united nations educational, scientific and cultural organization
international atomic energy agency
the abdus salam international centre for theoretical physics
40th anniversary 1964 2004

H4.SMR/1586-22

"7th Workshop on Three-Dimensional Modelling of Seismic Waves Generation and their Propagation"

25 October - 5 November 2004

Continental Deformation and Earthquakes

Part 1, Part 2, Part 3

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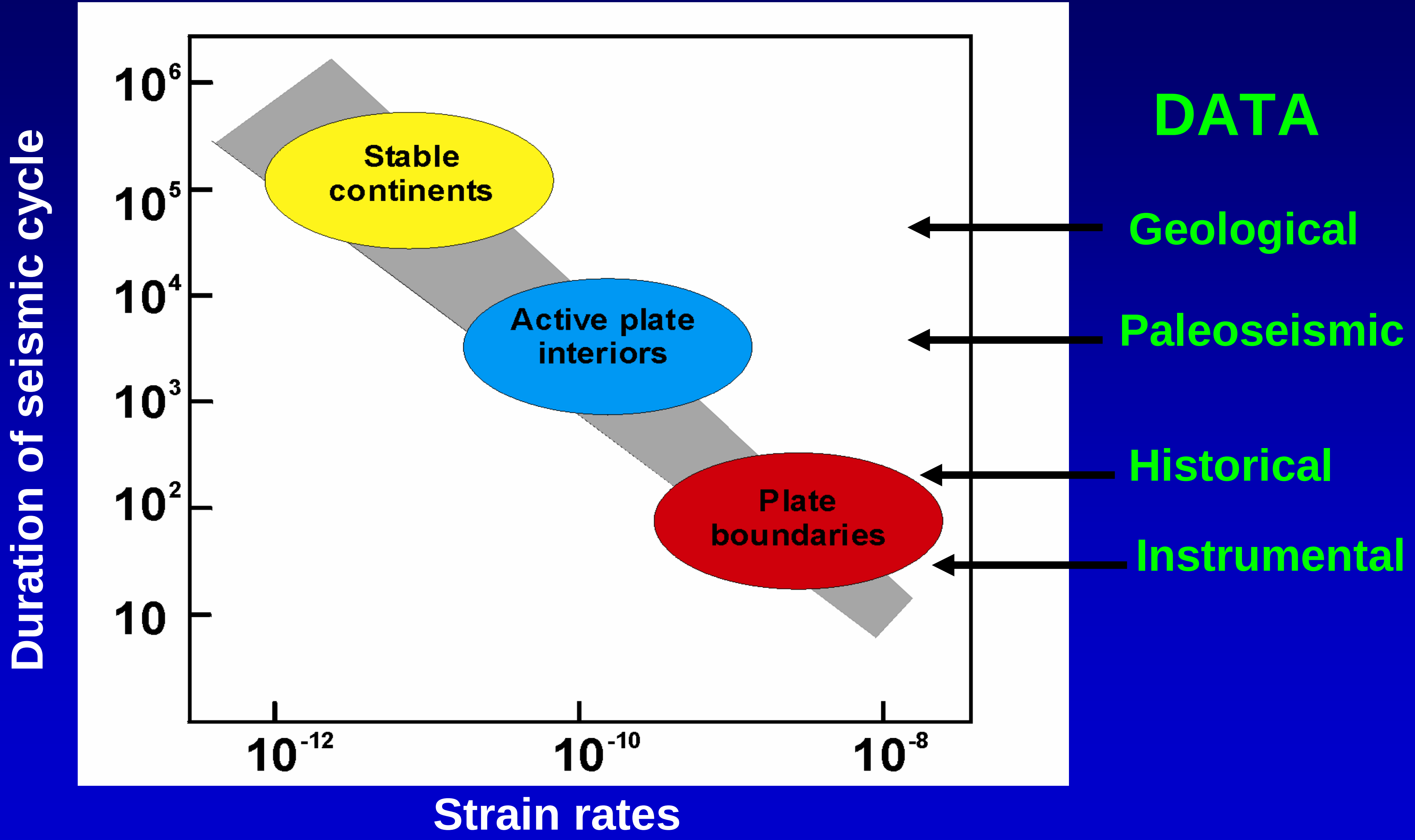
Continental tectonics?
Continental deformation?
Active tectonics?

- ***Continental tectonics:*** **a term used to include the large-scale motions, interactions and deformation of the continental lithosphere. It is often used in contrast to "Plate tectonics".**

- ***Continental deformation:*** **a term often used to emphasize the contrast between deforming zones in the oceans and on the continents.**

- ***Active tectonics:*** **present-day tectonic movements or tectonic movements expected to occur within a future time span of concern to society.**

The seimic cycle



How to view Continental Tectonics?

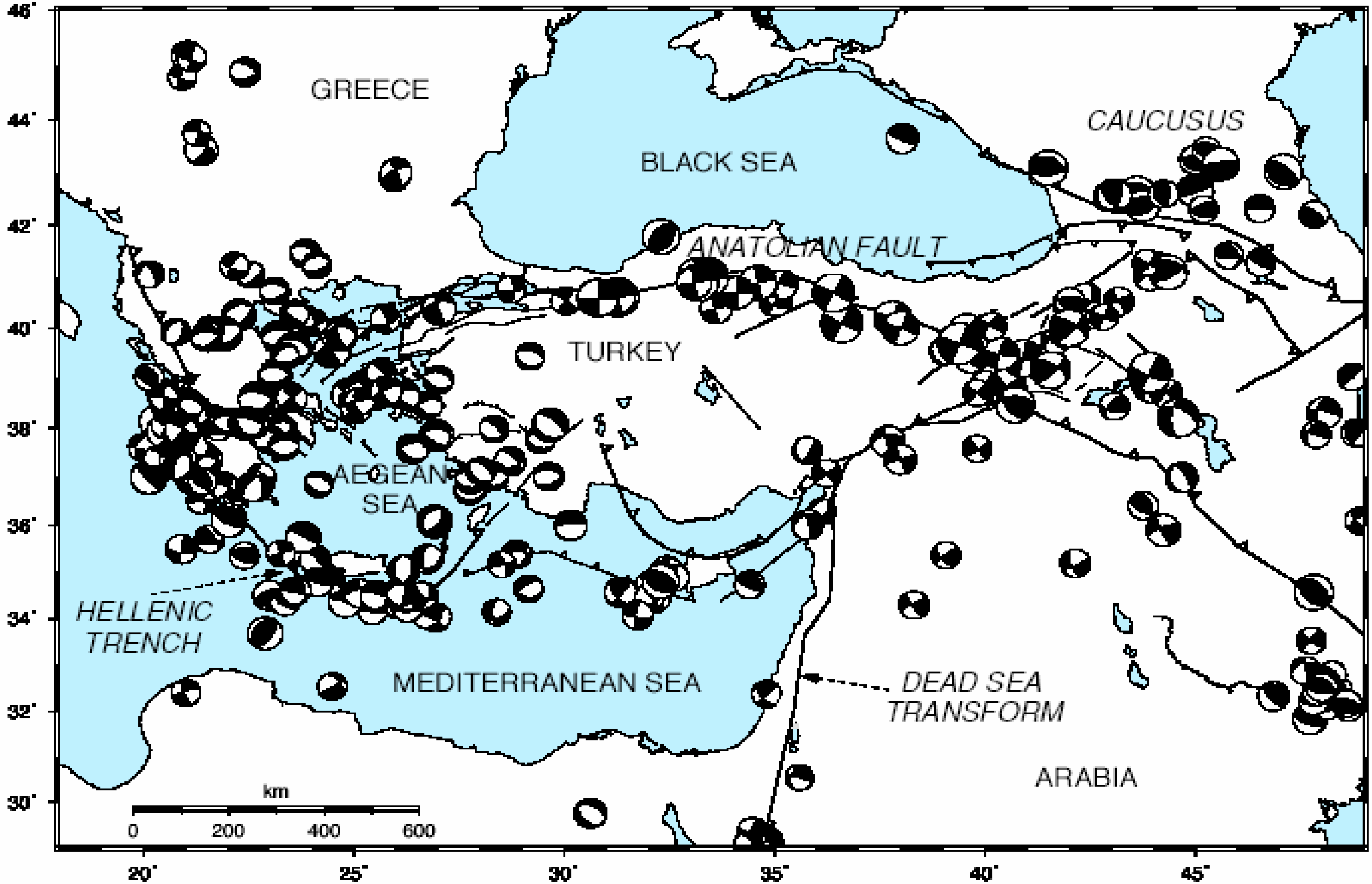
Continental tectonics is not plate tectonics…

Whereas deforming zones in the oceans are usually narrow and confined, on continents they are often spread over wide areas, requiring a different approach to their description and analysis.

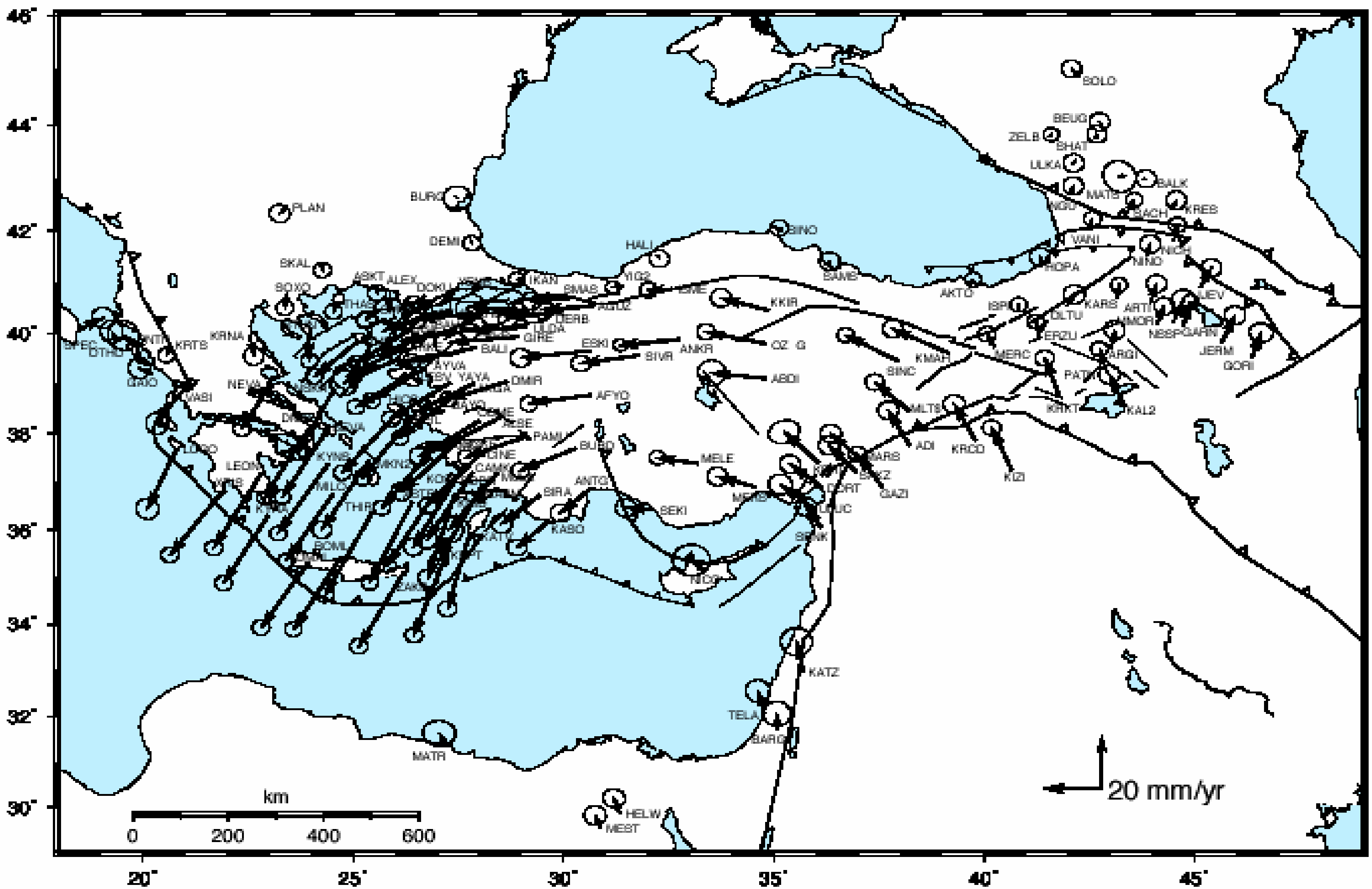
In oceans plate boundaries are effectively single faults on which the long-term rate and direction of slip are entirely determined by the relative motion of the bounding plates.

On the continents, earthquakes are usually distributed over zones hundreds or thousands of kilometers wide.

As we shall see, what is happening in the Eastern Mediterranean and in Italy is not predictable knowing just the relative motion between Africa and Eurasia.



GREECE
BLACK SEA
CAUCUSUS
ANATOLIAN FAULT
TURKEY
AEGEAN
SEA
HELLENIC
TRENCH
MEDITERRANEAN SEA
DEAD SEA
TRANSFORM
ARABIA
km
0
200
400
600
46°
44°
42°
40°
38°
36°
34°
32°
30°
20°
25°
30°
35°
40°
45°


46°
44°
42°
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32°
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km
0
200
400
600
20 mm/yr
SOLO
BEUG
ZELB
SHAT
ULKA
BALK
KRES
PLAN
BURG
DEMI
HALI
SINO
SAMS
AKTO
VANI
HOPA
SKAL
SOXO
ALEX
IKAN
KKIR
ANKR
SIVR
ESKI
BALI
GIRE
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AFYO
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ISPI
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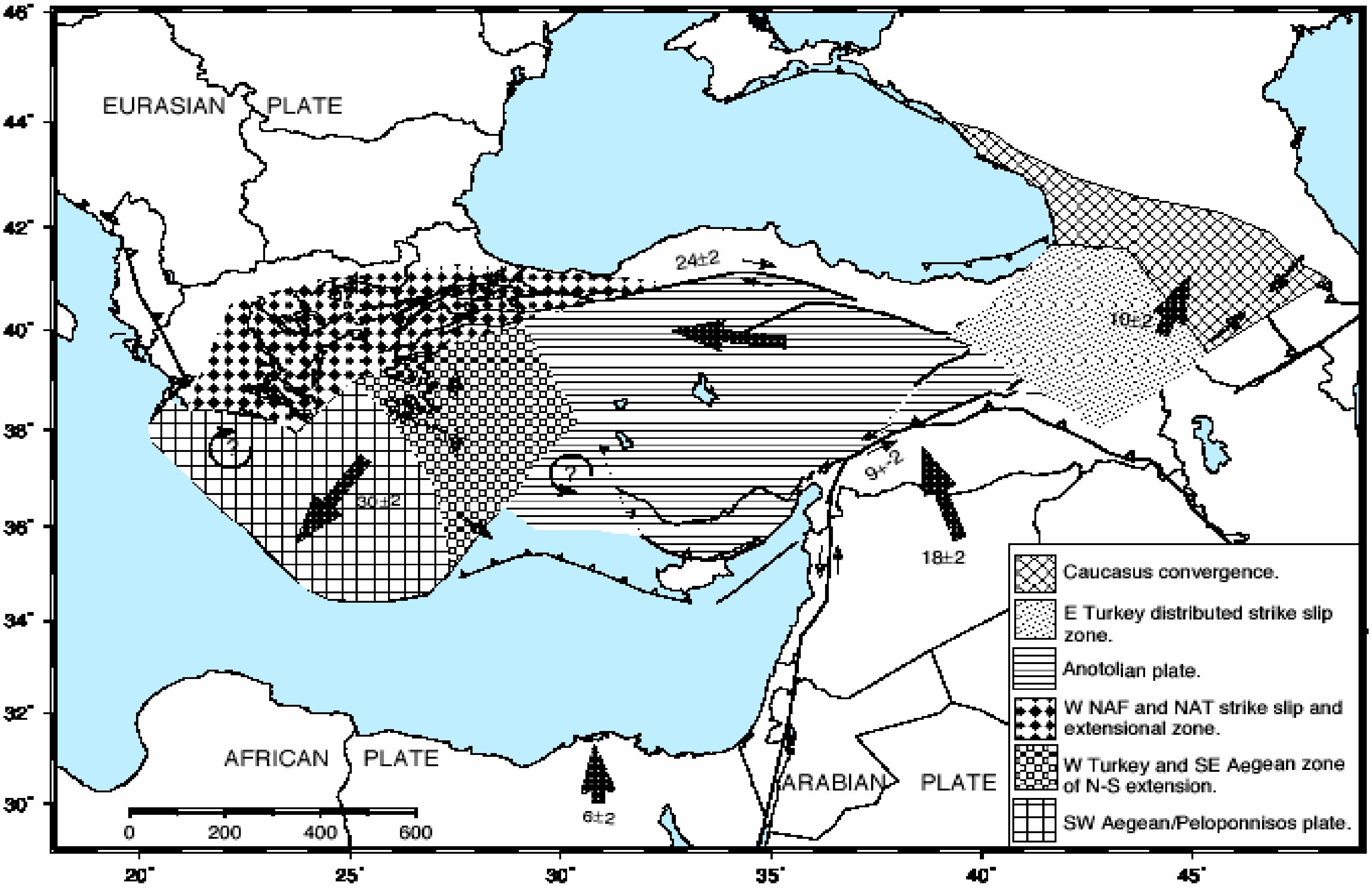
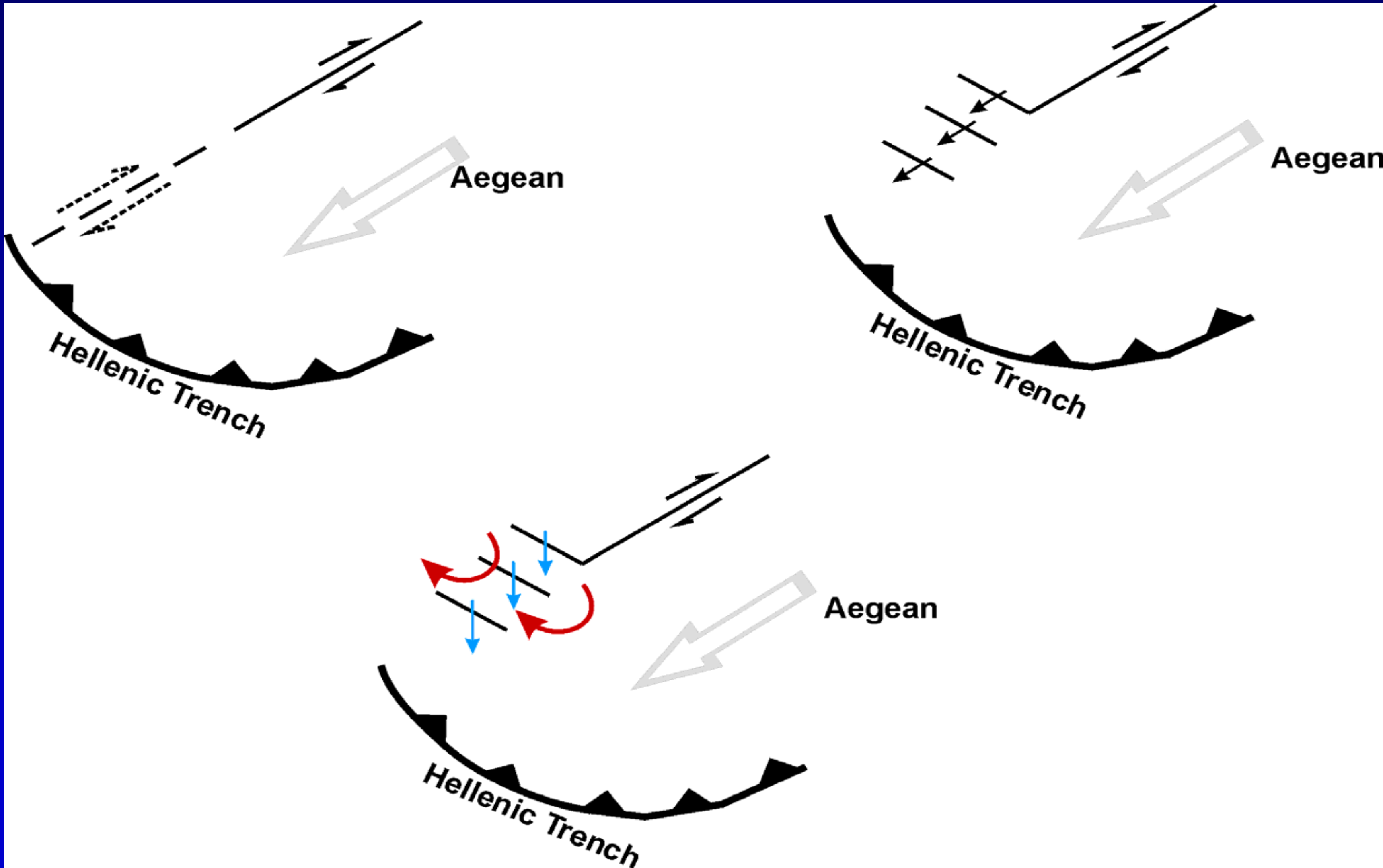


EURASIAN PLATE
AFRICAN PLATE
ARABIAN PLATE
24±2
10±2
30±2
9±2
18±2
6±2
0 200 400 600
46°
44°
42°
40°
38°
36°
34°
32°
30°
20°
25°
30°
35°
40°
45°
Caucasus convergence.
E Turkey distributed strike slip zone.
Anotolian plate.
W NAF and NAT strike slip and extensional zone.
W Turkey and SE Aegean zone of N-S extension.
SW Aegean/Peloponnisos plate.

Accommodation of SW movement of the southern Aegean relative to Europe by faulting in central Greece (After Jackson, 2001)



Continental deformation framework

- ***Velocity field for Continuous deformation:***
  GPS – SLR - VLBI
- ***Faulting for Discontinuous deformation:***
  Seismology, GPS, DinSAR,
  direct observations

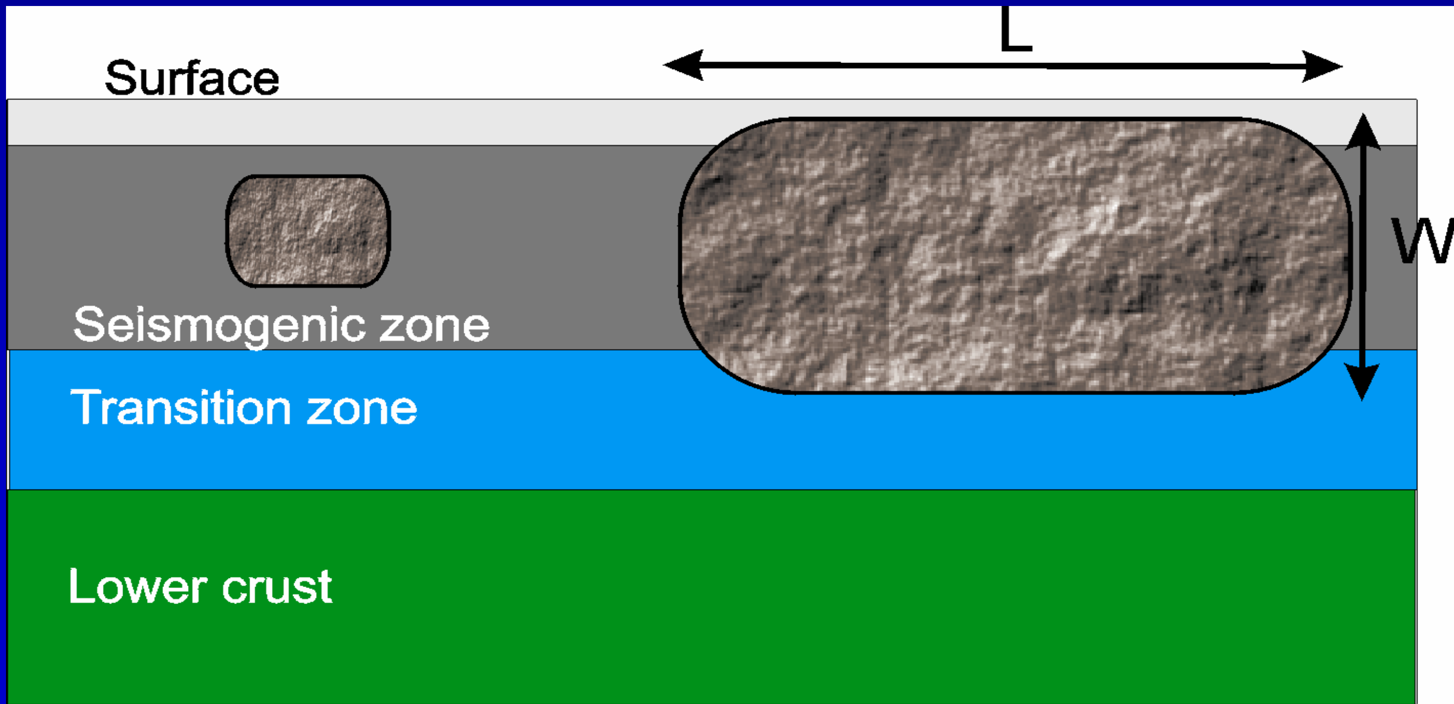
Crucial to this framework is the knowledge of the structure of the earth at the required length scale,

and an appreciation of the nature and scale of the mechanical properties of the continental lithosphere.

Scaling and organisation of the strain field

Two length scales against which geological, geodetic and seismological data should be compared:

- thickness of the crust;
- thickness of the lithosphere



Tools and Techniques: The future..

- Quality and abundance of Seismological, GPS and SAR data
- Abilities of the analytical techniques that use such data to constrain the geometry, segmentation and slip distribution on active faults

RESULTS: details of the faulting and rupture process that would have been impossible to see 10 years ago..

CONCERN is now focusing on differences between results obtained by seismology, GPS surveying and SAR interferometry for the same earthquake.

The three techniques are looking at different spatial and temporal resolutions. But whether they actually do so, or whether the currently observed differences are within the noise and resolution errors of the various techniques, is still not certain.

IMPLICATION: enormous power of modern methods, particularly when used in combination, to reveal details of the faulting in earthquakes.

GPS is cool...
but there are many layers to the onion...

- ***Phase biases***
- ***Imperfect clocks***
- ***Indices of refraction***
- ***Satellite-Earth-GPS geometry***
- ***Other effects***
  - ***Loading (tidal, hydrological, ...)***
  - ***Electrical environment (satellite antennas, receiving antennas)***
  - ***Use of different antennas for the same monument***
  - ***Dome...***

More of this during the next IAG-IASPEI Joint Capacity Building Workshop on Deformation Measurements and Understanding Natural Hazards in Developing Countries, ICTP - Trieste Jan. 17-23, 2005.

Motivation: Kinematic matters

- what is the velocity field that describes the average, or long-wavelength deformation in the active diffuse belts?
- how is it achieved by faulting?
- what is the relation between the two?

Motivation: Rheology matters

Improved understanding of the rheology of the Earth's crust and upper mantle and faults is fundamental to studies of:

- **mantle flow & plate tectonics**
- **earthquake cycle, fault interaction & earthquake hazard**

stress ← rheology → strain

Top Questions

Q1: what is the appropriate model of deformation below the seismogenic zone?

two models of deformation:

1. **distributed deformation: creeping below mid-crust.**
2. **localized shear zones: "rigid" down to mantle.**

Q2: what is the rheology of the crust-upper mantle rocks and constitutive properties of fault zones?

Changes in Crustal Conditions with Depth

Temperature

15 - 45°C/km

Overburden

26 – 30 MPa/km

Lithology

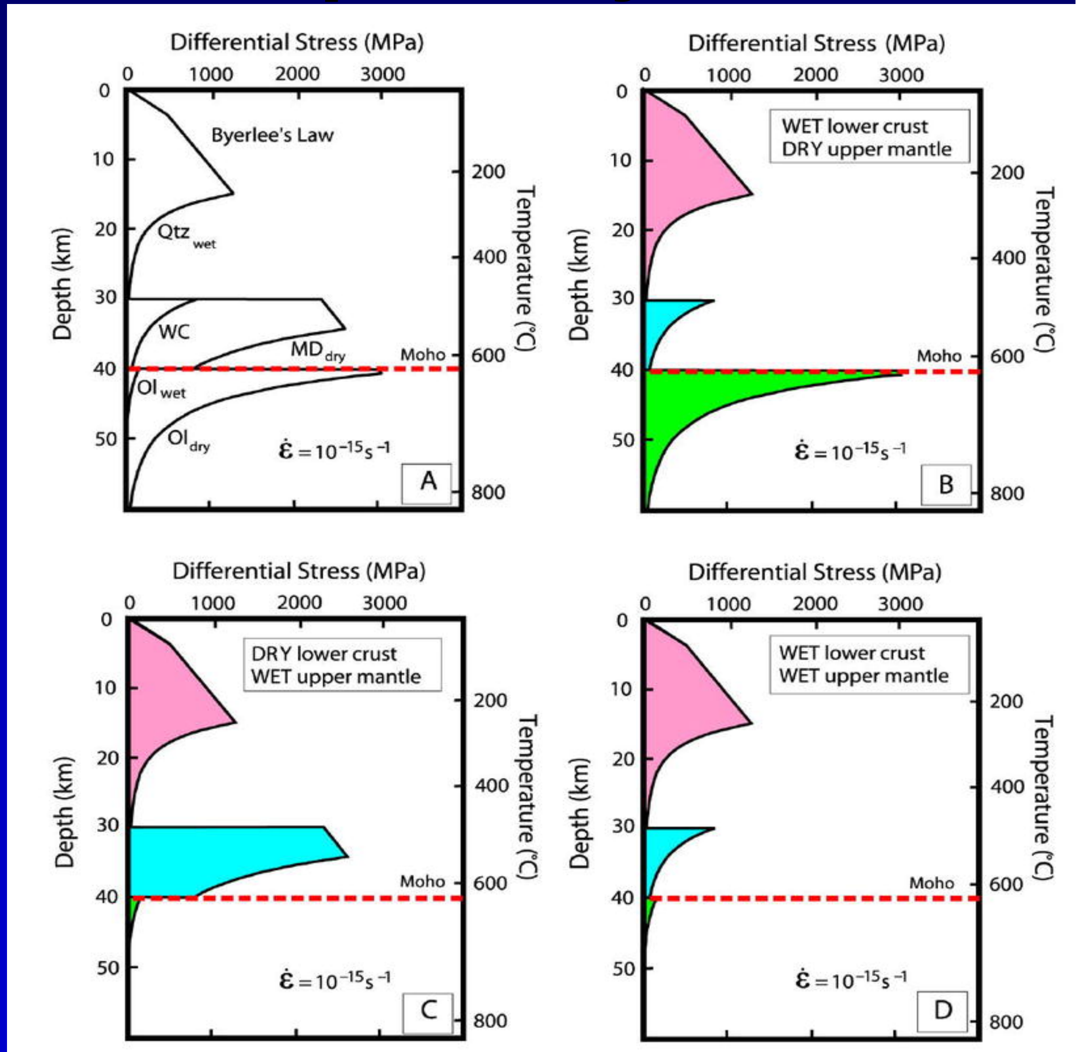
Quartz to Plag/Px to Olivine dominated

Q1

Distributed deformation

Mechanics of the earthquake cycle

- transition from brittle to “ductile” deformation at mid-crustal depth
- the earthquake cycle is modeled as a system of interacting elastic and viscoelastic layers
- laboratory experiments suggest non-linear environment and lithology dependent rheology

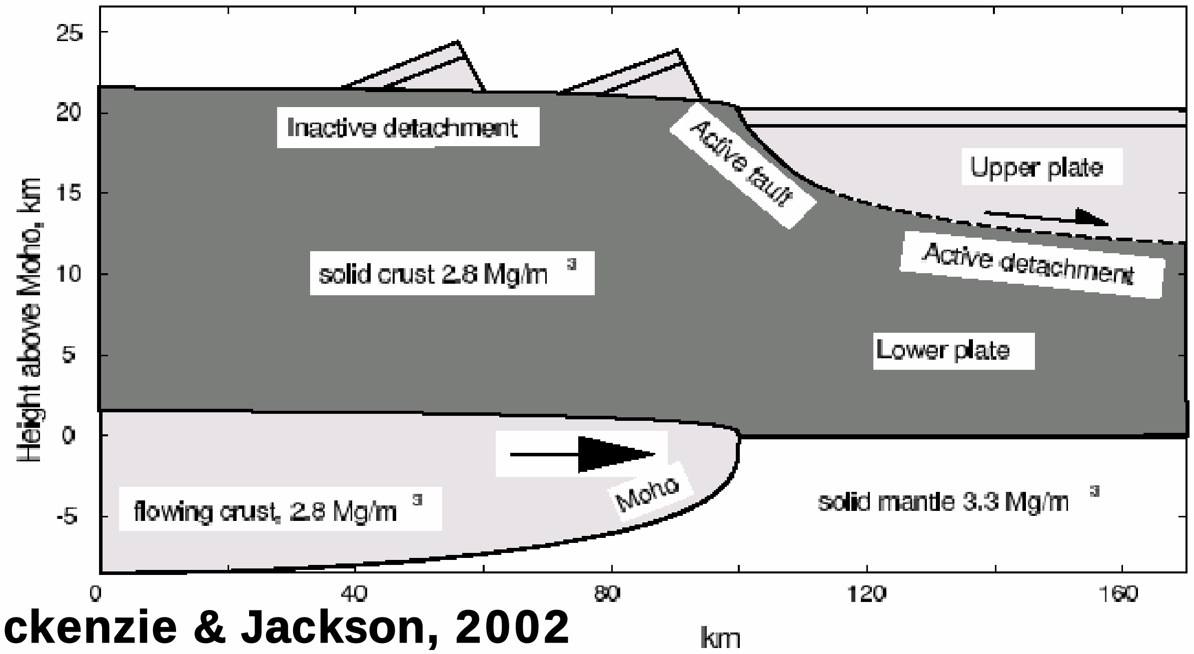


Jackson, 2002

Q1

Conditions for flow in the continental crust

1. **Igneous underplating and intrusion**
2. **Addition of water-rich fluids**



Mckenzie & Jackson, 2002

Heating by magmatism imposes a timing constraint that will govern the time and length scale of the flow

Q1

Distributed vs. Localized deformation:

Mechanics of the earthquake cycle

distributed	localized
transition from brittle to “ductile” deformation at mid-crustal depth	transition from stick slip (velocity weakening) to stable (velocity strengthening) sliding at mid-crustal depth
the earthquake cycle is modeled as a system of interacting elastic and viscoelastic layers	the earthquake cycle is modeled as a system of slipping fault patches (dislocations)
laboratory experiments suggest non-linear environment-and-lithology dependent rheology	laboratory experiments suggest complex depth, -environment-, scale- and material dependent rate-and-state dependent rheology with changes in strength and slip stability

Q2

From the laboratory ….

