Understanding the Alpine Mediterranean chains

How we go from observations to mountain-building processes

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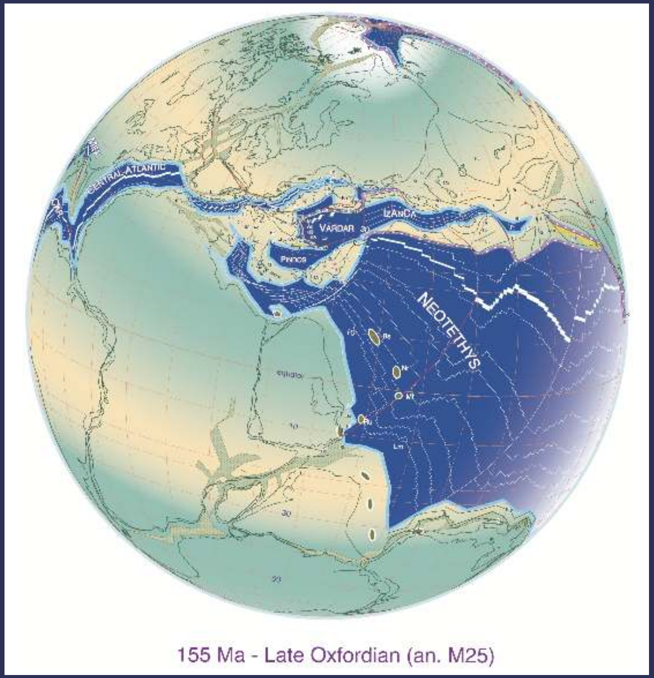
How is orogenic history reconstructed ?

The scale of rocks at present

=>

The scale of continents & oceans in past



Stampfli et al. 2004

- Time
- Space
- Motion

Maps

- Geologic
- Tectonic
- Metamorphic
- Geodetic
- Paleogeographic

Geologic map of the Central Alps

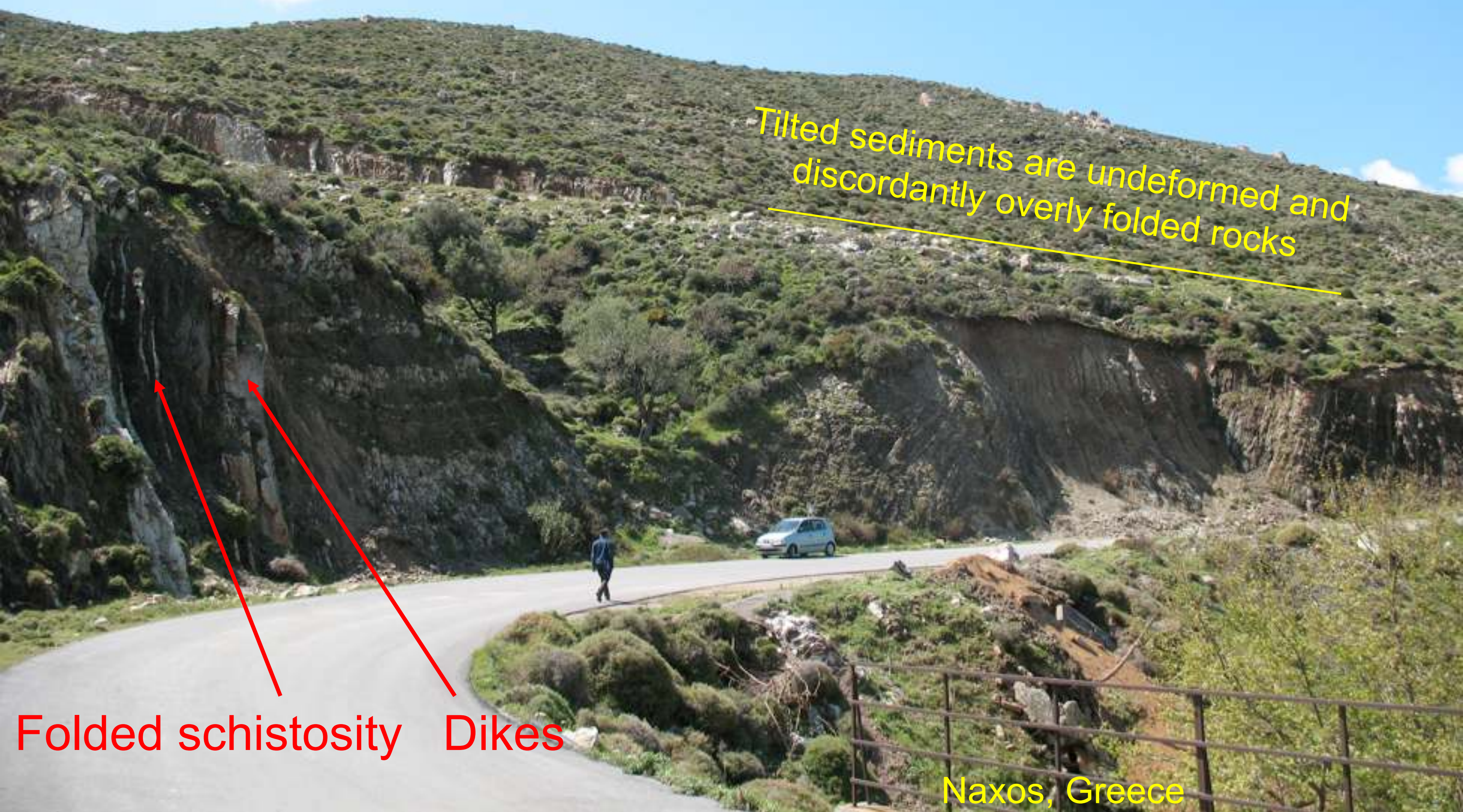
- Large-scale geologic maps show age of rock units
- Small-scale geologic maps show lithologies

Methods for constraining Time

- Biostratigraphy
- Magnetostratigraphy
- Isotope Geochemistry

Dating deformation with structural relationships

Age of deformed and undeformed strata
bracket age of the deformation




Dikes cut schistosity, ergo they must be younger
Naxos, Greece

Interpreted sequence of events

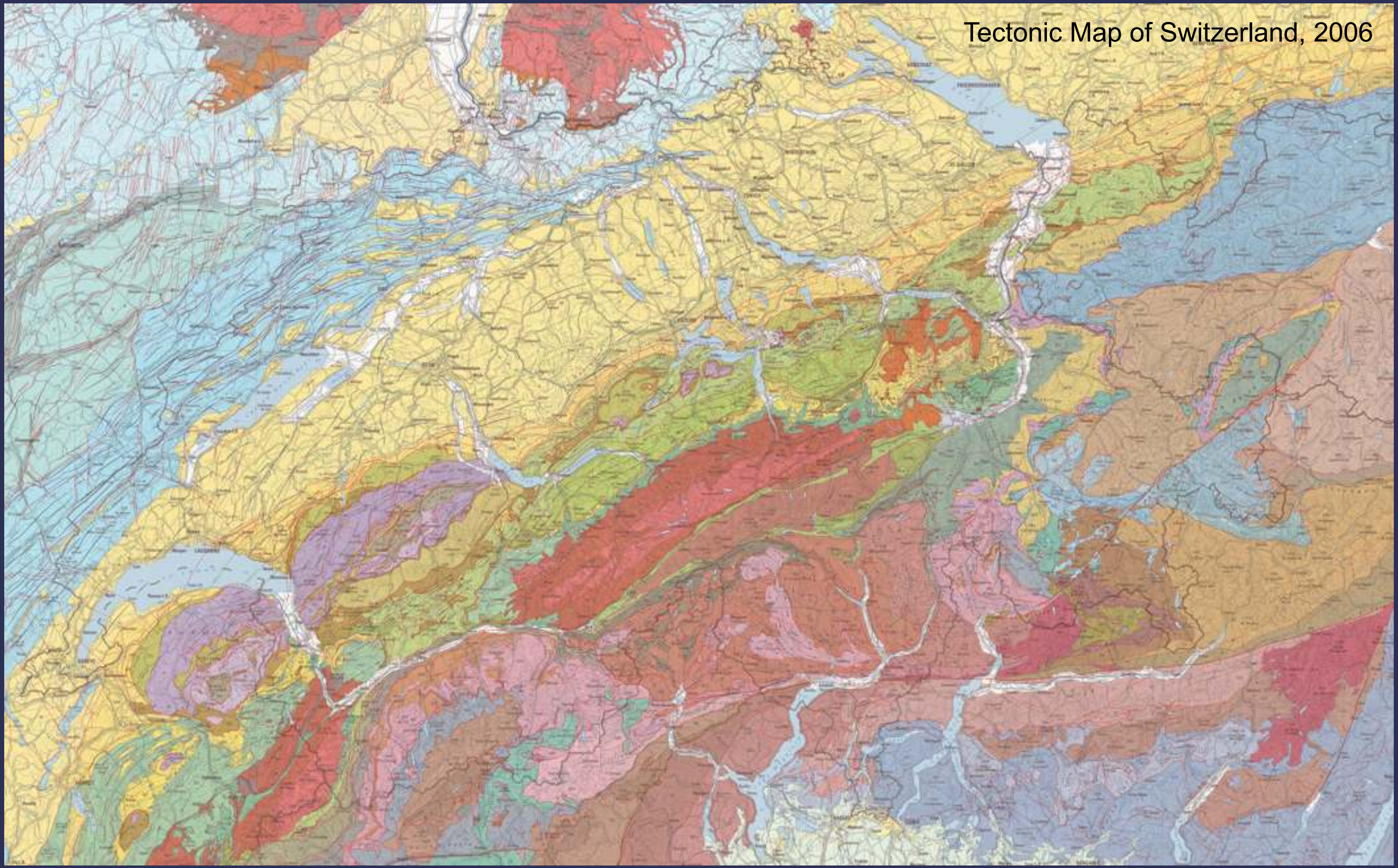
1. Folding and shearing (greensch f. schistosity)
2. Dike intrusion
3. Sedimentation
4. Tilting

Dike intrusion at 15 Ma (U-Pb on magmatic zircons)
Sedimentation at 12,000 yrs (fauna)

- Folding > 15 Ma (depositon of gravel, minimum age)
- Tilting < 12,000 yrs

Problem: Age brackets provided by dikes and sediments may be too wide to be of use, e.g., what happe

