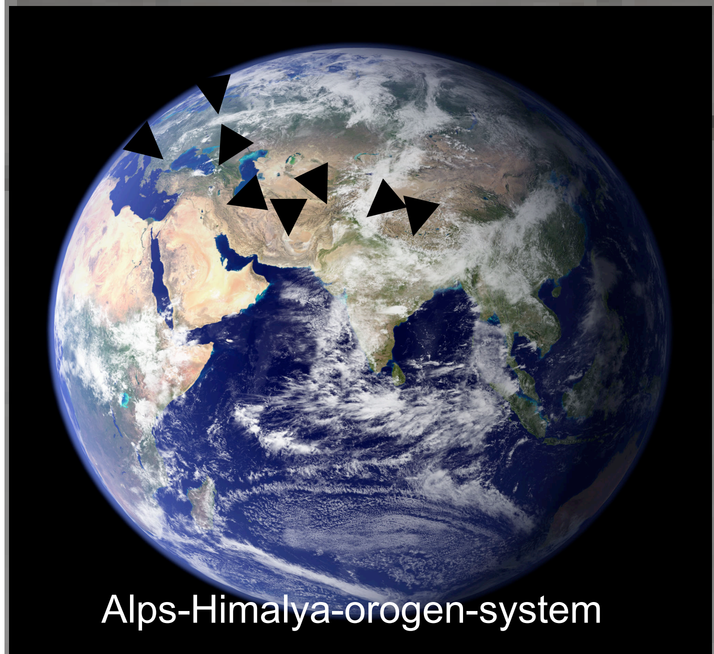
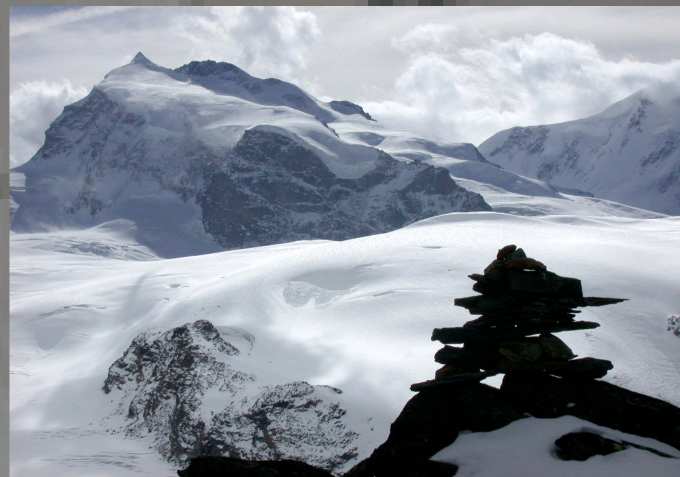
11th workshop on Modeling of Mantle Convection and Lithosphere Dynamics

Alpine lithosphere tectonics and geodynamics

+ a few hypotheses based on deep structure and geologic record

Edi Kissling, ETH Zürich





June 29 -July 3, 2009 Braunwald, Switzerland

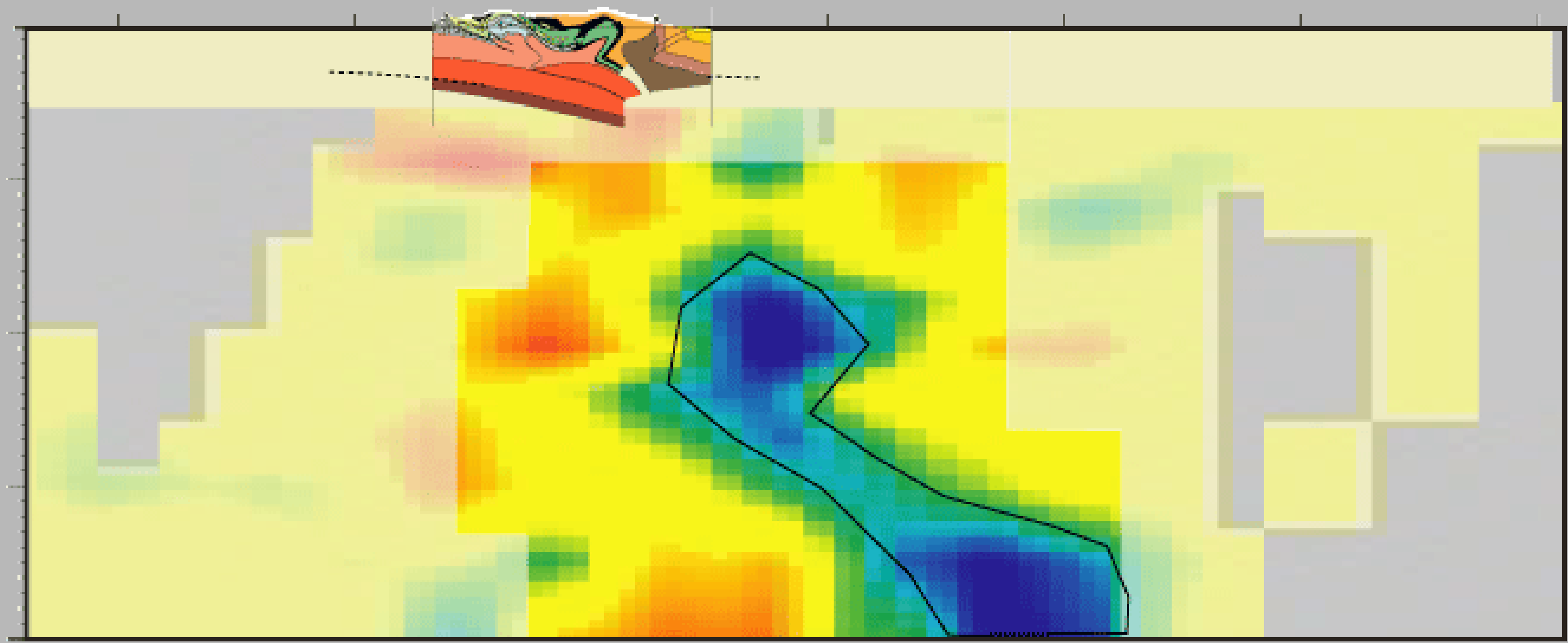
Objective of study and presentation summary

to further our understanding of past and current orogenic driving forces by Alpine-plate tectonics model

to discuss pivotal roles

of geologic record
of deep lithosphere structure
of kinematic record

for geodynamic modelling



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Swiss Federal Institute of Technology Zurich

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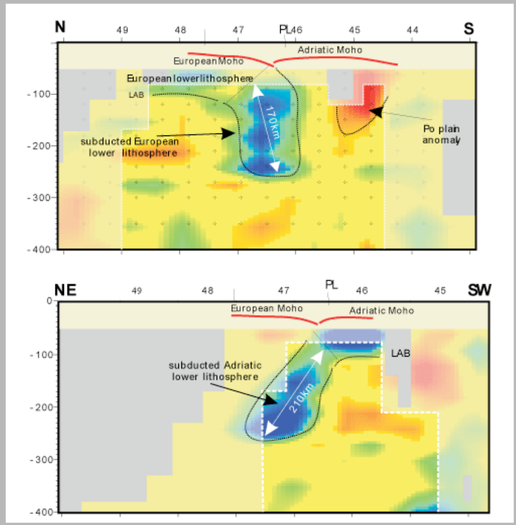


Tectonic setting and geologic overview Alps

Summary of information on deep structure of Alps

Analysis of present collision tectonics => lithosphere isostasy and main orogenic forces

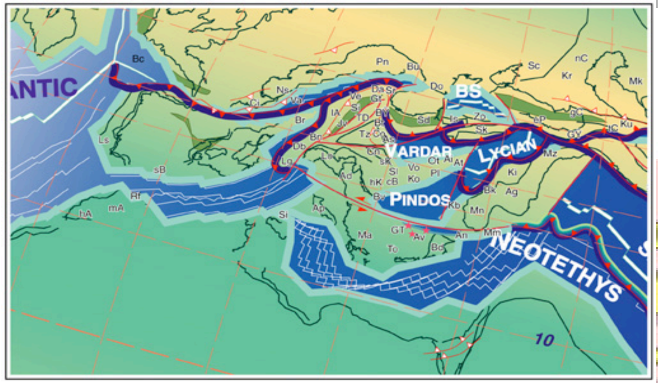
Application of generic plate models to episodes of Alpine evolution

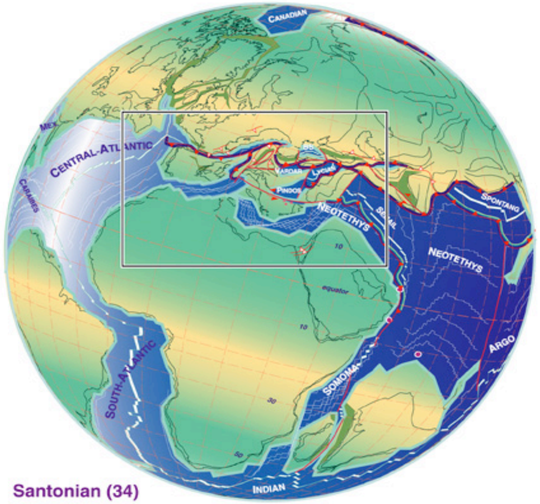
(hypotheses for testing by geodynamic modelling)

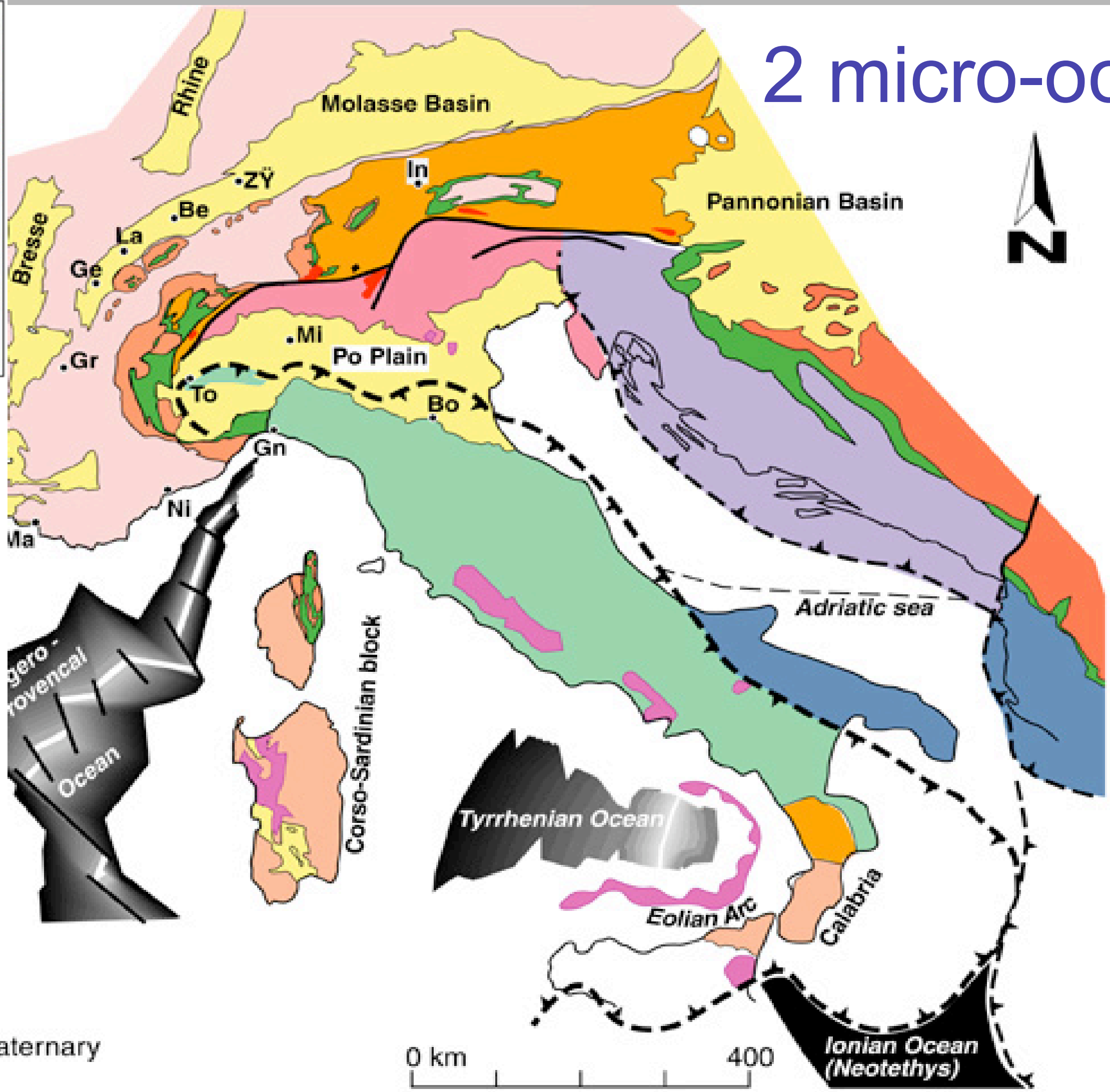
Present situation in Alpine-Mediterranean region: 2 big plates

+ 2 micro-continents

2 micro-oceans

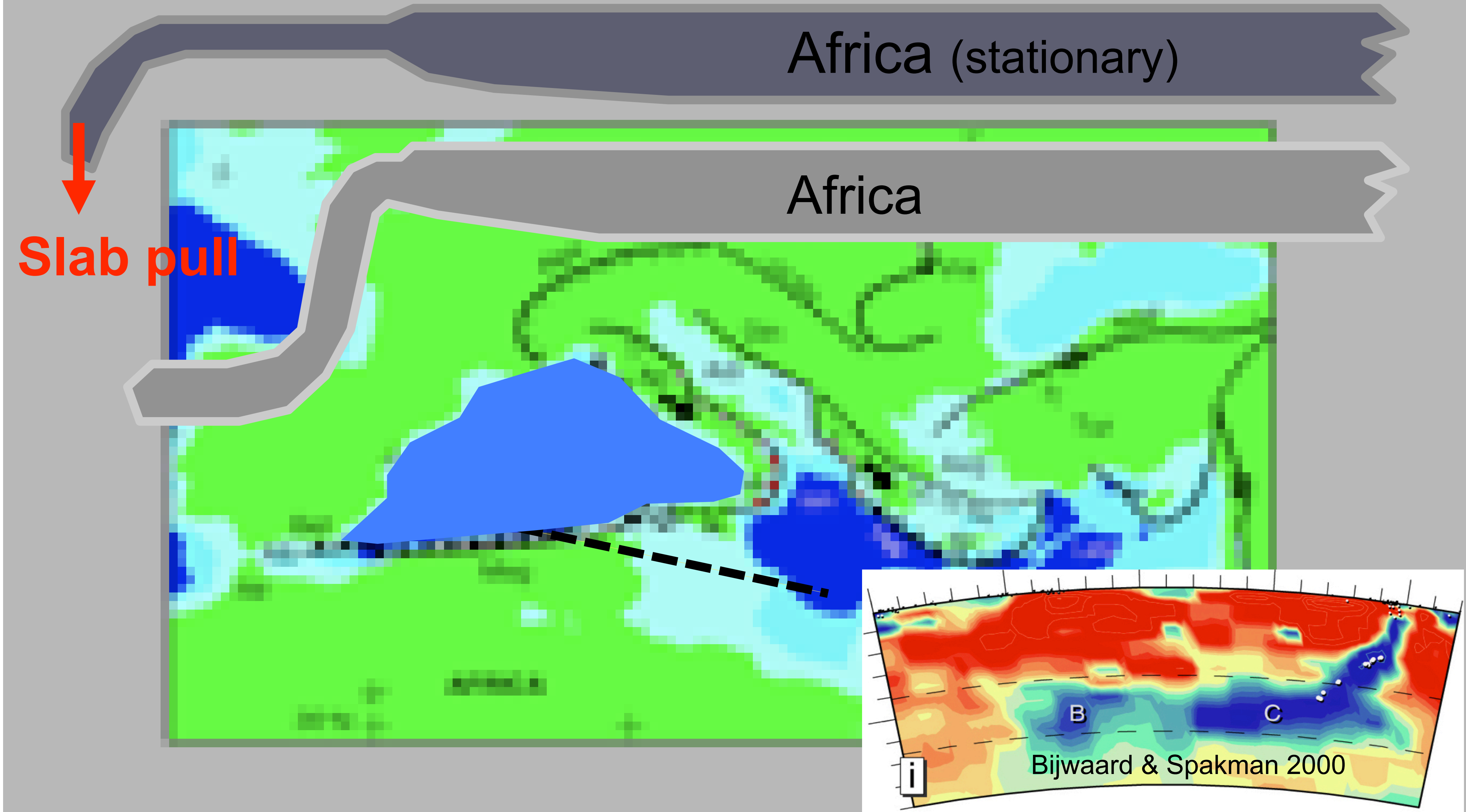






(from Stampfli et al., 2002)

Small oceans attached to large plate: slab retreat



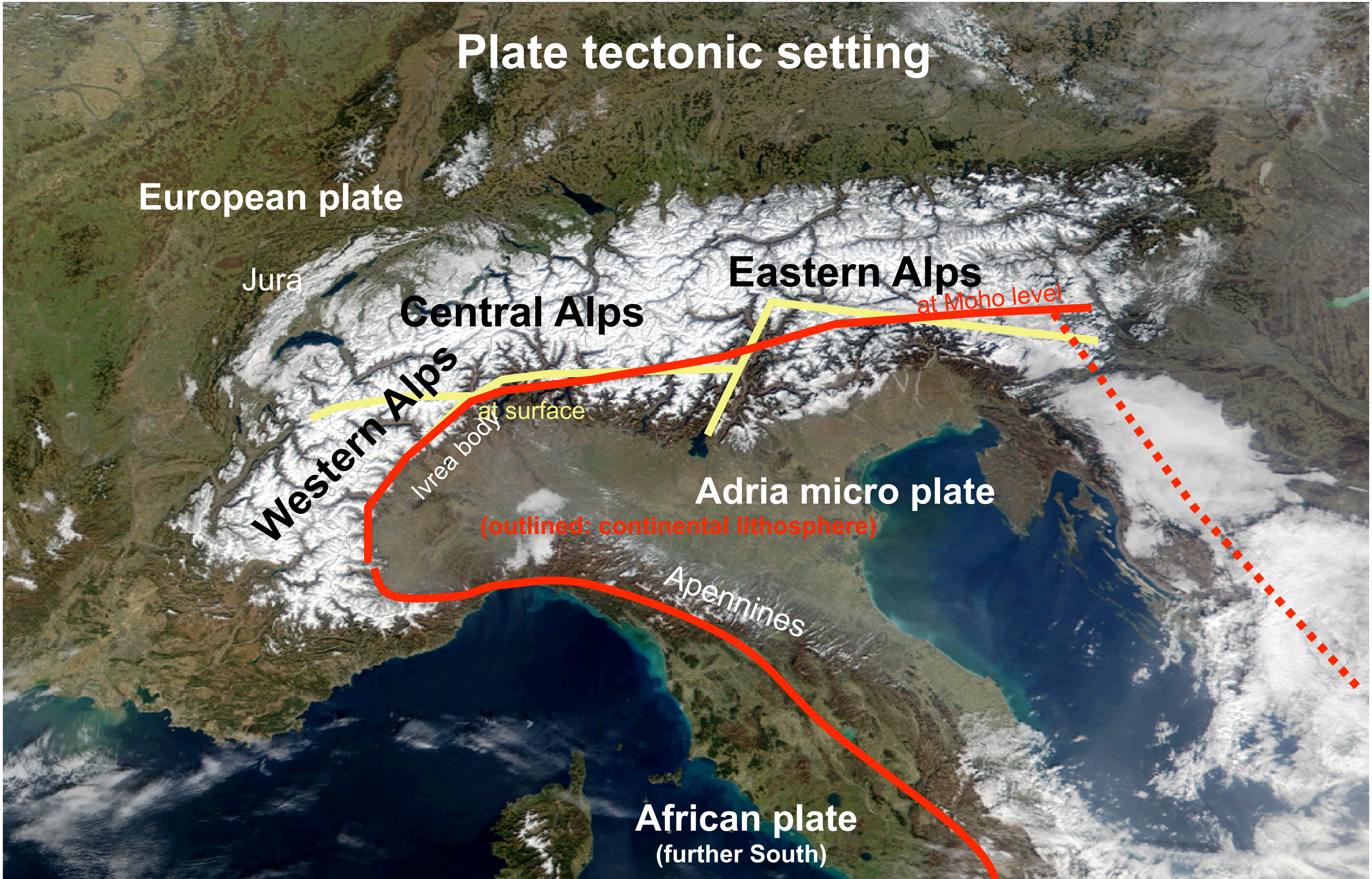
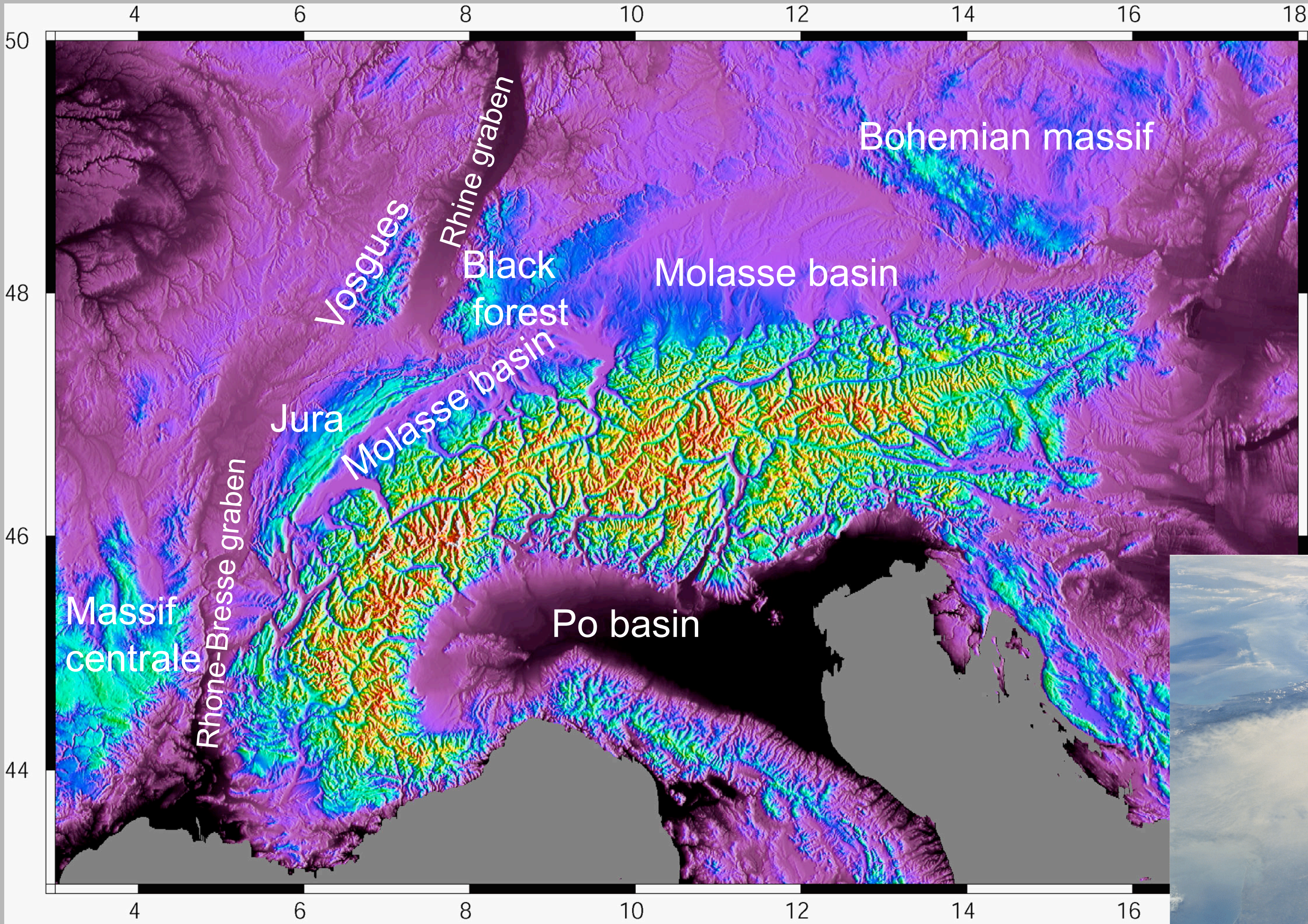


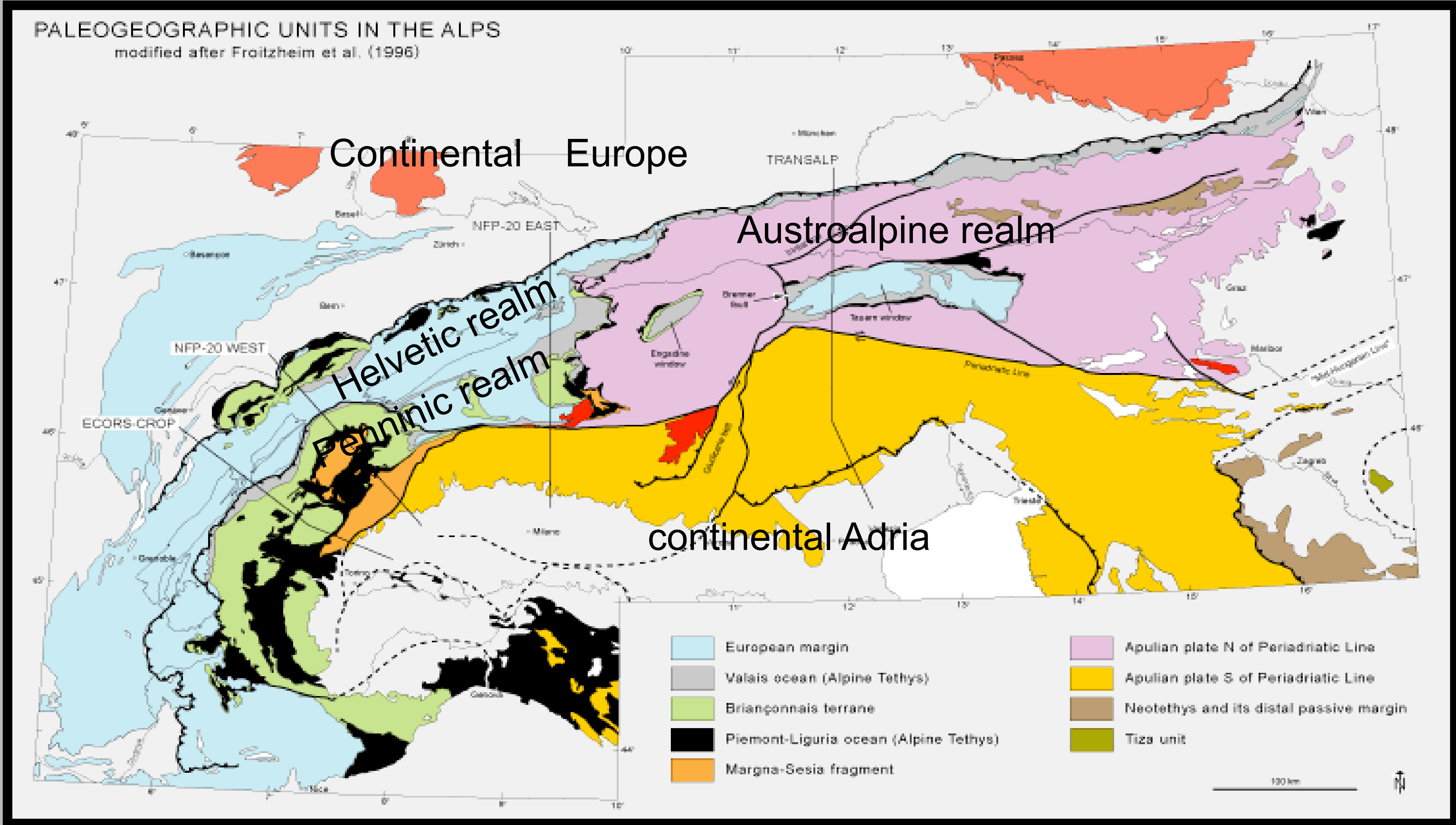
Plate tectonic setting
European plate
Jura
Central Alps
Eastern Alps
at Moho level
Western Alps
at surface
Ivrea body
Adria micro plate
(outlined: continental lithosphere)
Apennines
African plate
(further South)

Tectonic setting European foreland



Main tectonic units of Alpine orogen

Alps: tertiary orogeny (subduction since 65Ma, collision since 35Ma



continental Europe (cE), continental Adria (cA)

Nappes systems: Helvetic (cE margin), Penninic (extended fromer cE, oceanised), Austroalpine (southern derived thrust sheet of upper crust, cretacious orogeny)

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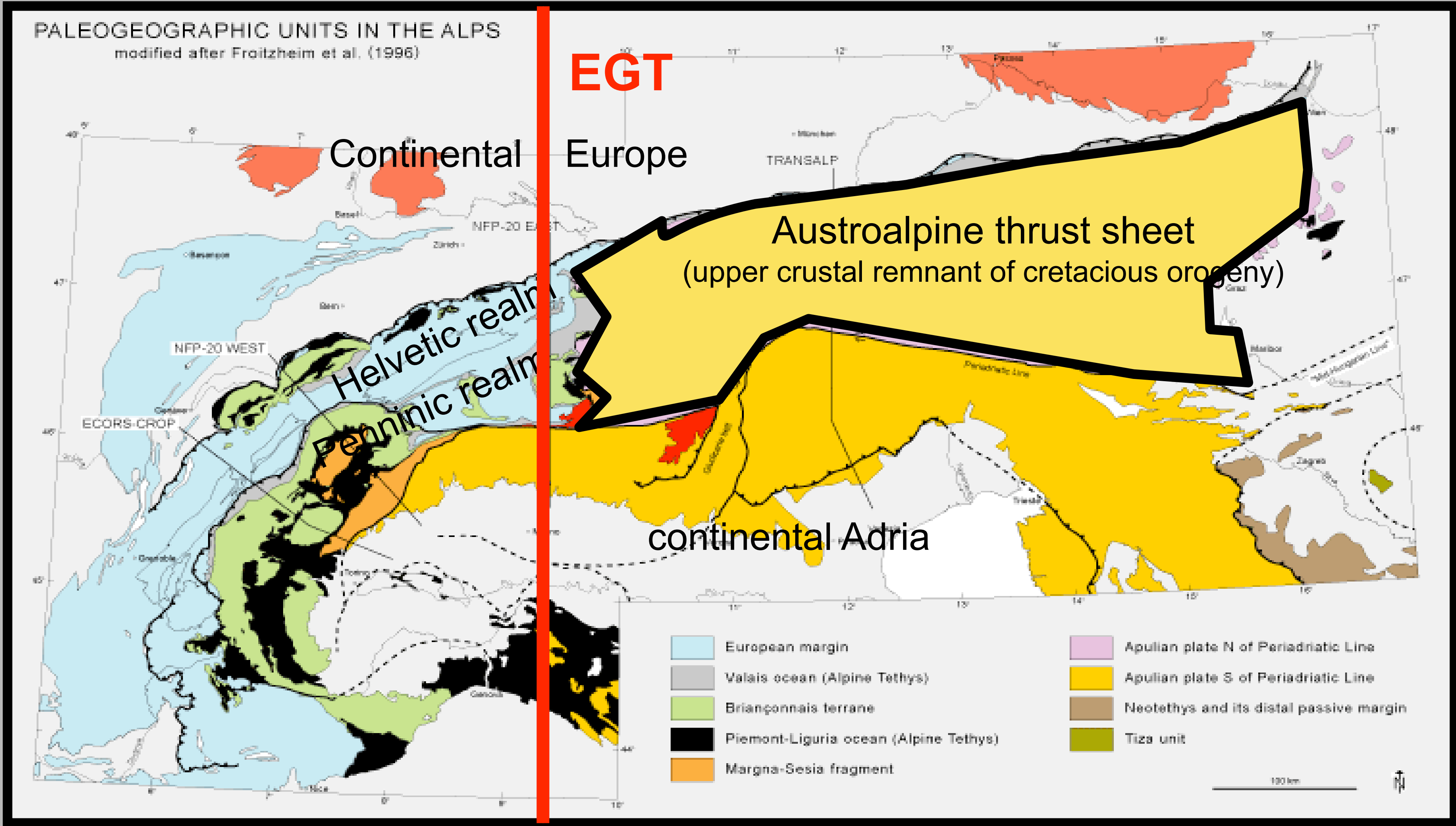