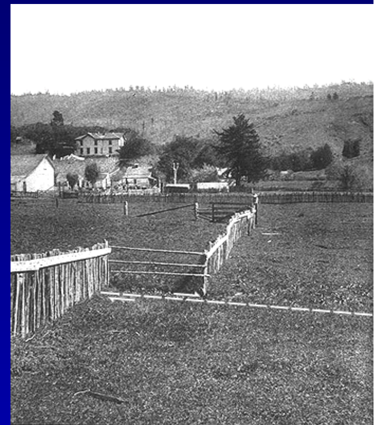
By necessity, rock and fault mechanics lab experiments have to be run on spatial and temporal scales and under conditions far from natural environment




Q2

…. to the Natural Laboratory

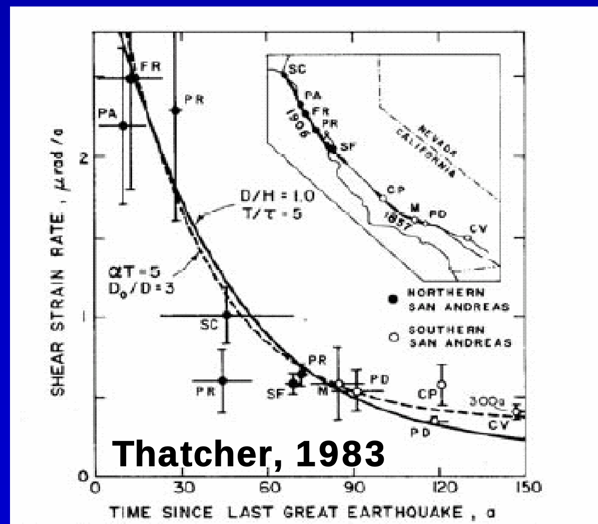
Elastic rebound



a large earthquake initiates a lithosphere-scale rock mechanics experiment

- establish geometry, initial and boundary conditions
- take relevant deformation measurments
- use models to resolve fault / rock constitutive properties

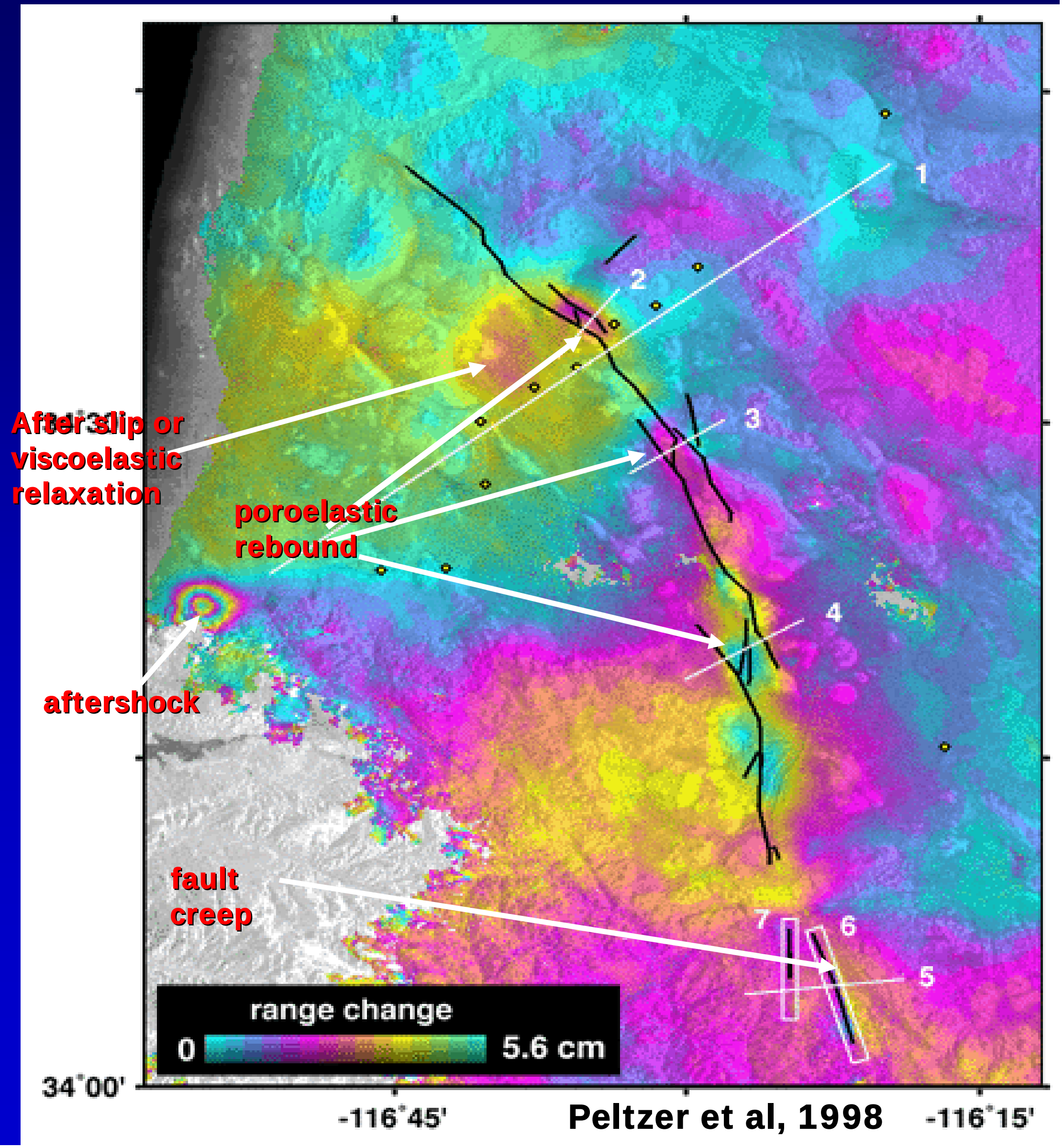
Postseismic relaxation



.... to the Natural Laboratory

Challenges

- limited precision and space-time density of measurements
- limited modelling and computational ressources
- limited resolution and uniqueness in determining source of deformation
- limited ability to resolve multiple processes



Peltzer et al, 1998

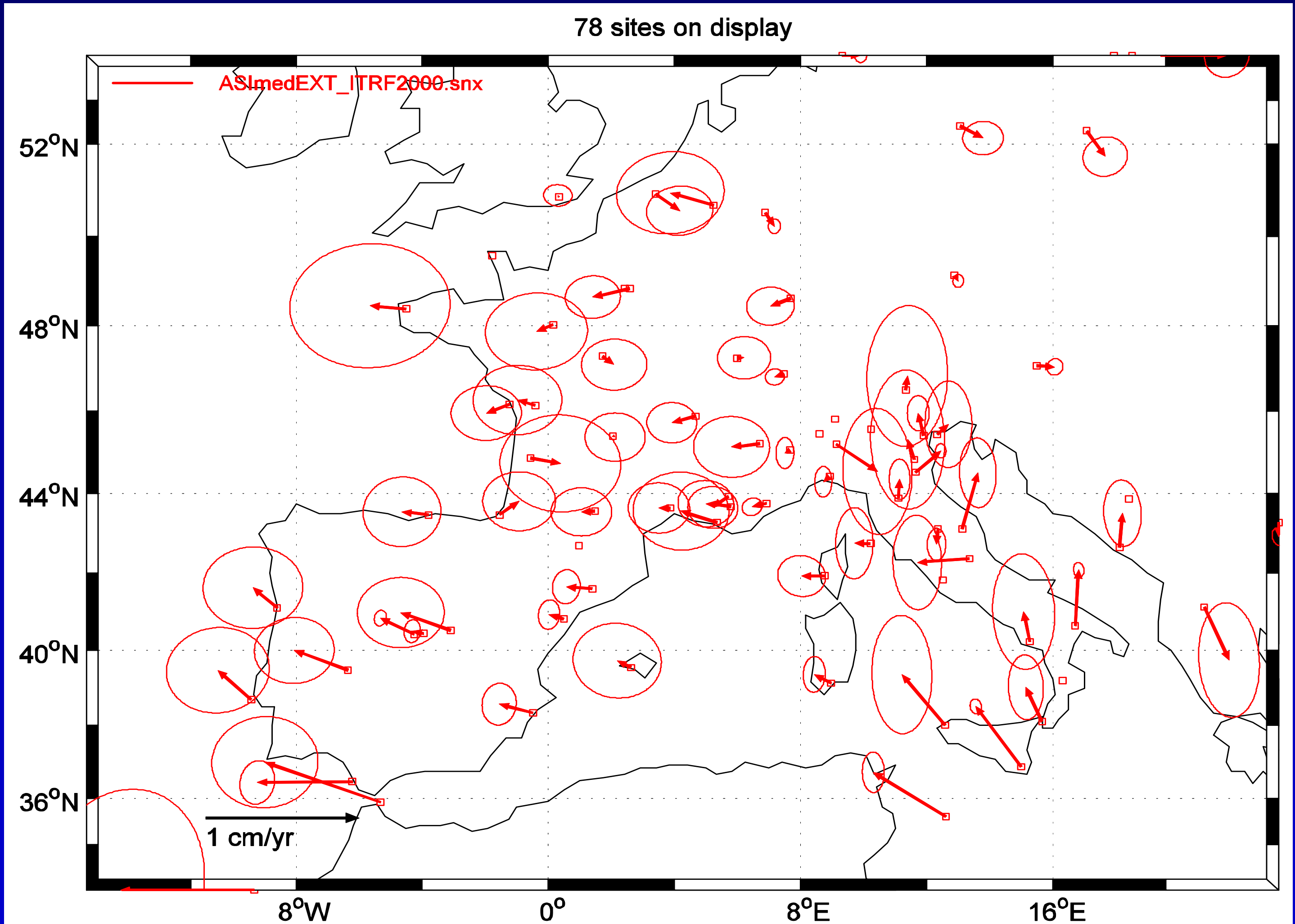
Q2

non-unique models

some solutions

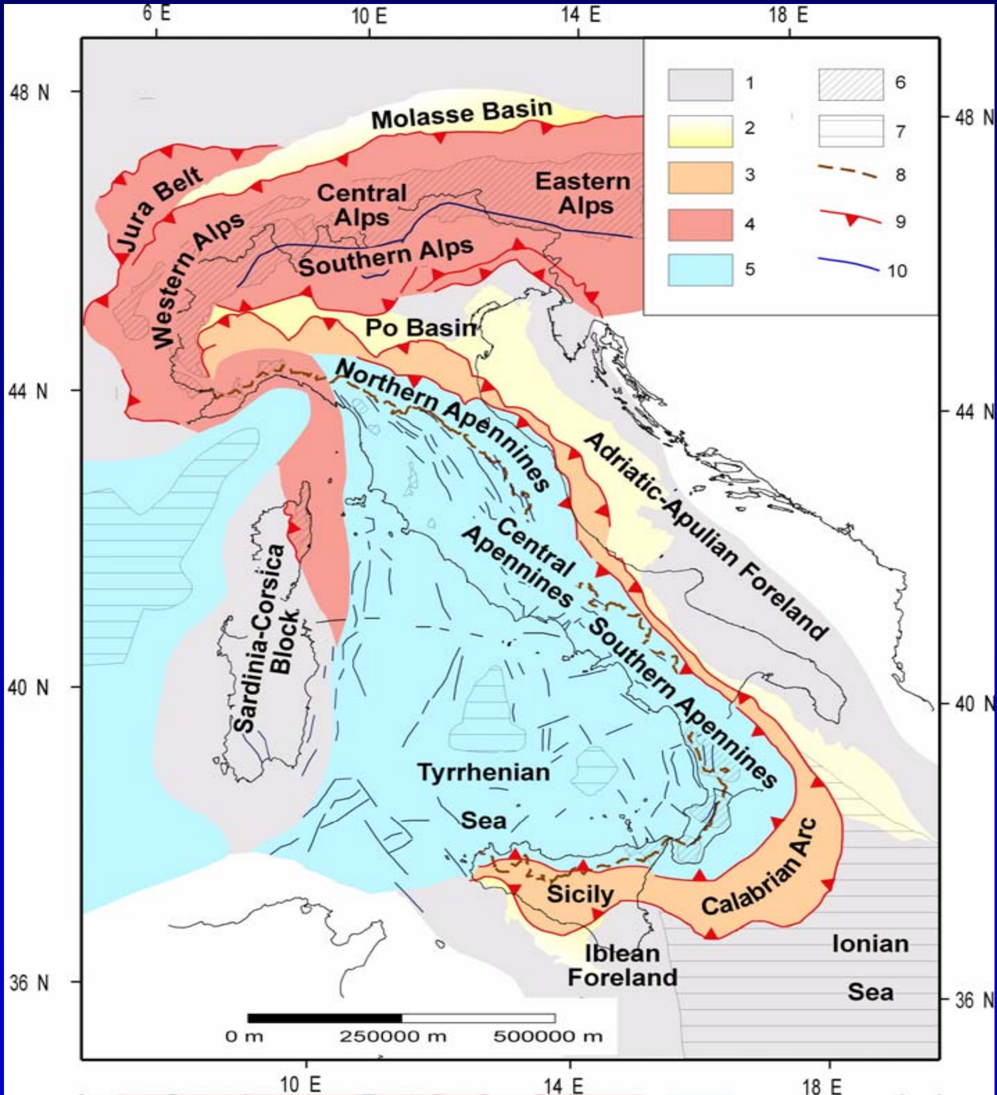
- take geological reality into account
- require models to be consistent with deformation at all time scales, not just single snapshot of the velocity field

GPS Geodesy:
ASI-Geodaf GPS-VLBI-SLR solution

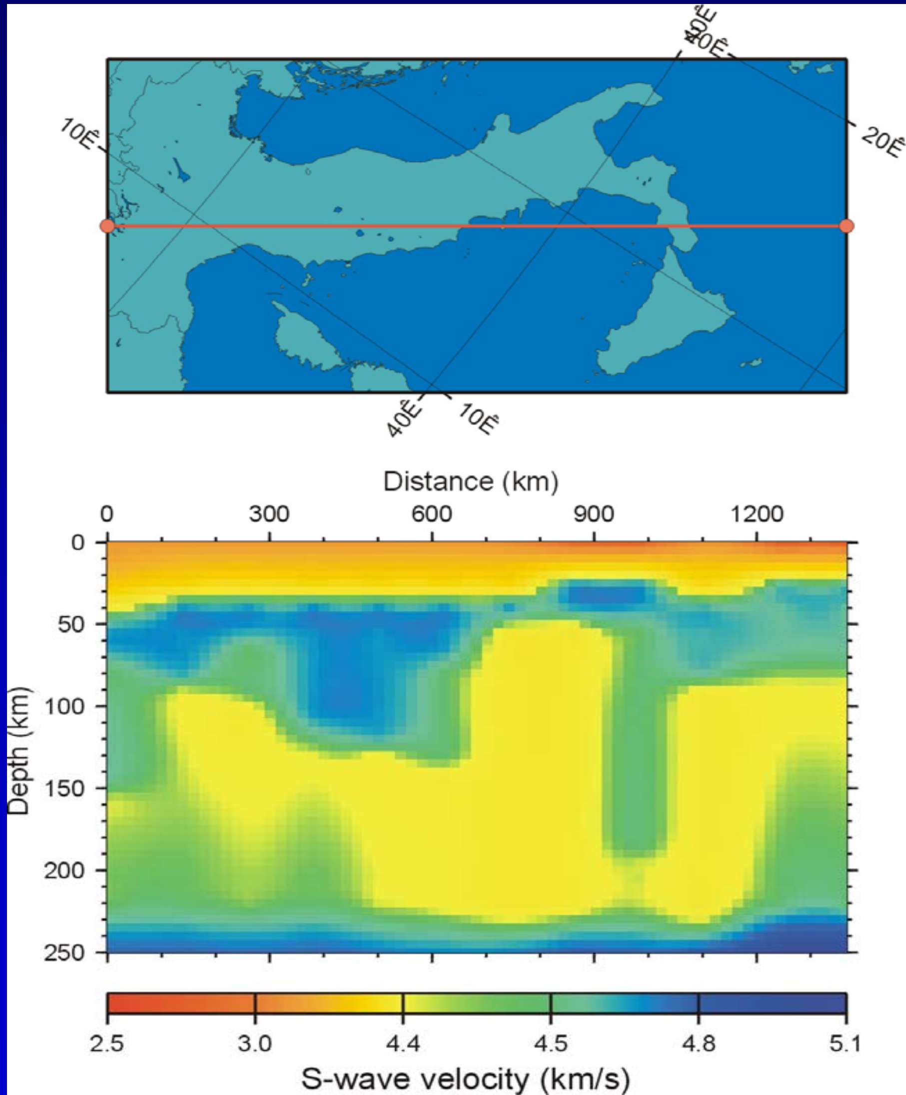


*Src: **Devoti***

General framework

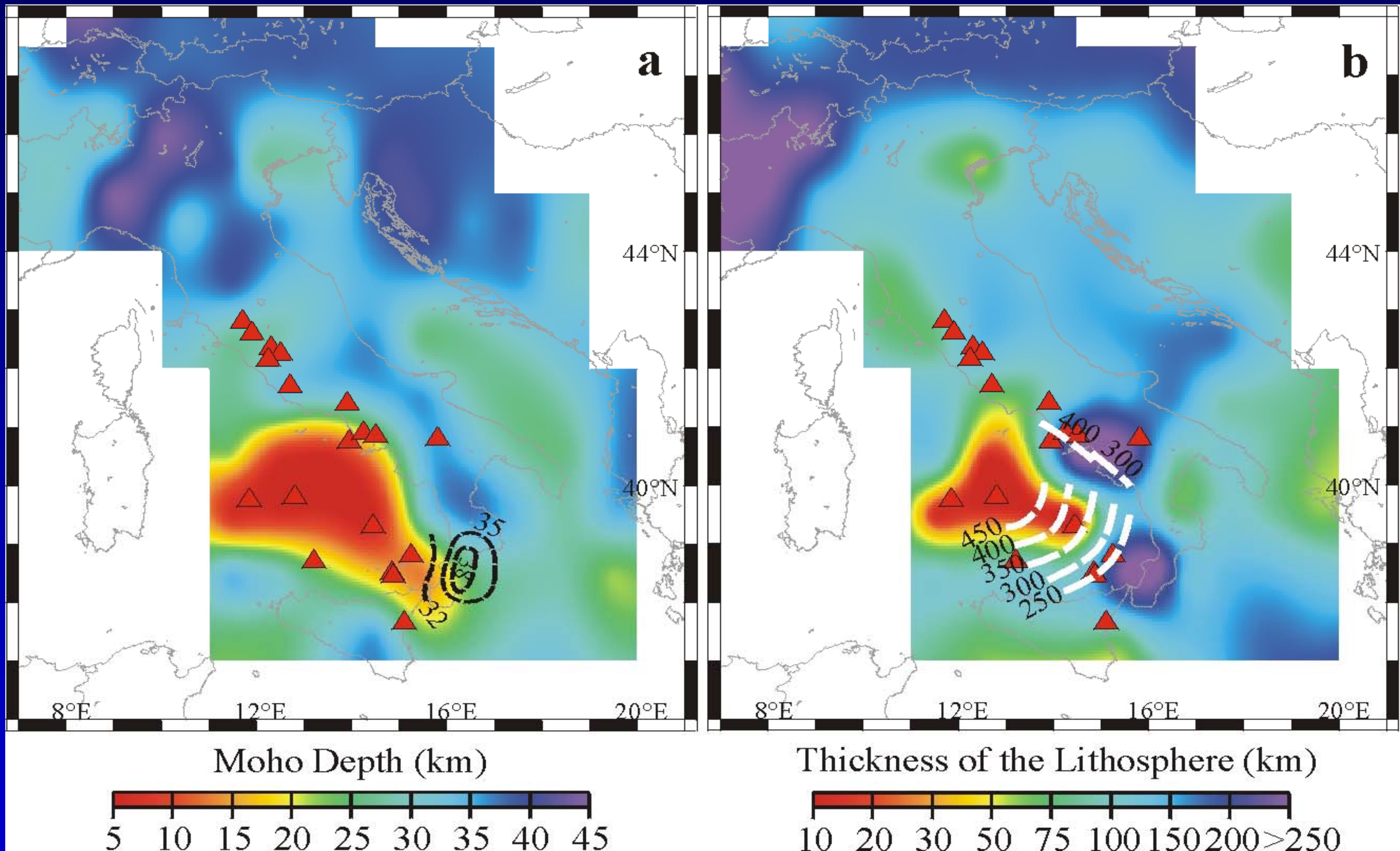


Src: *Doglioni*



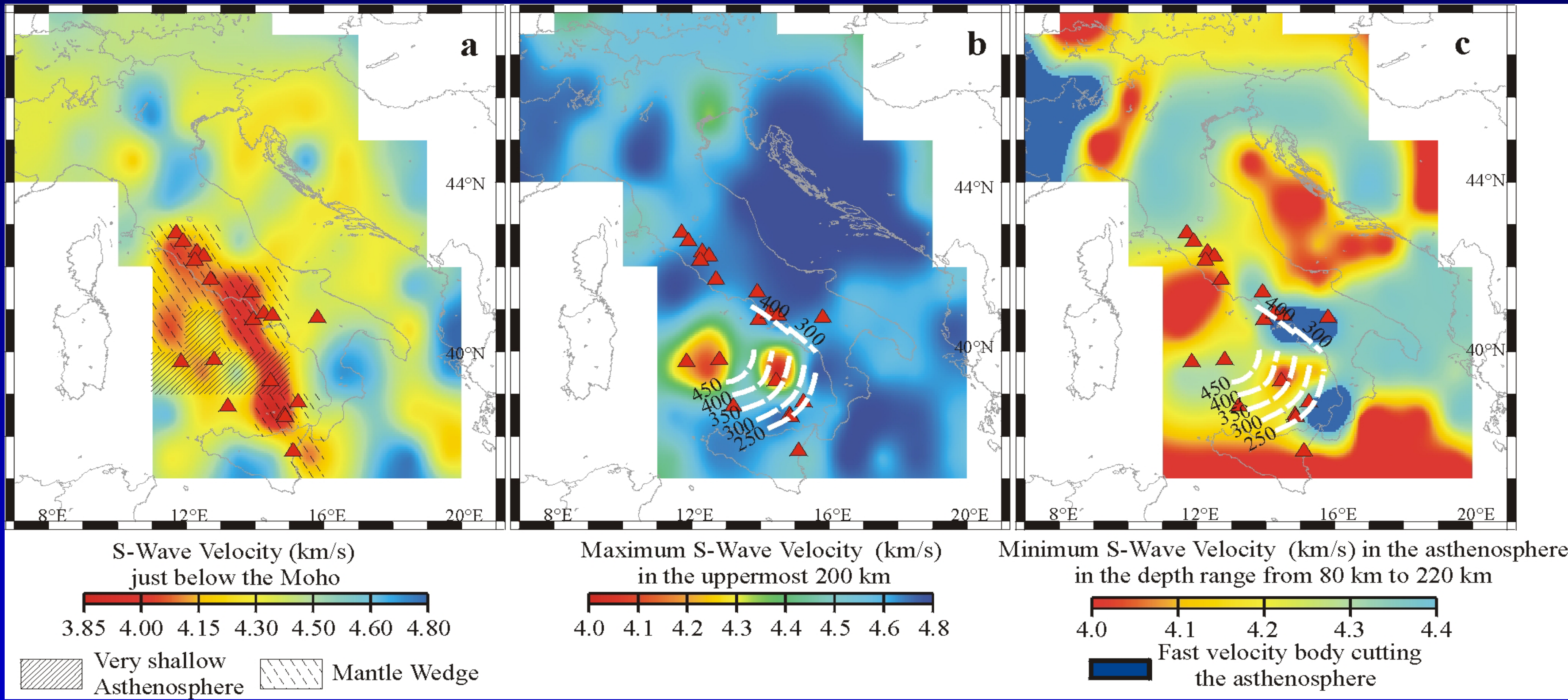
Src: *Du et al., 1998*

Structure of the lithosphere-asthenosphere system



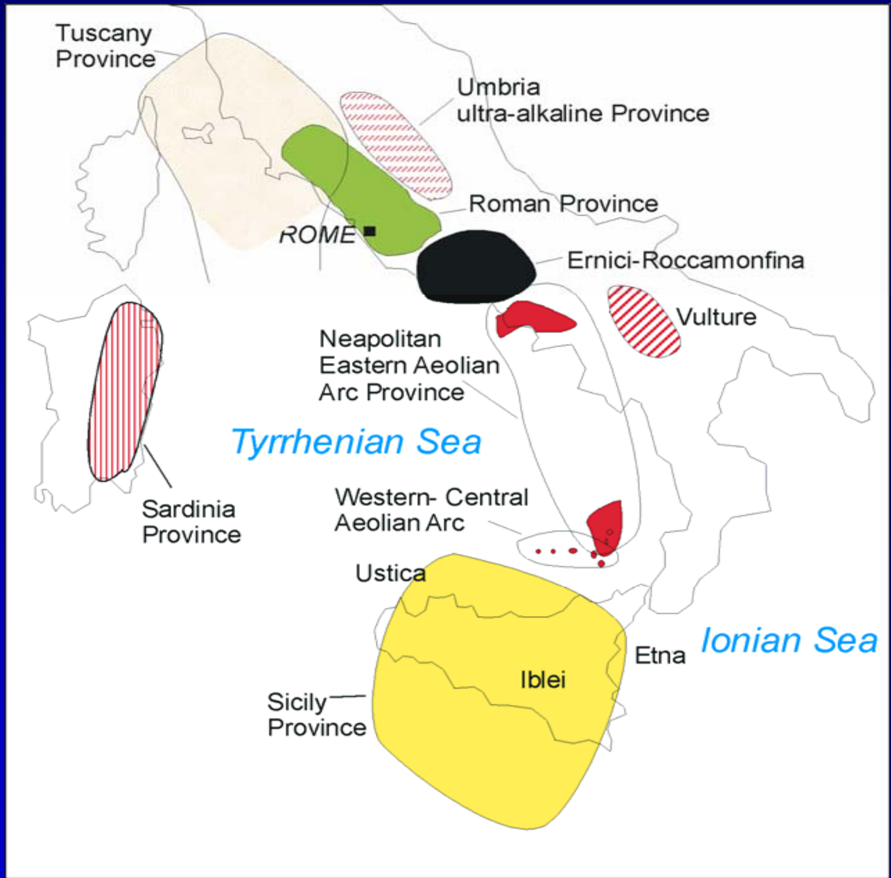
Panza et al. 2003, Episodes

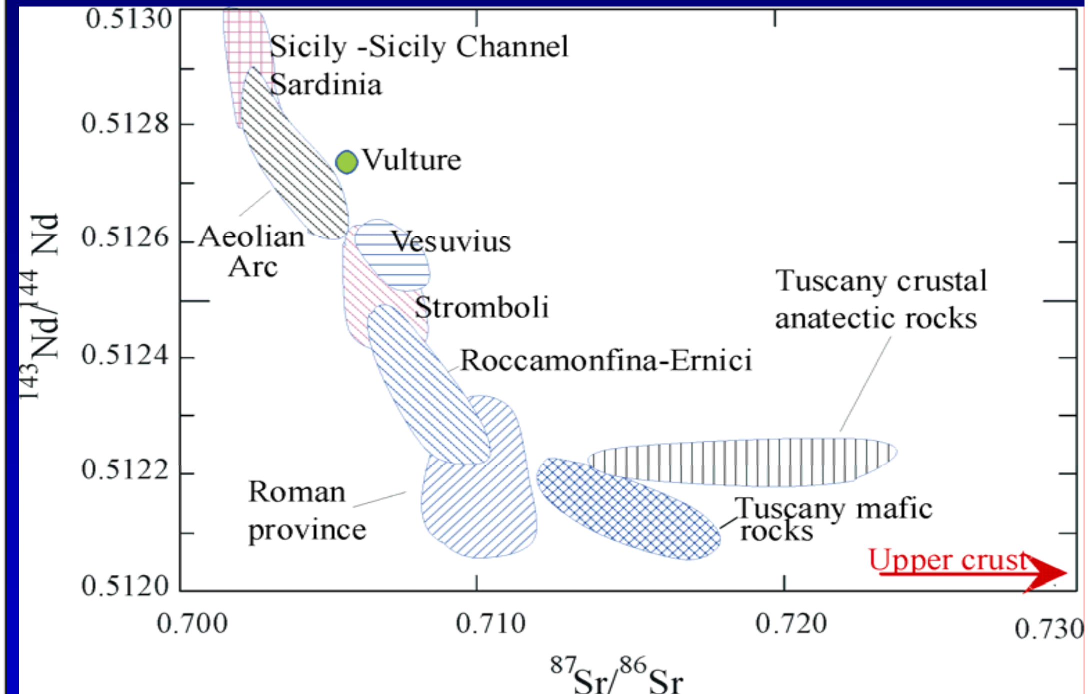
Structure of the lithosphere-asthenosphere system