Tectonic map of the Central Alps

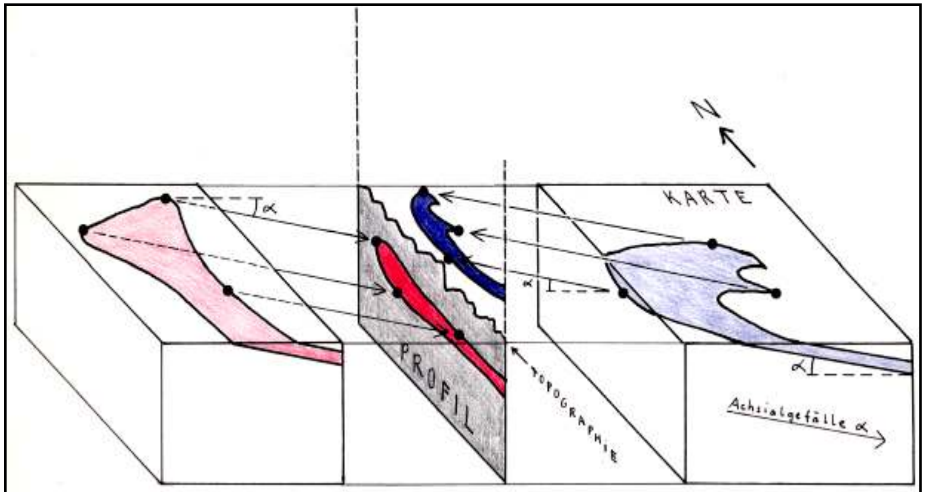


Tectonic maps show rock units
with common motion histories

Combining surface and deep structure

Projecting surface geology for the uppermost 20 km

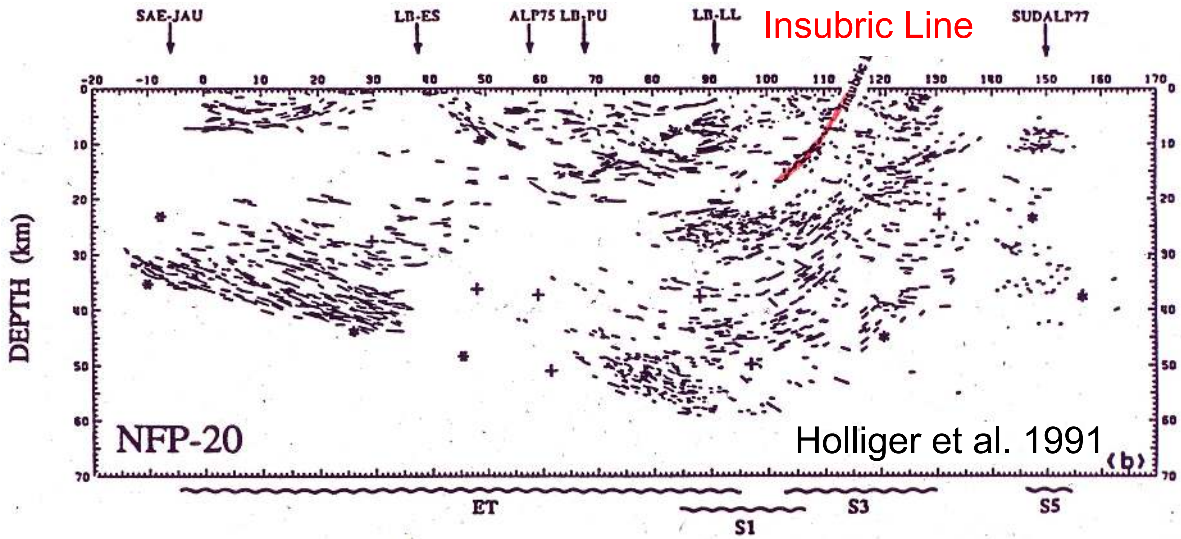
Bigi et al. 1989



from S.M. Schmid

Seismology > 20 km

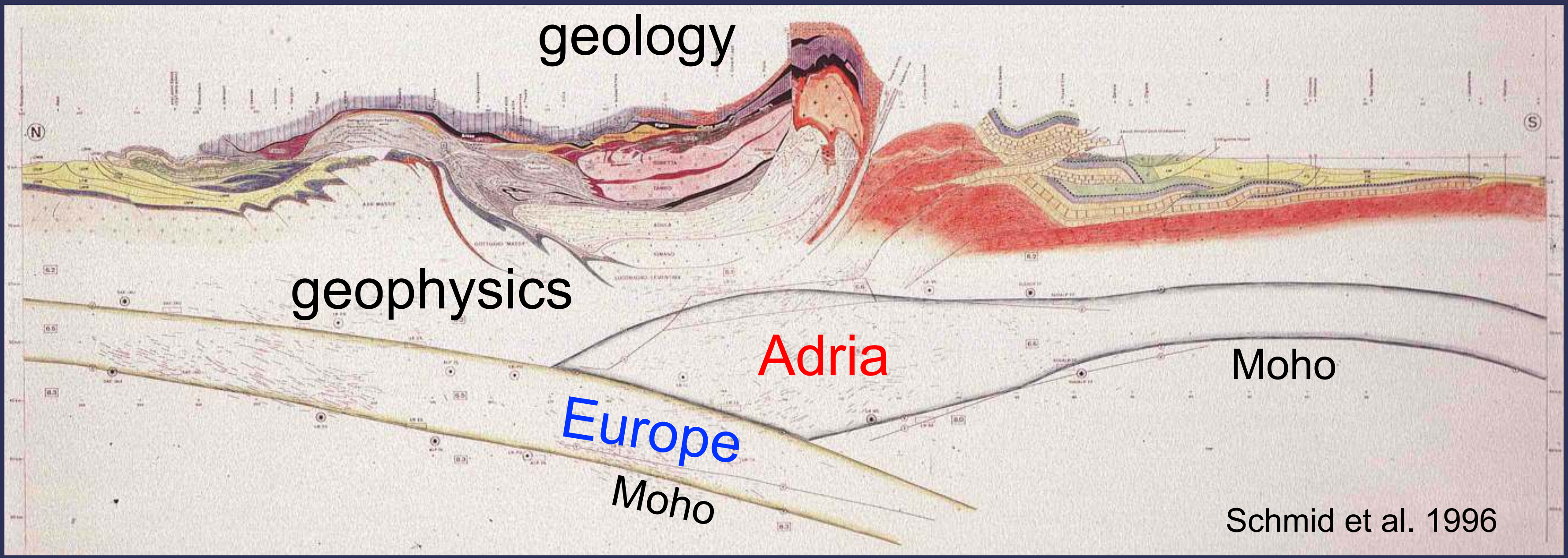
active-source seismology

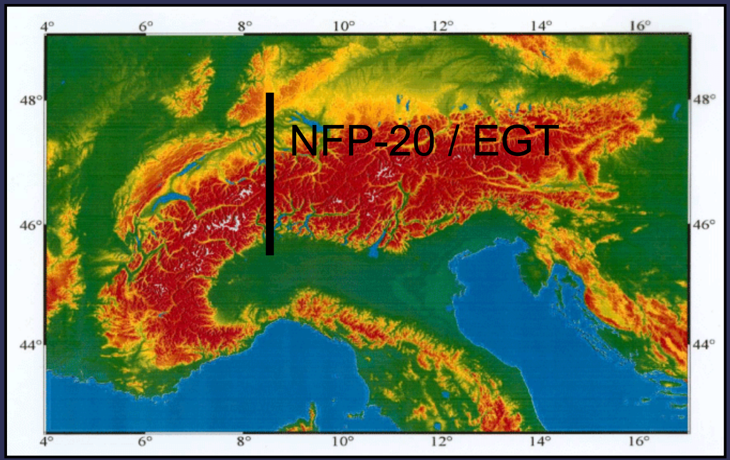


Holliger et al. 1991

=> difficult to image steep structures

Example - integrated cross section of the Alps





Physical Conditions of Subduction & Exhumation

- Temperature evolution
- Pressure, Differential stress
- Fluid composition

Petrological methods:

- Geothermometry, geobaromtery
- Phase equilibria
- Fluid inclusions

Metamorphic conditions

kyanite oriented and stretched parallel to schistosity
=> mineral grew before or during shearing

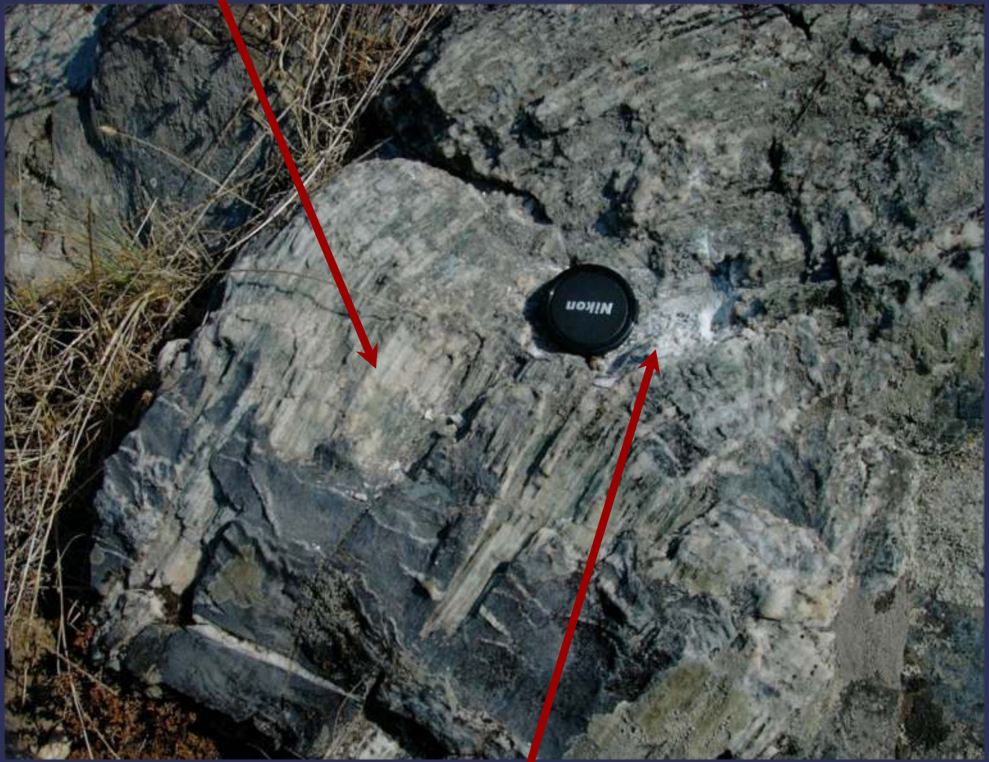
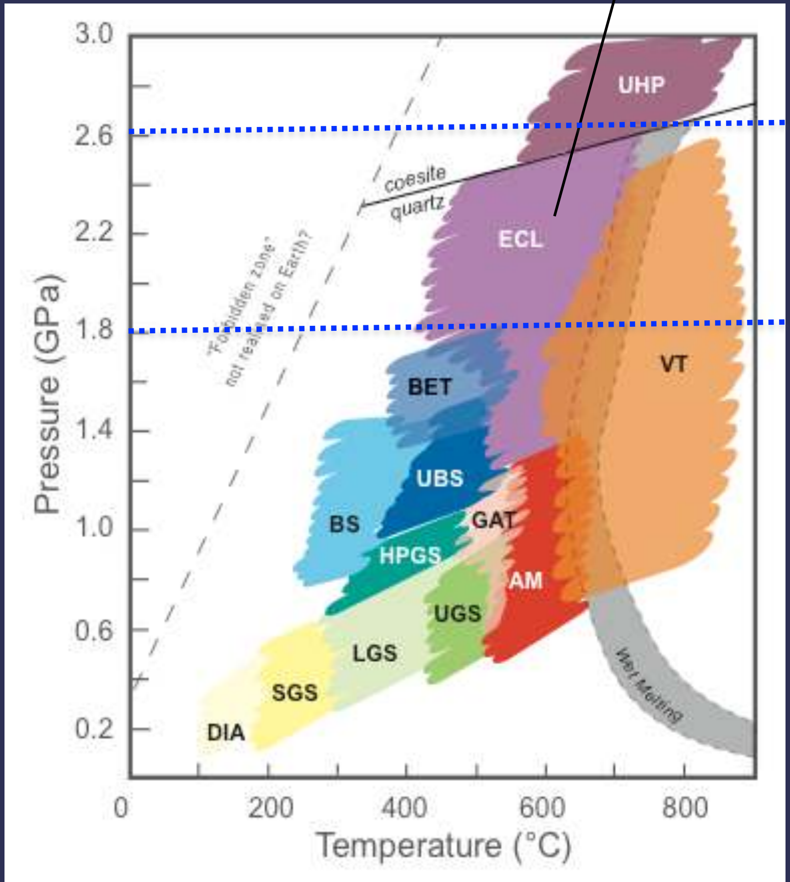


