The Abdus Salam International Centre for Theoretical Physics

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Advanced School on Direct and Inverse Problems of Seismology

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Structural models of the lithosphere-asthenosphere system in the Mediterranean and volcanic activity

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Structural models of the lithosphere-asthenosphere system in the Mediterranean and volcanic activity

Giuliano F. Panza

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Part 1

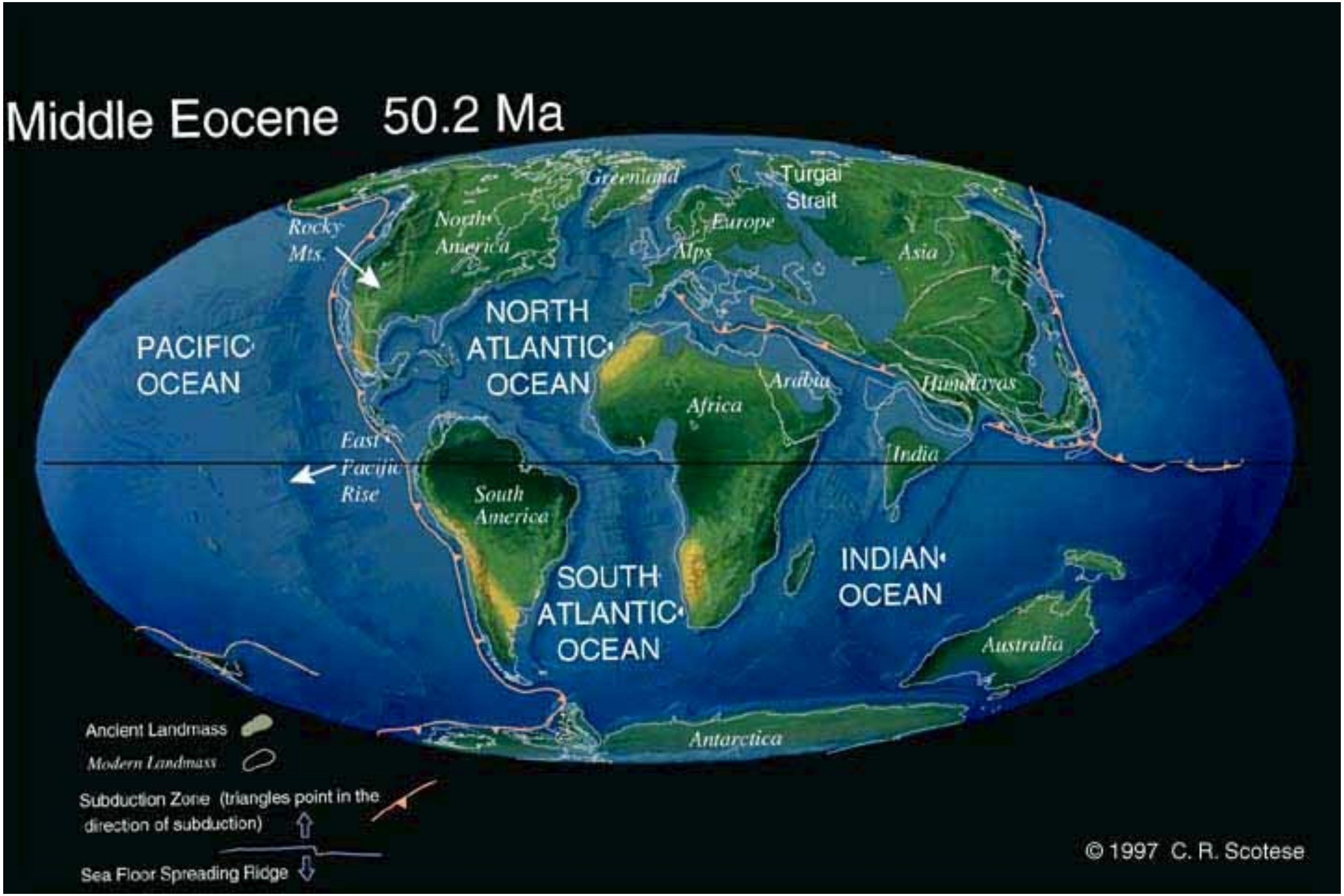
Advanced School on
Direct and Inverse
Problems of Seismology

ICTP - 27-9/9-10 2010

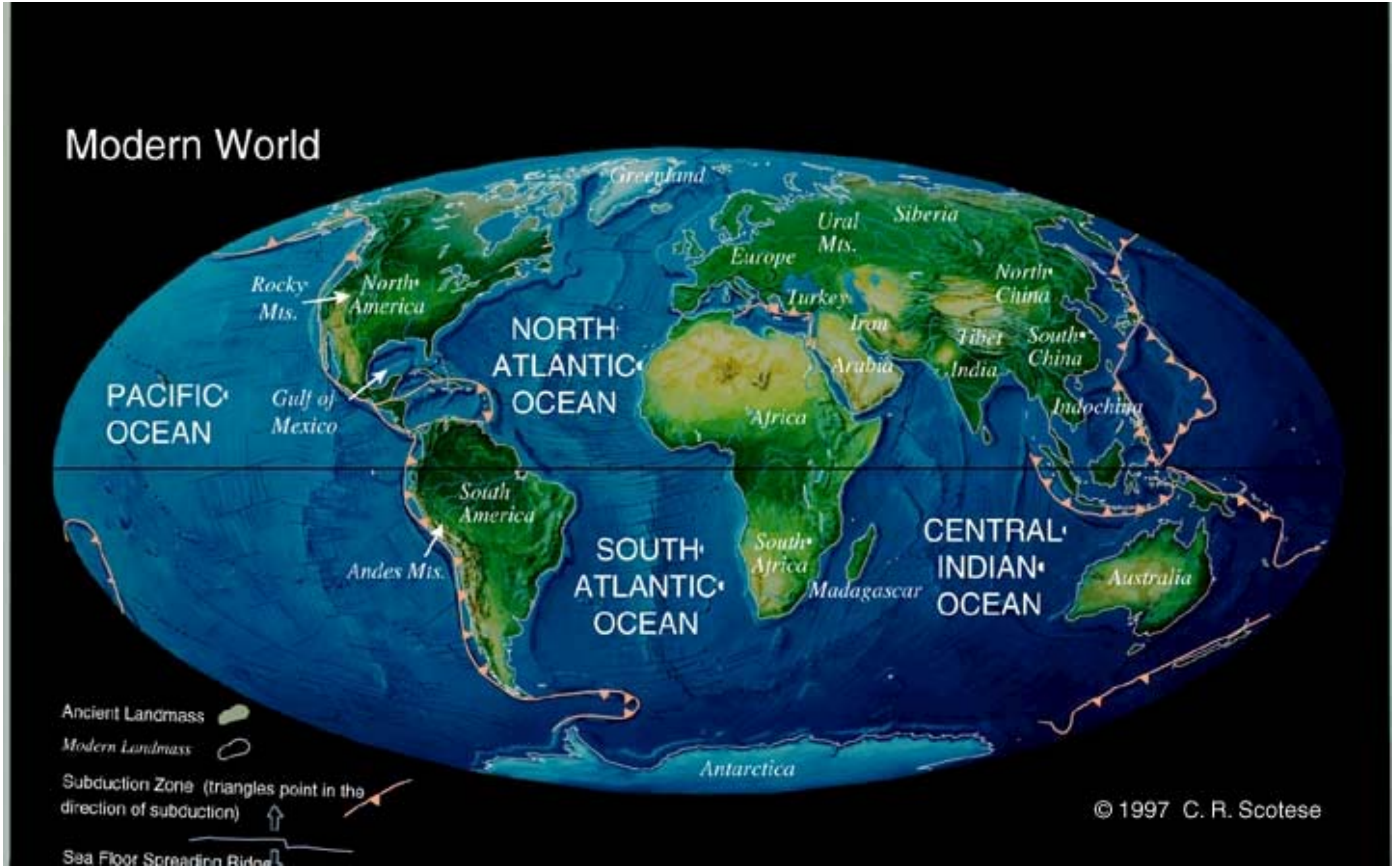
SAND - Structure and Non-Linear Dynamics of the Earth

The first line of reserach of the ICTP SAND activity, started in 1991, is on non-linear dynamics with application to earthquake prediction and to the estimation of seismic risk including: non-linear dynamics of lithosphere blocks and development and testing of algorithms for earthquake prediction. The second line is structure of the earth with application to seismic risk mitigation including: physical instability of megacities (PIOM), deterministic seismic hazard assessment, 3D mapping.

Plates move



Middle Eocene 50.2 Ma
Greenland
Turgai Strait
Rocky Mts.
North America
Europe
Alps
Asia
NORTH ATLANTIC OCEAN
PACIFIC OCEAN
Arabia
Himalayas
Africa
East Pacific Rise
India
South America
SOUTH ATLANTIC OCEAN
INDIAN OCEAN
Australia
Antarctica
Ancient Landmass
Modern Landmass
Subduction Zone (triangles point in the direction of subduction)
Sea Floor Spreading Ridge
© 1997 C. R. Scotese


Modern World
Greenland
Ural Mts.
Siberia
Europe
Rocky Mts.
North America
North China
Turkey
Iran
NORTH ATLANTIC OCEAN
Tibet
South China
Arabia
India
PACIFIC OCEAN
Gulf of Mexico
Africa
Indochina
South America
SOUTH ATLANTIC OCEAN
South Africa
CENTRAL INDIAN OCEAN
Andes Mts.
Madagascar
Australia
Antarctica
Ancient Landmass
Modern Landmass
Subduction Zone (triangles point in the direction of subduction)
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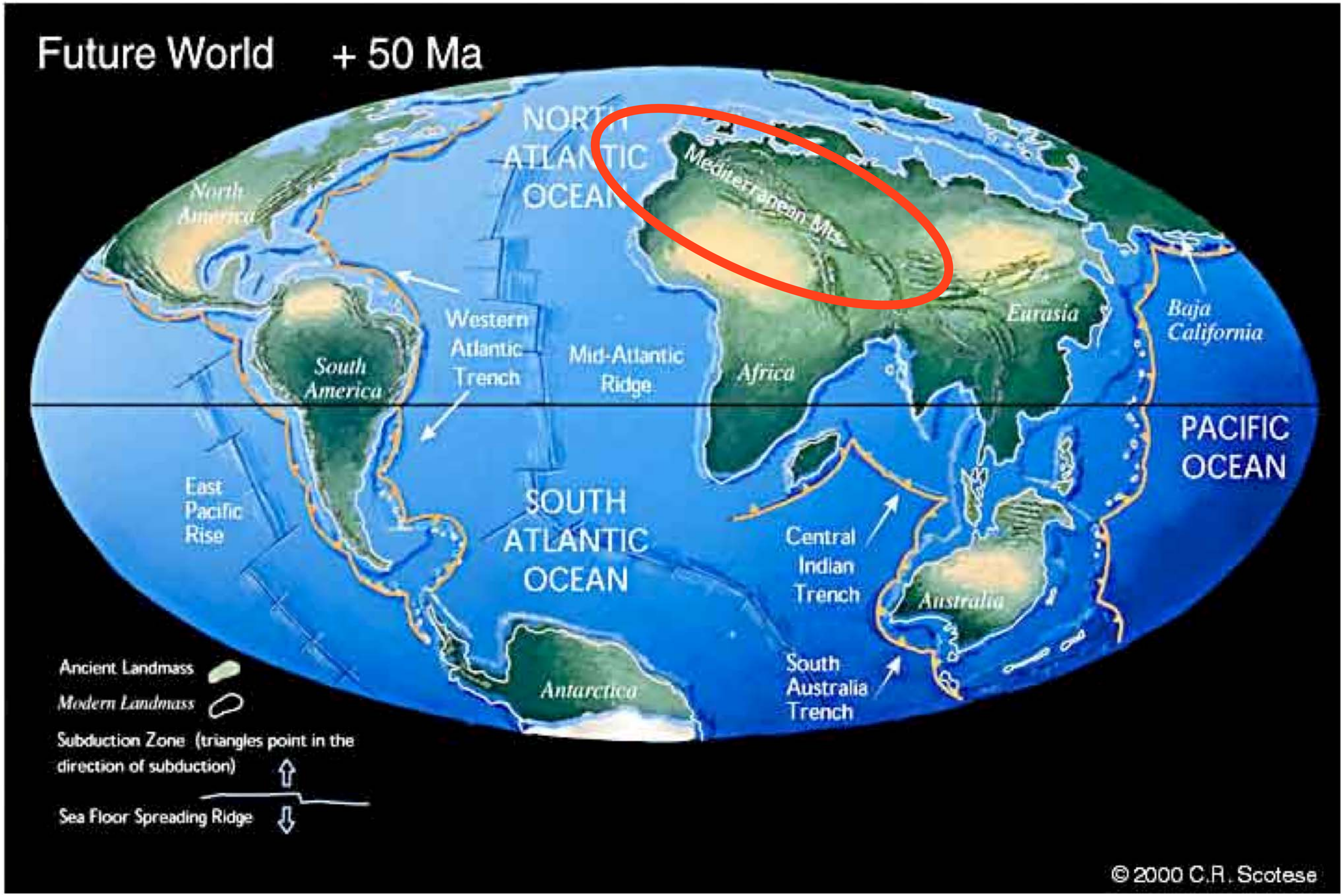
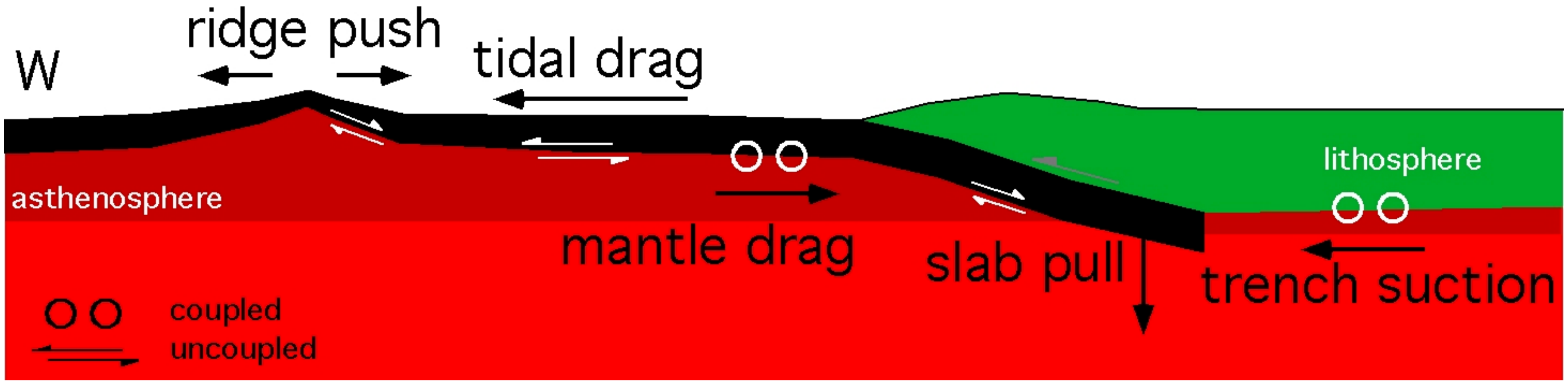


Future World + 50 Ma
NORTH ATLANTIC OCEAN
Mediterranean Mts.
North America
South America
Western Atlantic Trench
Mid-Atlantic Ridge
Africa
Eurasia
Baja California
PACIFIC OCEAN
East Pacific Rise
SOUTH ATLANTIC OCEAN
Central Indian Trench
Australia
Antarctica
South Australia Trench
Ancient Landmass
Modern Landmass
Subduction Zone (triangles point in the direction of subduction)
Sea Floor Spreading Ridge
© 2000 C.R. Scotese

However, there are still fundamental questions to be answered: are plates dragged horizontally by mantle convection? Are they dragged and sheared at the base by a faster moving mantle? Are they rather pulled by slab pull forces? Could they be driven by Earth’s rotation and tidal drag? If ridges and subduction zones trigger convection, but are nevertheless still passive features, what moves plates?

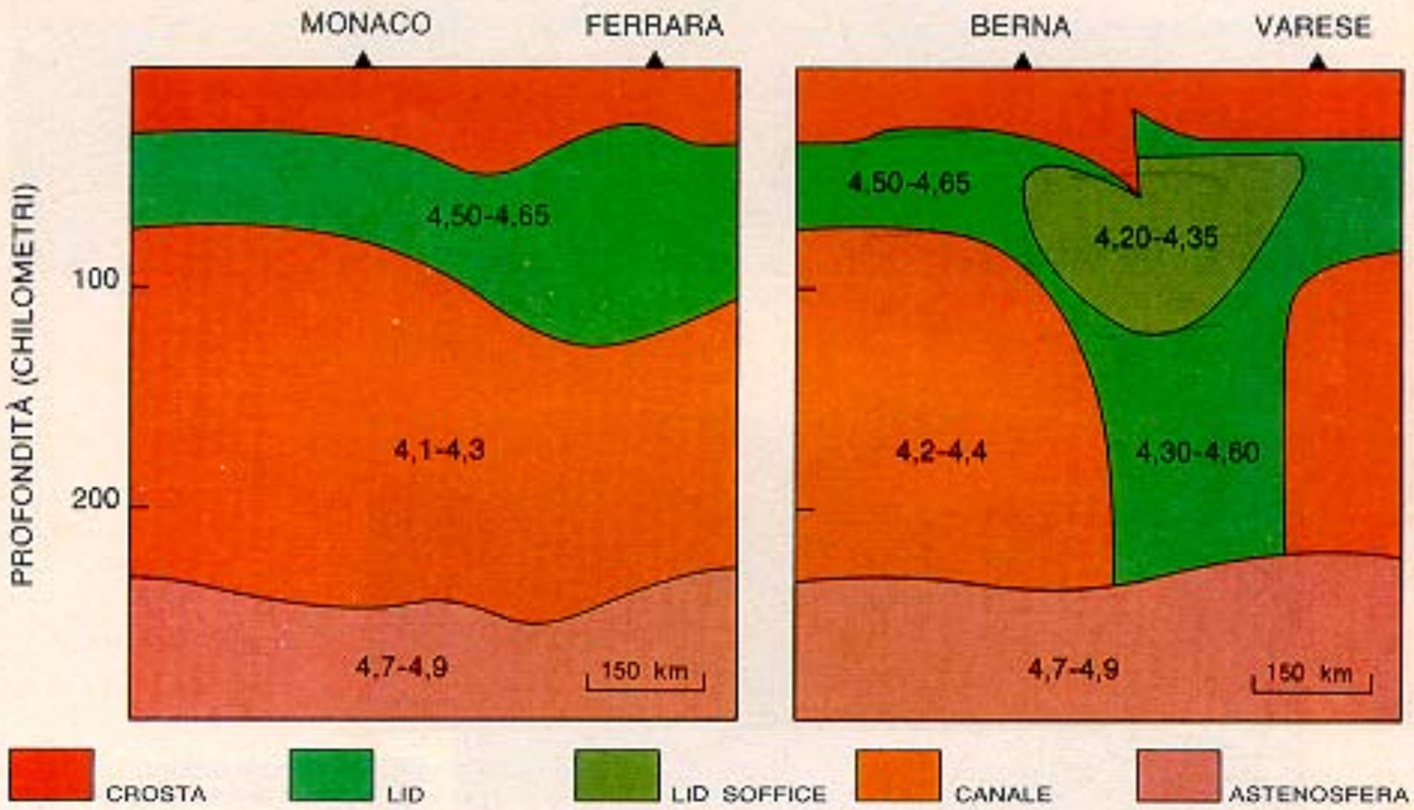


Main forces acting on the lithosphere. Mantle drag and trench suction need high coupling (higher viscosity) between lithosphere and asthenosphere to be more effective. Ridge push, slab pull and tidal drag should rather need low coupling (lower viscosity) to be efficient. Since the lithosphere is decoupled with respect to the asthenosphere, possibly more than one force is actively forcing plate motions. Circles indicate coupled forces, white half arrows show the uncoupled forces (after Doglioni et al., 2007).