Panza et al. 2003, Episodes

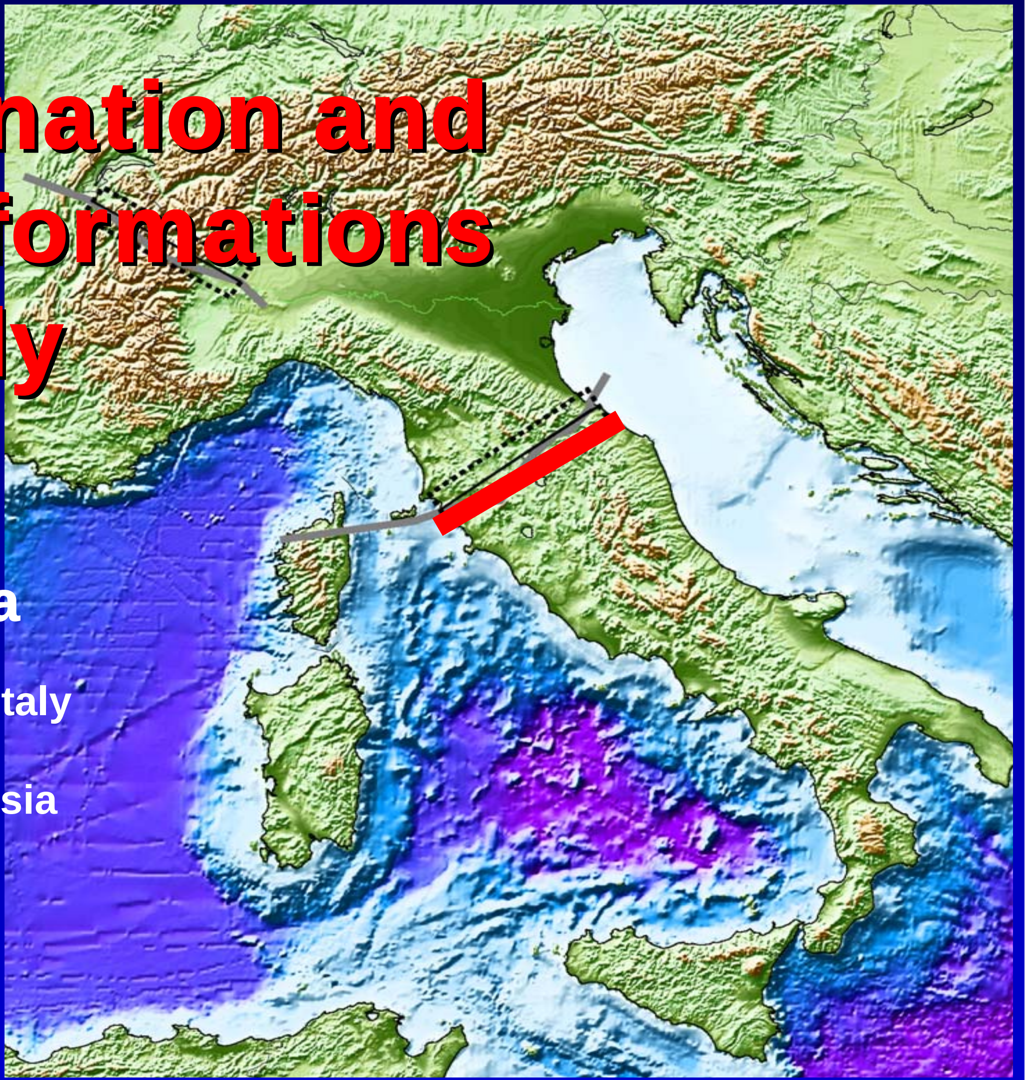
Recent Magmatism





*Src: **Peccerillo***

Lithospheric delamination and buoyancy driven deformations beneath Central Italy

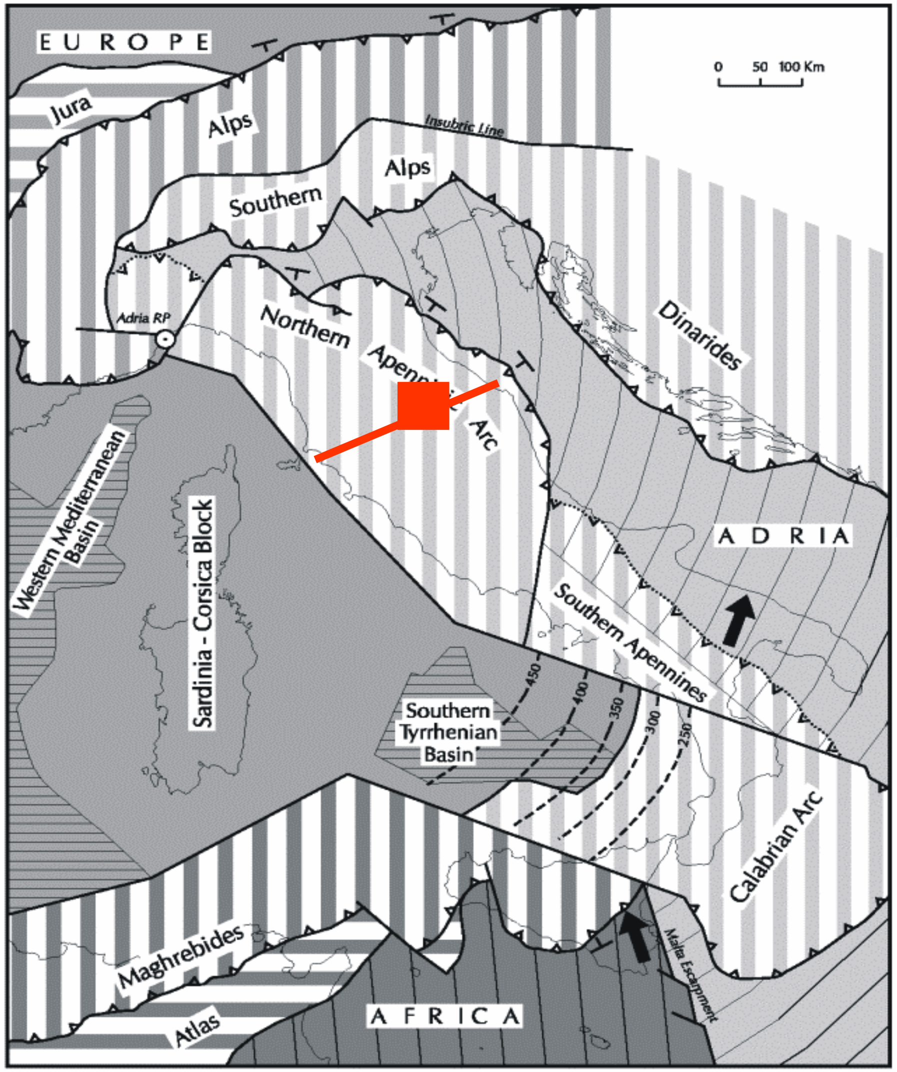


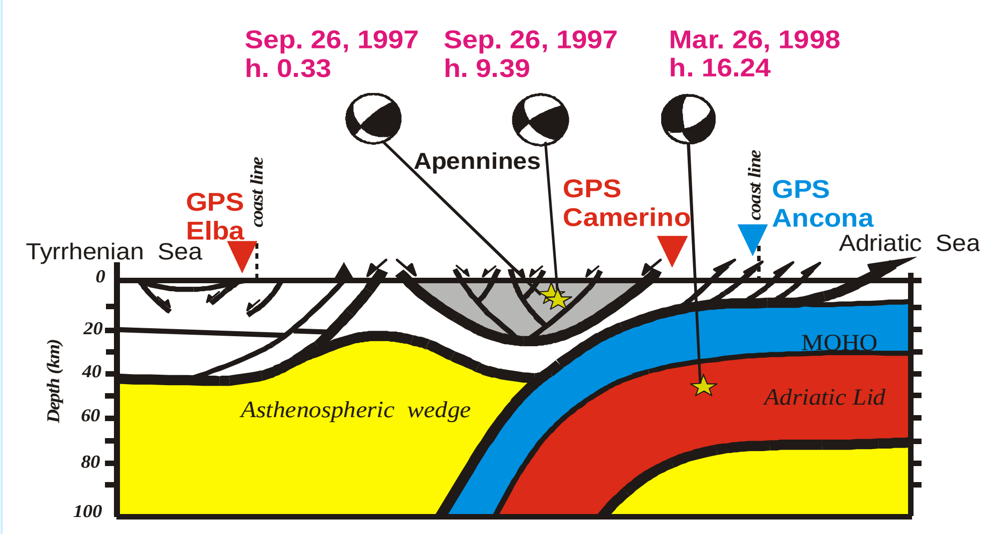
Aoudia, Ismail-Zadeh & Panza

International Centre for Theoretical Physics, Italy
DST, University of Trieste, Italy
MITPAN, Russian Academy of Sciences, Russia

Central Italy

coexisting extension - contraction





Models invoking external forces

- Interactions along plate margins or at the base of the lithosphere
- Subduction processes:
  - slab roll-back,
  - slab pull,
  - slab break-off

What next?

image the continental deformation over the widest possible range of spatial and temporal scales

Scale of the FAULT zone

Scale of the PLATE boundary: lithosphere-asthenosphere

- **knowledge of the structure of the earth at the required length scale,**
- **particular emphasis on detection of transient deformation signals**

appreciation of the nature and scale of the mechanical properties of the continental lithosphere

stress ← rheology → strain

GPS monitoring

- **monumentation on rock**

- **antenna forced centering with sub-millimetre repeatabiliy (*ad hoc* designed antenna mount, thoroidal level for vertical positioning)**

- **spirit levelling on each site to check for local vertical stability**

how did we proceed?

image the fault zone and the lithosphere (Chimera et al., PEPI 2003)

- **Surface wave tomography,**
- **Non-linear inversion for the earth structure retrieval with CROP as a-priori data (*resolution and lateral variations*),**
- **Surface wave and complete waveform inversion for the source moment tensors**

chase the viscosity in the lithosphere (Aoudia et al., GRL 2003)

- **Post-seismic deformation following the Umbria-Marche 1997 earthquake sequence;**
- **Postseismic deformation vs. geodynamics**

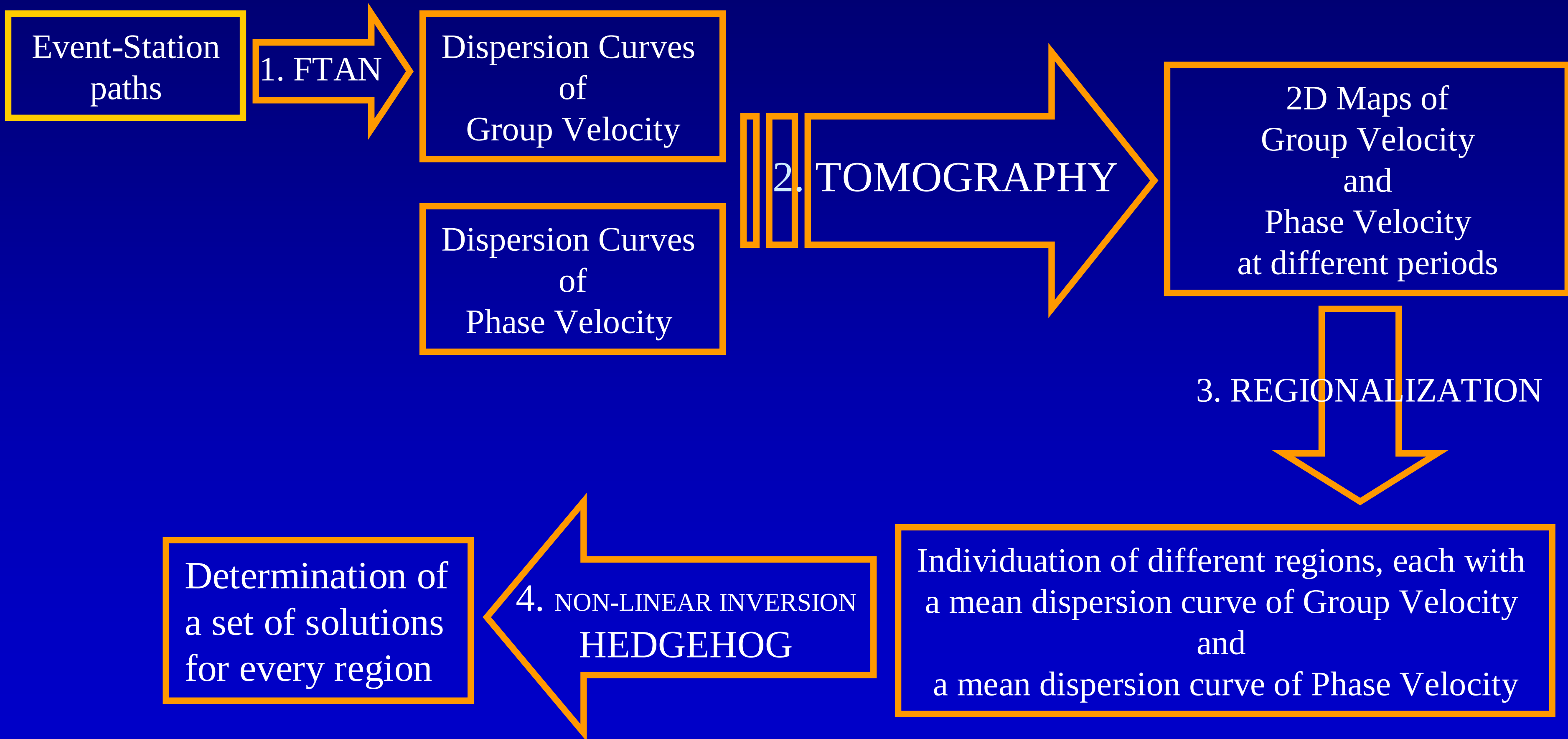
integrate a number of different geophysical observations into one unified model (Aoudia et al., GRL 2004)

- **finite element modeling of the lithosphere flow,**
- **solve for a velocity and stress field**

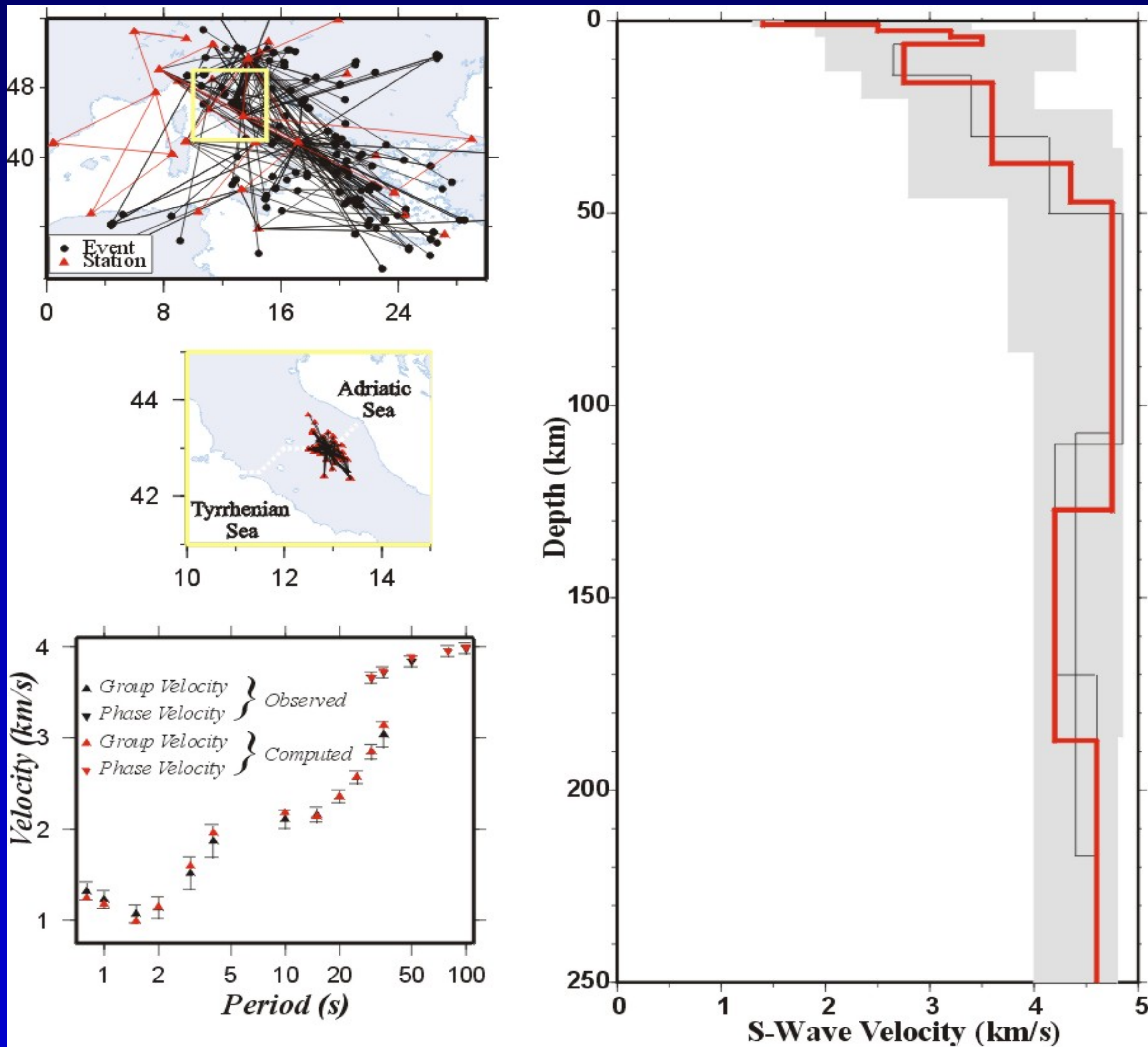
Data

- **Seismic waveforms: GNDT-OGS, SSN, VBB Stations;**
- **Existing Velocity Models: EurId (Du et al. PEPI-1998; Pontevivo & Panza, PEPI-2002), Deep seismic soundings: CROP and similar (e.g. Pialli et al. MSGI-1998; Bally et al. MSGI-1986);**
- **Active Faults (INGV-GNDT)**
- **Gravimetry (Marson) and Heat flow data (Della Vedova)**

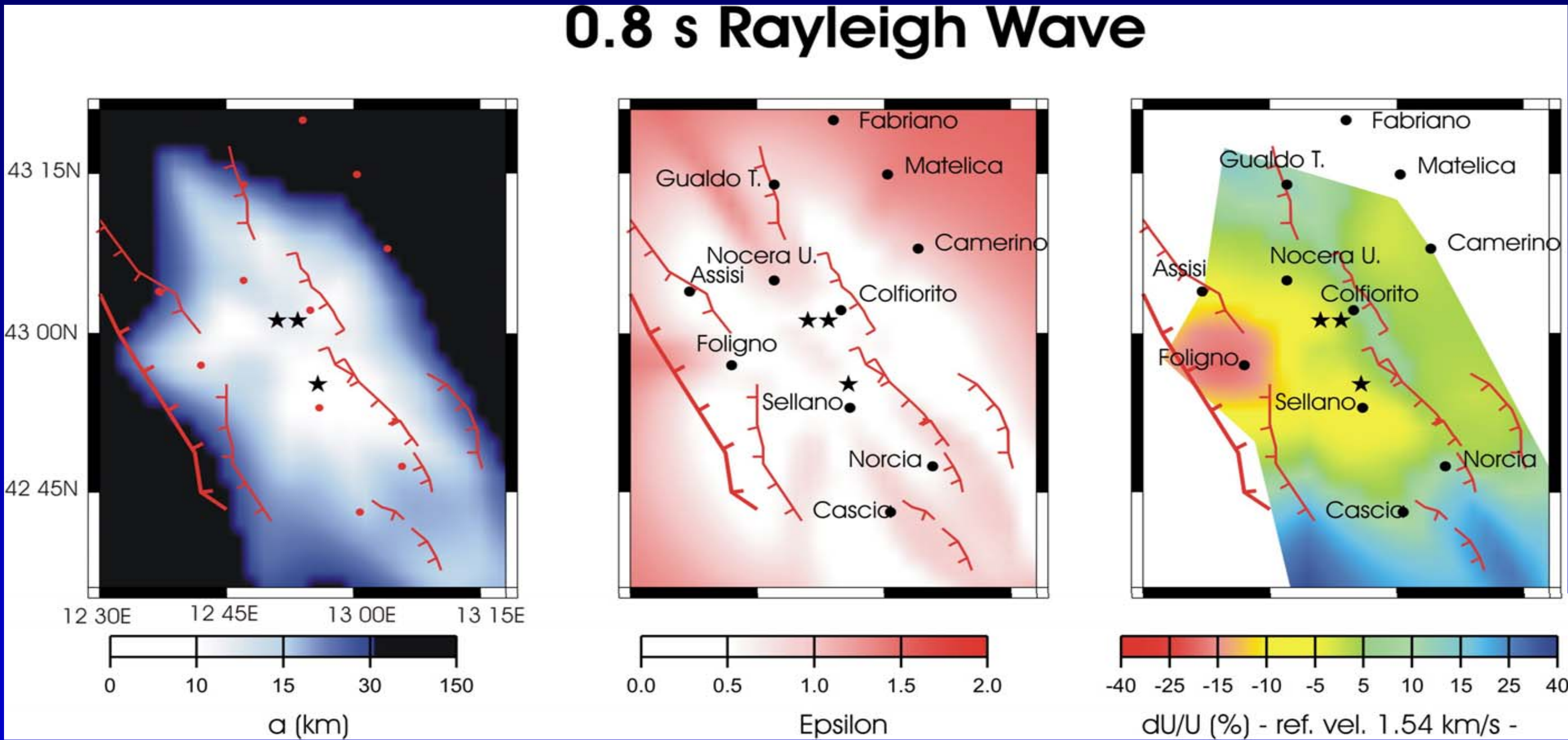
The Method


Event-Station paths
1. FTAN
Dispersion Curves of Group Velocity
Dispersion Curves of Phase Velocity
2. TOMOGRAPHY
2D Maps of Group Velocity and Phase Velocity at different periods
3. REGIONALIZATION
Individuation of different regions, each with a mean dispersion curve of Group Velocity and a mean dispersion curve of Phase Velocity
4. NON-LINEAR INVERSION HEDGEHOG
Determination of a set of solutions for every region

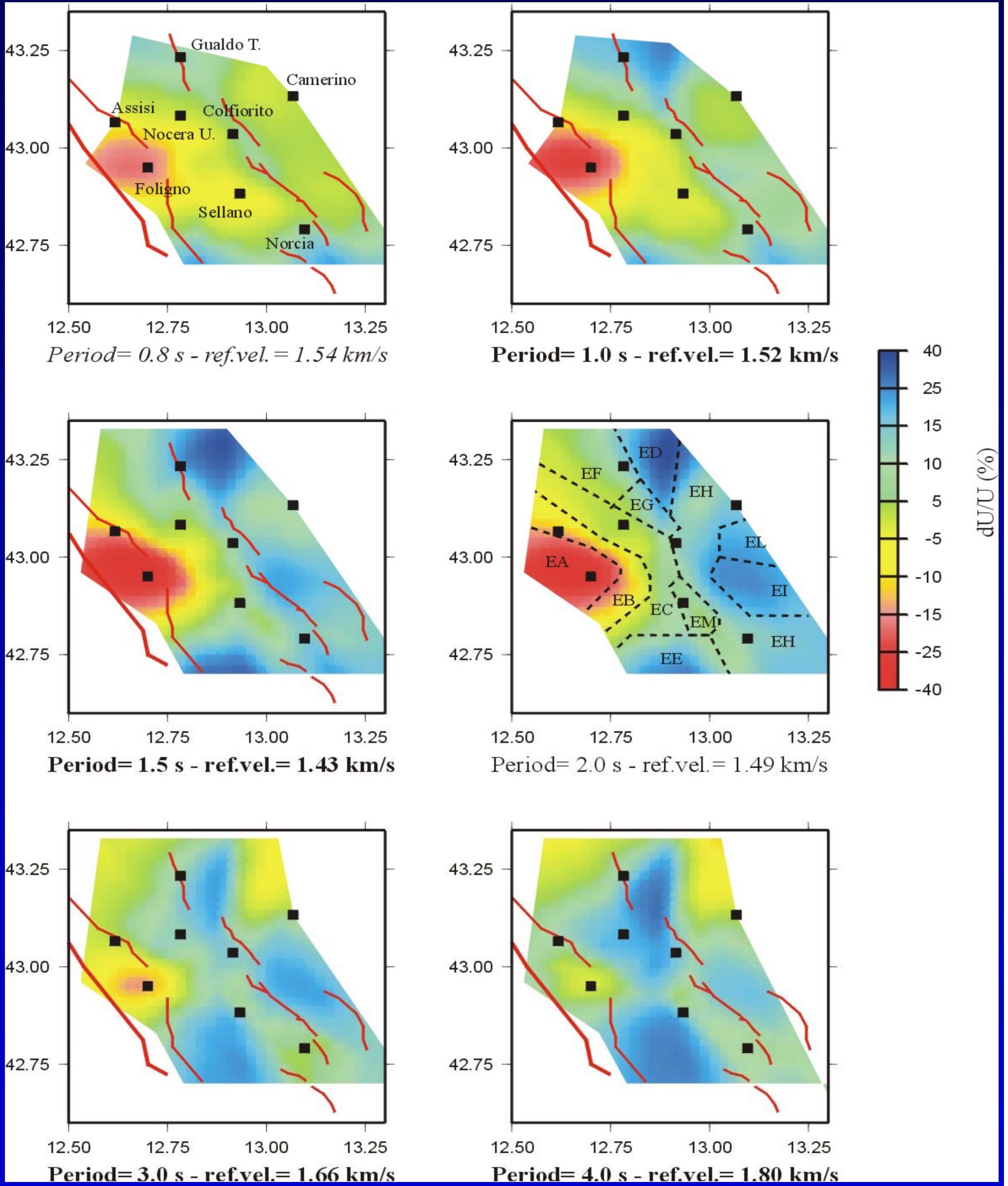
Synoptic view of all dispersion profiles considered and observed dispersion measurements compared with the group and phase velocity values computed for the accepted S-wave solution



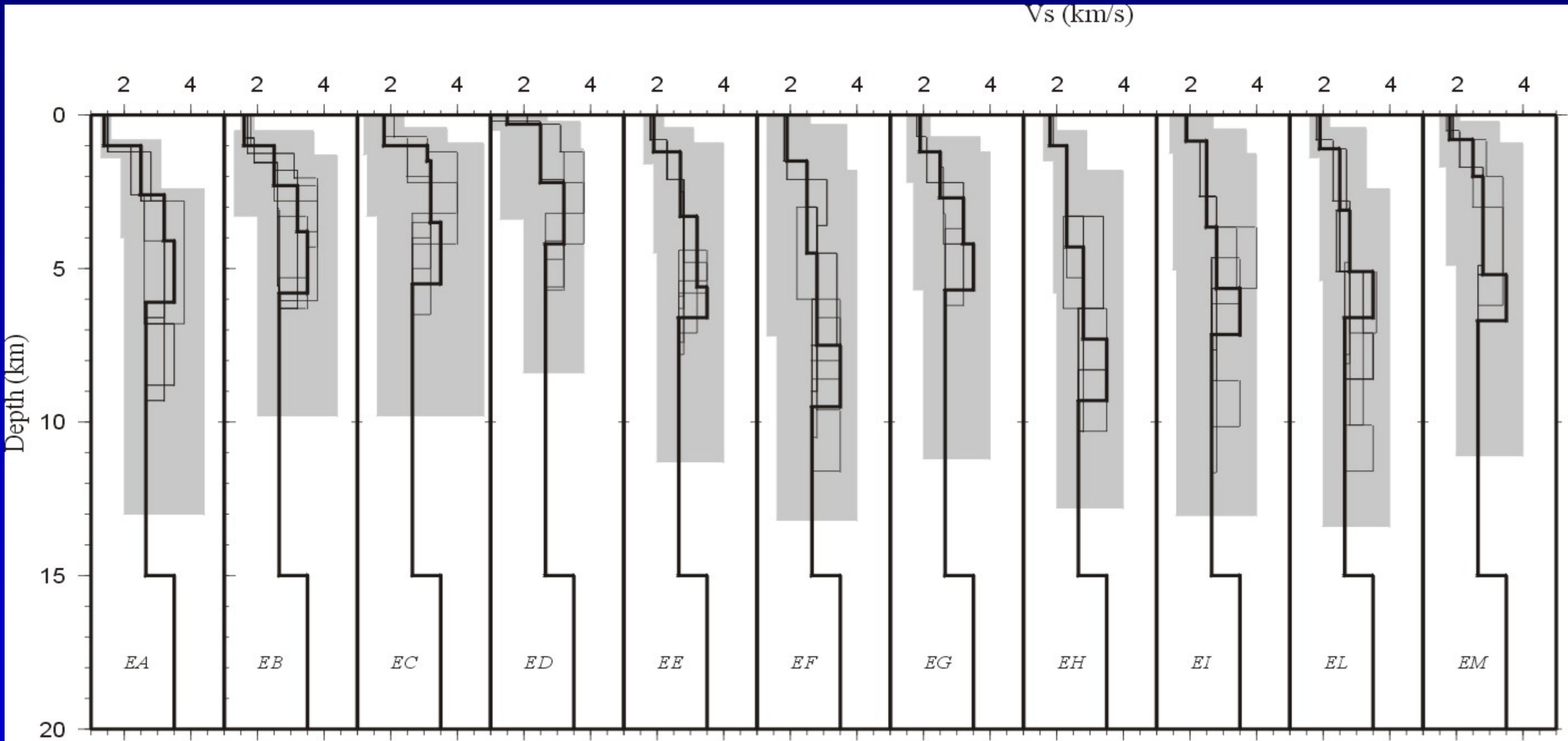
Resolution and tomography maps



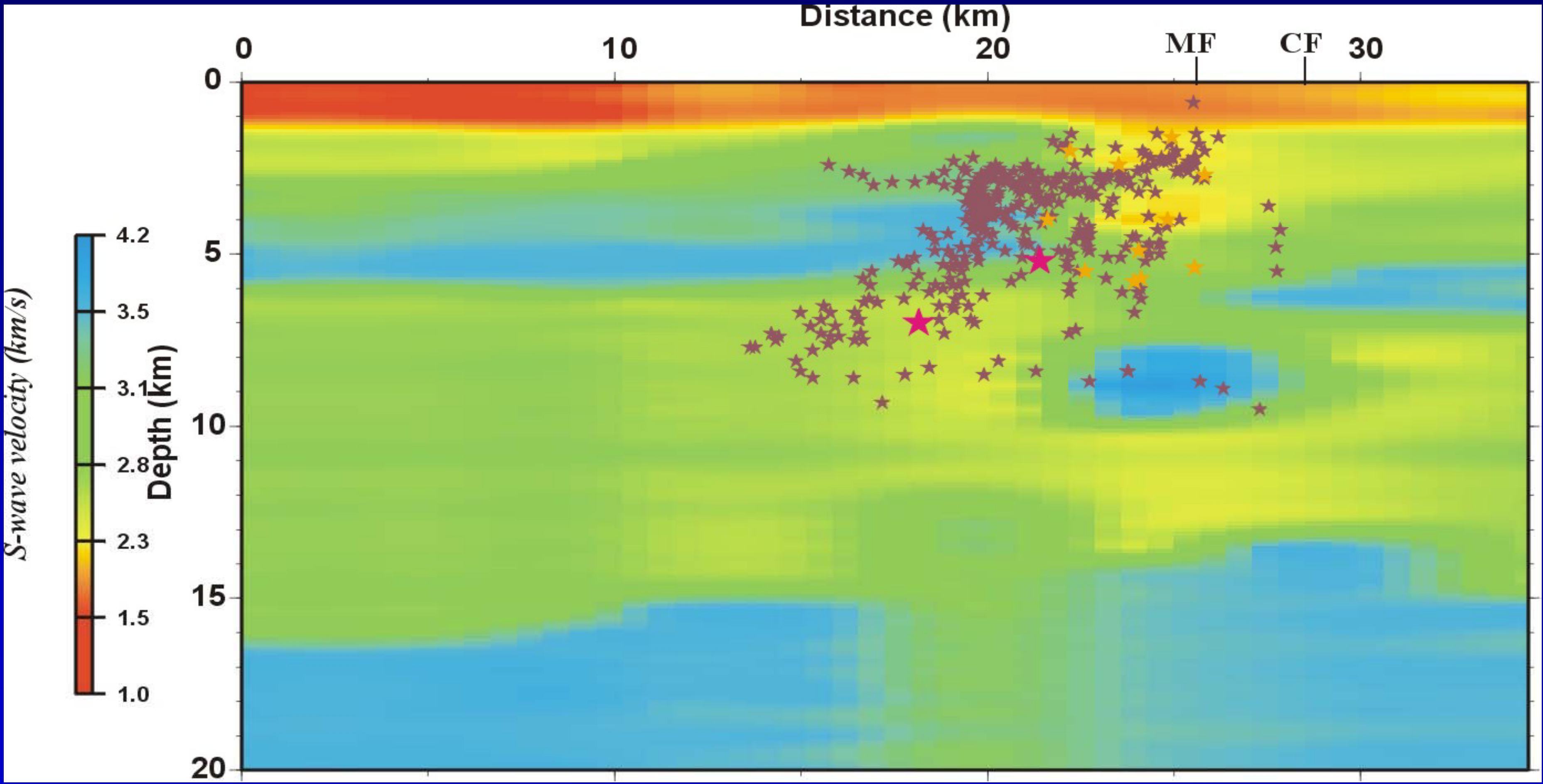
Active faults in Umbria-Marche and Rayleigh waves group velocity variations, at different periods, from the average reference velocity (% deviation)