Photo from R. Bousquet

*Fibers of **carpholite + quartz***

High pressure



72 km

54 km

Structural & metamorphic overprinting

Blueschist-facies protolith

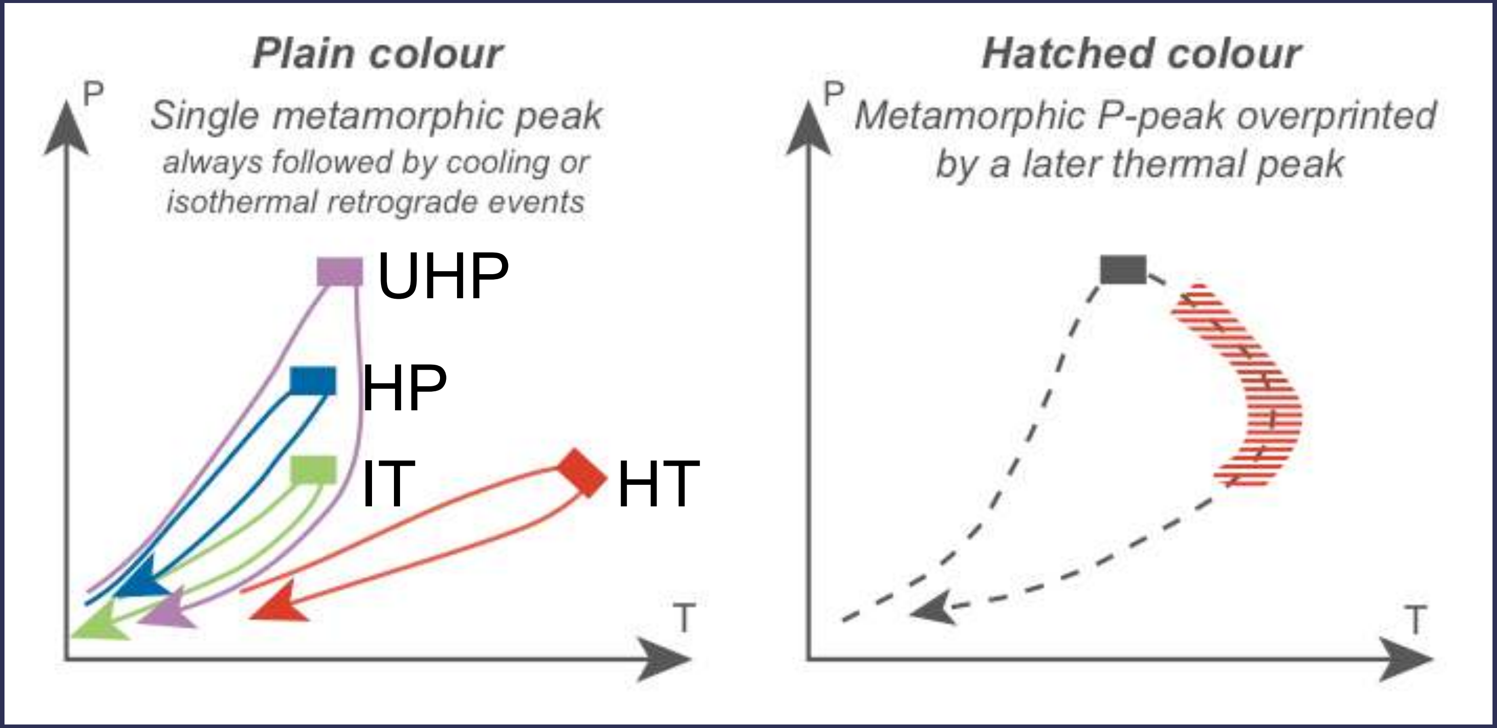
<u>Assemblage</u>:
- garnet
- lawsonite
- glaucophane
- white mica
- quartz

Ile de Groix, Brétagne

Greenschist-facies overprint

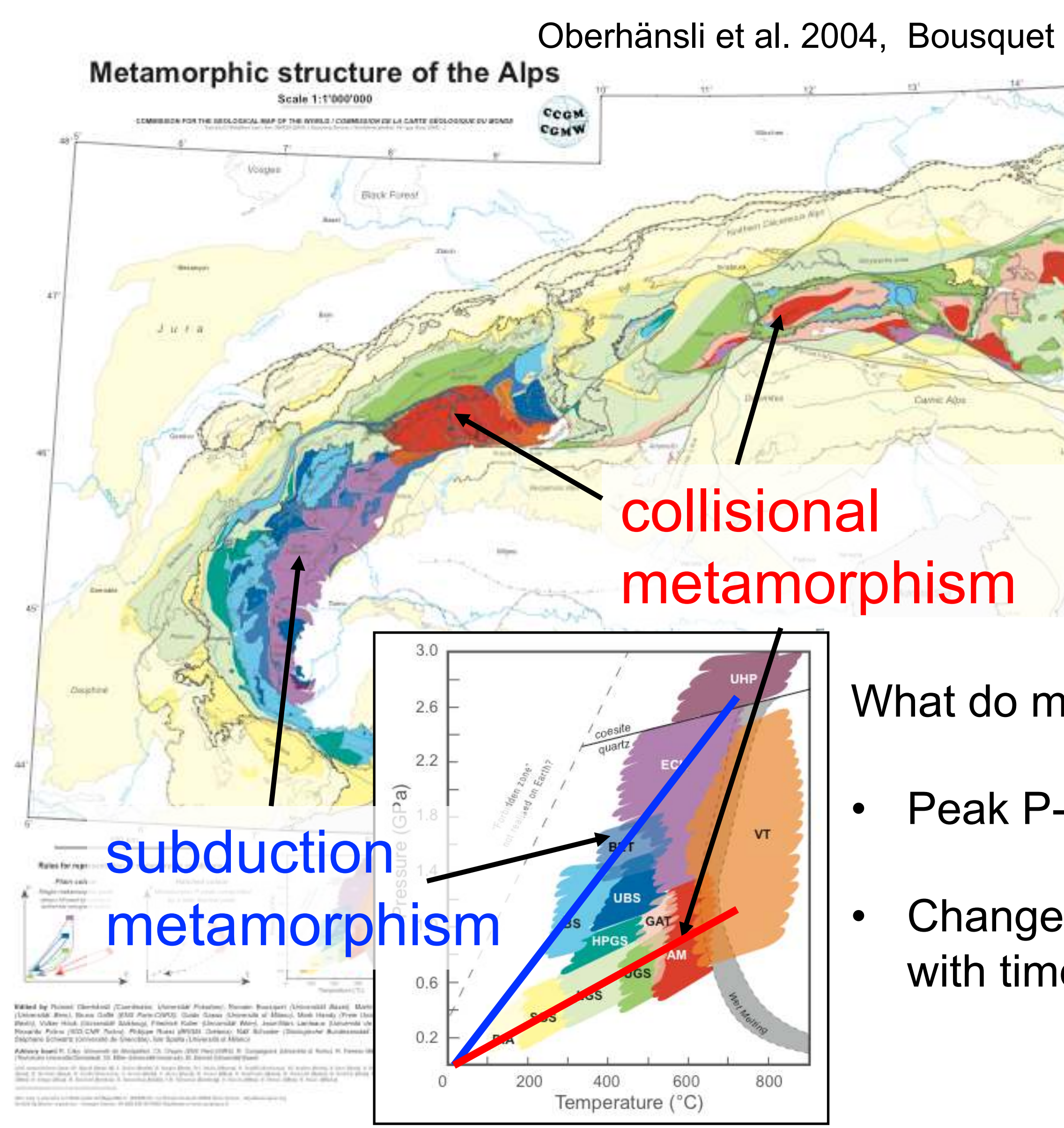
- epidote
- chlorite
- quartz

Pressure-Temperature path



Sequence of preserved tectono-metamorphic facies
defines a path of exhumation

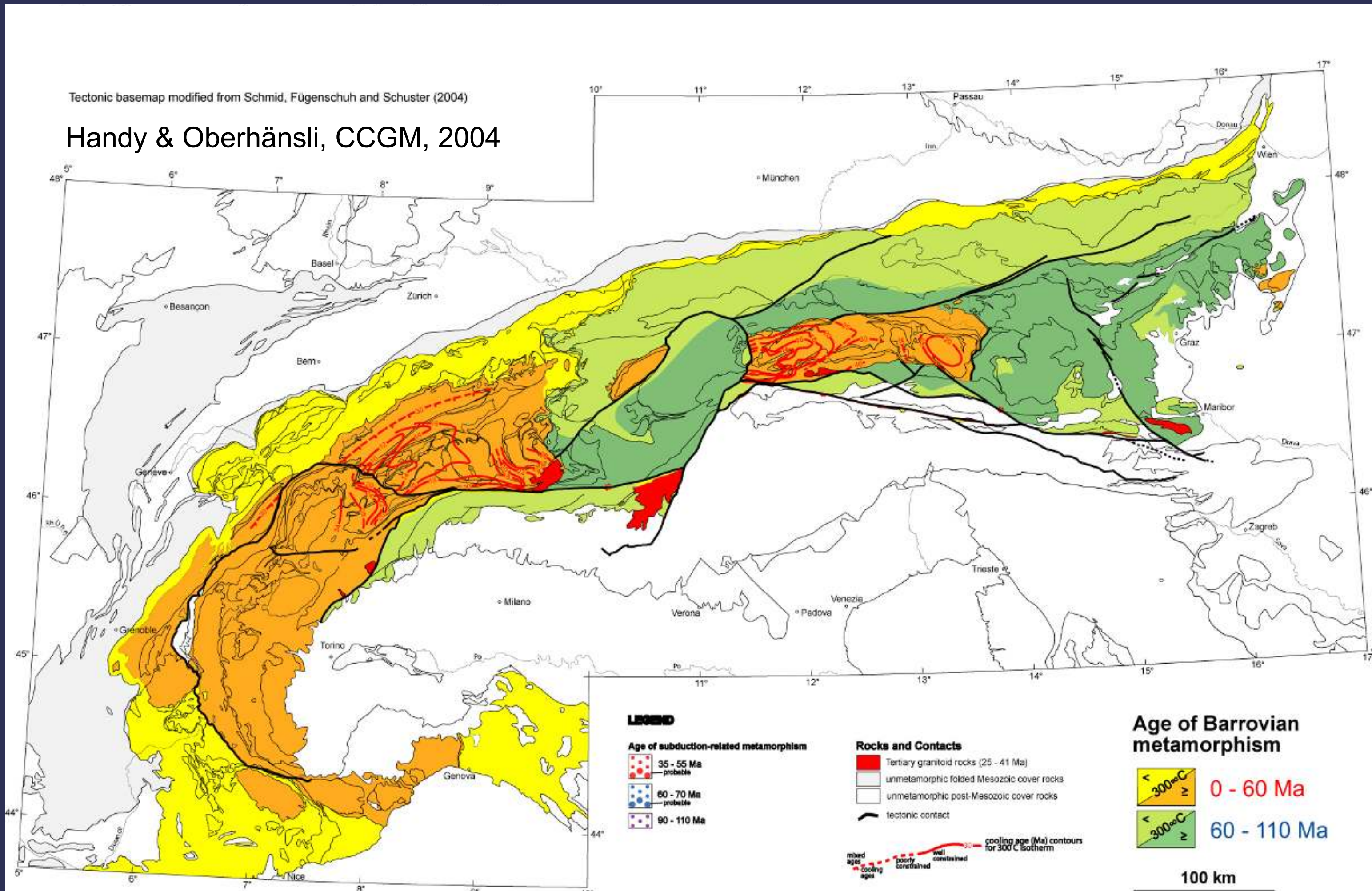
Metamorphic map



What do maps like this tell us?