The subduction of continental lithosphere is a paradox accordingly with the most popular interpretations of global tectonics, which state that subduction and plate’s tectonics are, as a rule, controlled by the weight of the slab. It is well known that continental lithosphere (not only the crust, but also the lithospheric mantle) is lighter than the underlying mantle, nevertheless the subduction of continental lithosphere, proposed by Ampferer in 1906 and proven by Panza & Muller in 1978, is now widely accepted.

Cross-sections along the Alps,

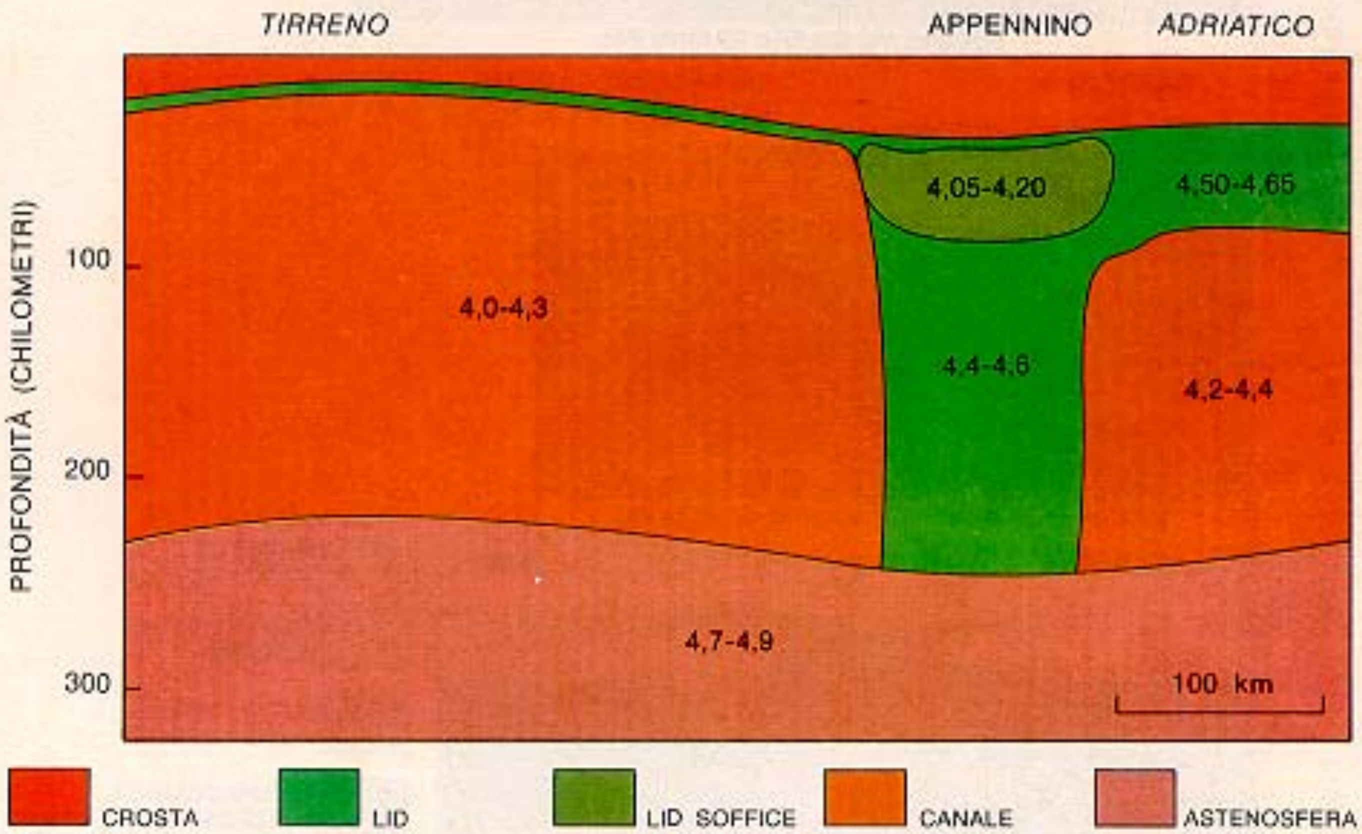
Panza et al., Le Scienze, 1980



Sezioni verticali attraverso le Alpi orientali *(a)*, centro-occidentali *(b)* e attraverso gli Appennini *(c)*. Nella sezione *a* il massimo ispessimento del lid è spostato verso sud rispetto alle radici crostali. (La radice profonda è interpretata come un raddoppiamento litosferico conseguente la collisione Europa-Africa.) È evidente la assoluta inadeguatezza del concetto di radici crostali per le catene montuose, poiché le variazioni laterali in corrispondenza di zone orogeniche si estendono a profondità superiori ai 200 chilometri. Anche il concetto di isostasia crostale deve essere rivisto perché sia possibile assegnare alle anomalie isostatiche un realistico significato geodinamico. Nella sezione *b*, in corrispondenza della zona di massima deformazione, vi è una porzione di mantello soffice che sovrasta una radice litosferica caratterizzata da alti valori di rigidità, che interrompe il canale a bassa velocità. Anche l'Appennino è caratterizzato (sezione *c*) da una porzione di mantello soffice sovrastante una radice litosferica con rigidità elevata. Notevole è la differenza di spessore tra il lid dell'Adriatico e quello del Tirreno. Tutte e tre le sezioni presentano forti variazioni laterali nelle proprietà elastiche del sistema litosfera--astenosfera (la cui entità è stimata in base agli intervalli di variabilità delle velocità delle onde di taglio riportate nelle sezioni) che interessano anche la base del canale-astenosfera.

Cross-sections along the Apennines

Panza et al., Le Scienze, 1980



Sezioni verticali attraverso le Alpi orientali *(a)*, centro-occidentali *(b)* e attraverso gli Appennini *(c)*. Nella sezione *a* il massimo ispessimento del lid è spostato verso sud rispetto alle radici crostali. (La radice profonda è interpretata come un raddoppiamento litosferico conseguente la collisione Europa-Africa.) È evidente la assoluta inadeguatezza del concetto di radici crostali per le catene montuose, poiché le variazioni laterali in corrispondenza di zone orogeniche si estendono a profondità superiori ai 200 chilometri. Anche il concetto di isostasia crostale deve essere rivisto perché sia possibile assegnare alle anomalie isostatiche un realistico significato geodinamico. Nella sezione *b*, in corrispondenza della zona di massima deformazione, vi è una porzione di mantello soffice che sovrasta una radice litosferica caratterizzata da alti valori di rigidità, che interrompe il canale a bassa velocità. Anche l'Appennino è caratterizzato (sezione *c*) da una porzione di mantello soffice sovrastante una radice litosferica con rigidità elevata. Notevole è la differenza di spessore tra il lid dell'Adriatico e quello del Tirreno. Tutte e tre le sezioni presentano forti variazioni laterali nelle proprietà elastiche del sistema litosfera-astenosfera (la cui entità è stimata in base agli intervalli di variabilità delle velocità delle onde di taglio riportate nelle sezioni) che interessano anche la base del canale-astenosfera.

Reprinted from Nature, Vol. 296, No. 5854, pp.238-239, 18 March 1982

Delineation of the North Central Italian upper mantle anomaly

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The Italian peninsula is the focus of intense deformational tectonic activity. It is underlain by mantle material whose inferred, relatively anomalous properties[1,2] are not inconsistent with the seismic, volcanic and thermal activity that is manifested in this region. The most effective geophysical tool for mapping the structure of the uppermost 200–300 km of the Earth is the observation and analysis of seismic surface-wave dispersion on a regional scale. Here we synthesize the interpretations of Rayleigh wave dispersion measurements made by several authors, each for different parts of North Central Italy[3-8], to delineate the lateral extent of the upper mantle anomaly in this region.

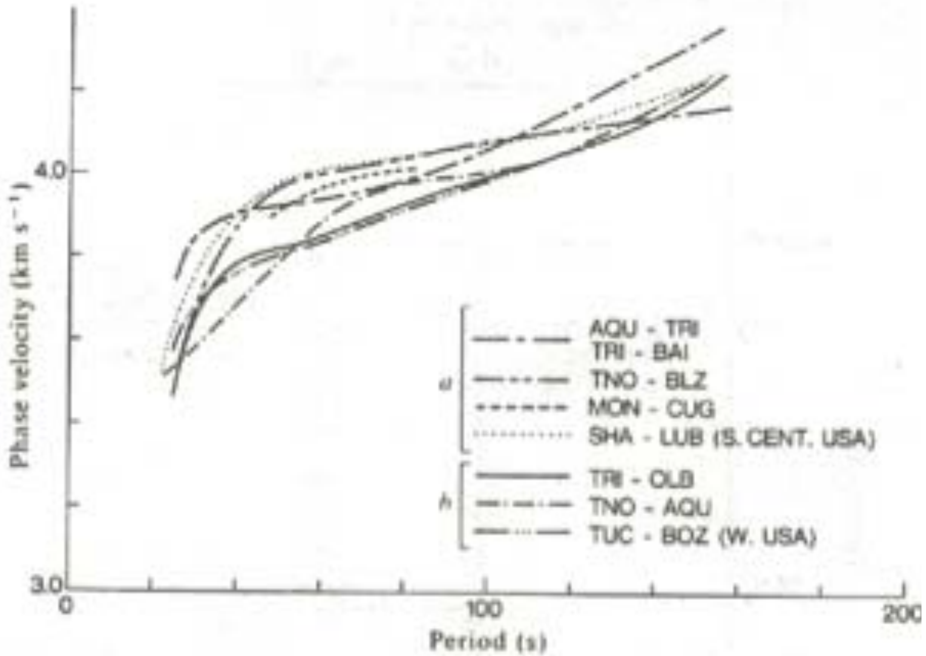


Fig. 2 Phase velocities used to delineate the North Central Italian anomaly and comparison with dispersion relations for western and South-Central USA. The r.m.s. errors for each curve are $\sim\pm 0.03$ km s^{-1} in the period range 40–60 s and are larger at the extremes of the period range[3,5-9]. Curves in group *a* are for regions without tectonic involvement and in group *b* for regions with tectonic involvement.

Mountain ranges sitting on continental lithosphere subduction form both:

(a) when the subduction hinge approaches the overriding plate (Alps, Dinarides, Zagros, Himalaya) - type-A subduction or upduction

and

(b) when the subduction hinge departs from it (Apennines, Carpathians, Banda) - type-B subduction.

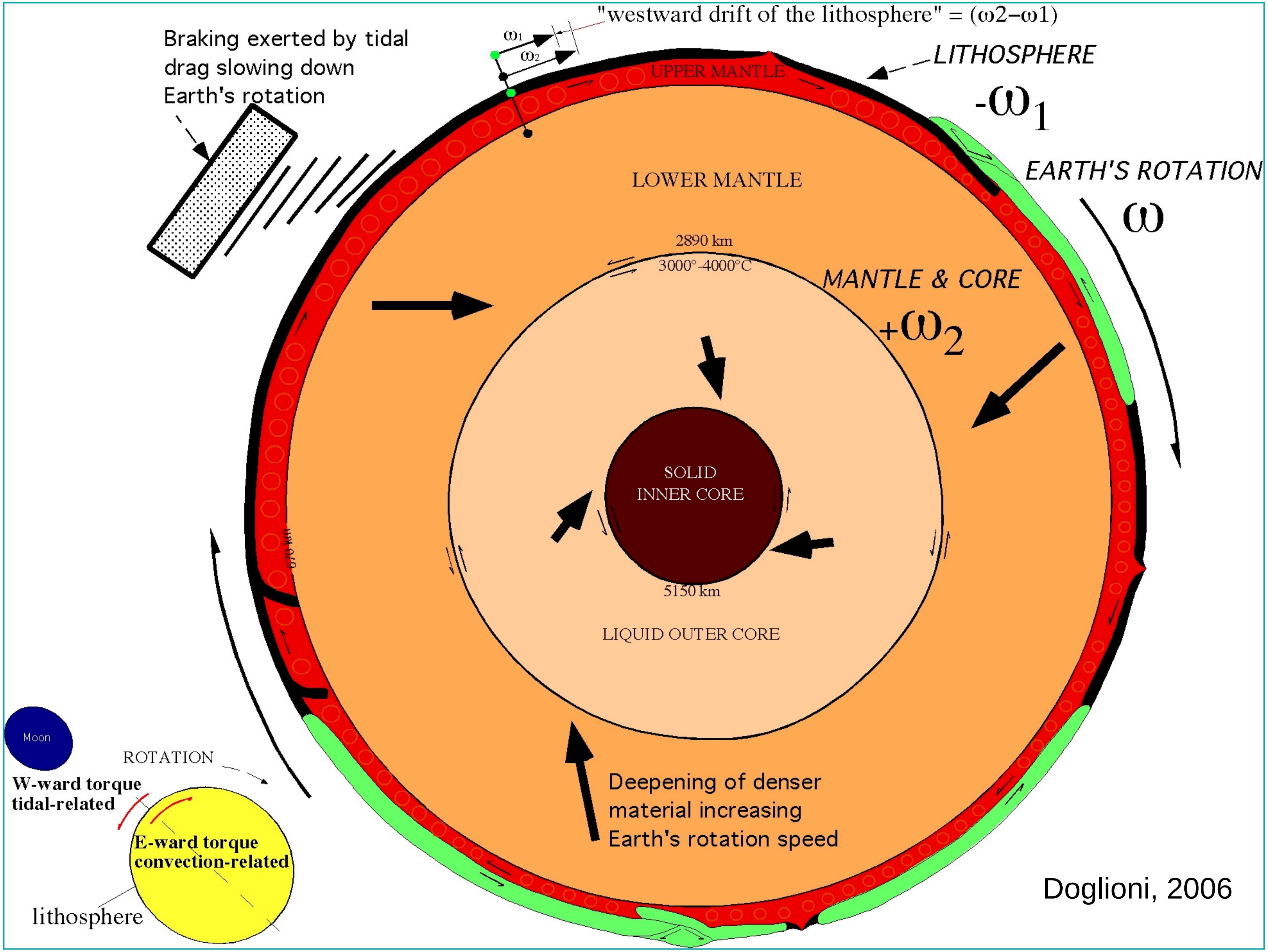
These two modes of continental lithosphere subduction have significantly different characters:

(1) in type-A subduction the mountain ranges are quite high (on average>1500m), show a complete metamorphic cycle and extended basement outcrops, double vergence, two foredeeps subsiding at a rate<0.3mm/y, detachment planes involving the entire crust and the lid and relatively low effusive magmatism;

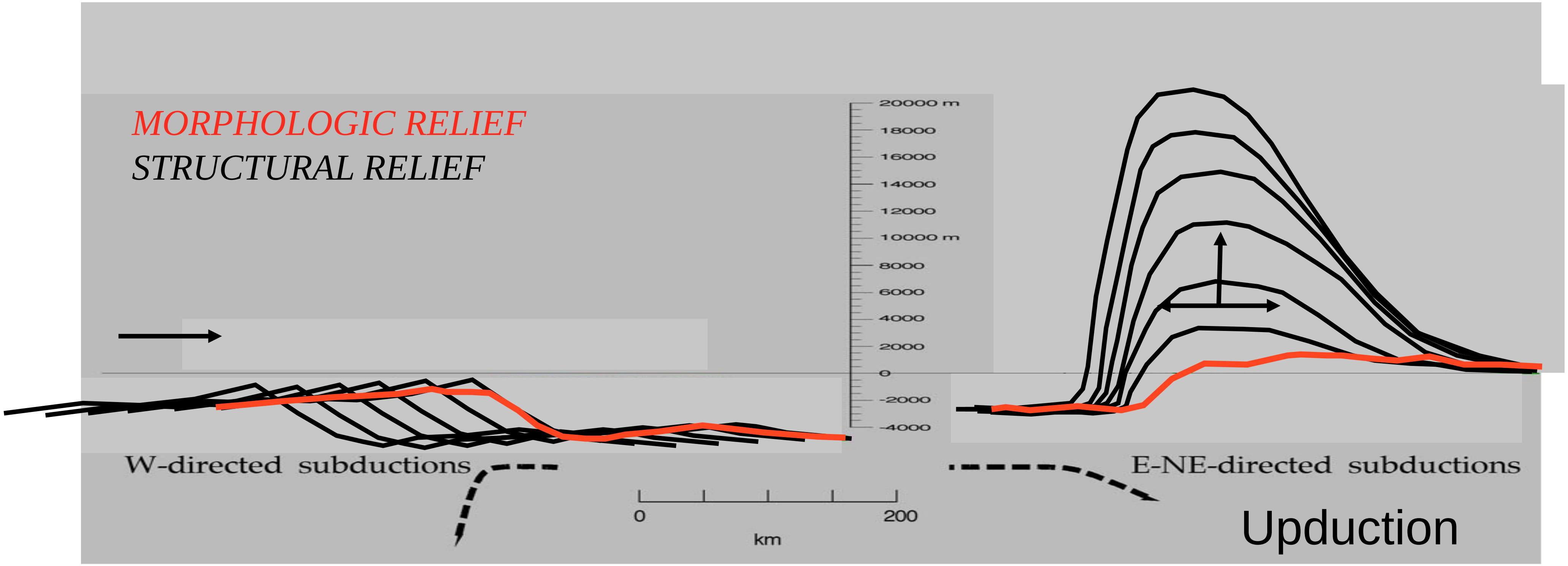
(2) in type-B subduction the elevation is low, the vergence is single, the well pronounced foredeep subsides at a rate>1mm/y, detachment planes involve mostly the uppermost (1-12 km) subducting crust. At global scale, type-B subductions are west directed, and are overridden by a back-arc basin.