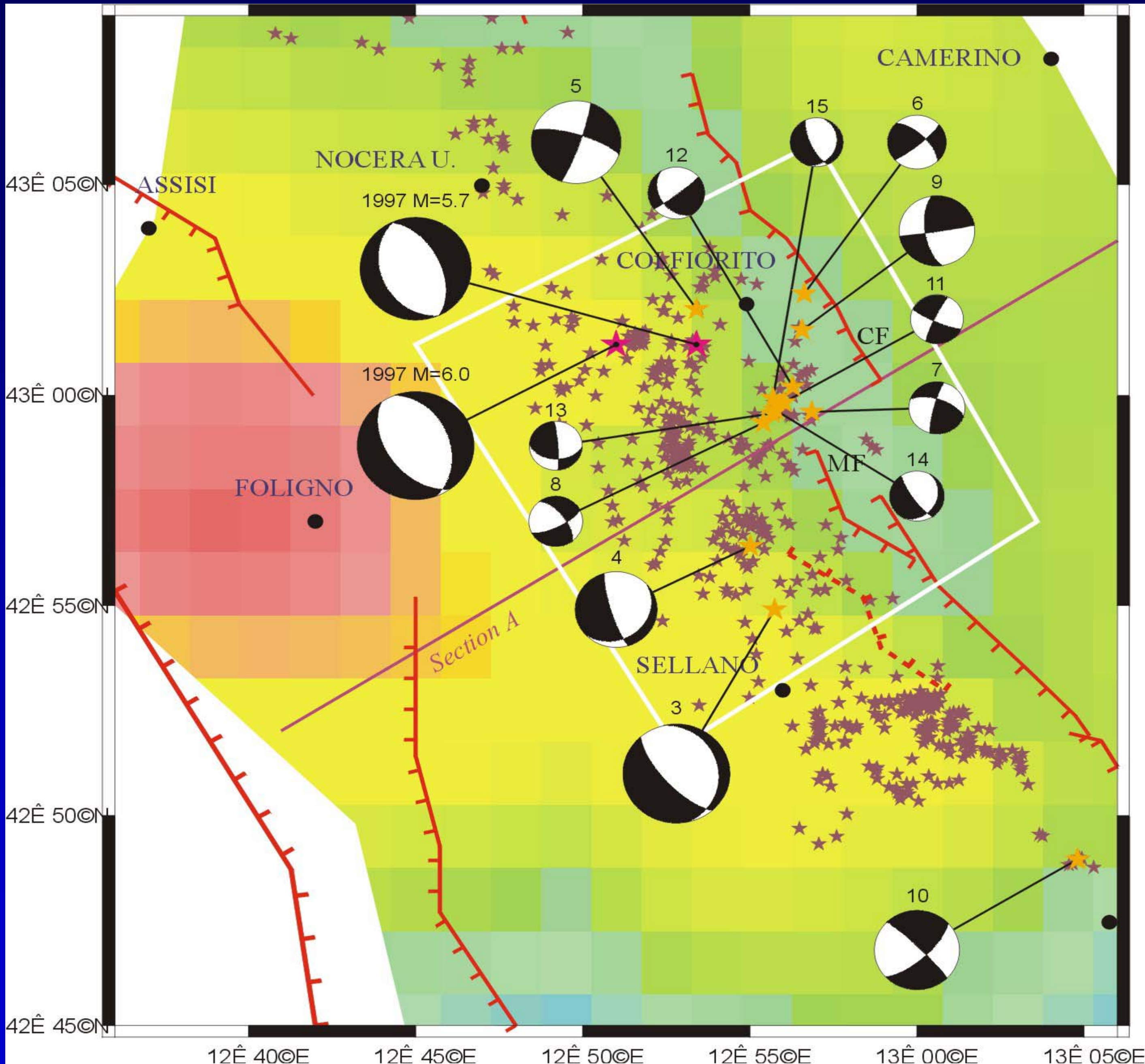
Shallow Velocity models beneath the Umbria-Marche Apennines



Section across the fault zone

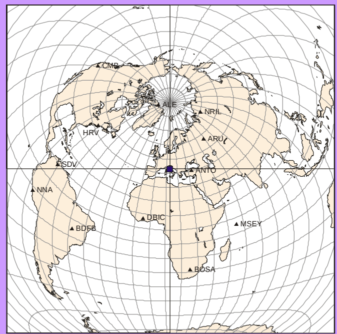


Fault plane solutions of the 1997 Umbria-Marche earthquake sequence

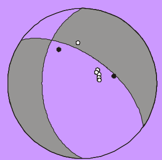


Umbria earthquake, 1997/09/26 00:33, M_b=5.5, M_s=5.6

Stations used for source parameters
determination from long period surface wave spectra (50s-80s)

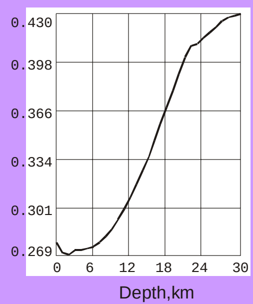


The best double couple obtained
by joint inversion of surface wave
amplitude spectra and
first arrival polarities



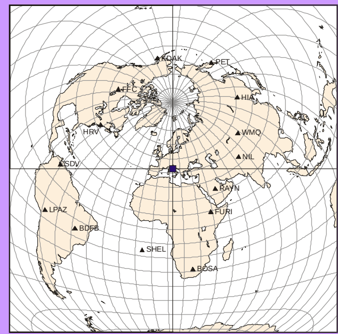
Residual=0.269 Mo=.39e+18N•m
P1: 180°,45°, -45°, P2:305°,60°, -125°

Residual as function of source depth

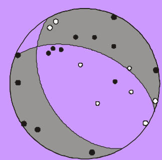


Umbria earthquake, 1997/09/26 09:40, M_b=5.7, M_s=6.0

Stations used for source parameters
determination from long period surface wave spectra (60s-100s).

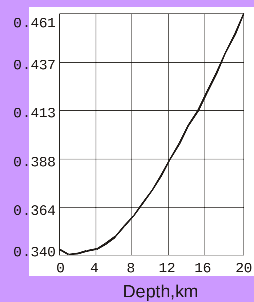


The best double couple obtained
by joint inversion of surface wave
amplitude spectra and
first arrival polarities

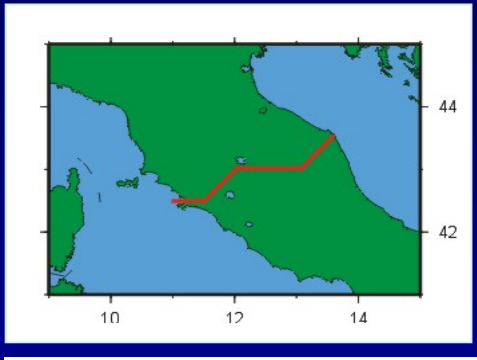


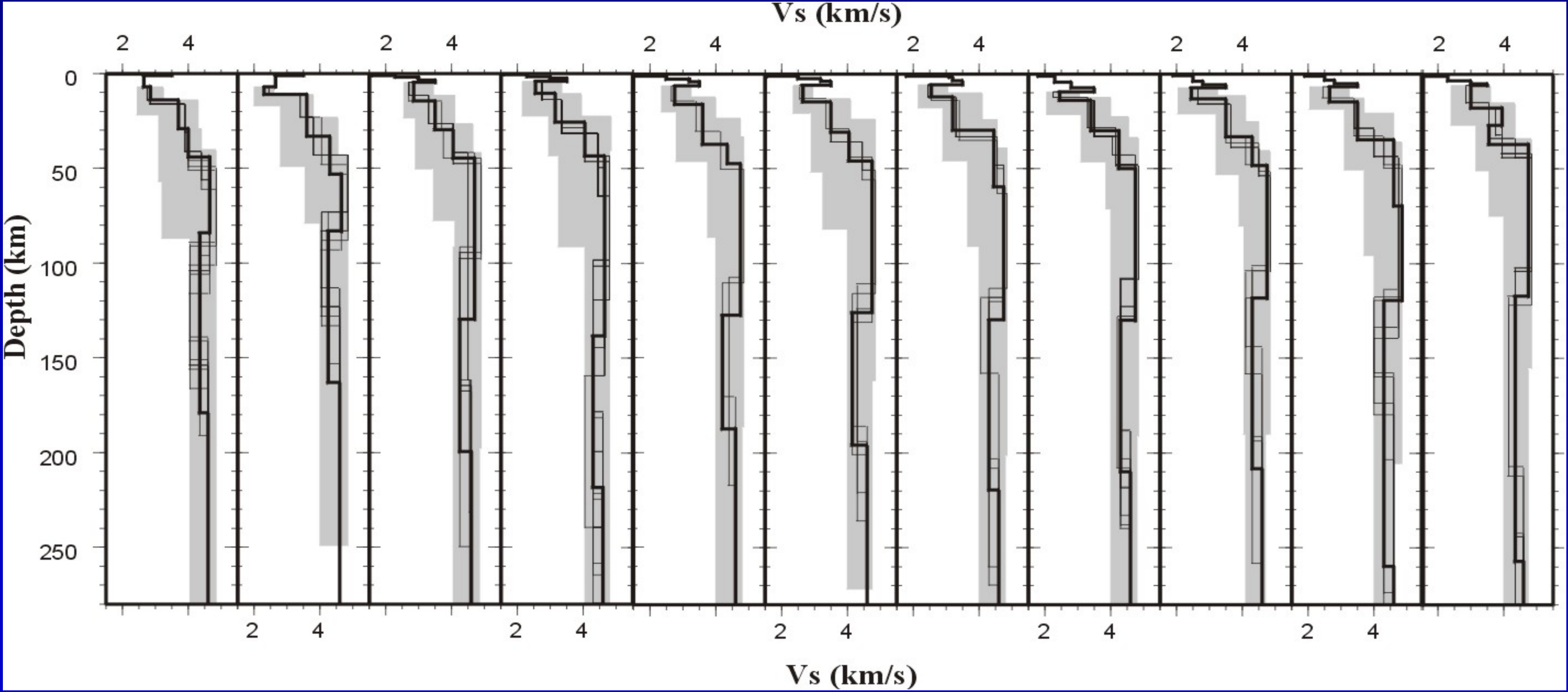
Residual=0.340 Mo=.11e+19N•m
P1: 150°,45°, -60°, P2:291°,52°, -117°

Residual as function of source depth

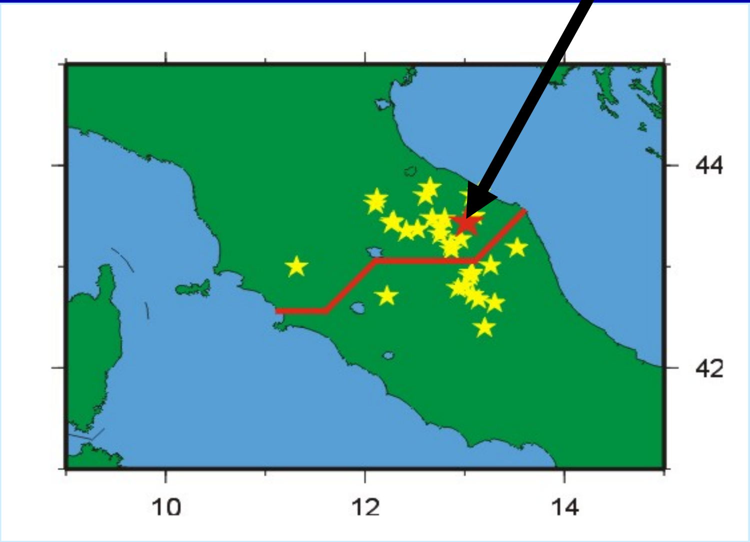


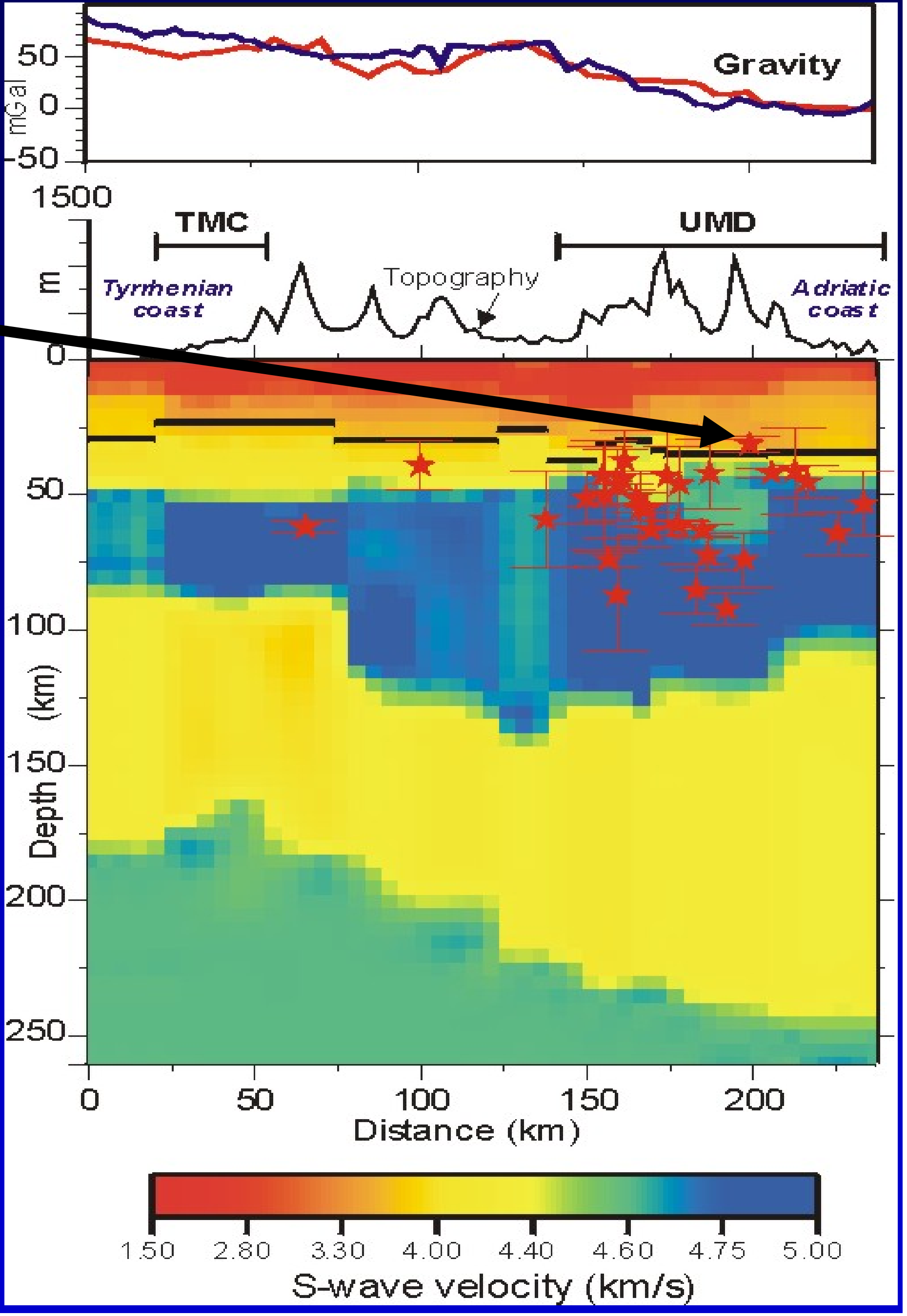
Velocity Models beneath North-Central Italy



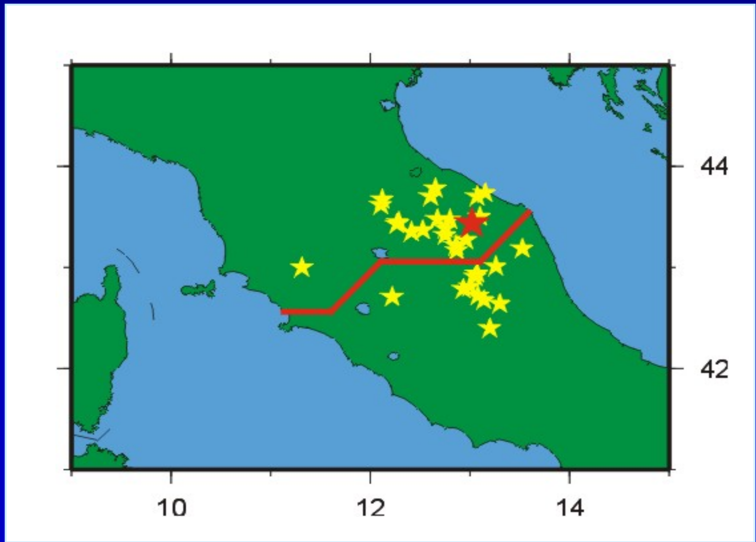


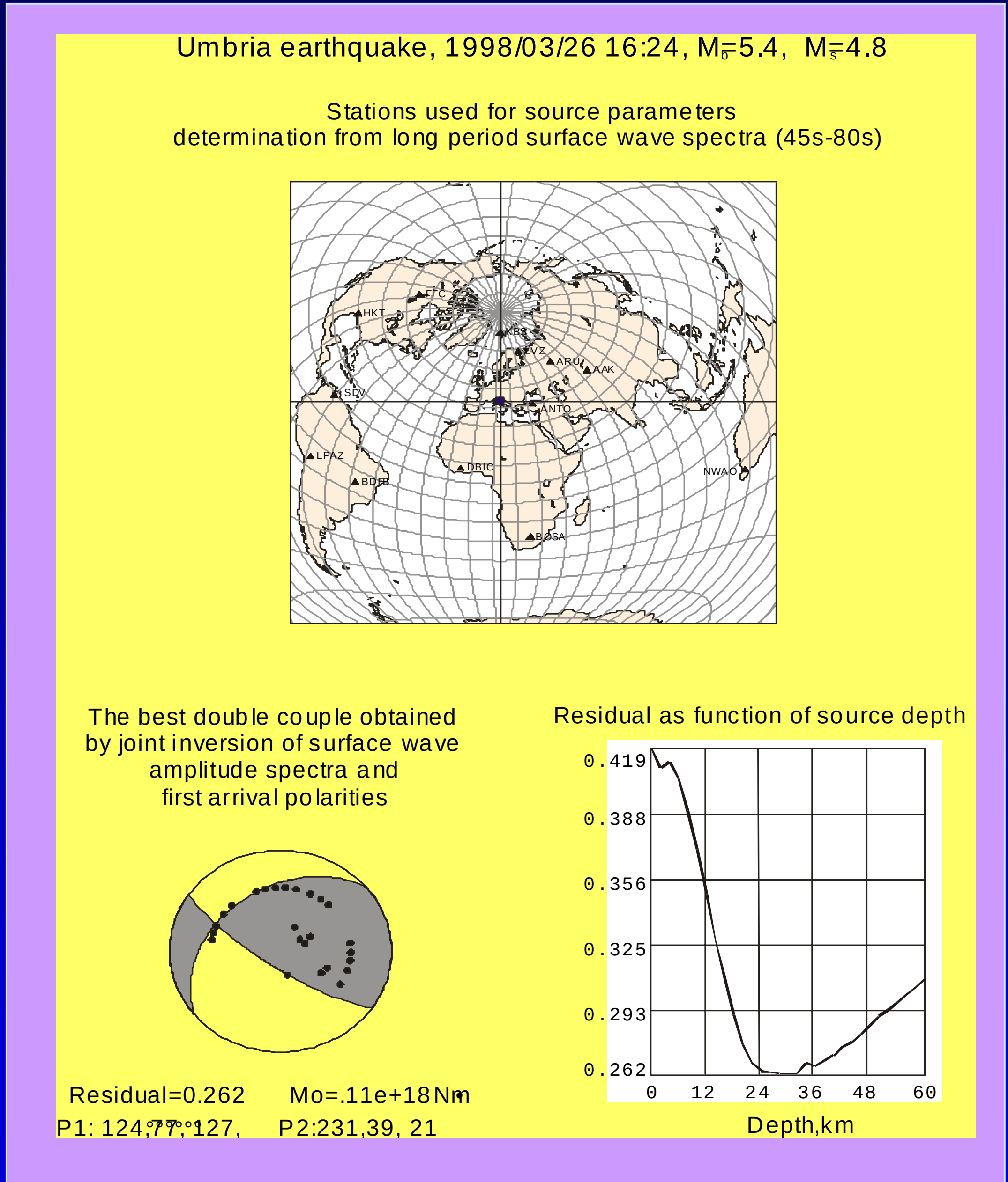
Crust-upper mantle structure beneath North-Central Italy supports delamination processes



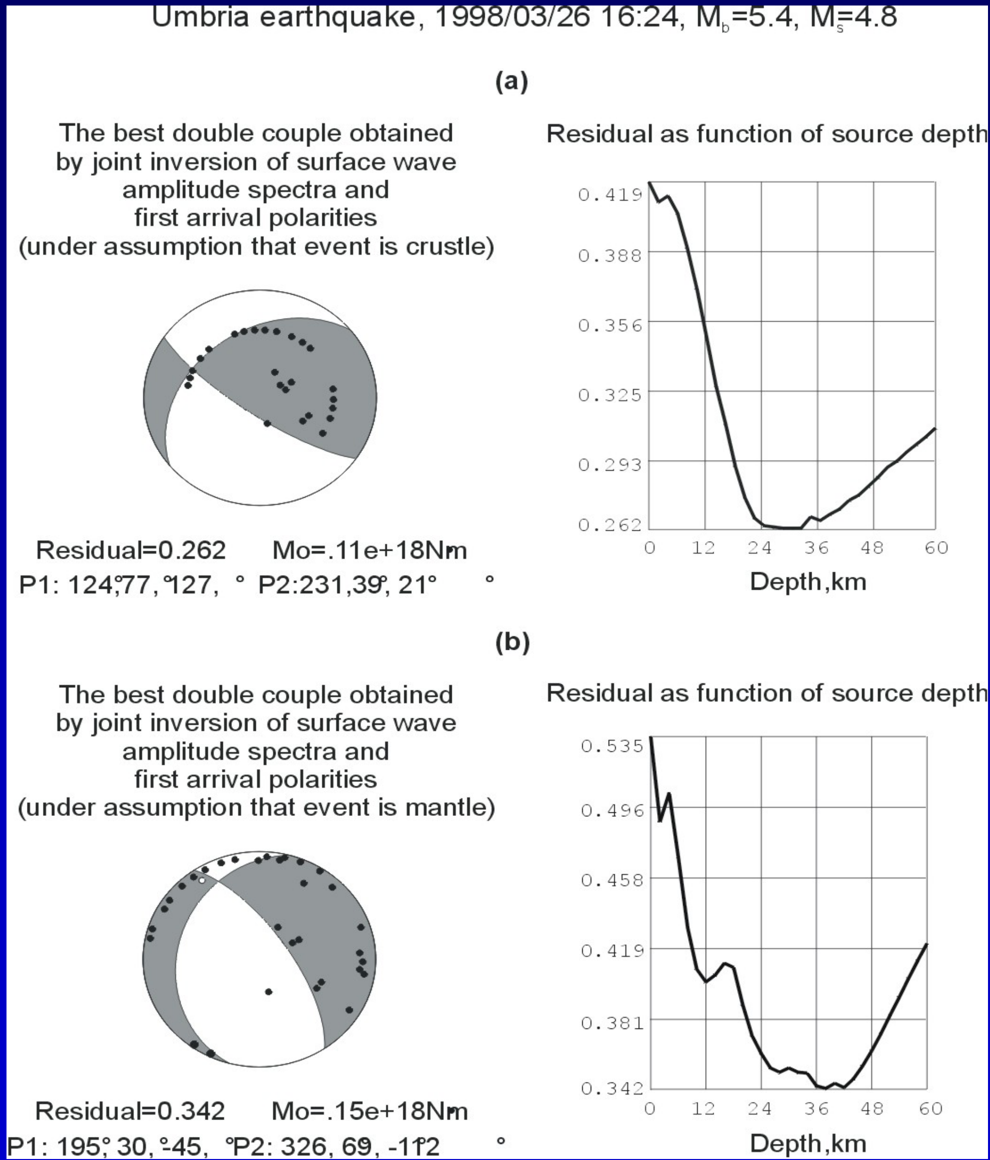


The 1998 March 26 Umbria-Marche “MANTLE” event?

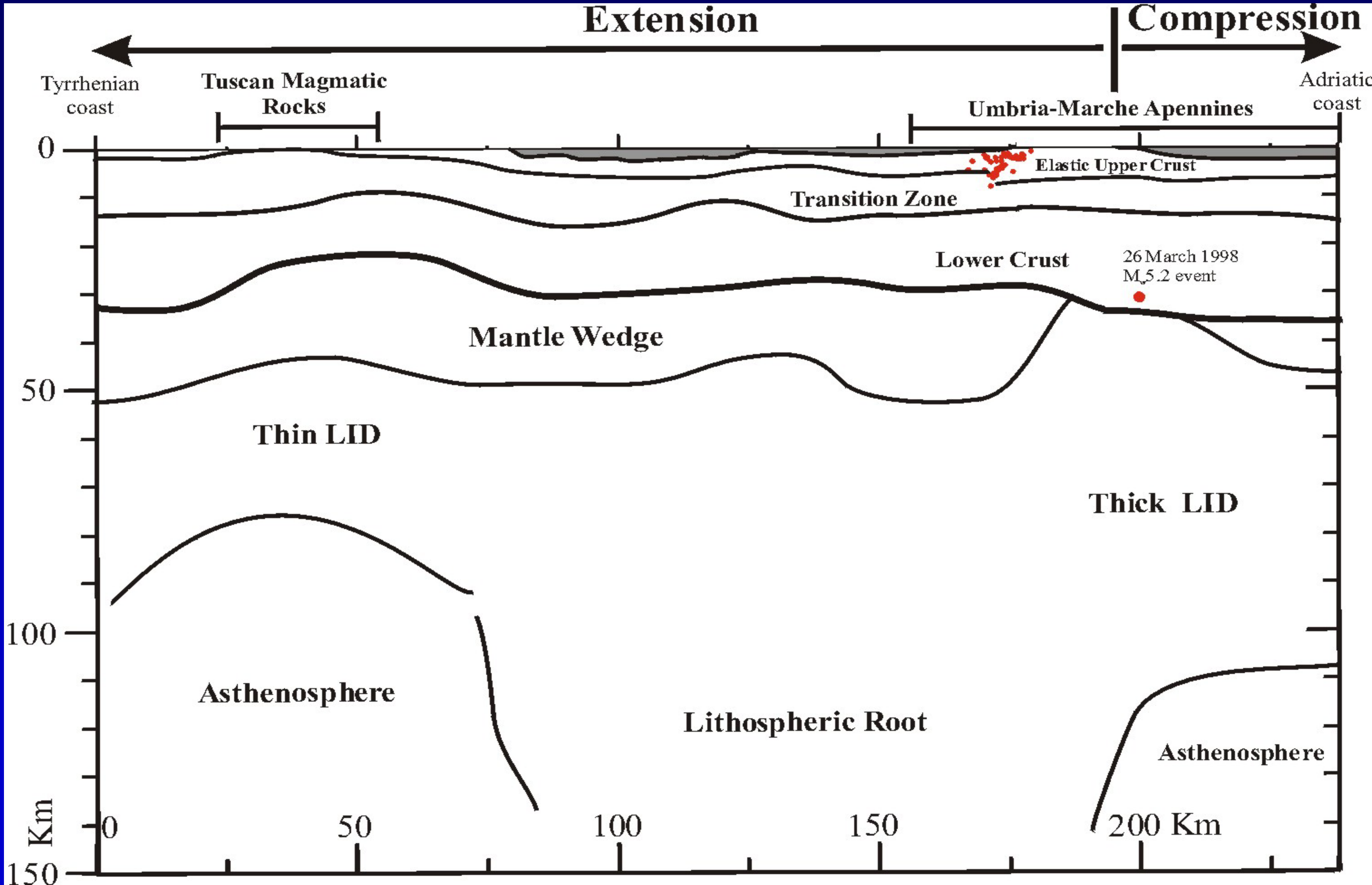




The March 26, 1998 is a crustal event



Crust-upper mantle structure

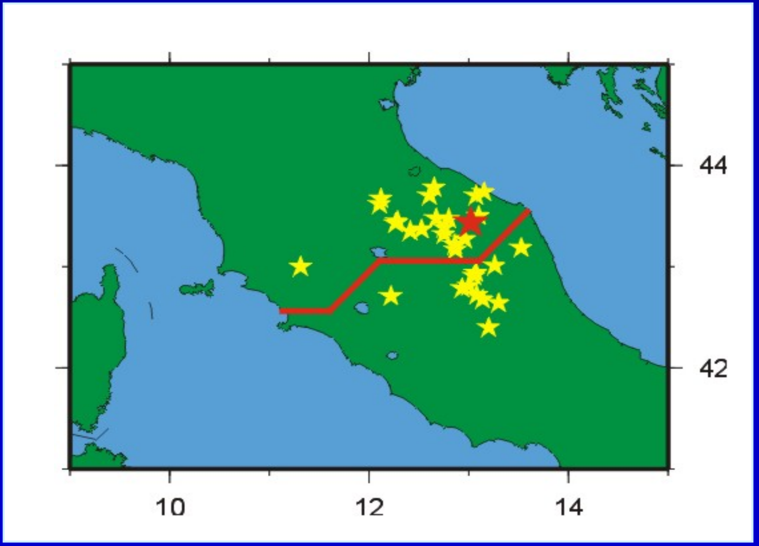


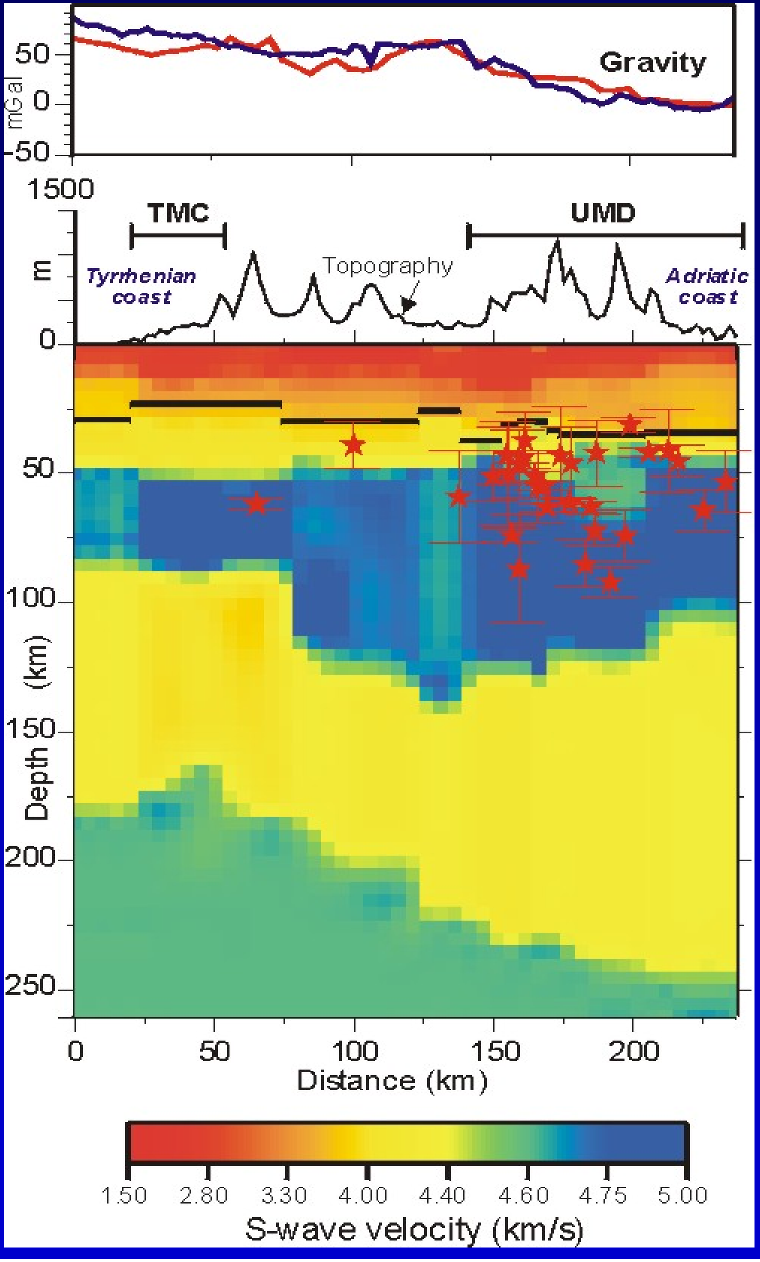
The juxtaposed contraction and extension observed in the crust of the Italian Apennines and elsewhere has, for a long time, attracted the attention of geoscientists and is a long-standing enigmatic feature.

