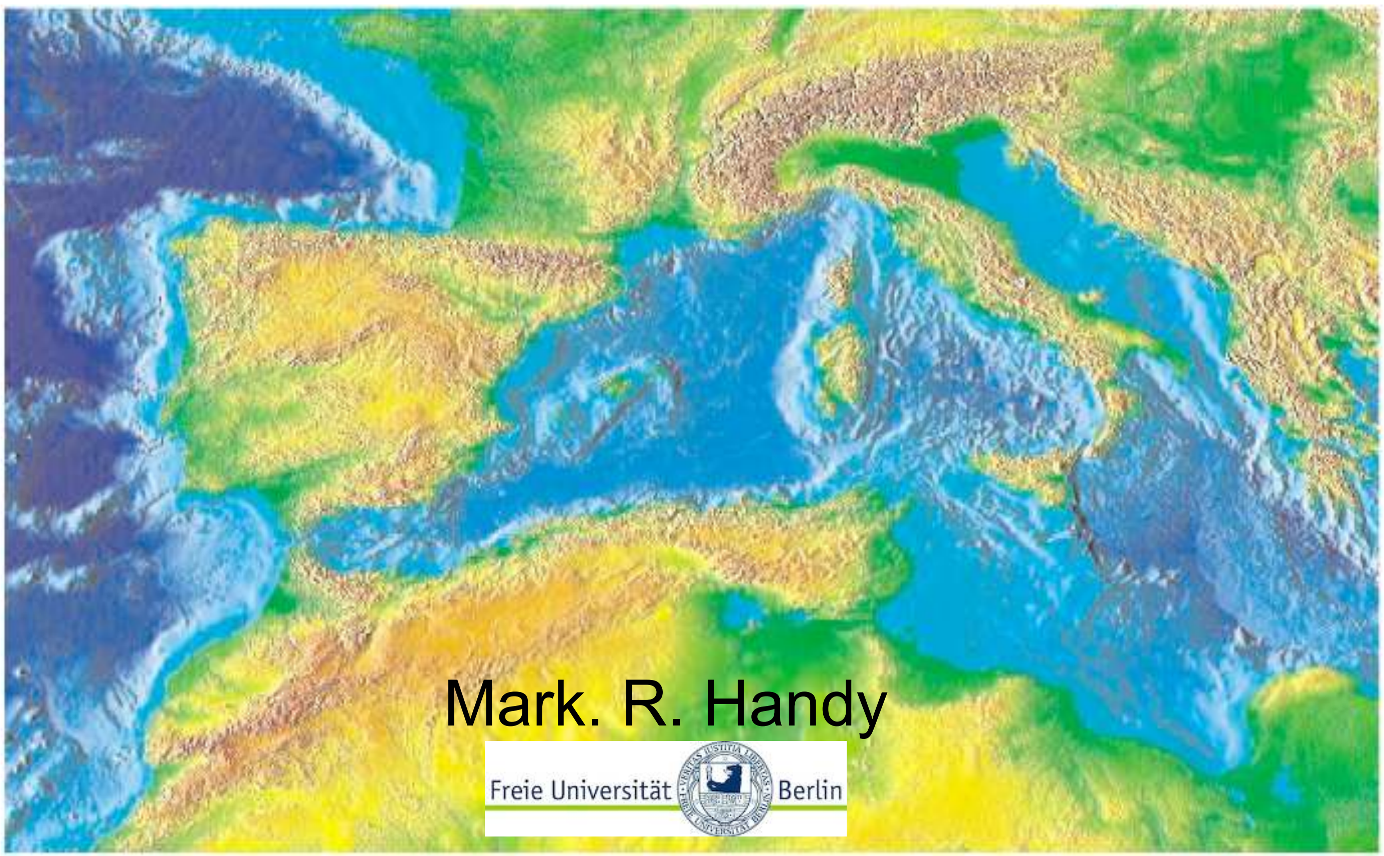
Geodynamics of the Alpine Mediterranean chains

Overview of their structure & history



Mark. R. Handy

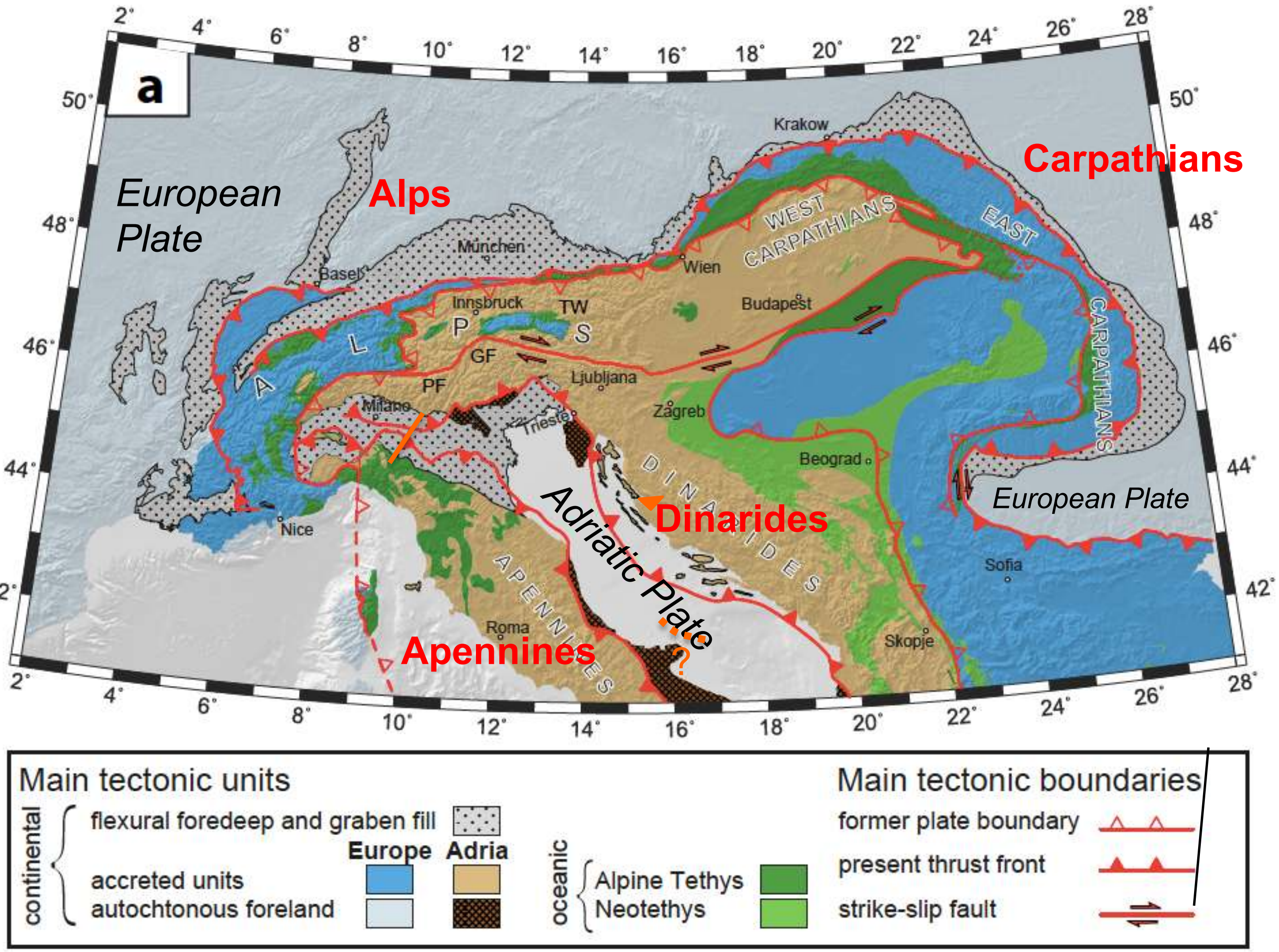
Freie Universität Berlin

Outline

- Alps
- Carpathians & Pannonian Basin
- Dinarides
- Northern Apennines
- Summary of tectonic history

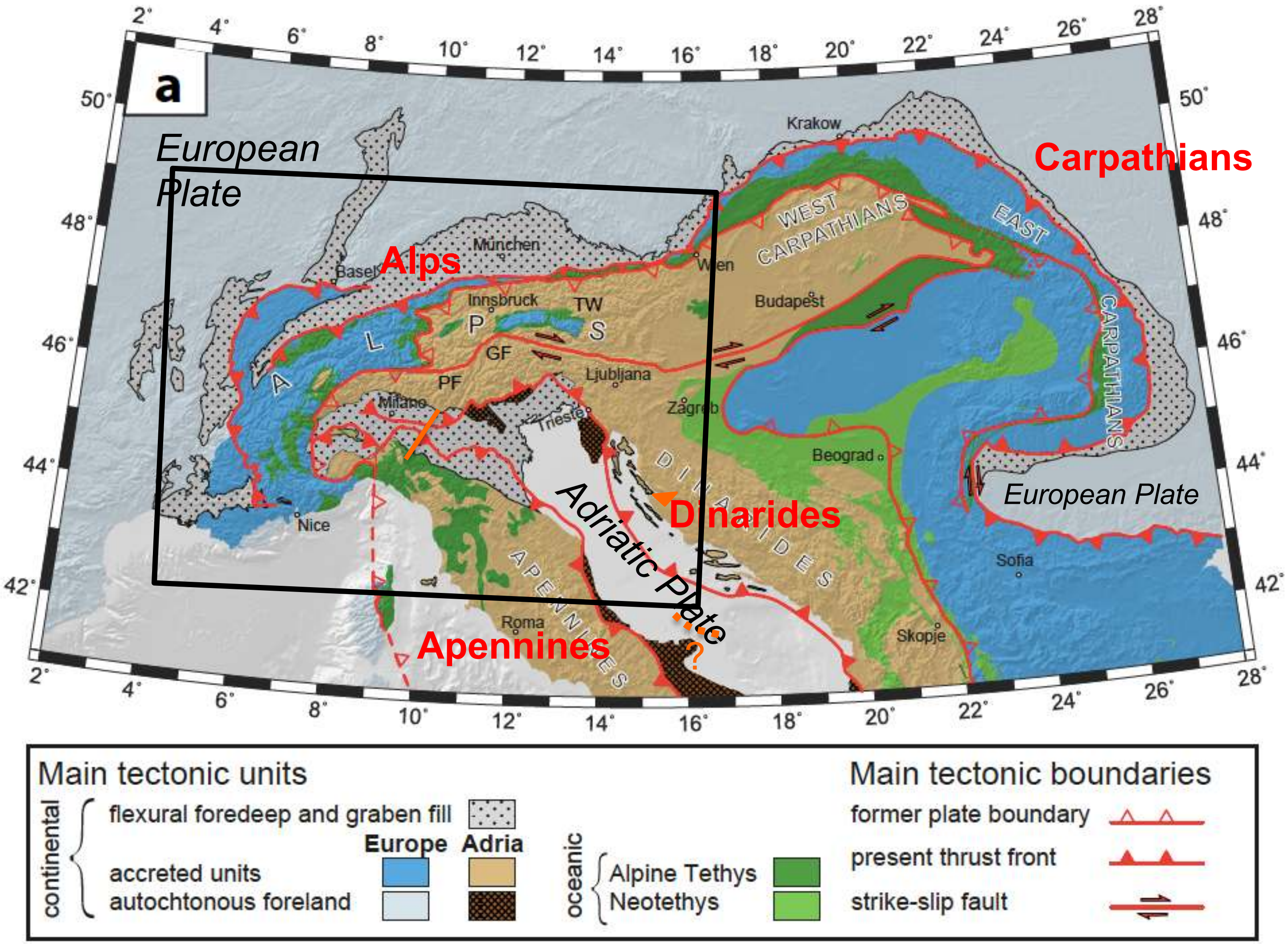
Accreted Adriatic & European units

Handy et al., simplified from Schmid et al. 2004, 2008



Alps

Handy et al., simplified from
Schmid et al. 2004, 2008



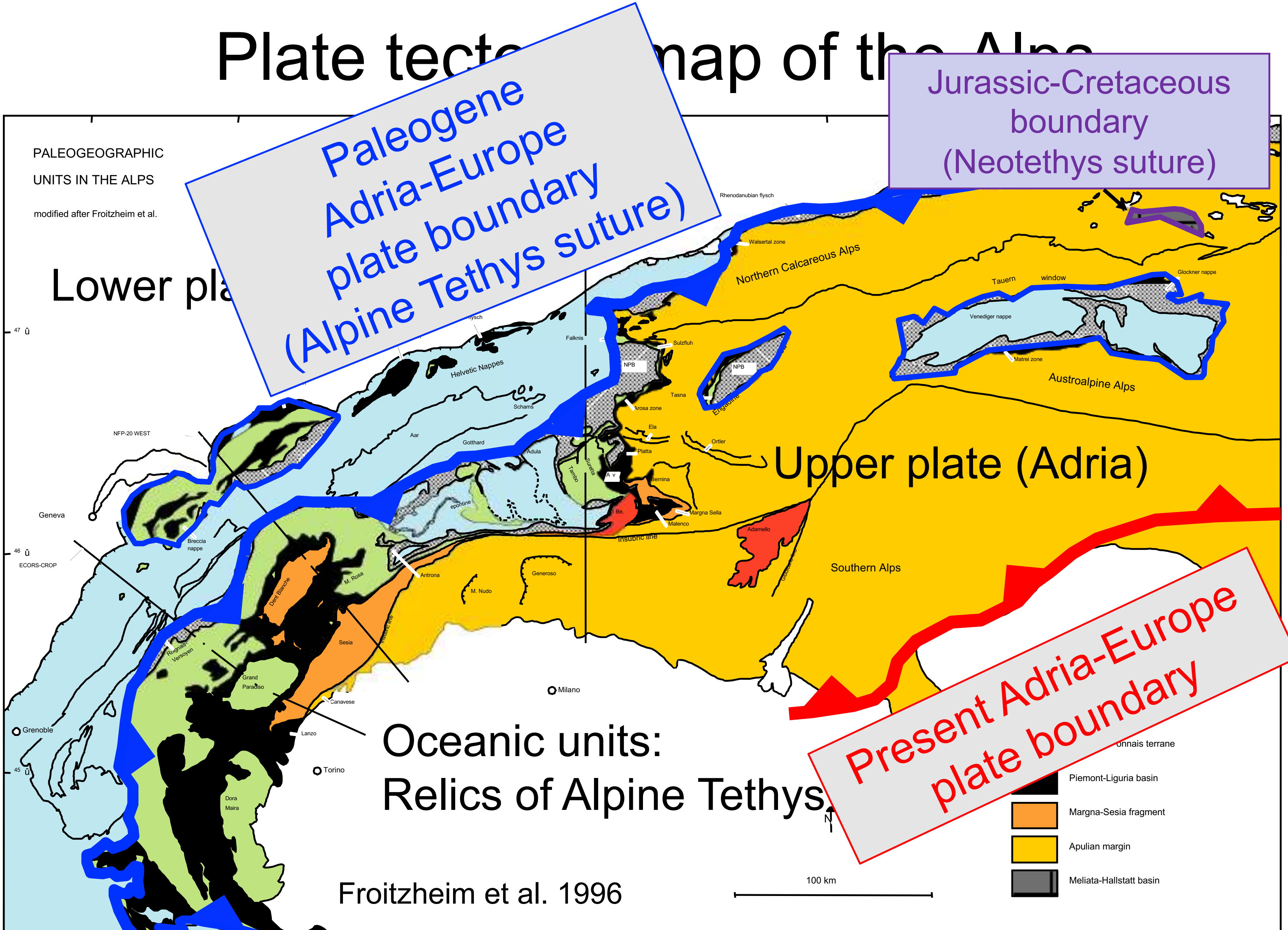
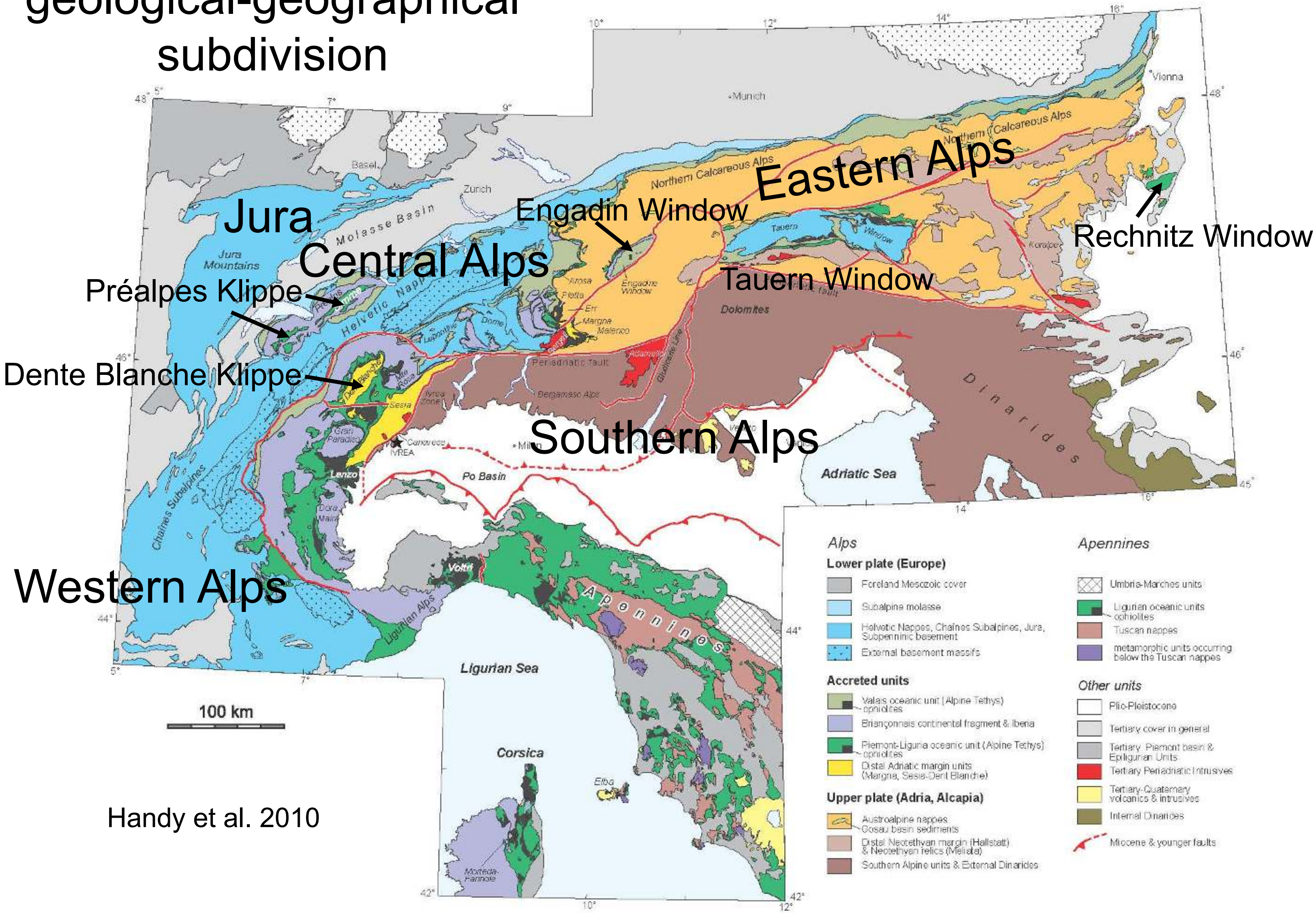


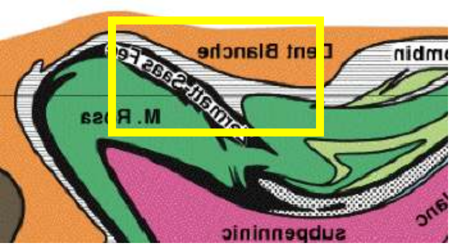
Plate tect
map of th
Paleogene
Adria-Europe
plate boundary
(Alpine Tethys suture)
Jurassic-Cretaceous
boundary
(Neotethys suture)
PALEOGEOGRAPHIC
UNITS IN THE ALPS
modified after Froitzheim et al.
Lower pla
Upper plate (Adria)
Oceanic units:
Relics of Alpine Tethys
Present Adria-Europe
plate boundary
Froitzheim et al. 1996
Rhenodanubian flysch
Walsertal zone
Northern Calcareous Alps
Tauern
window
Glockner nappe
Venediger nappe
Matrei zone
Austroalpine Alps
Helvetic Nappes
Falknis
Sulzfluh
NPB
Tasna
Arosa zone
Engadine
Ela
Ortler
Platta
Bernina
Margna Sella
Malenco
Insubric line
Adamello
Southern Alps
Schams
Aar
Gotthard
Adula
Tambo
Suretta
Lepontine
Antrona
Generoso
M. Nudo
NFP-20 WEST
Geneva
Breccia
nappe
ECORS-CROP
M. Rosa
Dent Blanche
Sesia
Rognais-Versoyen
Grand
Paradiso
Canavese
Lanzo
Milano
Grenoble
Torino
Dora
Maira
47
46
45
N
100 km
Piemont-Liguria basin
Margna-Sesia fragment
Apulian margin
Meliata-Hallstatt basin

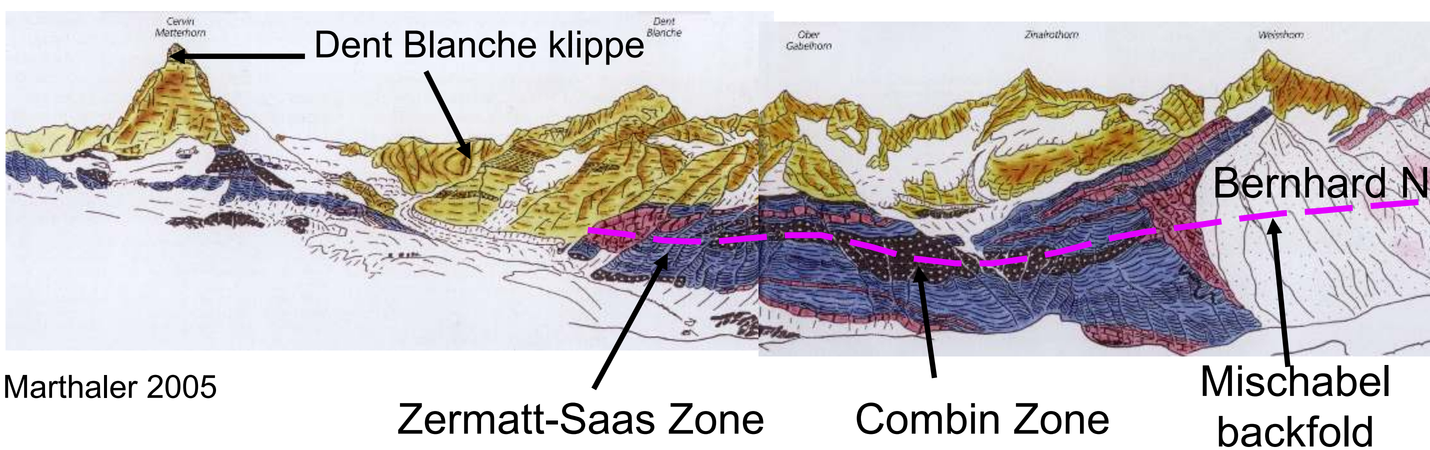
The Alps – the traditional geological-geographical subdivision



Handy et al. 2010

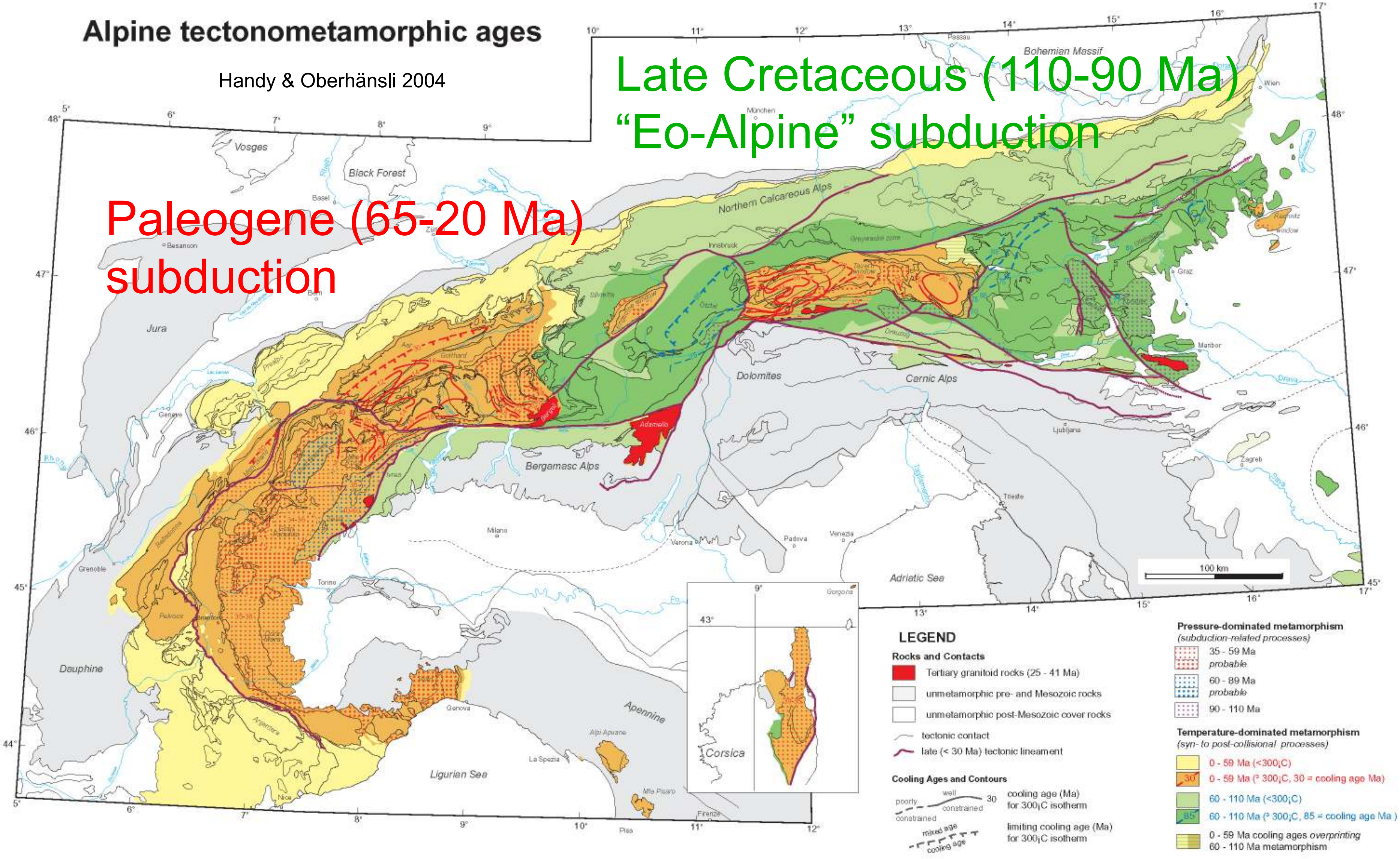
Zermatt area - the Matterhorn-Dent Blanche Klippe



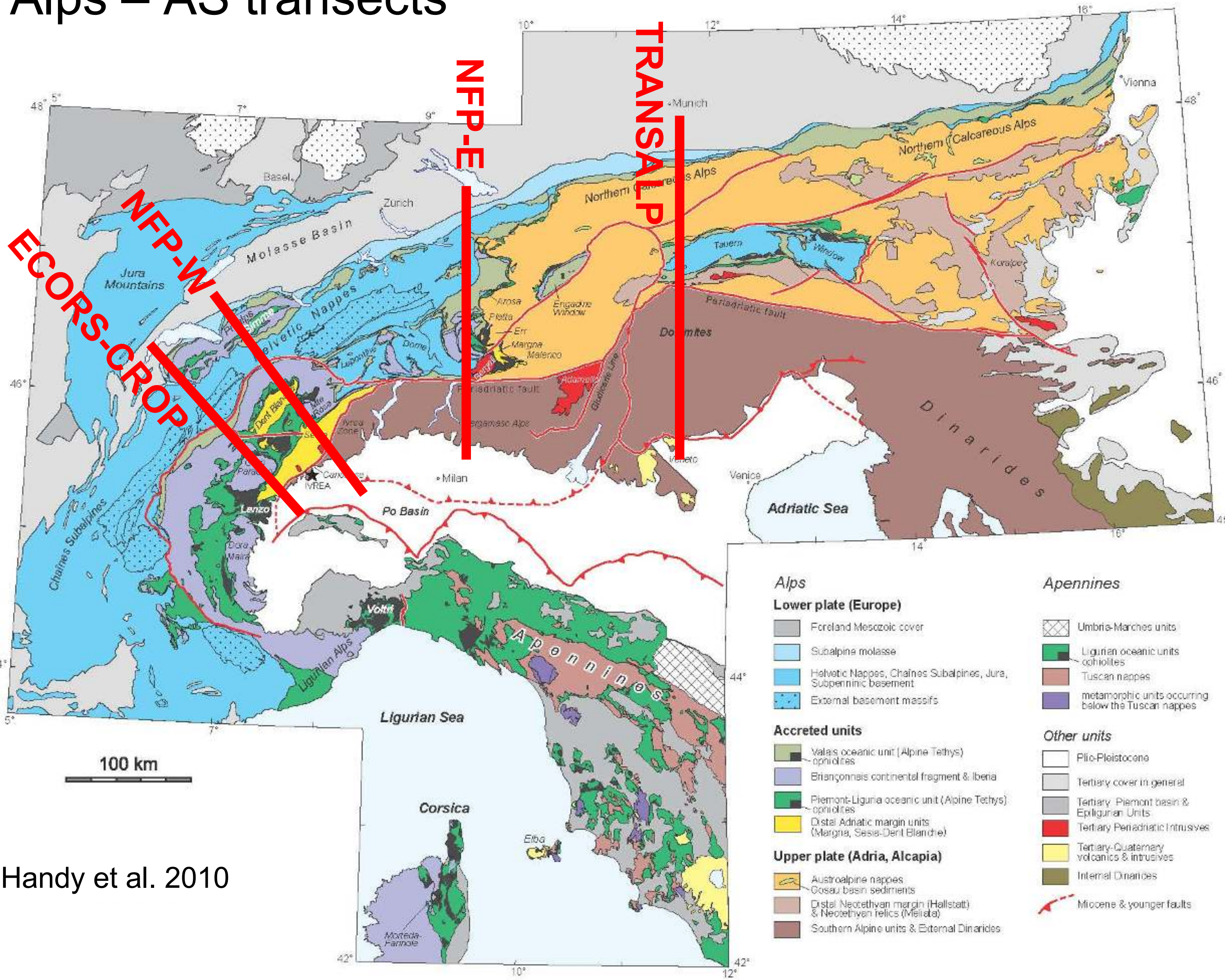


Marthaler 2005

Two orogens – two baric events



The Alps – AS transects



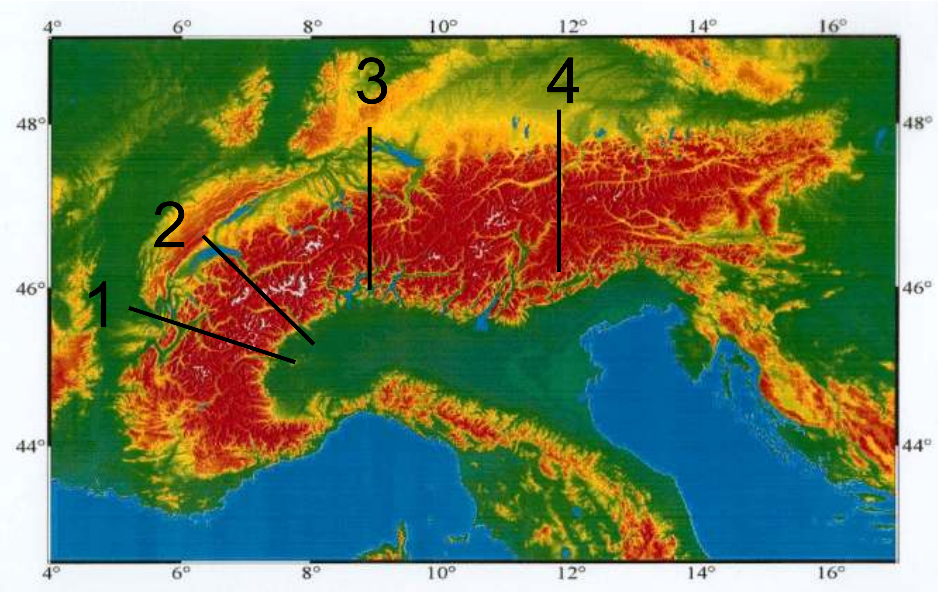
Handy et al. 2010

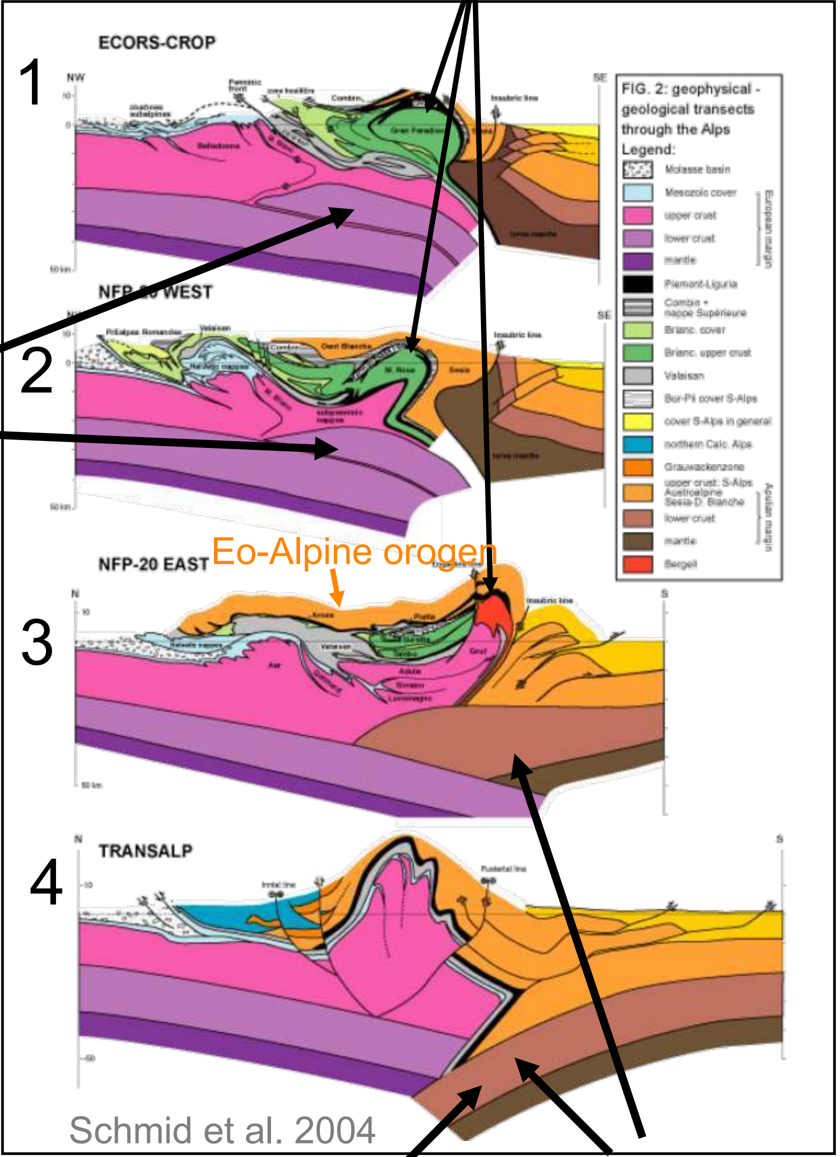
Crustal structure

- very non-cylindrical structure
- lower crustal wedges
- two orogens
- massive accretion of lower plate

“Backfolds” & Periadriatic Fault

European lower crust



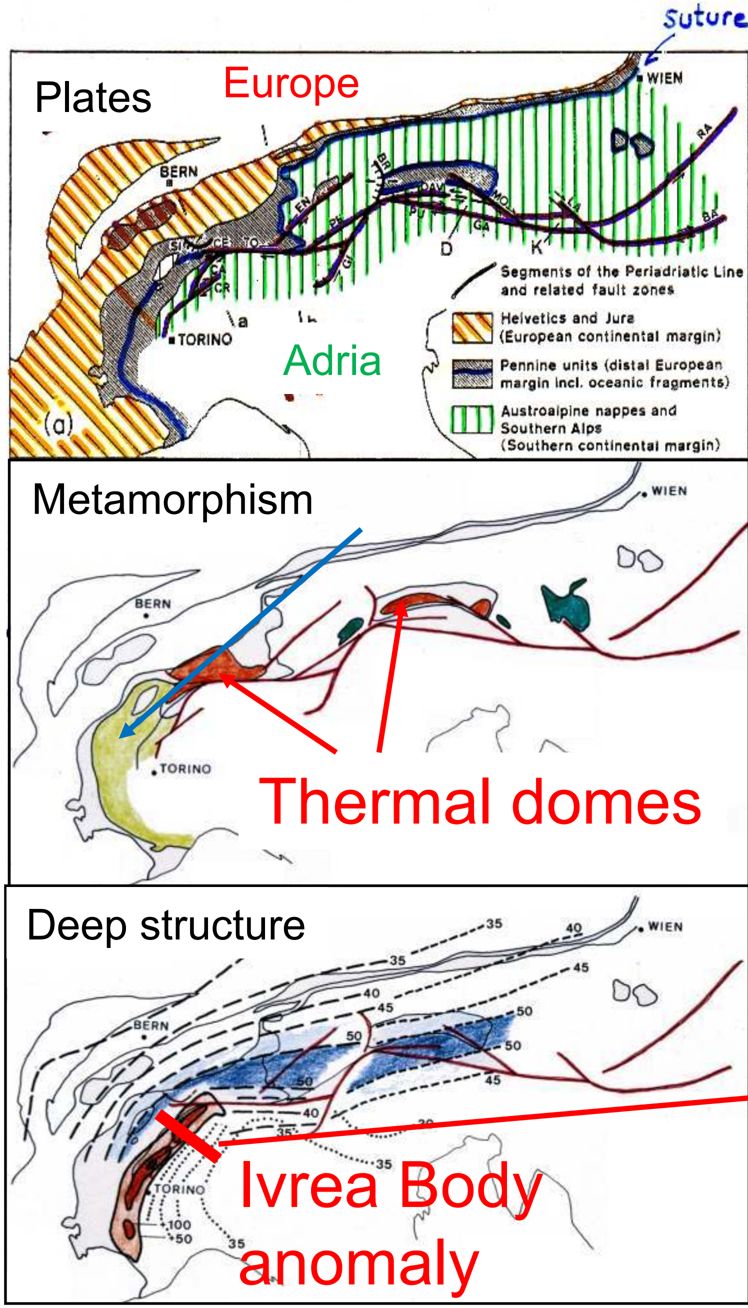


Subduction polarity reversal

Adriatic lower crust

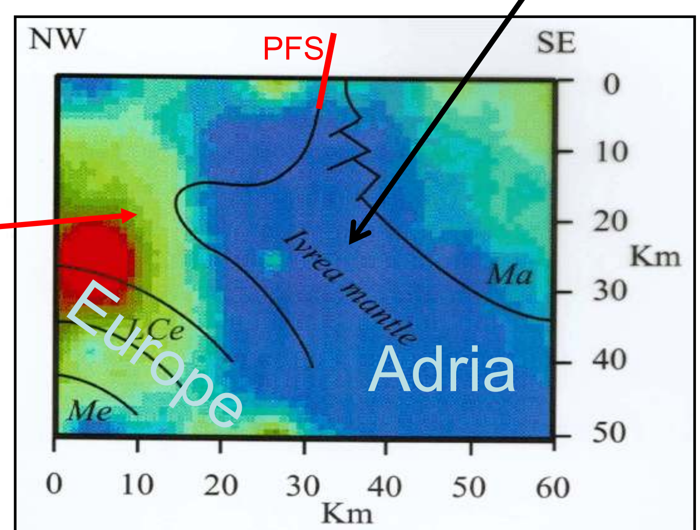
Periadriatic Fault System & first-order crust-mantle structures

- The PFS is NOT the Alpine suture
- The PFS is different in the E than in the W!