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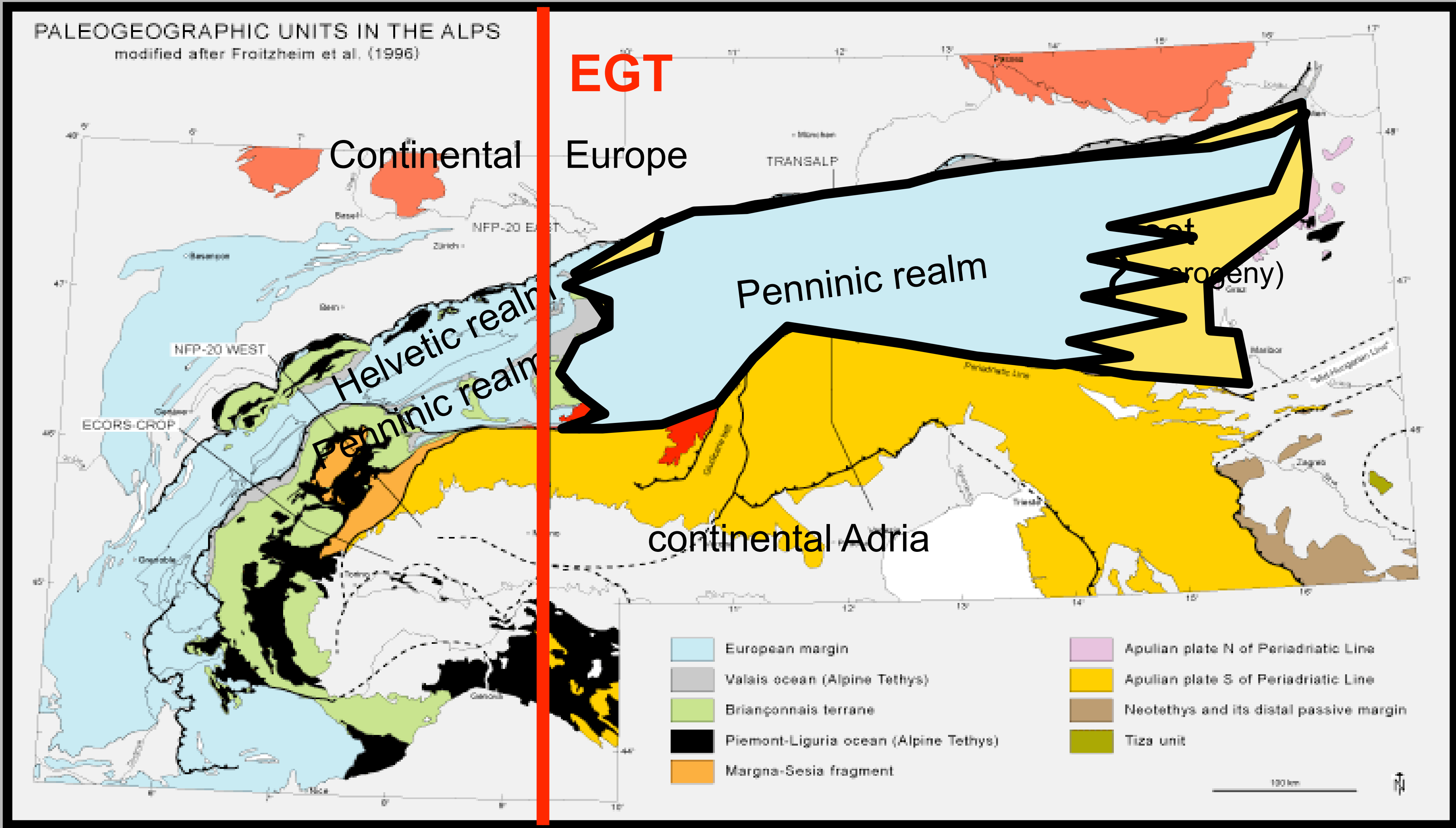

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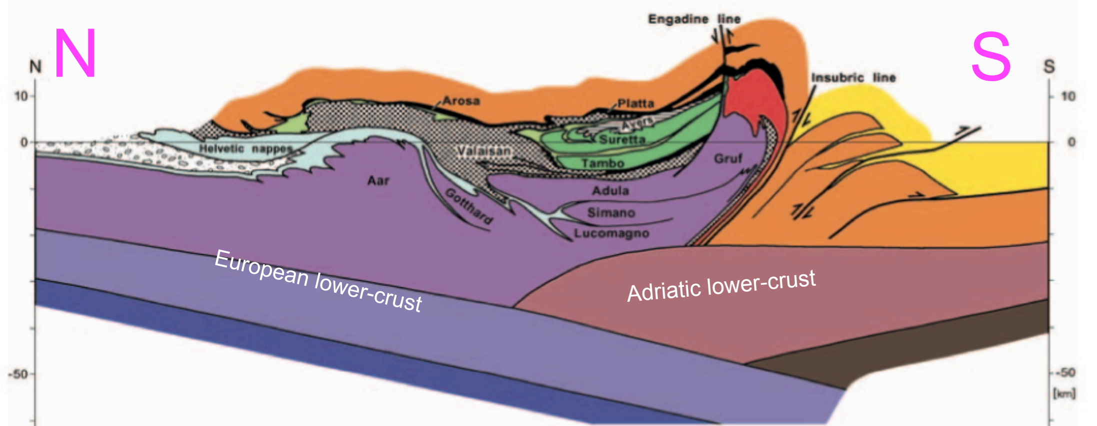
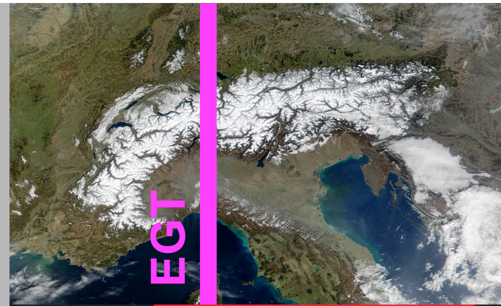
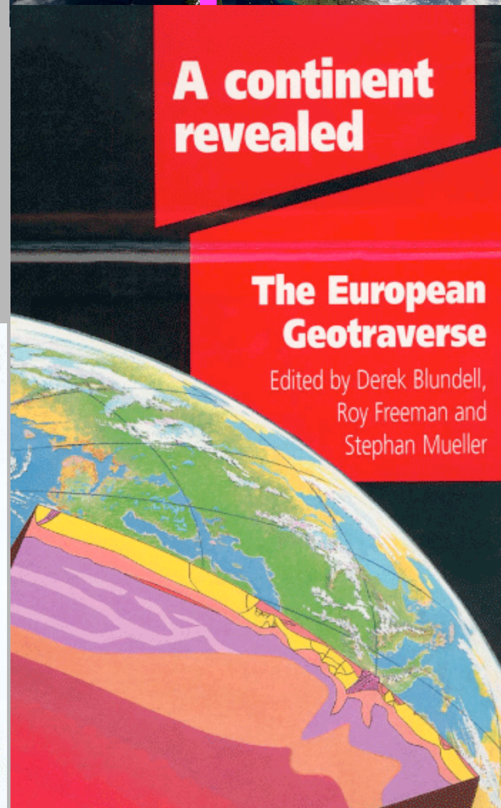
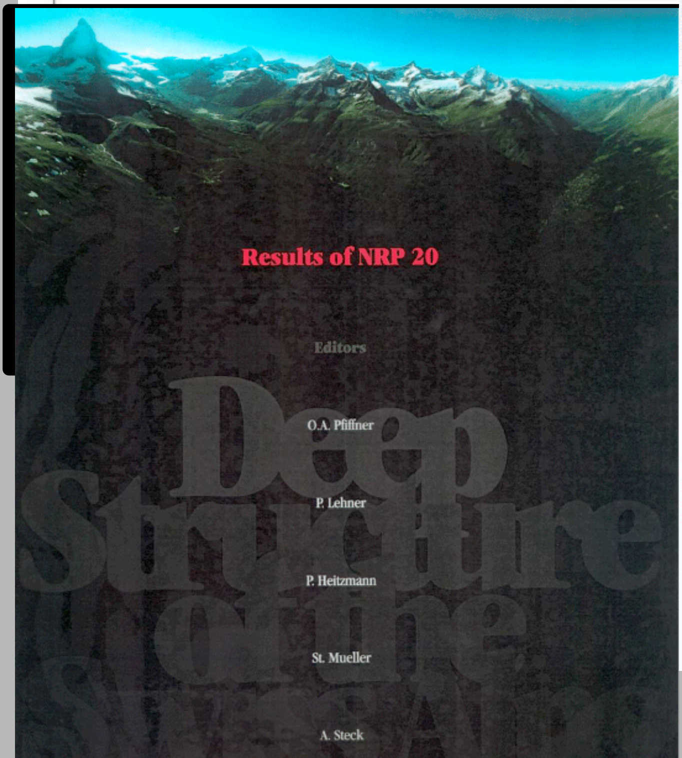
Alps are the best documented orogen!

(at all lithosphere levels)



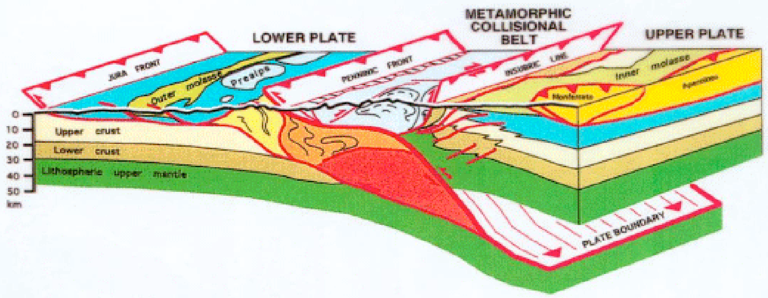






THE ECORS-CROP ALPINE SEISMIC TRAVERSE

Roure, F., Bergerat, F., Damotte, B., Mugnier, J.-L., Polino, R. (eds.)
Mém. Soc. Géol. France, 170, 1996.



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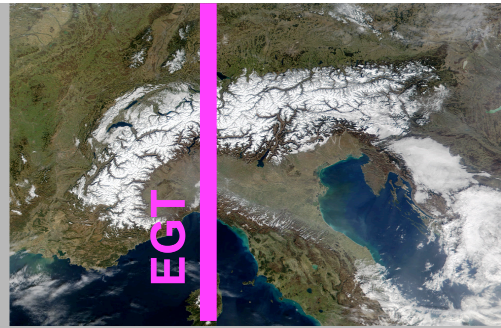
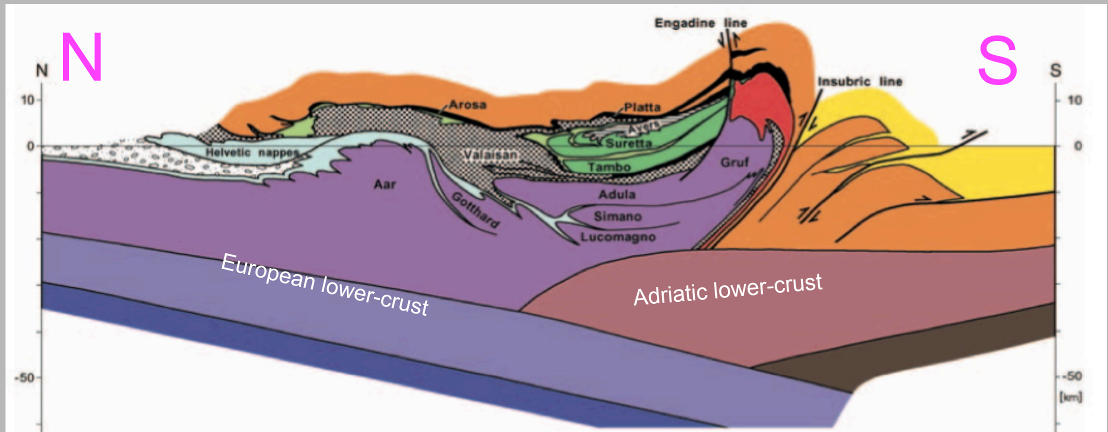
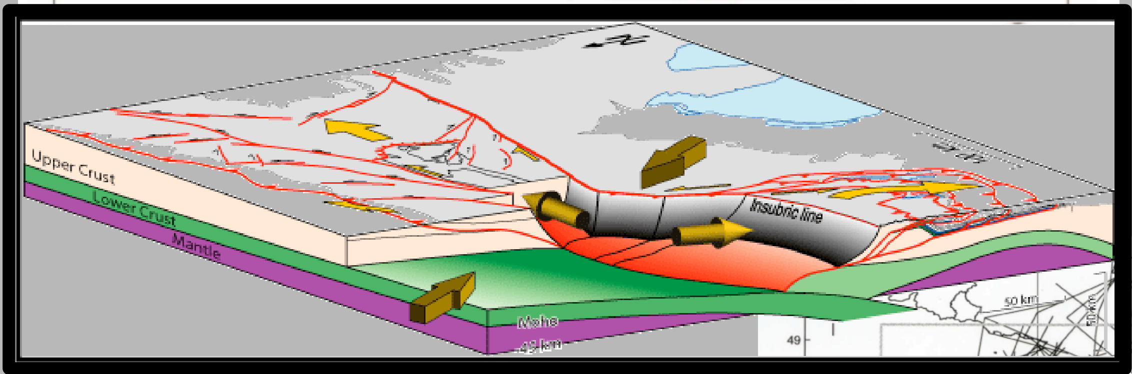
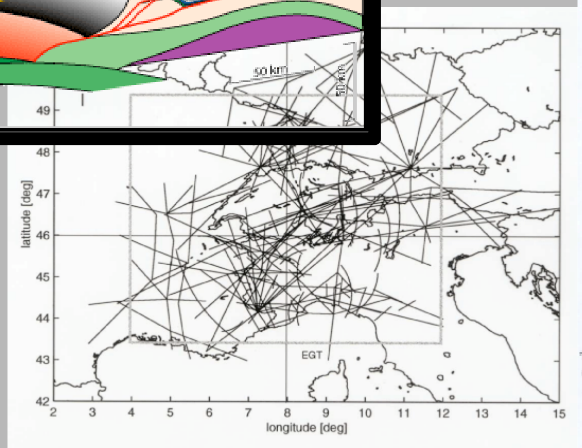
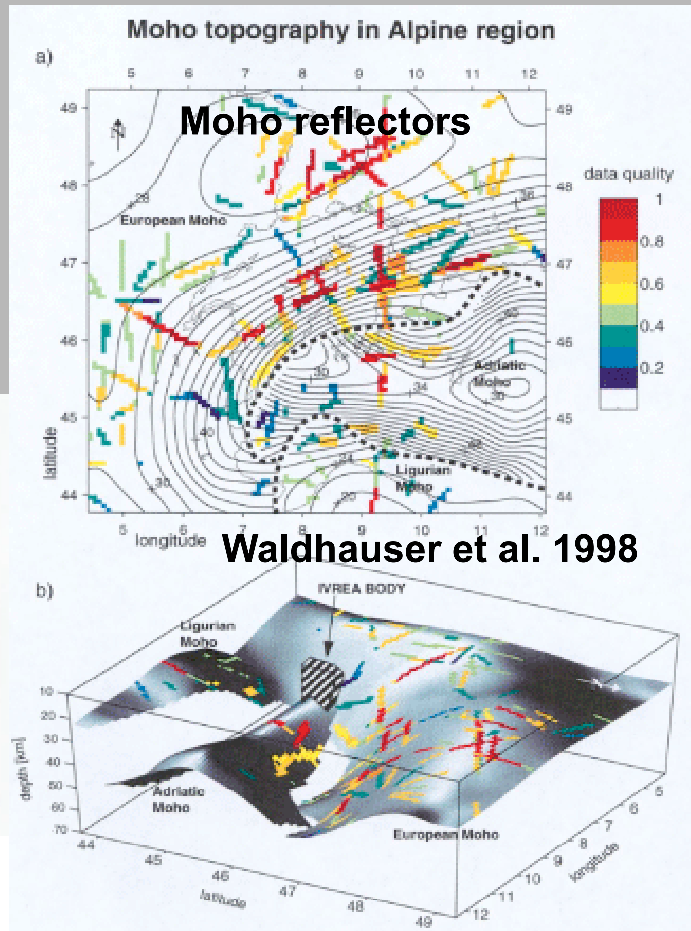








(Moho particularly well sampled)



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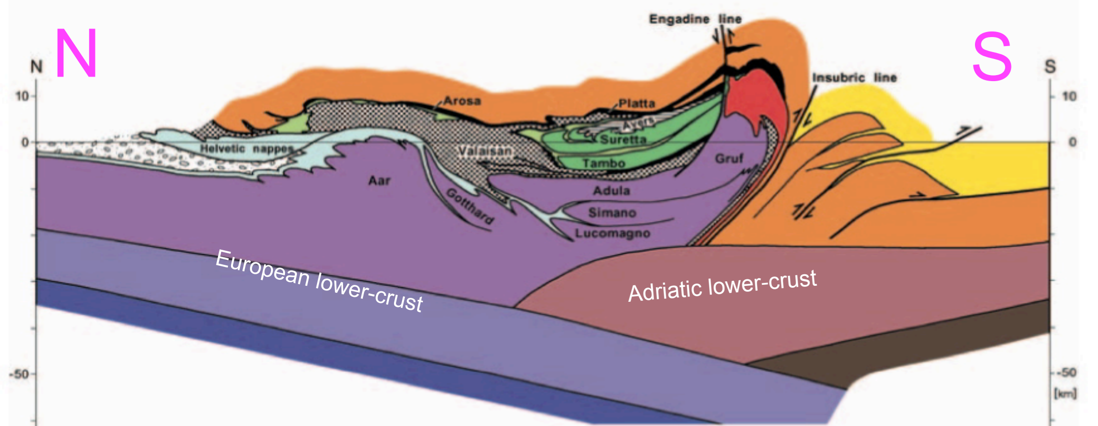
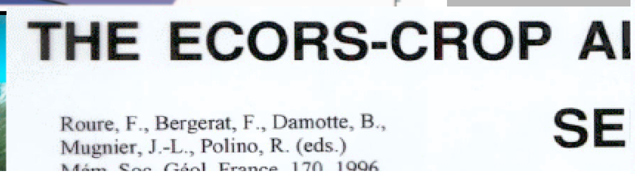
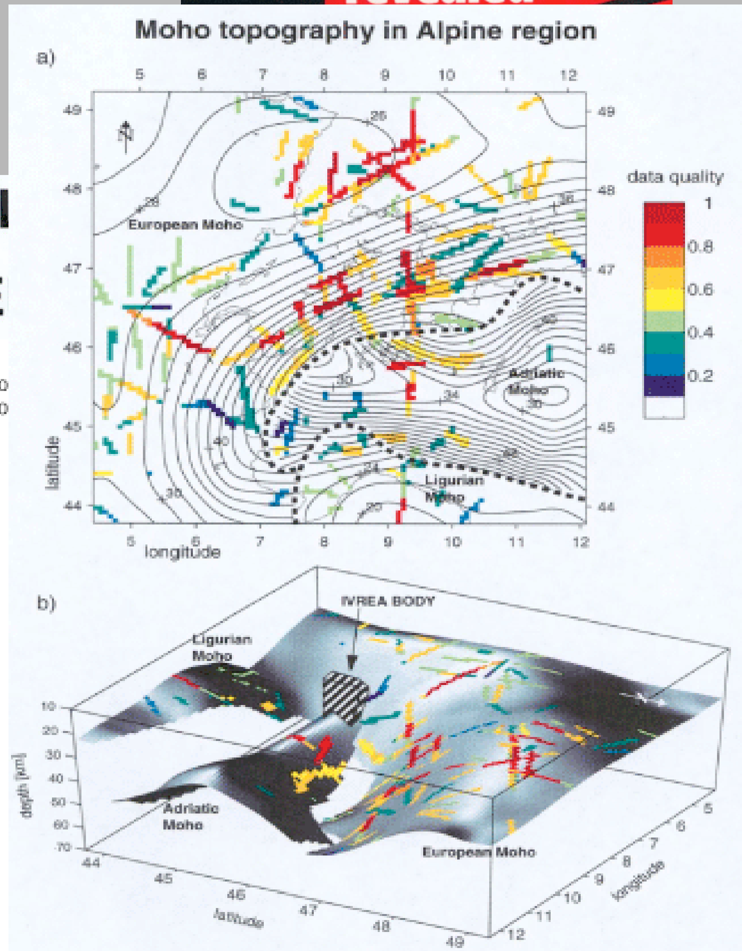
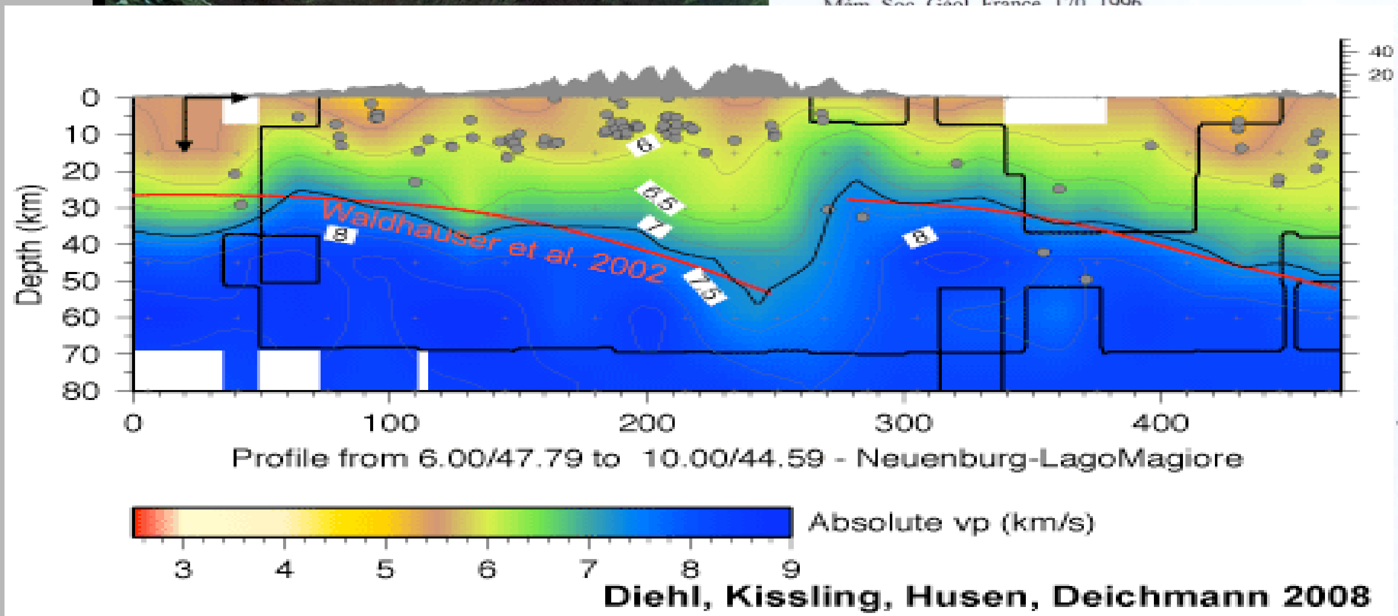
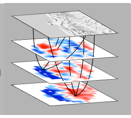