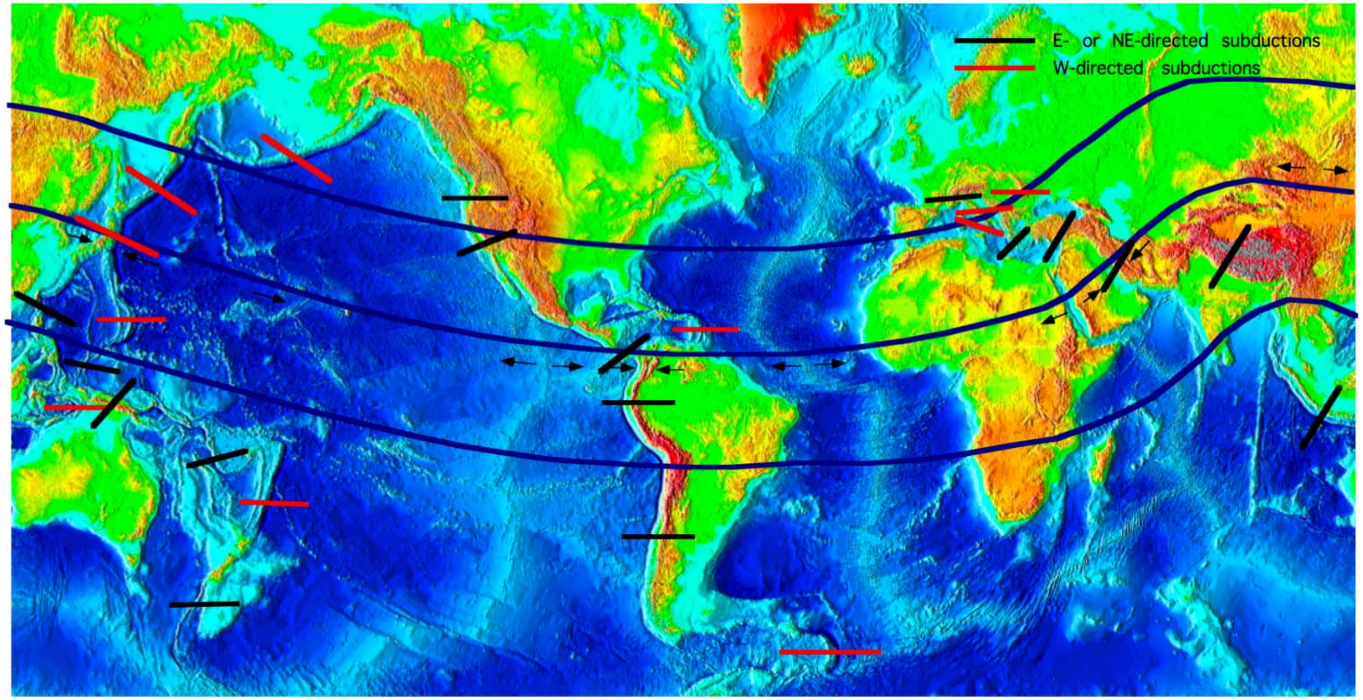
In the central Mediterranean area the examples are Alps (A), Dinarides (A), Apennines (B), Carpathians(B), where the subduction of continental material is a well-documented phenomenon by the geochemical properties of magmatism (Peccerillo, 2005).

Still the engine of plate tectonics in not too well known. In fact, convection alone seem not able to supply enough energy. This deficit is made even more severe by the the results of Laio, Chiarotti, Scandolo, Bernard and Tosatti who reproduced in the computer the same conditions at the Earth core by solving the fundamental equations governing the dinamics of Iron atoms and estimated a temperature for the Earth core of about 5400 °C, i.e. at least 1000°C less than what previously estimated. Some relevant amount of energy may be supplied by the deceleration of the Earth rotation due to the Moon (Sun) tidal effect.

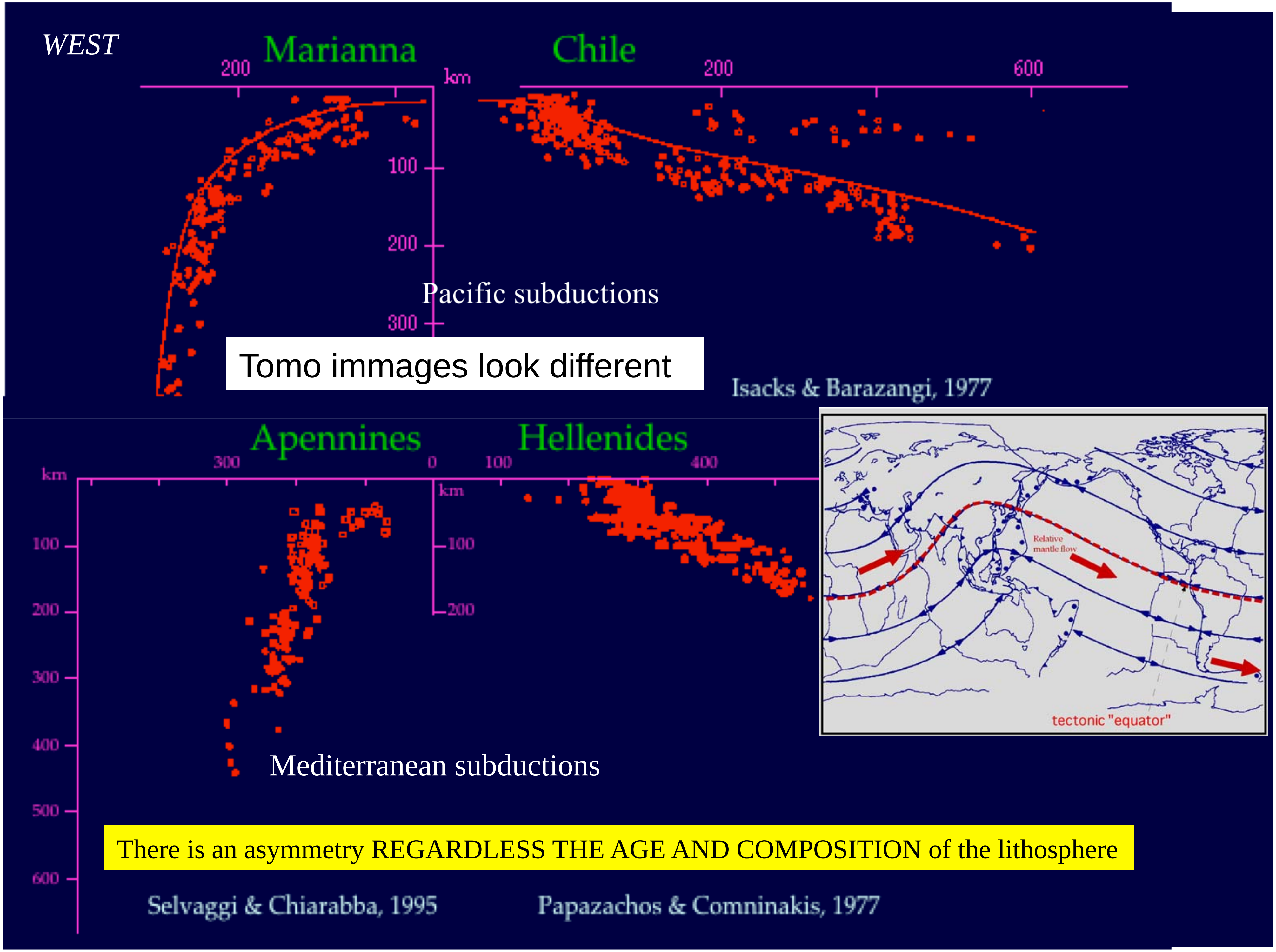

"westward drift of the lithosphere" = (ω2−ω1)
Braking exerted by tidal drag slowing down Earth's rotation
ω1
ω2
UPPER MANTLE
LITHOSPHERE
-ω1
EARTH'S ROTATION
ω
LOWER MANTLE
2890 km
3000°-4000°C
MANTLE & CORE
+ω2
SOLID INNER CORE
5150 km
670 km
LIQUID OUTER CORE
Moon
ROTATION
W-ward torque tidal-related
E-ward torque convection-related
lithosphere
Deepening of denser material increasing Earth's rotation speed
Doglioni, 2006

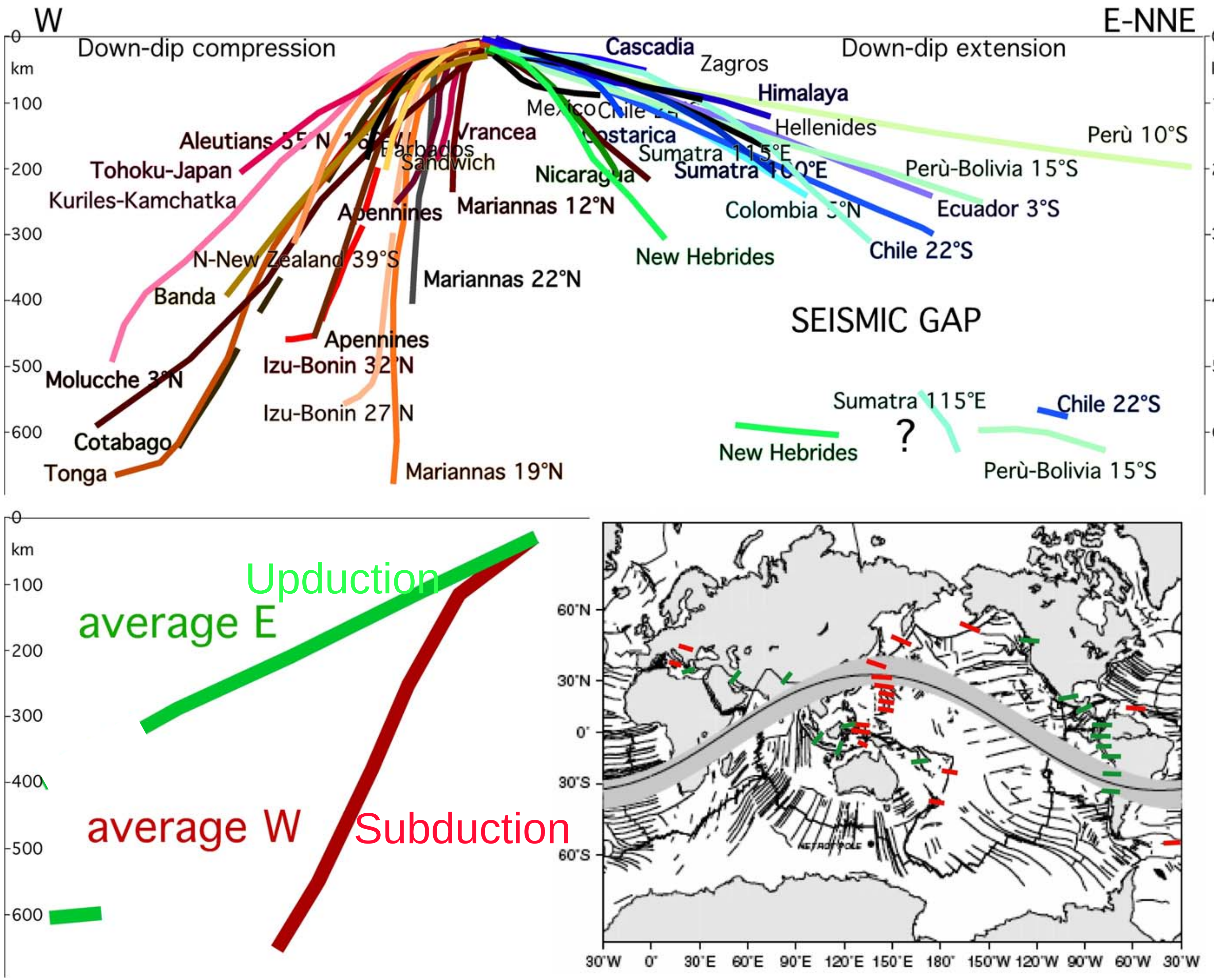
Mountain ranges



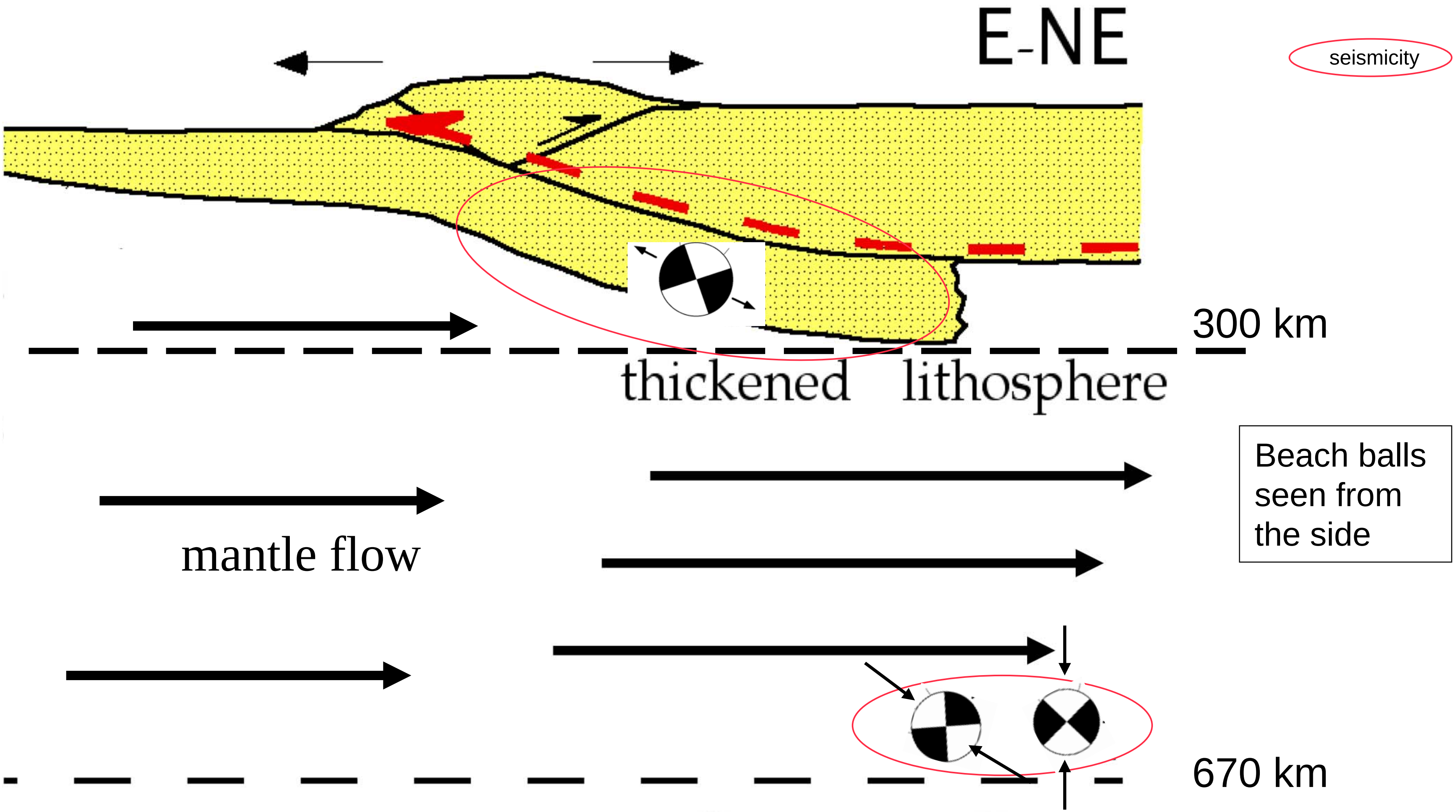


Space geodesy data show that all plates move orderly ‘westward’ along the tectonic mainstream at different velocities and the equator of the lithospheric net rotation lies inside the corresponding tectonic mainstream latitude band


WEST
Marianna
Chile
km
Pacific subductions
Tomo immages look different
Isacks & Barazangi, 1977
Apennines
Hellenides
km
Relative mantle flow
tectonic "equator"
Mediterranean subductions
There is an asymmetry REGARDLESS THE AGE AND COMPOSITION of the lithosphere
Selvaggi & Chiarabba, 1995
Papazachos & Comninakis, 1977

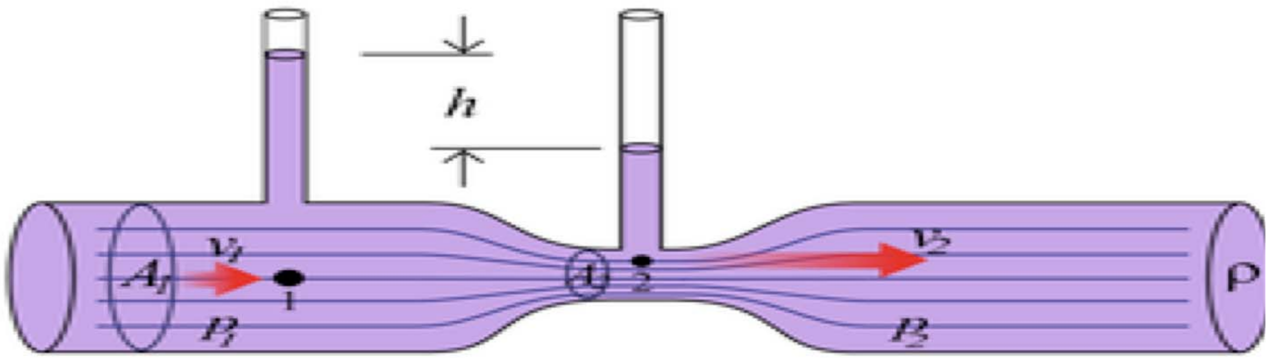


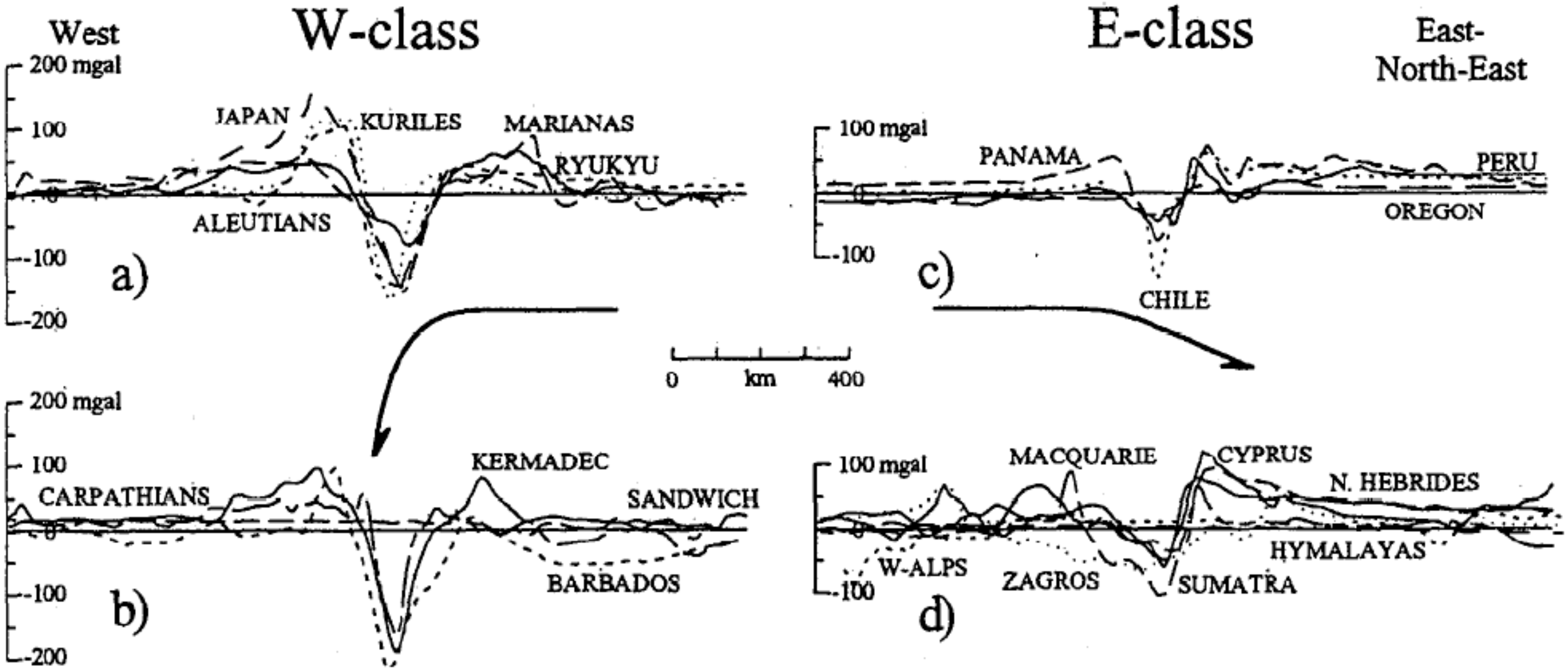
W
E-NNE
Down-dip compression
Down-dip extension
km
Cascadia
Zagros
Himalaya
Hellenides
Perù 10°S
Costarica
Sumatra 115°E
Perù-Bolivia 15°S
Nicaragua
Ecuador 3°S
Colombia
Chile 22°S
New Hebrides
Aleutians
Tohoku-Japan
Kuriles-Kamchatka
Vrancea
Sandwich
Apennines
Mariannas 12°N
N-New Zealand 39°S
Mariannas 22°N
Banda
Apennines
Molucche
Cotabago
Tonga
Mariannas 19°N
SEISMIC GAP
Sumatra 115°E
Chile 22°S
?
New Hebrides
Perù-Bolivia 15°S
0
100
200
300
400
500
600
Upduction
average E
average W
Subduction
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