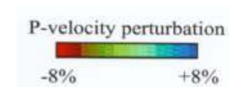


Schmid et al. 1989

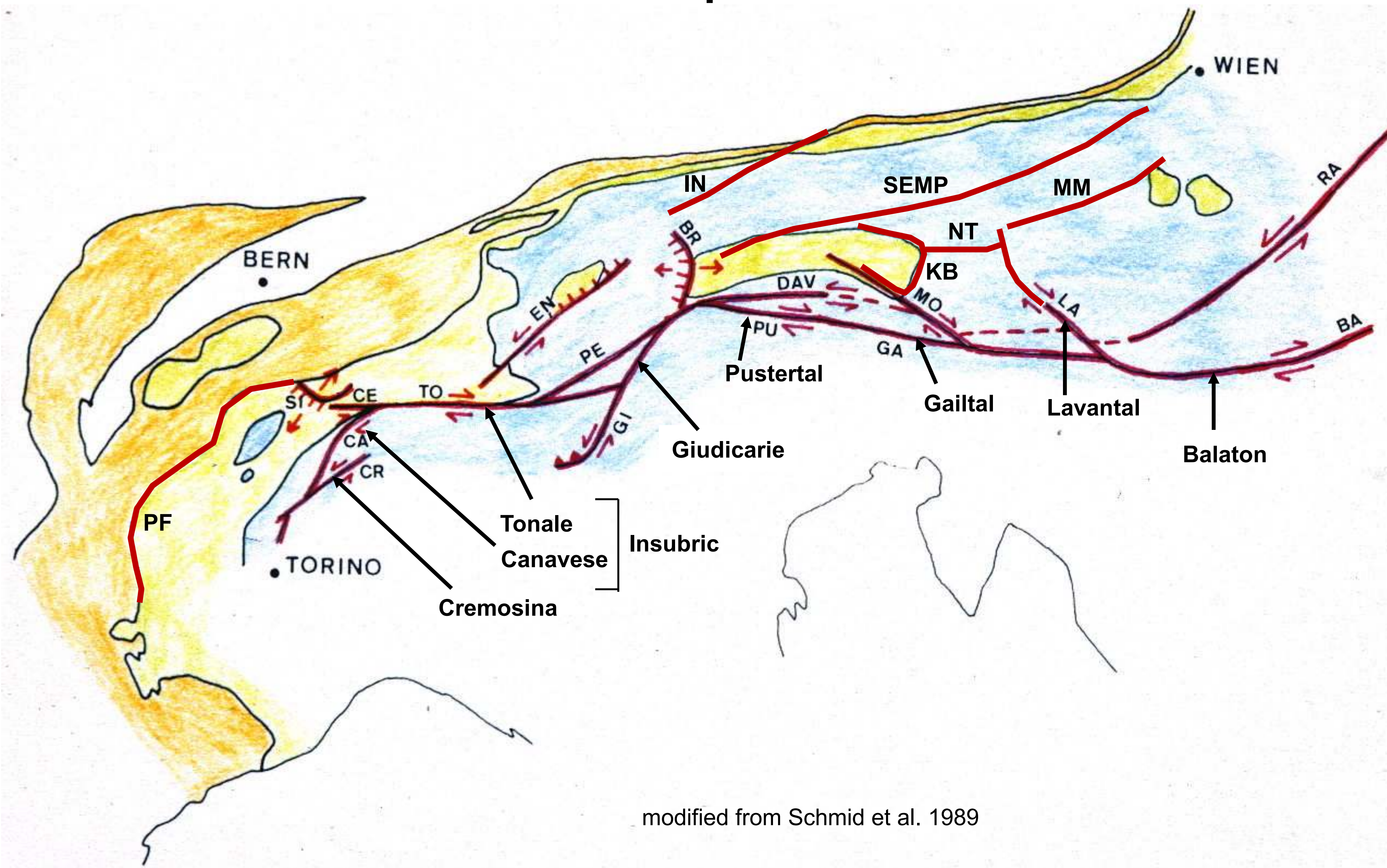
upper mantle of Adria at crustal levels!



Solarino & Kissling 1997

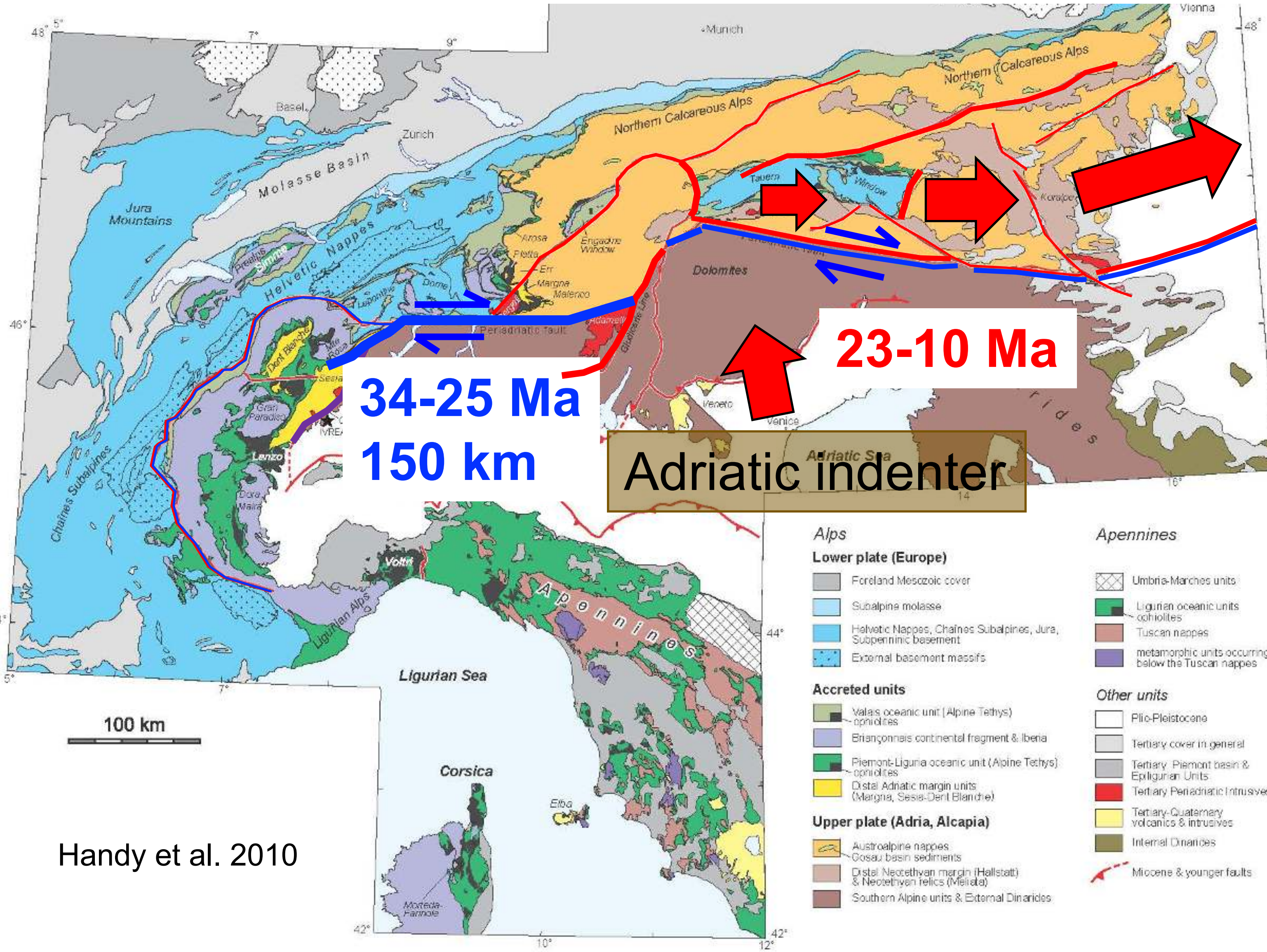


The Periadriatic Fault System - its components



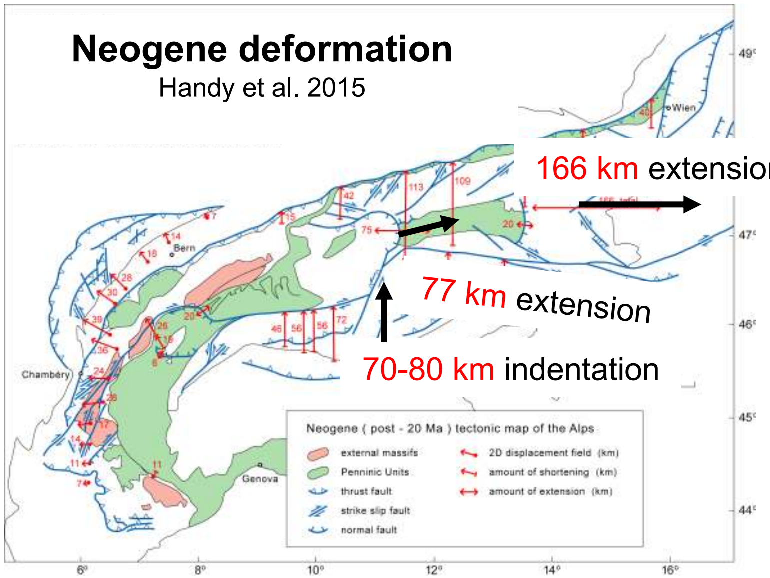
modified from Schmid et al. 1989

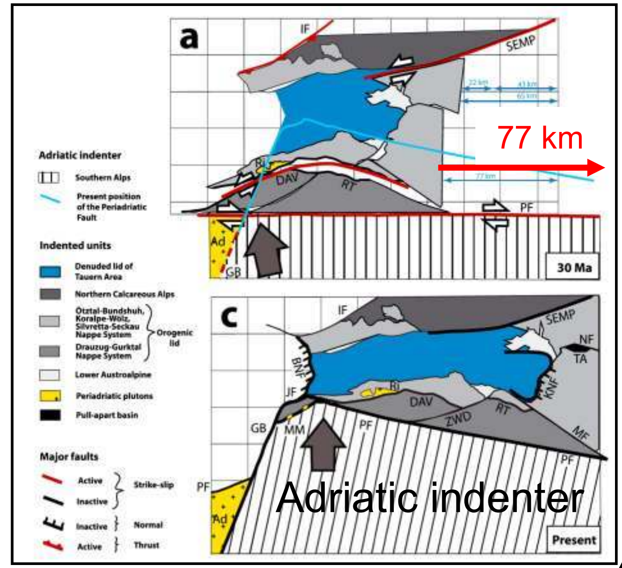
Periadriatic Fault System & related magmatites



Handy et al. 2010

Post-20 Ma lateral extrusion in the E. Alps

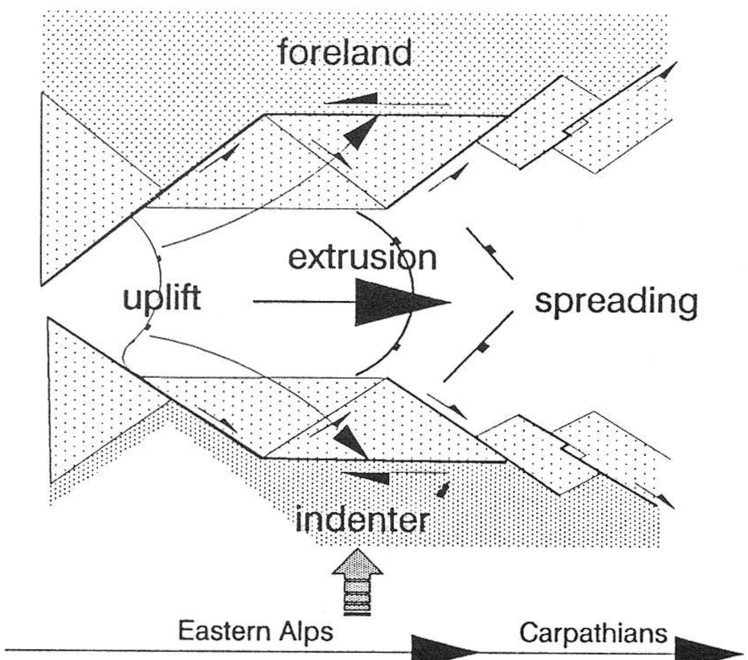




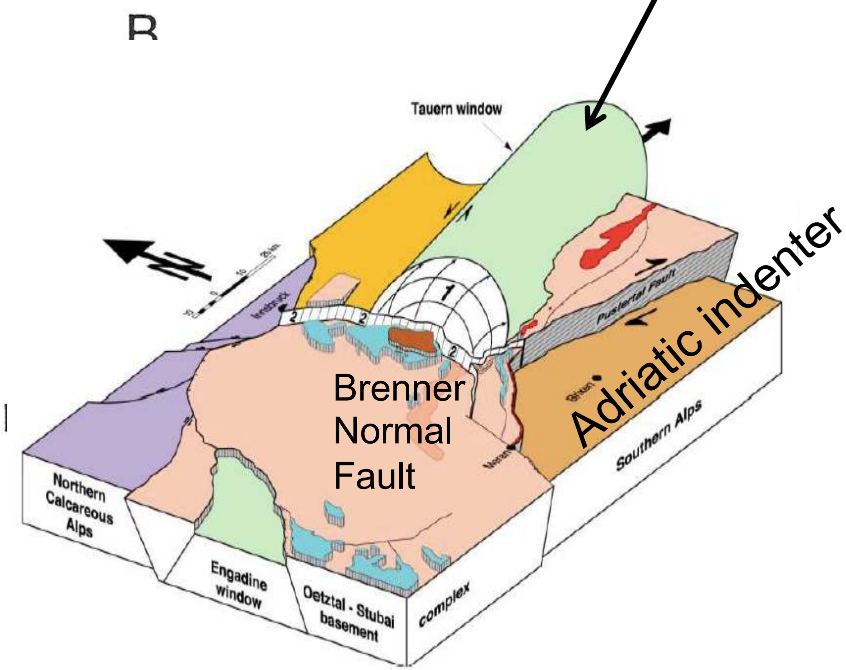
Denudation since 30 Ma:

- 1/3 due to extensional unroofing
- 2/3 due to post-nappe folding & erosion

Favaro et al. 2017



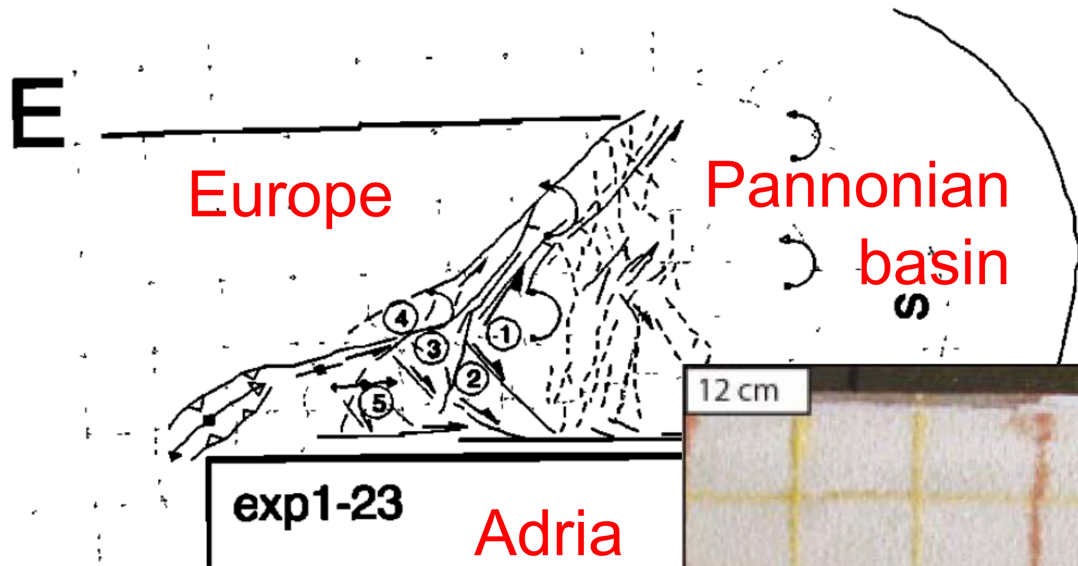
Ratschbacher et al. 1991



Fügenschuh et al. 1997

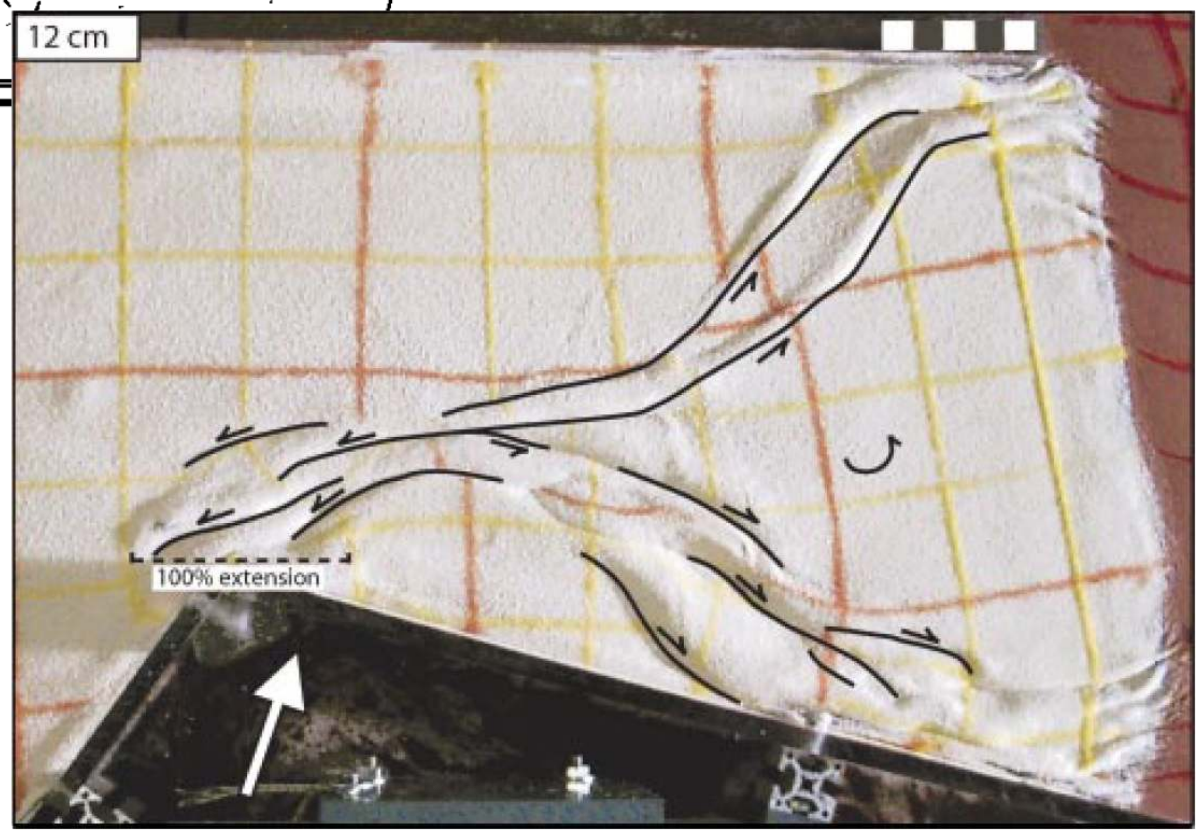
Analogue models of lateral extrusion

Ratschbacher et al. 1991



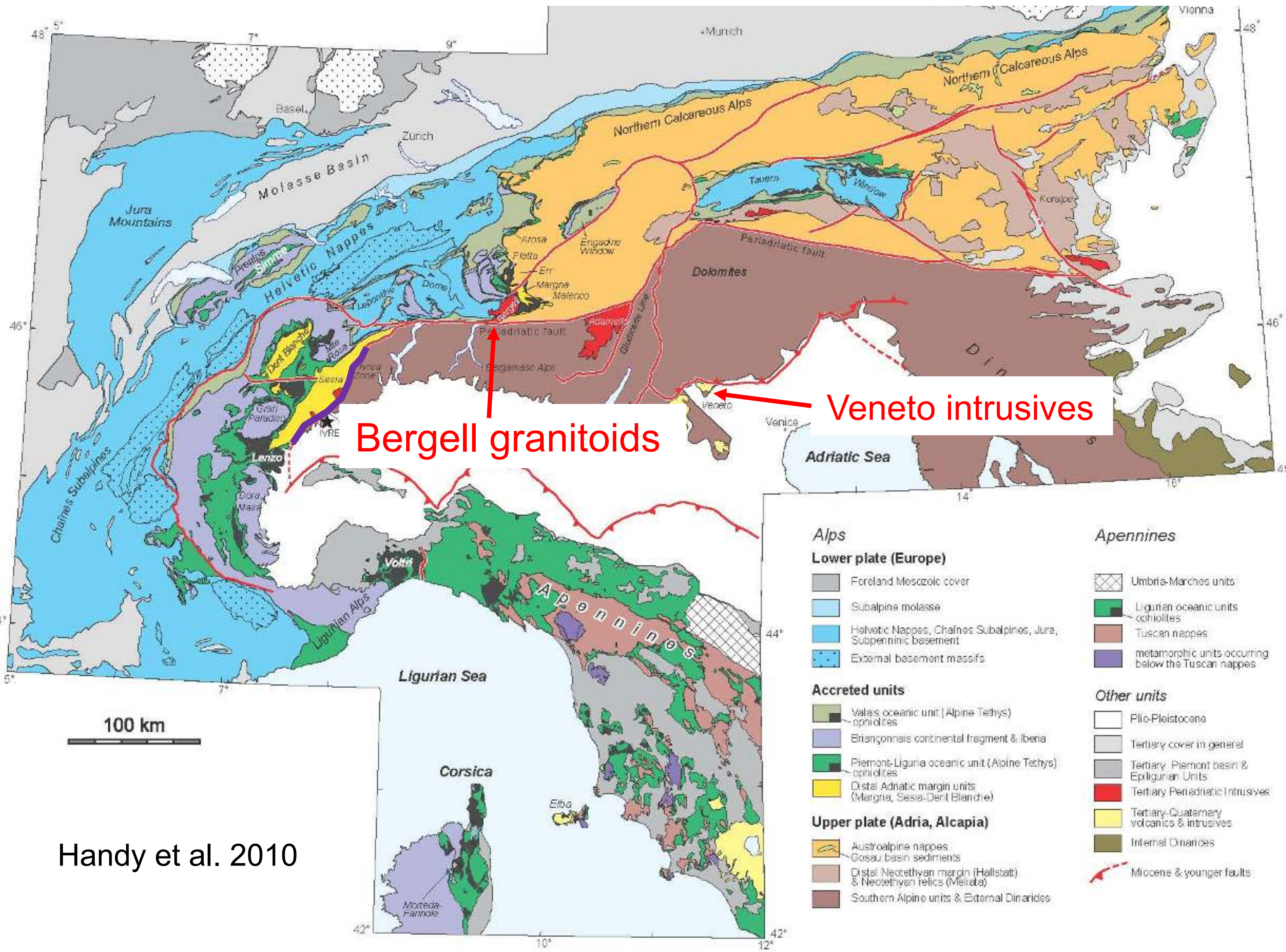
Free side =
Carpathian rollback
subduction orogen

Rosenberg et al. 2007



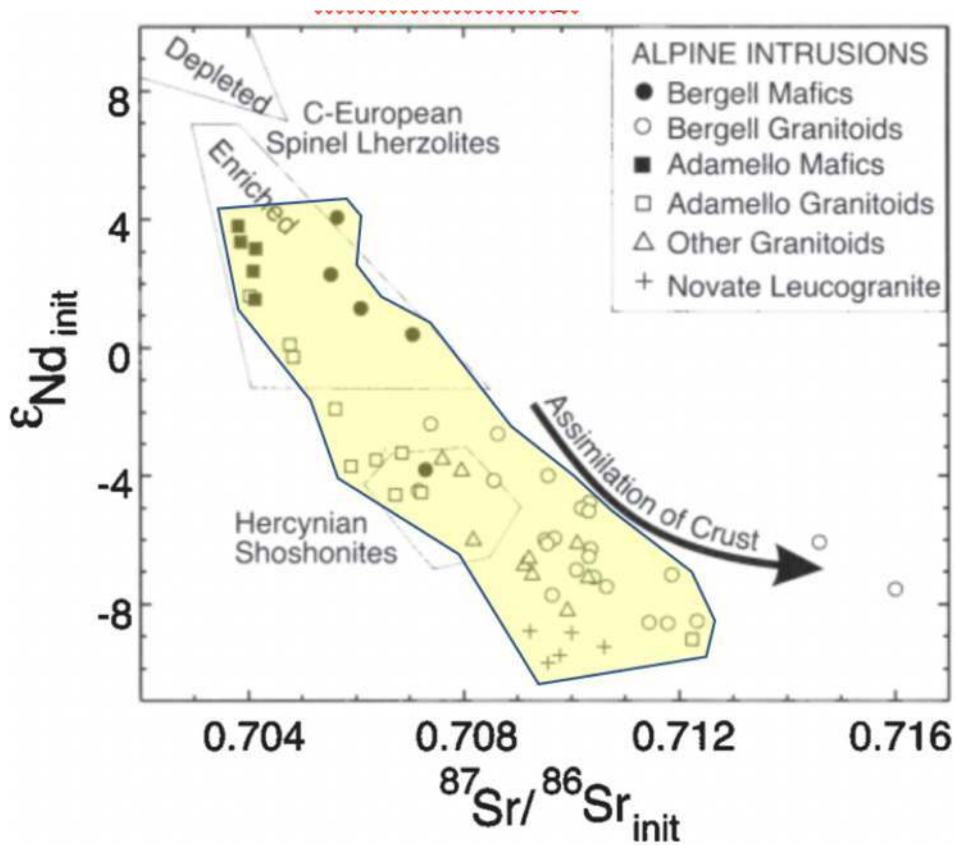
Indentation
produces coeval
folds, conjugate
strike-slip faulting
and block rotation

Periadriatic Fault System & related magmatites

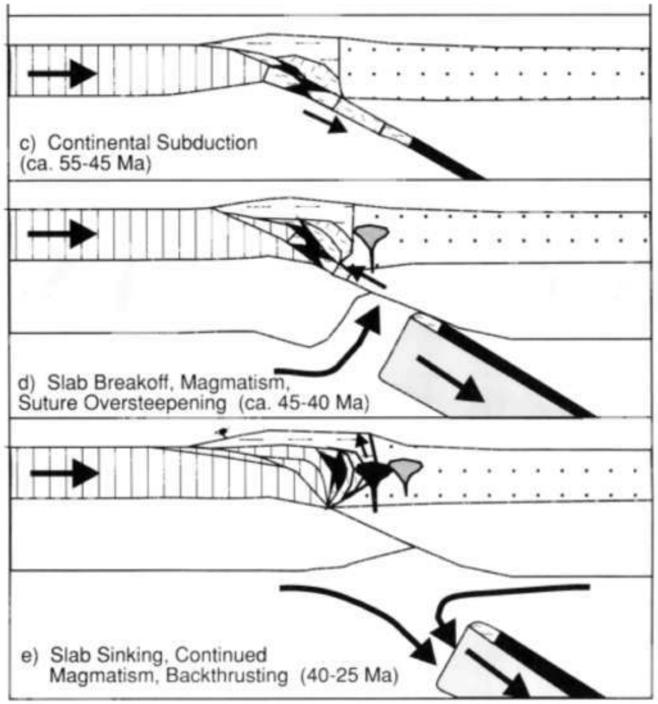


Handy et al. 2010

Lithospheric mantle source of Periadriatic granitoids



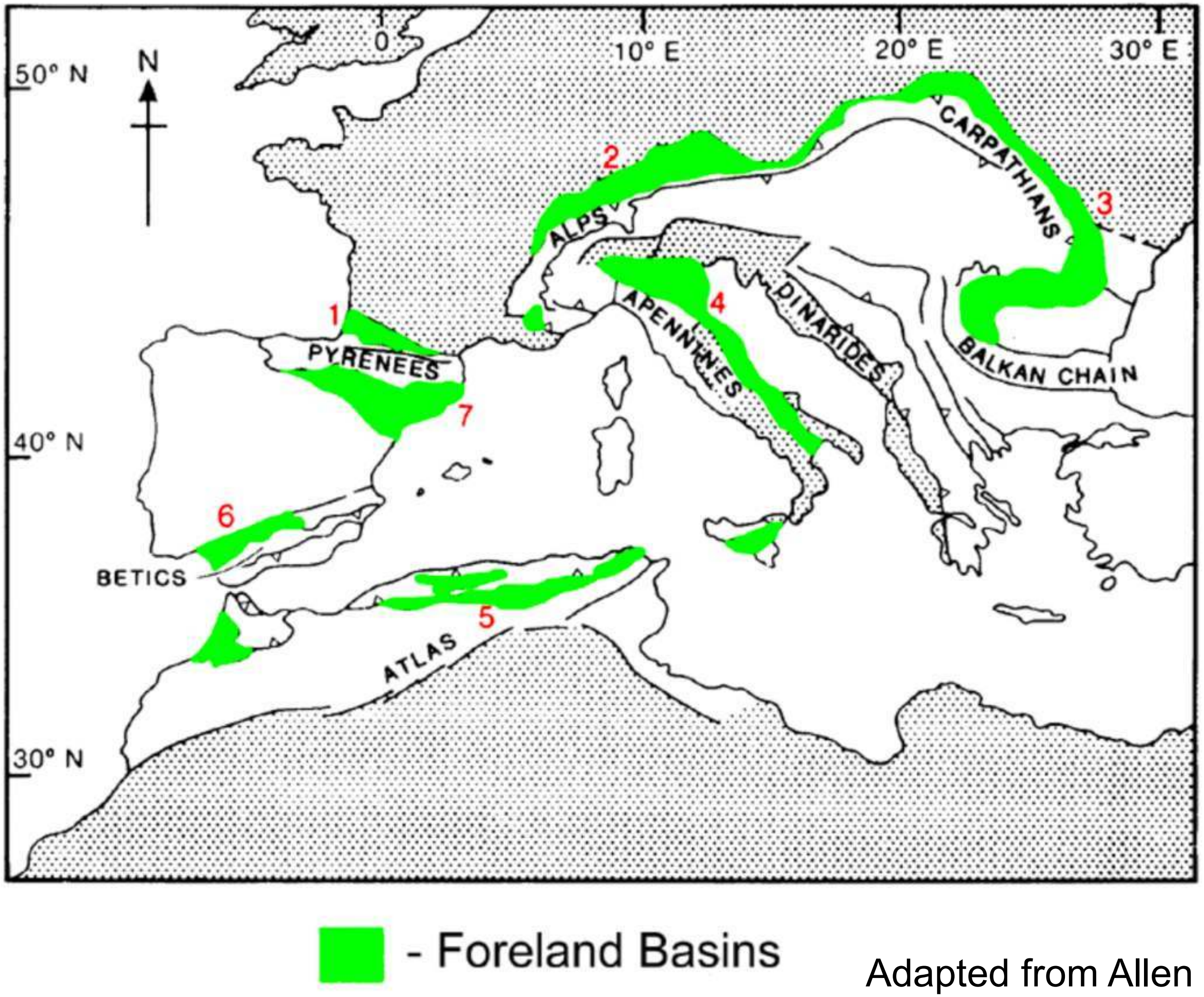
“Trace element and isotopic composition suggest that they have been formed by low-degree melting of the mechanically stable lithospheric mantle. There is no evidence for melting of asthenospheric mantle.”



