Paris, November, 2013

Mountain building and the style of mantle convection beneath convergent margin

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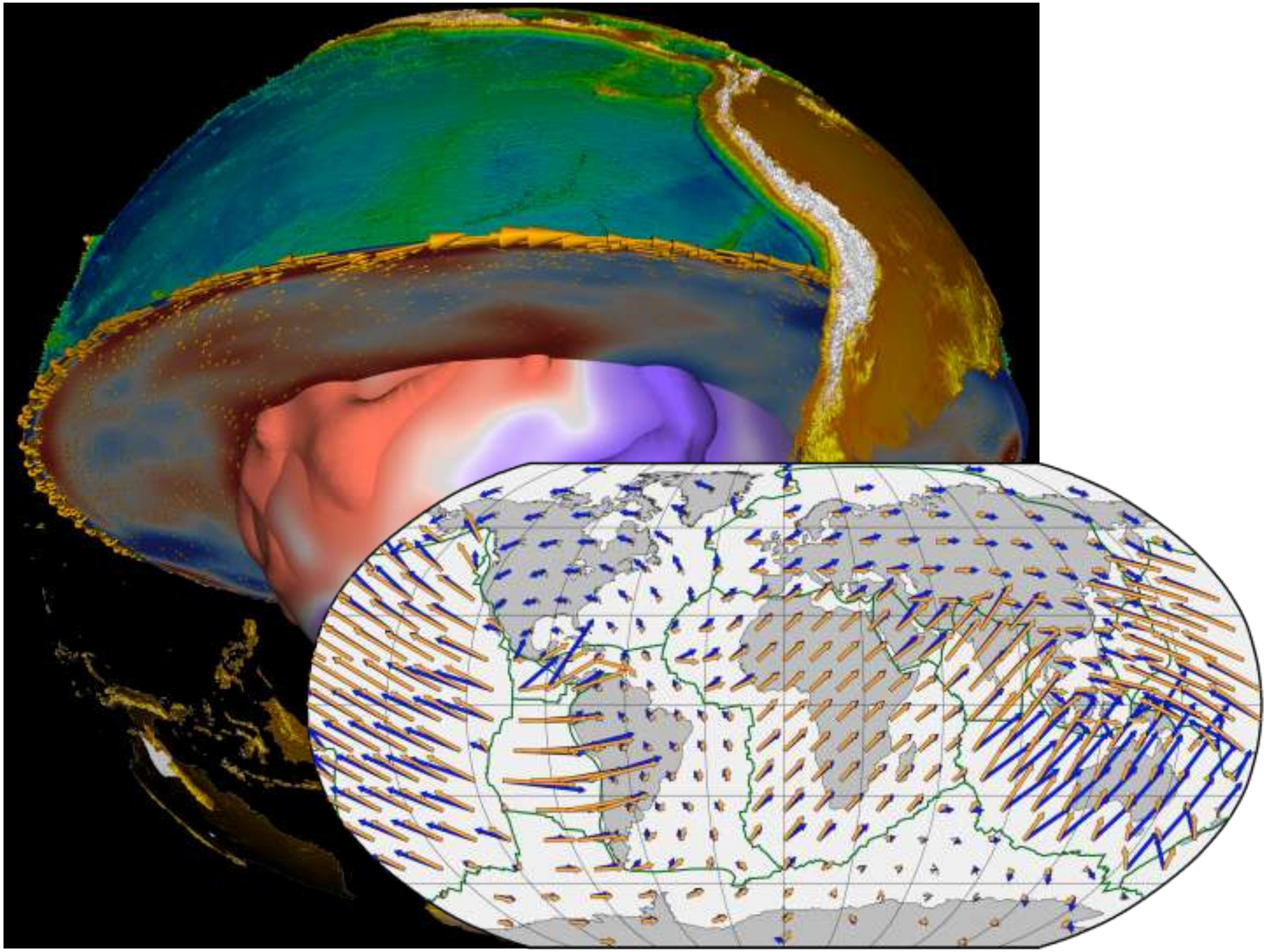
Contribution of Clint Conrad (Hawaii) and Laurent Husson (Nantes)

ROMA TRE
UNIVERSITÀ DEGLI STUDI

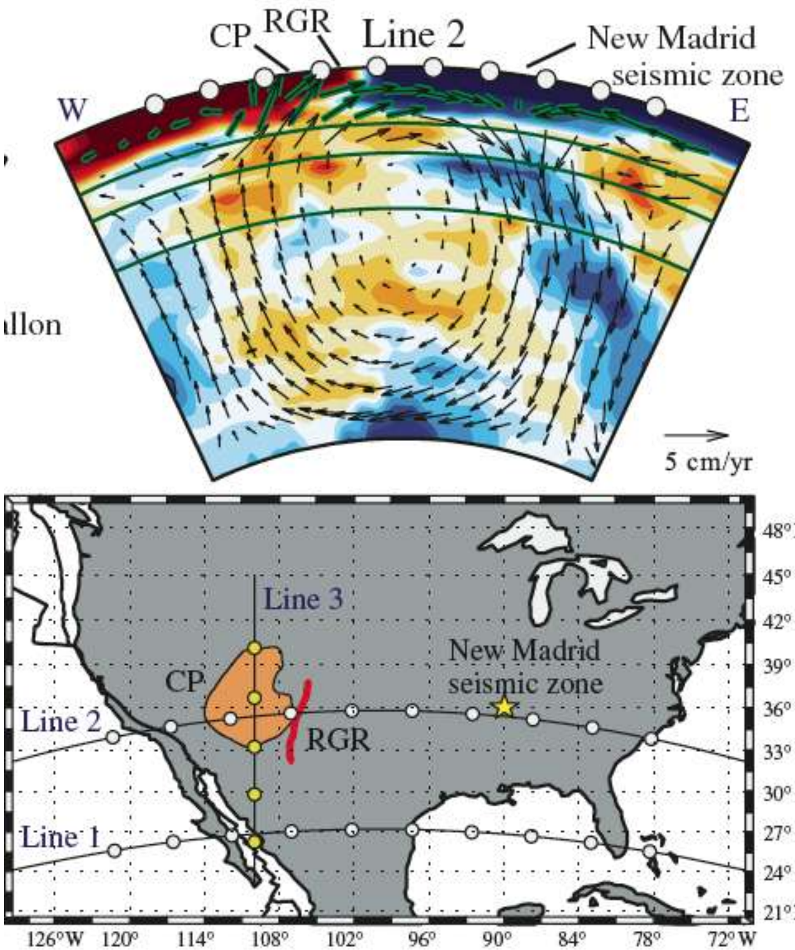
LET
LABORATORY EXPERIMENTAL TECTONICS

Mantle convection models

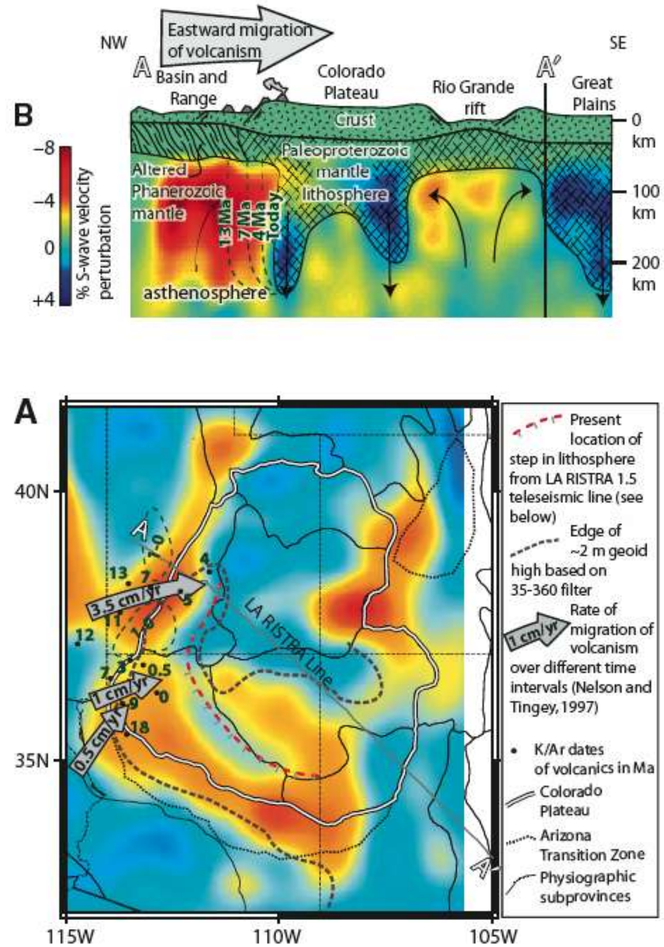


convection models properly simulate the motion of oceanic plates….

convection beneath the continent is more uncertain…

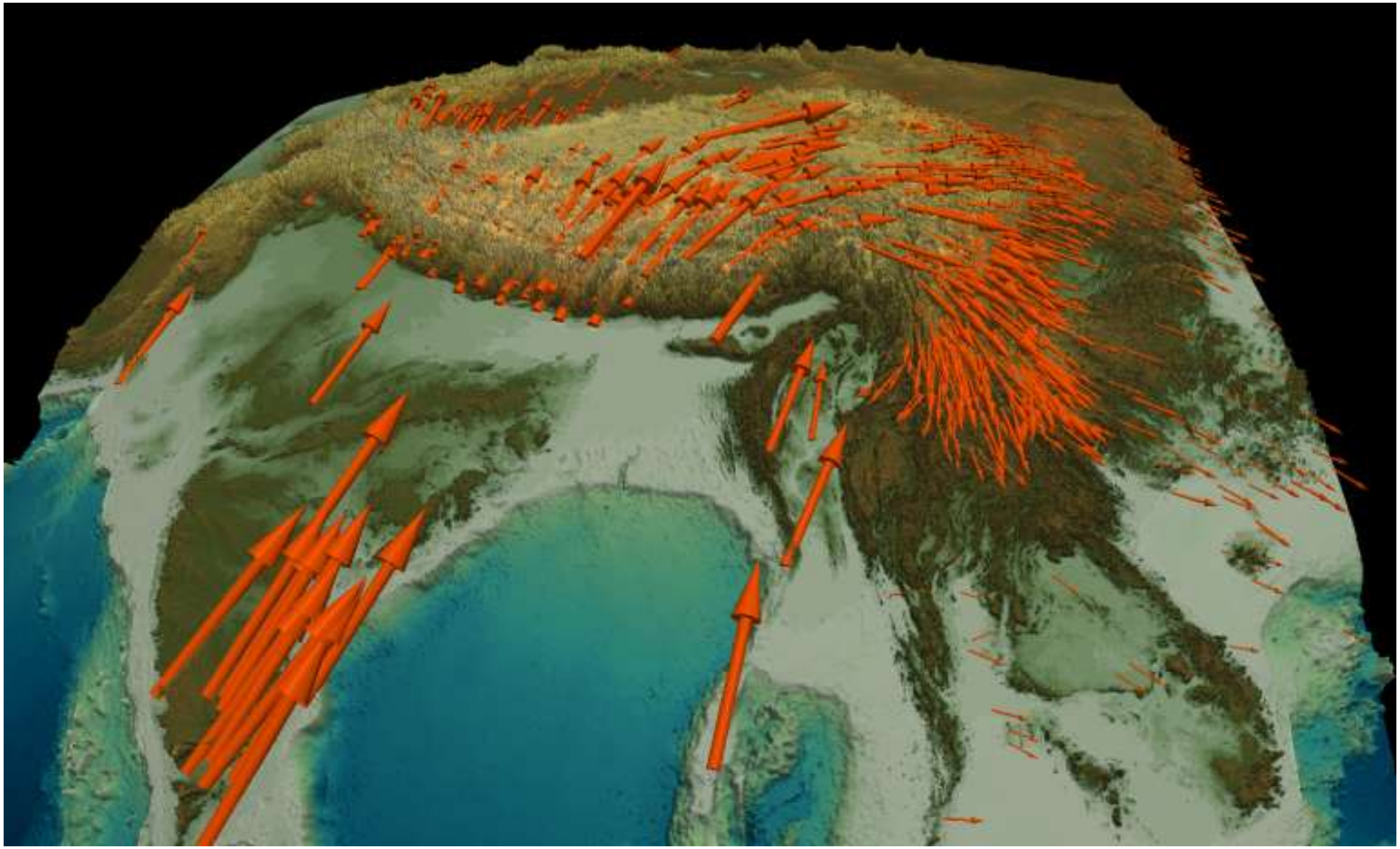


Moucha et al., 2008



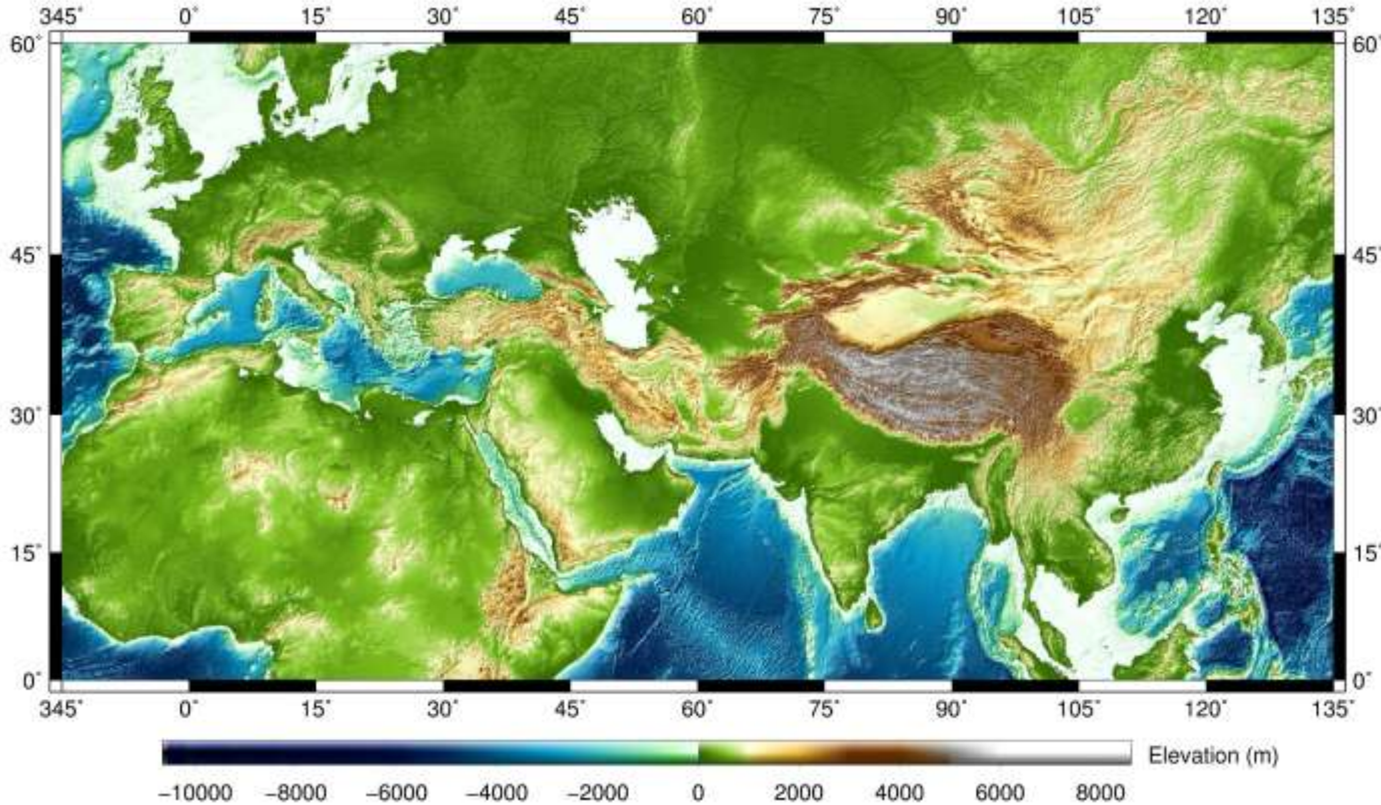
Karlstrom et al., 2008

….because of the slow motion and of lithosphere heterogeneity



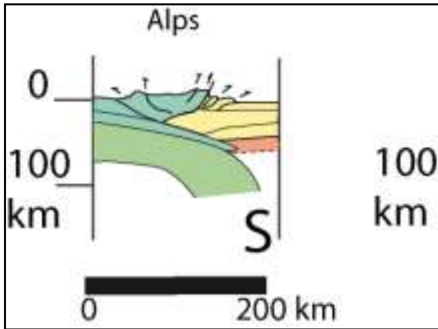
What does sustain mountain building?
What is the role of the mantle ?

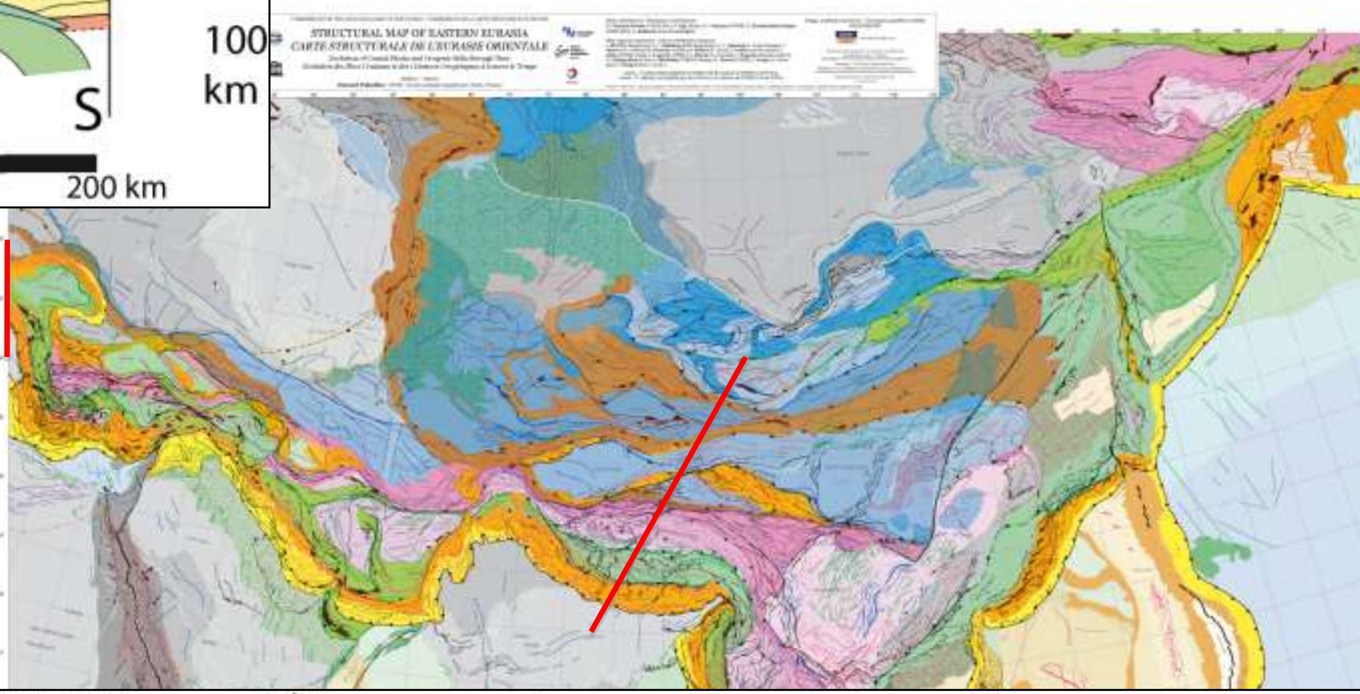
Journey on the Tethyan belt

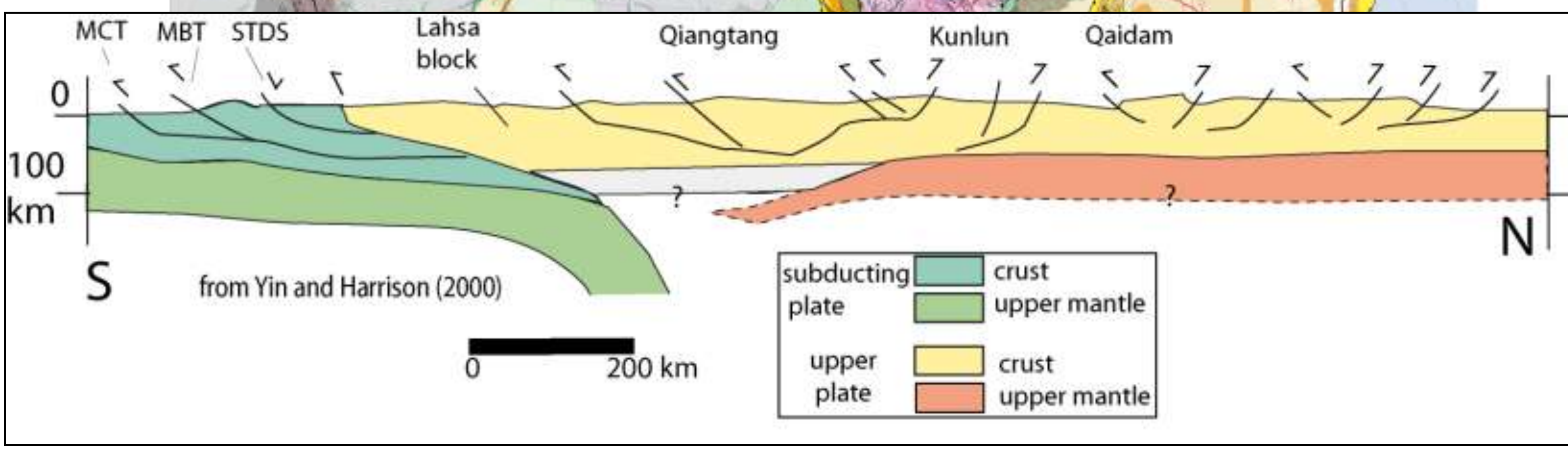


Style of deformation and mountain bulding is related to the scale of mantle convection

The Tethyan belt



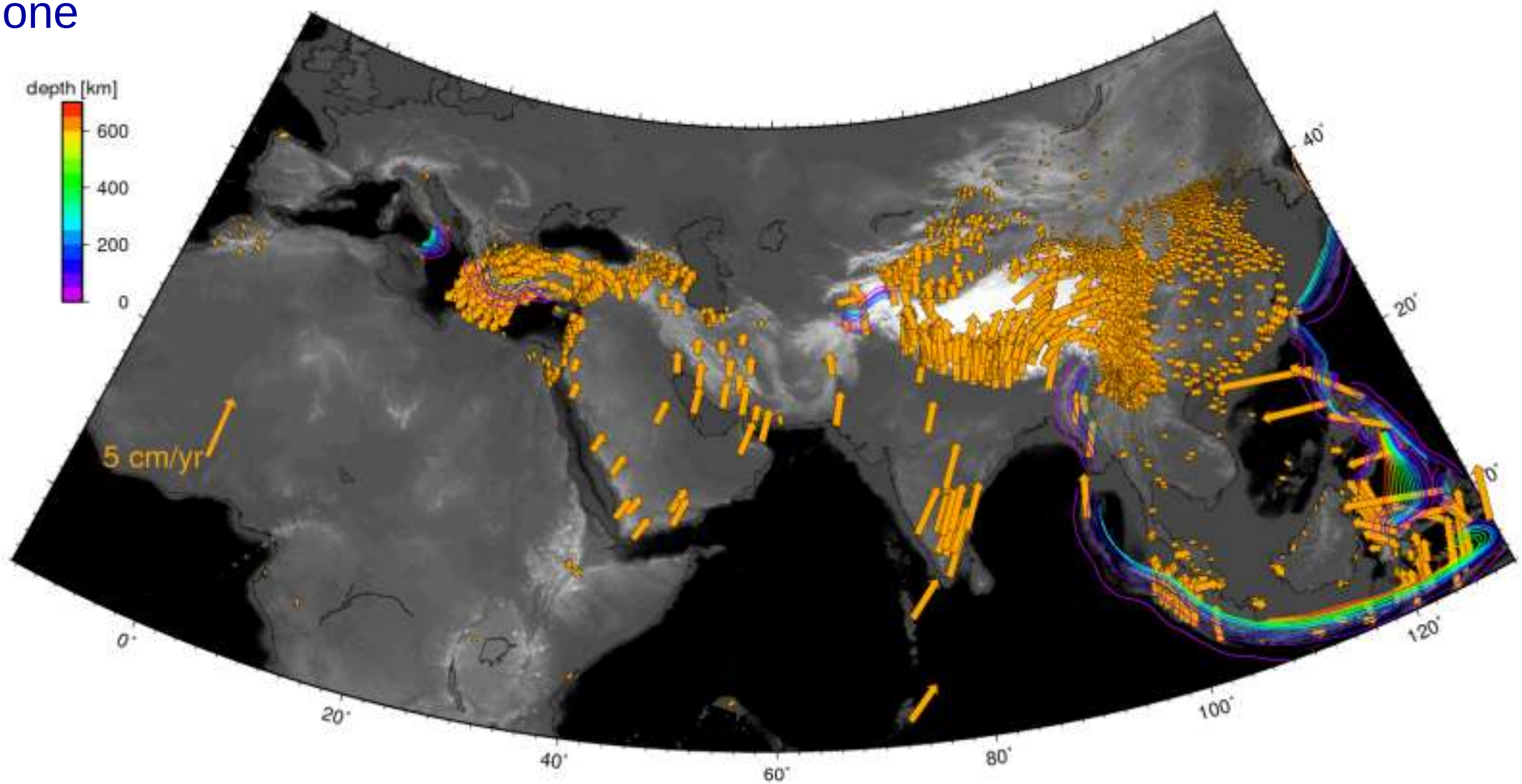




a record of long- term accrection of crustal blocks with different scale orogenic belt

Geodesy

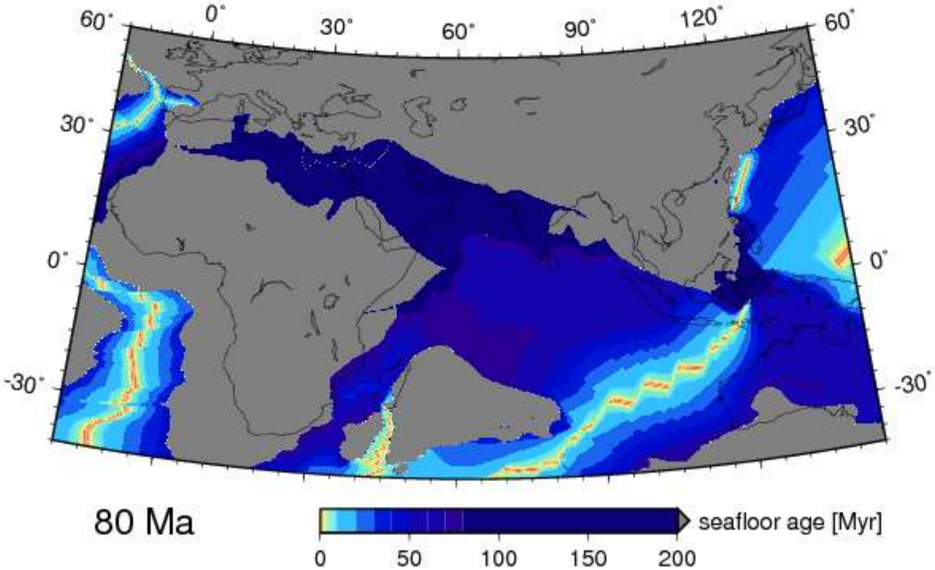
zone



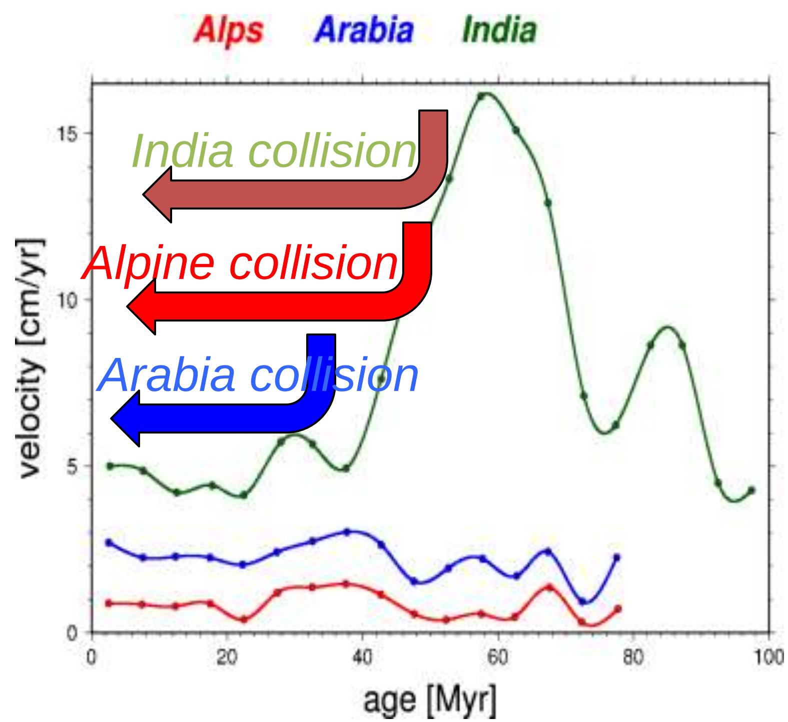
arrows: GPS motion (compiled from various sources)

deformation spreads over continents

Adria, Arabia and India kinematics

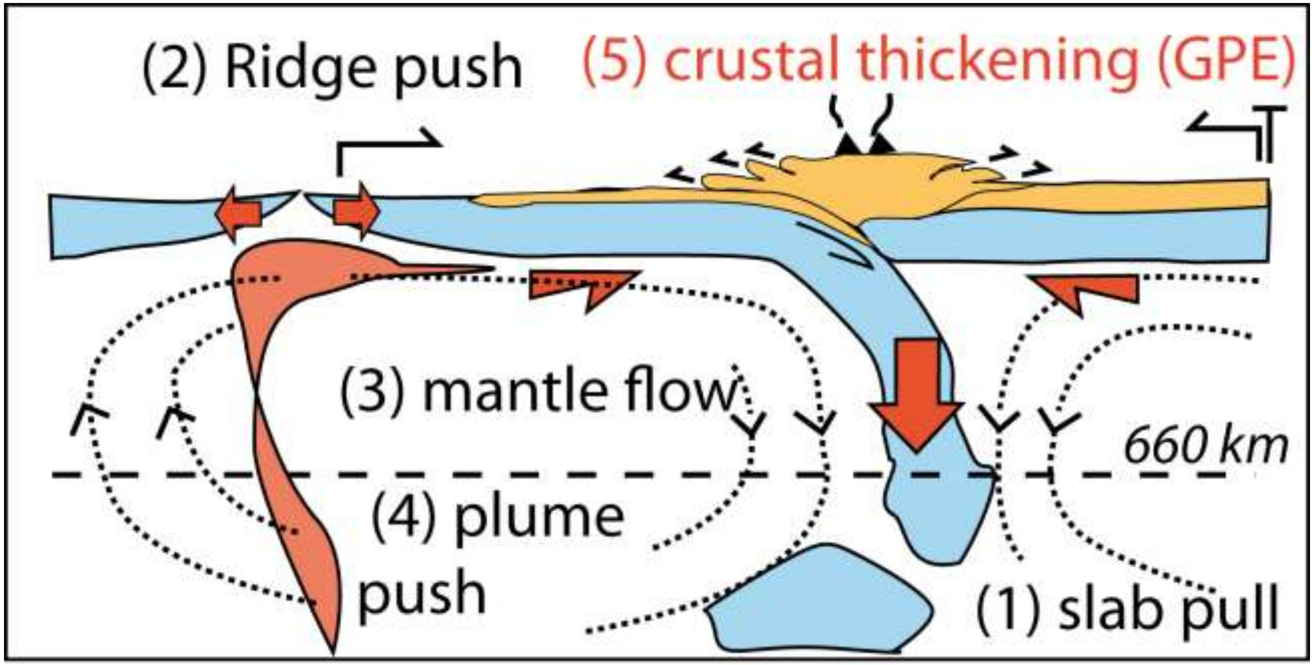


Müller et al. (2008)



….a protracted continental collision

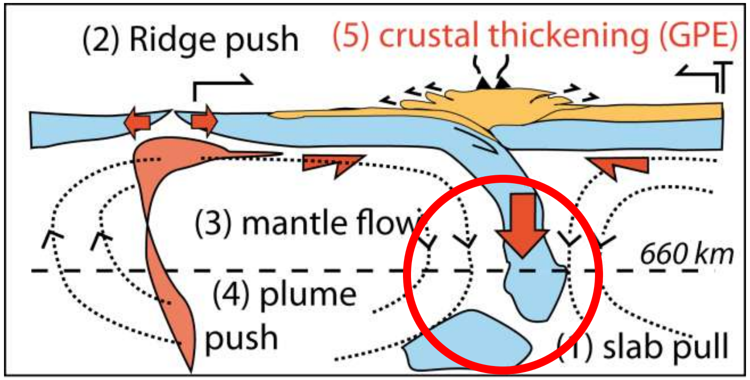
Forces at work during collision

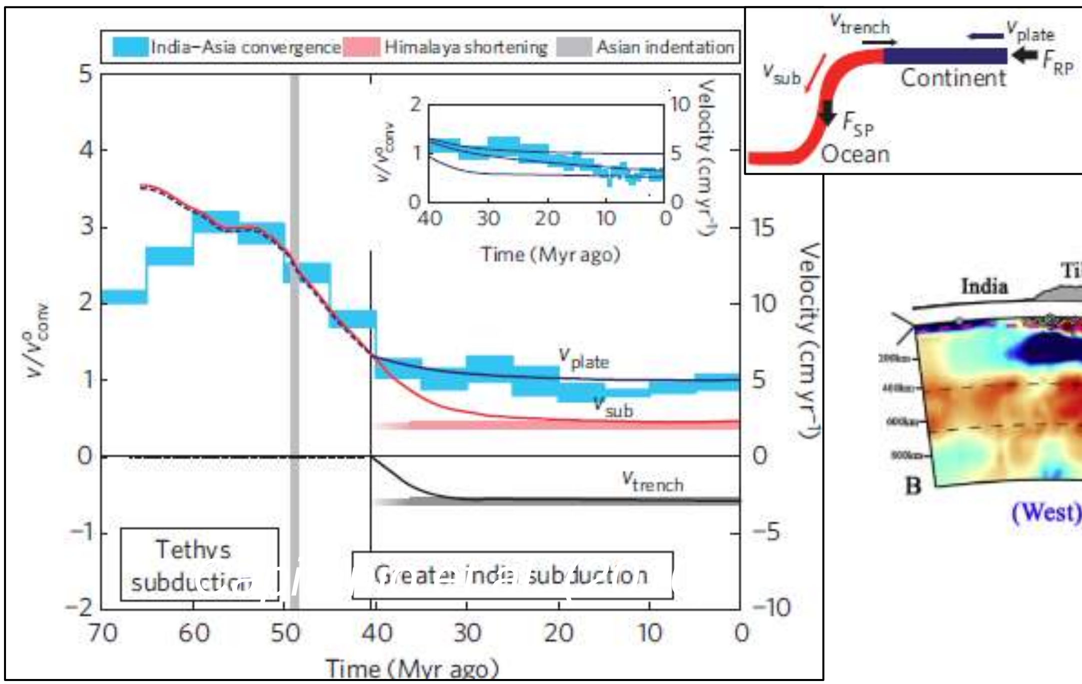


condition to sustain orogen **: 1 + 2 + 3 + 4 = 5**

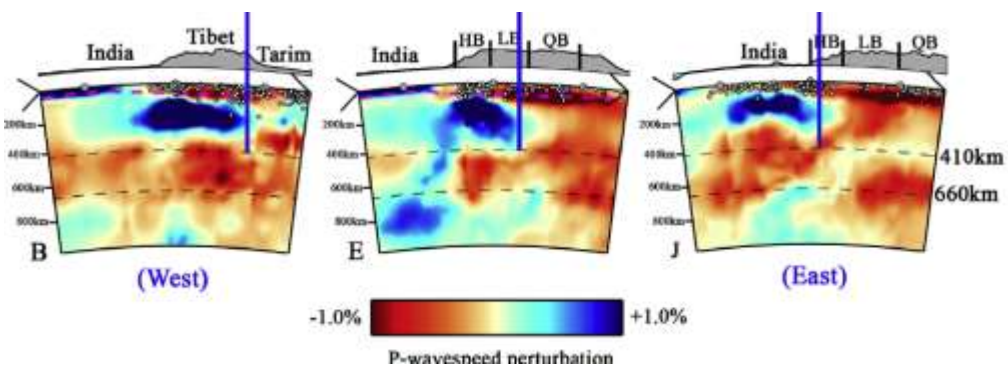
where **5** is ~ 8-9 X 10^{12} N/m (*Gosh et al., 2006; Husson et al., 2010*)

I) Slab Pull





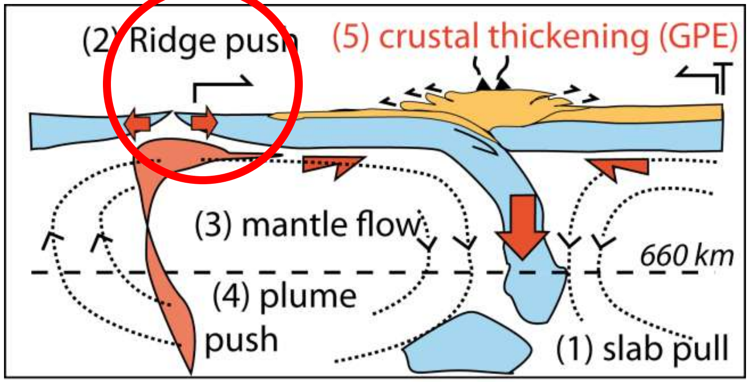
Capitanio et al., 2010



Li et al., 2008

It fits the velocity reduction collision but not the protracted velocity after collision

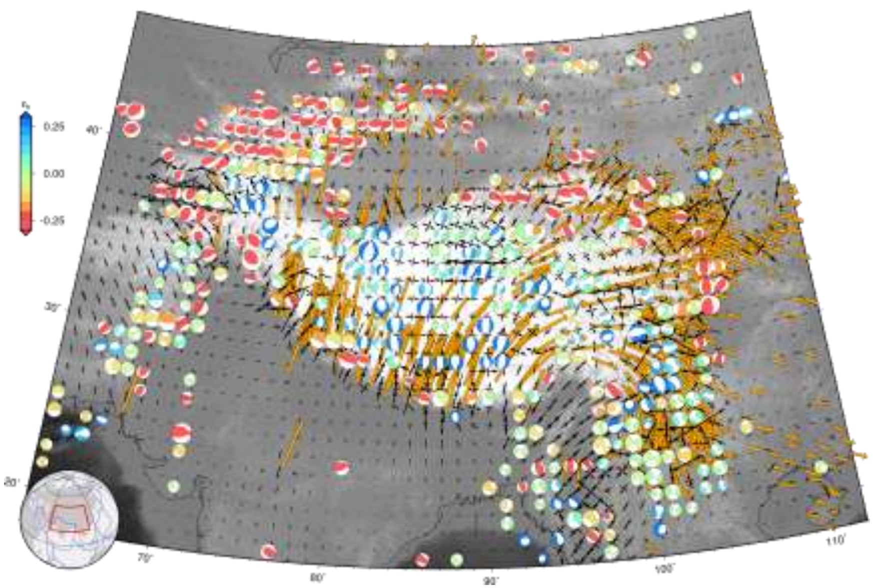
Slab pull likely reduced by break-off



II) Ridge push

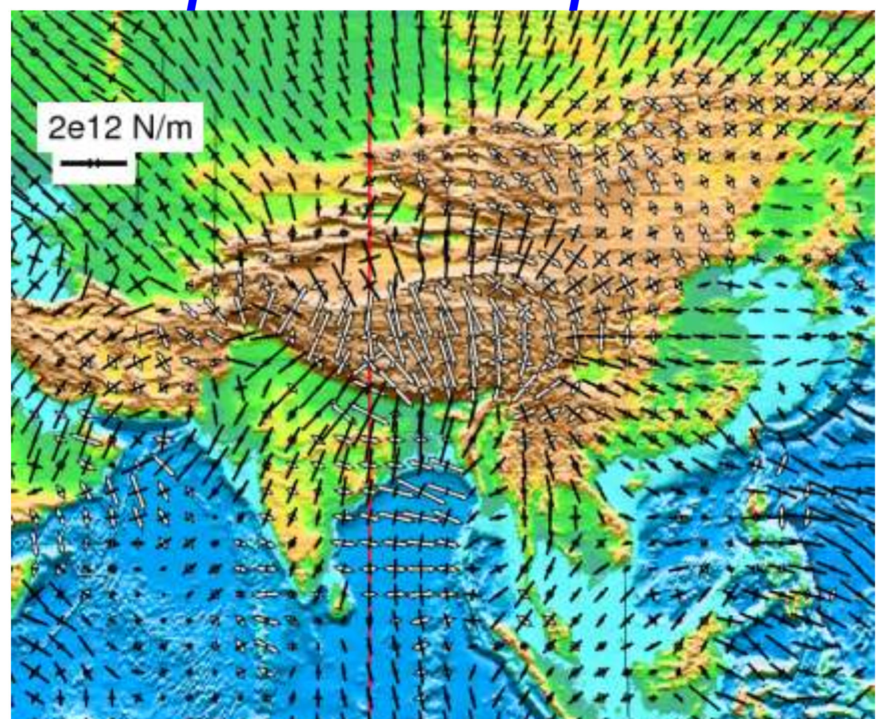
- Ridge push ain't doing it
- Need additional N-S compressive (India driving) force from the mantle (~2.5 10^{12} N/m)

Geodetic and coseismic deformation



White sticks: major extensional axes,
Black sticks: compressive Axes (*Ghosh et al., 2006*)

Lithospheric model predictions



Suggested force systems for the continued convergence

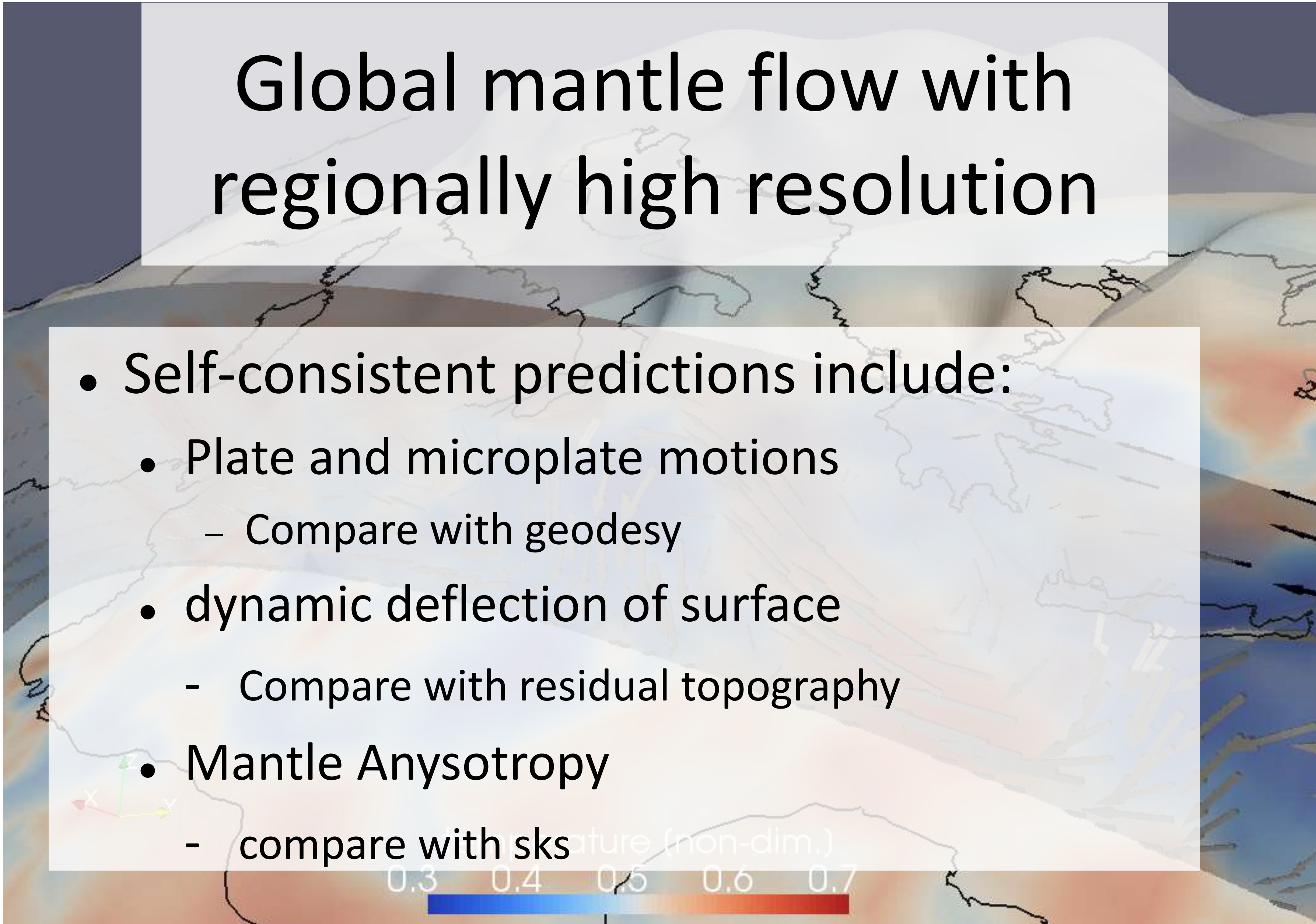
- Ridge push: too small (e.g. Ghosh et al., 2006)
- Slab pull: too small or none (slab break-off) (e.g. Copley et al. 2010; Capitanio et al., 2010)
- Plume push: too time-dependent speedup, too small (e.g. Gurnis and Torsvik, 1994; van Hinsbergen et al., 2010; Cande & Stegman, 2011)
- Large scale mantle flow ? may drag the plates (Alvarez, 1990)