Venturi effect may explain seismic gap

The pressure at "1" is higher than at "2" because the fluid speed at "1" is lower than at "2"

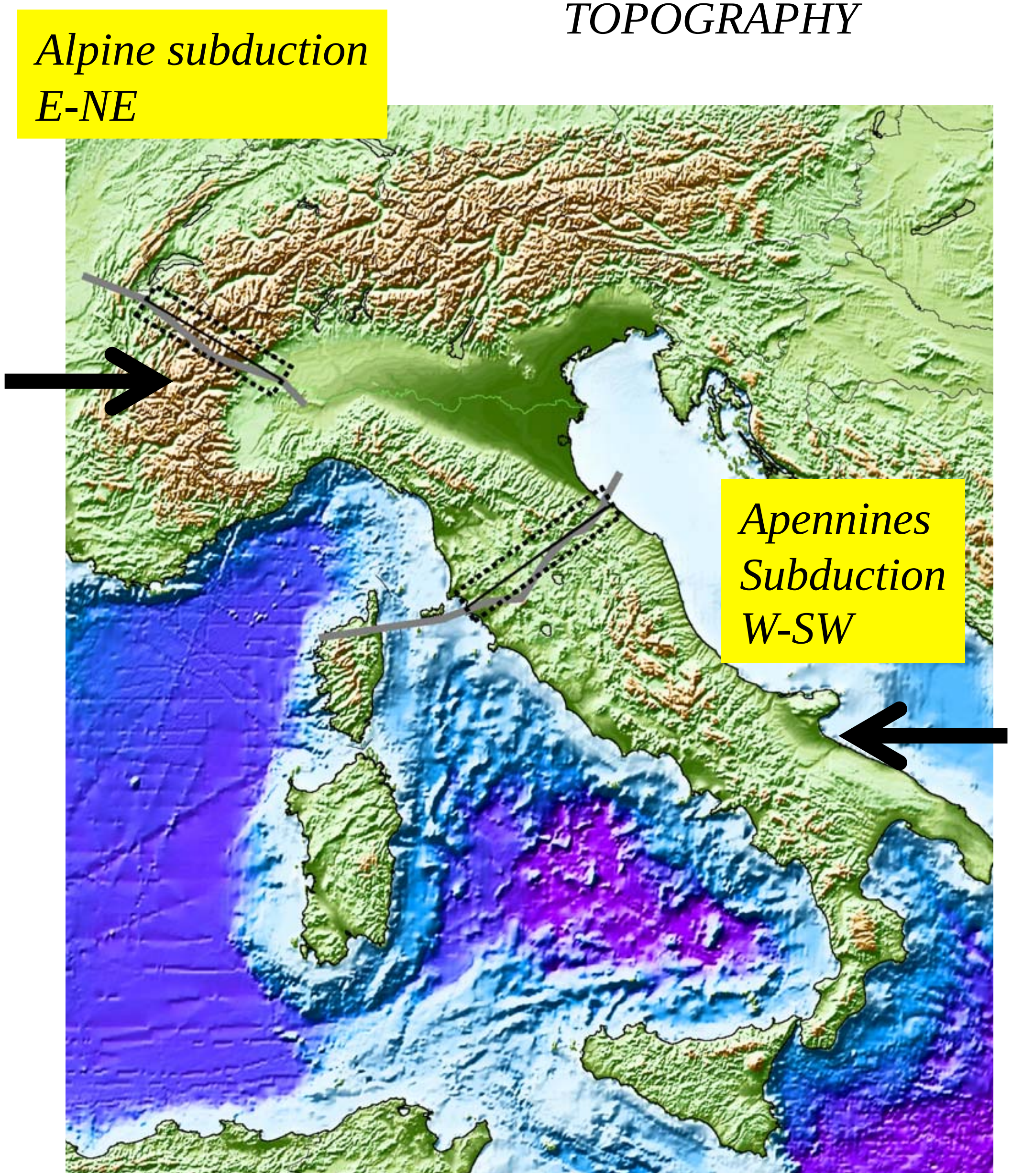


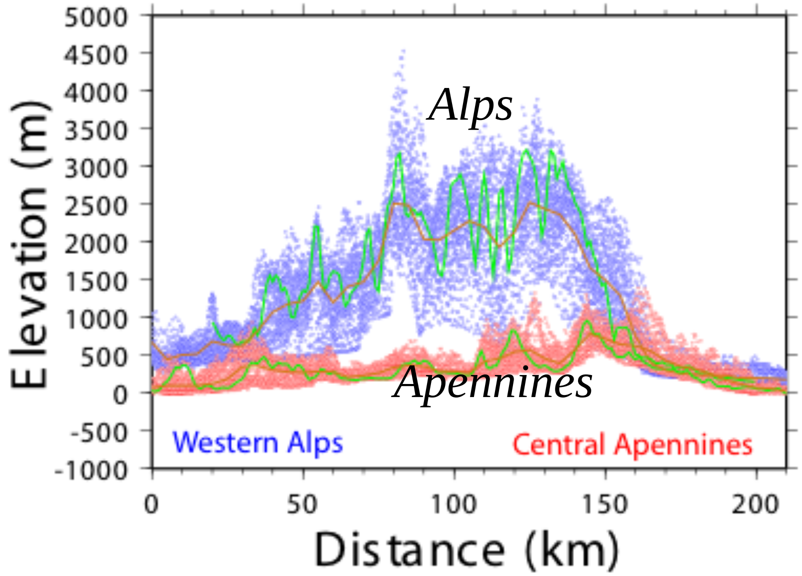


Free-air gravimetric profiles grouped into

W-class and E-class

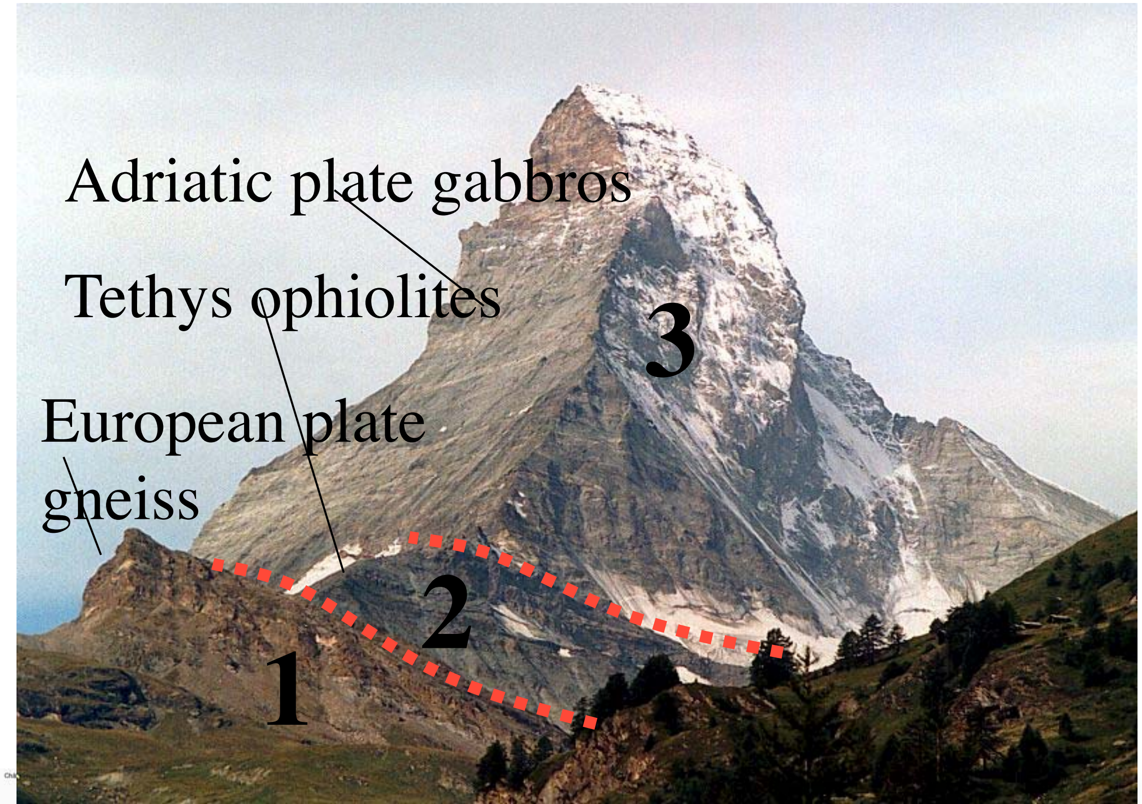
TOPOGRAPHY

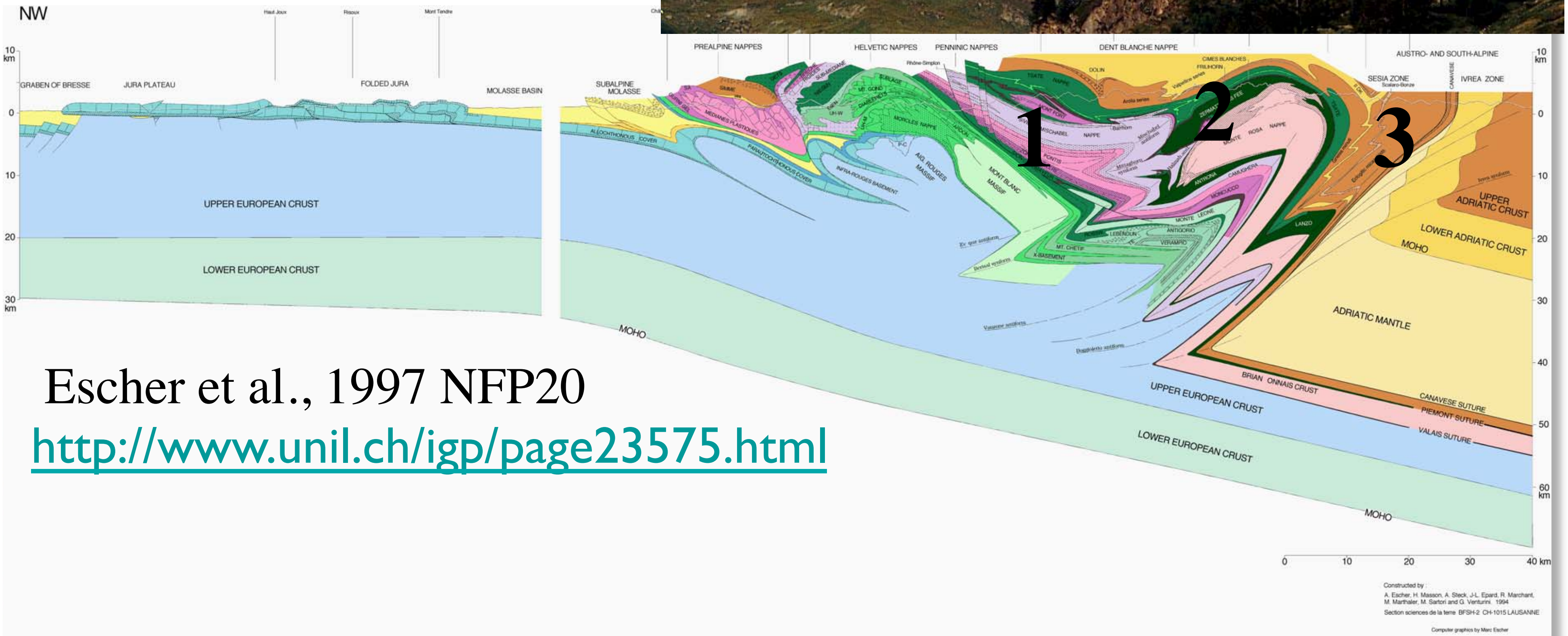




Carminati et al., 2004 SGI

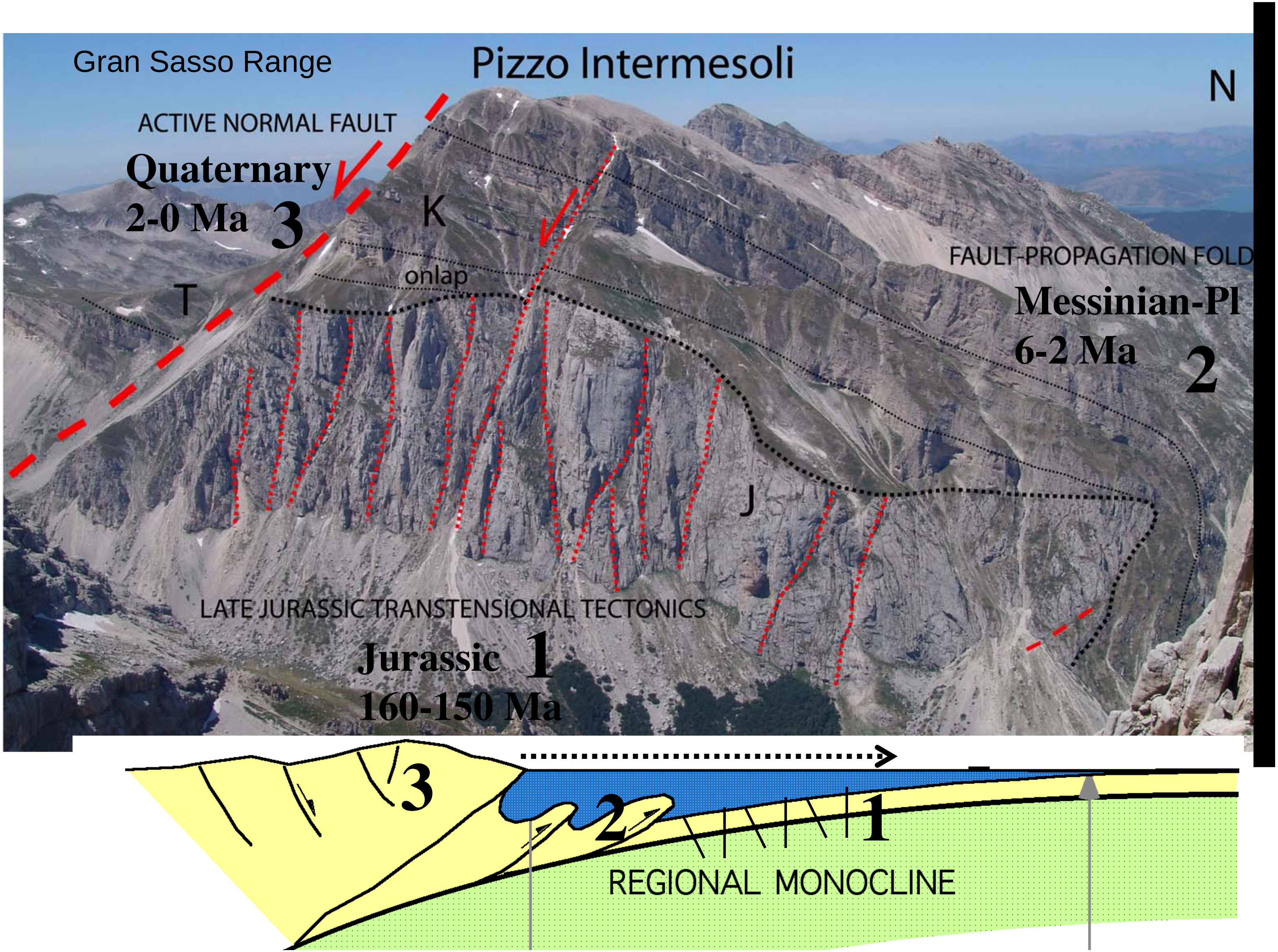
Cervino





Escher et al., 1997 NFP20

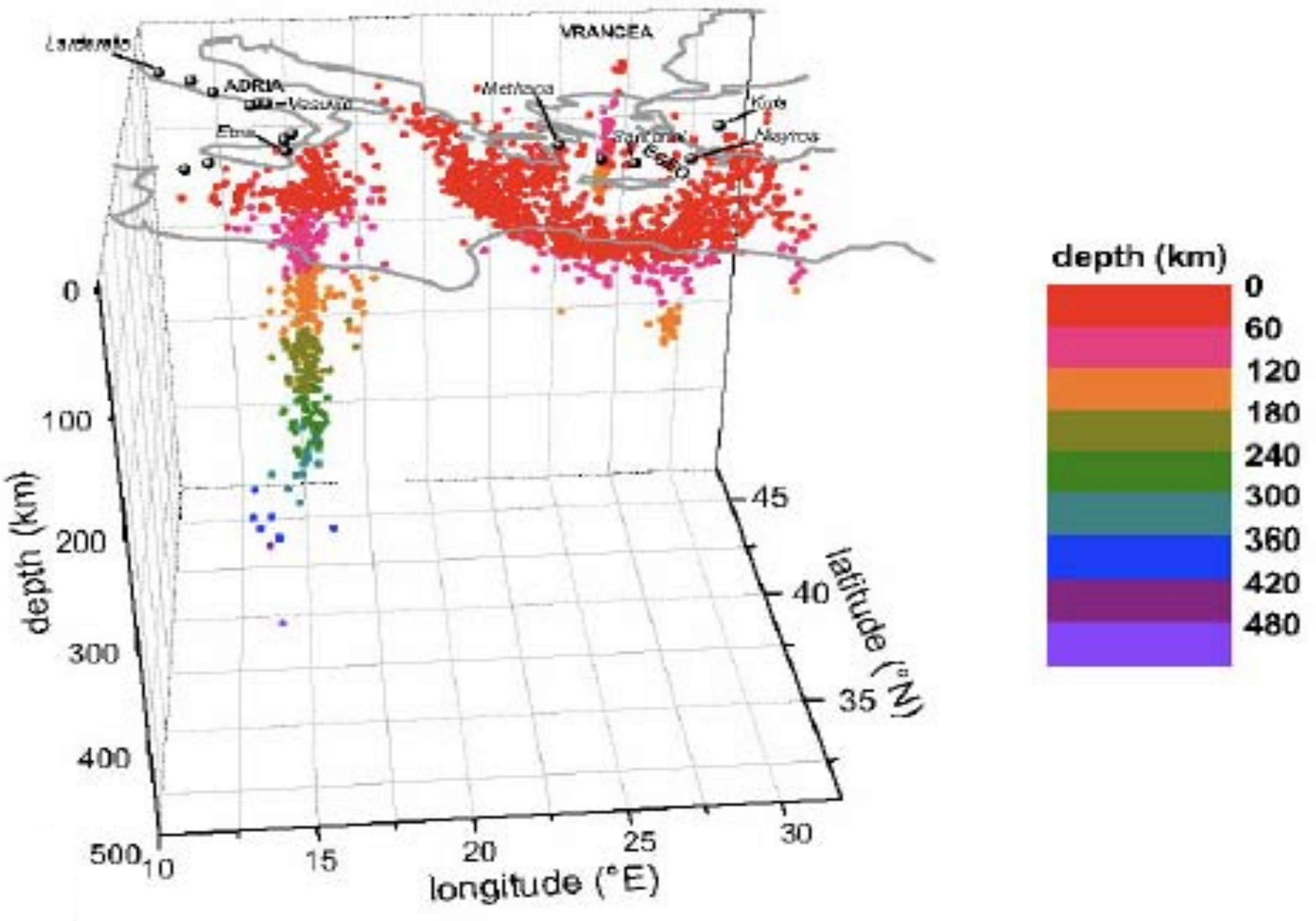
http://www.unil.ch/igp/page23575.html



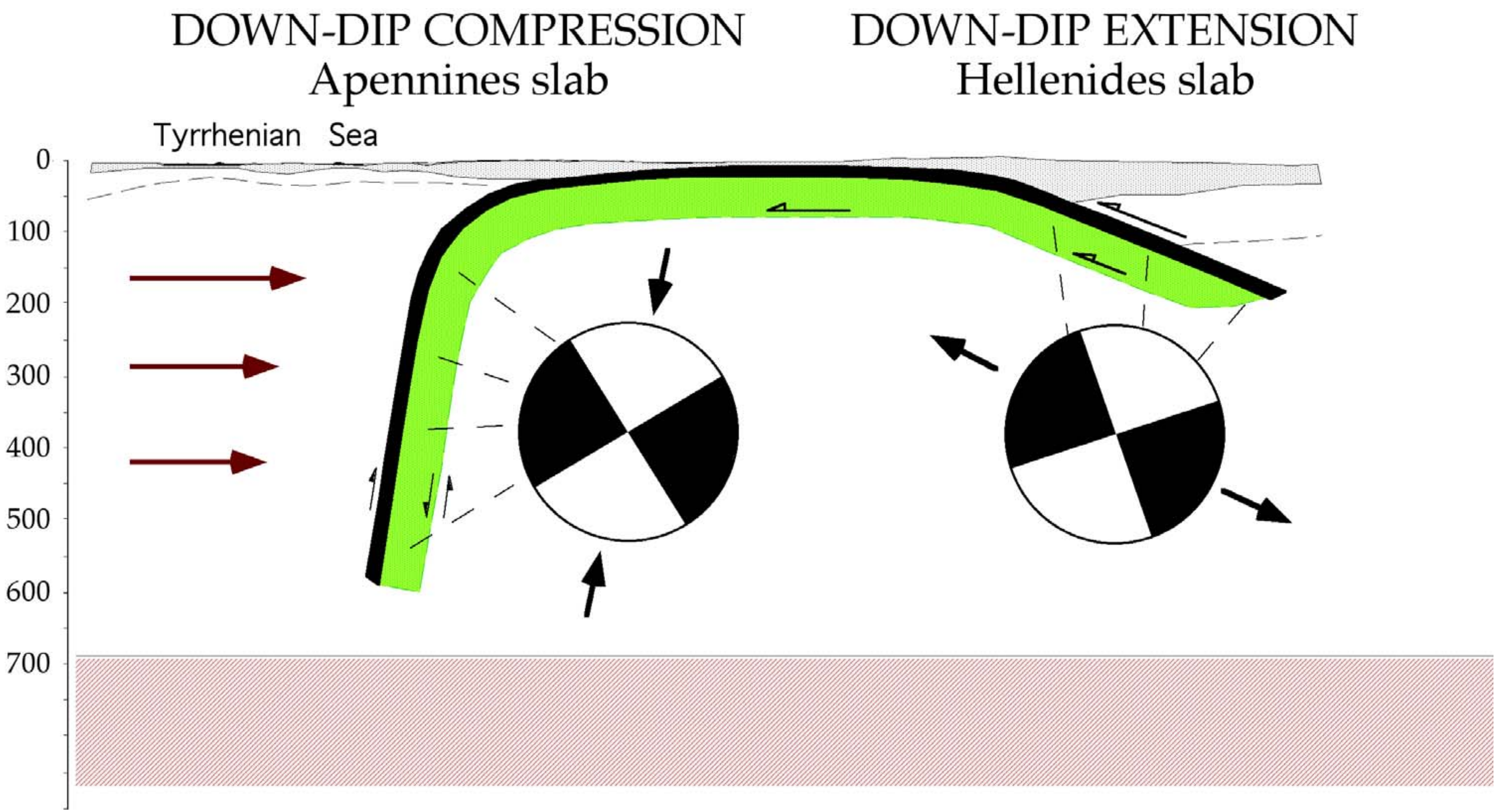
Gran Sasso Range
Pizzo Intermesoli
N
ACTIVE NORMAL FAULT
Quaternary
2-0 Ma
3
K
T
onlap
FAULT-PROPAGATION FOLD
Messinian-Pl
6-2 Ma
2
J
LATE JURASSIC TRANSTENSIONAL TECTONICS