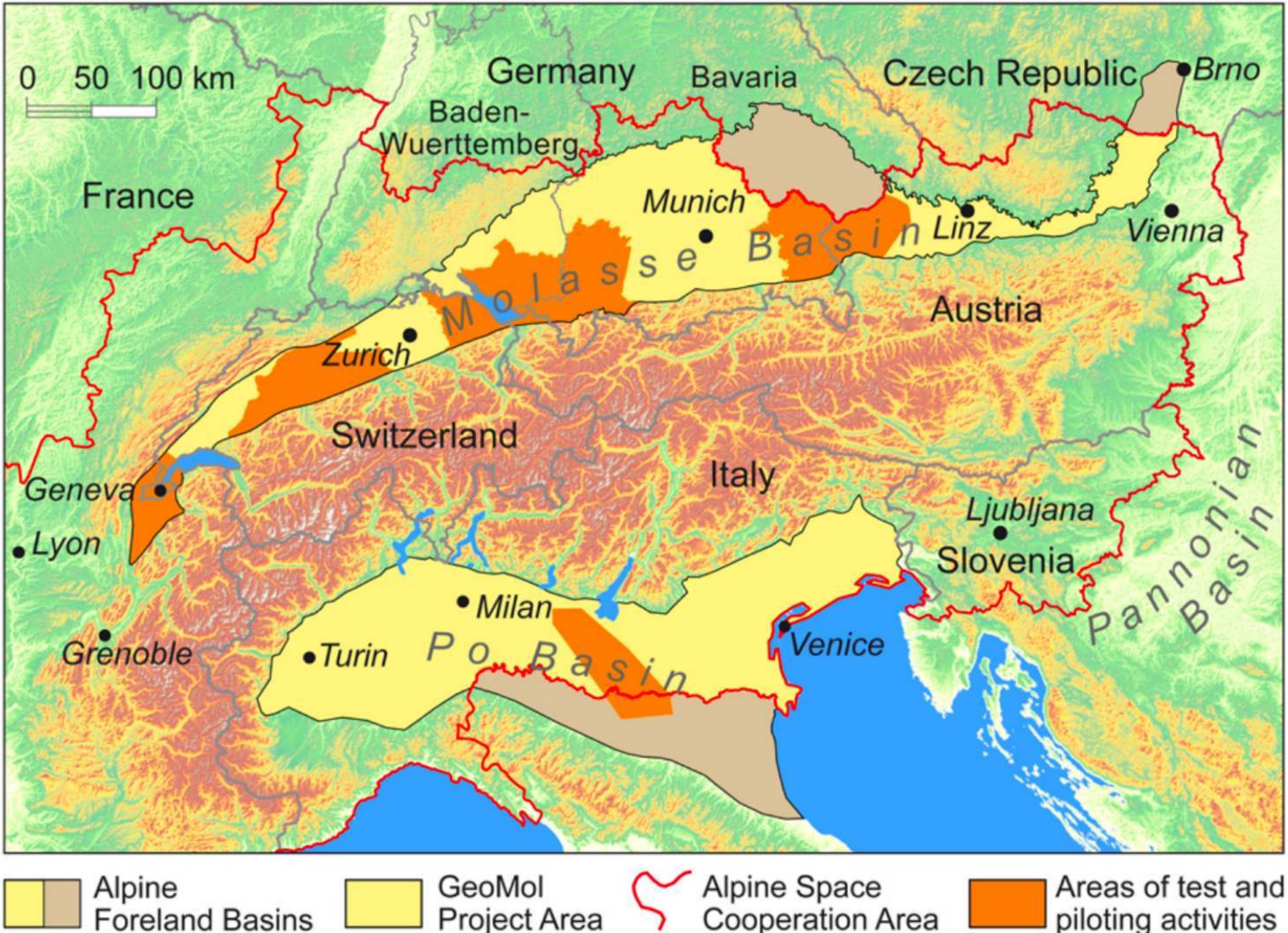
“Slab breakoff led to heating of the overriding lithospheric mantle by upwelling asthenosphere, melting of its enriched layers, and thus to bimodal magmatism.”

von Blanckenburg & Davies 1995

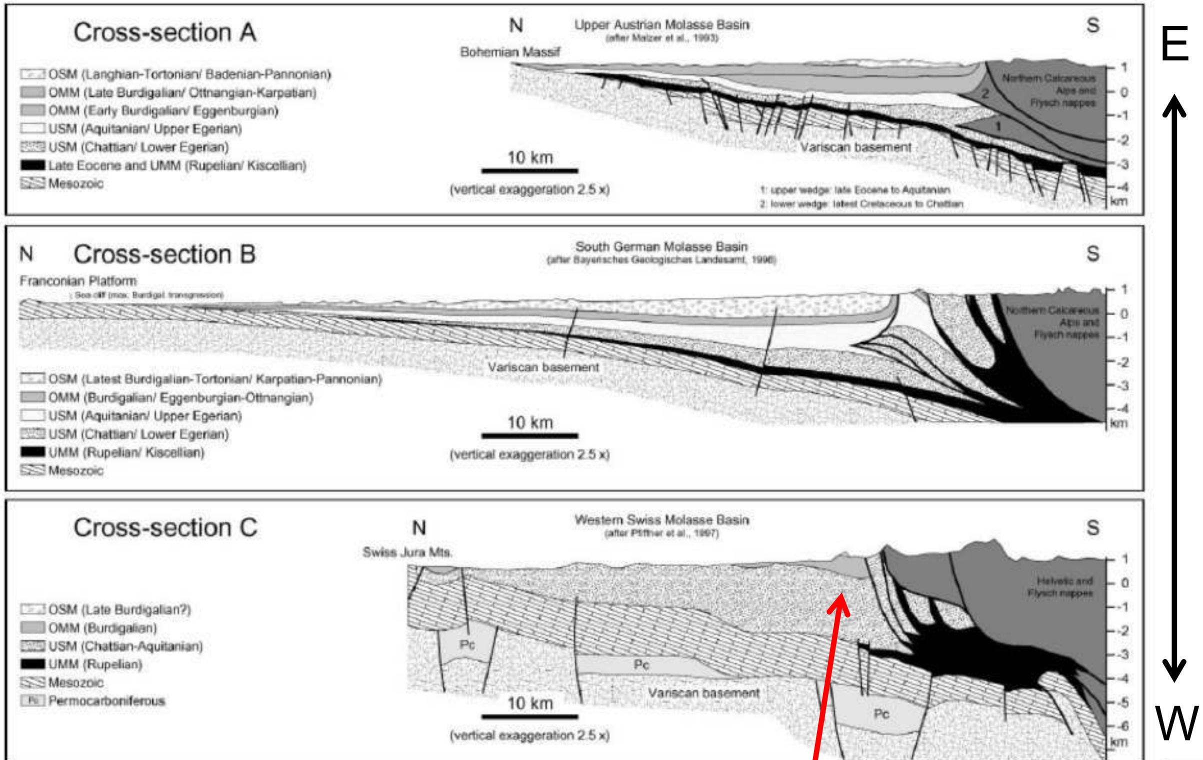
Peripheral basins of the Alpine chains

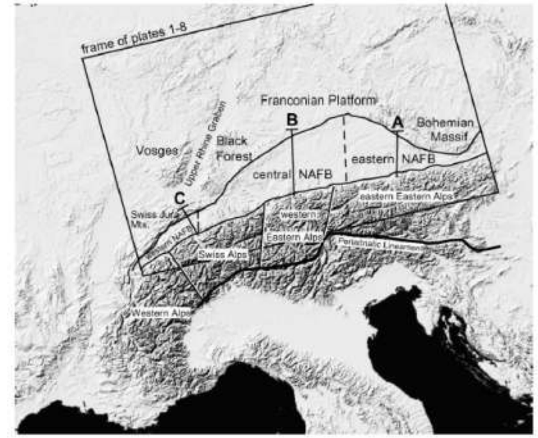


Adapted from Allen et al. 1986


0 50 100 km
Germany
Bavaria
Czech Republic
Brno
Baden-
Wuerttemberg
France
Munich
Linz
Vienna
Molasse Basin
Austria
Zurich
Switzerland
Italy
Geneva
Lyon
Ljubljana
Slovenia
Pannonian Basin
Milan
Grenoble
Turin
Po Basin
Venice
Alpine Foreland Basins
GeoMol Project Area
Alpine Space Cooperation Area
Areas of test and piloting activities

Structure of the „Molasse“ Basin

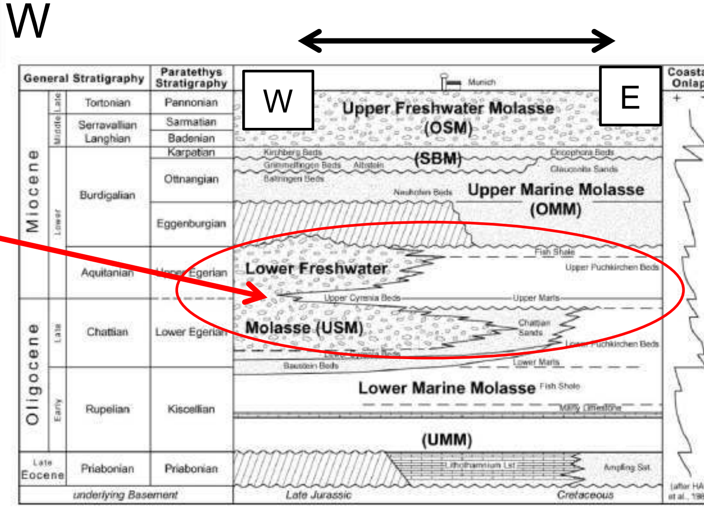




Kuhlemann & Kempf 2002

- Basin is deeper and more deeply eroded in the W than in the E
- Shortening stops at 17 Ma in E

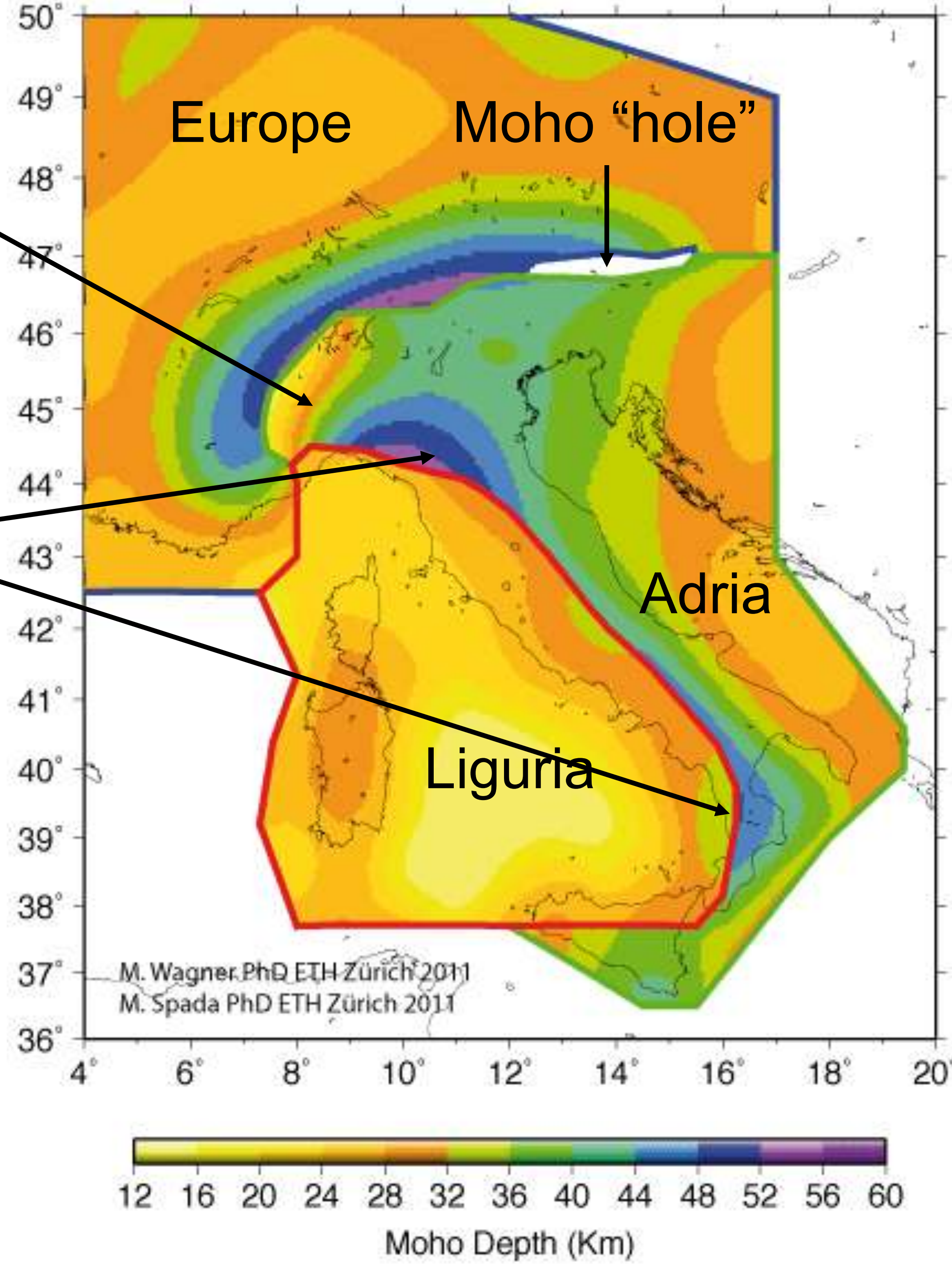
Oligo-Miocene coarse clastics (USM) in W are reduced in E



At c. 20-18 Ma, the E. Molasse basin became overfilled and orogen-parallel flow of rivers in the basin changed from W-to-E to E-to-W overlapping Adriatic. & European Mohos (Ivrea anomaly)

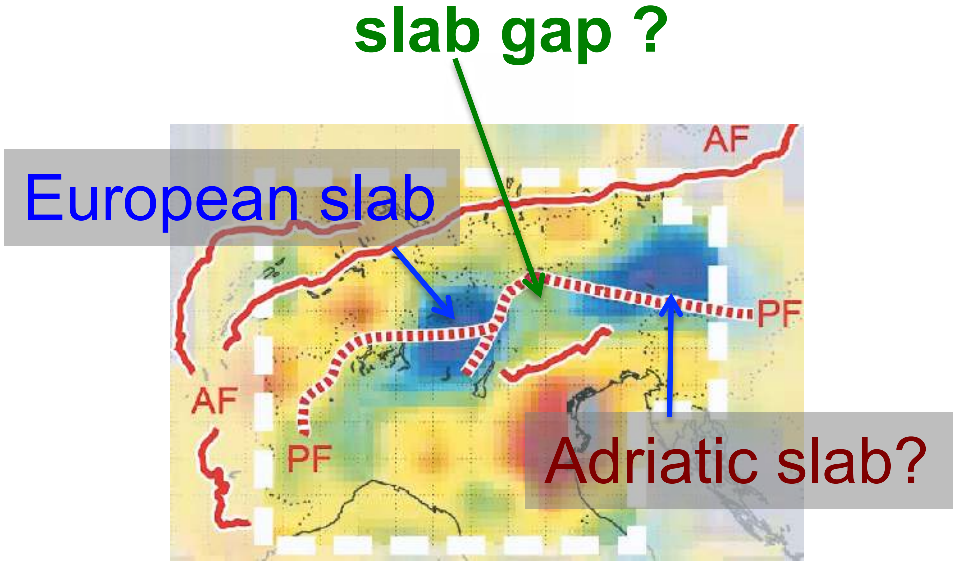
depressed Moho above hanging Adriatic slab

Moho depth map of Alps & Apennines

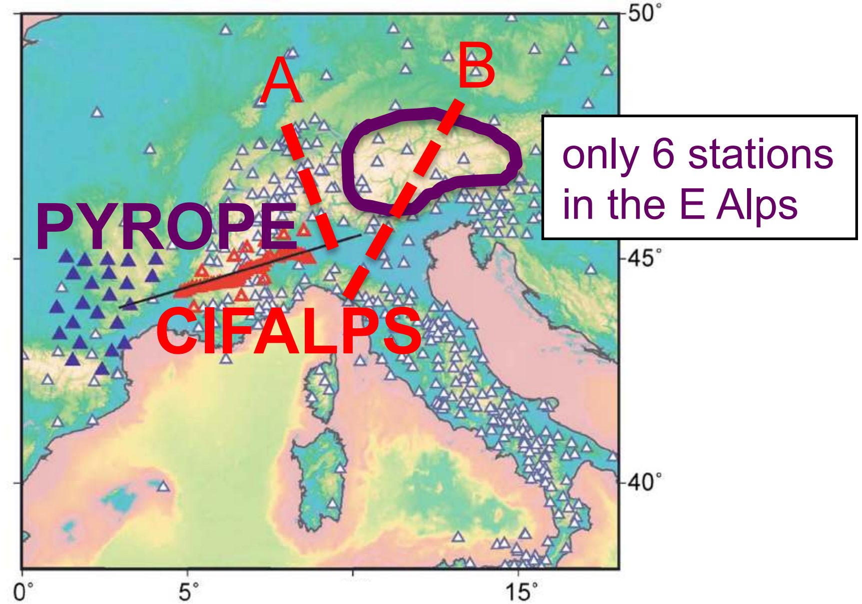


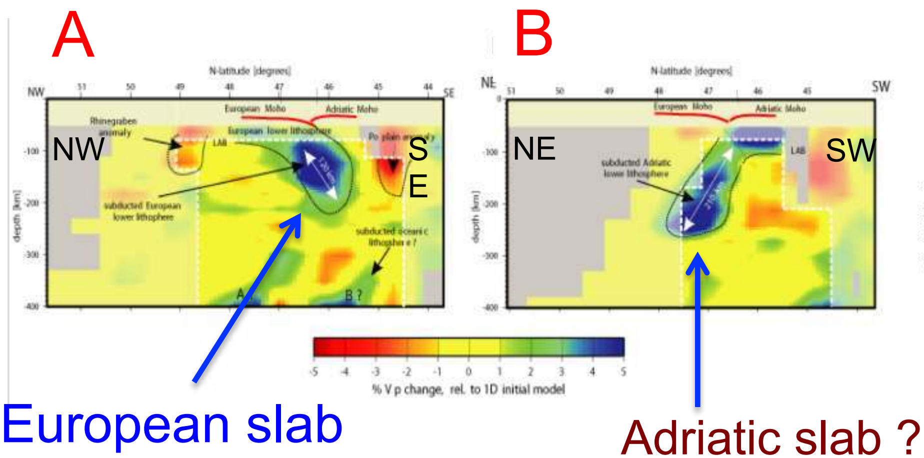
Spada et al. 2013, Fig. 11

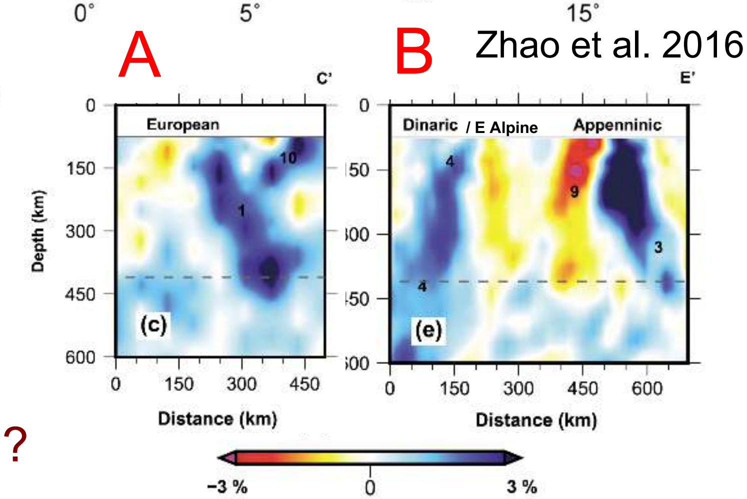
Subduction polarity beneath the Alps



Lippitsch et al. 2003







Zhao et al. 2016

$+V_p$ anomalies down to 200 km

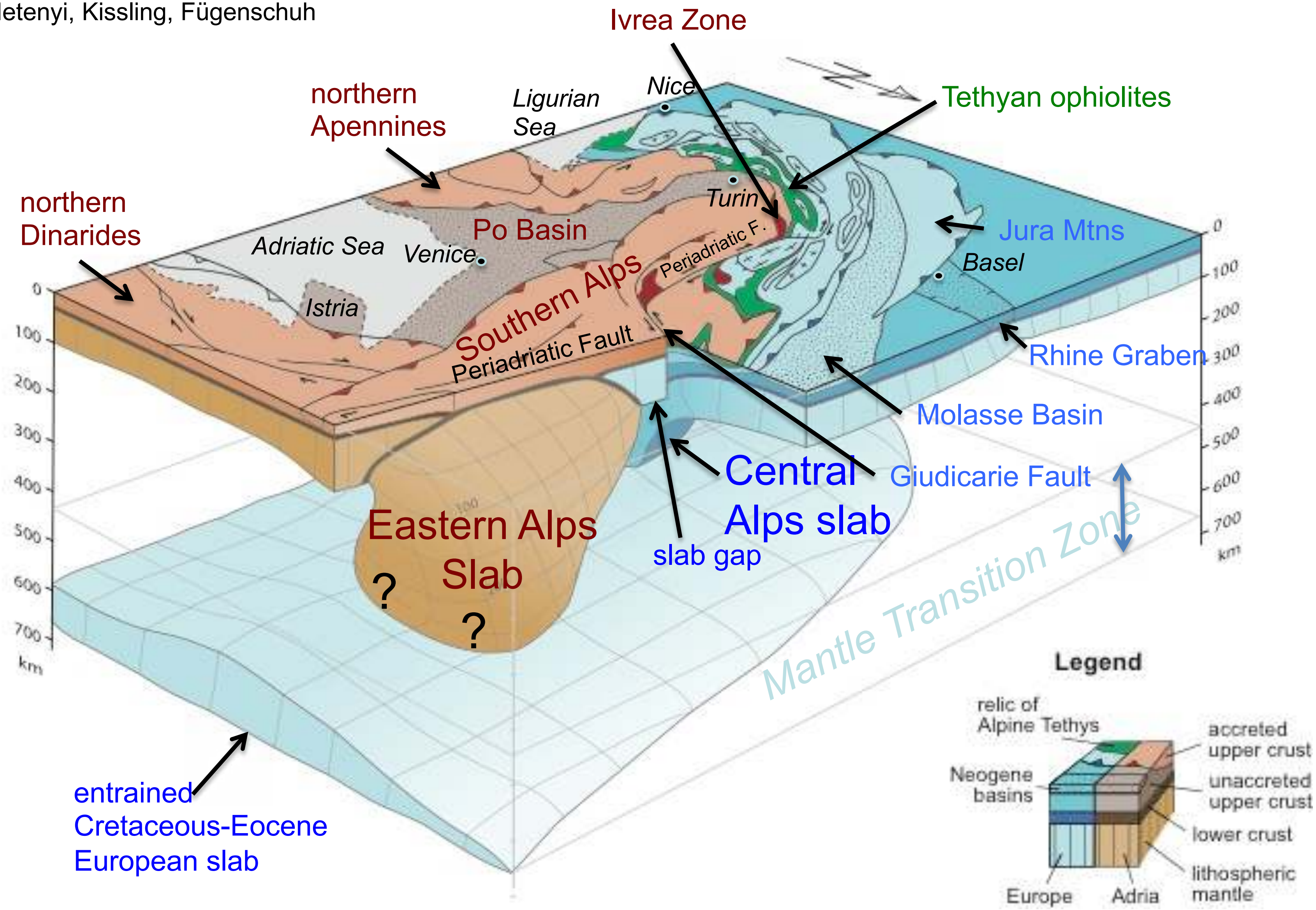
=> Slabs above Oligo-Miocene breakoff

$+V_p$ anomalies down to 450 km!

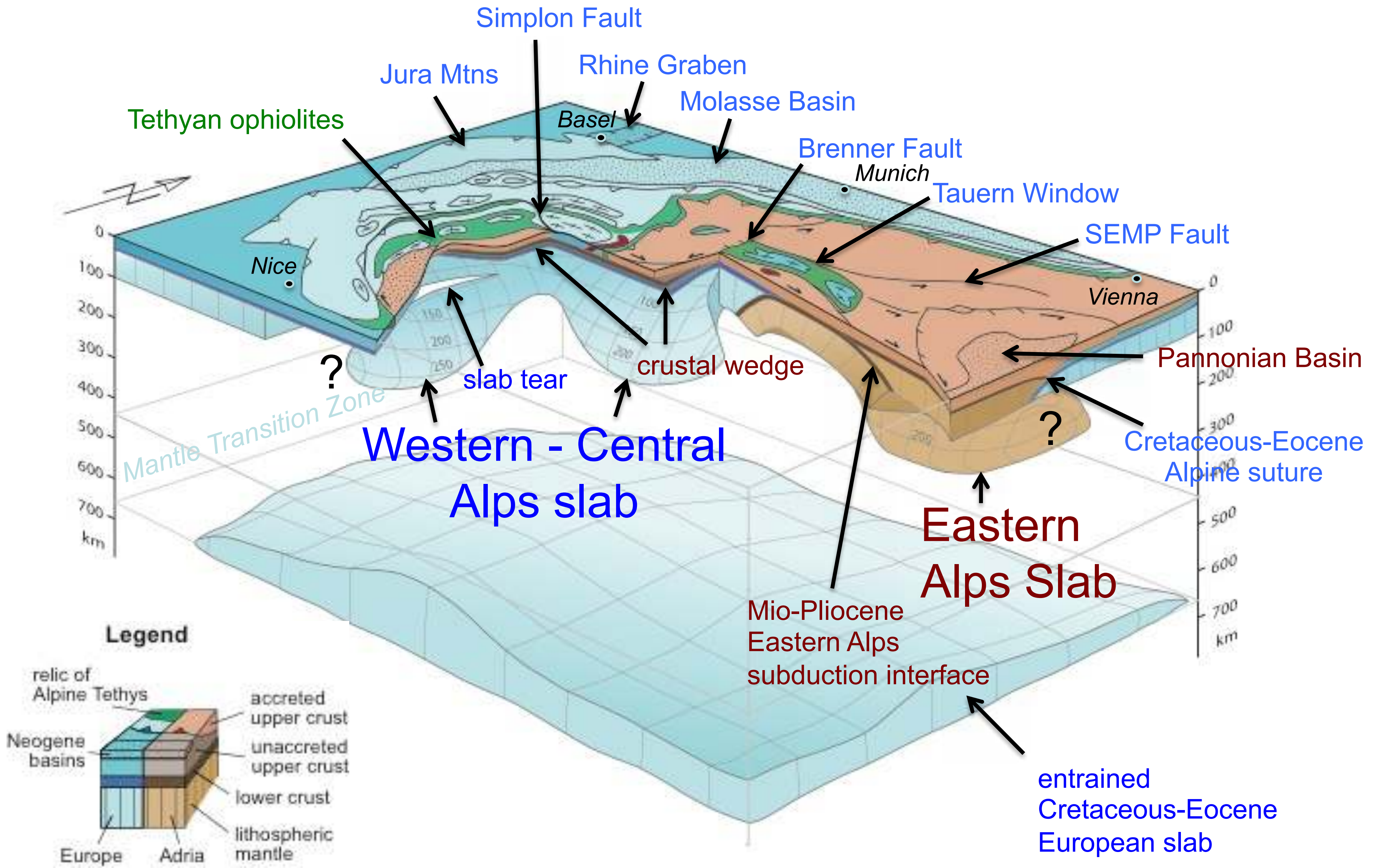
=> Slabs never broke off ?

Alps surface & subsurface viewed from NE

Handy, Hetenyi, Kissling, Fügenschuh

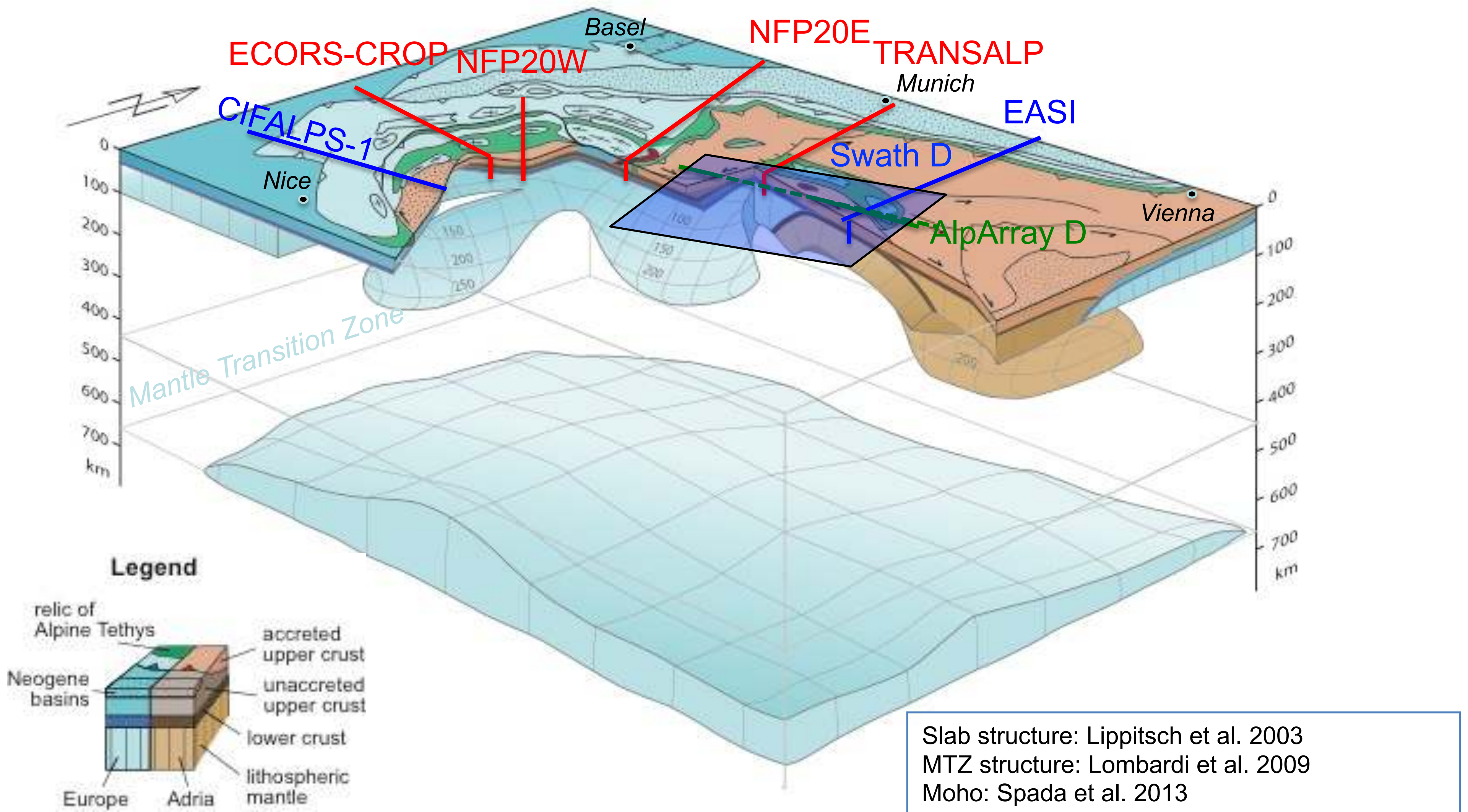


Alps surface & subsurface features viewed from SE



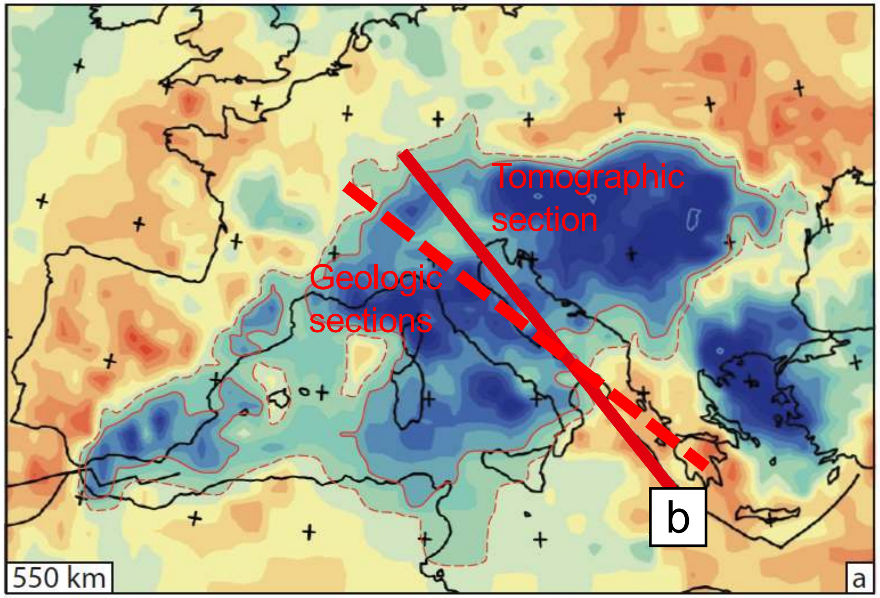
Transects of Alps viewed from the SE

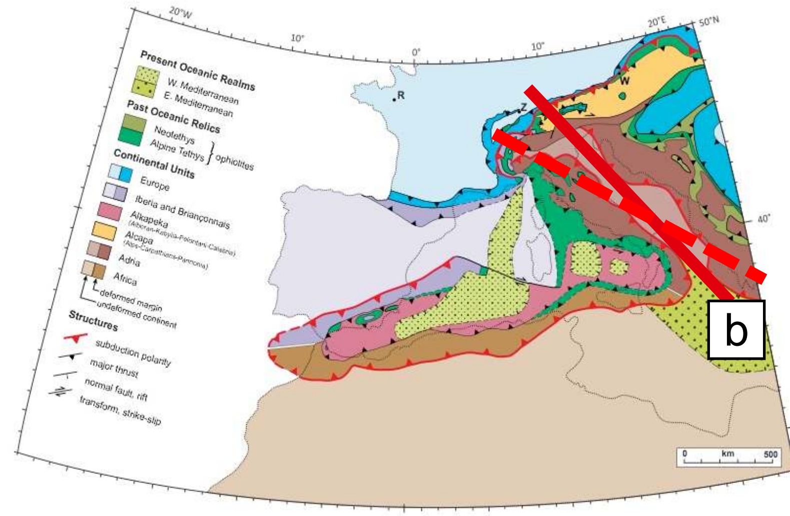
Active seismic transects of the 1980s & 1990s
Passive seismic swaths (*AlpArray, CIFALPS-1*)
Passive swaths transects (*AlpArray, 4D-MB*)

