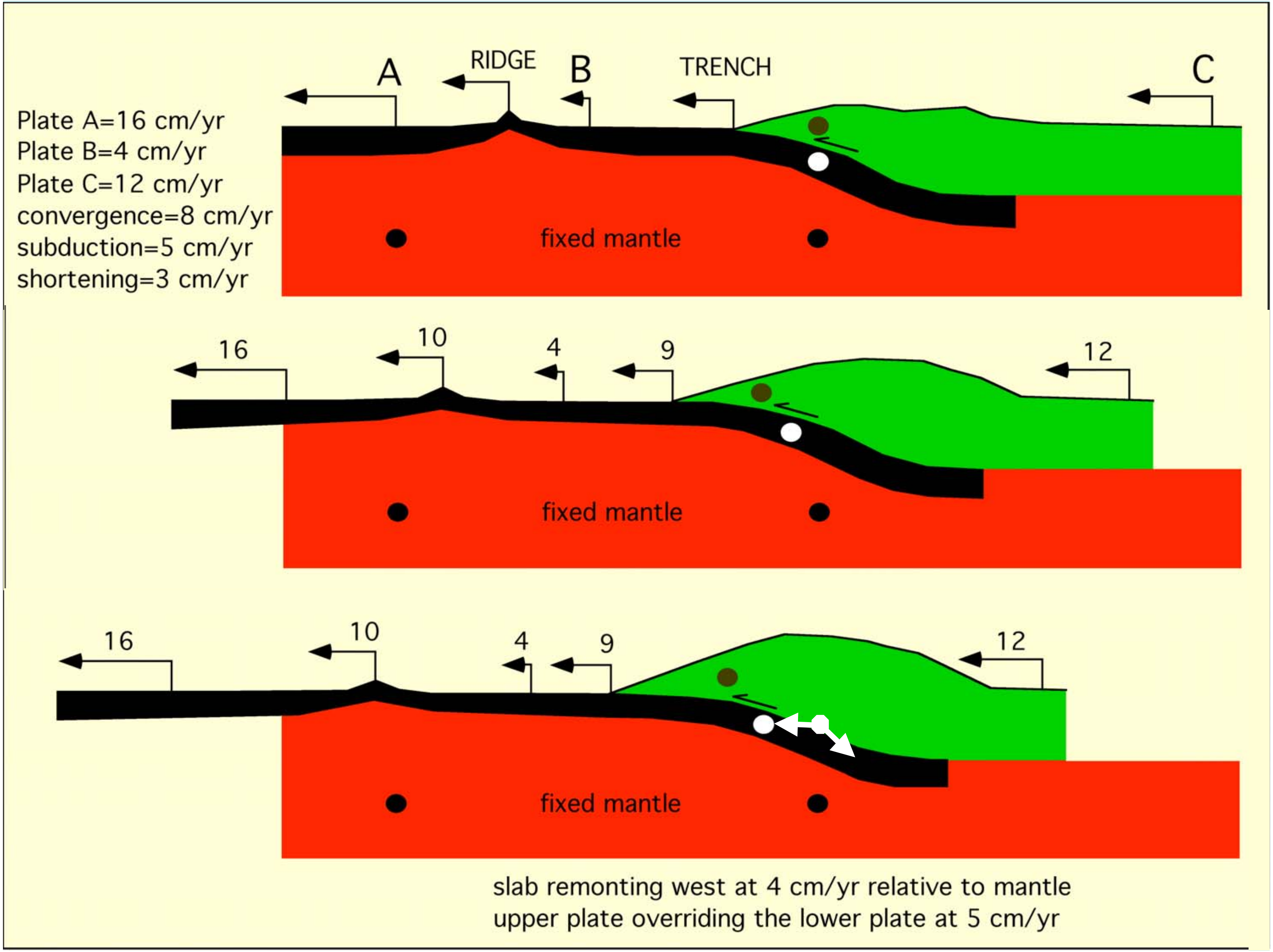
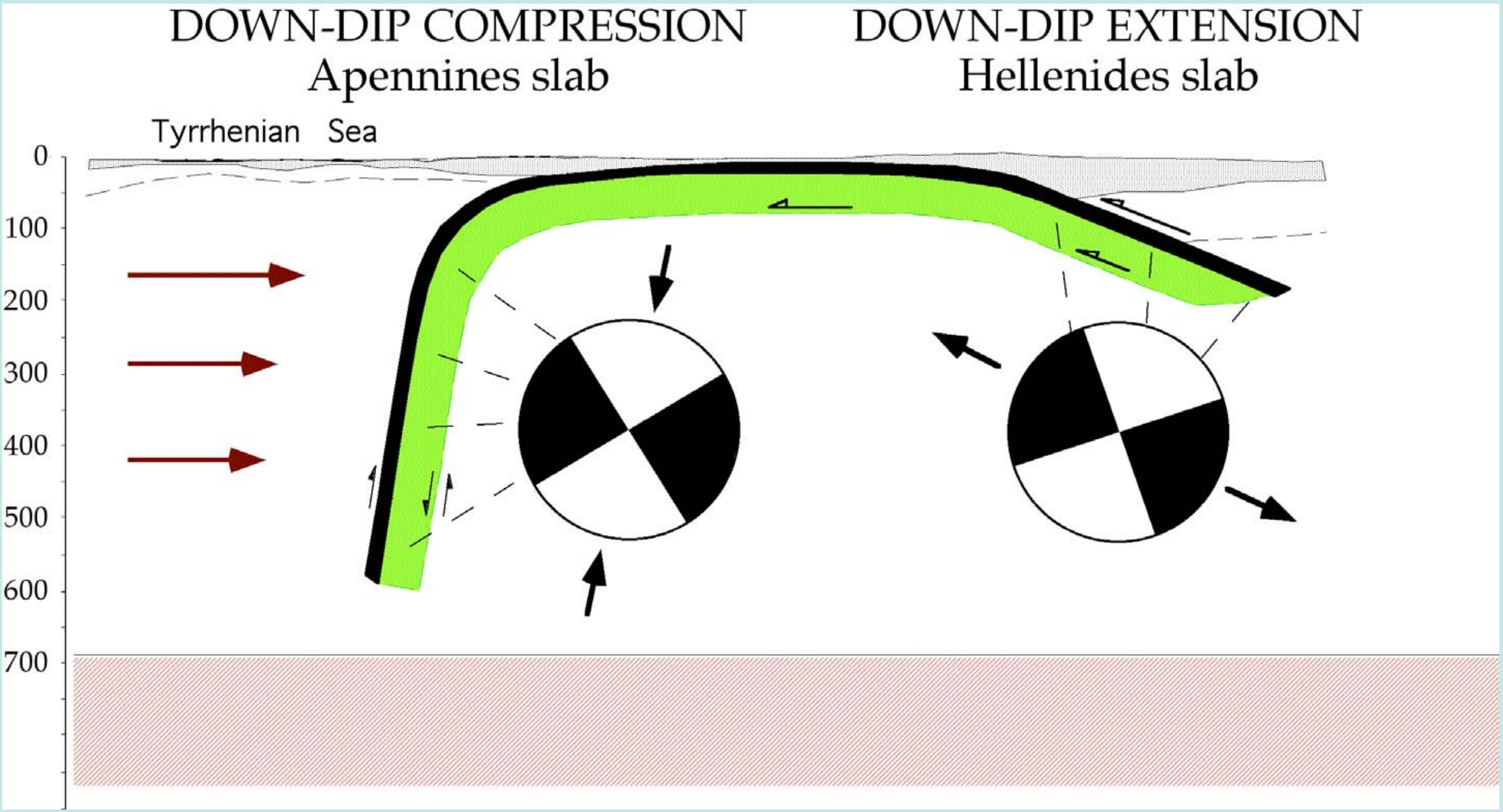
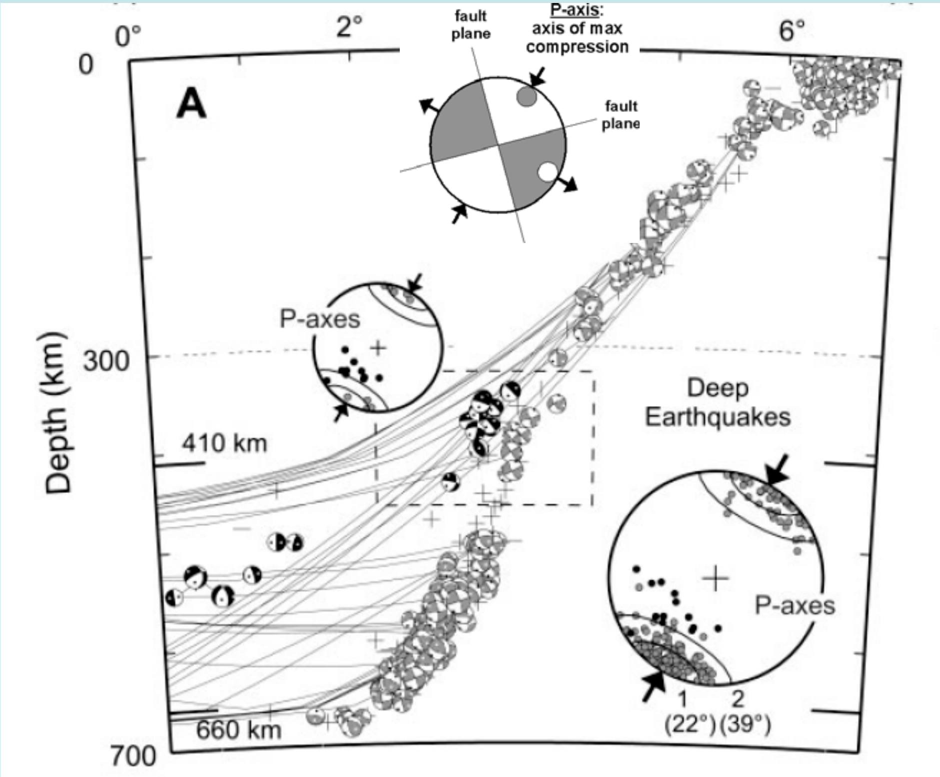


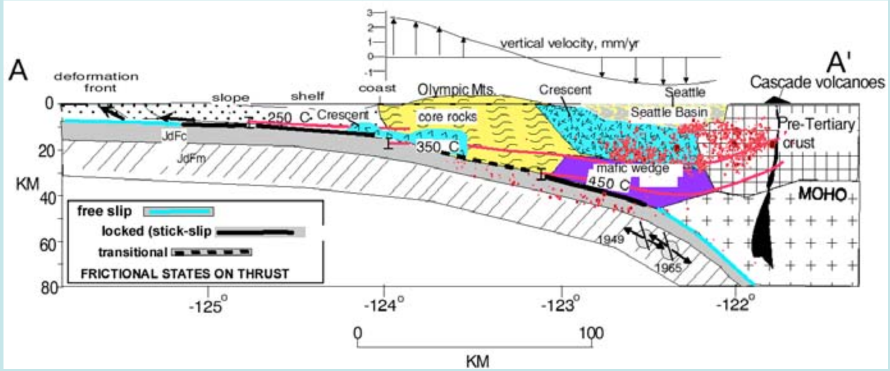
Plate A=16 cm/yr
Plate B=4 cm/yr
Plate C=12 cm/yr
convergence=8 cm/yr
subduction=5 cm/yr
shortening=3 cm/yr
A
RIDGE
B
TRENCH
C
fixed mantle
16
10
4
9
12
fixed mantle
16
10
4
9
12
fixed mantle
slab remonting west at 4 cm/yr relative to mantle
upper plate overriding the lower plate at 5 cm/yr



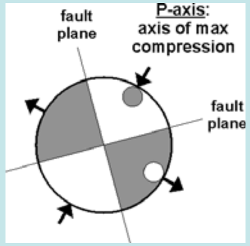
DOWN-DIP COMPRESSION
Apennines slab
DOWN-DIP EXTENSION
Hellenides slab
Tyrrhenian Sea
0
100
200
300
400
500
600
700

TONGA

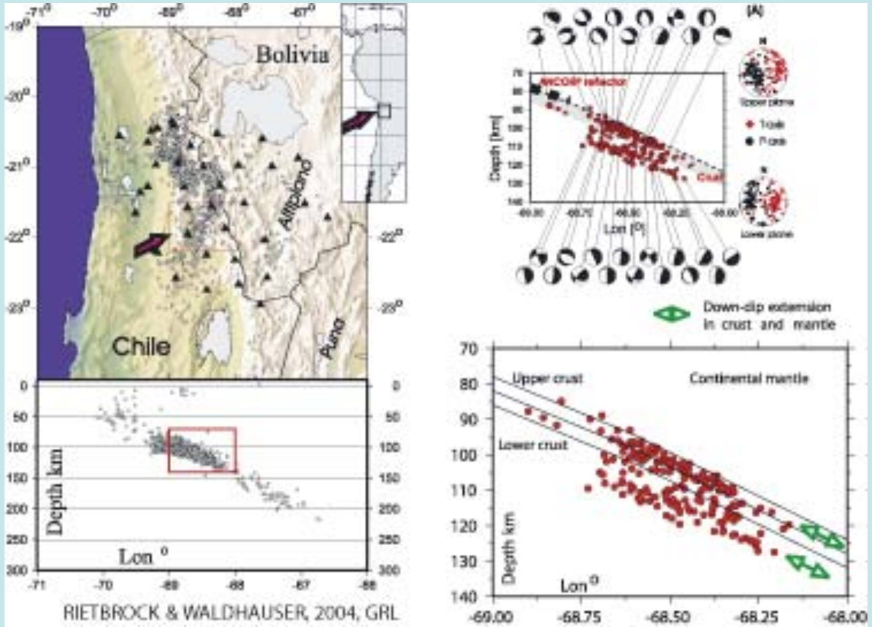


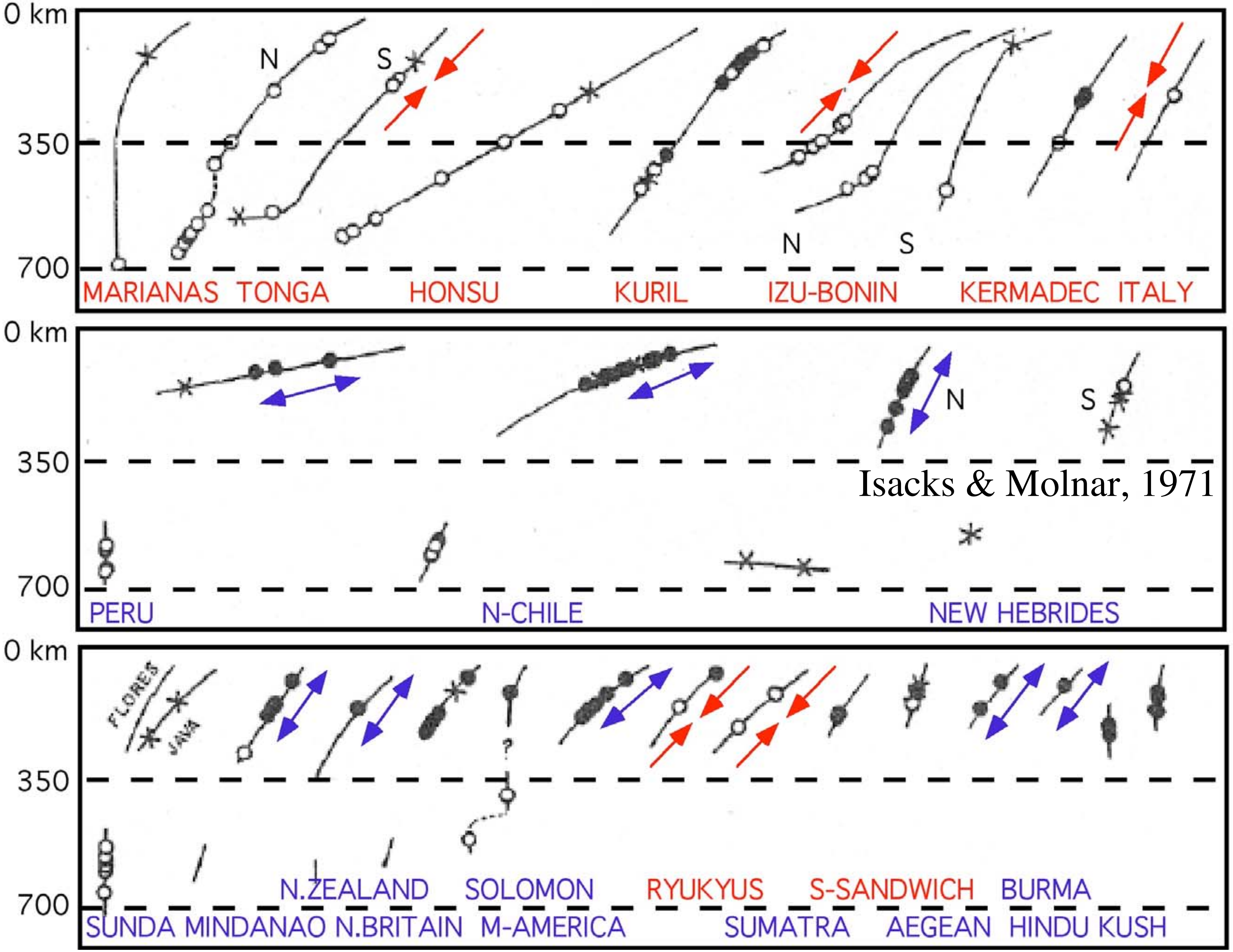


CASCADIA

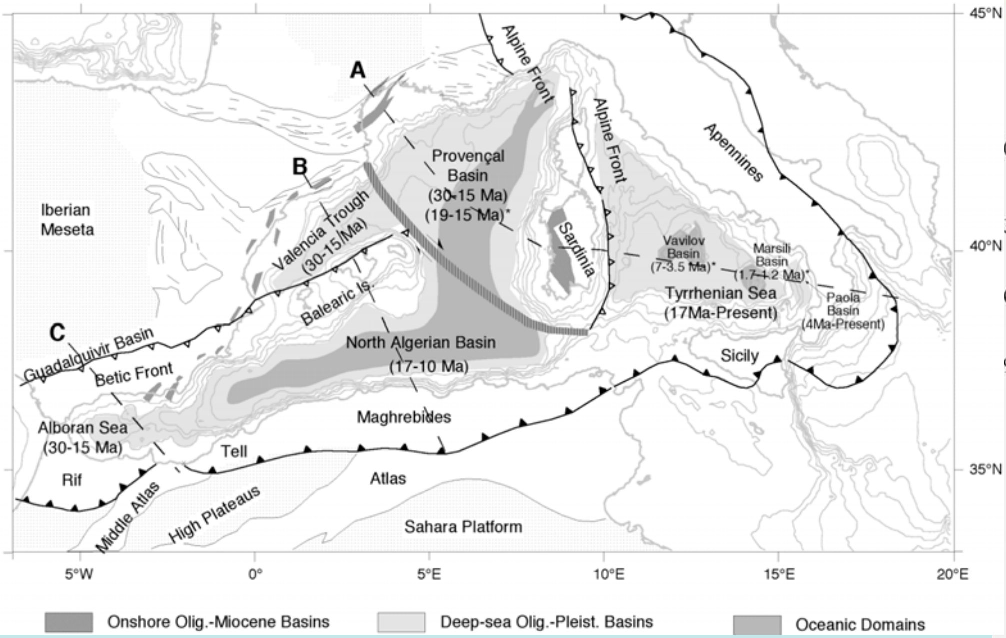


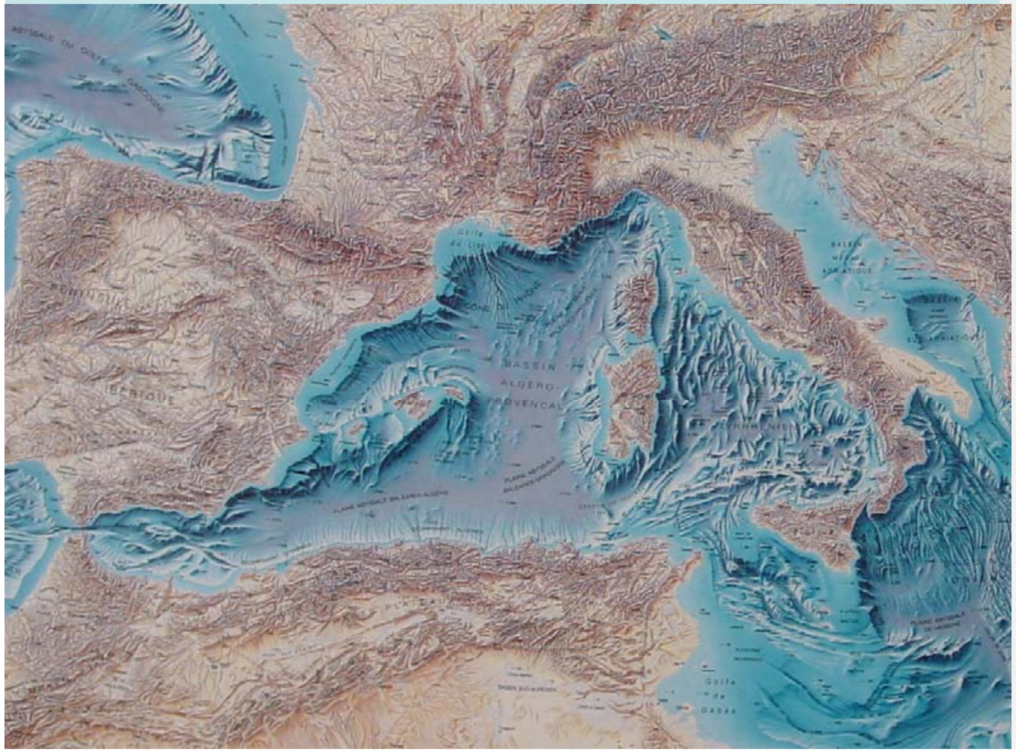
CHILE

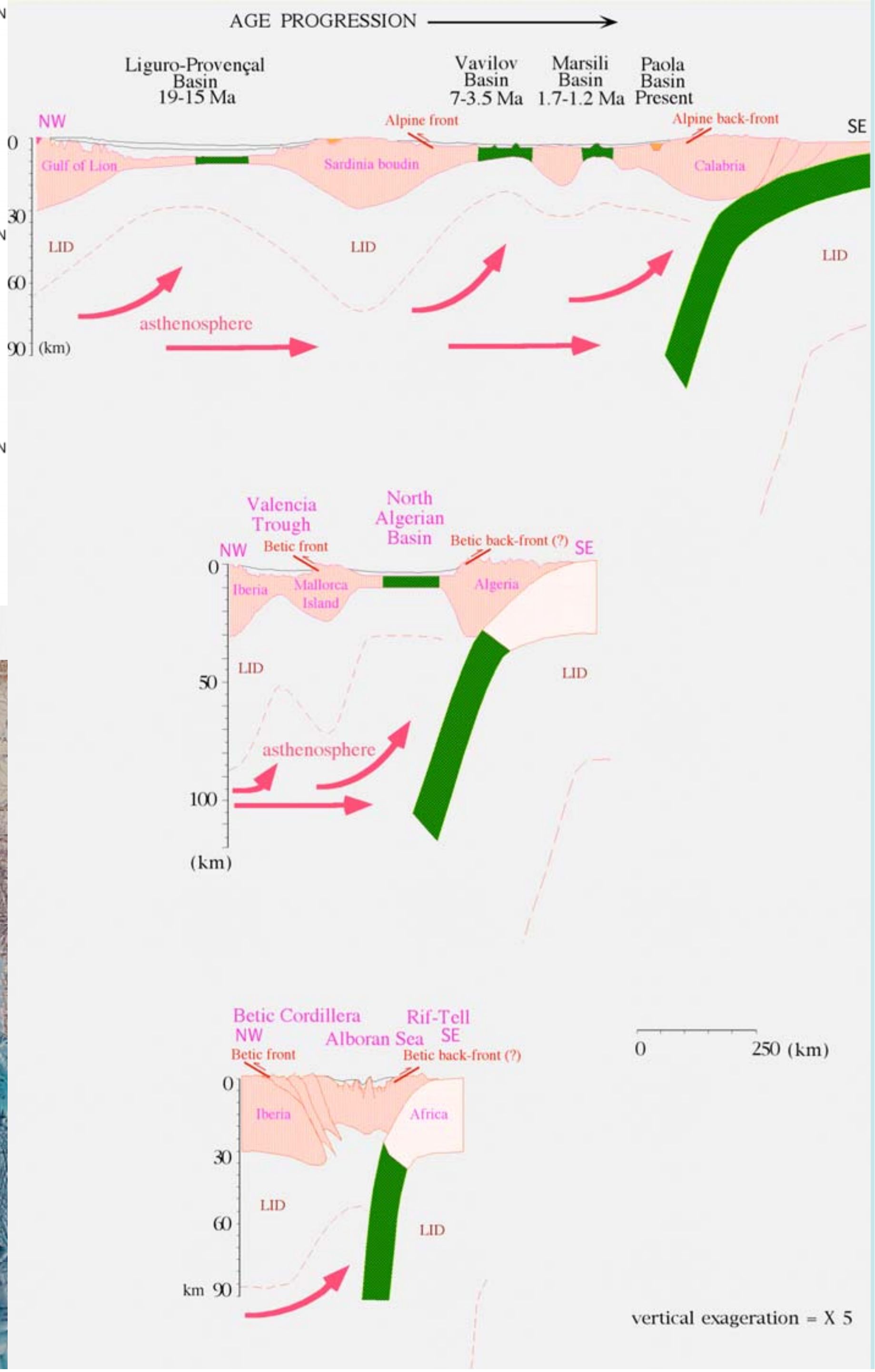


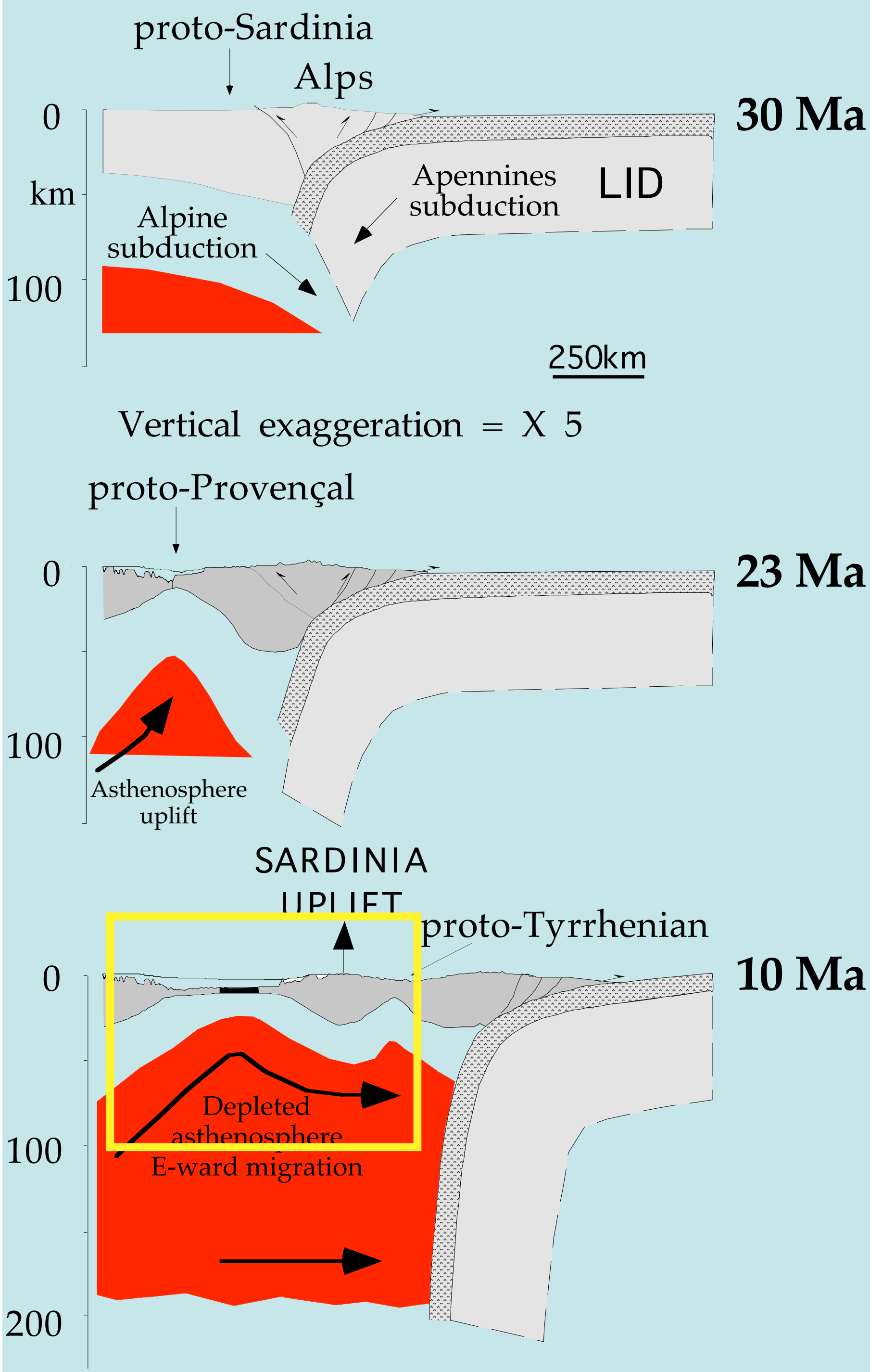


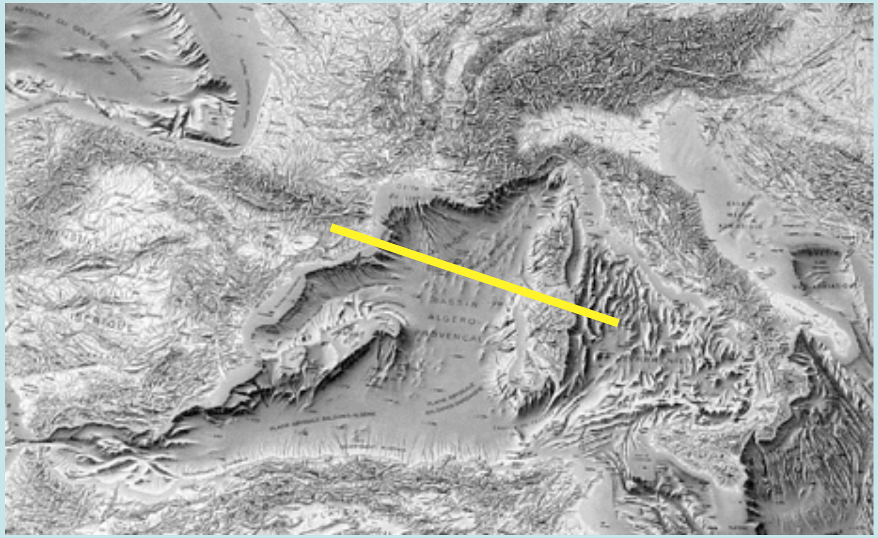
W-directed E-NE-directed

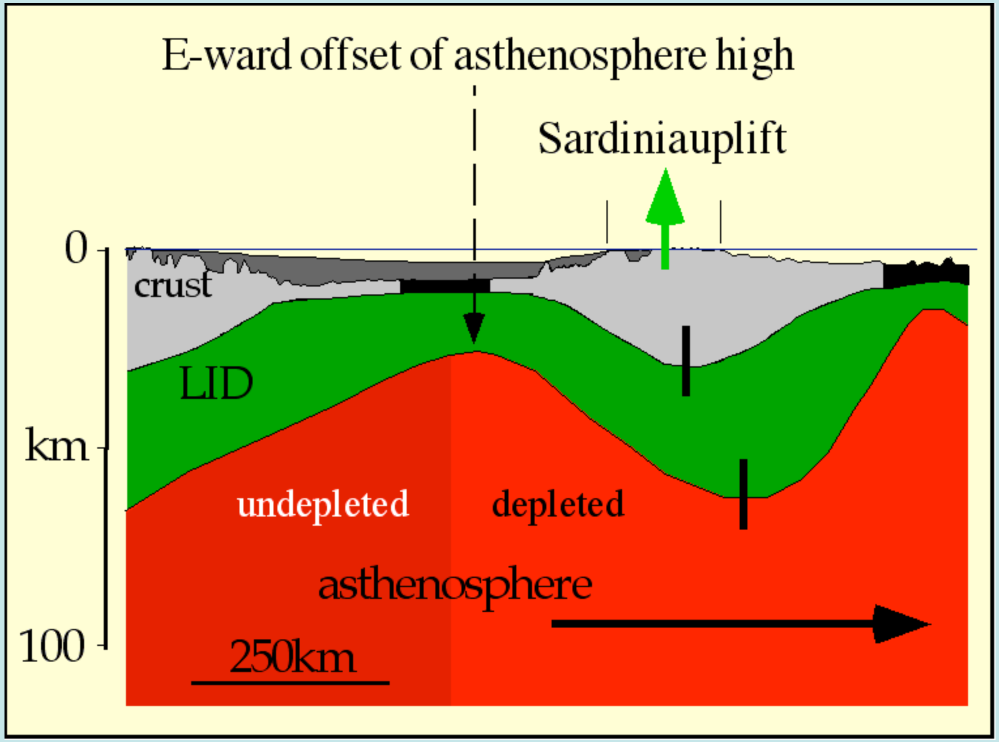

45°N
40°N
35°N
5°W
0°
5°E
10°E
15°E
20°E
A
B
C
Alpine Front
Alpine Front
Apennines
Iberian Meseta
Provençal Basin (30-15 Ma) (19-15 Ma)*
Valencia Trough (30-15 Ma)
Balearic Is.
Sardinia
Vavilov Basin (7-3.5 Ma)*
Marsili Basin (1.7-1.2 Ma)*
Tyrrhenian Sea (17Ma-Present)
Paola Basin (4Ma-Present)
Sicily
Guadalquivir Basin
Betic Front
North Algerian Basin (17-10 Ma)
Alboran Sea (30-15 Ma)
Maghrebides
Tell
Rif
Atlas
Middle Atlas
High Plateaus
Sahara Platform
Onshore Olig.-Miocene Basins
Deep-sea Olig.-Pleist. Basins
Oceanic Domains

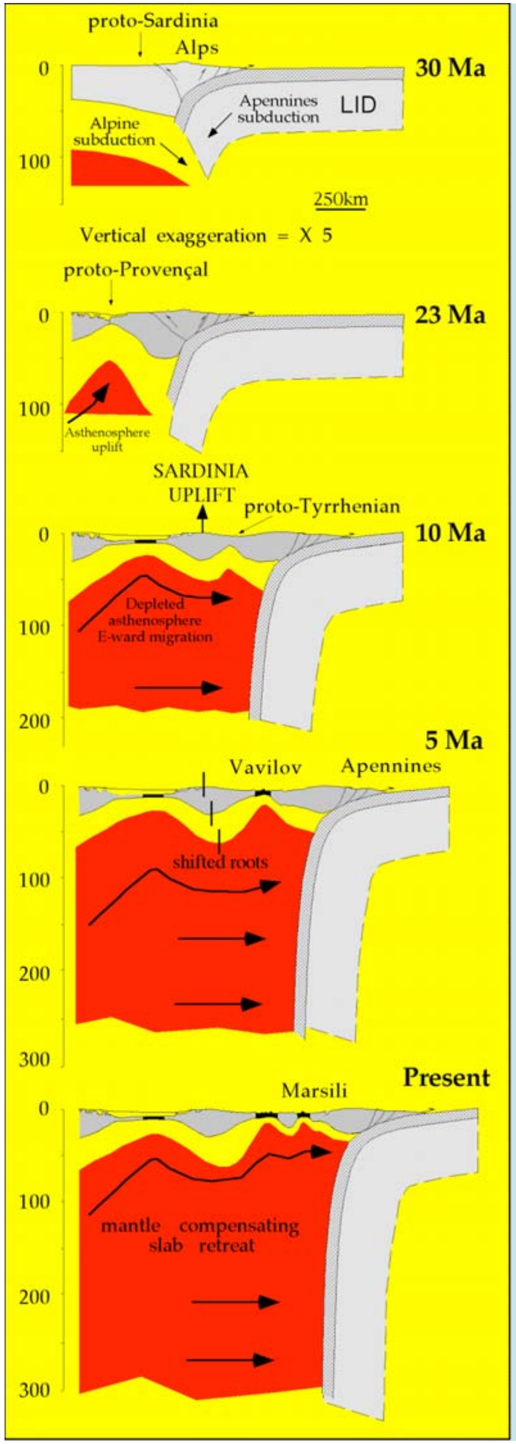



AGE PROGRESSION
Liguro-Provençal Basin 19-15 Ma
Vavilov Basin 7-3.5 Ma
Marsili Basin 1.7-1.2 Ma
Paola Basin Present
NW
SE
Alpine front
Alpine back-front
Gulf of Lion
Sardinia boudin
Calabria
LID
asthenosphere
0
30
60
90 (km)
Valencia Trough
North Algerian Basin
Betic front
Betic back-front (?)
Iberia
Mallorca Island
Algeria
50
100
(km)
Betic Cordillera
Rif-Tell
Alboran Sea
Africa
km 90
0
250 (km)
vertical exageration = X 5

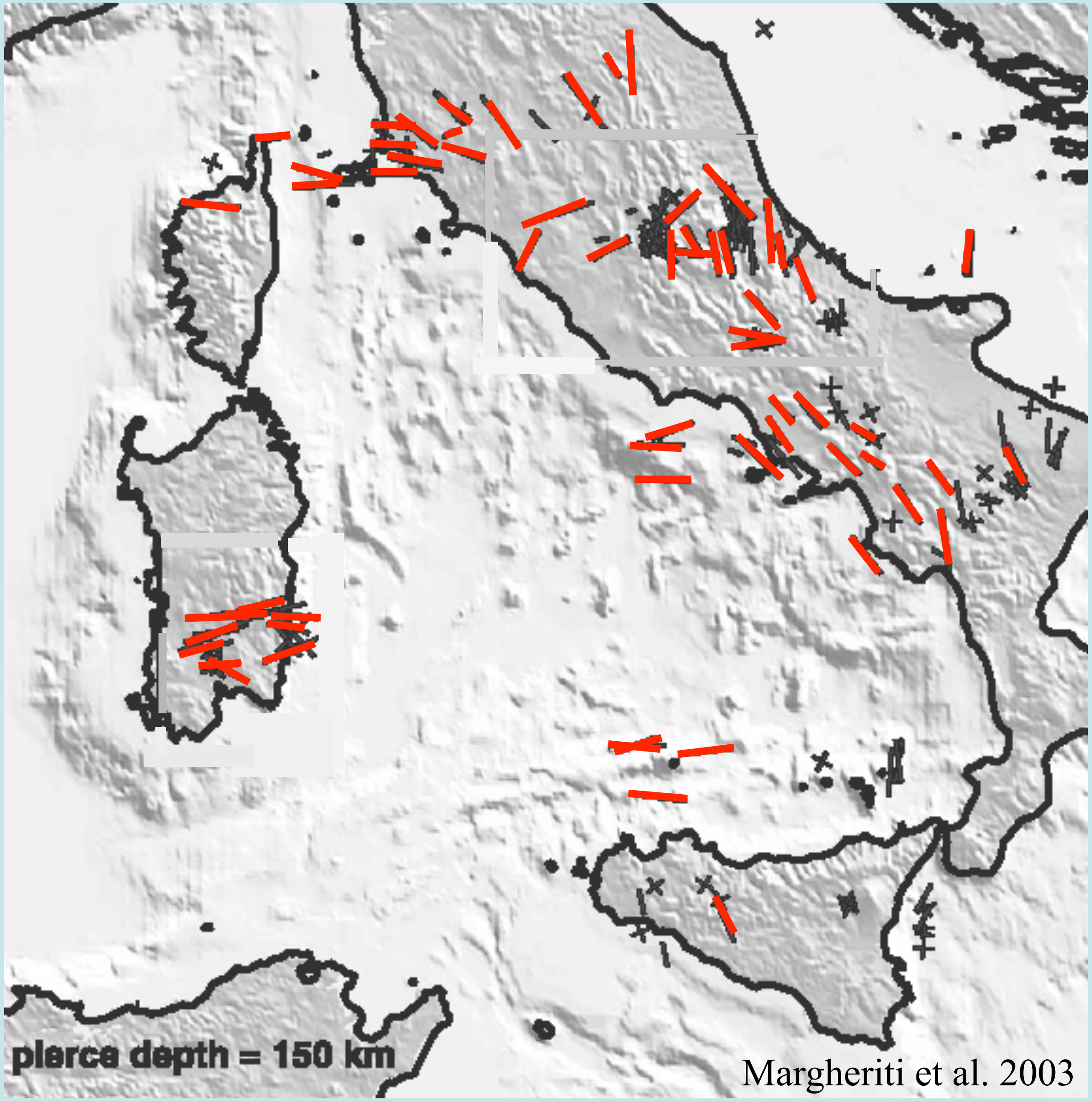

proto-Sardinia
Alps
0
km
100
Apennines subduction
LID
Alpine subduction
30 Ma
250km
Vertical exaggeration = X 5
proto-Provençal
0
100
23 Ma
Asthenosphere uplift
SARDINIA UPLIFT
proto-Tyrrhenian
0
100
200
10 Ma
Depleted asthenosphere
E-ward migration