Jurassic
160-150 Ma
1
3
2
1
REGIONAL MONOCLINE

UPDUCTION

(E-NE verging subduction)



The Mediterranean is characterized by four deep-earthquake zones: Tyrrhenian, Aegean, West Turkey, Vrancea, modified from Scalera, 2008.


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

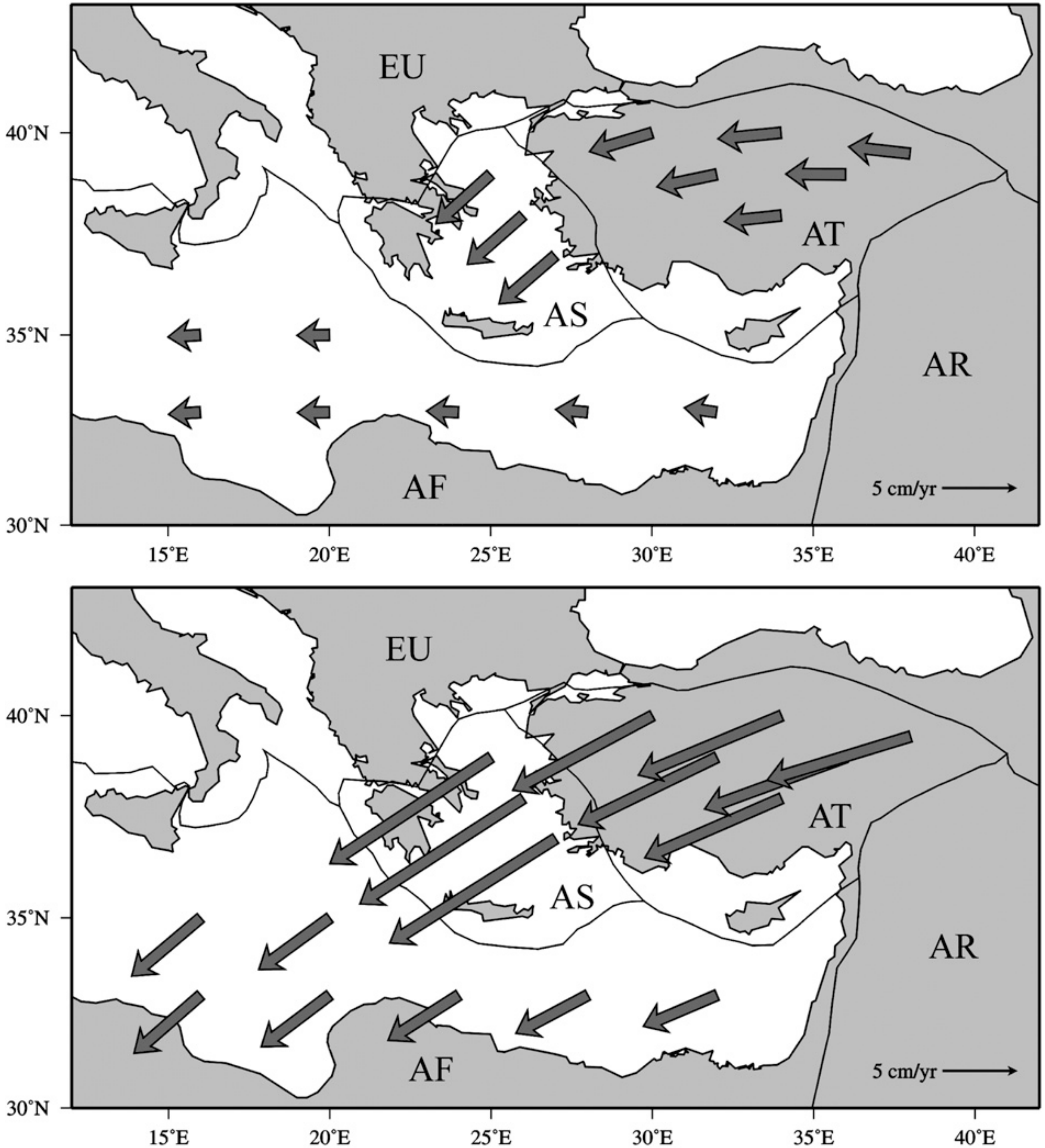
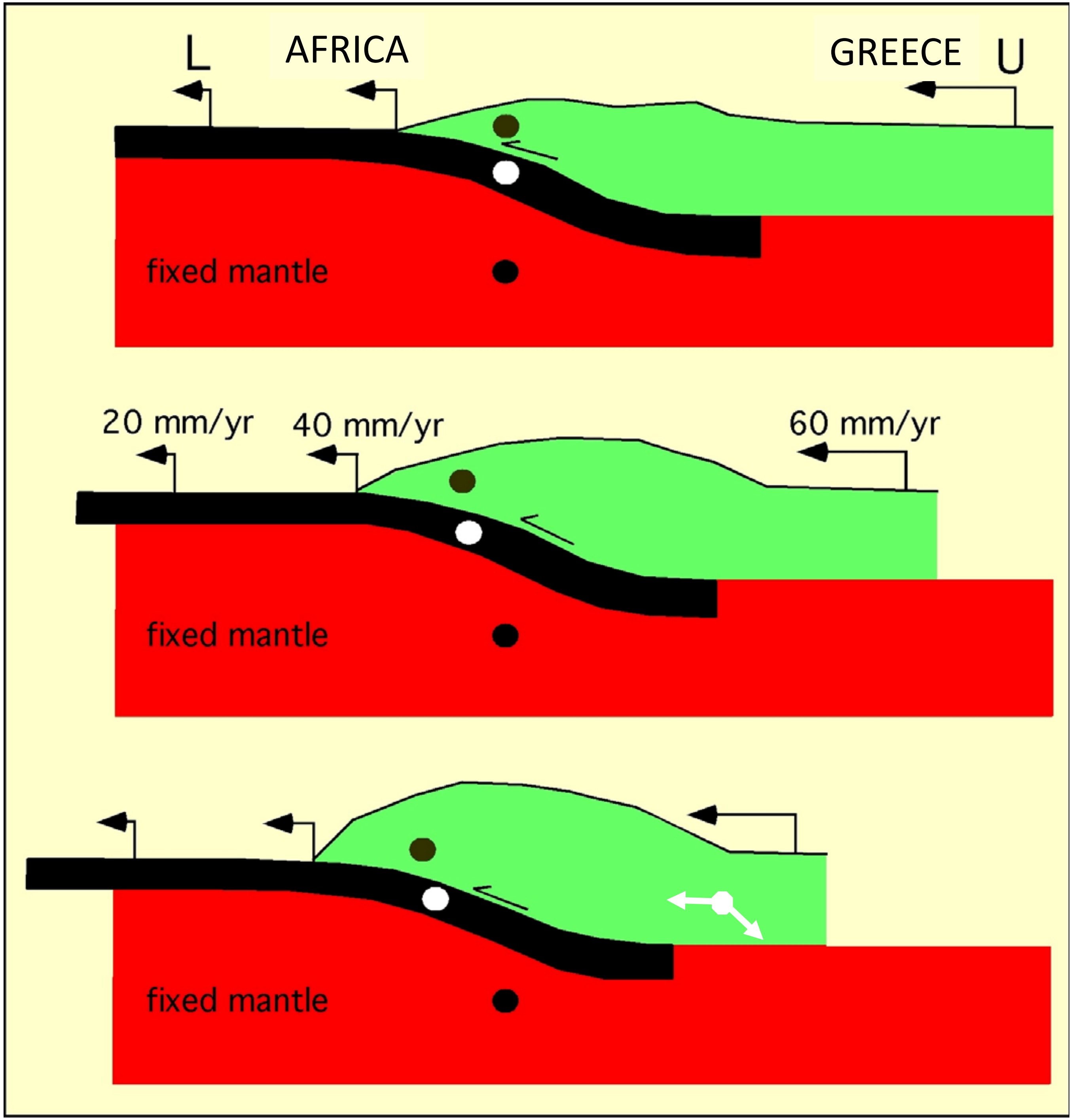
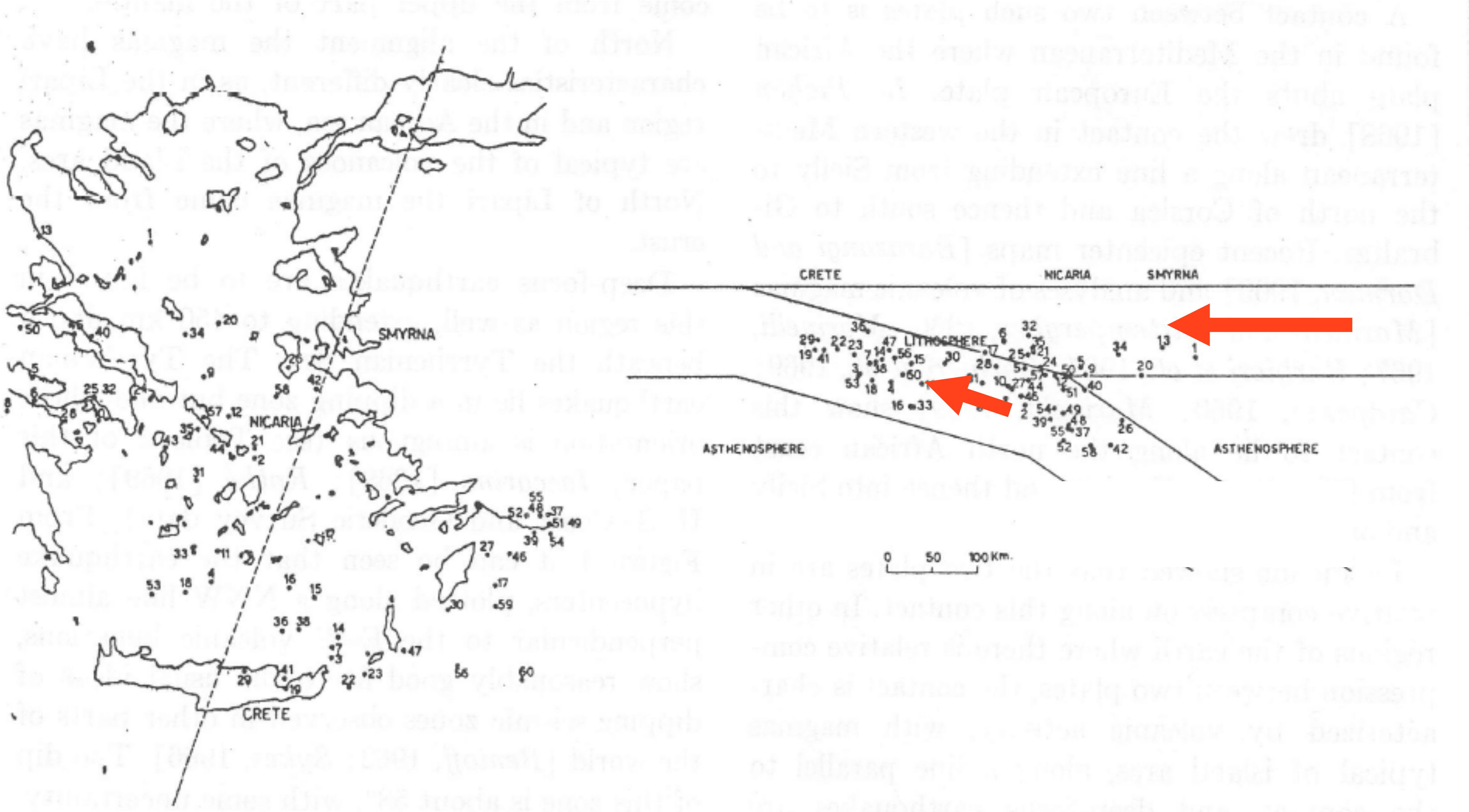


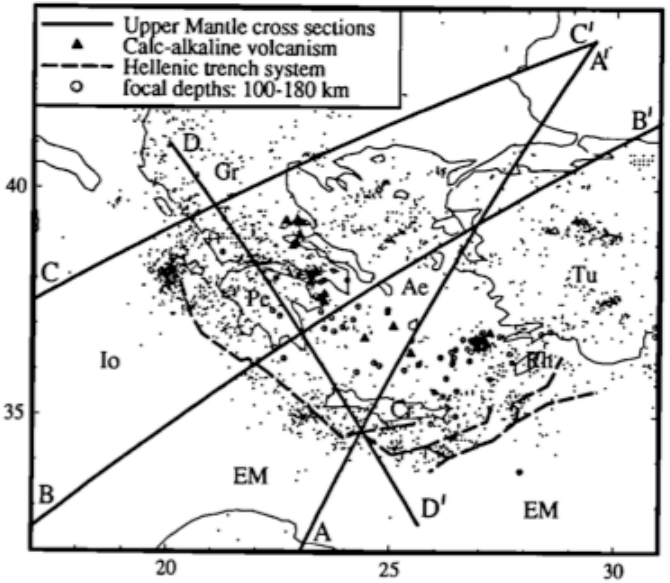
Plate motions of Africa and Greece relative to the mantle in the deep hotspot reference frame (above) and in the shallow hotspot reference frame. In both cases Africa is moving westward faster than the underlying mantle, escaping from the subduction under the Hellenic arc (Doglioni et al. 2007, Earth-Science Reviews, 83 125–175).