Several models, invoking mainly external forces, have been put forward to explain the close association of these two end-member deformation mechanisms clearly observed by geophysical and geological investigations.

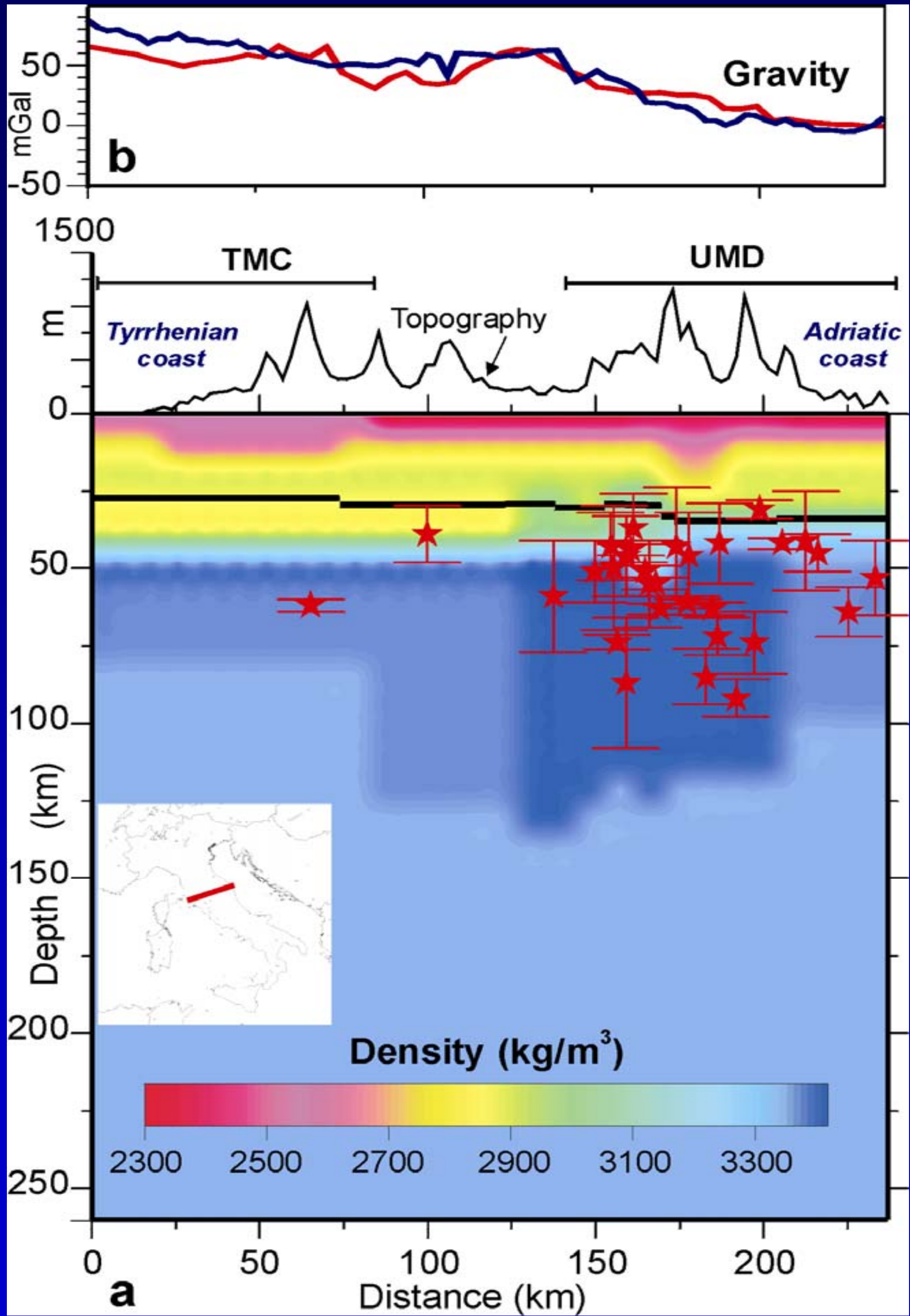
These models appeal to interactions along plate margins or at the base of the lithosphere such as back-arc extension or shear tractions from mantle flow or to subduction processes such as slab pull, roll back or retreat and detachment.

Crust-upper mantle structure beneath North-Central Italy supports delamination processes

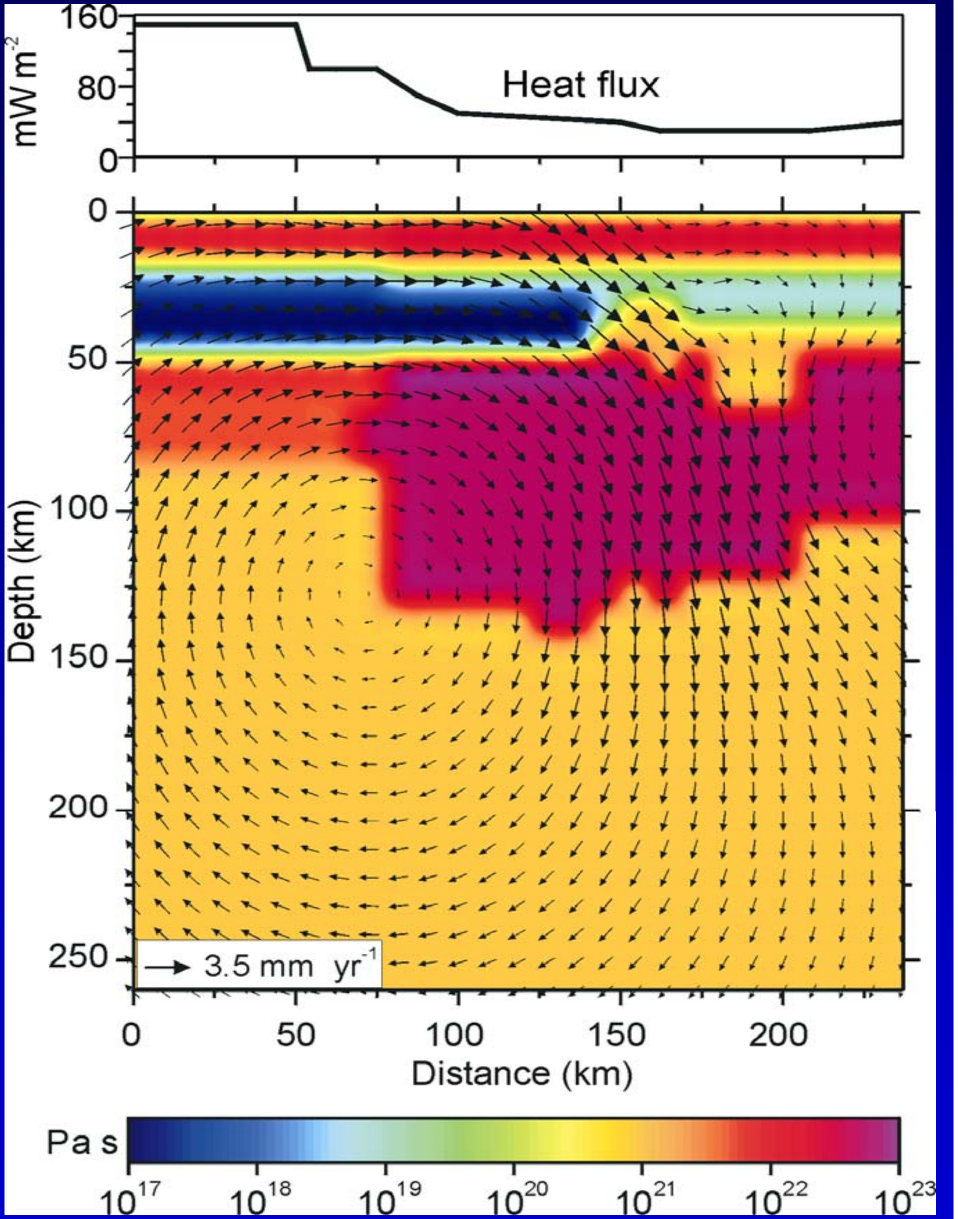




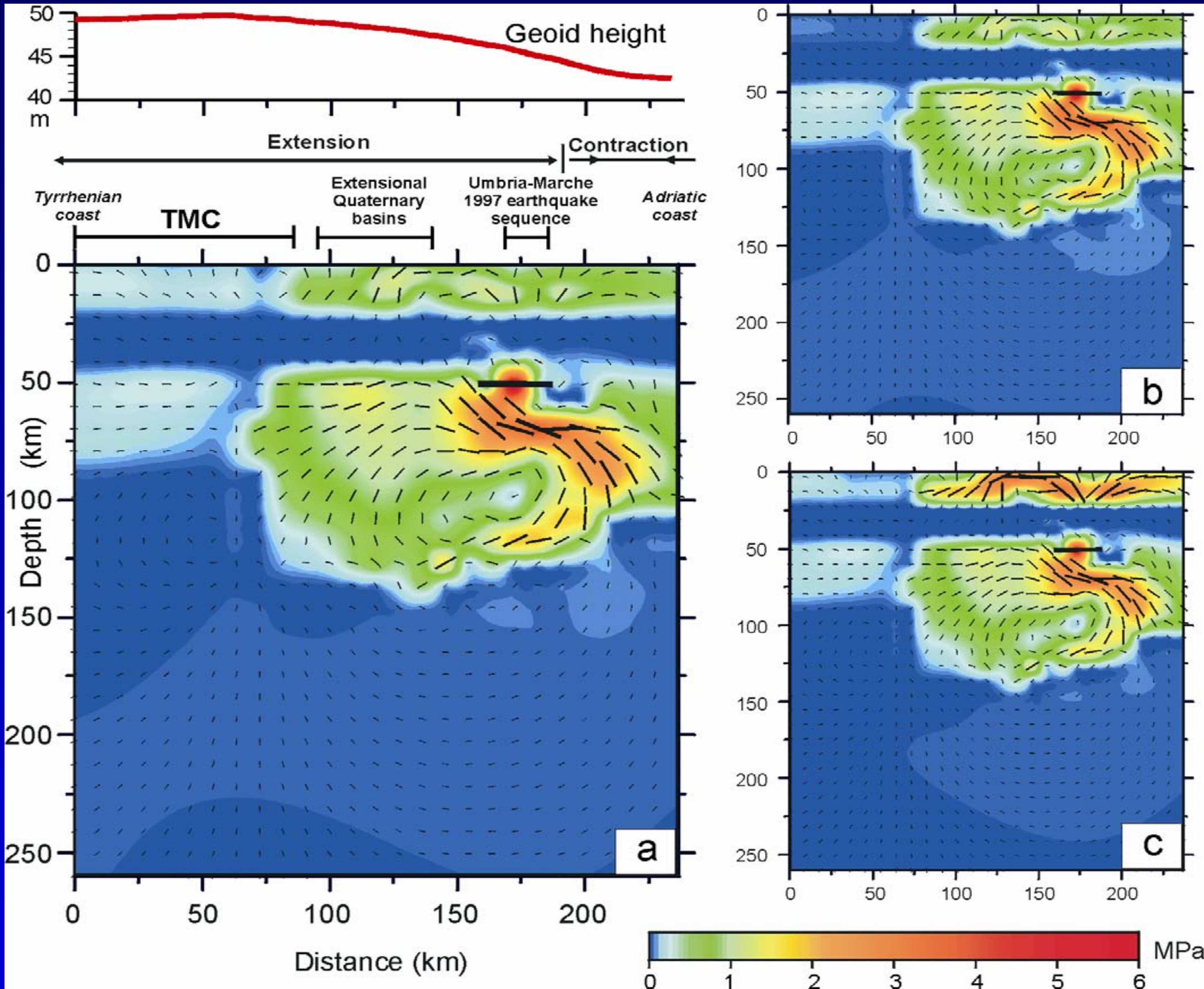
Density model



Viscosity model and predicted flow field



Tectonic shear stress



Conclusions

- **The revisited crust and uppermost mantle Earth structure beneath Central Italy supports delamination processes,**
- **The rate and patterns of the modeled lithospheric flow:**
  - **is in agreement with GPS data;**
  - **explain the heat flux, the regional geology;**
  - **provide a new background for the genesis and age of the recent Tuscan magmatism**
- **The modeled stress in the lithosphere:**
  - **is spatially correlated with gravitational potential energy patterns;**
  - **shows that internal buoyancy forces, solely, can explain the coexisting regional contraction and extension and the unusual intermediate depth seismicity**

Postseismic deformation

- ✓ **mainly modeled for large and deep earthquakes;**
- ✓ **after slip and viscoelastic relaxation in the lower crust and upper mantle are believed to be the important processes for explaining the increase of rates of deformation;**

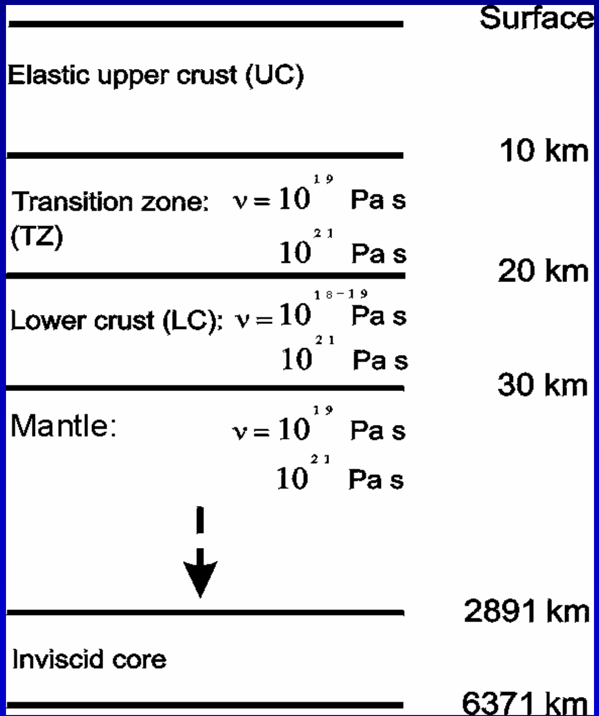
complexity exhibited by large earthquake faults and the deeper processes they involve during their postseismic deformation

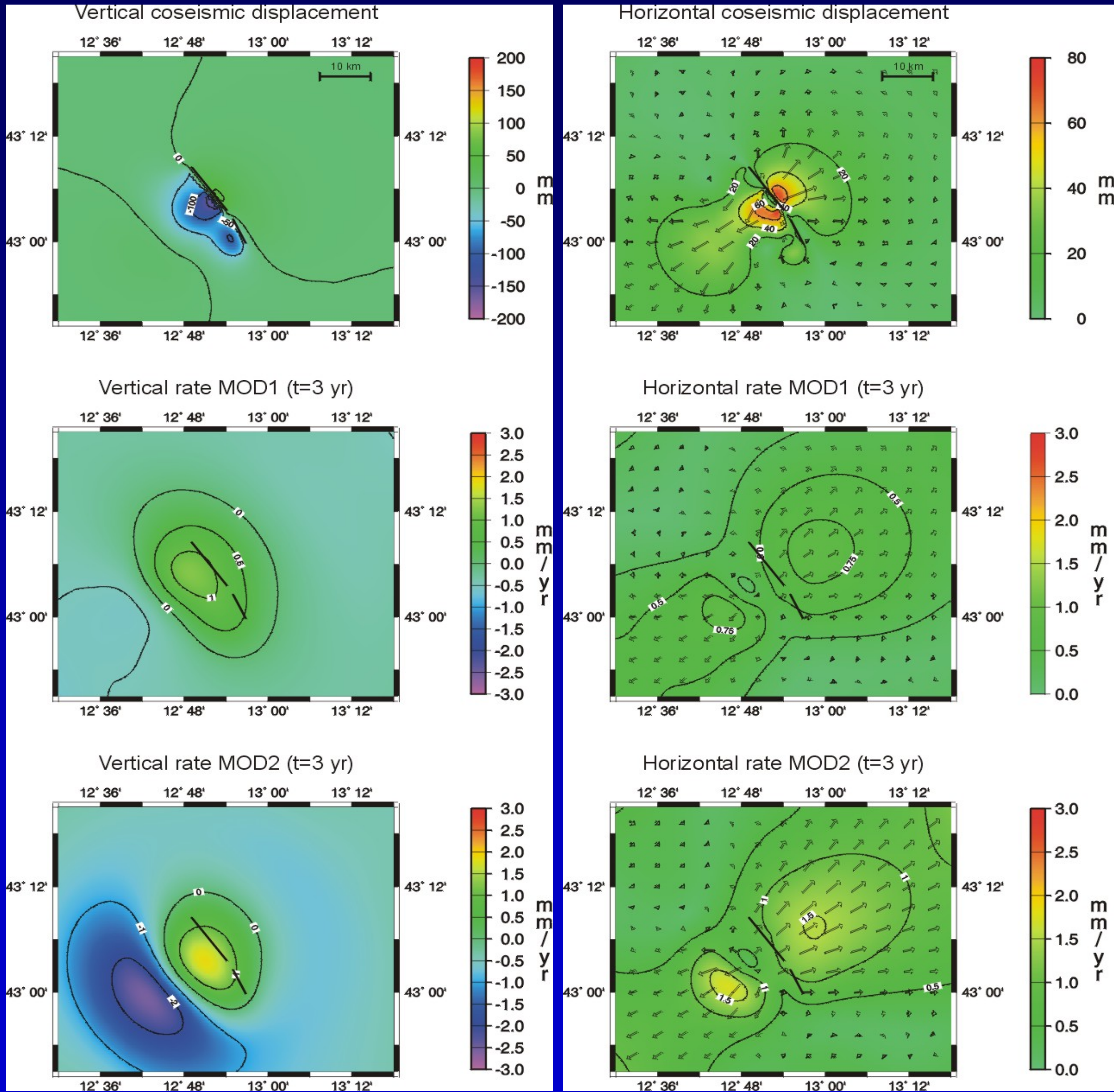
Postseismic deformation for moderate size earthquakes

- ✓ relatively simple rupture process;
- ✓ free from the influence of lower lithospheric viscous flow;
- ✓ excite noticeable postseismic signal that could be detected by accurate geodetic measurements.

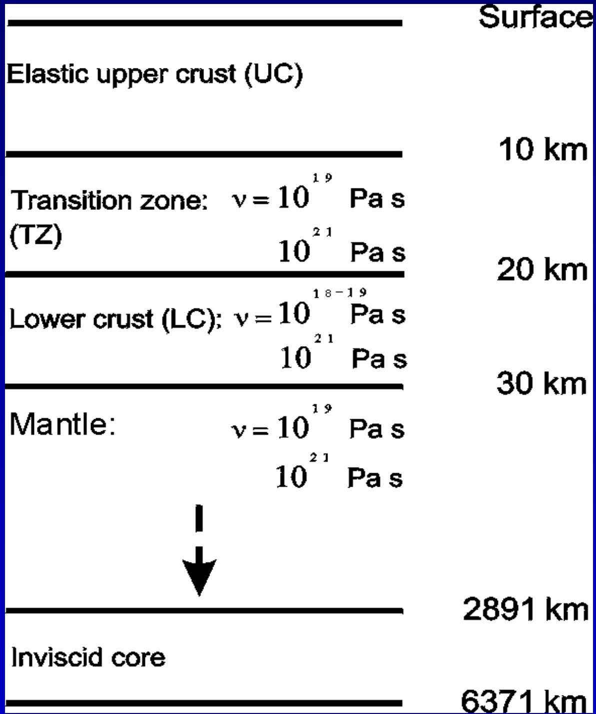
good candidates to investigate the component of the deformation driven by viscoelastic relaxation in the crust

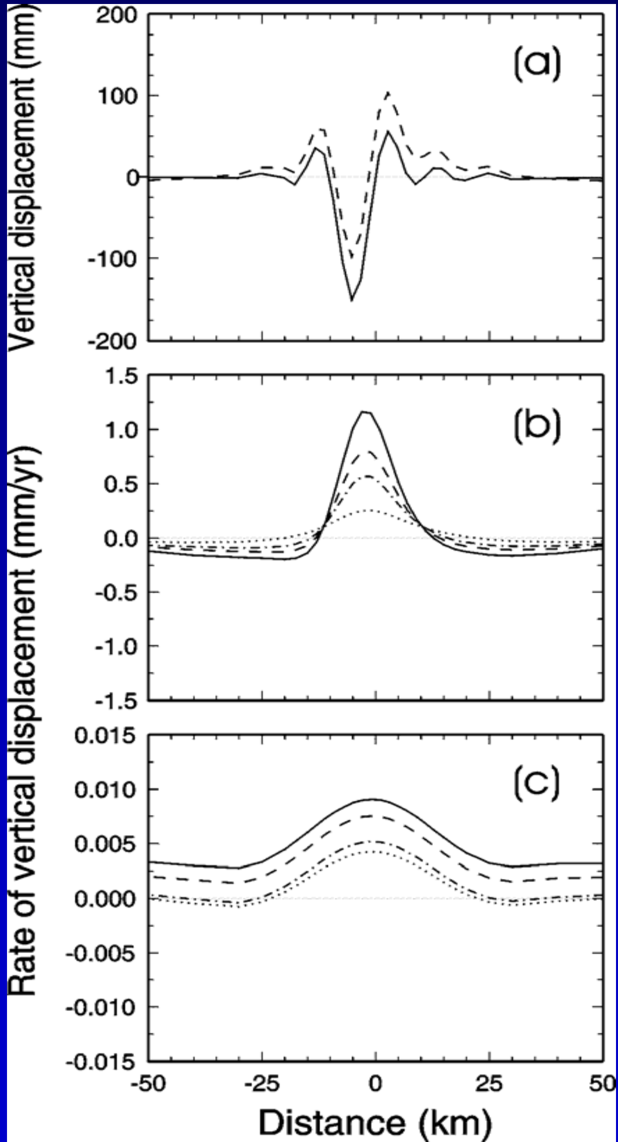
Crustal layering: pattern and scale of the deformation



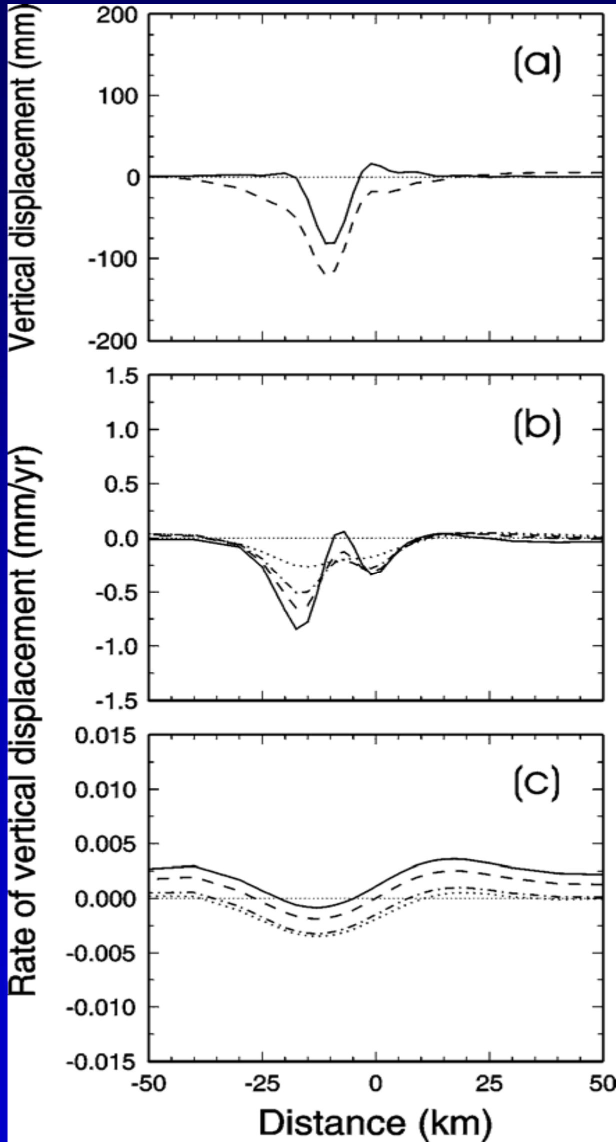


Source depth effects and mantle relaxation



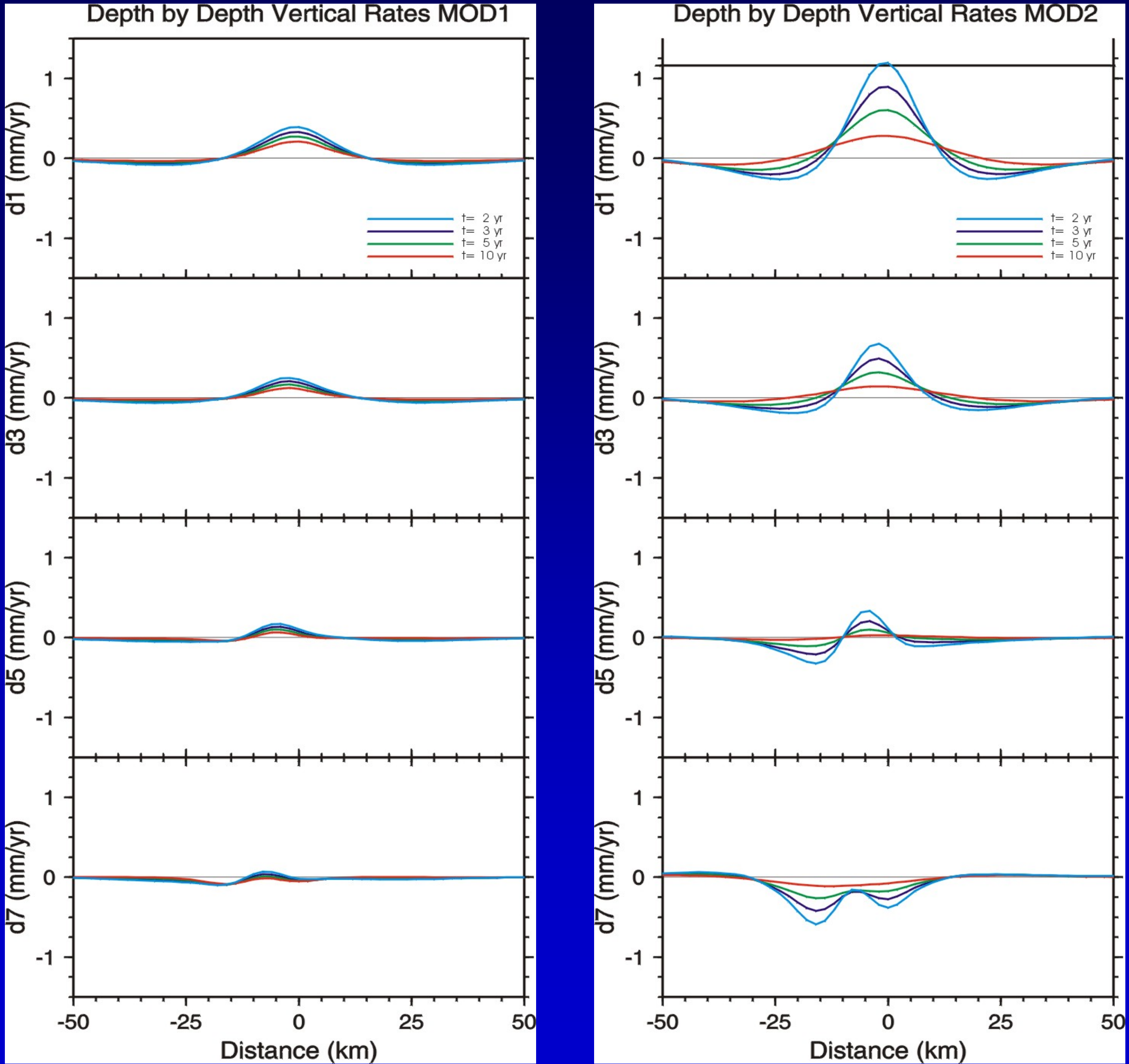


3 km

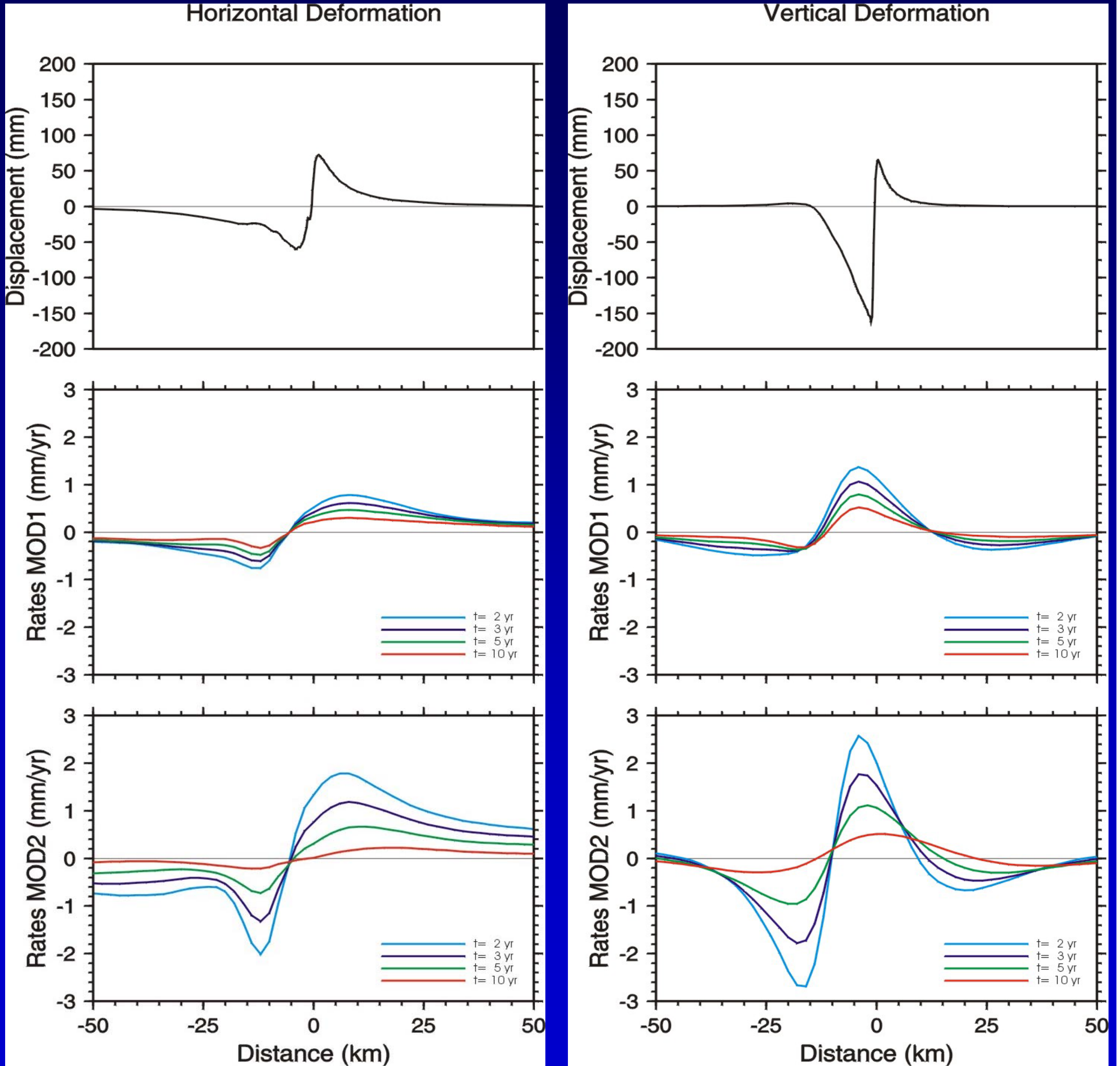


7 km

Source depth effects



Horizontal and vertical coseismic displacements and relaxation rates



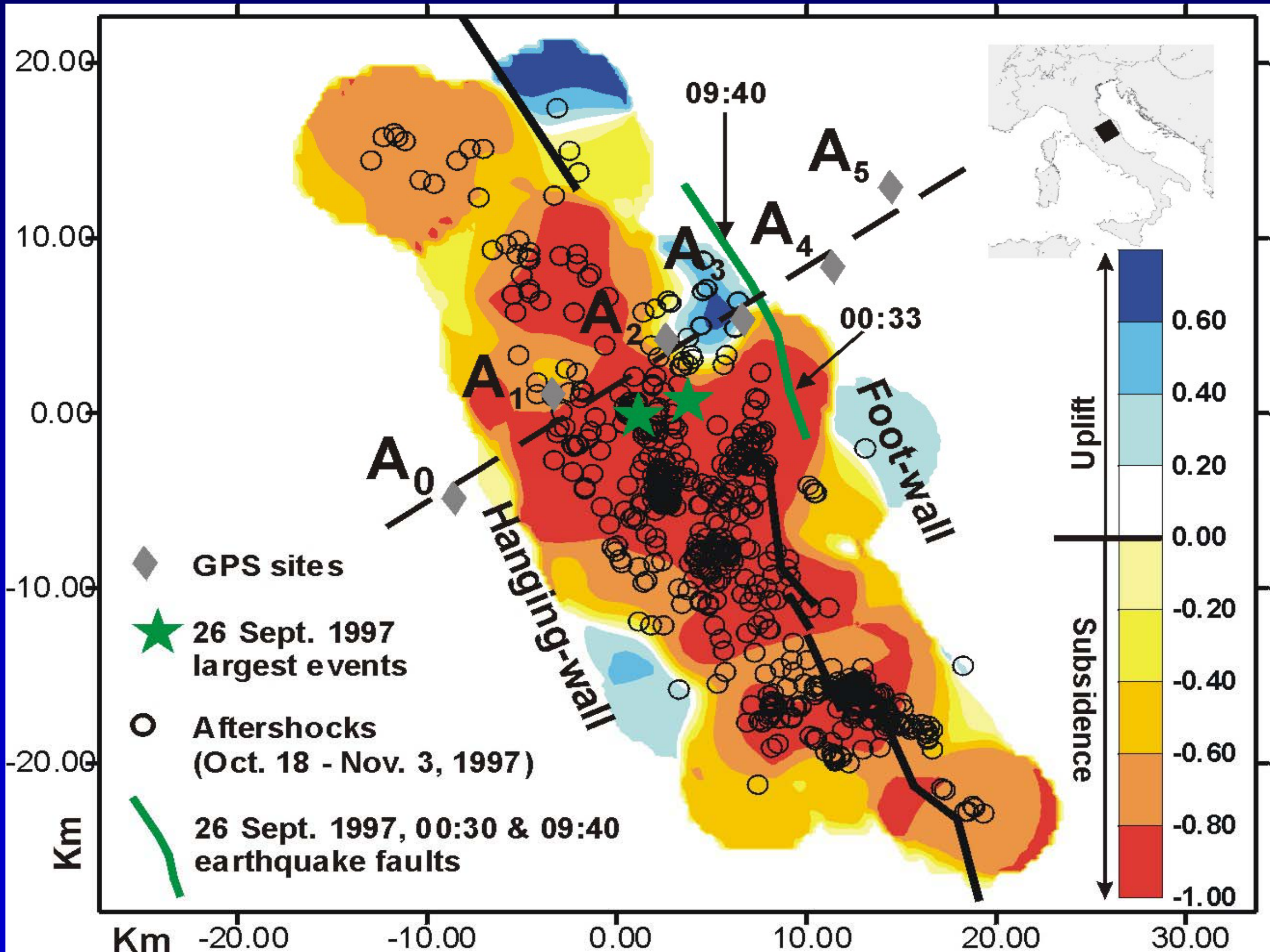
We combine:

- seismic strain mapping computed from early aftershocks;
- GPS measurements;
- published leveling profiles (Basili and Meghraoui, GRL 2001);
- forward analytical modeling of viscoelastic relaxation

In order to:

- better constrain the faulting geometry and related slip distribution;
- get insight into the rheology of the Earth's crust below the Central Apennines;
- show the feasibility of GPS monitoring of postseismic transients, for the first time in Italy, generated by shallow and moderate sources.