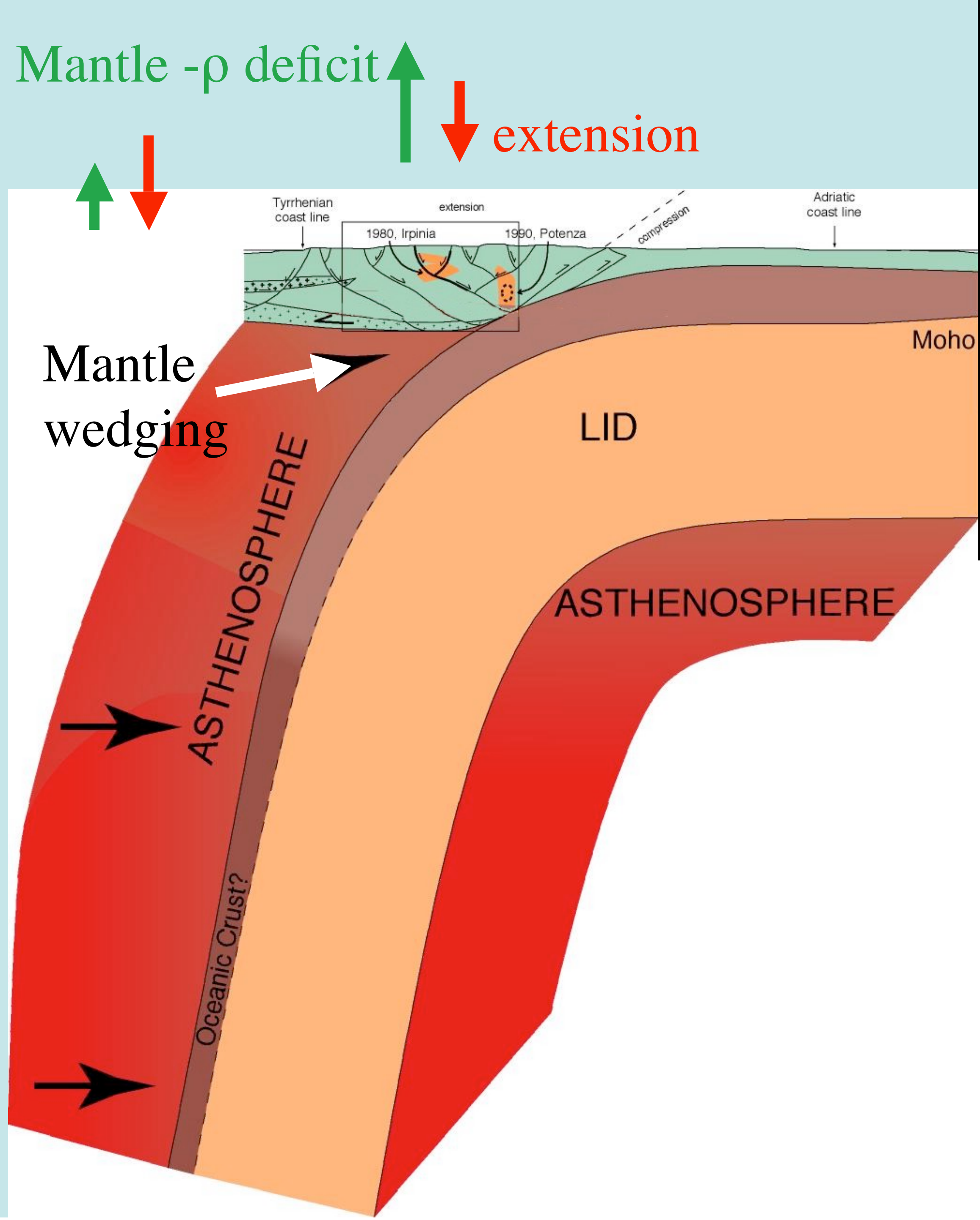


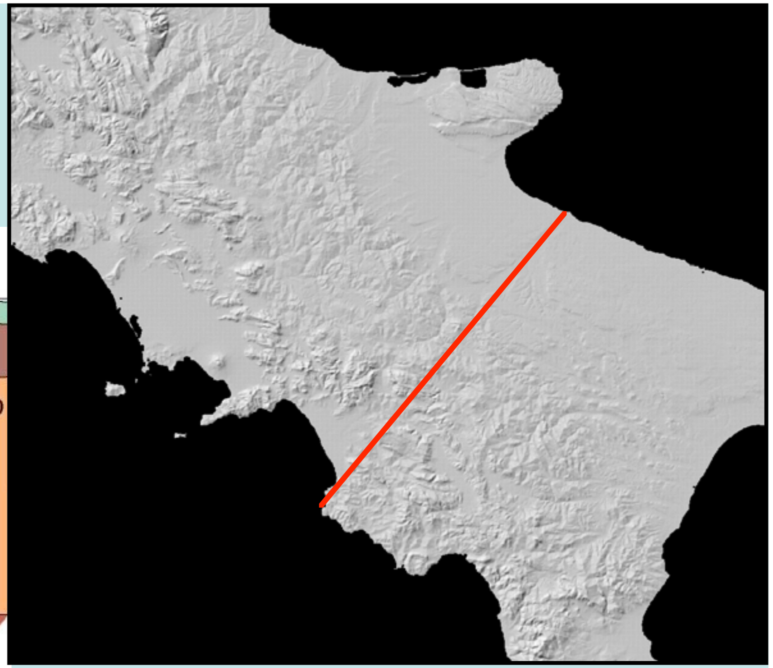

E-ward offset of asthenosphere high
Sardiniauplift
0
km
100
crust
LID
undepleted
depleted
asthenosphere
250km

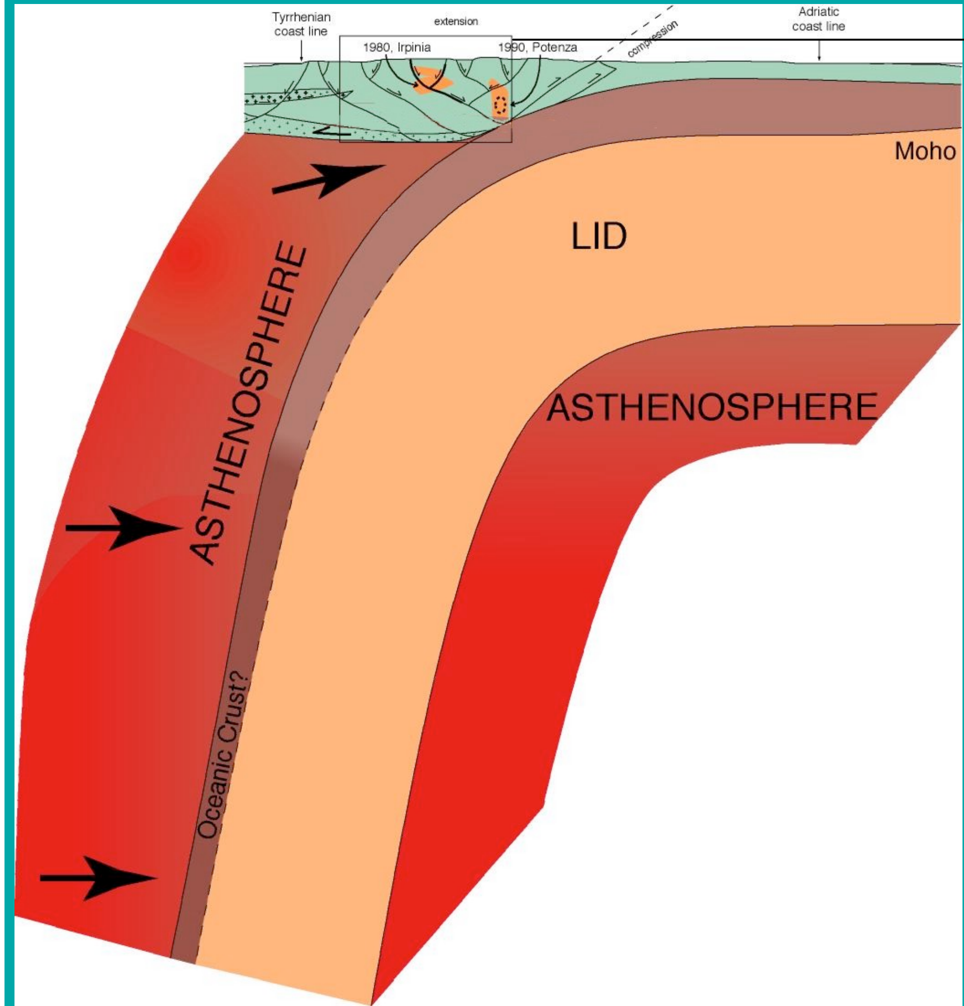


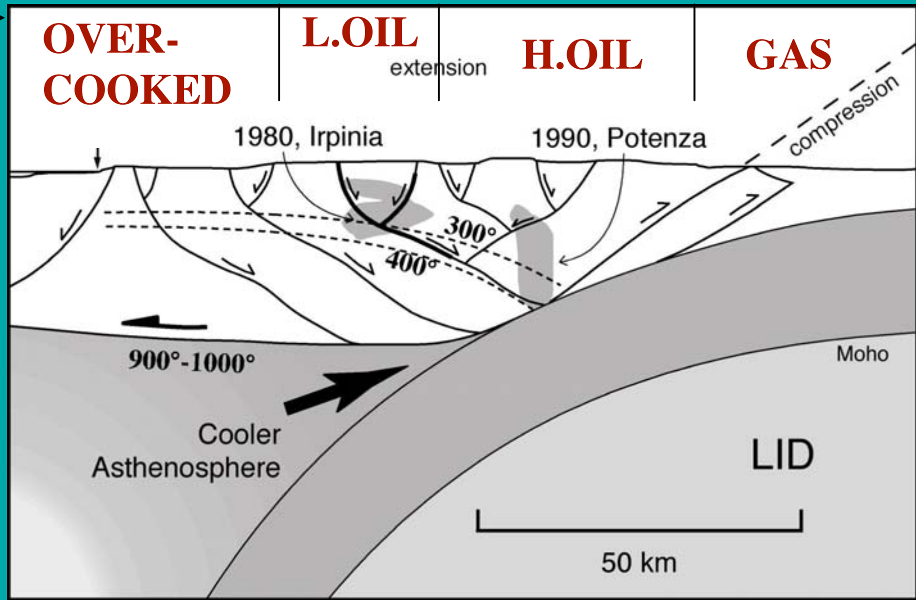
Shear Wave Splitting

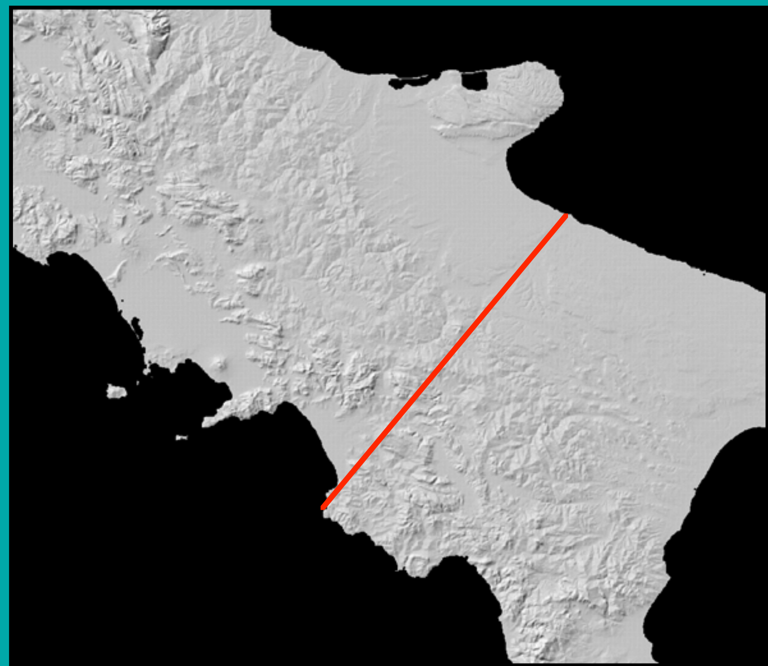



Mantle -ρ deficit
extension
Tyrrhenian coast line
extension
1980, Irpinia
1990, Potenza
compression
Adriatic coast line
Moho
Mantle wedging
LID
ASTHENOSPHERE
ASTHENOSPHERE
Oceanic Crust?

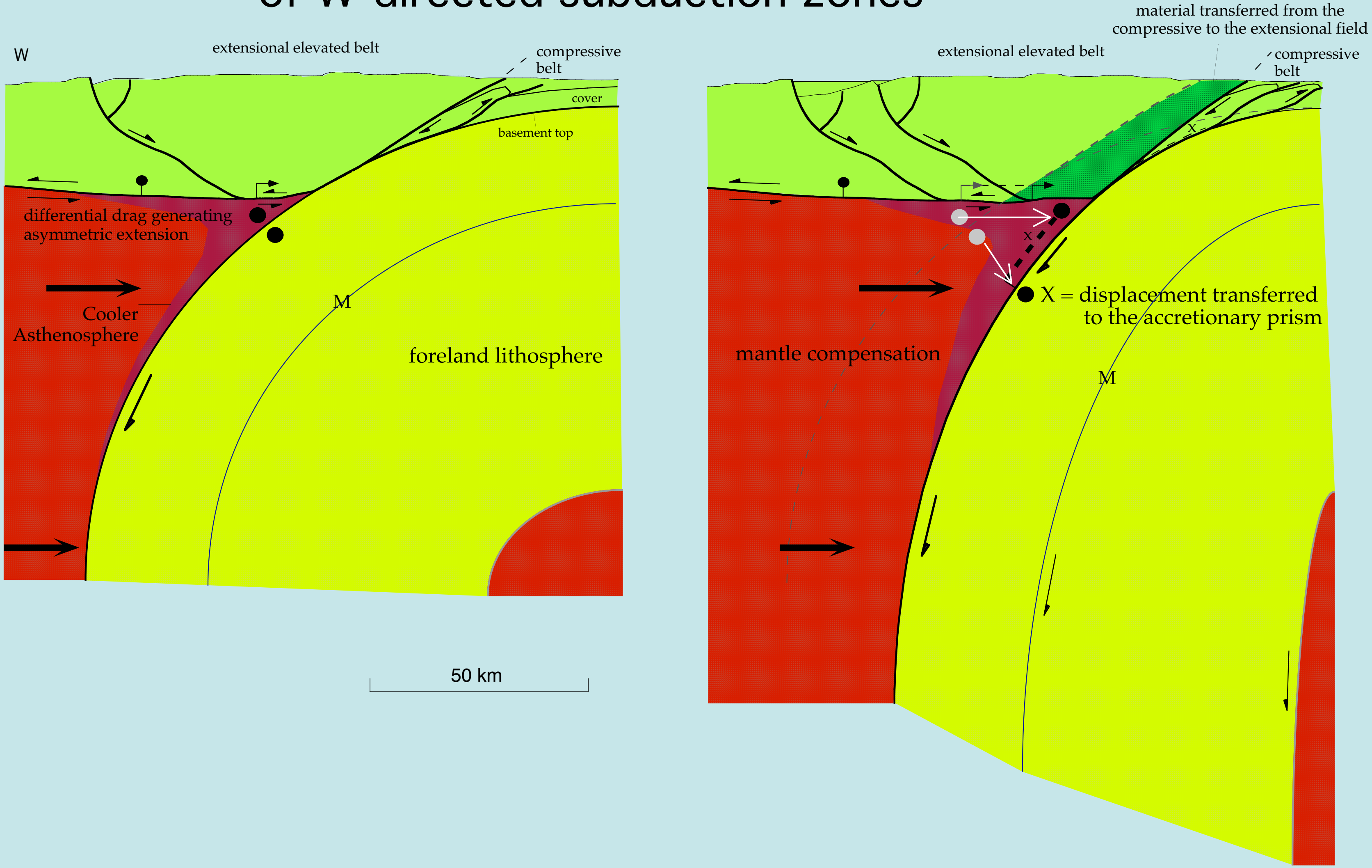


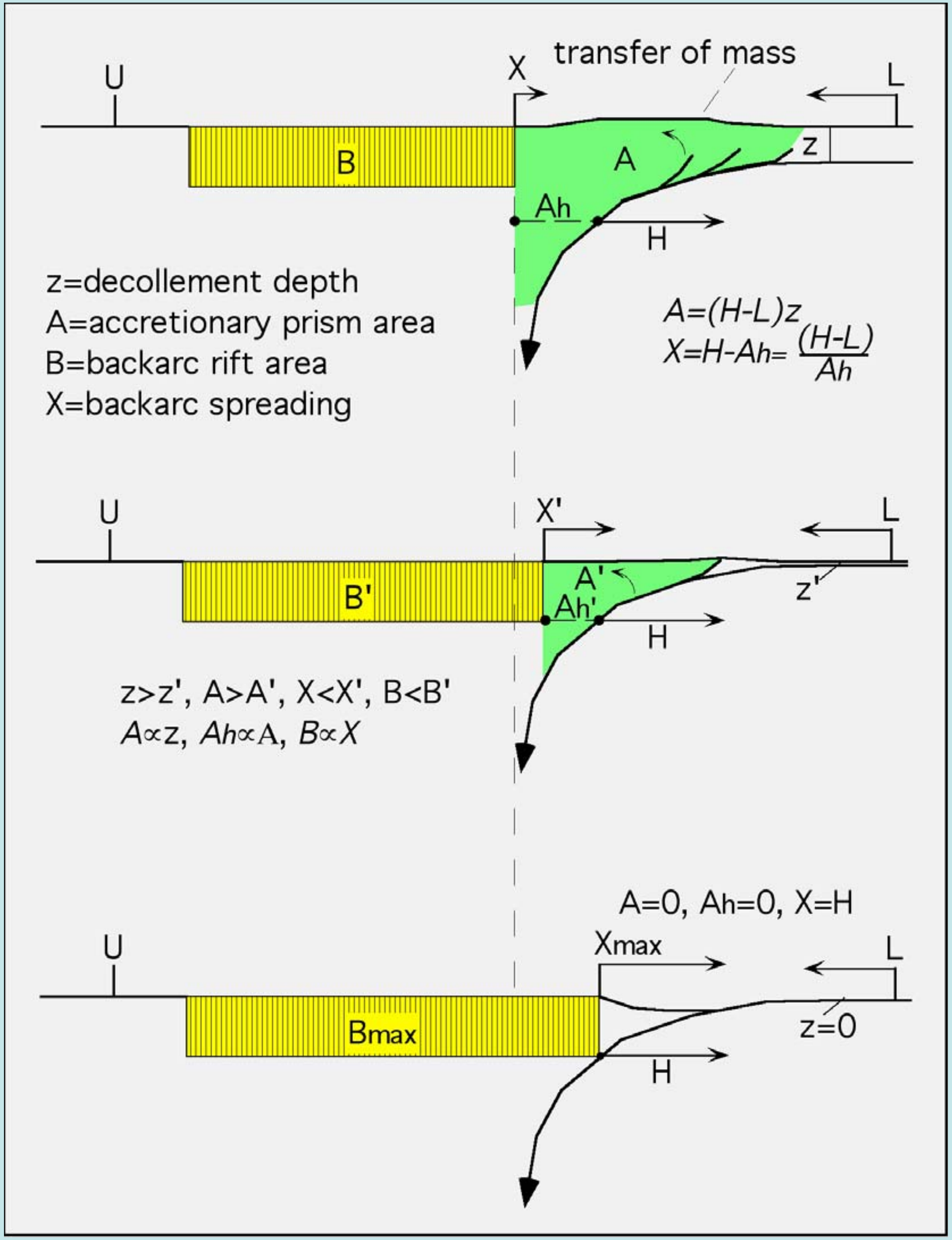

Tyrrhenian coast line
extension
1980, Irpinia
1990, Potenza
compression
Adriatic coast line
Moho
LID
ASTHENOSPHERE
ASTHENOSPHERE
Oceanic Crust?

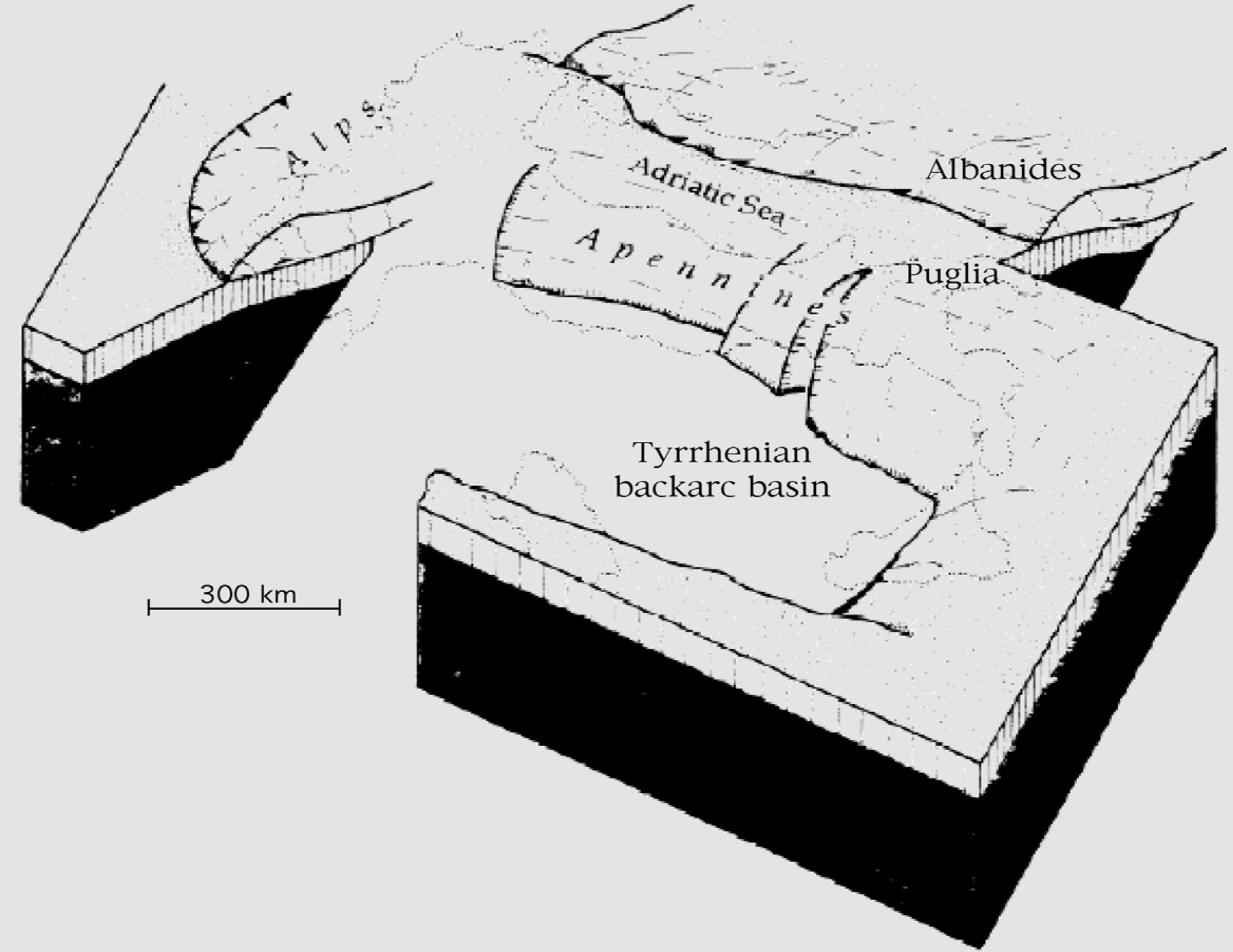

OVER-COOKED
L.OIL
H.OIL
GAS
extension
compression
1980, Irpinia
1990, Potenza
300°
400°
900°-1000°
Cooler Asthenosphere
Moho
LID
50 km



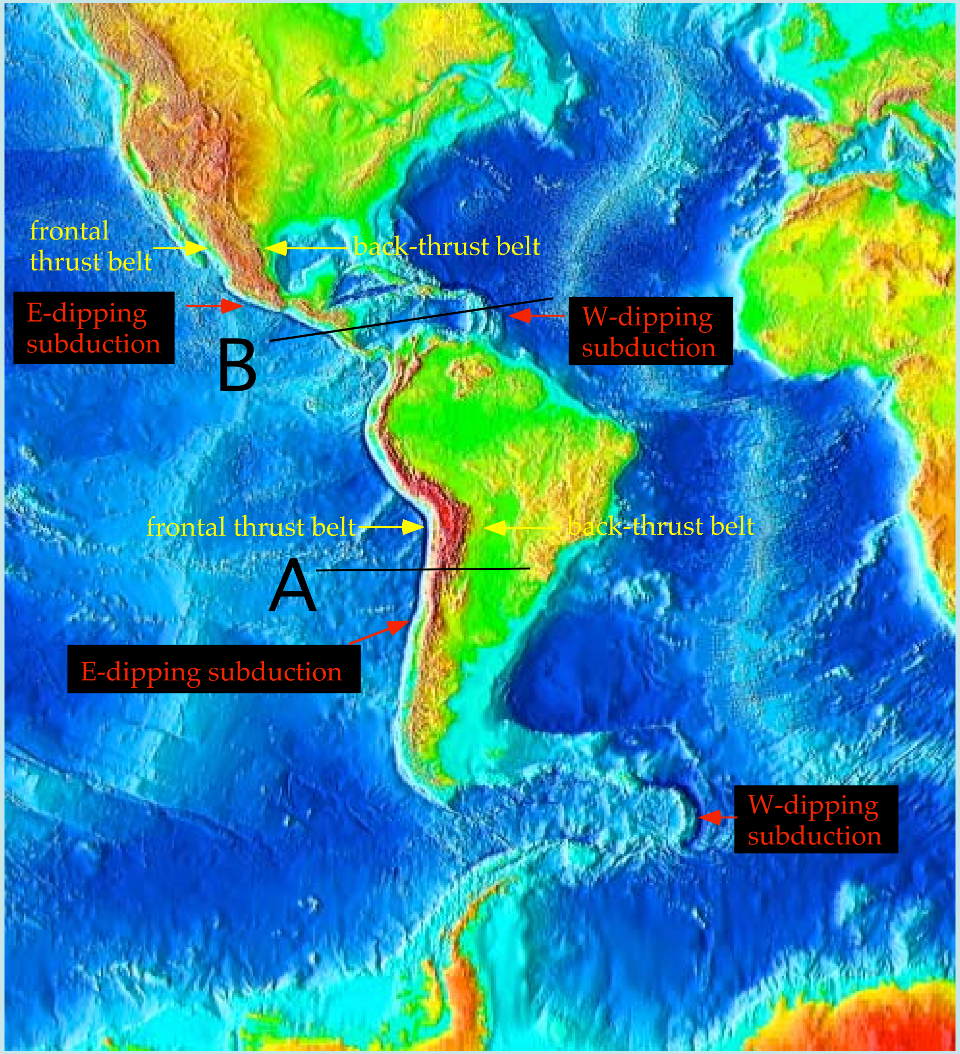
kinematics of the extensional and compressional belts of W-directed subduction zones

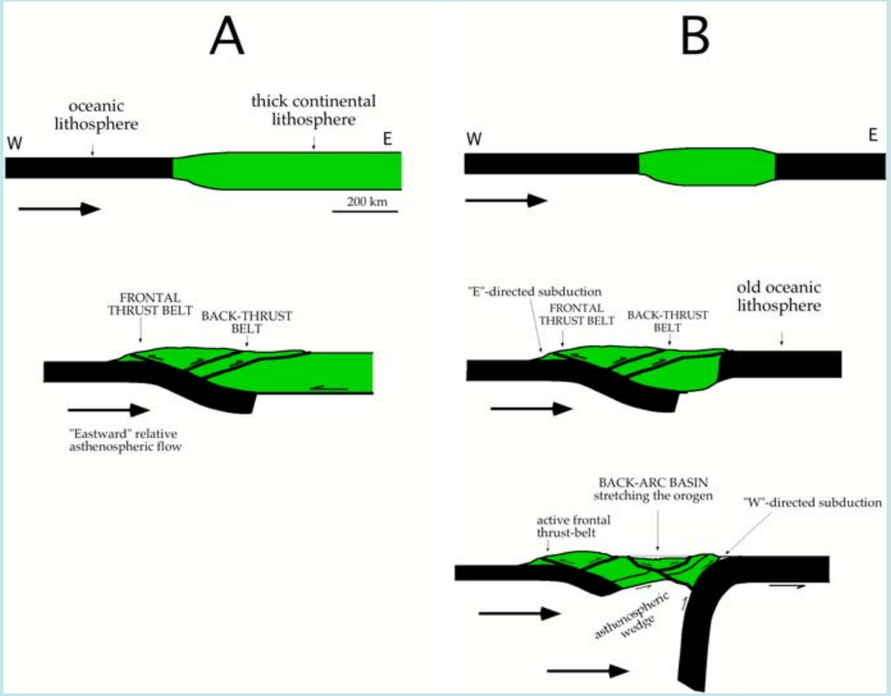


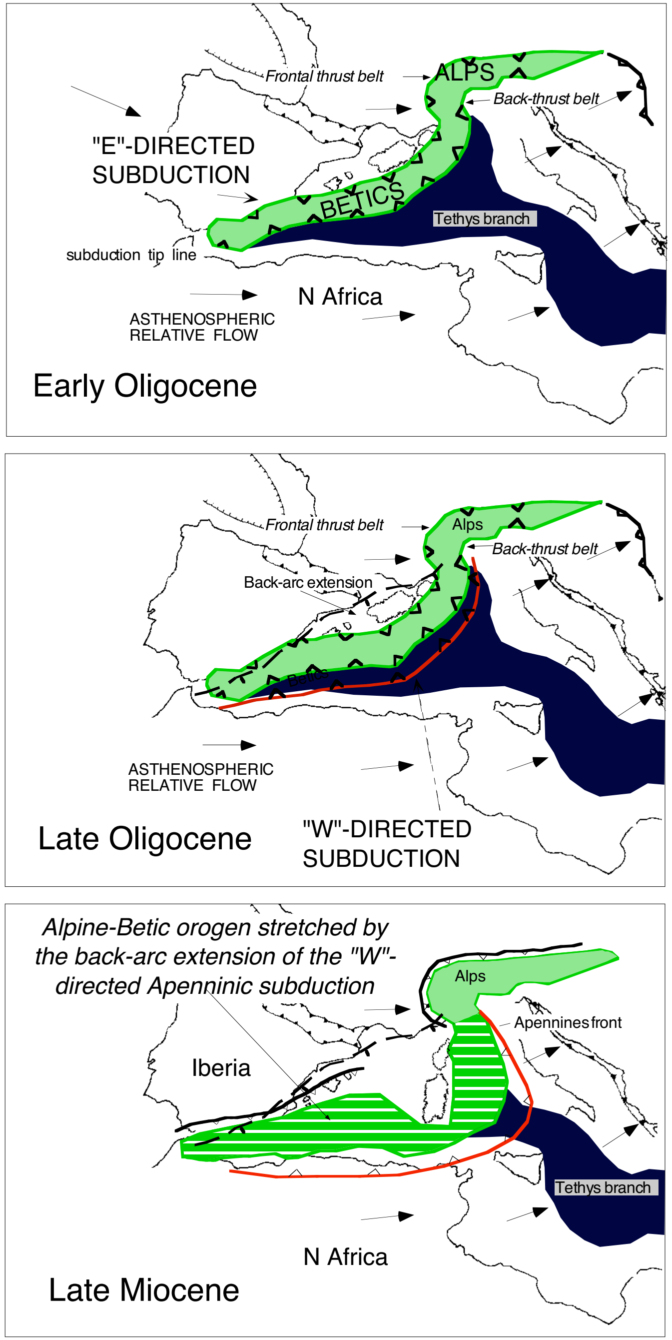

transfer of mass
U
X
L
B
A
z
Ah
H
z=decollement depth
A=accretionary prism area
B=backarc rift area
X=backarc spreading
A=(H-L)z
X=H-Ah= (H-L)/Ah
U
X'
L
B'
A'
Ah'
H
z'
z>z', A>A', X<X', B<B'
A∝z, Ah∝A, B∝X
A=0, Ah=0, X=H
U
Xmax
L
Bmax
H
z=0

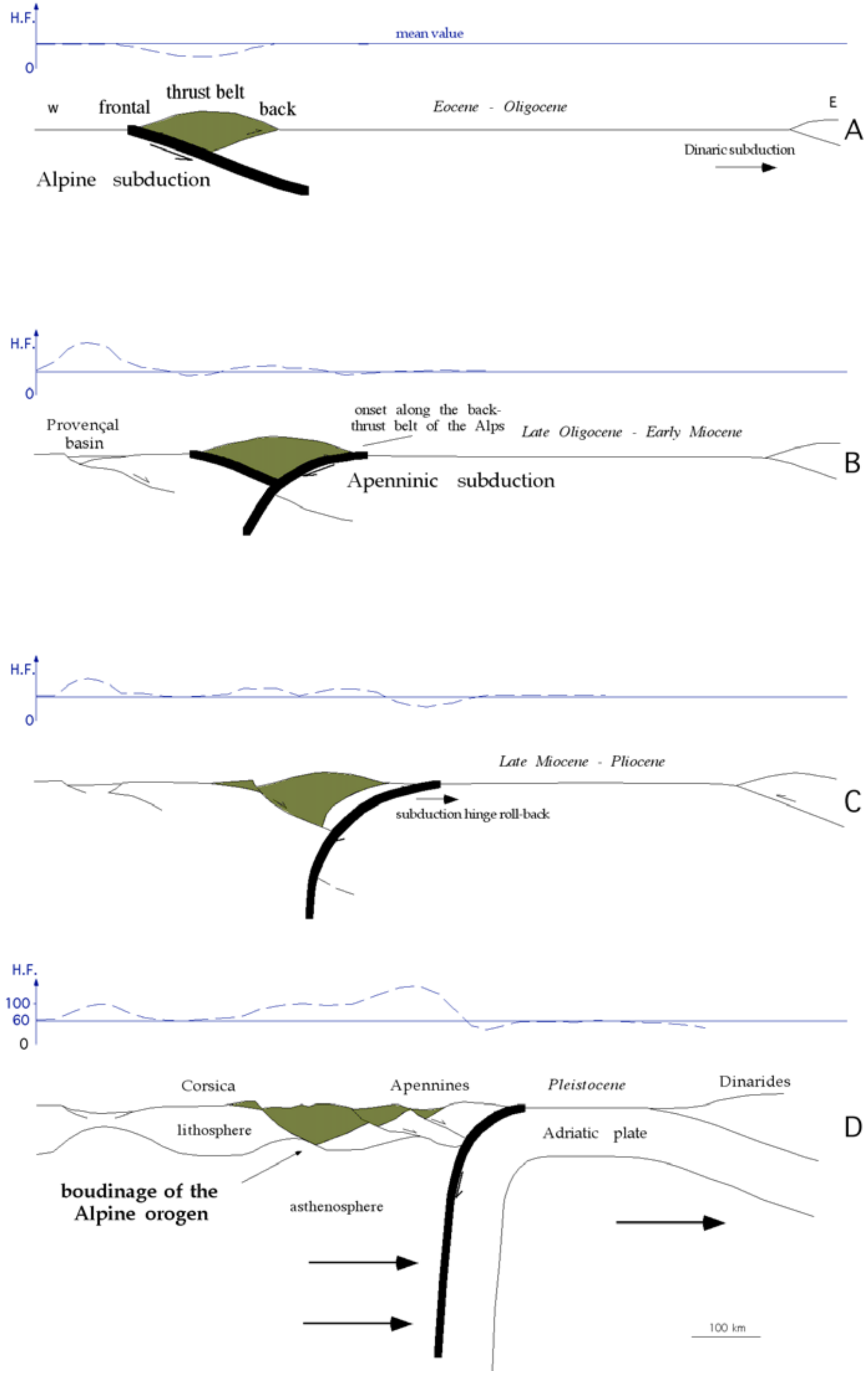


Alps
Adriatic Sea
Albanides
Apennines
Puglia
Tyrrhenian
backarc basin
300 km

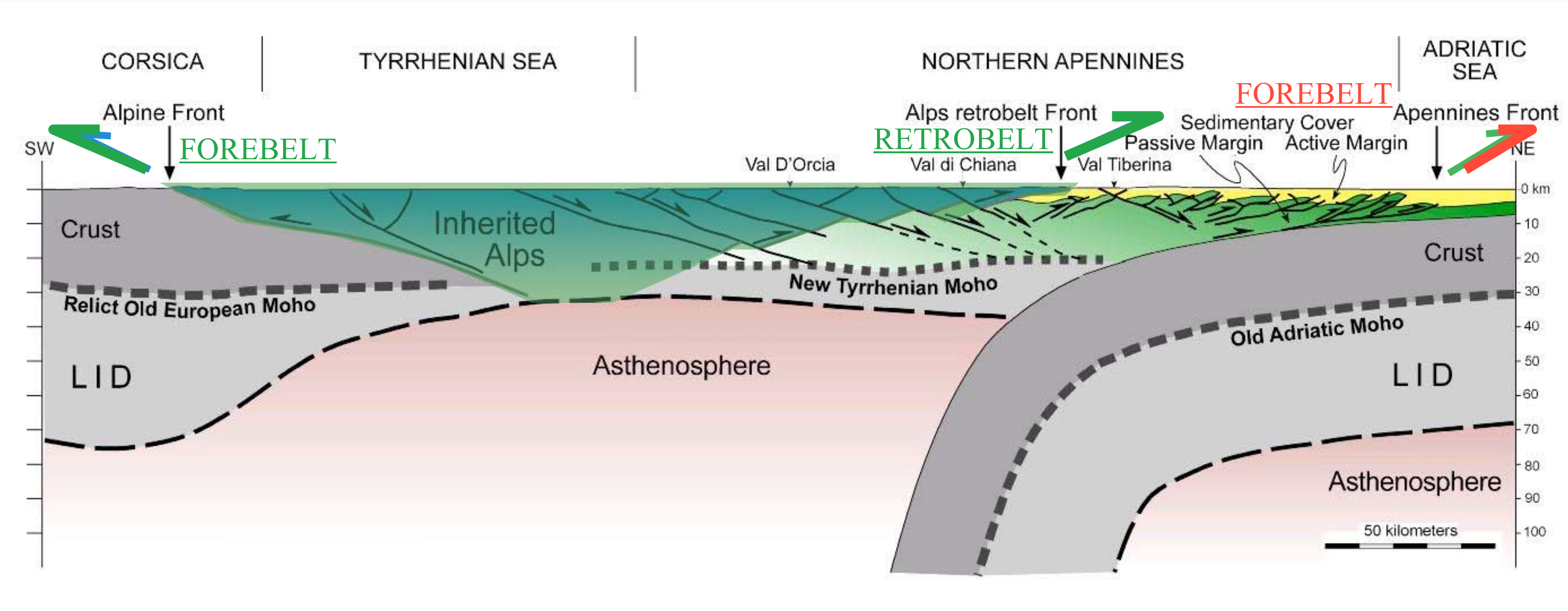

frontal
thrust belt
back-thrust belt
E-dipping
subduction
B
W-dipping
subduction
frontal thrust belt
back-thrust belt
A
E-dipping subduction
W-dipping
subduction

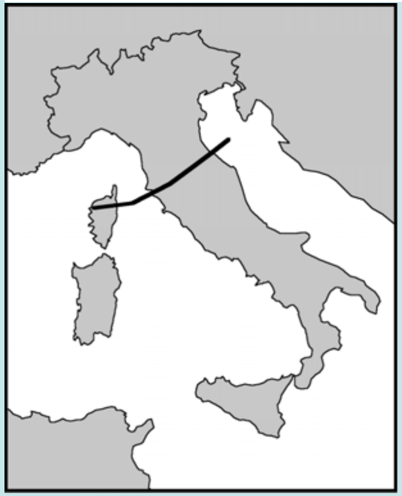

A
B
oceanic
lithosphere
thick continental
lithosphere
W
E
200 km
W
E
FRONTAL
THRUST BELT
BACK-THRUST
BELT
"Eastward" relative
asthenospheric flow
"E"-directed subduction
FRONTAL
THRUST BELT
BACK-THRUST
BELT
old oceanic
lithosphere
BACK-ARC BASIN
stretching the orogen
"W"-directed subduction
active frontal
thrust-belt
asthenospheric
wedge

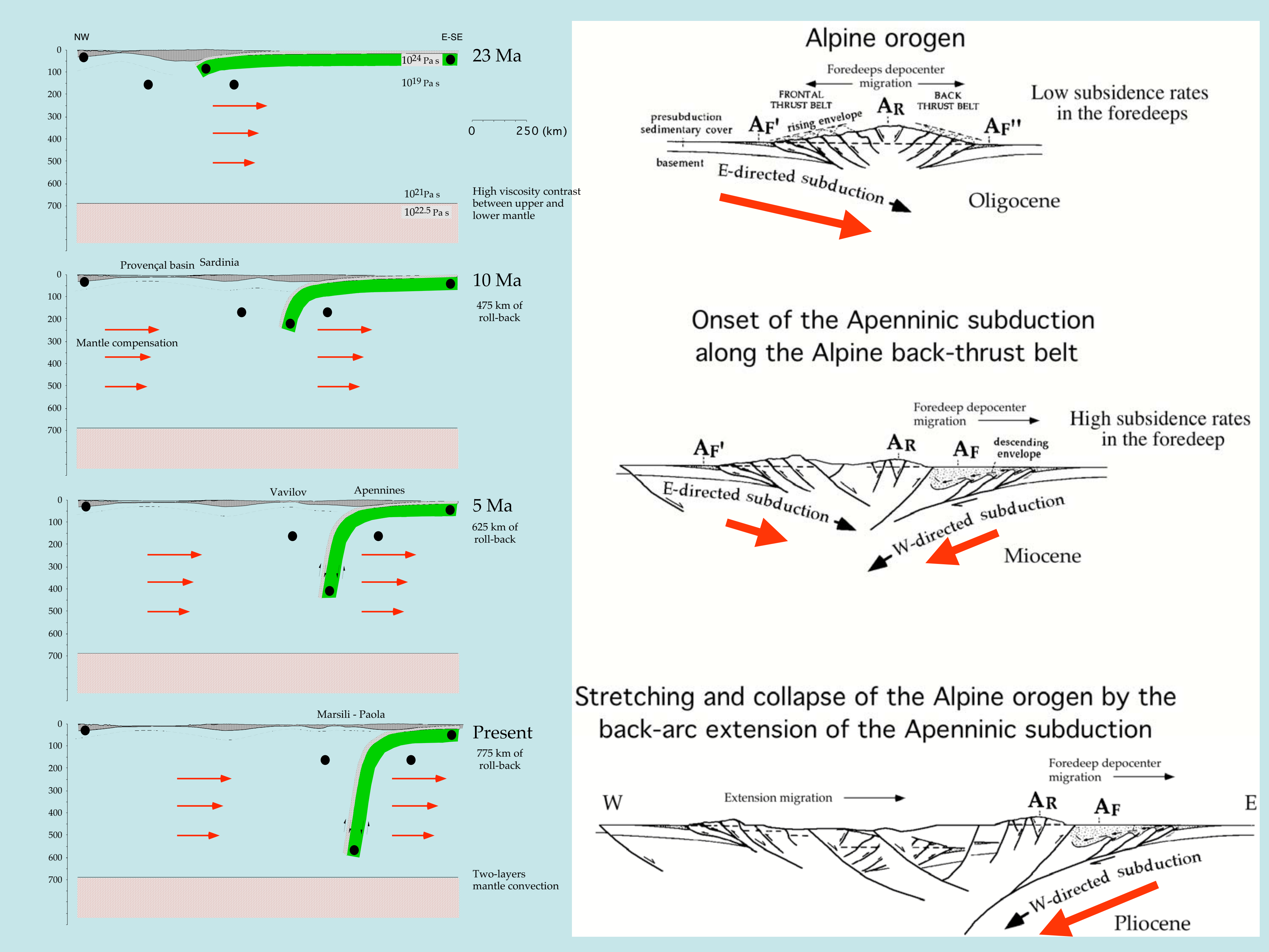

Frontal thrust belt
ALPS
Back-thrust belt
"E"-DIRECTED
SUBDUCTION
BETICS
Tethys branch
subduction tip line
N Africa
ASTHENOSPHERIC
RELATIVE FLOW
Early Oligocene
Frontal thrust belt
Alps
Back-thrust belt
Back-arc extension
ASTHENOSPHERIC
RELATIVE FLOW
Late Oligocene
"W"-DIRECTED
SUBDUCTION
Alpine-Betic orogen stretched by
the back-arc extension of the "W"-
directed Apenninic subduction
Alps
Apennines front
Iberia
Tethys branch
N Africa
Late Miocene


H.F.
0
mean value
W
frontal
thrust belt
back
Eocene - Oligocene
E
A
Alpine subduction
Dinaric subduction
H.F.
0
Provençal
basin
onset along the back-
thrust belt of the Alps
Late Oligocene - Early Miocene
B
Apenninic subduction
H.F.
0
Late Miocene - Pliocene
C
subduction hinge roll-back
H.F.
100
60
0
Corsica
Apennines
Pleistocene
Dinarides
lithosphere
Adriatic plate
D
boudinage of the
Alpine orogen
asthenosphere
100 km