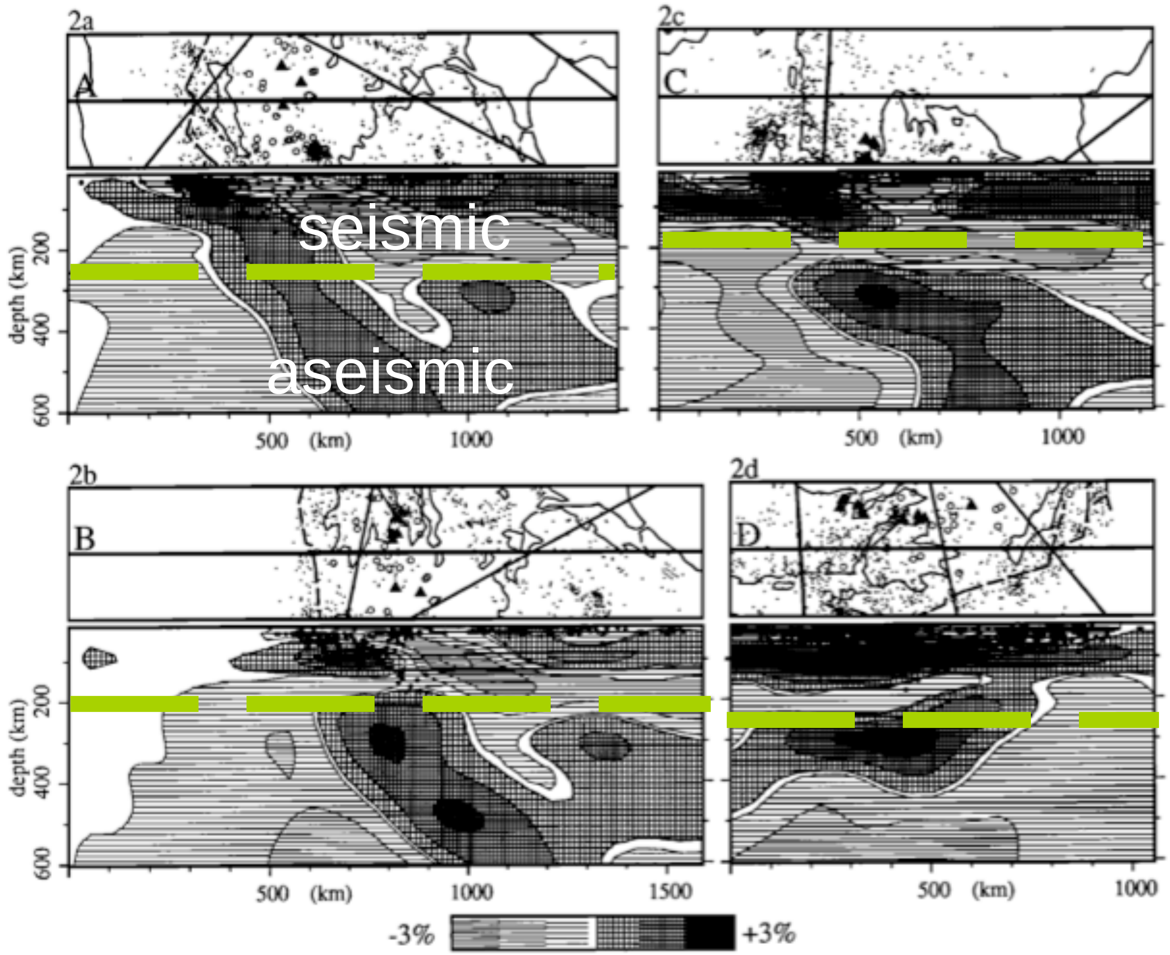
When plate motions are considered relative to the hotspot reference frame, i.e., assuming fixed the mantle, the slabs of E- or NE-directed subduction zones may move out of the mantle (upduction). In the three stages sketch the white dot moves leftward relative to the underlying black dot in the mantle. Subduction occurs because the upper plate dark gray dot moves leftward faster than the white circle in the slab. In this model, the slab moves west at 20 mm/yr relative to mantle. The subduction rate is the convergence minus the orogenic shortening. With different velocities, this seems to apply, in the shallow hotspot reference frame, also to the Andean subduction. This kinematic evidence of upducting slabs casts doubts on the slab pull as the dominant driving mechanism of plate motions. (Doglioni et al. 2007, Earth-Science Reviews, 83 125–175).



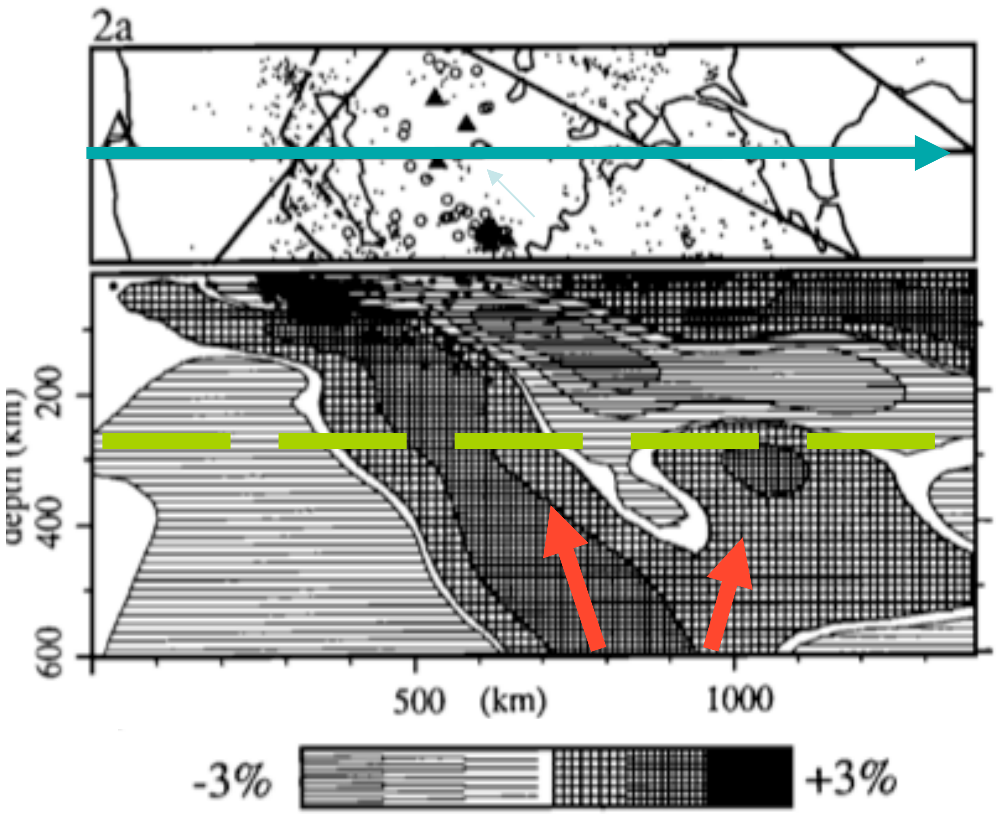
Caputo, M., Panza, G.F. and Postpischl, D., (1970). Deep structure of the Mediterranean basin. J. Geophys. Res., 75, 4919-4923 (modified).



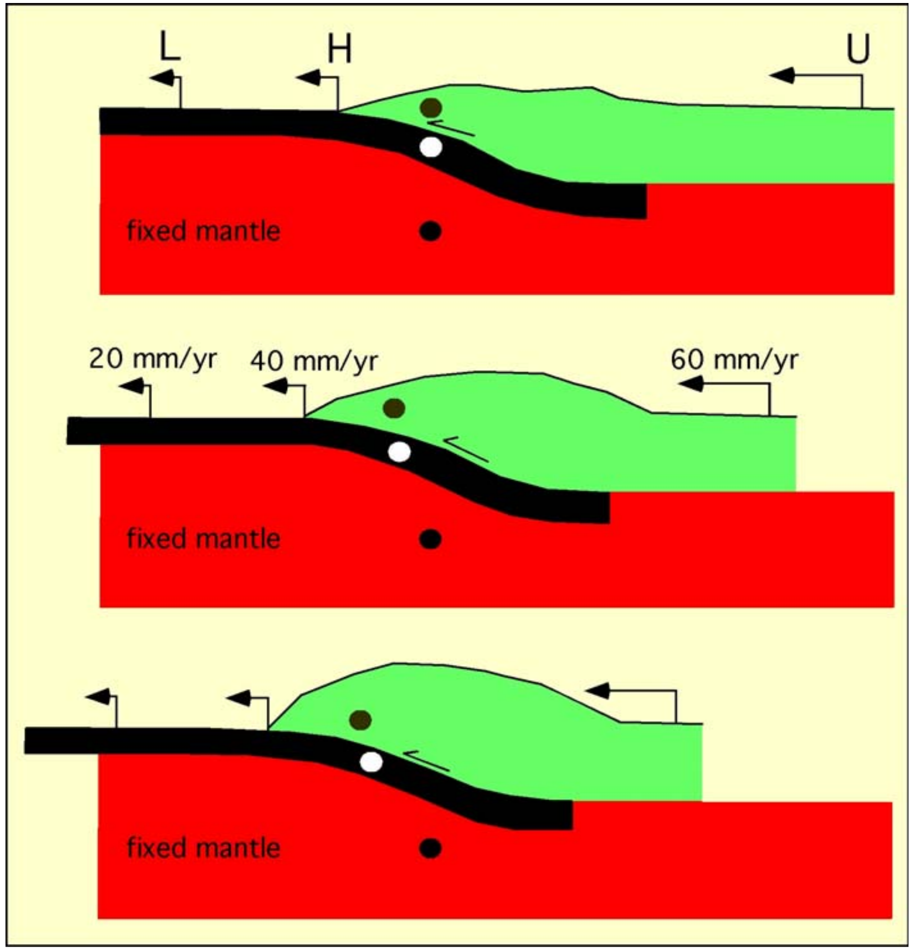
Location map of the Eastern Mediterranean and Aegean area. Thick solid lines indicate the location of Upper Mantle cross sections. Dots indicate the epicenters of earthquakes with M>4 and focal depths less than 100 km that occurred from 1964-1984. Ae=Aegean basin, Cr=Crete, EM=Eastern Mediterranean, Gr=Greece, Io=Ionian basin, Pe=Peleponnesus, Rh=Rhodes, Tu=Turkey, for remaining items see key.



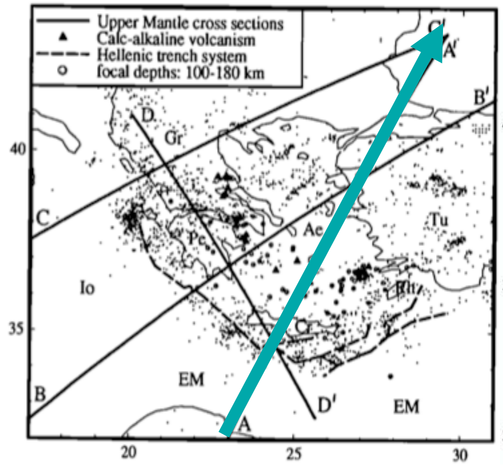
Tomographic images of the Aegean/Eastern Mediterranean Upper Mantle for the sections shown on the left (The upper panels in a-d display a small location map for orientation). The contouring is in percentages of the ambient Jeffreys-Bullen Upper Mantle velocity (see legend). Cross (horizontal) hatching indicates positive (negative) anomalies. Regions with poor spatial resolution are not contoured (large white areas). The interval -0.1%/+0.1% is also indicated in white. Horizontal and depth axes given without vertical exageration. Black symbols are the projection of hypocenters with M>4 are located within 100 km from the plane. The width of the location map is 3 degrees (Spakman, et al., 1988. THE HELLENIC SUBDUCTION ZONE: A TOMOGRAPHIC IMAGE AND ITS GEODYNAMIC IMPLICATIONS, G.R.L., 15, 60-63).



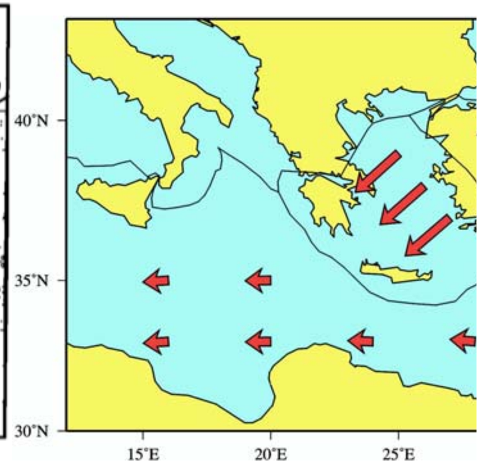
2a
200
400
600
500 (km)
1000
-3%
+3%



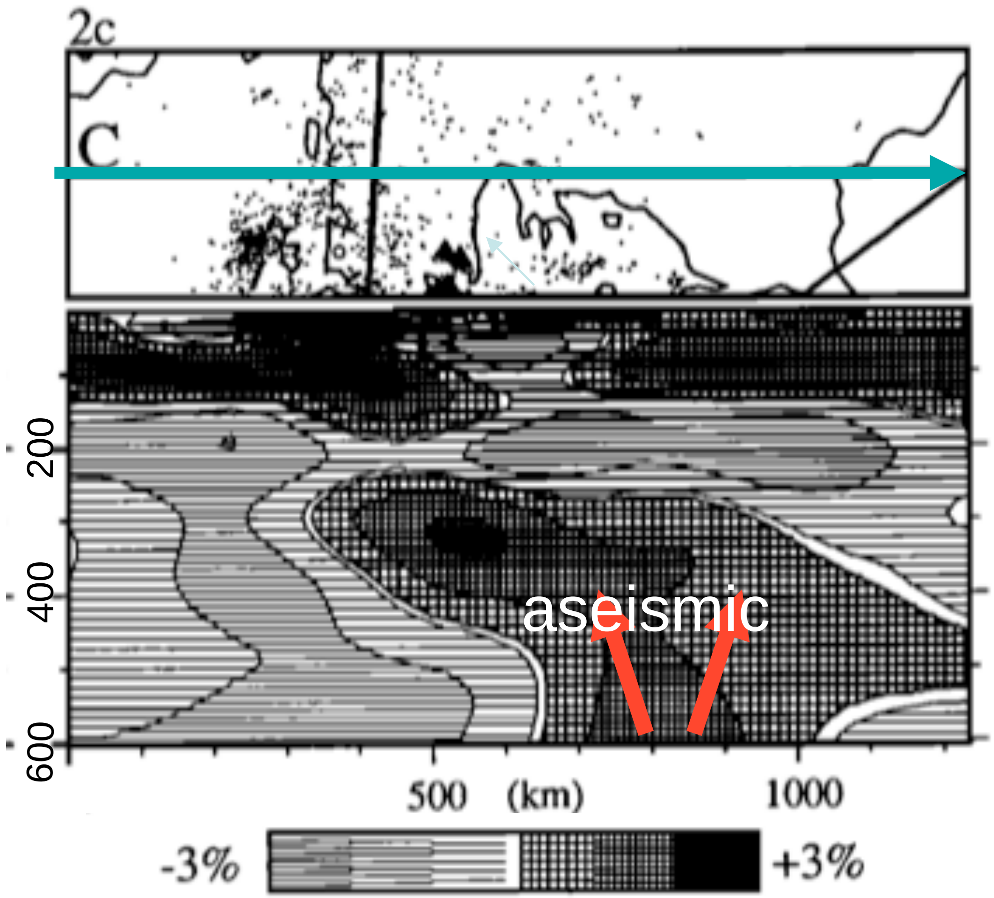
L
H
U
fixed mantle
20 mm/yr
40 mm/yr
60 mm/yr
fixed mantle
fixed mantle

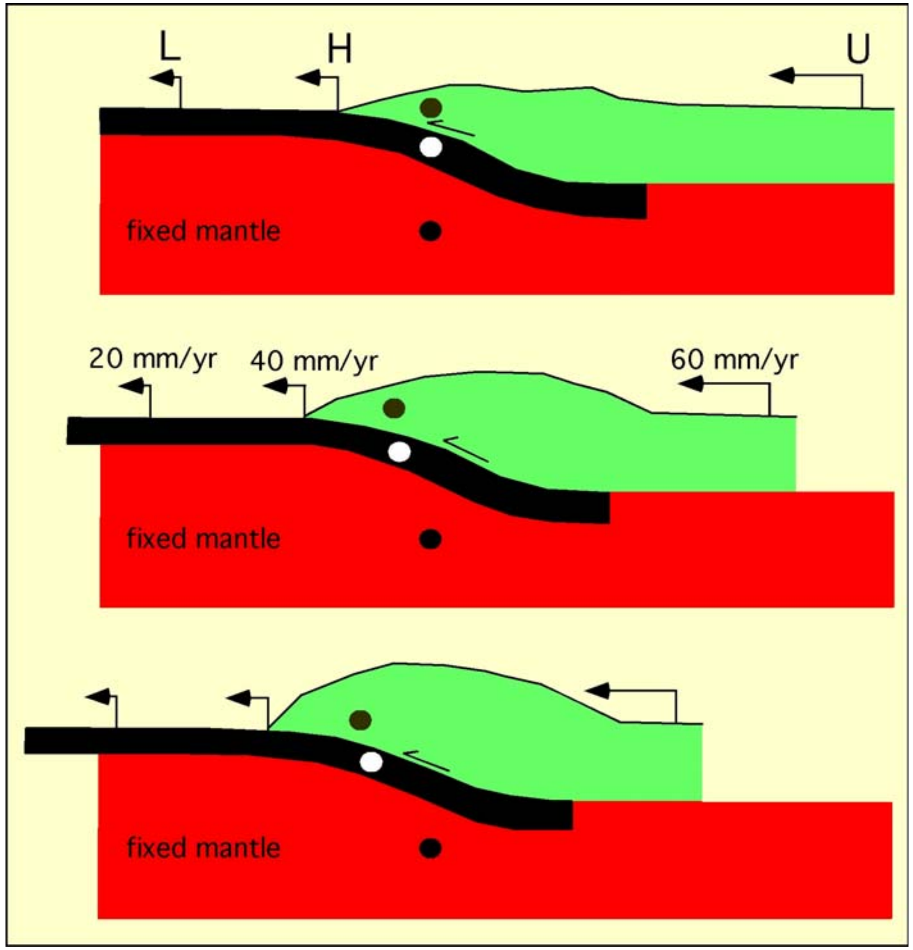


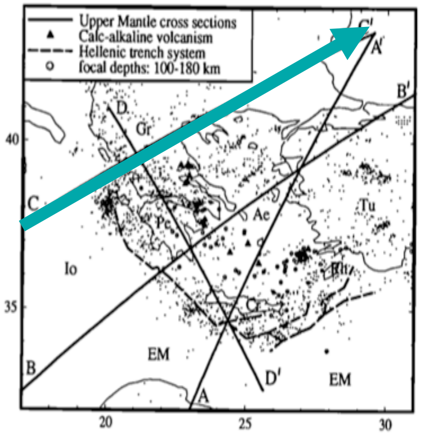
Upper Mantle cross sections
Calc-alkaline volcanism
Hellenic trench system
focal depths: 100-180 km
C'
A'
B'
D
Gr
C
Ae
Tu
Io
EM
EM
B
A
D'
40
35
20
25
30