Postseismic deformation following the 1997 Umbria-Marche normal faulting earthquakes

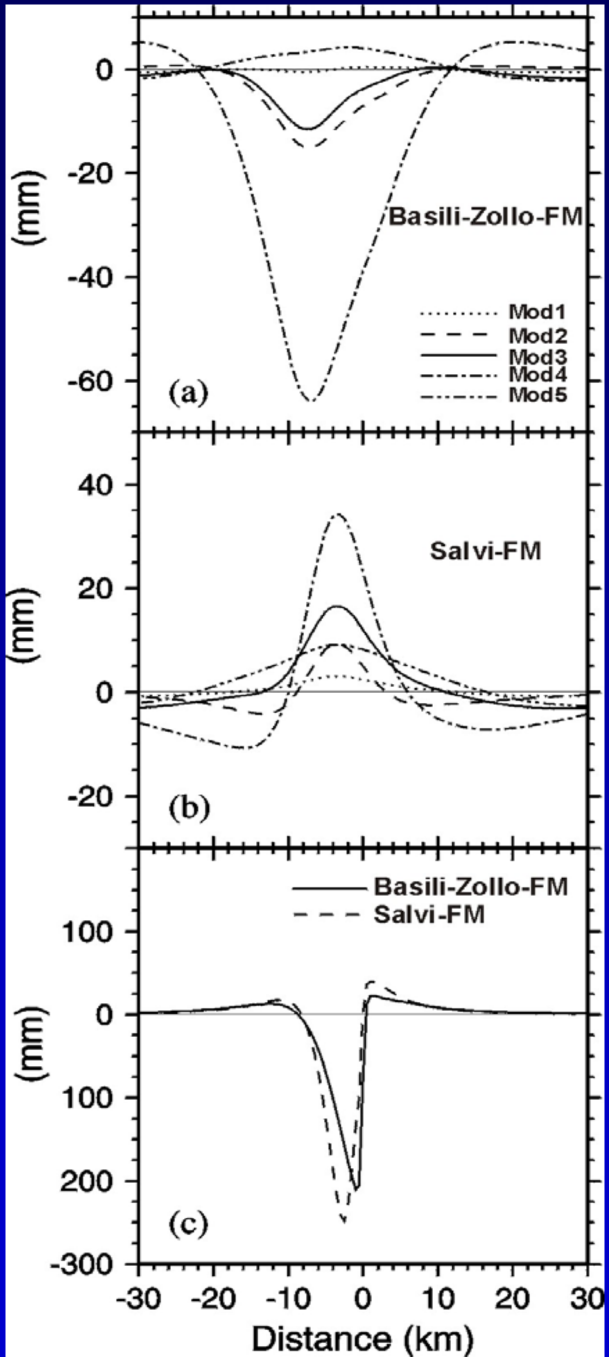


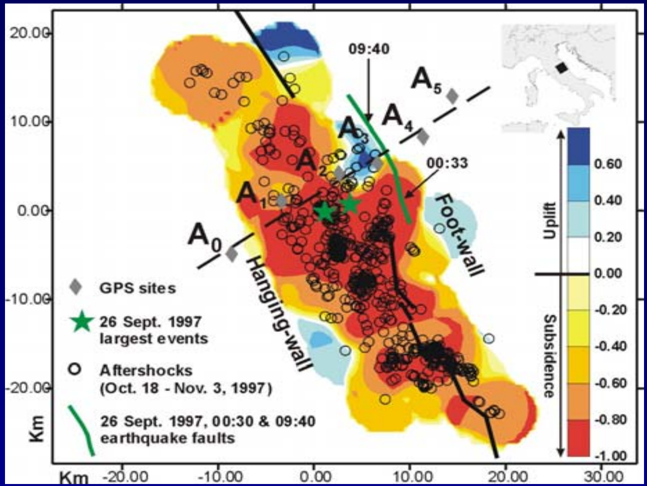
Fault models for the 26 September 1997 earthquakes

- Zollo et al. (GRL, 1999): Inversion of strong motion data
- Salvi et al. (JOSE,2001): Forward modeling of InSAR and GPS data
- Basili and Meghraoui (GRL, 2001): Zollo et al. fault models readjusted with an up-dip extension to fit leveling profiles performed soon after the largest earthquakes

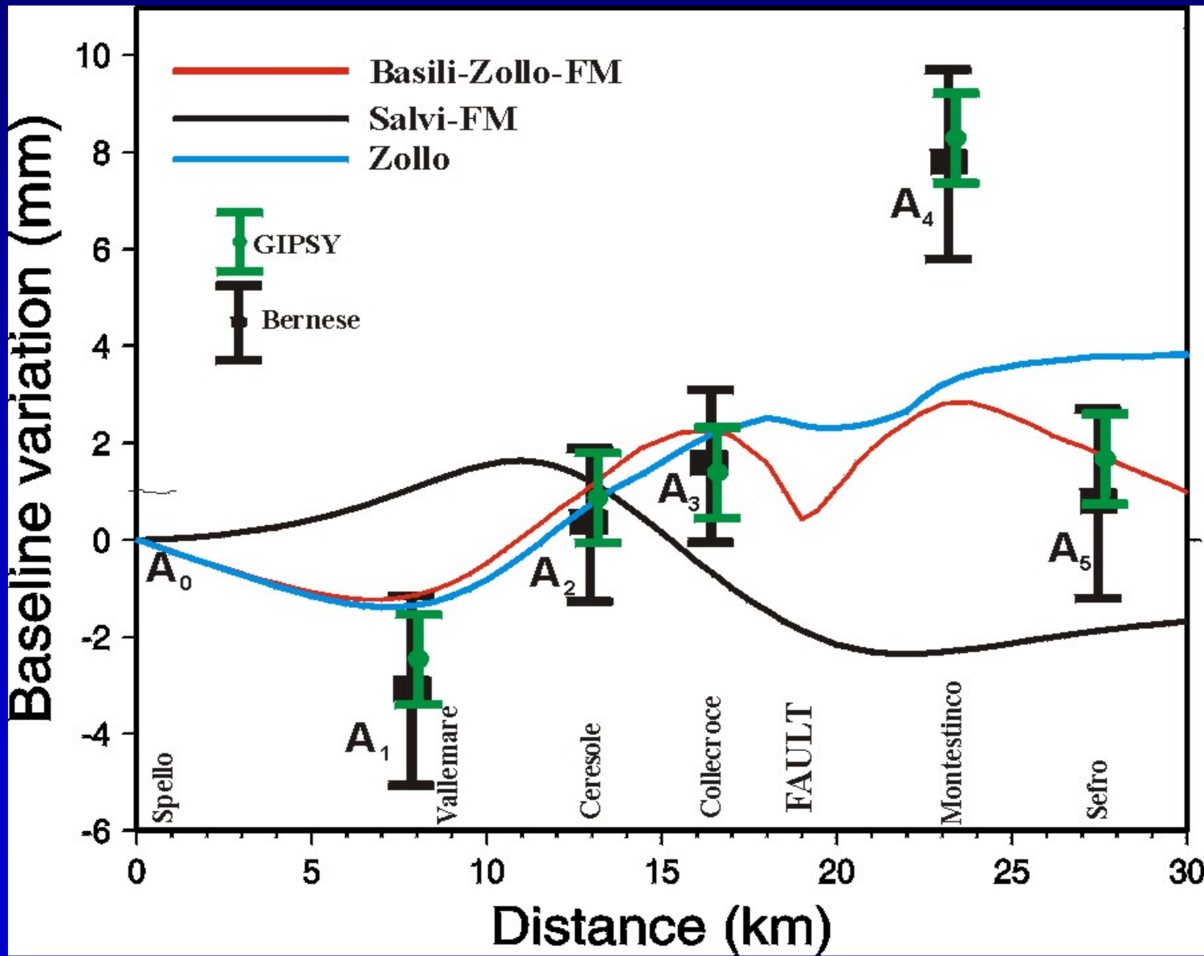
Vertical viscoelastic relaxation over 1 year for different fault models using different viscosity models

Layer	Thickness km	Viscosity Pa s
UC	8	Elastic
TZ	12	10^{19}-10^{17}
LC	15	10^{18}-10^{17}
Mantle	2856	10^{21}
Core	3480	Inviscid

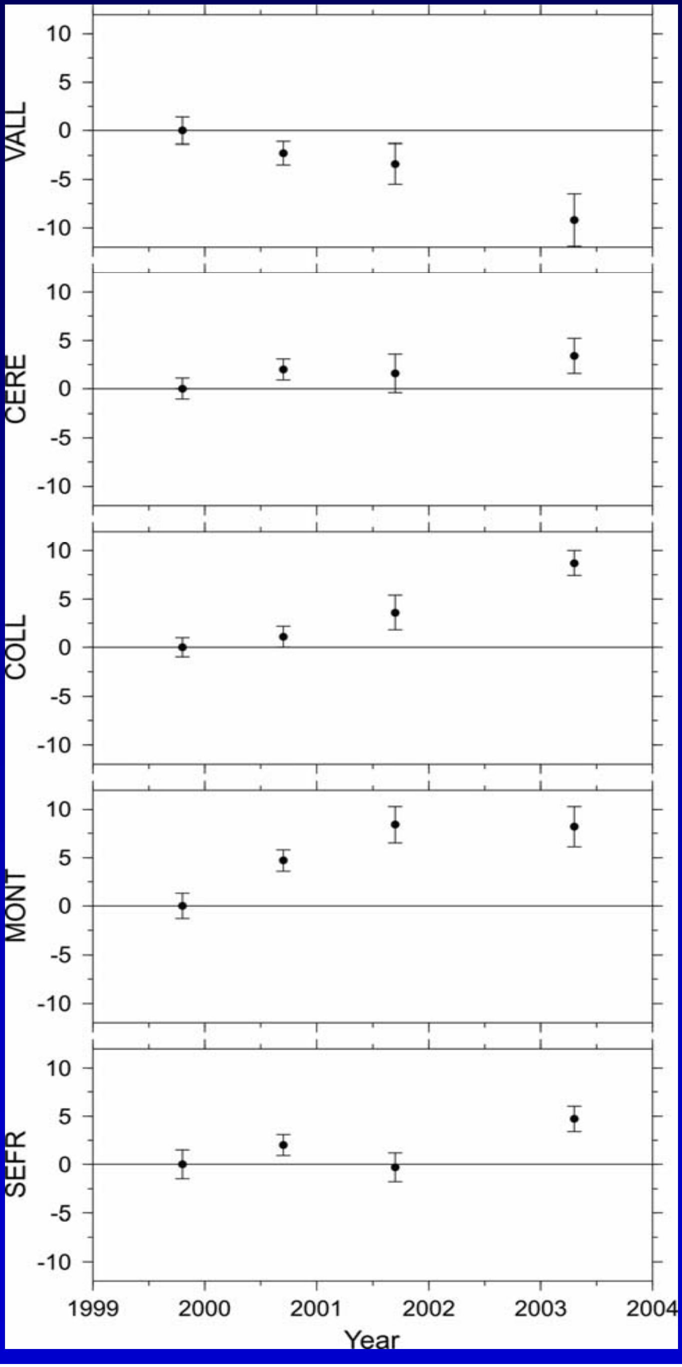


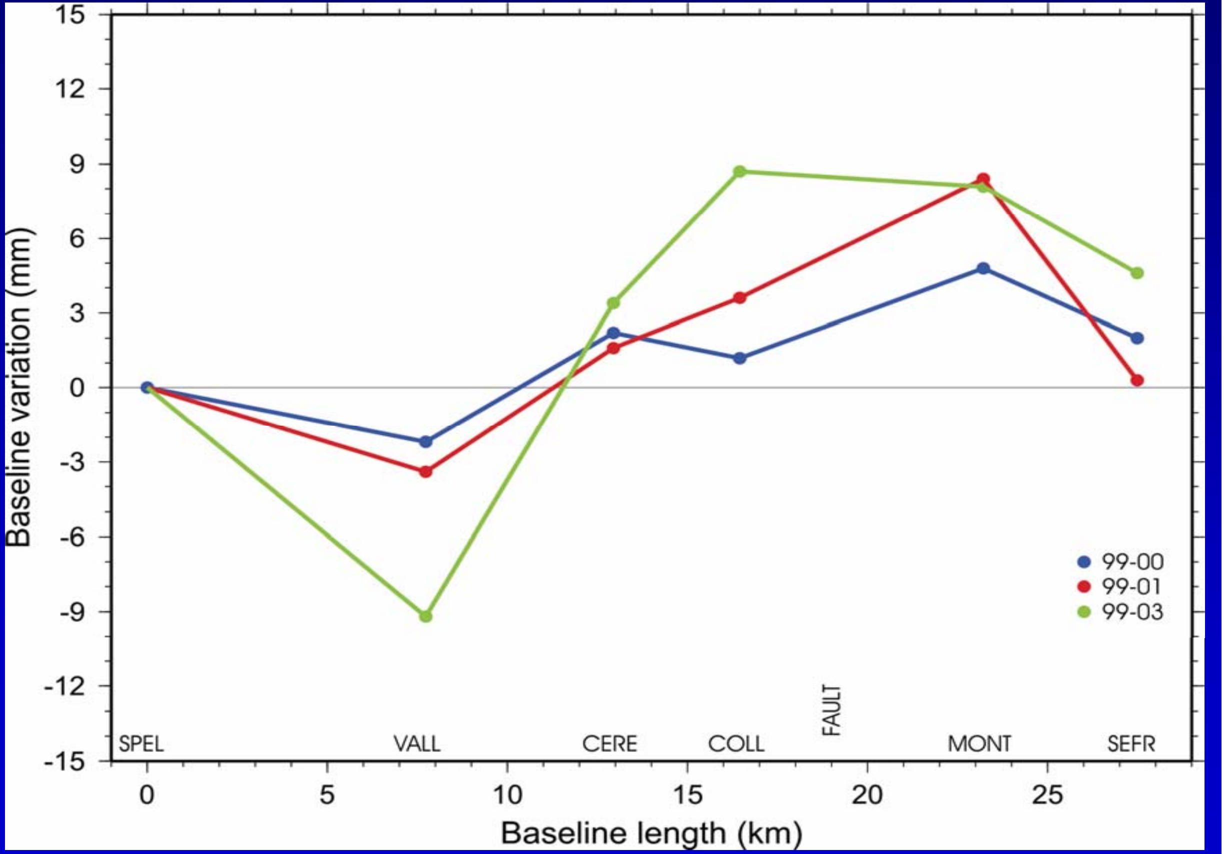


GPS (baseline length variations) vs. model predictions for different fault models using the preferred rheological model

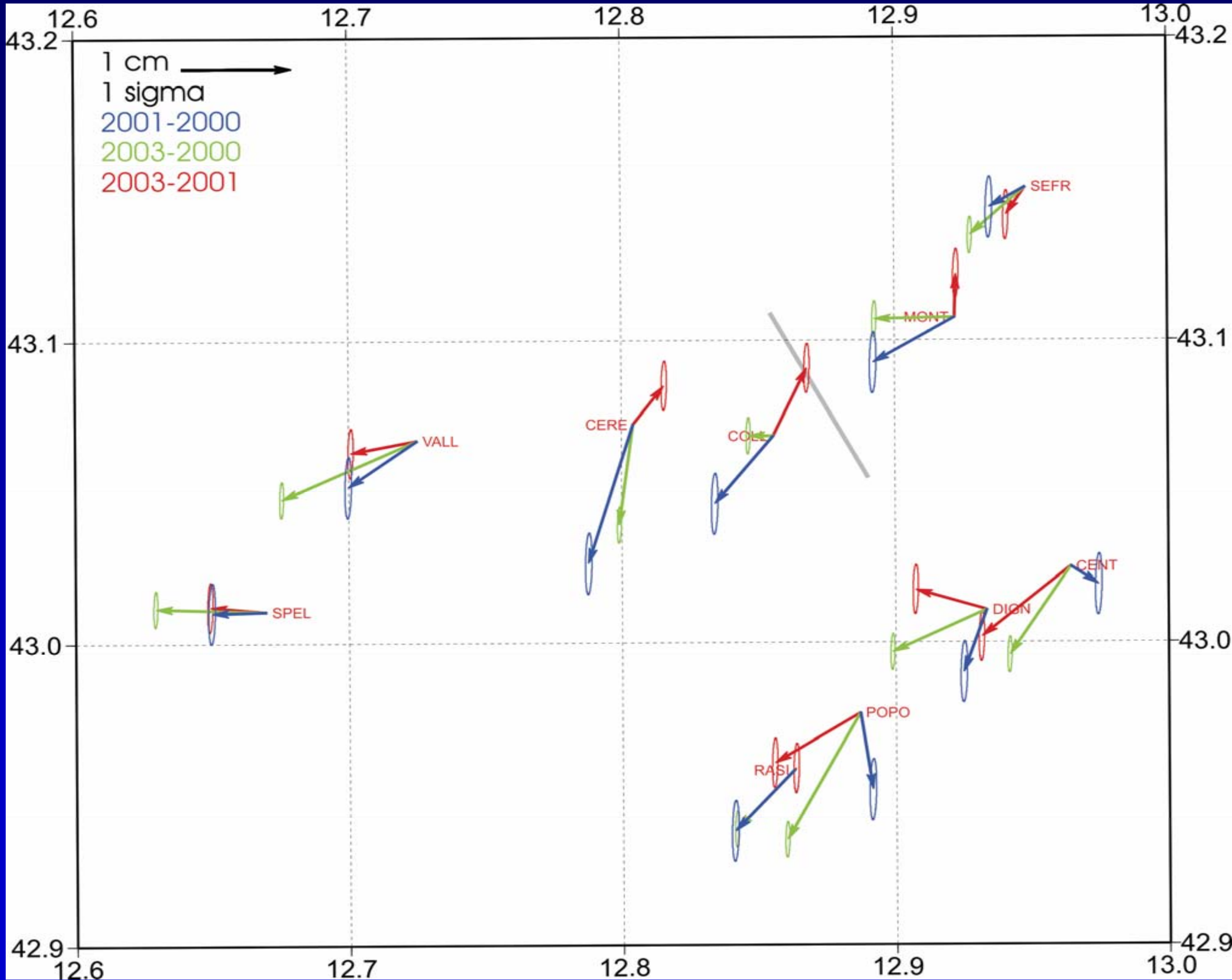


GPS time series: baseline length variations w.r.t Spello 1999-2003

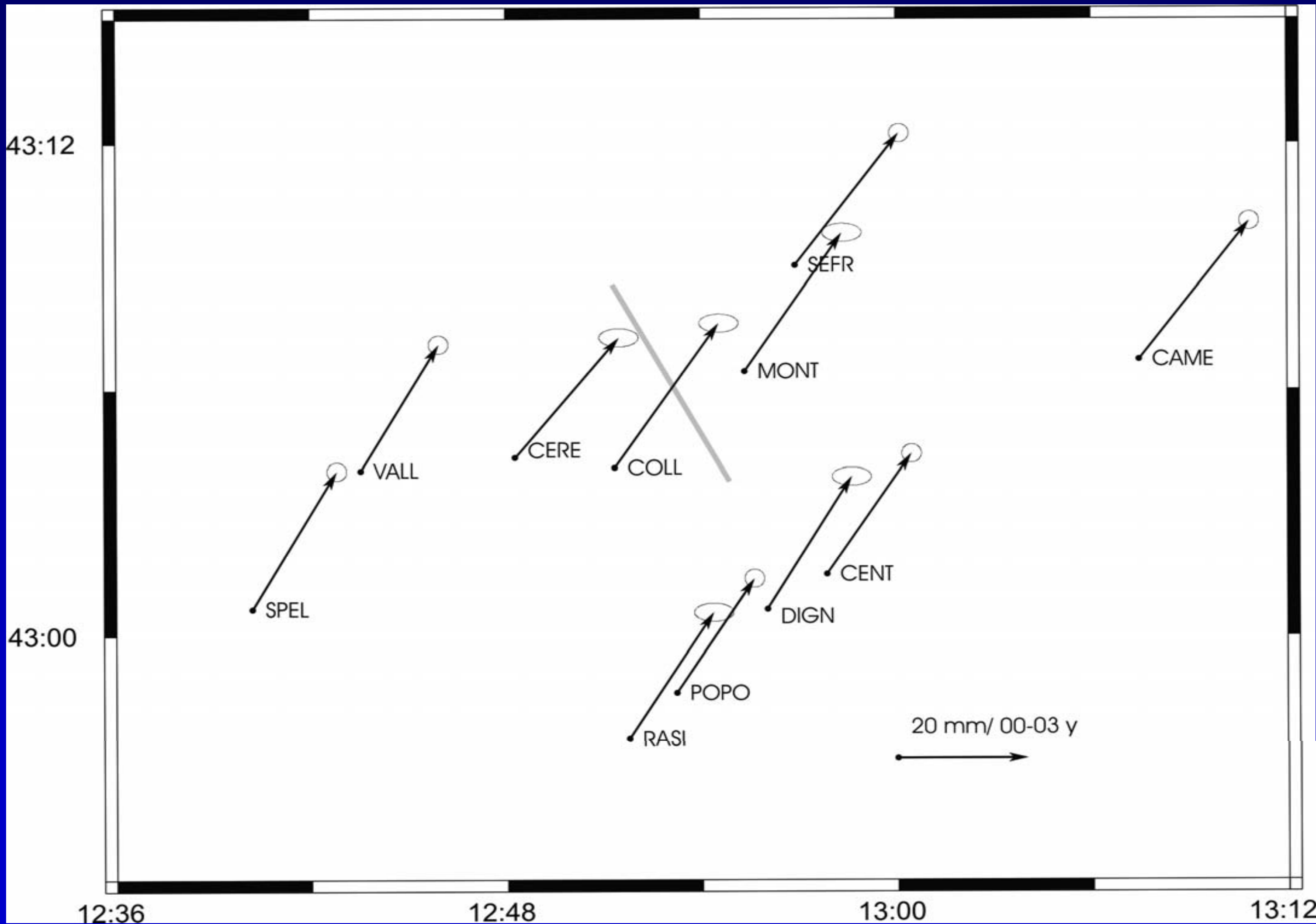




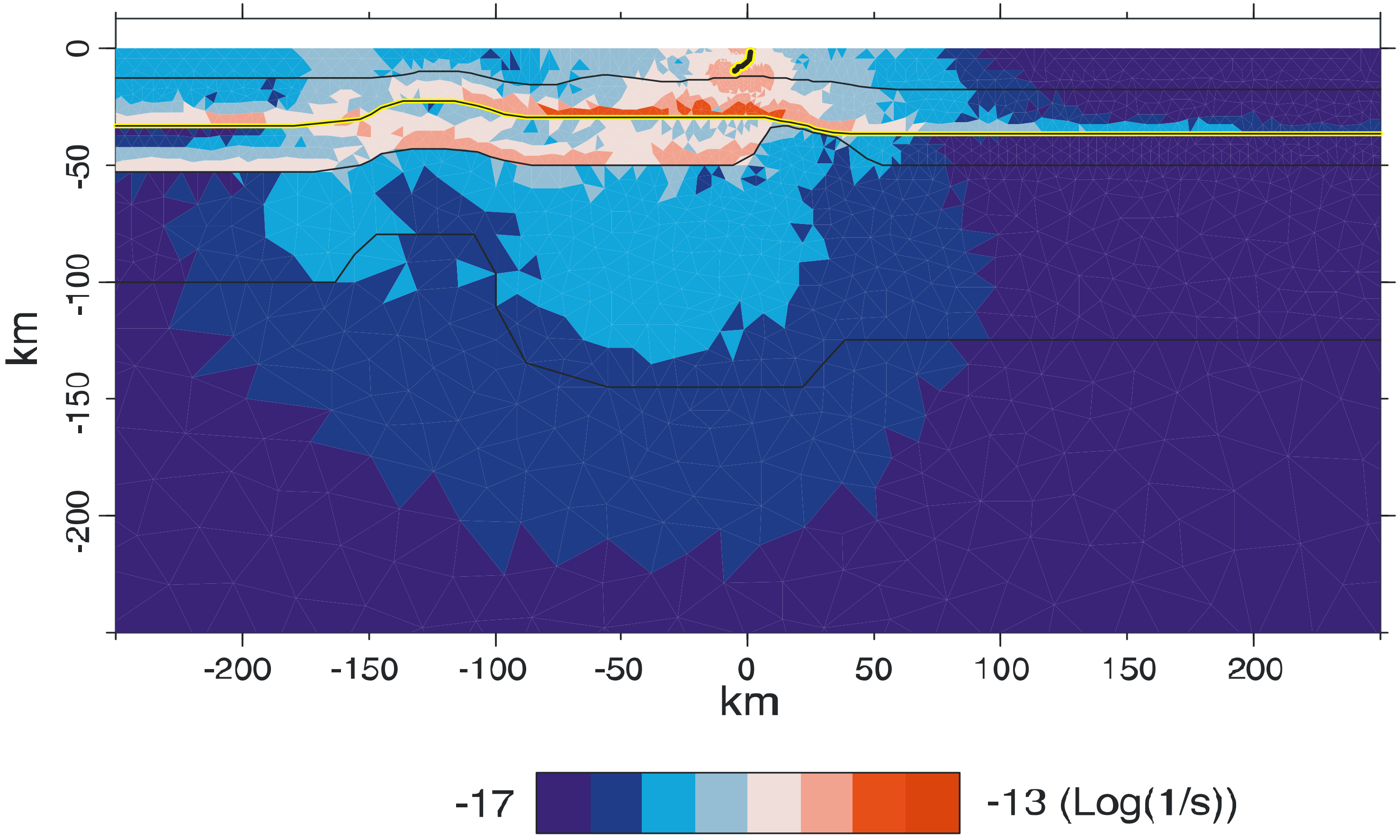
Displacement w.r.t CGPS Camerino 2000-2003



GPS w.r.t Eurasia 2000-2003

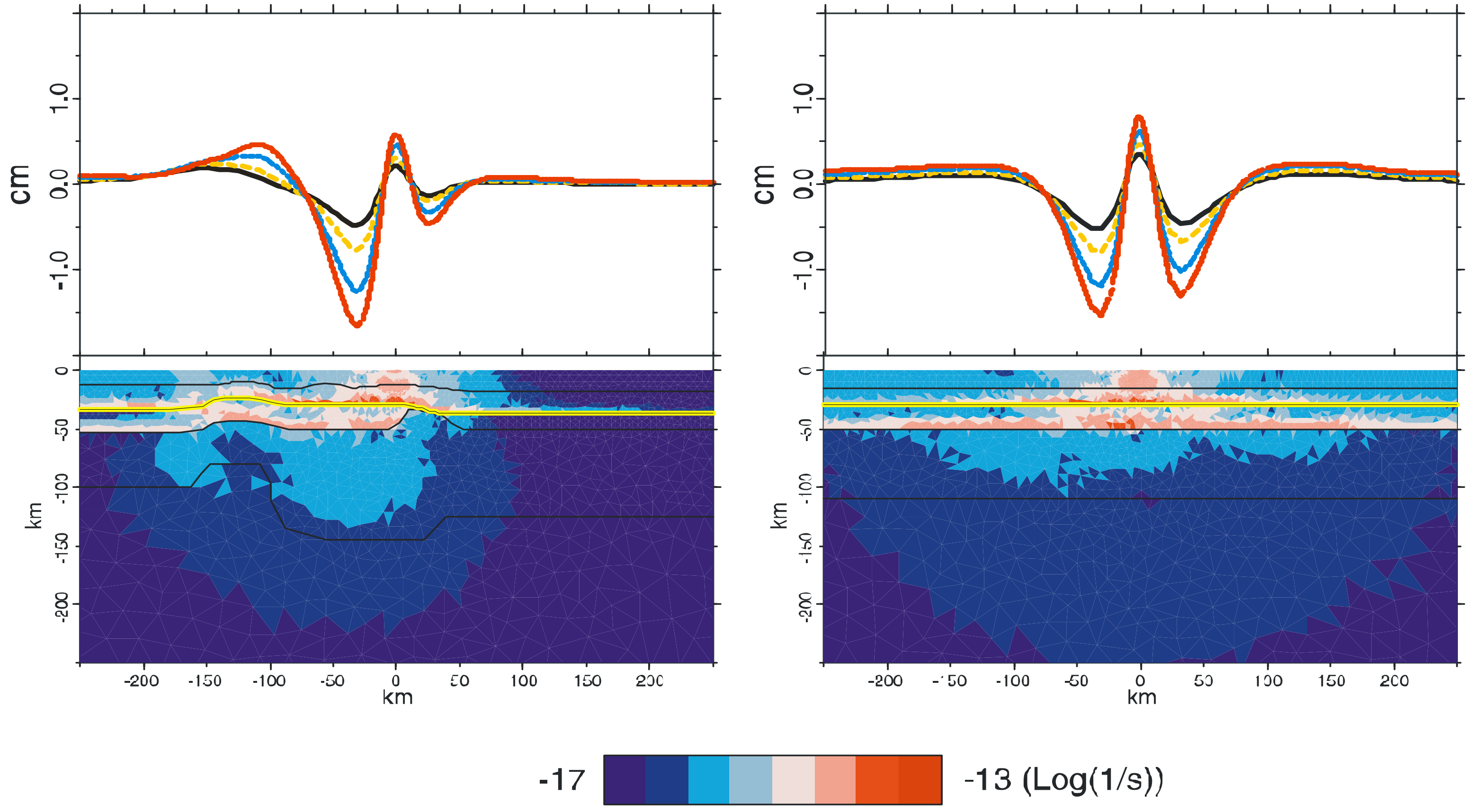


postseismic strain rates: heterogeneous model



Riva et al., 2004

Postseismic deformation: Vertical deformation



Riva et al., 2004

Conclusions:

- The faulting model requires a listric geometry with most of the energy released in the lower half part of the elastic crust ;
- The rheological model consists of an elastic thin upper crust, a transition zone of about 10^{18} Pa s underlain by a low-viscosity lower crust, ranging from 10^{17} to 10^{18} Pa s;
- The postseismic deformation is, both distributed in the transition zone - lower crust and confined to the fault zone:
  - 0-1 year: 7% of viscoelastic deformation
  - 2-3 year: 35 % of viscoelastic deformation
- The agreement between the results of the Bernese and the GIPSY analyses is remarkable.
- The postseismic deformation may have relevant effects on the ongoing geodynamics.