- Peak P-T conditions
- Change in geothermal gradient with time

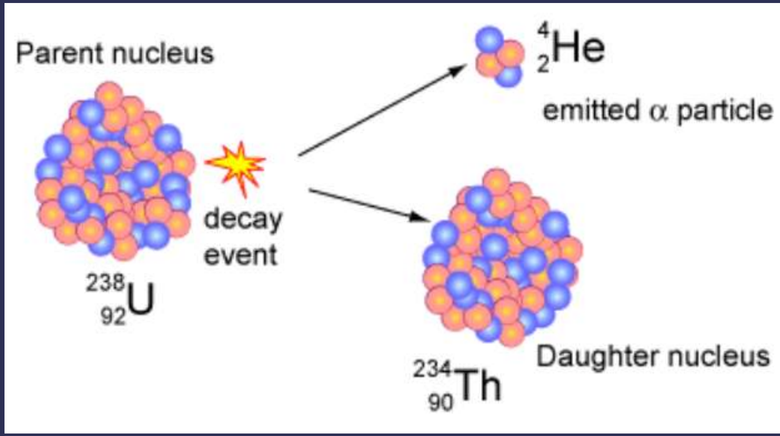
Thermochronological map



Geochronological maps show rock units according to their thermal age (crystallization, cooling age)

Radiometric dating

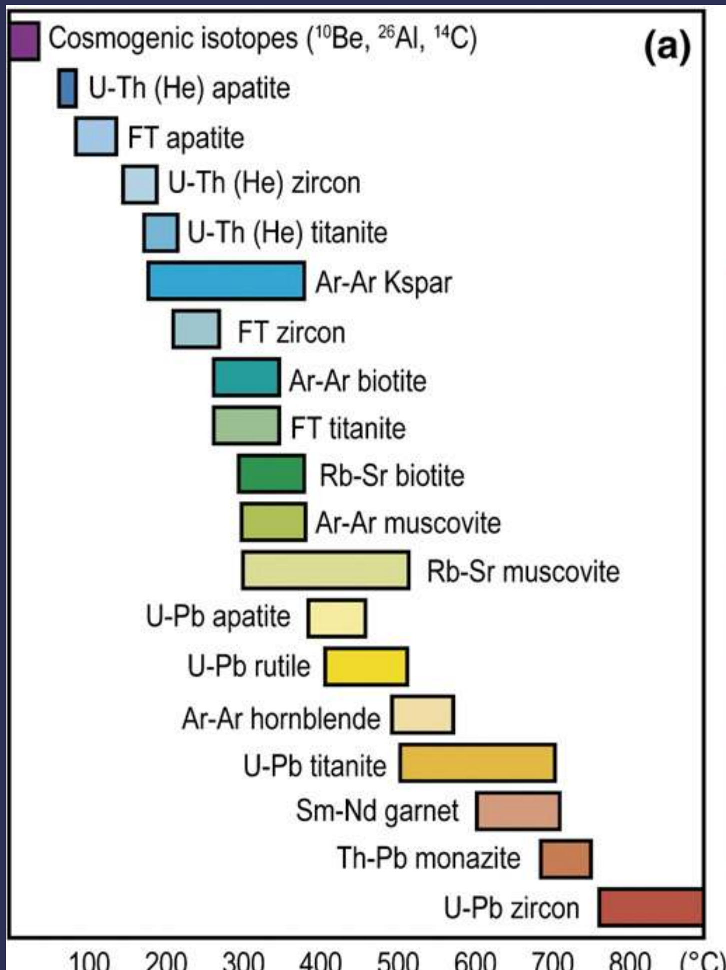
- Crystallization age
- Cooling age
- Mixed age



Example: decay of ^{238}U to ^{206}Pb via ^{234}Th
(8α, 6β; Half time: 4.468 billion years)

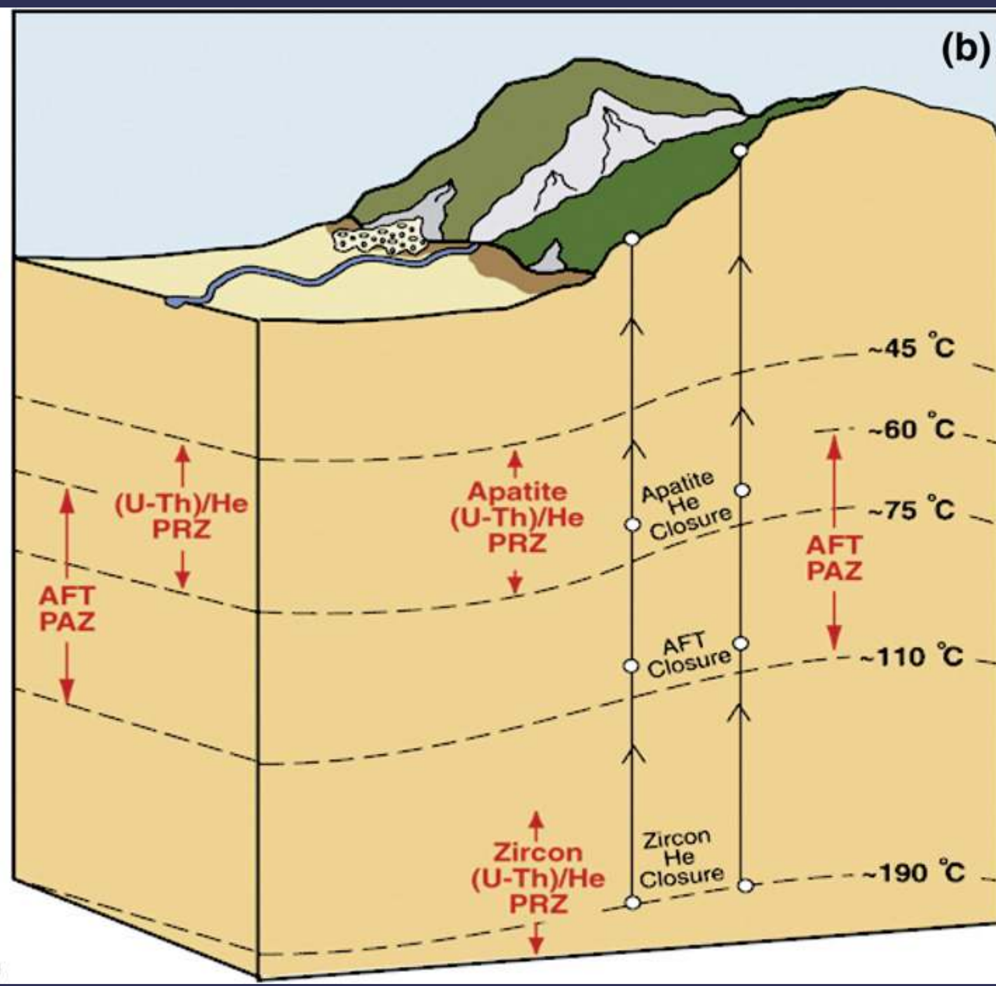
Temperature-dependence of isotopic systems

Cooling ages



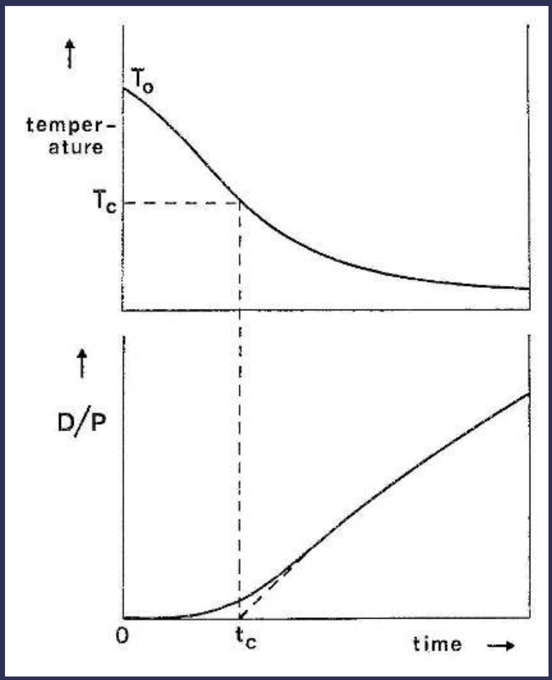
Reiners & Brandon 2006

Ages of retention & partial retention

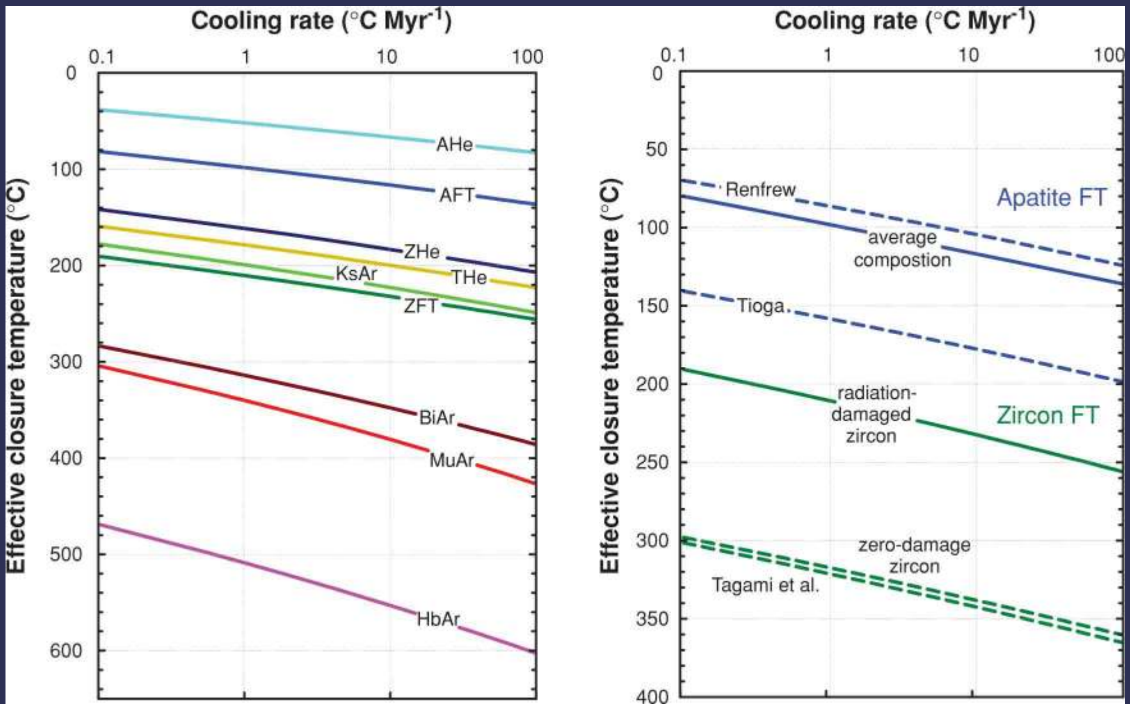


Cloetingh et al. 2007

Concept of a cooling age



Dodson 1973



Reiner & Brandon 2006

Reiners & Brandon 2006

System opens and remains open under certain conditions
(e.g., when $T > T_{critical}$ for given grainsize and rate of T change)