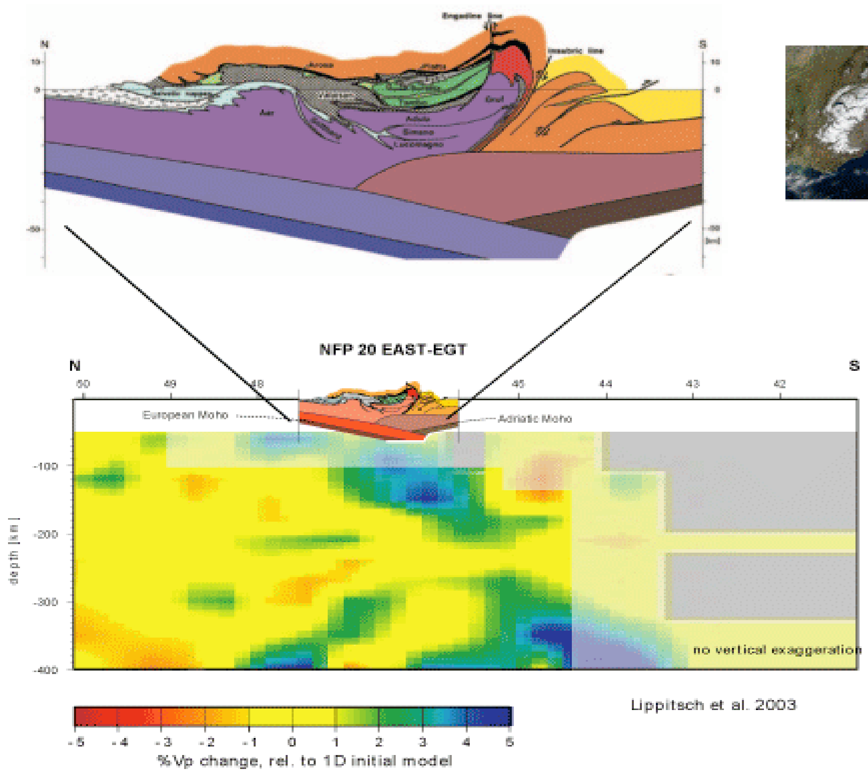


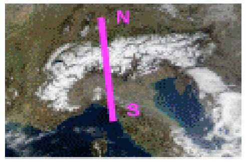






3D – structure known from surface to 660km depth

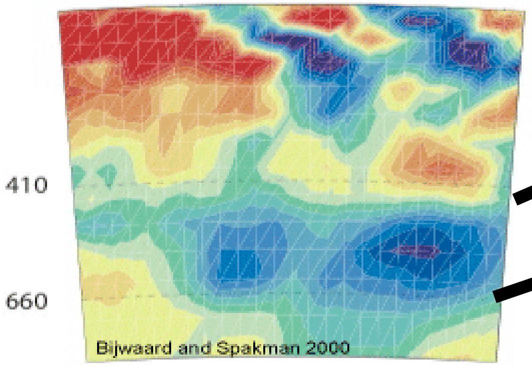


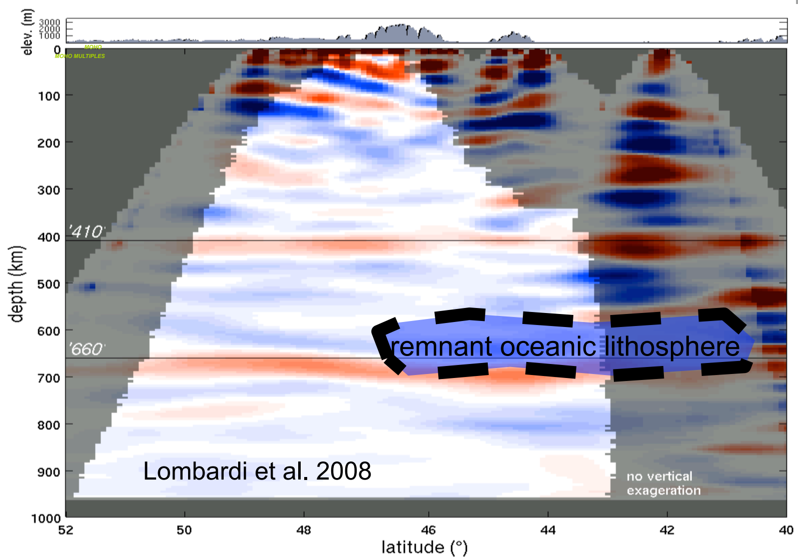


combine shallow with deep structure

combine structure with plate dynamics

derive plate tectonic model of Alpine orogeny

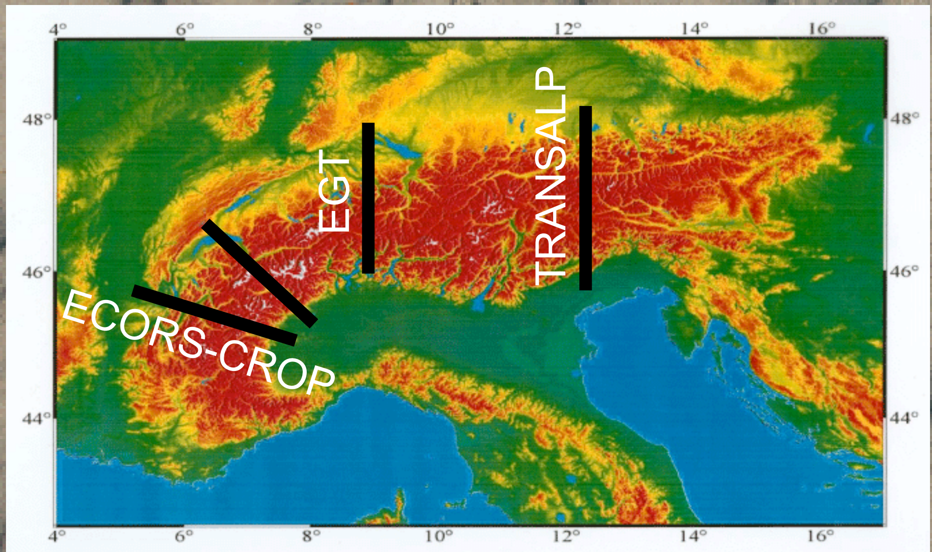


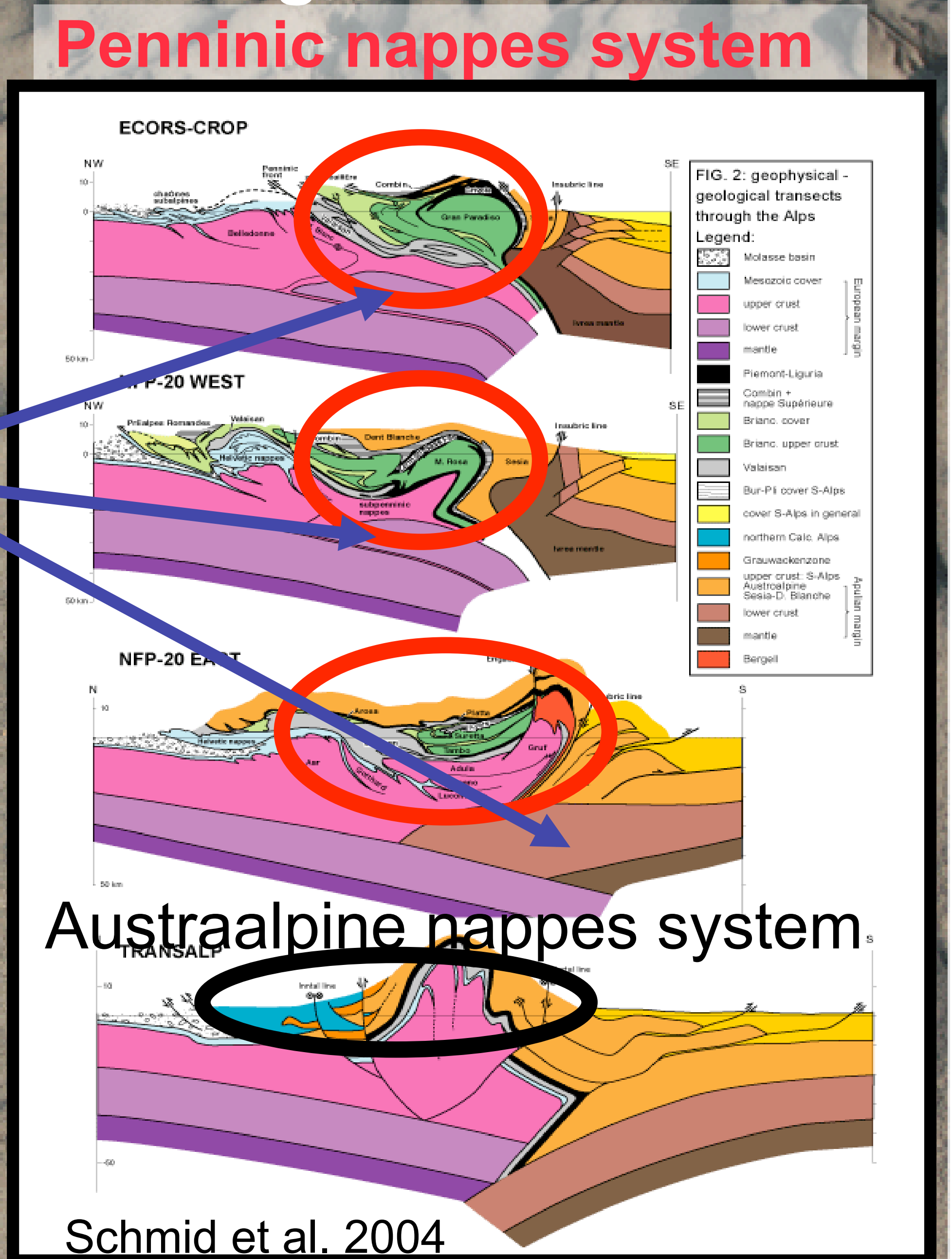


3D crustal structure: lower crustal wedges Penninic and Austraalpine nappes

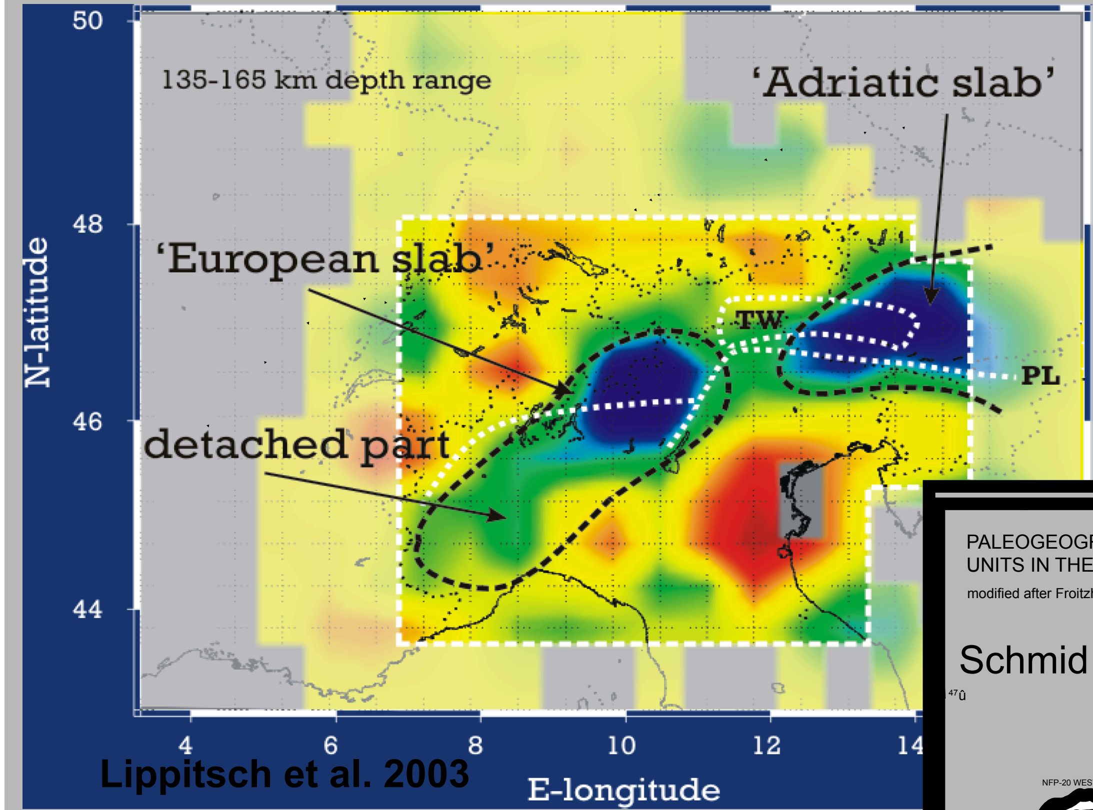
crustal traverses document:
non-cylindric structure,
wedge tectonics dominant
at crustal levels

Lower crust indenters





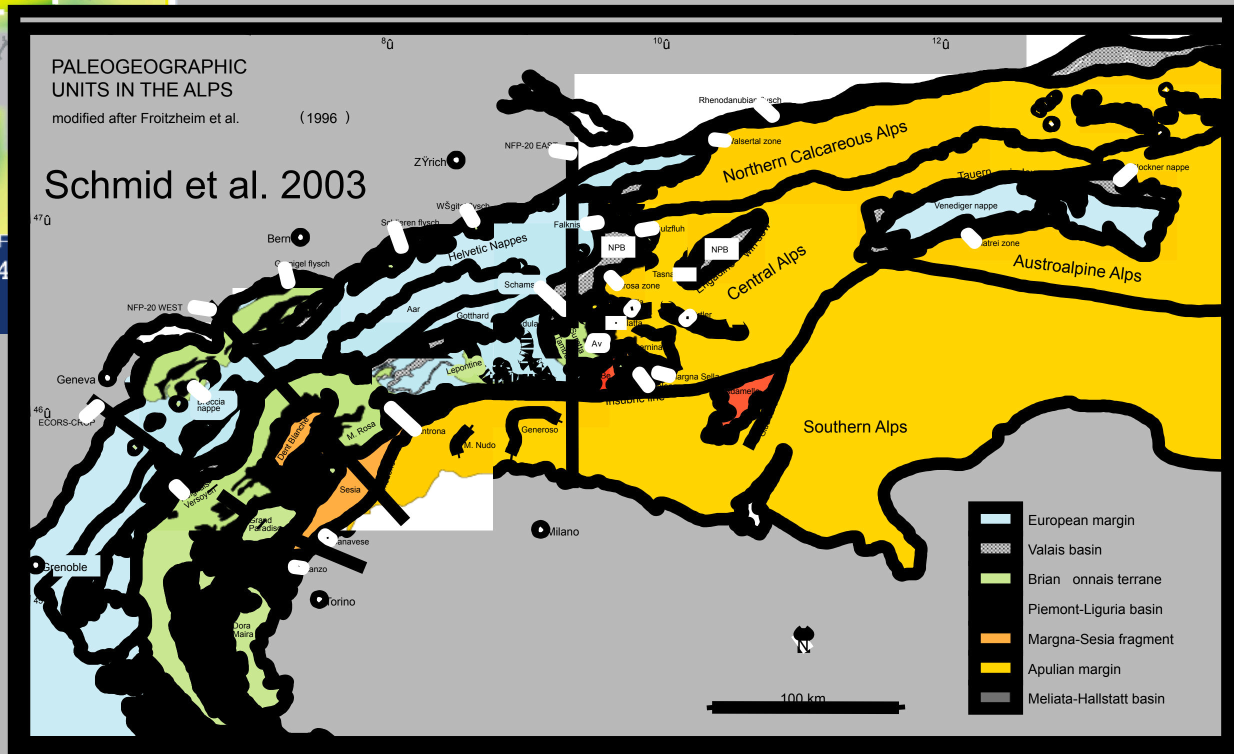
The lithosphere structure: two independent slabs beneath Alps!



Lippitsch et al. 2003

lithospheric slabs at 150km depth and surface geology

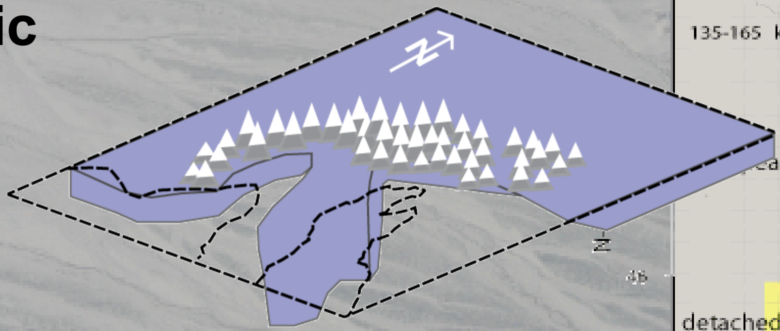
Two different orogenies in west and east at surface and two slabs at depth!

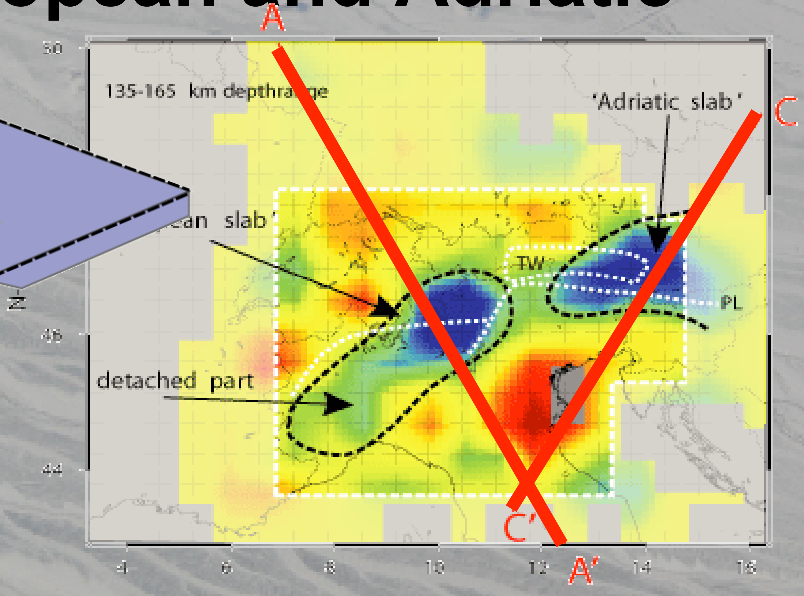


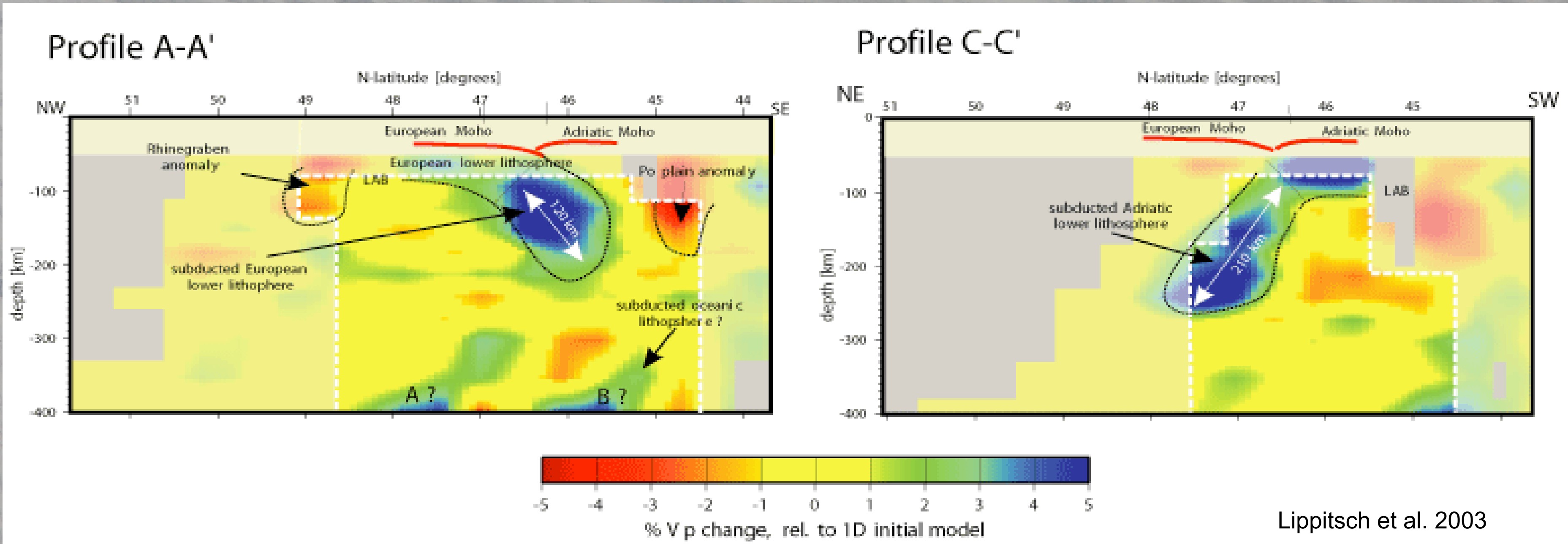
Schmid et al. 2003

Two lithospheric slabs: European and Adriatic

European lithospheric slab probably all continental mantle lithosphere







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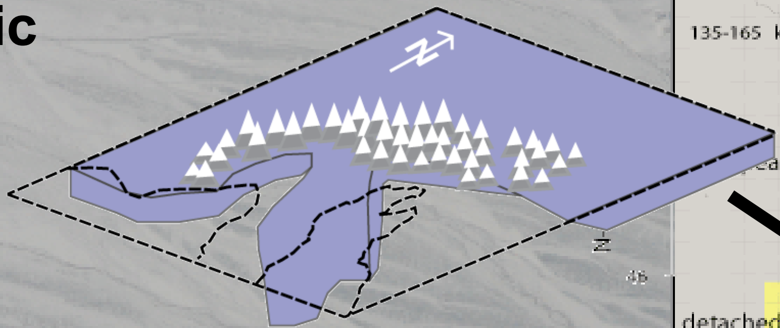
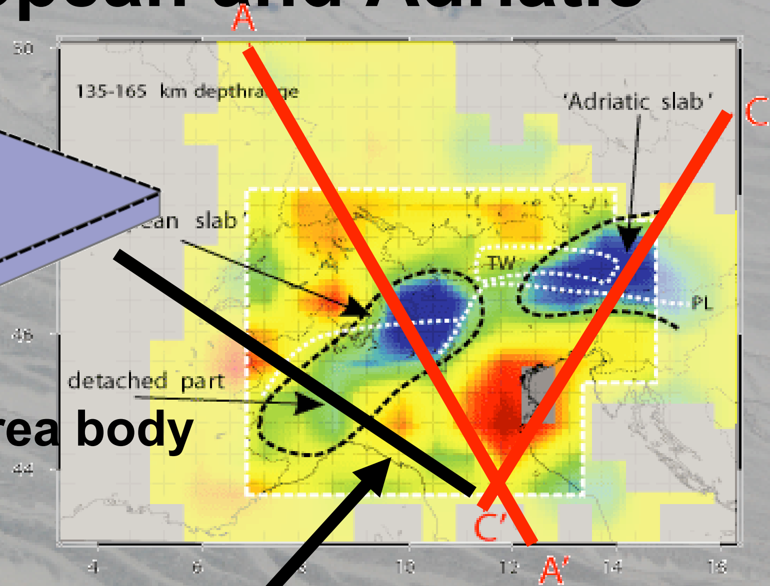
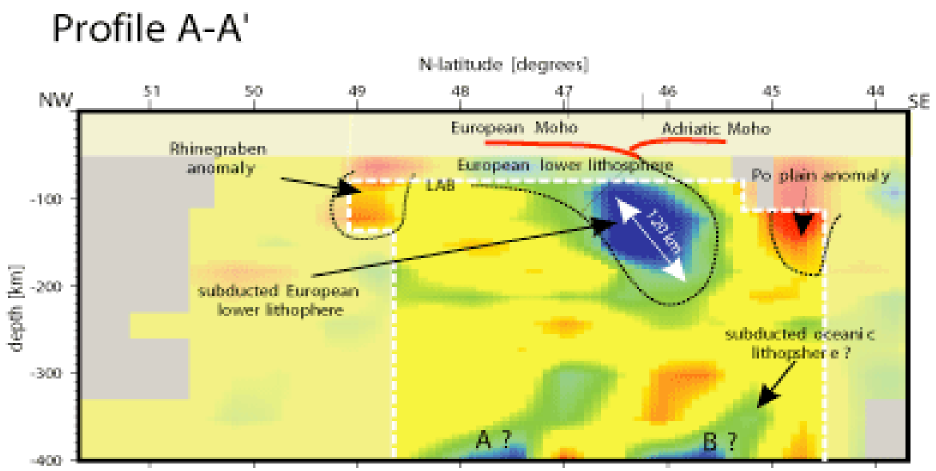
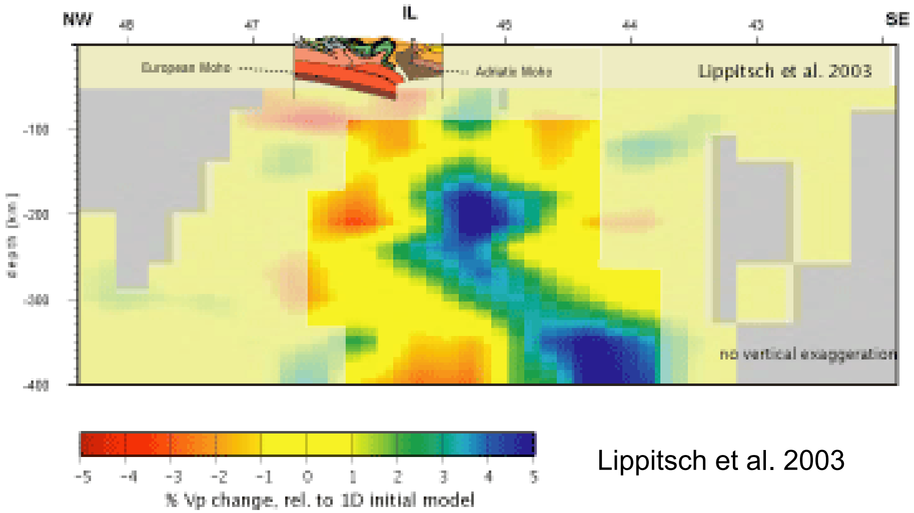




with an eastward propagating tear beneath the Ivrea body

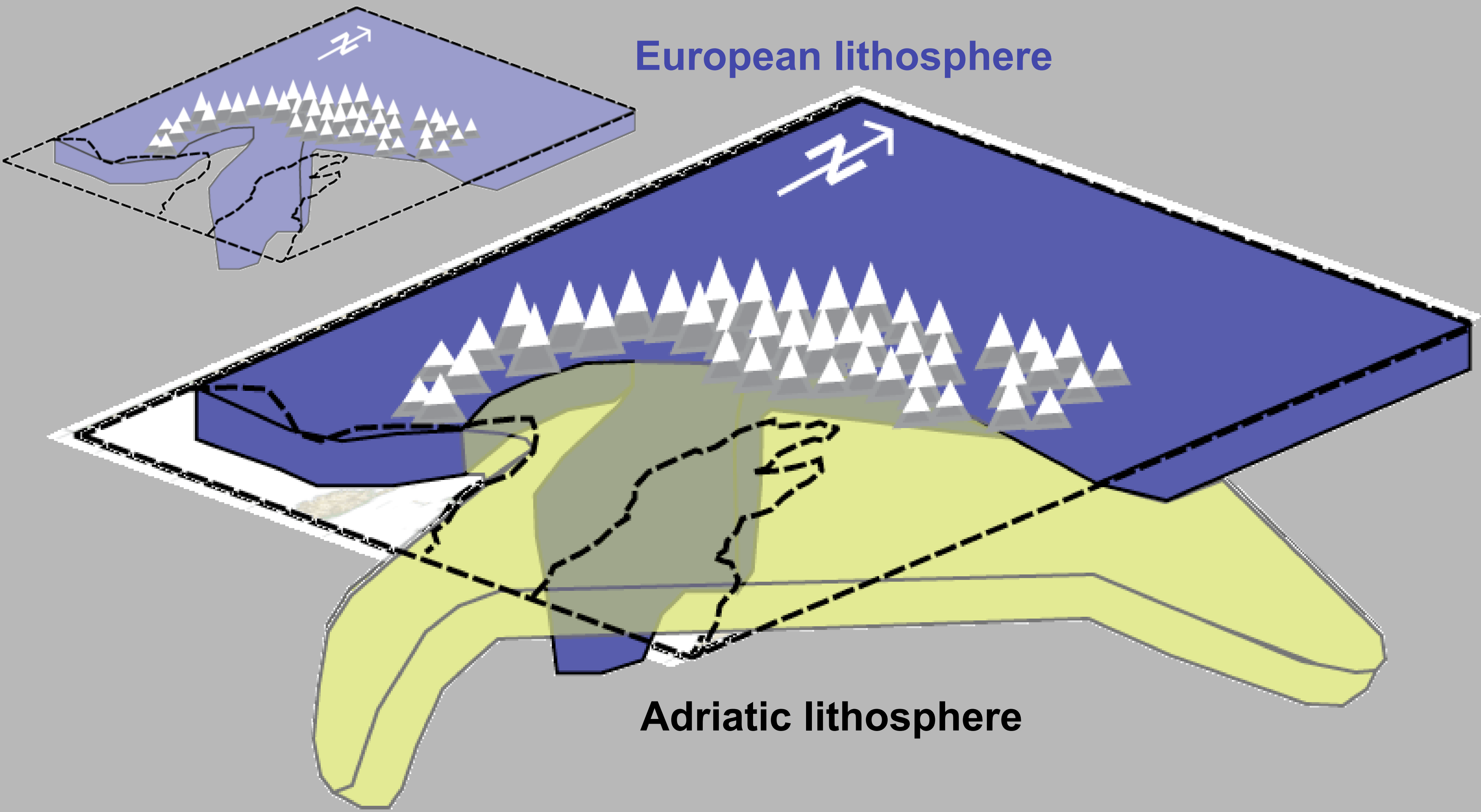


ECORS-CROP Profile

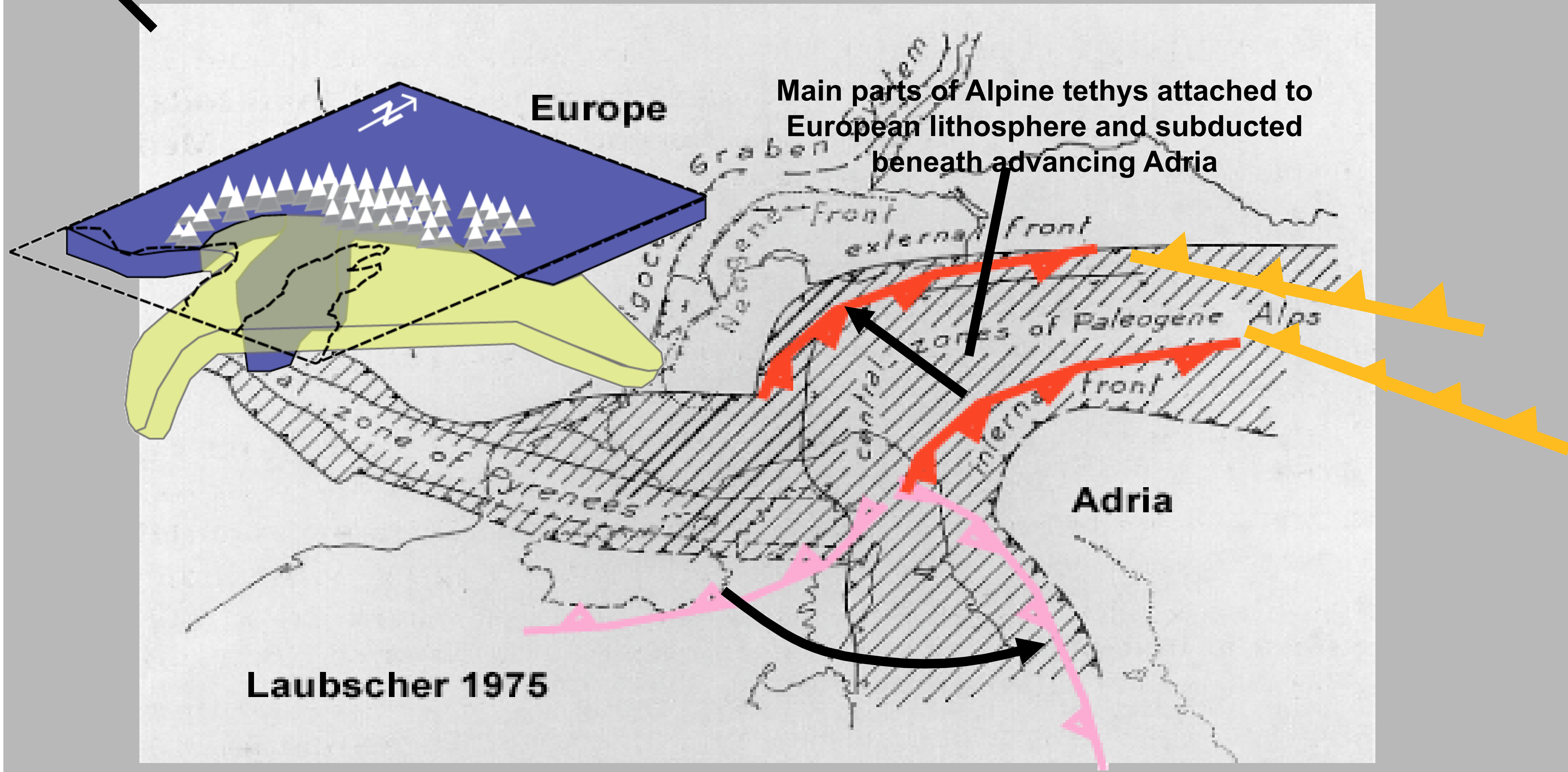


Lippitsch et al. 2003

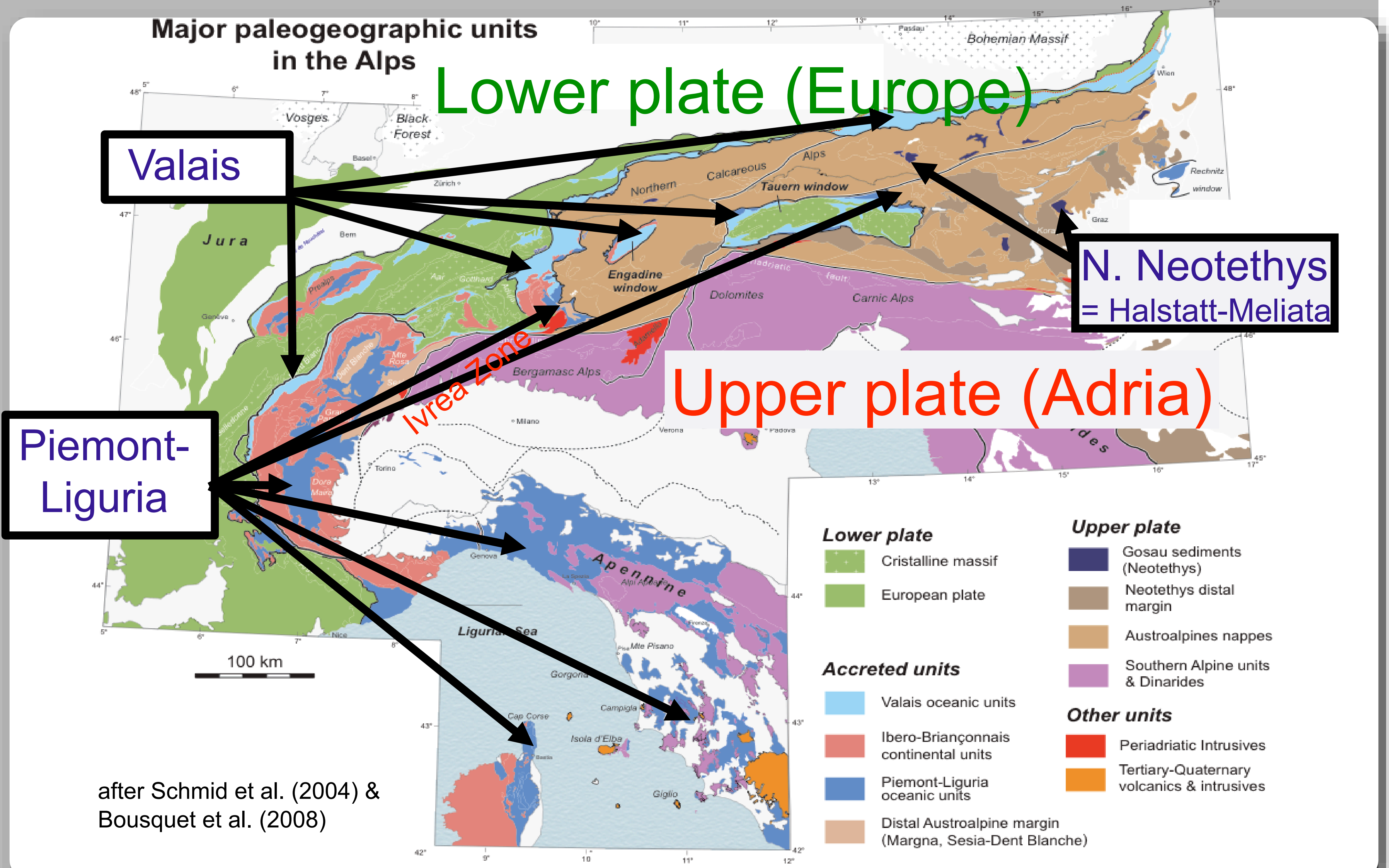
Perspective View of 3D Alpine Lithospere Slabs