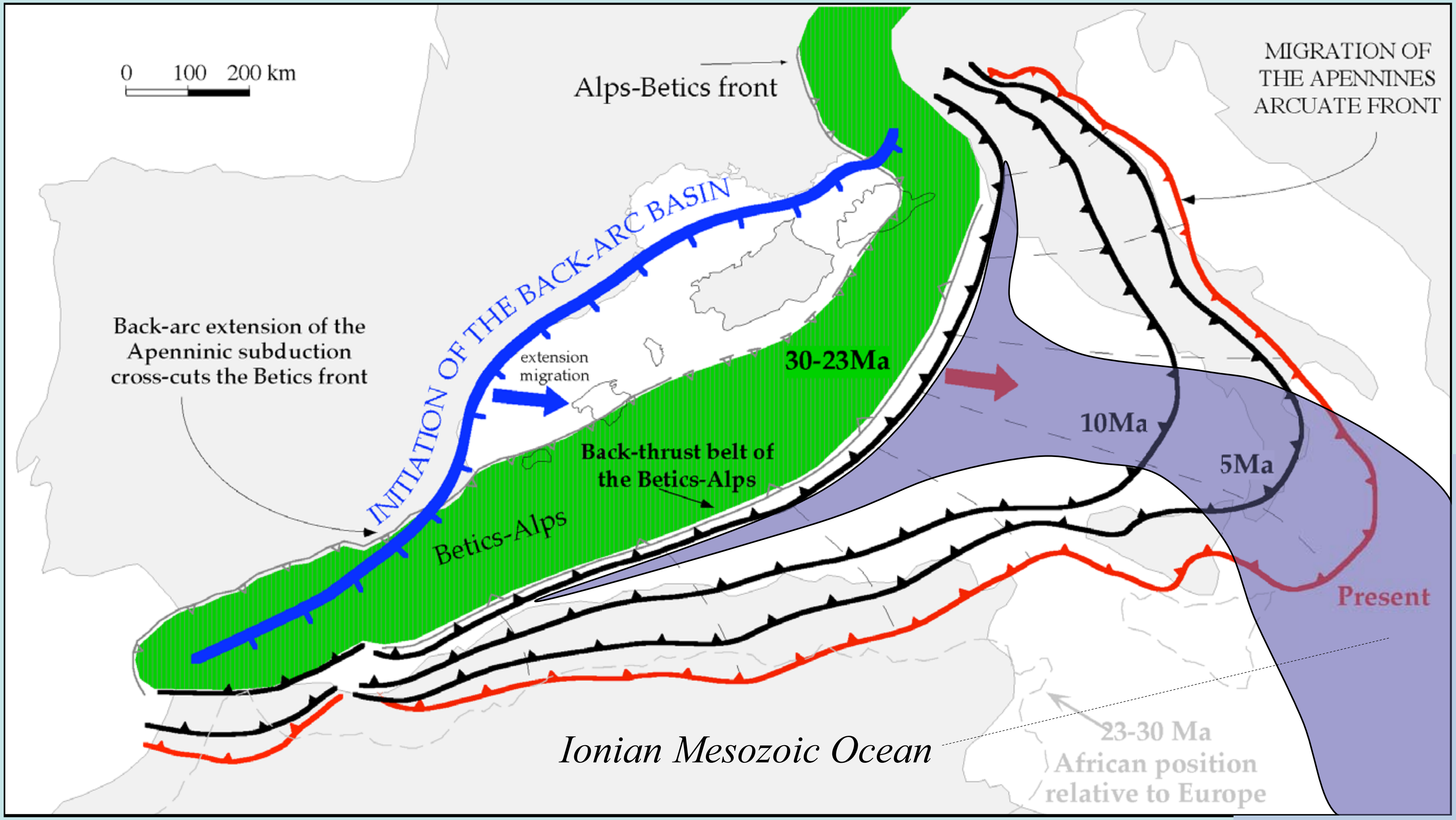
THE ALPS IN THE APENNINES



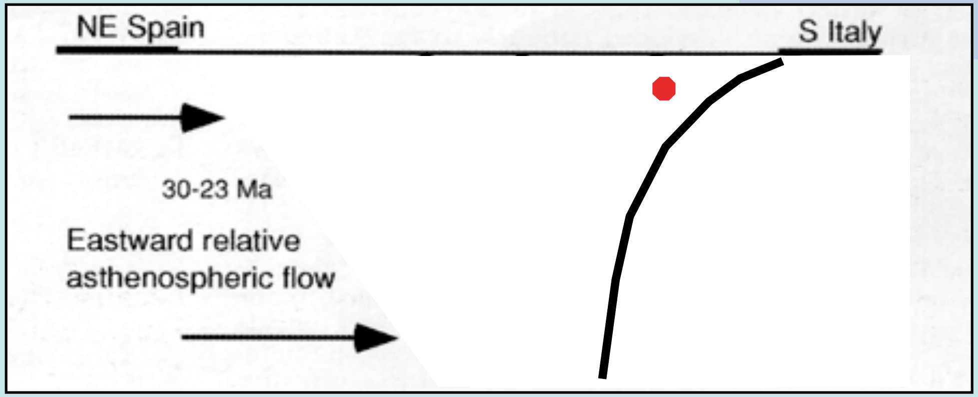




NW
E-SE
23 Ma
10^24 Pa s
10^19 Pa s
0 250 (km)
10^21 Pa s
10^22.5 Pa s
High viscosity contrast between upper and lower mantle
Provençal basin
Sardinia
10 Ma
475 km of roll-back
Mantle compensation
Vavilov
Apennines
5 Ma
625 km of roll-back
Marsili - Paola
Present
775 km of roll-back
Two-layers mantle convection
0
100
200
300
400
500
600
700
Alpine orogen
Foredeeps depocenter migration
FRONTAL THRUST BELT
BACK THRUST BELT
AR
AF'
AF''
rising envelope
presubduction sedimentary cover
basement
E-directed subduction
Low subsidence rates in the foredeeps
Oligocene
Onset of the Apenninic subduction along the Alpine back-thrust belt
Foredeep depocenter migration
High subsidence rates in the foredeep
AF'
AR
AF
descending envelope
E-directed subduction
W-directed subduction
Miocene
Stretching and collapse of the Alpine orogen by the back-arc extension of the Apenninic subduction
Foredeep depocenter migration
W
E
Extension migration
AR
AF
W-directed subduction
Pliocene

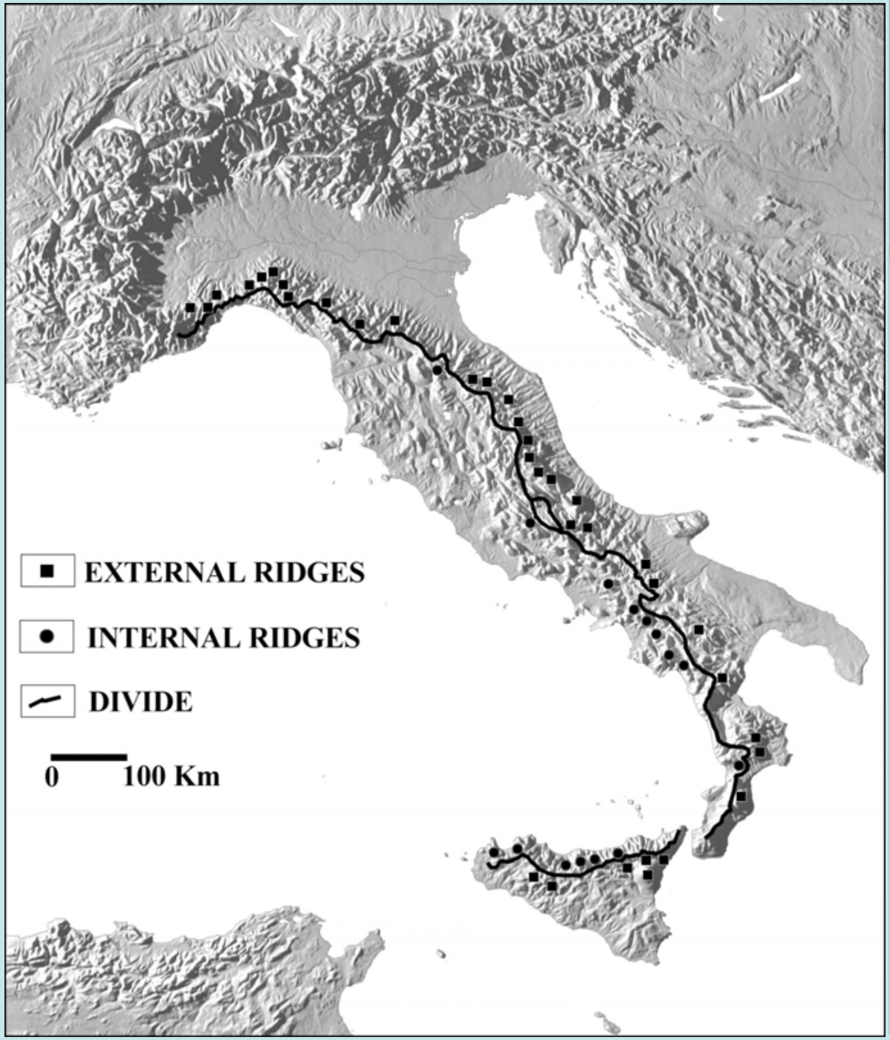


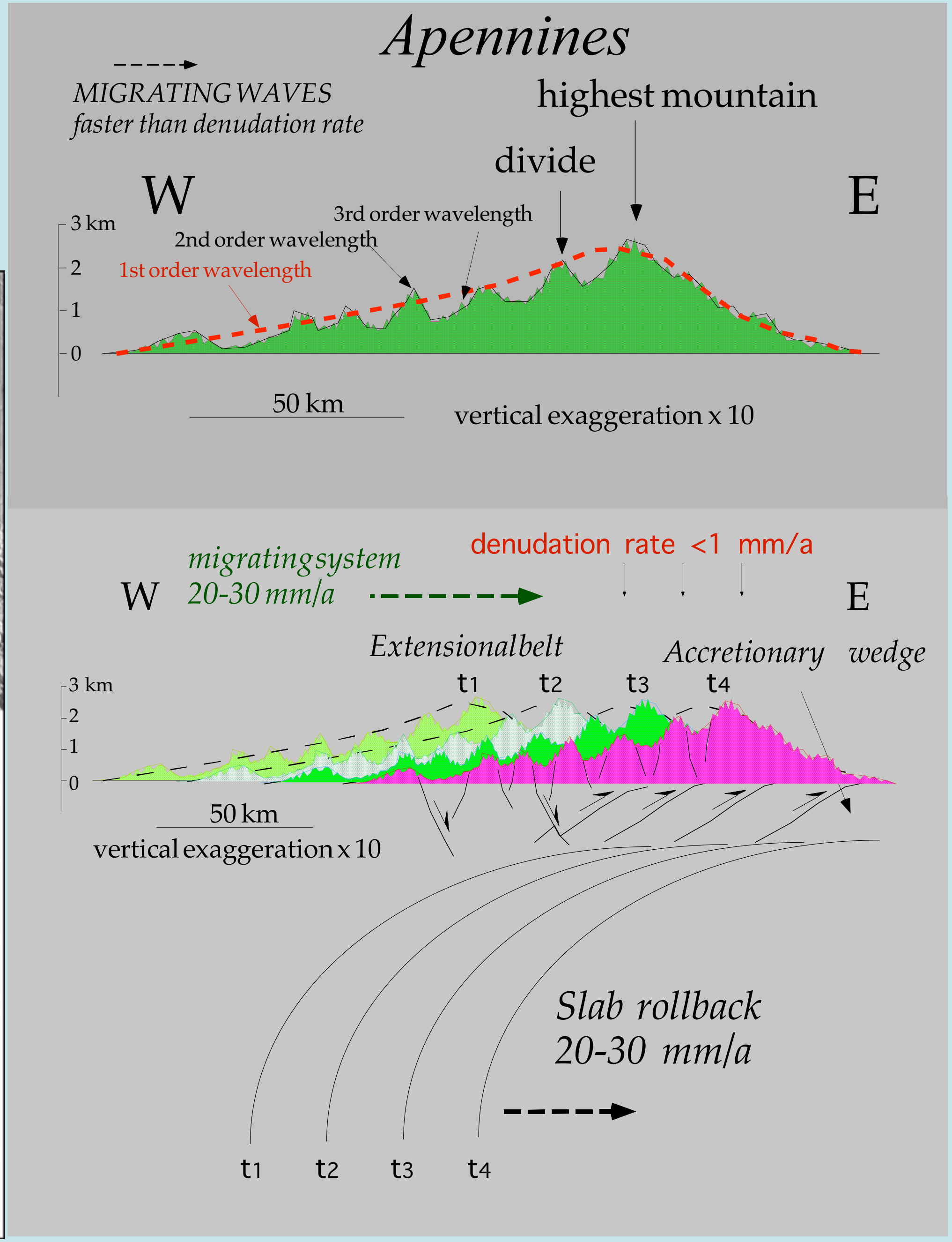
E-ward slab retreat
5 times faster than N-S
convergence



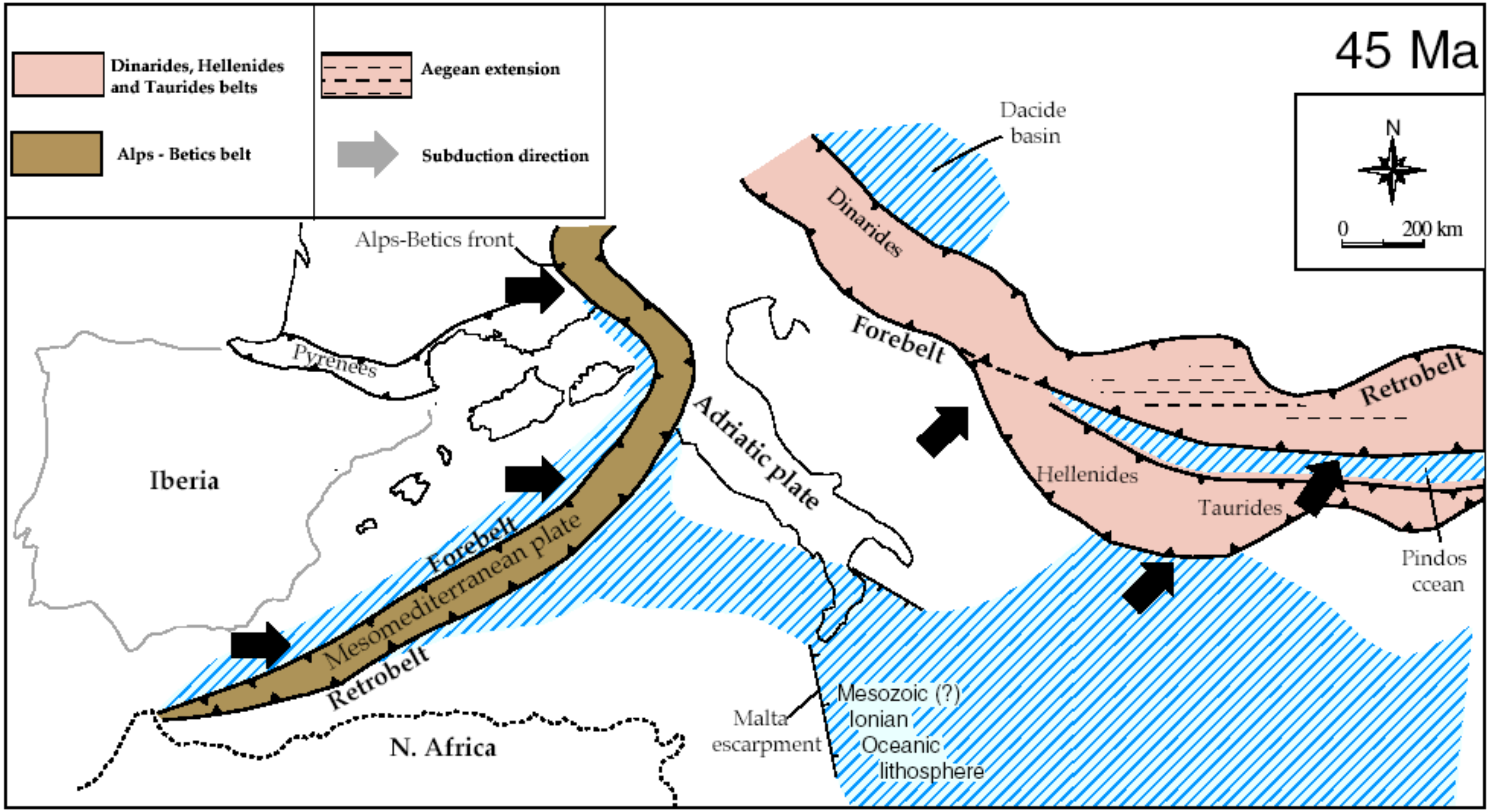
Water divide Vs Highest peaks

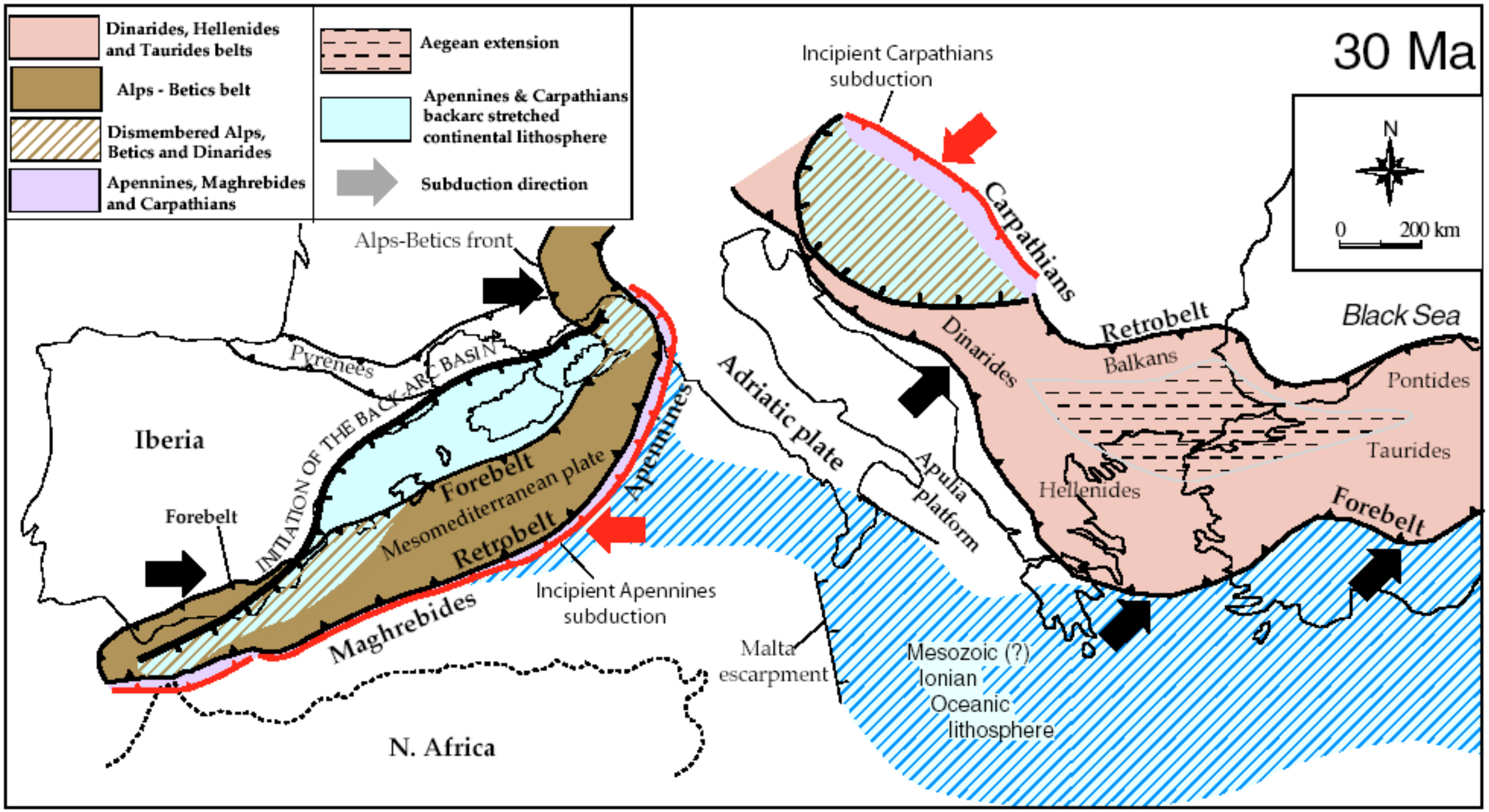
Water divide Vs Highest peaks



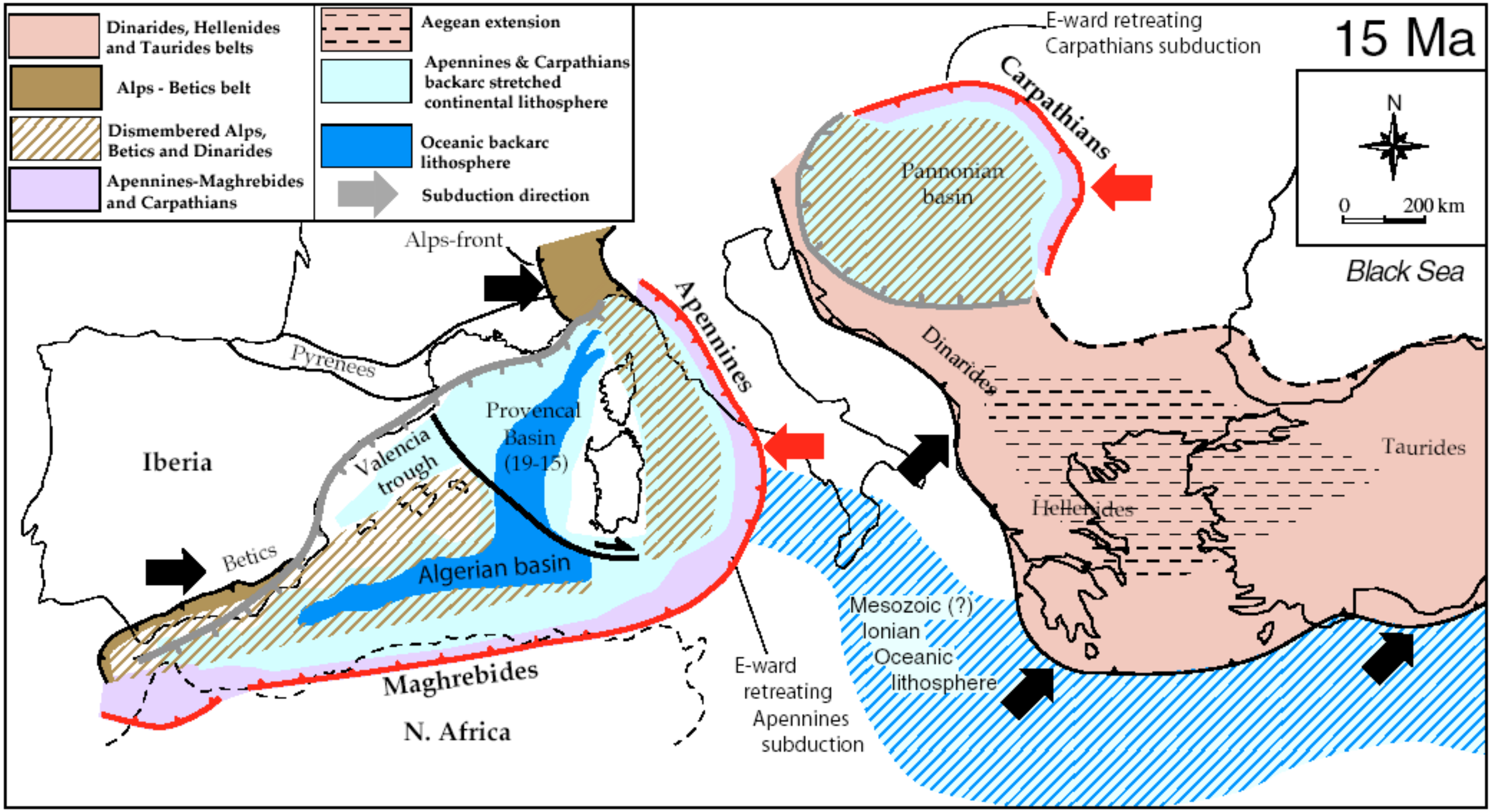


Salustri et al., 2002

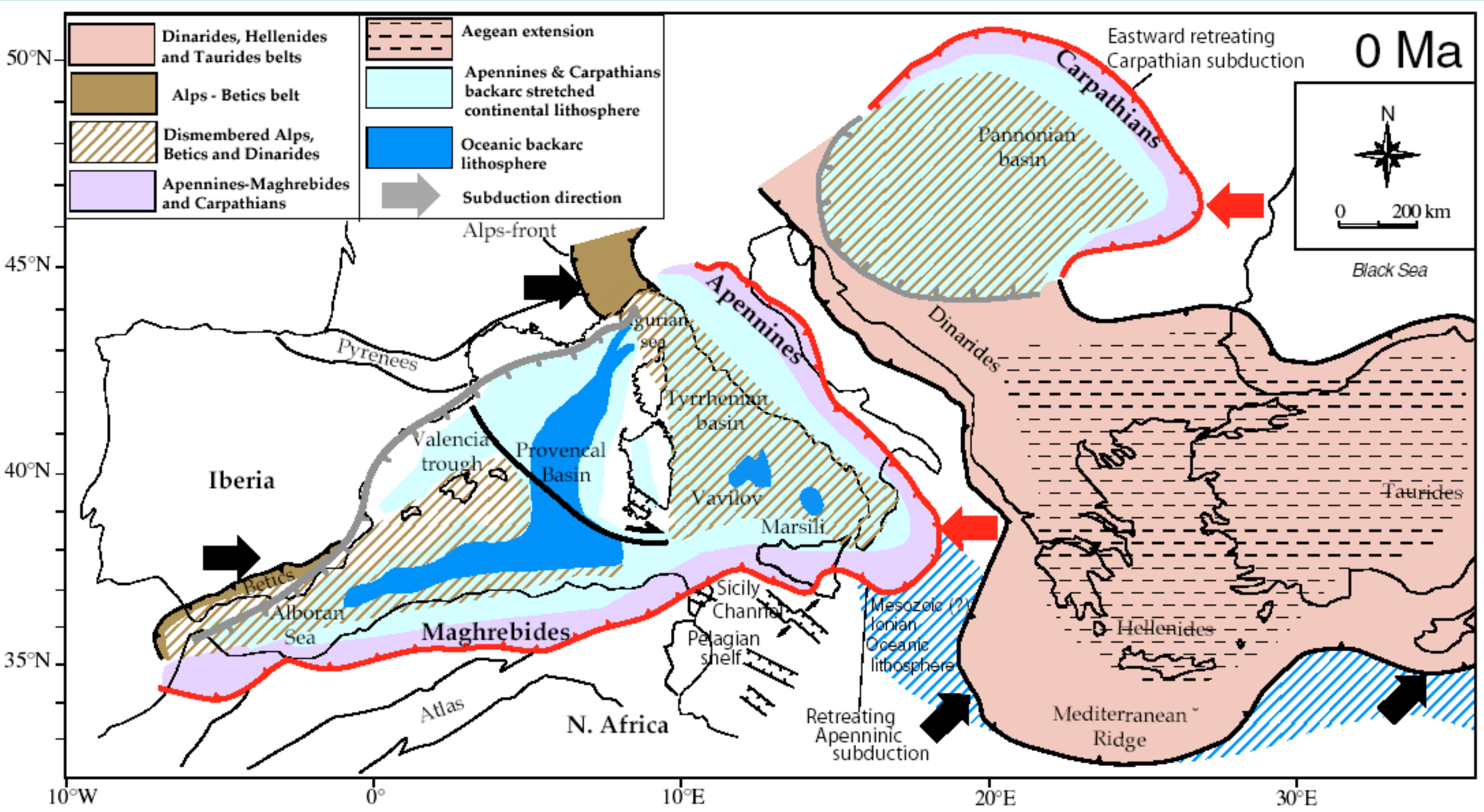

Dinarides, Hellenides and Taurides belts
Aegean extension
Alps - Betics belt
Subduction direction
45 Ma
N
0
200 km
Dacide basin
Dinarides
Alps-Betics front
Pyrenees
Forebelt
Retrobelt
Iberia
Adriatic plate
Hellenides
Taurides
Forebelt
Mesomediterranean plate
Pindos ocean
Retrobelt
Malta escarpment
Mesozoic (?) Ionian Oceanic lithosphere
N. Africa



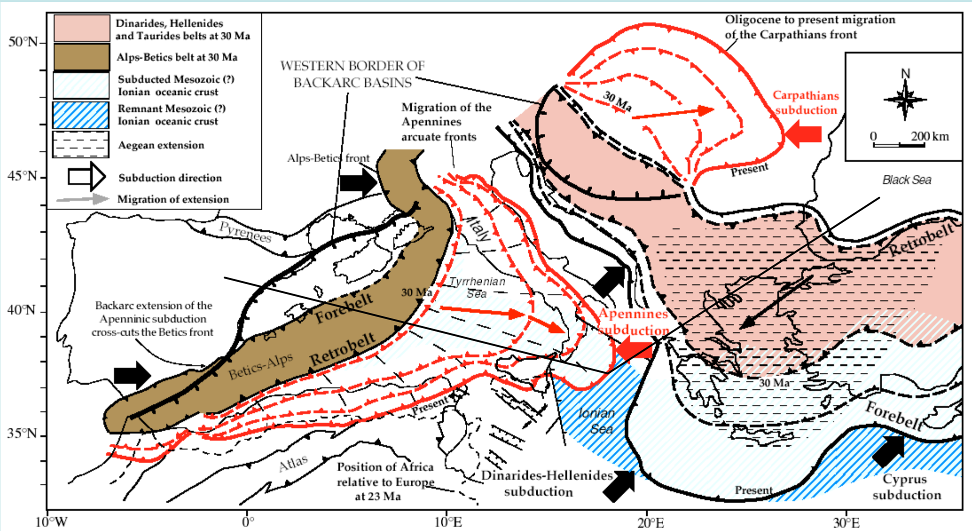
Dinarides, Hellenides and Taurides belts
Alps - Betics belt
Dismembered Alps, Betics and Dinarides
Apennines, Maghrebides and Carpathians
Aegean extension
Apennines & Carpathians backarc stretched continental lithosphere
Subduction direction
30 Ma
Incipient Carpathians subduction
N
0 200 km
Carpathians
Black Sea
Retrobelt
Balkans
Pontides
Dinarides
Taurides
Hellenides
Forebelt
Alps-Betics front
Pyrenees
INITIATION OF THE BACK-ARC BASIN
Iberia
Forebelt
Mesomediterranean plate
Retrobelt
Apennines
Adriatic plate
Apulia platform
Maghrebides
Incipient Apennines subduction
Malta escarpment
Mesozoic (?) Ionian Oceanic lithosphere
N. Africa



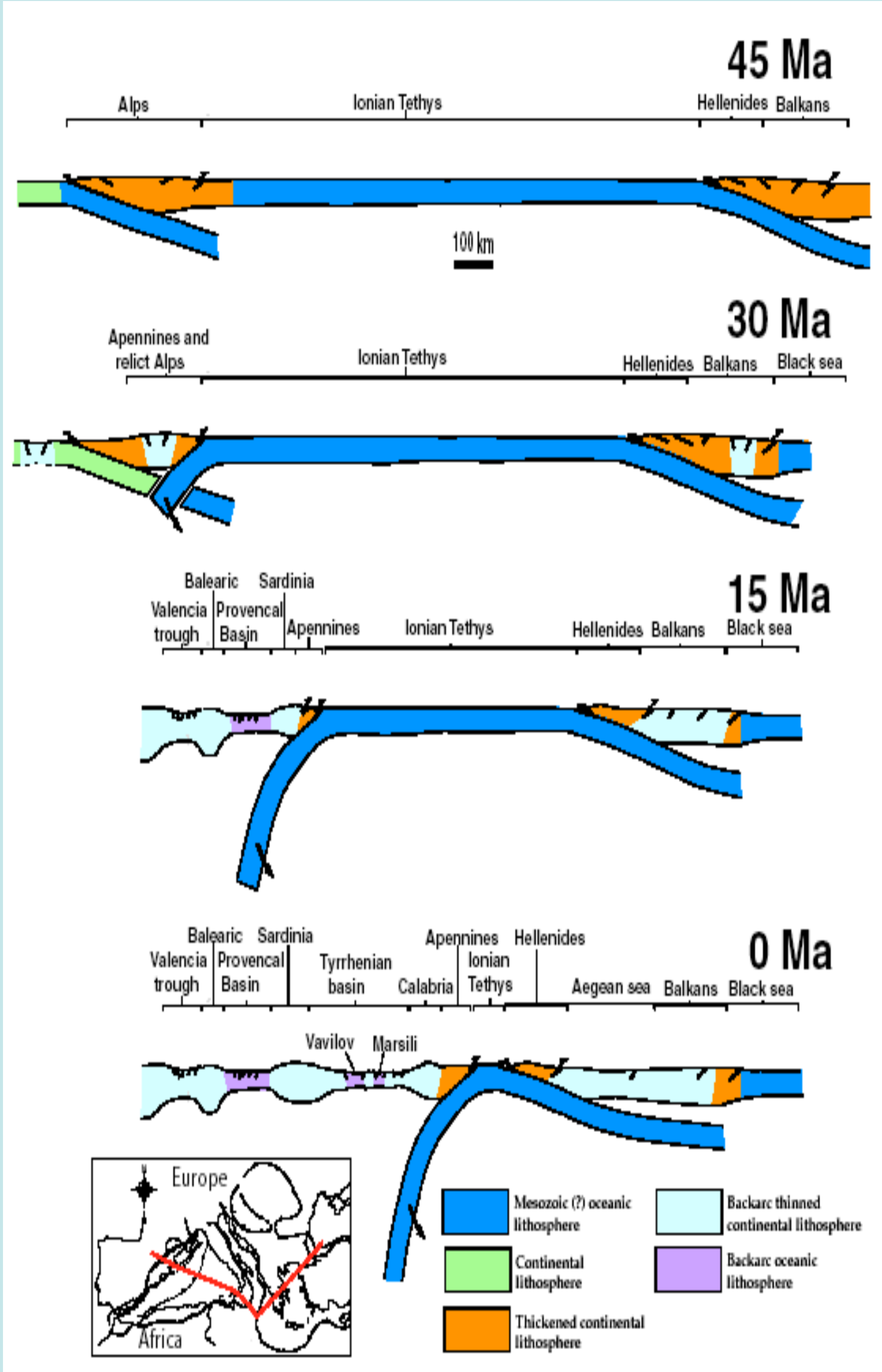
Dinarides, Hellenides and Taurides belts
Alps - Betics belt
Dismembered Alps, Betics and Dinarides
Apennines-Maghrebides and Carpathians
Aegean extension
Apennines & Carpathians backarc stretched continental lithosphere
Oceanic backarc lithosphere
Subduction direction
E-ward retreating Carpathians subduction
15 Ma
N
0
200 km
Black Sea
Carpathians
Pannonian basin
Alps-front
Apennines
Pyrenees
Iberia
Valencia trough
Provencal Basin (19-15)
Dinarides
Taurides
Hellenides
Betics
Algerian basin
Mesozoic (?) Ionian Oceanic lithosphere
E-ward retreating Apennines subduction
Maghrebides
N. Africa



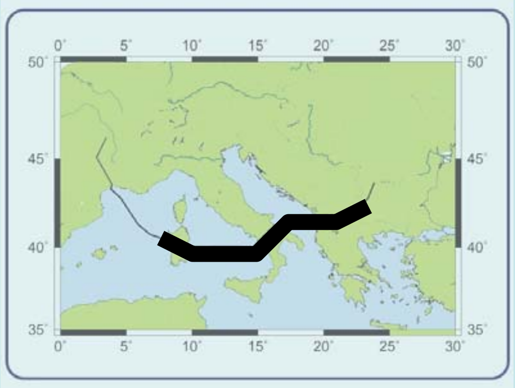
Dinarides, Hellenides and Taurides belts
Alps - Betics belt
Dismembered Alps, Betics and Dinarides
Apennines-Maghrebides and Carpathians
Aegean extension
Apennines & Carpathians backarc stretched continental lithosphere
Oceanic backarc lithosphere
Subduction direction
Eastward retreating Carpathian subduction
0 Ma
N
0 200 km
Black Sea
Carpathians
Pannonian basin
Dinarides
Apennines
Alps-front
Pyrenees
Ligurian sea
Tyrrhenian basin
Valencia trough
Provencal Basin
Iberia
Vavilov
Marsili
Betics
Alboran Sea
Maghrebides
Sicily Channel
Pelagian shelf
Mesozoic (?) Ionian Oceanic lithosphere
Taurides
Hellenides
Mediterranean Ridge
Retreating Apenninic subduction
Atlas
N. Africa
50°N
45°N
40°N
35°N
10°W
0°
10°E
20°E
30°E

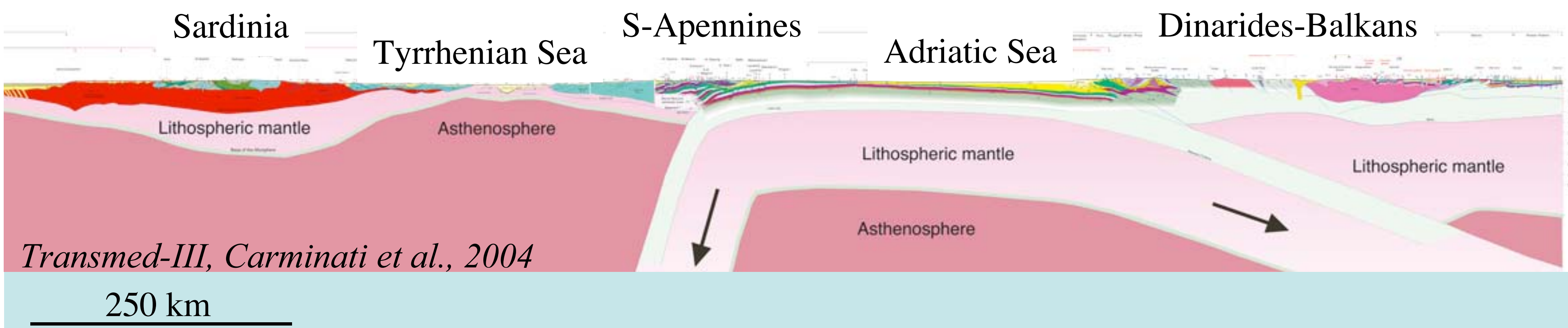


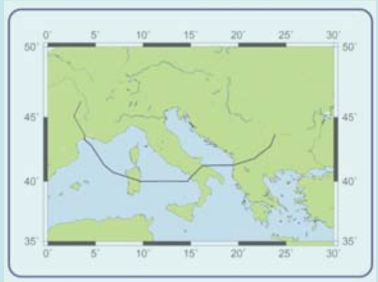
Dinarides, Hellenides and Taurides belts at 30 Ma
Alps-Betics belt at 30 Ma
Subducted Mesozoic (?) Ionian oceanic crust
Remnant Mesozoic (?) Ionian oceanic crust
Aegean extension
Subduction direction
Migration of extension
WESTERN BORDER OF BACKARC BASINS
Migration of the Apennines arcuate fronts
Oligocene to present migration of the Carpathians front
Carpathians subduction
Alps-Betics front
Pyrenees
Italy
Tyrrhenian Sea
Forebelt
Retrobelt
Betics-Alps
30 Ma
Present
Apennines subduction
Backarc extension of the Apenninic subduction cross-cuts the Betics front
Black Sea
Ionian Sea
Atlas
Position of Africa relative to Europe at 23 Ma
Dinarides-Hellenides subduction
Cyprus subduction
N
0 200 km
50°N
45°N
40°N
35°N
10°W
0°
10°E
20°E
30°E

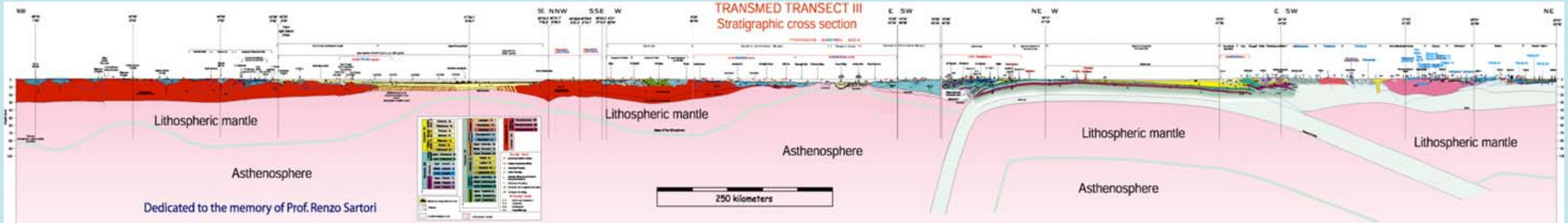


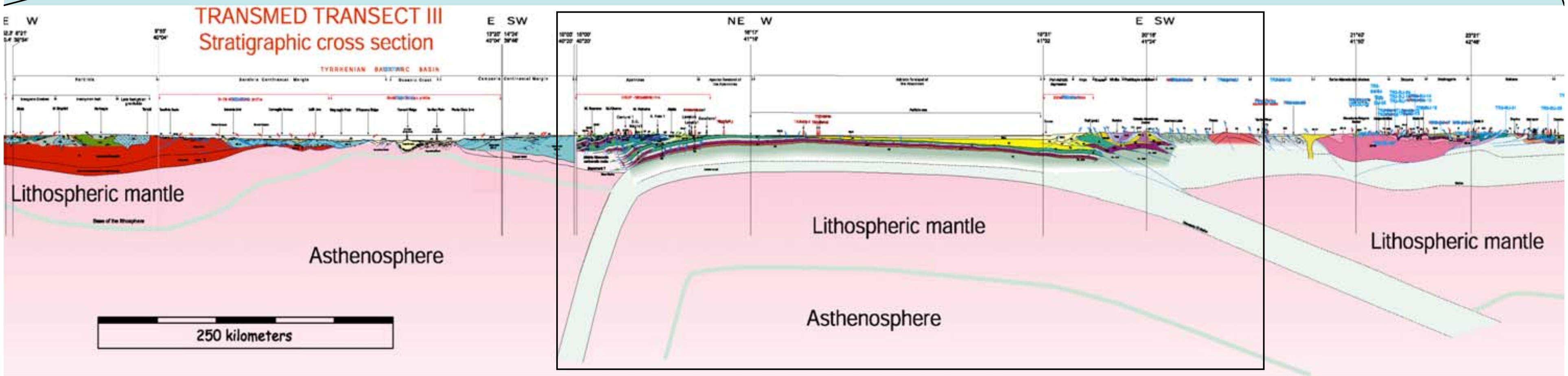
45 Ma
Alps
Ionian Tethys
Hellenides Balkans
100 km
30 Ma
Apennines and relict Alps
Ionian Tethys
Hellenides Balkans Black sea
15 Ma
Valencia trough
Balearic Provencal Basin
Sardinia
Apennines
Ionian Tethys
Hellenides Balkans
Black sea
0 Ma
Valencia trough
Balearic Provencal Basin
Sardinia
Tyrrhenian basin
Calabria
Apennines
Ionian Tethys
Hellenides
Aegean sea
Balkans
Black sea
Vavilov
Marsili
Europe
Africa
Mesozoic (?) oceanic lithosphere
Continental lithosphere
Thickened continental lithosphere
Backarc thinned continental lithosphere
Backarc oceanic lithosphere