Mantle circulation modeling

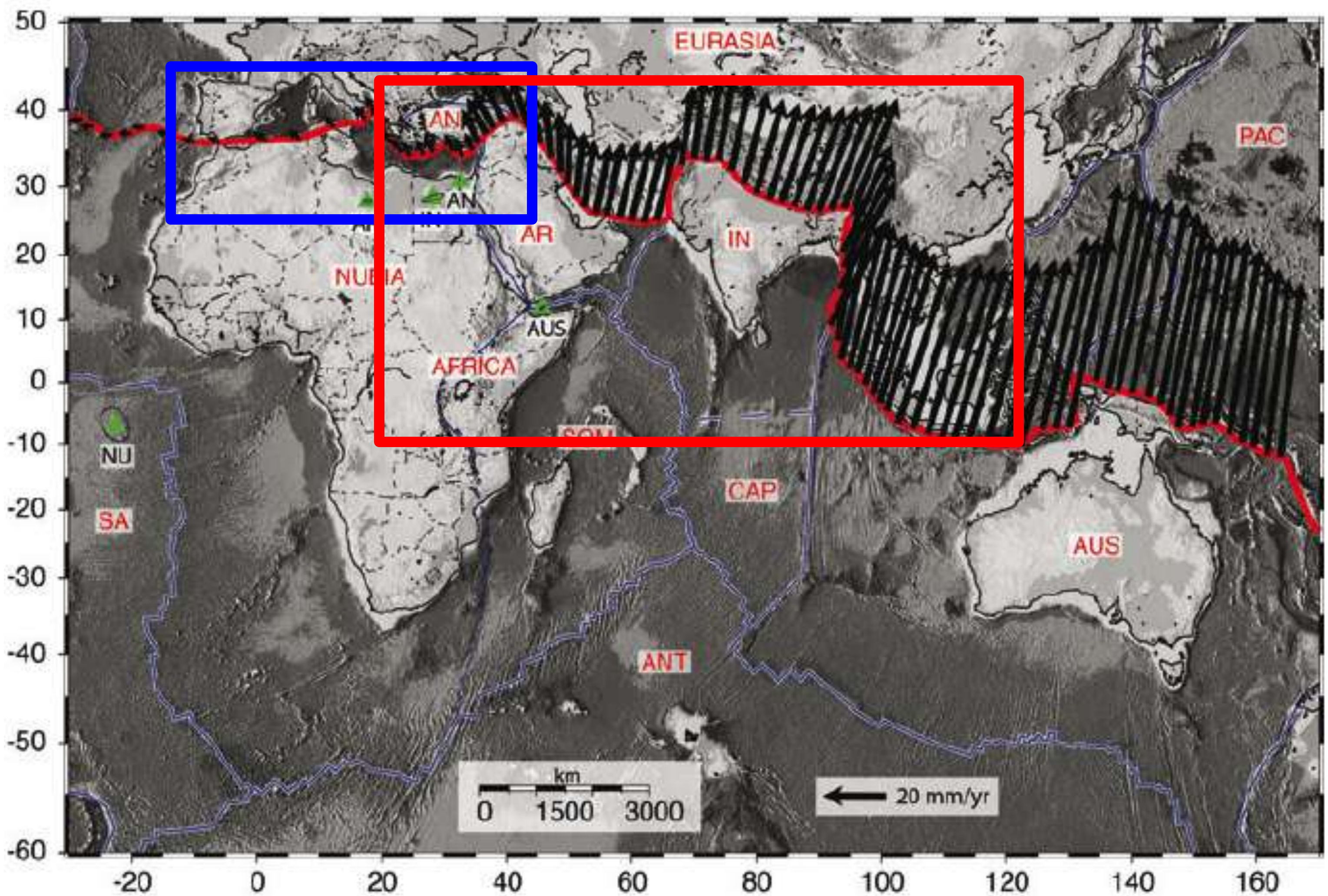
- Incompressible, laminar (Stokes) flow
- Boundary conditions: surface and core free slip
- Solve with CitcomS (Zhong et al., 2000; Tan et al. 2006), with modifications as in Faccenna & Becker (2010)
- Rheology:
  - Layered viscosity structure, with lateral viscosity variations, Newtonian
  - Plate boundaries are weak (low viscosity) zones
- Density anomalies:
  - Simple scaling of velocity anomalies from *S* and *P* wave tomography, no chemical anomalies besides continental keels which are assumed neutrally buoyant
  - Density anomaly prescribed along Wadati-Benioff zone

Global mantle flow with regionally high resolution

- Self-consistent predictions include:
  - Plate and microplate motions
    - Compare with geodesy
  - dynamic deflection of surface
    - Compare with residual topography
  - Mantle Anysotropy
    - compare with sks

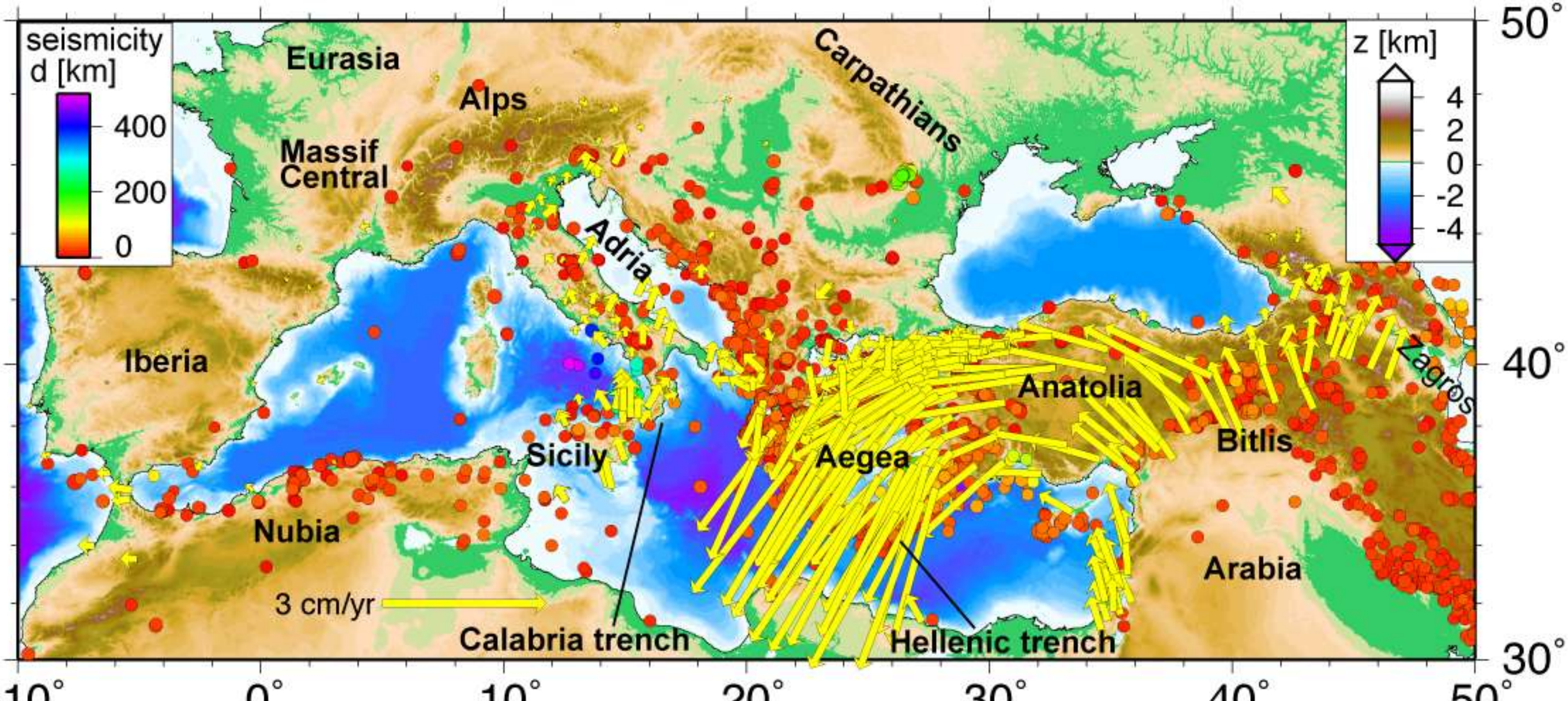


Contribution of mantle flow beneath the Tethyan belt



Reilinger and Mcklusky, 2011

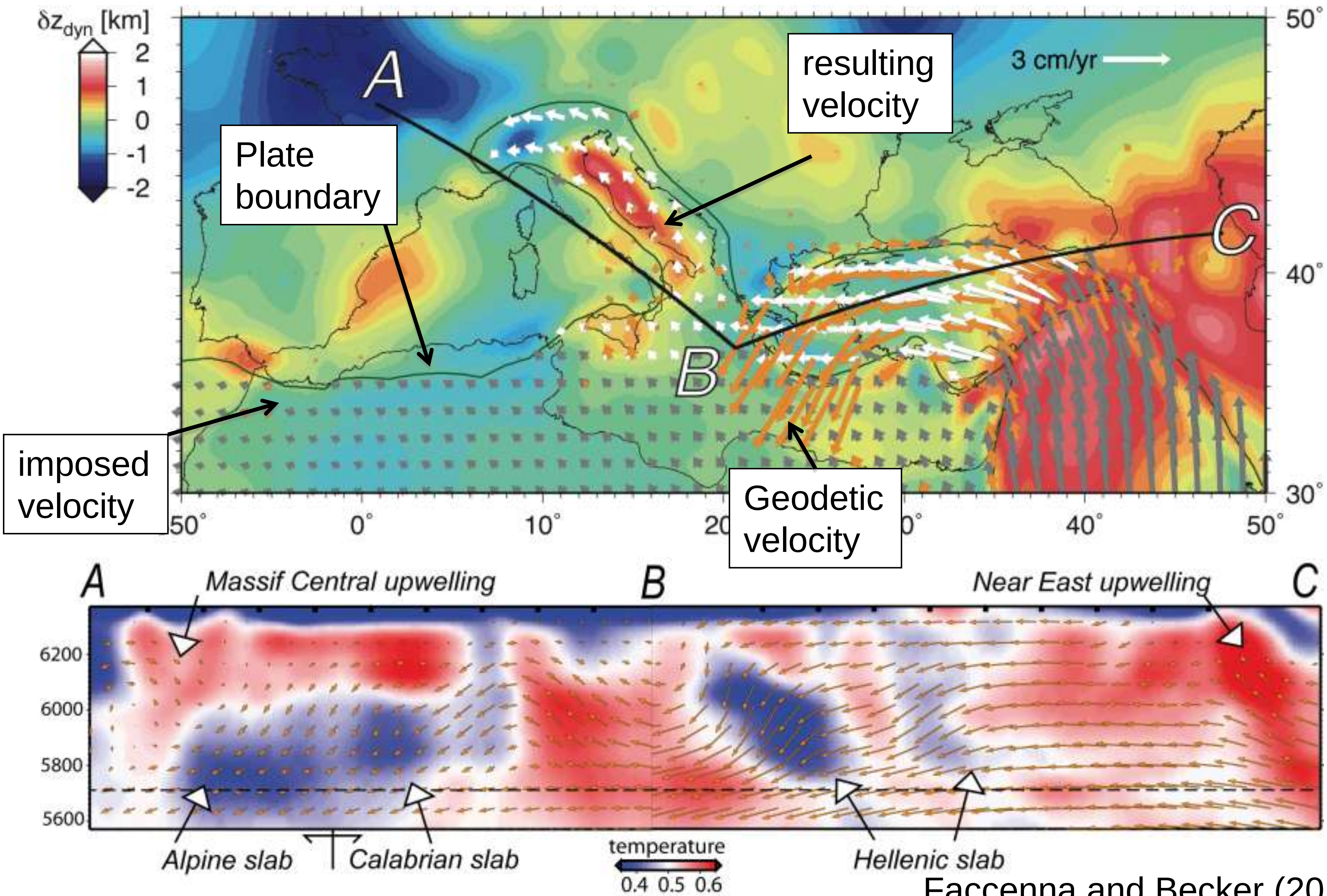
The Mediterranean



GPS *Serpelloni et al. 2007*

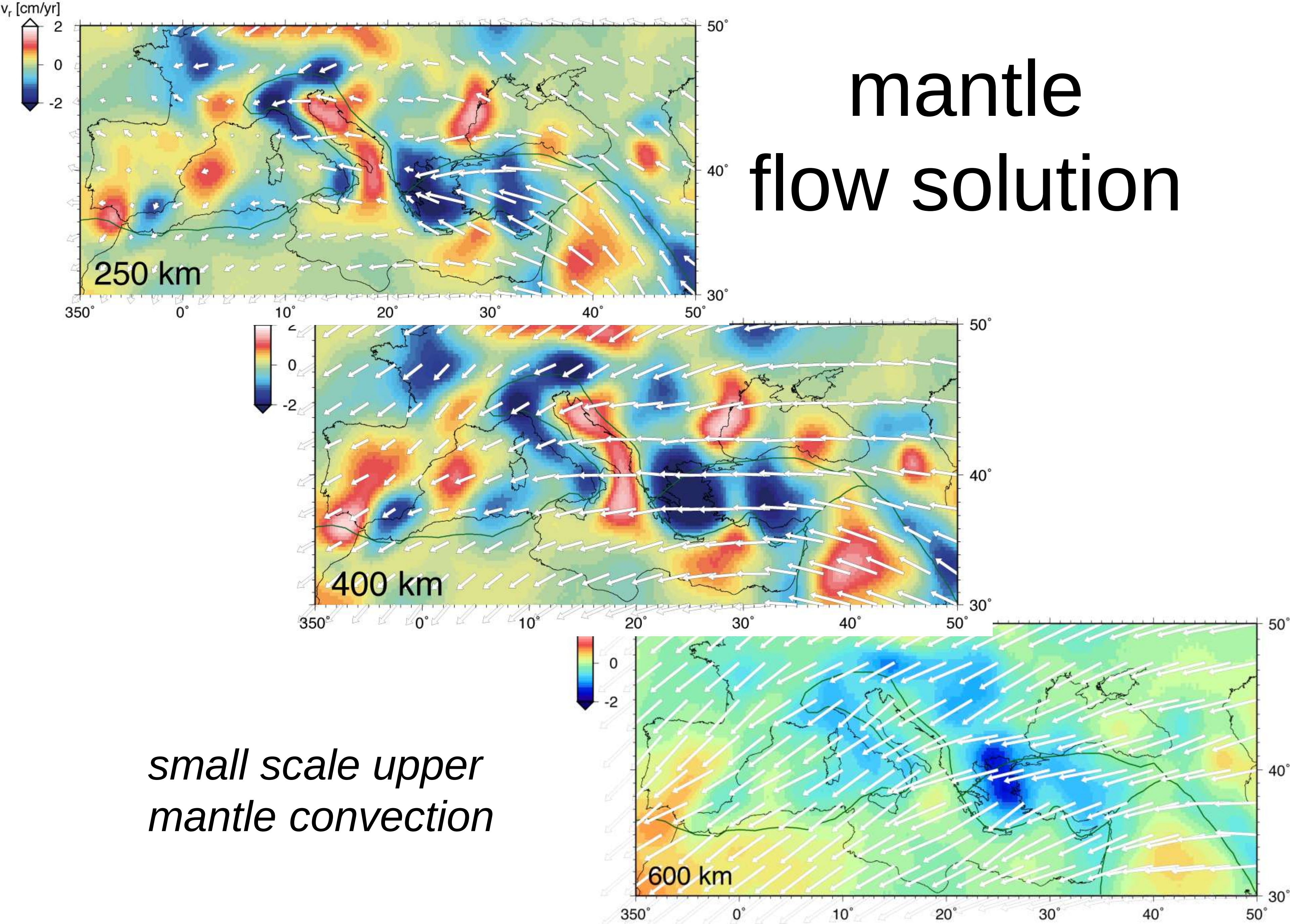
What's drive microplates? Fast motion of Anatolia?
What does generate plateaux and mesetas?

Upper Mantle flow



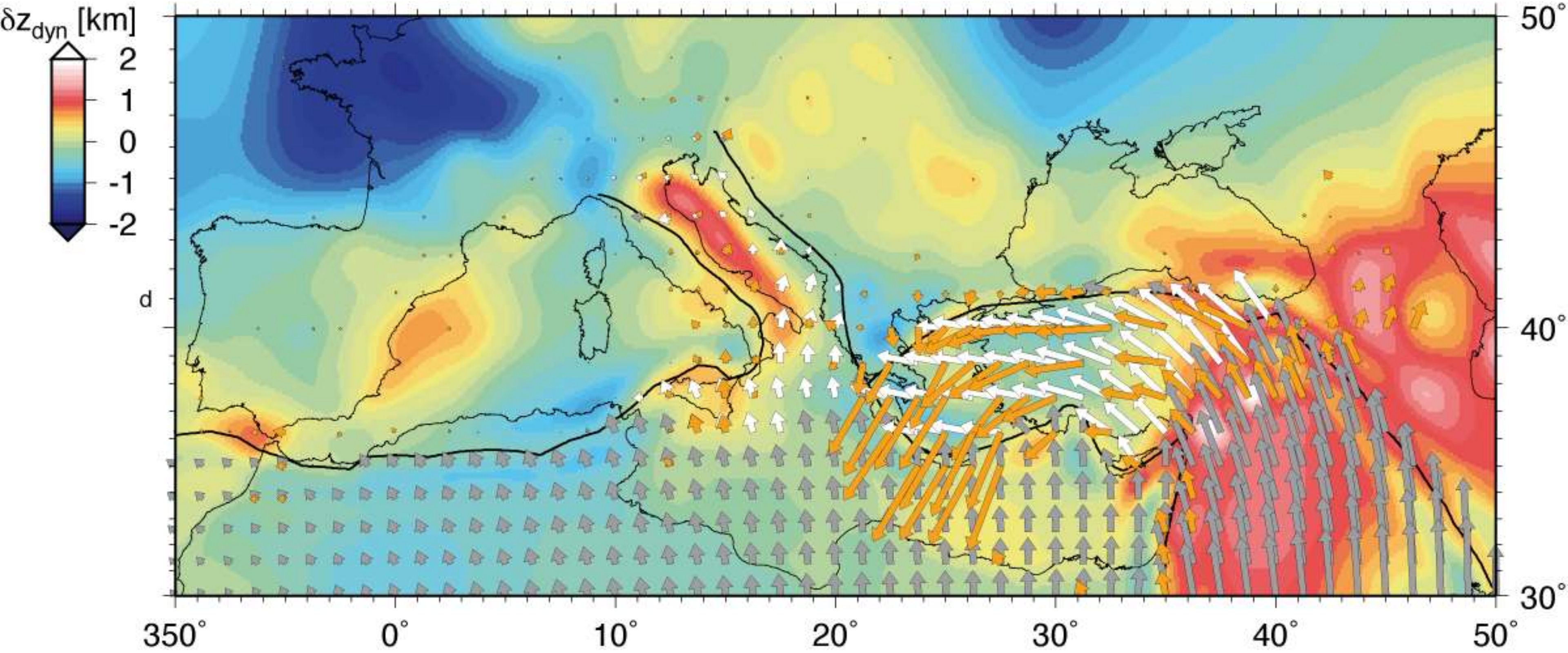
Faccenna and Becker (2010)

mantle flow solution



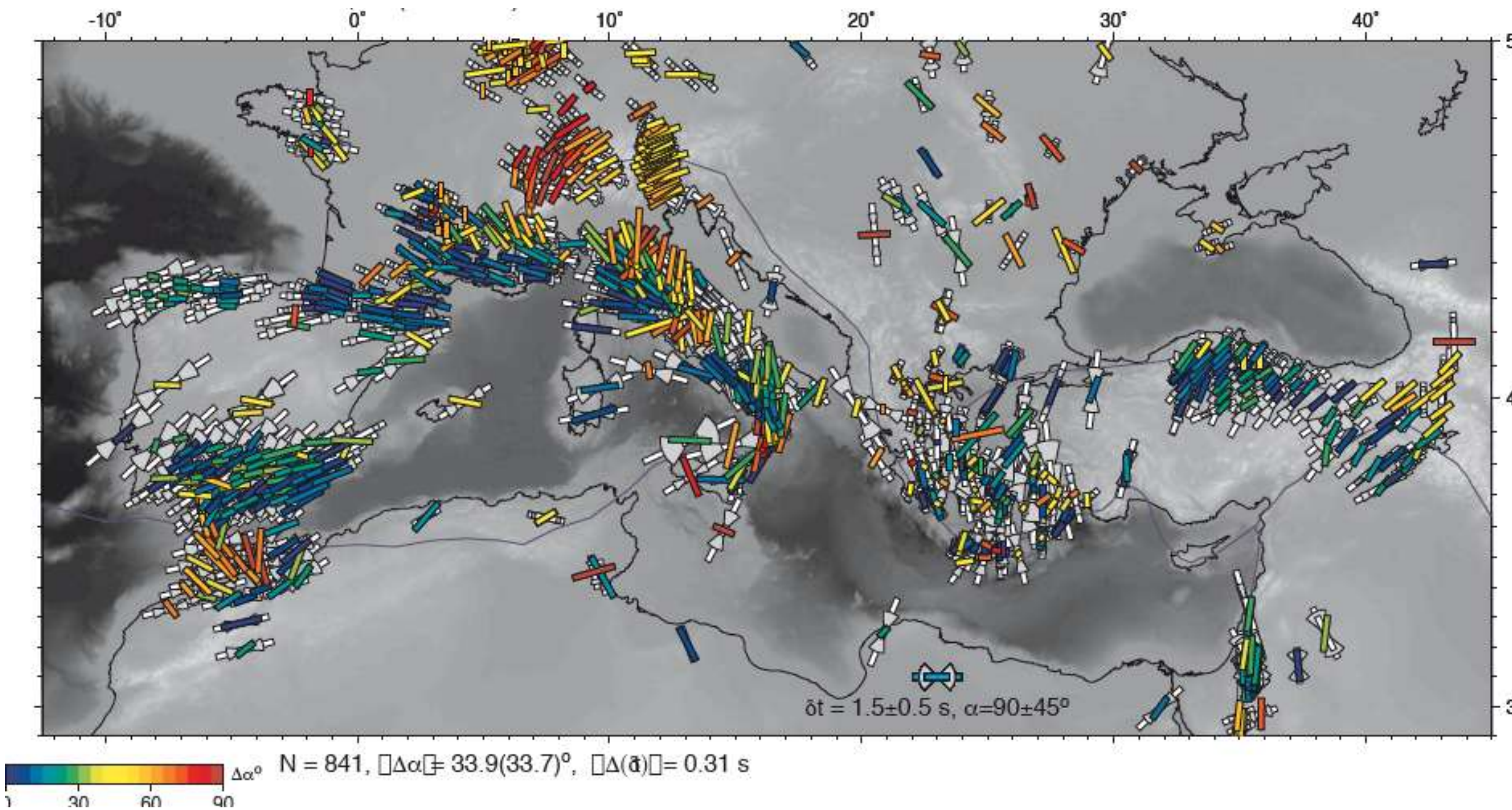
small scale upper mantle convection

Plate coupling



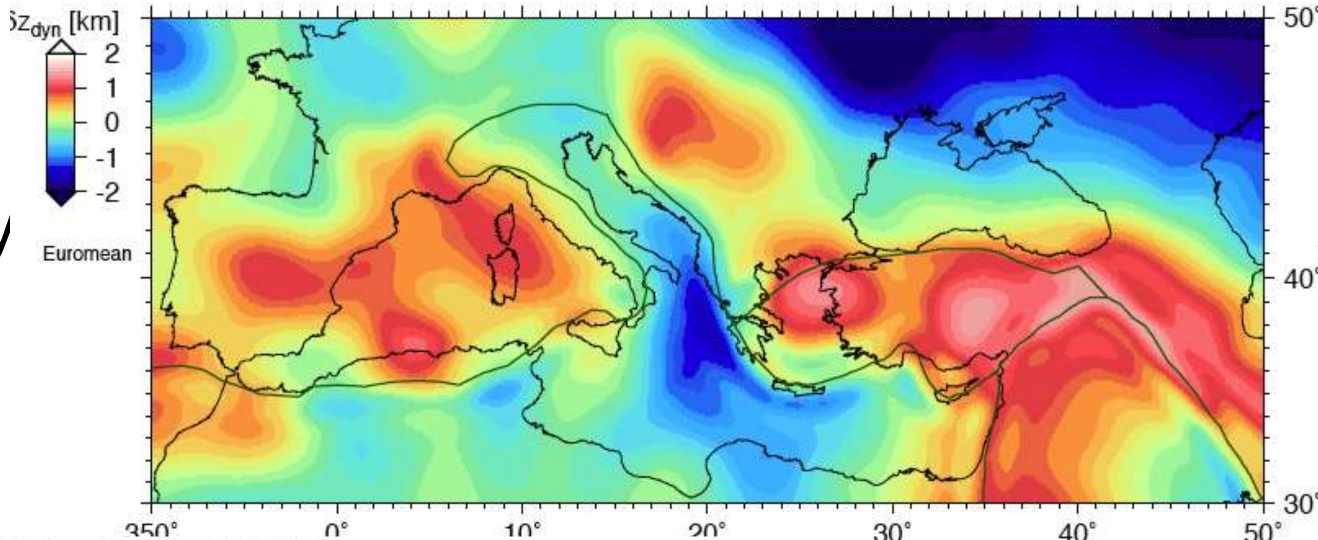
Alpine collision drive Adria correctly!

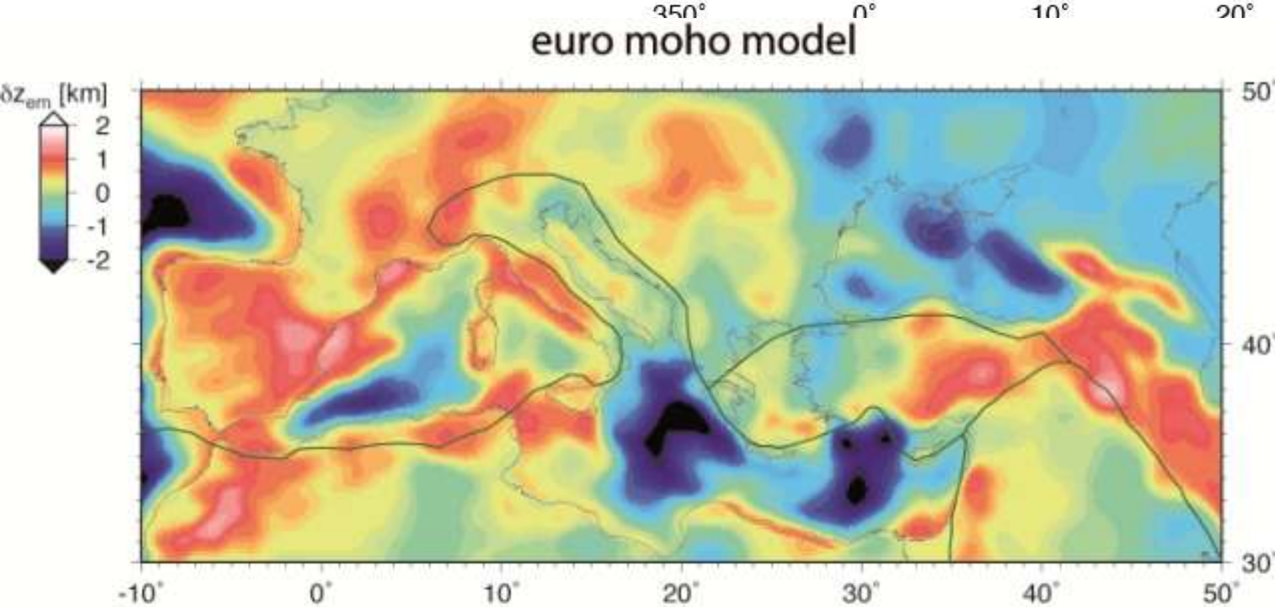
Prediction for anisotropy from tomography + subduzion zones



Euromean tomography (Boschi et al., '11)

Dynamic topography



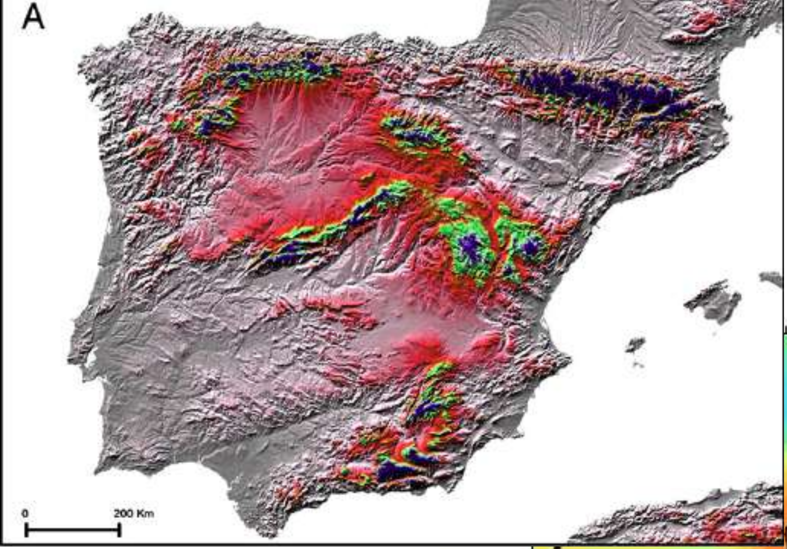


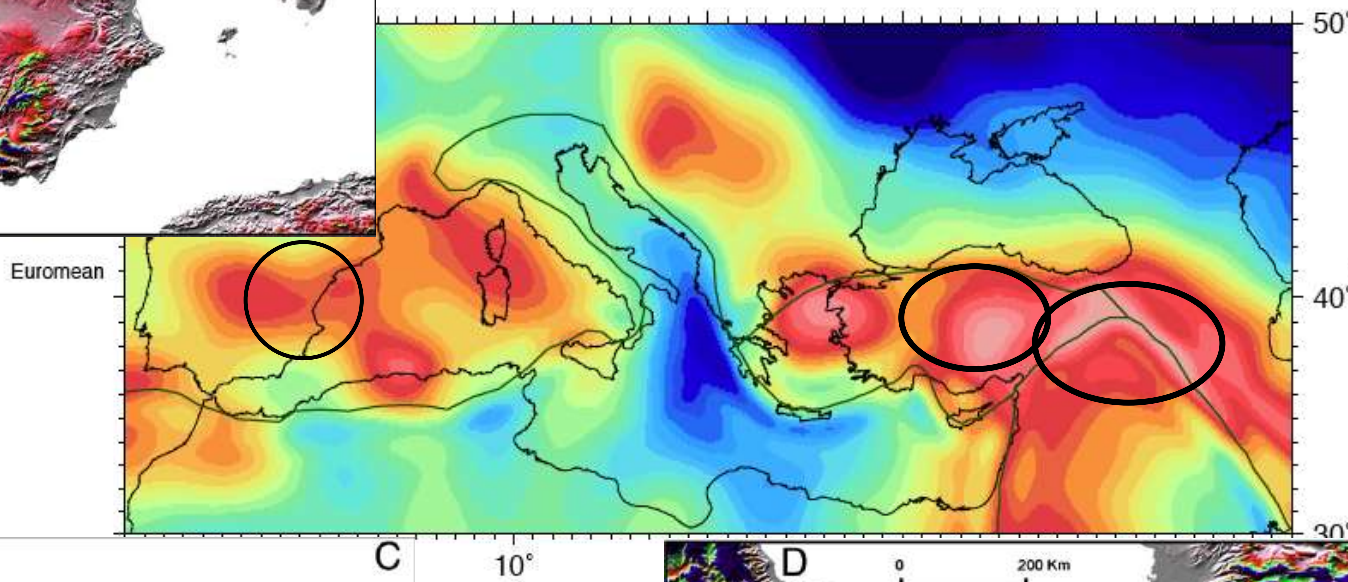
Residual topography

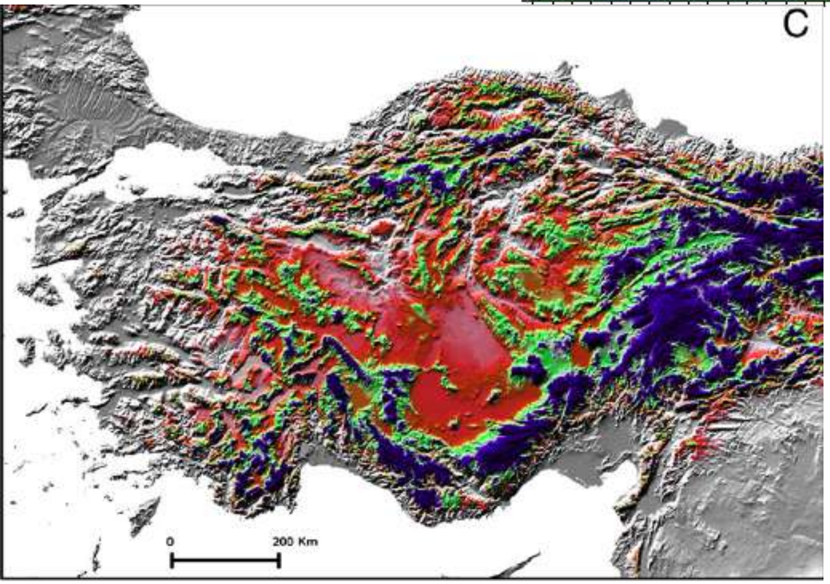
(topography filtered by crustal isostasy)

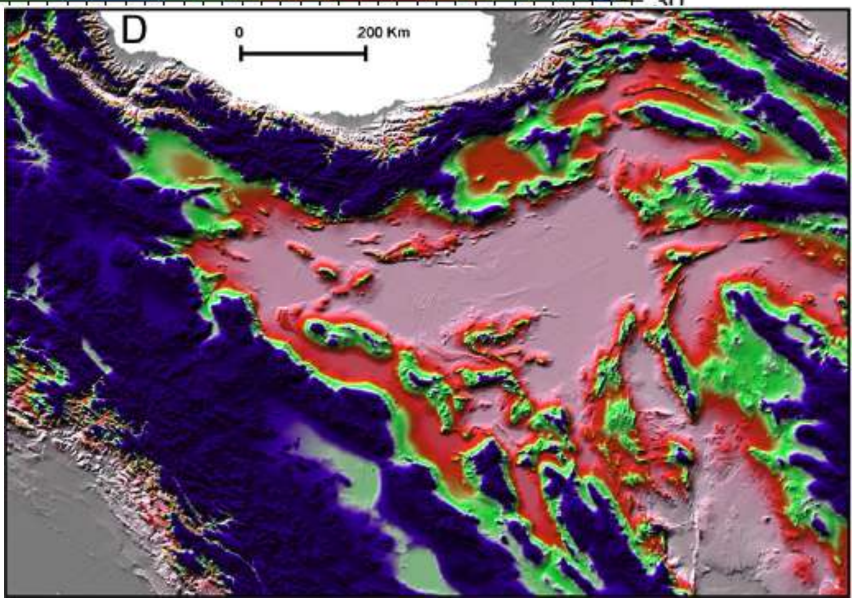
Boschi, Becker and Faccenna (2010)

Dynamic topography signal on surface





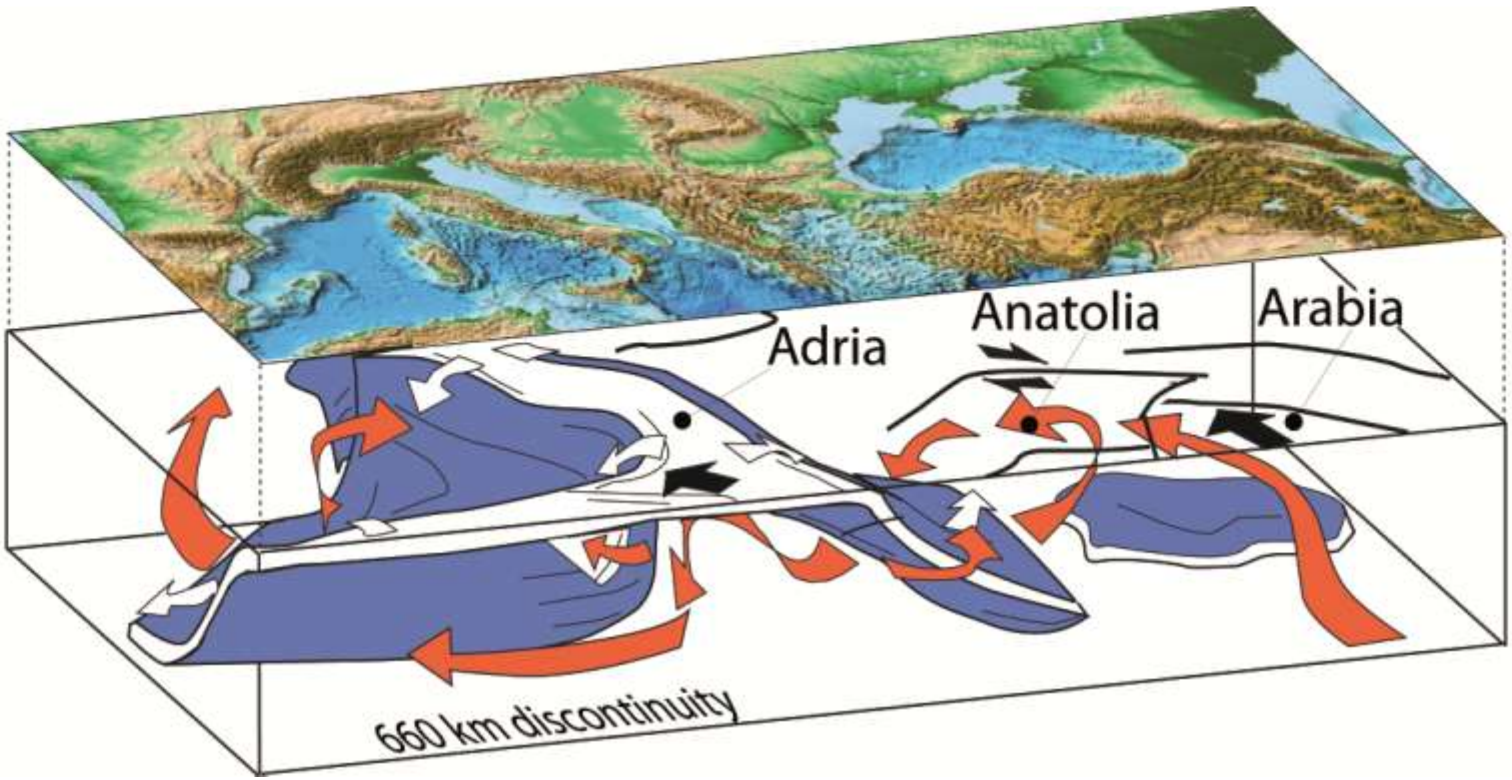




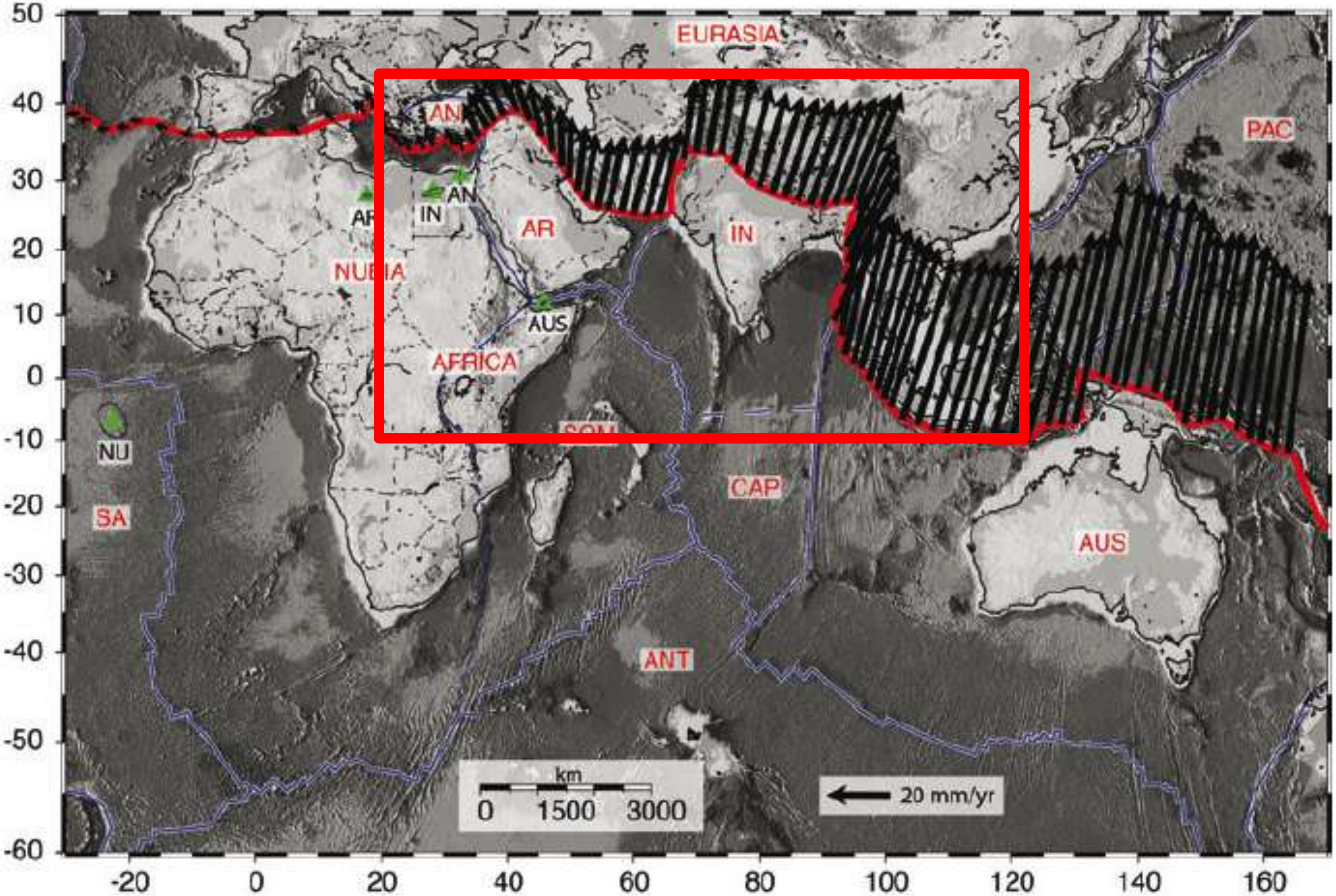
Summary

Small scale convection in the Mediterranean :

-rapid intermittent pulse tectonic,
back arc basin and the formation of narrow arcs;
-Sharp topographic feature
-microplate motions (i.e. Adria, Anatolia)