NE-ward (Dinarides-Eastern Alps) and SW-ward (Apennine) subduction of oceanic parts of Adriatic microplate

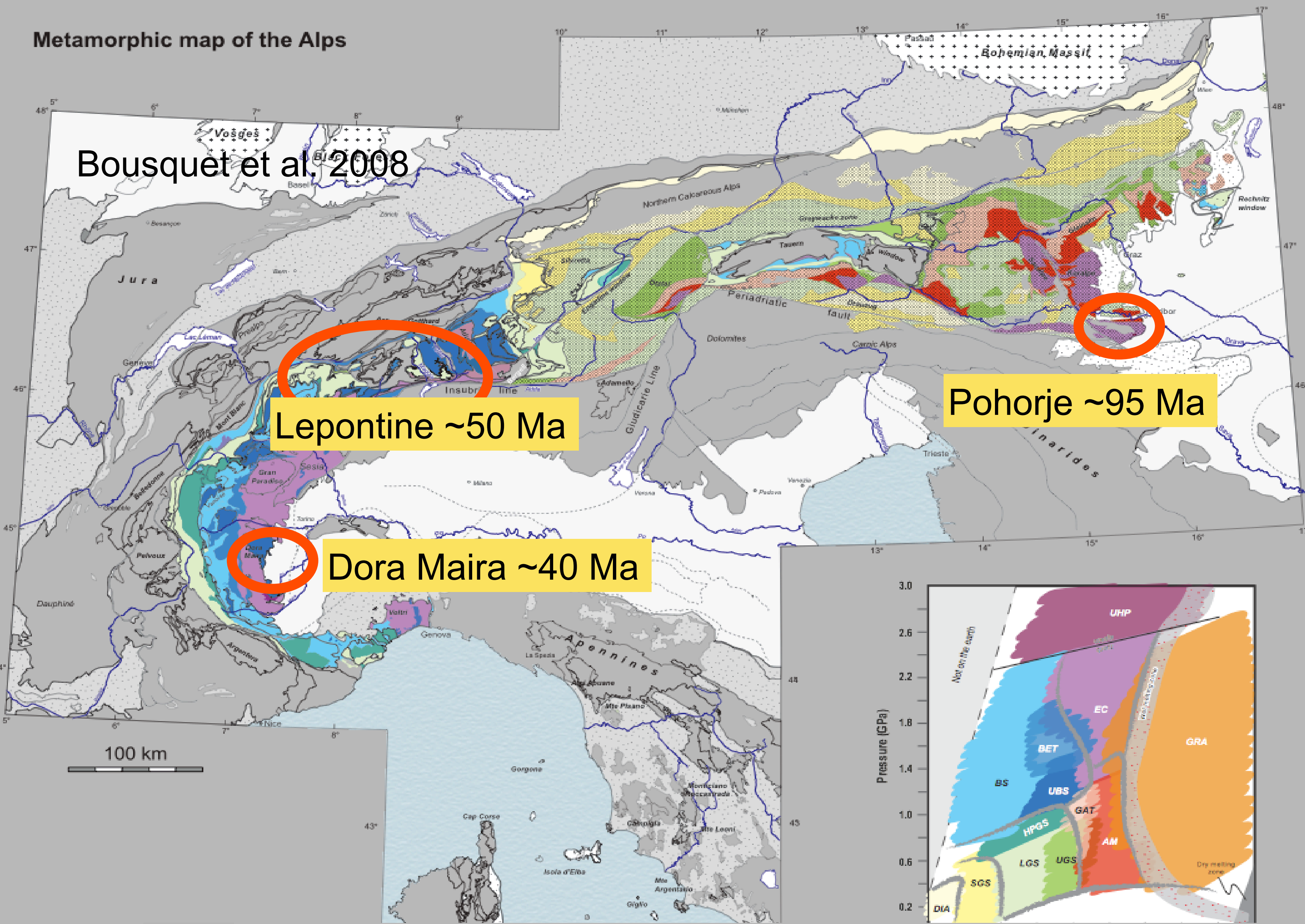


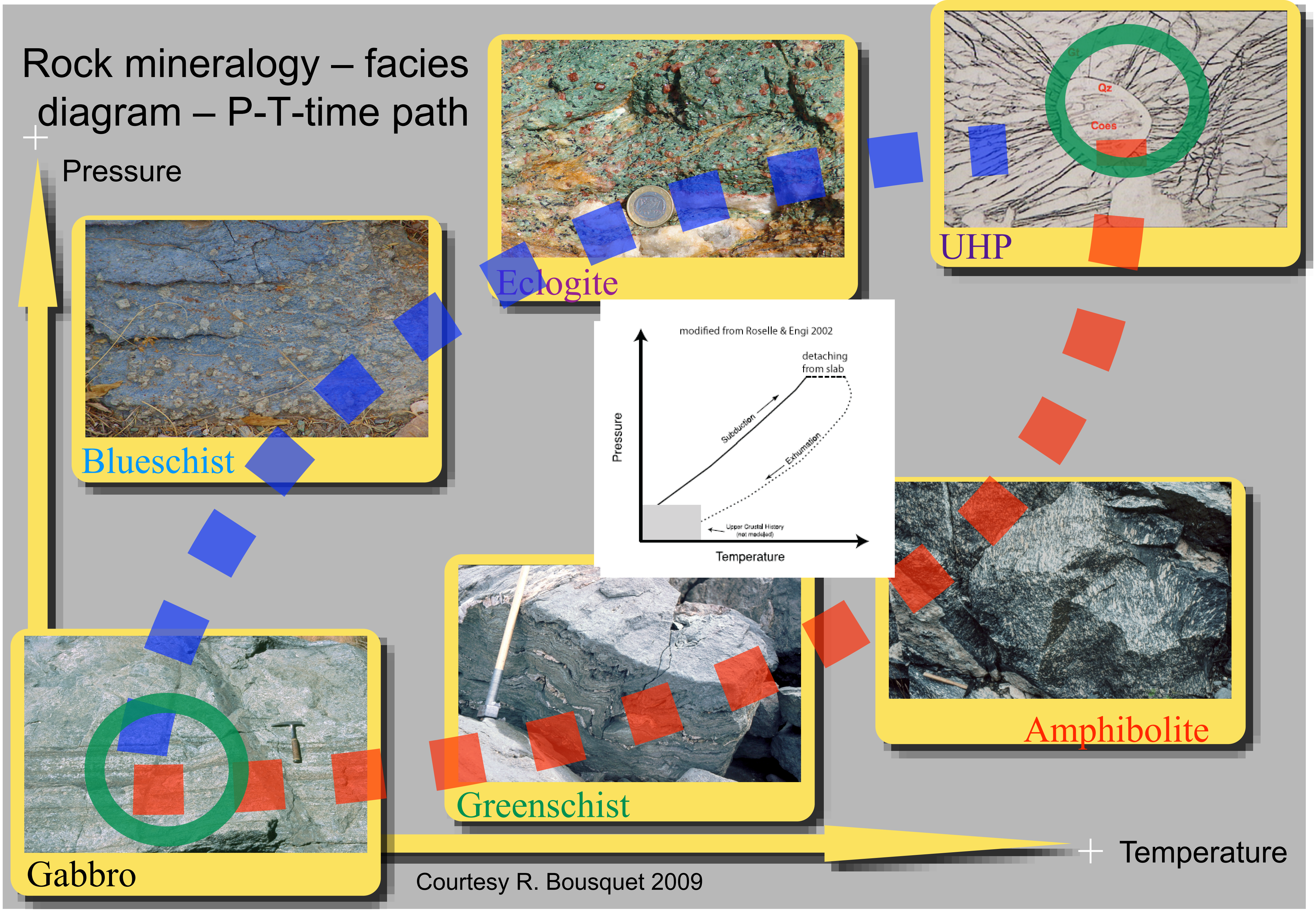
Relics of Tethys in the Alps at surface today



after Schmid et al. (2004) &
Bousquet et al. (2008)

Metamorphic record – indicators for subduction mechanisms

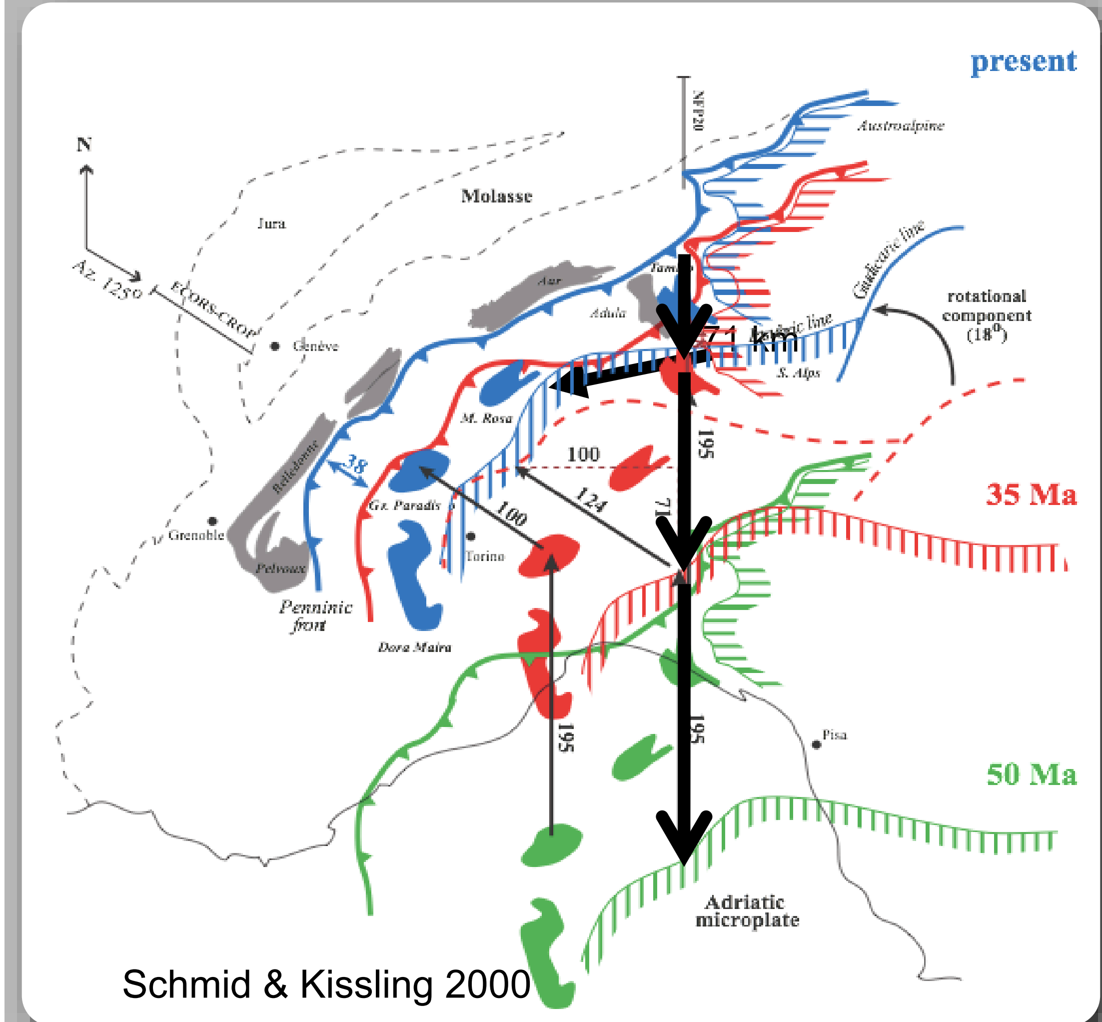



Rock mineralogy – facies diagram – P-T-time path
Pressure
Eclogite
UHP
Qz
Coes
Blueschist
modified from Roselle & Engi 2002
detaching from slab
Subduction
Exhumation
Pressure
Upper Crustal History (not modeled)
Temperature
Amphibolite
Greenschist
Gabbro
Temperature
Courtesy R. Bousquet 2009

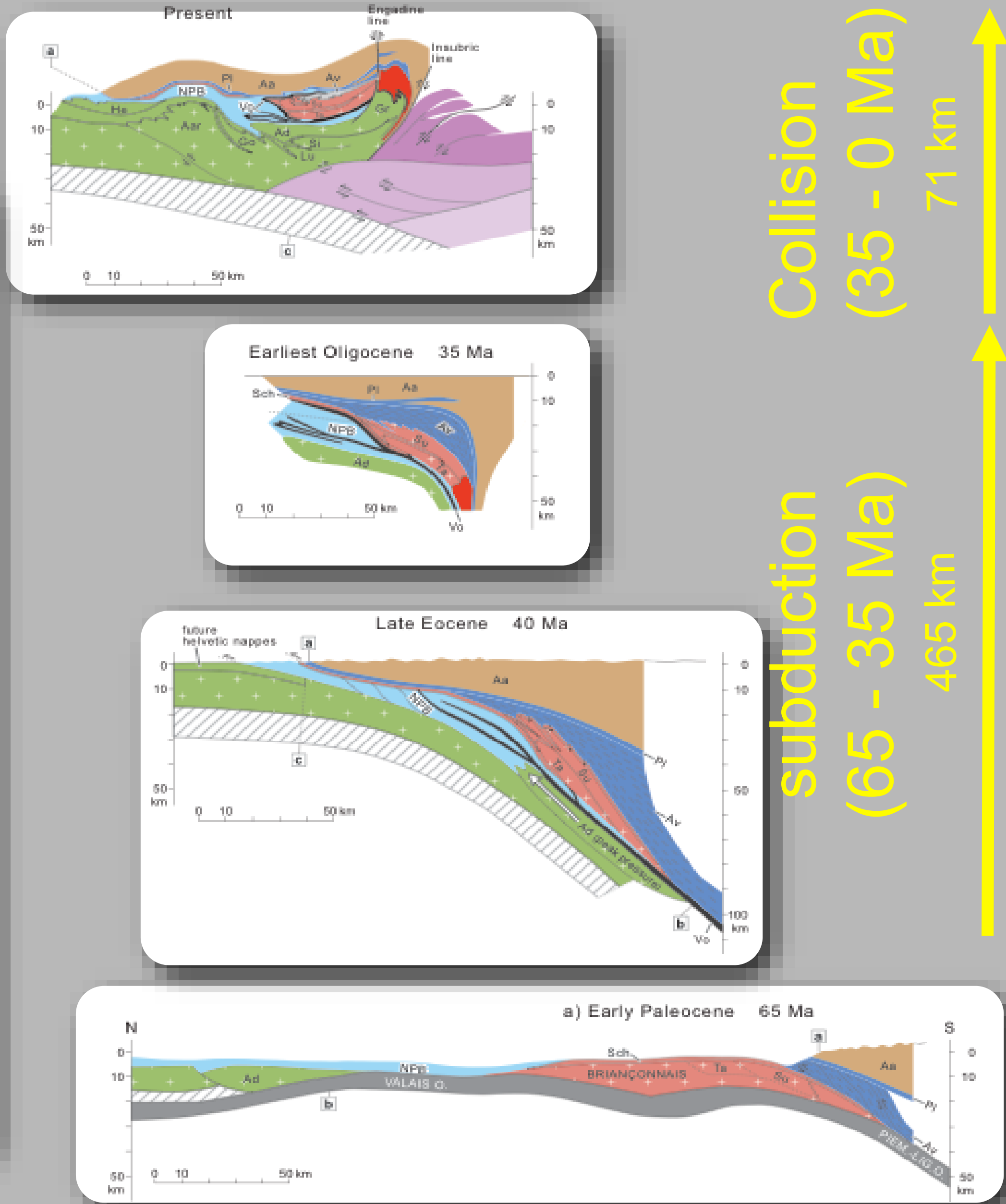
Retrodeformation N-S (Present - 65 Ma)

N-S displacement (NFP20E section)

N-S displacement &
rotation in map view (Insubric event)



Schmid & Kissling 2000



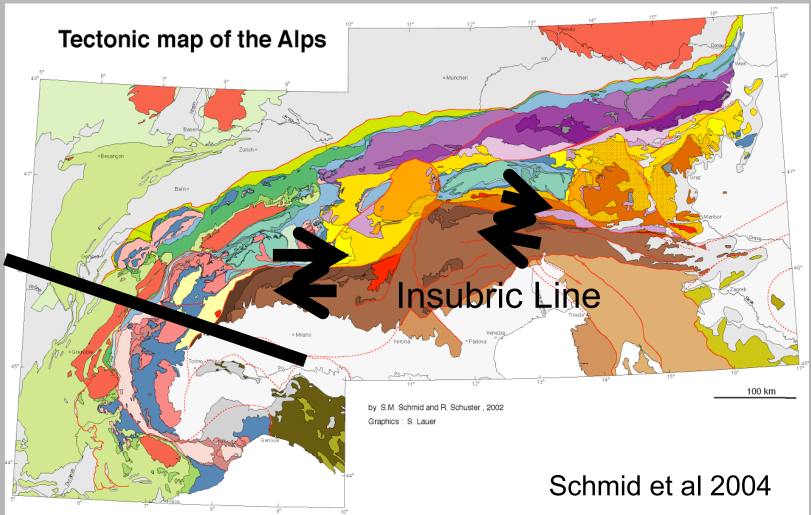
Collision (35 - 0 Ma) 71 km

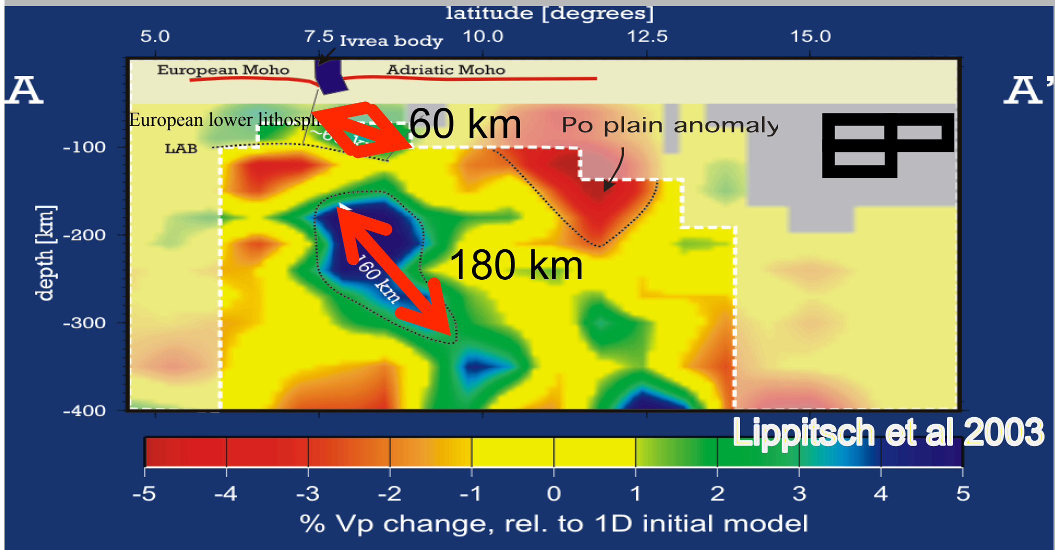
Subduction (65 - 35 Ma) 465 km

Schmid et al. 1996

Post-collisional evolution of central Alps

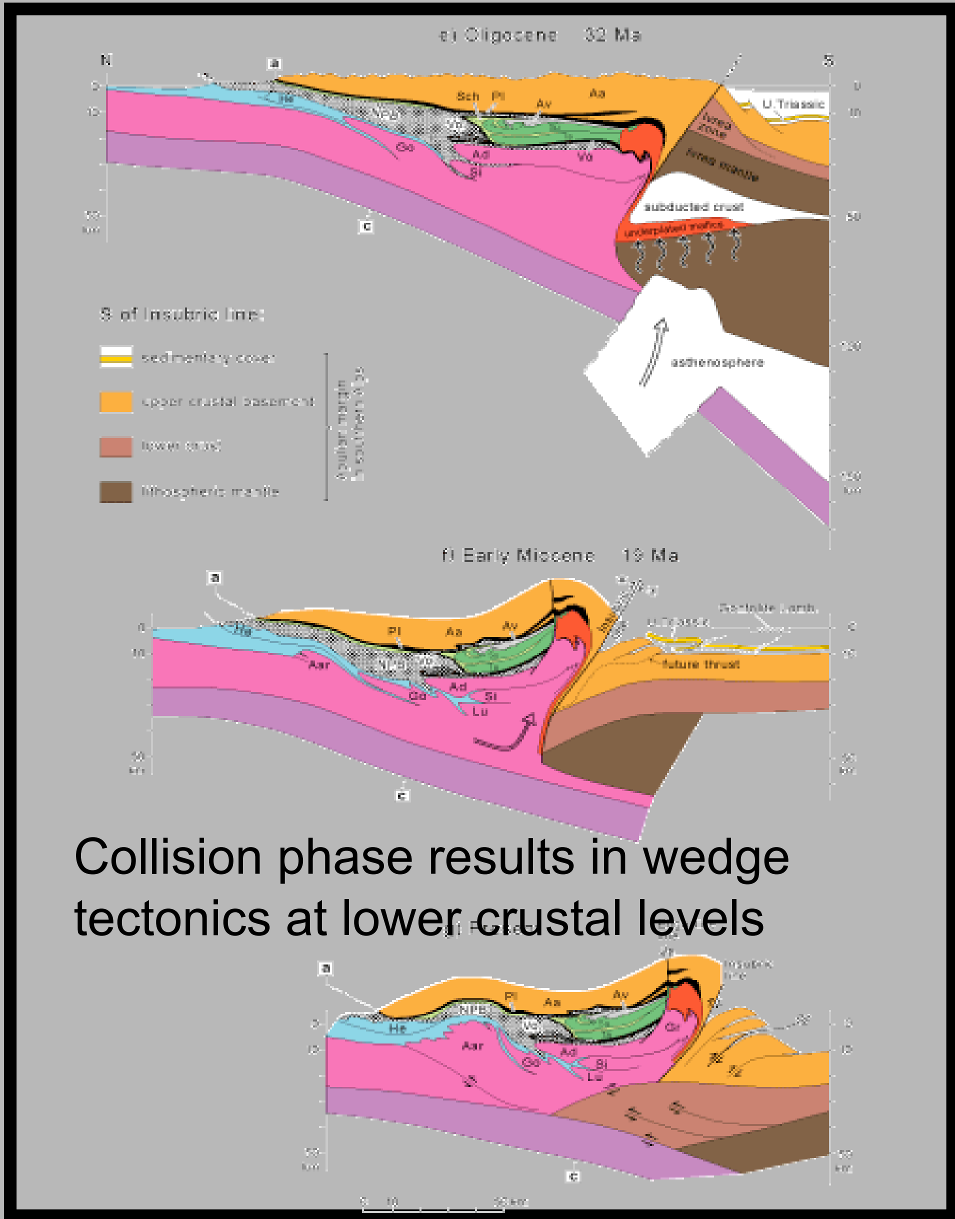
Retrodeformation at lithosphere scale E-W (Present – 35 Ma)





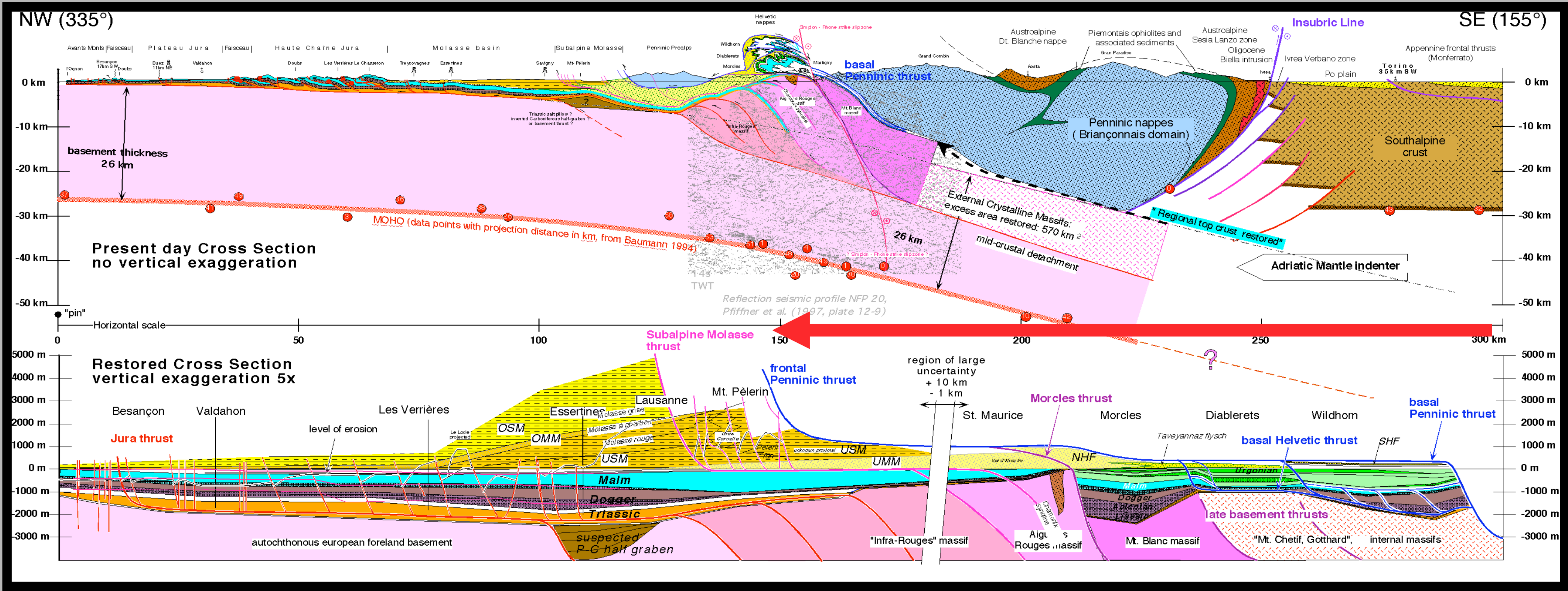
180 + 60 km = 240 km, compare to 300 km Laubscher 1971