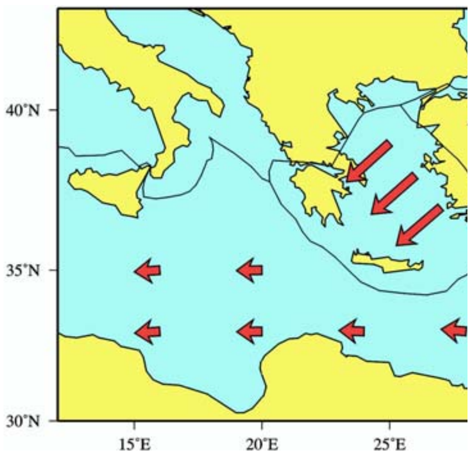


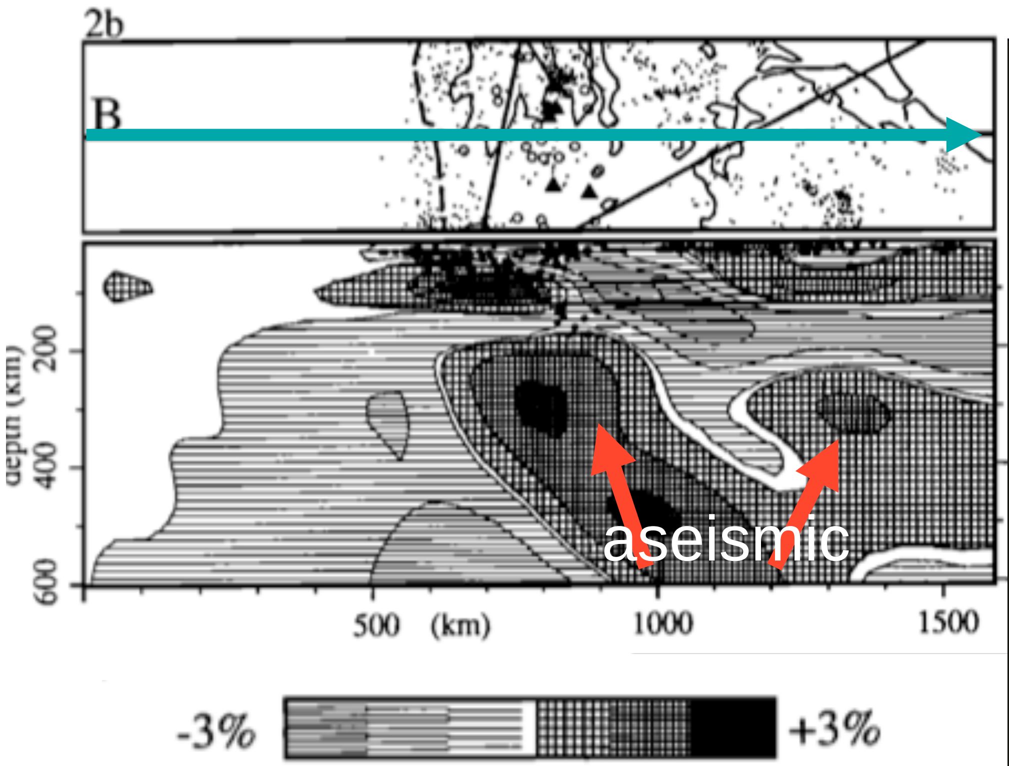
40°N
35°N
30°N
15°E
20°E
25°E

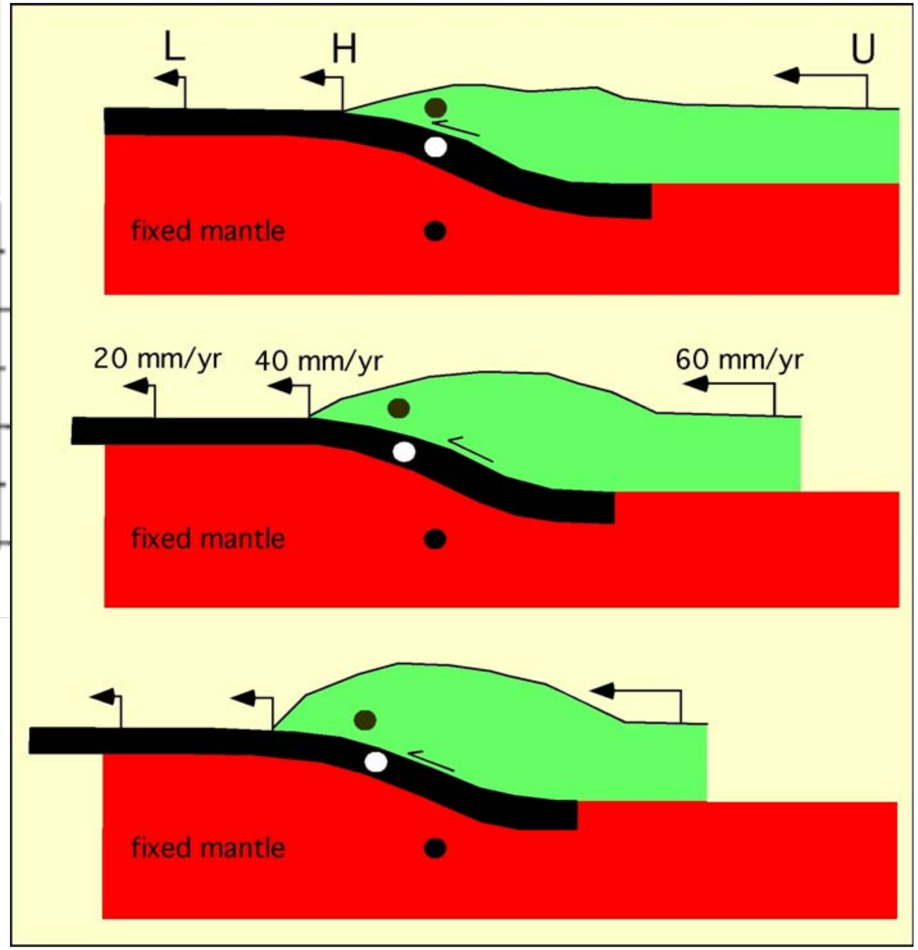

2c
C
200
400
600
500 (km)
1000
-3%
+3%
aseismic

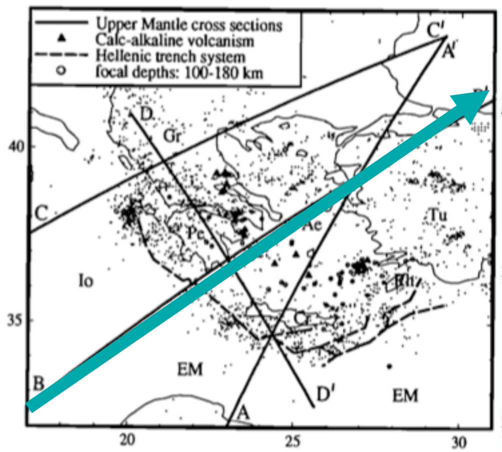

L
H
U
fixed mantle
20 mm/yr
40 mm/yr
60 mm/yr
fixed mantle
fixed mantle

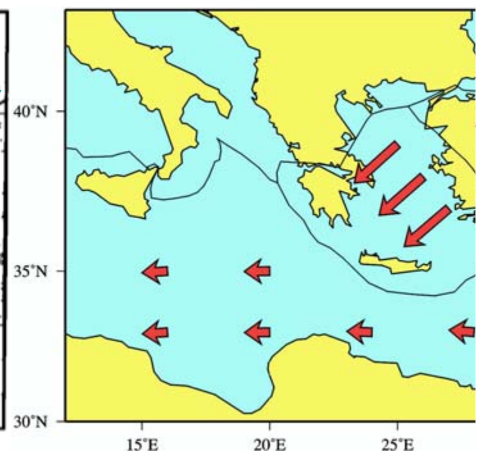

Upper Mantle cross sections
Calc-alkaline volcanism
Hellenic trench system
focal depths: 100-180 km
Gr
Ae
Tu
Io
EM
EM
40
35
20
25
30

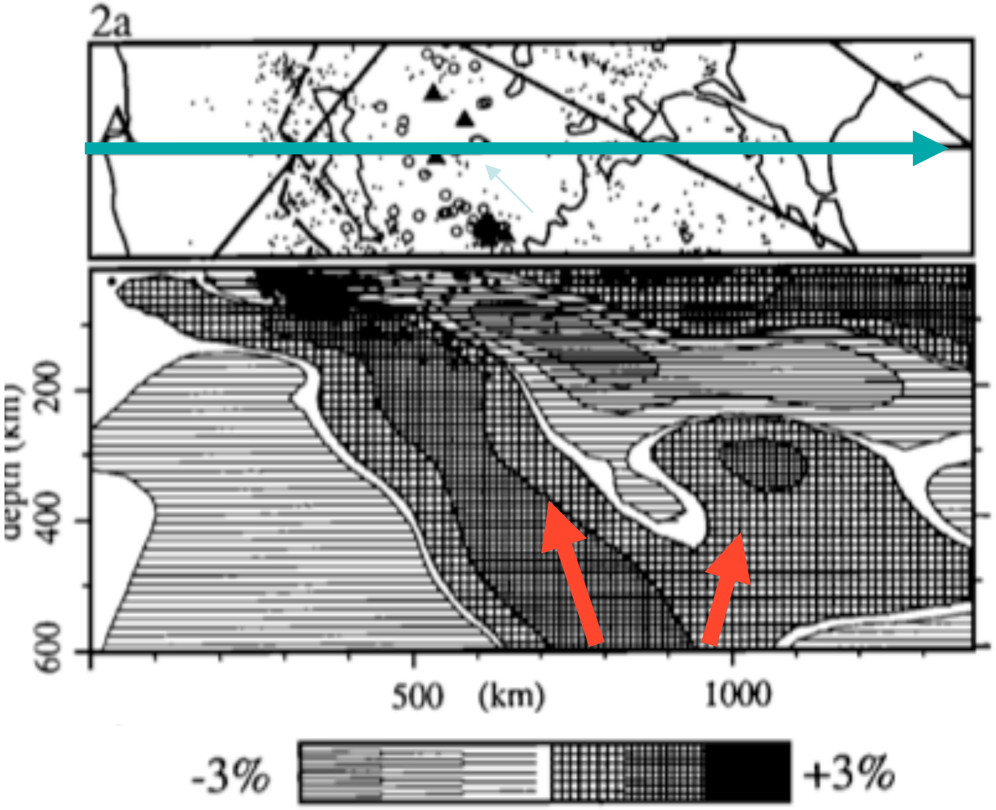

40°N
35°N
30°N
15°E
20°E
25°E

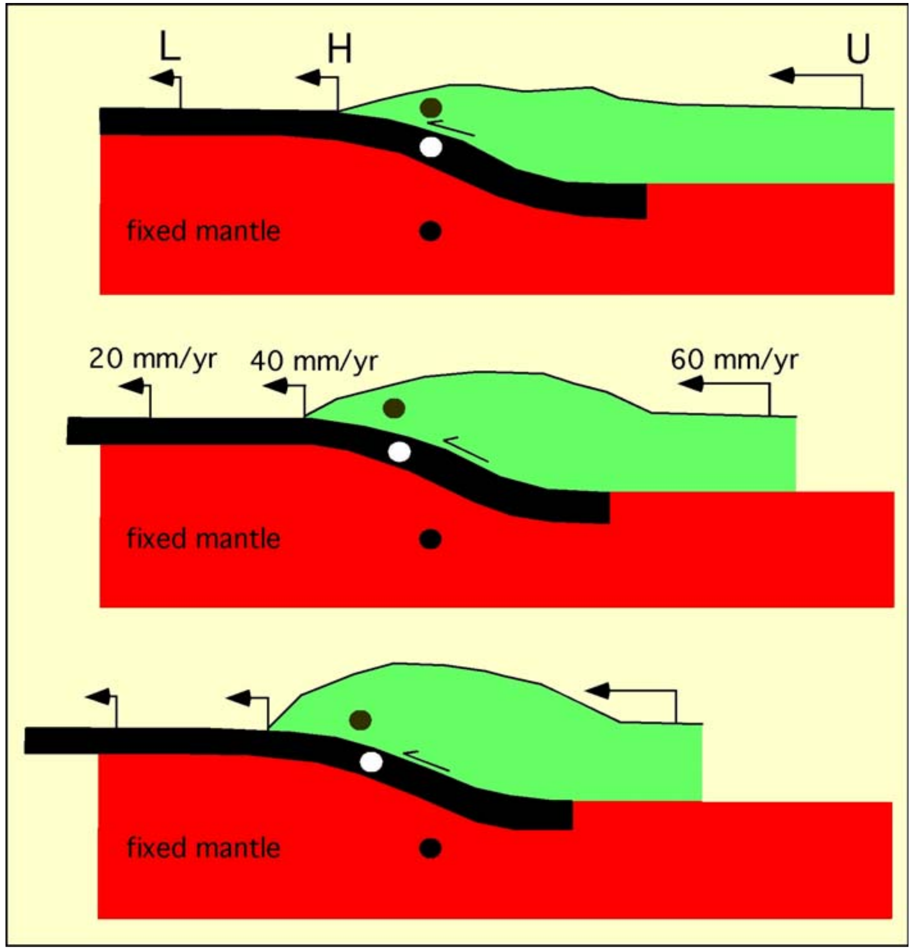

2b
B
depth (km)
200
400
600
500 (km)
1000
1500
aseismic
-3%
+3%

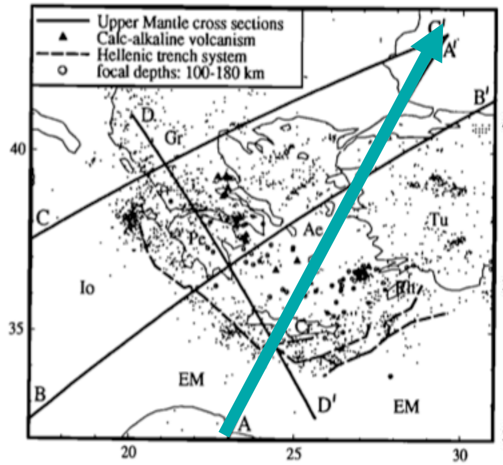

L
H
U
fixed mantle
20 mm/yr
40 mm/yr
60 mm/yr
fixed mantle
fixed mantle

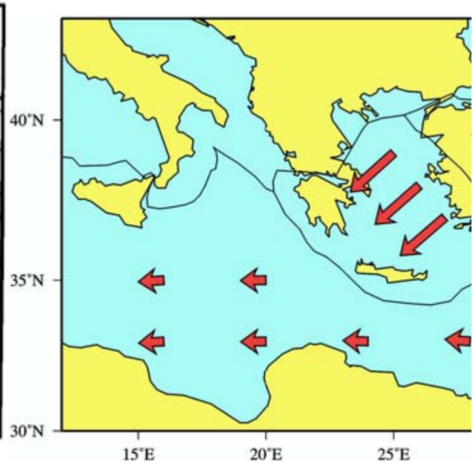

Upper Mantle cross sections
Calc-alkaline volcanism
Hellenic trench system
focal depths: 100-180 km
C'
A'
D
Gr
C
Io
Tu
B
EM
A
D'
EM
40
35
20
25
30

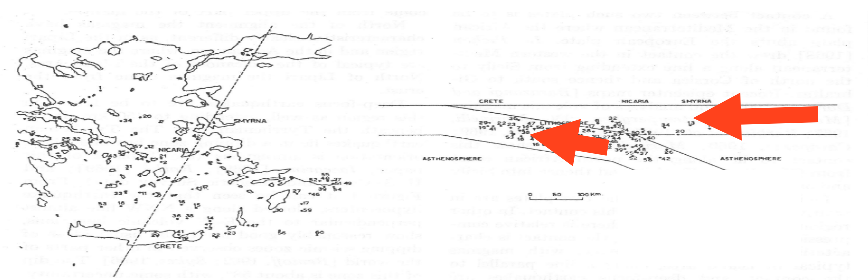

40°N
35°N
30°N
15°E
20°E
25°E


2a
depth (km)
200
400
600
500 (km)
1000
-3%
+3%

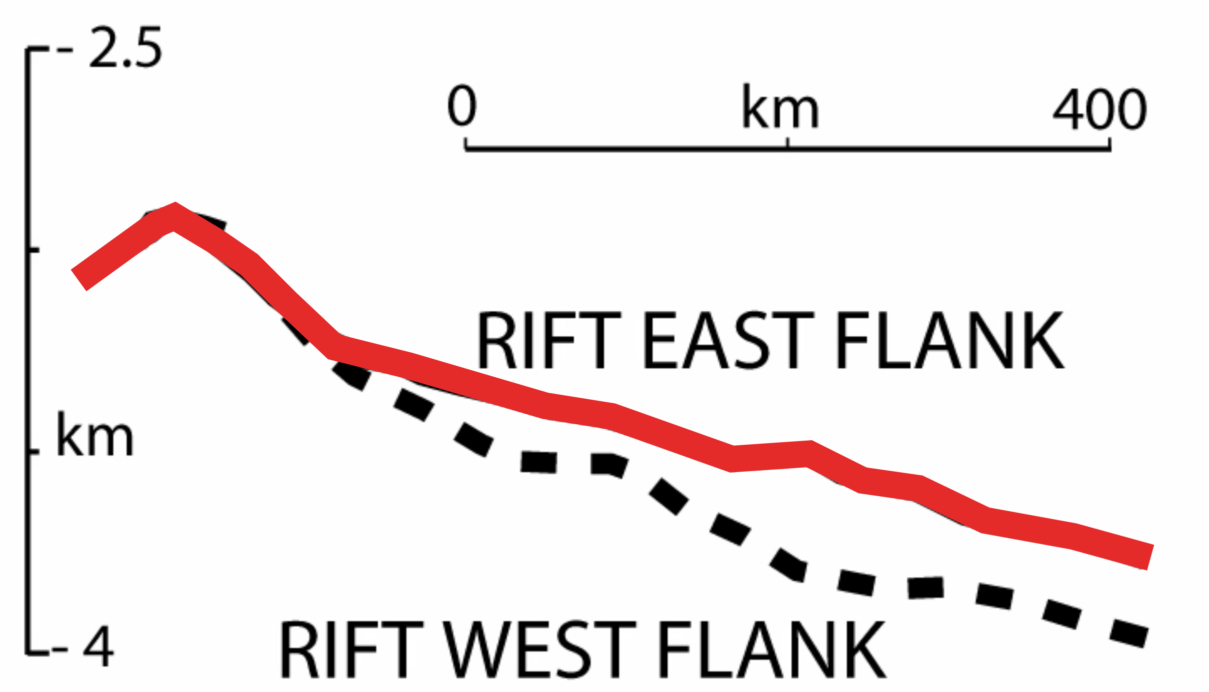

L
H
U
fixed mantle
20 mm/yr
40 mm/yr
60 mm/yr
fixed mantle
fixed mantle

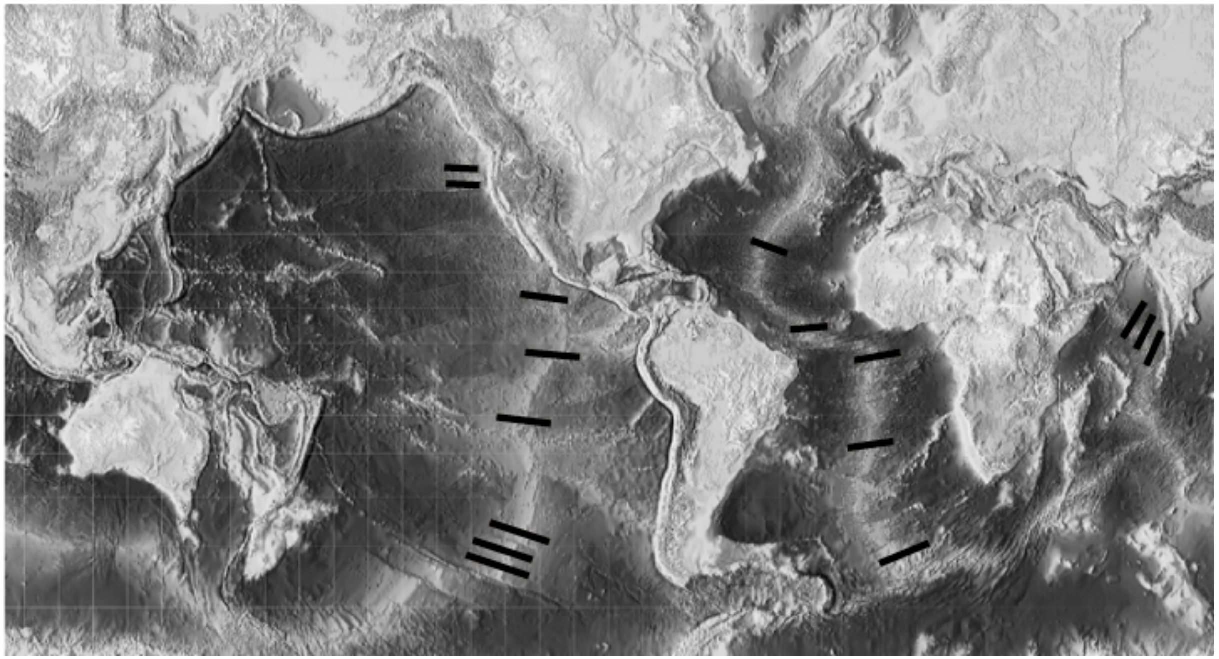

Upper Mantle cross sections
Calc-alkaline volcanism
Hellenic trench system
focal depths: 100-180 km
C'
A'
B'
D
Gr
C
Ae
Tu
Pe
Io
Rh
Cr
EM
B
D'
EM
A
40
35
20
25
30