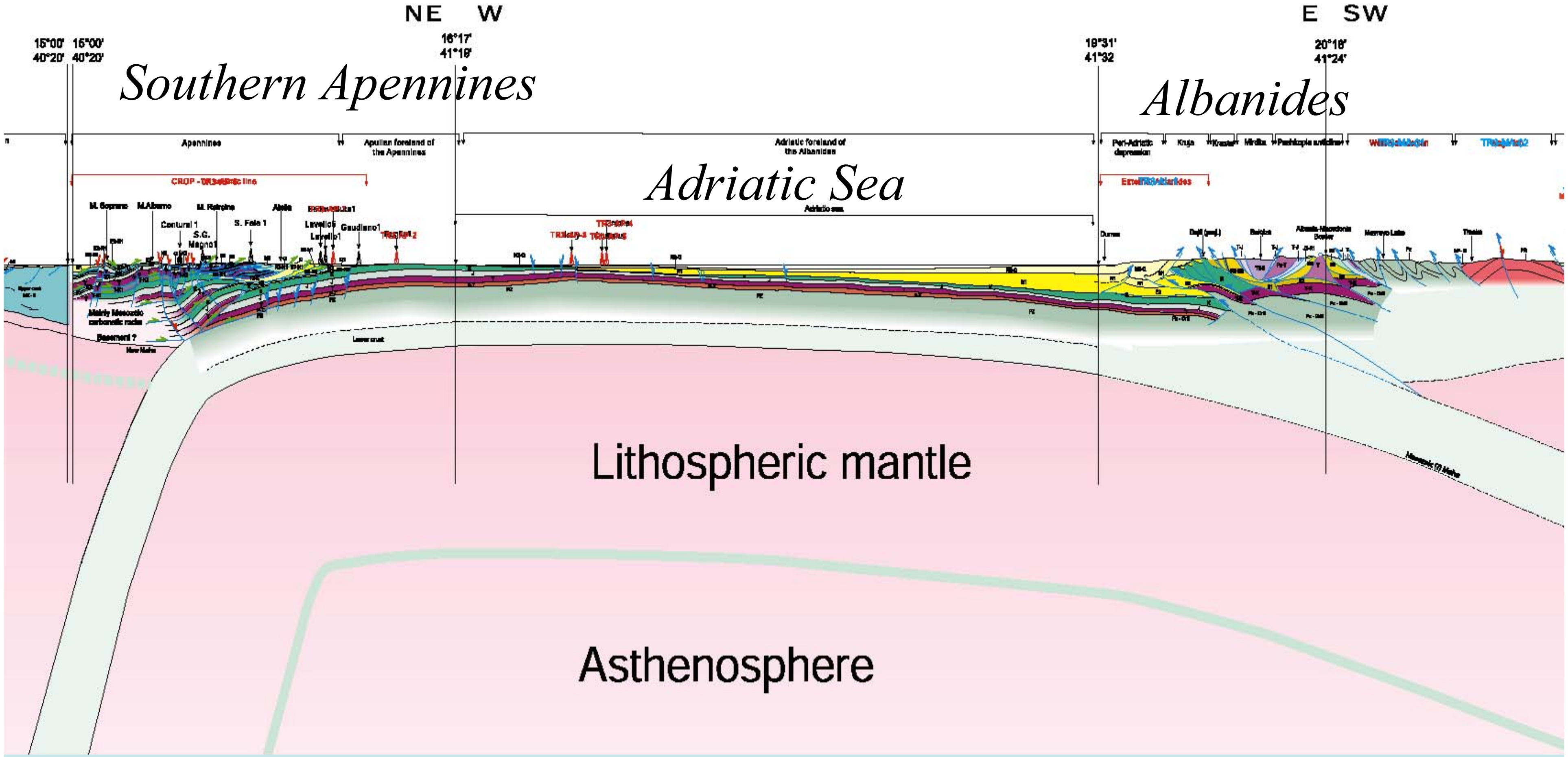

0°
5°
10°
15°
20°
25°
30°
50°
45°
40°
35°


Sardinia
Tyrrhenian Sea
S-Apennines
Adriatic Sea
Dinarides-Balkans
Lithospheric mantle
Asthenosphere
Lithospheric mantle
Asthenosphere
Lithospheric mantle
Transmed-III, Carminati et al., 2004
250 km




TRANSMED TRANSECT III
Stratigraphic cross section
Lithospheric mantle
Asthenosphere
Lithospheric mantle
Asthenosphere
Lithospheric mantle
Asthenosphere
Lithospheric mantle
250 kilometers
Dedicated to the memory of Prof. Renzo Sartori


TRANSMED TRANSECT III
Stratigraphic cross section
E W
E SW
NE W
E SW
Lithospheric mantle
Asthenosphere
Lithospheric mantle
Asthenosphere
Lithospheric mantle
250 kilometers


NE W
E SW
15°00' 40°20'
15°00' 40°20'
16°17' 41°18'
19°31' 41°32
20°18' 41°24'
Southern Apennines
Albanides
Adriatic Sea
Apennines
Apulian foreland of the Apennines
Adriatic foreland of the Albanides
Peri-Adriatic depression
Kruja
Mirdita
Lithospheric mantle
Asthenosphere

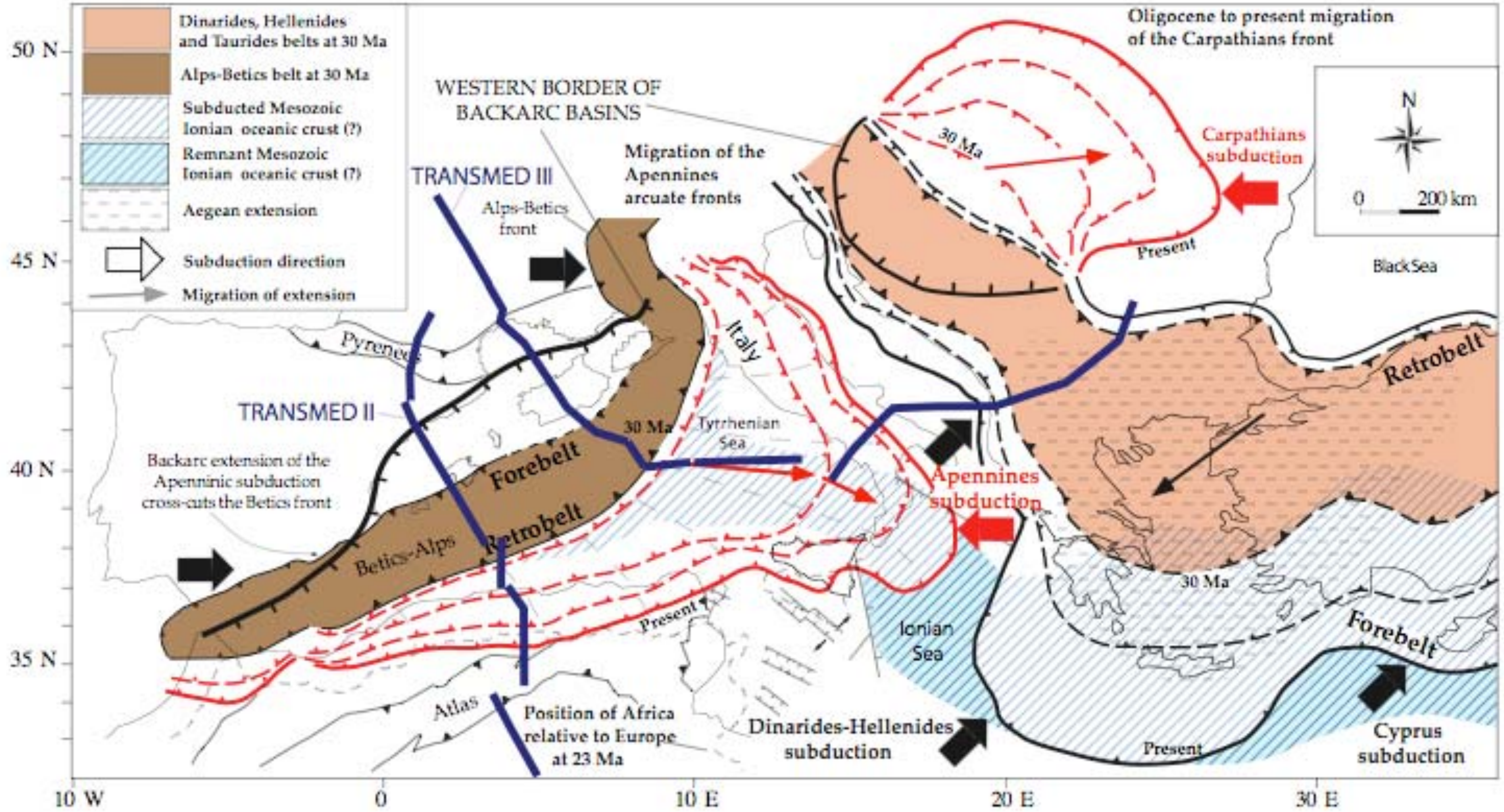
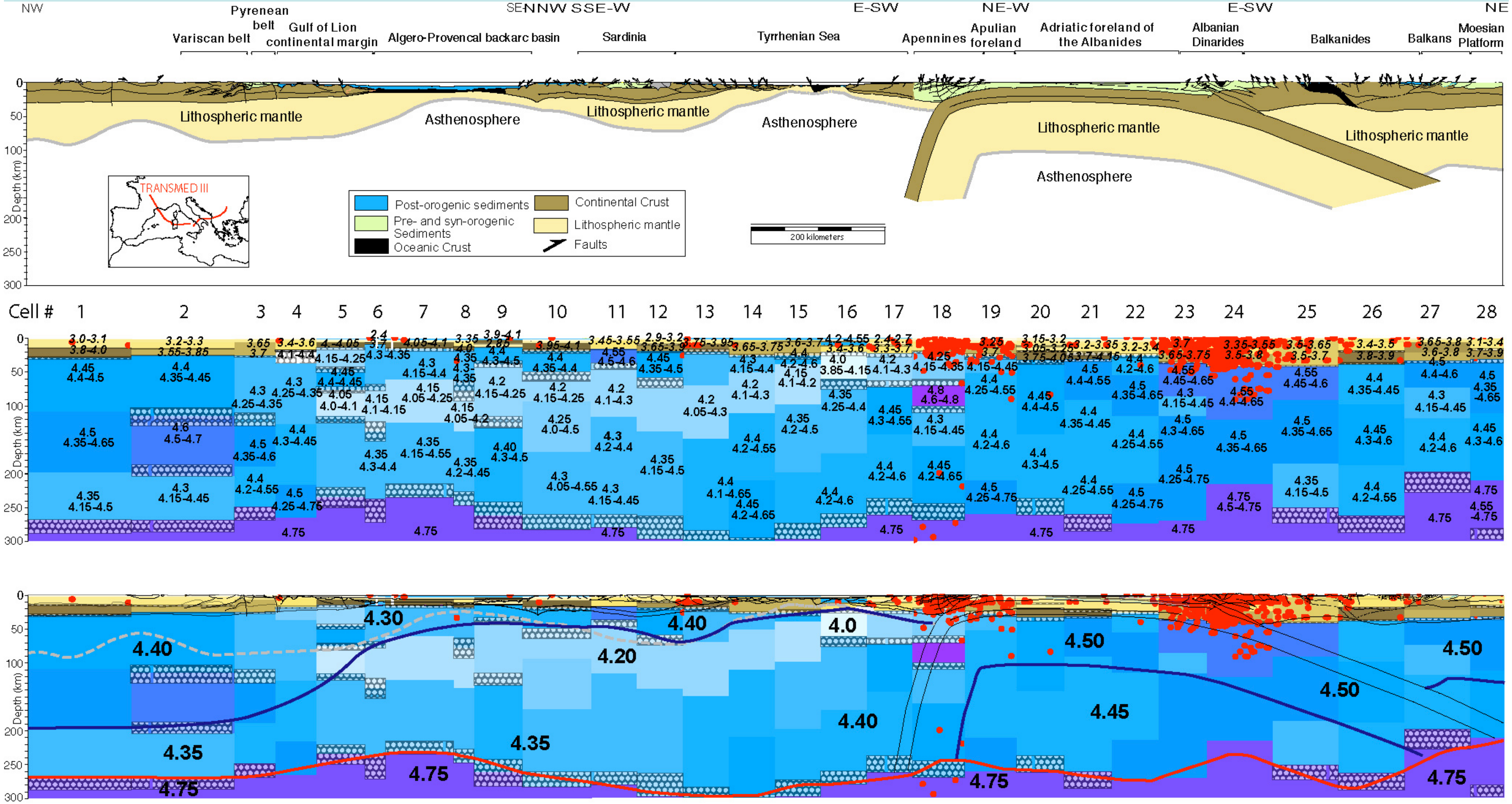
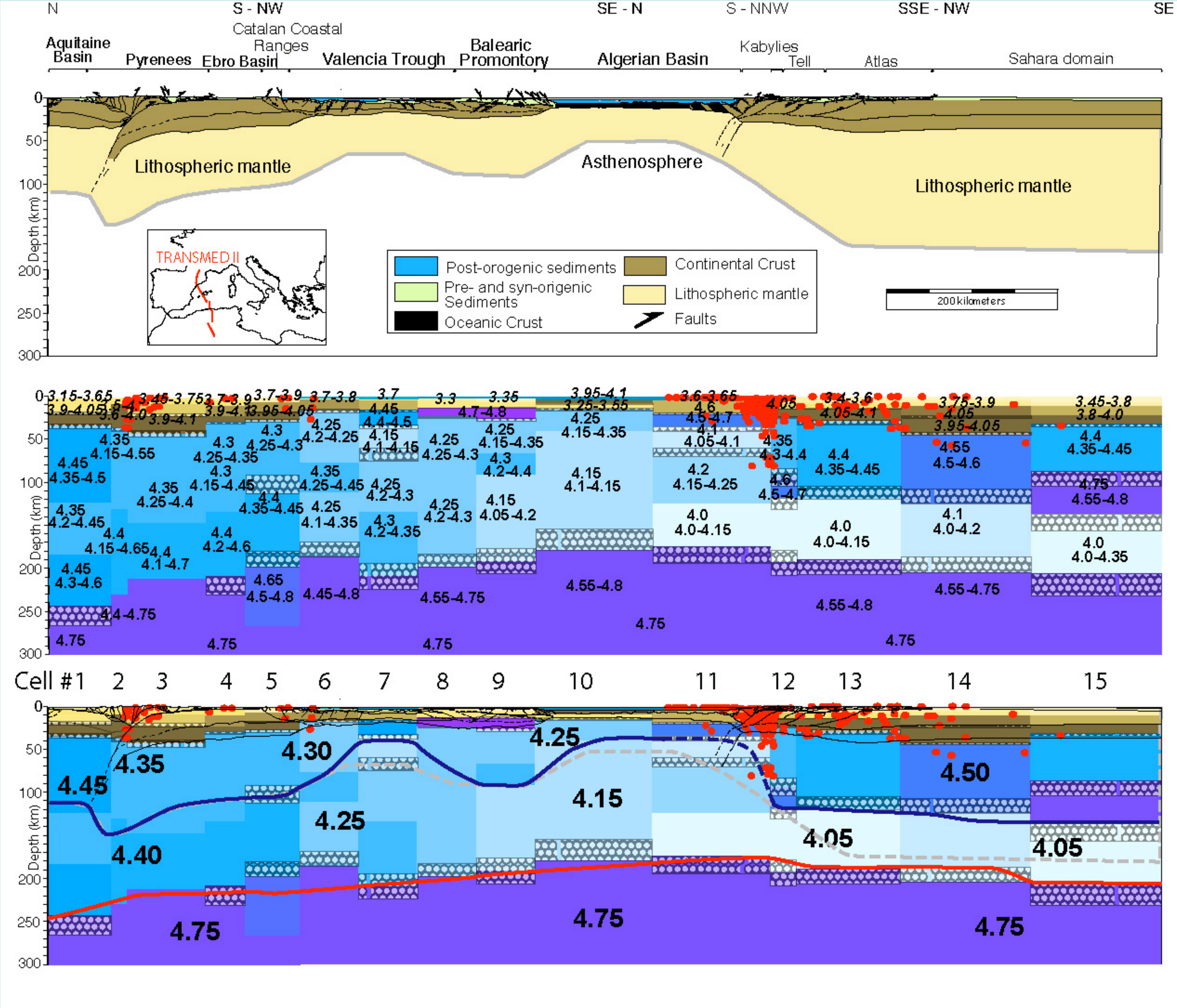

Dinarides, Hellenides and Taurides belts at 30 Ma
Alps-Betics belt at 30 Ma
Subducted Mesozoic Ionian oceanic crust (?)
Remnant Mesozoic Ionian oceanic crust (?)
Aegean extension
Subduction direction
Migration of extension
WESTERN BORDER OF BACKARC BASINS
TRANSMED III
TRANSMED II
Alps-Betics front
Migration of the Apennines arcuate fronts
Oligocene to present migration of the Carpathians front
Carpathians subduction
30 Ma
Present
Black Sea
0 200 km
N
Pyrenees
Italy
Tyrrhenian Sea
Forebelt
Retrobelt
Betics-Alps
Backarc extension of the Apenninic subduction cross-cuts the Betics front
Apennines subduction
Ionian Sea
Atlas
Position of Africa relative to Europe at 23 Ma
Dinarides-Hellenides subduction
Cyprus subduction
50 N
45 N
40 N
35 N
10 W
0
10 E
20 E
30 E

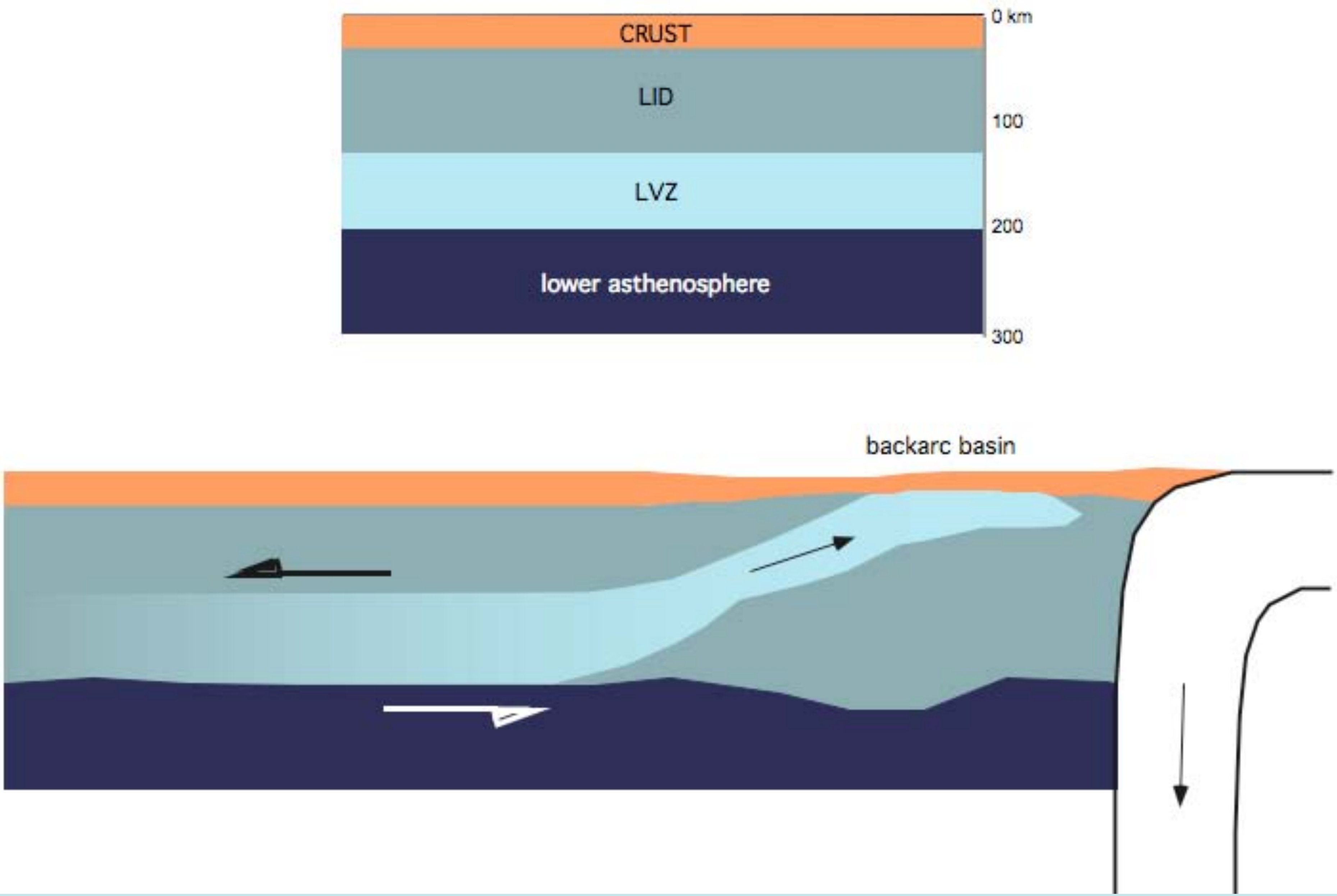
Fig.1



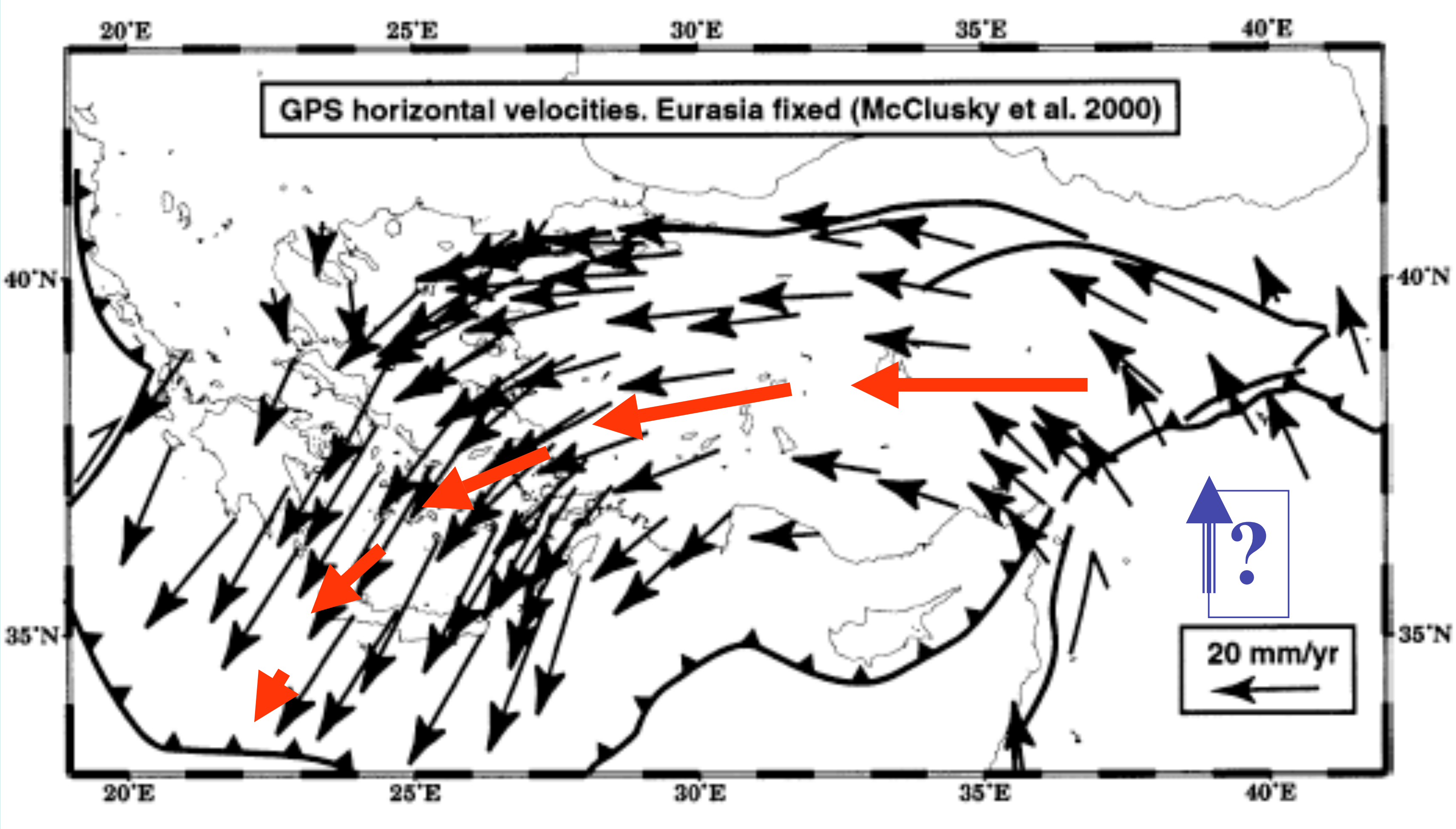
Panza et al. 2006



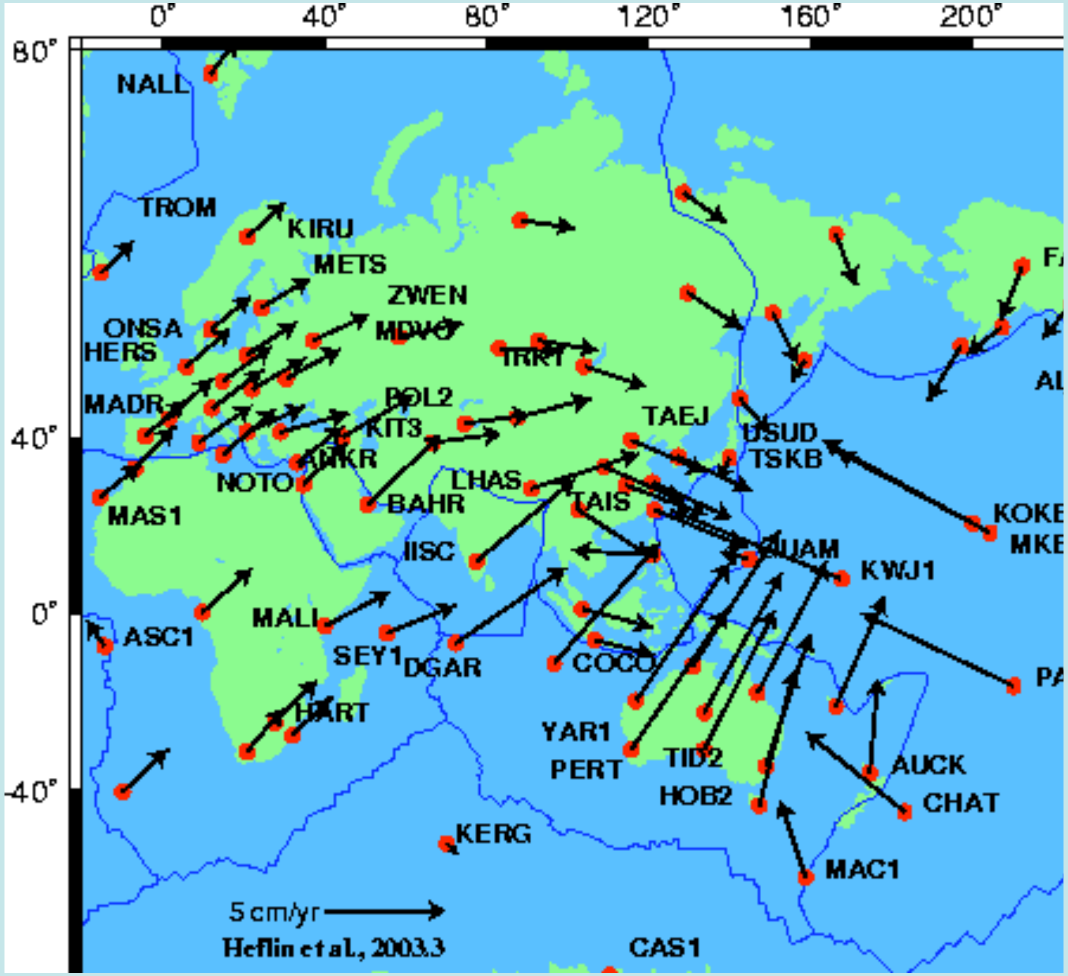
Panza et al. 2006

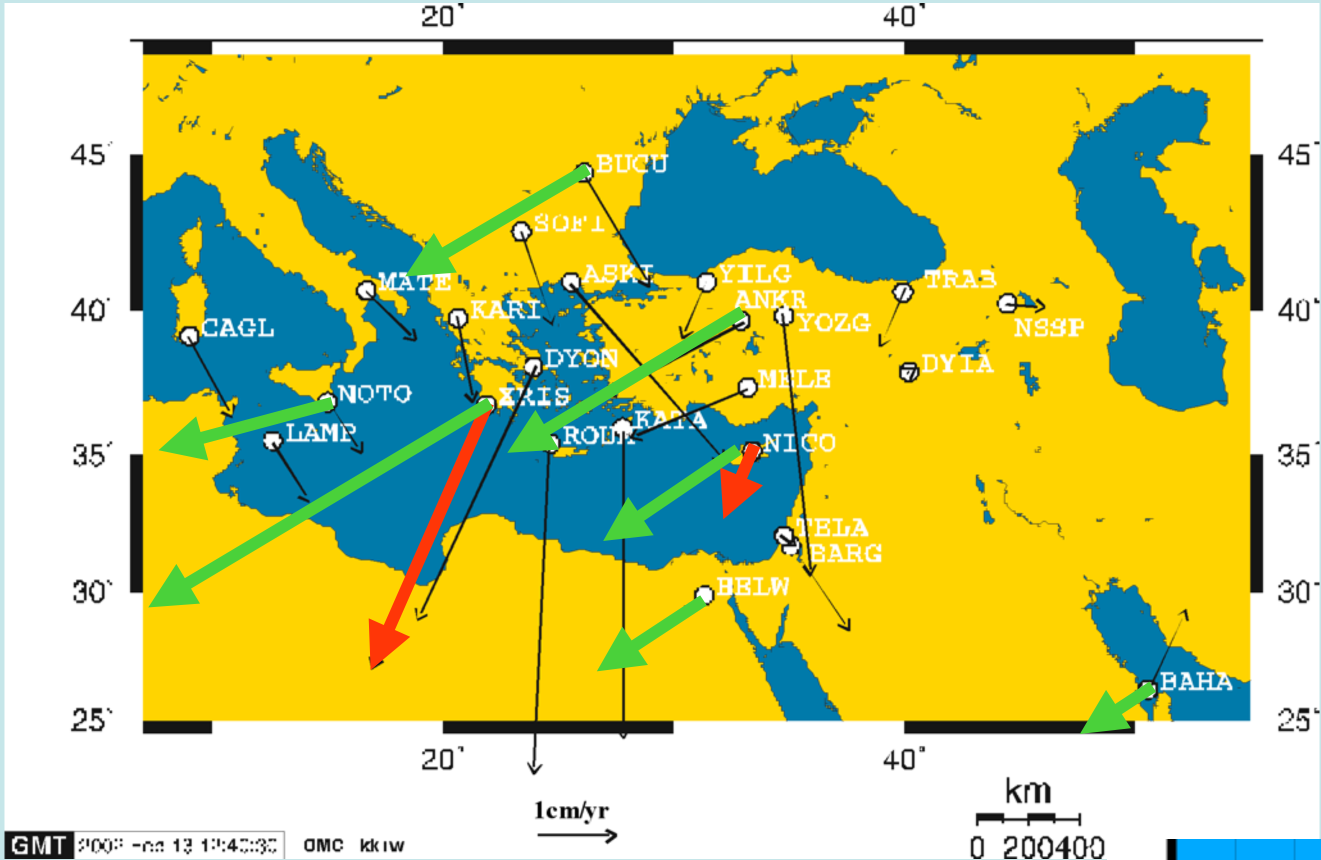


CRUST
LID
LVZ
lower asthenosphere
0 km
100
200
300
backarc basin


GPS horizontal velocities. Eurasia fixed (McClusky et al. 2000)
20°E
25°E
30°E
35°E
40°E
40°N
35°N
?
20 mm/yr

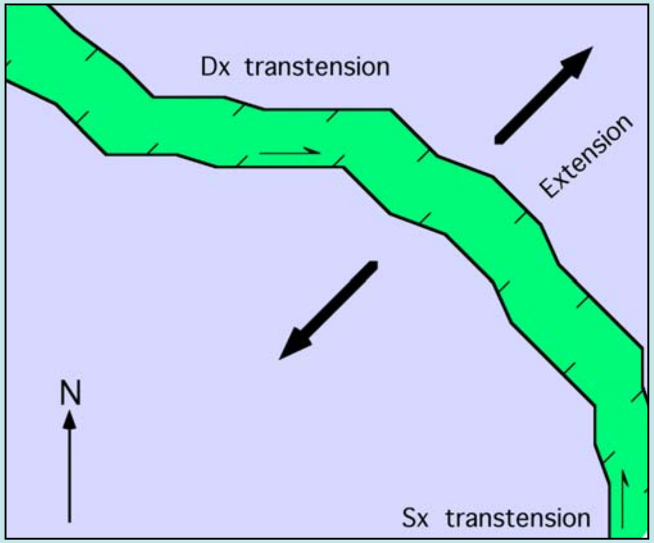
E-Med subductions relate Greece & Turkey to Africa

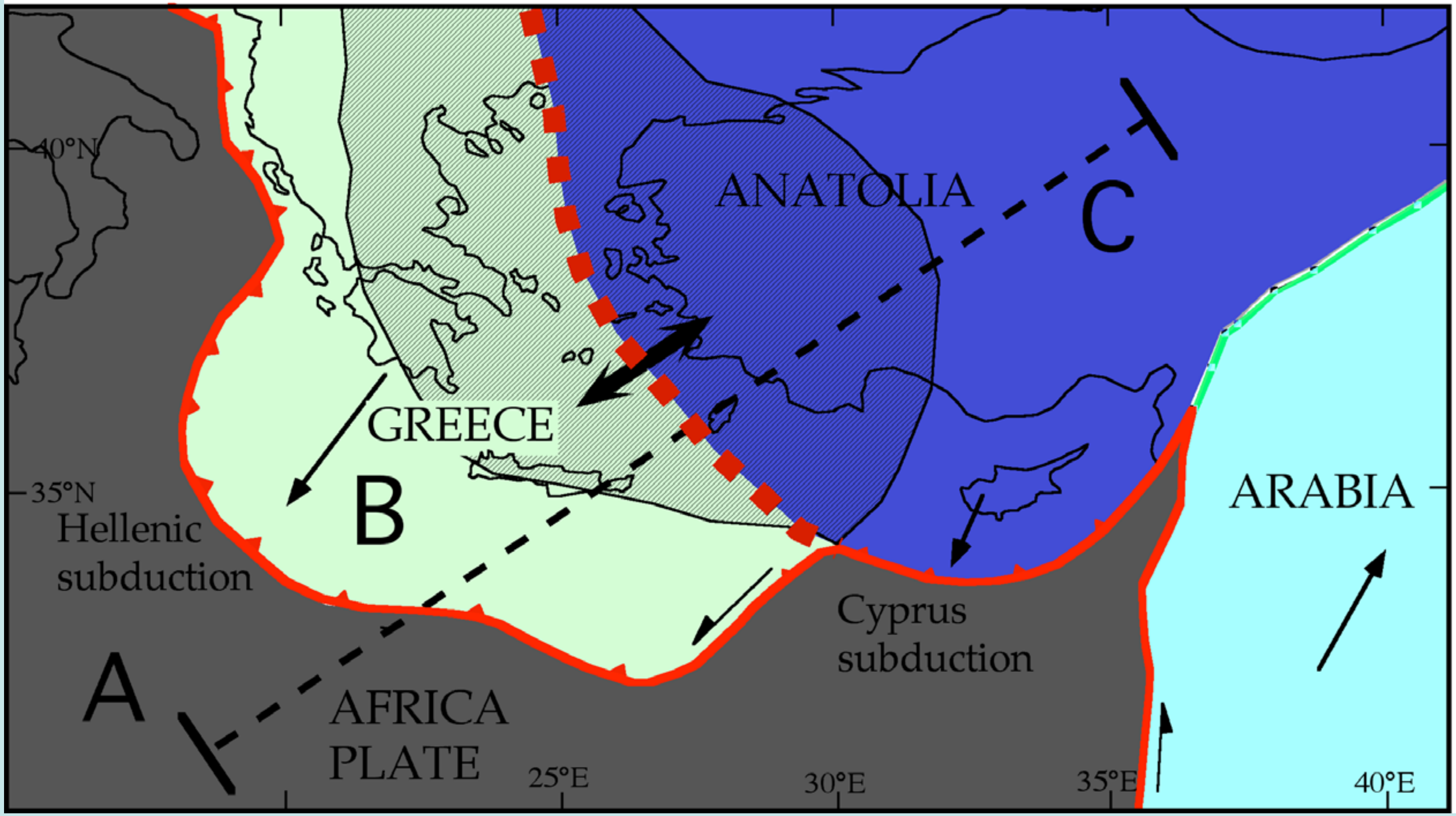


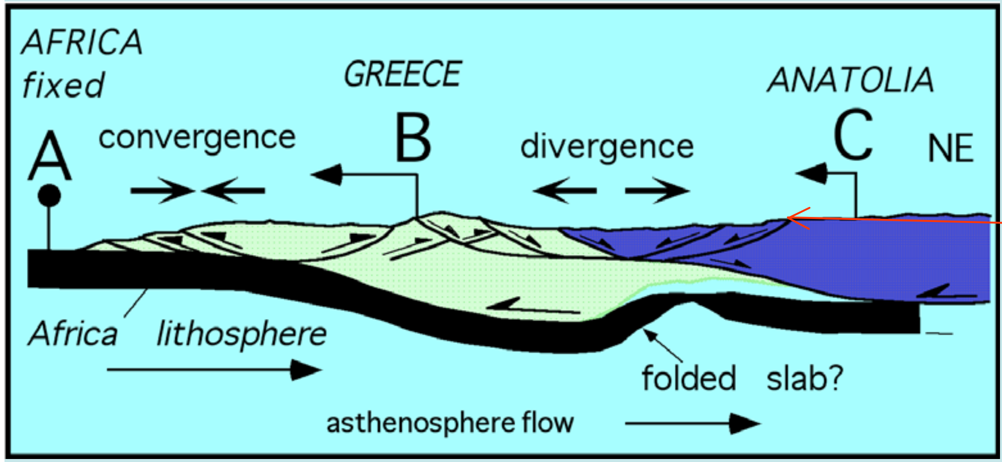


Africa fixed

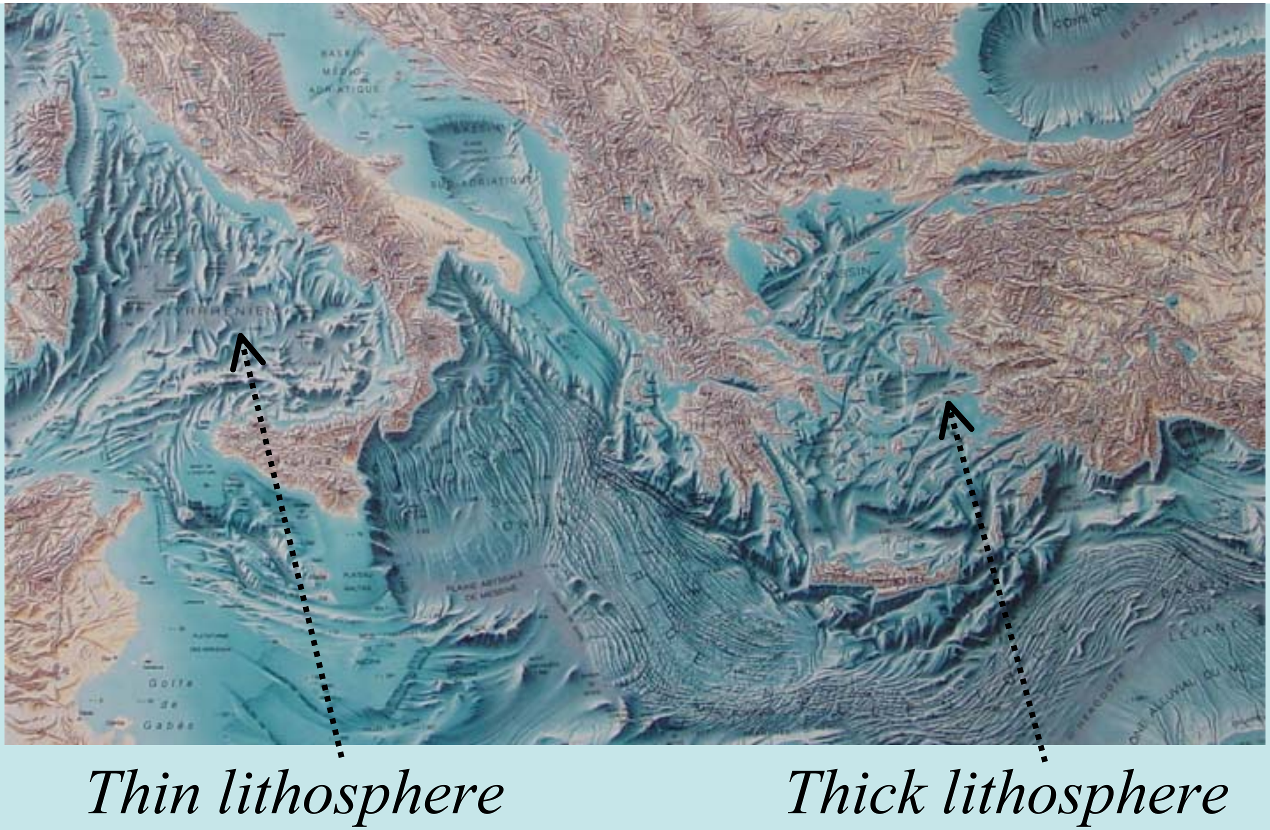
Hawaii fixed

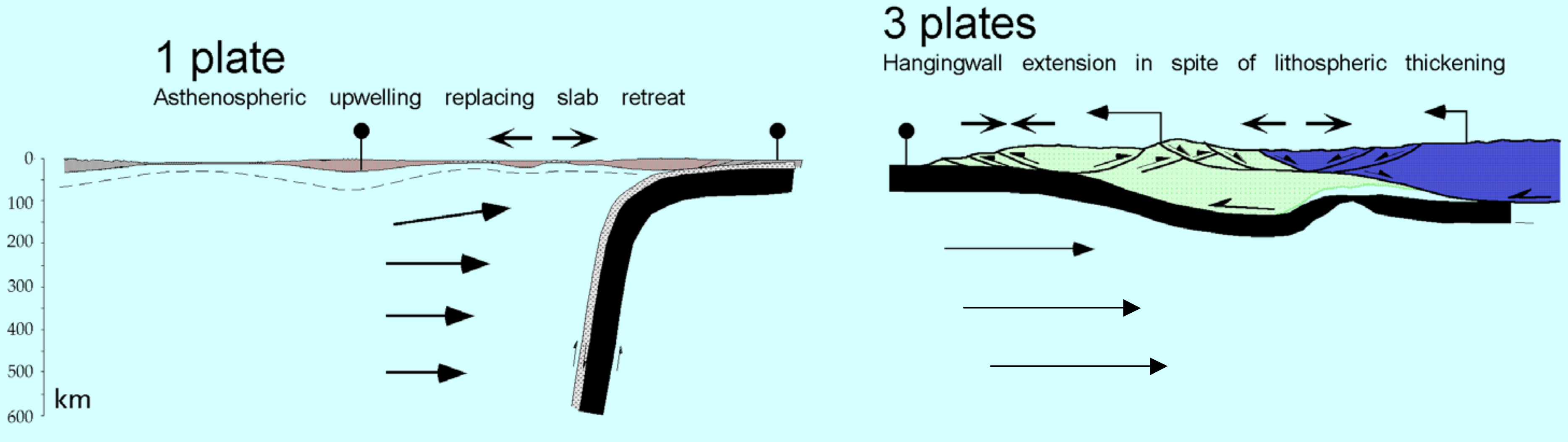


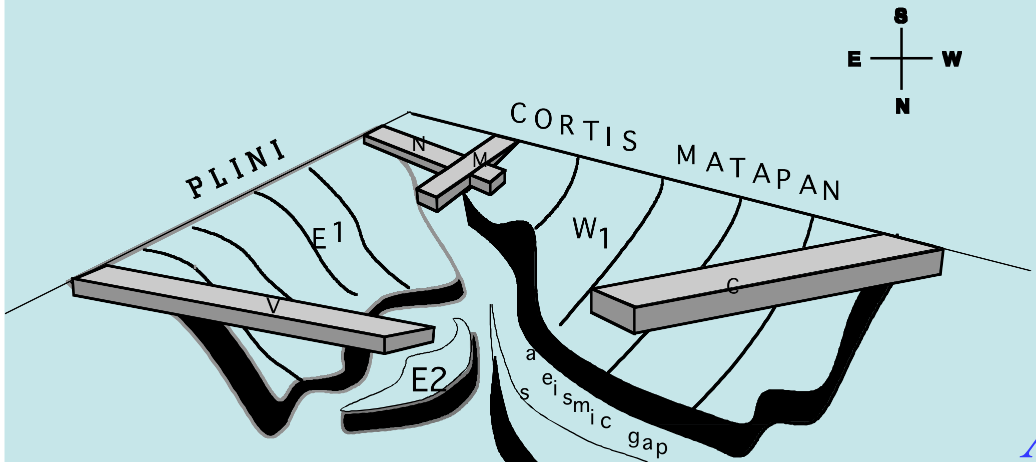

40°N
35°N
ANATOLIA
C
GREECE
B
Hellenic
subduction
A
AFRICA
PLATE
Cyprus
subduction
ARABIA
25°E
30°E
35°E
40°E