Evolution at crustal scale N-S (32 Ma – Present) Schmid et al. 1996, 2000, 2004



Collision phase results in wedge tectonics at lower crustal levels

Post-collisional NW Migration of thrust front in Central Alps

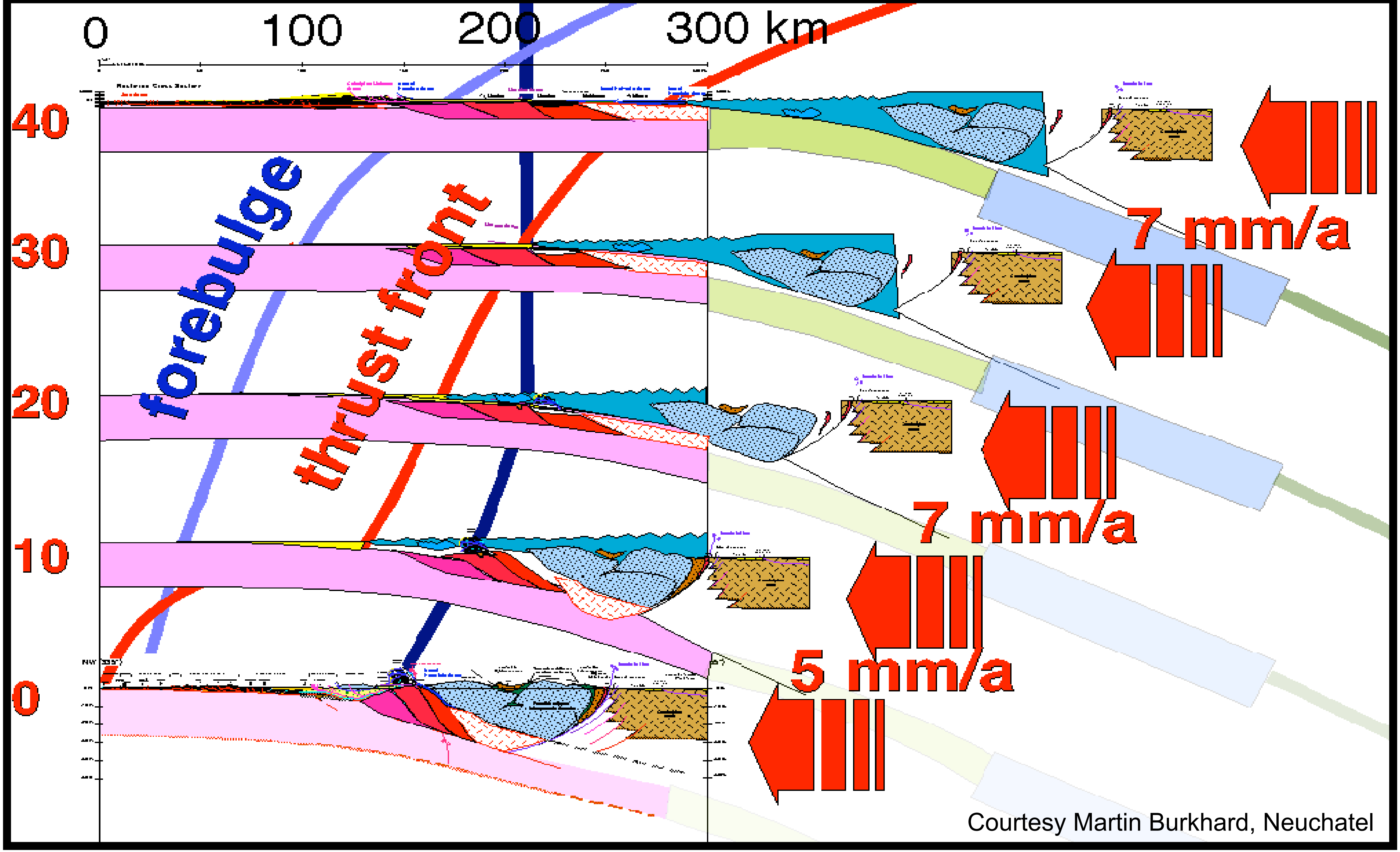


⇒ **horizontal displacement NW-SE : 150 km / 30 Ma**

(minimum !) average : **5 mm/an**

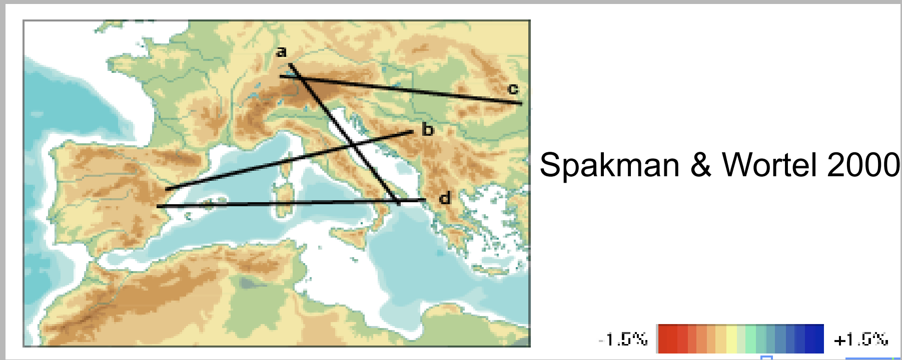
Courtesy Martin Burkhard, Neuchatel

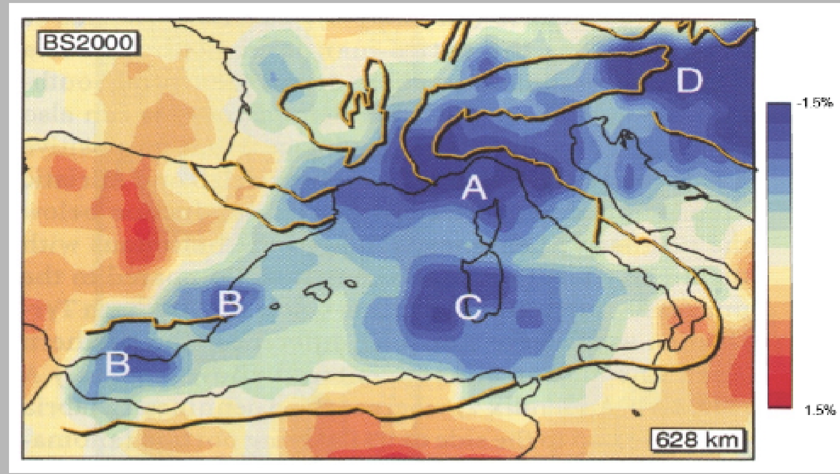
Post-collisional NW Migration of thrust front in Central Alps



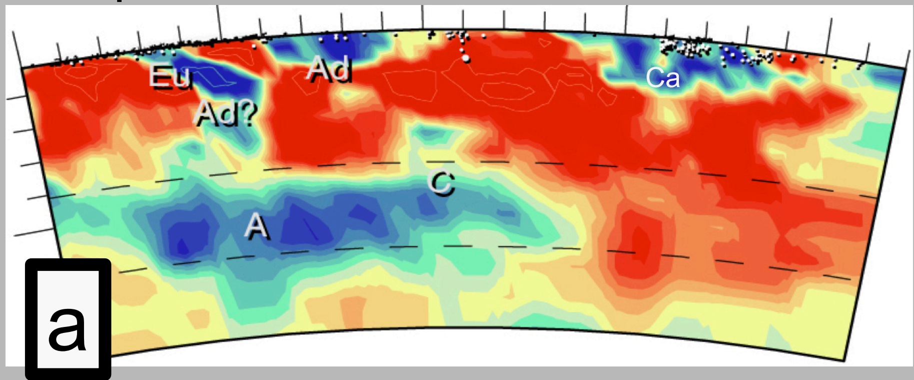
Courtesy Martin Burkhard, Neuchatel

Relicts of Alpine Tethys in tomographic sections

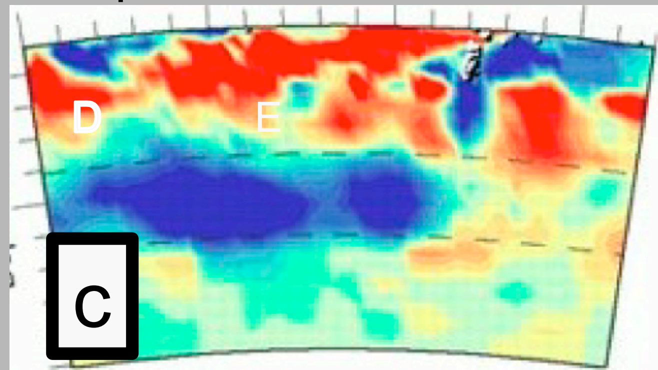




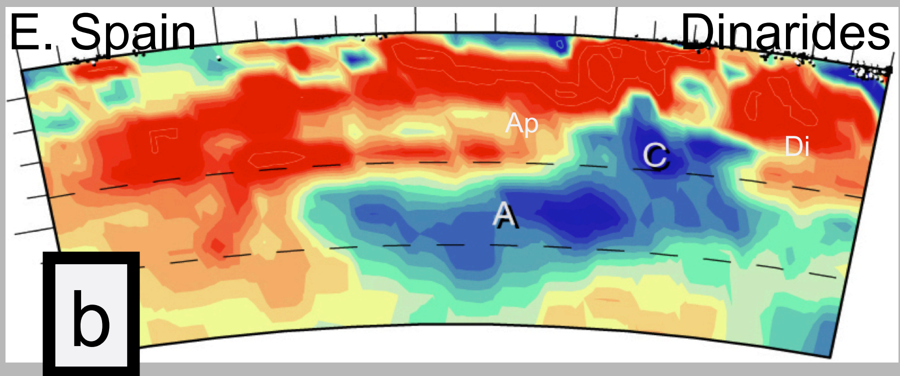
C. Alps Calabria



E. Alps Vr Vrancea



E. Spain Dinarides



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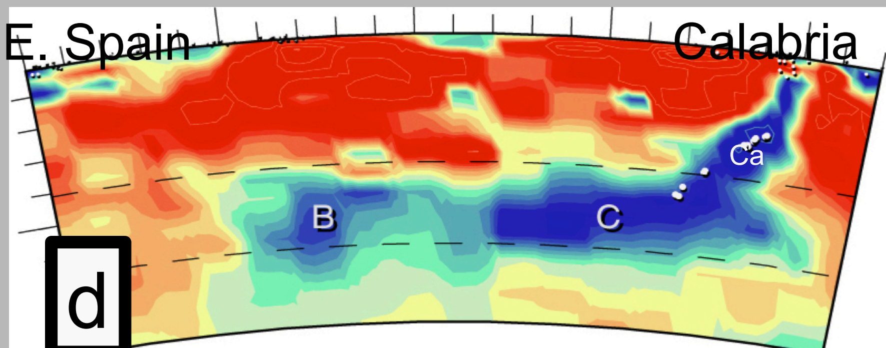

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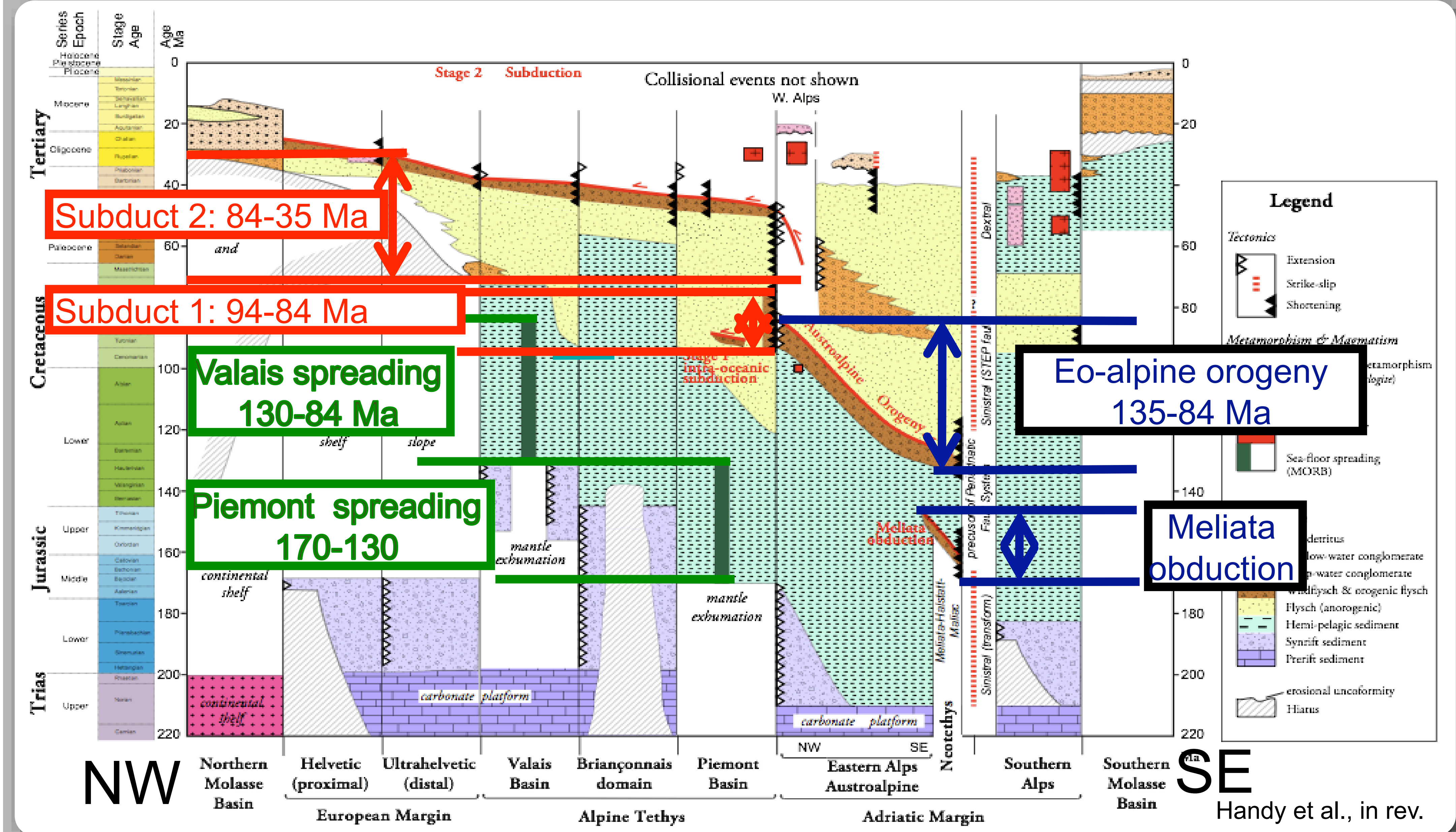
Swiss Federal Institute of Technology Zurich

Summary Geologic Record

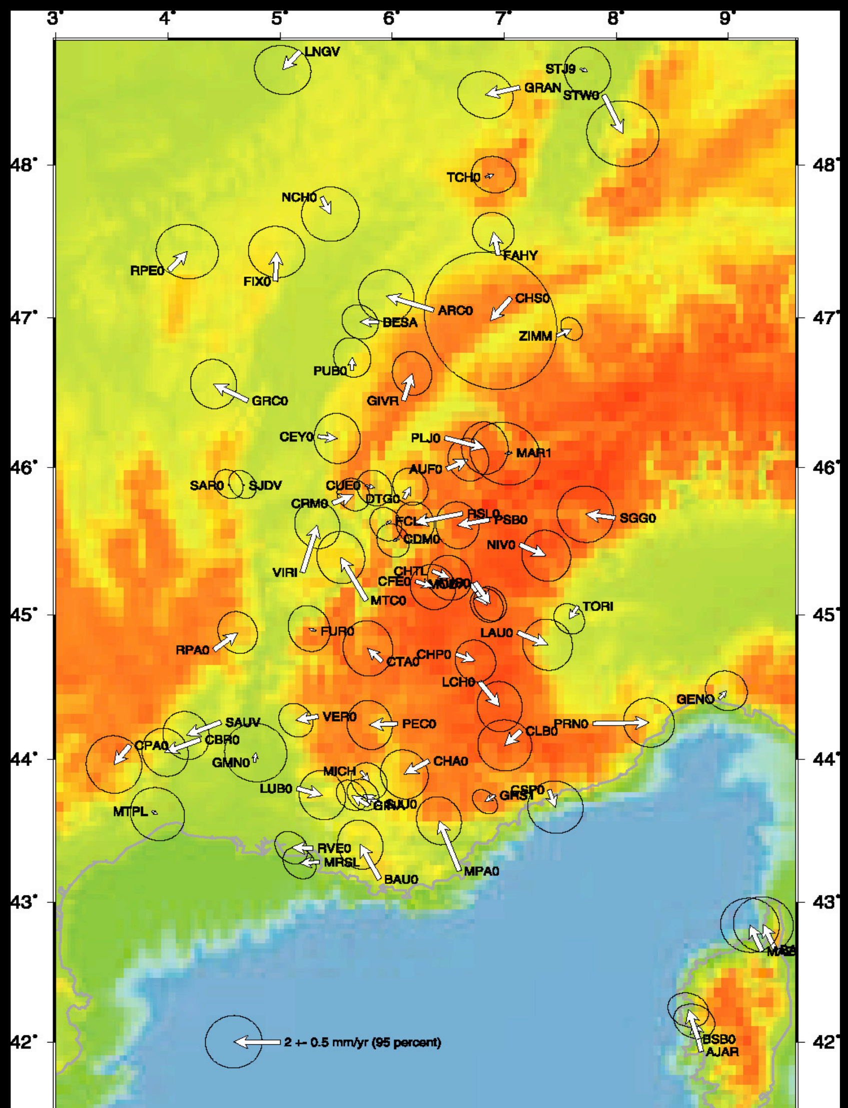
Pre-collisional timetable for Alpine Tethys



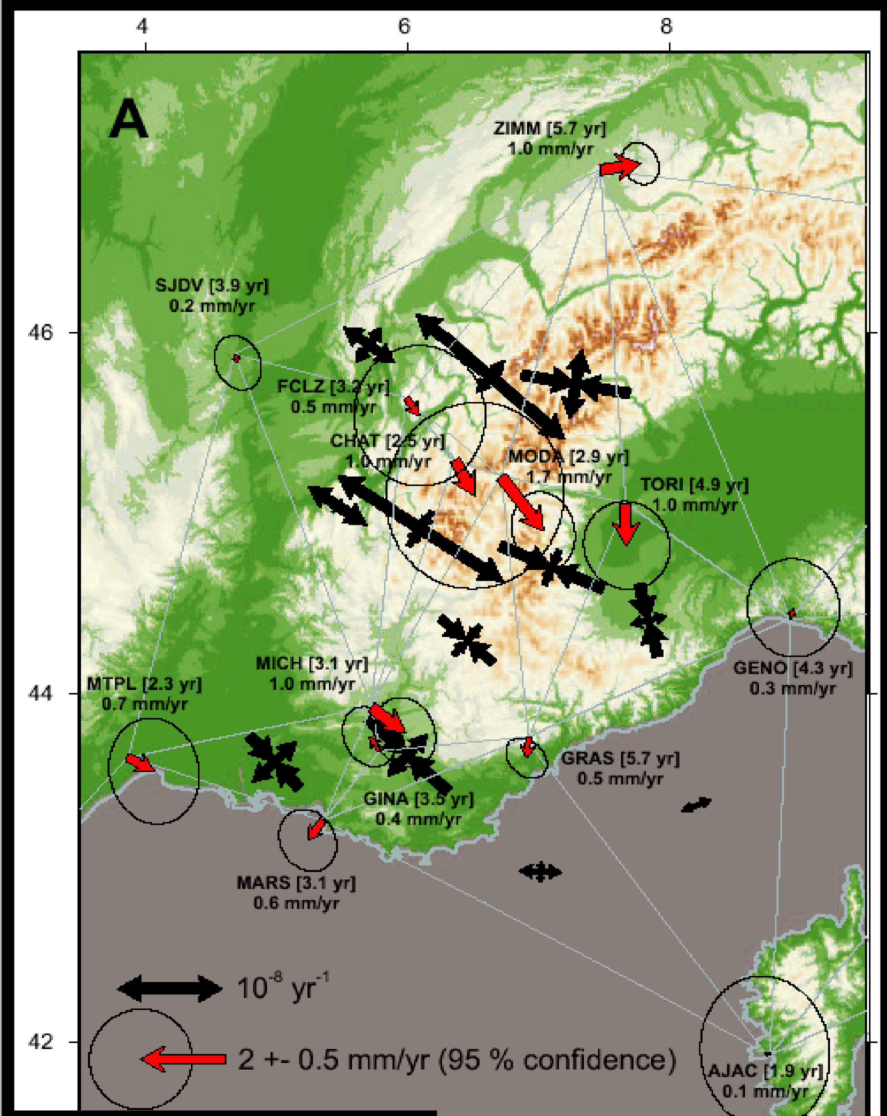
Handy et al., in rev.

Current strain field

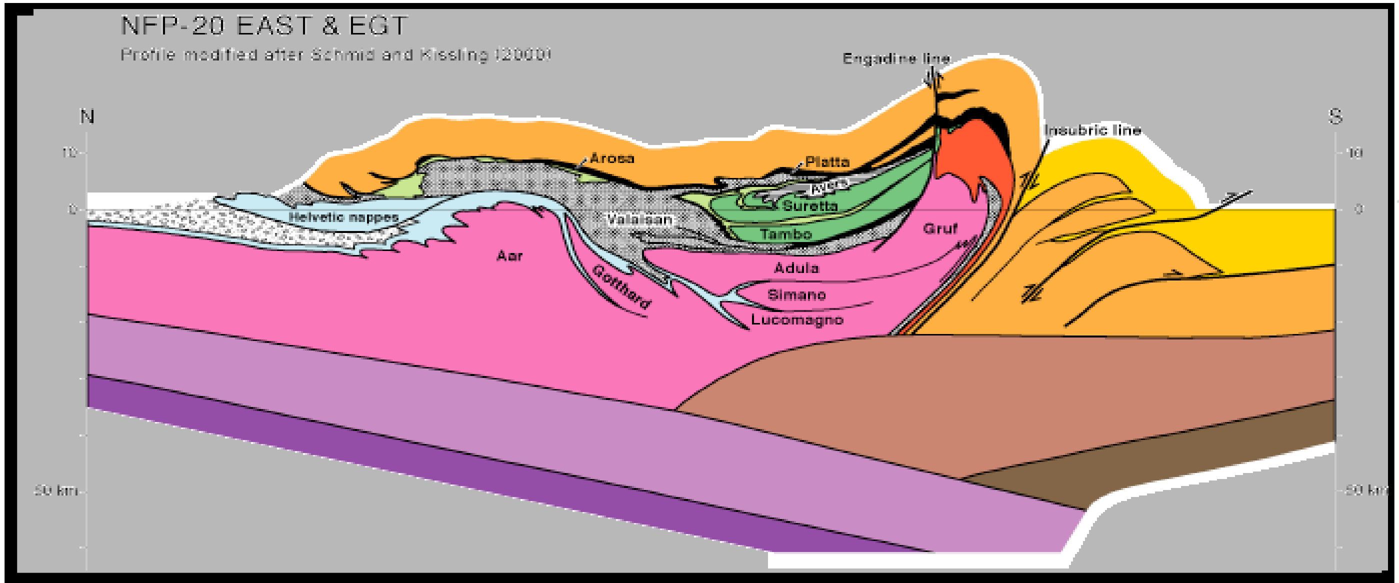
GPS – W-ALPS: 1 to 2mm/a across chain



C. Vigny et al., J. Geod. 2000; Noquet, 2002

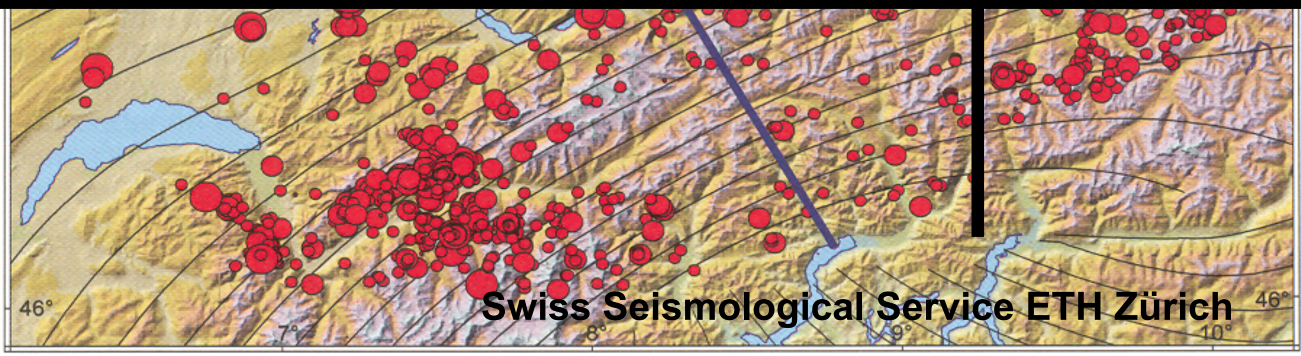


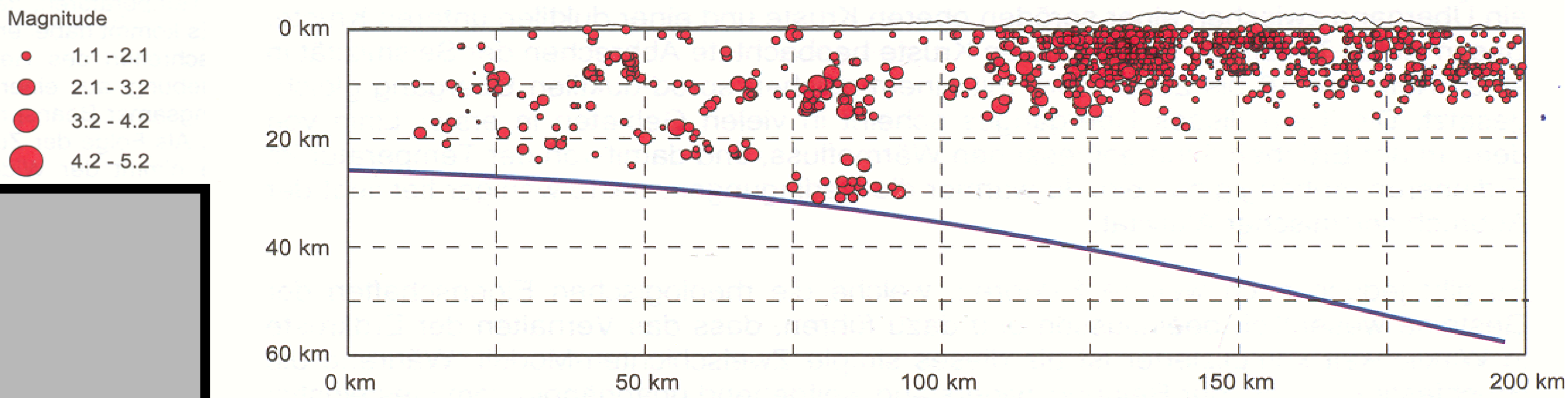
E. Calais et al., Geology, 2002



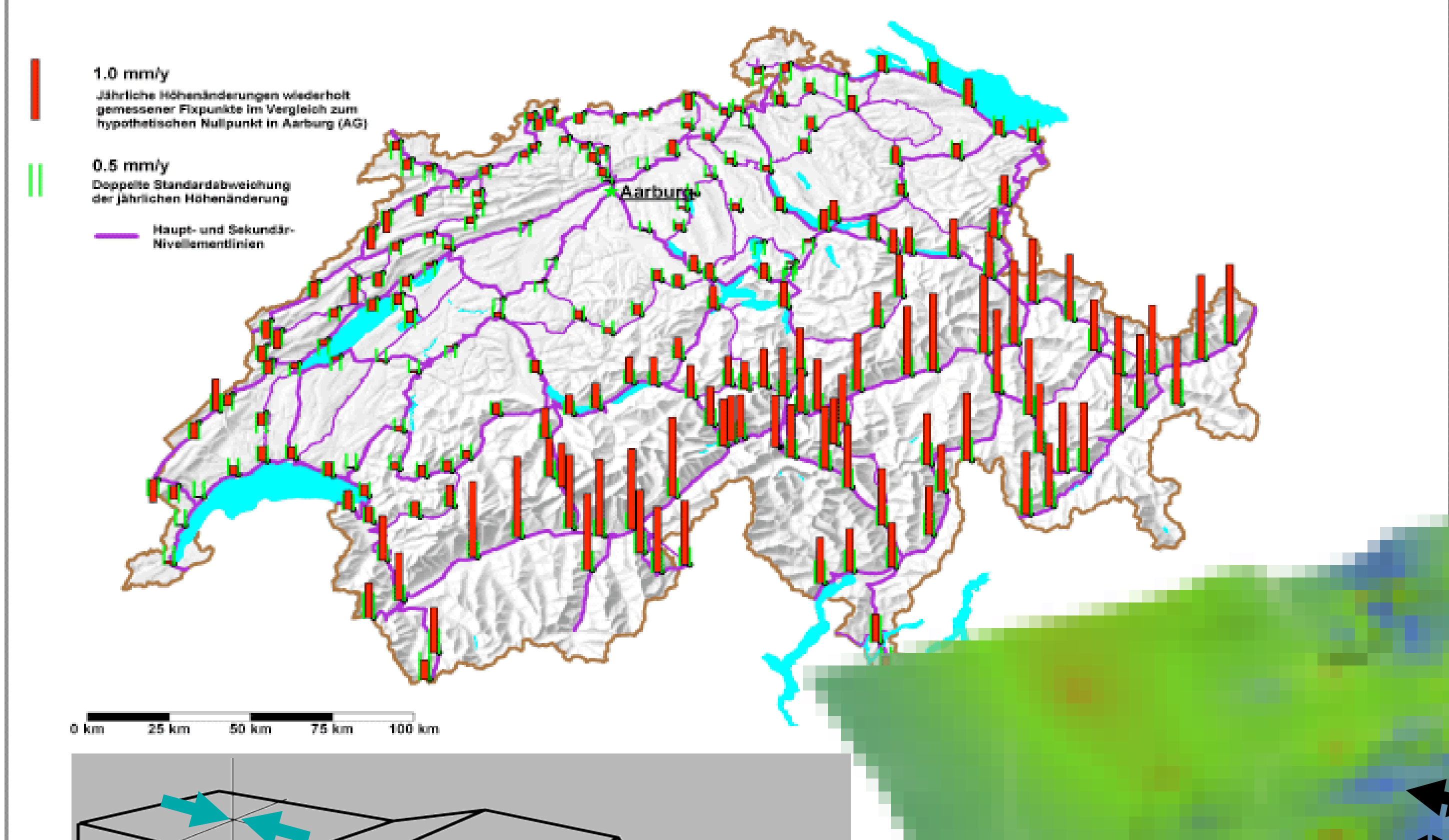
Epicenters and Hypocenters 1975 – 1999 in Central Alps