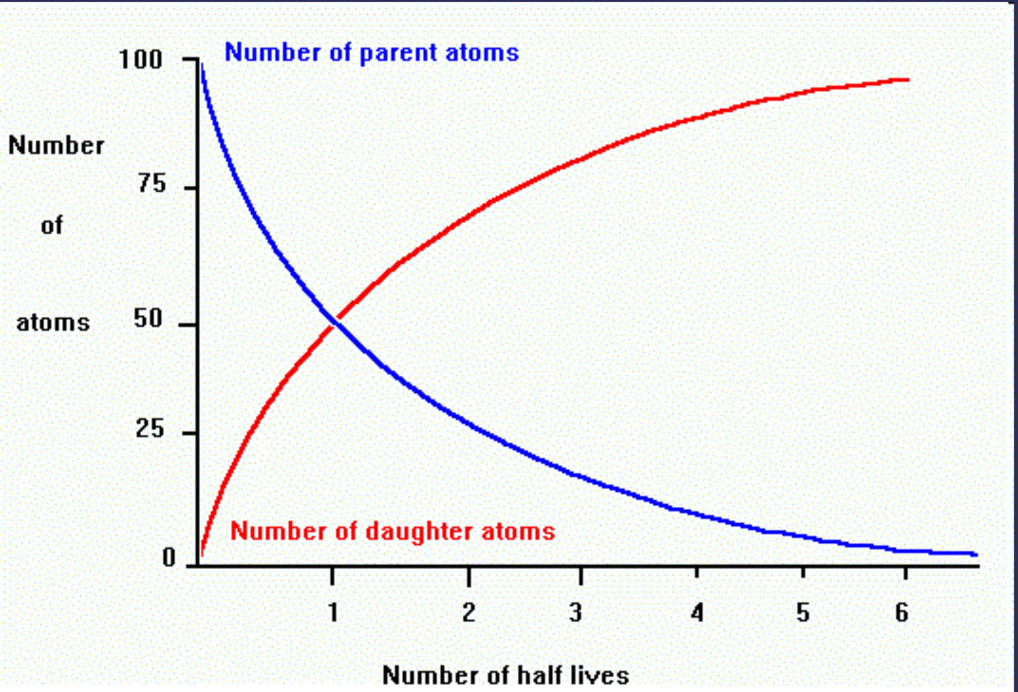
Factors that can affect T_c: deformation of mineral system, fluids

Radioactive decay

Mineral crystallizes with
N number of parent atoms:

N: # of parent atoms
D: # of daughter atoms
λ: decay constant ($\ln 2/t_{1/2}$)
t: geologic time

$$\boxed{D_{(t)} = N(e^{\lambda t} - 1)}$$



graph courtesy of www.gpc.peachnet.edu/%7Epgore/geology/geo102/radio.htm

In reality, minerals already have daughter atoms when they crystallize:

D_o: # of daughter atoms already present

=> Basic equation to determine age $\boxed{D_{(t)} = D_o + N(e^{\lambda t} - 1)}$

Pitfalls of radiometric dating

Precision and accuracy of an age determination is dependent on parameters like time, isotopic system, N/D ratio…

N # of parent atoms
measurable only if present in reasonable quantity

D # of daughter atoms
measurable only if present in reasonable quantity

λ decay constant ($\ln 2/t_{1/2}$)
more or less well known

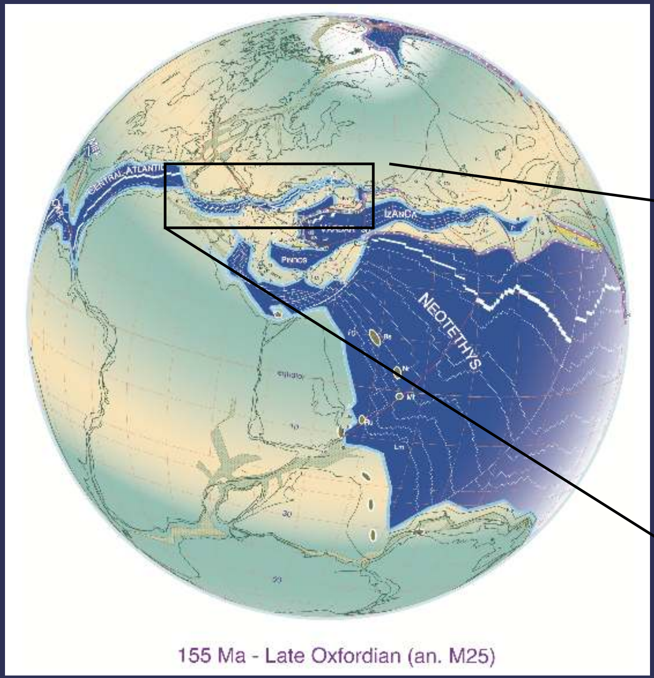
D_o # of daughter atoms present already when mineral crystallizes
must be inferred (e.g., assumed to be 0) or corrected for

An „age“ is only meaningful if it can be interpreted in a broad geological context

Motion - Kinematics

- Path (direction)
- Shortening (amount)
- Rates (speed)

The product – a quantified paleogeographic map



155 Ma - Late Oxfordian (an. M25)

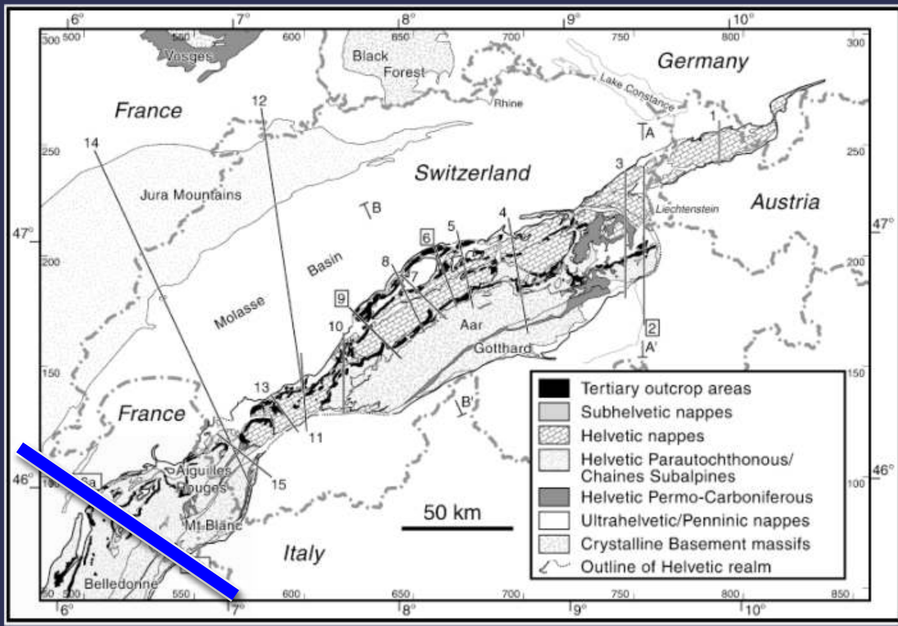
Stampfli et al 2004

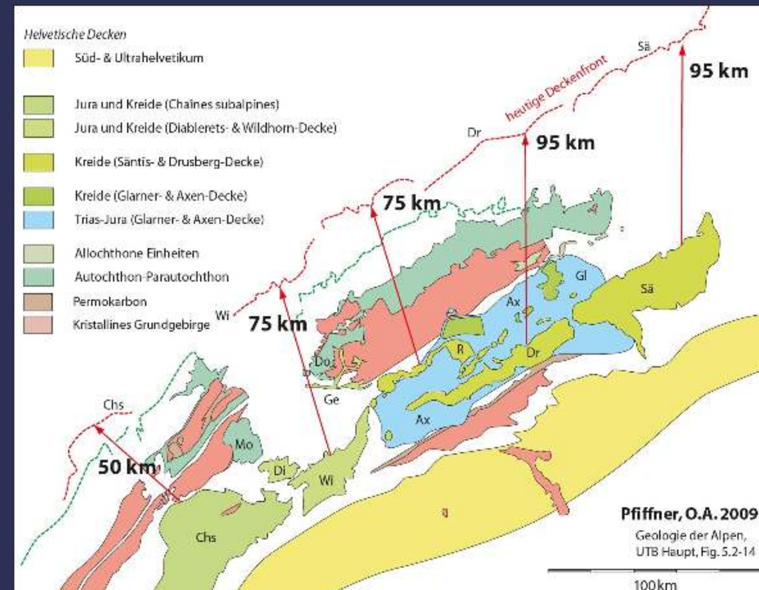
Paleogeographic maps show old geologic boundaries e.g., plate boundaries, ocean-continent crust boundaries

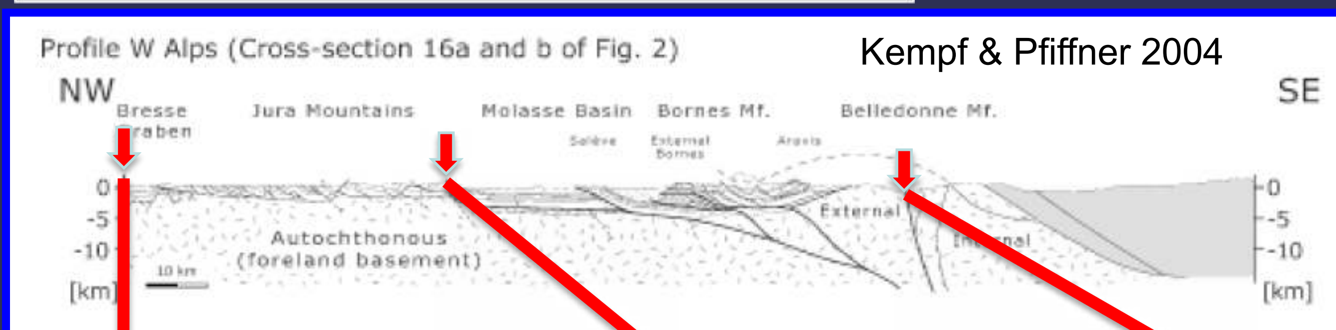
Paleo-transport direction from shear-sense indicators

Structures that indicate the transport direction of a package of rocks with respect to neighboring rocks