AFRICA
fixed
GREECE
ANATOLIA
A
convergence
B
divergence
C
NE
Africa
lithosphere
folded
slab?
asthenosphere flow


Kula OIB basalts W-Turkey


Thin lithosphere
Thick lithosphere

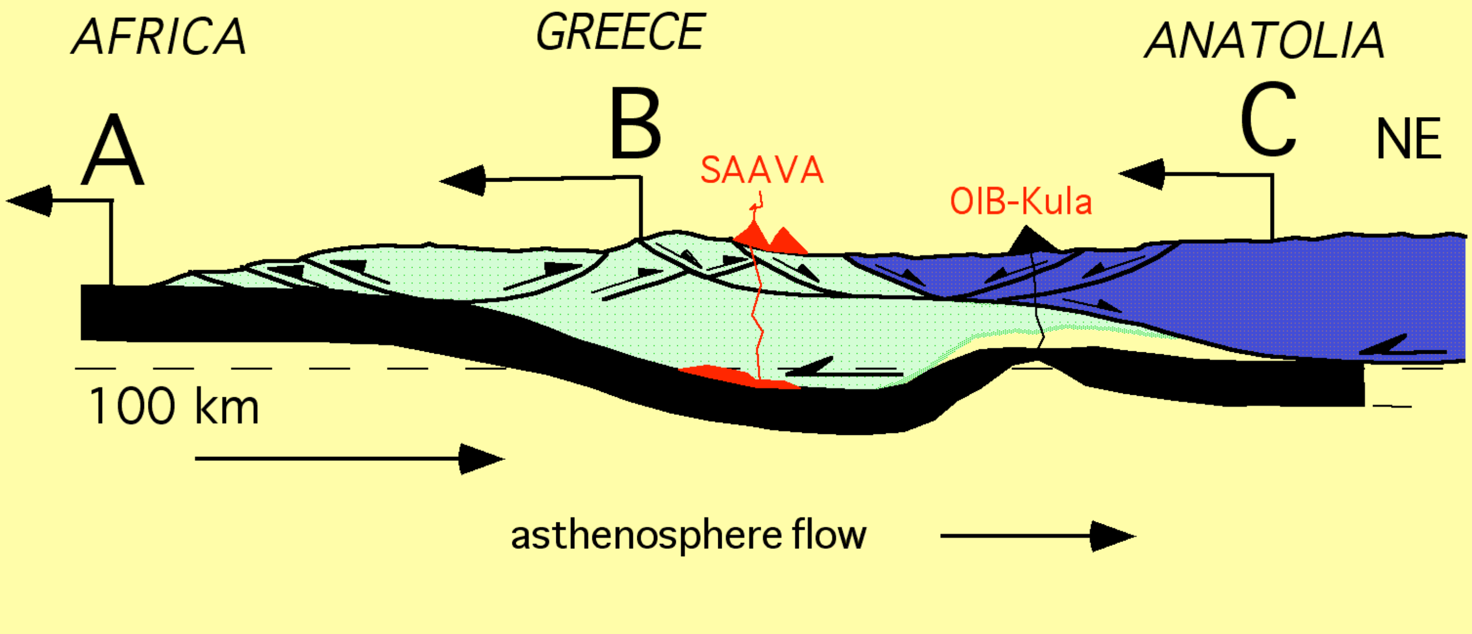

1 plate
Asthenospheric upwelling replacing slab retreat
0
100
200
300
400
500
600
km
3 plates
Hangingwall extension in spite of lithospheric thickening



Christova & Nikolova, 1992

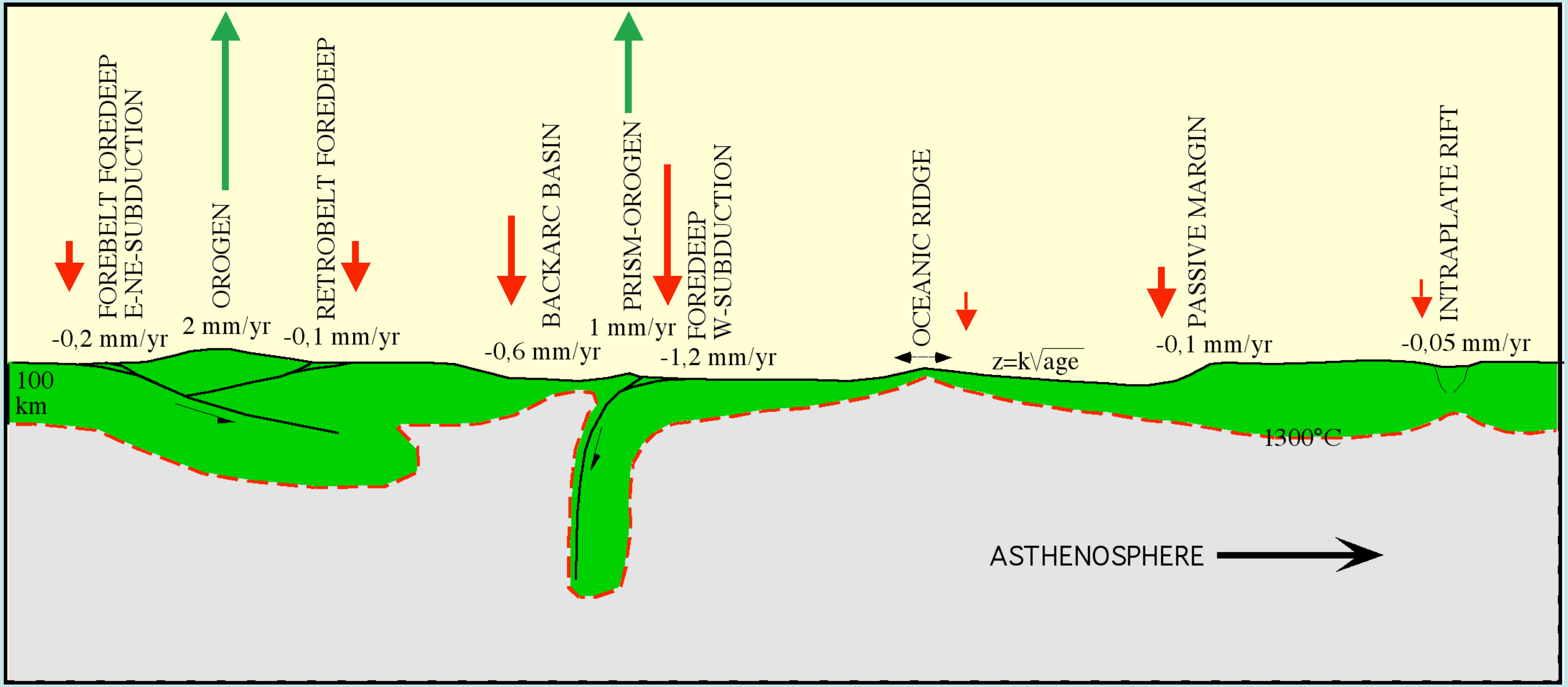
FASTER CONVERGENCE =>
LARGER MAGMATISM

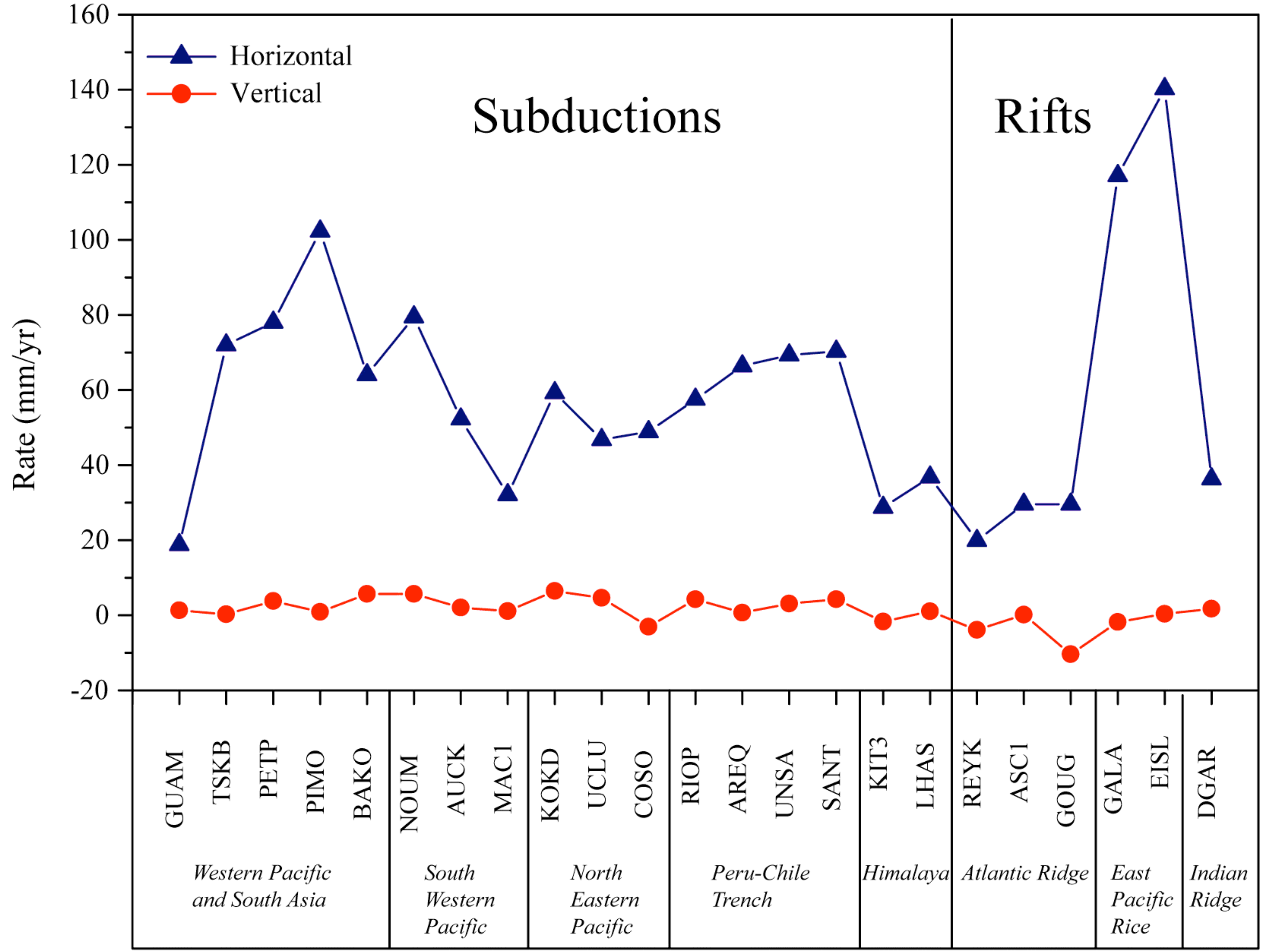
A working hypothesis
for the SAAVA magmatism:
Shear heating ?



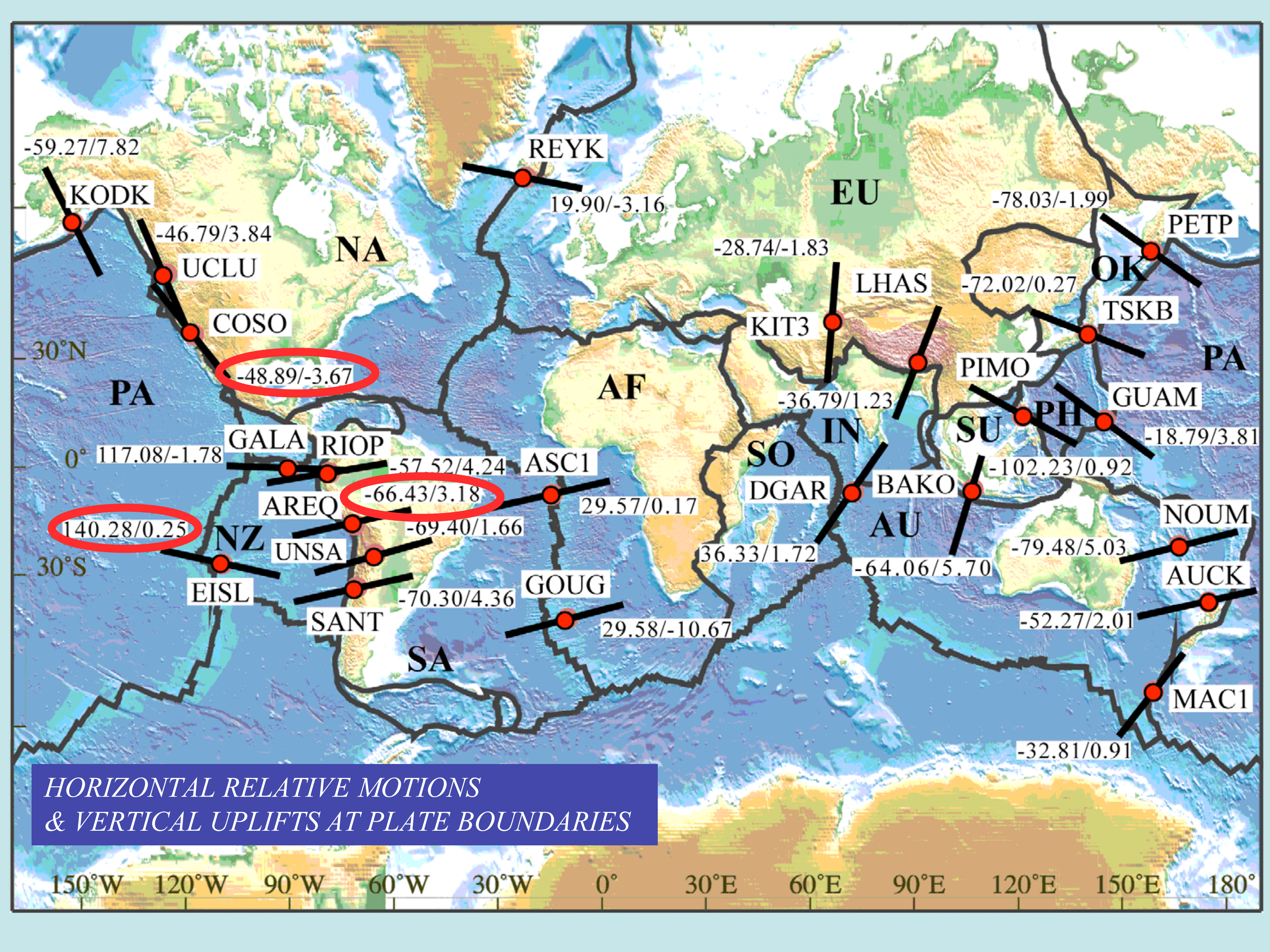
SW-velocity relative to the mantle = B>C>A

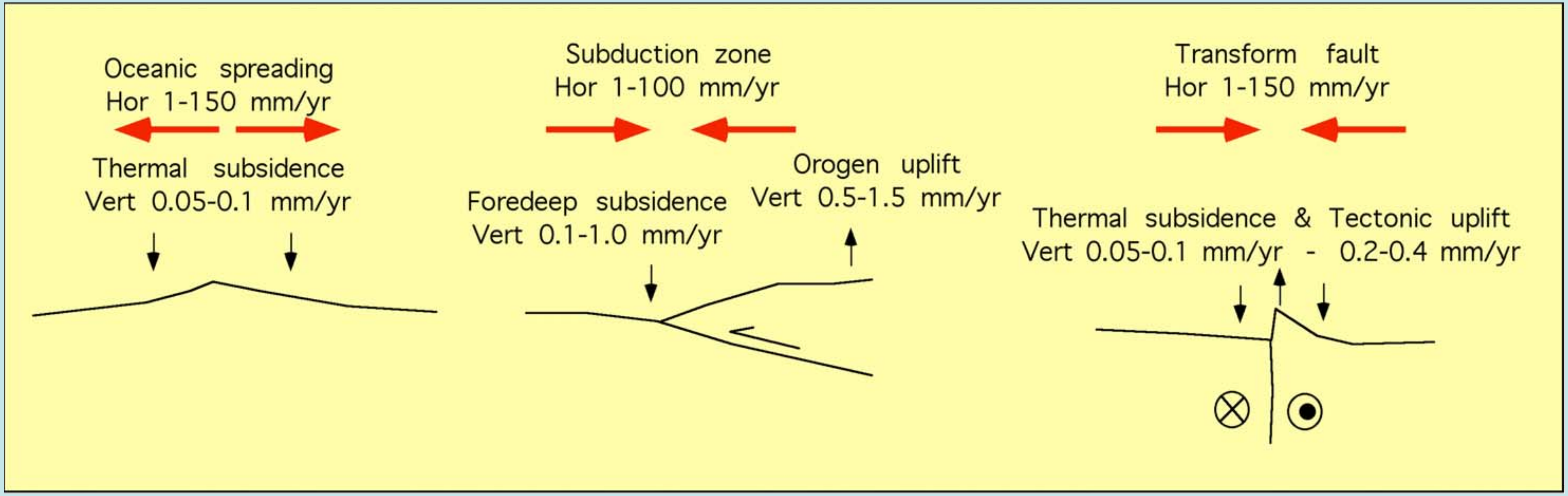
VERTICAL MOVEMENTS - PLATE TECTONICS RELATED





Horizontal
Vertical
Subductions
Rifts
Rate (mm/yr)
160
140
120
100
80
60
40
20
0
-20
GUAM
TSKB
PETP
PIMO
BAKO
NOUM
AUCK
MAC1
KOKD
UCLU
COSO
RIOP
AREQ
UNSA
SANT
KIT3
LHAS
REYK
ASC1
GOUG
GALA
EISL
DGAR
Western Pacific and South Asia
South Western Pacific
North Eastern Pacific
Peru-Chile Trench
Himalaya
Atlantic Ridge
East Pacific Rice
Indian Ridge


HORIZONTAL RELATIVE MOTIONS
& VERTICAL UPLIFTS AT PLATE BOUNDARIES
-59.27/7.82
KODK
-46.79/3.84
UCLU
COSO
NA
REYK
19.90/-3.16
EU
-78.03/-1.99
PETP
-28.74/-1.83
LHAS
-72.02/0.27
OK
TSKB
KIT3
30°N
-48.89/-3.67
PA
AF
PIMO
PA
GUAM
-36.79/1.23
IN
PH
SU
-18.79/3.81
GALA
RIOP
0°
117.08/-1.78
-57.52/4.24
ASC1
SO
DGAR
BAKO
-102.23/0.92
AREQ
-66.43/3.18
29.57/0.17
AU
NOUM
140.28/0.25
NZ
-69.40/1.66
UNSA
36.33/1.72
-64.06/5.70
-79.48/5.03
30°S
EISL
GOUG
AUCK
-70.30/4.36
SANT
29.58/-10.67
-52.27/2.01
SA
MAC1
-32.81/0.91
150°W
120°W
90°W
60°W
30°W
0°
30°E
60°E
90°E
120°E
150°E
180°



- HORIZONTAL MOTIONS 10-100 TIMES FASTER THAN VERTICAL

- TANGENTIAL FORCES DOMINATE PLATE TECTONICS

Forces acting on the lithosphere

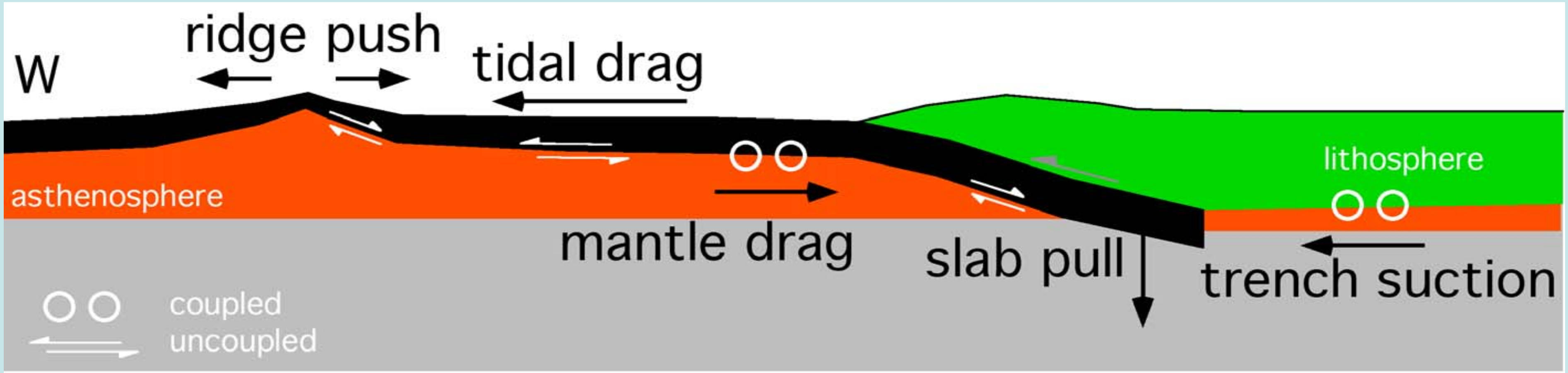
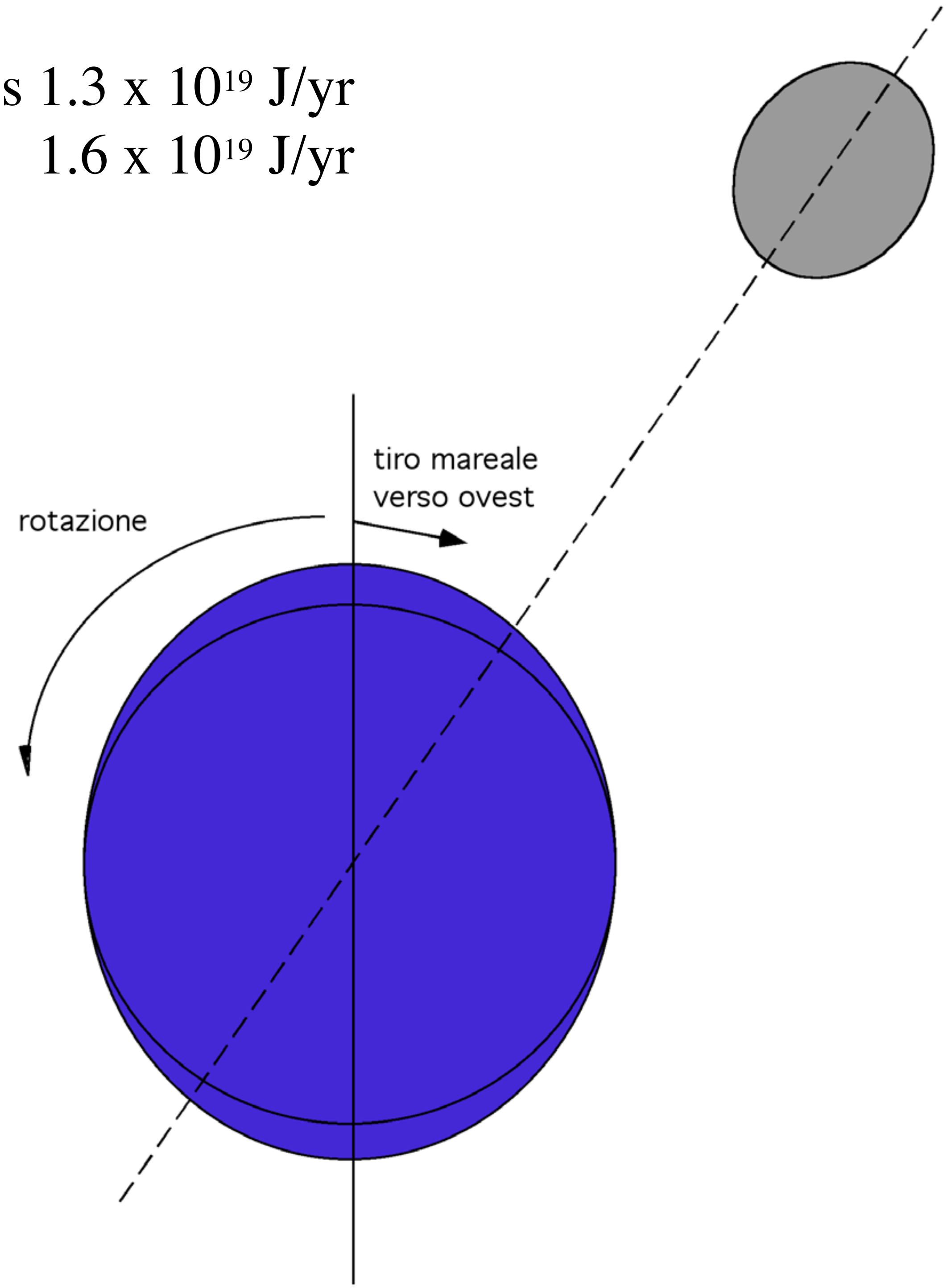
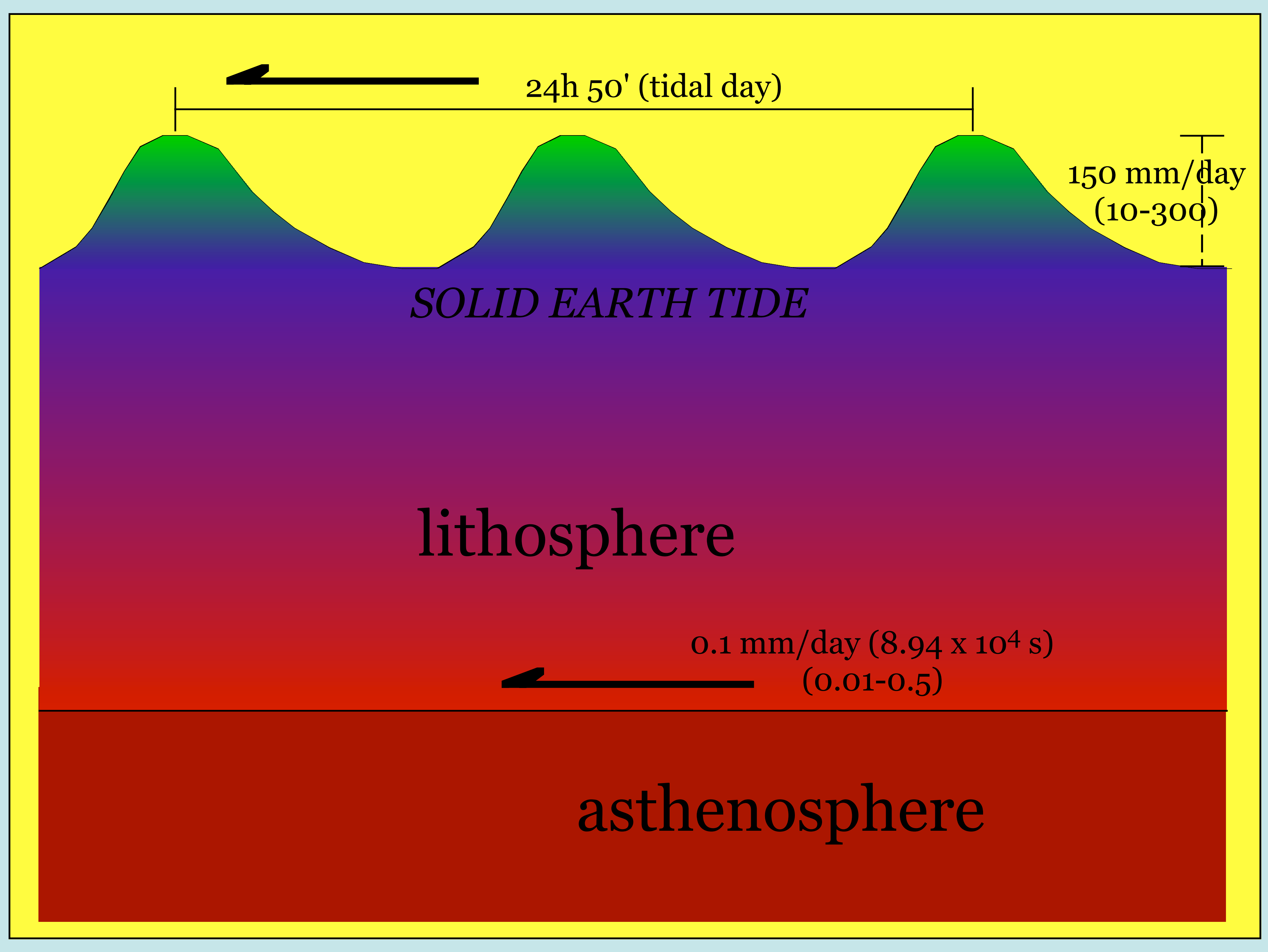
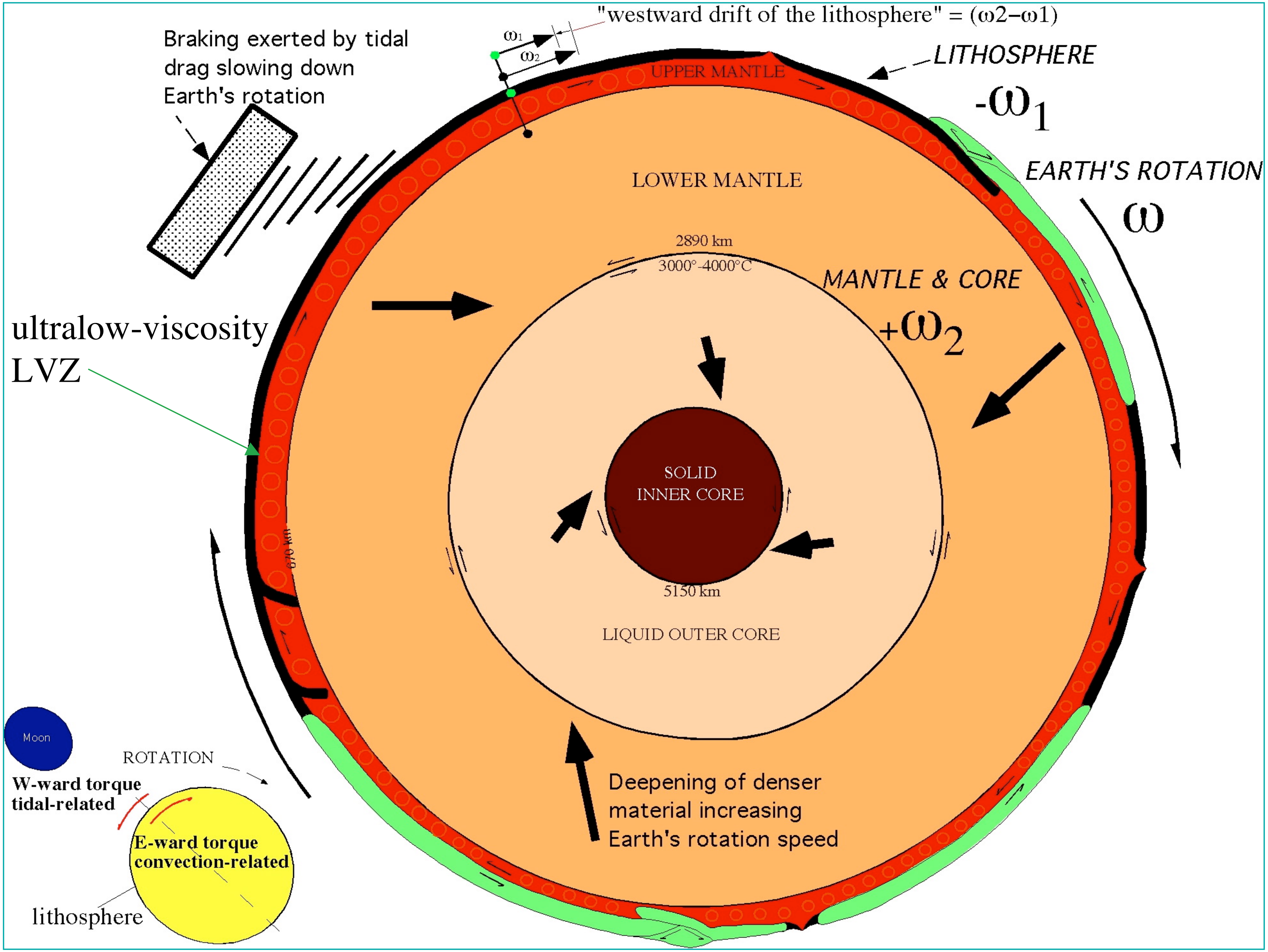


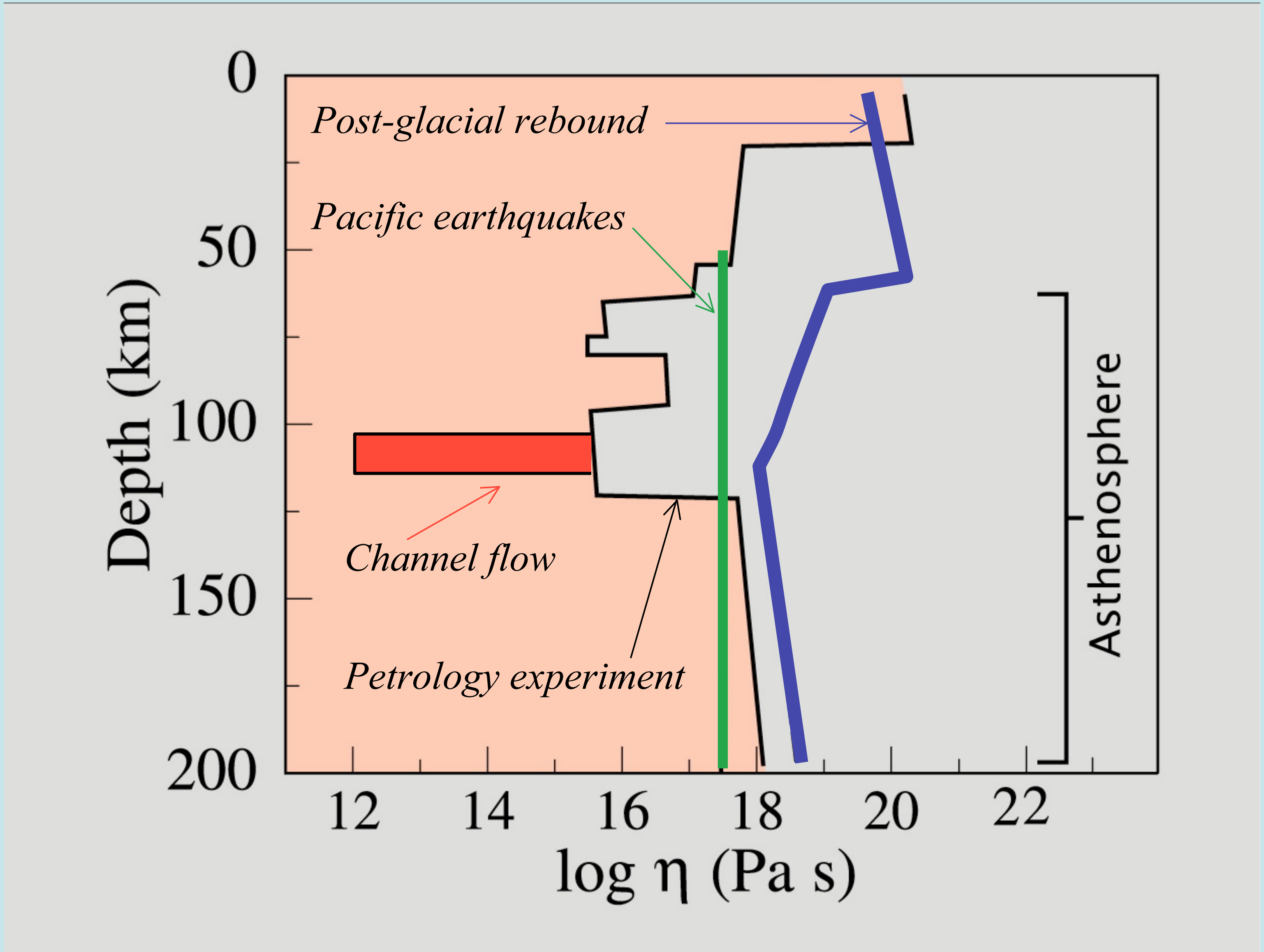
Plate tectonics 1.3 x 10^{19} J/yr
Tidal friction 1.6 x 10^{19} J/yr



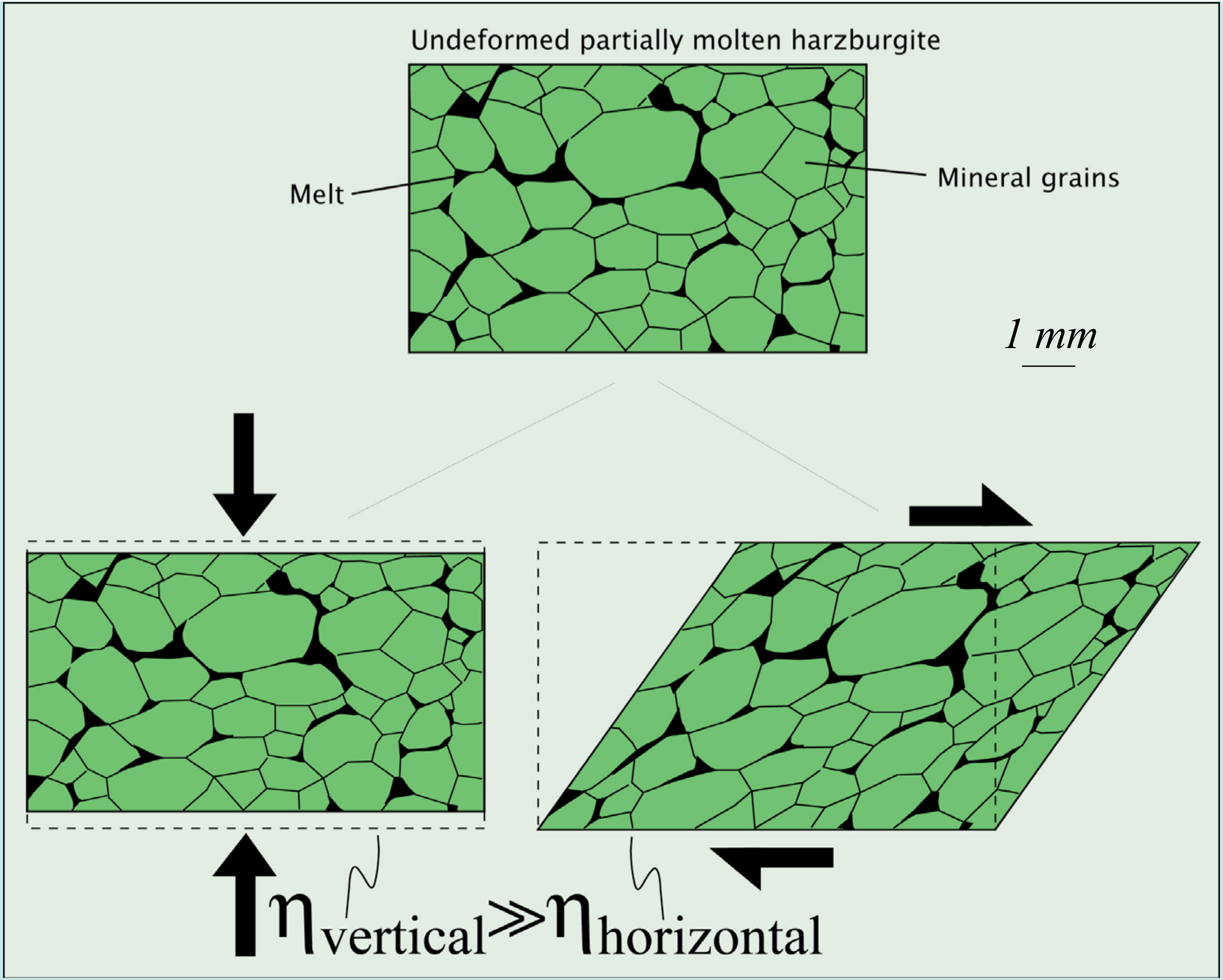

24h 50' (tidal day)
150 mm/day
(10-300)
SOLID EARTH TIDE
lithosphere
0.1 mm/day (8.94 x 10⁴ s)
(0.01-0.5)
asthenosphere