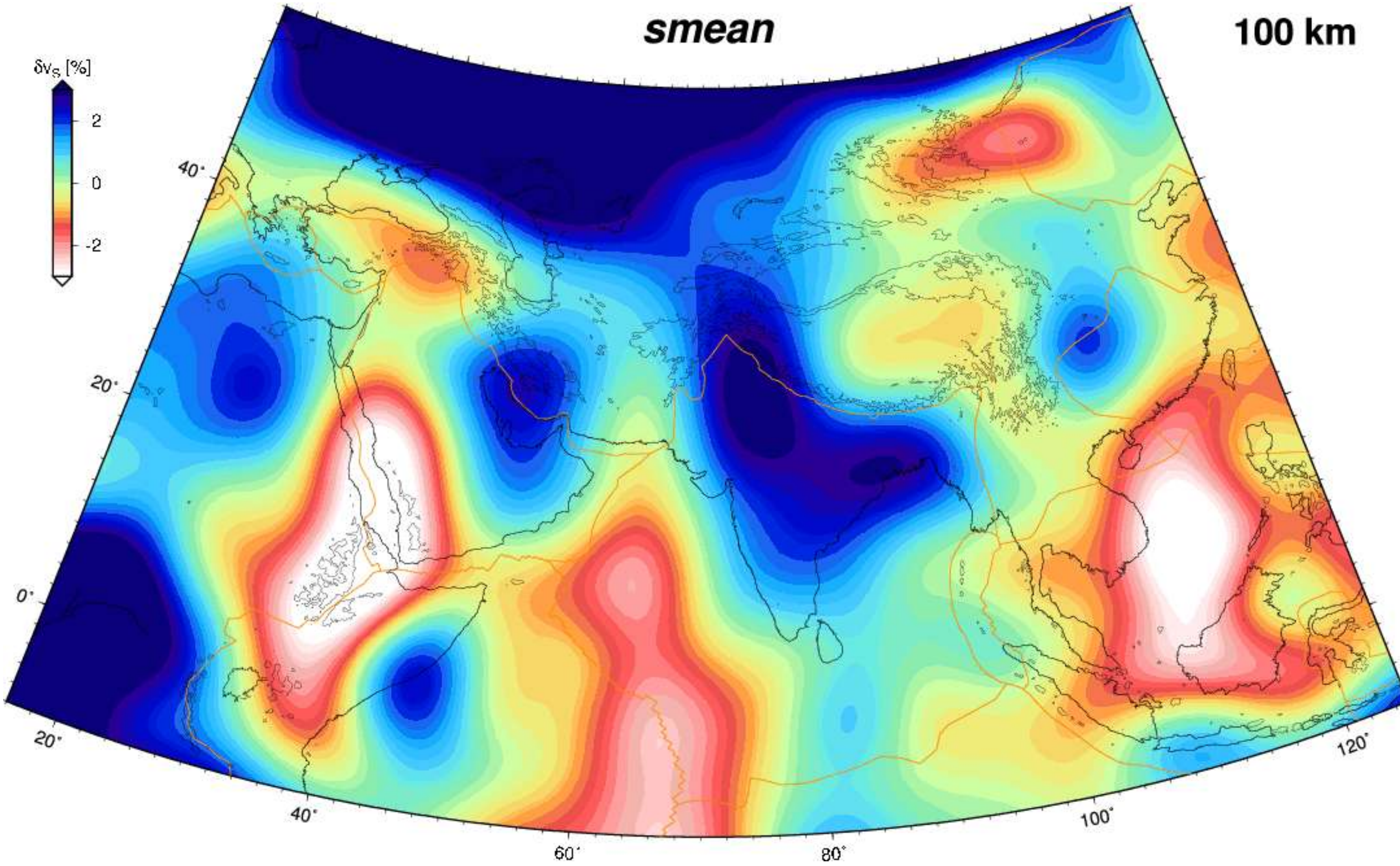


Zoom out over the entire Tethyan belt



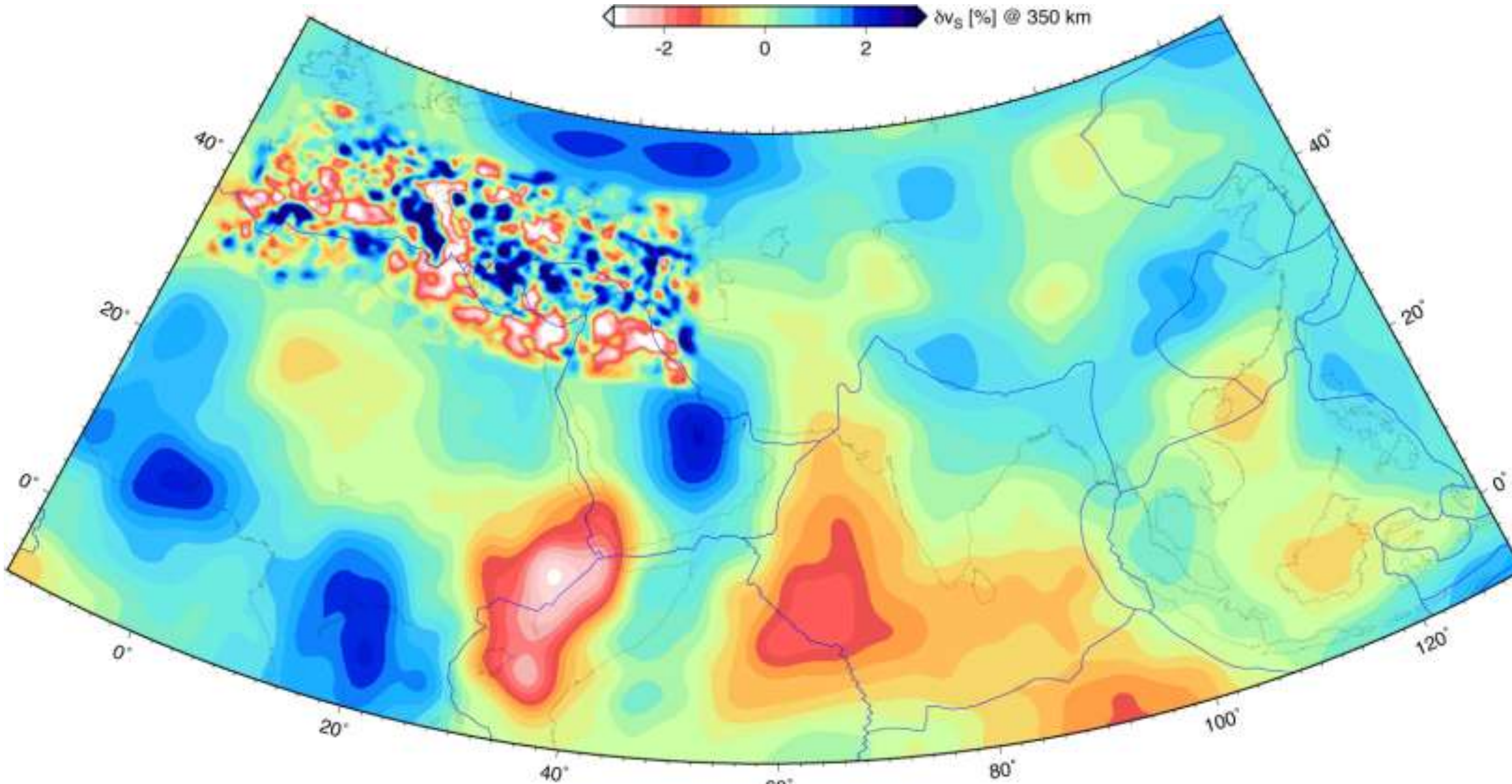
Reilinger and McKlusky 2011

Reference tomography

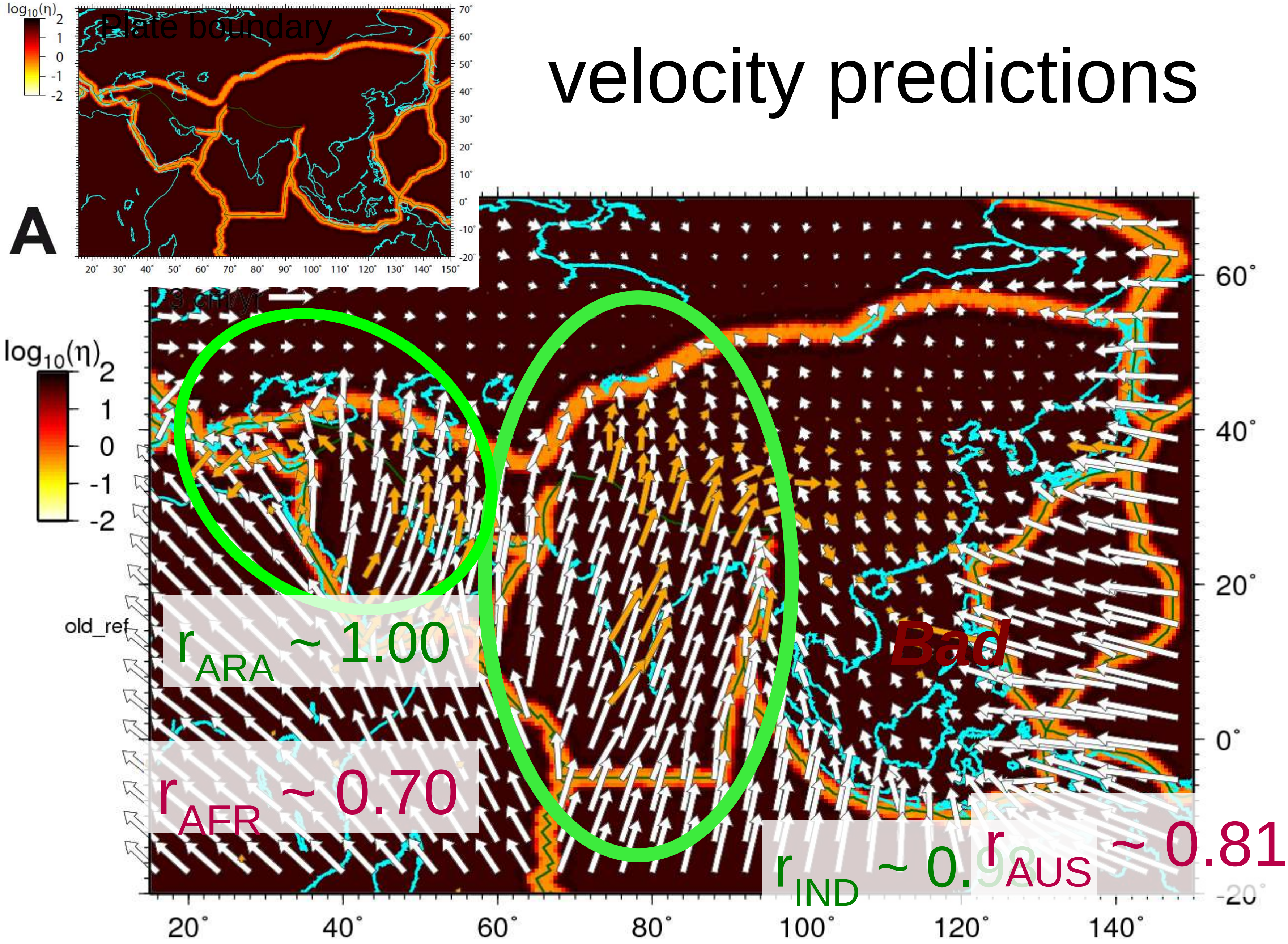


Becker and Boschi (2003)

The resolution jump



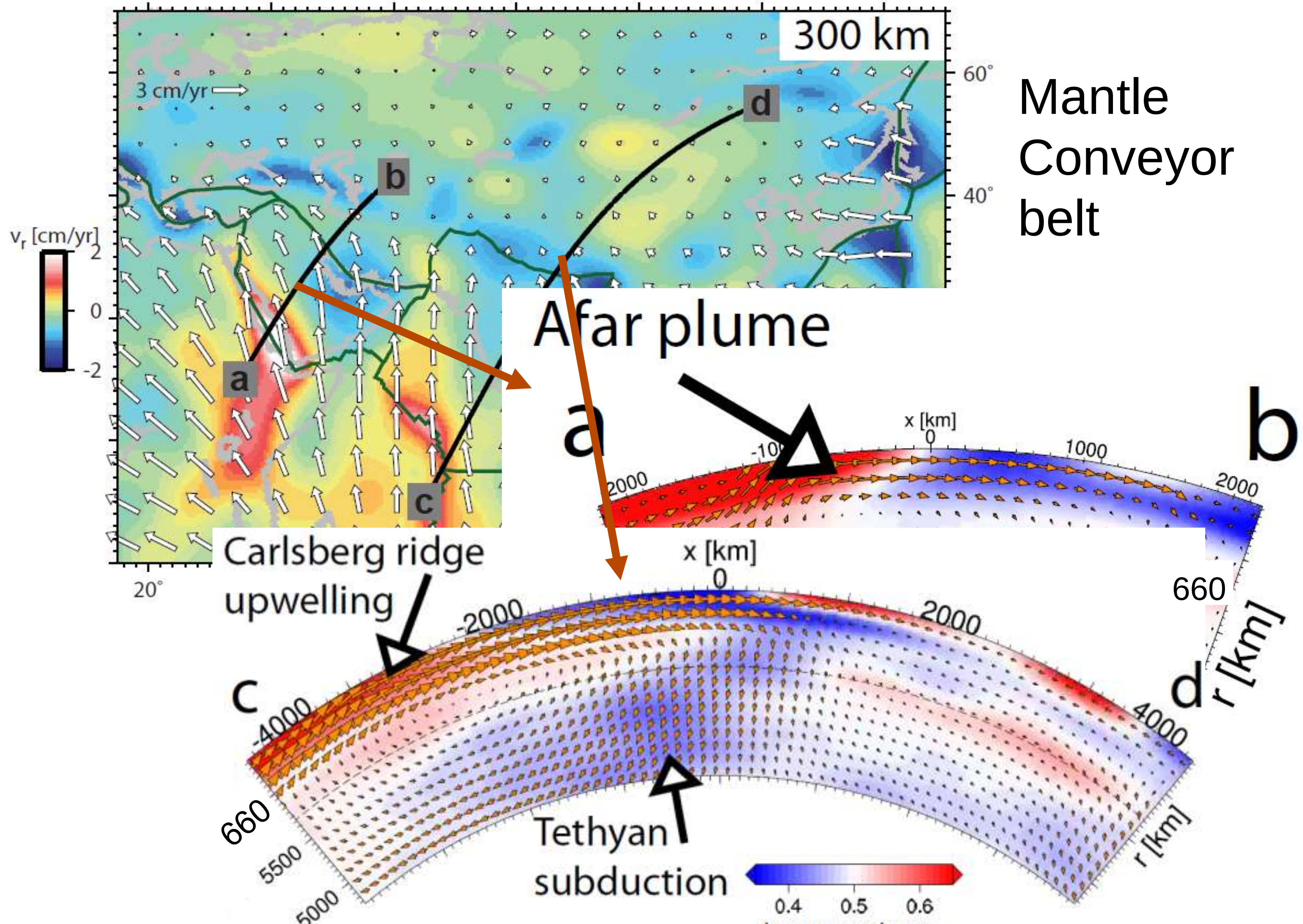
velocity predictions



Becker & Faccenna (2011)

Best-fit Eurasia fixed reference frame

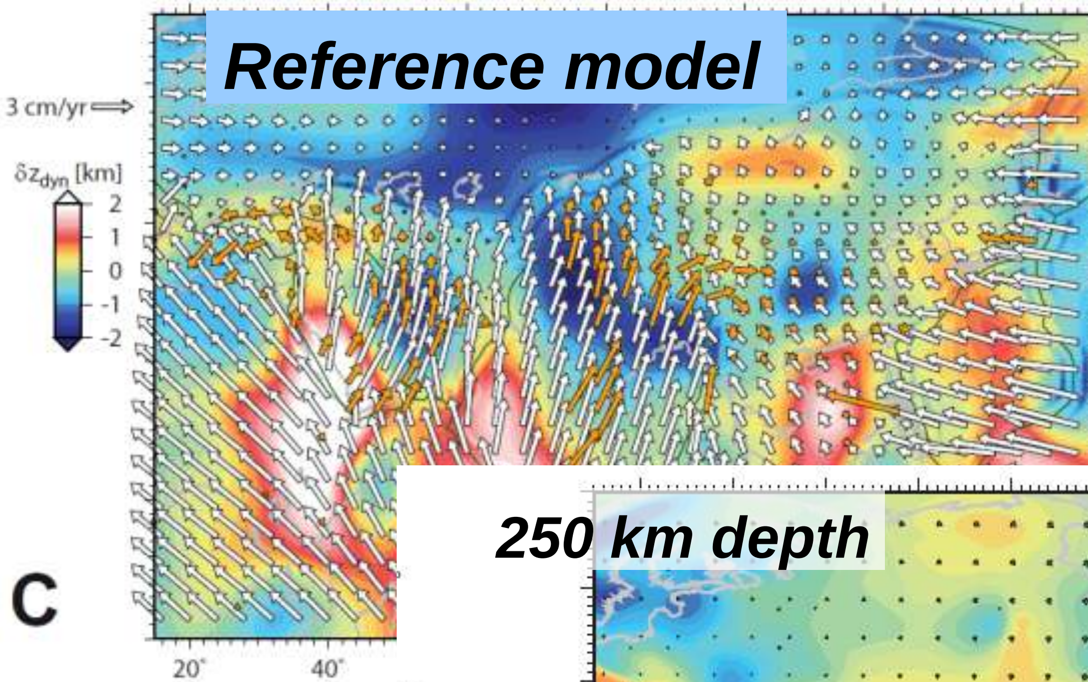
Mantle Conveyor belt

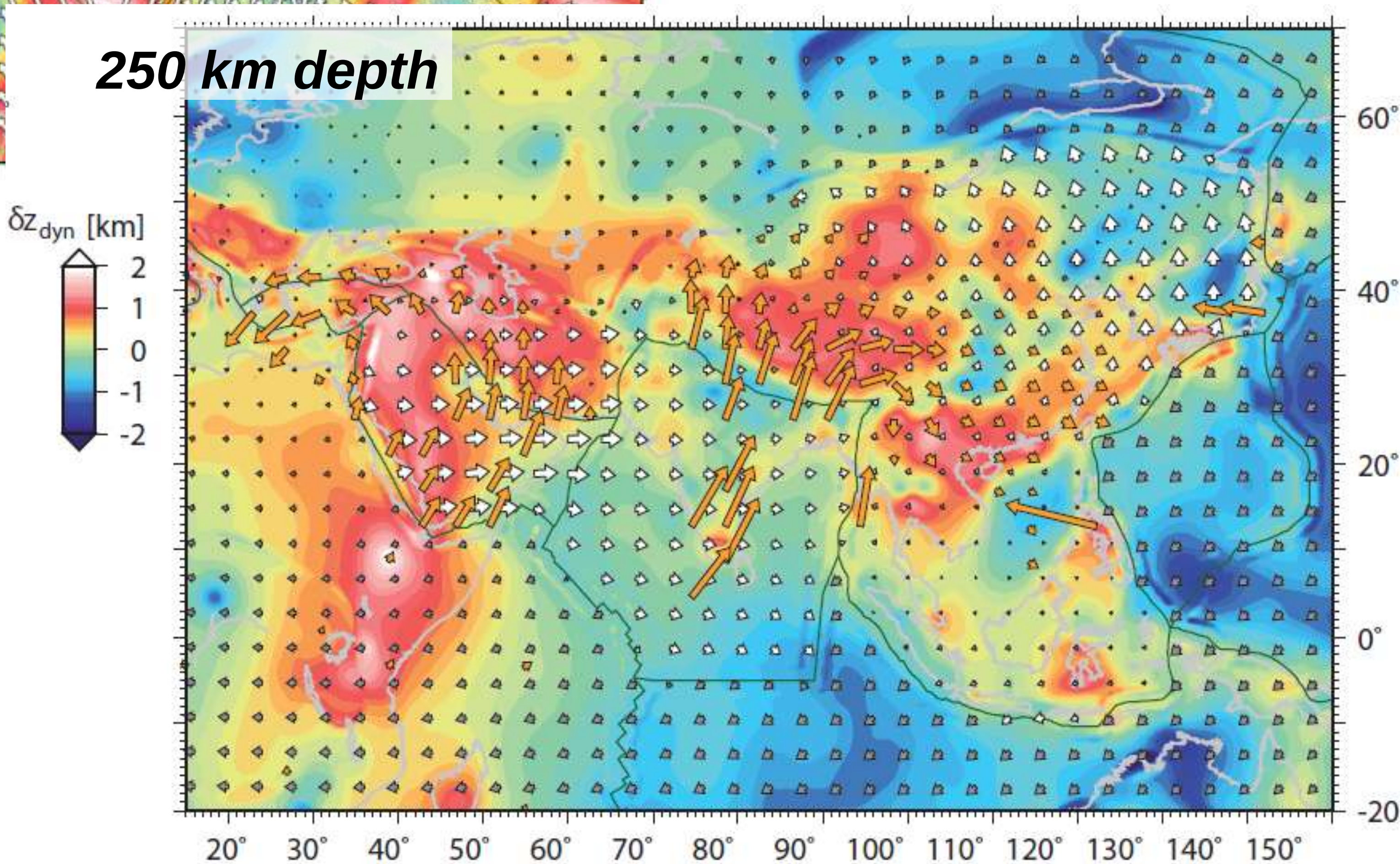


Becker & Faccenna (2011)

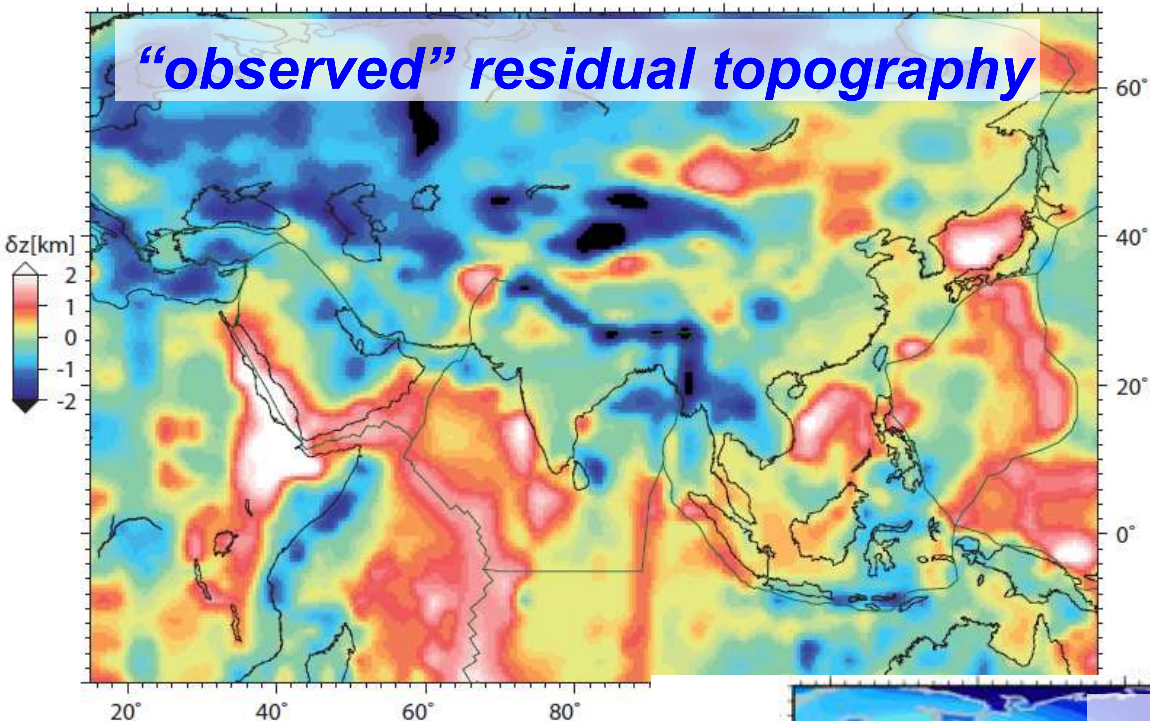
Tomographic models: SMEAN

Li et al. (2008)

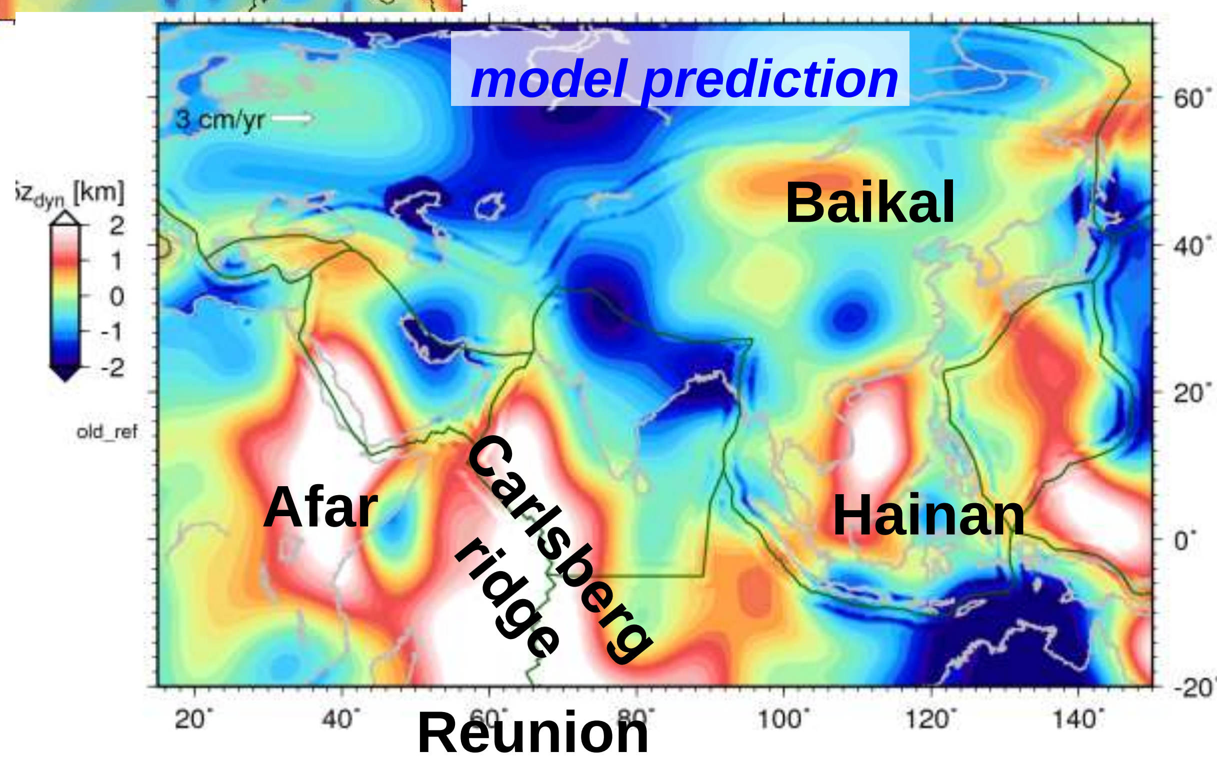




Role of Carlsberg Ridge anomaly



Assumption:
All non-crustal isostasy effects are due to active mantle flow

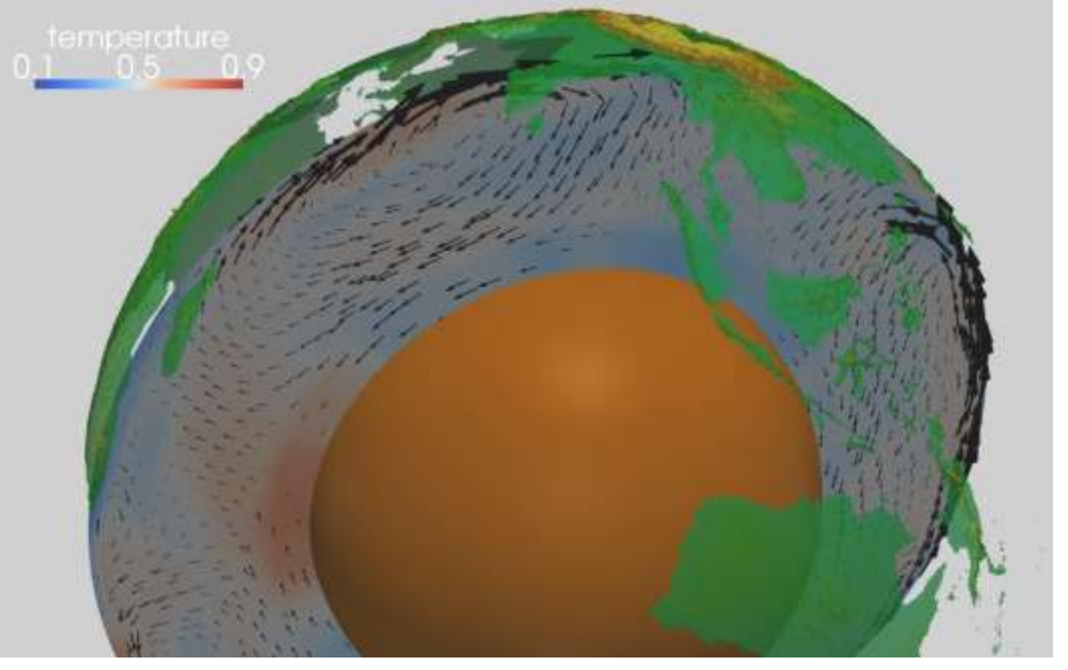


Africa plume context:

- Southern Africa uplift (Lithgow-Bertelloni & Silver, 1998; Gurnis et al. 2000)
- Arabia titling (Daradich et al., 2003)

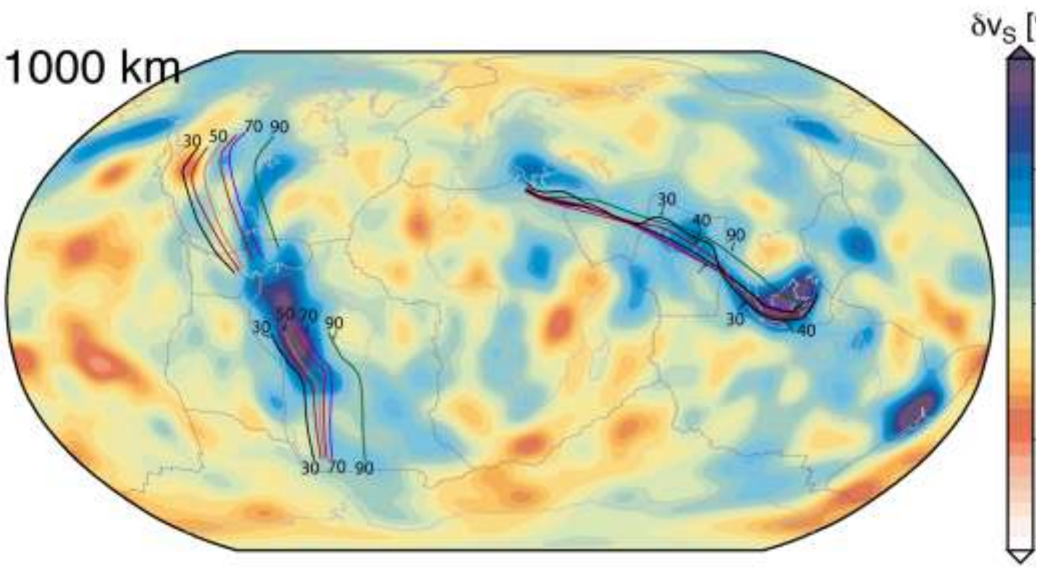
Summary

- Role of density distribution
  - Slab effect insufficient to drive India motion, but leads to slab suction as seen in geodesy
  - Active upwelling component associated with African plume/Carlsberg ridge main driver of India motion

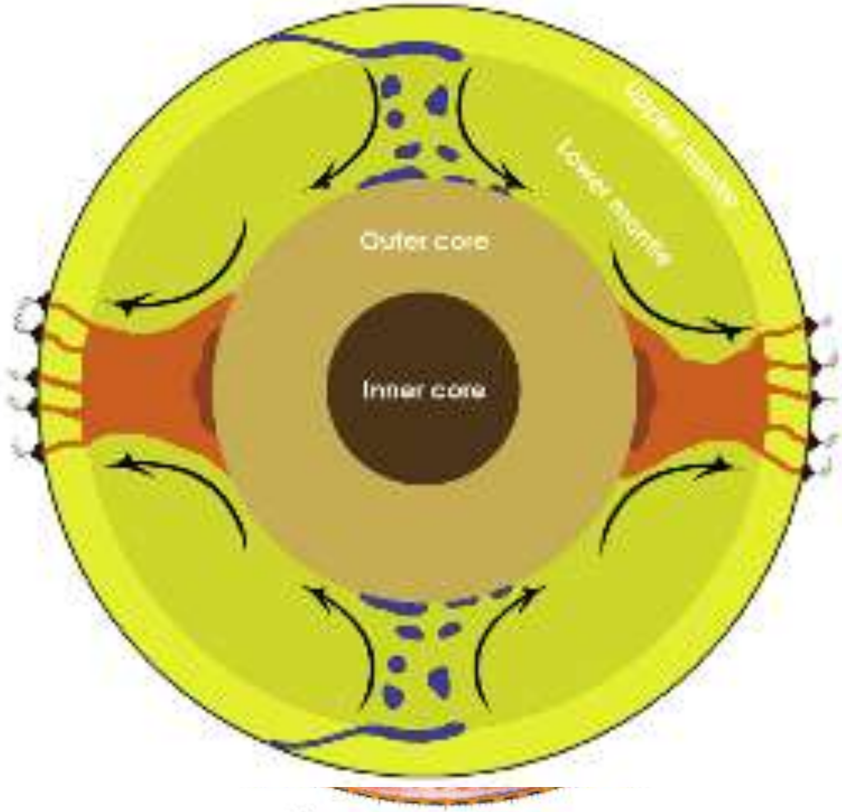


- Can not fit SE escape motion, perhaps due to decoupling and/or driving by GPE (not included) (e.g. Clark et al., 2005; Sol et al., 2007)

Zooming out:
The Tehyan and the Cordillera…



trenches from Muller et al. (2008) model

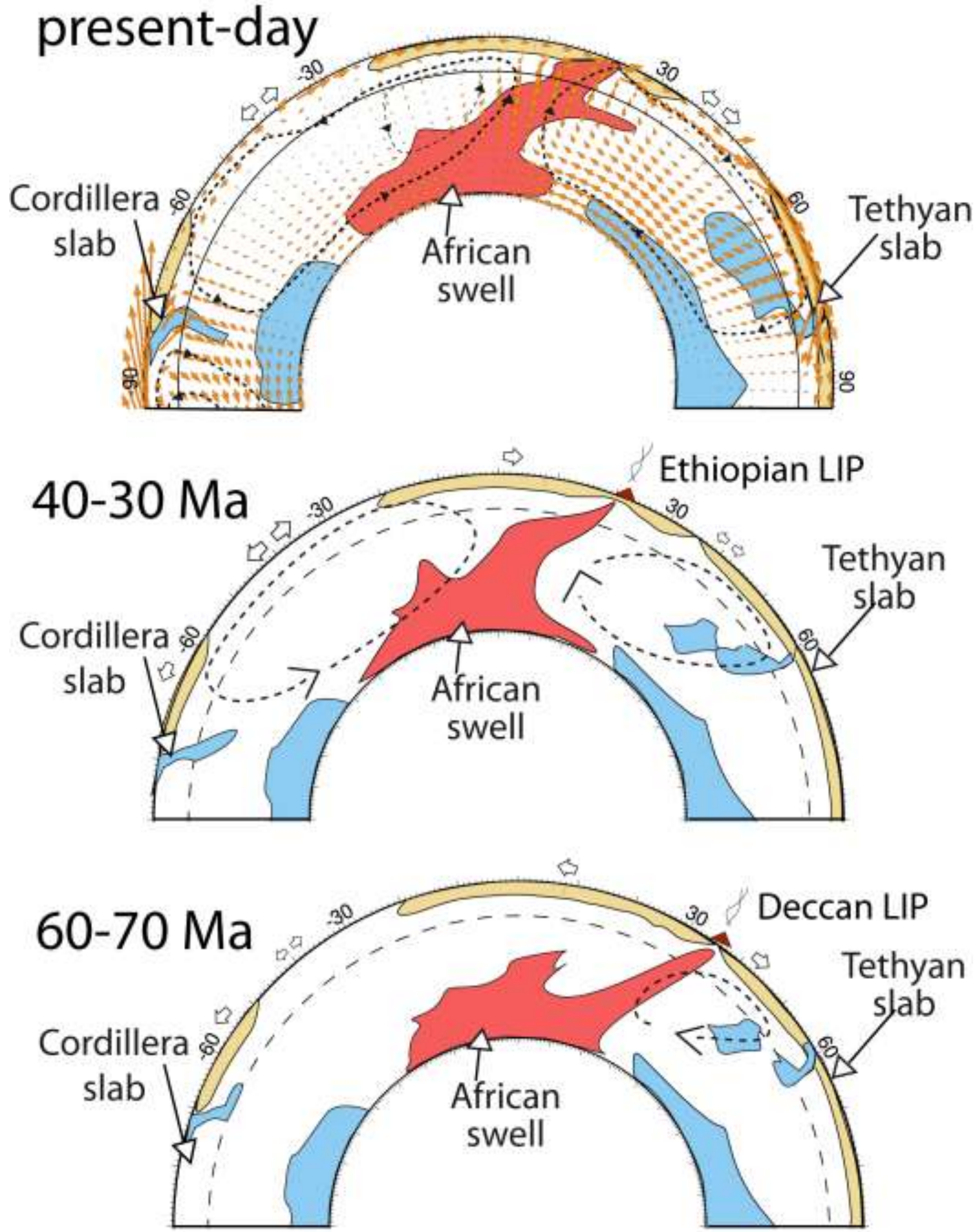


Dziewonski, Levik and Romanowicz (2010)

…and the Indo-Atlantic box

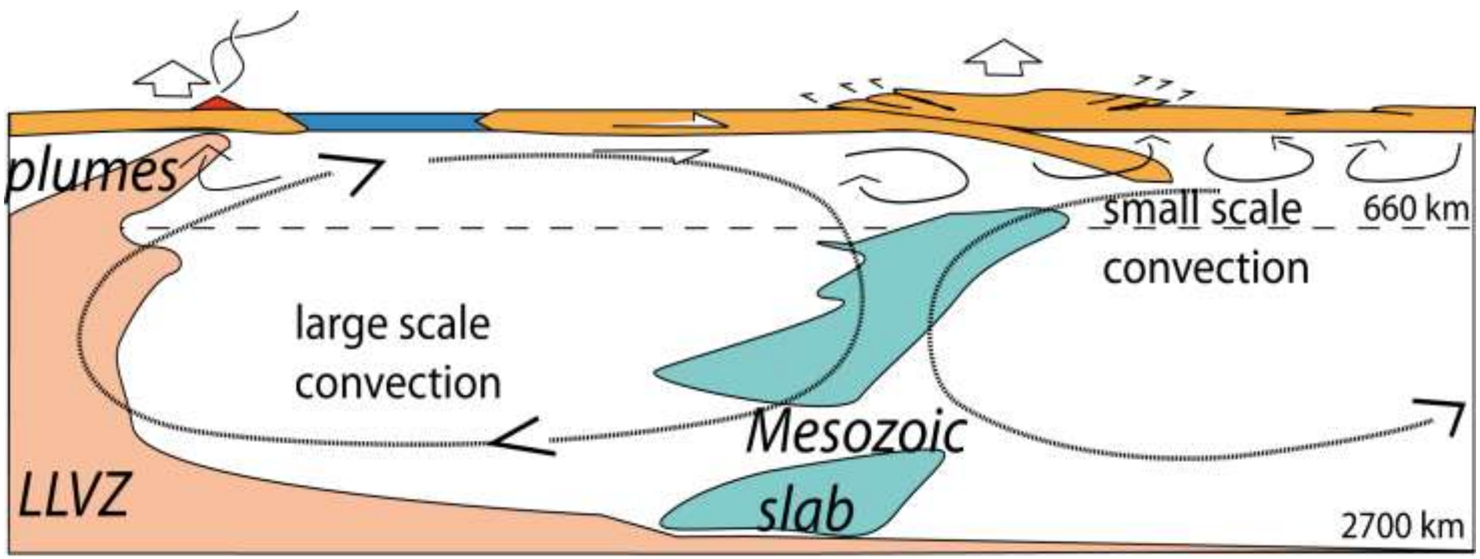
(Davaille et al., 2005)

Deep root of
The Andes
and
The Himalayas
And the
Indo-Atlantic
box

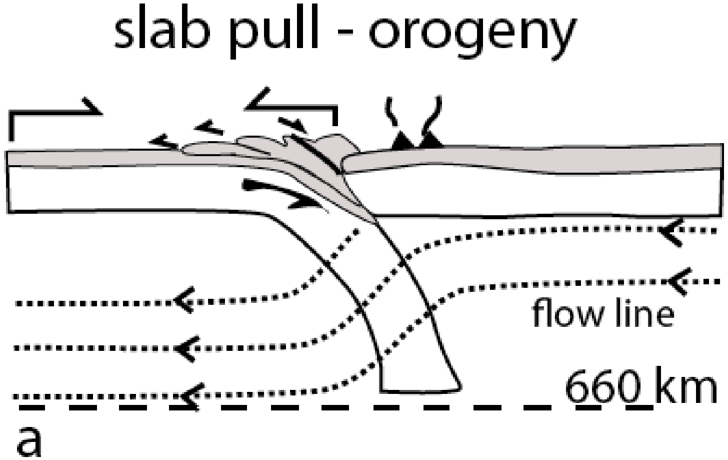


Concluding Remarks

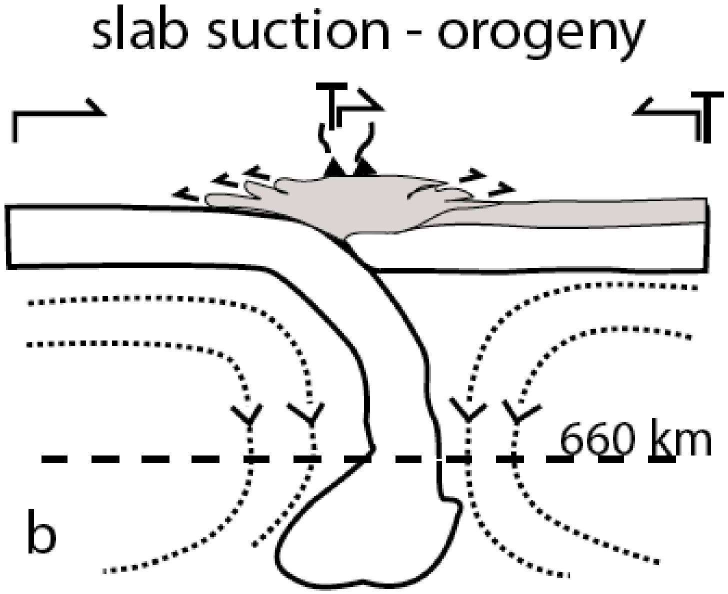
- High resolution seismic data reveals multiscale style of convection
- A whole mantle convection cell exists between Africa and India with a strong, plume-associated upwelling component sustains the Tethyan collision
- Similar setting can hold for the Africa-South America system and the Cordillera
- Mountain building episodes in geological record can be used to identify episodes of vigorous whole mantle convection