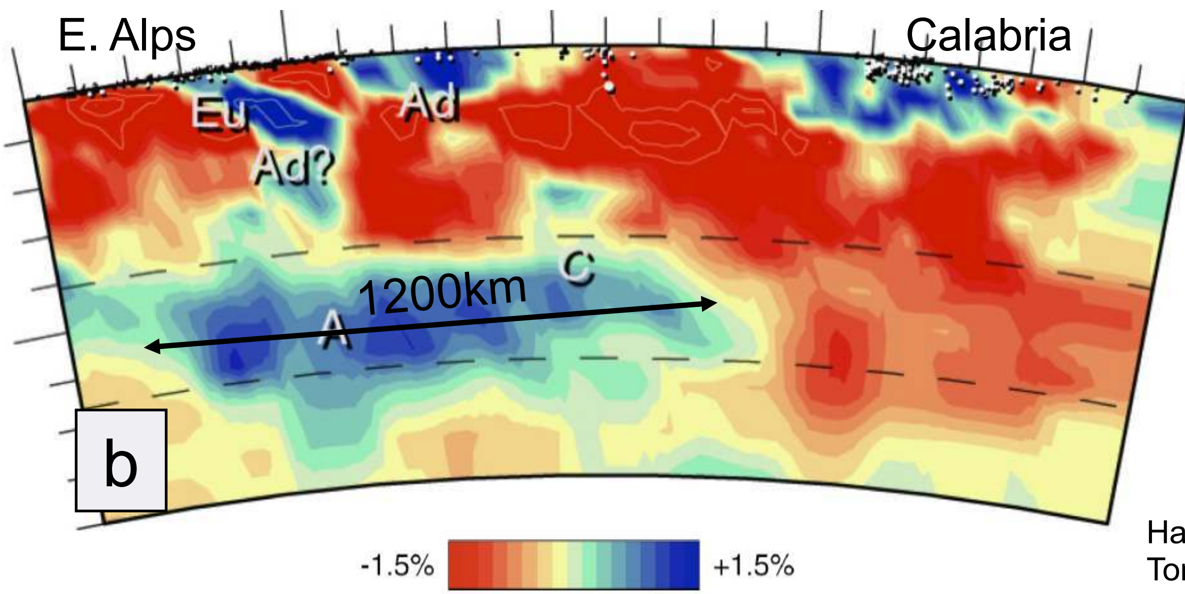


Slab structure: Lippitsch et al. 2003
MTZ structure: Lombardi et al. 2009
Moho: Spada et al. 2013

The Alpine (European) slab in tomography



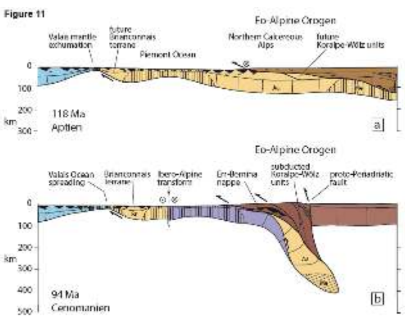


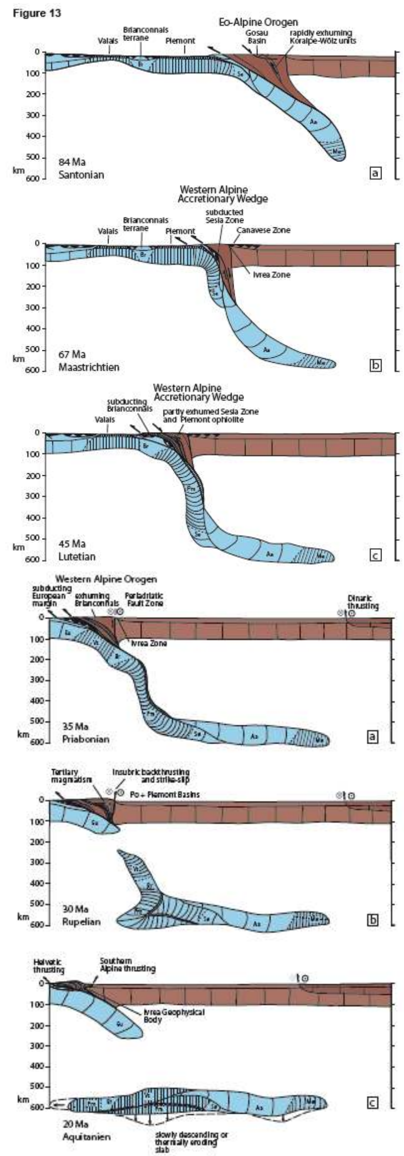


Handy et al. 2010
Tomography W. Spakman

Development of the Alpine Slab

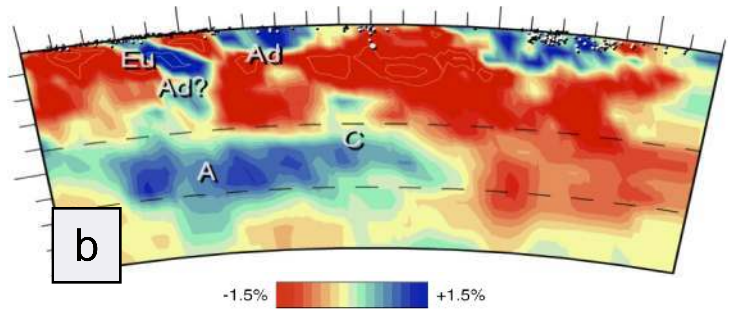
118 Ma

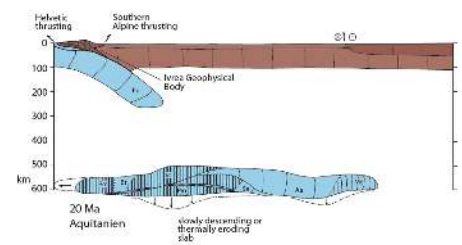




20 Ma

Tomography & Geology
on the same scale





20 Ma

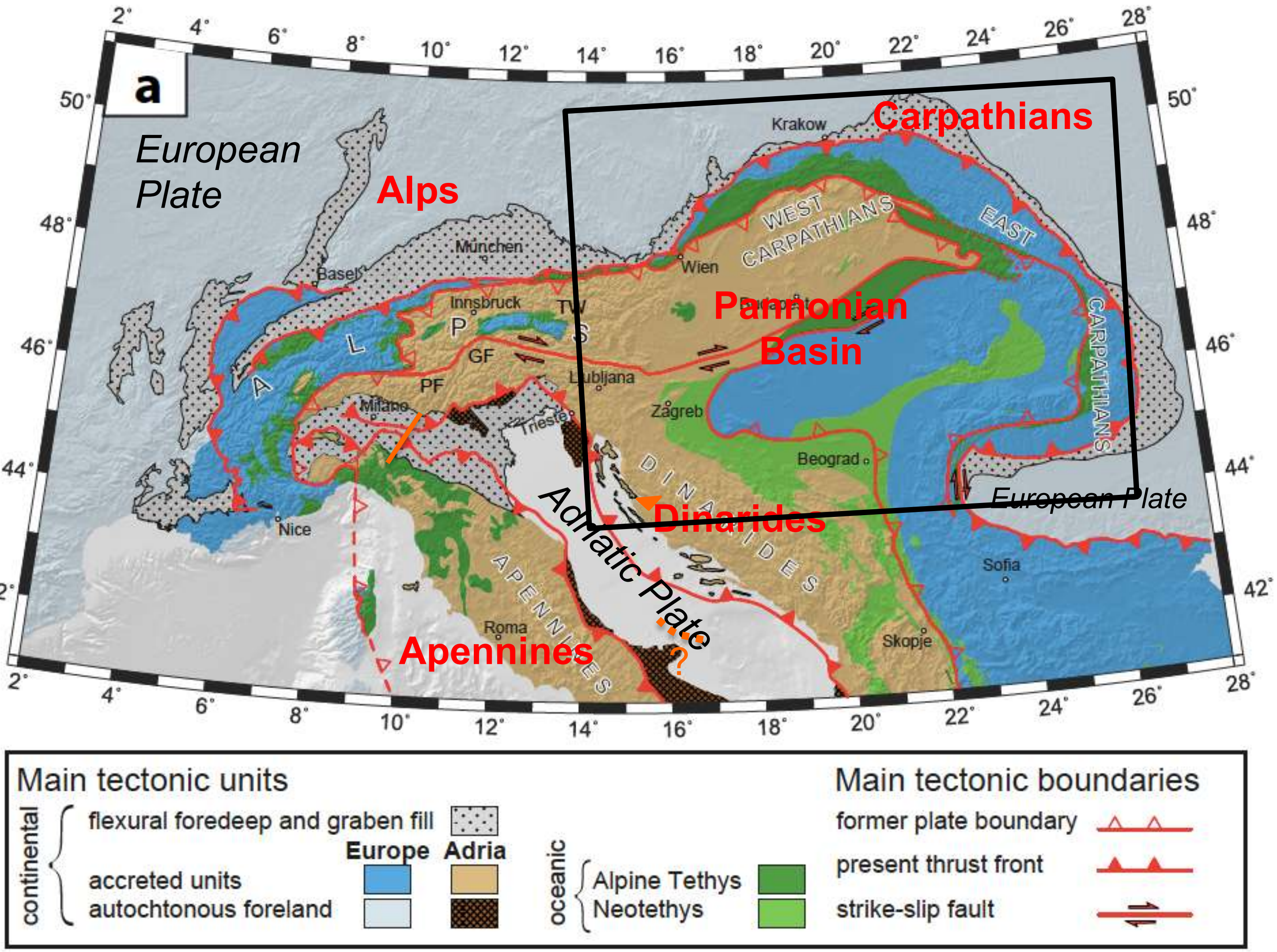
1200 km

obtained from
minimum shortening
in the C. Alps

Handy et al. 2010
Tomography W. Spakman

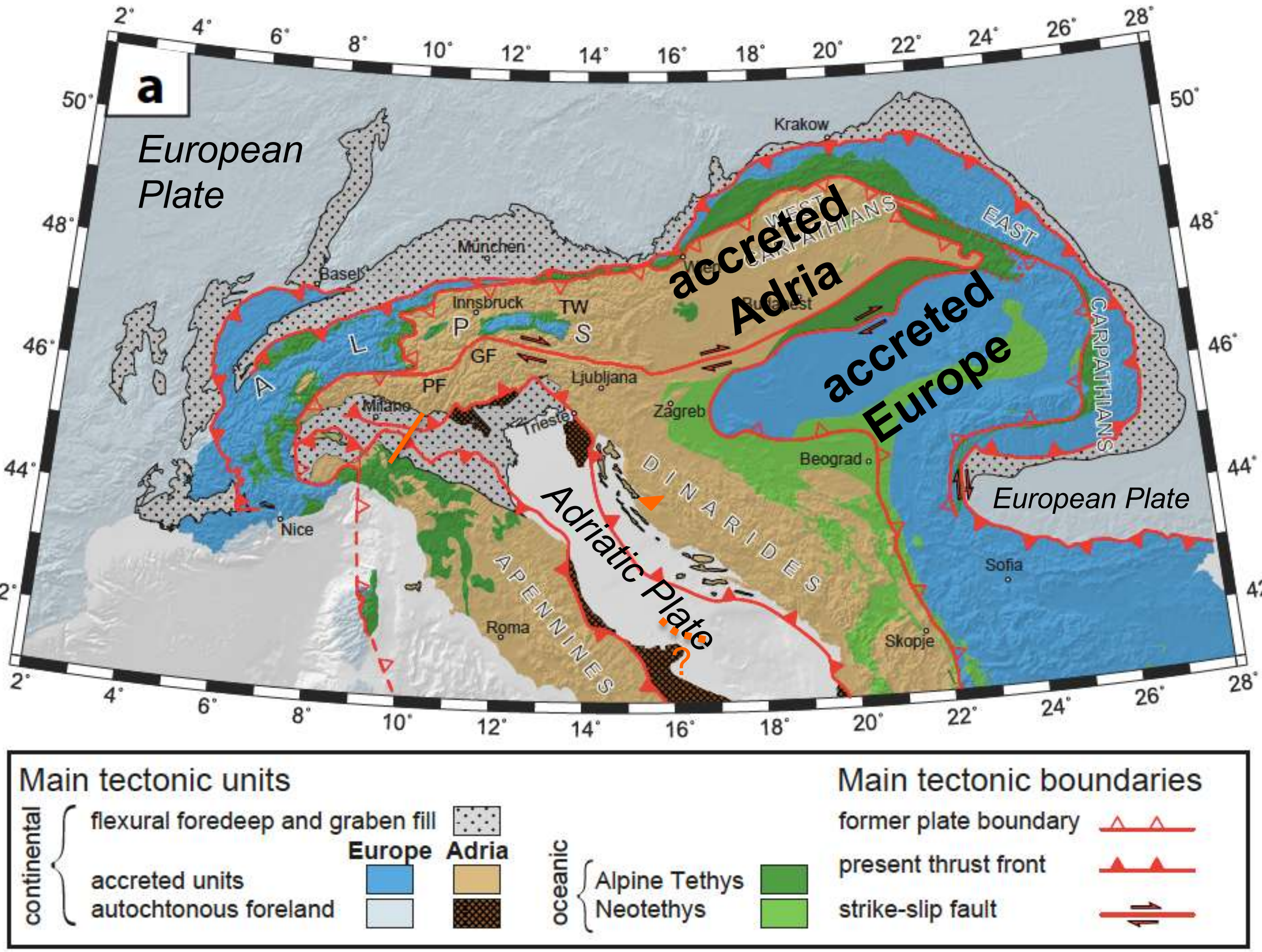
Carpathian-Pannonian System

Handy et al., simplified from
Schmid et al. 2004, 2008

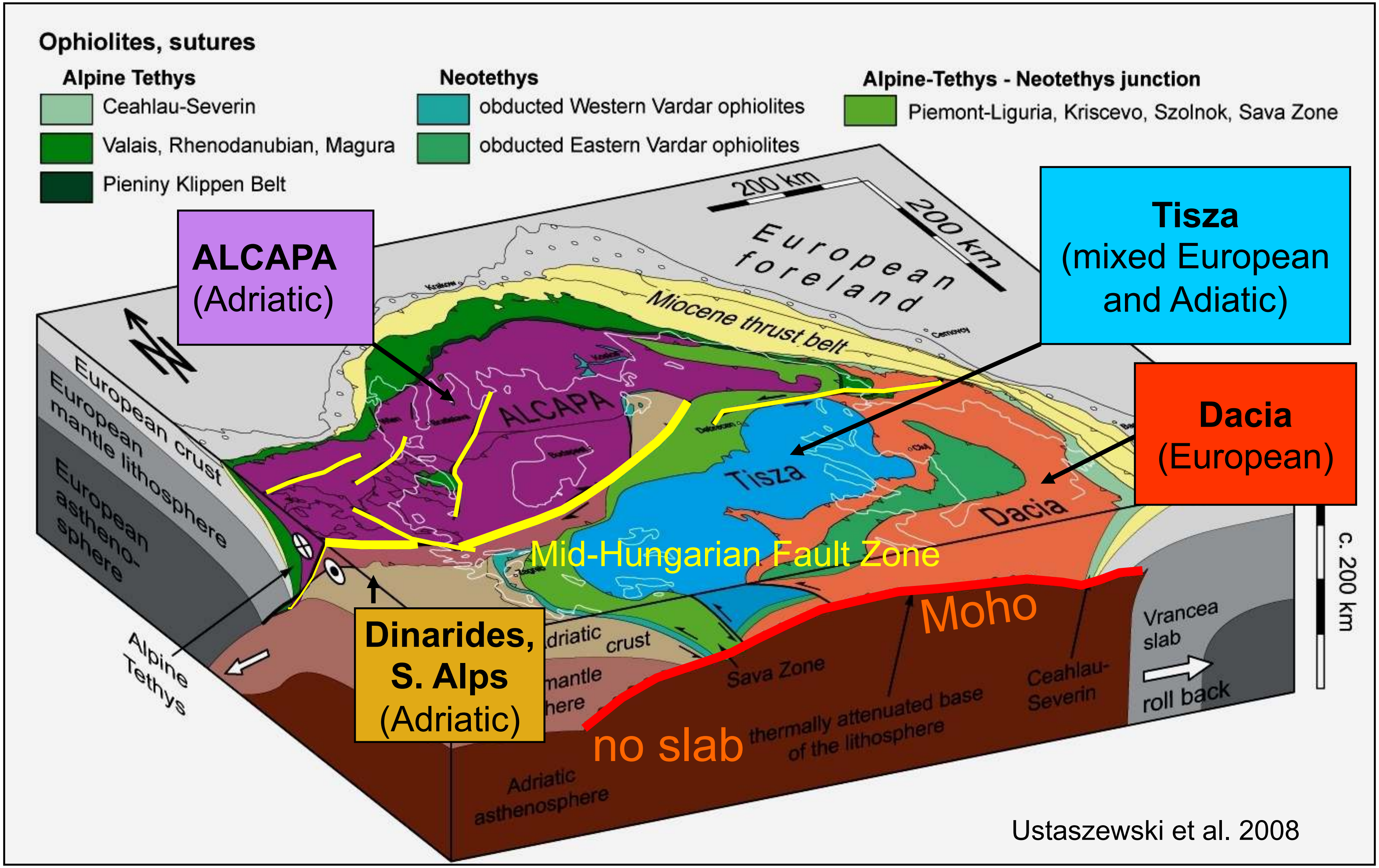


Carpathian-Pannonian System

Handy et al., simplified from
Schmid et al. 2004, 2008

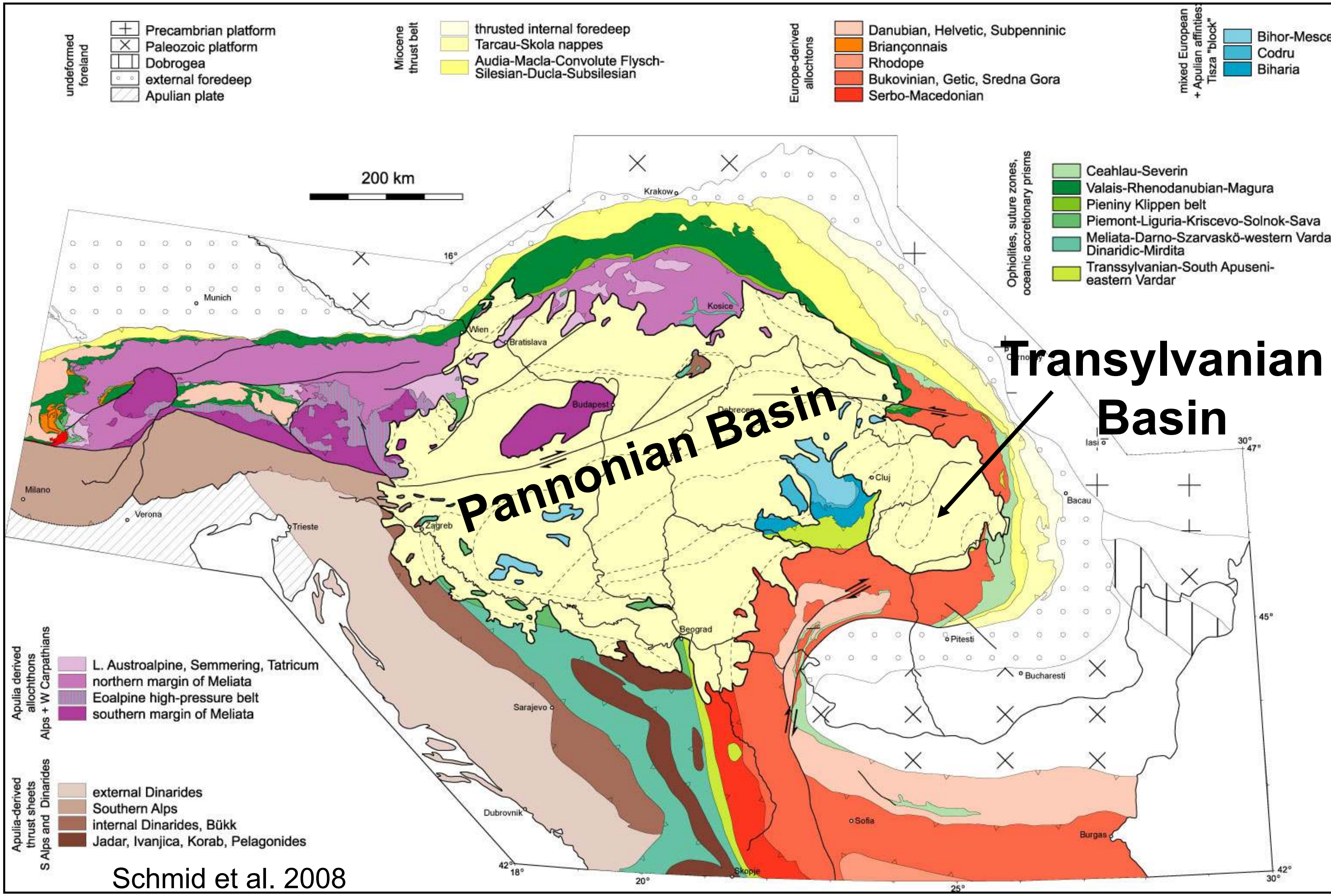


3D diagram of Carpathian-Pannonian system

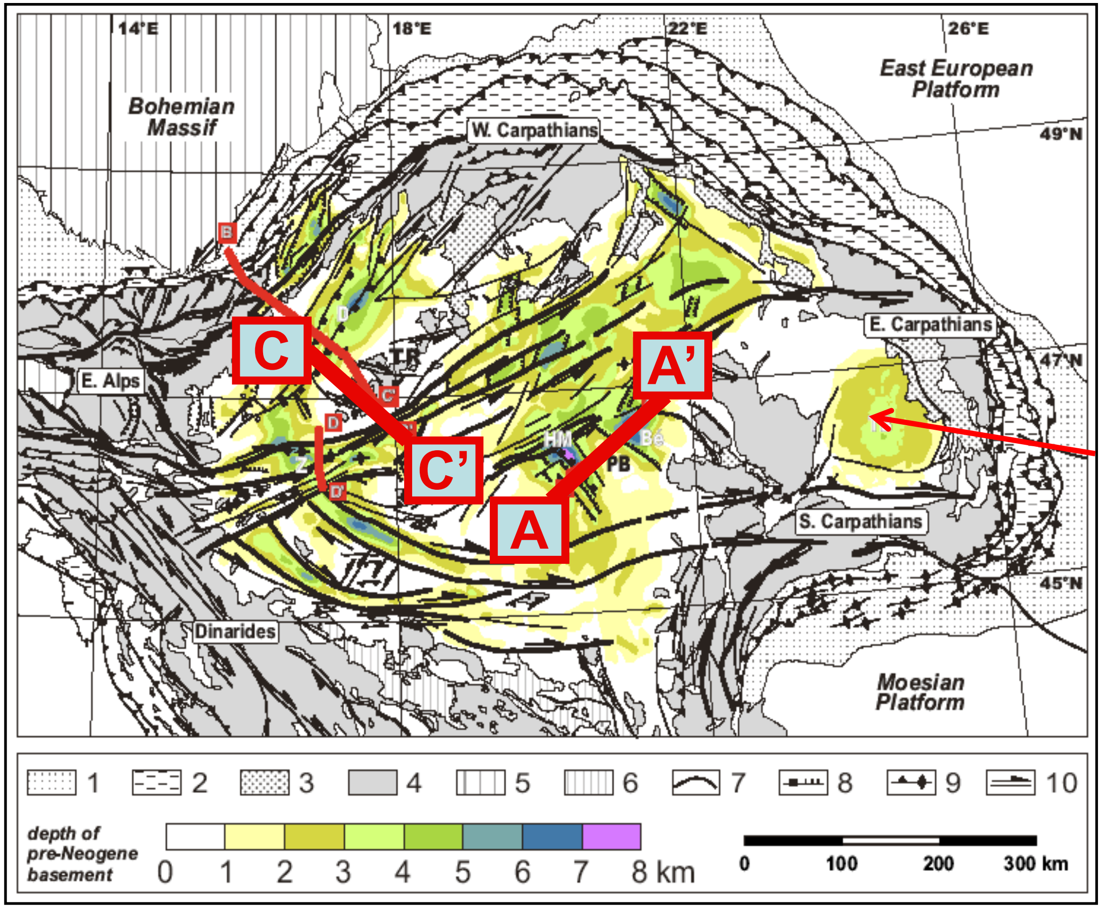


Ustaszewski et al. 2008

Neogene Basins

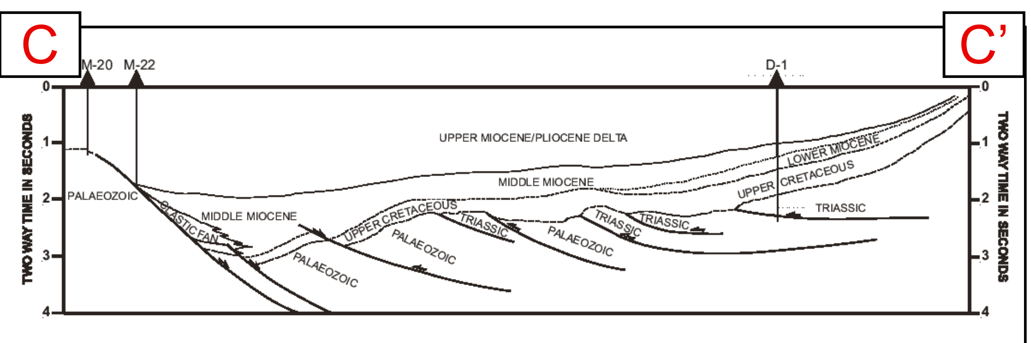


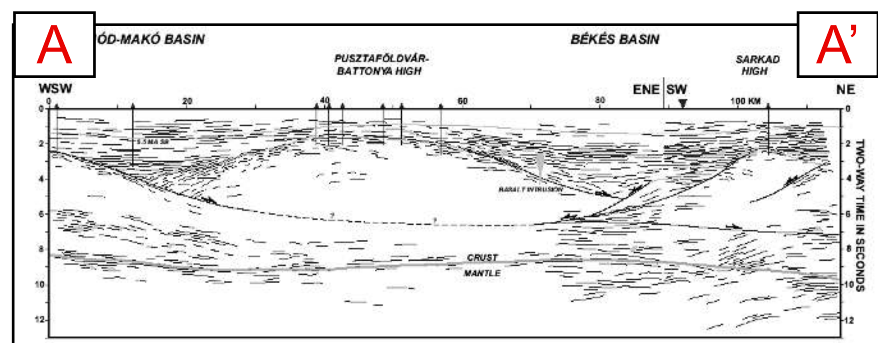
Neogene extensional structures of the Pannonian Basin



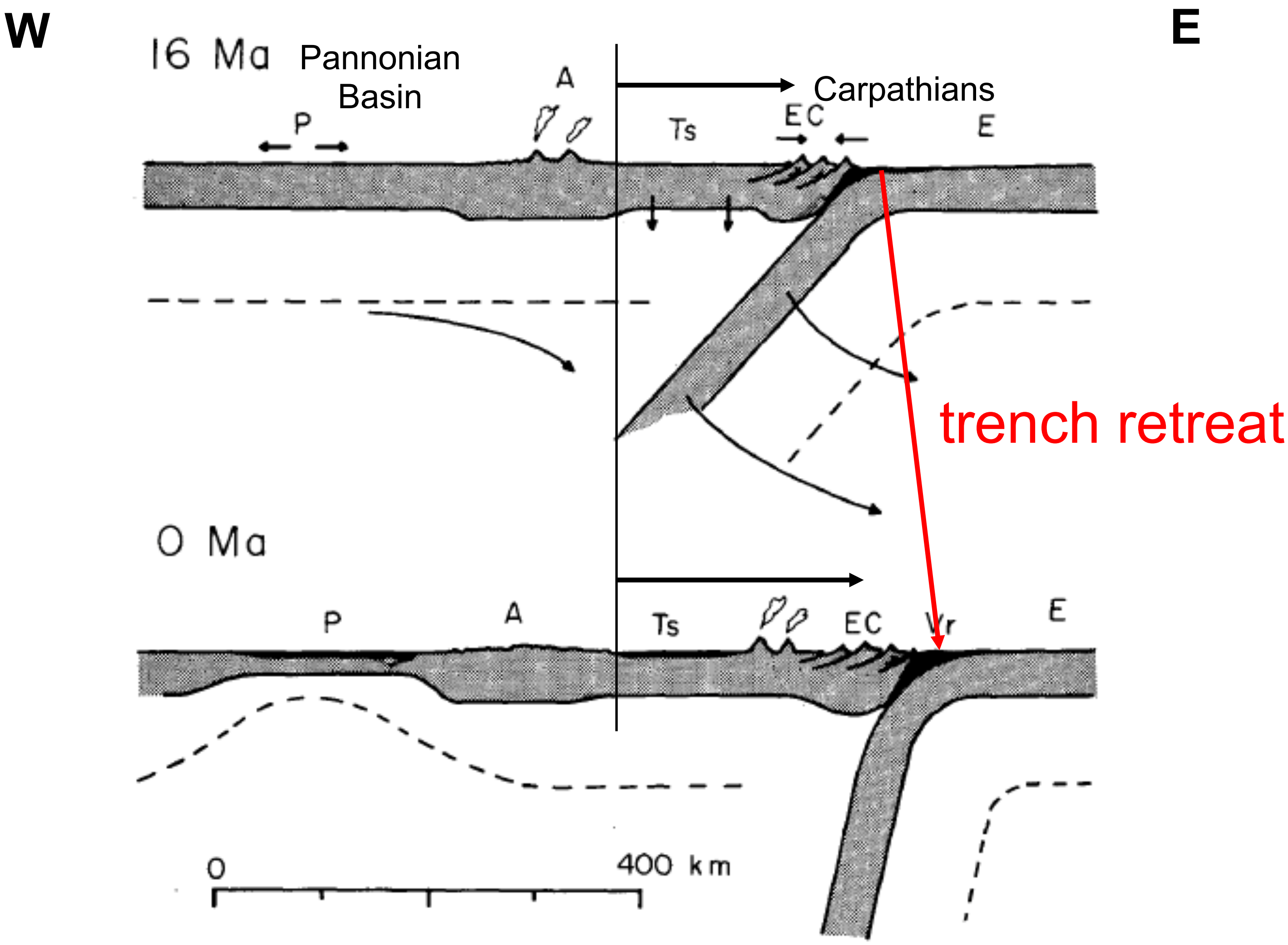
Transylvanian Basin

Horvath et al 2006



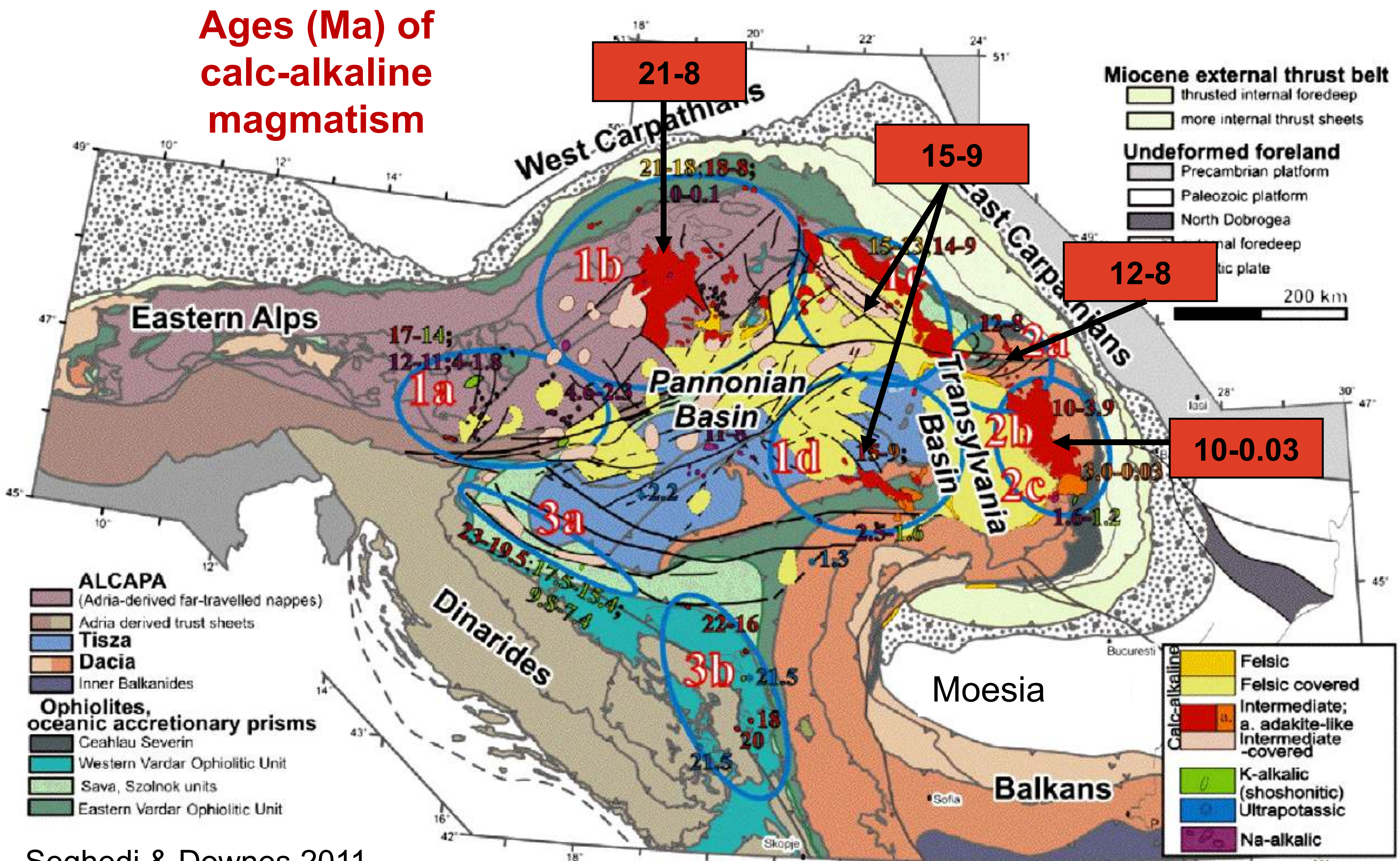


Rollback Subduction



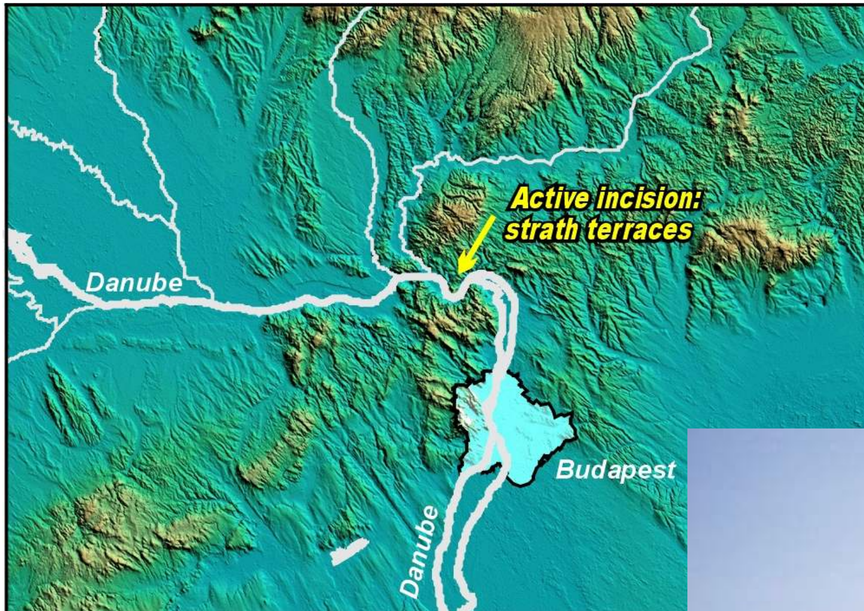
Royden, Horvath, and Burchfiel, 1982, *GSA Bull, 23, 717-725*