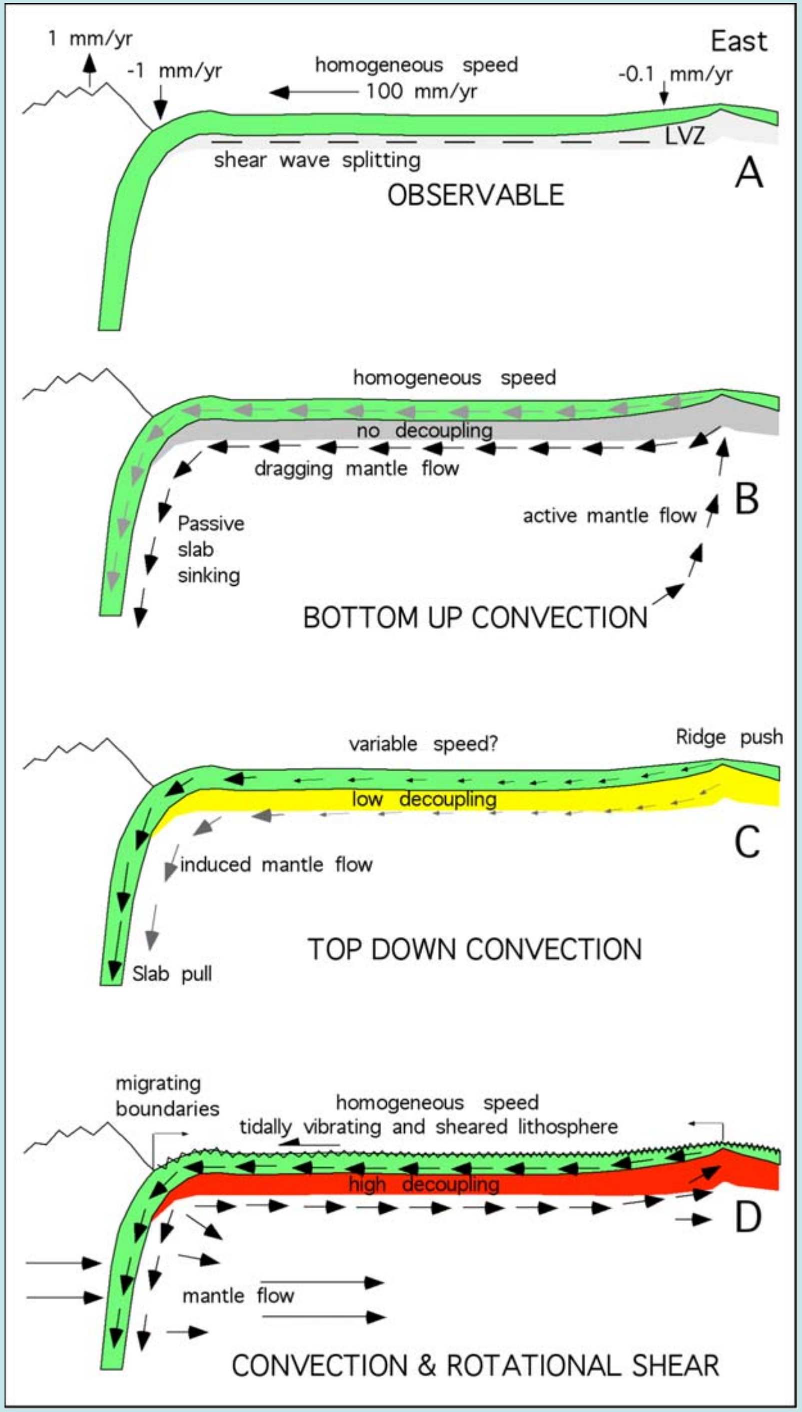


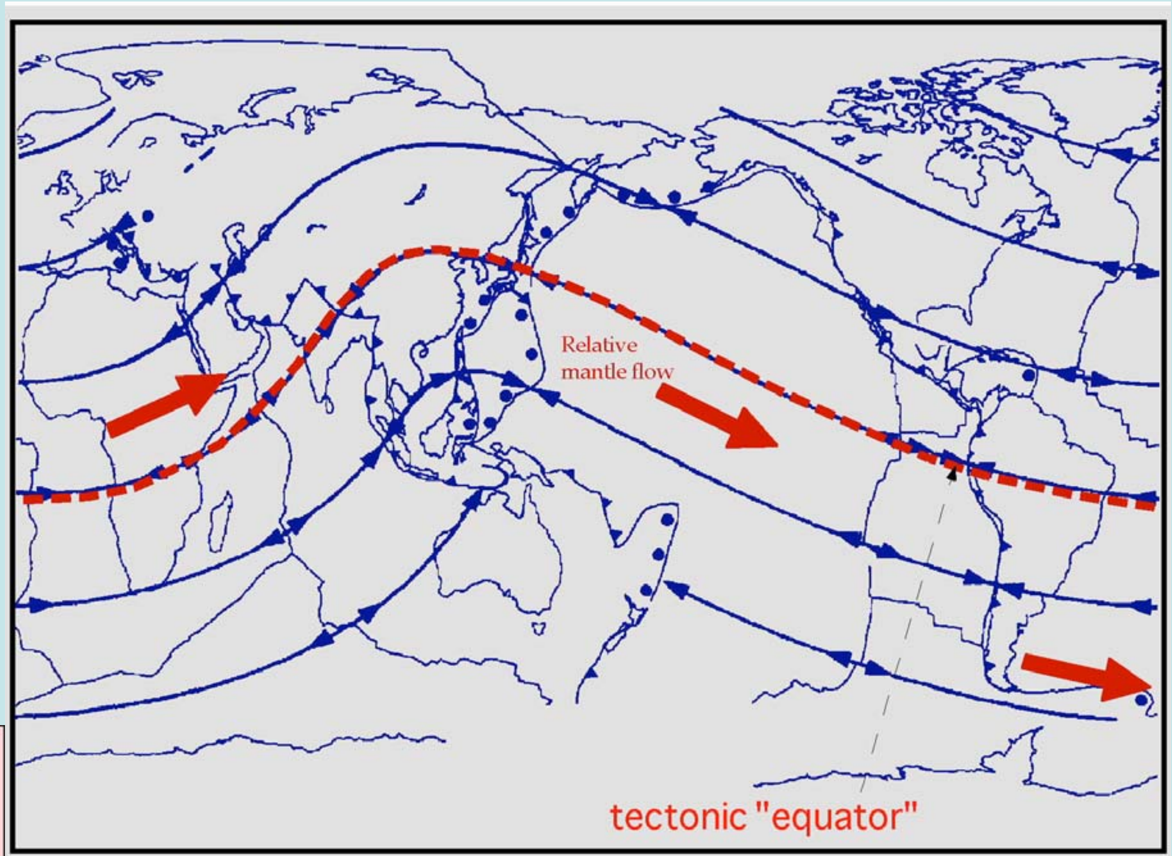
"westward drift of the lithosphere" = (ω2−ω1)
Braking exerted by tidal drag slowing down Earth's rotation
ω1
ω2
UPPER MANTLE
LITHOSPHERE
-ω1
EARTH'S ROTATION
ω
LOWER MANTLE
2890 km
3000°-4000°C
MANTLE & CORE
+ω2
ultralow-viscosity LVZ
SOLID INNER CORE
5150 km
LIQUID OUTER CORE
670 km
Moon
ROTATION
W-ward torque tidal-related
E-ward torque convection-related
lithosphere
Deepening of denser material increasing Earth's rotation speed

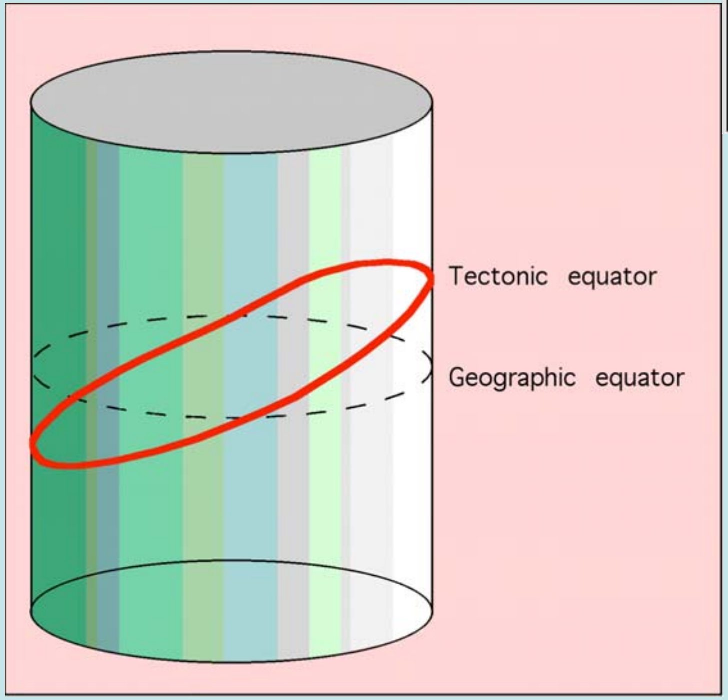


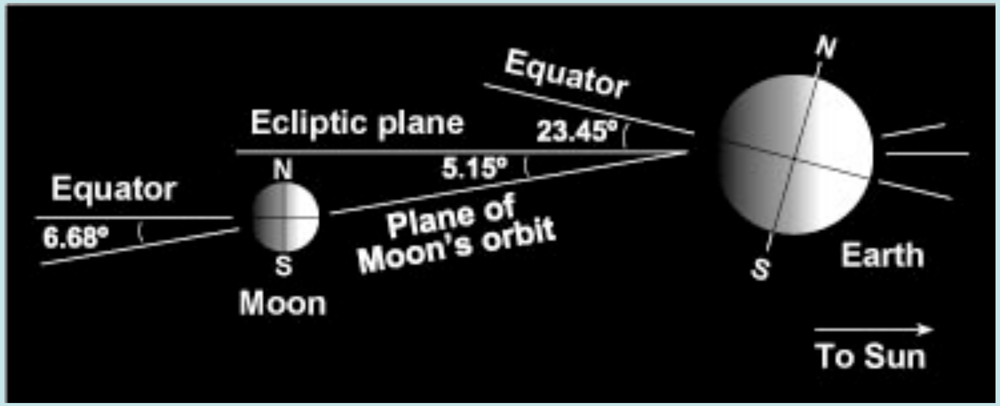
Is the asthenosphere viscosity sufficiently low?

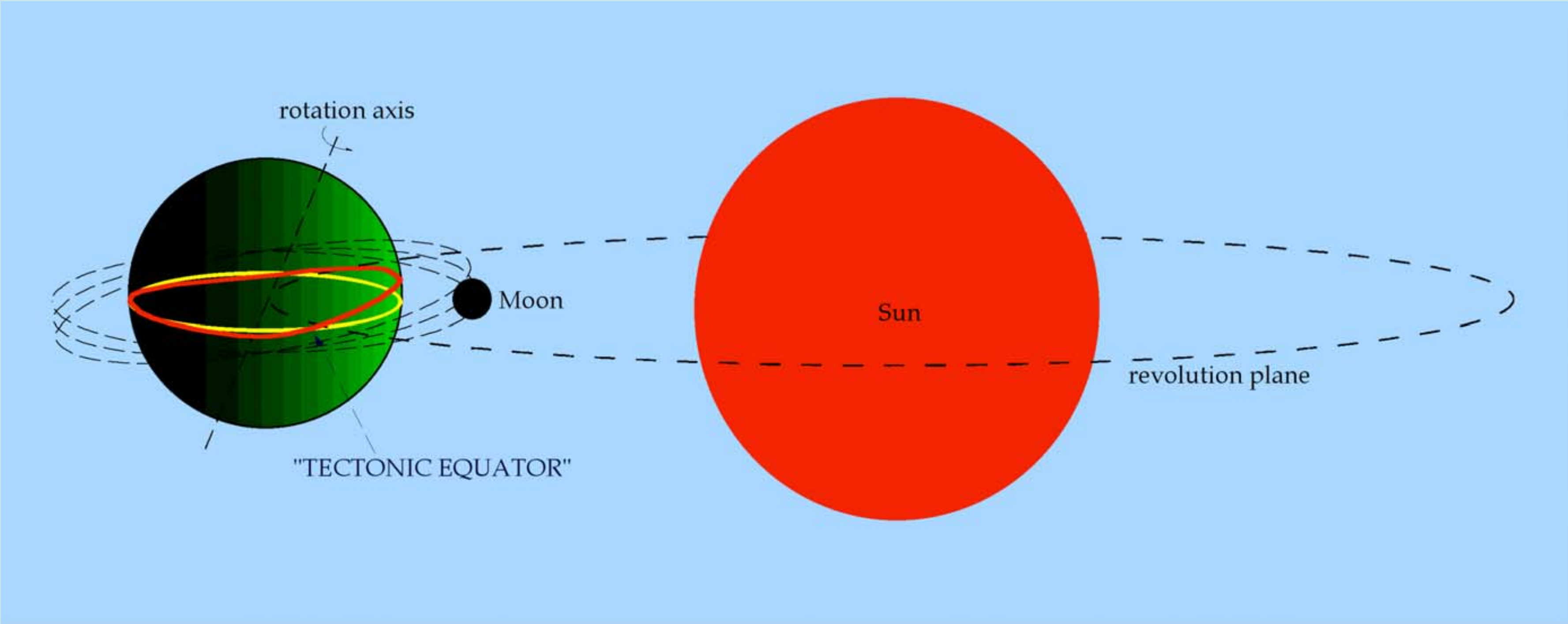

Undeformed partially molten harzburgite
Melt
Mineral grains
1 mm
η vertical ≫ η horizontal


1 mm/yr
-1 mm/yr
homogeneous speed
100 mm/yr
-0.1 mm/yr
East
LVZ
shear wave splitting
A
OBSERVABLE
homogeneous speed
no decoupling
dragging mantle flow
B
active mantle flow
Passive
slab
sinking
BOTTOM UP CONVECTION
variable speed?
Ridge push
low decoupling
C
induced mantle flow
TOP DOWN CONVECTION
Slab pull
migrating
boundaries
homogeneous speed
tidally vibrating and sheared lithosphere
high decoupling
D
mantle flow
CONVECTION & ROTATIONAL SHEAR


Relative
mantle flow
tectonic "equator"

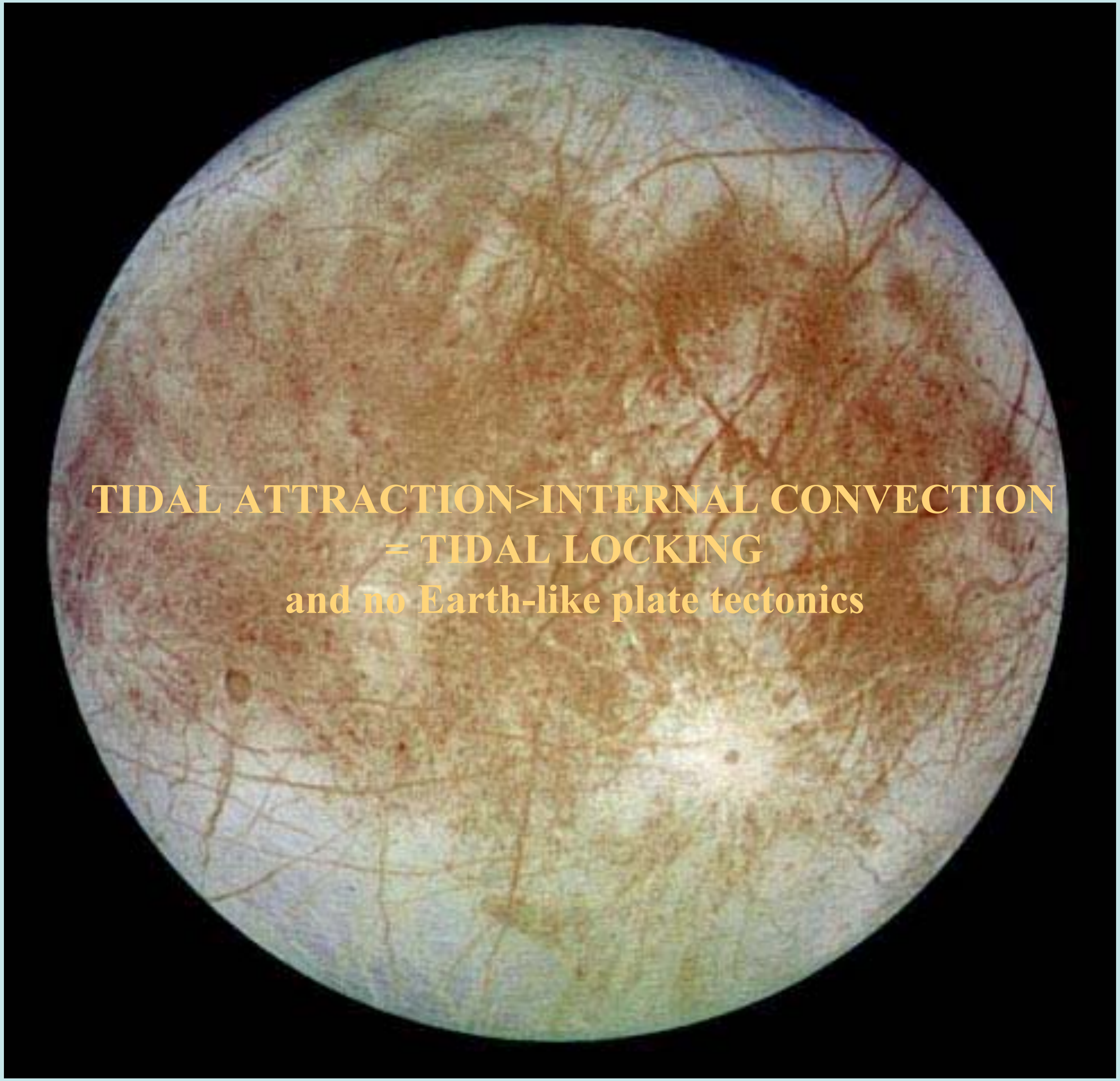

Tectonic equator
Geographic equator


Equator
Ecliptic plane
23.45°
5.15°
N
Equator
6.68°
Plane of
Moon's orbit
S
Moon
N
S
Earth
To Sun


rotation axis
Moon
Sun
revolution plane
"TECTONIC EQUATOR"

EUROPE is a Jupiter's satellite

Rotation period 3d 13h 14.6m
Revolution period 3d 13h 14.6m
(RESONANCE)
diameter3,138 km
Mean density3.01 g/cm3
Surface gravity1.42 m/s2



1) The lithosphere moves along a westerly polarized flow

2) There is a global tectonic asymmetry

3) Plate boundaries are passive features

4) Dominant ductile deformation contained in GPS data

5) Plate tectonics is tuned by Earth's rotation

Thanks

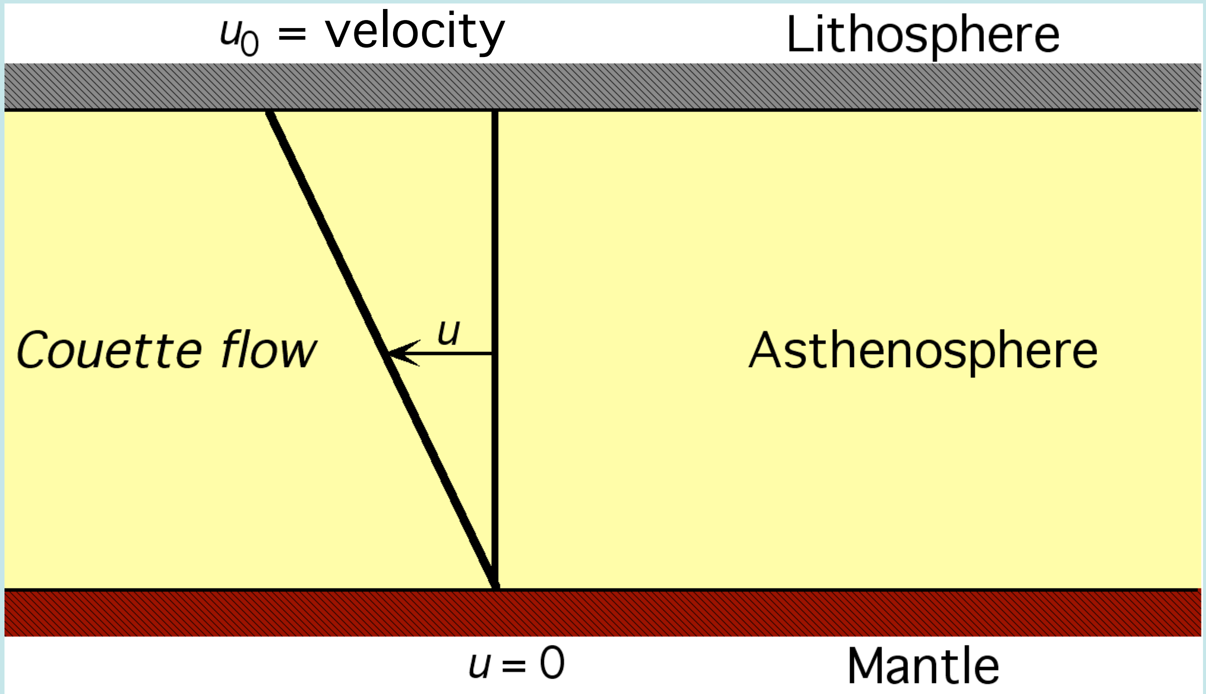
M. BABINET PREVÉNU PAR SA PORTIÈRE
DE LA VISITE DE LA COMÈTE
Lithograph. Honoré Daumier, French, 1808-1879
MUSEUM OF FINE ARTS, BOSTON

The maximum excess temperature due to frictional heating with respect to the temperature linear profile in a Couette flow is:

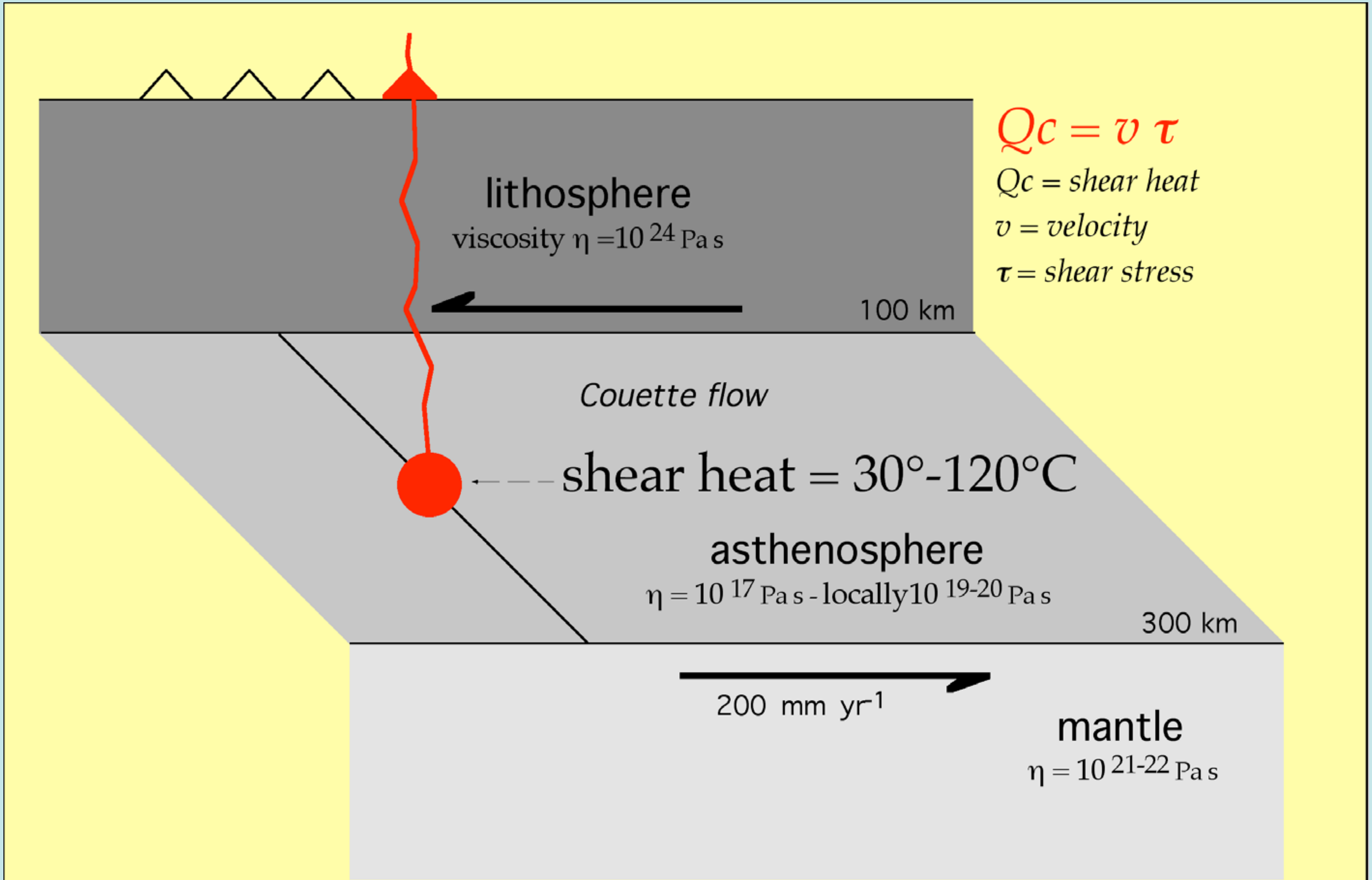
$$\theta_e^{max} = \frac{\Pr E}{8}$$

and occurs in the middle of the flow

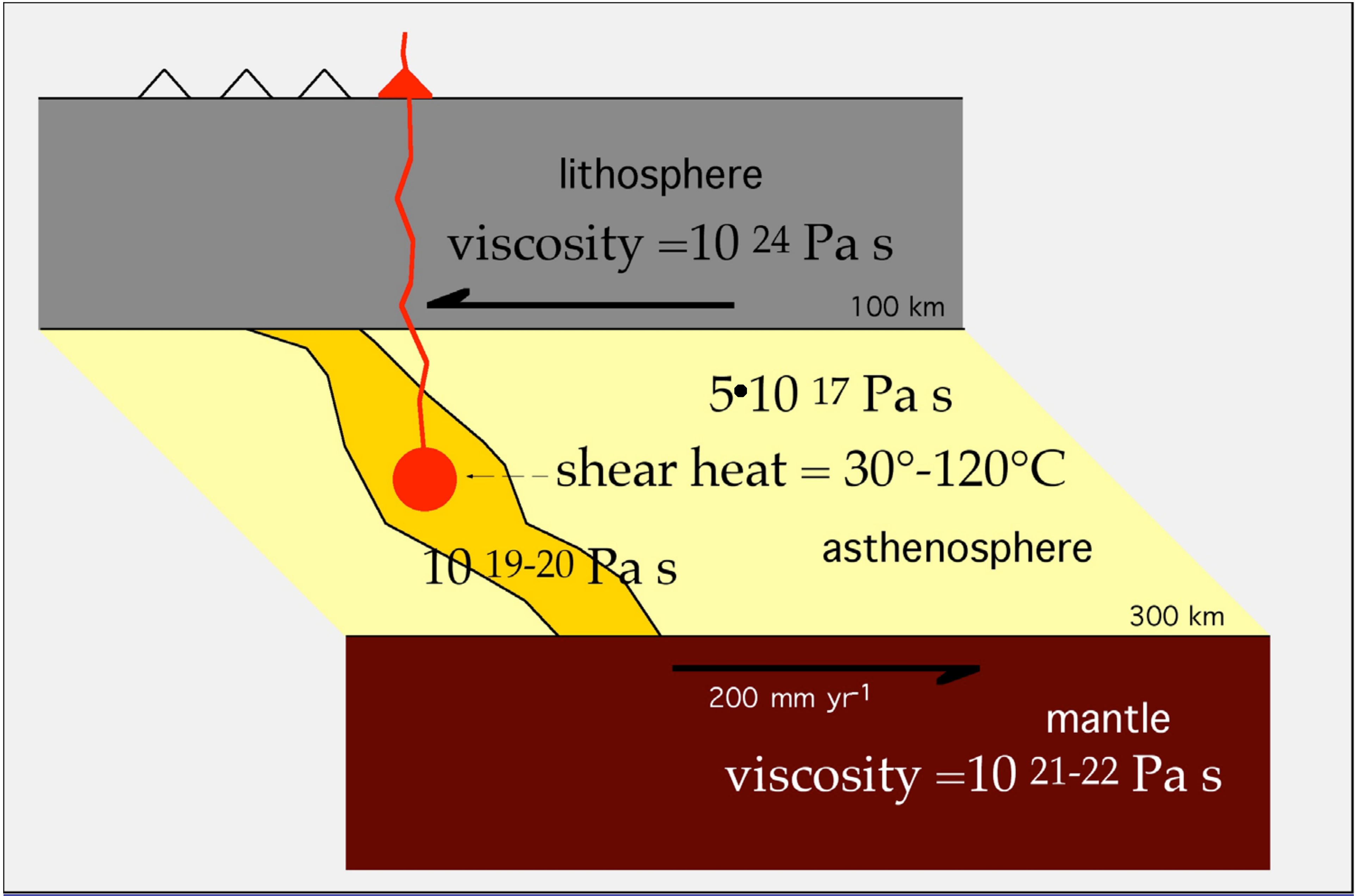
where E is the Eckert number and Pr is the Prandtl number (Turcotte and Schubert, 2002)



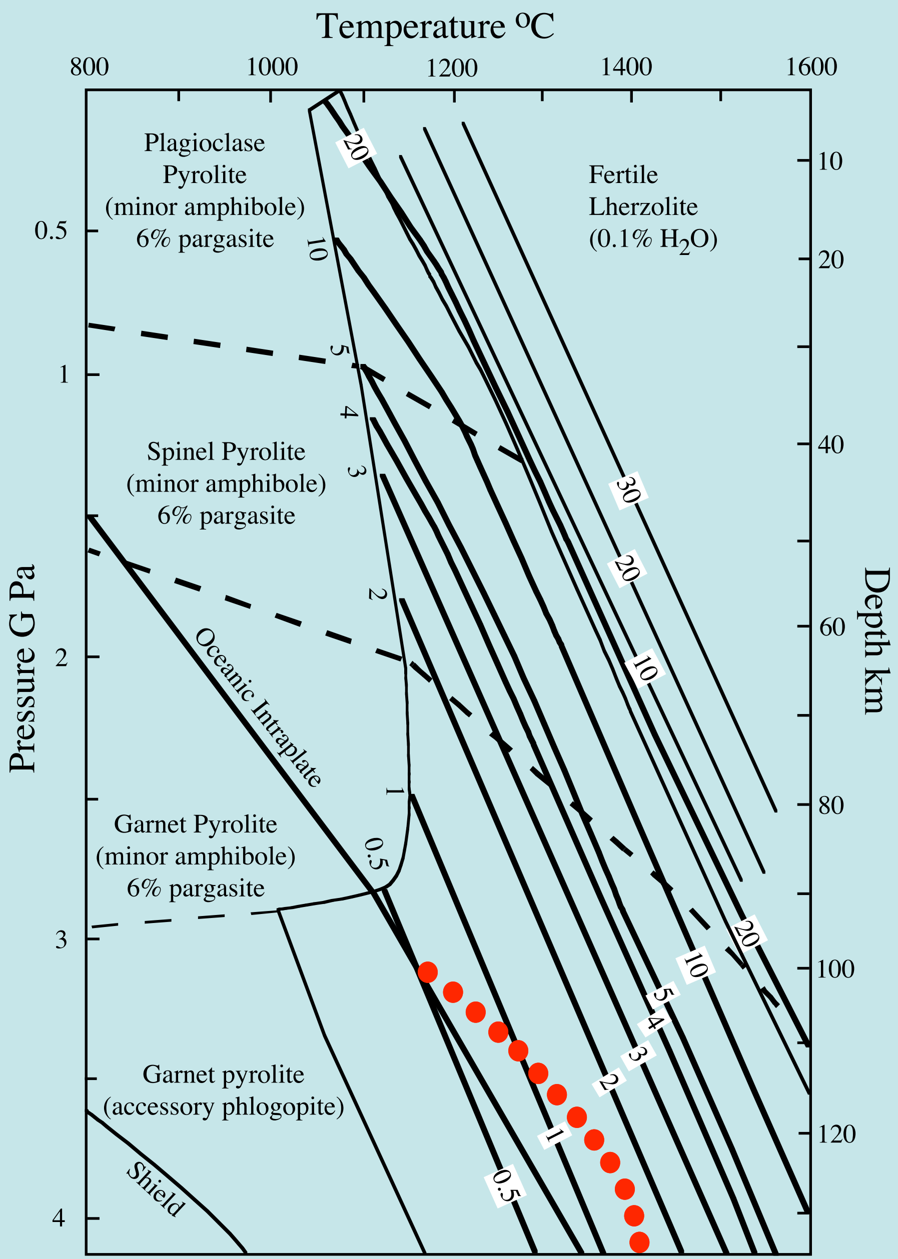
Doglioni, Green and Mongelli, 2005



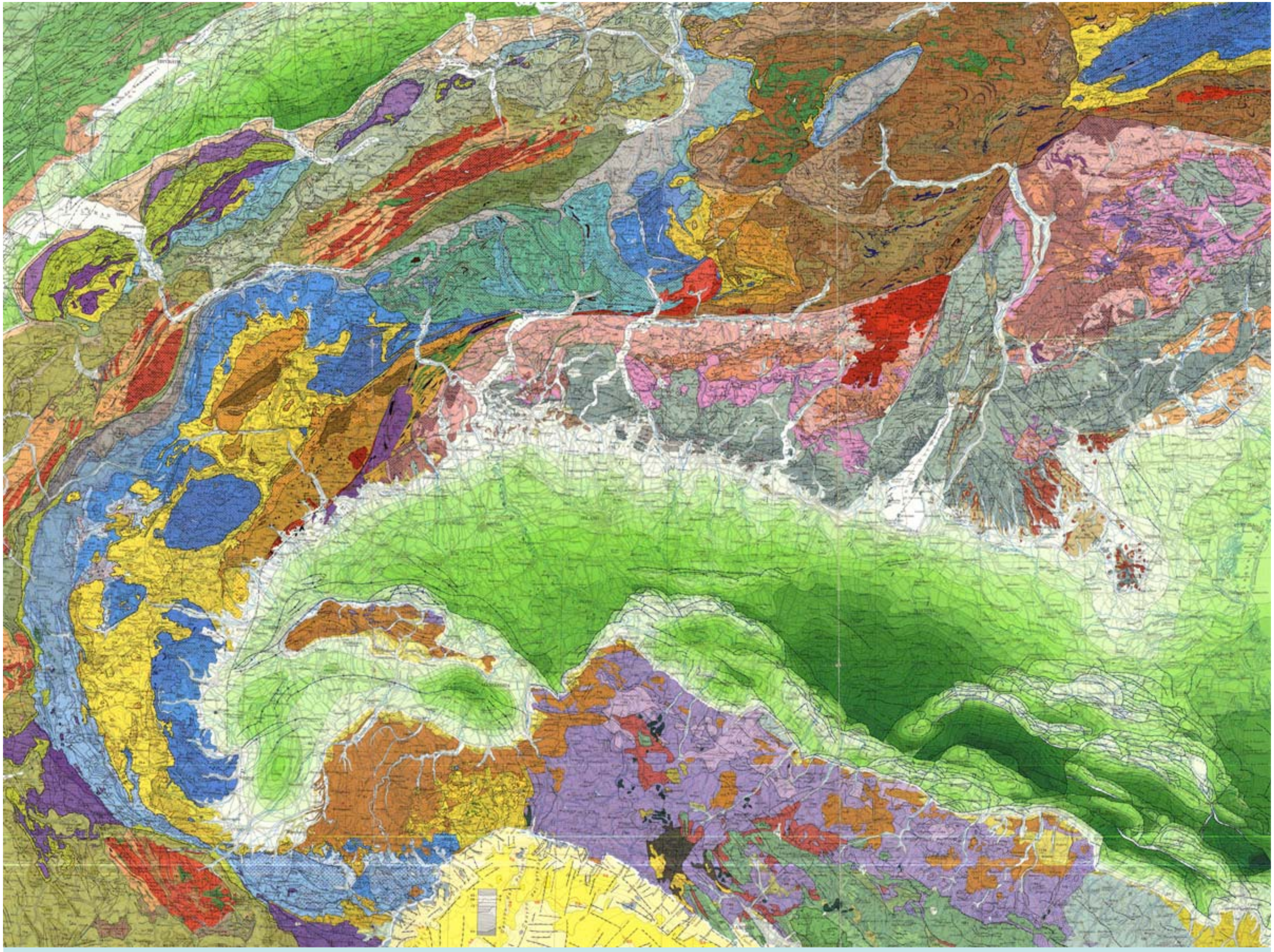
- *Local increase of the asthenospheric viscosity can generate extra T (i.e. higher viscosity = larger amount of melting?)*

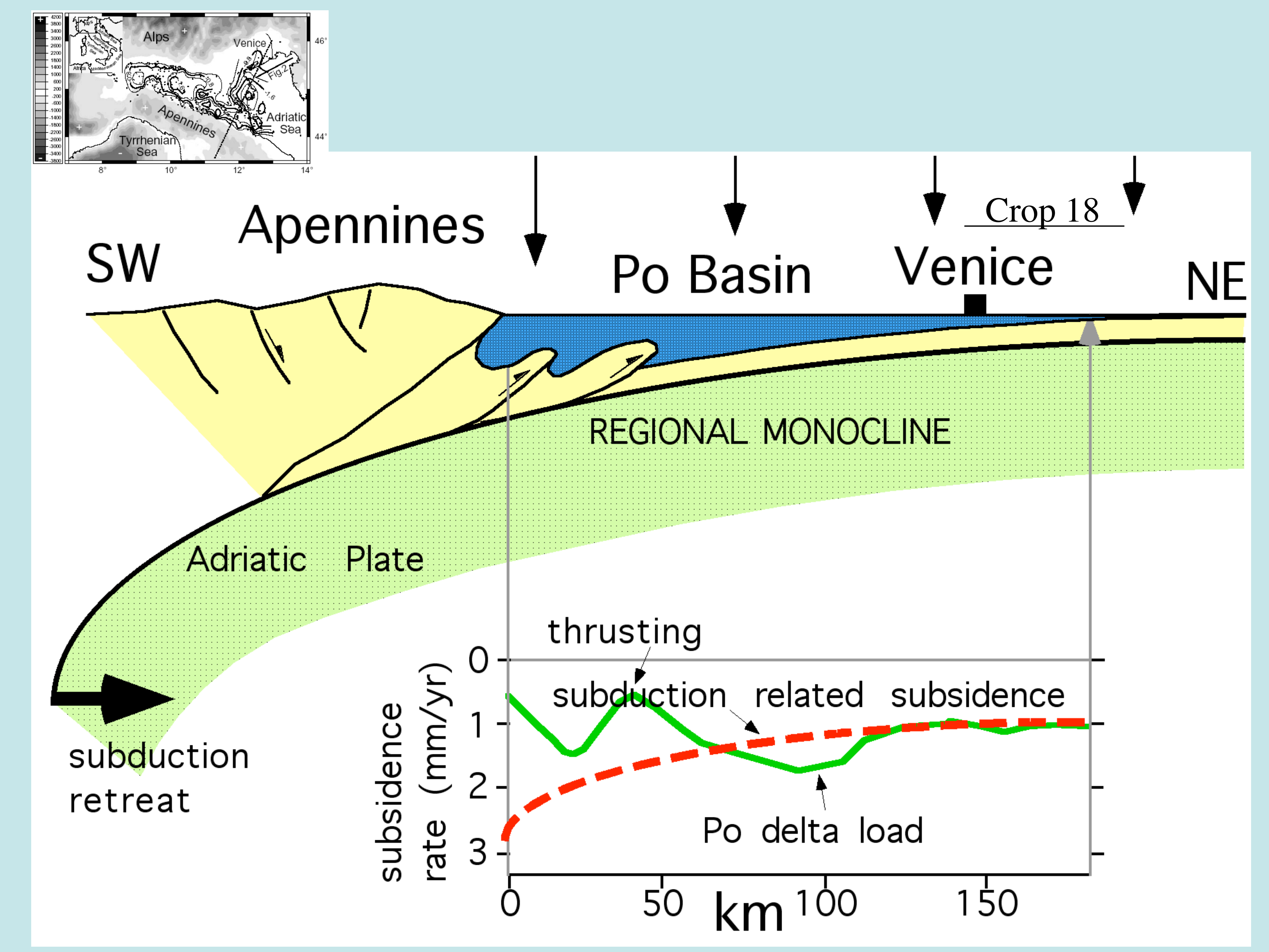


- Local increase of the asthenospheric viscosity can generate extra T (i.e. higher viscosity = larger amount of melting?)