Mountain bulding and mantle convection



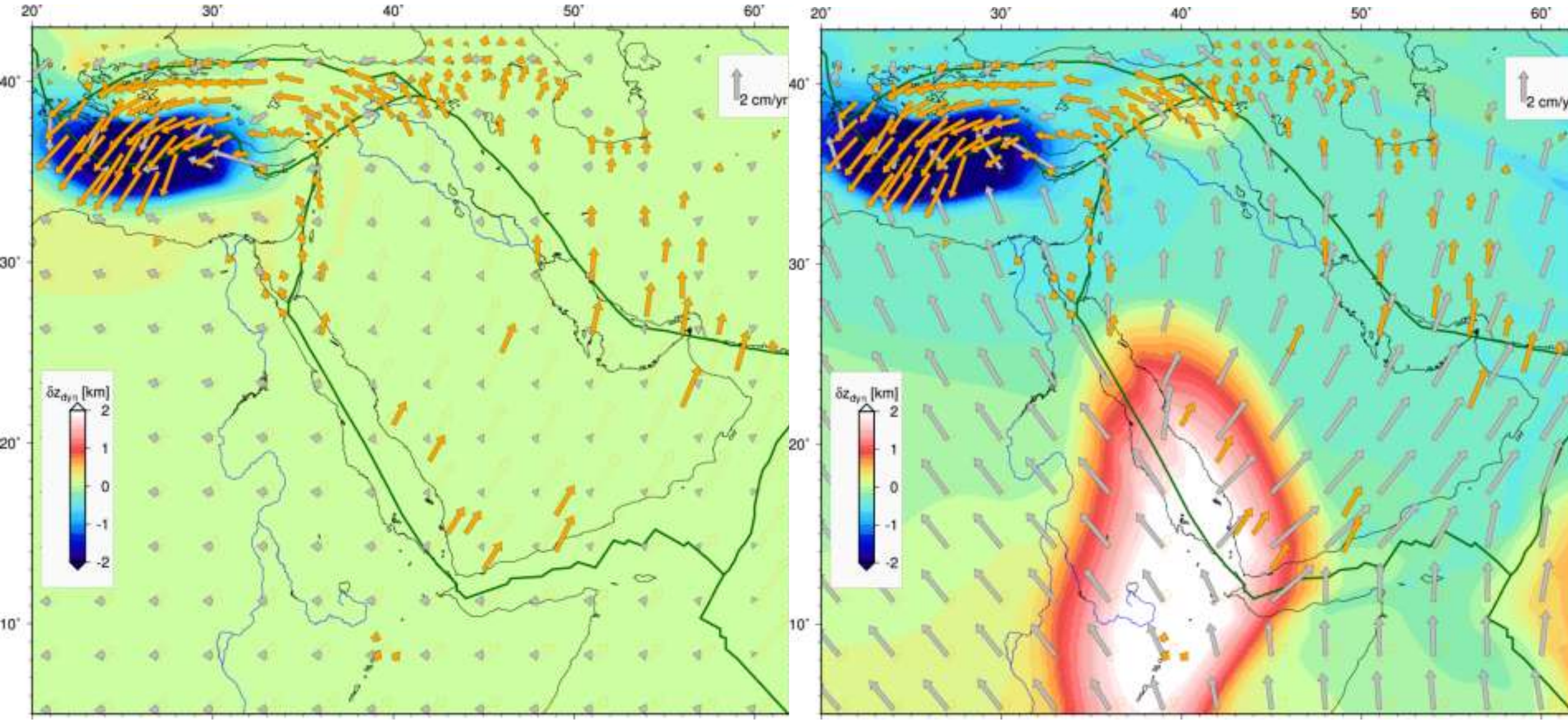
Slab pull orogeny (Mediterranean)
Small scale upper mantle convection
Trench rollback and small crustal
Thicknening



Slab suction orogeny (Himalaya-Tibet;
Cordillera).
Whole upper mantle convection
Trench fixed/advancing,
Crustal Thicknening

Inspired by Conrad and Lithgow Bertelloni (2002)

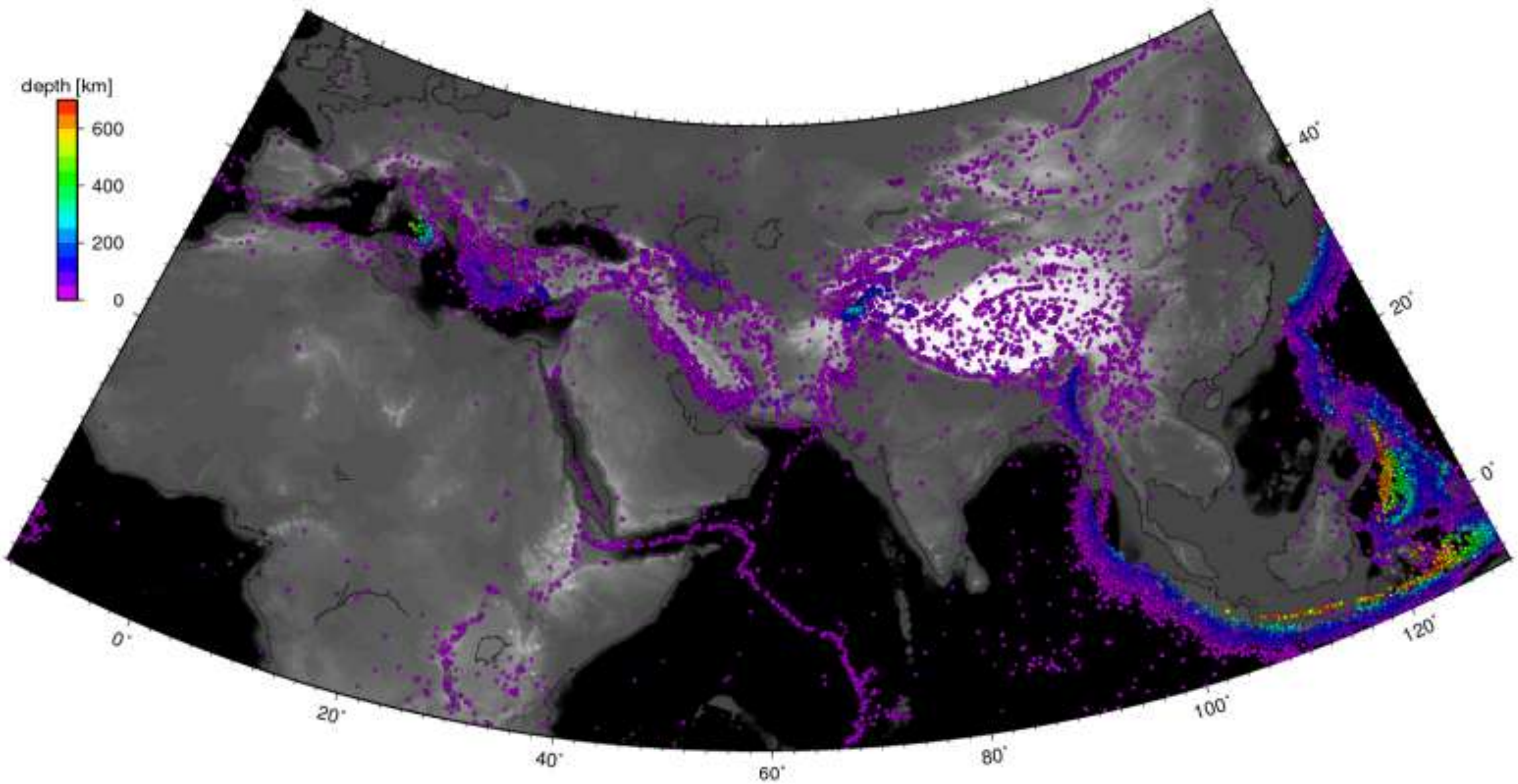
slab pull vs. slabpull + mantle drag



Results from global mantle flow model with high regional resolution

Faccenna et al. (2013)

Seismicity

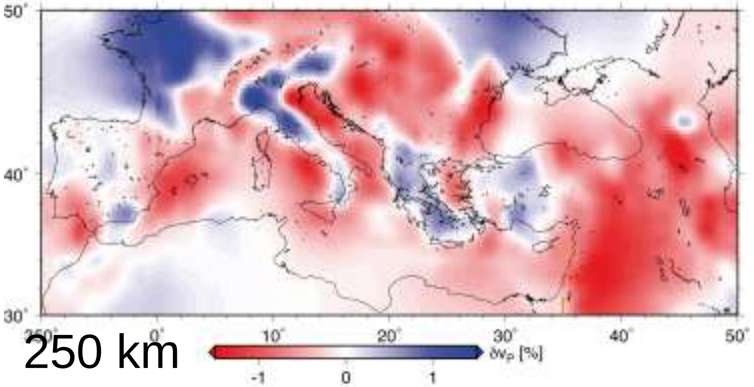


Circles: Hypocenters, color coded by depth (*Engdahl et al., 1998; 2010*)

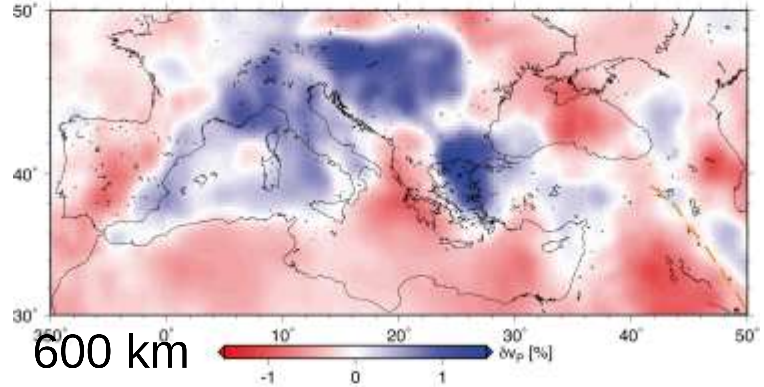
crustal seismicity over a diffuse plate boundary


Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Image Landsat
Image IBCAO
©2009 Google
Data di acquisizione delle immagini: 10 Apr 2013
28°11'20.08" N 60°16'11.12" E 1567 m elev
6675.24 km Alt

Boundary conditions

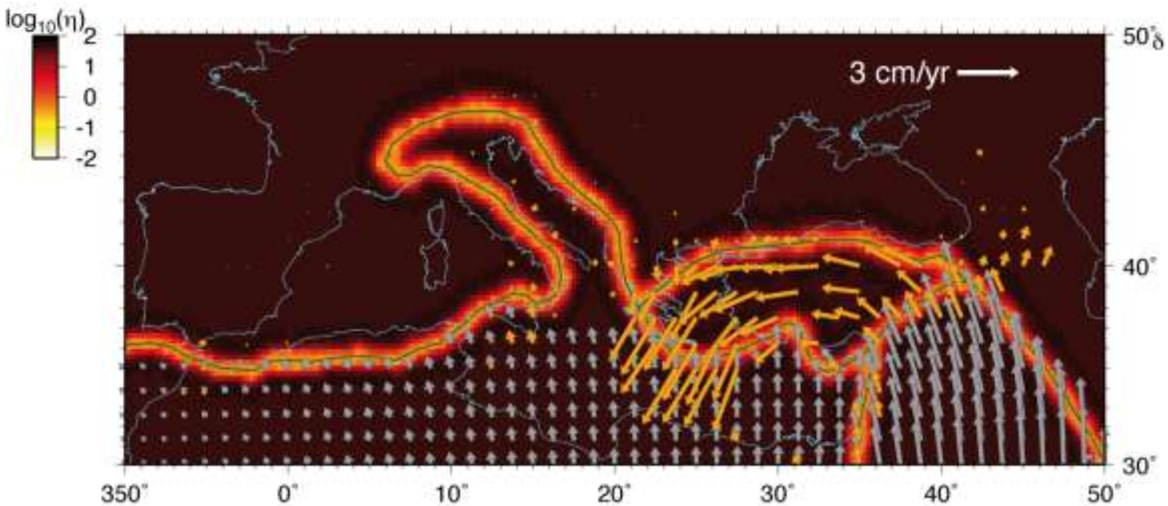


250 km



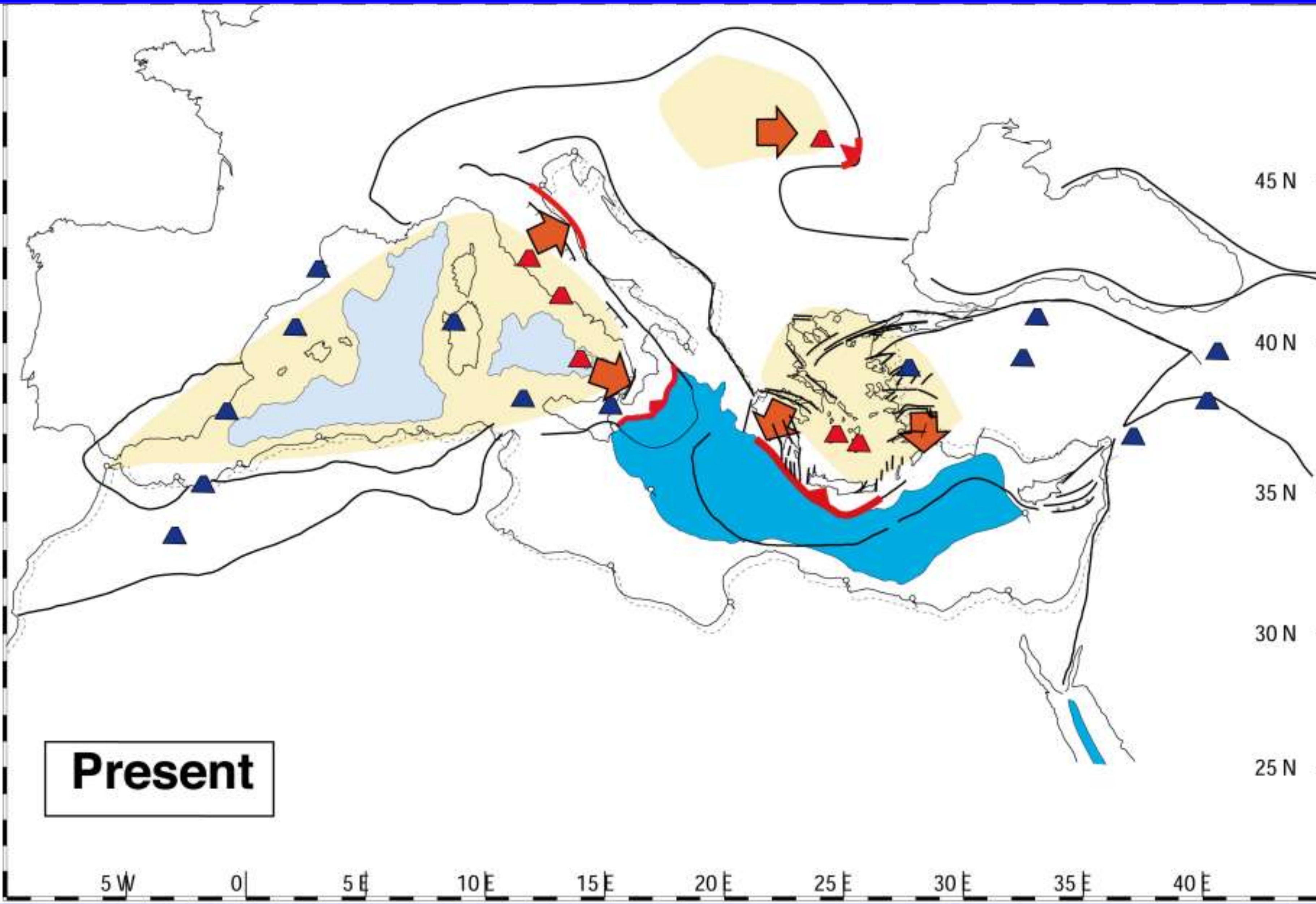
600 km

MIT 08 model (Li et al., 2008) assuming velocity dependent on temperature

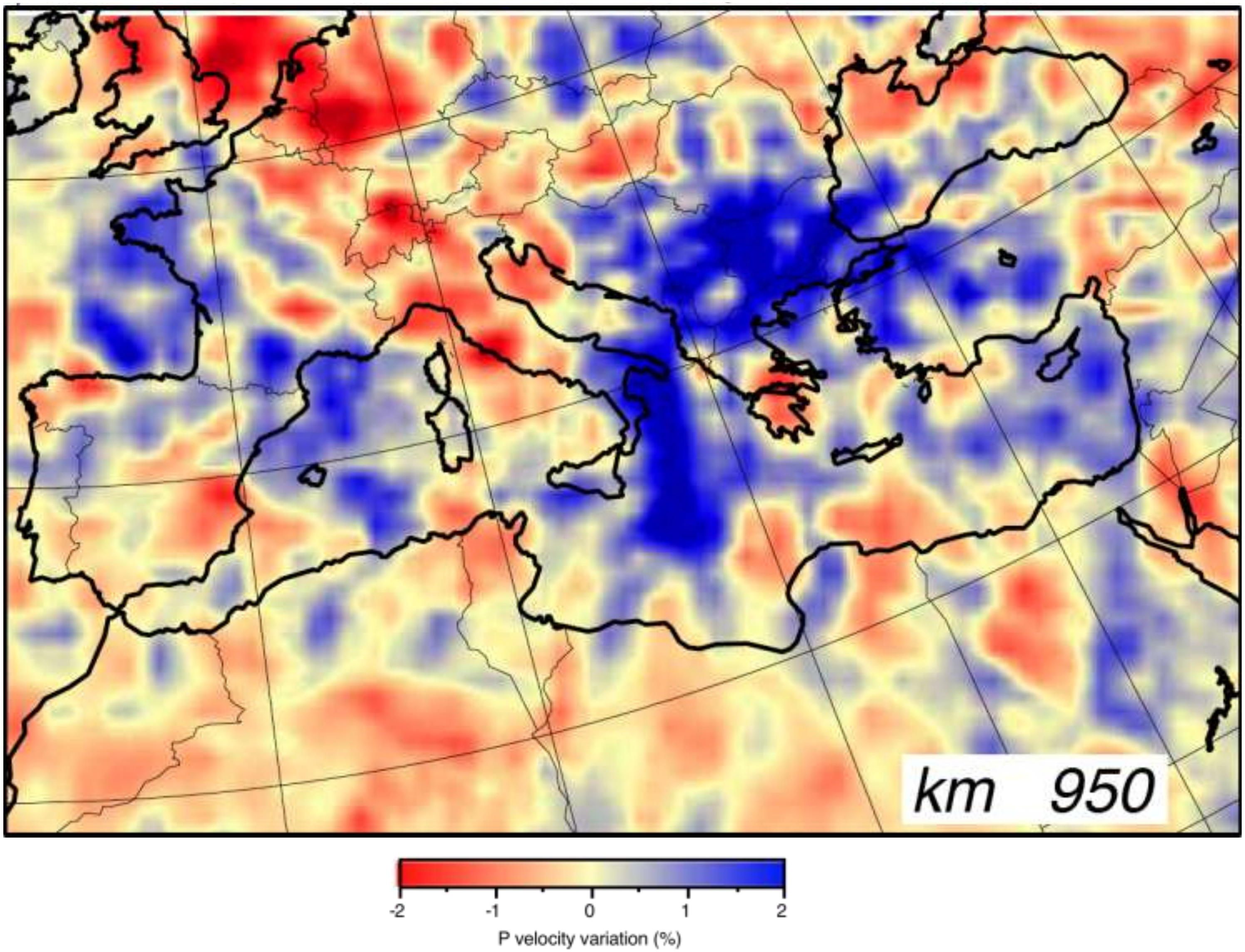


Nuvel 1A model - Geodetic model (Serpelloni et al., 2007)

the Mediterranean evolution

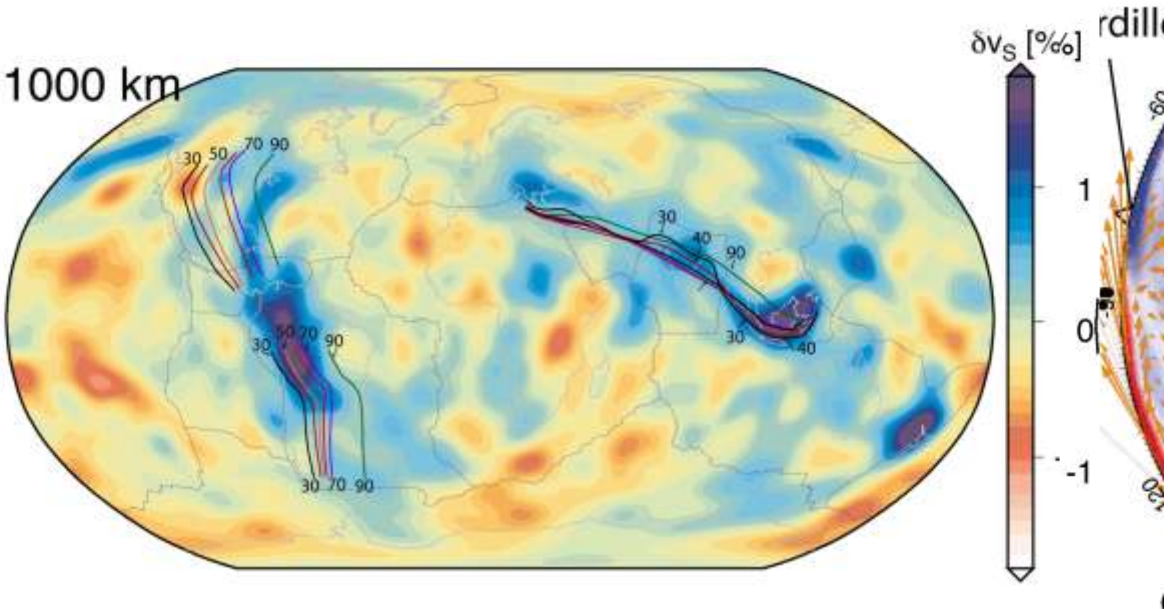


The Mediterranean Mantle structure



Piromallo and Morelli, 2003

Zooming out:
The Tehyan and the Cordillera…



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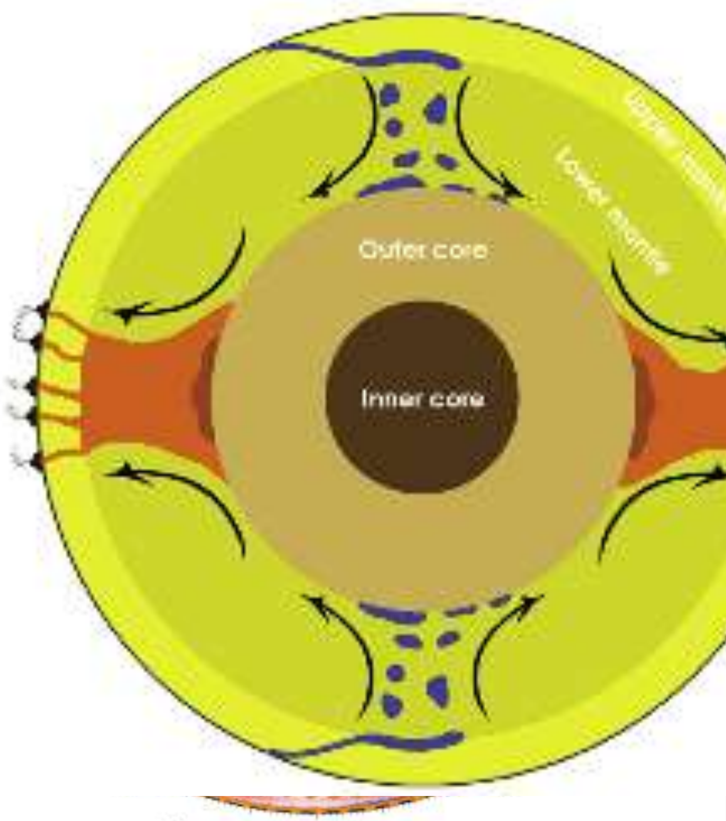

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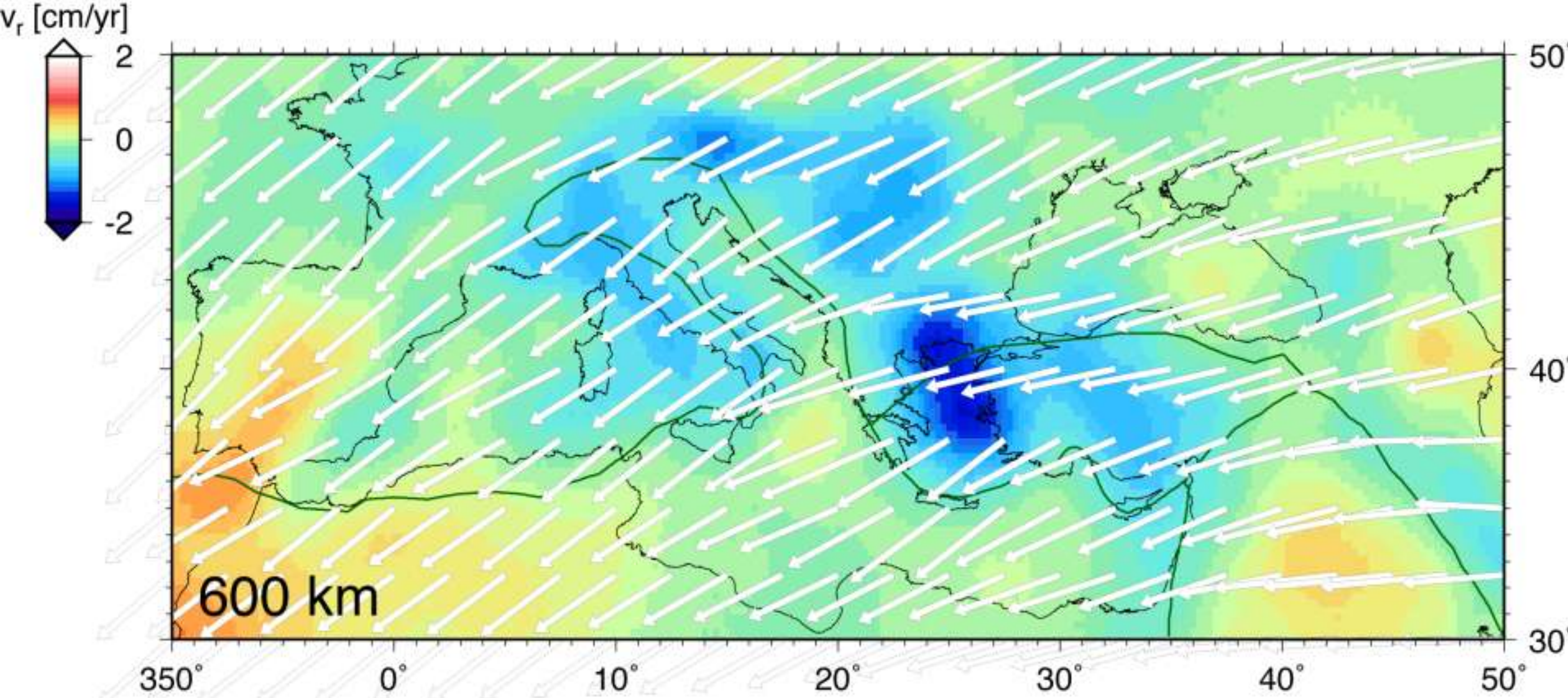
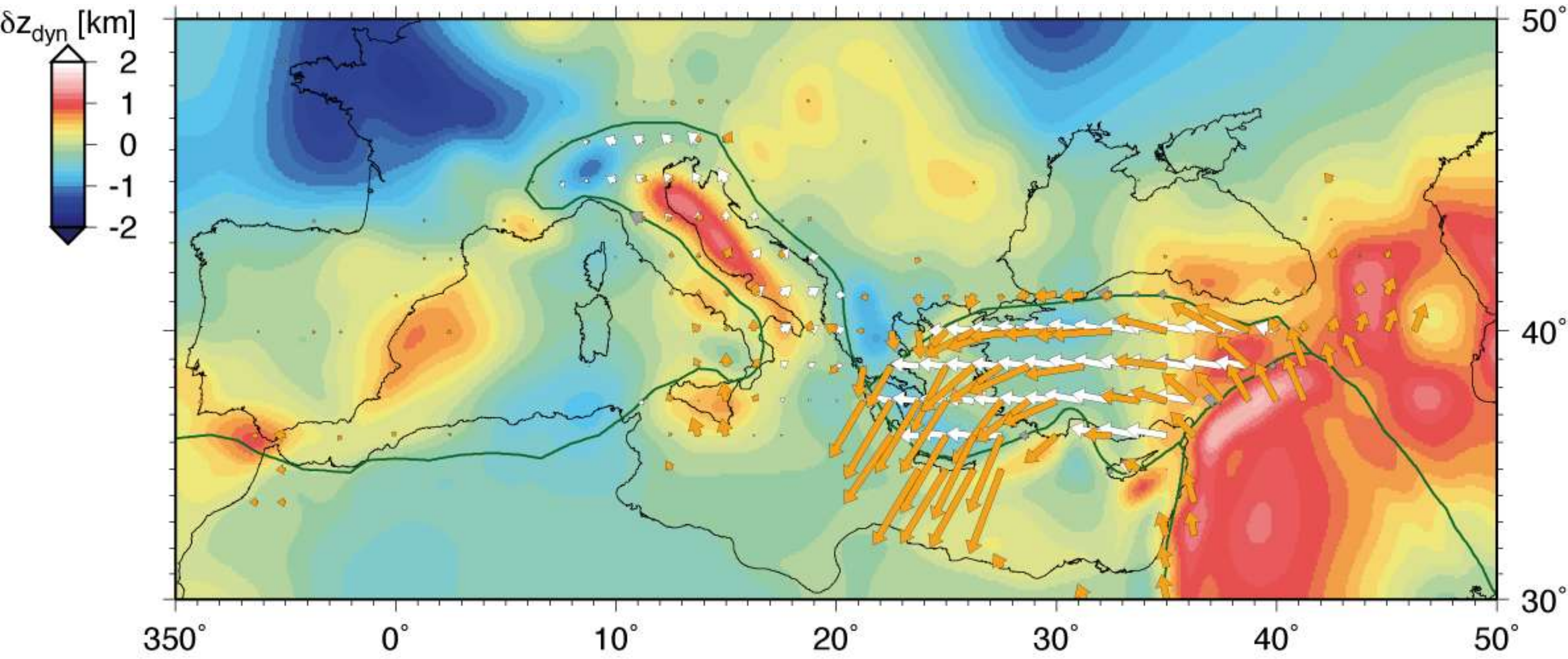


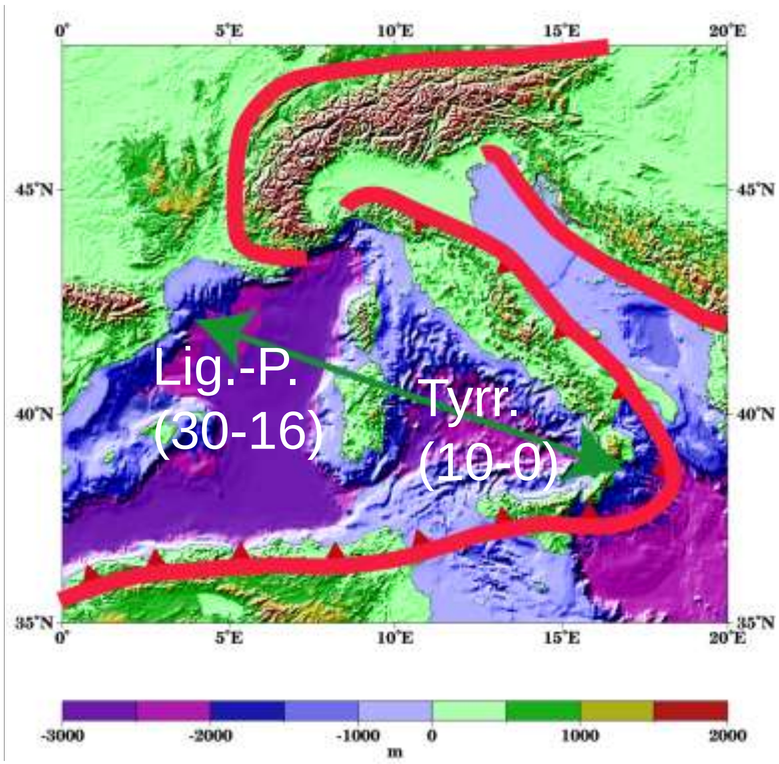
Small scale convection embedded within large-scale toroidal mantle wind from the SE

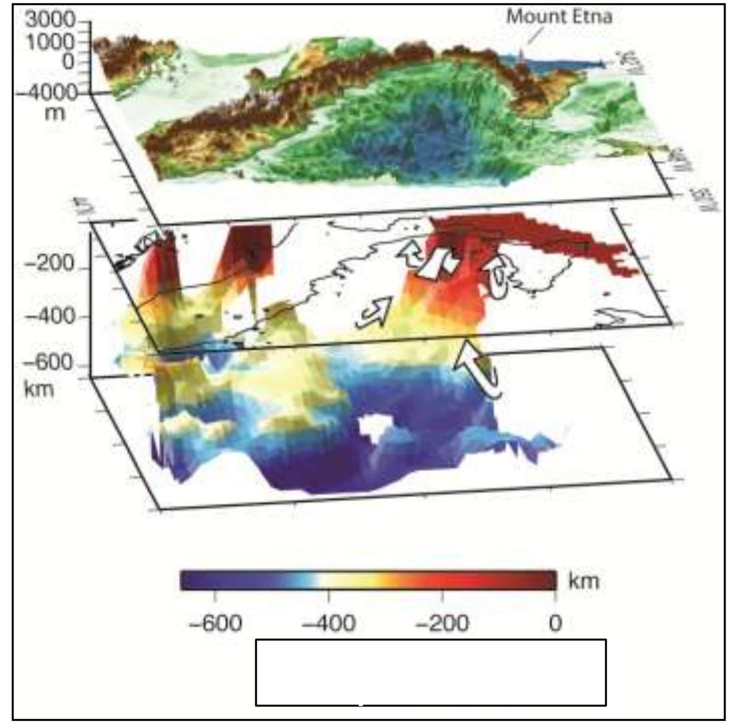
No plate motion



mantle drives Anatolia

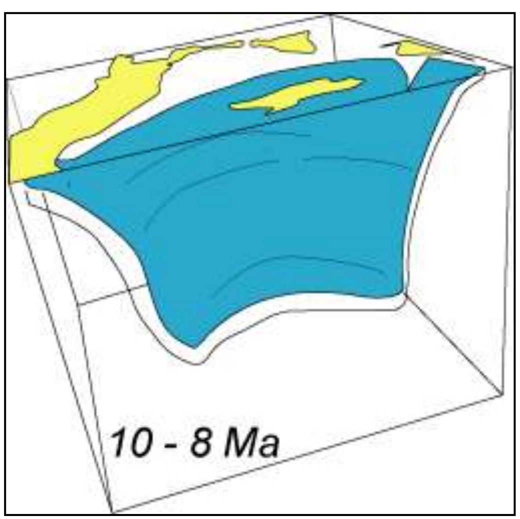
the Mediterranean backarc basin

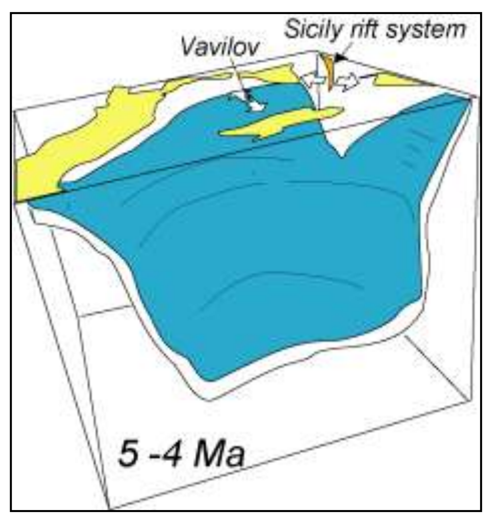


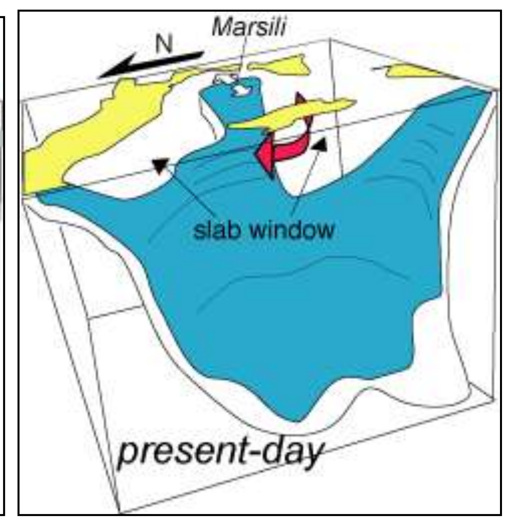


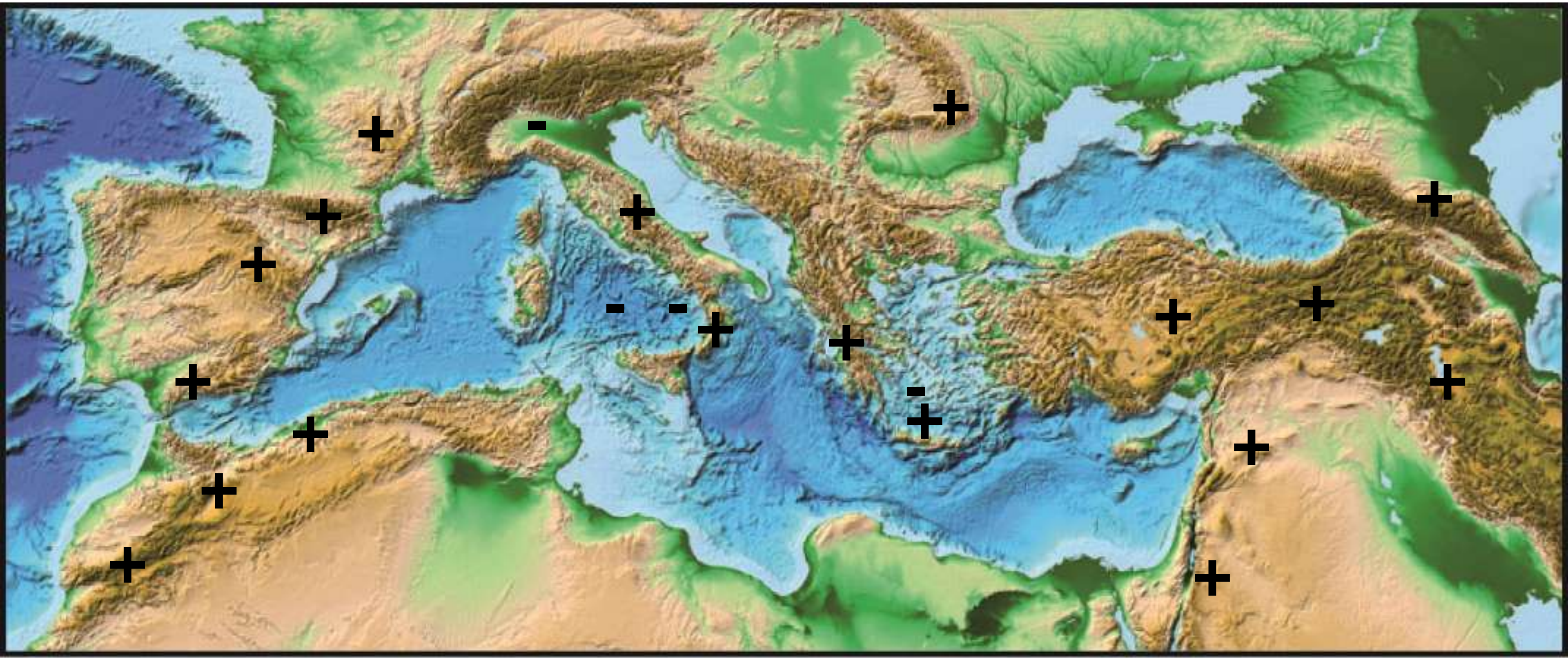
Piromallo and Morelli (2003) P wave

Scenario
Evolution
Central
Med.