Miocene-recent magmatism as a tracer of rollback subduction

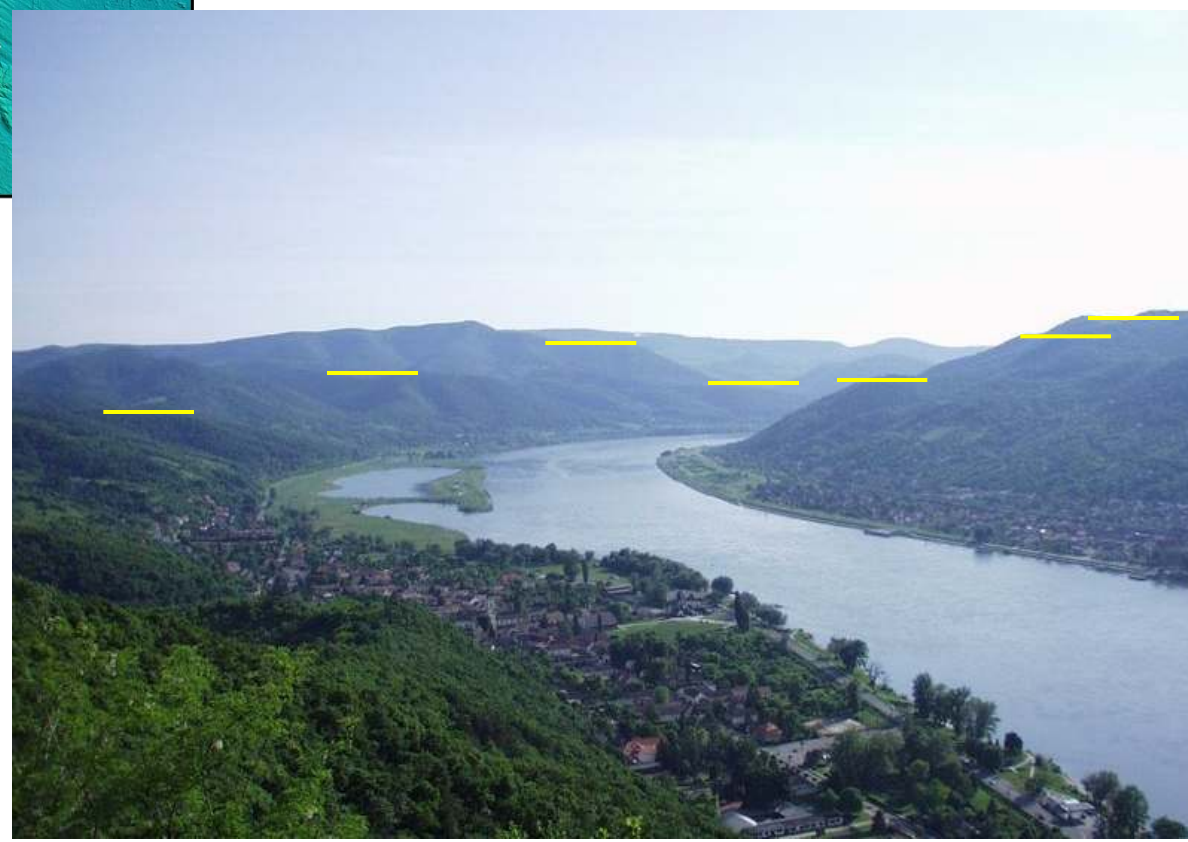


Seghedi & Downes 2011

Surface uplift & Pannonian tectonics



Strath terraces at Visegrad



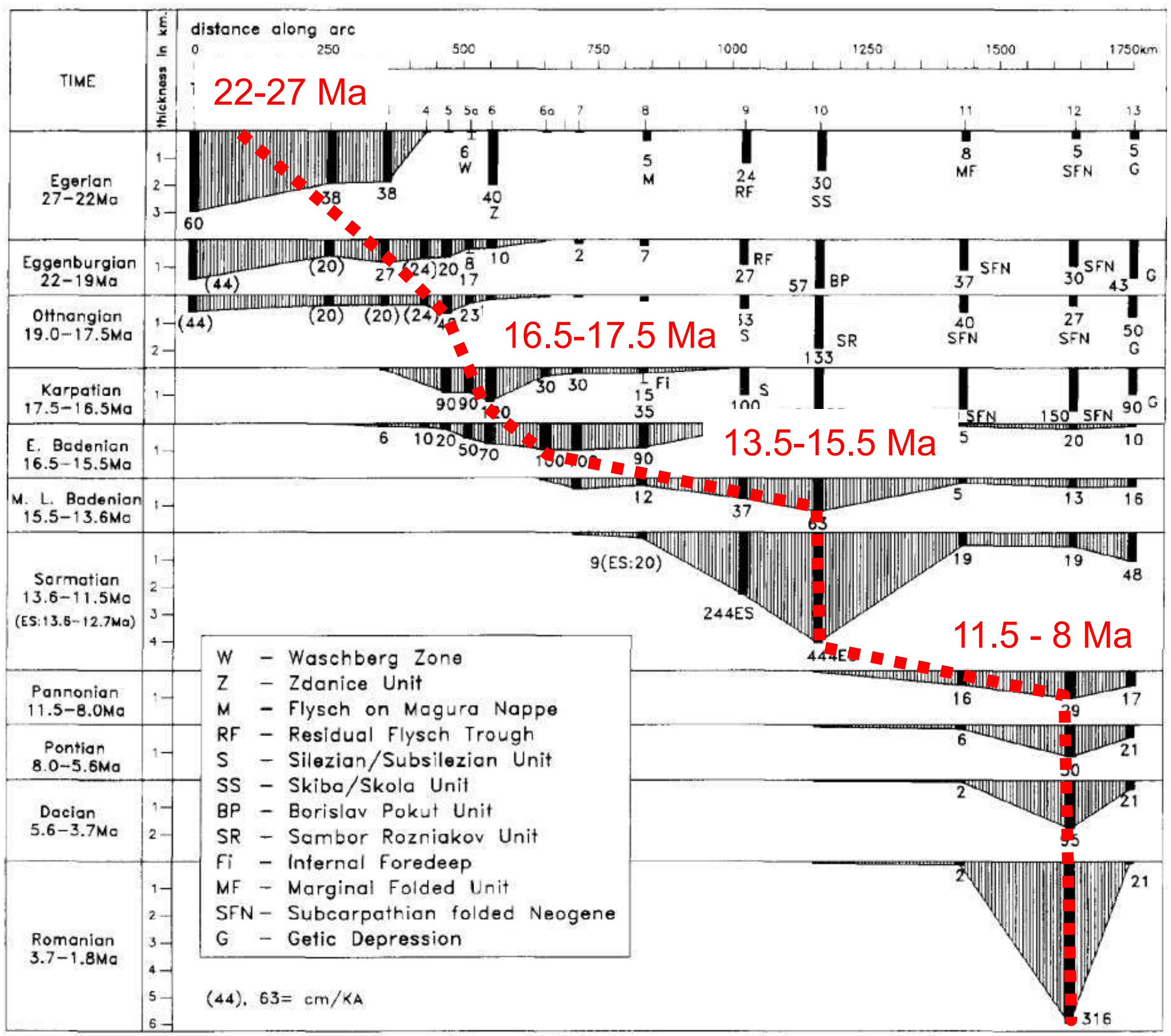
Uplift, river incision and erosion shown by ancient Danube strath terraces at Visegrád, upstream of Budapest.

Exposure age of terraces:
0 to 250ky

Incision rate: ~1.5 mm/y

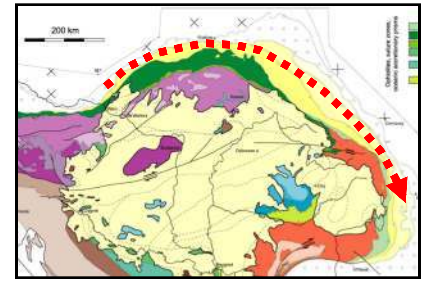
From S.Cloetingh

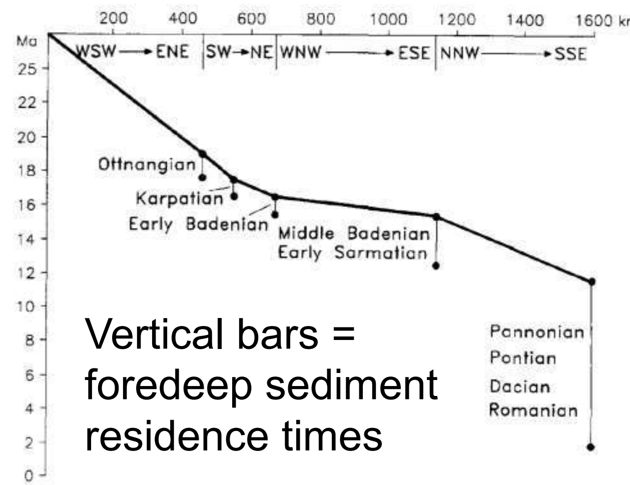
Clockwise migration of foredeep deposition around the Carpathian arc



Meulenkamp et al. 1996

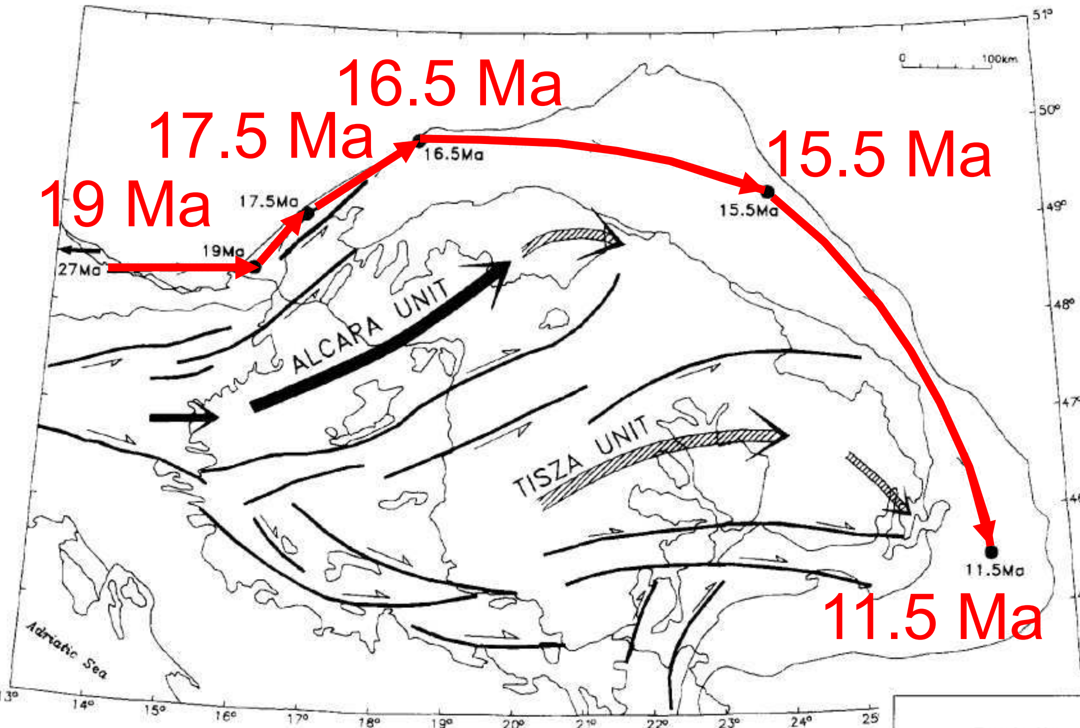
3.7 – 1.8 Ma





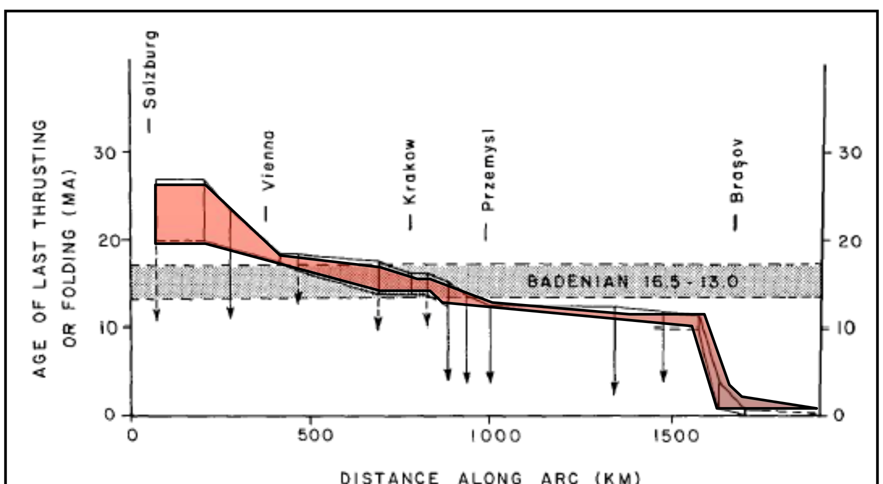
Internal to external and lateral shifts in foredeep depocentre accellerated in latest Early-Mid Miocene time (from 7 to 45 cm/y at 15.5 Ma)

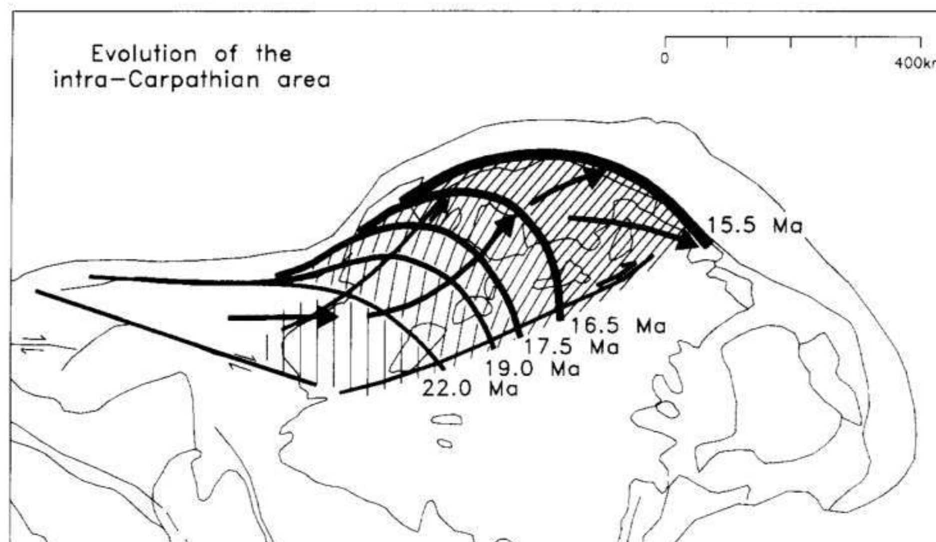
Foredeep migration related to rollback subduction & Pannonian extension



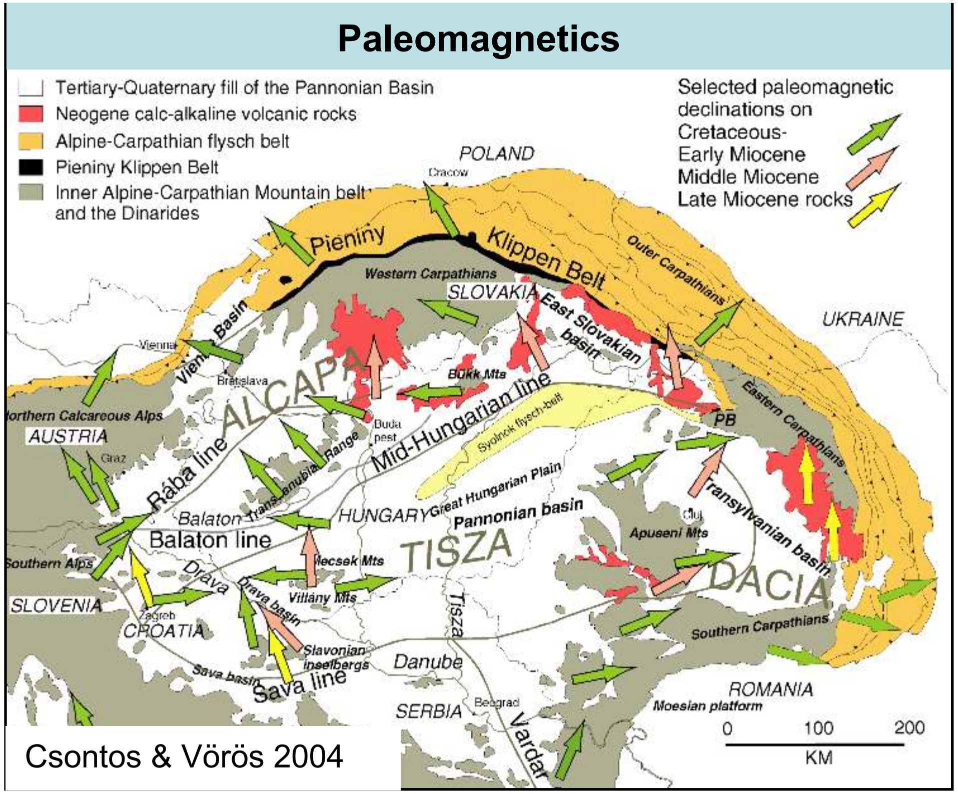
- Drastic increase at 16.5 Ma
- Clockwise foredeep migration probably traces direction of Miocene slab tearing