=> current stress field



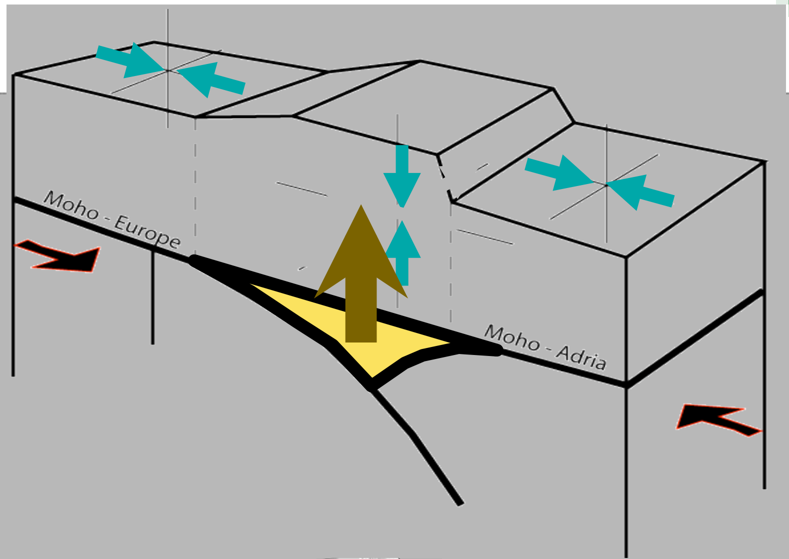


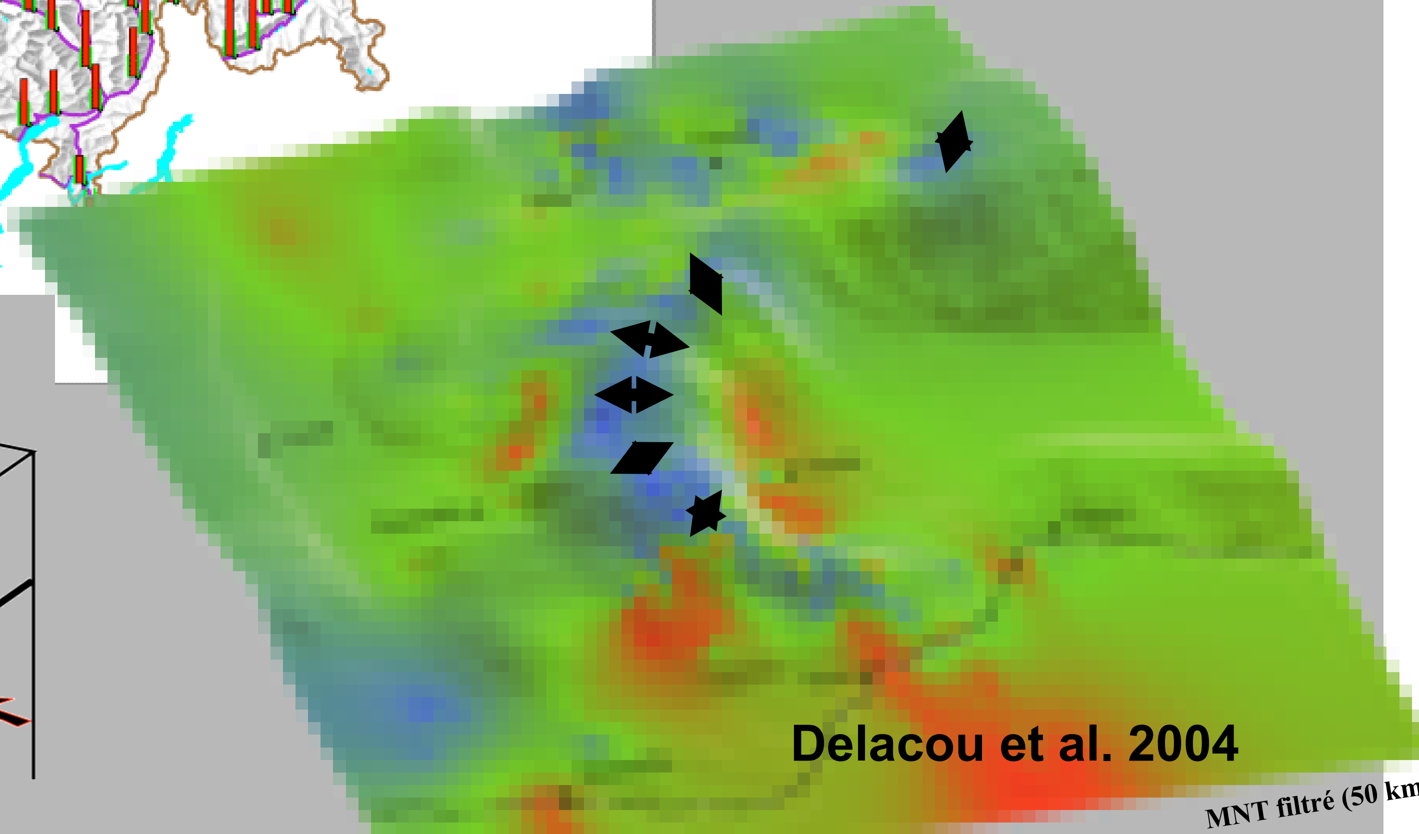
Recent Uplift and Seismic Stress Field



estimated current convergence rate: 1-3 mm/y

uplift rate: 2 mm/y





Delacou et al. 2004

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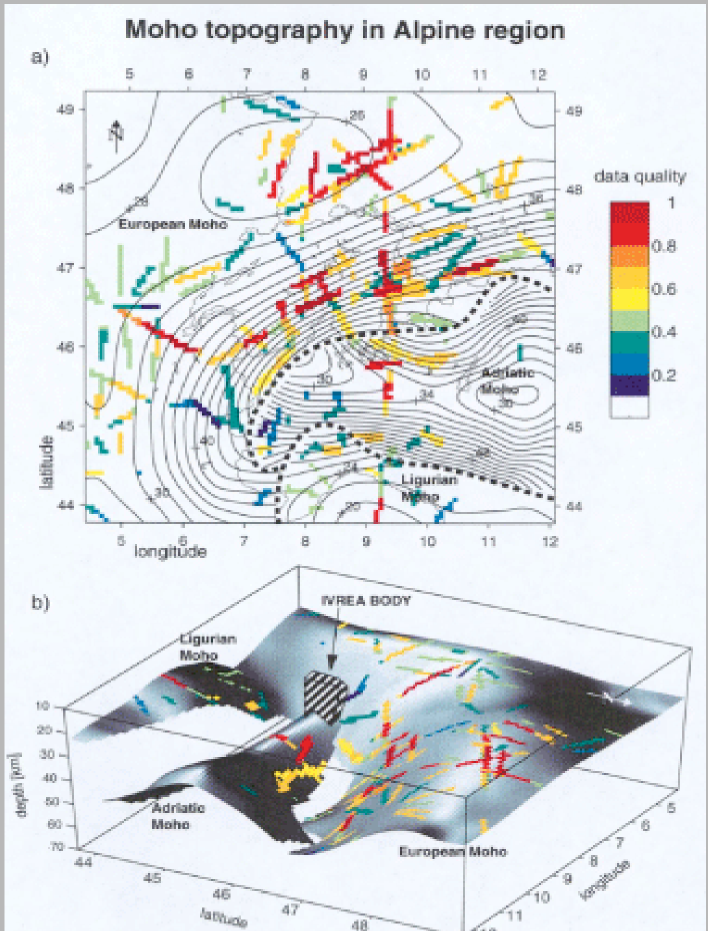
Alpine isostasy

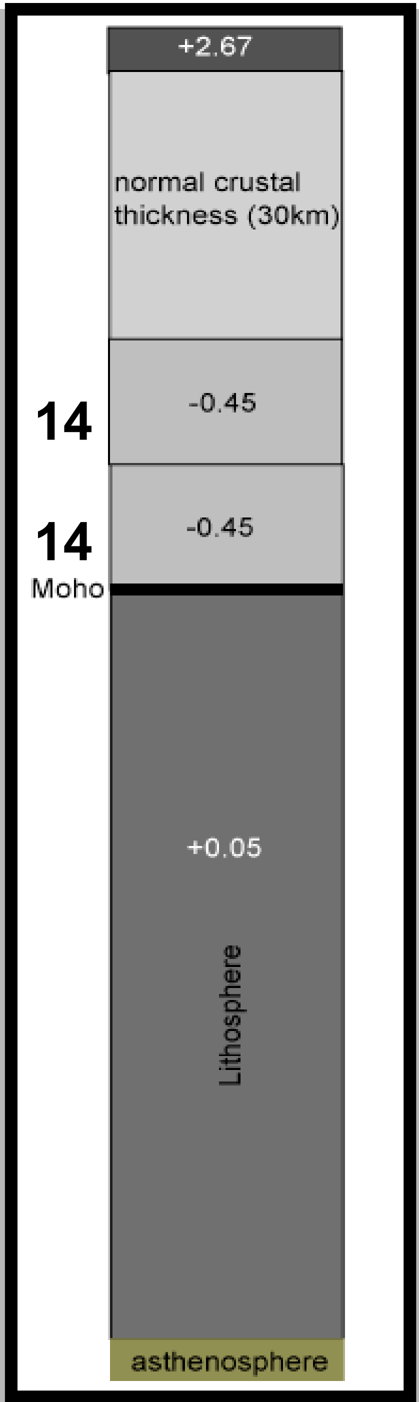
in relation to such a deep Moho of down to 58km:

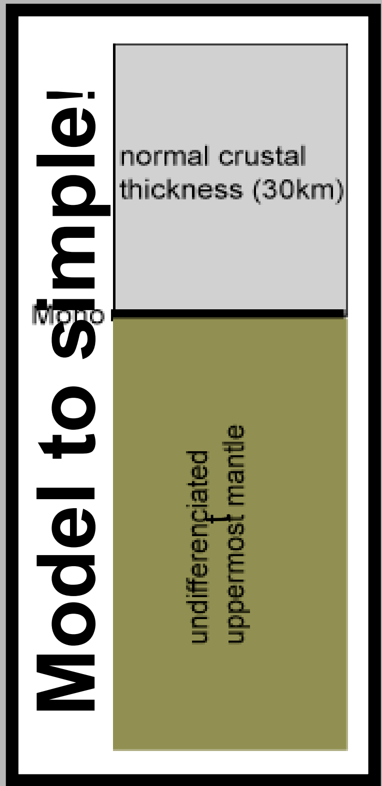
How comes the Alps are not higher?

Why are the Bouguer anomalies not more negative than 180mgal?

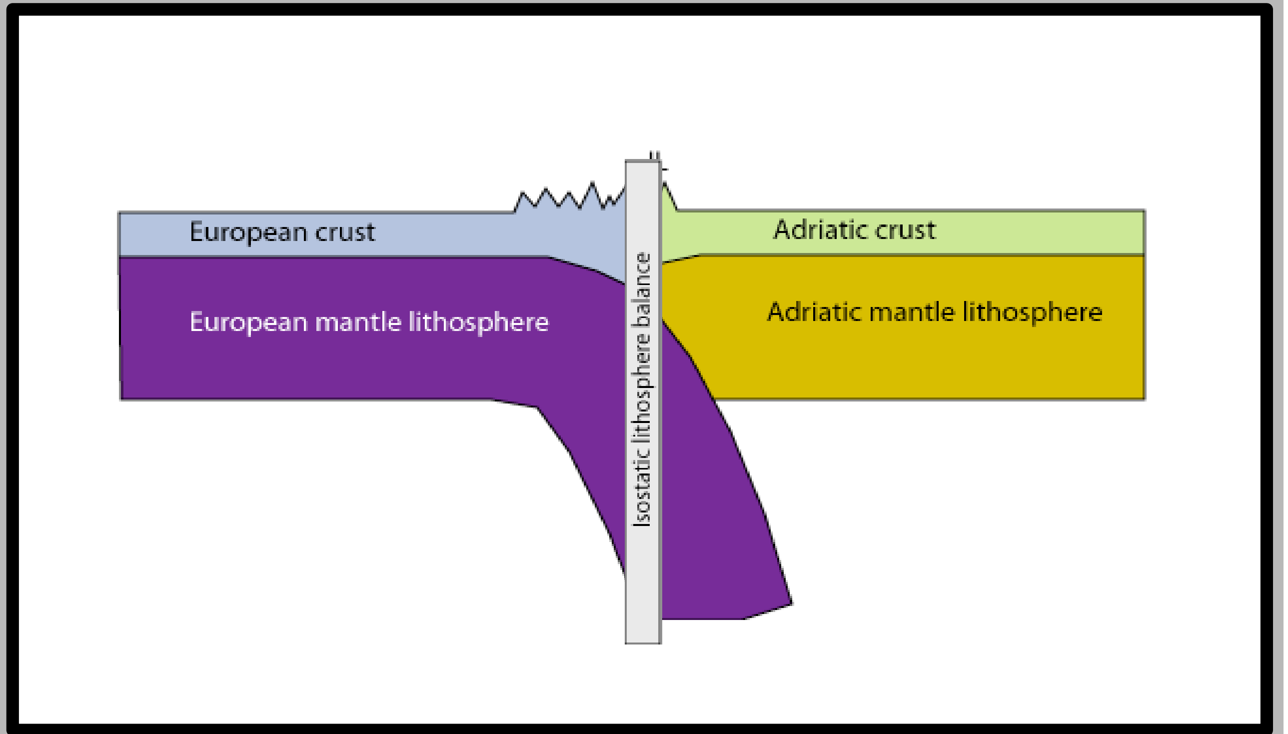


2km topographic mass approximately compensated by 14 km crustal root (observed 28km thick root)





Alpine Lithosphere Isostasy



Since erosion and uplift eventually remove the crustal root, two more questions remain in the case of the Alps:

1. **After all the previous uplift and erosion, how comes the Alps are still strongly overcompensated?**
2. **How did the crustal root get so deeply buried?**

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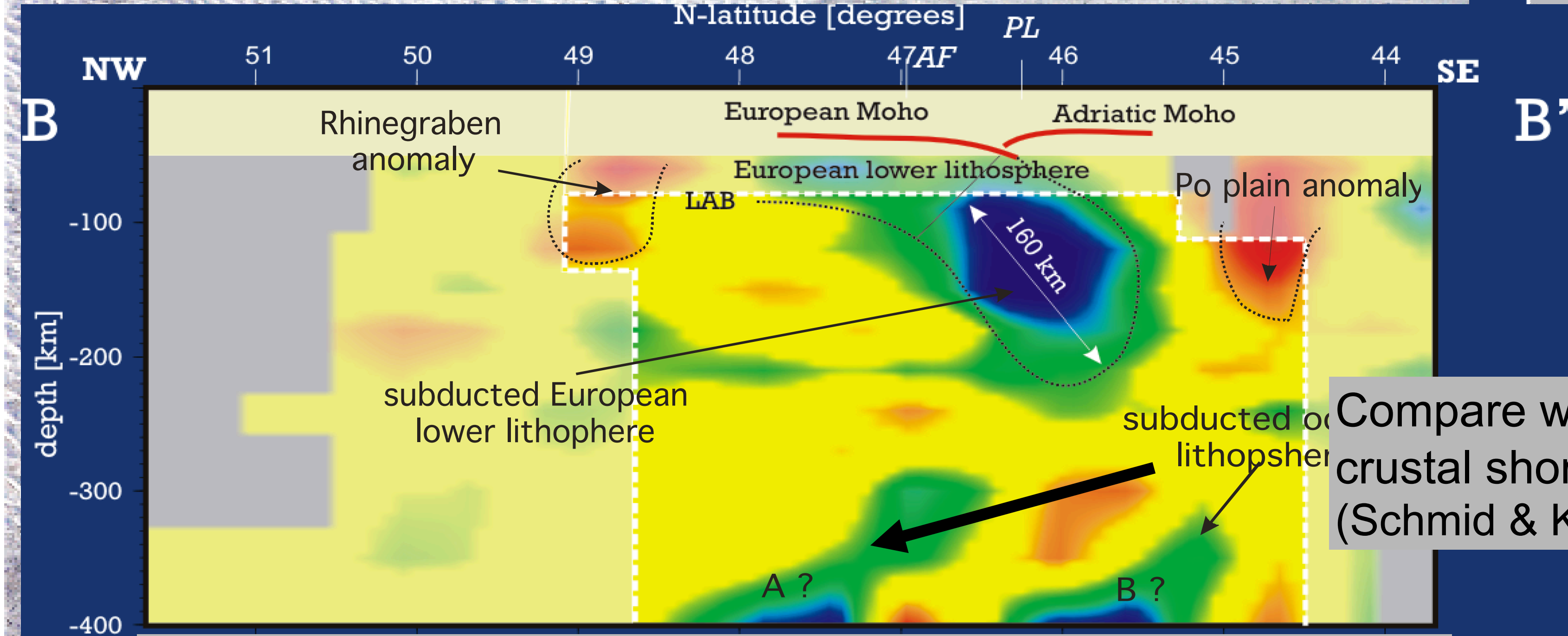
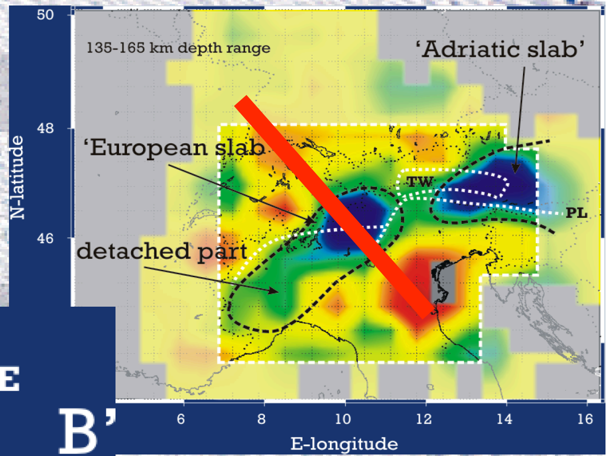
S-vergent subduction of E- mantle lithosphere beneath Central Alps

Lippitsch et al. 2003



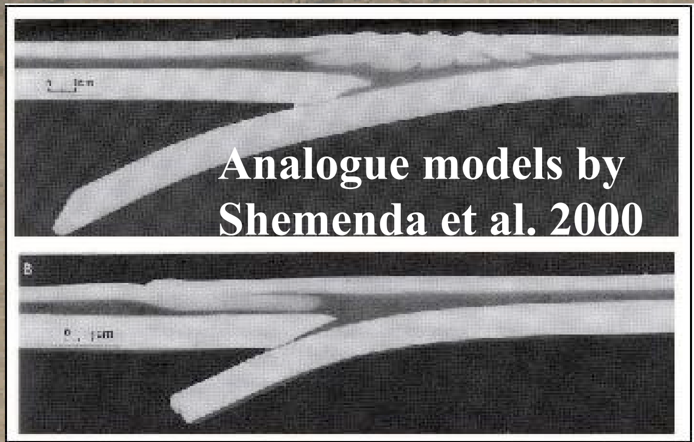


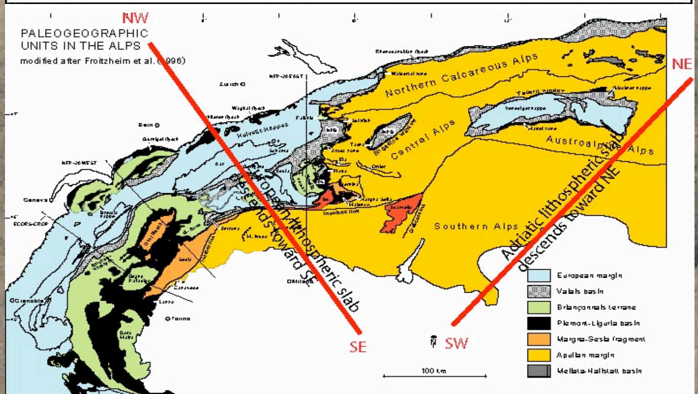
Compare with post-collisional crustal shortening of 140 km (Schmid & Kissling 2000)

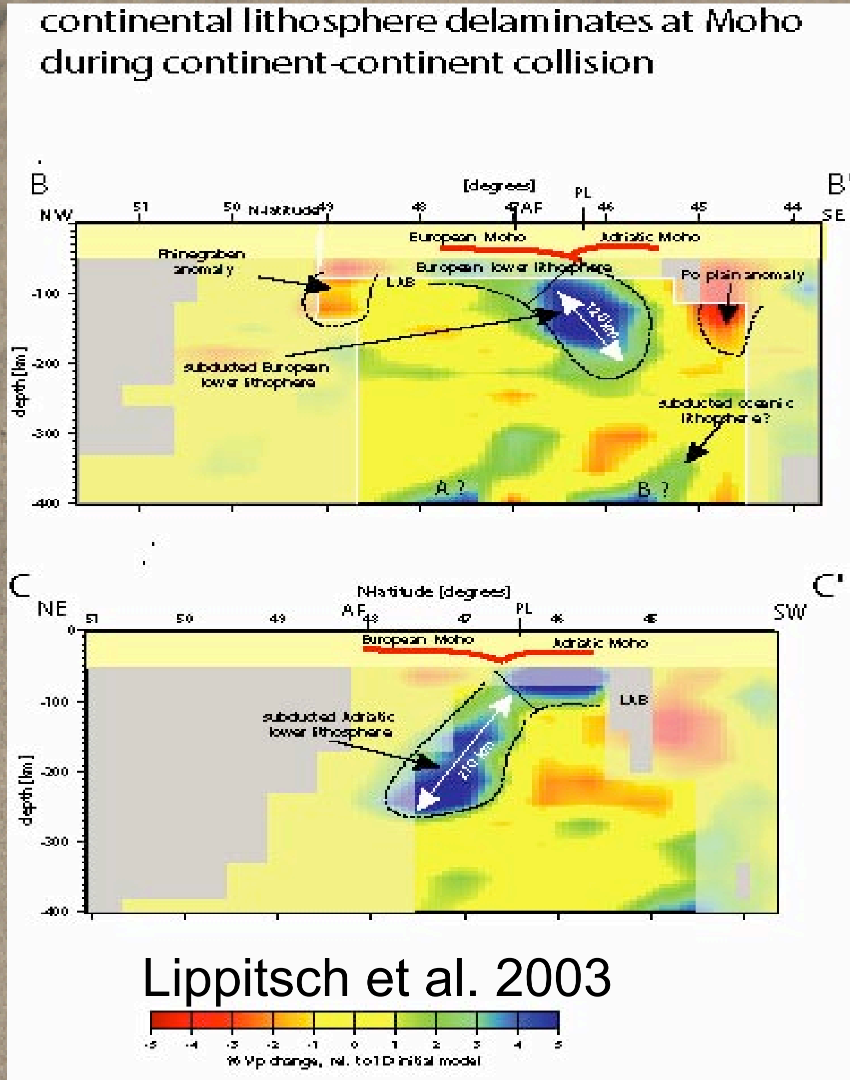
=> negative bouancy of continental mantle lithosphere

In collision, continental lithosphere delaminates near Moho

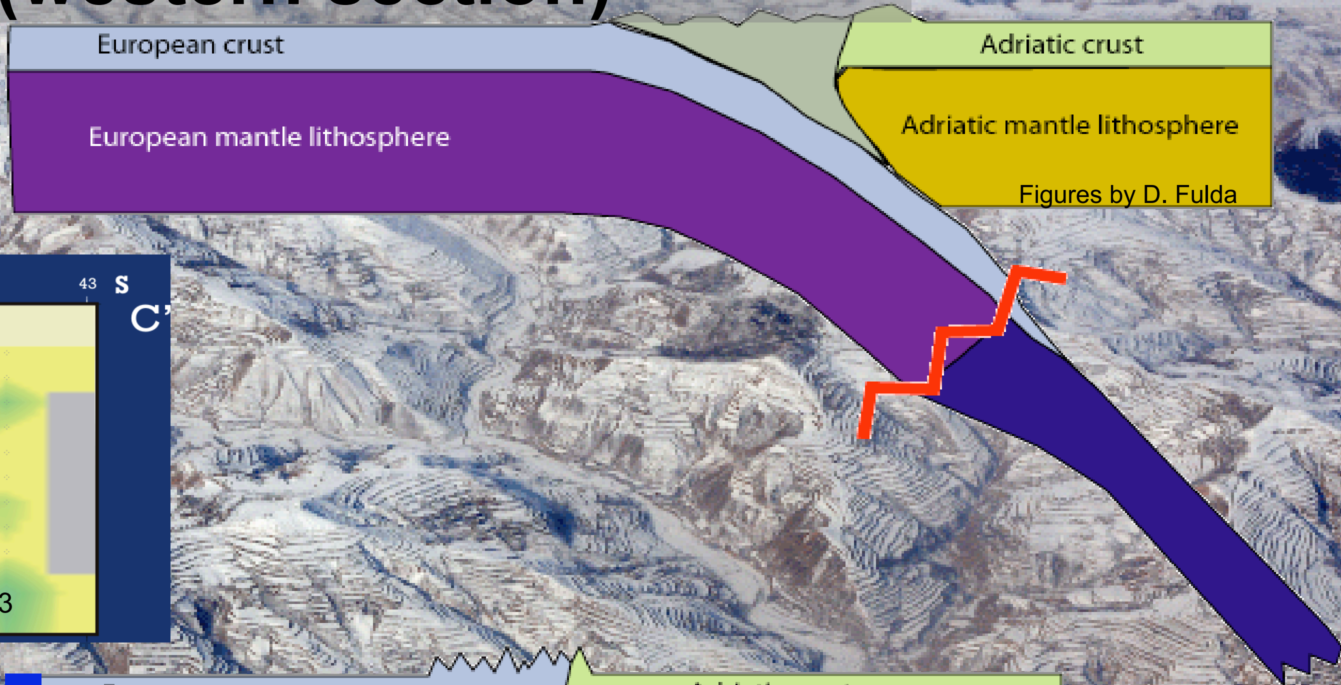
Compare location of suture at Moho level, geometry of lithosphere slab, and results of analogue modelling

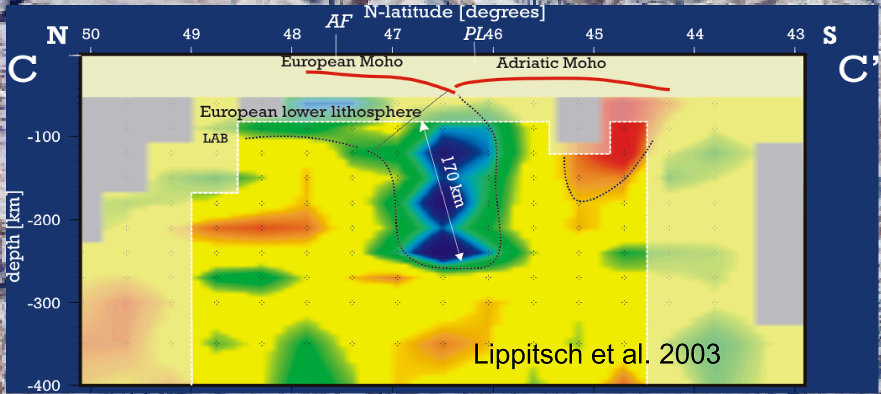


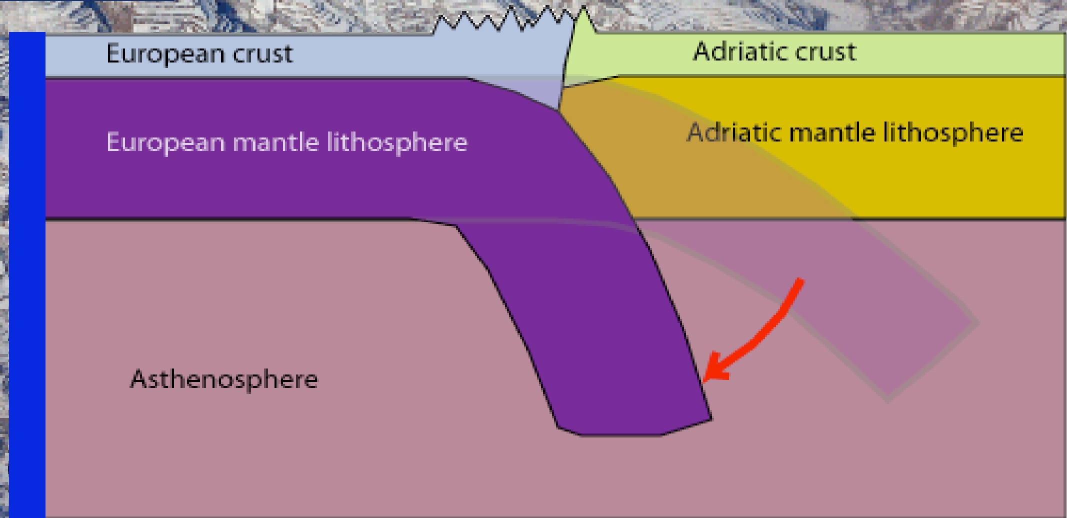




Evolution of Alpine Collision (western section)



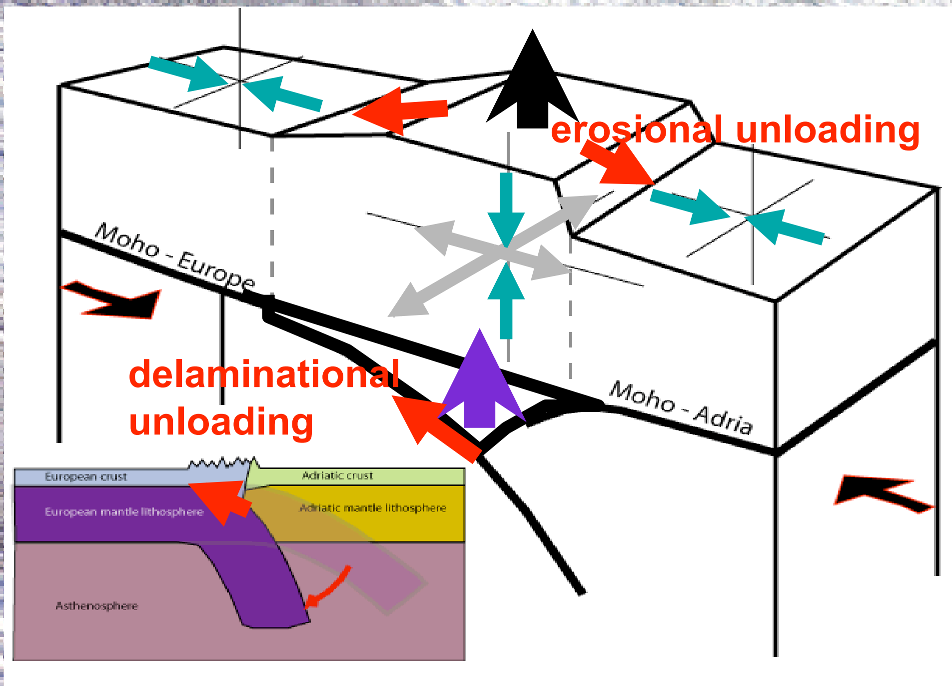


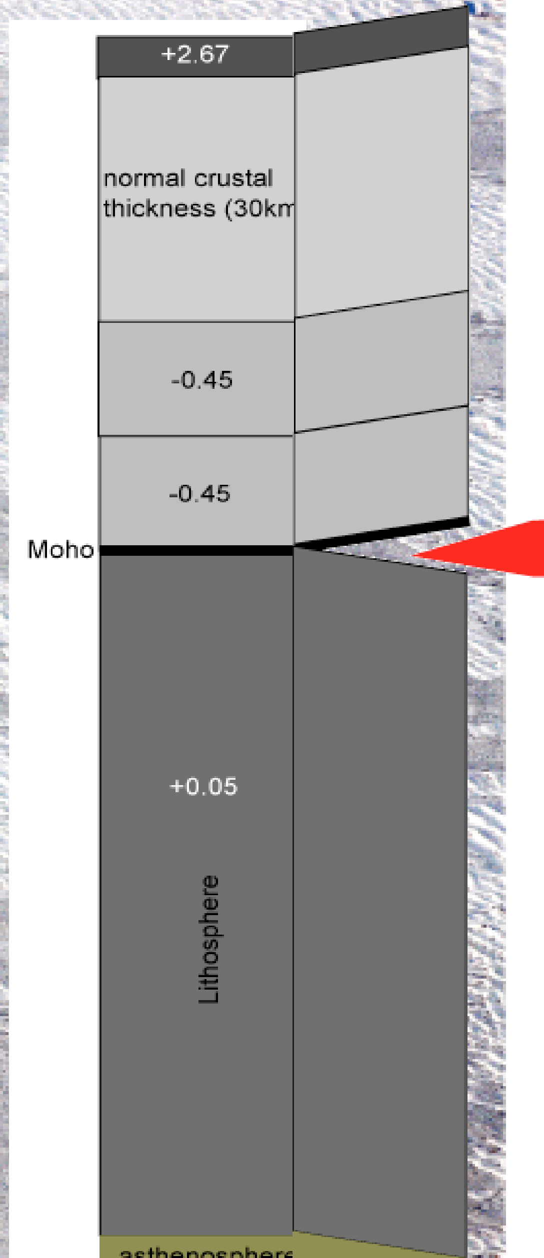


Conclusions “Alpine lithosphere structure”

1) Slightly negative buoyancy of mantle lithosphere (relative to asthenosphere)
2) Continental lithosphere delaminates near Moho
3) Oceanic lithosphere has been detached upon collision
4) European slab retreated during subduction-collision