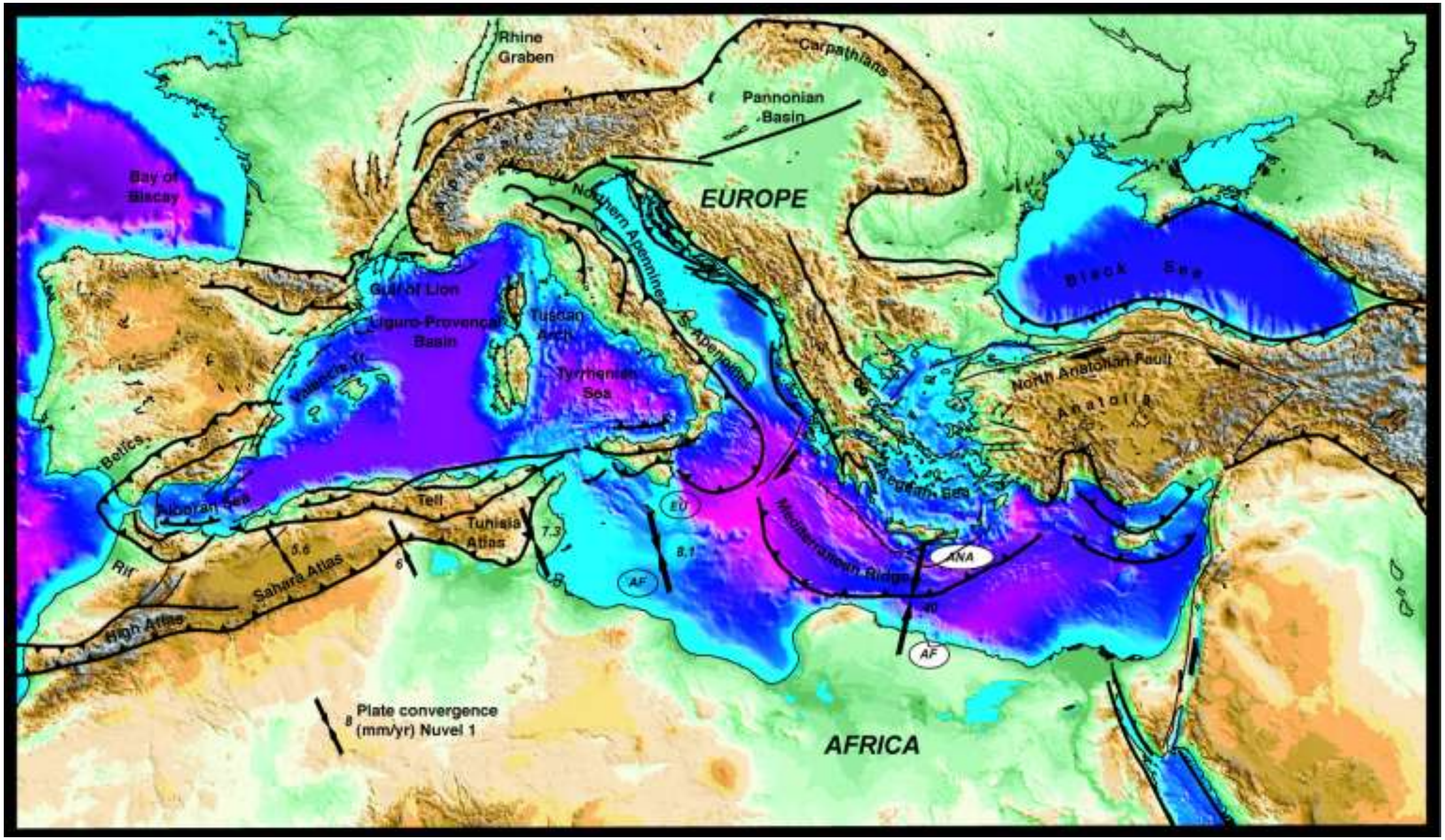




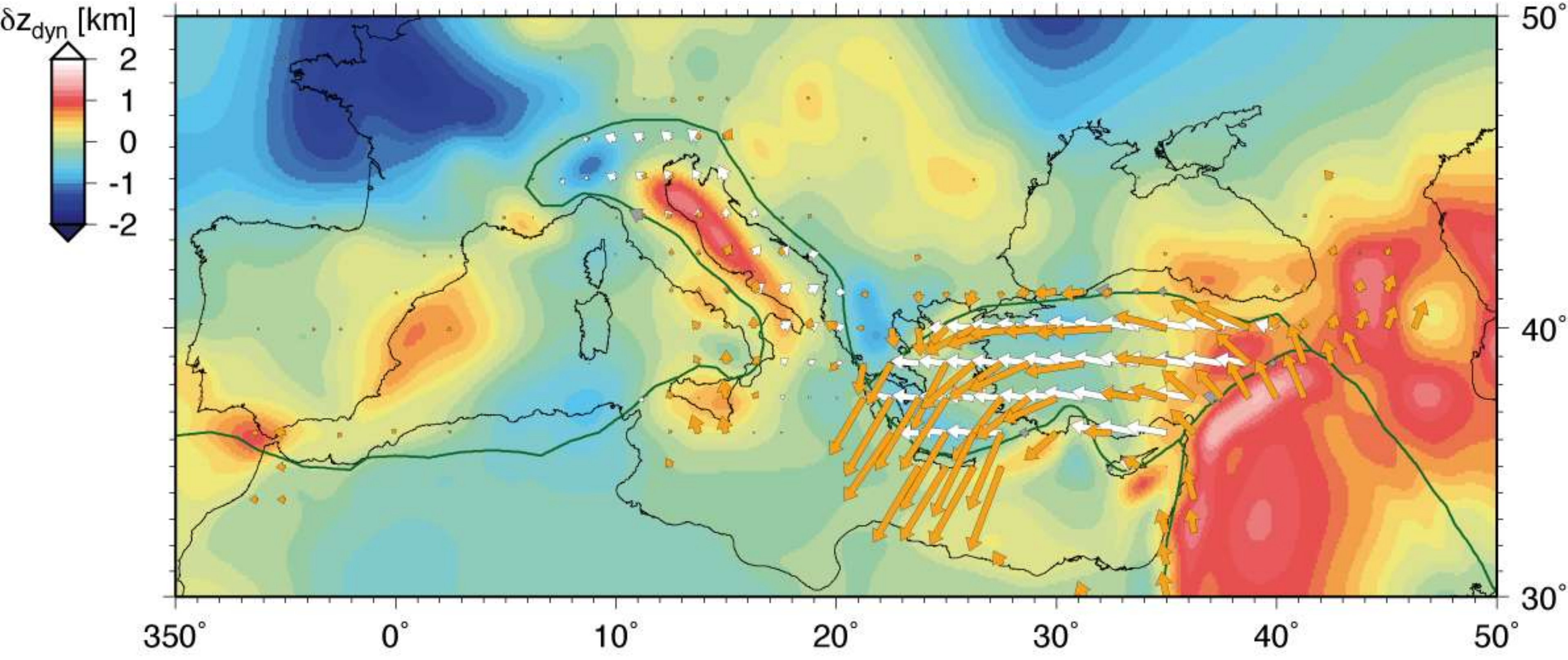


+ uplifting region
- subsiding region

The Mediterranean tectonics

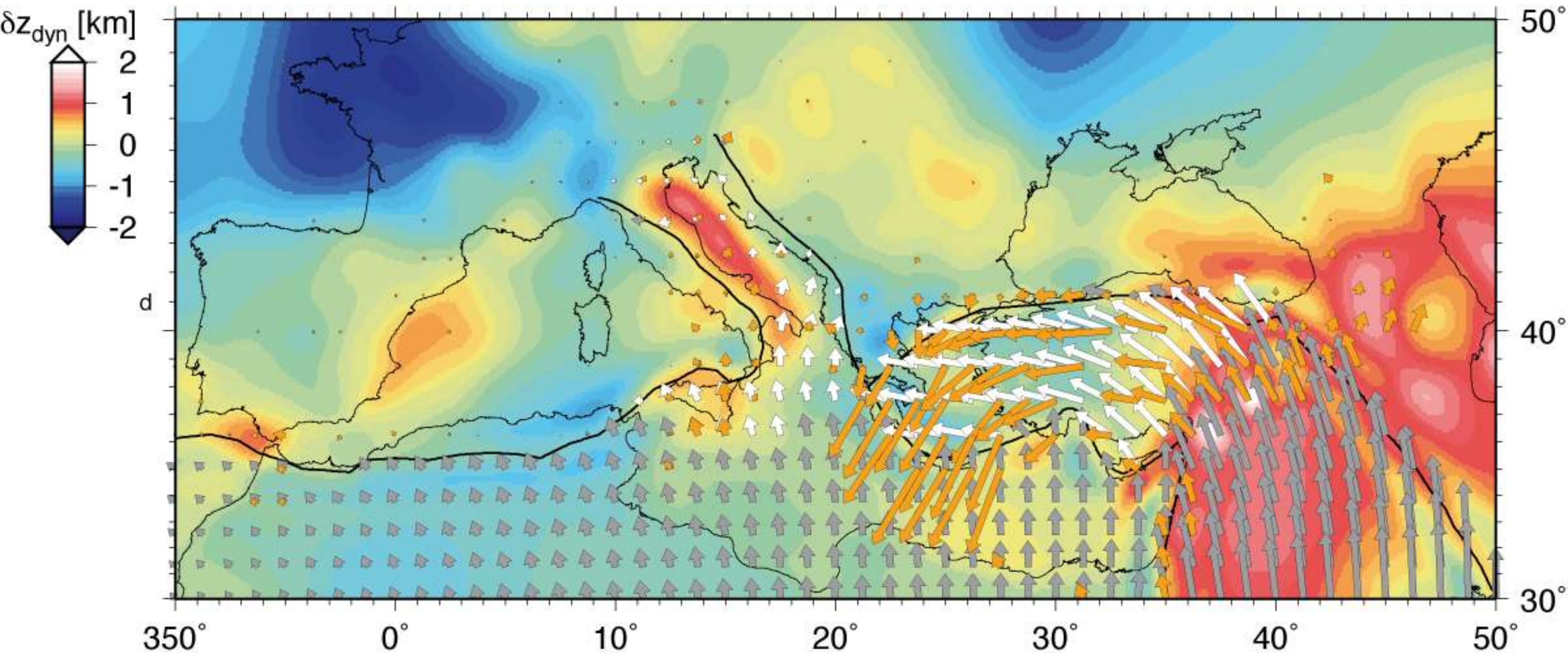


No plate motion



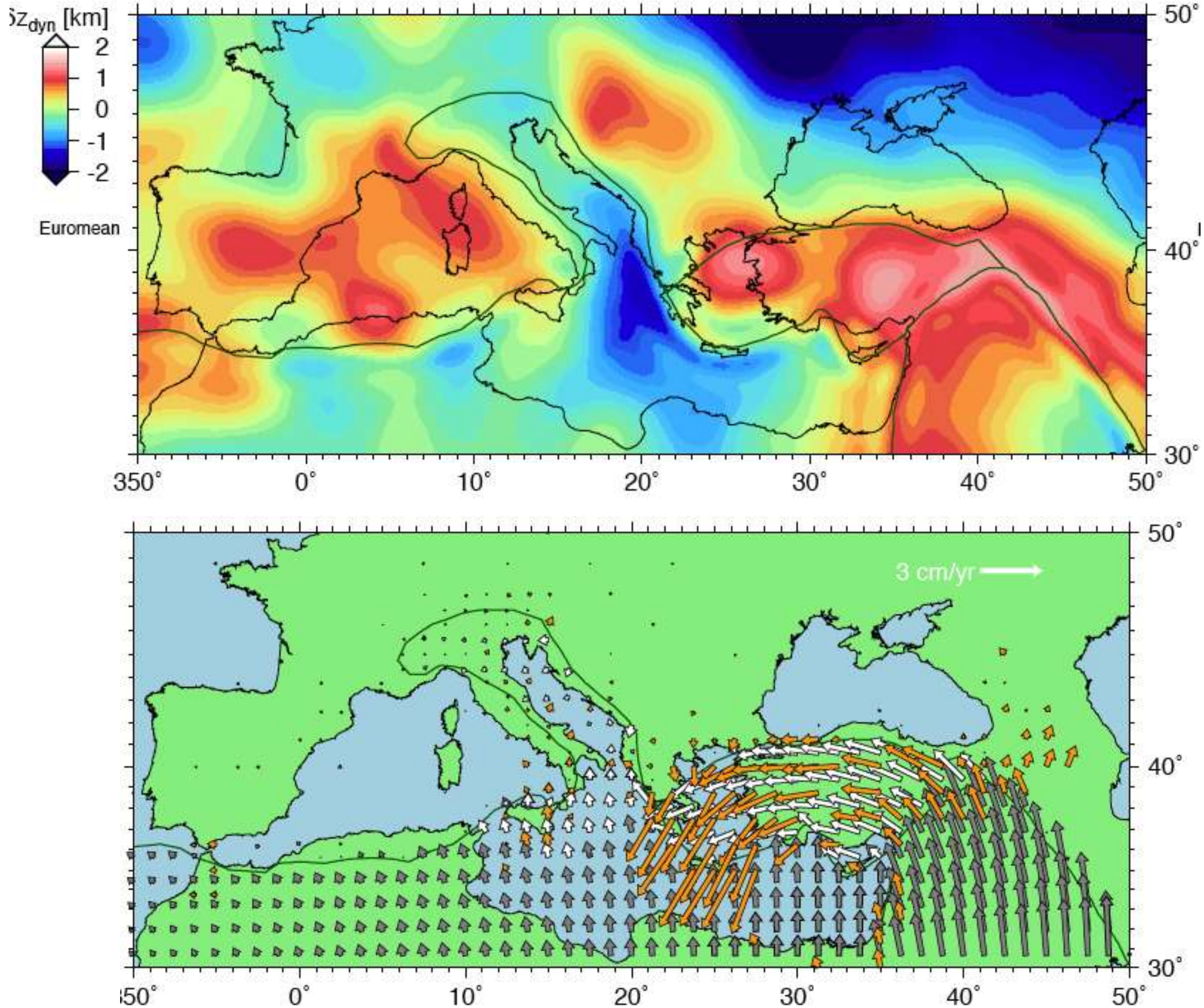
How mantle drives Anatolia and Adria

Plate coupling at collision zone (Alps and Bitlis)



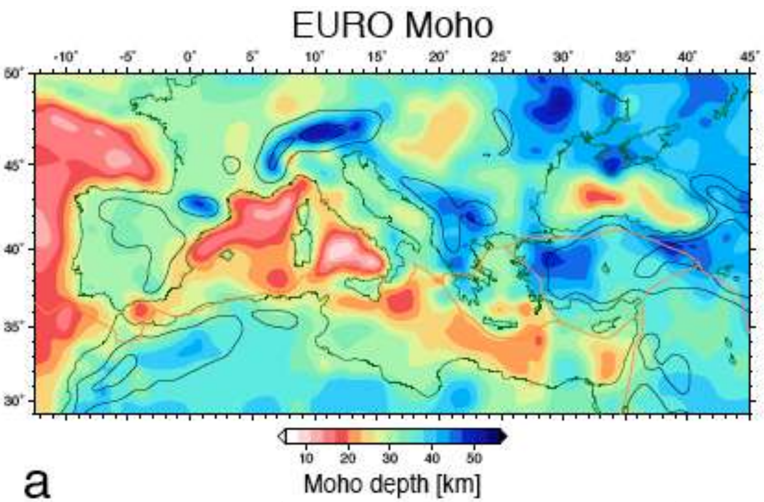
Better Adria fit!

S wave model (Boschi et al., 2009, 2010)

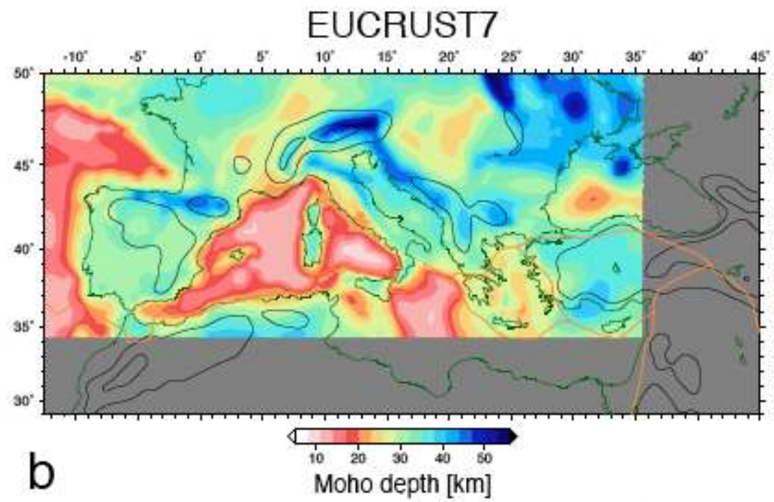


Better Agea fit!

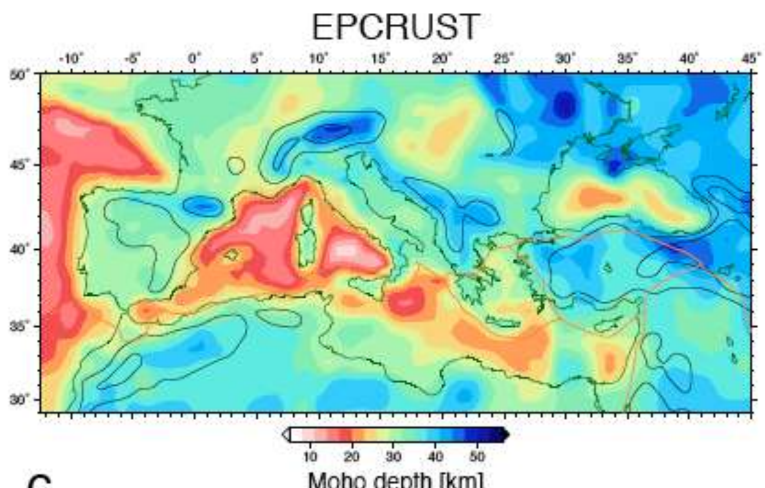
Crustal structure



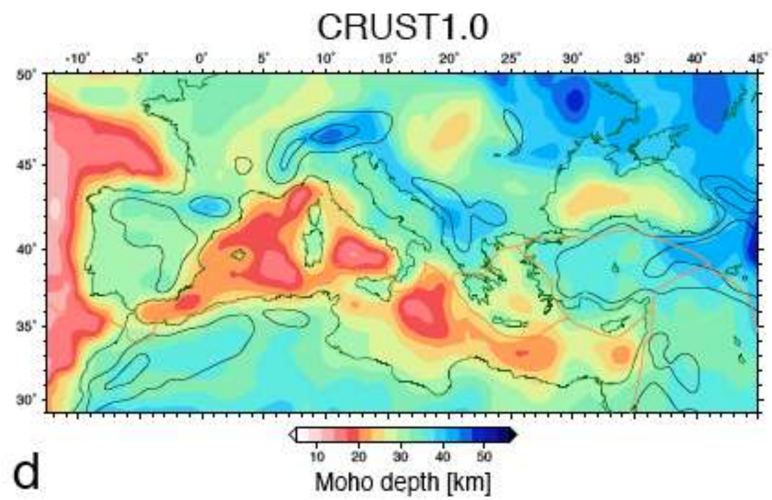
EuroMoho (Grad and Tire, 2009)



EuCrust07 (Tesauro et al., 2008),



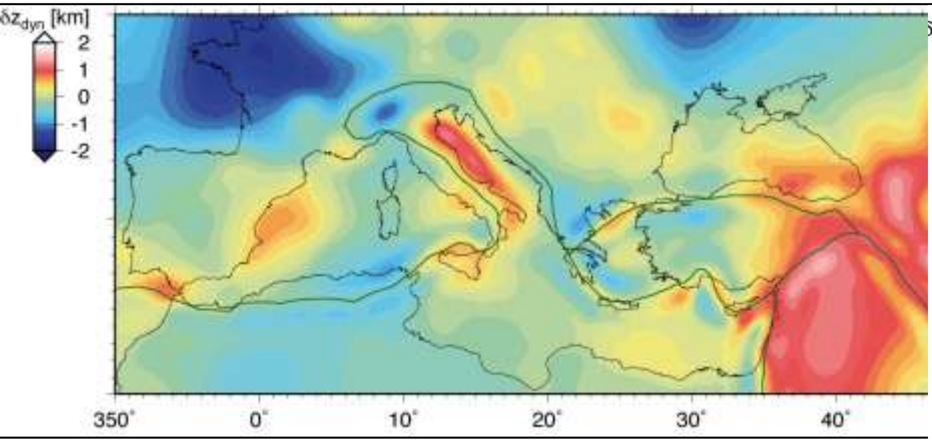
EpCrust (Molinari and Morelli, 2011)



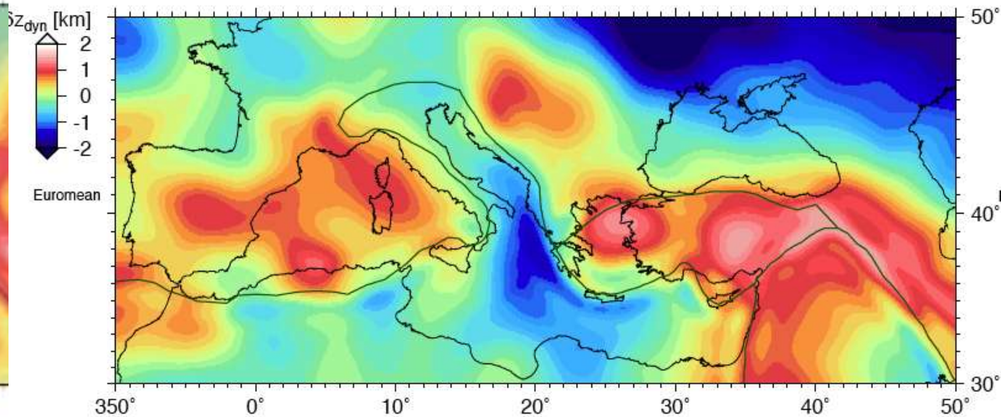
CRUST1.0 (Bassin et al., 2013)

Dynamic topography

MIT07 tomography (Li et al.08)

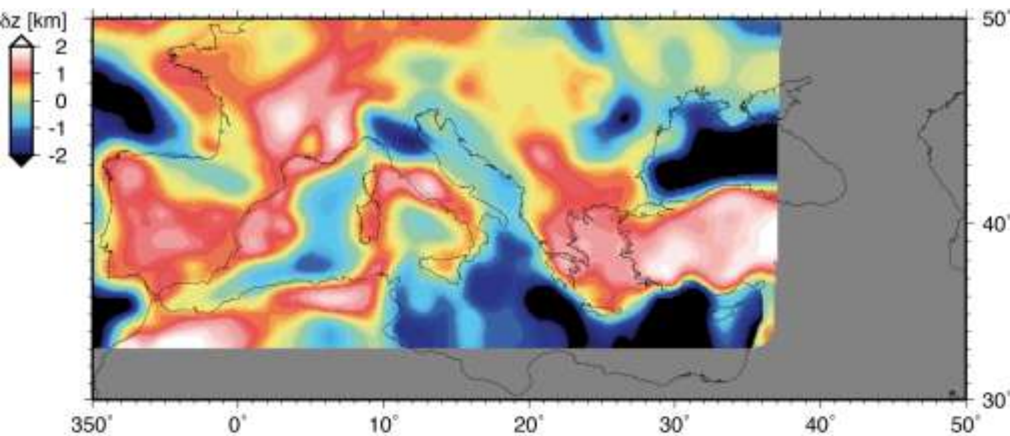


Euromean tomography (Boschi et al., '11)

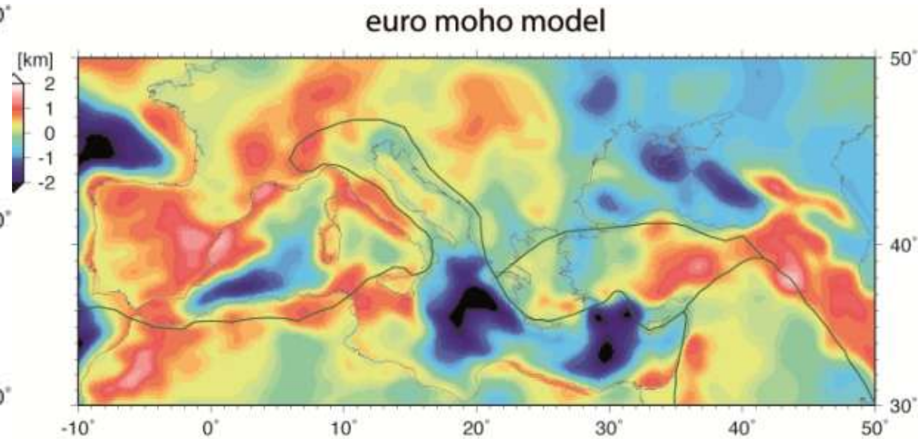


Residual topography

Eurocrust (Tesauro et al., 07)



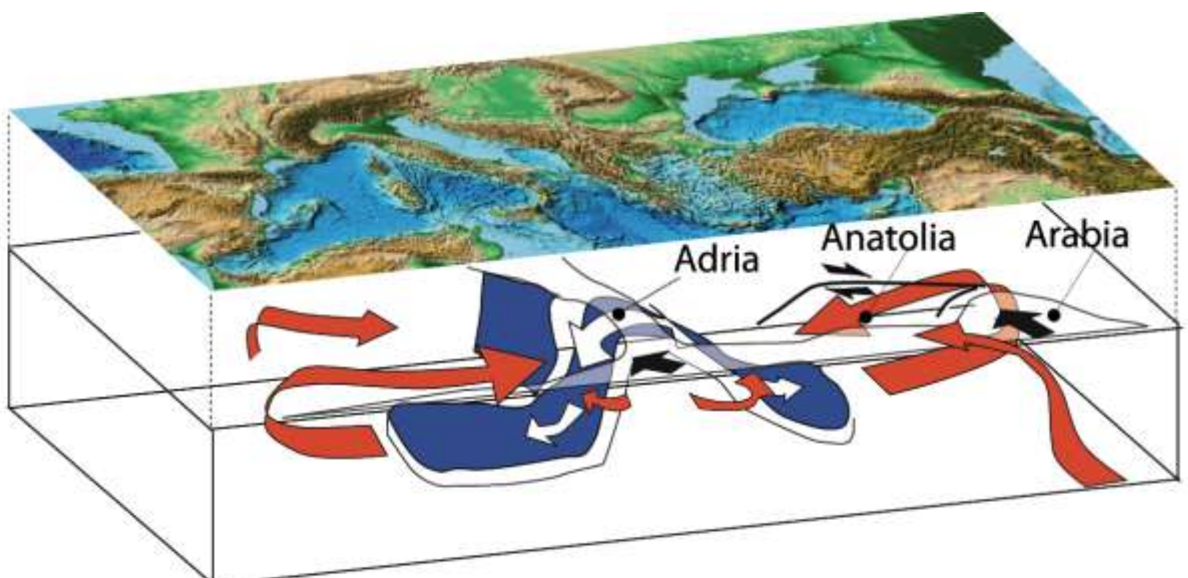
Euromoho



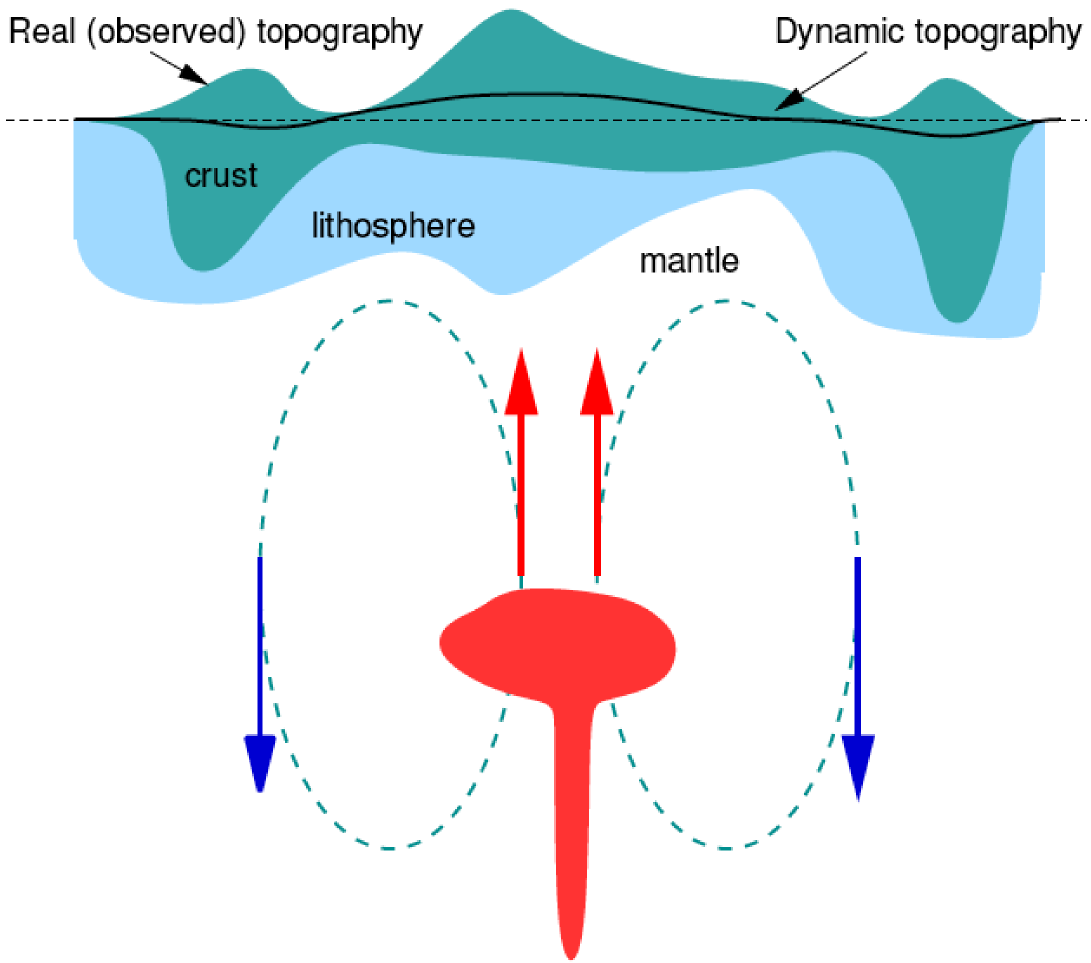
(topography filtered by of crustal isostasy)

The Mediterranean convection

- Vigorous flow restricted in the shallow upper mantle
- Downwelling in the Central Mediterranean (attraction zone)
- Return flow with upwelling beneath Anatolia, souther France and Iberia
- Lateral connection with Arabia and Atlantic

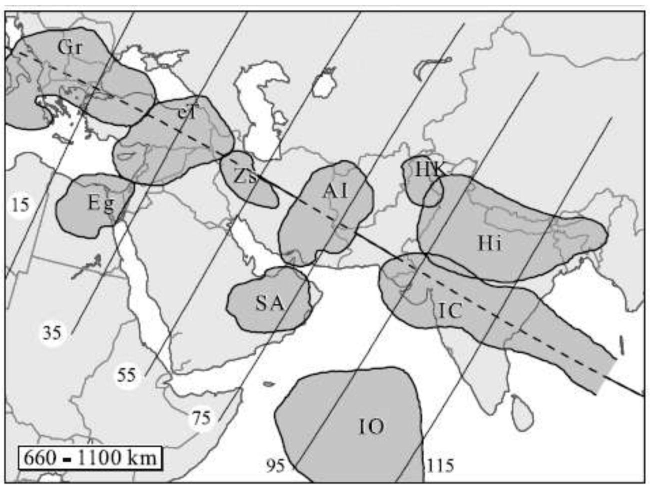


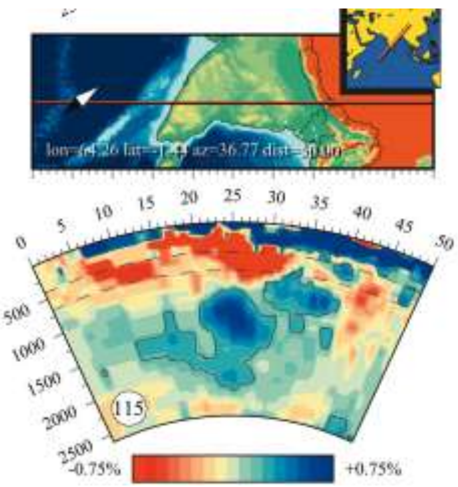
Topography=
Dynamic topography +
Isostatic topography

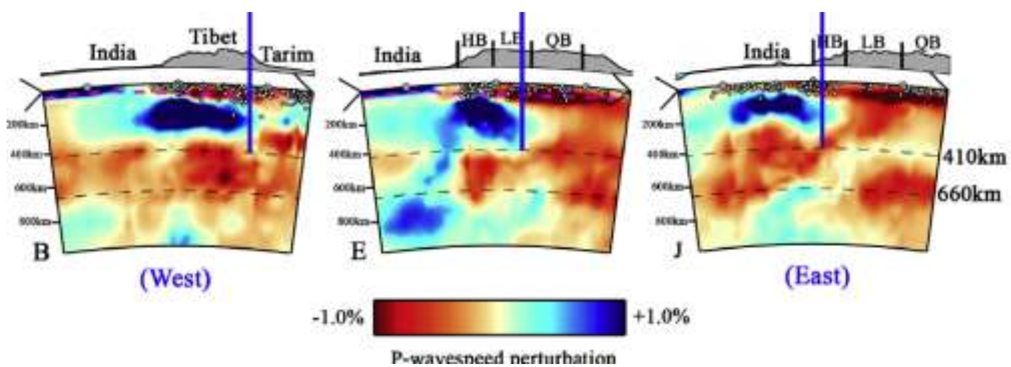


loss of slab pull after lithosphere and slab break-off after continent arrival

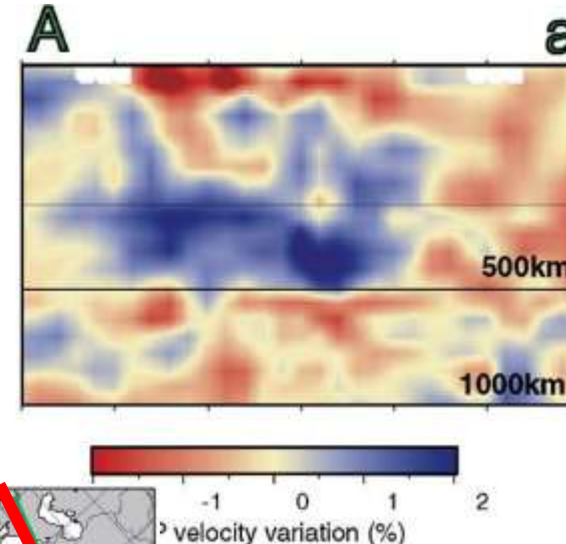
India

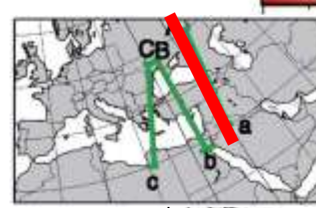


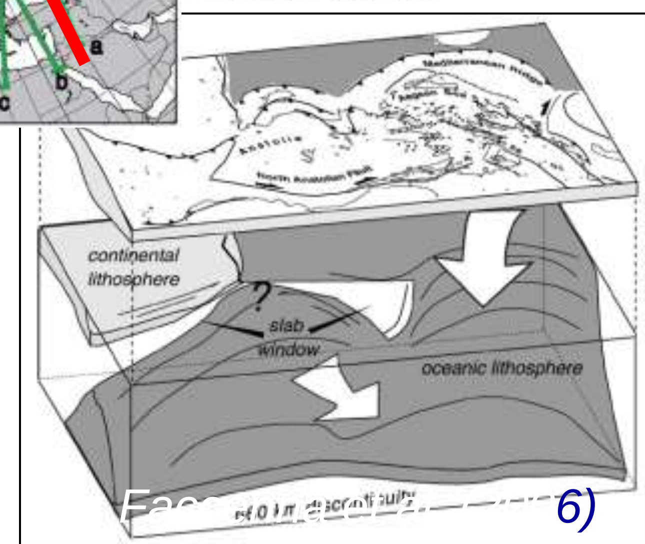




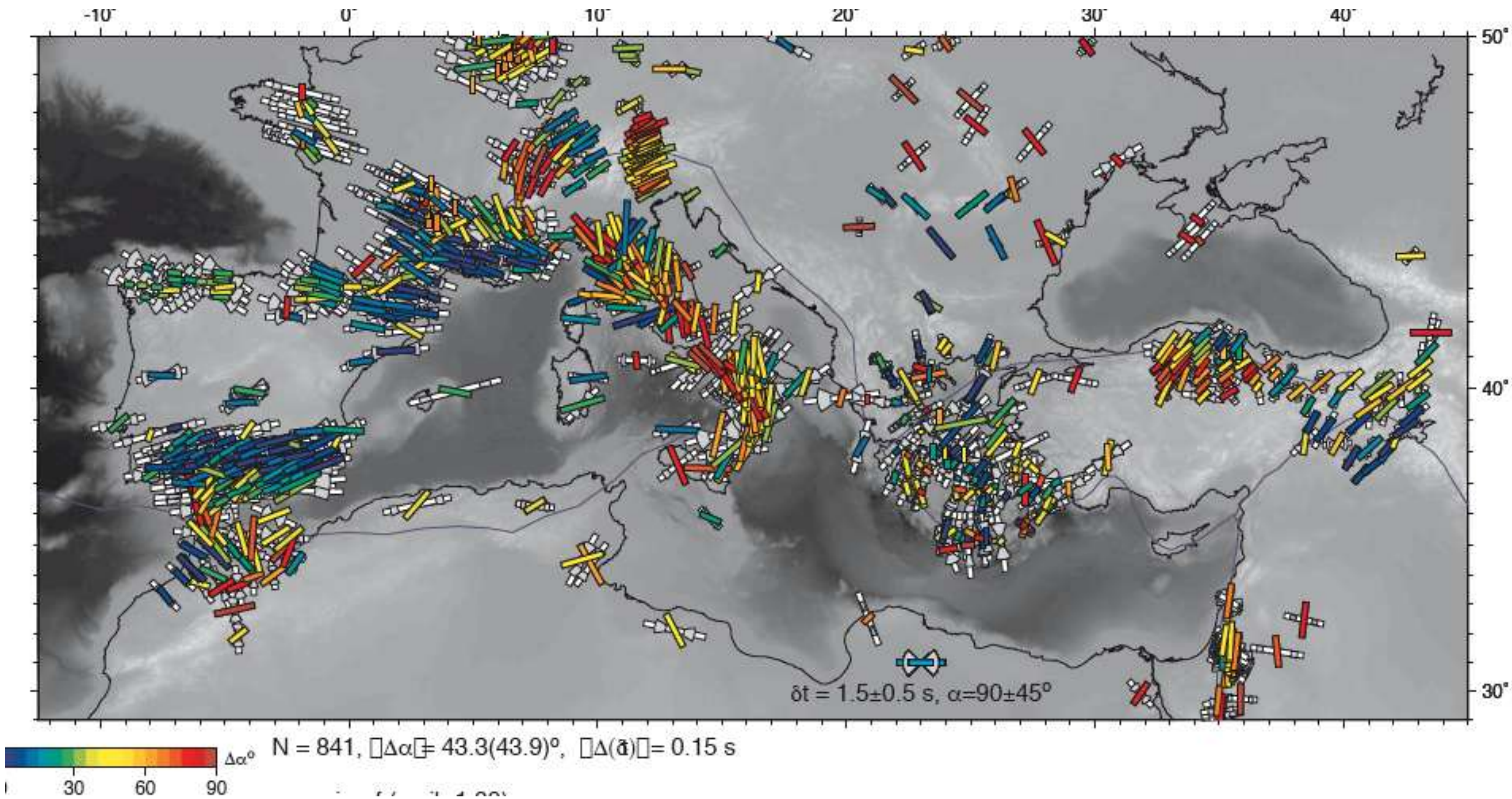
Arabia



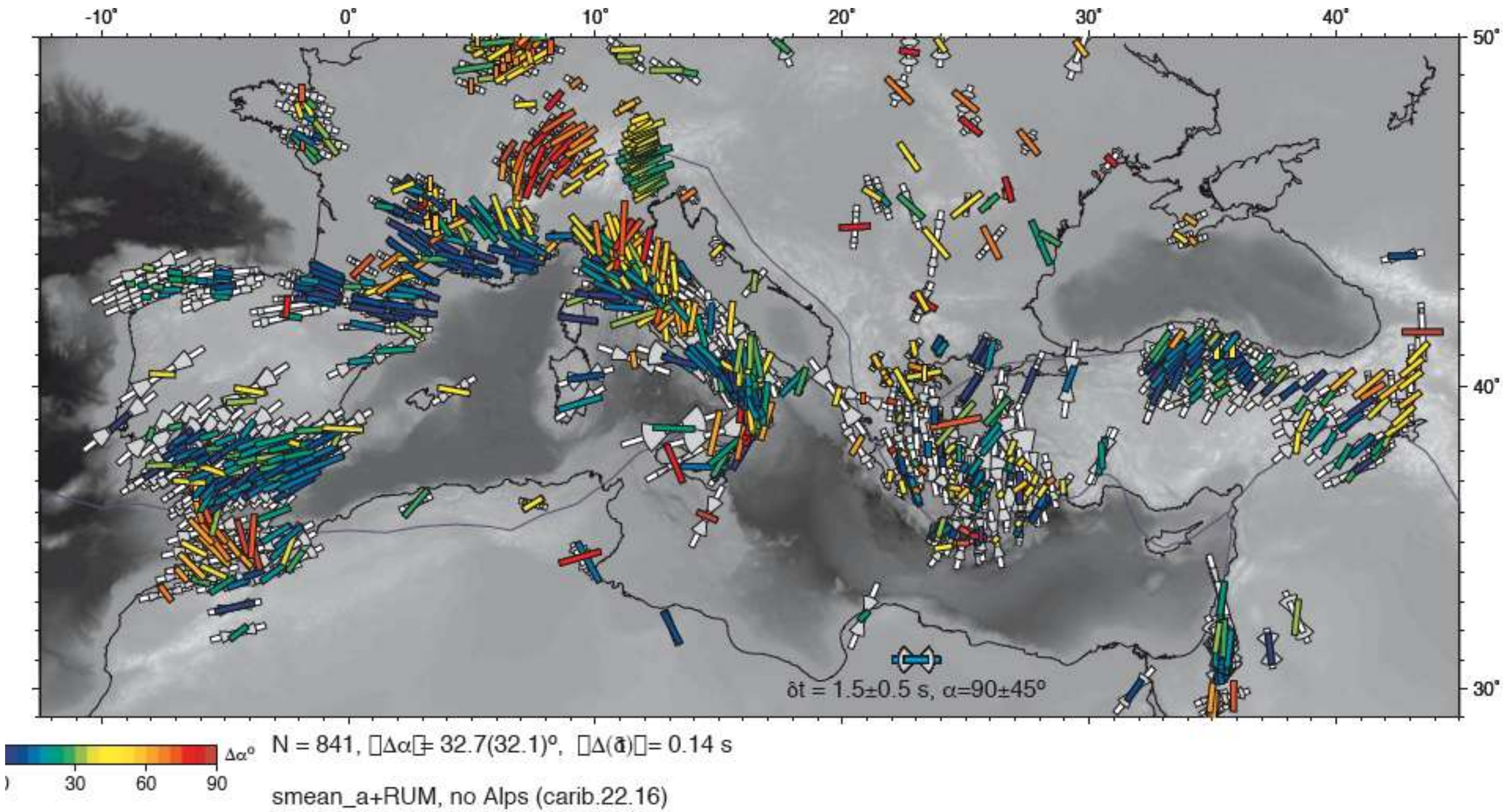


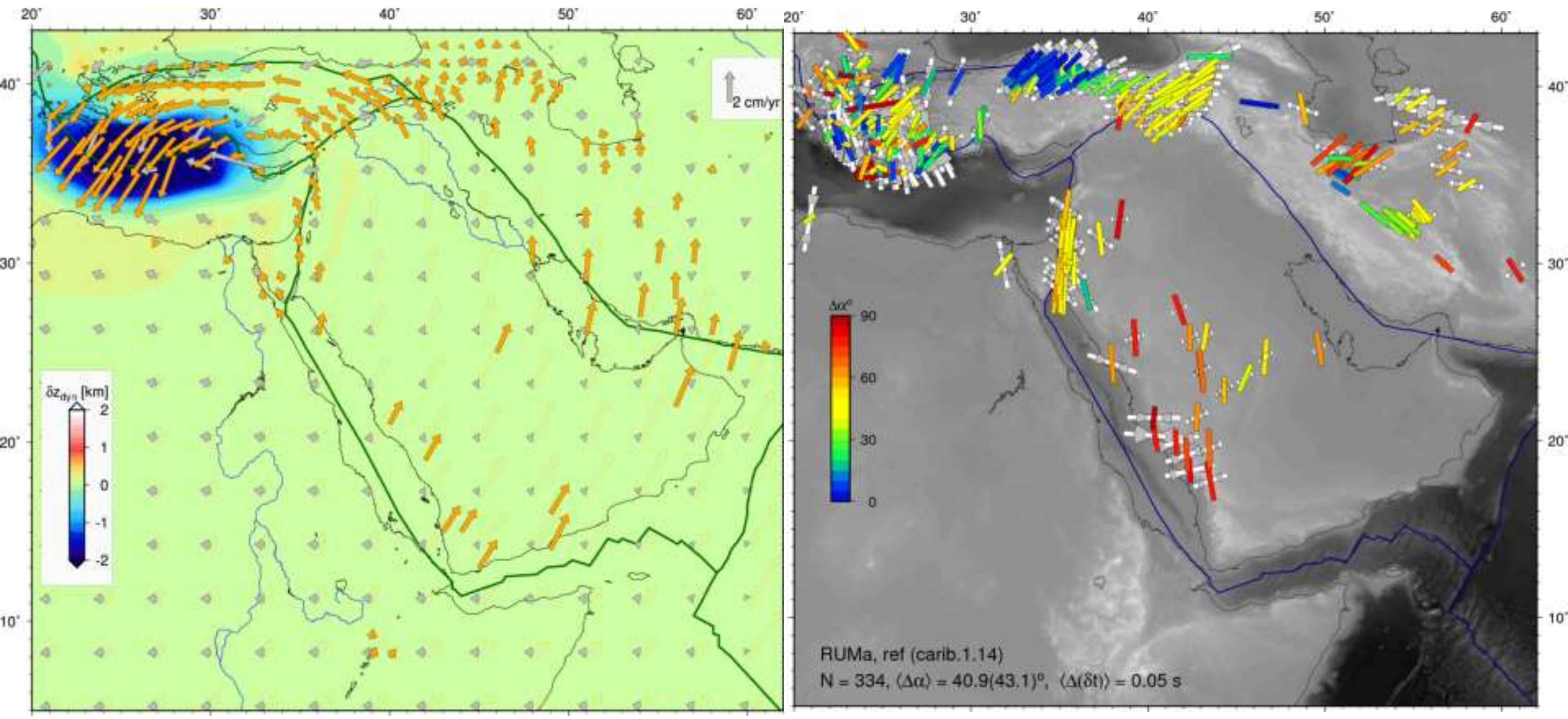


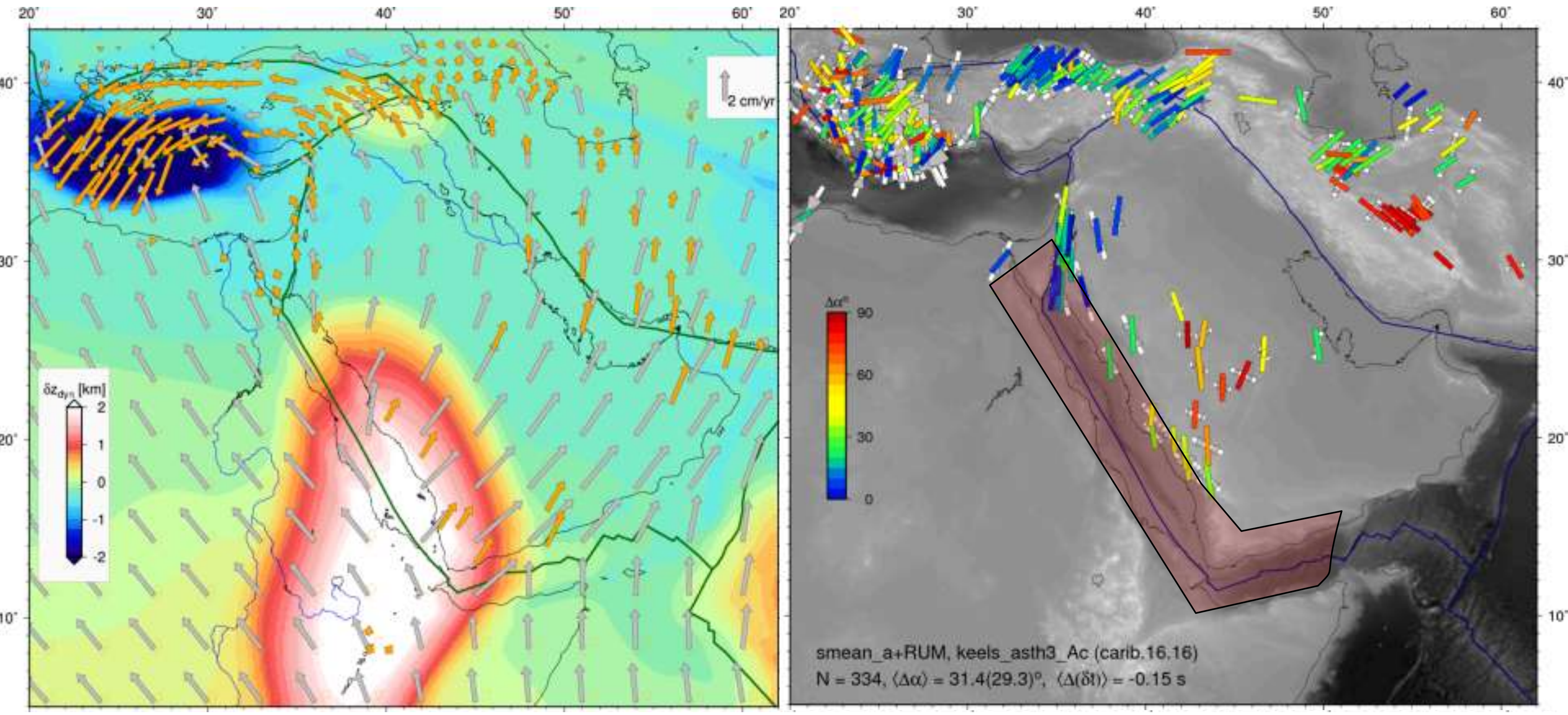
Large scale tomography (Smean)

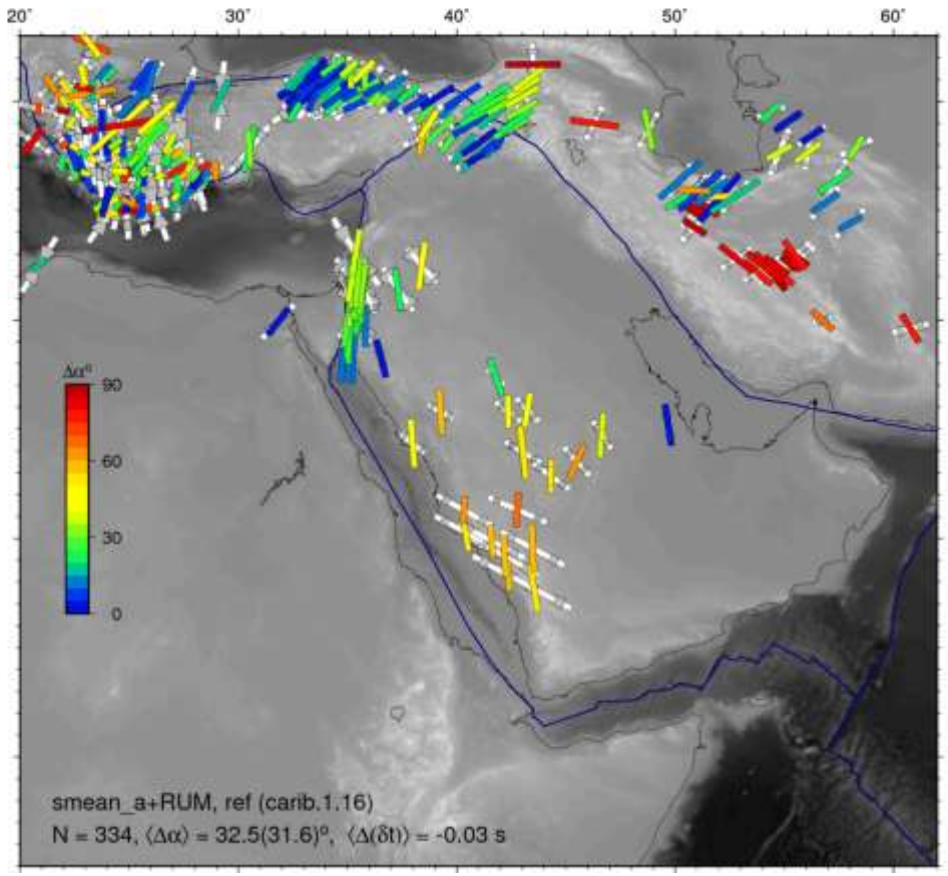


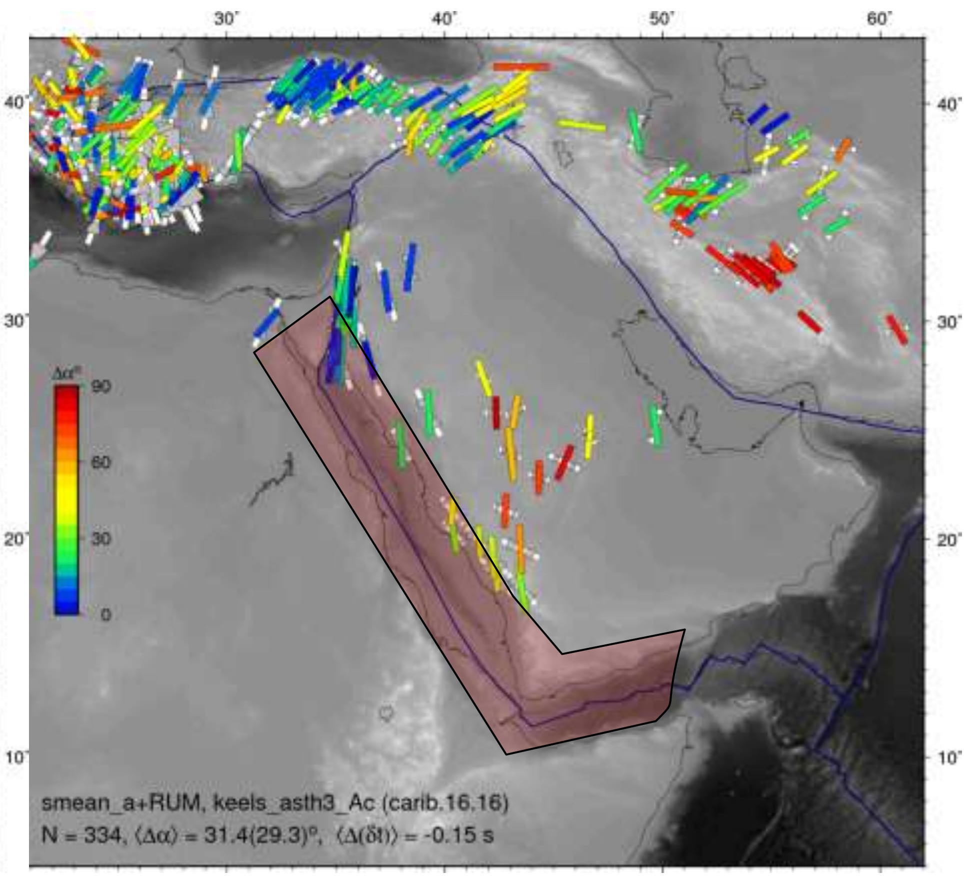
Large scale tomography (Smean) and subduzion zones. Alps coupled.