Meulenkamp et al. 1996

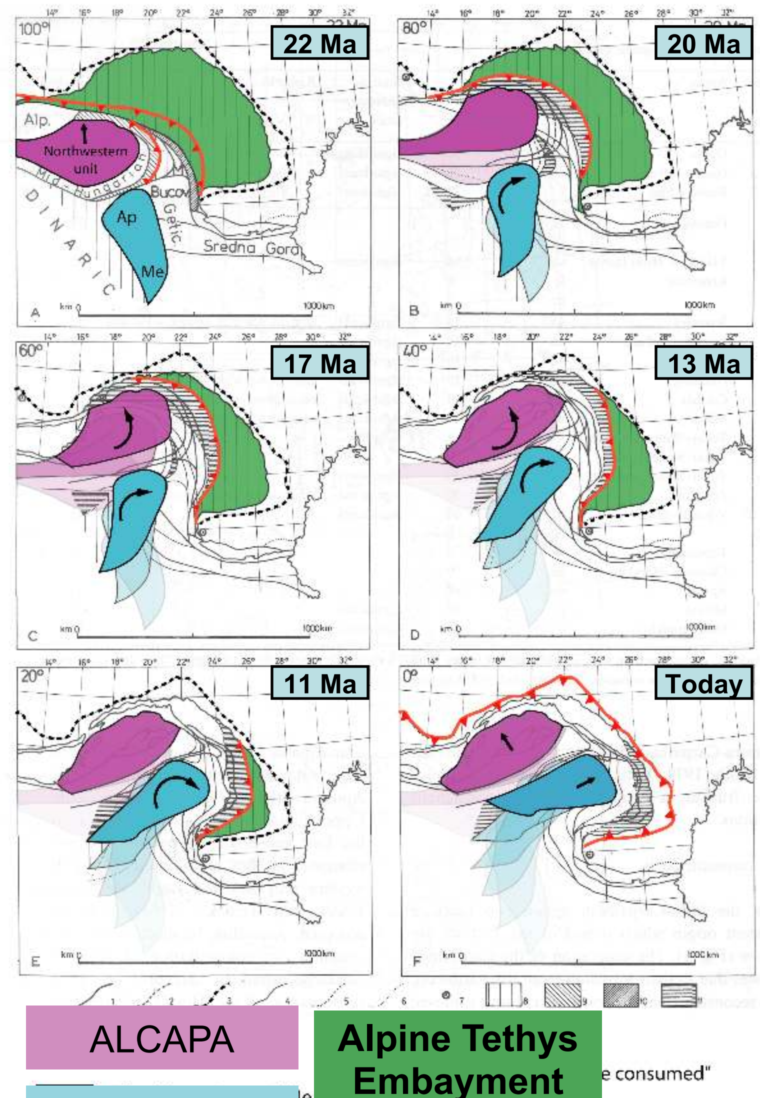




Block rotations during rollback subduction

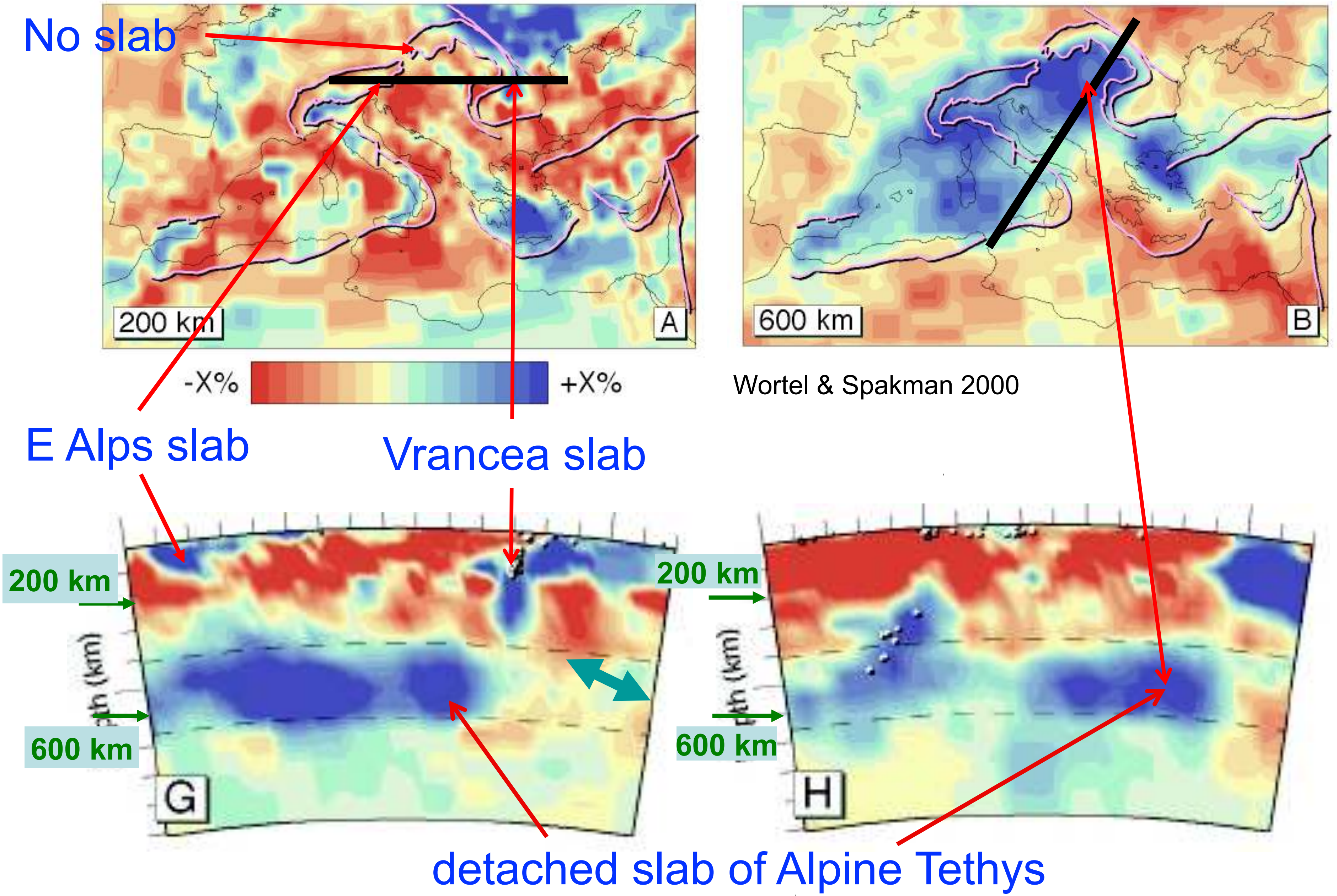


Csontos & Vörös 2004

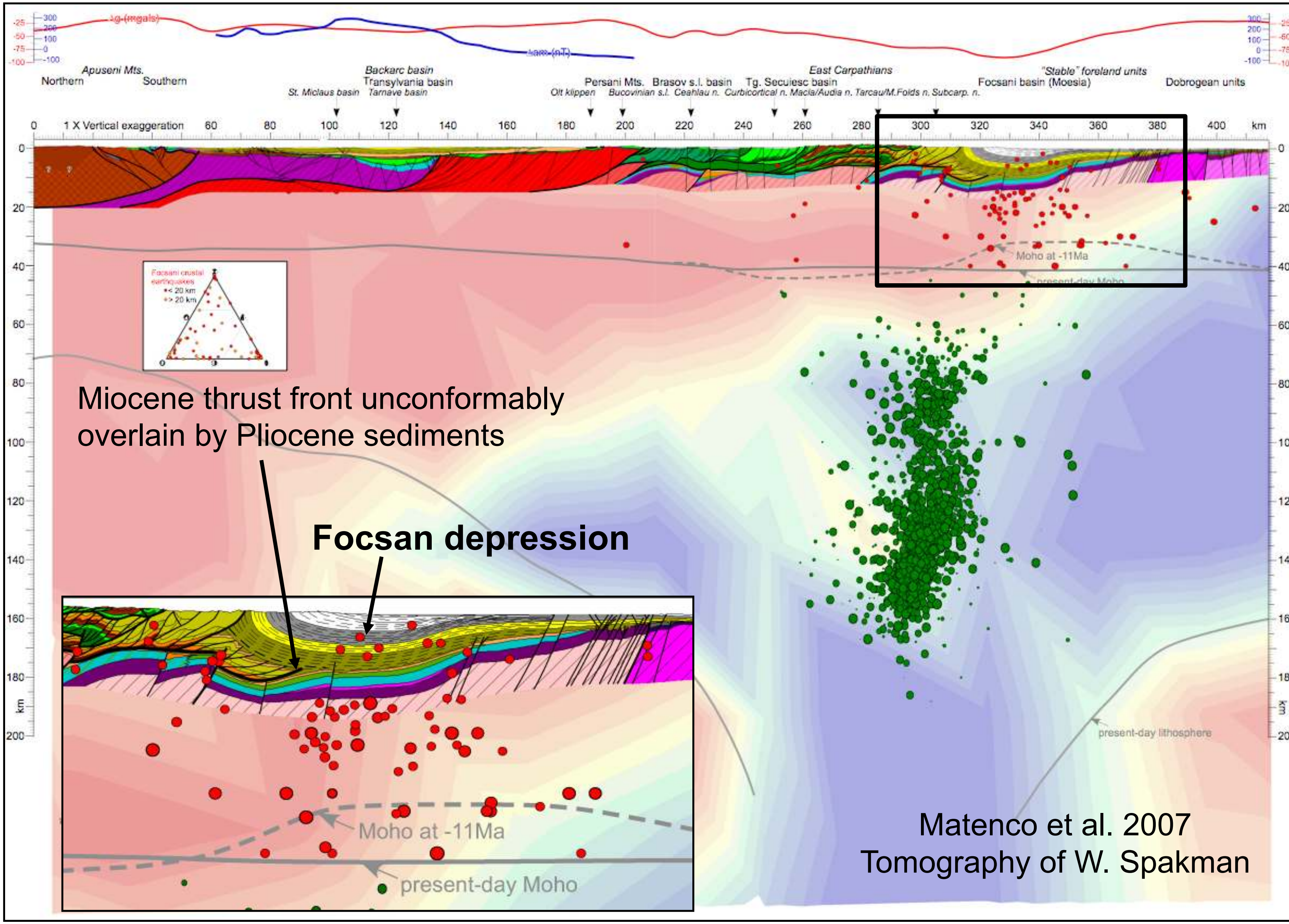


Balla 1987

Detached slabs & the slab „graveyard“

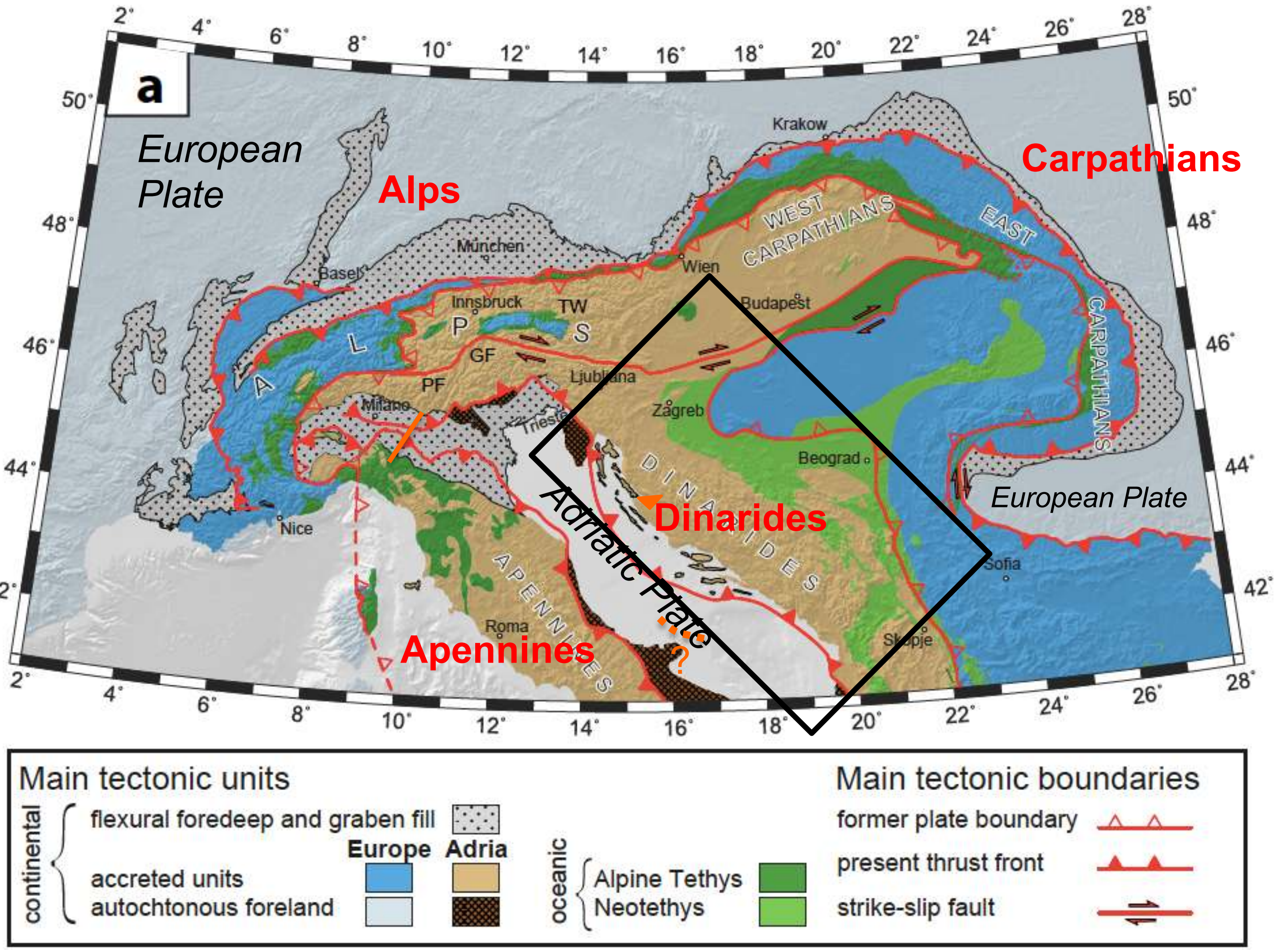


Vrancea slab – hangs in the "wrong" place, just below the orogenic front

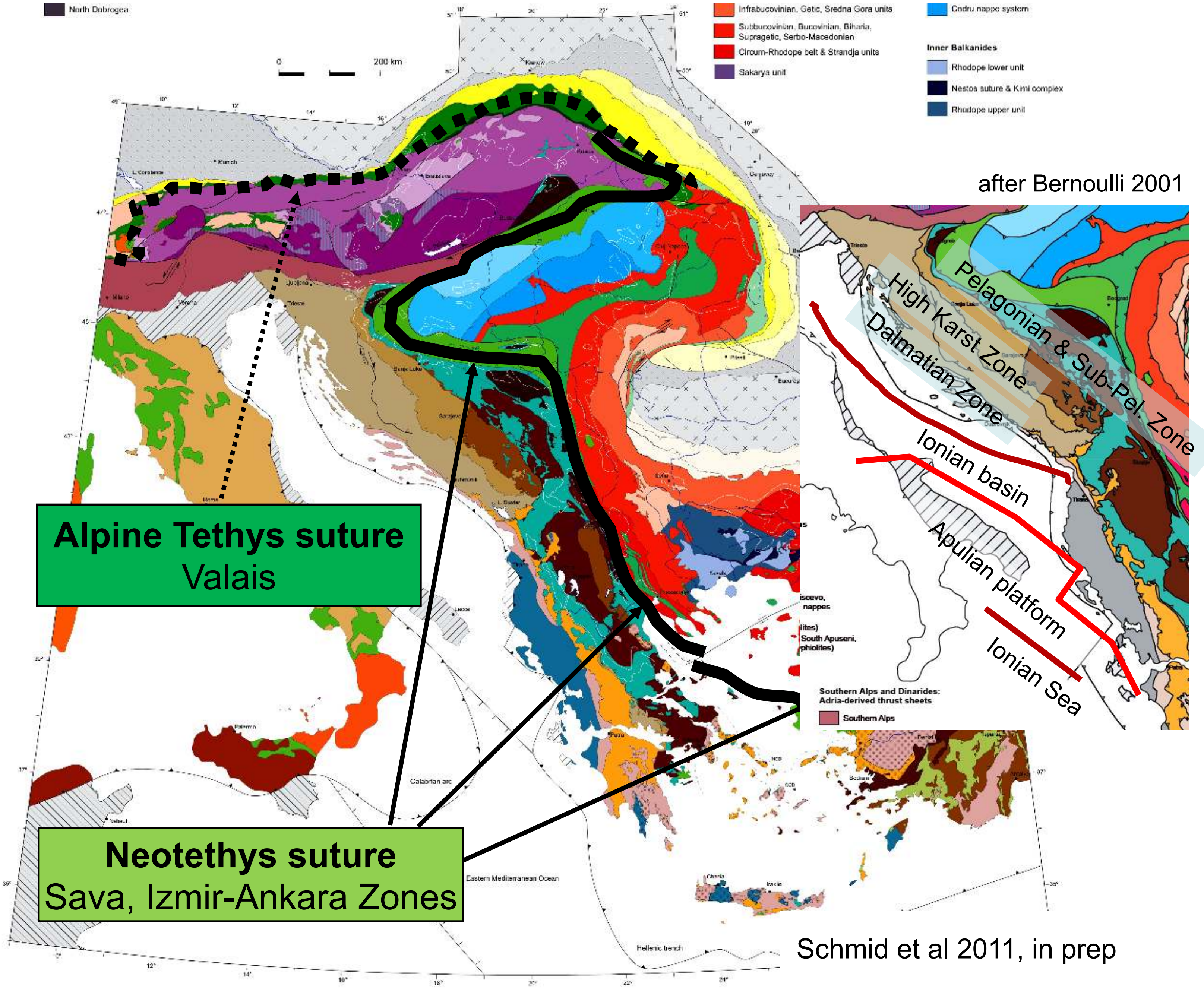


Dinarides

Handy et al., simplified from
Schmid et al. 2004, 2008



Sutures of two oceans - Alpine Tethys & Neotethys



Schmid et al 2011, in prep

Cross section of the Dinarides

LOWER PLATE = ADRIA

Paleogene nappe stack topped by obducted W. Vardar ophiolite nappe

Dinaric orogen

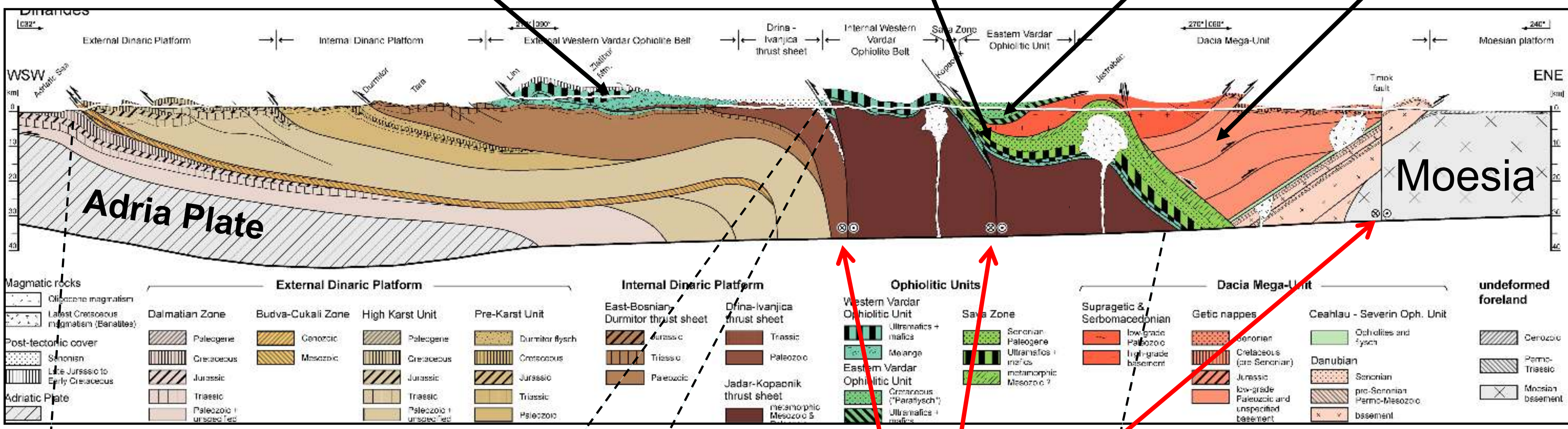
Paleogene Suture

Sava ophiolites

UPPER PLATE = EUROPE

Late Cretaceous nappe stack topped by obducted E. Vardar ophiolites

Carpatho-Balkan orogen



Proximal Adria, External Dinarides

in-sequence thrusts

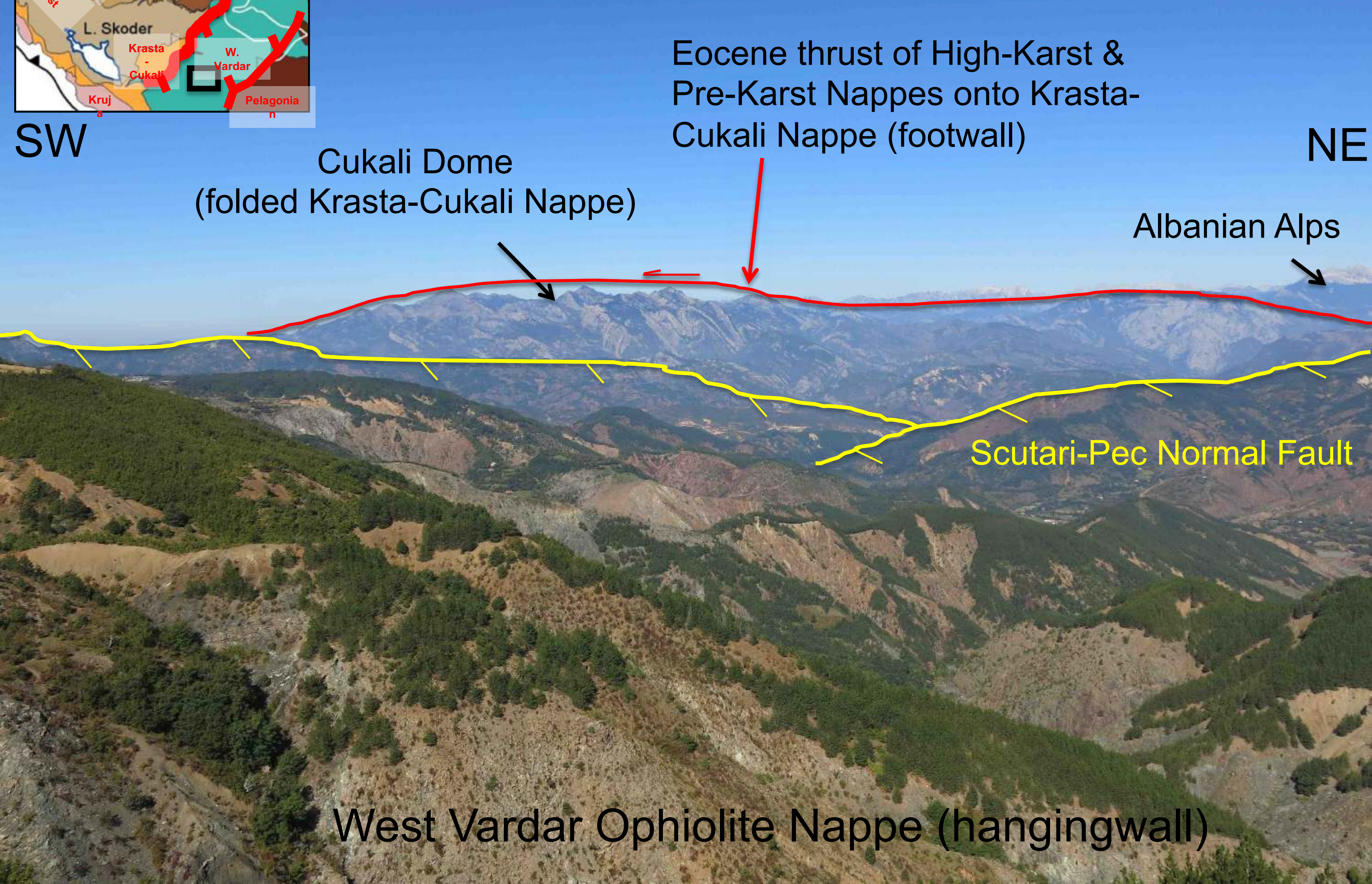
Distal Adria, Internal Dinarides

contain out-of-sequence thrusts

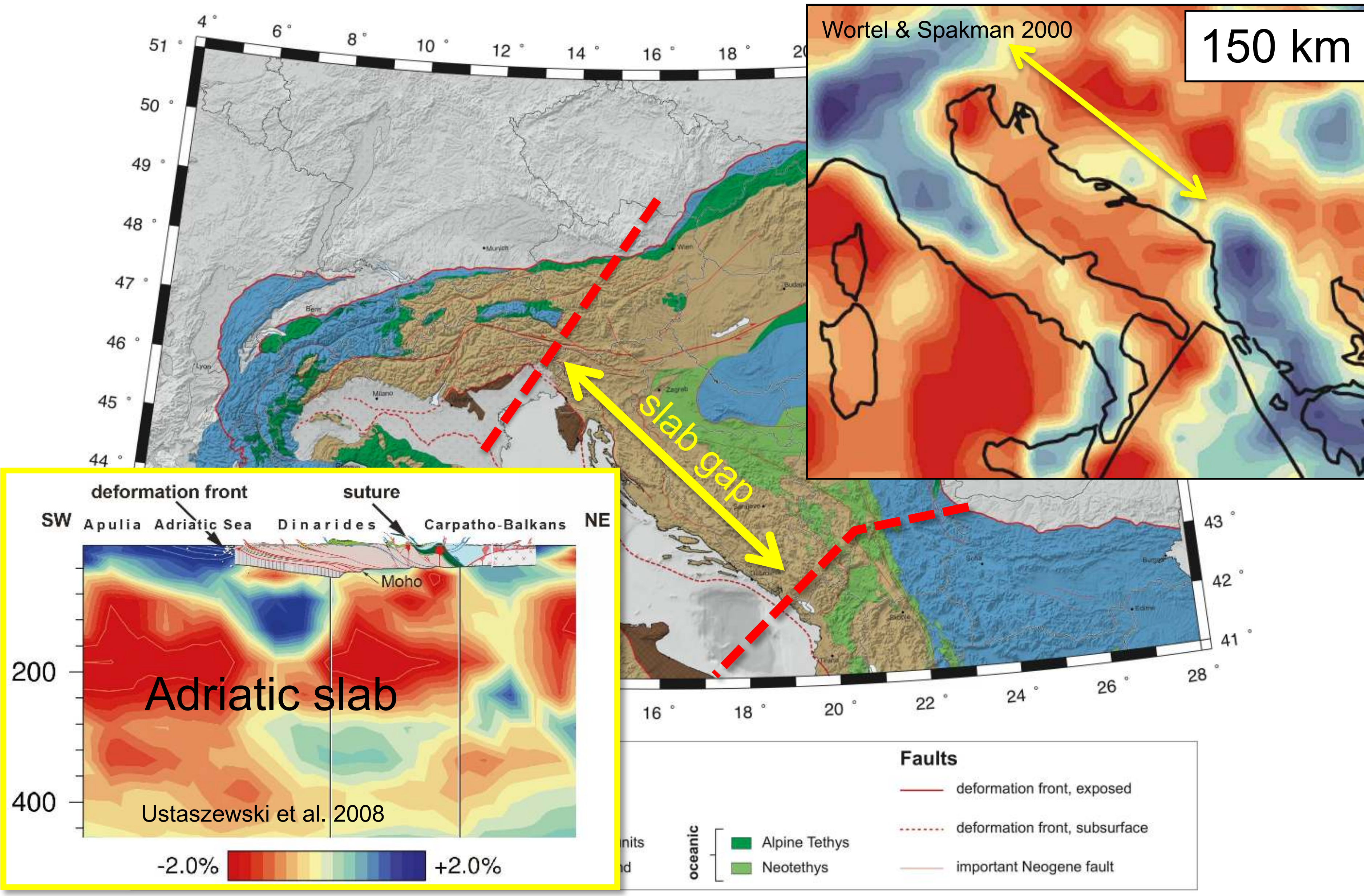
Neogene strike-slip faults

Schmid et al. 2008

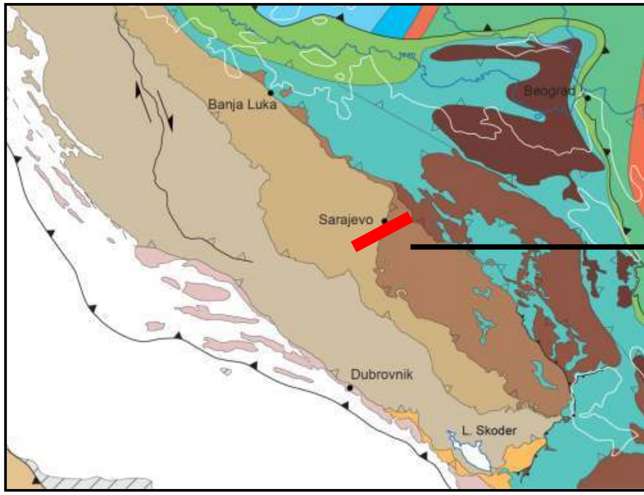
Dinaric fold-and-thrust belt exposed in the Cukali Dome



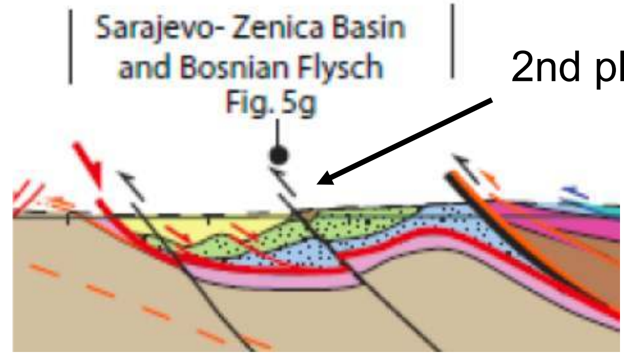
Enigmatic feature - Slab gap beneath Dinarides



Miocene extension of Dinaric nappe stack

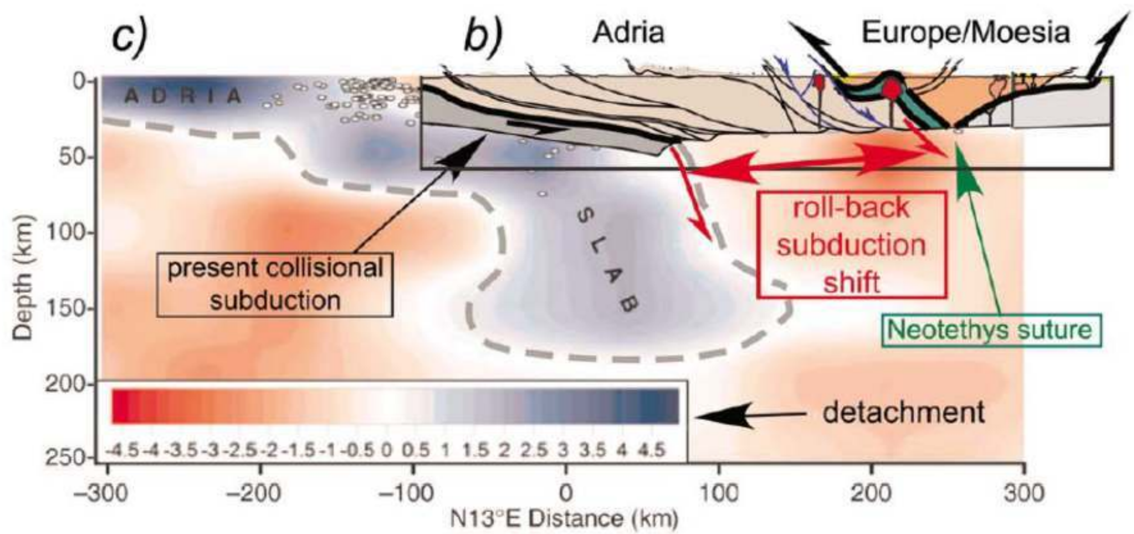


Schmid et al. 2011, in prep



2nd phase of thrusting

Unen et al. 2018



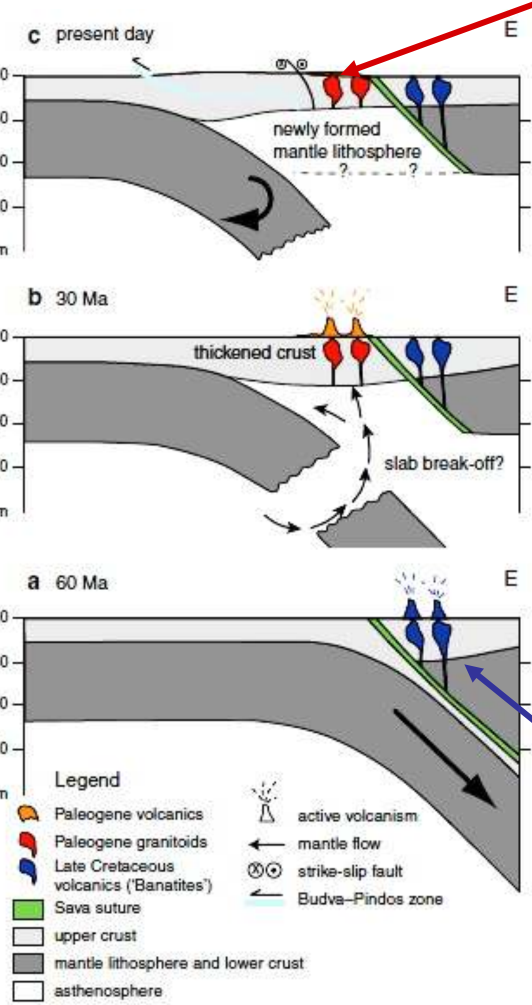
Matenco & Radivojevic 2012

Slab is too short given the amount of shortening

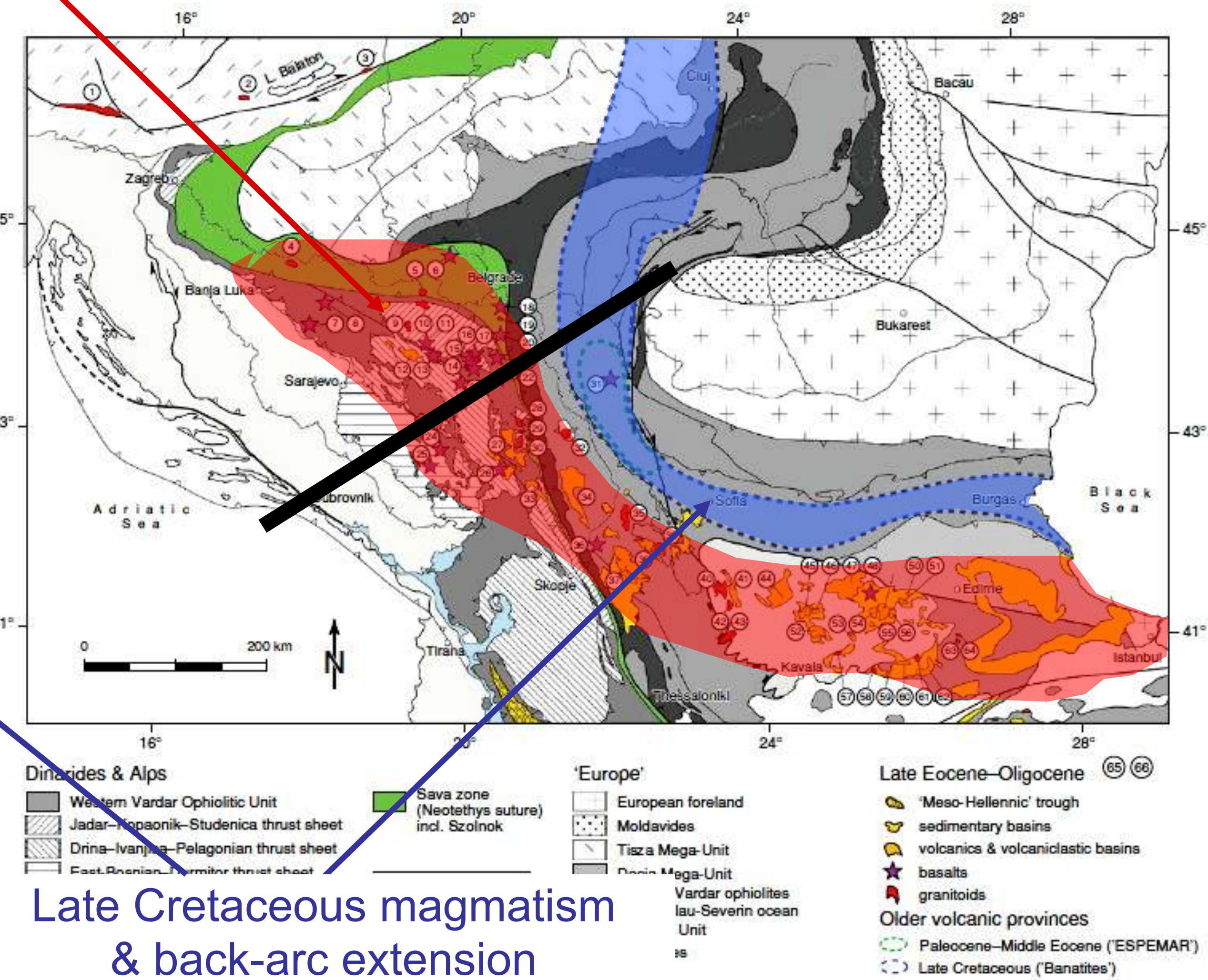
=> slab breakoff in Oligocene?

Late Paleogene magmatism in the Dinarides & Carpatho-Balkan

Paleogene magmatism -
back-arc extension and breakoff of Adria slab?



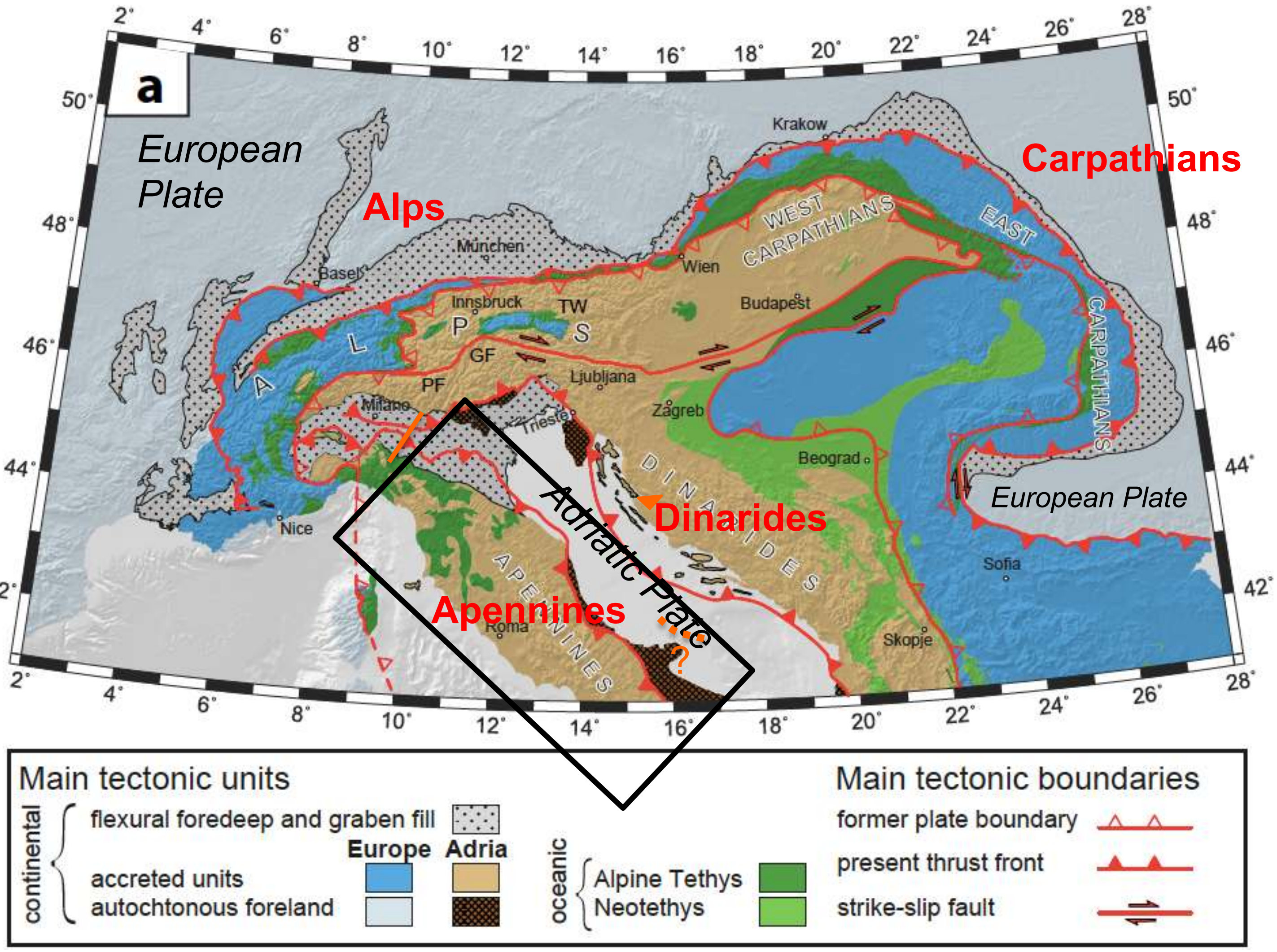
Schefer et al 2011



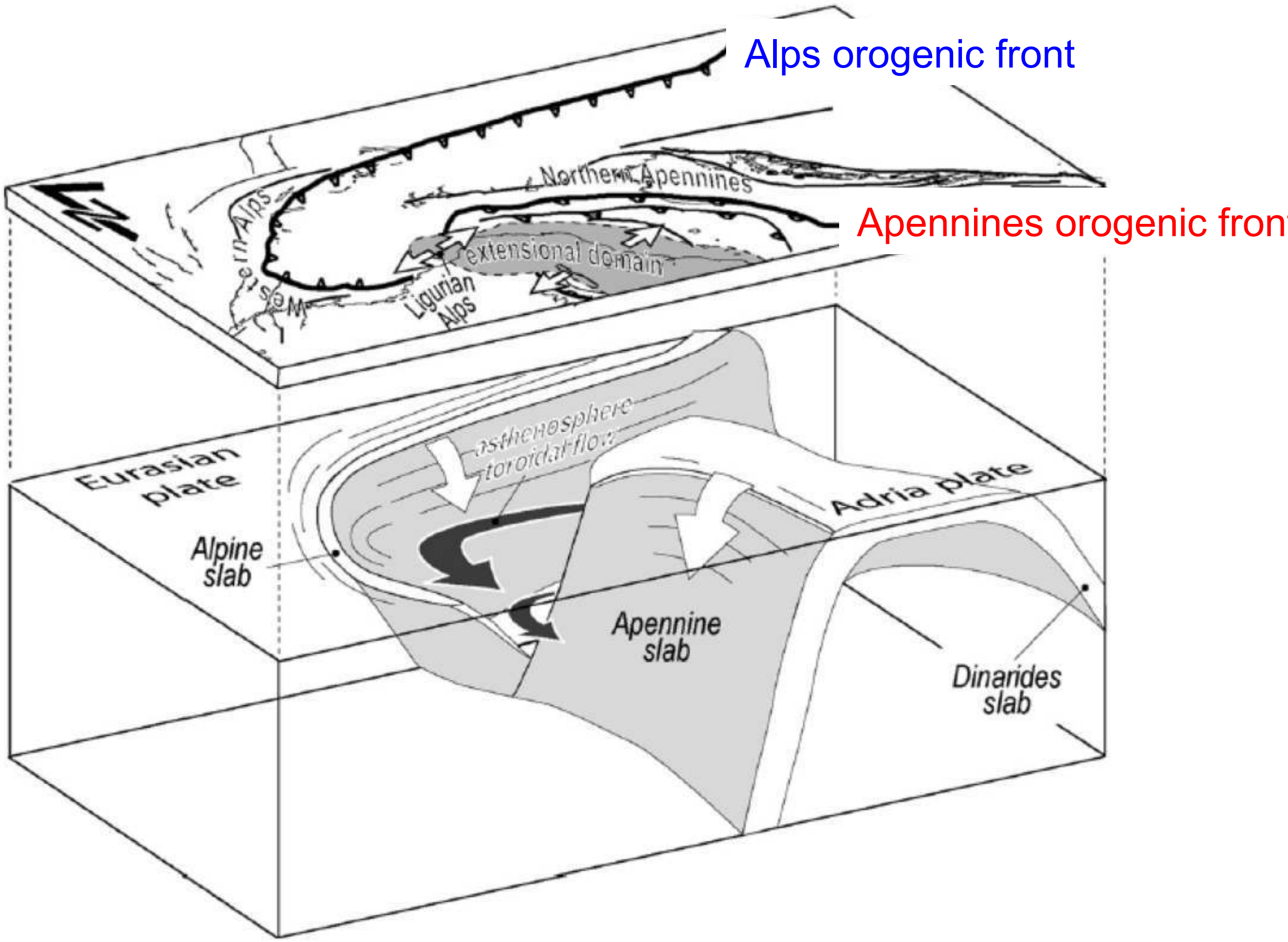
Late Cretaceous magmatism
& back-arc extension