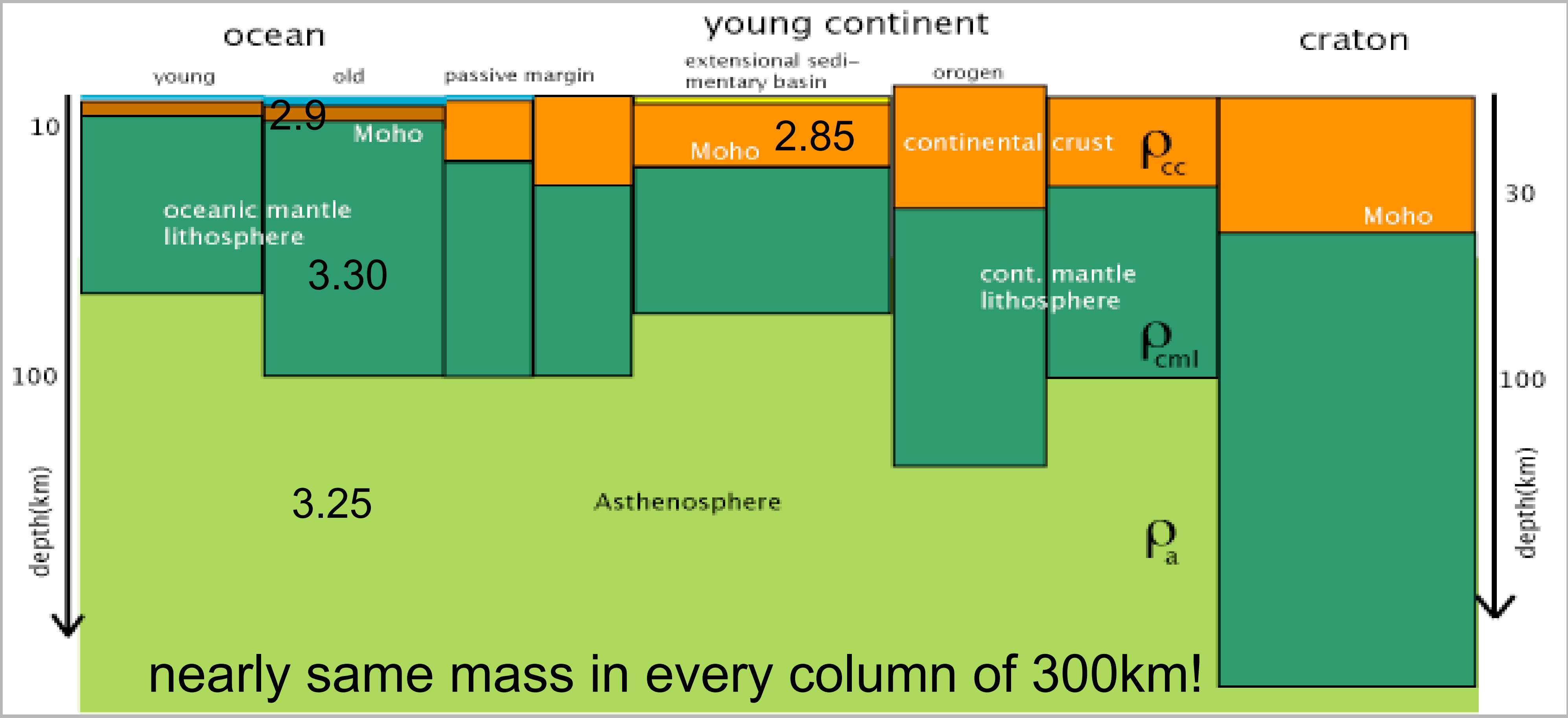
Thick crustal root balances topography and lithosphere slab, NW-ward propagation of delamination near Moho causes NW migration of isostatic uplift





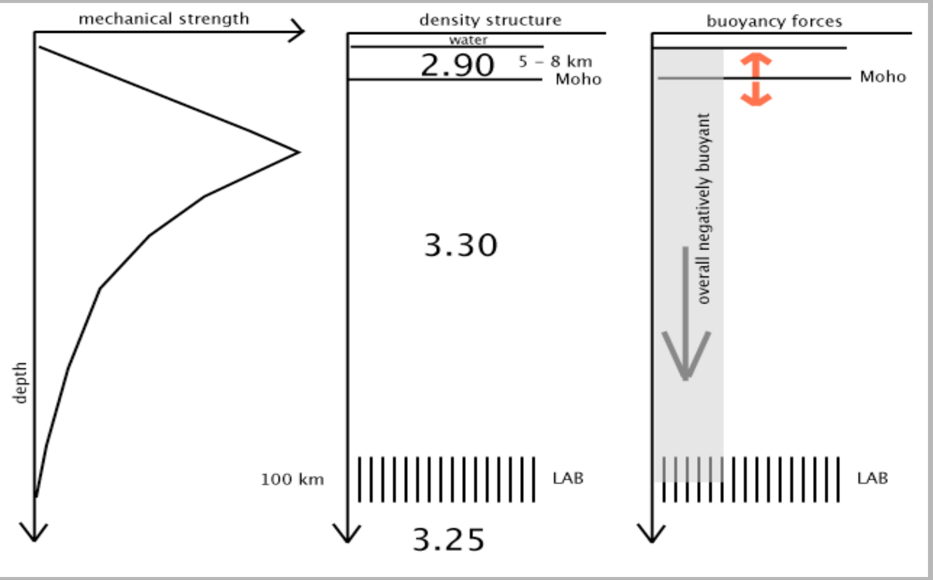
Principle of approach: Lithosphere isostasy

in isostatic equilibrium floating plate experiences divergent buoyancy forces across Moho

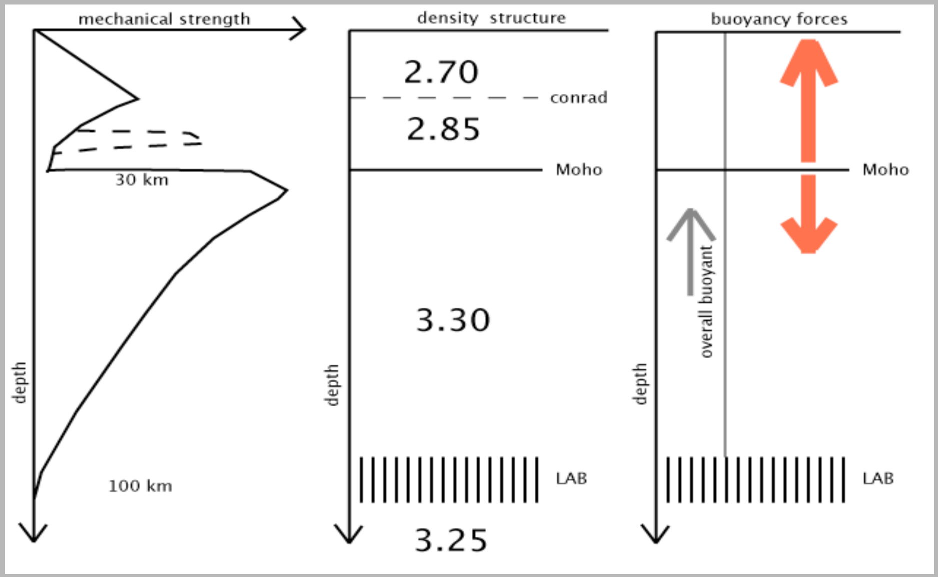


Lithosphere isostasy and mechanics (1)

Mature oceanic lithosphere



Young continental lithosphere

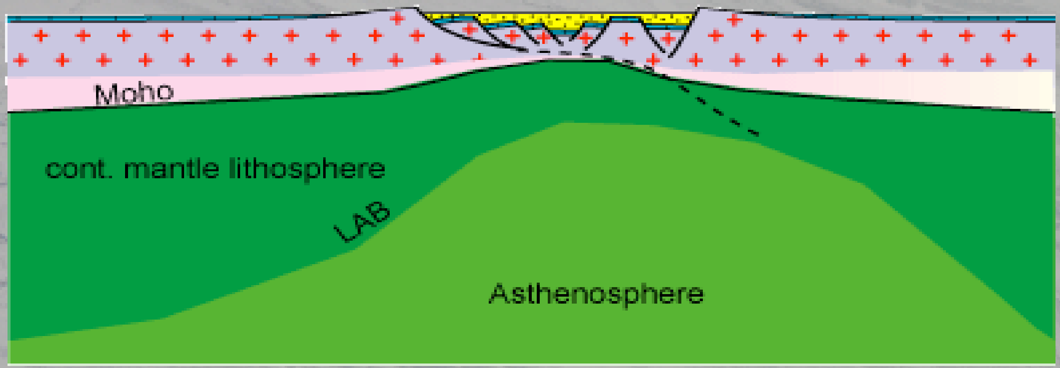


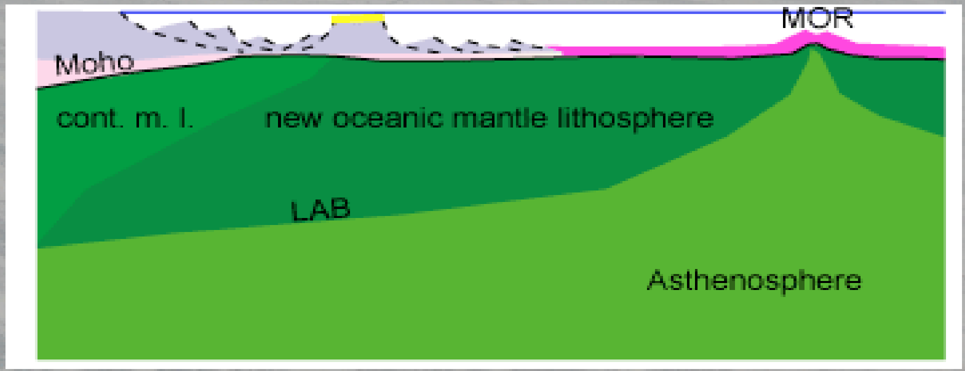
For oceanic lithosphere: single mechanically strong layer!

For continental lithosphere: weak point at Moho levels!

Lithosphere isostasy and mechanics (2)

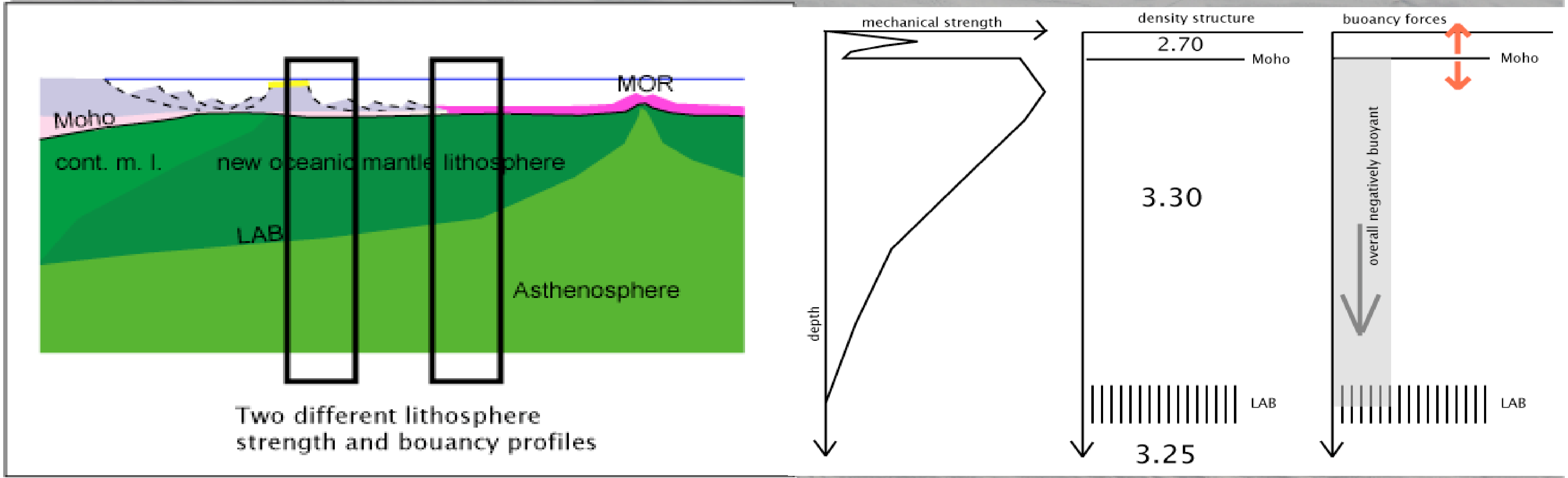
Opening of Piemont ocean





Lithosphere isostasy and mechanics (2)

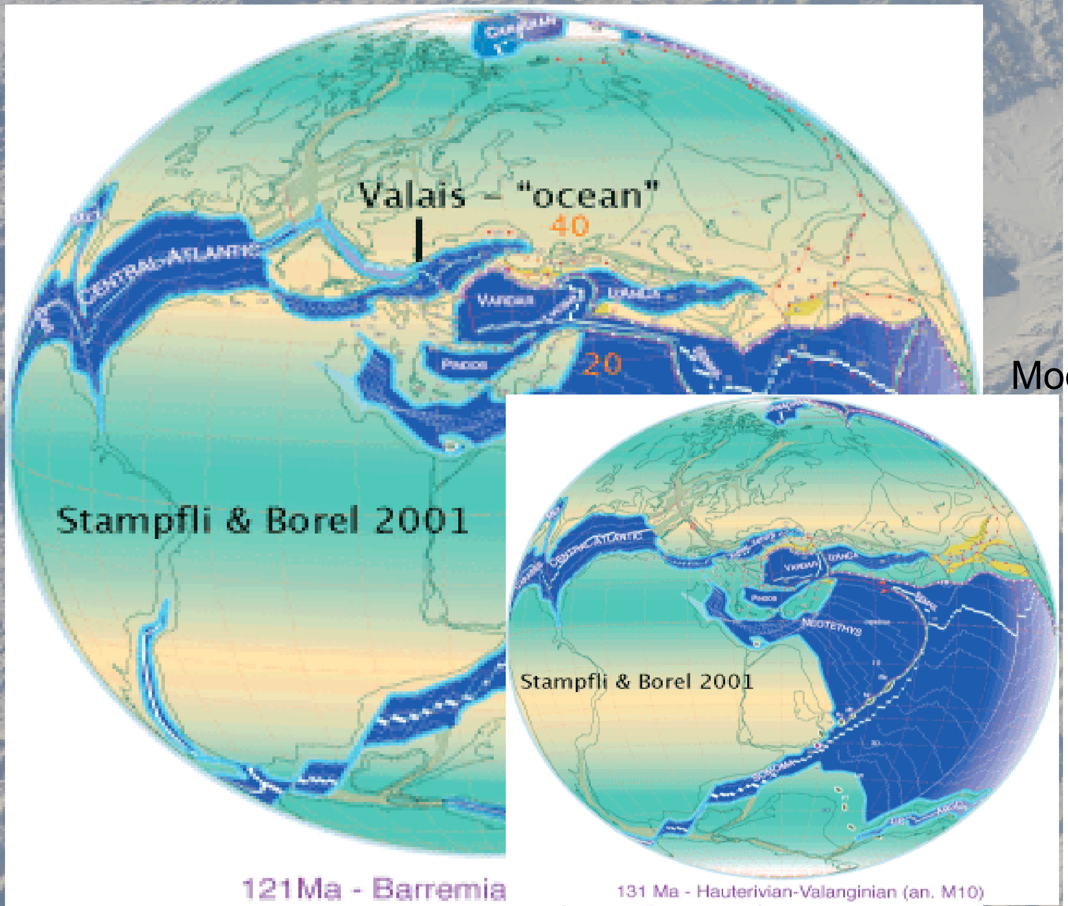
Opening of Piemont ocean

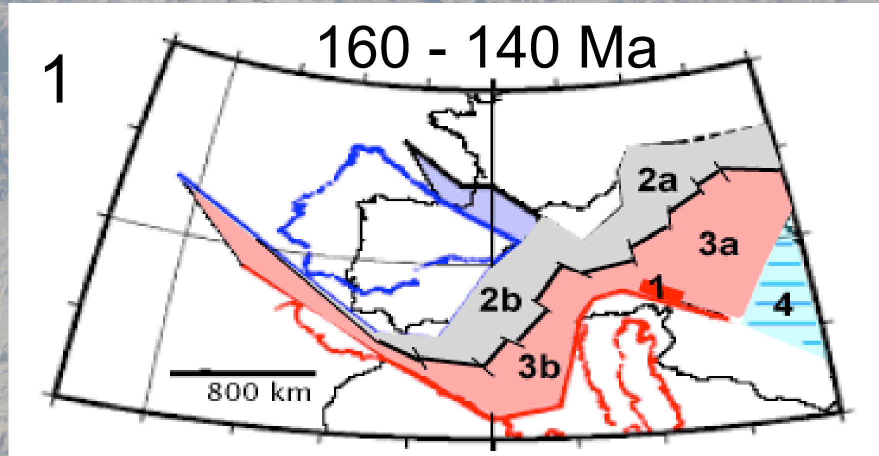


Strongly extended formerly continental lithosphere (Penninic nappes, Brianconnais domain etc.): strongly thinned lower continental crust, pieces of upper continental crust overlying newly formed (oceanic) mantle lithosphere => locally strong divergent buoyancy forces across Moho, easily detached in subduction and exhumed as nappes.

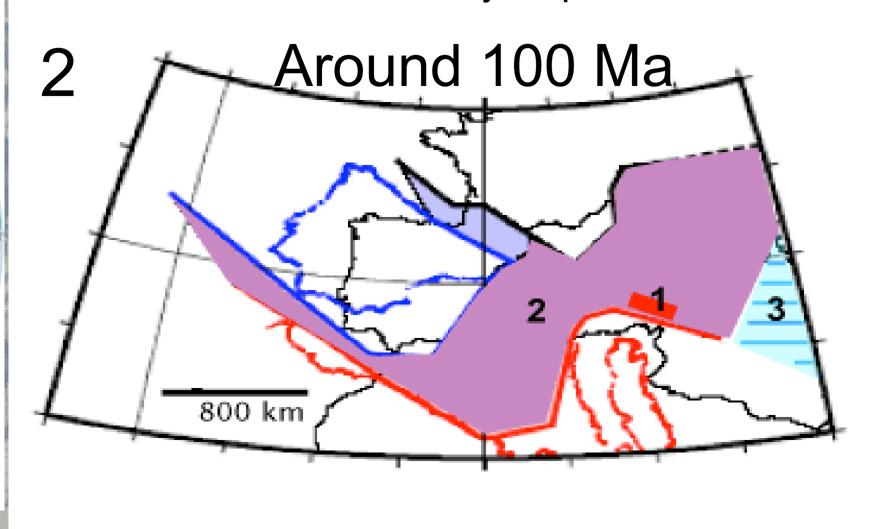
Spreading and evolution of Piemont ocean

1. Spreading in Ligurian-Piemont oceans





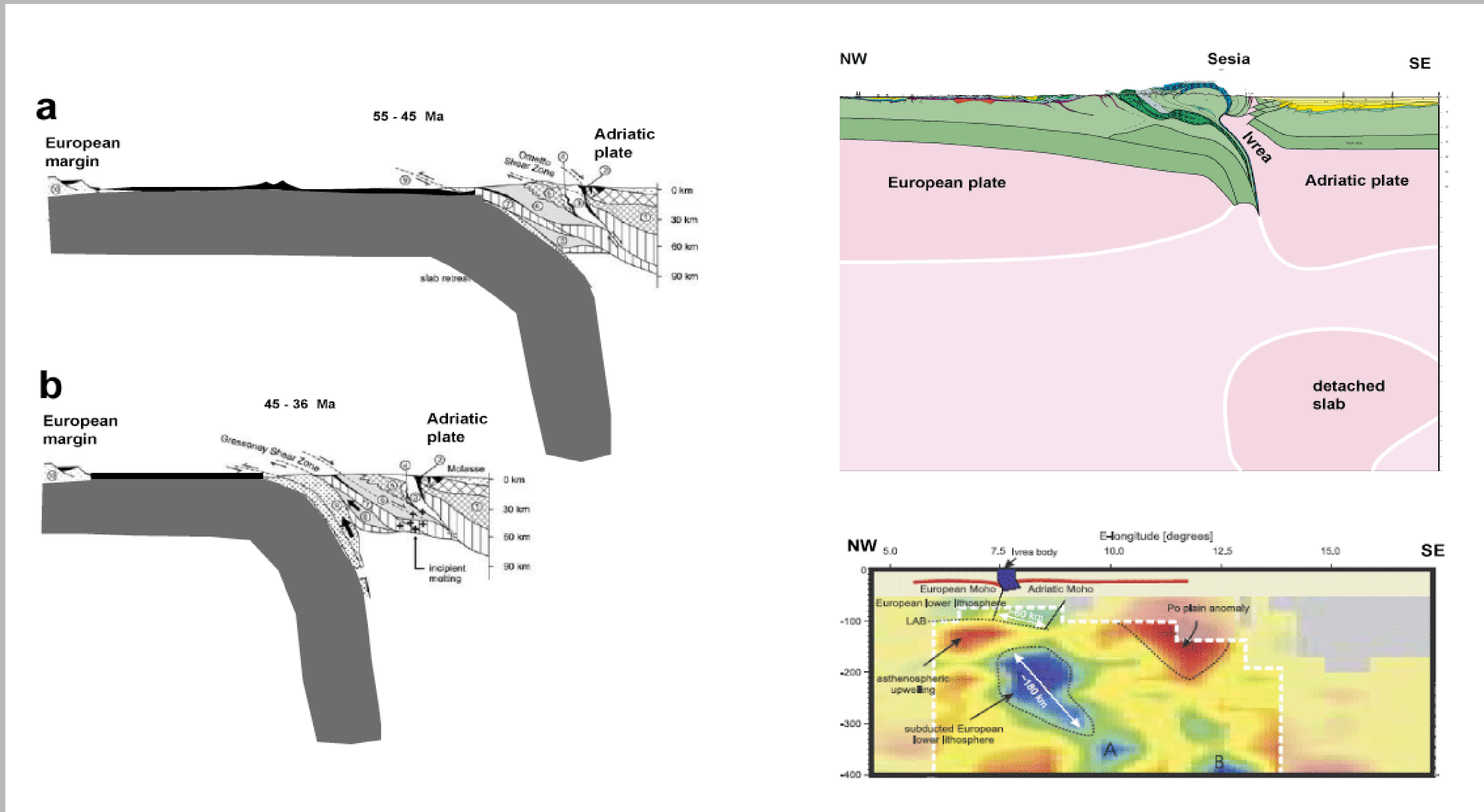
Modified from reconstruction by Capitanio & Goes 2006



2. "Freezing" of Ligurian-Piemont oceanic lithosphere => no intra-oceanic plate boundary existing

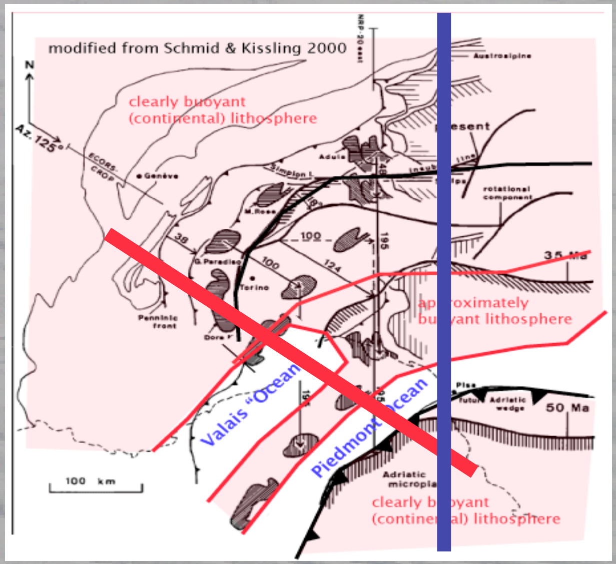
Subduction of Piemont ocean: the story told by Sesia nappes

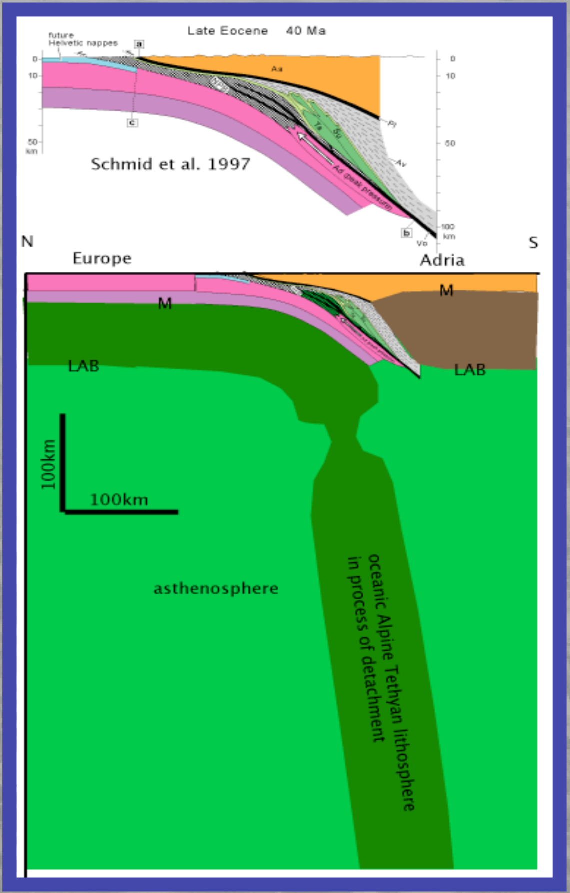
Slightly modified from Babist et al. 2007

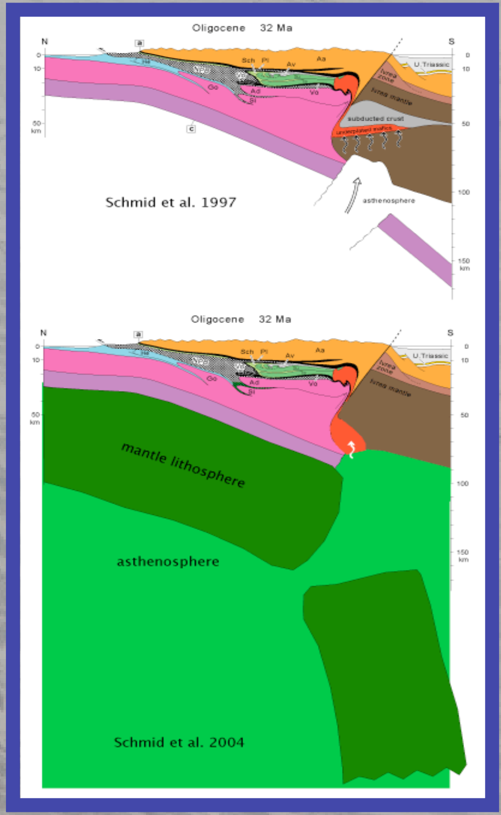


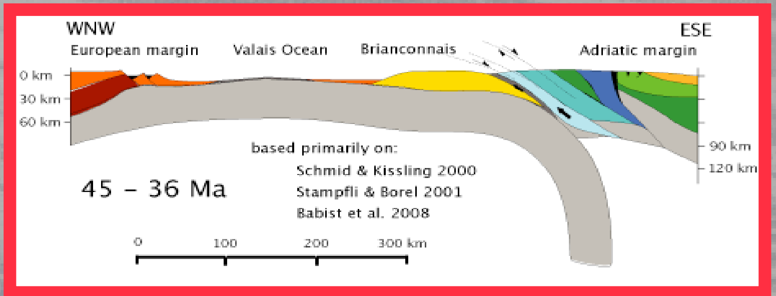
Piemont slab roll back and N to NW movement of Adria

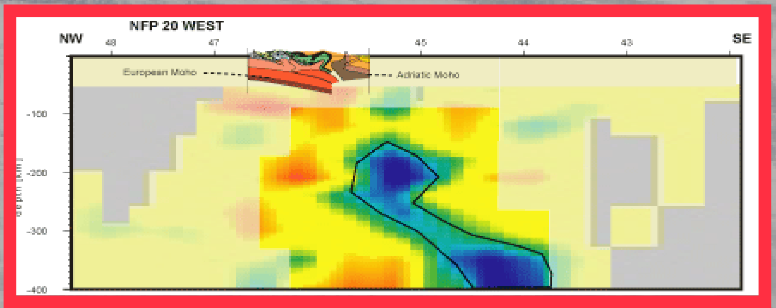
Valais ocean and evolution of Western Alps

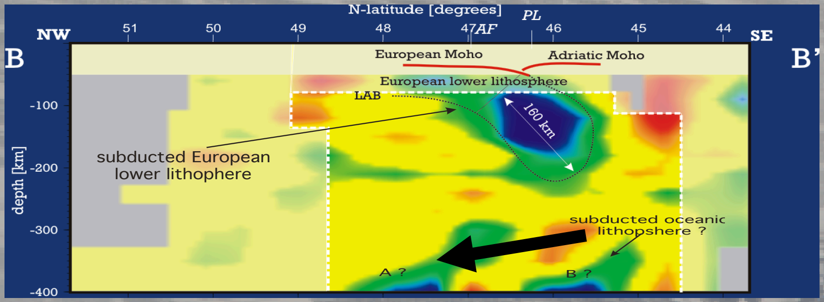






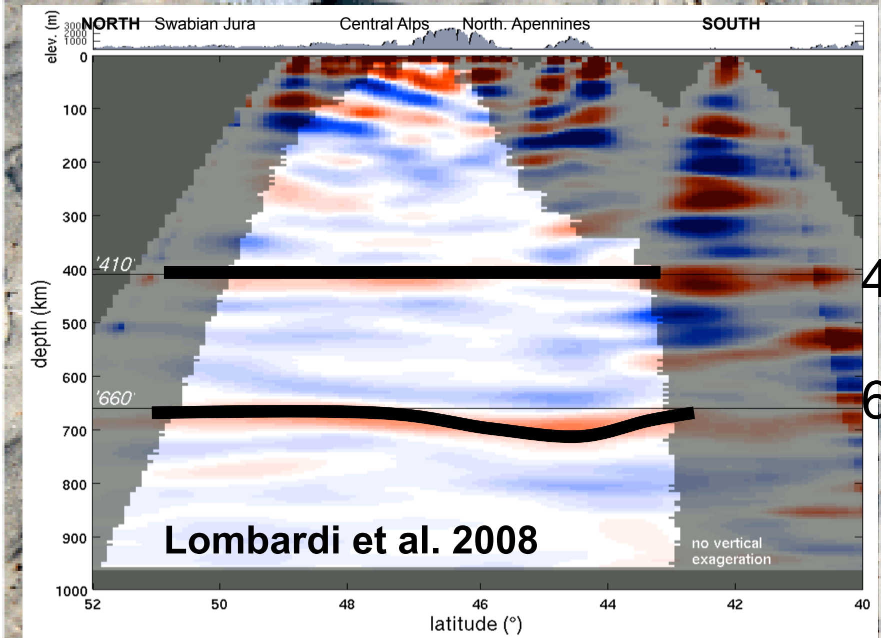


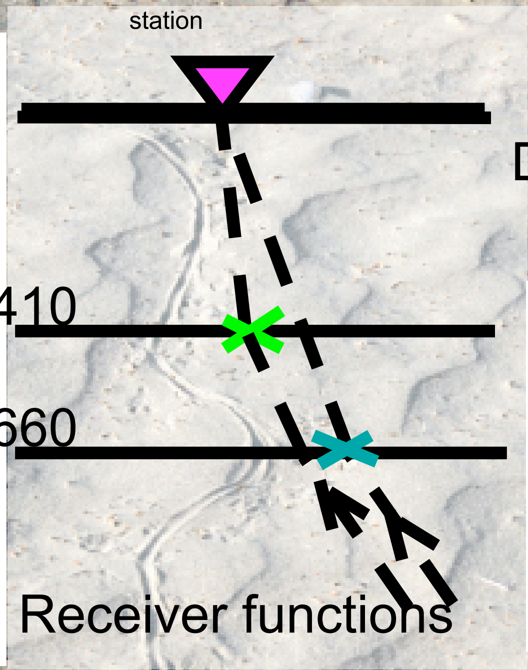




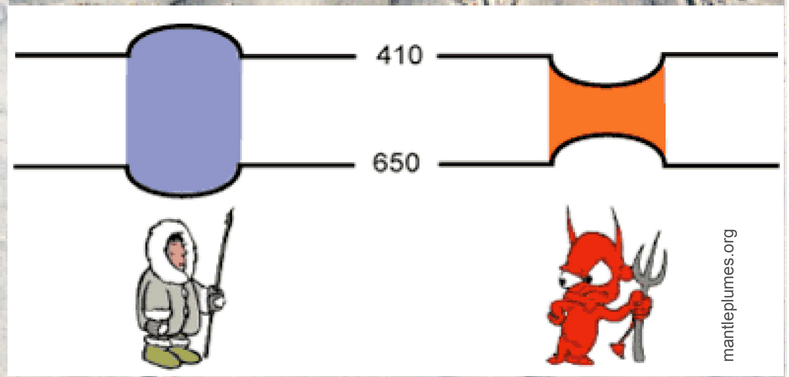
Pre-collision evolution of Alpine orogeny: where is the subducted ocean?