European Union -Alpine Space Interreg III-B Project

Alpine Integrated GPS Network: Near Real-Time Monitoring and Master Model for Continental Deformation and Earthquake Hazard (ALPS-GPSQUAKENET)

ALPS-GPSQUAKENET

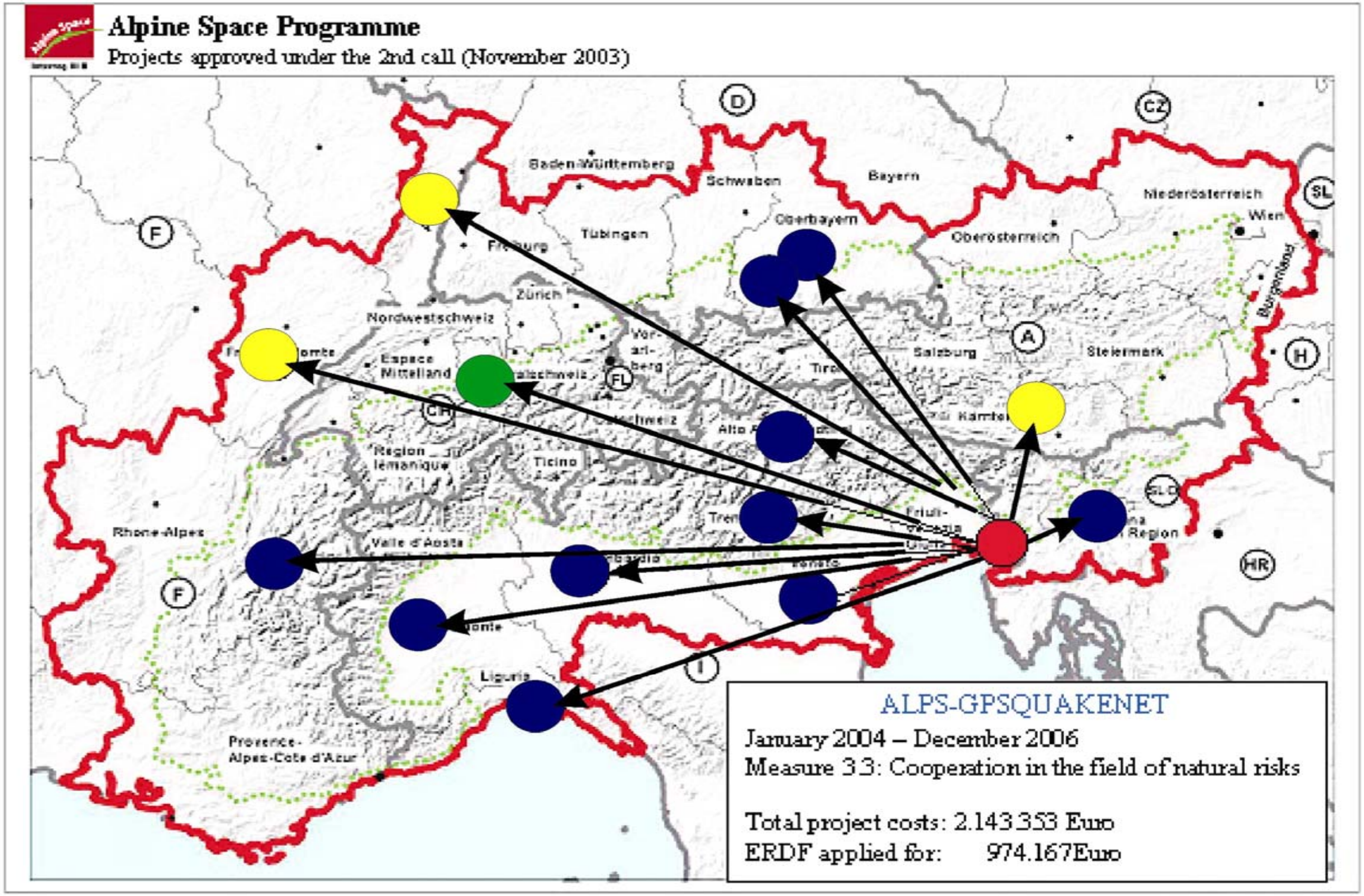
build-up a high-performance transnational space geodetic network of GPS receivers in the Alpine Space

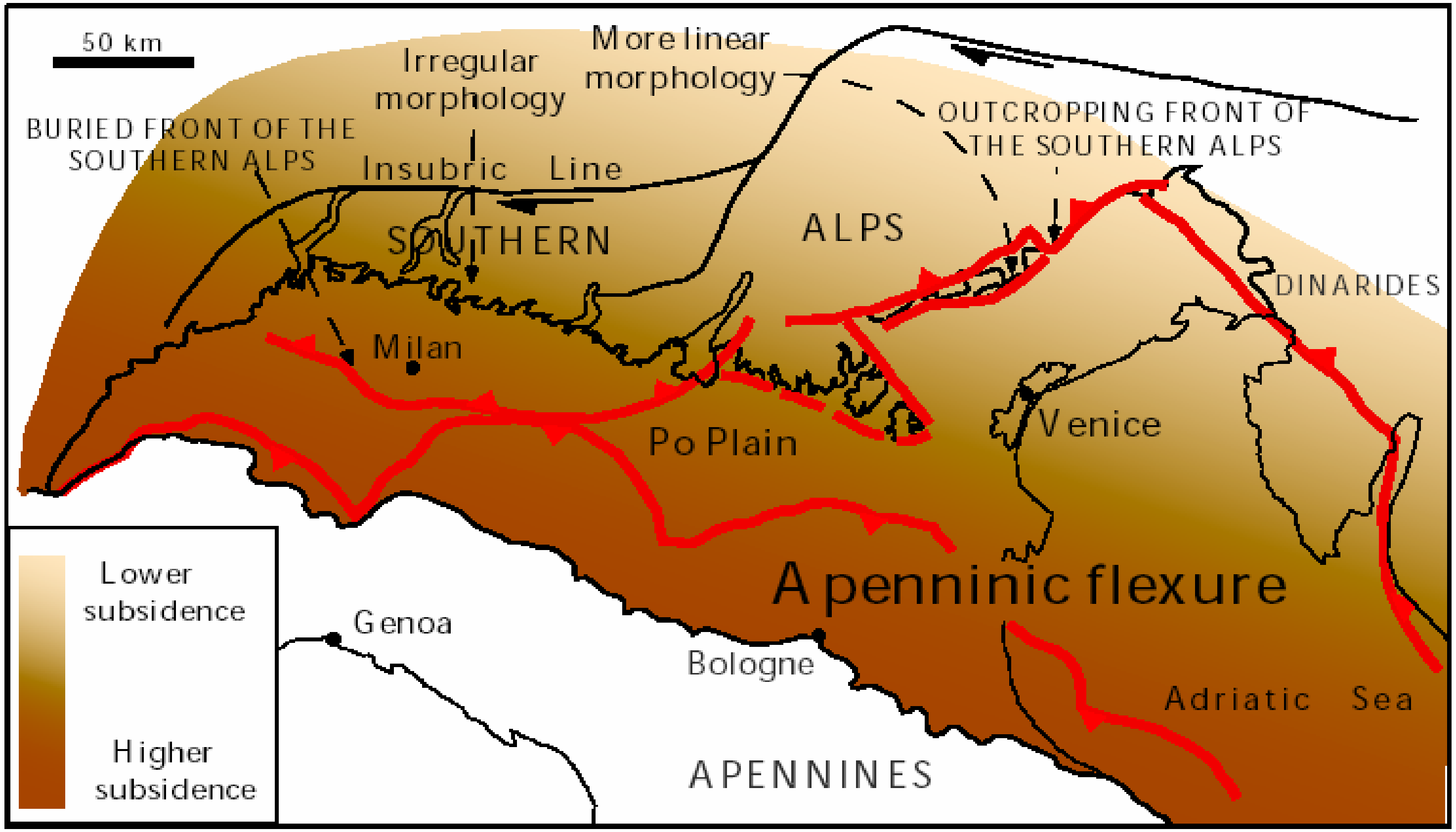
support the use of space based techniques: crustal deformation for earthquake potential, meteorology, landslide monitoring, agriculture, navigation, transportation, mapping, surveying, recreation & sports...)

cross-training and interaction of scientists and environmental officers

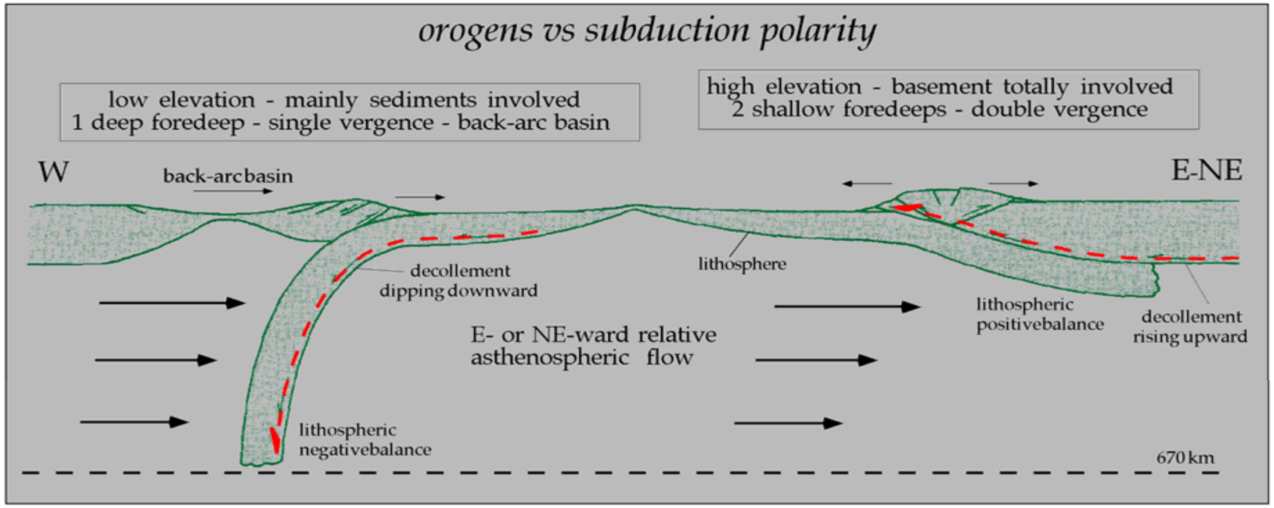
monitor and prevent natural risk, reduce economic losses, and save lives

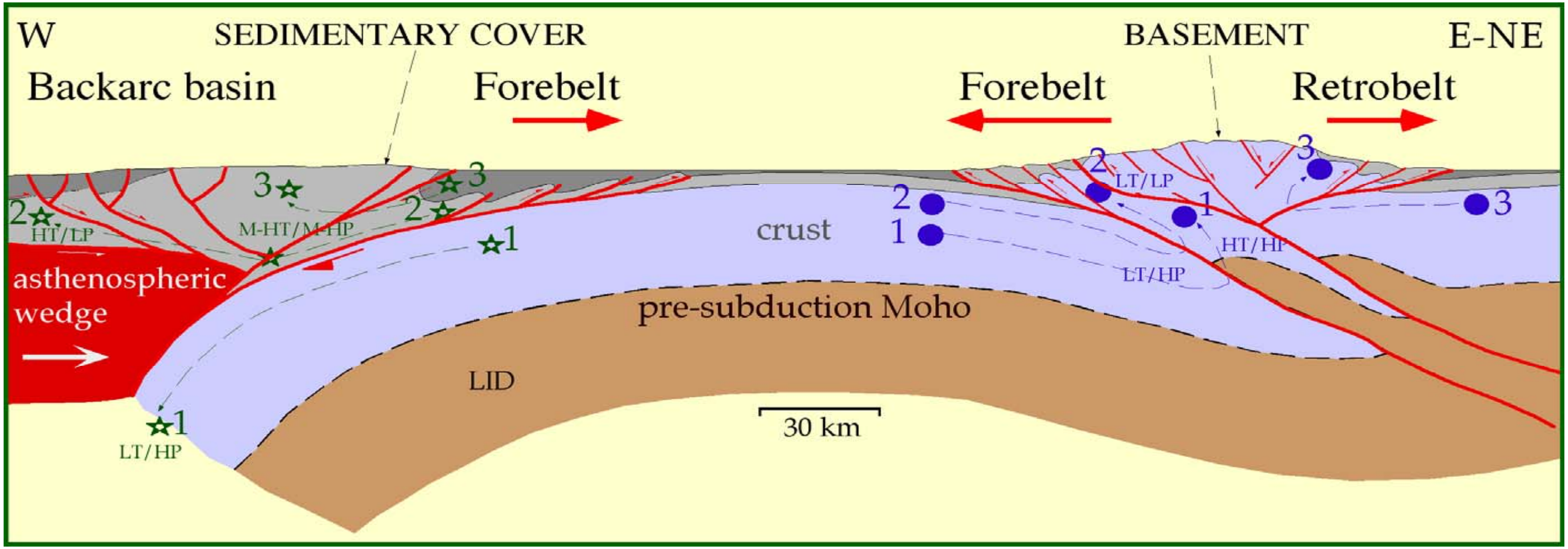
Project Partnership





Source: Carlo Doglioni

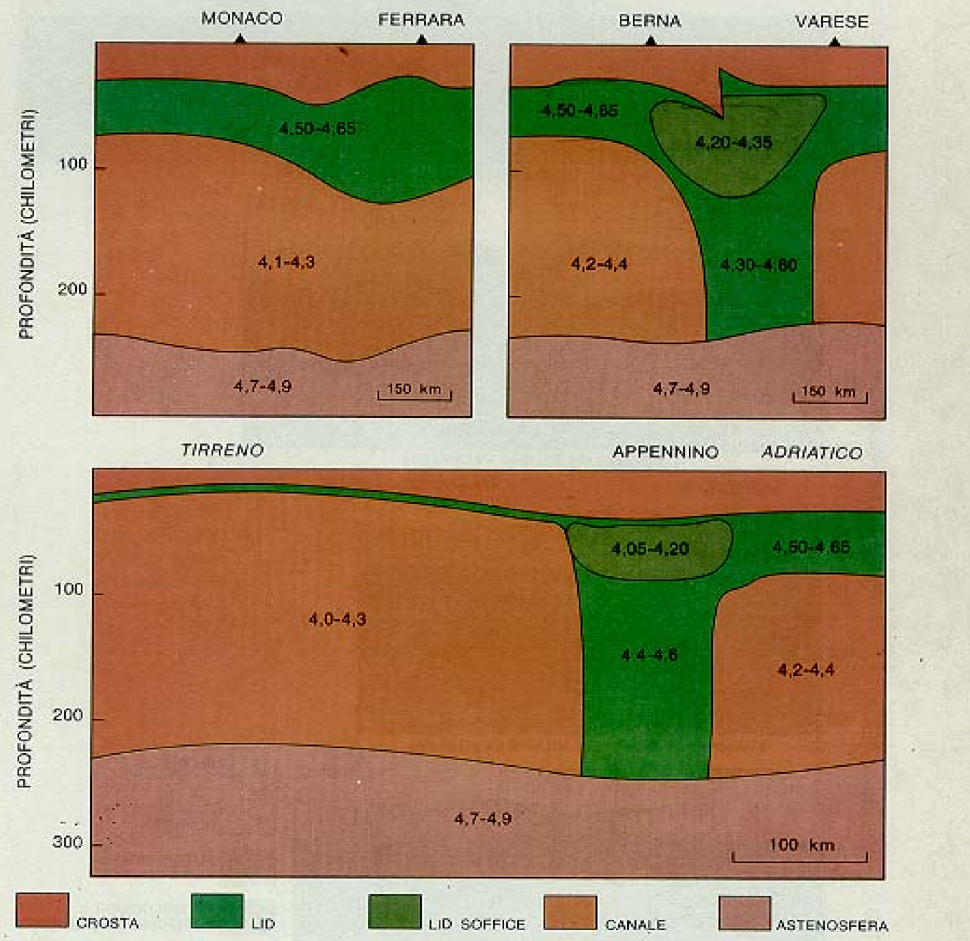




Source: Carlo Doglioni

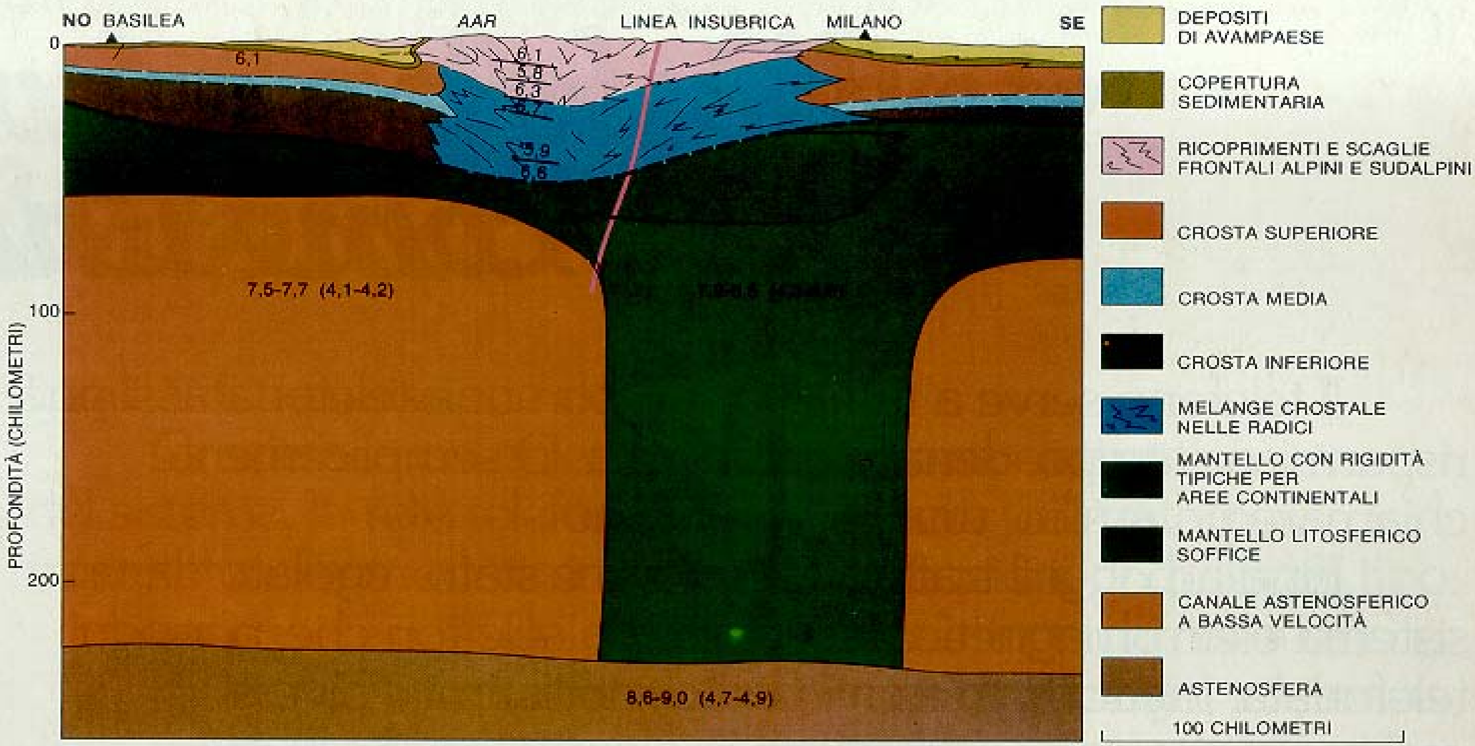
Scientific American

Panza et al., 1980



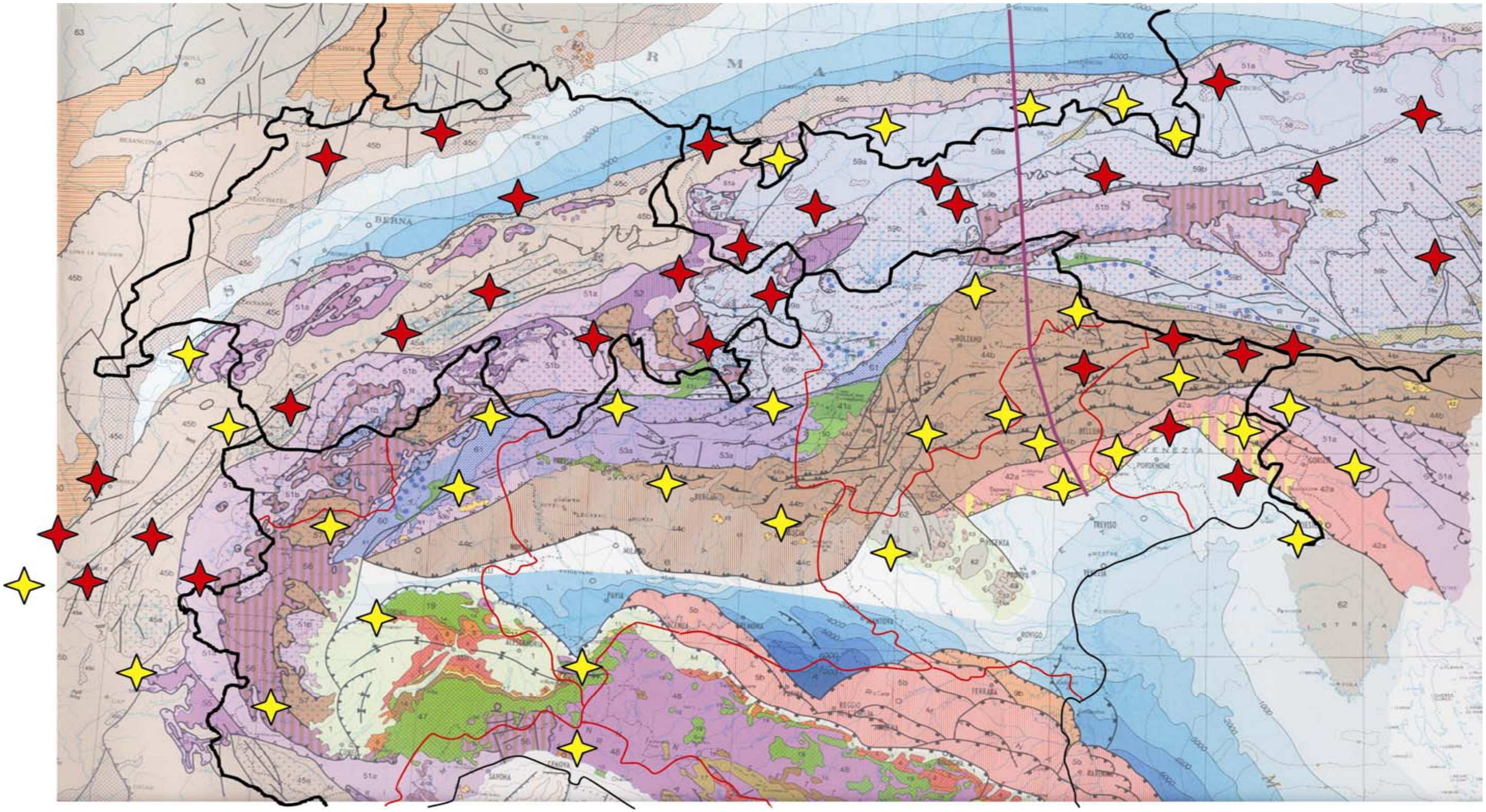
Sezioni verticali attraverso le Alpi orientali *(a)*, centro-occidentali *(b)* e attraverso gli Appennini *(c)*. Nella sezione *a* il massimo ispessimento del lid è spostato verso sud rispetto alle radici crostali. (La radice profonda è interpretata come un raddoppiamento litosferico conseguente la collisione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

Scientific American   Panza et al., 1980

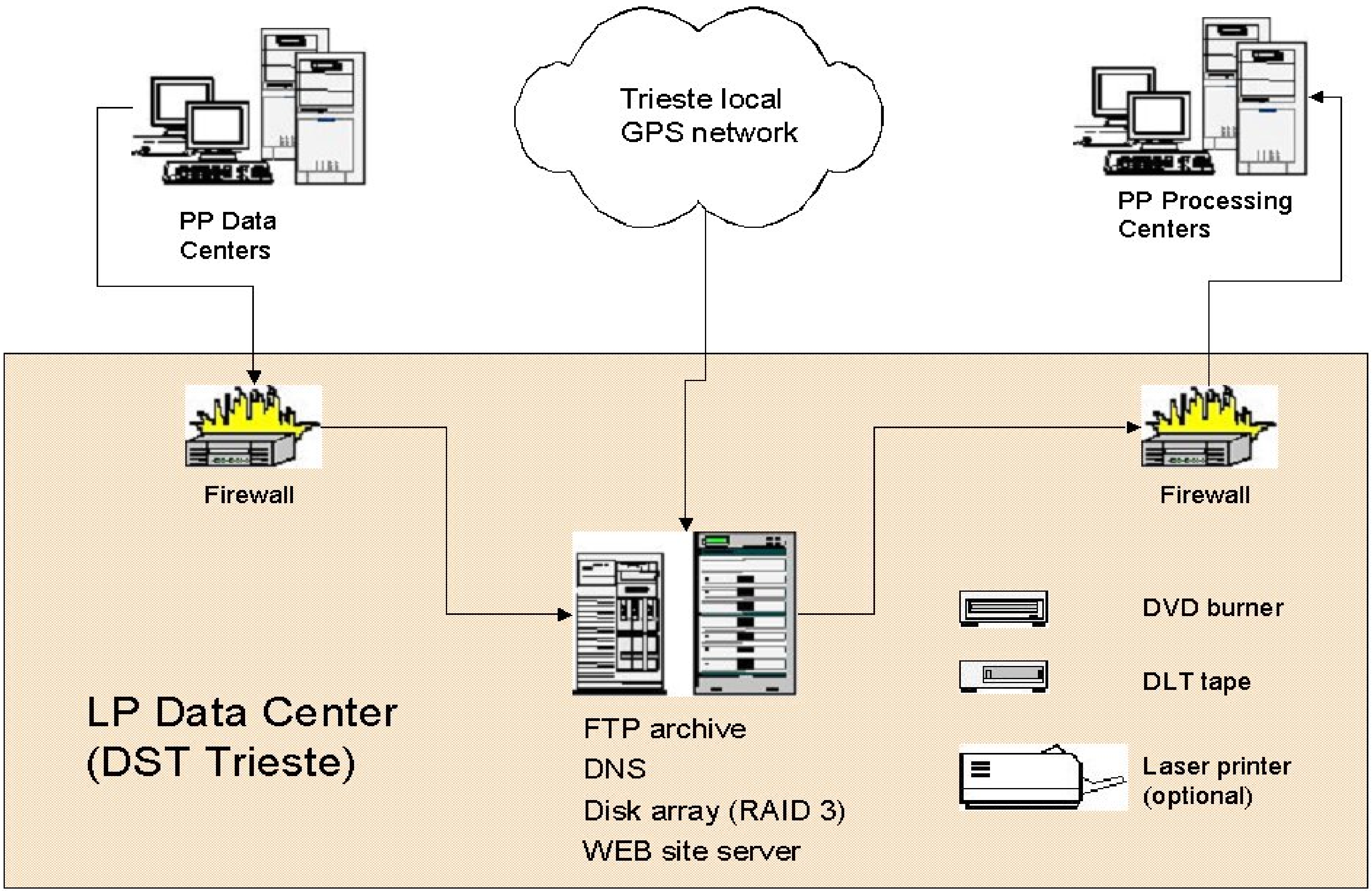


A differenza di quanto mostrato nella figura della pagina a fronte, nelle Alpi è possibile individuare delle radici crostali ben sviluppate. In corrispondenza delle radici non è possibile operare una distinzione in crosta superiore, media e inferiore, ma i dati geofisici indicano che questa zona è caratterizzata da un *mélange* di materiali crostali distribuiti in modo ancora disordinato. La radice litosferica è spostata verso sud-est rispetto alla radice crostale ed è rilevante la continuità esistente tra la proiezione della linea insubrica e il bordo settentrionale della litosfera in subduzione, al punto da far ritenere la linea insubrica una faglia litosferica. È notevole la differenza tra la litosfera del blocco europeo (circa 50 chilometri, un terzo dei quali di crosta inferiore) e quella del blocco africano (spessore litosferico di circa 90 chilometri nel quale la crosta nella sua totalità costituisce un terzo dello spessore litosferico). I numeri rappresentano la velocità di propagazione delle onde sismiche di compressione, mentre le cifre tra parentesi sono relative alle onde di taglio, velocità sempre espresse in chilometri al secondo.

GAIN - CGPS Network



GAIN - CGPS Data Center



GAIN - CGPS Network

more than 40 Continuous GPS (CGPS) across the Alps plus campaign GPS in different test sites

image the distributed continental deformation over the widest possible range of spatial and temporal scales

two length scales against which the data should be compared:

- **thickness of the crust**
- **thickness of the lithosphere**

particular emphasis on detection of transient deformation signals in test sites

GPS can help with...