Displacement of markers - Example: Paleogene shortening in Helvetic units

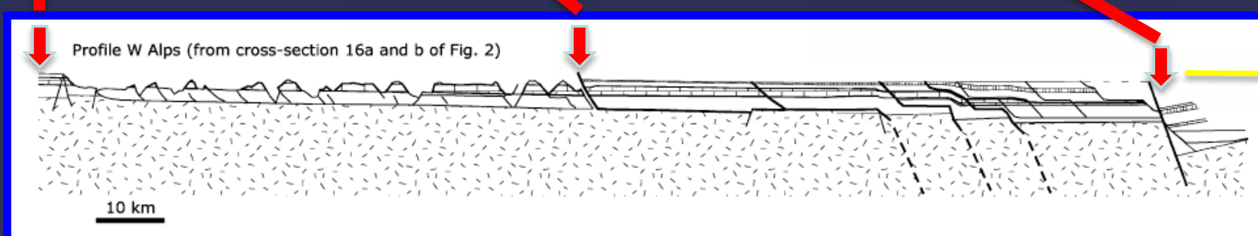






Thrust fronts are erosional - hangingwall cutoffs are unknown

⇒ Minimum shortening estimates



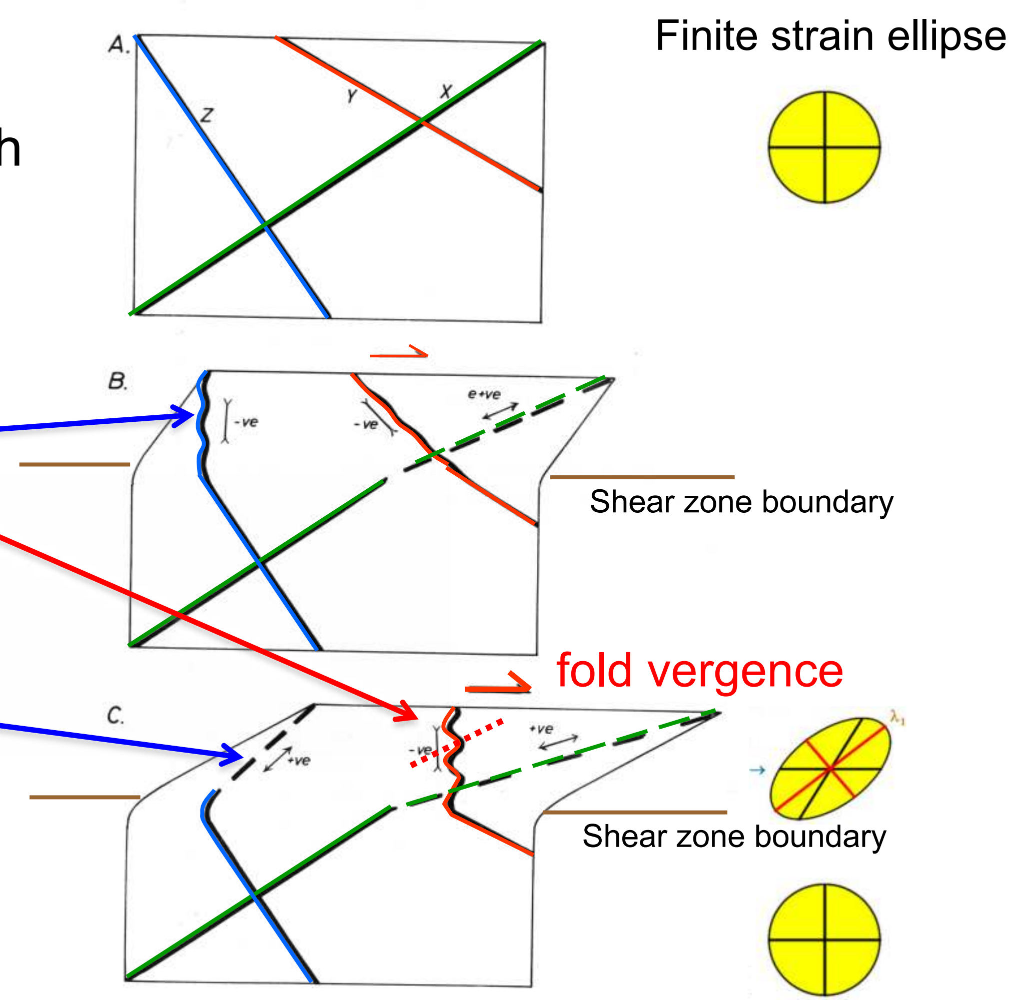
units S of this point move 50 km

Passive indicators

Rotational shearing of existing planar and linear structures with different orientations

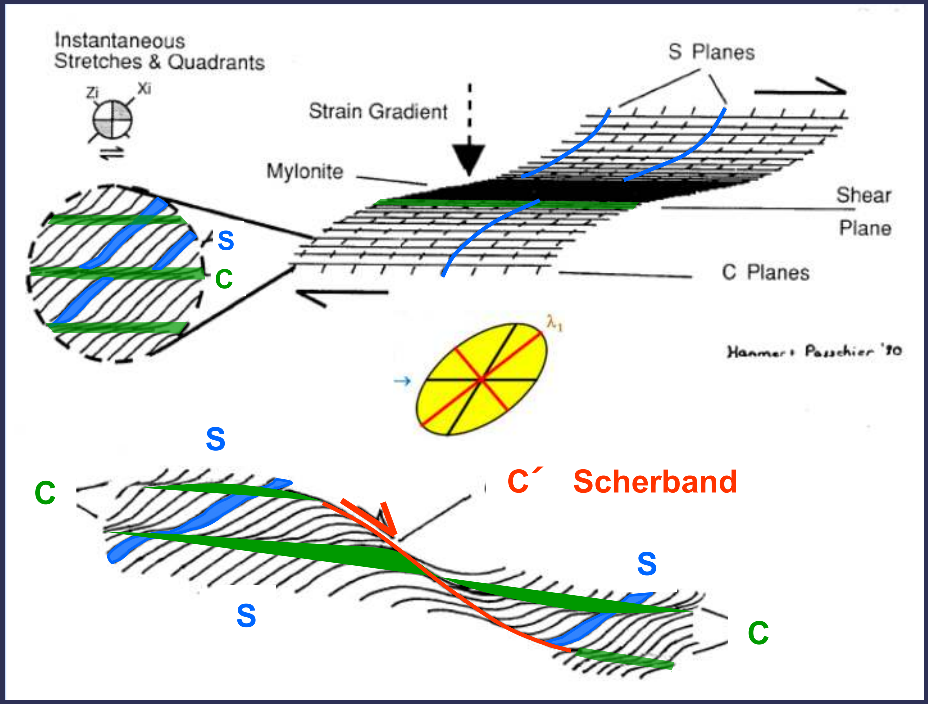
Folding of structures in the incremental shortening field

Stretching („boudinage“) of stuctures in the incremental stretching field

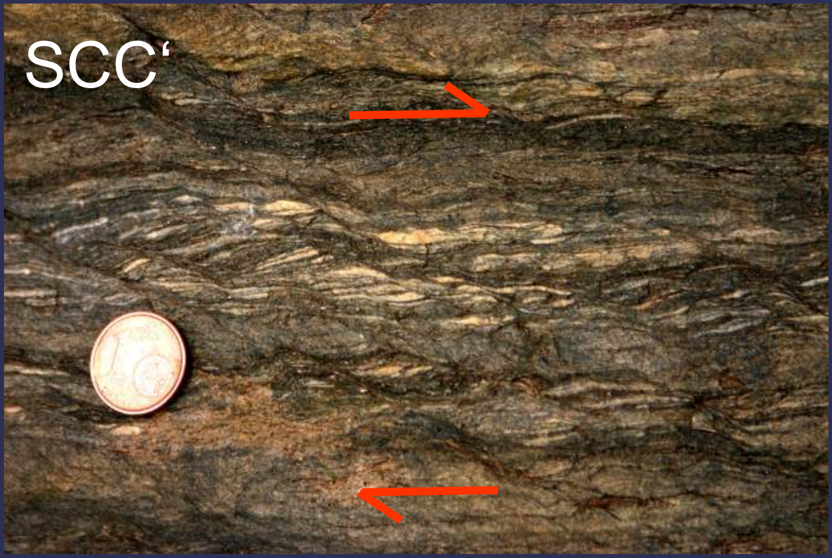


Active indicators

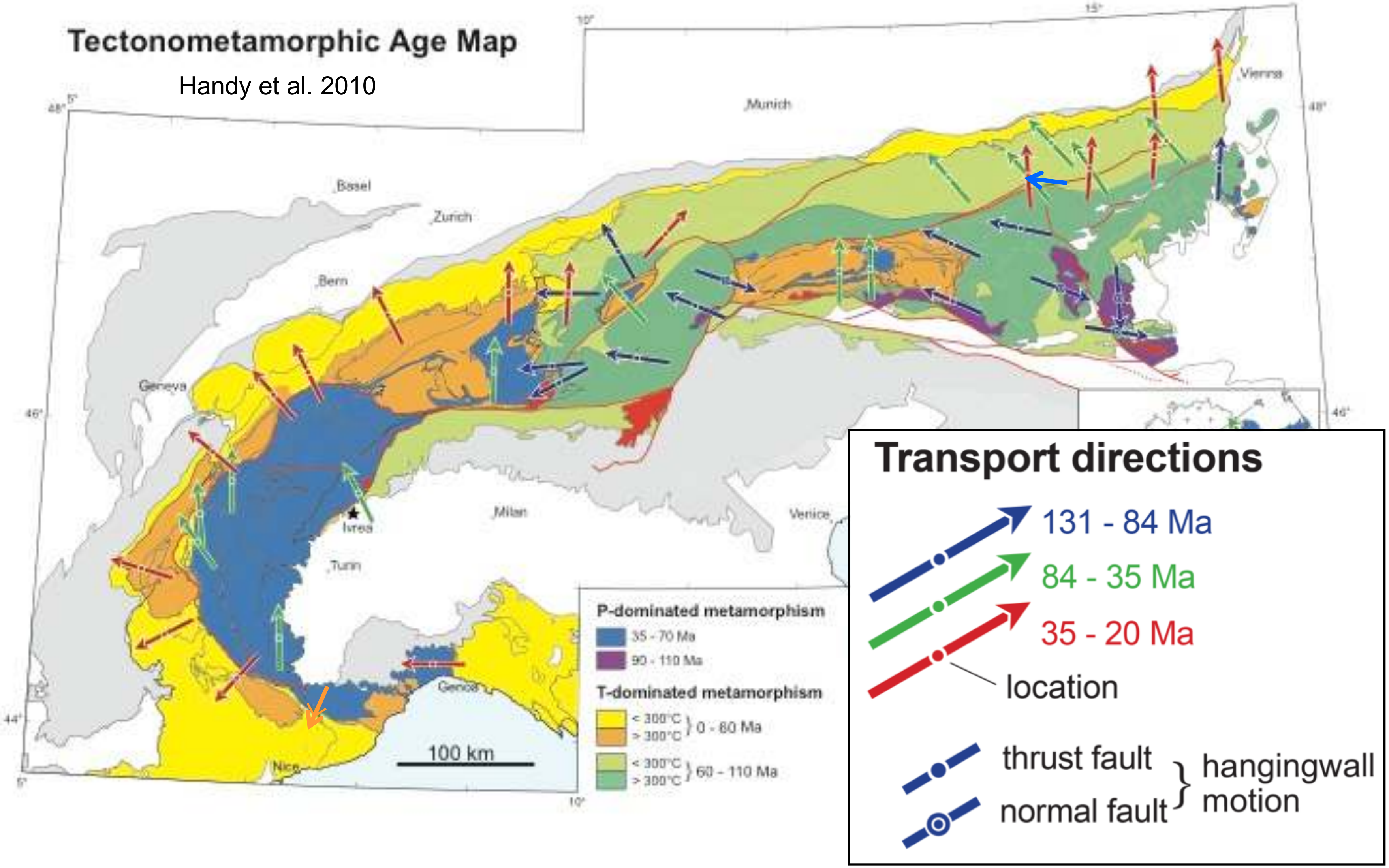
for example, S-C surfaces & shear bands (relaxation structures)



Hanmer & Passschier (1990)