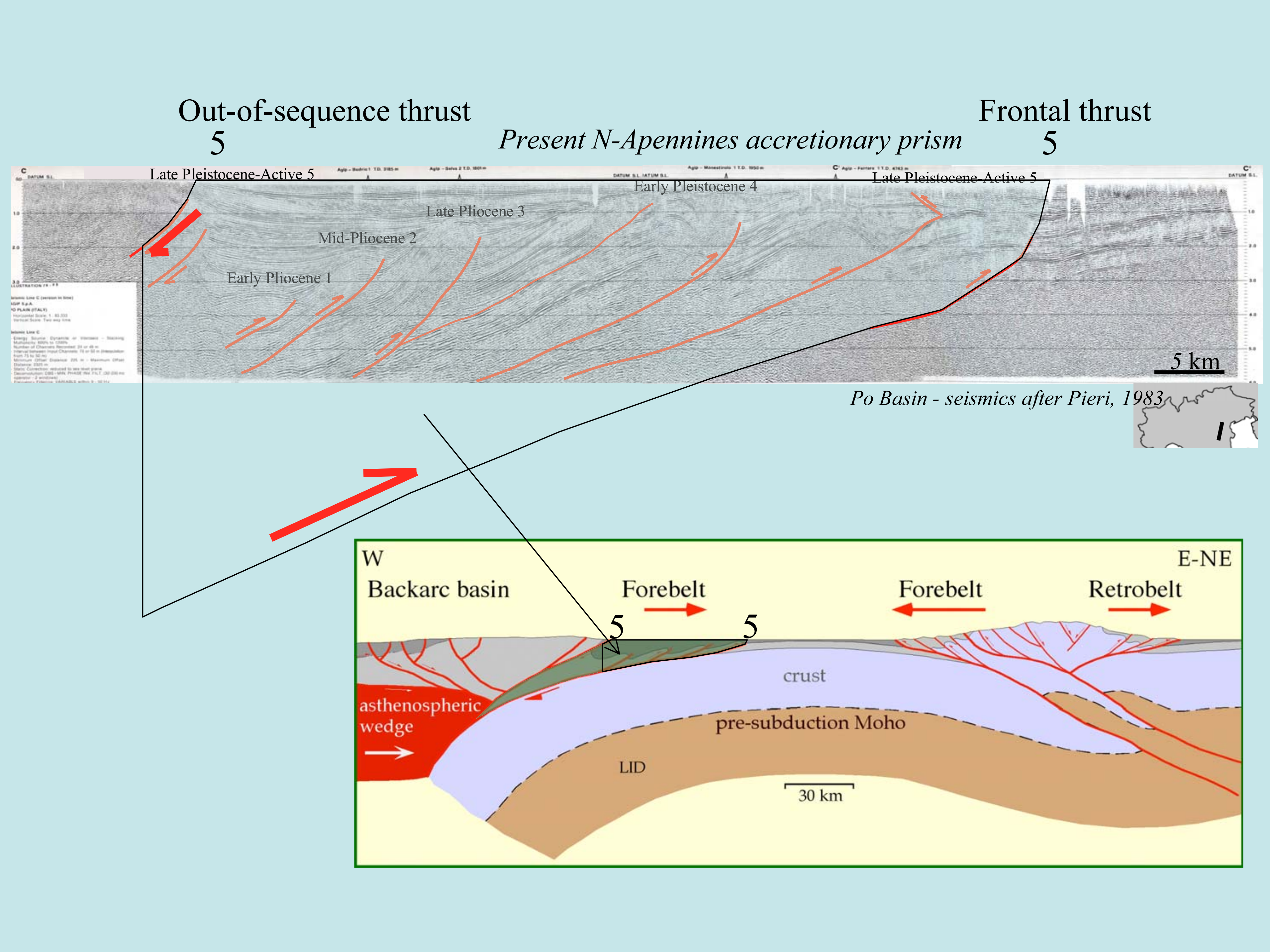


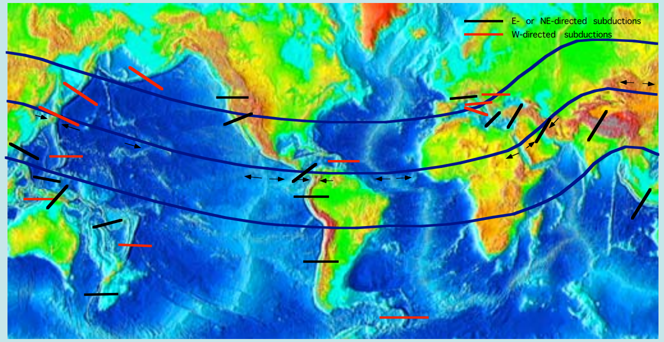
Temperature ºC
800
1000
1200
1400
1600
Pressure G Pa
0.5
1
2
3
4
Depth km
10
20
40
60
80
100
120
Plagioclase
Pyrolite
(minor amphibole)
6% pargasite
Fertile
Lherzolite
(0.1% H_2O)
Spinel Pyrolite
(minor amphibole)
6% pargasite
Oceanic Intraplate
Garnet Pyrolite
(minor amphibole)
6% pargasite
Garnet pyrolite
(accessory phlogopite)
Shield
20
10
5
4
3
2
1
0.5
30
20
10
20
10
5
4
3
2
1
0.5

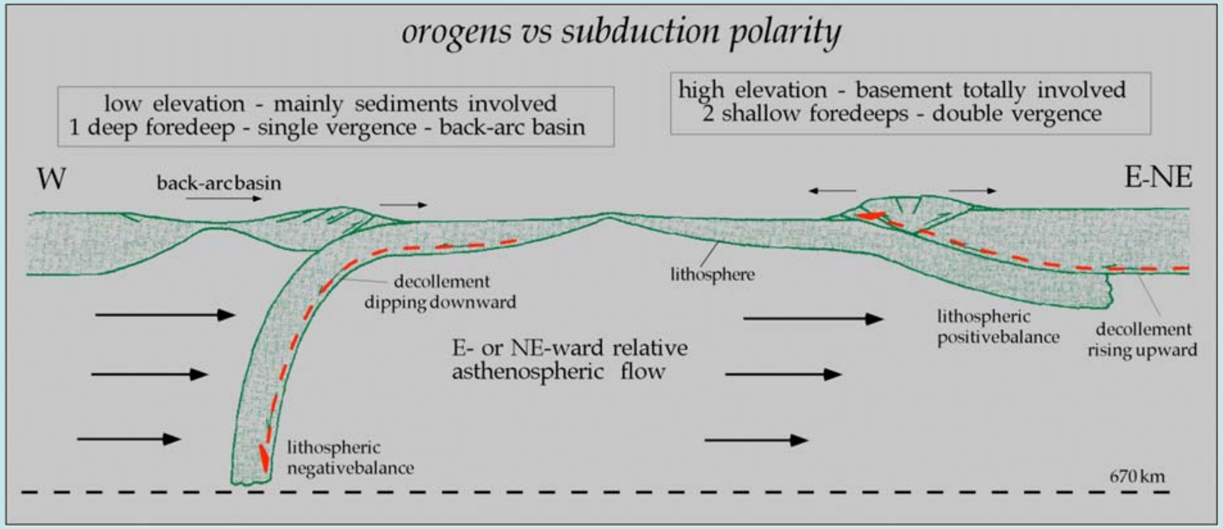


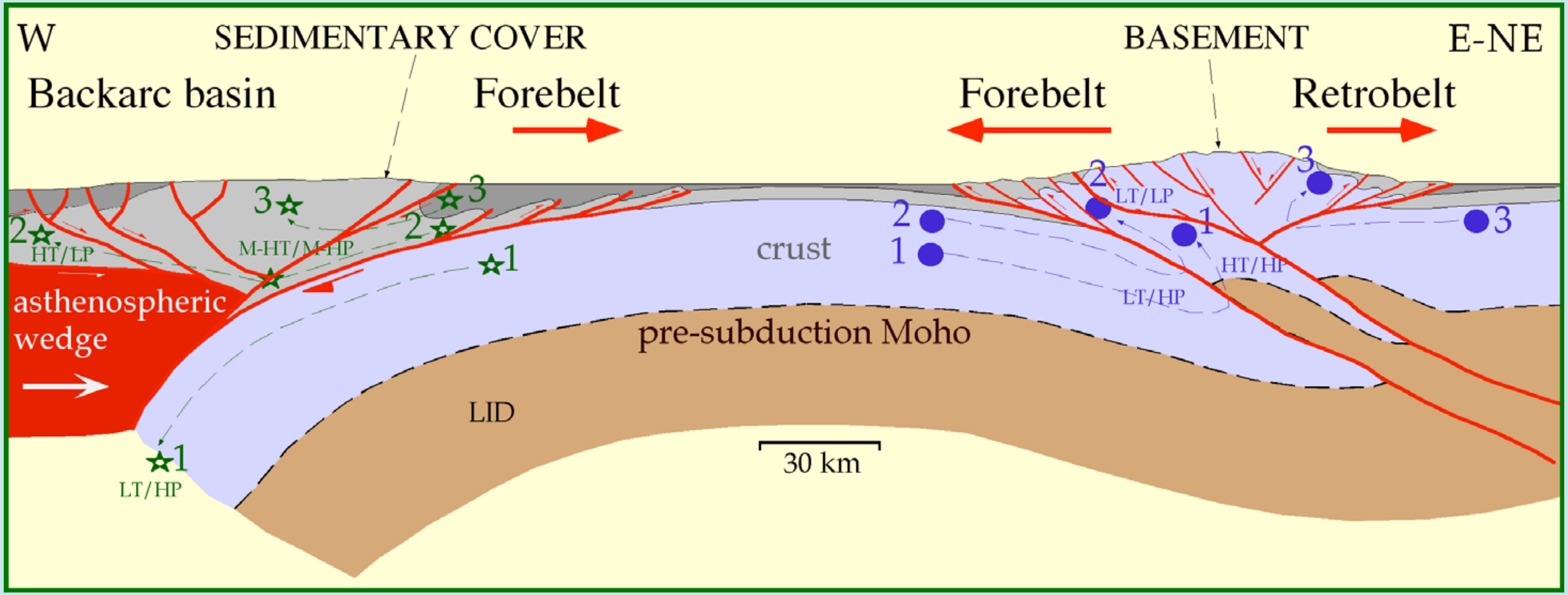


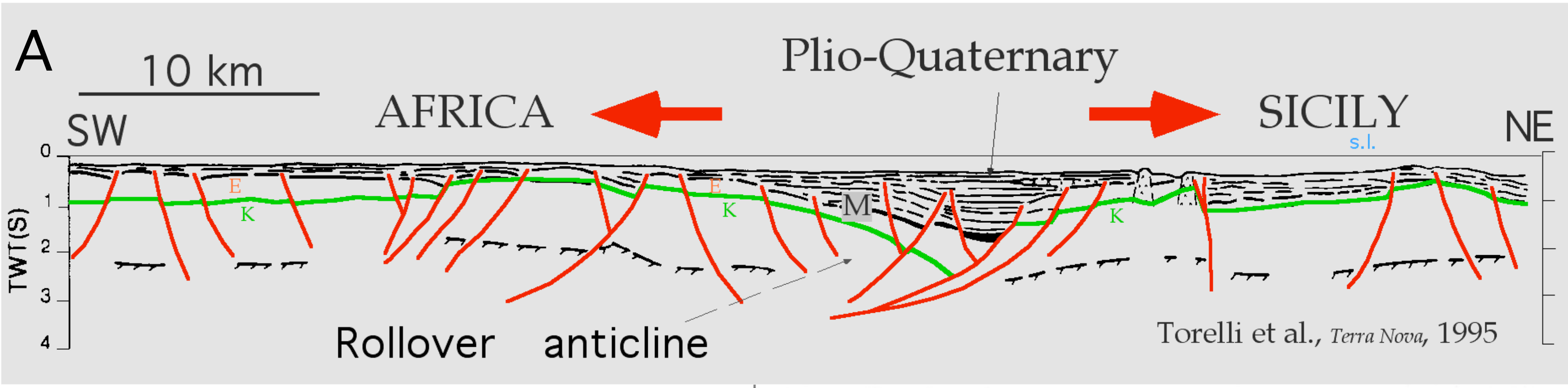
Alps
Venice
Fig.2
Apennines
Adriatic
Sea
Tyrrhenian
Sea
46°
44°
8°
10°
12°
14°
Crop 18
Apennines
SW
Po Basin
Venice
NE
REGIONAL MONOCLINE
Adriatic Plate
subduction
retreat
thrusting
subduction related subsidence
Po delta load
subsidence rate (mm/yr)
0
1
2
3
0
50
100
150
km

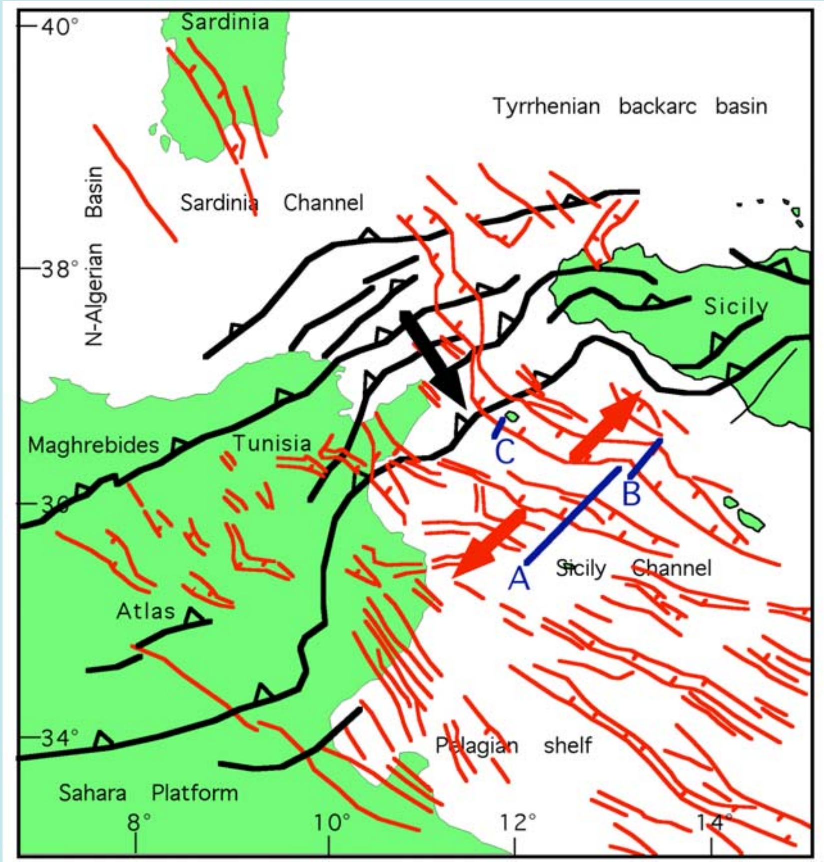

Out-of-sequence thrust
5
Present N-Apennines accretionary prism
Frontal thrust
5
Late Pleistocene-Active 5
Early Pleistocene 4
Late Pliocene 3
Mid-Pliocene 2
Early Pliocene 1
Late Pleistocene-Active 5
5 km
Po Basin - seismics after Pieri, 1983
W
E-NE
Backarc basin
Forebelt
Forebelt
Retrobelt
5
5
crust
asthenospheric
wedge
pre-subduction Moho
LID
30 km


E- or NE-directed subductions
W-directed subductions

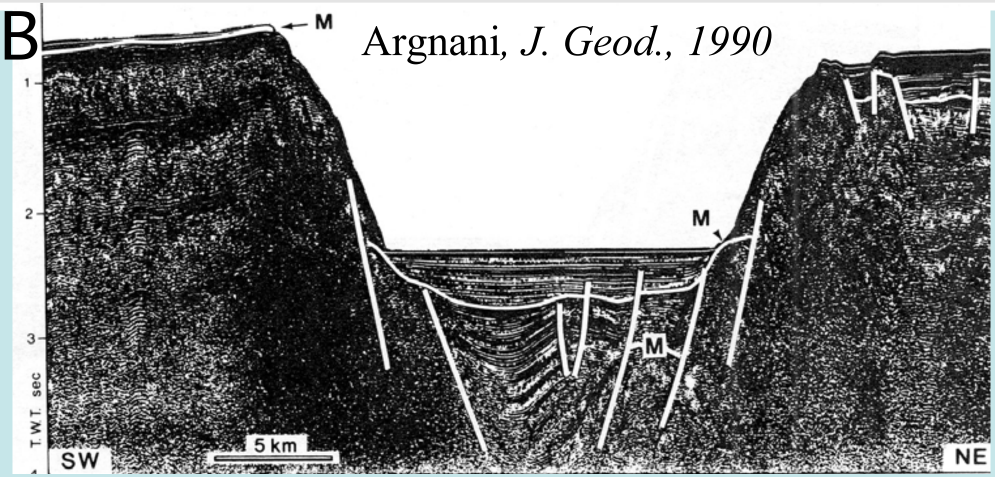

orogens vs subduction polarity
low elevation - mainly sediments involved
1 deep foredeep - single vergence - back-arc basin
high elevation - basement totally involved
2 shallow foredeeps - double vergence
W
E-NE
back-arcbasin
decollement
dipping downward
lithosphere
lithospheric
positivebalance
decollement
rising upward
E- or NE-ward relative
asthenospheric flow
lithospheric
negativebalance
670 km

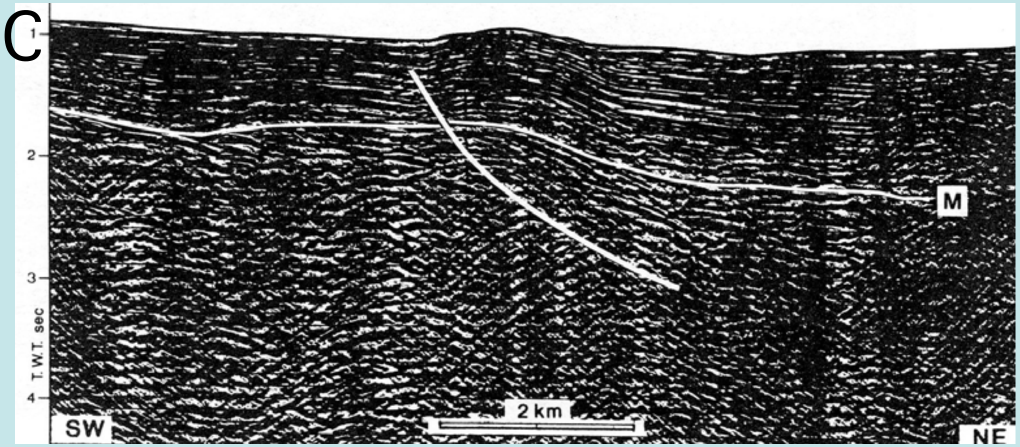

W
SEDIMENTARY COVER
BASEMENT
E-NE
Backarc basin
Forebelt
Forebelt
Retrobelt
HT/LP
M-HT/M-HP
LT/LP
crust
HT/HP
LT/HP
asthenospheric
wedge
pre-subduction Moho
LID
30 km
LT/HP

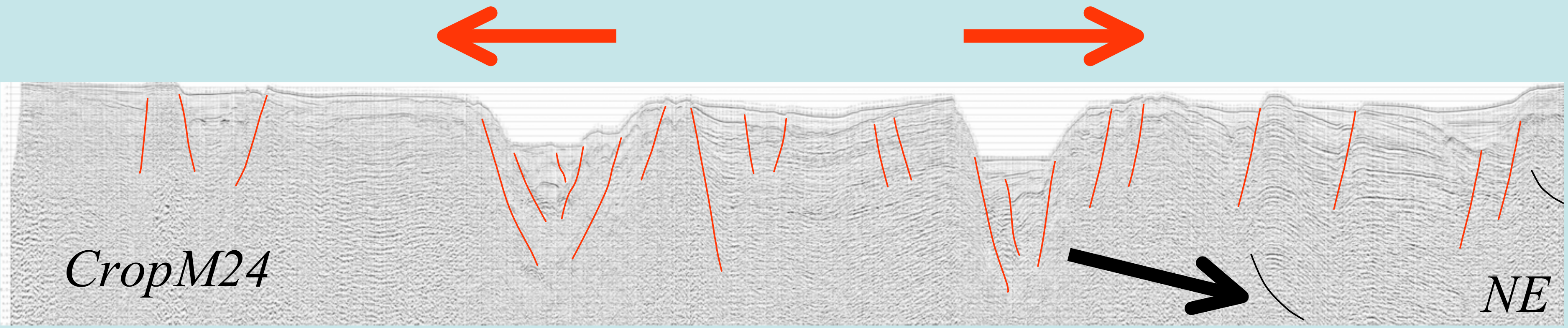


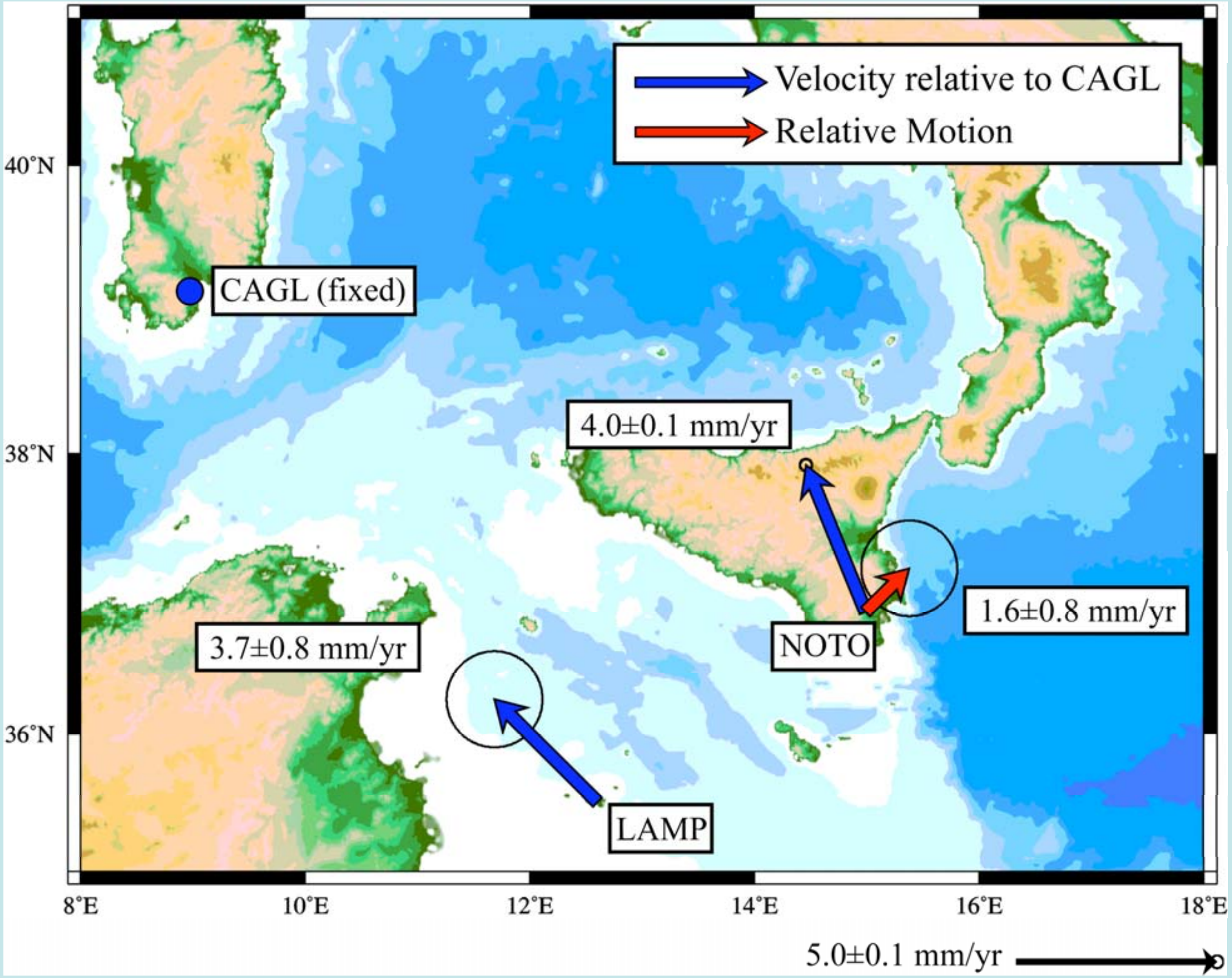


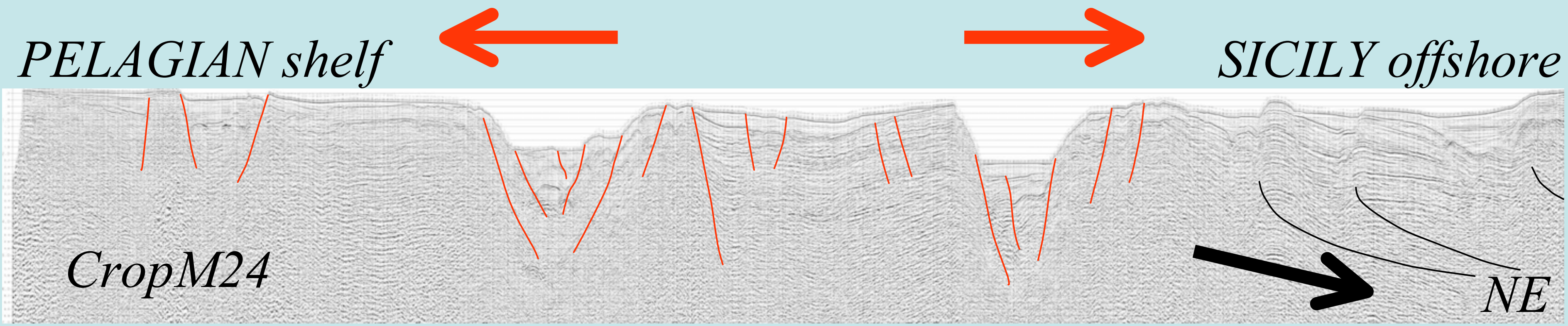
Tricart et al., Tectonophysics,1994

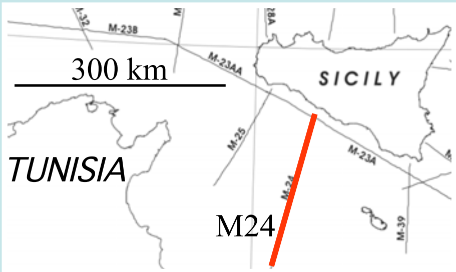




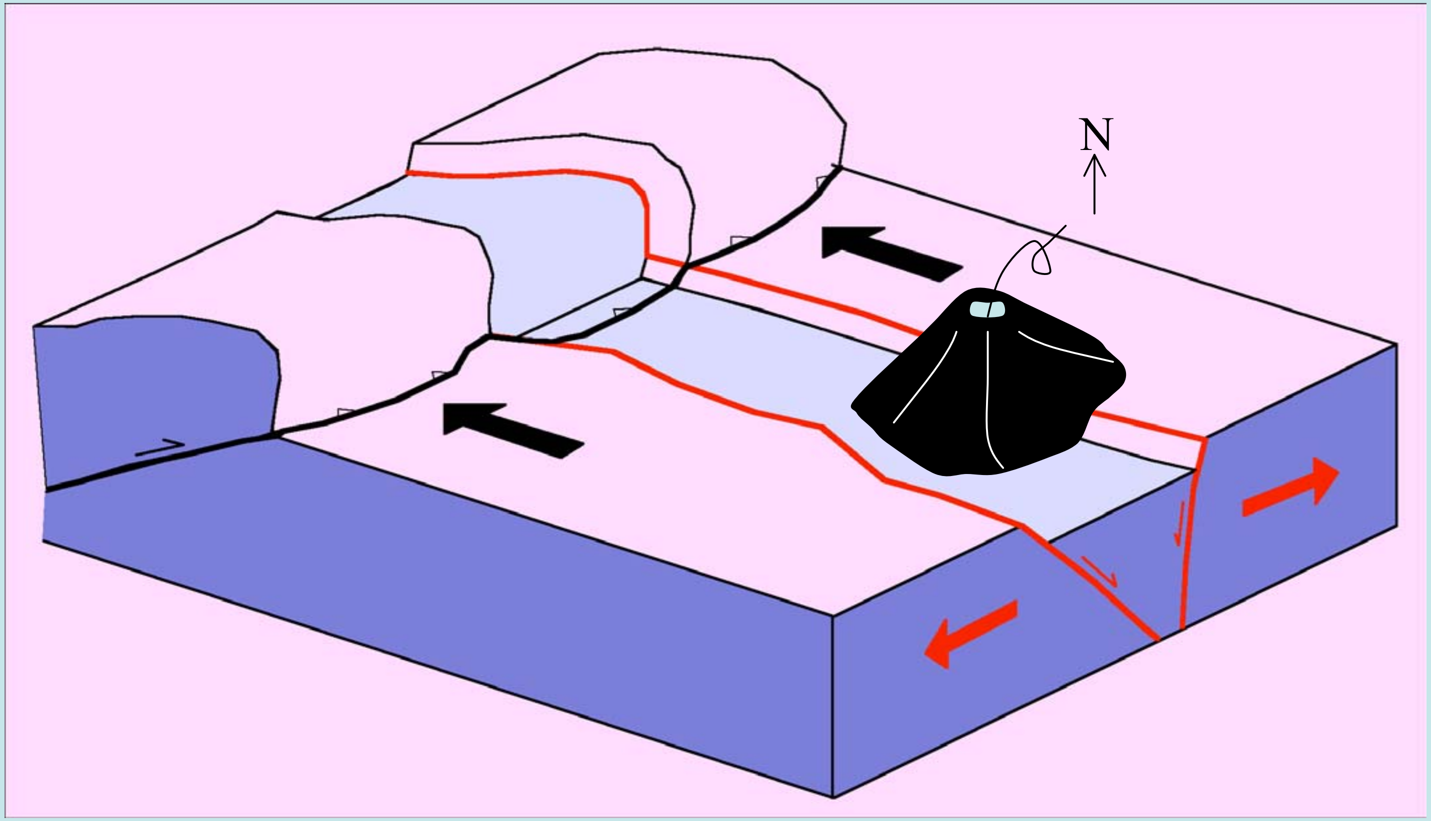

CropM24
NE

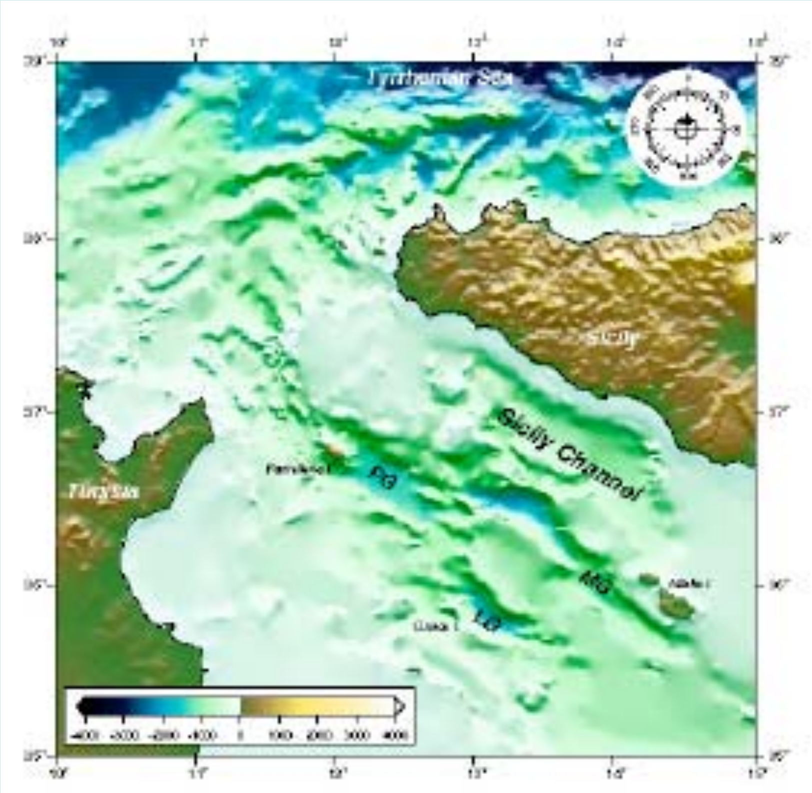

Velocity relative to CAGL
Relative Motion
CAGL (fixed)
4.0±0.1 mm/yr
1.6±0.8 mm/yr
3.7±0.8 mm/yr
NOTO
LAMP
40°N
38°N
36°N
8°E
10°E
12°E
14°E
16°E
18°E
5.0±0.1 mm/yr

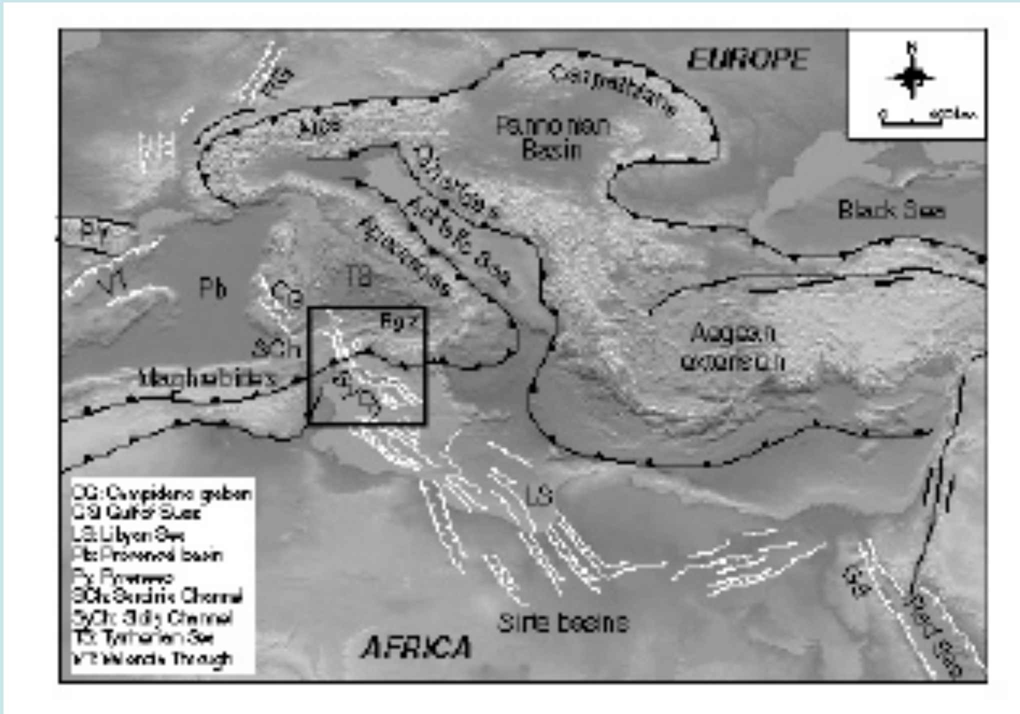


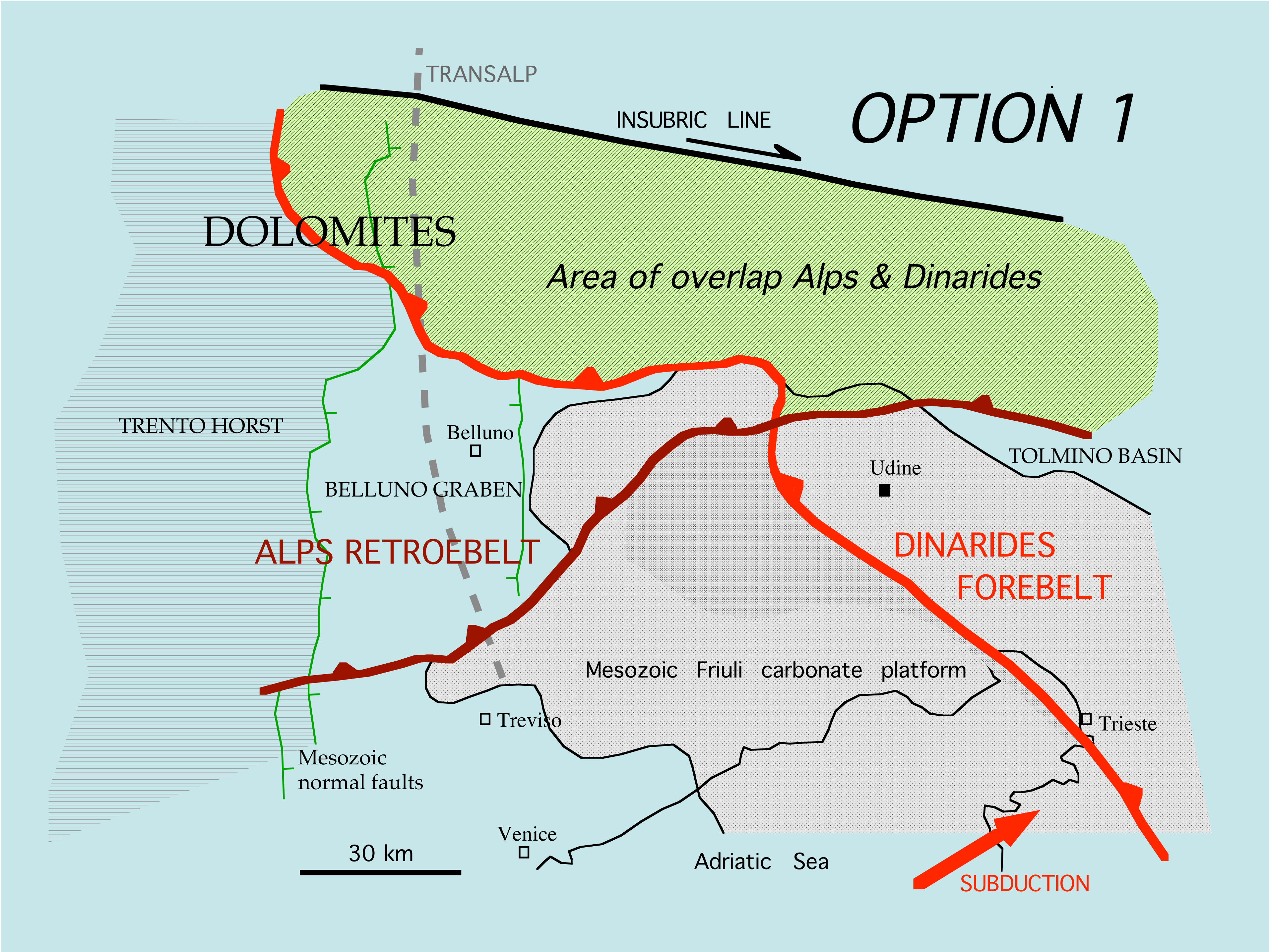


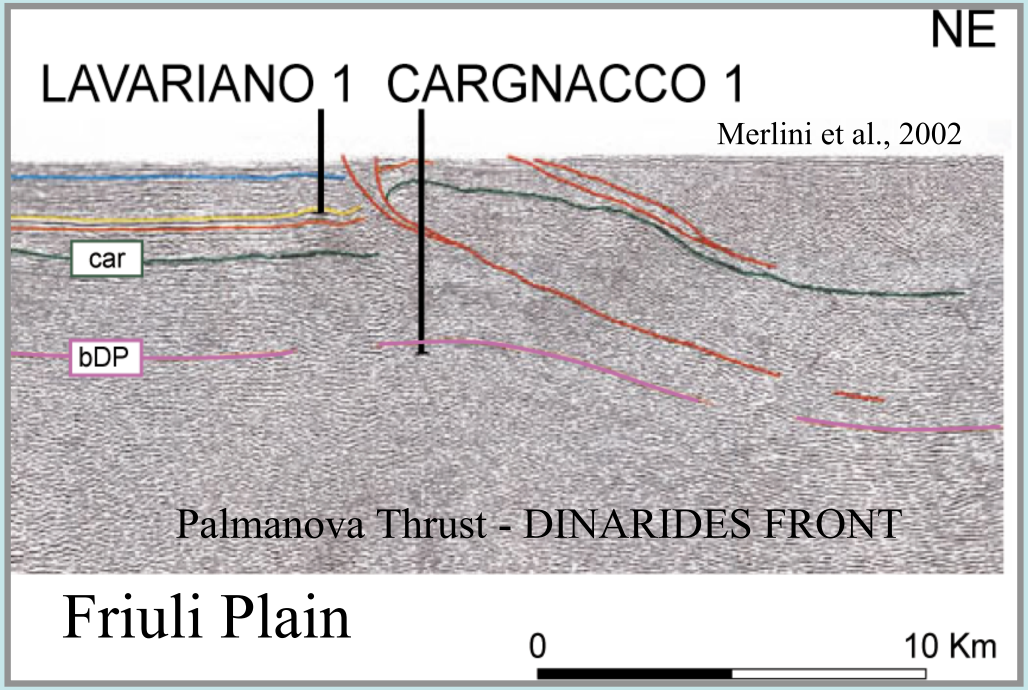
Coexisting tectonic fields

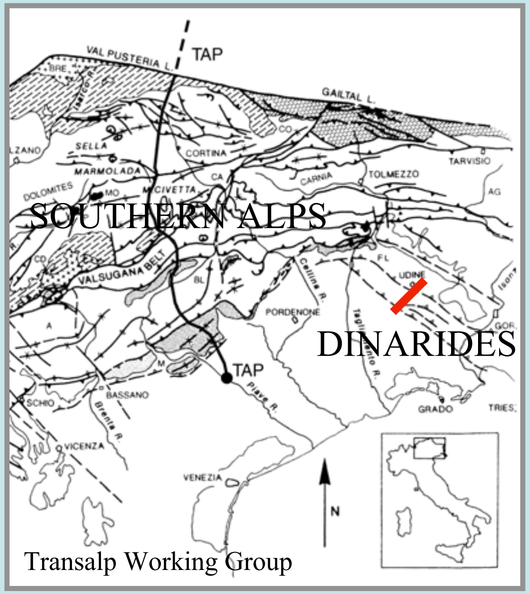


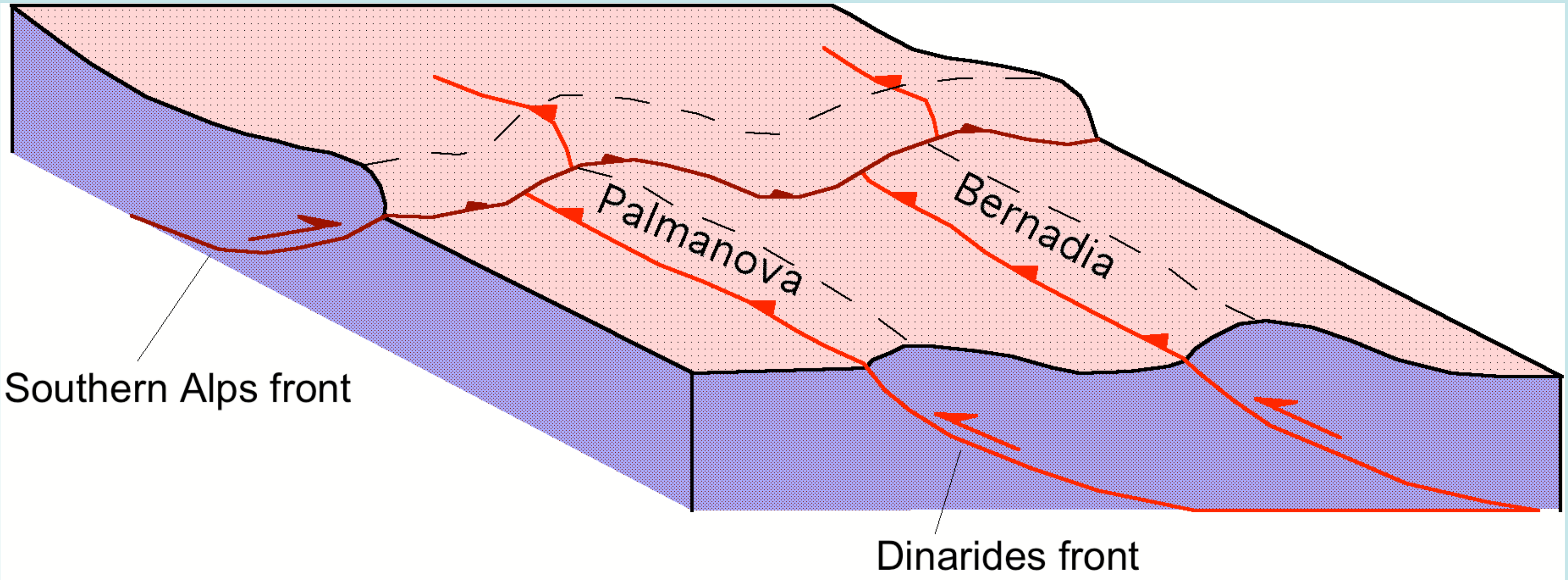

Tyrrhenian Sea
Sicily
Sicily Channel
Tunisia


EUROPE
Carpathians
Pannonian Basin
Black Sea
Adriatic Sea
Apennines
TB
Pb
CG
SCh
Maghrebides
Aegean extension
LS
Sirte basins
AFRICA
Red Sea

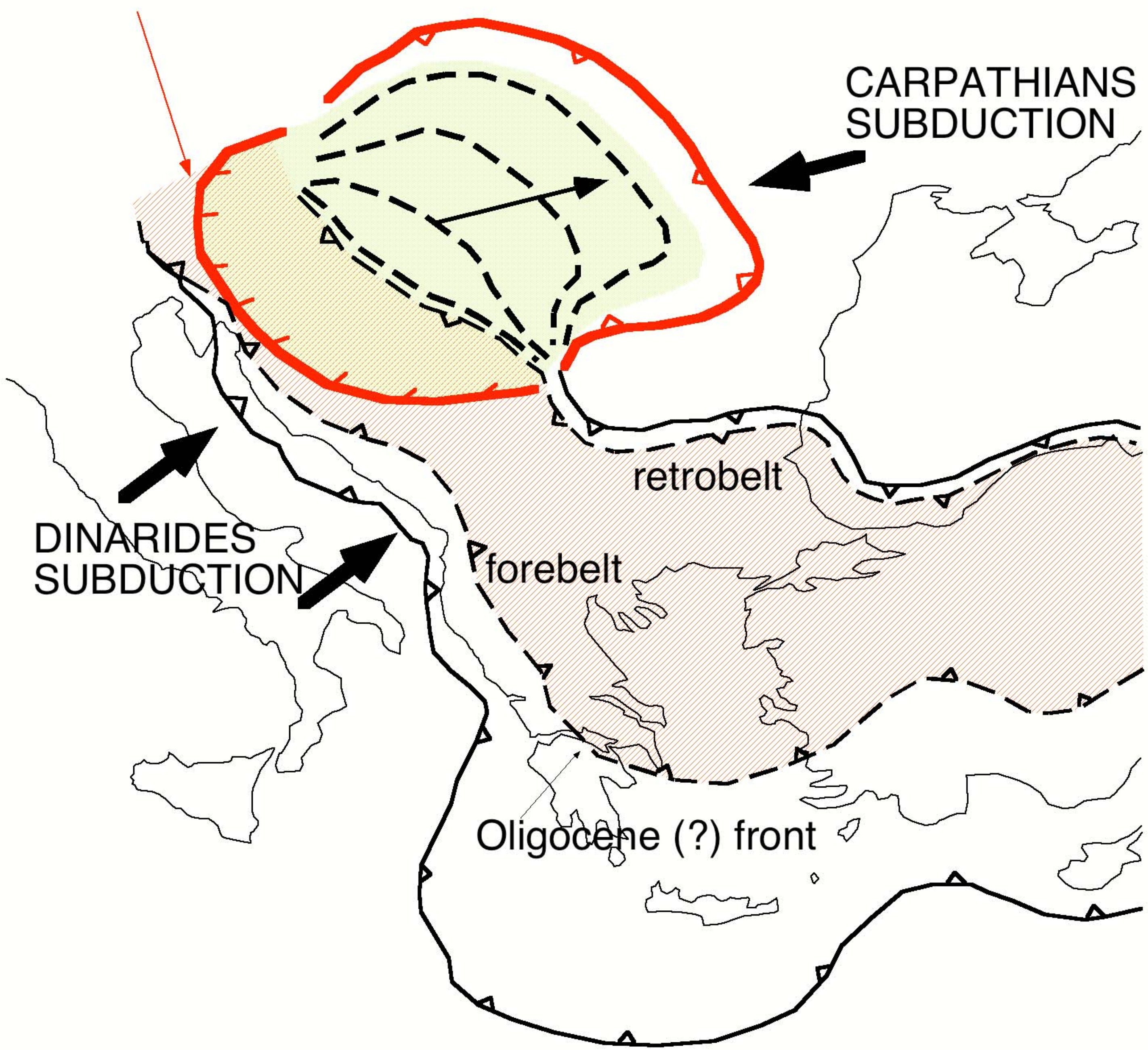

TRANSALP
INSUBRIC LINE
OPTION 1
DOLOMITES
Area of overlap Alps & Dinarides
TRENTO HORST
Belluno
BELLUNO GRABEN
TOLMINO BASIN
Udine
ALPS RETROEBELT
DINARIDES
FOREBELT
Mesozoic Friuli carbonate platform
Treviso
Trieste
Mesozoic
normal faults
Venice
30 km
Adriatic Sea
SUBDUCTION