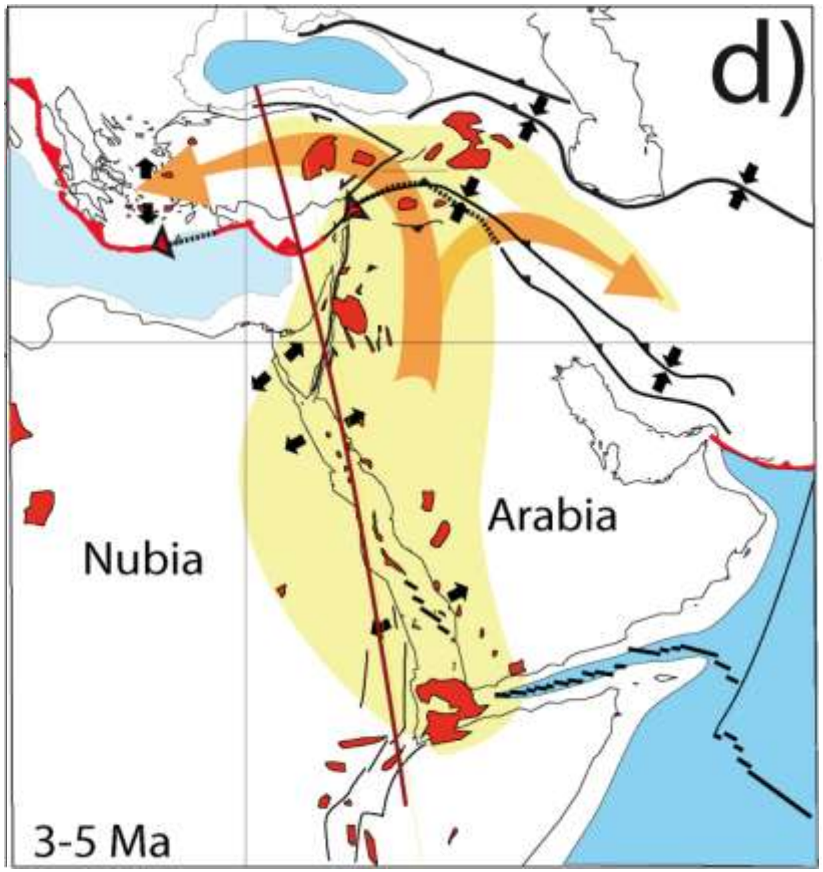

2 cm/yr
δz_dyn [km]
Δα°
RUMa, ref (carib.1.14)
N = 334, ⟨Δα⟩ = 40.9(43.1)°, ⟨Δ(δt)⟩ = 0.05 s

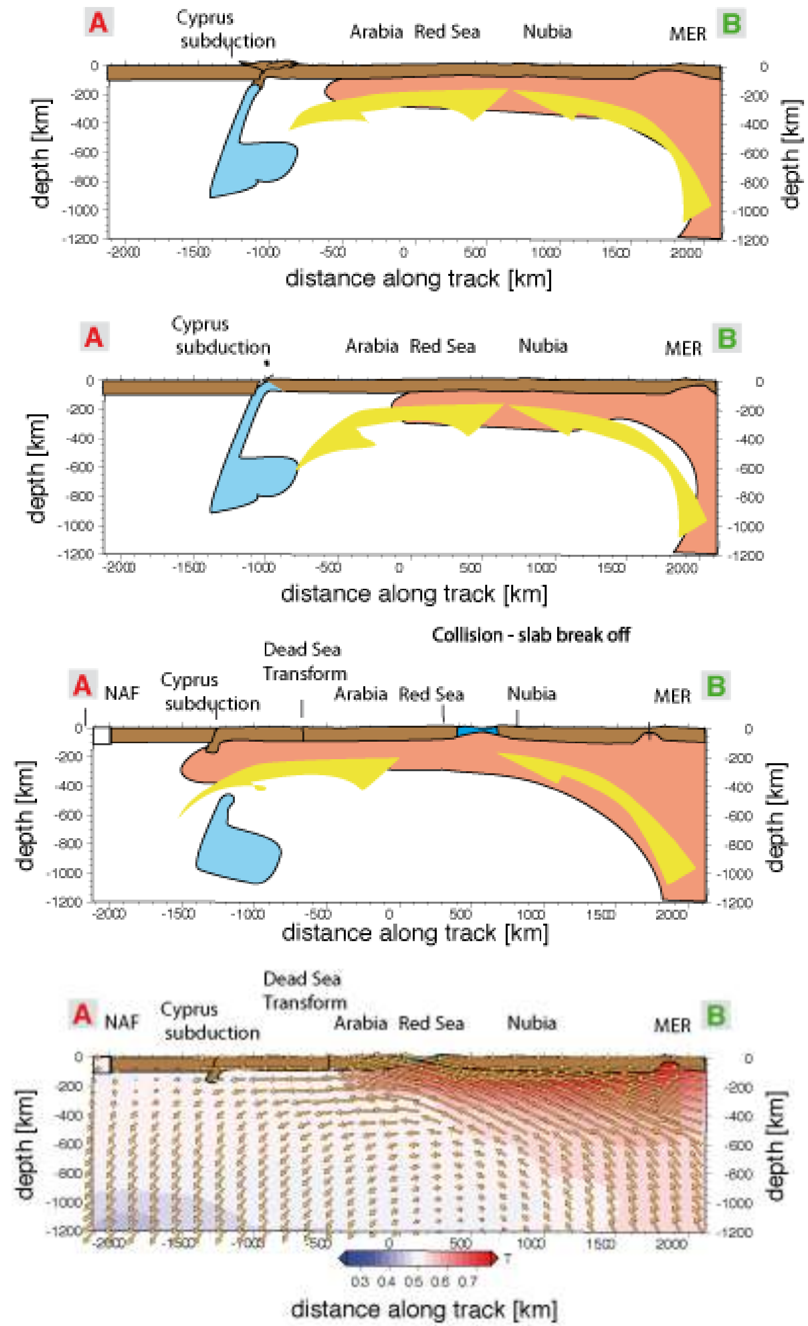

20°
30°
40°
50°
60°
2 cm/yr
δz_dyn [km]
2
1
0
-1
-2
Δα°
90
60
30
0
smean_a+RUM, keels_asth3_Ac (carib.16.16)
N = 334, ⟨Δα⟩ = 31.4(29.3)°, ⟨Δ(δt)⟩ = -0.15 s


smean_a+RUM, ref (carib.1.16)
N = 334, ⟨Δα⟩ = 32.5(31.6)°, ⟨Δ(δt)⟩ = -0.03 s
Δα°
0
30
60
90
20°
30°
40°
50°
60°


smean_a+RUM, keels_asth3_Ac (carib.16.16)
N = 334, ⟨Δα⟩ = 31.4(29.3)°, ⟨Δ(δt)⟩ = -0.15 s
Δα°
0
30
60
90
30°
40°
50°
60°
10°
20°
30°
40°

...



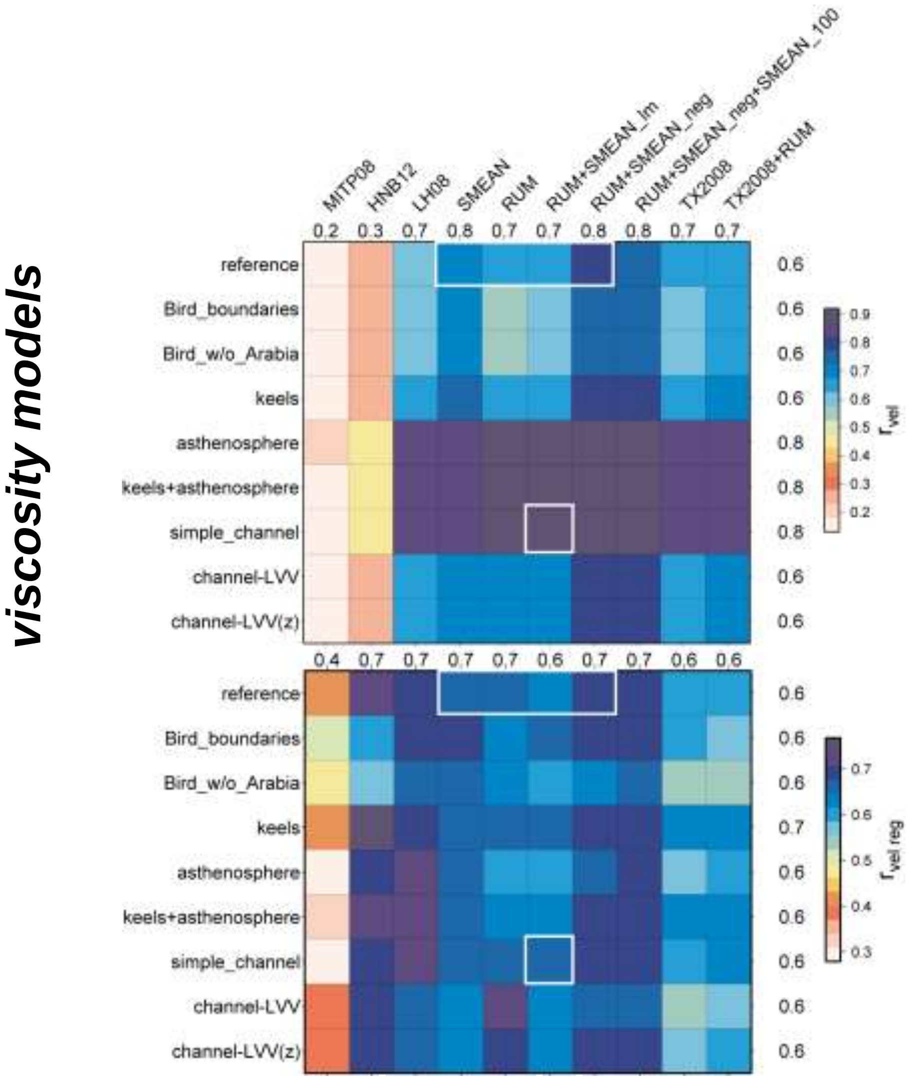


Key role of mantle flowing from Arabia towards the Hellenic trench

Best fit

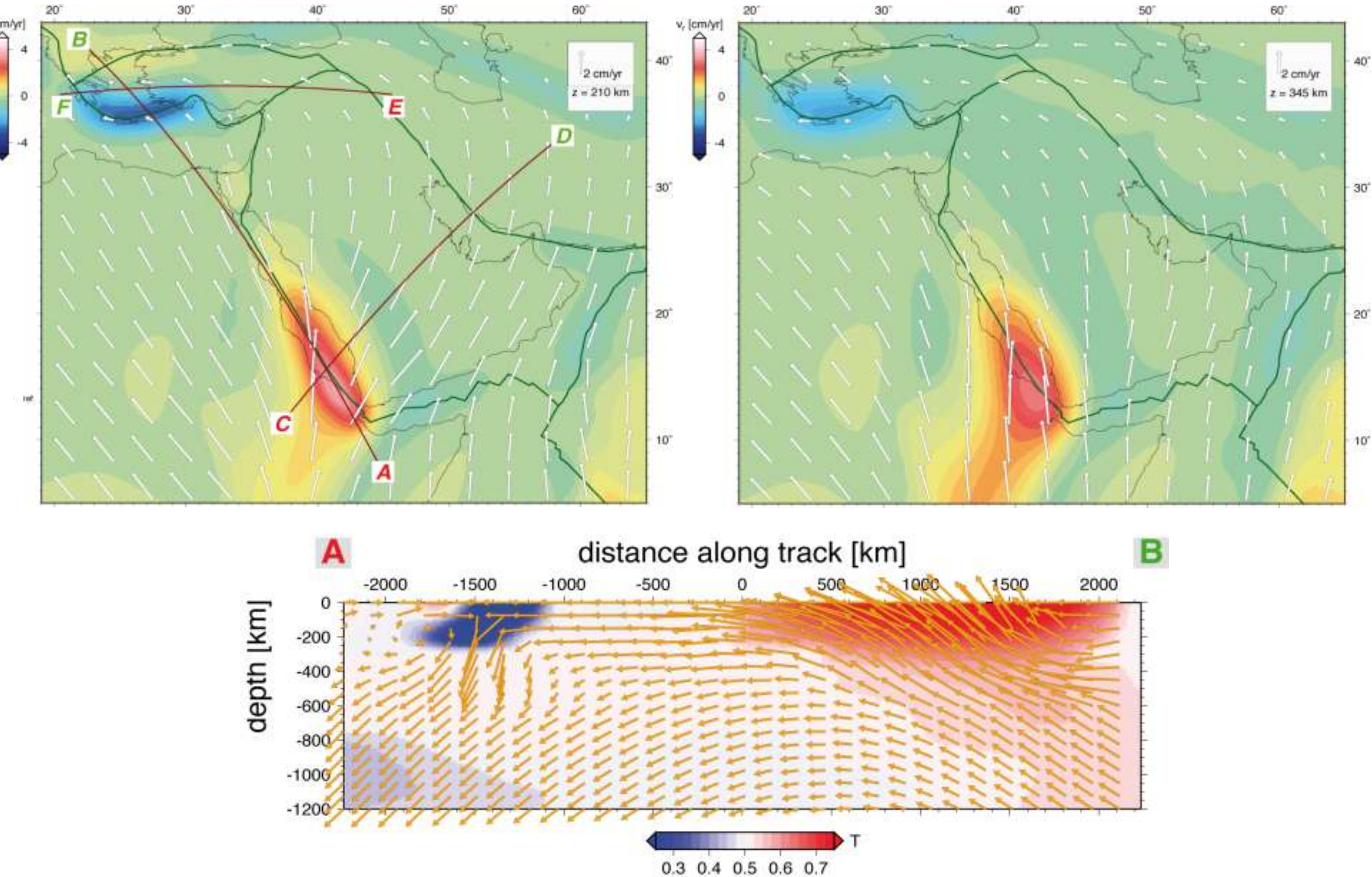
geodesy

anisotropy

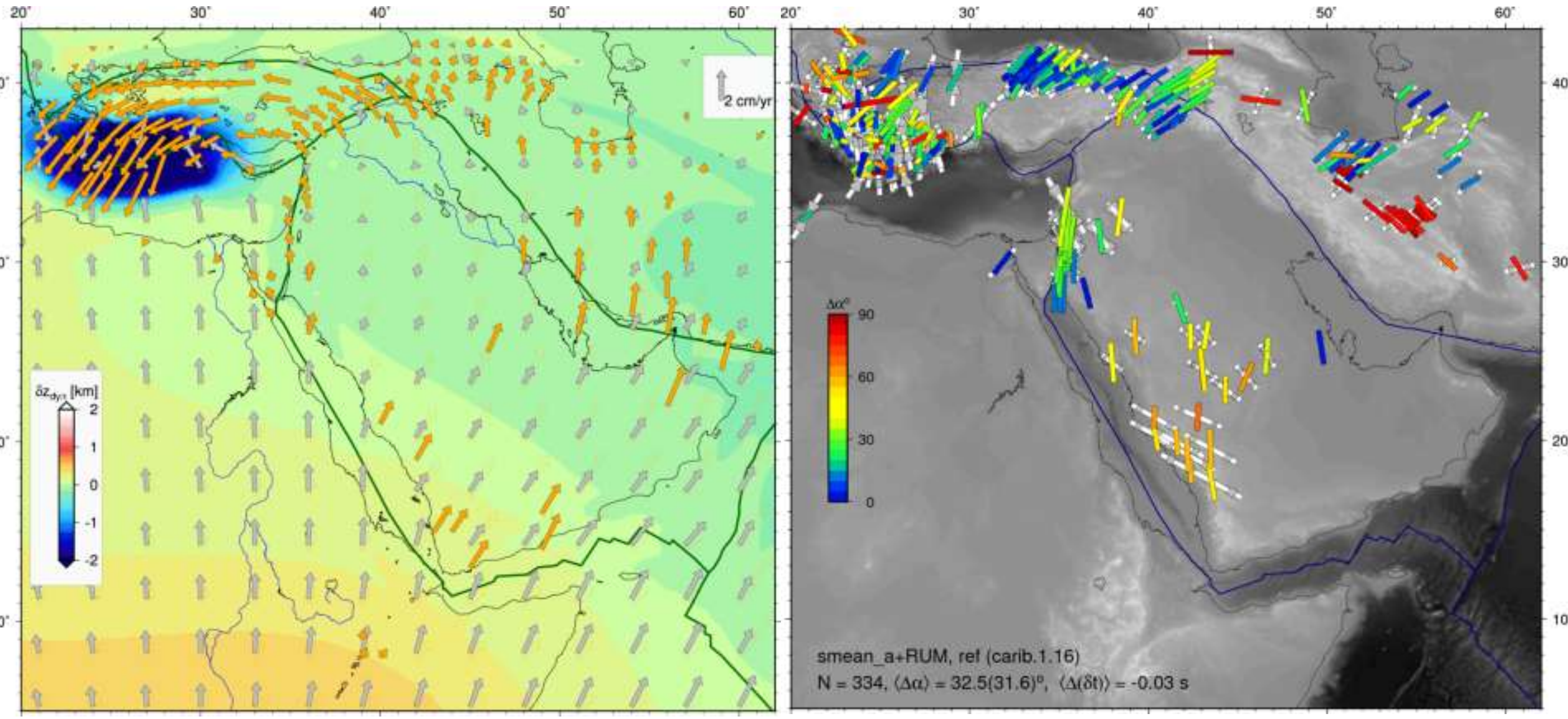


regional correlation with GPS

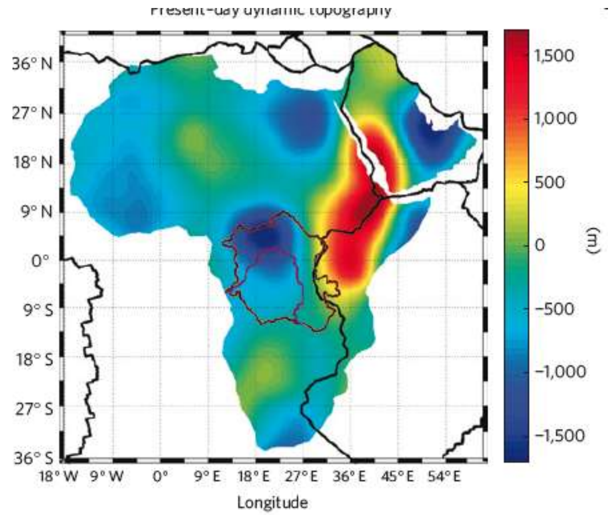
angular misfit of “fast splitting axes” [º]



20° 30° 40° 50° 60°
v_r [cm/yr]
4
0
-4
2 cm/yr
z = 210 km
z = 345 km
40° 30° 20° 10°
B
F
E
D
C
A
A
B
distance along track [km]
-2000 -1500 -1000 -500 0 500 1000 1500 2000
depth [km]
0 -200 -400 -600 -800 -1000 -1200
T
0.3 0.4 0.5 0.6 0.7



20°
30°
40°
50°
60°
10°
2 cm/yr
δz_dyn [km]
2
1
0
-1
-2
Δα°
90
60
30
0
smean_a+RUM, ref (carib.1.16)
N = 334, ⟨Δα⟩ = 32.5(31.6)°, ⟨Δ(δt)⟩ = -0.03 s



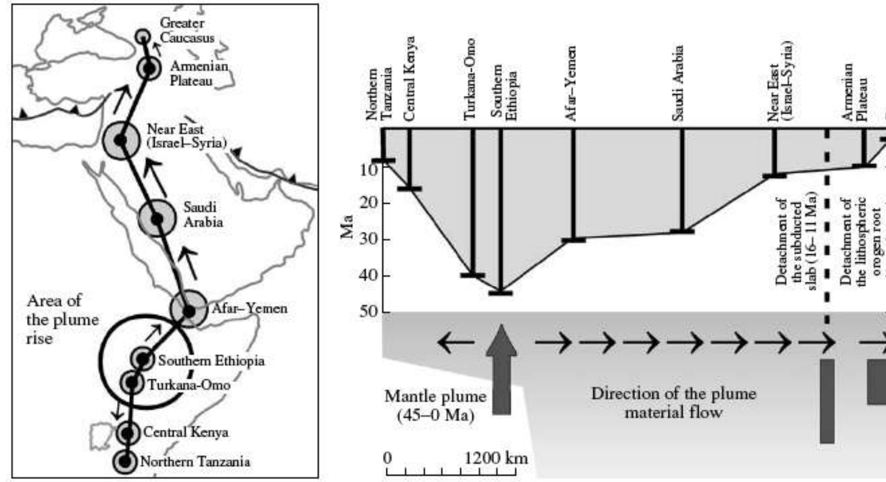
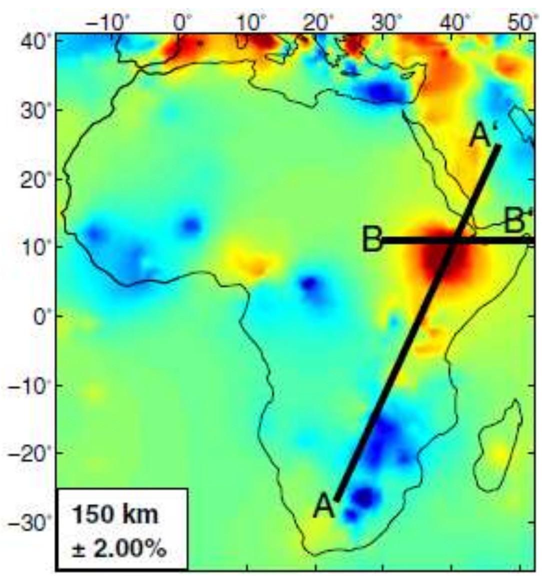
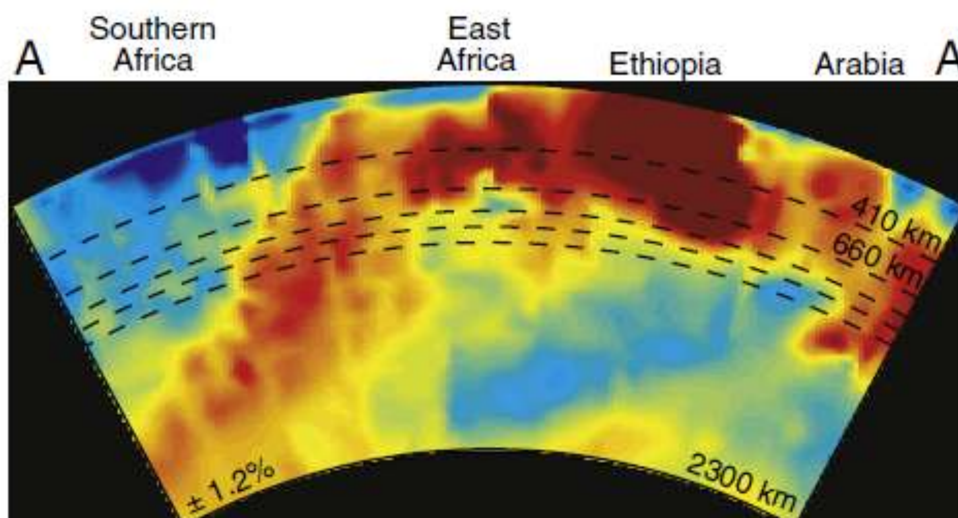
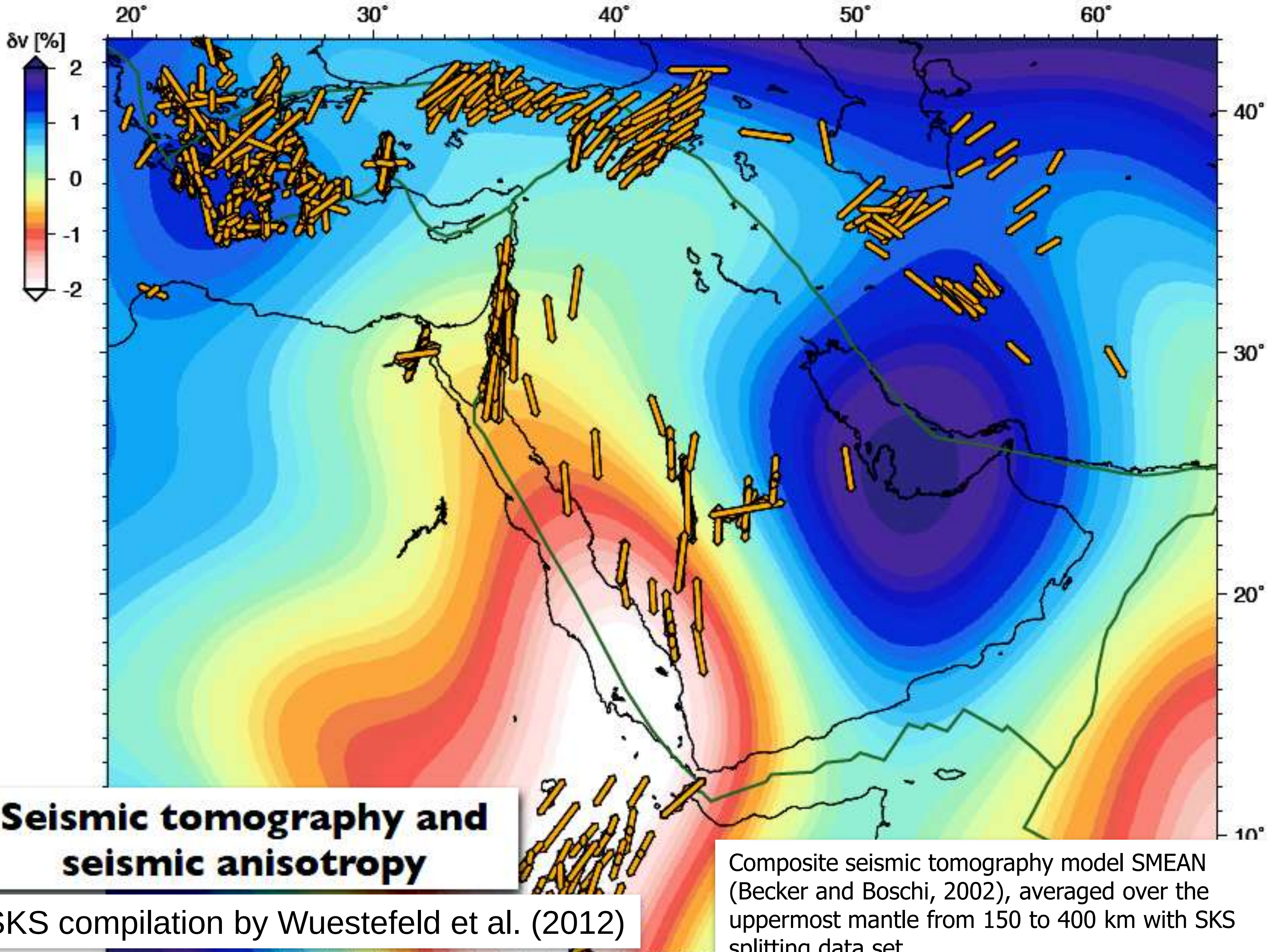


Fig. 2. Age of the initial volcanic activity versus distance along the hot belt.



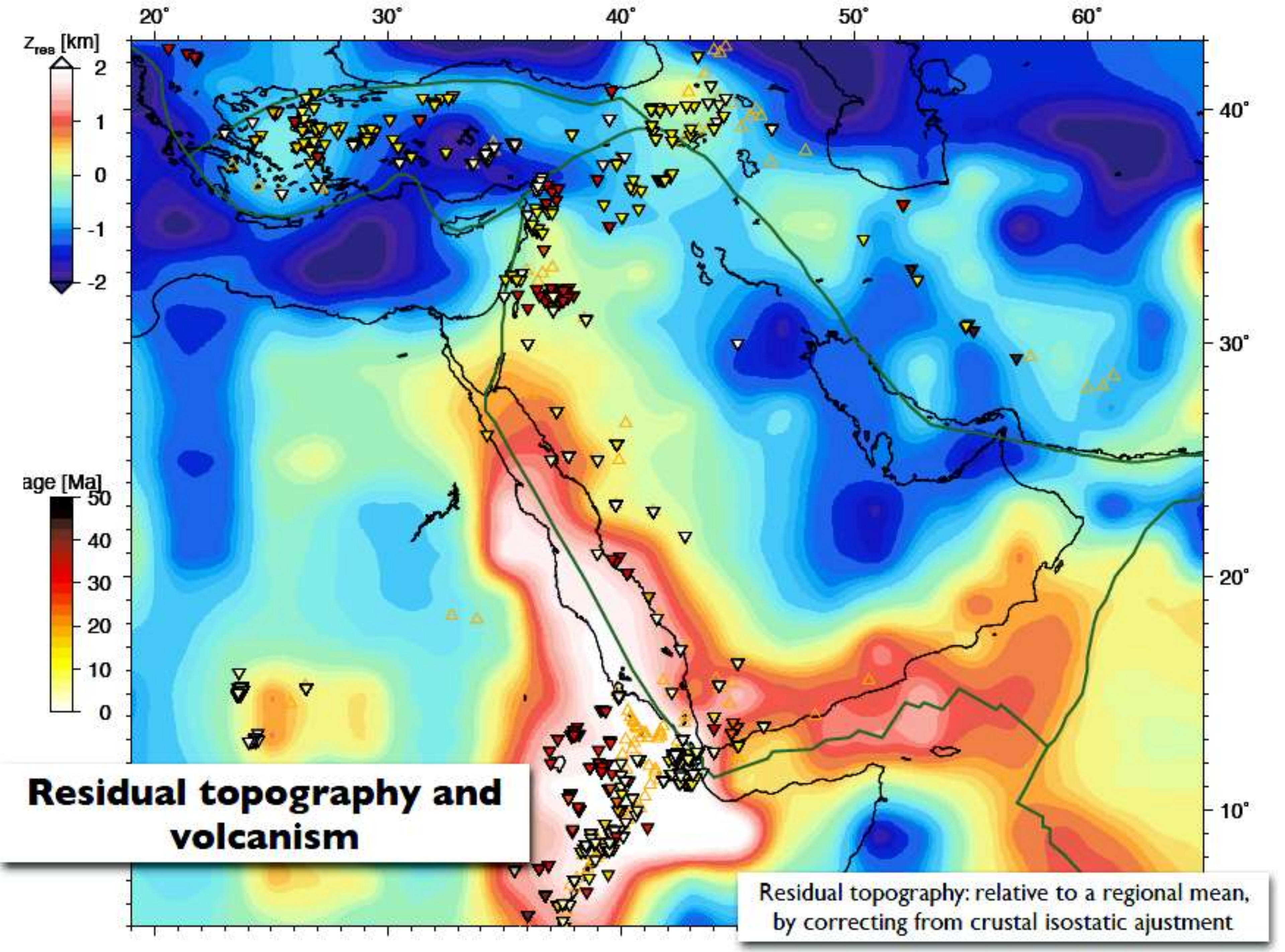




Seismic tomography and seismic anisotropy

SKS compilation by Wuestefeld et al. (2012)

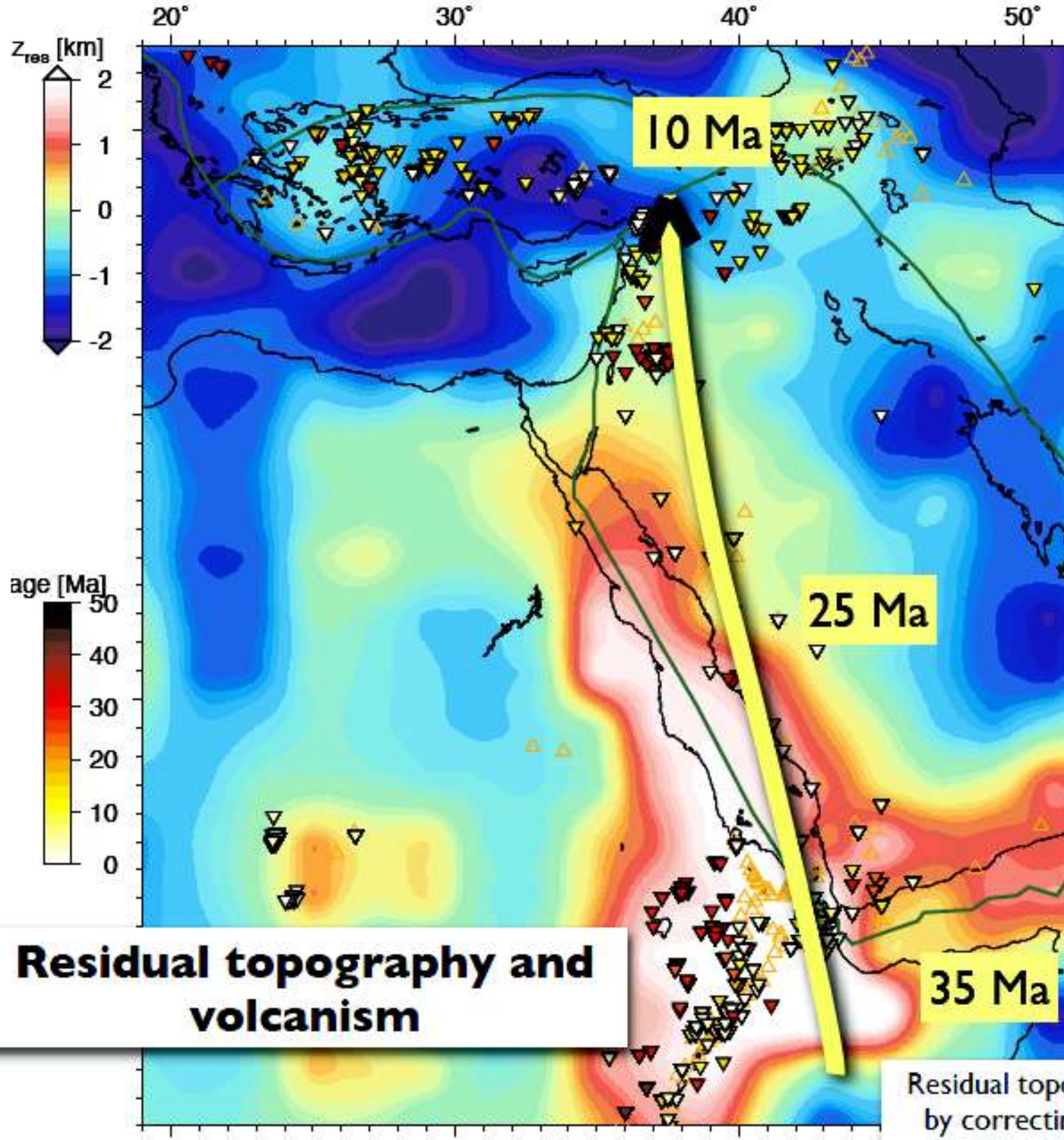
Composite seismic tomography model SMEAN (Becker and Boschi, 2002), averaged over the uppermost mantle from 150 to 400 km with SKS splitting data set.