Application of paleo-transport indicators on the scale of the orogen



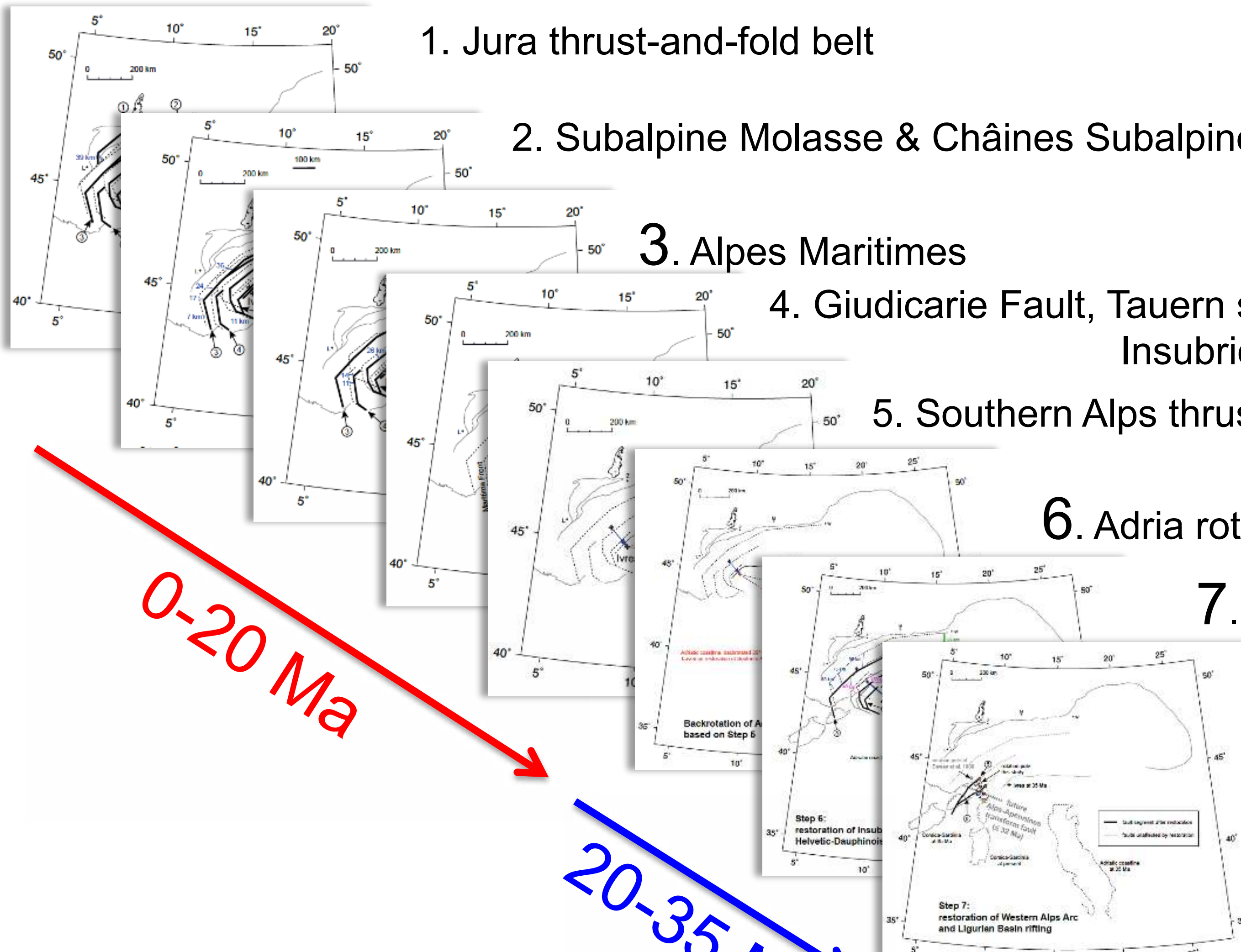
Combine shear indicators with radiometric dating

Methods of reconstructing past plate positions & plate motion

Geophysical methods:
- Width & age of oceanic magnetic anomalies
- Polar wandering paths
- Hot spot & mantle reference frames

Geological methods:
- Biostratigraphic correlation
- Pressure-temperatrure-time paths for rocks
- Palinspastic reconstructions (areal & volume balance)

Restoration steps back to 84 Ma



1. Jura thrust-and-fold belt
2. Subalpine Molasse & Chaînes Subalpine belts
3. Alpes Maritimes
4. Giudicarie Fault, Tauern shortening & Insubric backthrusting
5. Southern Alps thrust belt
6. Adria rotation of 20°
7. Helvetic nappes & Insubric strike-slip
8. Western Alps & Ligurian Basin

0-20 Ma

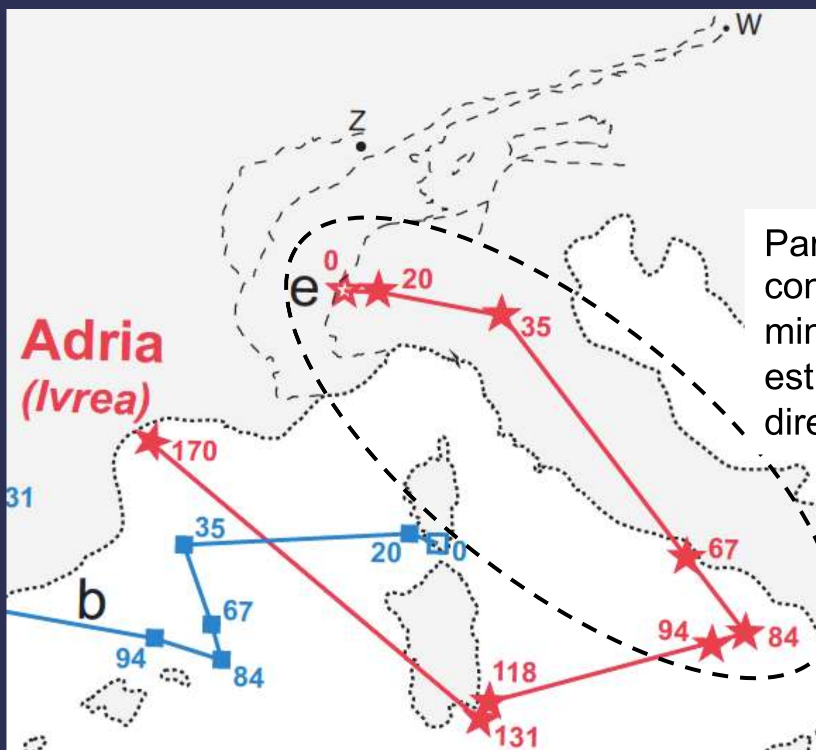
20-35 Ma

...and so forth, back to 84 Ma

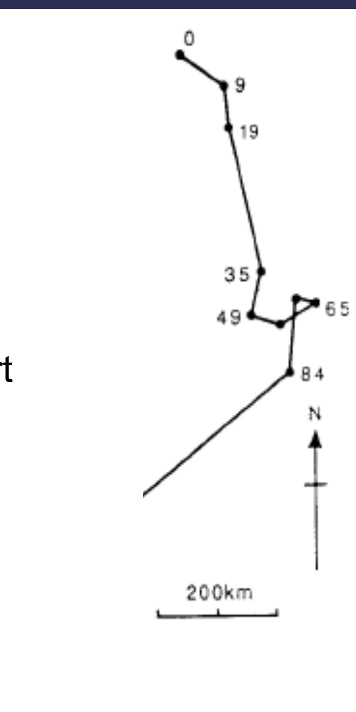
Application to plate motion

Motion path from structural geology
(Adria with respect to Europa)

Motion path from
paleomagnetic data



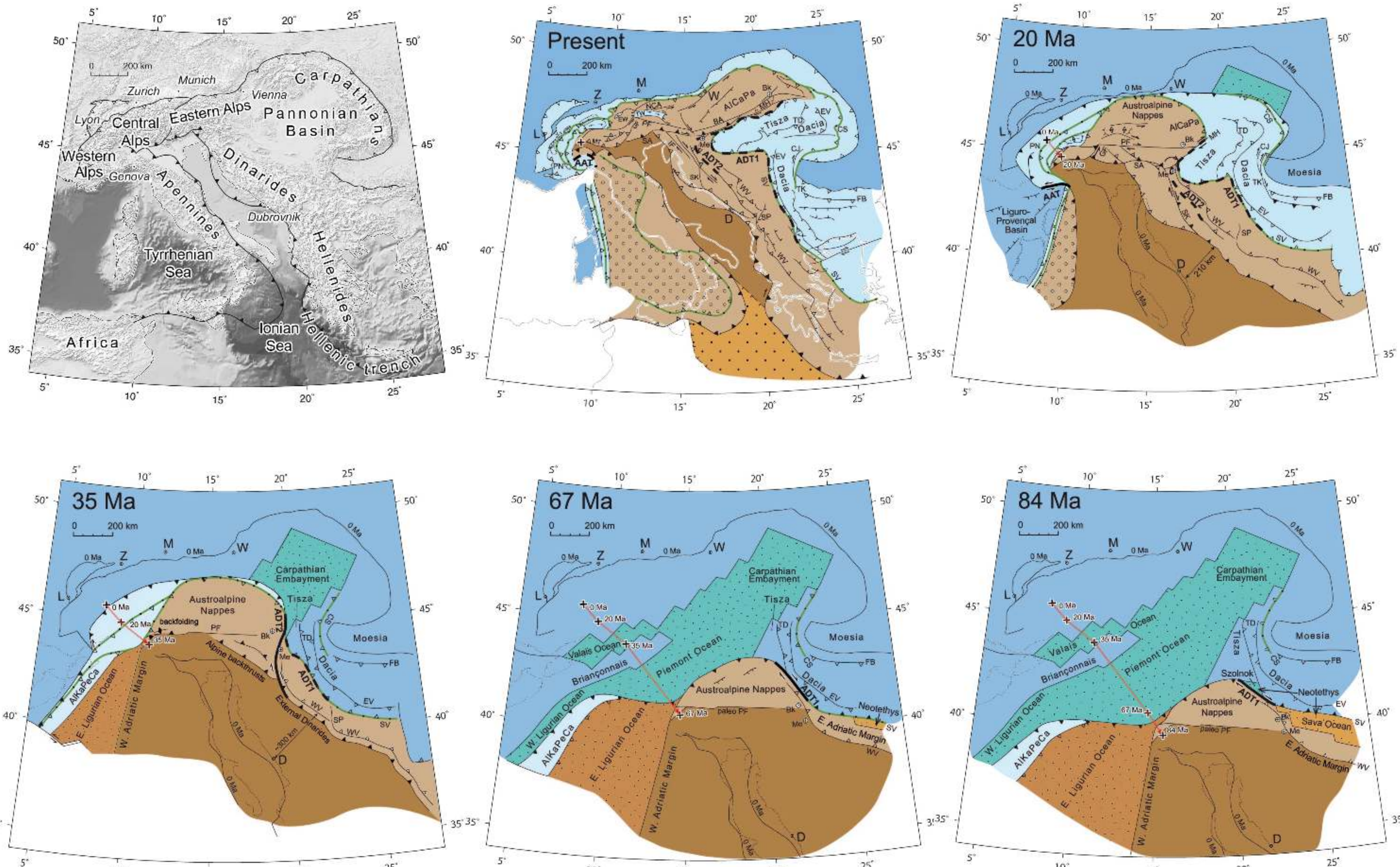
Part of path constrained by minimum shortening estimates & transport directions