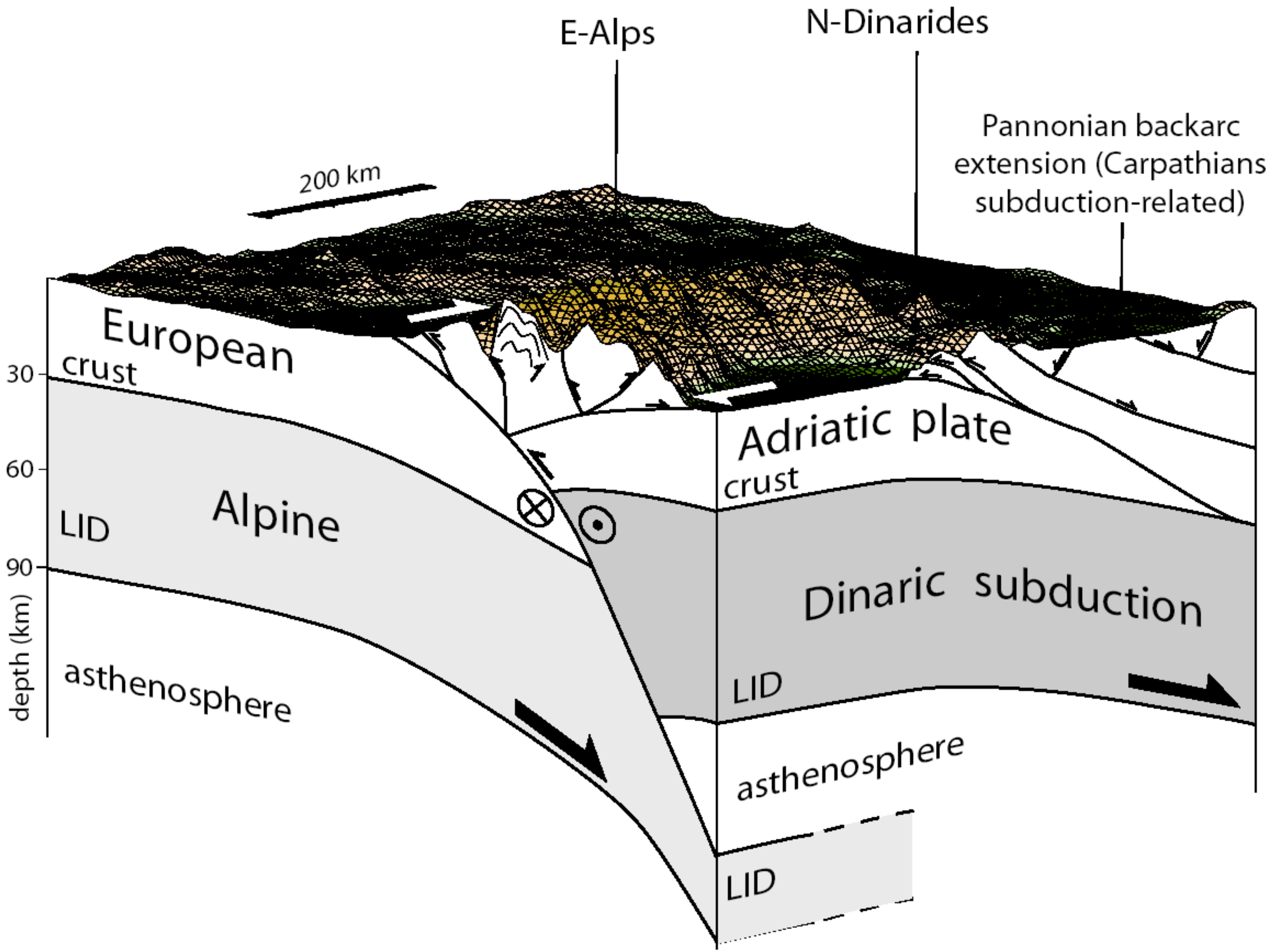

NE
LAVARIANO 1
CARGNACCO 1
Merlini et al., 2002
car
bDP
Palmanova Thrust - DINARIDES FRONT
Friuli Plain
0
10 Km


TAP
VAL PUSTERIA L.
GAILTAL L.
CORTINA
TOLMEZZO
TARVISIO
SOUTHERN ALPS
VALSUGANA BELT
PORDENONE
UDINE
DINARIDES
TAP
GRADO
VICENZA
VENEZIA
N
Transalp Working Group


Palmanova
Bernadia
Southern Alps front
Dinarides front

Pannonian extension western margin




E-Alps
N-Dinarides
Pannonian backarc extension (Carpathians subduction-related)
200 km
European crust
Alpine LID
asthenosphere
Adriatic plate crust
Dinaric subduction
LID
asthenosphere
LID
30
60
90
depth (km)

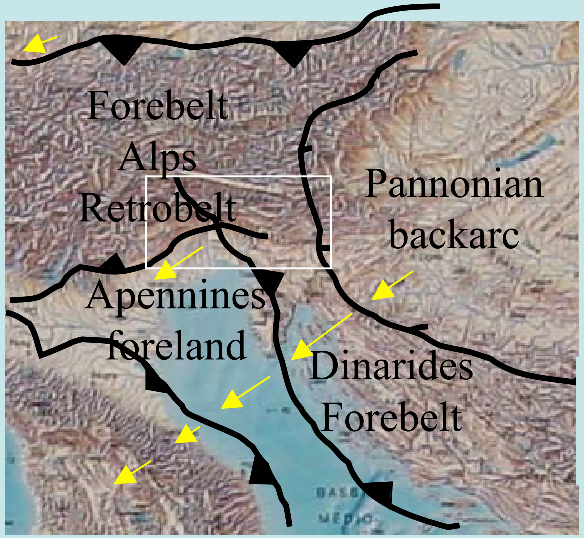
Four subduction zones contributed to deform the area:

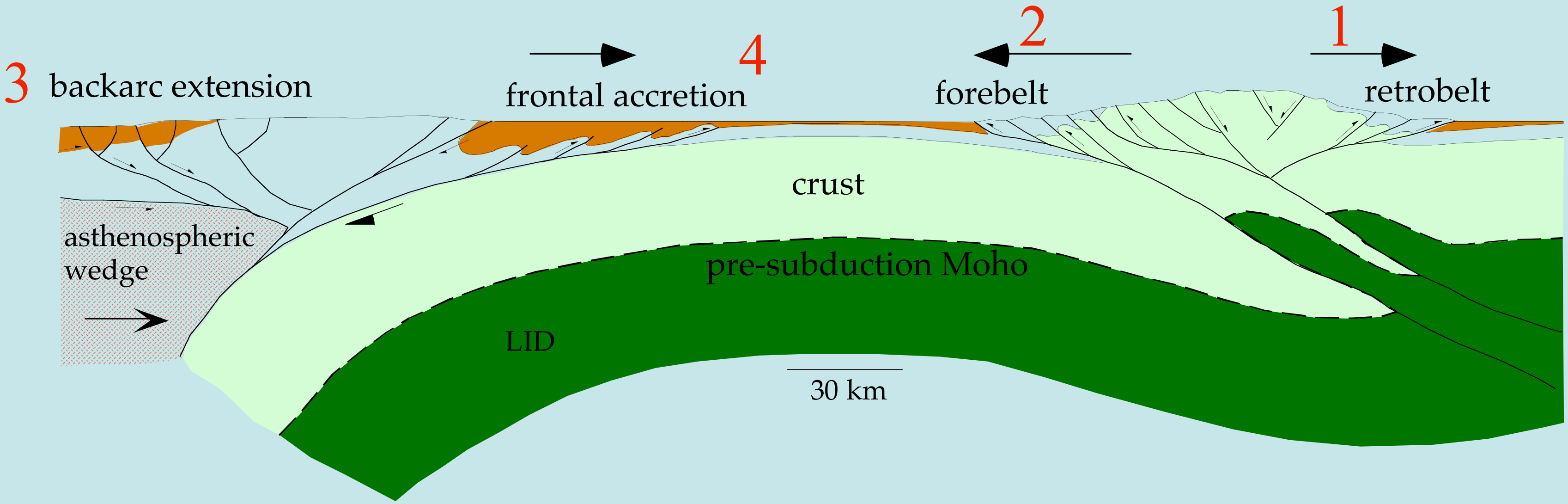
1 - ALPS (retrobelt)

2 - DINARIDES (forebelt)

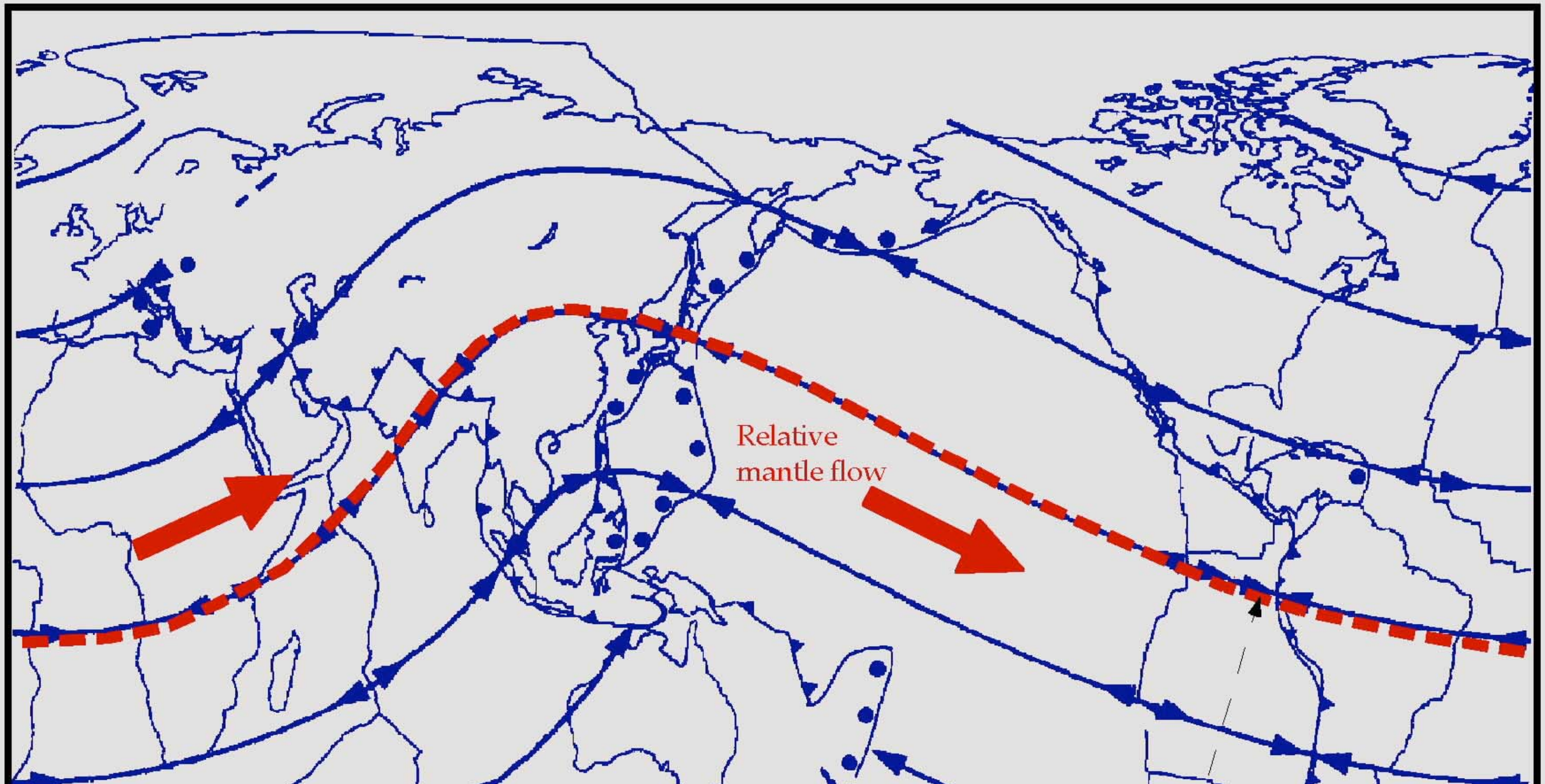
3 - CARPATHIANS (western backarc)

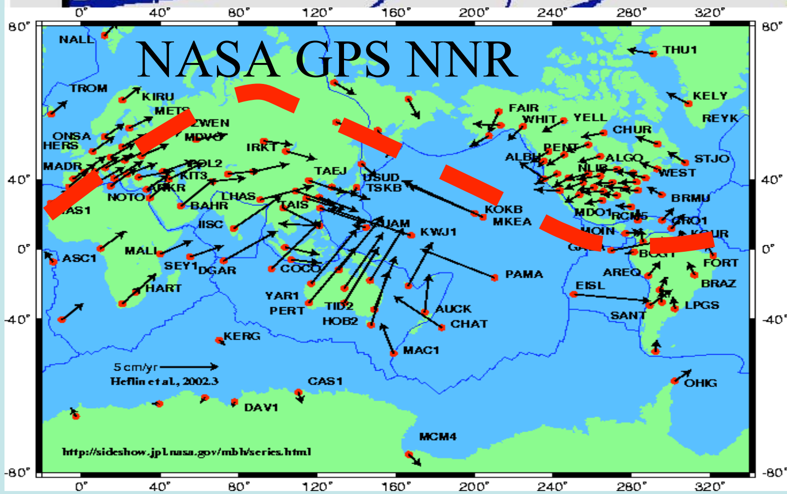
4 - APENNINES (foreland flexure)



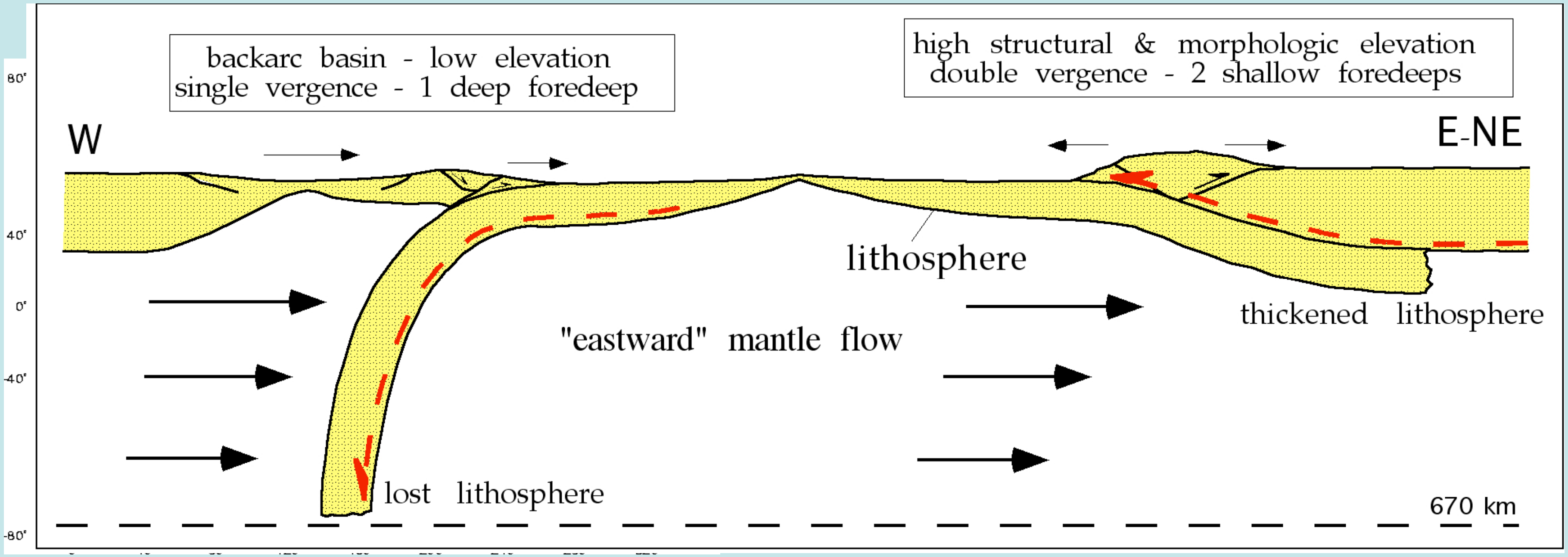


- Independent geodynamic processes may coexist in one area
- Contractional belts (e.g., Alps) may form without syn-orogenic collapse





Mainstream of plate motions based on tectonic features


backarc basin - low elevation
single vergence - 1 deep foredeep
high structural & morphologic elevation
double vergence - 2 shallow foredeeps
W
E-NE
lithosphere
thickened lithosphere
"eastward" mantle flow
lost lithosphere
670 km

Turcotte & Schubert, 1982

$$w = \frac{2\rho_m \alpha_v (T_m - T_0)}{\rho_m - \rho_w}\left(\frac{\kappa x}{\pi u}\right)^{1/2}$$

W = water depth

ρ_m = asthenosphere density

ρ_w = water density

T_m = mantle temperature

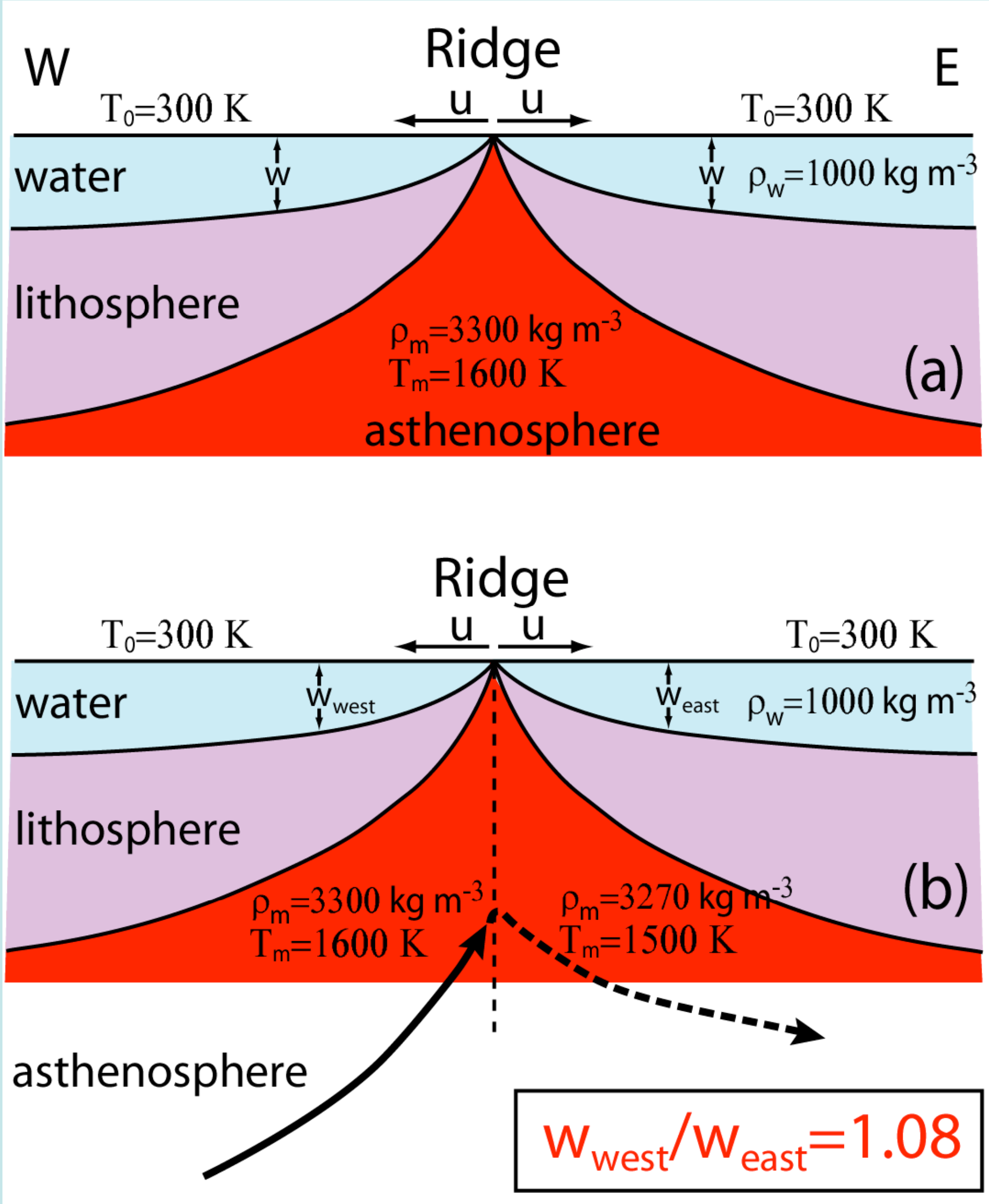
T_0 = surface temperature

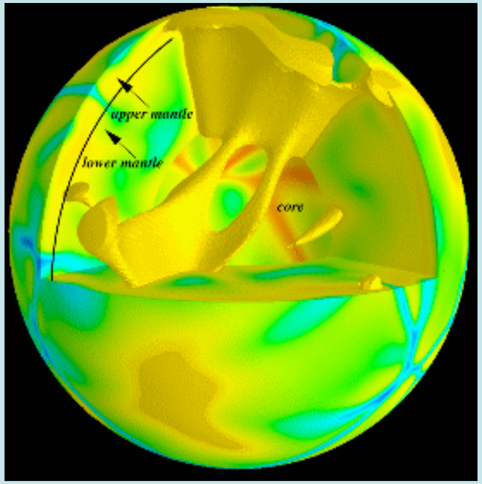
α_v = volumetric coefficient of thermal expansion

k = mantle thermal diffusivity

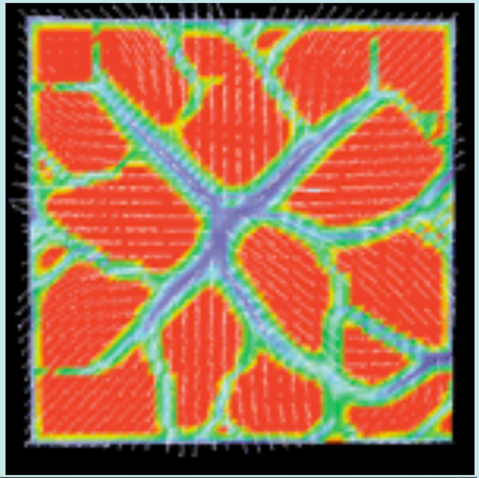
x = distance from the ridge

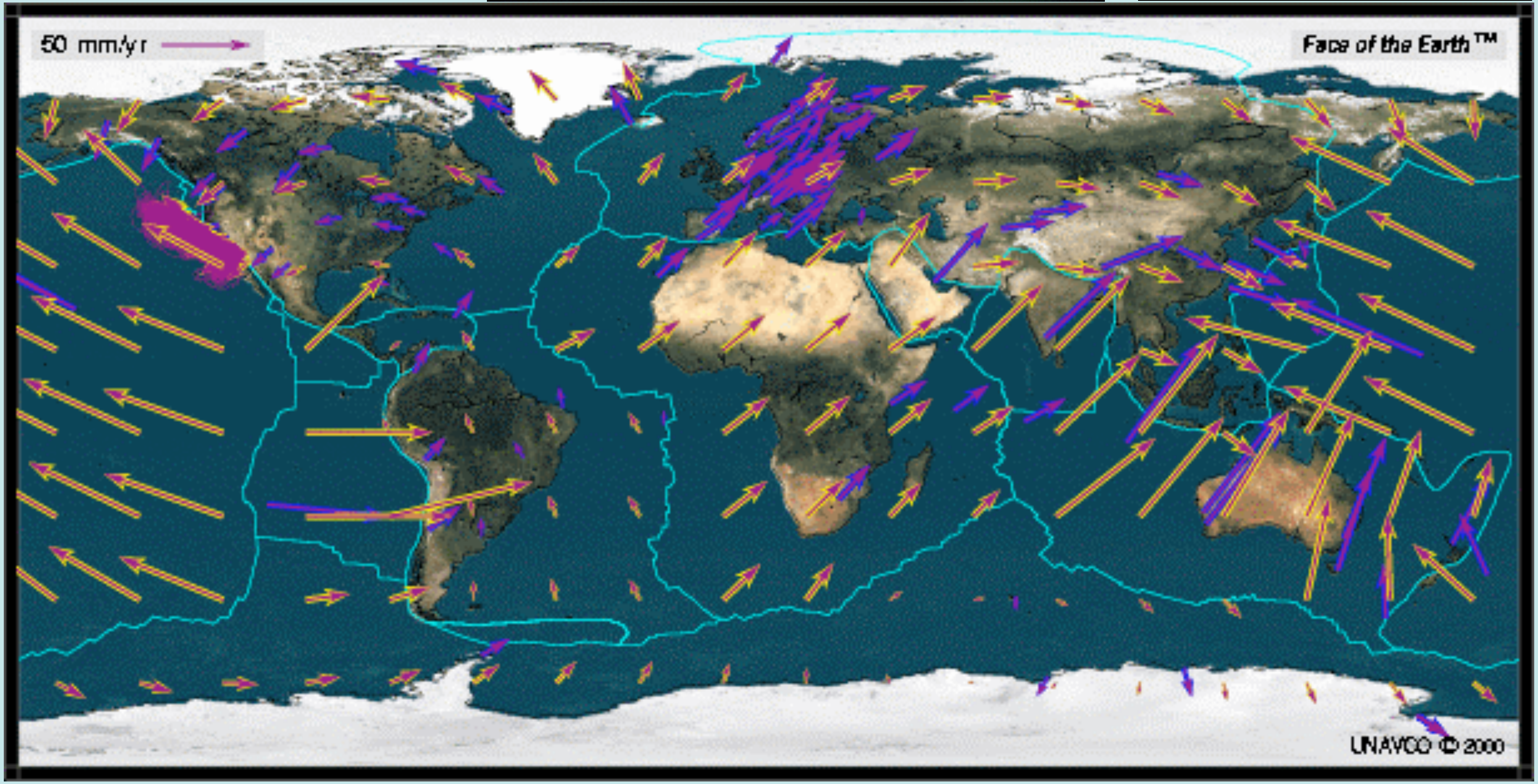
u = half spreading rate

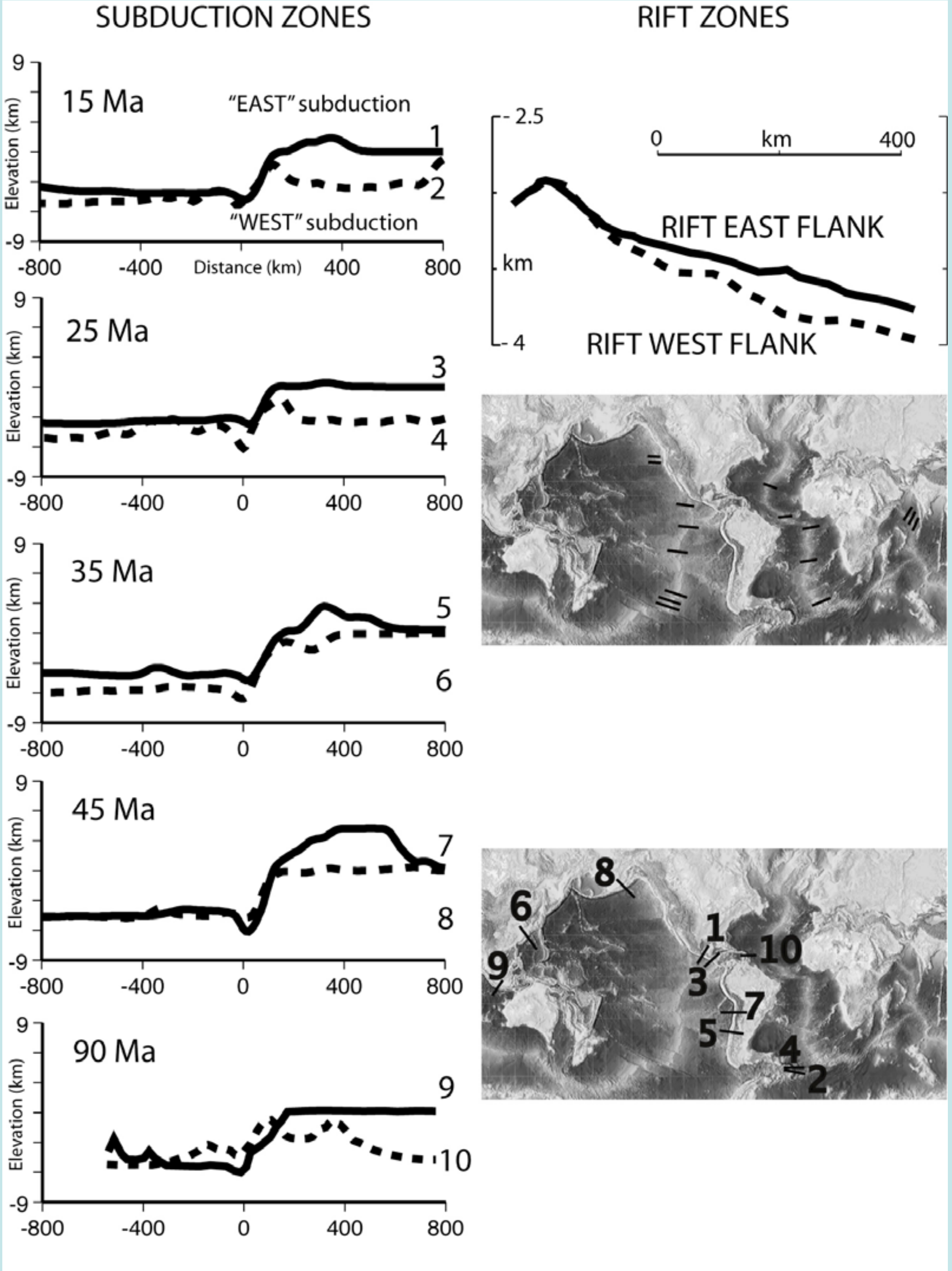



upper mantle
lower mantle
core

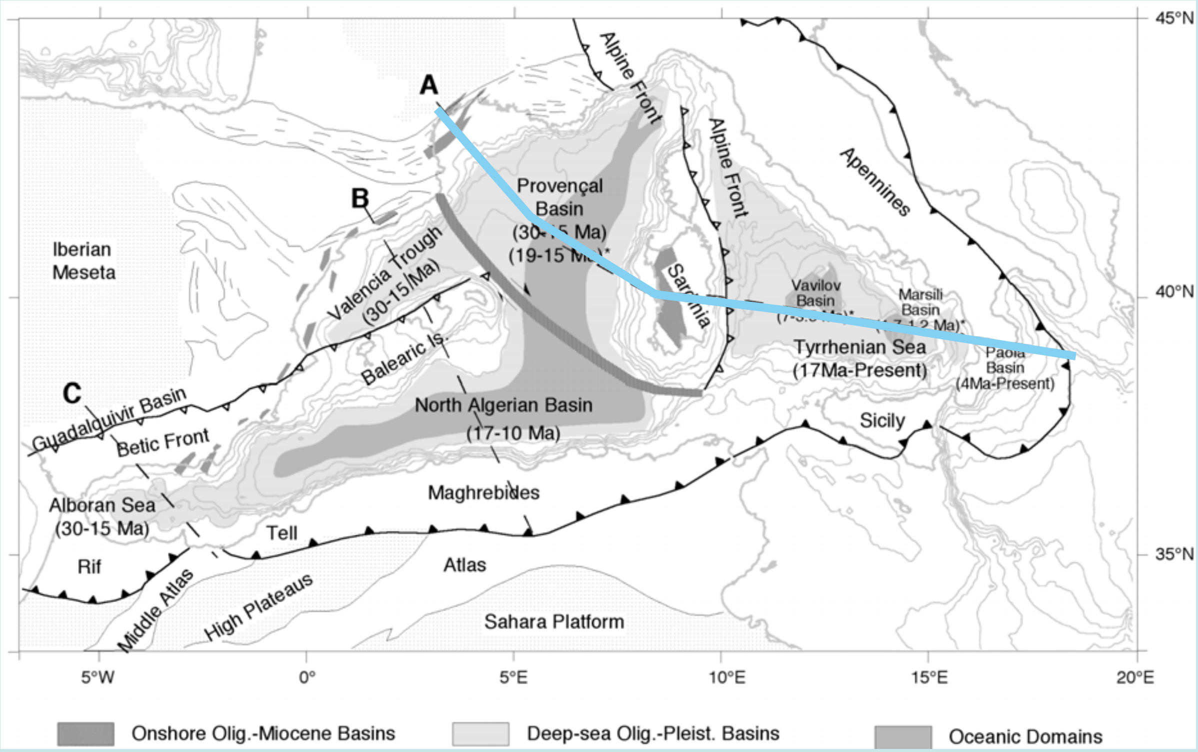

MANTLE CONVECTION SIMULATION

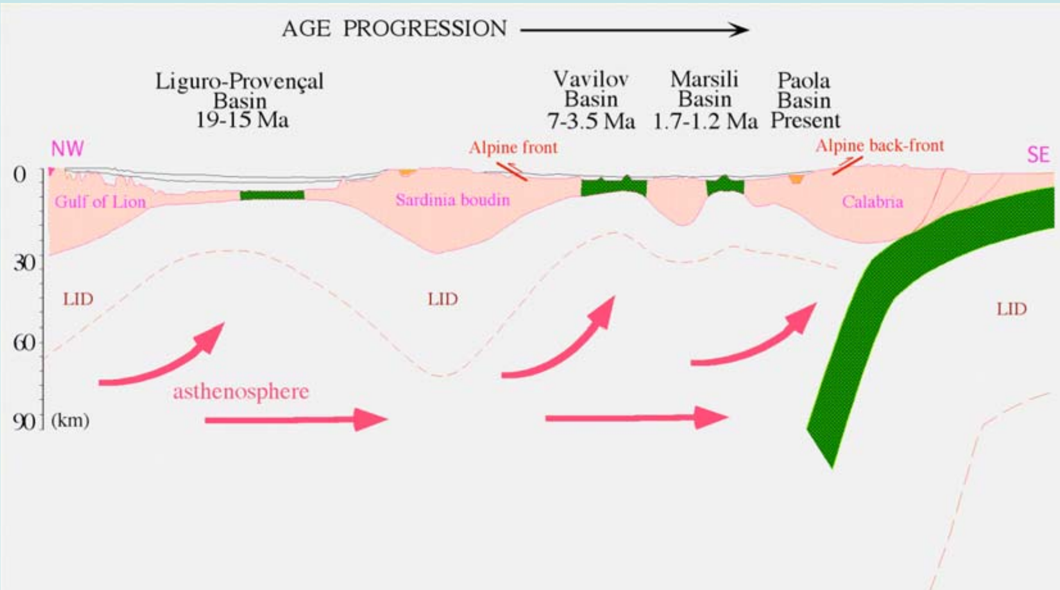


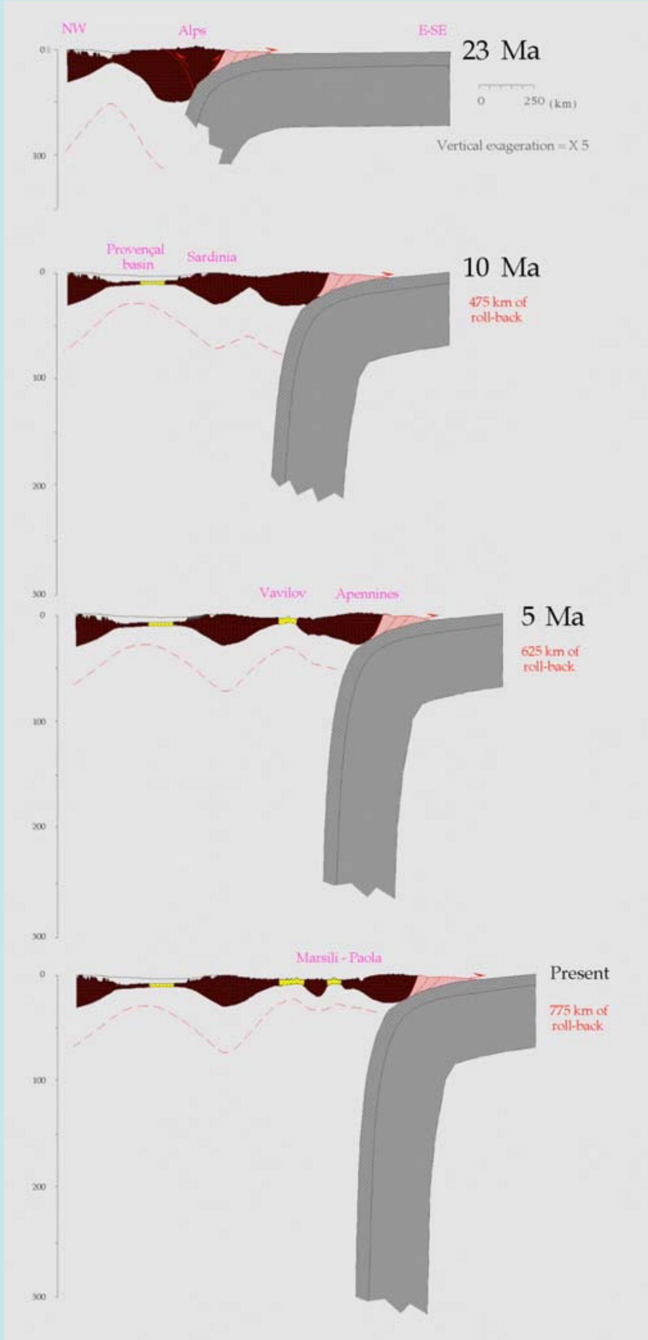

50 mm/yr
Face of the Earth™
UNAVCO © 2000



SUBDUCTION ZONES
RIFT ZONES
15 Ma
"EAST" subduction
"WEST" subduction
Elevation (km)
Distance (km)
25 Ma
35 Ma
45 Ma
90 Ma
RIFT EAST FLANK
RIFT WEST FLANK
km


A
B
C
Alpine Front
Alpine Front
Apennines
Provençal Basin (30-15 Ma) (19-15 Ma)*
Iberian Meseta
Valencia Trough (30-15 Ma)
Sardinia
Vavilov Basin
Marsili Basin
Tyrrhenian Sea (17Ma-Present)
Paola Basin (4Ma-Present)
Balearic Is.
North Algerian Basin (17-10 Ma)
Guadalquivir Basin
Betic Front
Sicily
Maghrebides
Alboran Sea (30-15 Ma)
Tell
Rif
Atlas
Middle Atlas
High Plateaus
Sahara Platform
45°N
40°N
35°N
5°W
0°
5°E
10°E
15°E
20°E
Onshore Olig.-Miocene Basins
Deep-sea Olig.-Pleist. Basins
Oceanic Domains

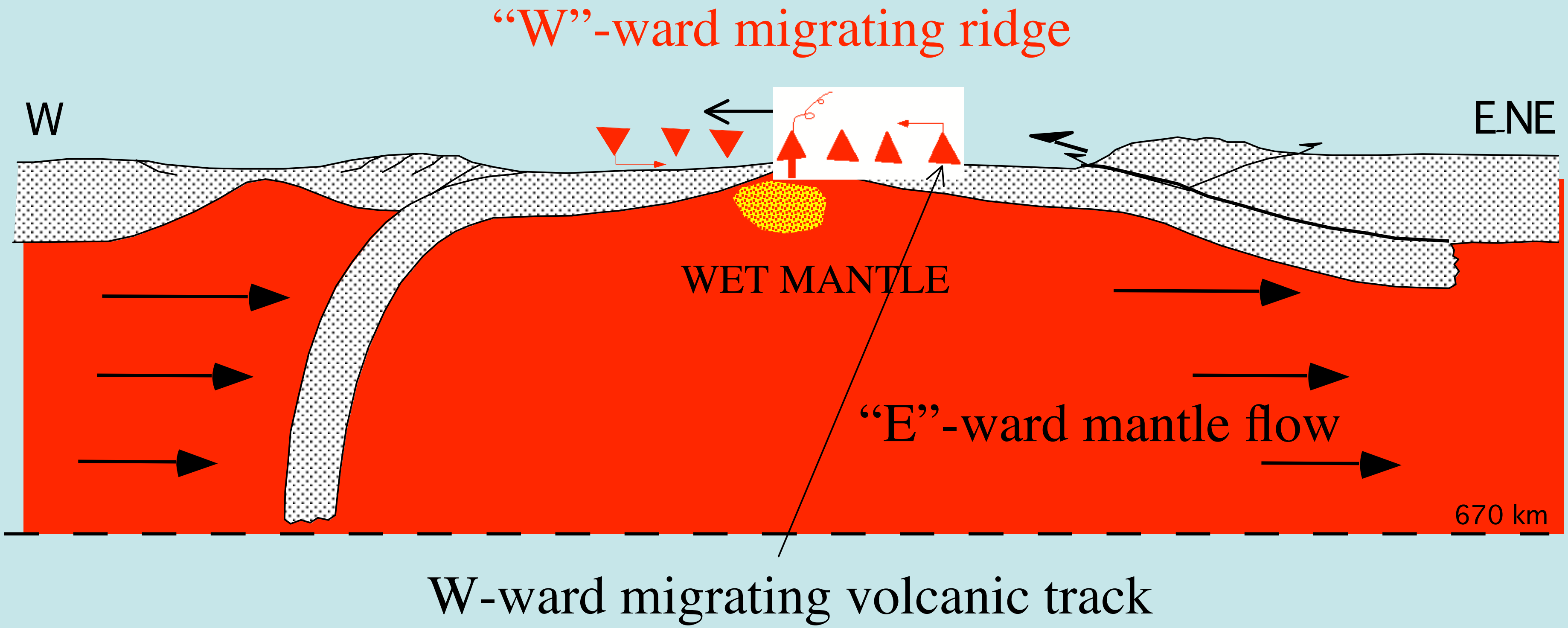

AGE PROGRESSION
Liguro-Provençal Basin 19-15 Ma
Vavilov Basin 7-3.5 Ma
Marsili Basin 1.7-1.2 Ma
Paola Basin Present
NW
SE
Alpine front
Alpine back-front
Gulf of Lion
Sardinia boudin
Calabria
LID
LID
LID
asthenosphere
0
30
60
90
(km)


NW
Alps
E-SE
23 Ma
0 250 (km)
Vertical exageration = X 5
Provençal basin
Sardinia
10 Ma
475 km of roll-back
Vavilov
Apennines
5 Ma
625 km of roll-back
Marsili - Paola
Present
775 km of roll-back

WESTWARD DRIFT OF THE LITHOSPHERE

- Asymmetry of subduction zones
- Asymmetry of rift zones

Evidences of mantle flow also from
- shear-wave splitting
- sheared asthenospheric xenoliths



SHALLOW SOURCE OF NOT SO HOT HOTSPOT

Tidal Friction