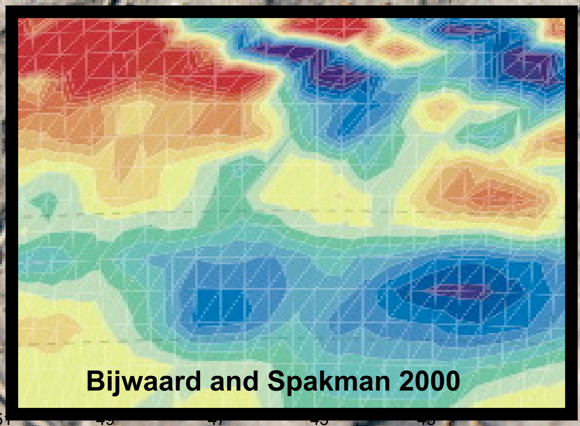
at bottom of mantle transition zone!

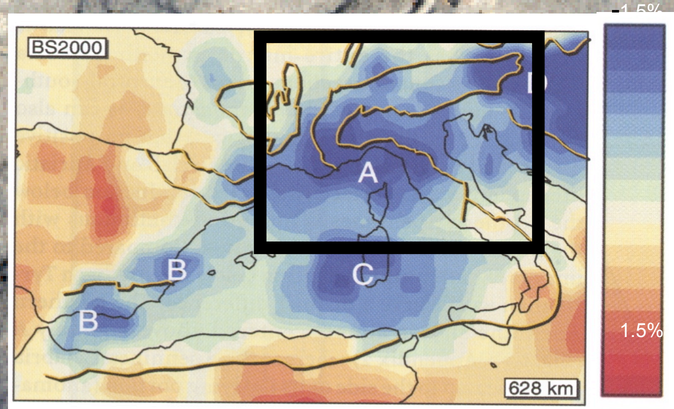




Diagnosis based on geometry of '410' and '660'







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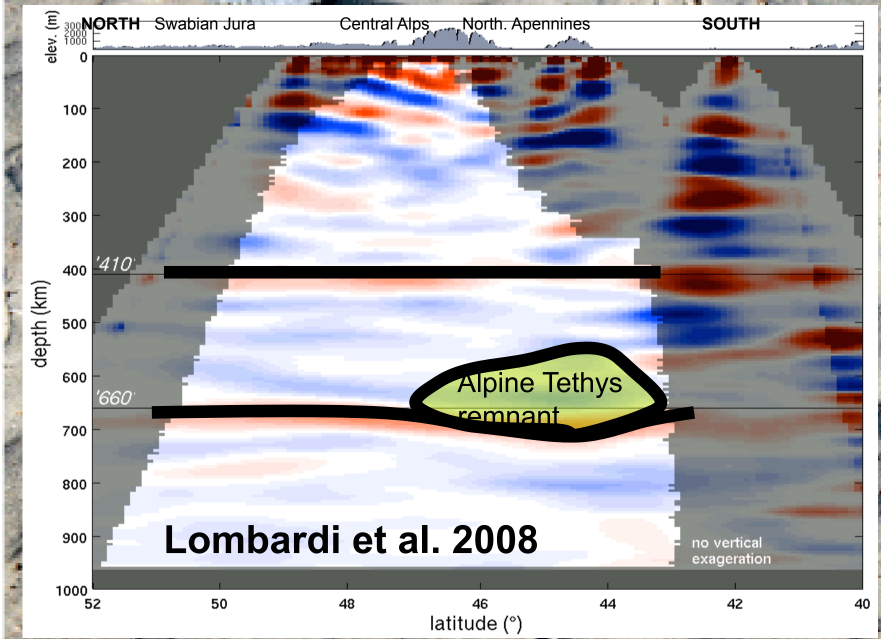
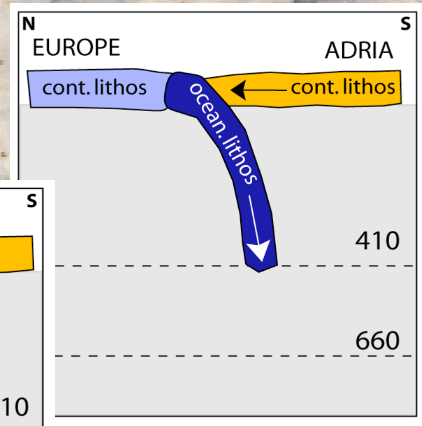
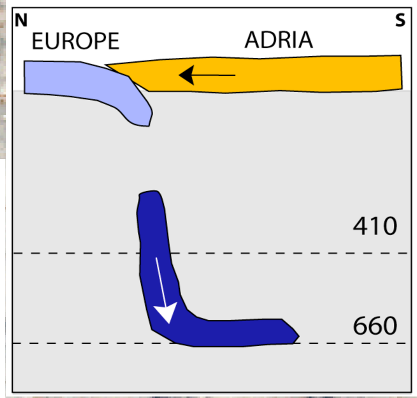
Pre-collision evolution of Alpine orogeny: where is the subducted ocean?

at bottom of mantle transition zone!

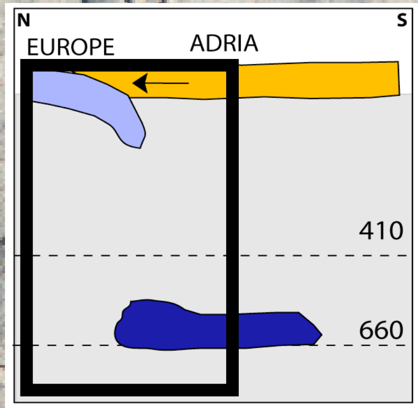




80 Ma

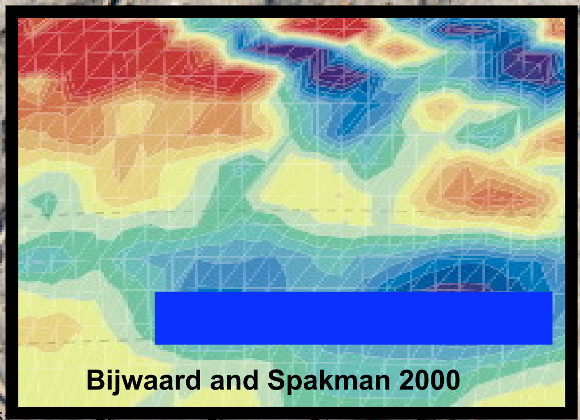


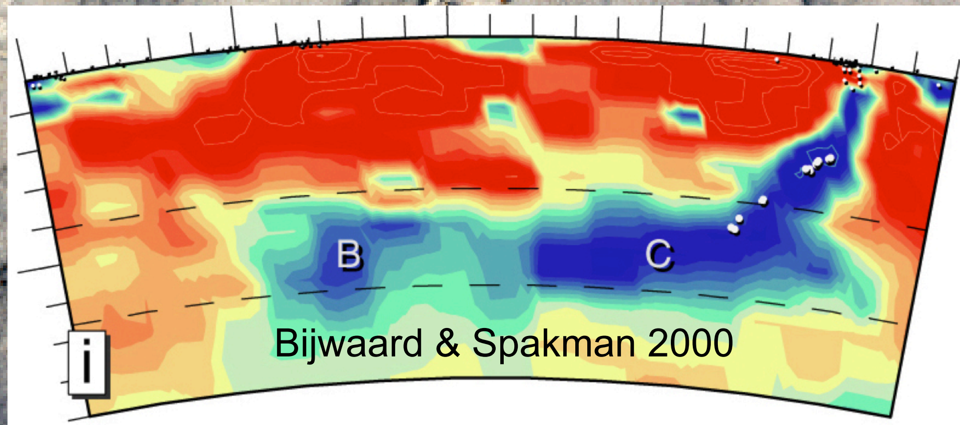
30 Ma



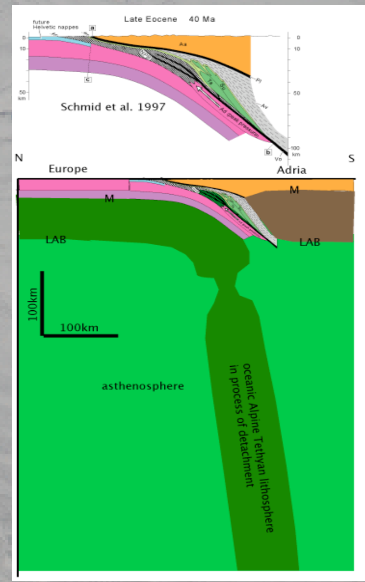
Present

after Piromallo and Faccenna 2004





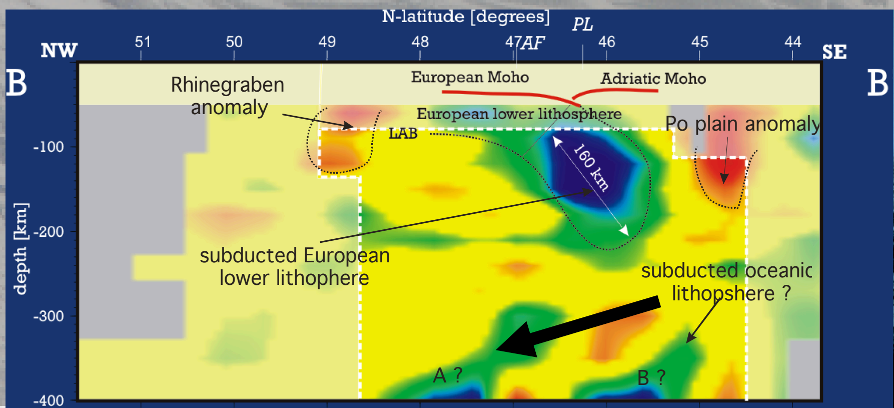
Conclusions (part 1)



buoyancy forces inherent in lithosphere structure drive (Alpine) **orogeny**

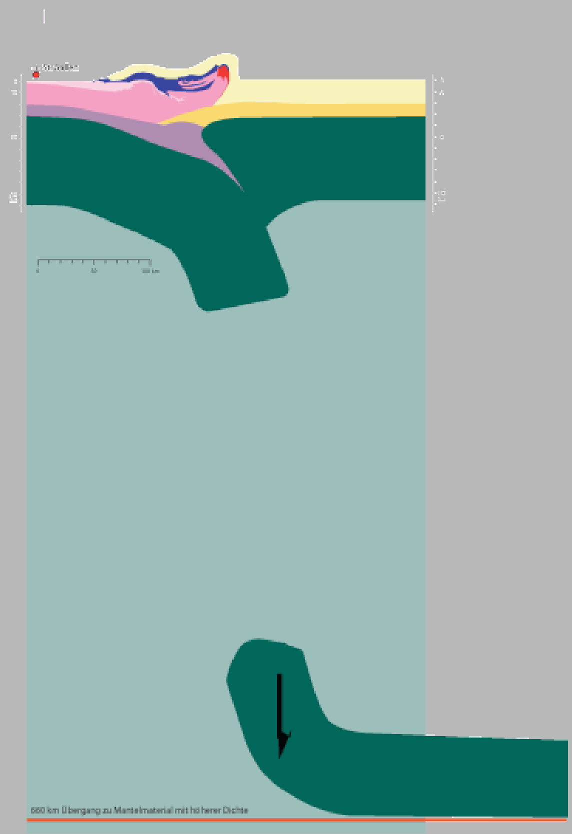
Alps are in isostatic equilibrium. With continued delamination and with current erosion rate, Alps will be of same height for several Ma to come!

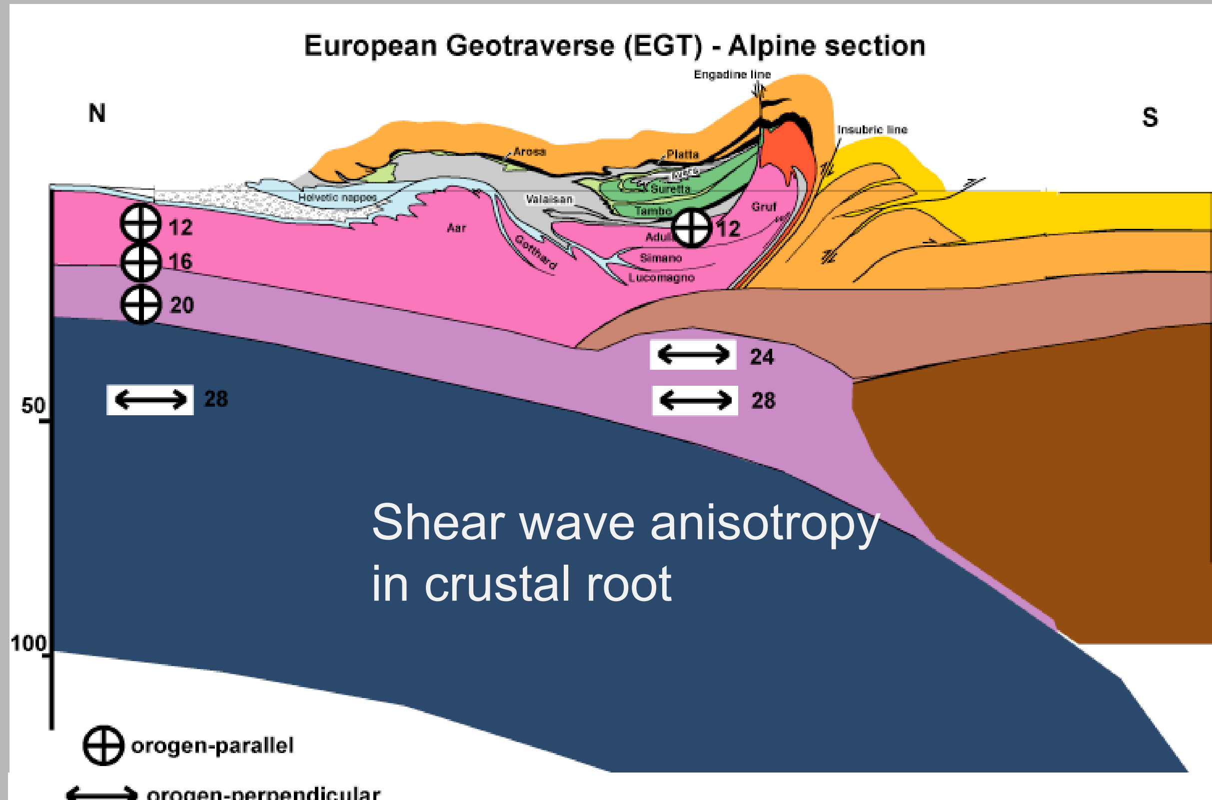
main forces currently shaping the Alps are lithosphere delamination and surface erosion, i.e. buoyancy forces!



Proposal geodynamic model process 1

Remaining very deep crustal root beneath W-Alps results from stacking of post-collisional delaminating of lower crust near Moho level while mantle lithosphere exhibits slow roll back.



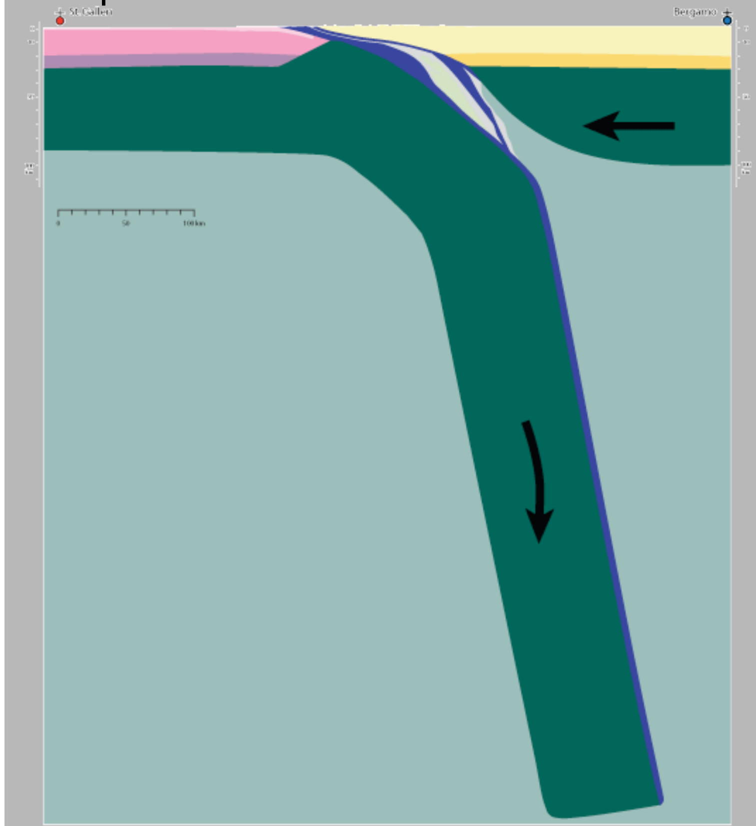


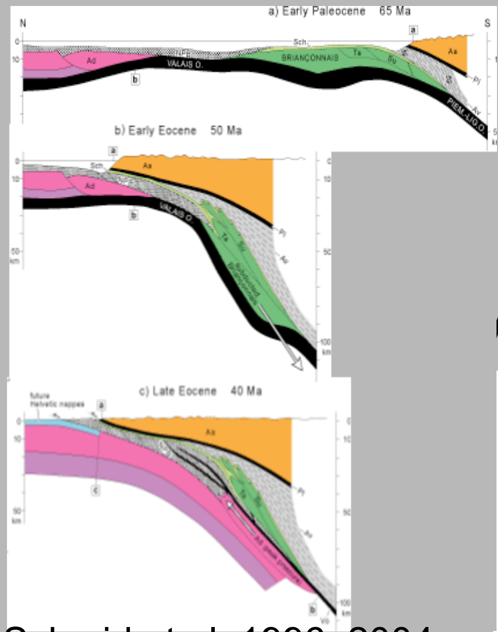
Fry, Deschamps, Kissling submitted 2009

Proposal geodynamic model process 2

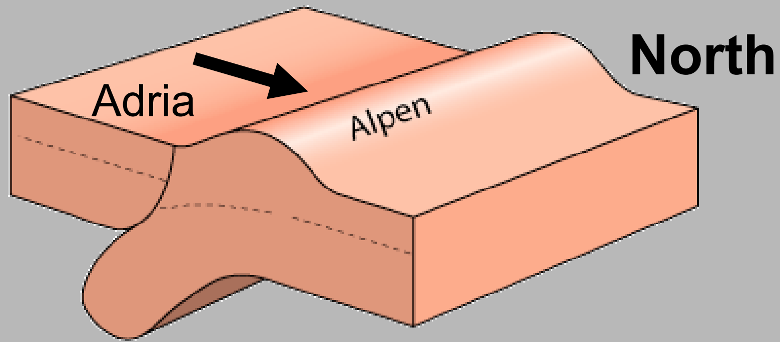
Rapid exhumation of deeply buried Penninic nappes may be linked to buoyancy forces in a non-compressive subduction channel as a consequence of slab-retreat of Alpine oceanic lithosphere slab attached to Europe.

Europe does not move south

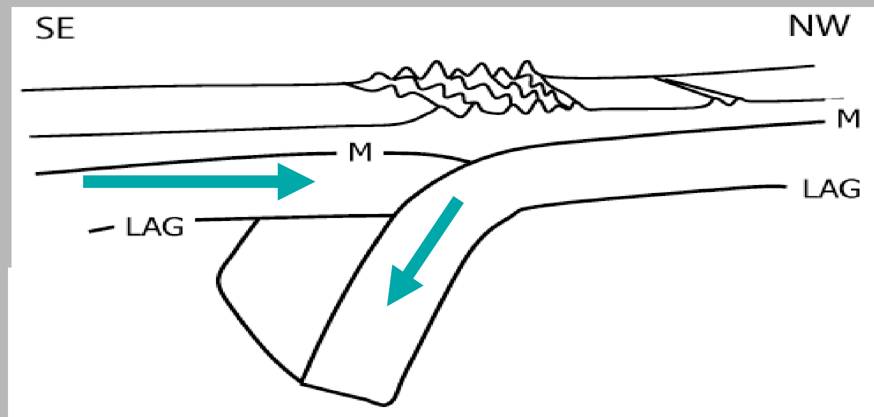




Schmid et al. 1996, 2004



Adria is following retreating European slab



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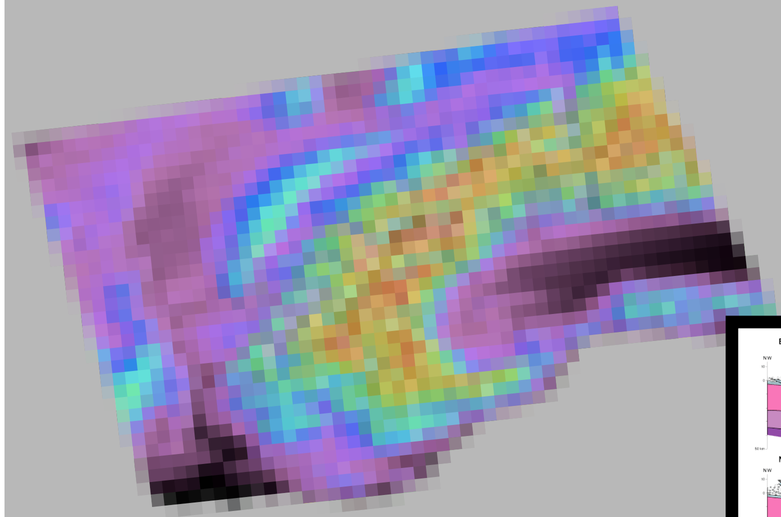
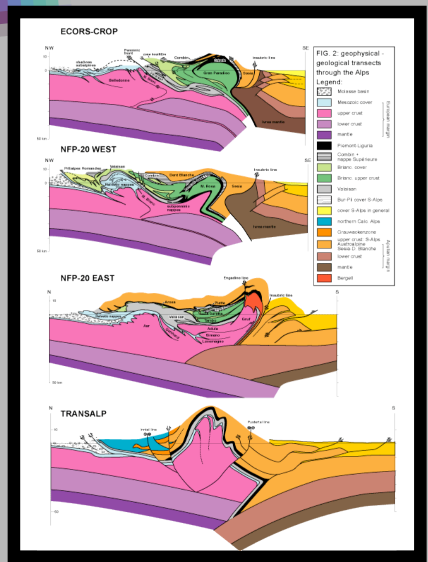
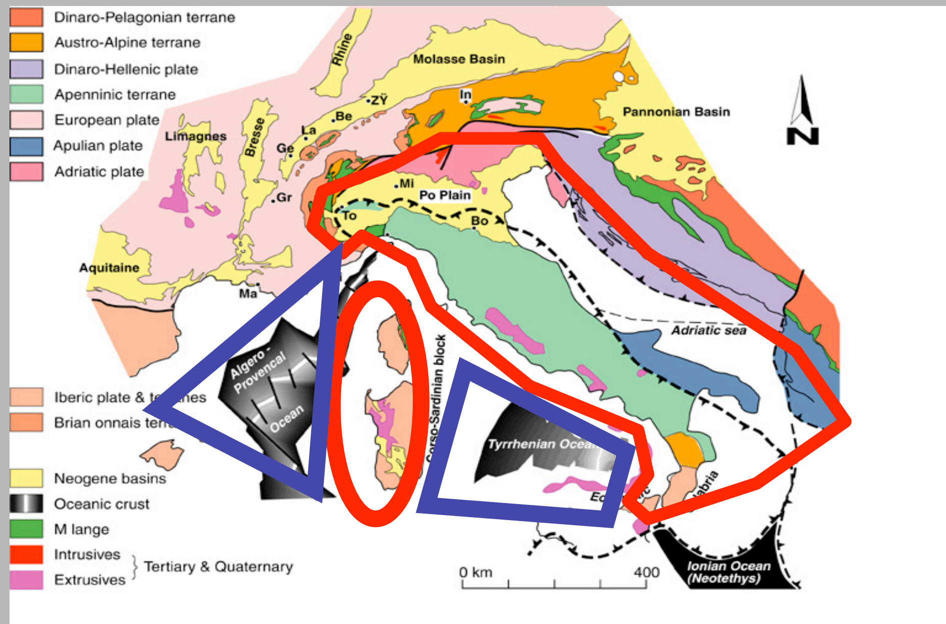
Proposal geodynamic model process 3

In the Alpine-Mediterranean environment tectonics and geodynamics are not only moderately influenced but **dominated by 3D effects**





Schmid et al. 2004



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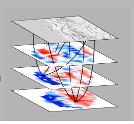
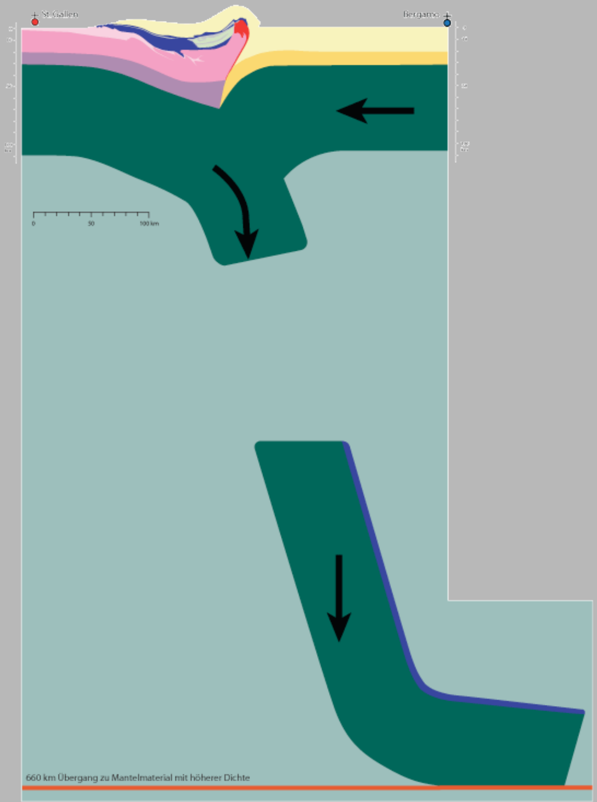


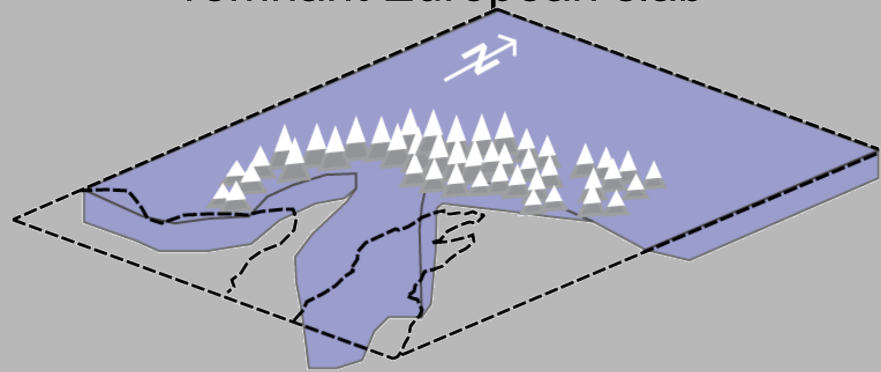
Proposal geodynamic model process 4

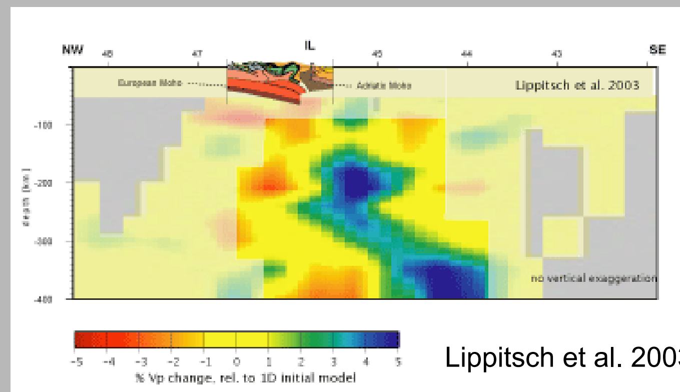
The Alpine Tethyian lithosphere attached to Europe exhibits two periods of slab break off.

At continent-continent collision time



Presently a tear is propagating in remnant European slab





Lippitsch et al. 2003

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