Handy et al. 2010

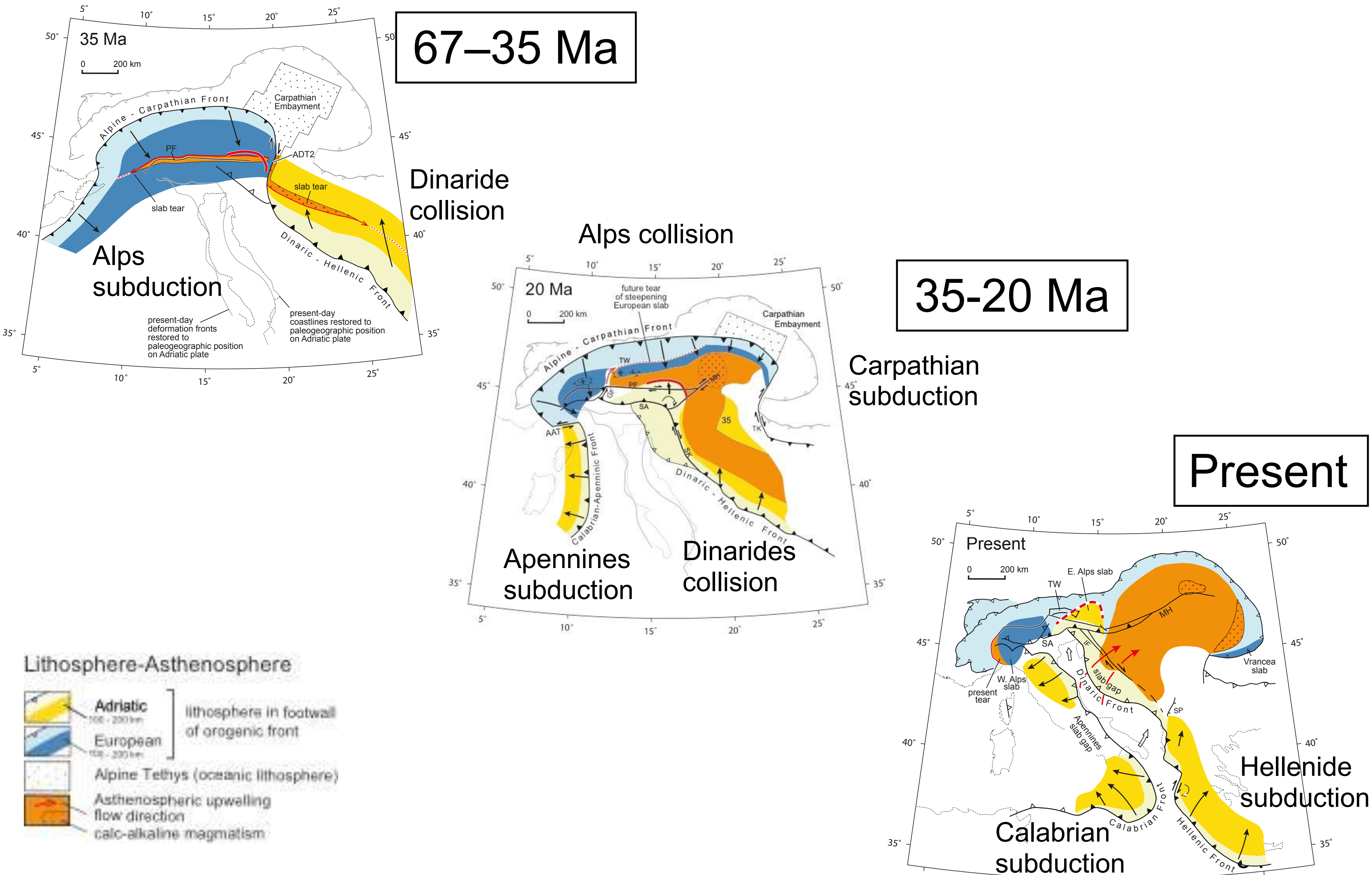
Platt et al. 1989

Map view reconstructions



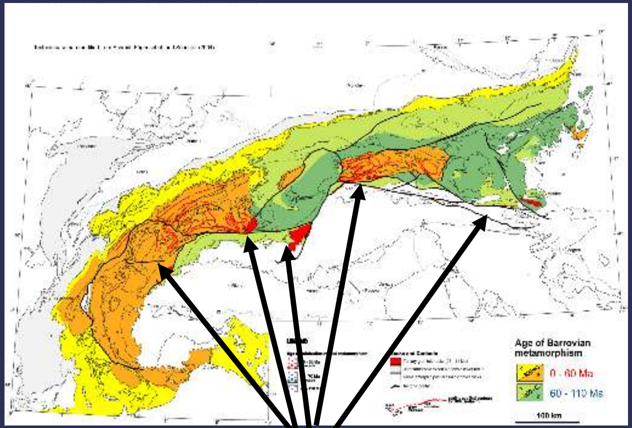
Handy et al. 2015

Conclusions – Slab motion maps

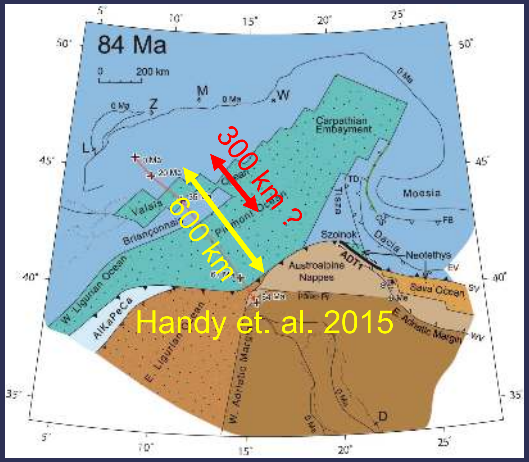


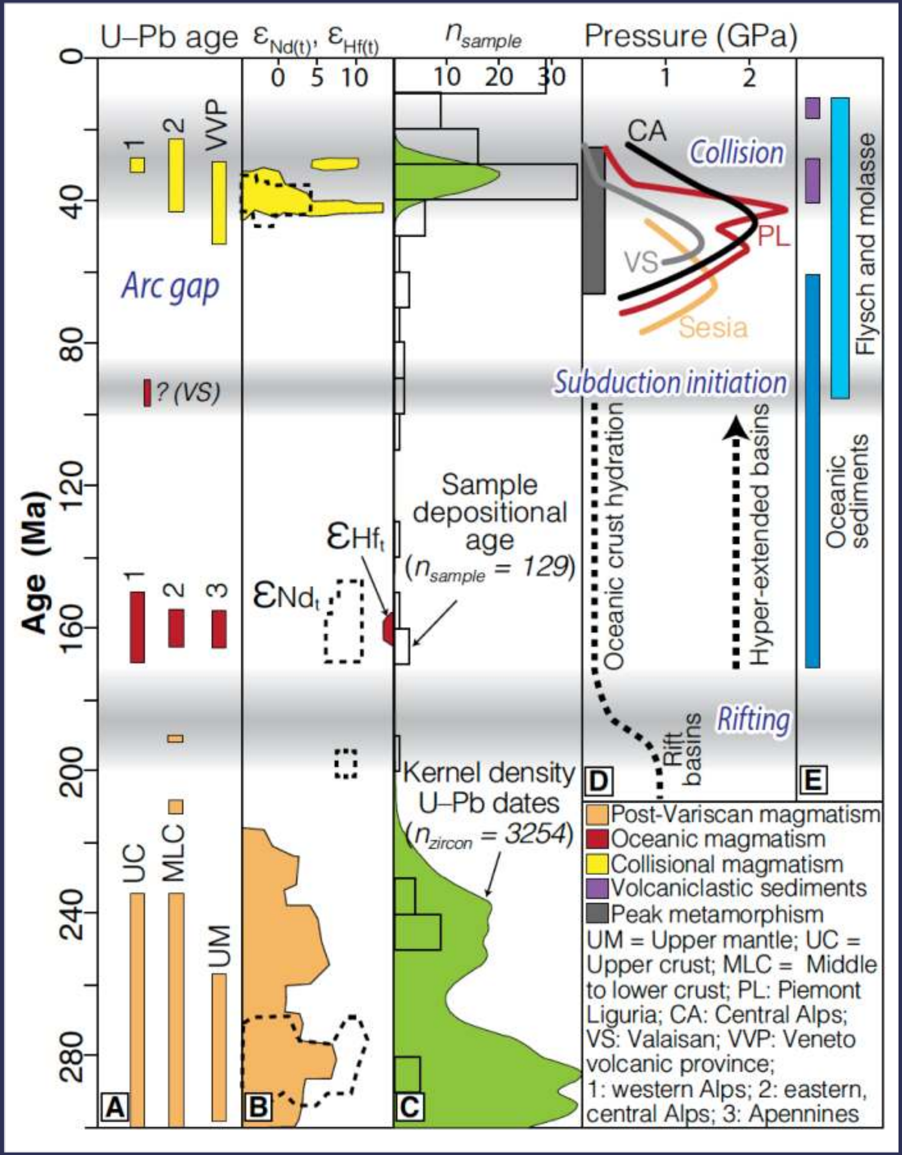
Handy et al. 2015

The problem of explaining minor magmatism in the Alps



Small intrusive volumes, negligible volcanism
=> Narrow Alpine Tethys





McCarthy et al. 2018

Summary

Dating tectonics events involves two steps:

1. Determining sequence of events (cross-cutting relations)
2. Dating superposed structural markers and rock layers
   => biostratigraphic and radiogenic ages

Motion determined by a combination of methods:

1. Kinematic indicators in deformed rocks
2. Biostratigraphic correlation
3. Paleomagnetic studies

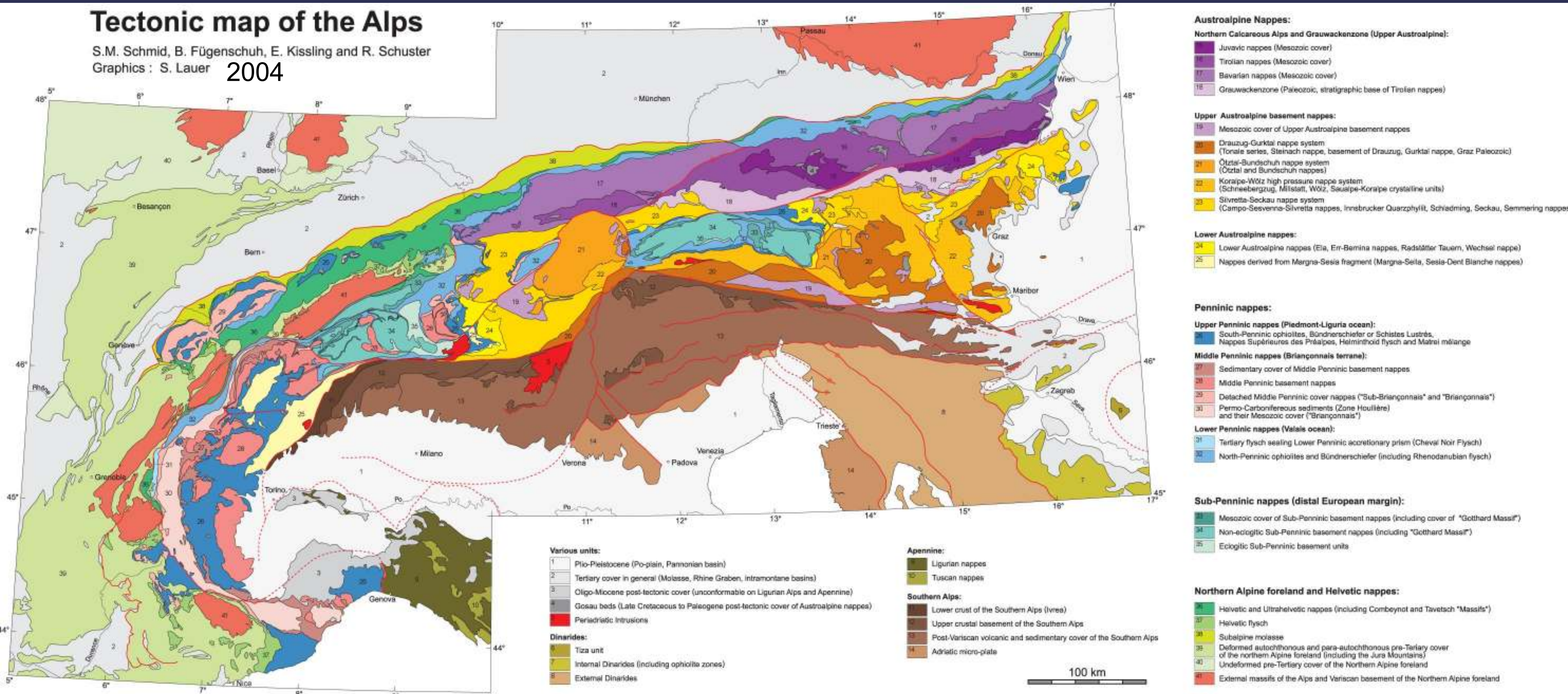
Physical conditions of burial (subduction) and exhumation determined in following way:

1. Geothermometry & geobarometry
2. Dating of minertal assemblages (formational, cooling, mixed ages)

The plausibility of a tectonic model can be judged by its ability to reconcile disparate datasets

Appendix

Tectonic map



Tectonic maps show rock units with common motion histories

Tectonic map with paleogeographic units