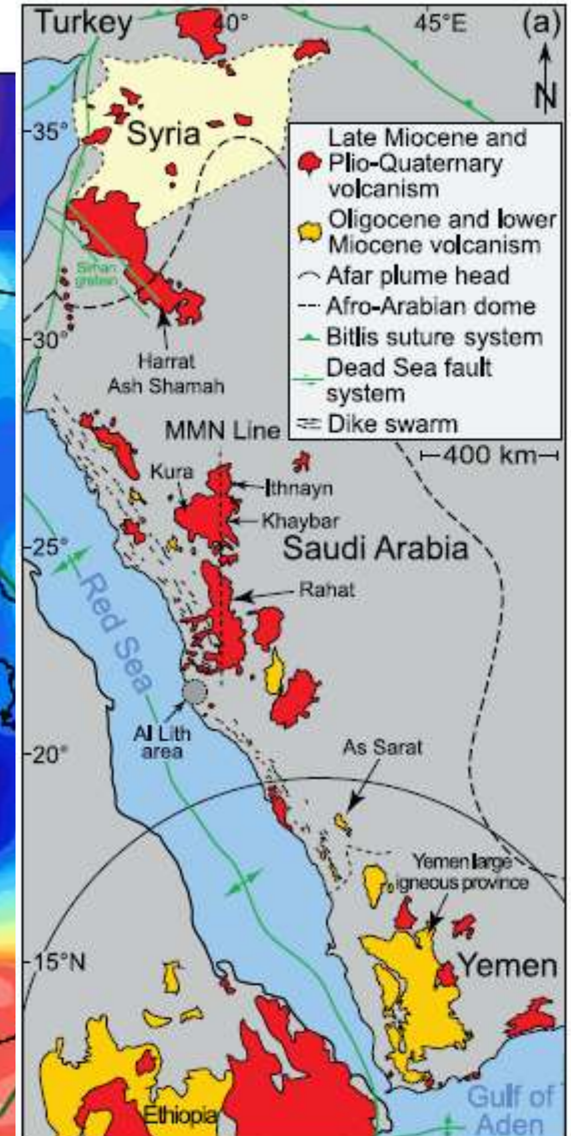


Residual topography and volcanism

Residual topography: relative to a regional mean, by correcting from crustal isostatic ajustment

Residual topography and volcanism

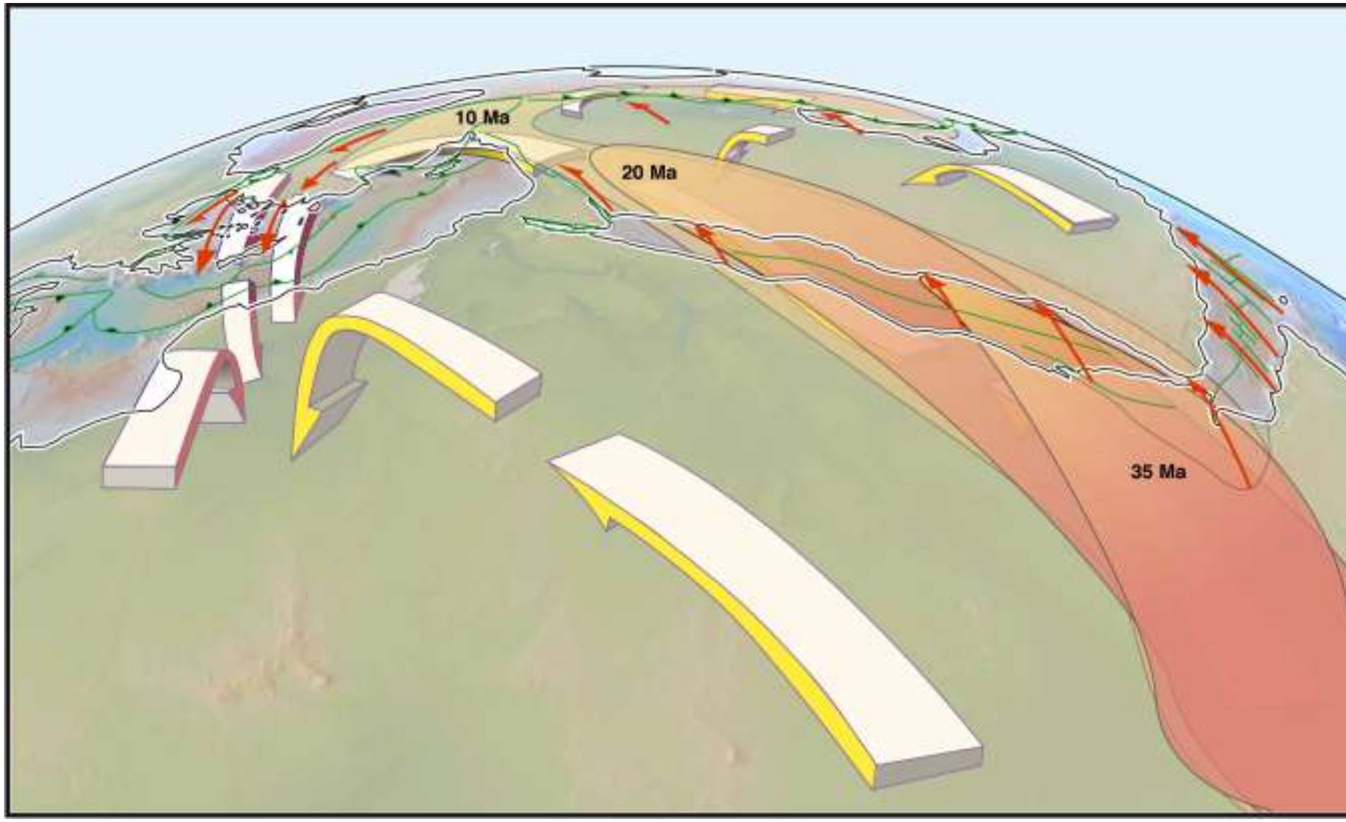




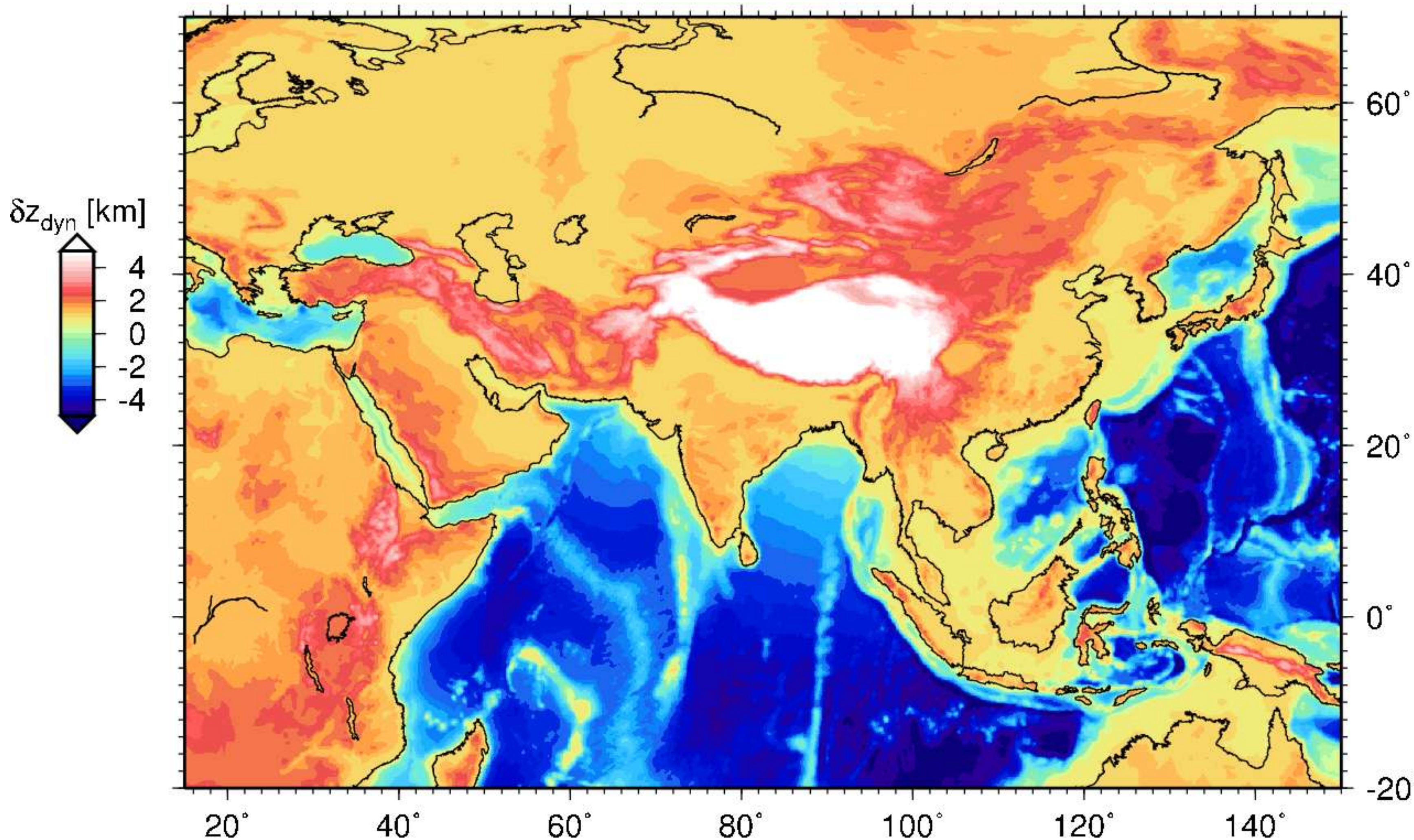
Krienitz et al. (2009)

Residual topography: relative to a regional mean, by correcting from crustal isostatic ajustment

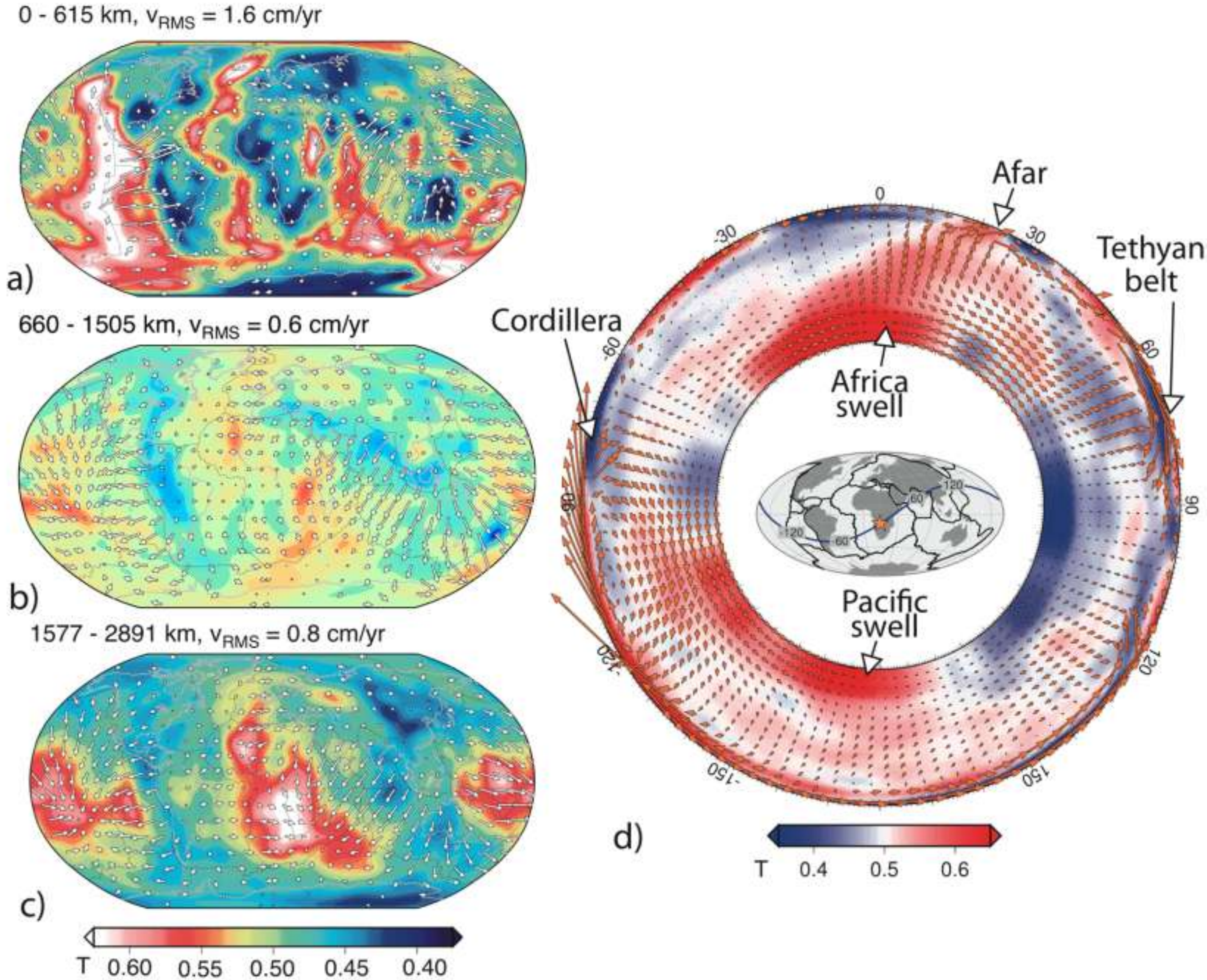
Summary



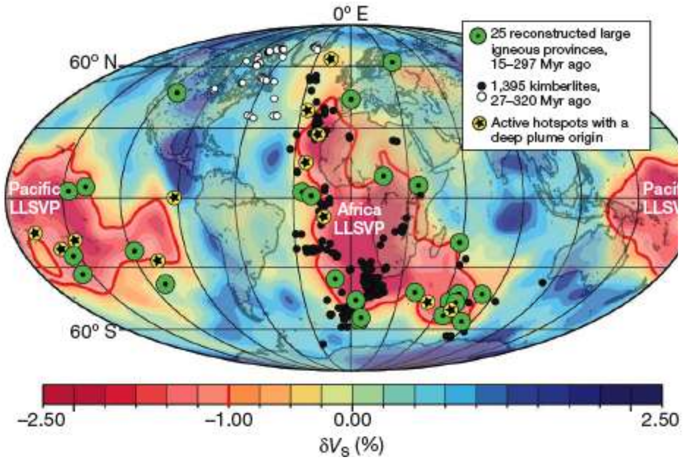
Mantle flows from Afar upwelling to Hellenic downwelling dragging Arabia towards the collisional zone and Anatolia towards the Hellenic subduction zone.

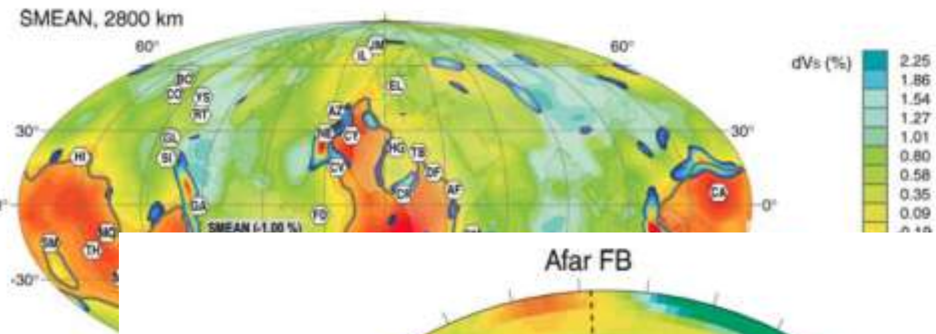


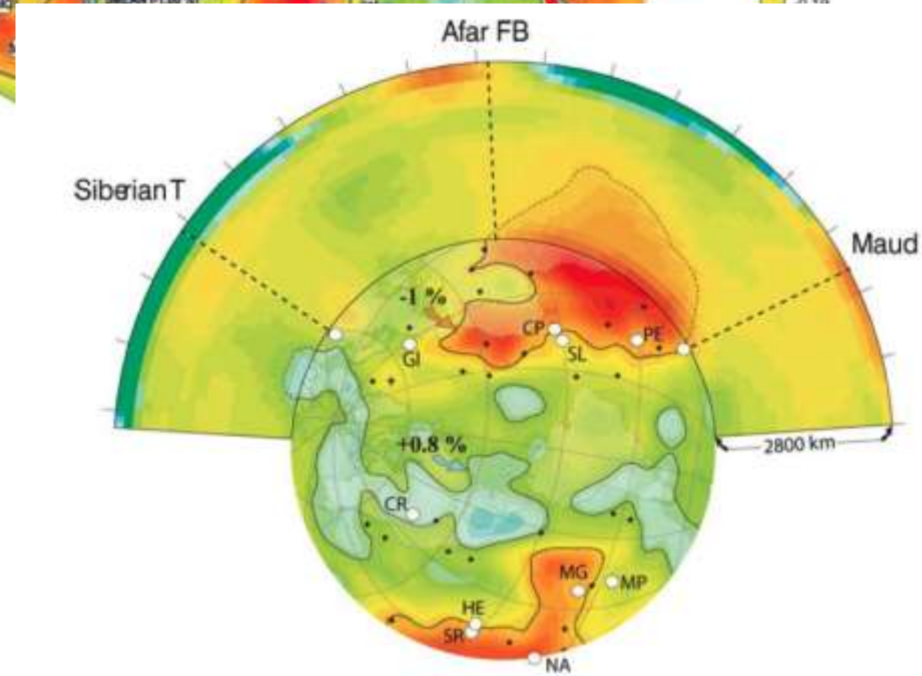
δz_dyn [km]
4
2
0
-2
-4
60°
40°
20°
0°
-20°
20°
40°
60°
80°
100°
120°
140°



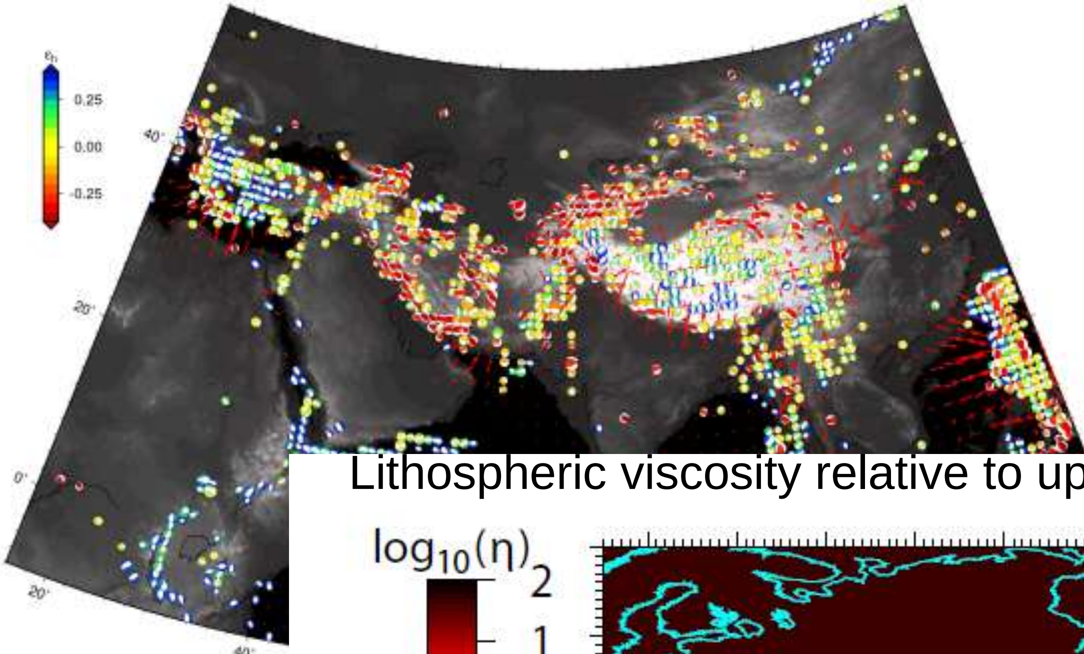
0 - 615 km, v_{RMS} = 1.6 cm/yr
a)
660 - 1505 km, v_{RMS} = 0.6 cm/yr
b)
1577 - 2891 km, v_{RMS} = 0.8 cm/yr
c)
T 0.60 0.55 0.50 0.45 0.40
Afar
Tethyan belt
Cordillera
Africa swell
Pacific swell
d)
T 0.4 0.5 0.6


0° E
60° N
60° S
Pacific LLSVP
Africa LLSVP
25 reconstructed large igneous provinces, 15–297 Myr ago
1,395 kimberlites, 27–320 Myr ago
Active hotspots with a deep plume origin
−2.50
−1.00
0.00
2.50
δV_S (%)

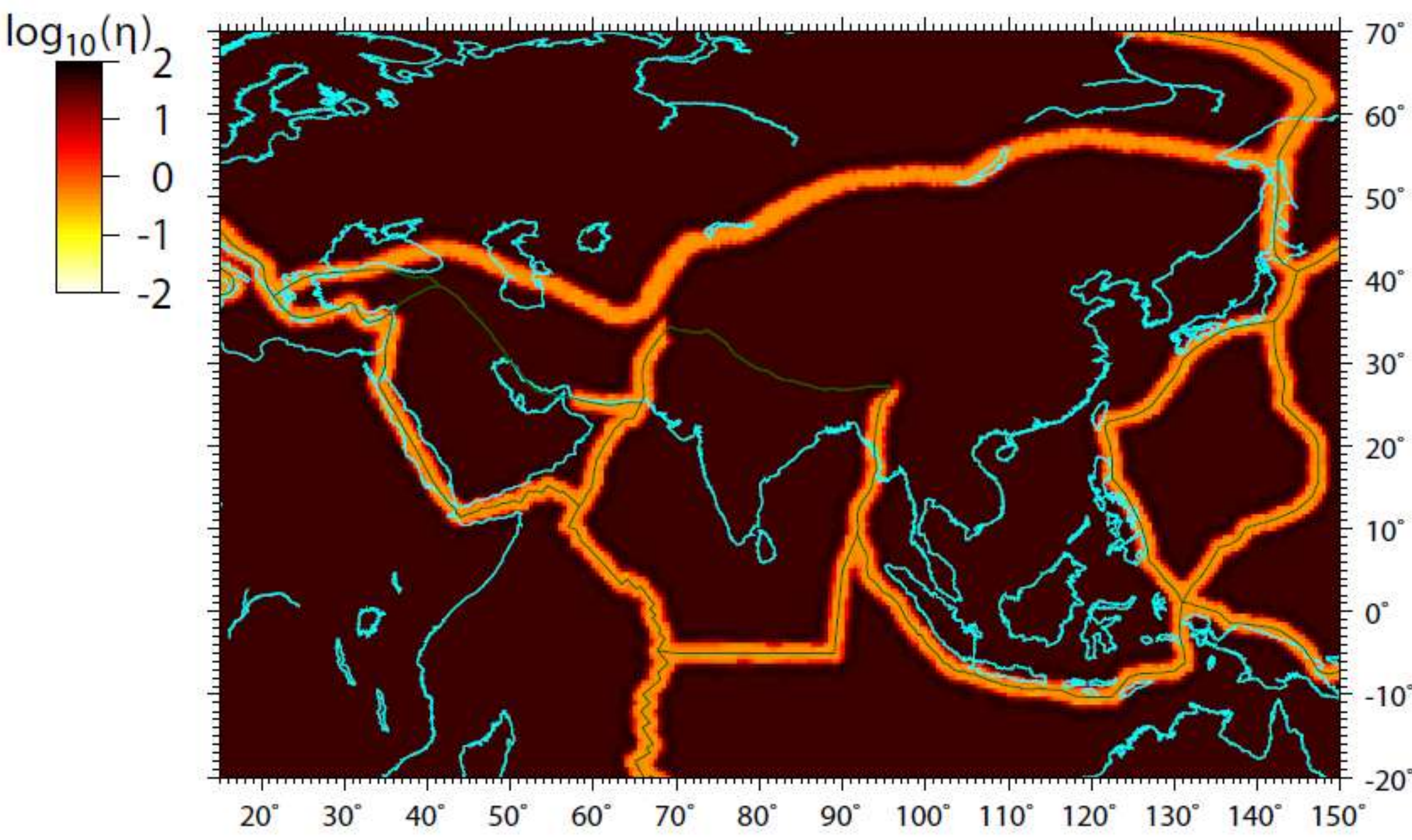

SMEAN, 2800 km
dVs (%)
2.25
1.86
1.54
1.27
1.01
0.80
0.58
0.35
0.09


Afar FB
Siberian T
Maud F
2800 km
-1 %
+0.8 %
CP
PE
SL
GI
CR
MG
MP
HE
SR
NA

Weak zone geometry

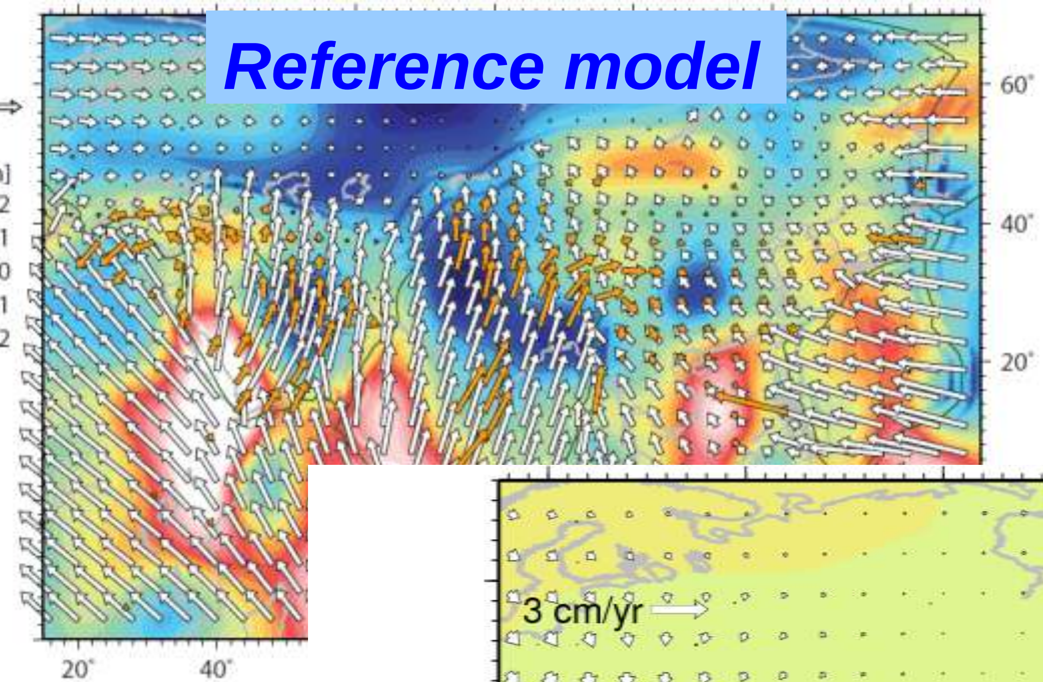


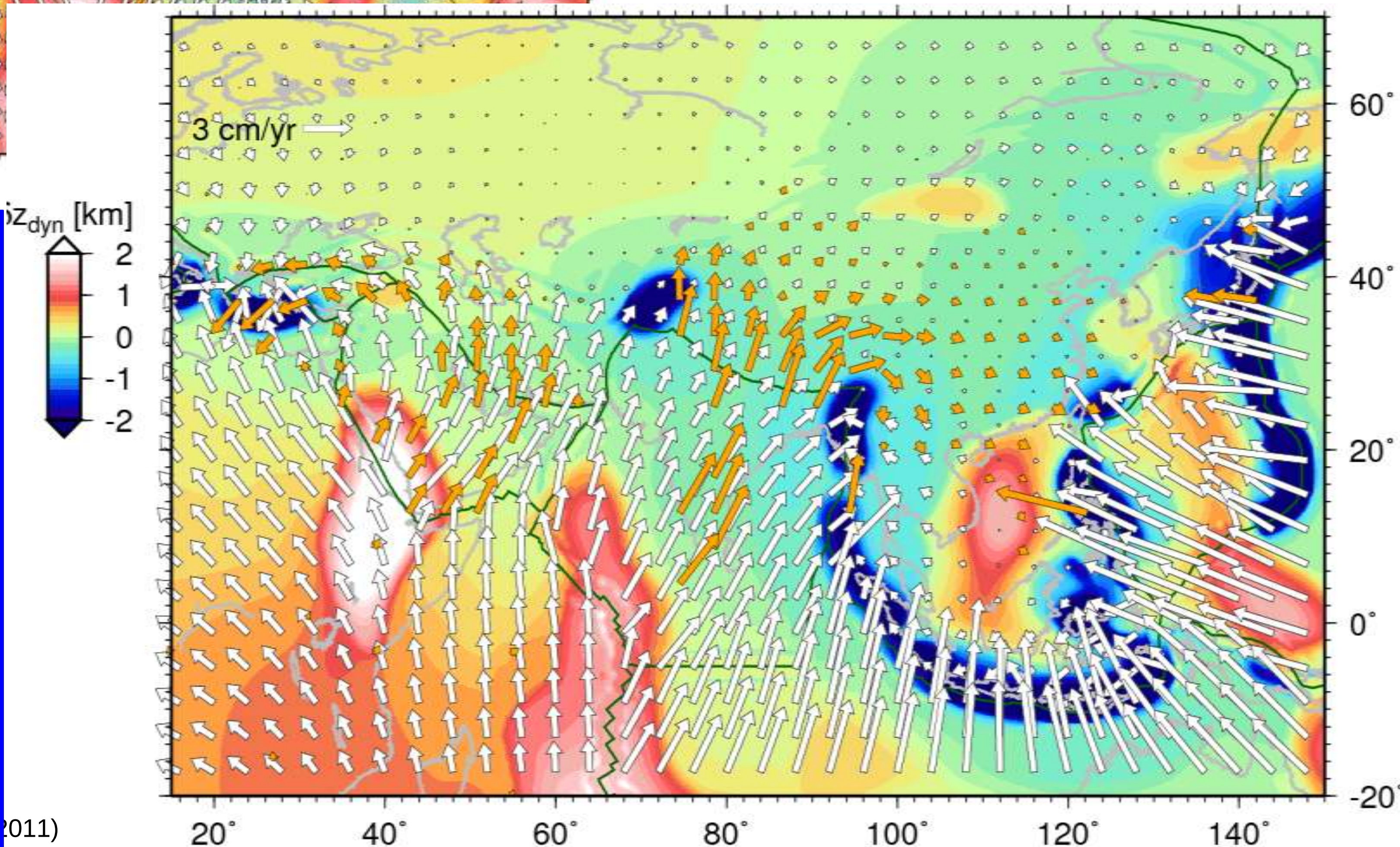
Lithospheric viscosity relative to upper mantle reference



Becker & Faccenna (2011)

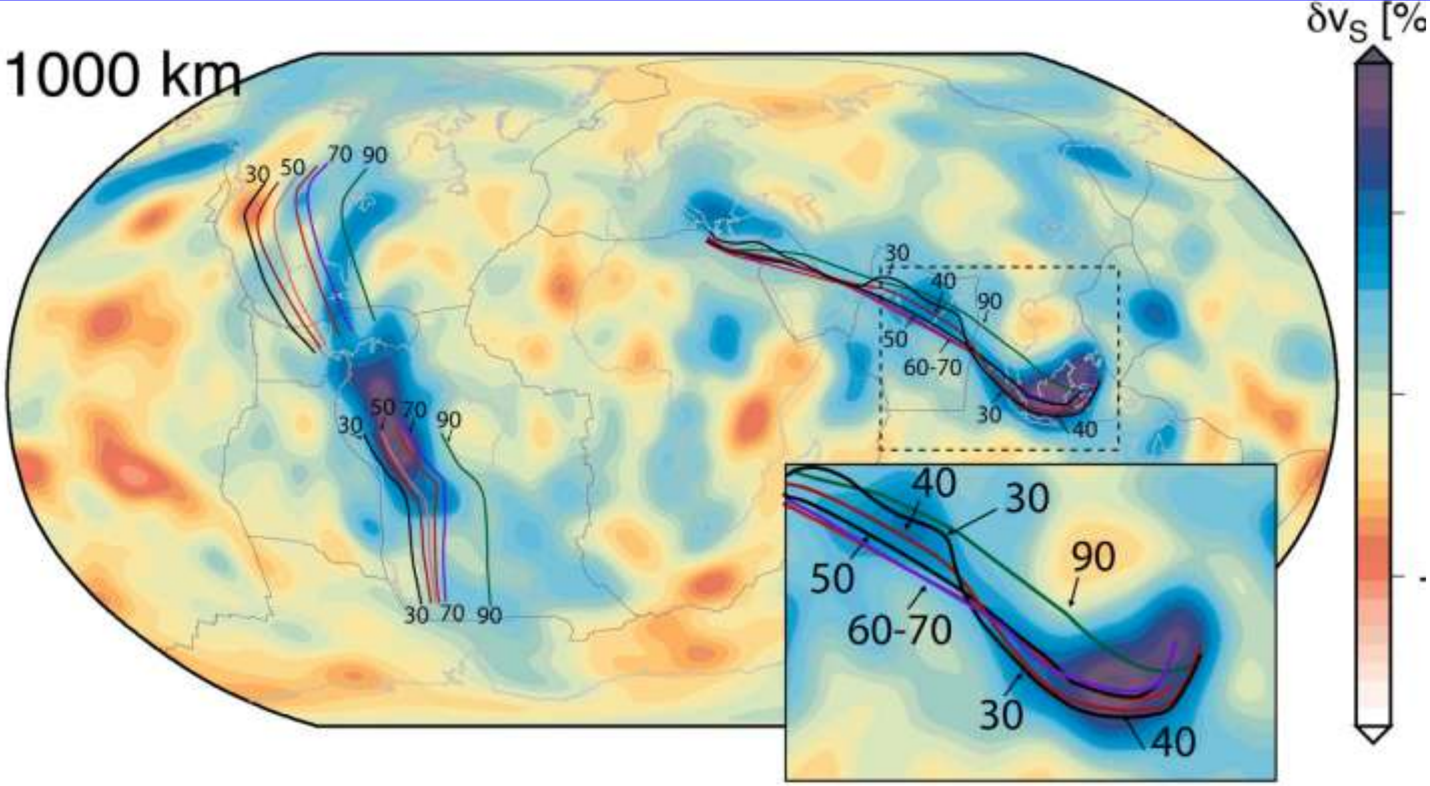
Reference model





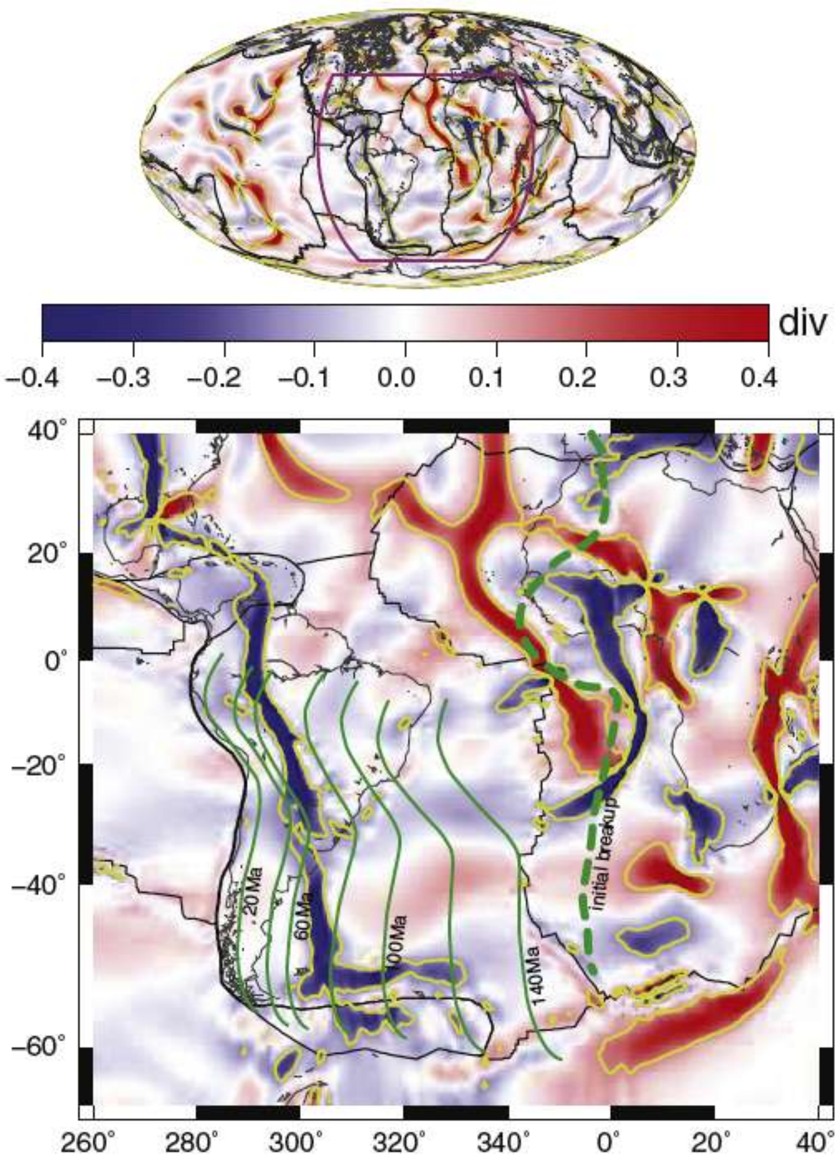
2011)

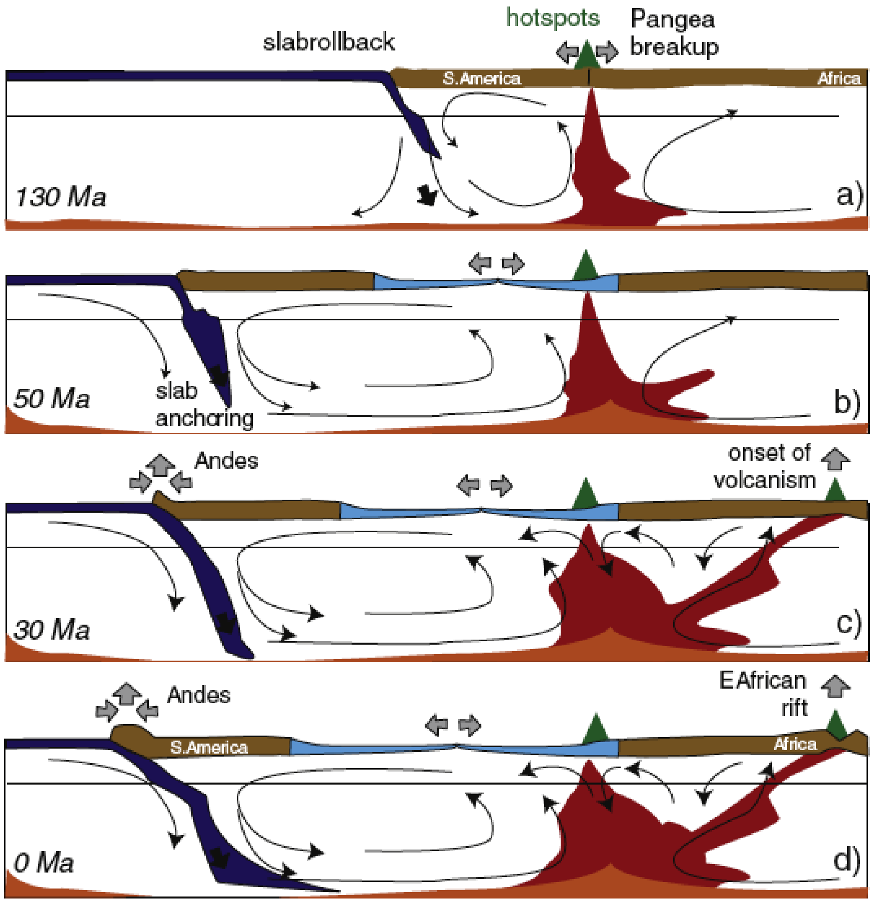
When the system started ?



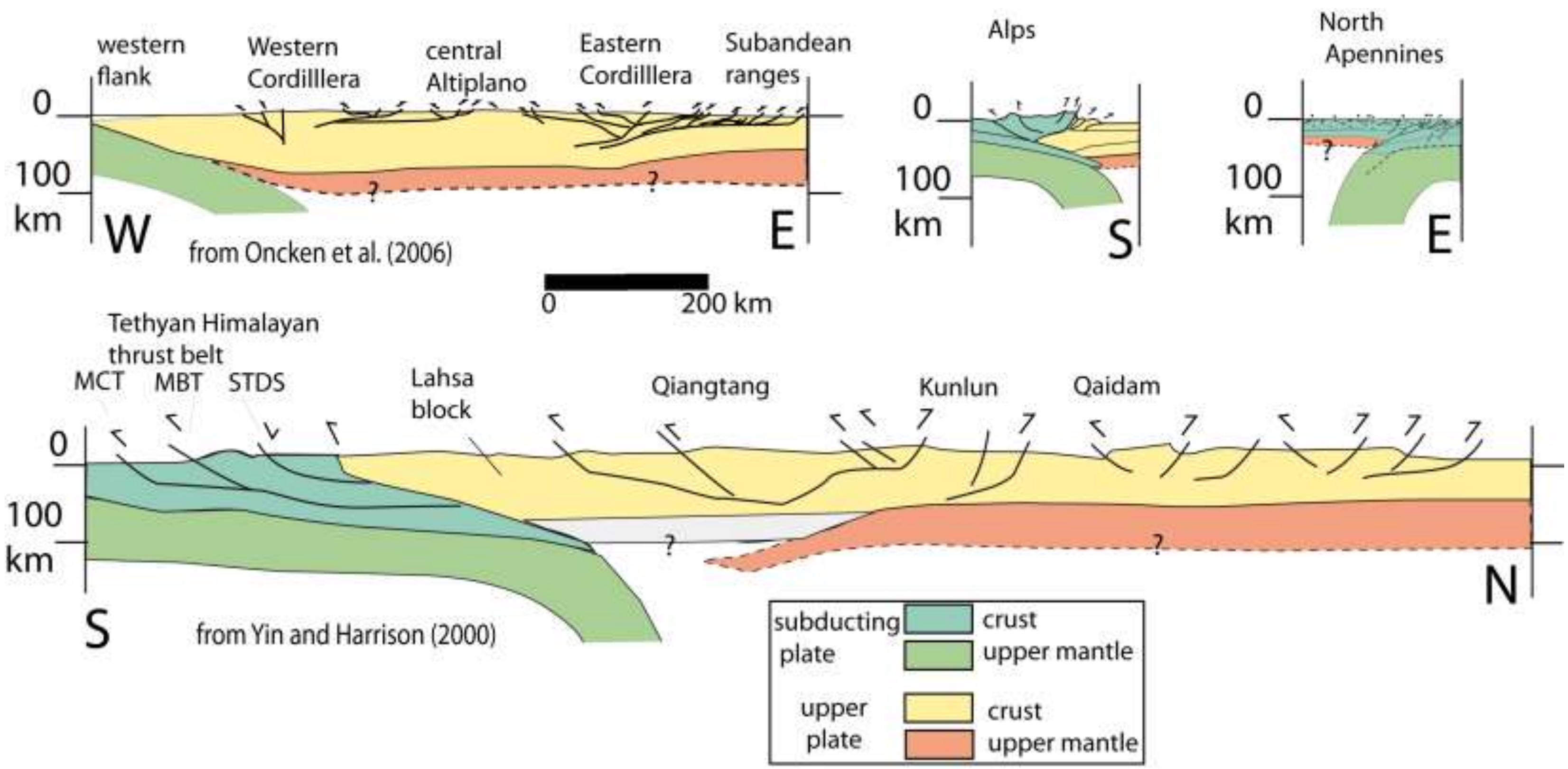
Absolute Trench position (Muller et al., 2008) with respect to deep high velocity anomaly (Smean) gives

The origin of the Andes

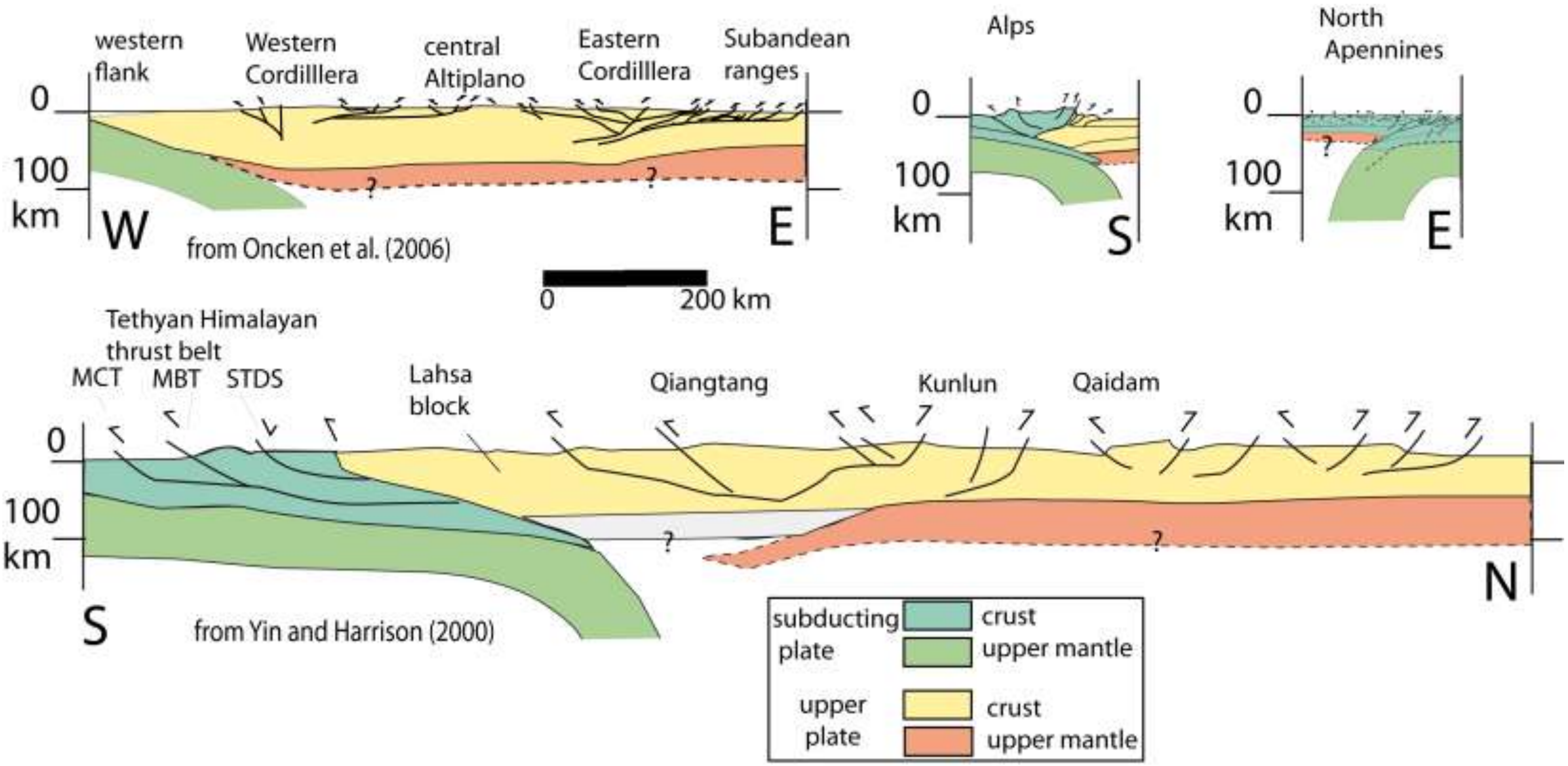


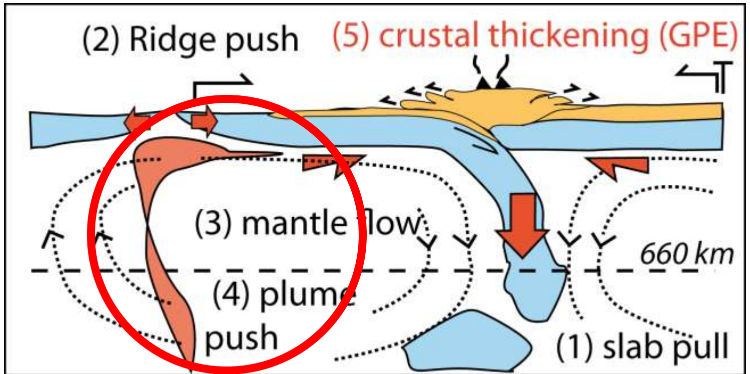


Onset of whole mantle
 convection
And the rise of the Andes

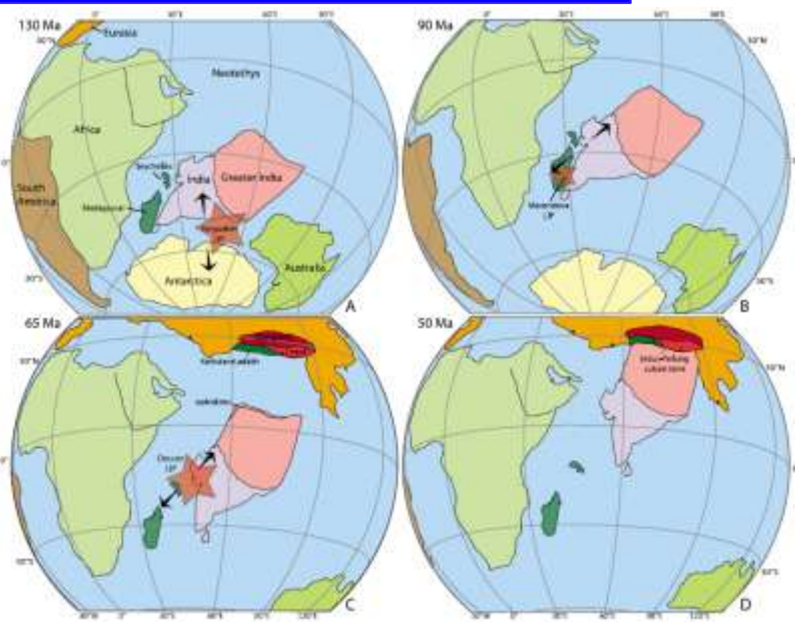

western
flank
Western
Cordilllera
central
Altiplano
Eastern
Cordilllera
Subandean
ranges
0
100
km
W
E
?
?
from Oncken et al. (2006)
Alps
0
100
km
S
North
Apennines
0
100
km
E
?
0
200 km
Tethyan Himalayan
thrust belt
MCT
MBT
STDS
Lahsa
block
Qiangtang
Kunlun
Qaidam
0
100
km
S
N
?
?
from Yin and Harrison (2000)
subducting
plate
crust
upper mantle
upper
plate
crust
upper mantle