Apennines

Handy et al., simplified from
Schmid et al. 2004, 2008

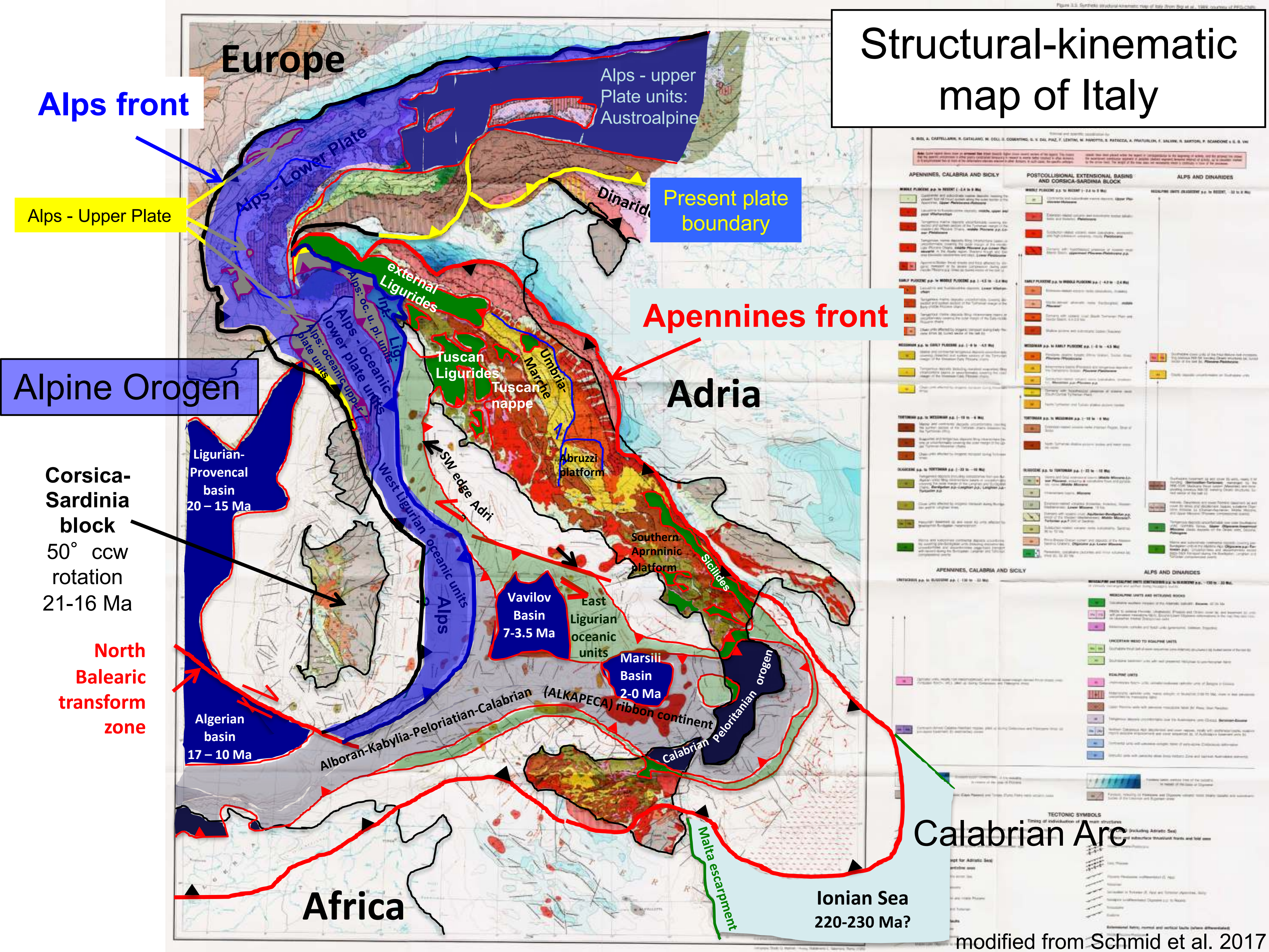


Alps-Apennines switch in subduction polarity



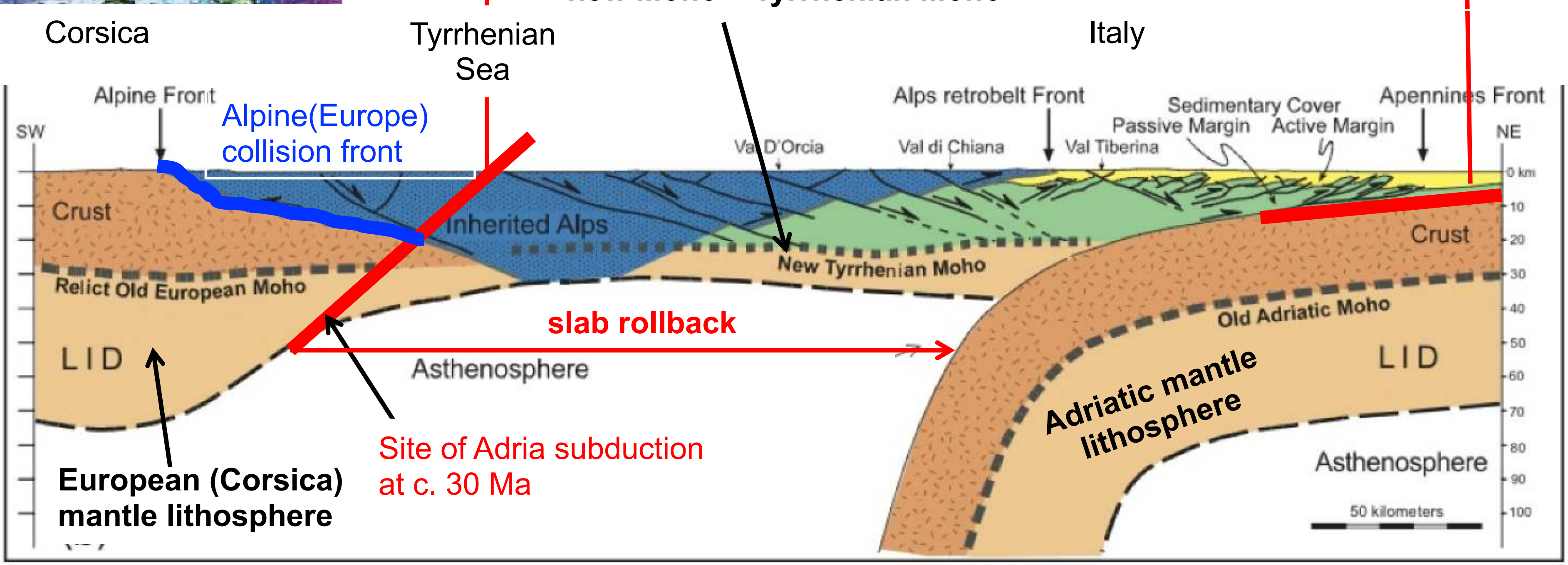
Vignarolli et al 2008

Structural-kinematic map of Italy



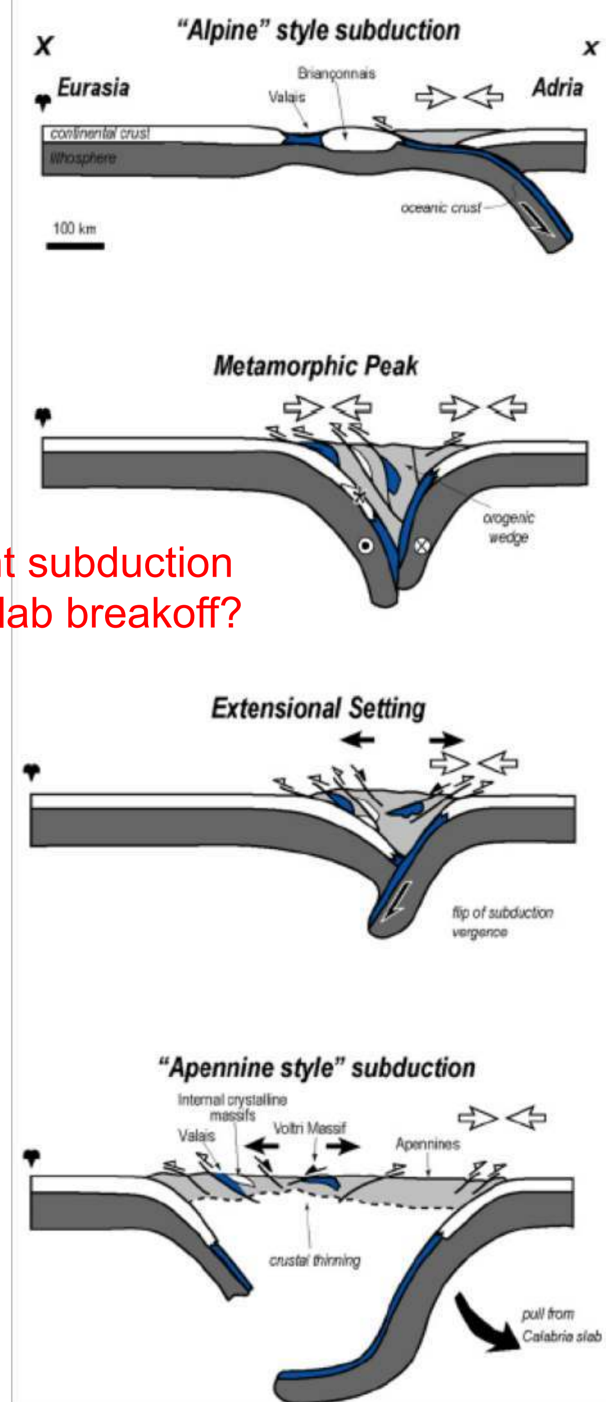
modified from Schmid et al. 2017

Roll-back and delamination in the Apennines



Carminati et al. 2010, *Journal of the Virtual Explorer*

Alps-Apennines switch in subduction polarity in Oligo-Miocene time



94-35 Ma

c. 30Ma

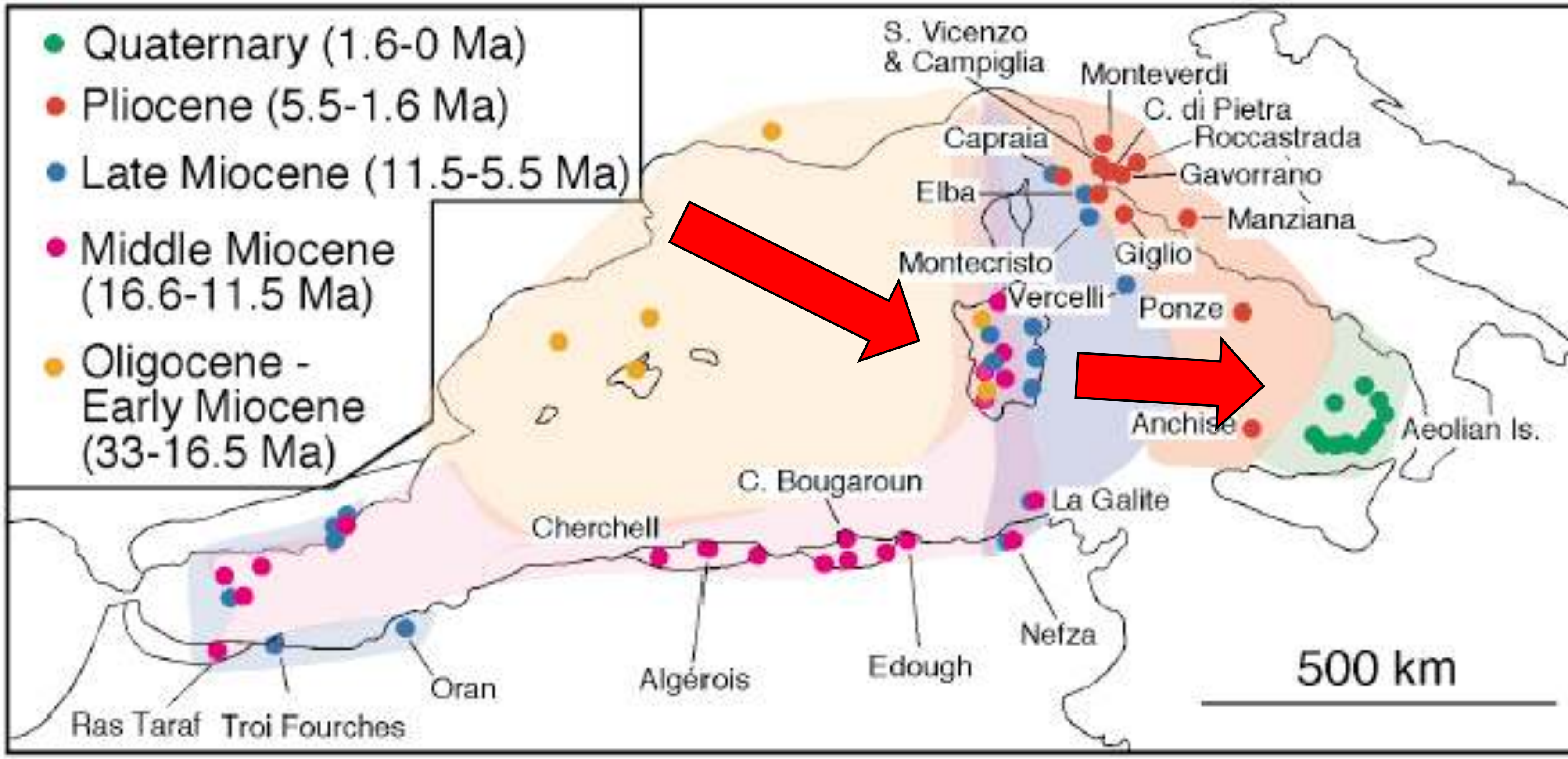
Doubly vergent subduction
or European slab breakoff?

c. 24 Ma

< 22-Ma

Vignarolli et al. 2008
Timing according to Molli et al. 2010

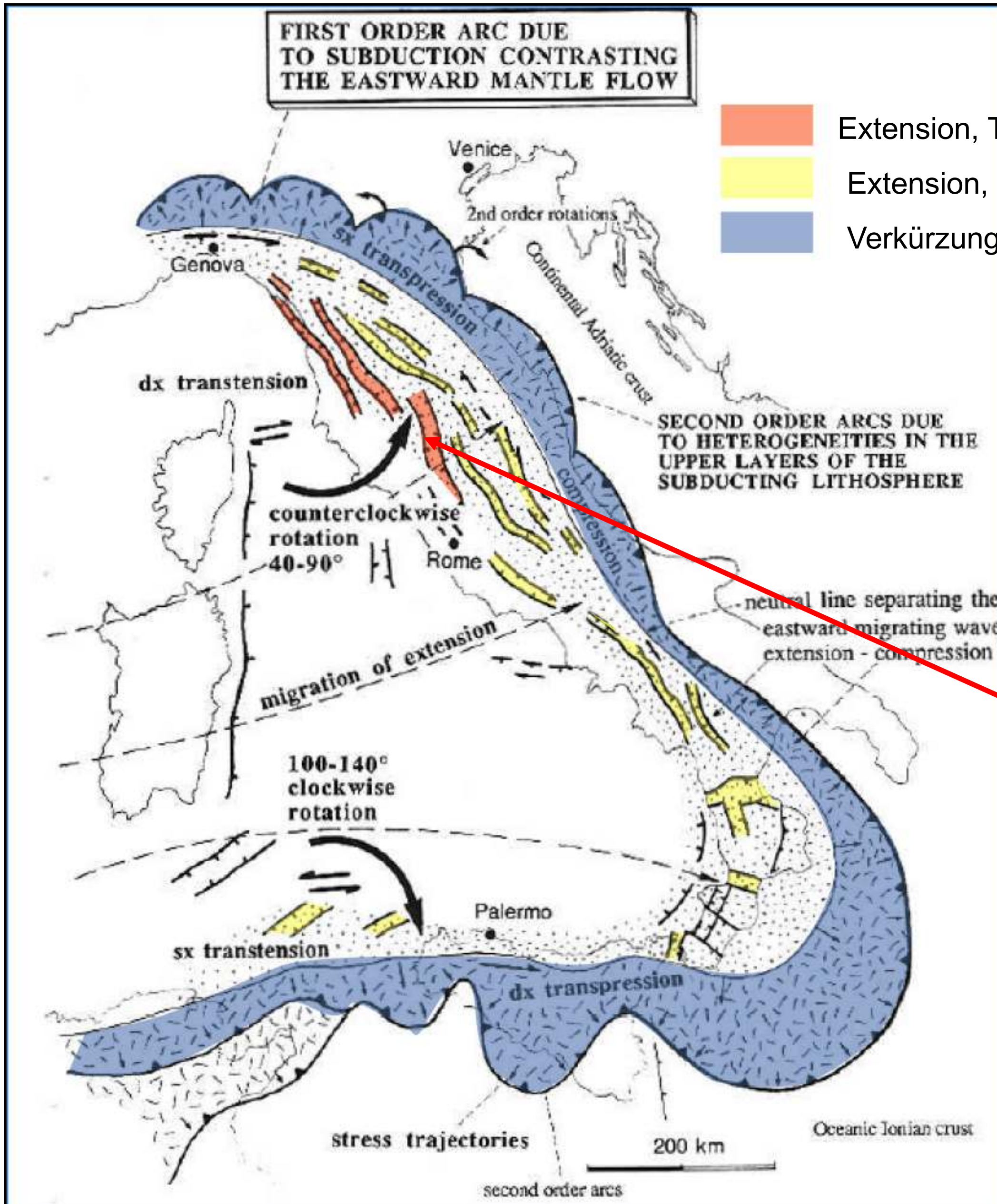
Magmatic record of rollback subduction in the Apennines

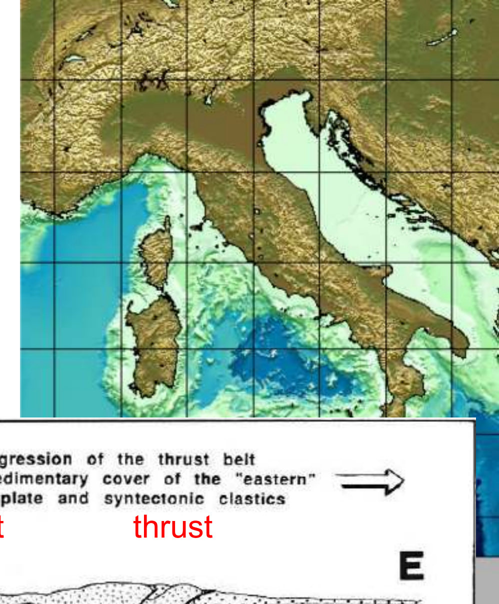


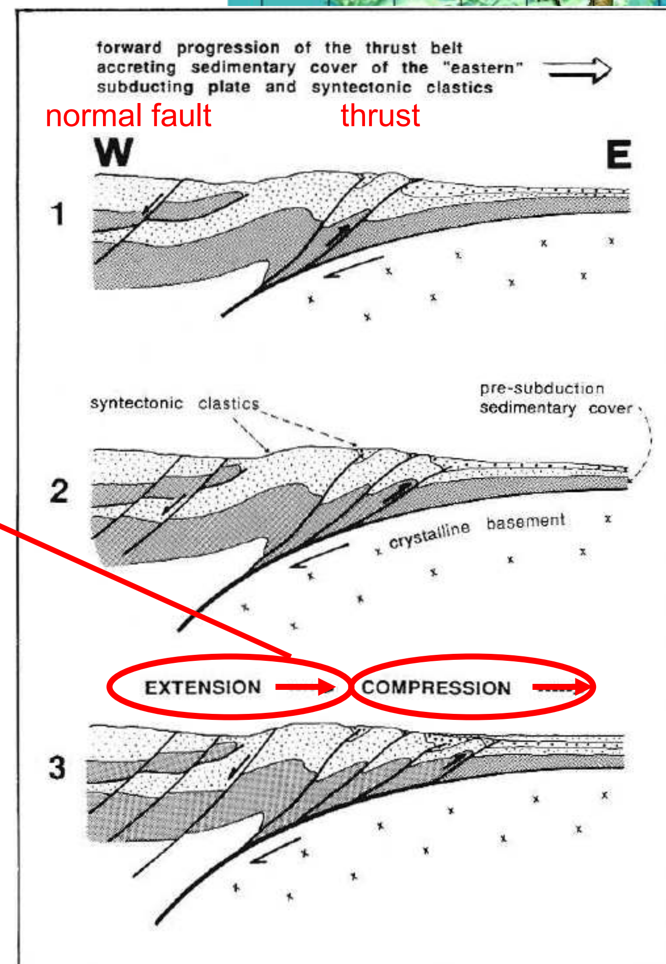
Rosenbaum et al., 2002, *Journal of the Virtual Explorer*, 8, 107-130

Volcanism youngs from Oligo-Miocene in NW (Liguro-Provencal Basin) to Pleistocene in SE (Tyrrhenian Basin) => this tracks the retreat of the Adriatic slab

Extension & shortening in the Apennines

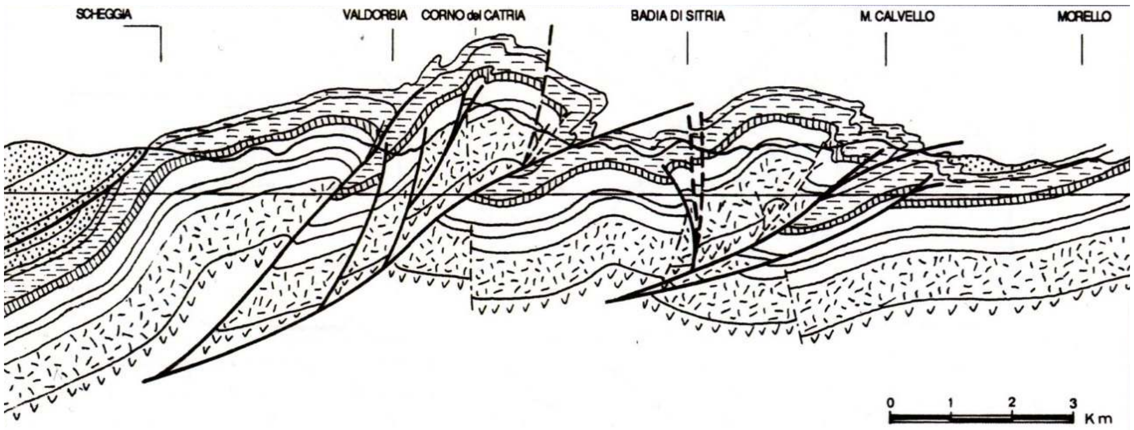




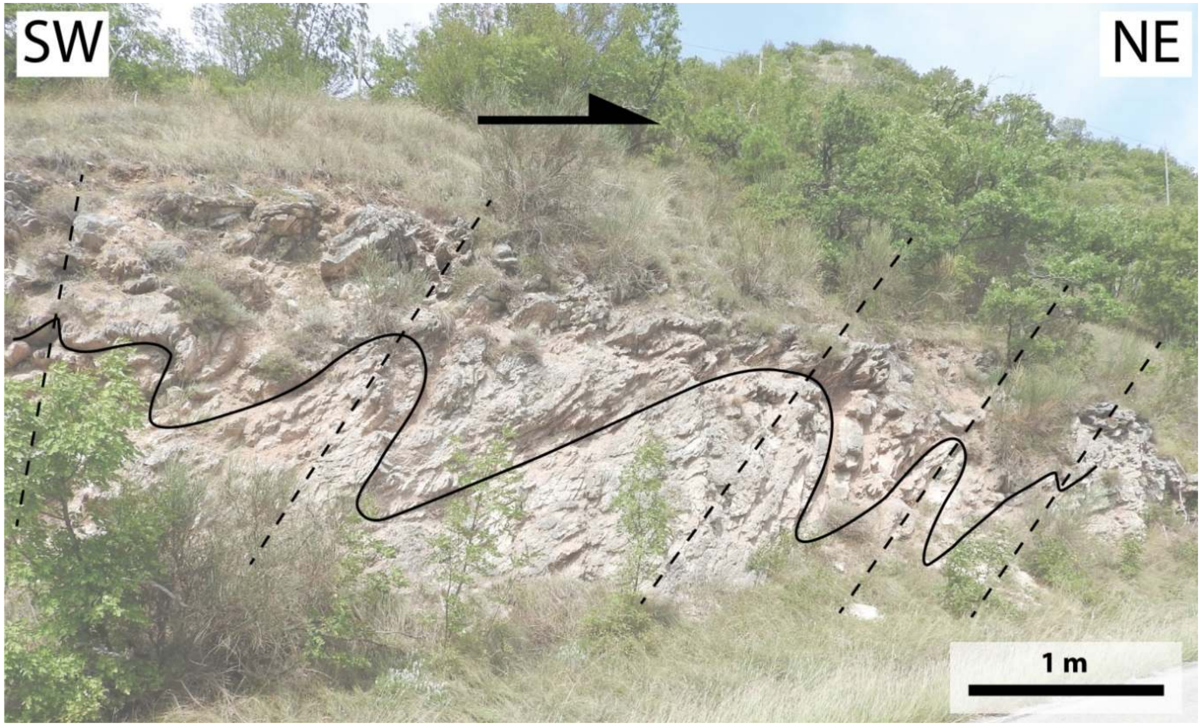


Doglioni, C., 1991, *Terra Nova*

Umbria – Marché fold-and-thrust belt

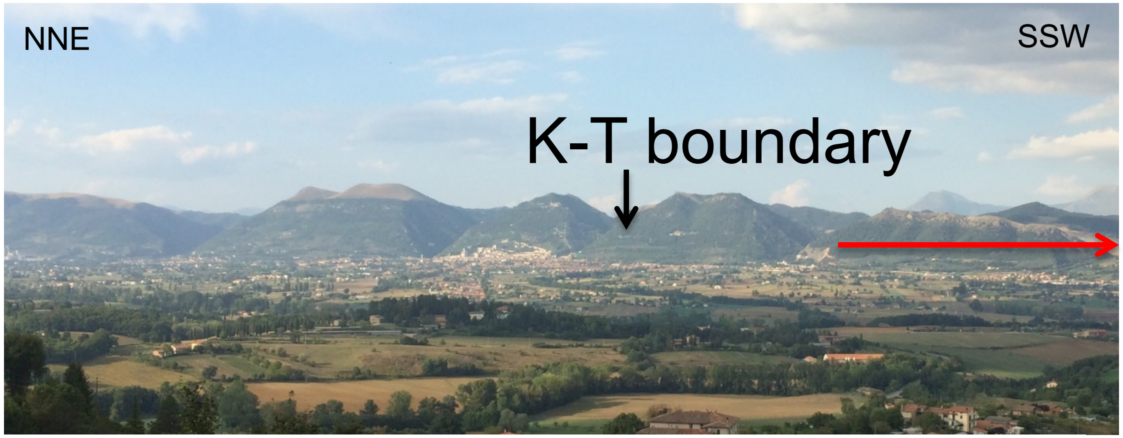


Mio-Pliocene to Pleistocene folding



NE-facing folds (Serra S. Abbondio)

Plio-Pleistocene extension

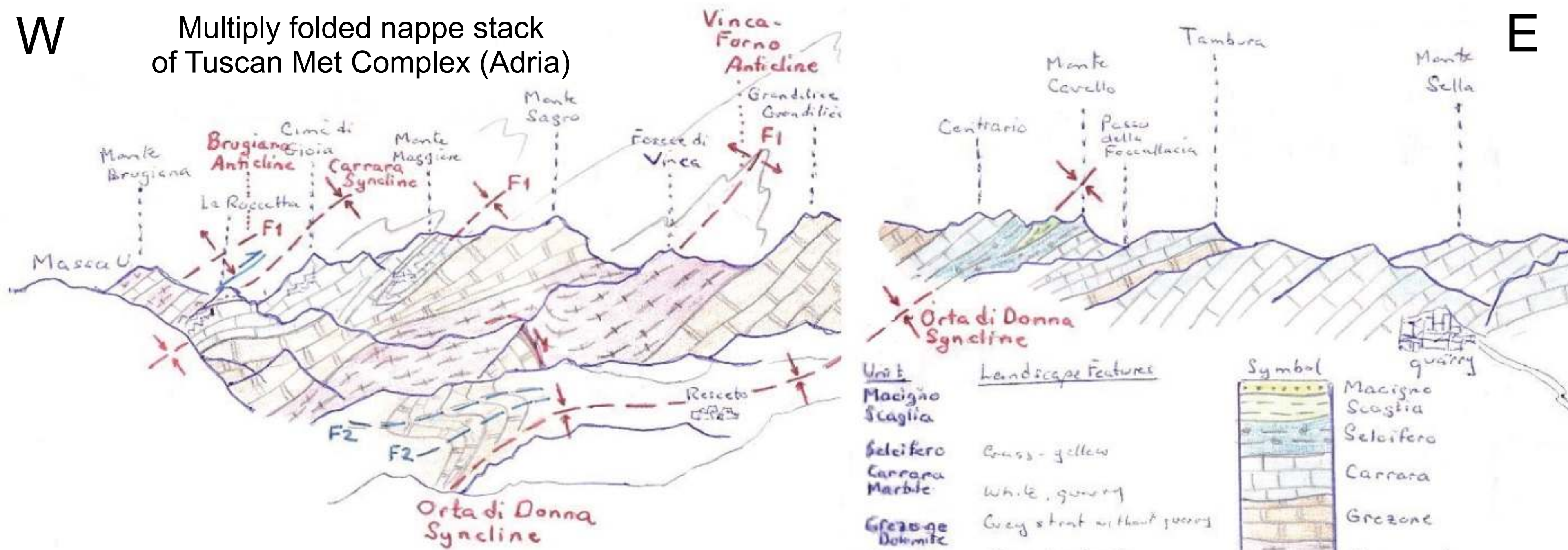


Gubbio Basin

Gubbio high-angle normal fault

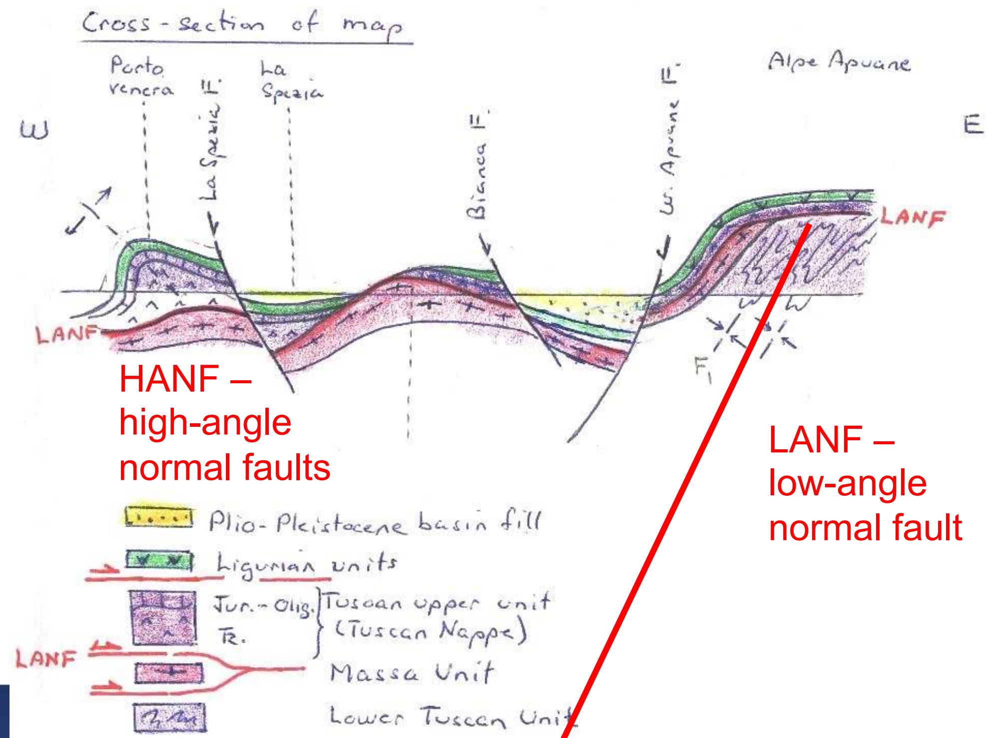
Mio-Plio & Plio-Pleistocene extension

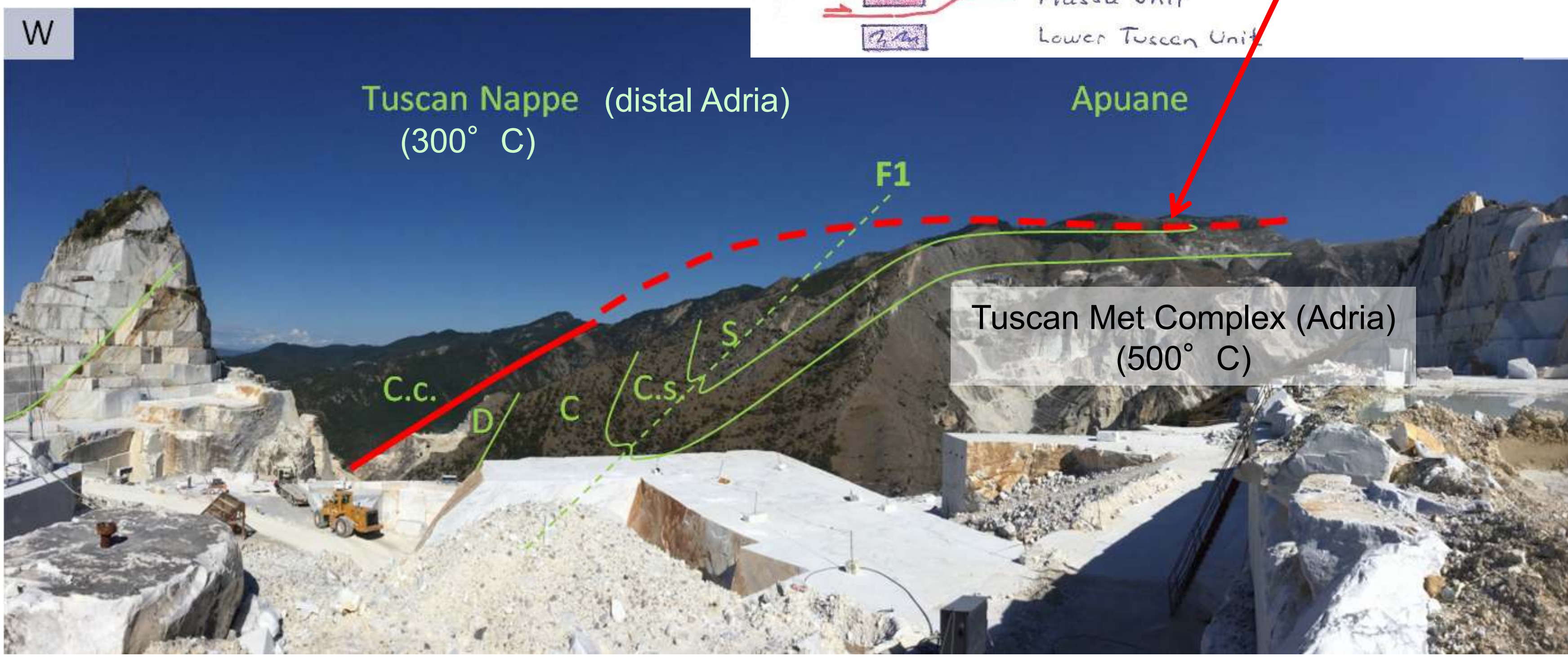
Apennines - Alpi Apuane



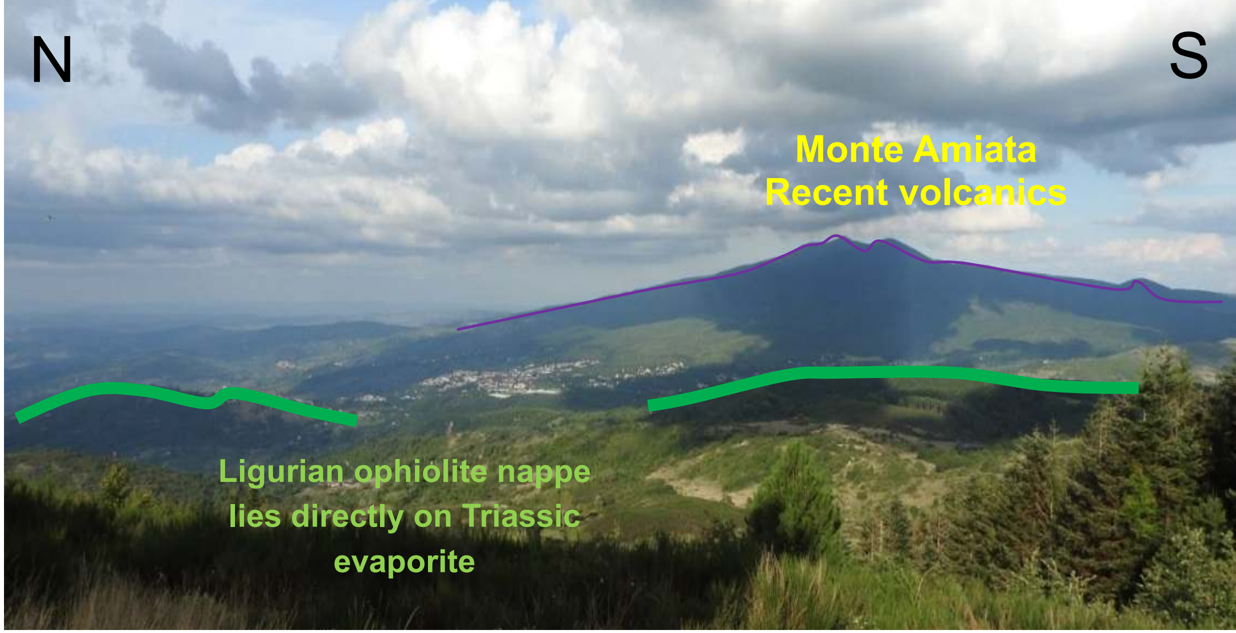
Handy & Le Breton

Apennines – Alpi Apuane

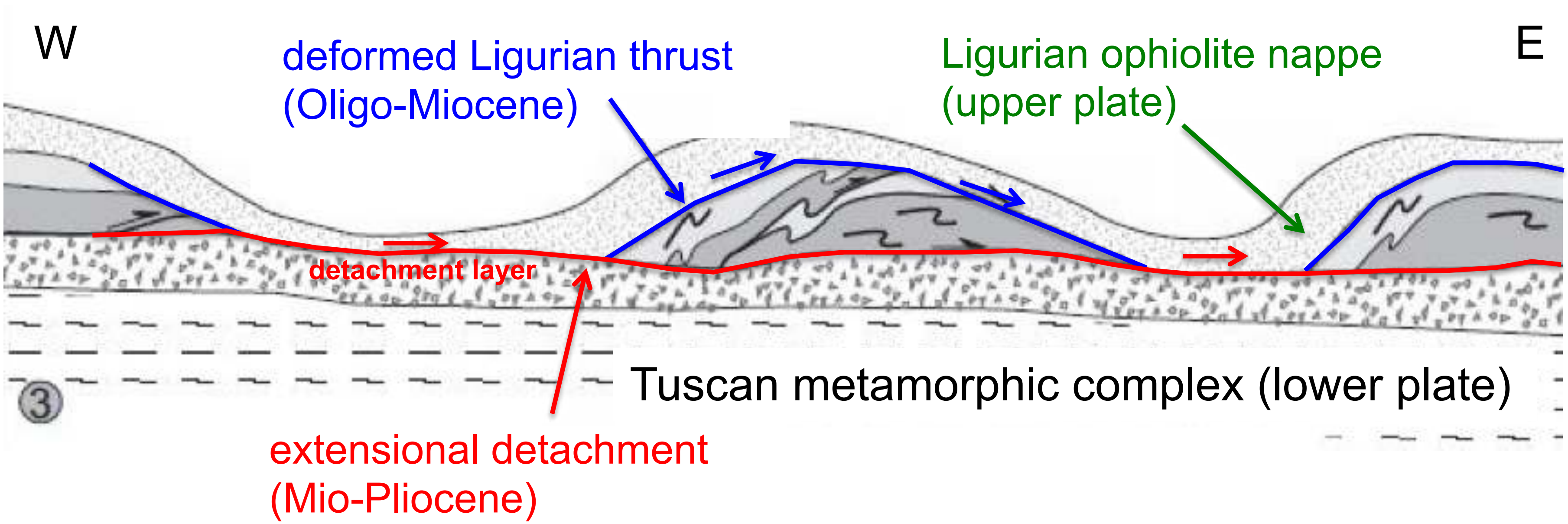




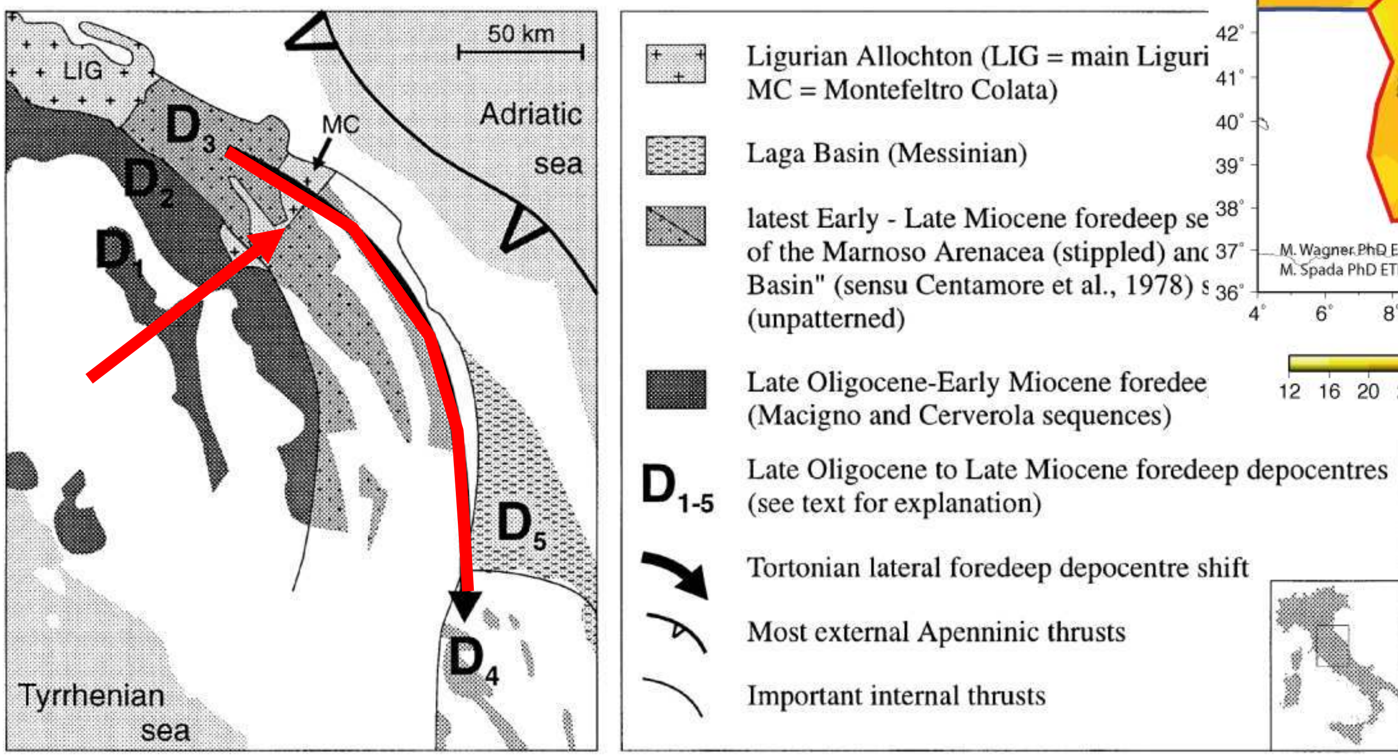
Mio-Pliocene extensional allochthons



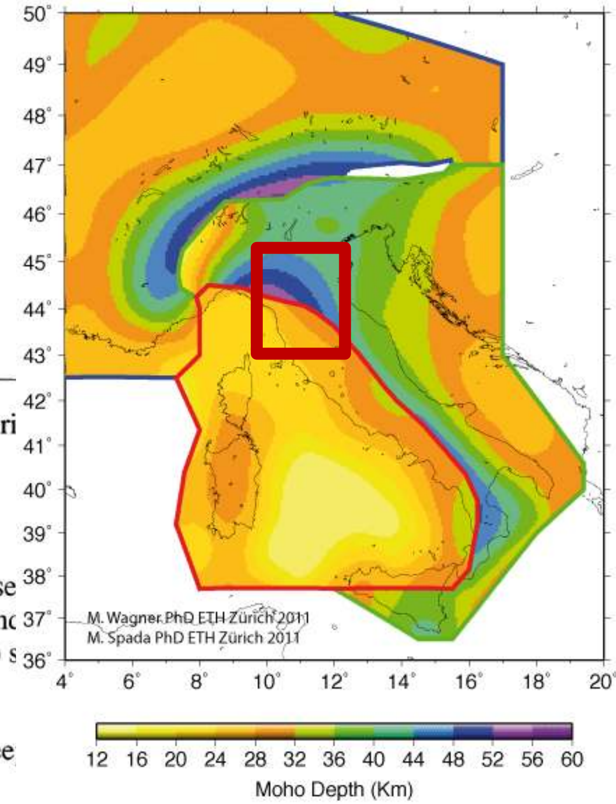
Extensional allochthons of Ligurian & Tuscan nappes