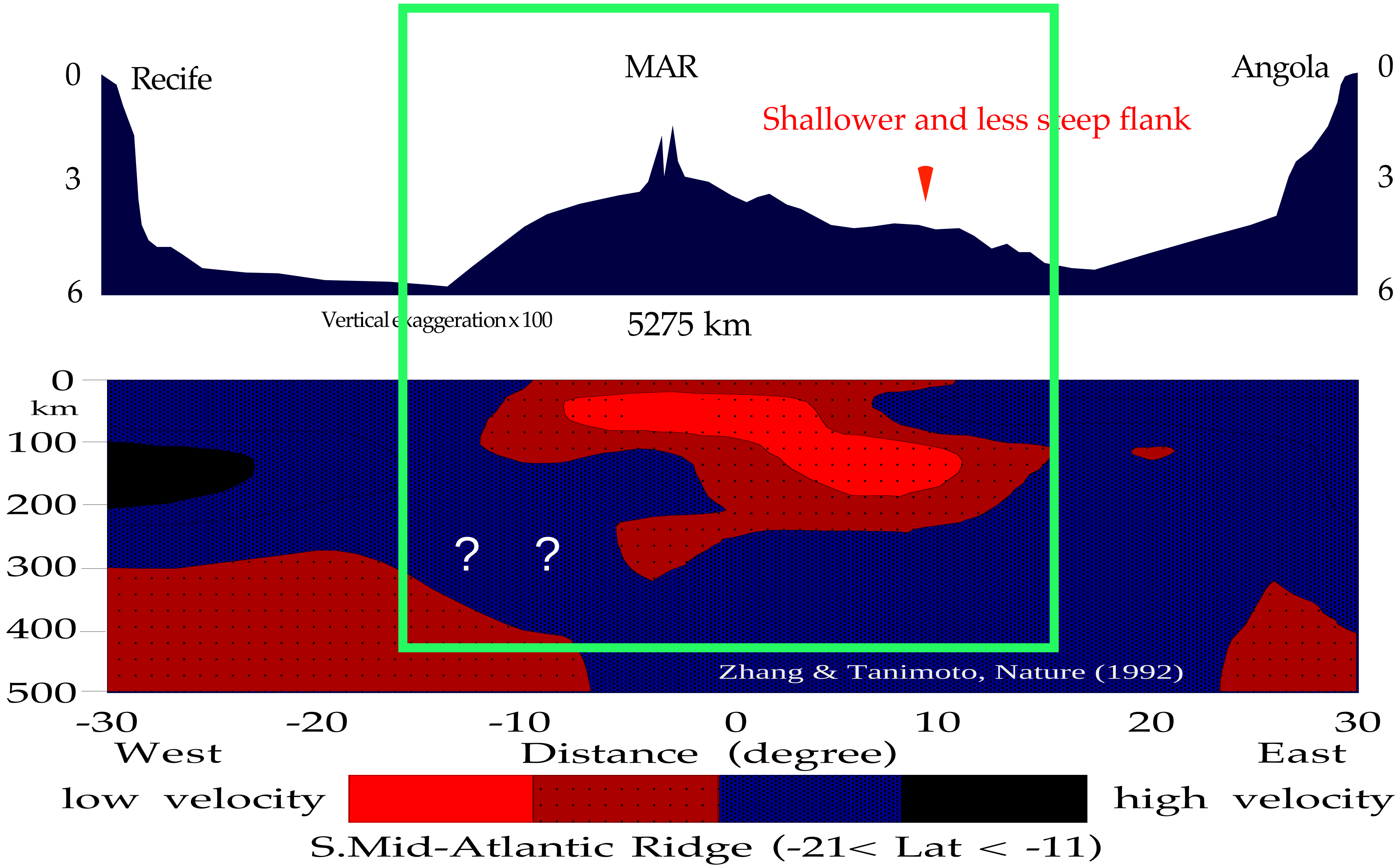

40°N
35°N
30°N
15°E
20°E
25°E


SMYRNA
NICARIA
CRETE
CRETE
NICARIA
SMYRNA
ASTHENOSPHERE
ASTHENOSPHERE

Rifts
are not symmetric at depth

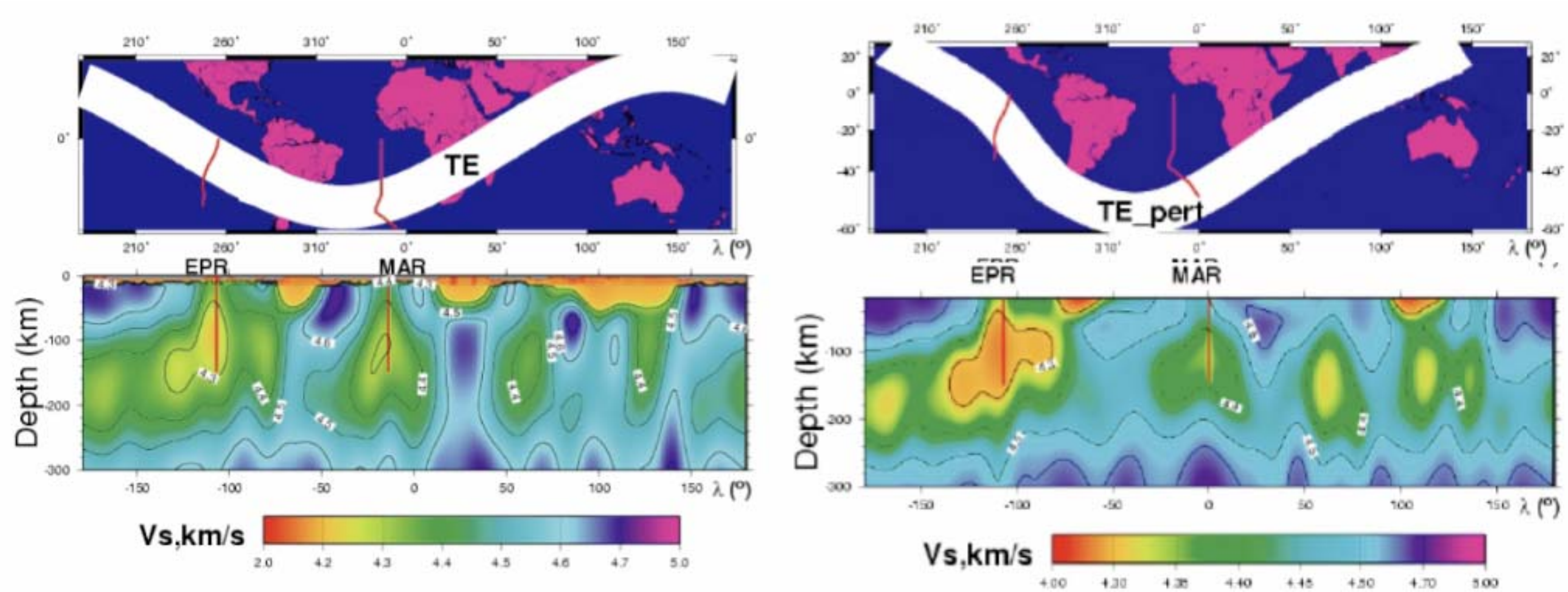

- 2.5
0
km
400
RIFT EAST FLANK
km
- 4
RIFT WEST FLANK



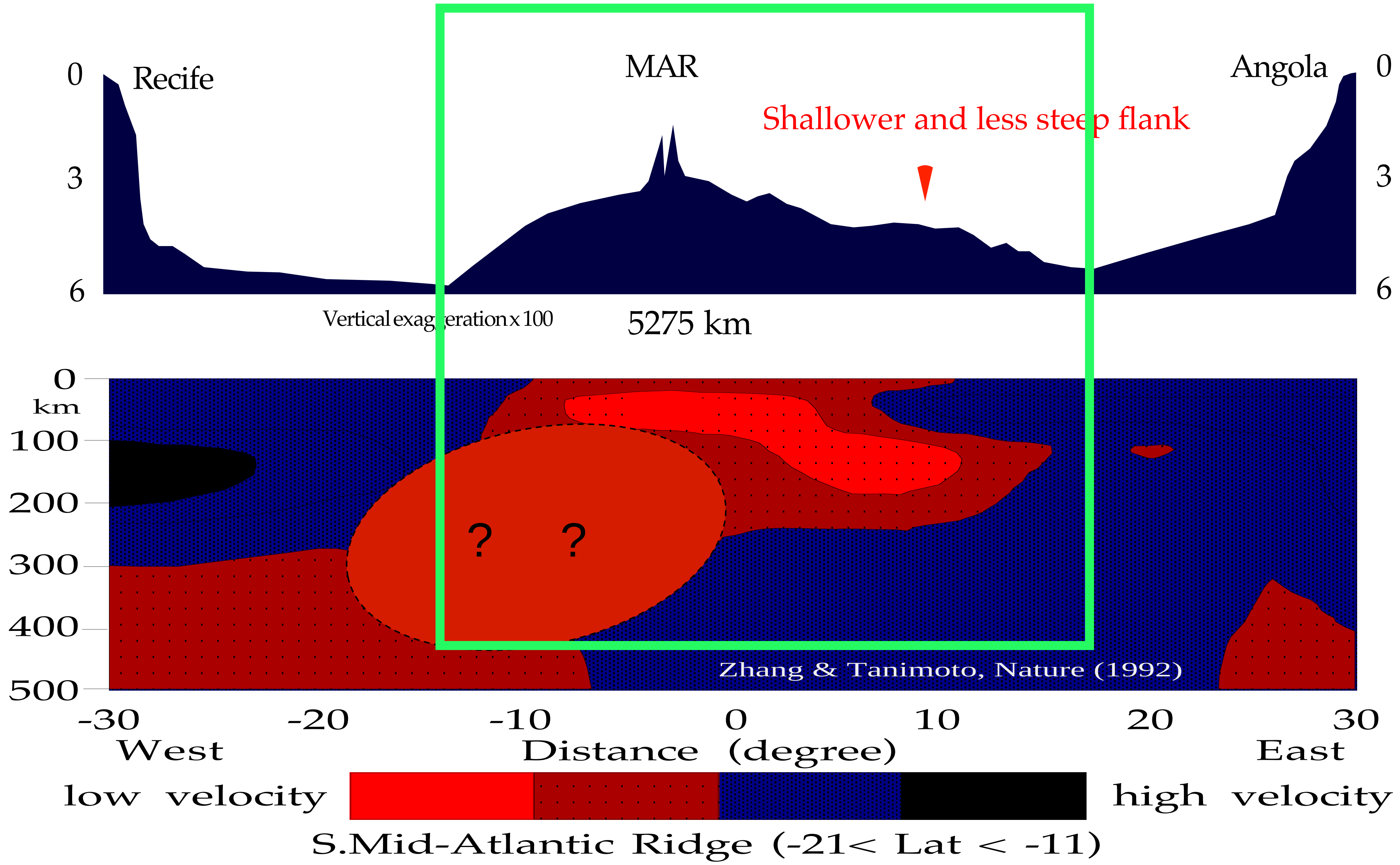


Recife
MAR
Angola
Shallower and less steep flank
0
3
6
Vertical exaggeration x 100
5275 km
0 km
100
200
300
400
500
? ?
Zhang & Tanimoto, Nature (1992)
-30 -20 -10 0 10 20 30
West
Distance (degree)
East
low velocity
high velocity
S.Mid-Atlantic Ridge (-21< Lat < -11)

modified

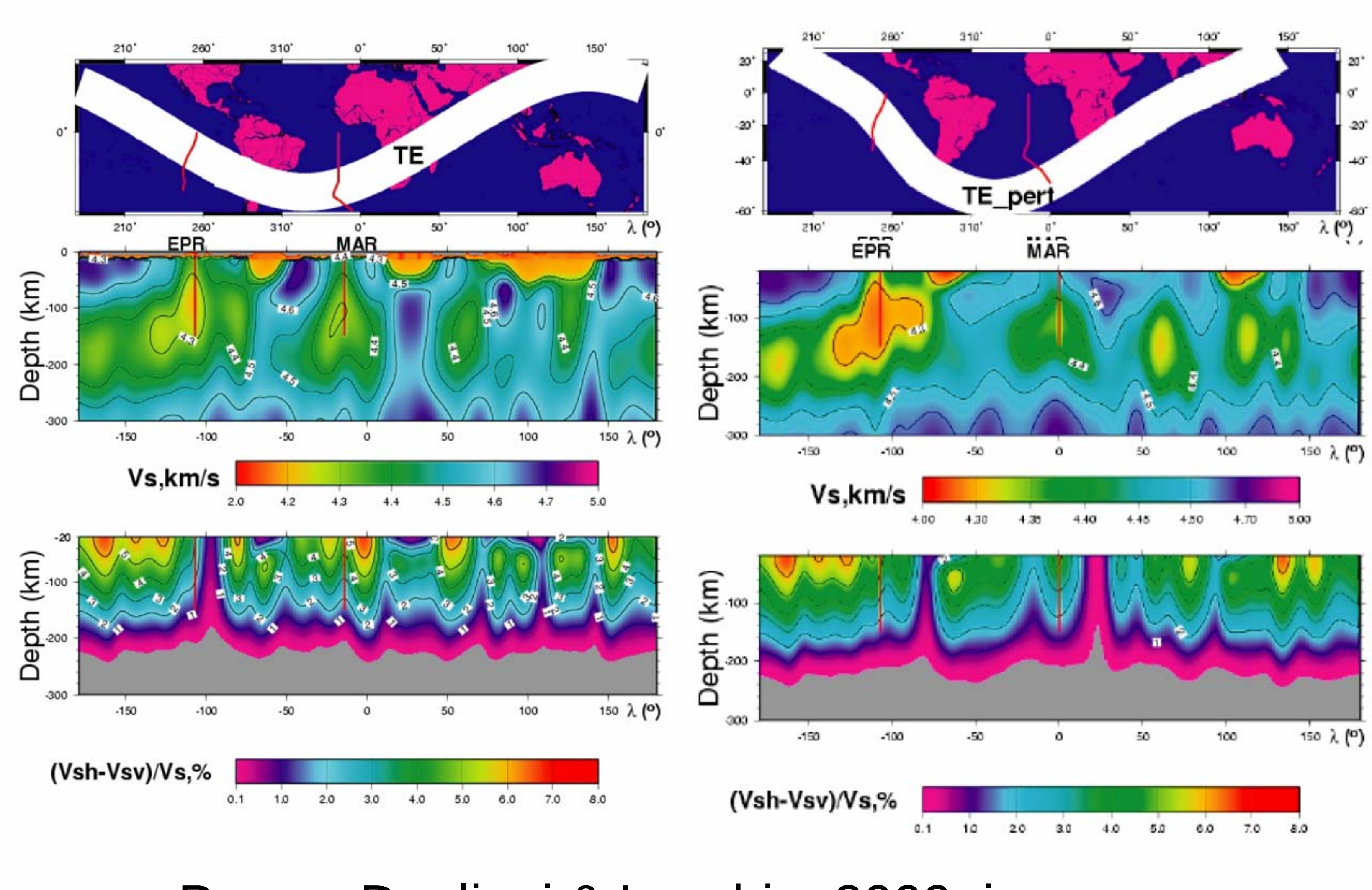


Panza, Doglioni & Levshin, 2009, in progress



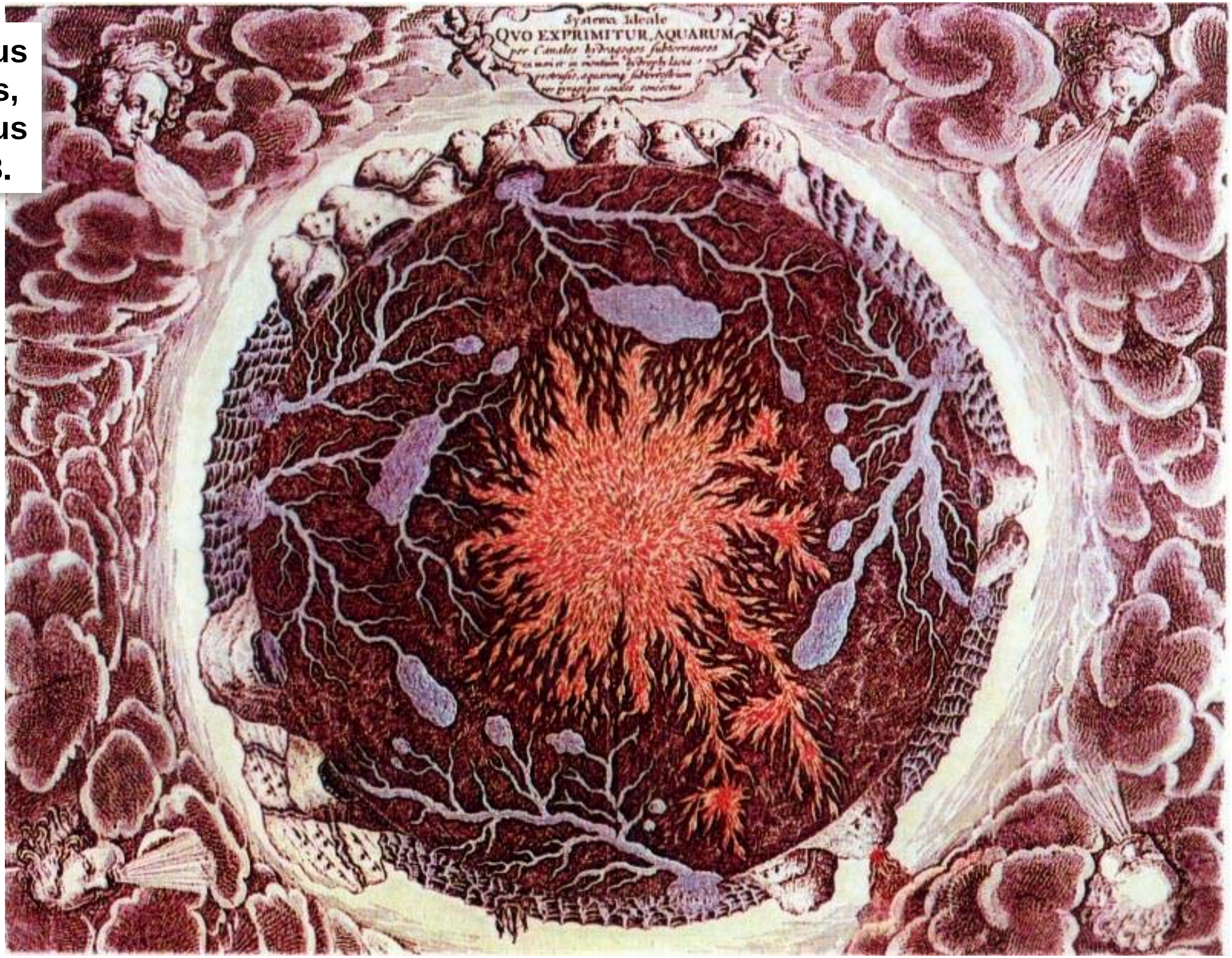
0
3
6
Recife
MAR
Angola
Shallower and less steep flank
Vertical exaggeration x 100
5275 km
0
km
100
200
300
400
500
? ?
Zhang & Tanimoto, Nature (1992)
-30
-20
-10
0
10
20
30
West
Distance (degree)
East
low velocity
high velocity
S.Mid-Atlantic Ridge (-21< Lat < -11)

modified



Panza, Doglioni & Levshin, 2009, in progress

From Mundus Subterraneus, by Athanasius Kircher, 1678.



Athanasius Kircher, depicted the most advanced thinking of his day. Earth's interior was supposed to contain a giant, fiery inferno.

The fires heated water that had seeped in from the ocean and gave rise to hot springs. Where tongues of fire came close to Earth's surface (lower right), they started volcanoes.