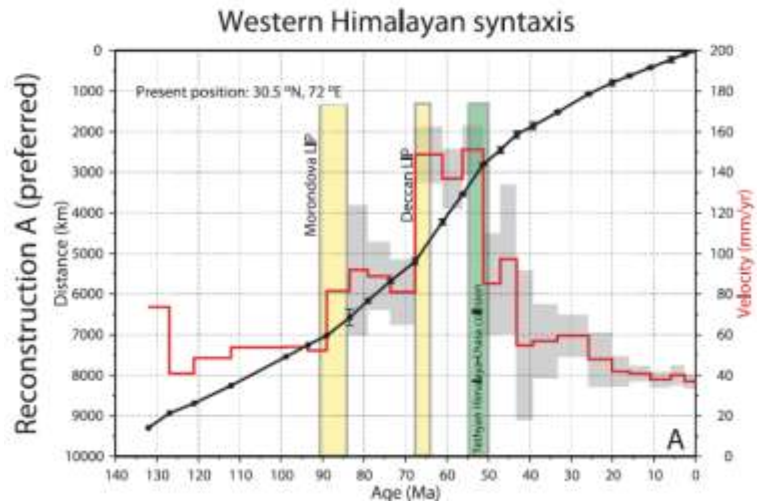
Scale of orogenic belts

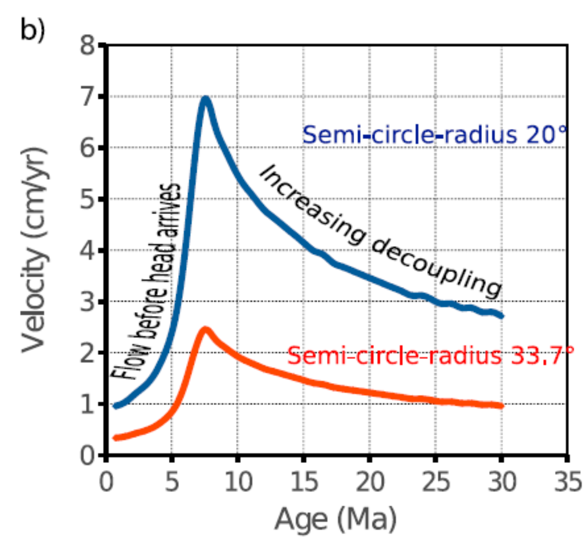




III) Plume push

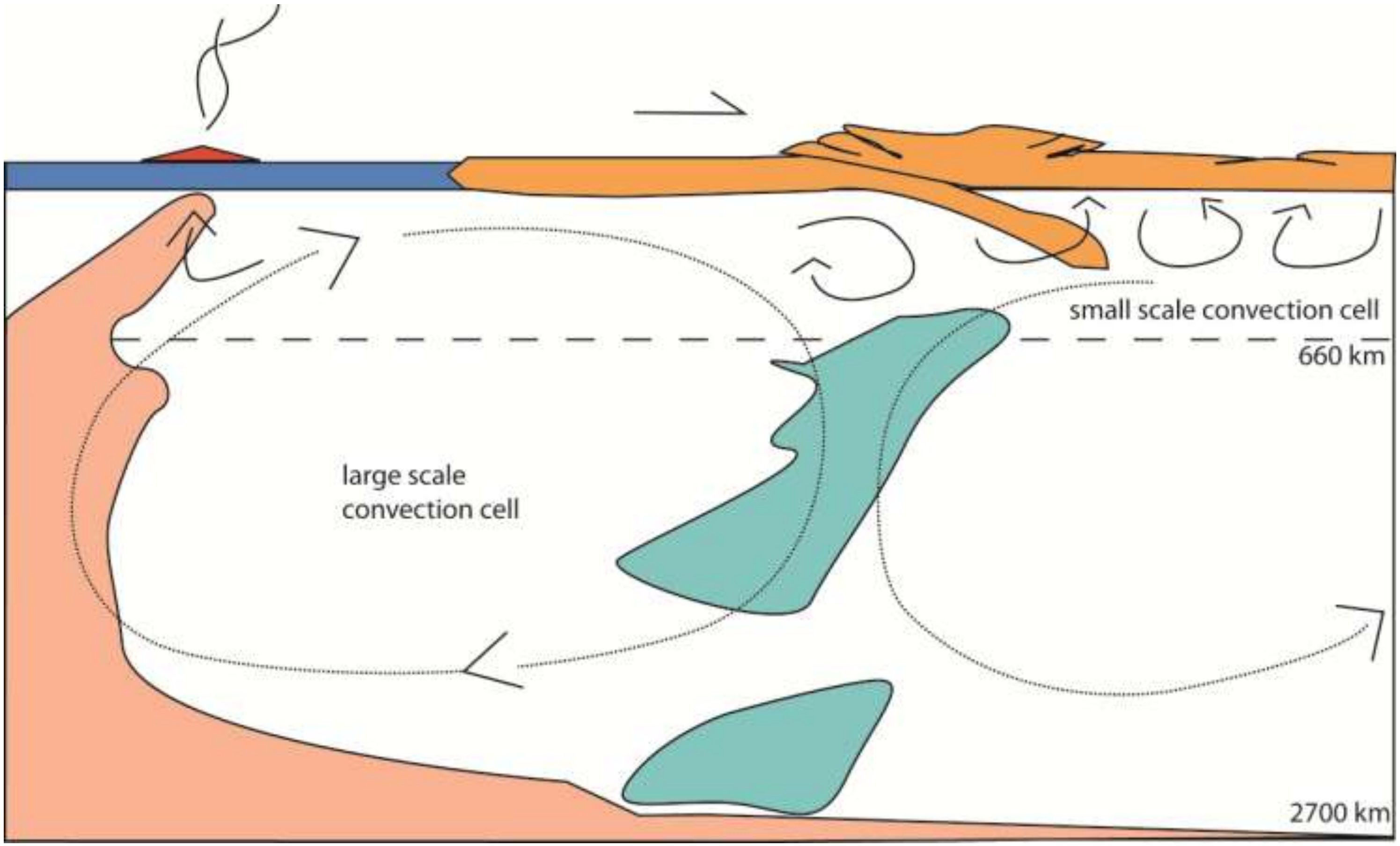






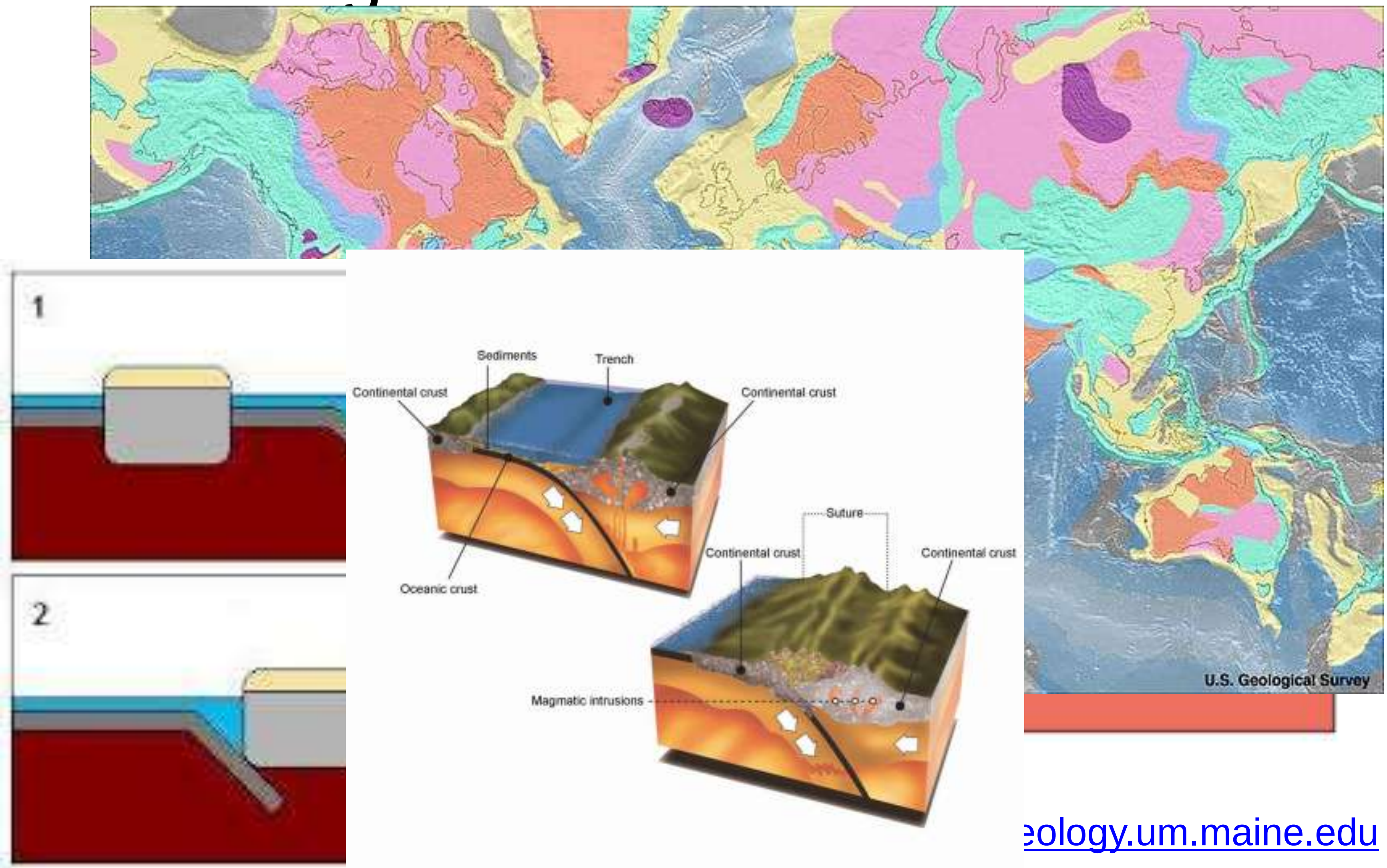
- Plume head arrival does lead to temporary increases in plate speeds
- Plume might weaken coupling to drag on plate from asthenosphere

multiscale convection model



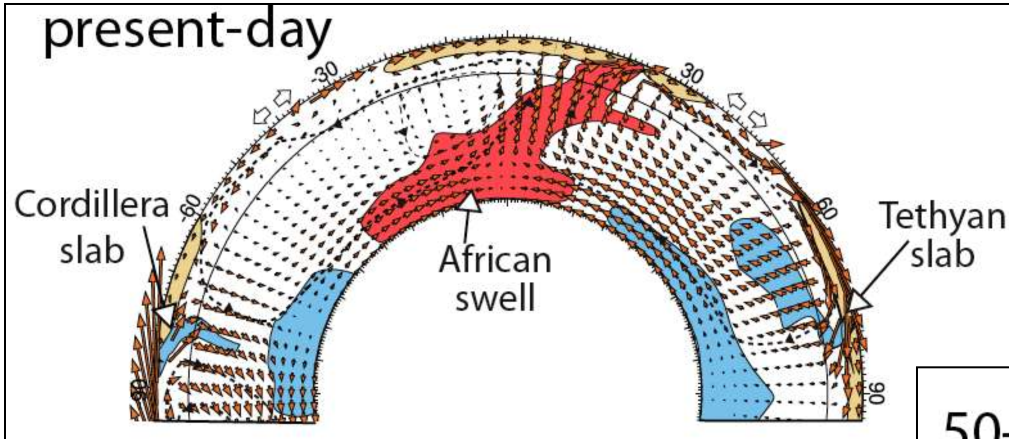
Mountain belt is generated and sustained by deep mantle flow

The style of mantle convection is particularly relevant to understand the growth of continental crust



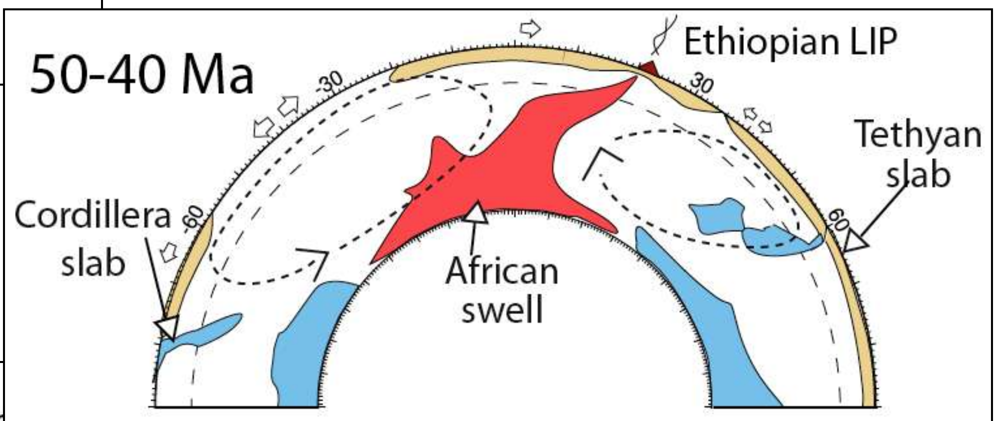
eology.um.maine.edu

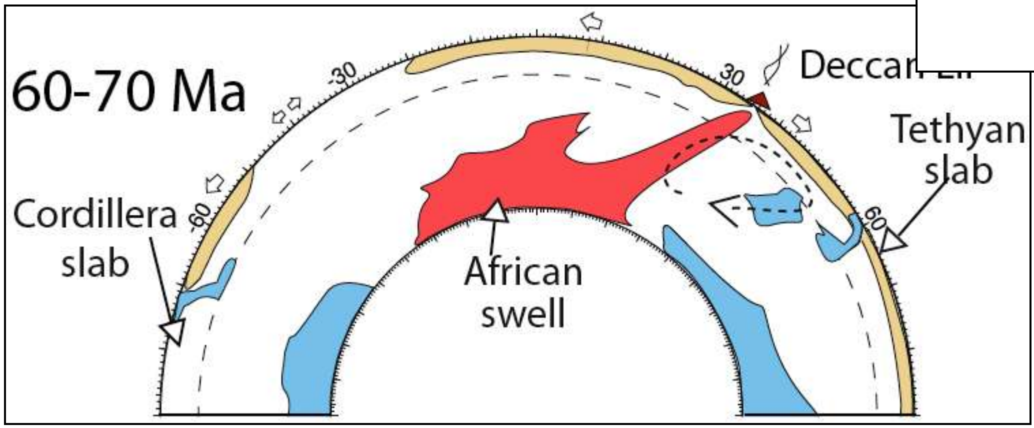
deep root of mountain building: Himalaya –Africa- Andes connection



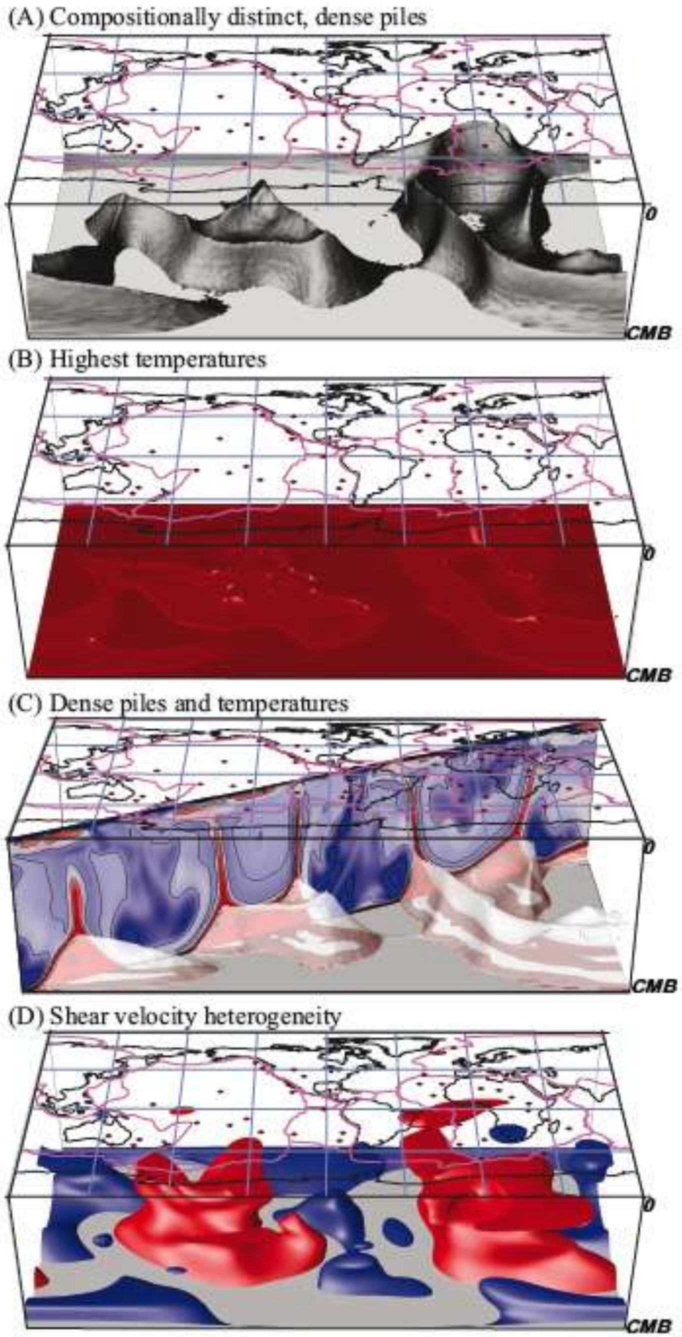
Indo-Atlantic circuit

Andean-Atlantic deep circuit:
Deep subduction and Afar upwelling





Tethyan deep circuit:
Onset of deep subduction and Reunion upwelling



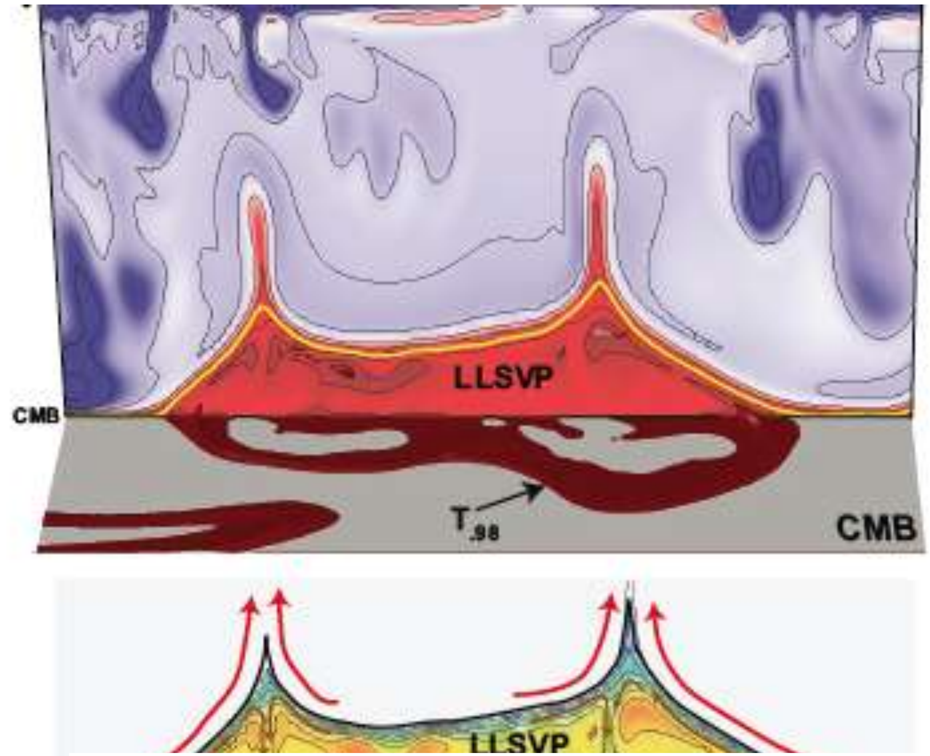
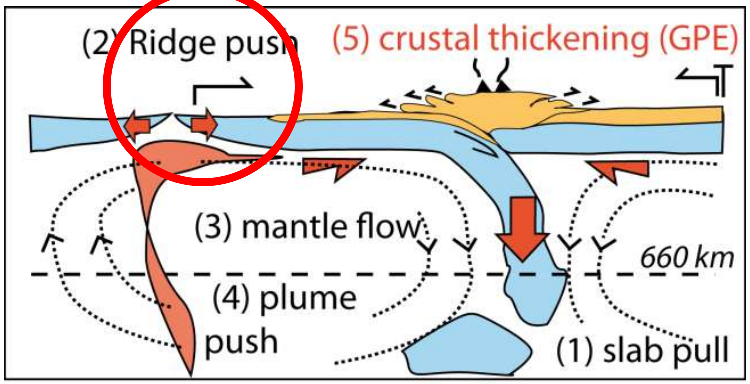


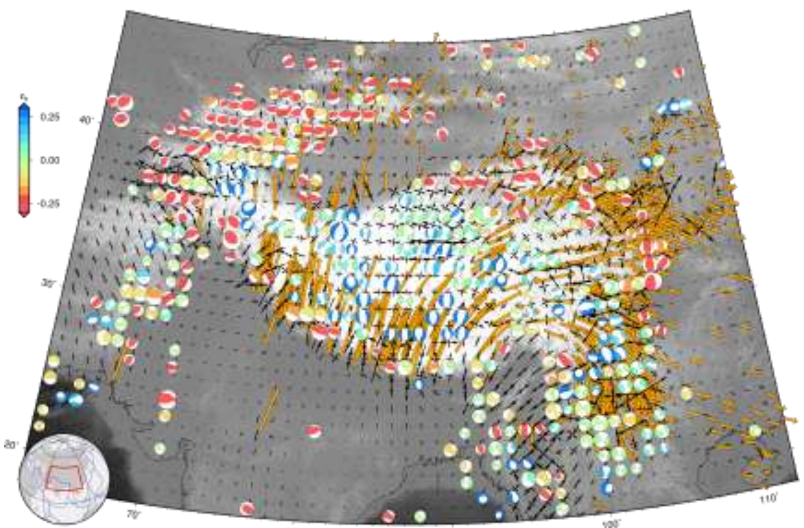
Figure 4. A close-up of the thermochemically dense pile beneath the Pacific Ocean in Figure 3A. (A) A cross-section from the surface to the core-mantle boundary (CMB) displays temperature variations, with the yellow line denoting the boundary of the chemically distinct material in the pile. We identify the thermochemical anomaly as the large low–shear velocity province (LLSVP). Part of the CMB surface is shown in front of the cross-section, along with an isotemperature contour (at 0.98, as in Fig. 3). (B) The same cross-section, but only the pile, with a more expanded color scale (colors span T = 0.7 to 1.0). Convective motions are indicated by the arrows. The hottest zones may invoke partial melt of LLSVP material, either at the CMB (denoted as an ultra-low velocity zone [ULVZ] in the figure), or in some isolated locations farther up within the LLSVP.

II) Ridge push



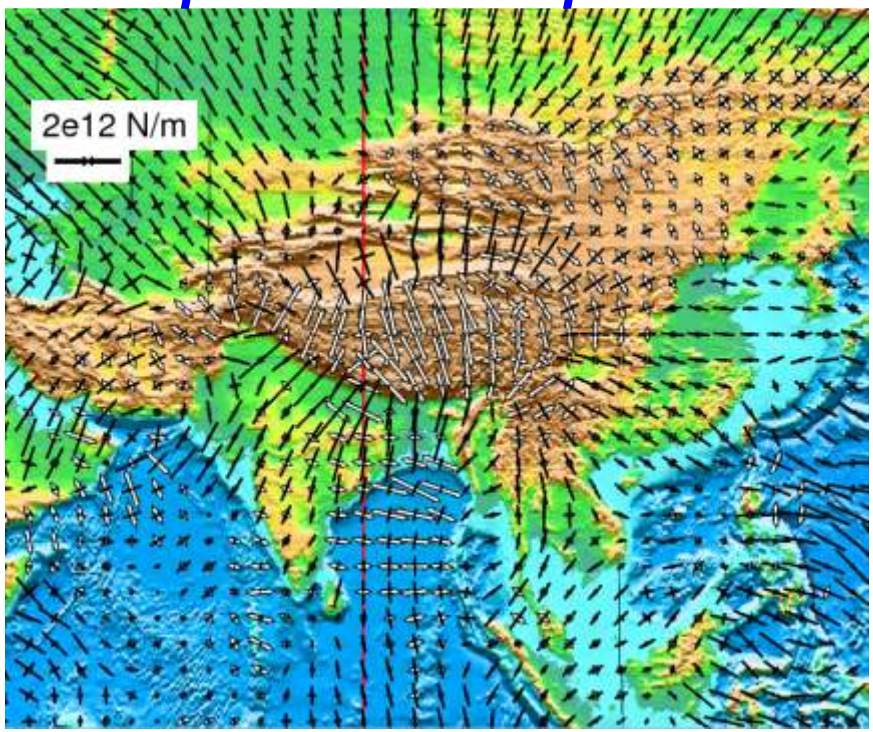
- Ridge push ain't doing it
- Need additional N-S compressive (India driving) force from the mantle (~2.5 10^{12} N/m)

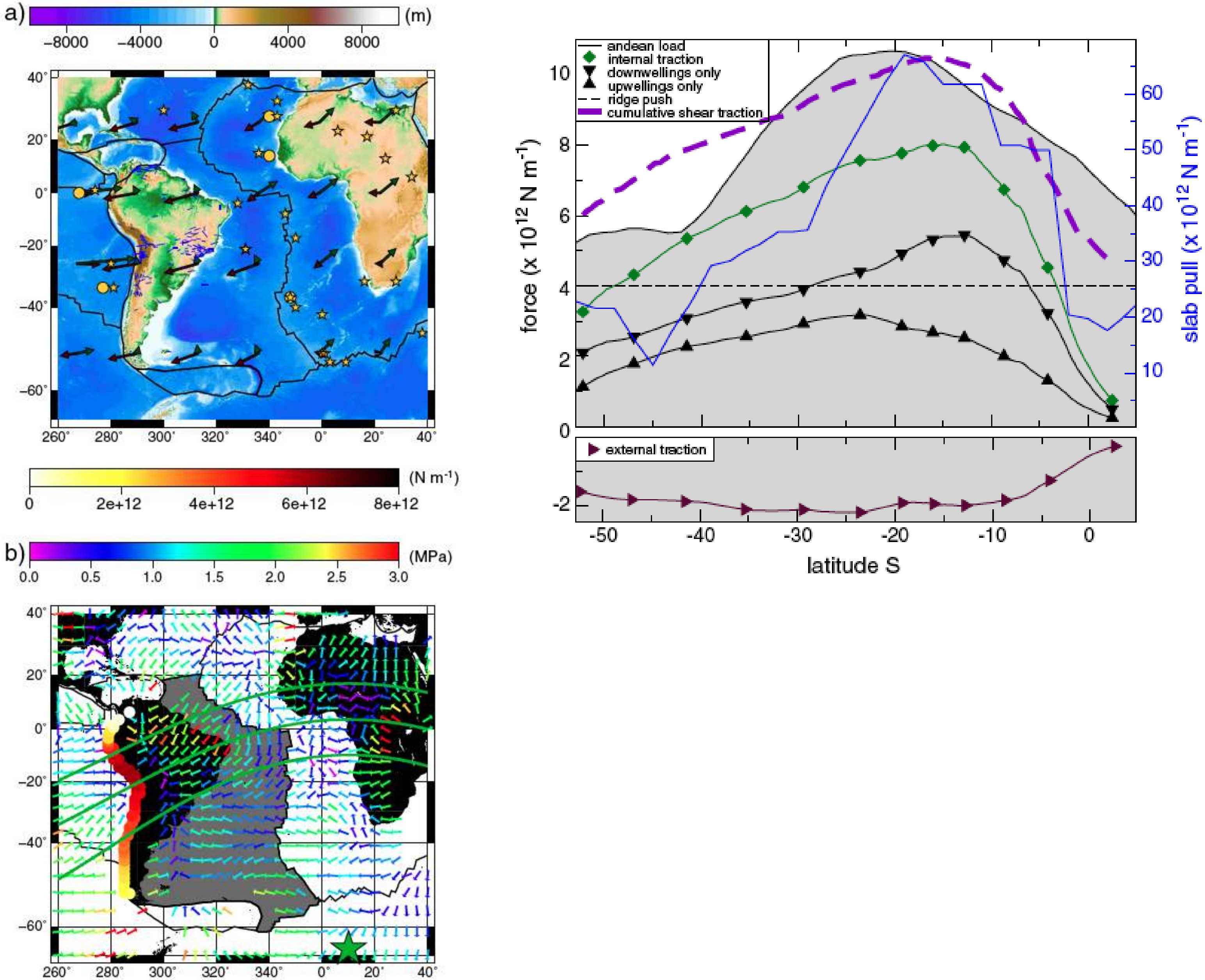
Geodetic and coseismic deformation



White sticks: major extensional axes,
Black sticks: compressive Axes (*Ghosh et al., 2006*)

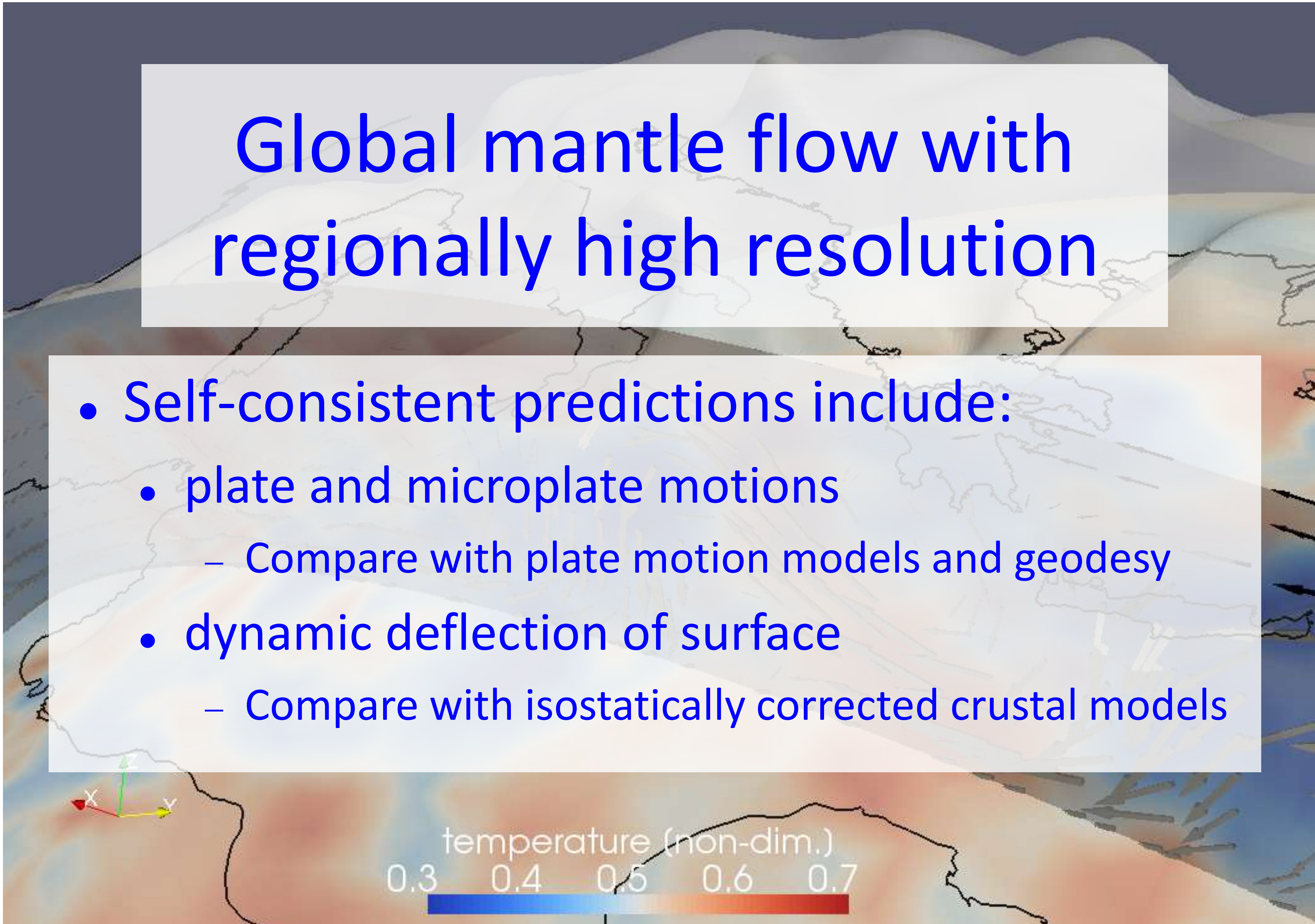
Lithospheric model predictions




a)
(m)
-8000 -4000 0 4000 8000
40° 20° 0° -20° -40° -60°
260° 280° 300° 320° 340° 0° 20° 40°
(N m-1)
0 2e+12 4e+12 6e+12 8e+12
b)
(MPa)
0.0 0.5 1.0 1.5 2.0 2.5 3.0
andean load
internal traction
downwellings only
upwellings only
ridge push
cumulative shear traction
force (x 10^12 N m^-1)
slab pull (x 10^12 N m^-1)
external traction
latitude S
-50 -40 -30 -20 -10 0

Global mantle flow with regionally high resolution

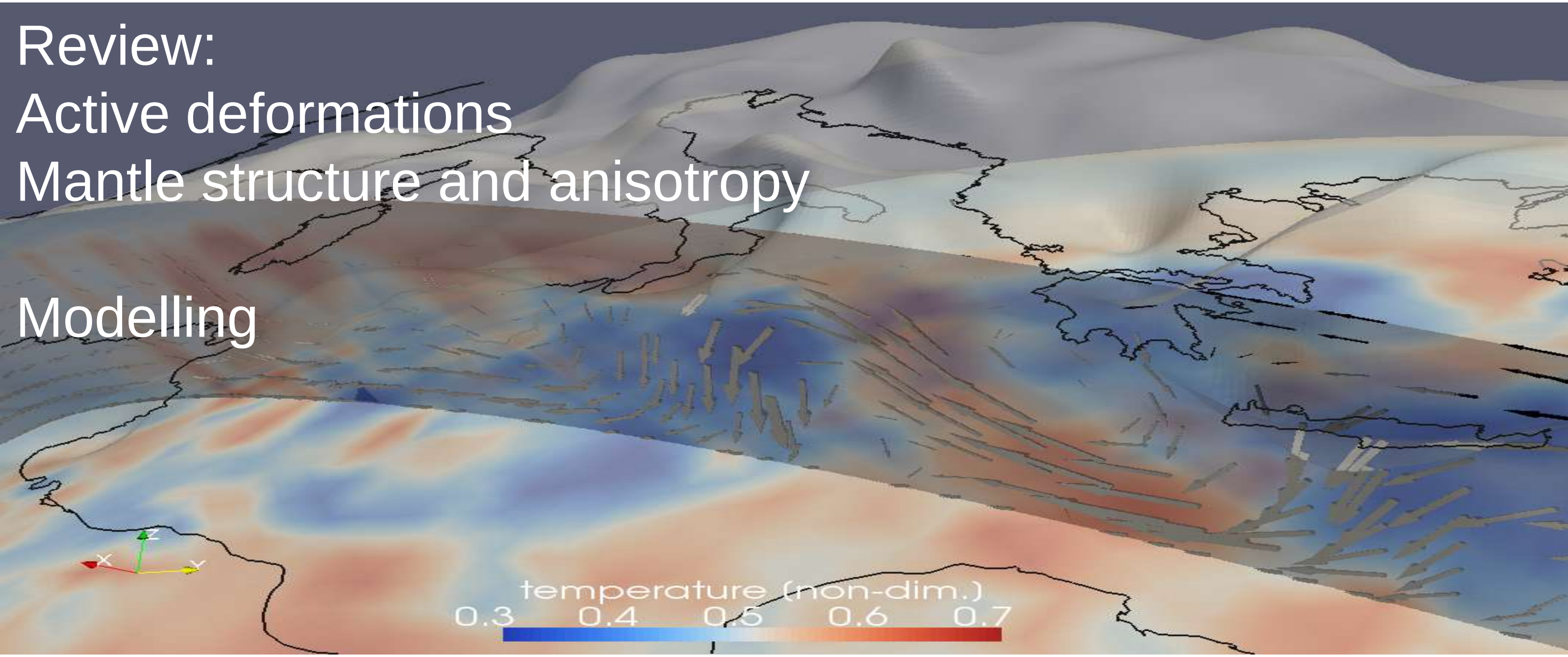
- Self-consistent predictions include:
  - plate and microplate motions
    - Compare with plate motion models and geodesy
  - dynamic deflection of surface
    - Compare with isostatically corrected crustal models



Can we reconstruct the pattern of mantle convection ?
What is the role –if any- of deep mantle processes in shaping surface deformation ?

Review:
Active deformations
Mantle structure and anisotropy

Modelling



Faccenna et al. (2013) submitted to Rev. of Geophys.

Results

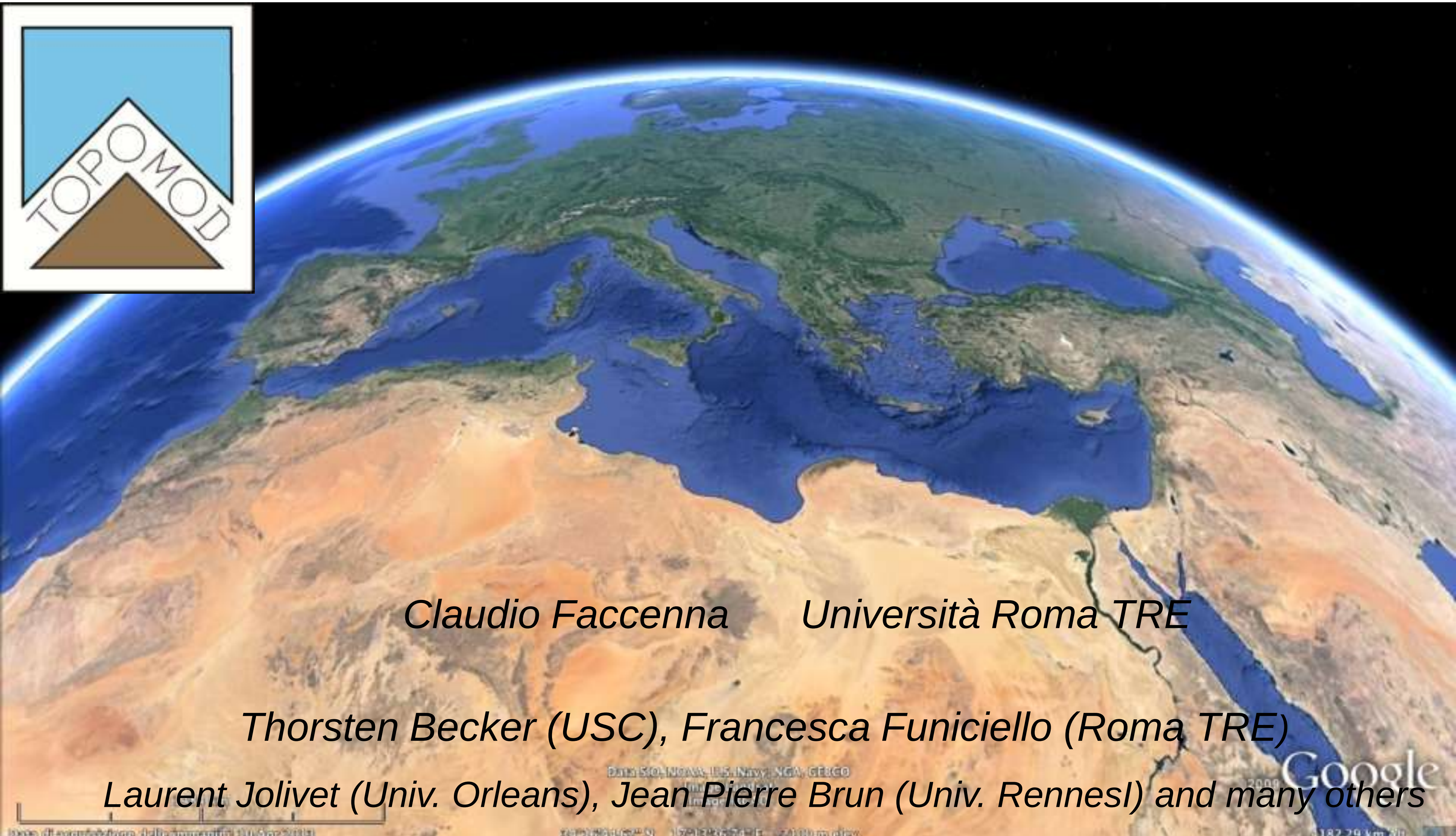
- Plate motion interactions play minor role
- Role of density distribution
    - Slab effect insufficient to drive India motion, but leads to slab suction as seen in geodesy
    - Active upwelling component associated with African plume/Carlsberg ridge main driver of India motion
- Can fit explain most present-day plate motions and dynamic topography by conveyor belt
- Can not fit SE escape motion, perhaps due to decoupling and/or driving by GPE (not included)

(e.g. Clark et al., 2005; Flesch et al., 2005; Sol et al., 2007)

Conclusions

- Global mantle circulation models can be used to probe intraplate deformation and plate motions with high regio realism
- A whole mantle convection cell exists between India wit strong upwelling, plume-associated component
- This conveyor belt sustains the Tethyan collision and Ar
- In region of high resolution seismic data, a multiscale s convection appears

Mantle dynamic in the Mediterranean



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Laurent Jolivet (Univ. Orleans), Jean Pierre Brun (Univ. Rennesl) and many others