Orogen-normal and –lateral migration of foredeep depocentre



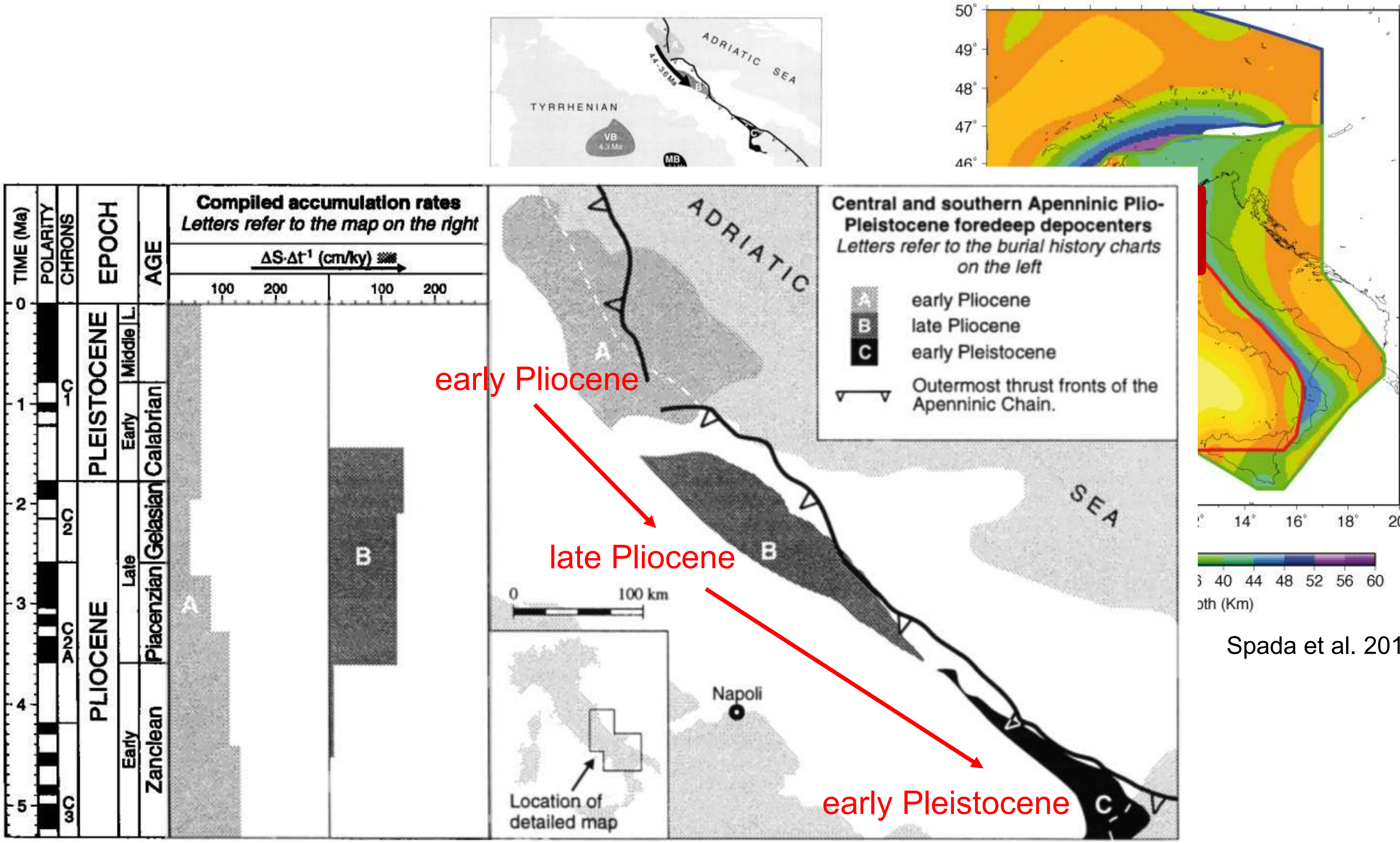
van der Meulen et al. 2000



Spada et al. 2013

This migration interpreted as a response to rollback (orogen-normal) and tearing (orogen-parallel) of the Adriatic slab

Lateral migration of foreland depocentre



Spada et al. 2013

van der Meulen et al. 2000

Foreland basin evolution & slab tearing

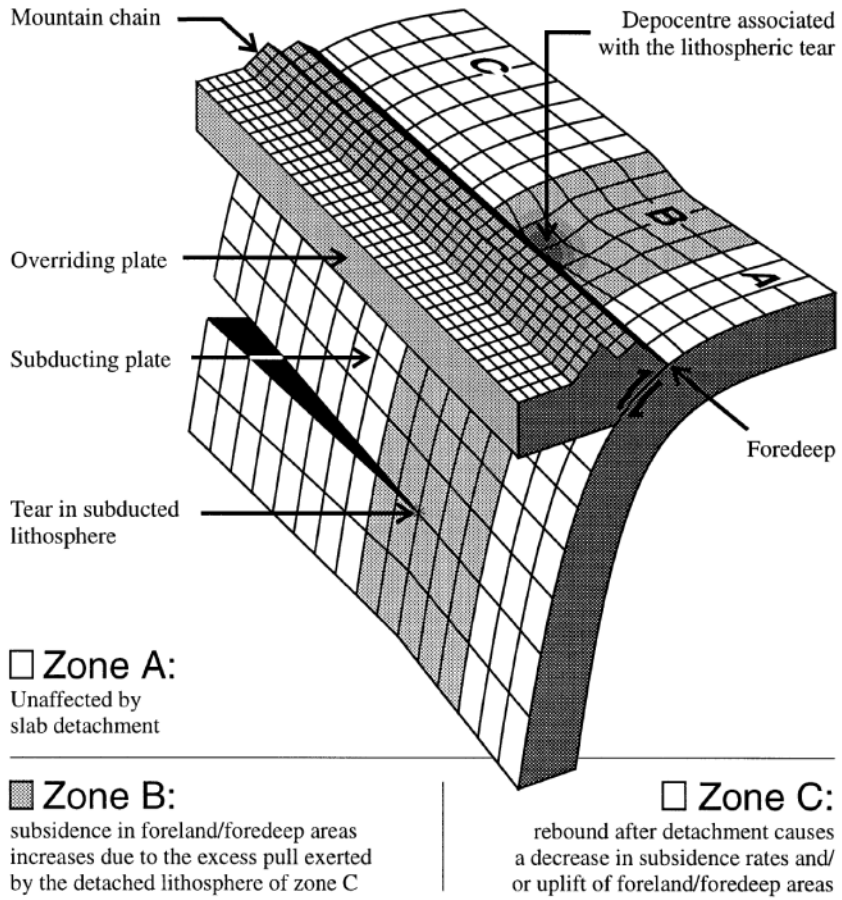
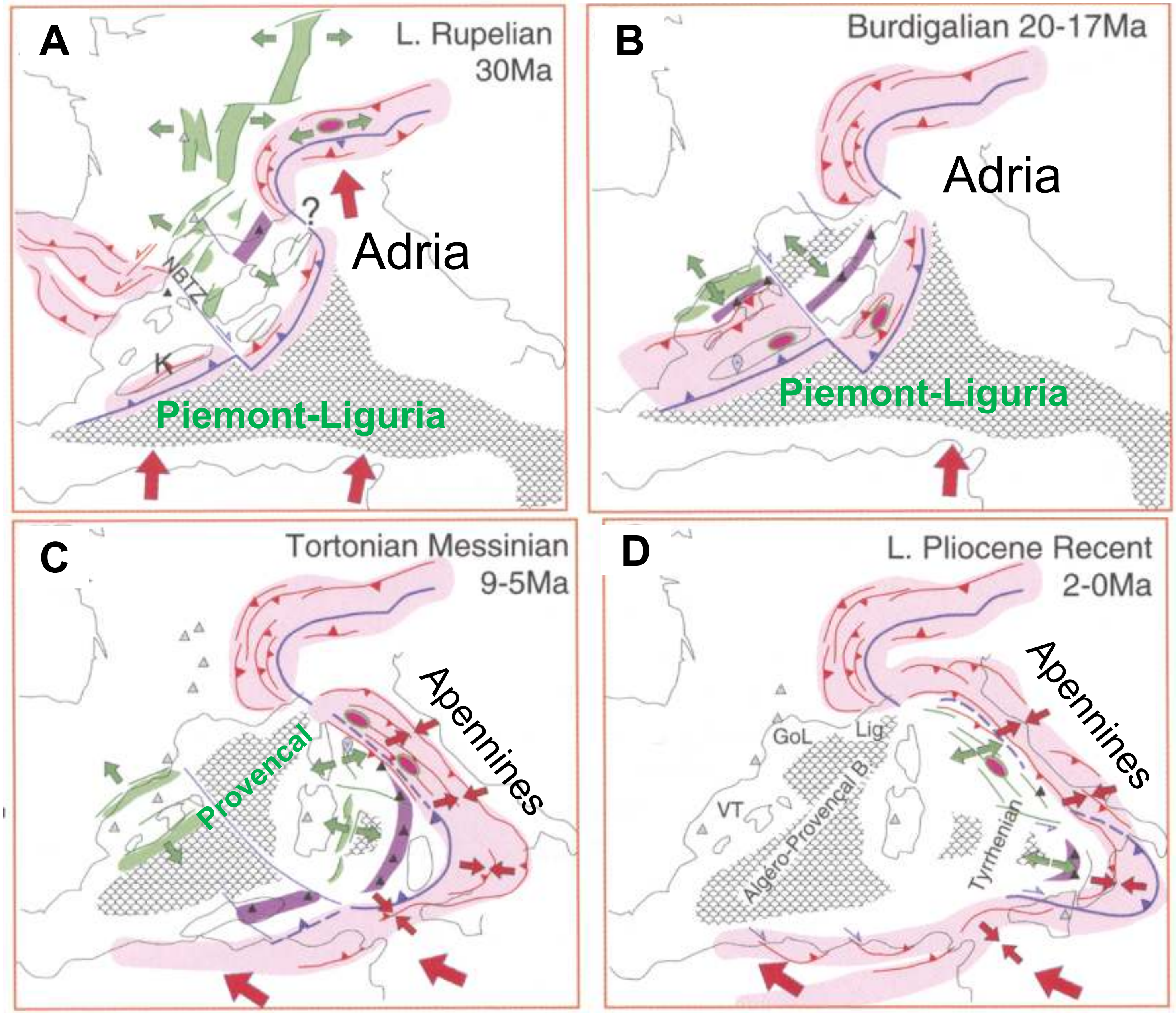


Fig. 1. Graphical representation of the hypothesis of lateral migration of slab detachment (Wortel and Spakman, 1992), and predicted surface effects. Reprinted from van der Meulen et al. (1998) with kind permission of Elsevier Science.

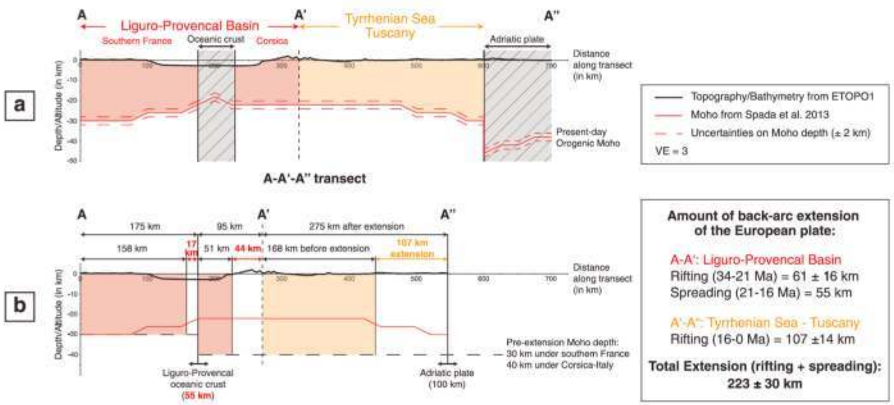
van der Meulen et al. 1998, 1999

Neogene Apenninic rollback subduction



Seranne et al. 1999

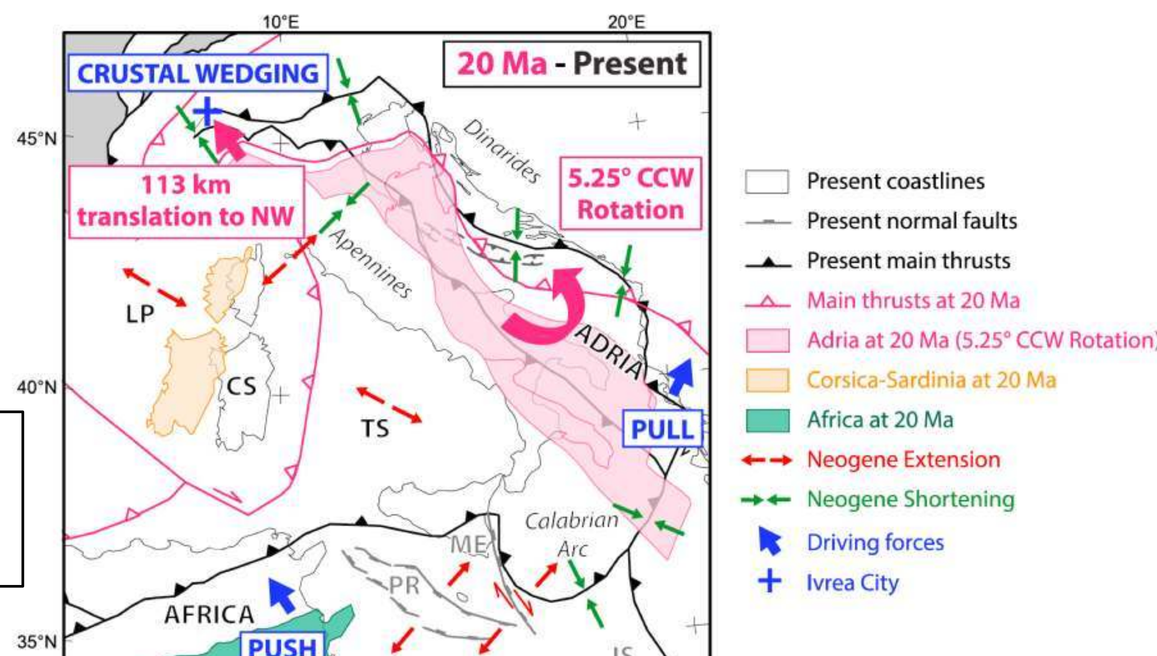
Neogene Adria rotation & Europe-Adria convergence in the Apennines



Upper plate extension (107 km) vs. subduction (115 km)
=> within error, **E-A convergence is near 0**

Subduction (115 km) > shortening (30-60 km, thick-skin)
=> Lots of **tectonic erosion**

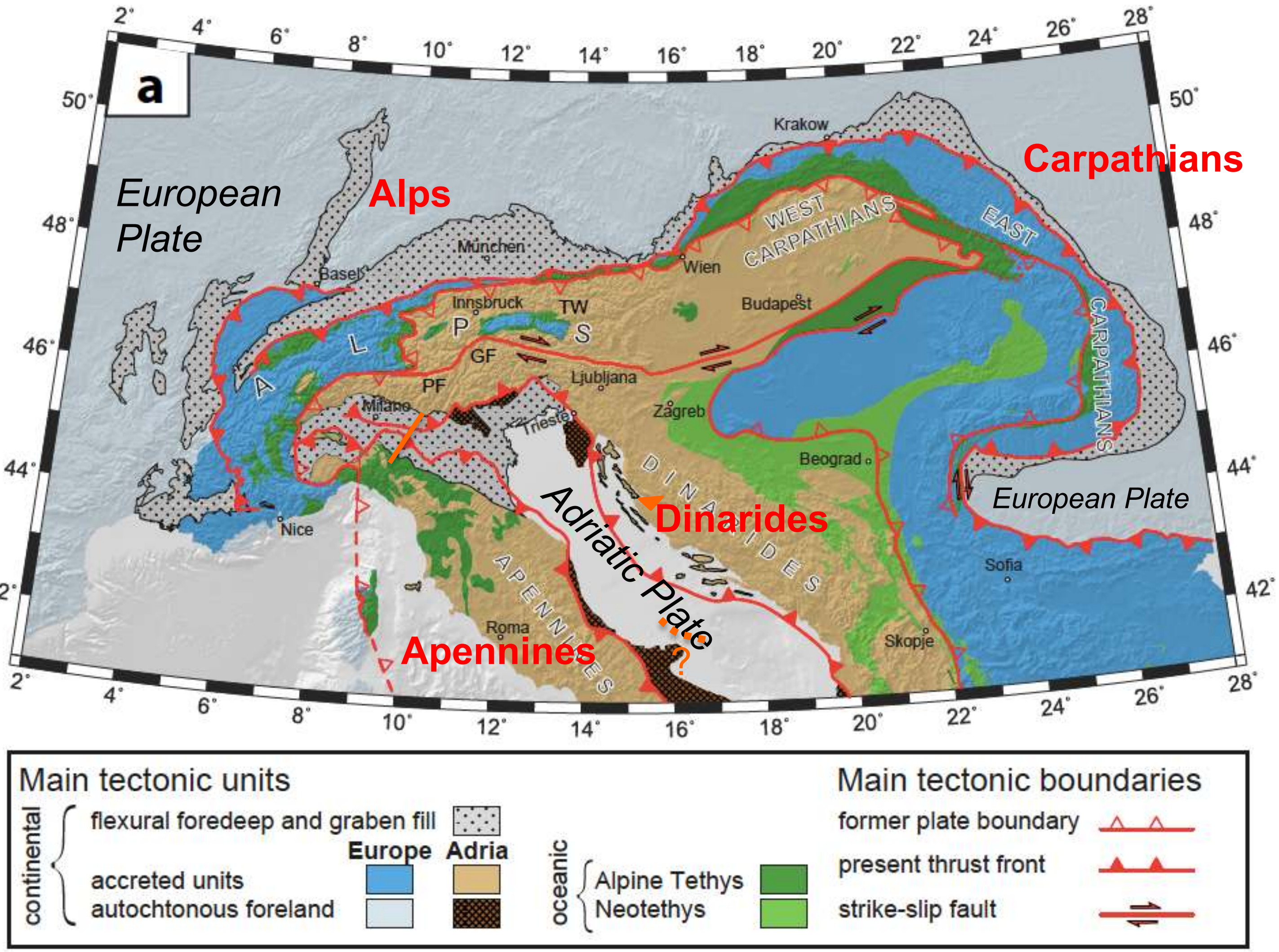
Areal balancing of crust along a section Europe-Corsica-Apennines



Adria has rotated counter-clockwise with respect to Europe by some 5° in the past 20 Ma

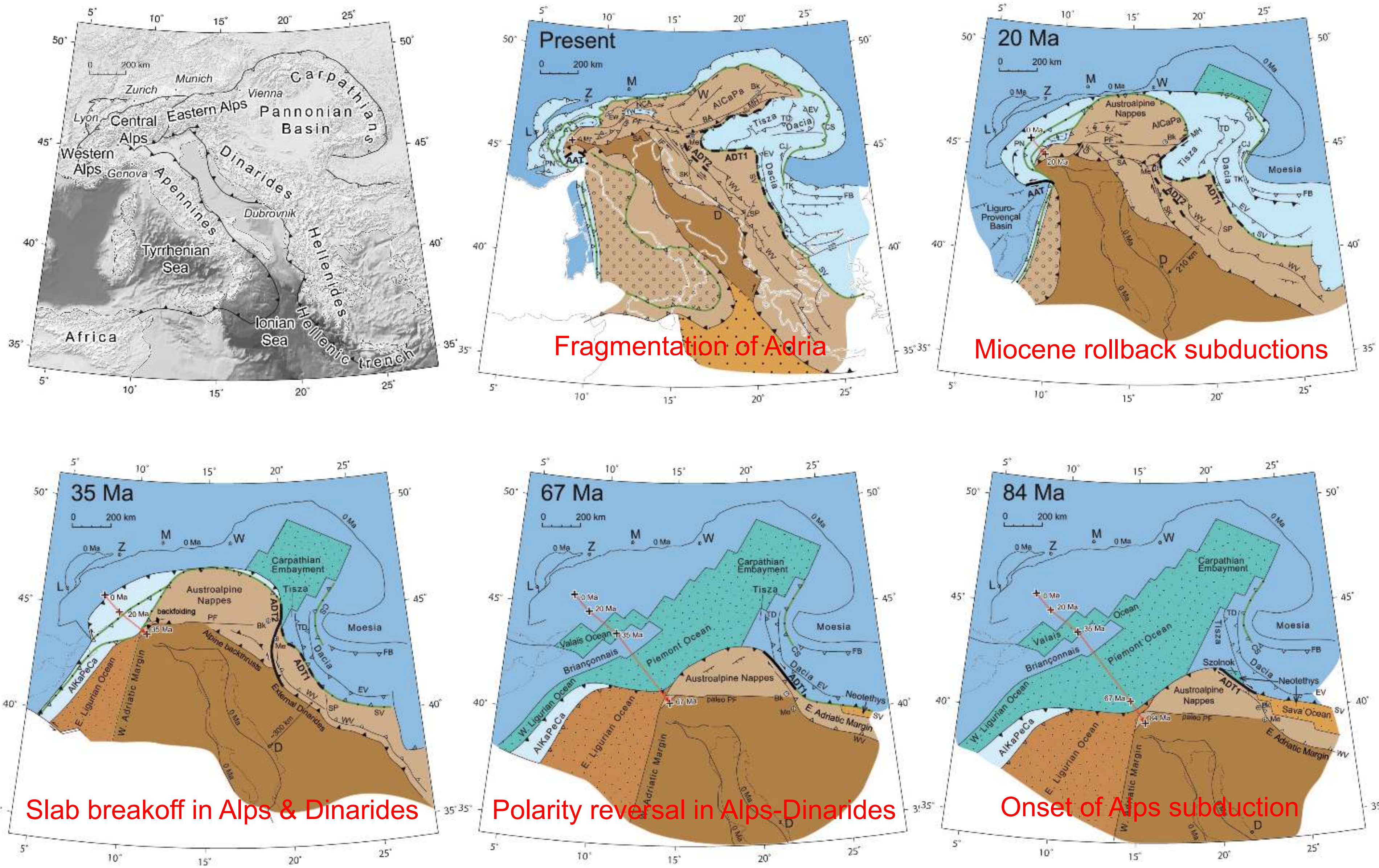
Le Breton et al. 2017

Synopsis



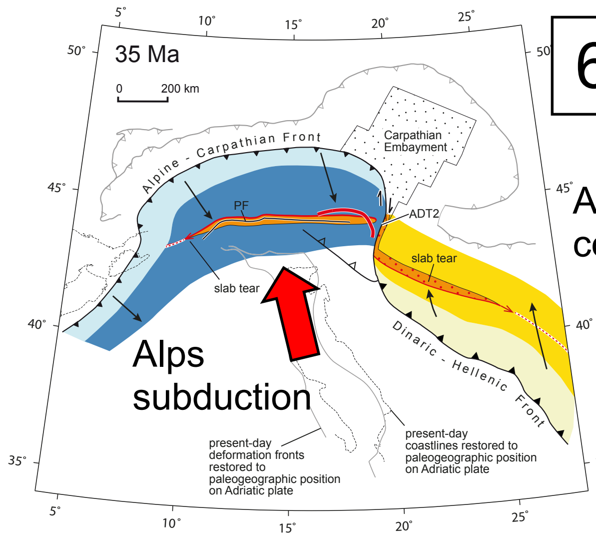
a
European Plate
Alps
Carpathians
WEST CARPATHIANS
EAST CARPATHIANS
Krakow
München
Basel
Wien
Budapest
Innsbruck
TW
P
S
L
A
GF
PF
Ljubljana
Milano
Trieste
Zagreb
Beograd
DINARIDES
Dinarides
Adriatic Plate
European Plate
Nice
Sofia
APENNINES
Apennines
Roma
Skopje
Main tectonic units
continental
flexural foredeep and graben fill
Europe
Adria
accreted units
autochtonous foreland
oceanic
Alpine Tethys
Neotethys
Main tectonic boundaries
former plate boundary
present thrust front
strike-slip fault

Evolution of the Alpine chains



Handy et al. 2015

Slab motion maps & possible driving forces



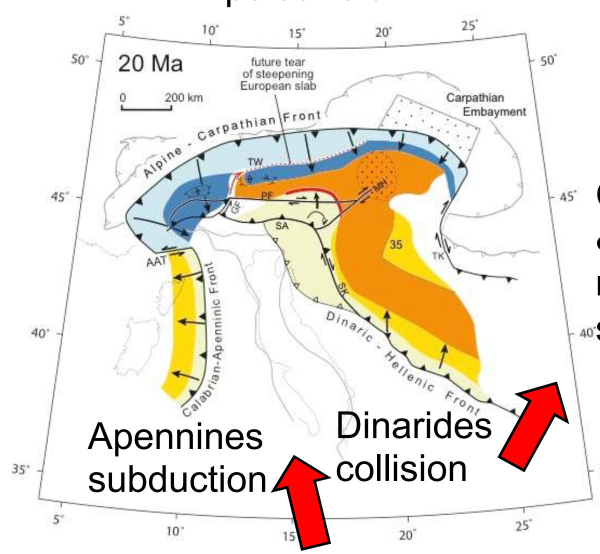
European slab/trench suction ?

67–35 Ma

Alps & Dinaride collisions

Slab breakoff events in Alps & Dinarides

Alps collision



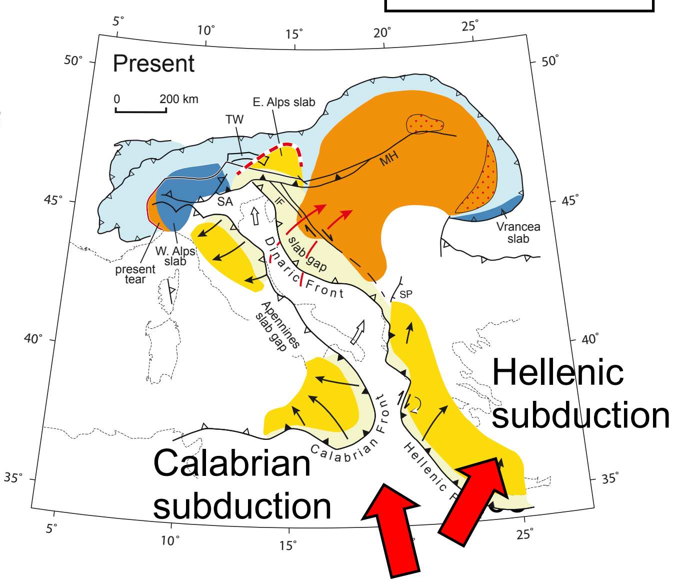
Nubia “push” & Aegean slab “pull” ?

35-20 Ma

Carpathian & Apenninic rollback subductions

Miocene „revolution“

Present

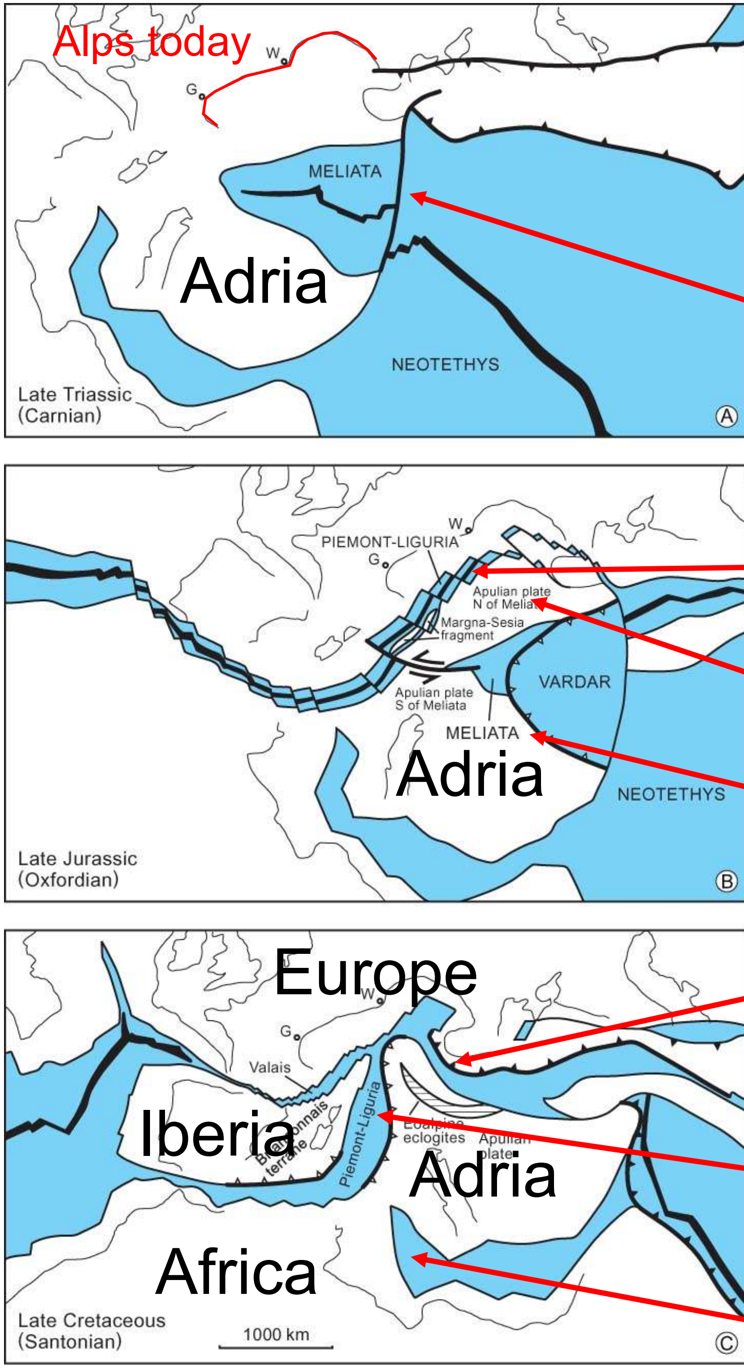


Handy et al. 2015

Mesozoic history

of the greater Tethyan domain

Schmid et al. 2004



Spreading of Neotethys

Spreading in Valais Basin

Future Eoalpine orogen

Obduction of Neotethys in Dinarides

Adria-Europe suturing in Dinarides

Closing of Piemont-Liguria

Southern Neotethys remains open

Summary

The Adriatic plate is surrounded by differently aged mountain belts:

- Dinarides - obduction from mid-Jurassic-early Cretaceous, collision from late Cretaceous-Oligocene
- Alps – late Cretaceous-Paleogene (86-35 Ma), collision Oligo-Miocene (35-10 Ma)
- Carpathians – Mio-Pliocene (24-11 Ma)
- Apennines – Mio-Pliocene (16-5 Ma)

Orogenic style contrasts around the Adriatic plate

- Alps – „hard“ collision (lots of accretion of lower plate, indentation), slabs well preserved, deep subduction and exhumation of both continental and oceanic crust
- Apennines & Carpathians – rollback subduction, soft collision, slabs
- Dinarides – modest exhumation

Summary

Slab breakoff occurred later in the younger orogens (Apennines, Carpathians) than in the older ones (Alps, Dinarides)

• Alps	34-28 Ma
• Dinarides	37-24 Ma
• Apennines	5-2 Ma
• Carpathians	22 Ma-Present (Vrancea slab)

Slab breakoff in Alps and Dinarides probably contributed to initiating rollback subduction in the Apennines and Carpathians

Summary

Geological evidence for rollback subduction

• Dinarides	Neogene basins bounded by faults, some of which reactivated Paleogene thrusts; extension generally youngs NE-to-SW, i.e., from internal to external Dinarides
• Apennines	NW-to-SE younging of foredeep sedimentation, arc volcanism and backarc basin subsidence from 35 Ma to the present
• Carpathians	WNW-to-ESE younging of foredeep sedimentation, volcanism and basin subsidence in the upper plate from 22 Ma to Recent (Transylvanian Basin)

Summary

Geological evidence for slab tearing and breakoff

- Alps: Calc-alkaline magmatism at 34-28 Ma, transition from underfilled foredeep (flysch) to overfilled foreland basin (molasse) basin at 32-35 Ma in Central Alps, at 20-18 Ma in Eastern Alps
- Dinarides: 37-24 Ma calc-alkaline magmatism, onset of E-W Neogene extension (core complexes and basins)
- Apennines: orogen-parallel, NW-to-SE younging of foredeep sedimentation in N Apennines
- Carpathians: clockwise migration of foredeep depocenter around the Carpathian arc from 17 Ma to present (Vrancea slab)