Earthquake response information

- identify fault source, extent and amount of slip
- model finite fault source
- measure and model deformation field
- provide all above to emergency responders

Damage estimation

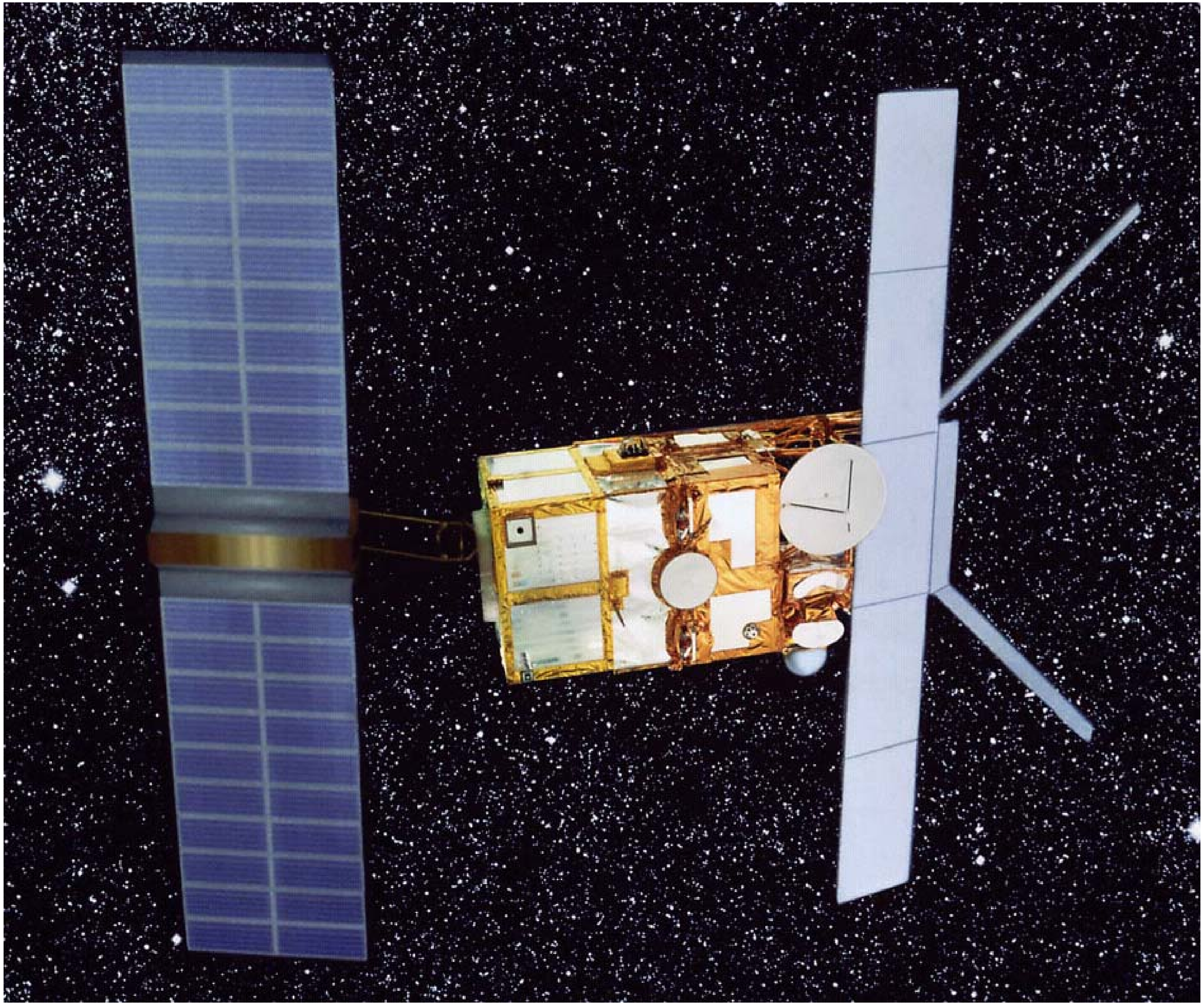
- provide data for use in shake maps
- support of remote sensing and positioning for accurate and timely collection, reporting and control of other data that require accurate position and/or timing
- monitor large engineered structure and lifeline systems

Early warning system

GPS fault slip sensors in real-time to detect fault slip at the surface

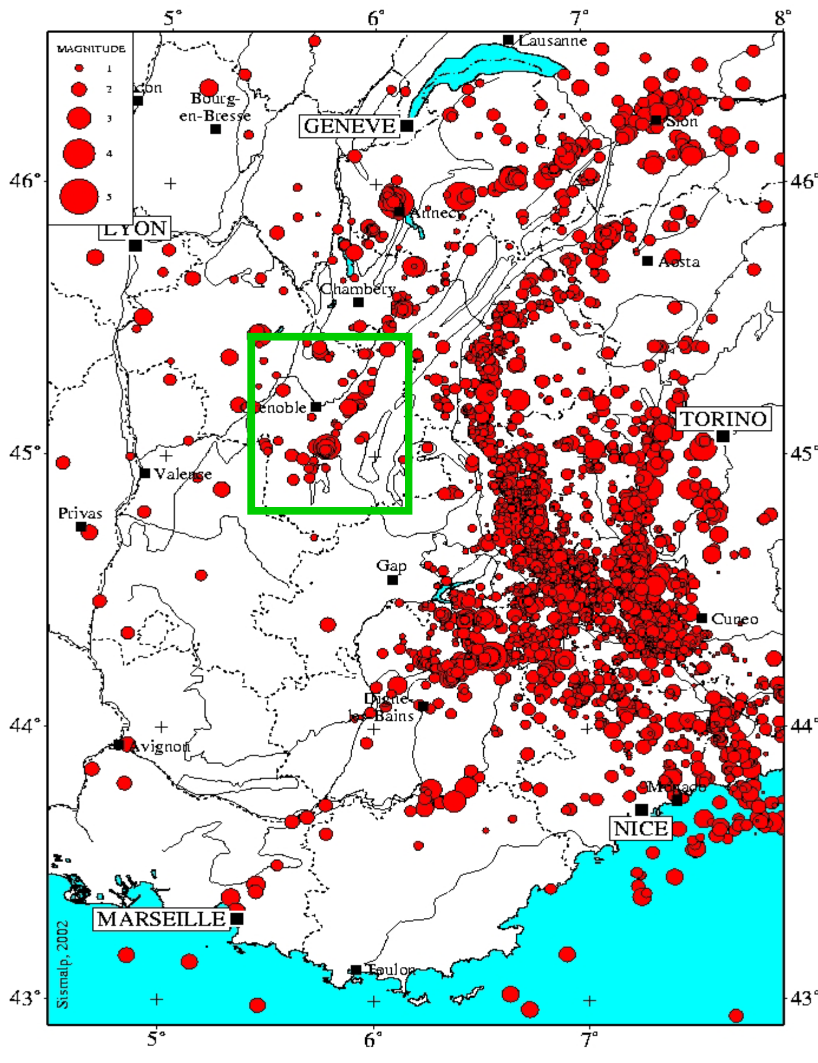
ERS-1/2

1991
to
2002

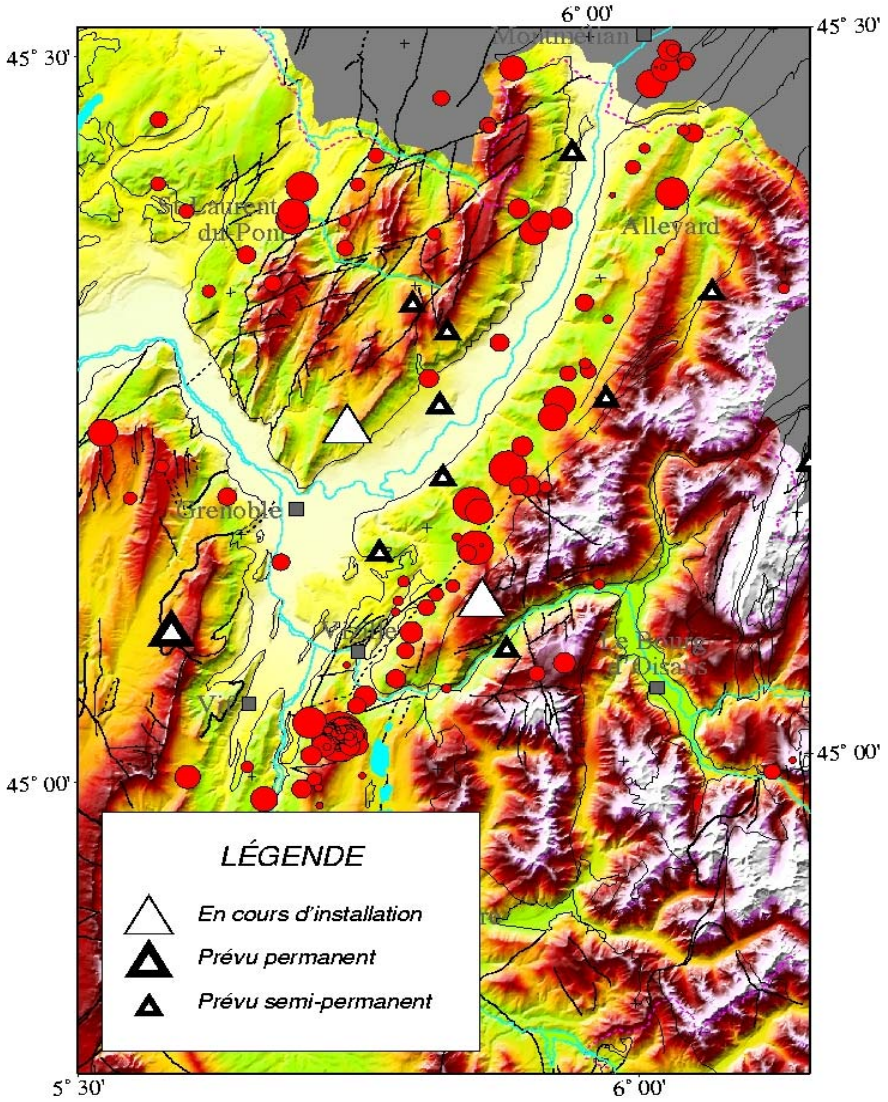


Measuring millimetric ground displacements from space

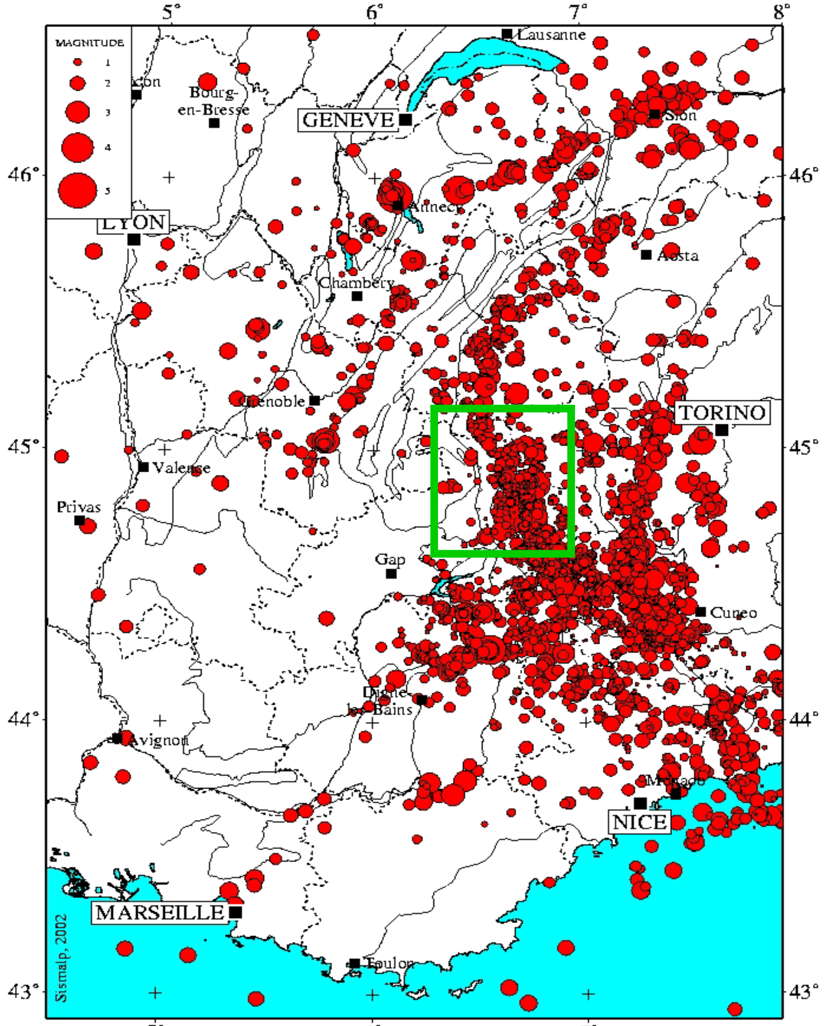
Test site Grenoble- Belledonne Fault:
CGPS - Campaign GPS monitoring



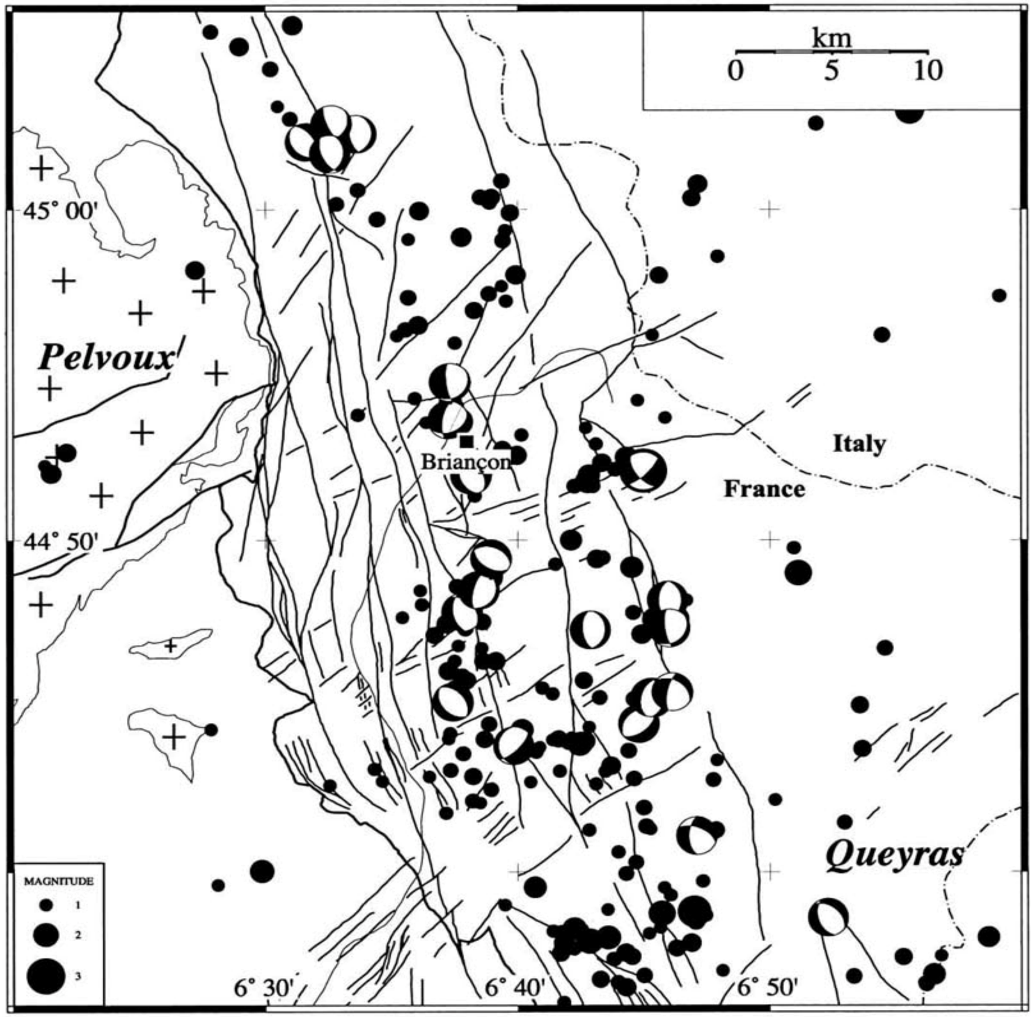
Sismicité naturelle Sismalp 1989-2000



Test site Briançonnais:
CGPS - Campaign GPS monitoring



Sismicité naturelle Sismalp 1989-2000



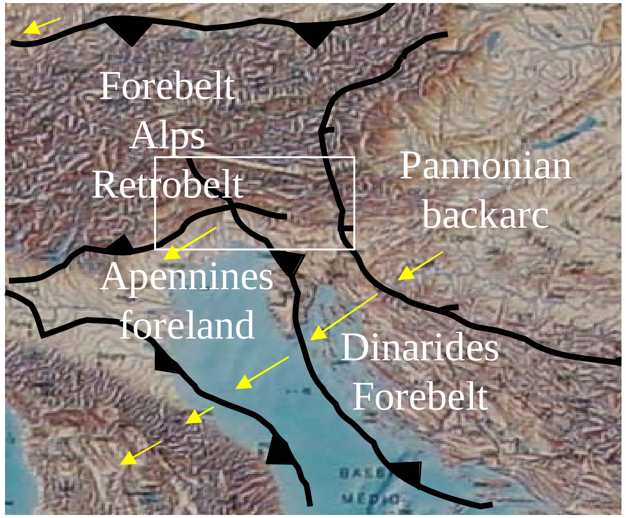
Four subduction zones contributed to deform the area:

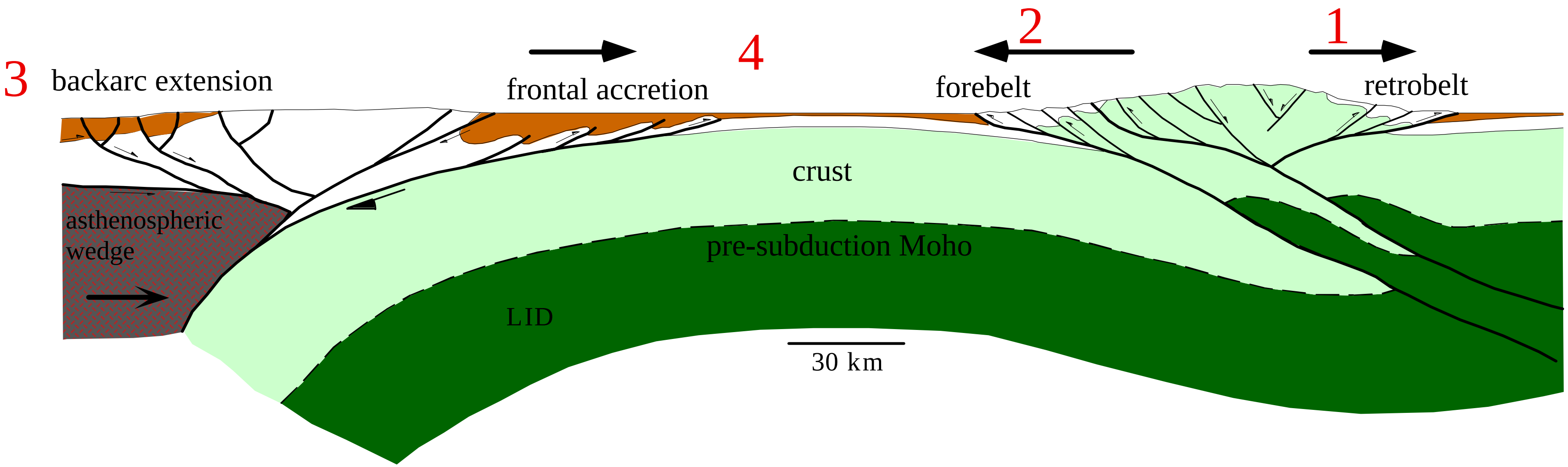
1 - ALPS (retrobelt)

2 - DINARIDES (forebelt)

3 - CARPATHIANS (western backarc)

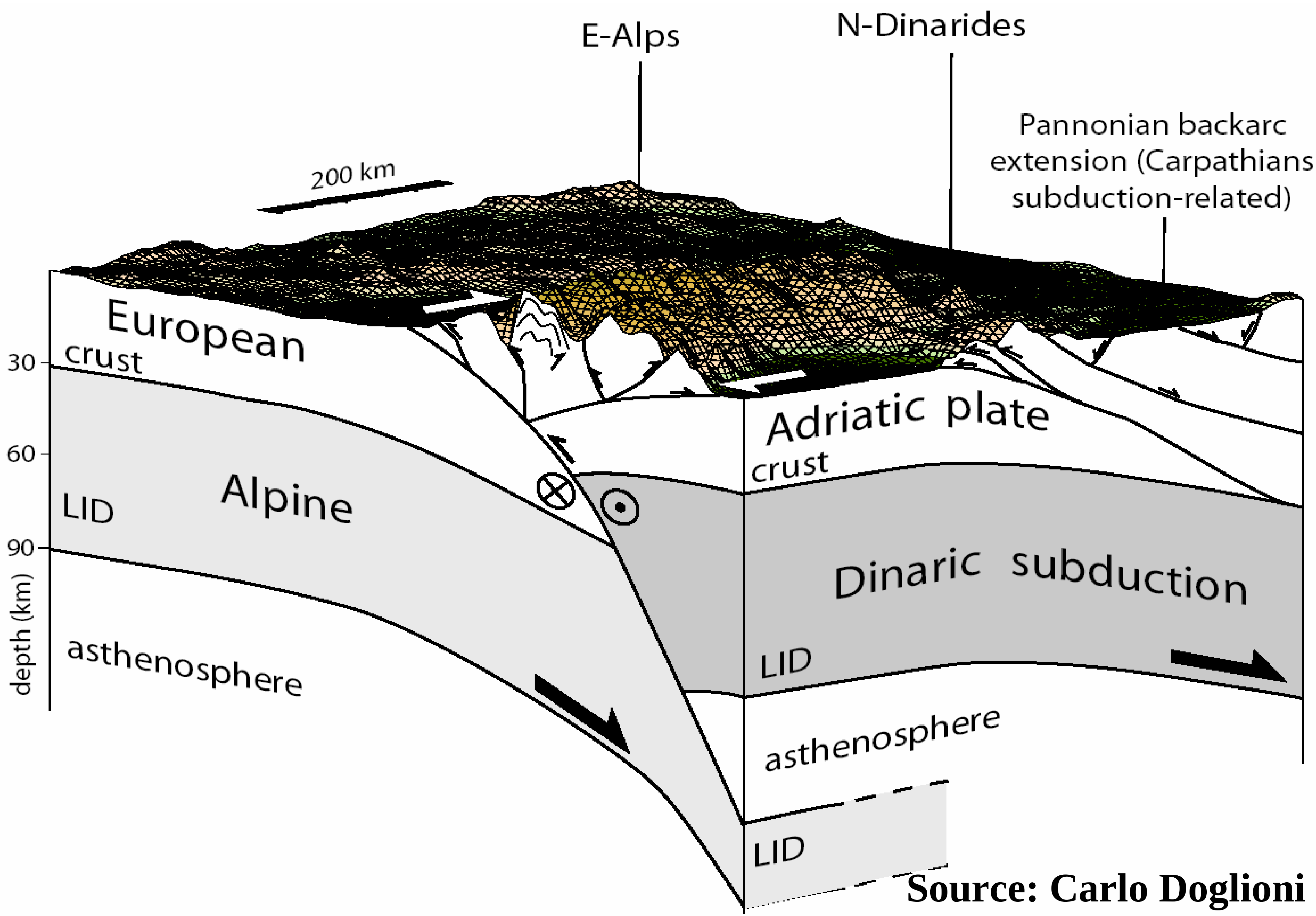
4 - APENNINES (foreland flexure)





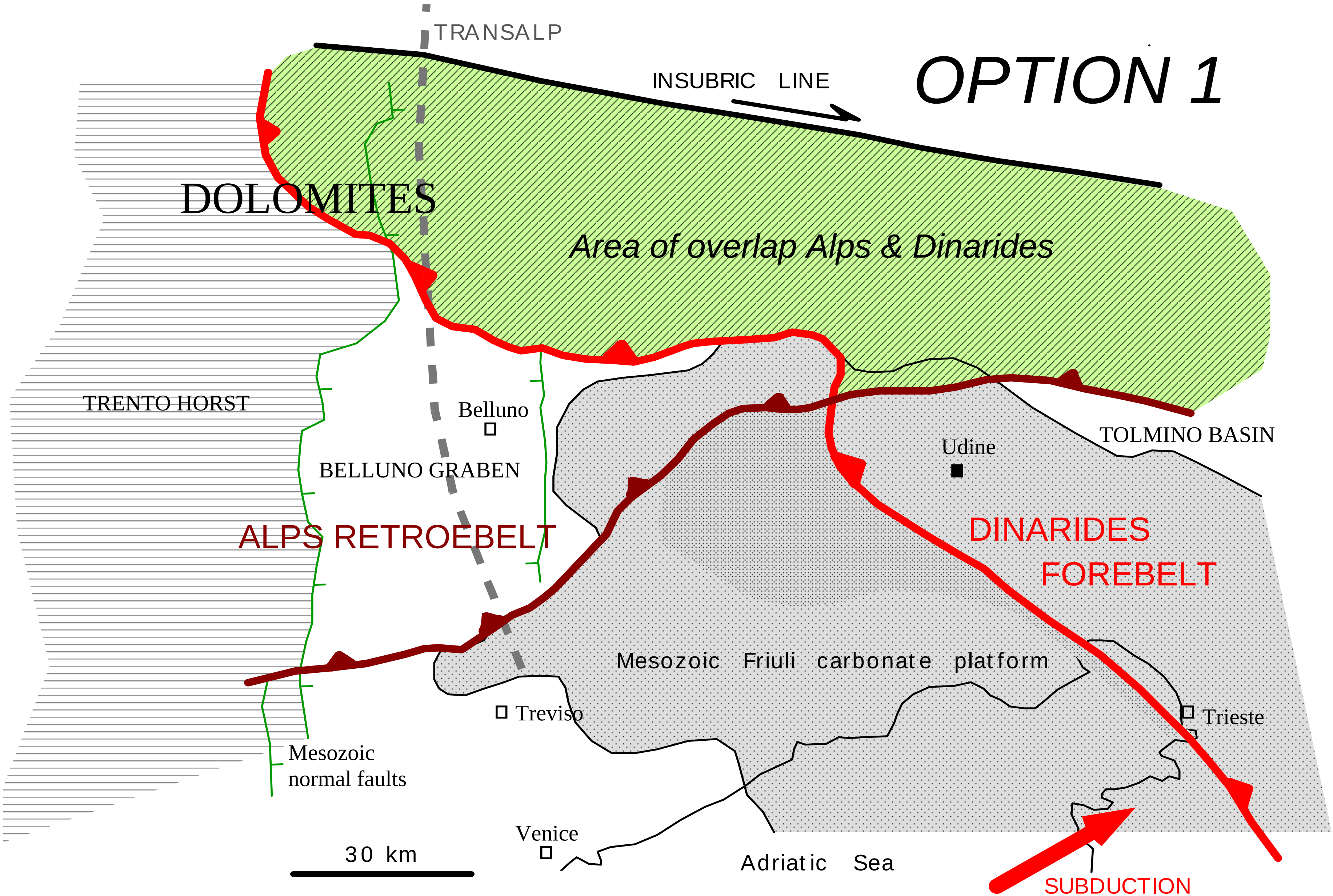
- Independent geodynamic processes may coexist in one area

Source: Carlo Doglioni



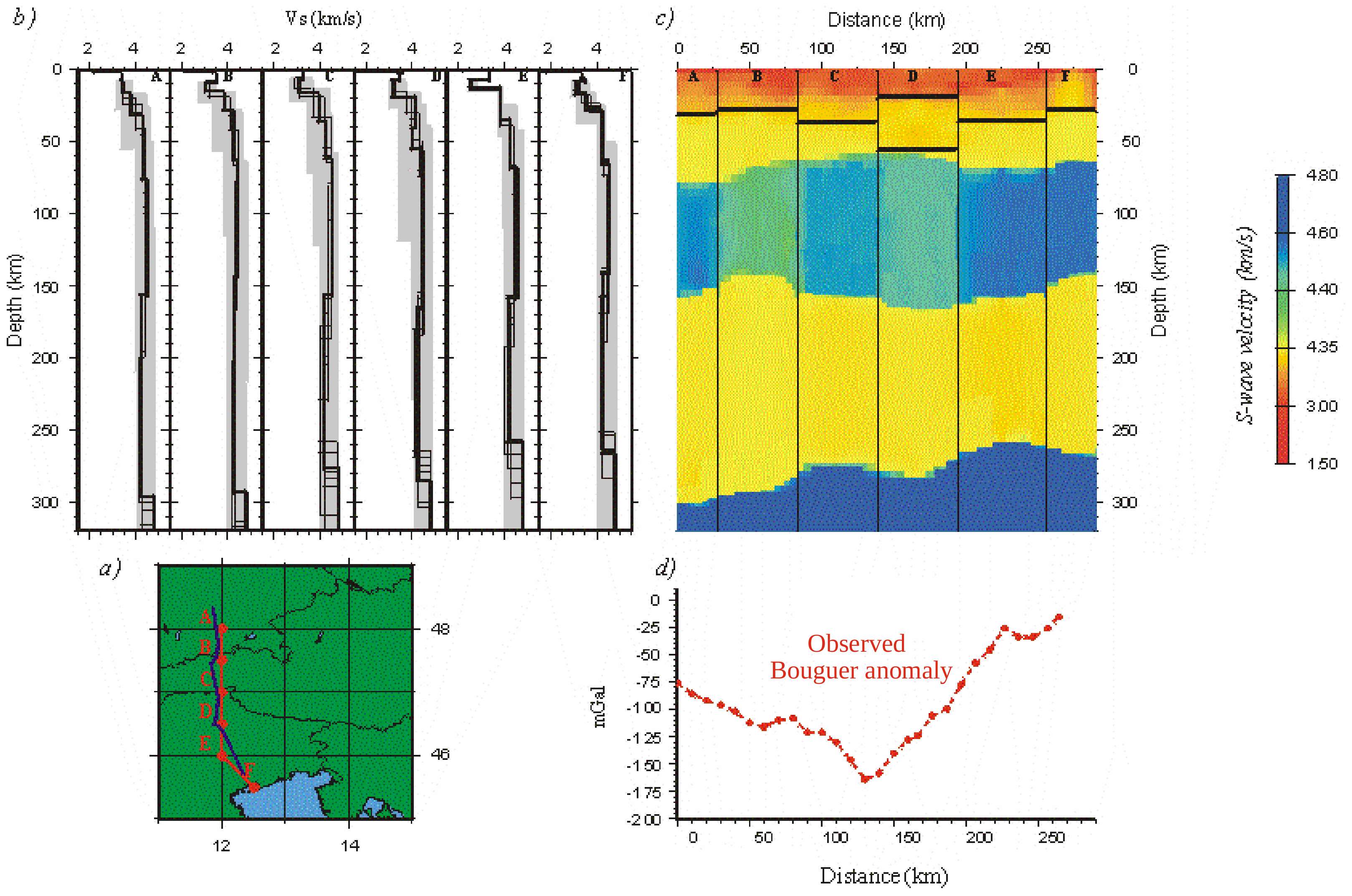
Source: Carlo Doglioni

OPTION 1

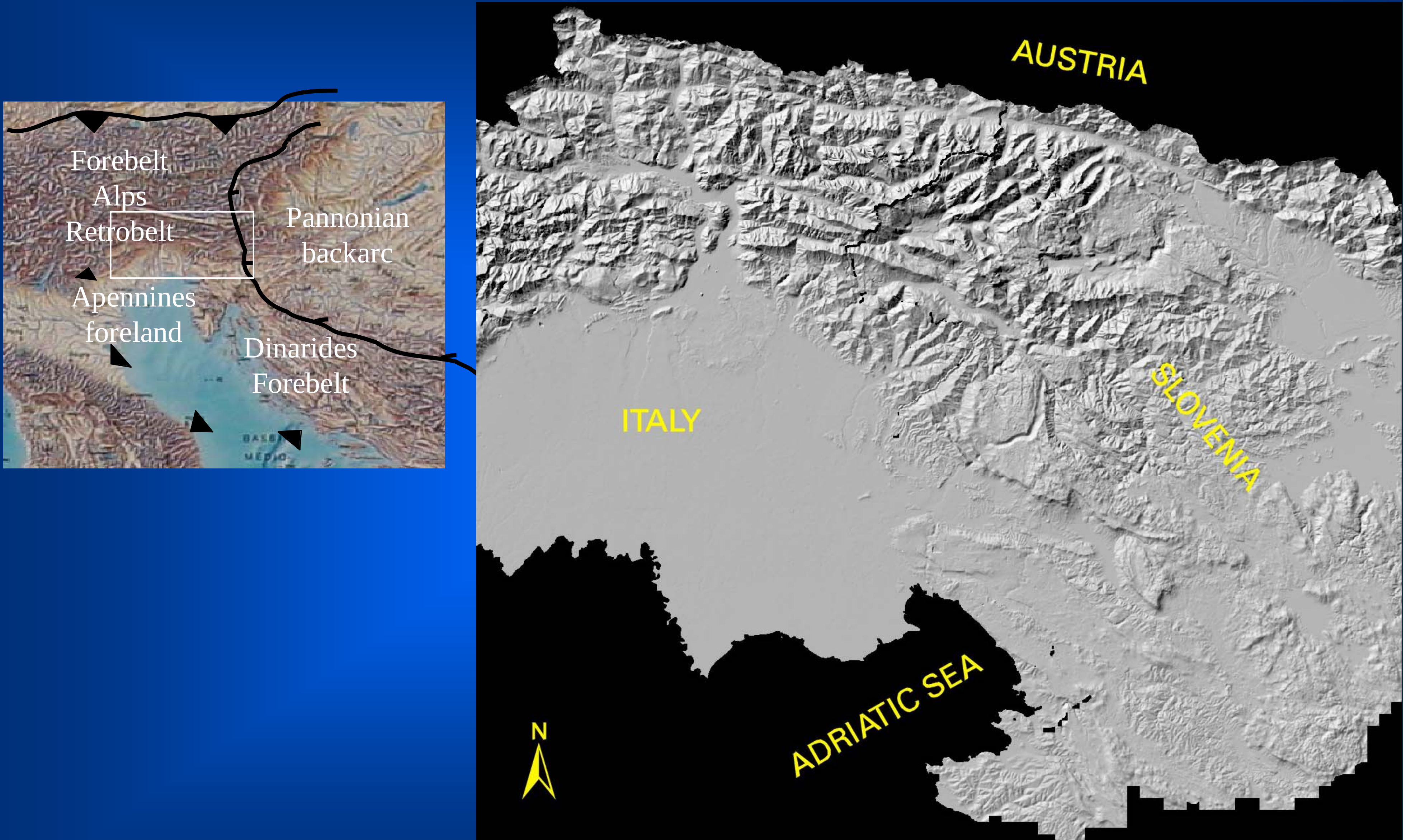


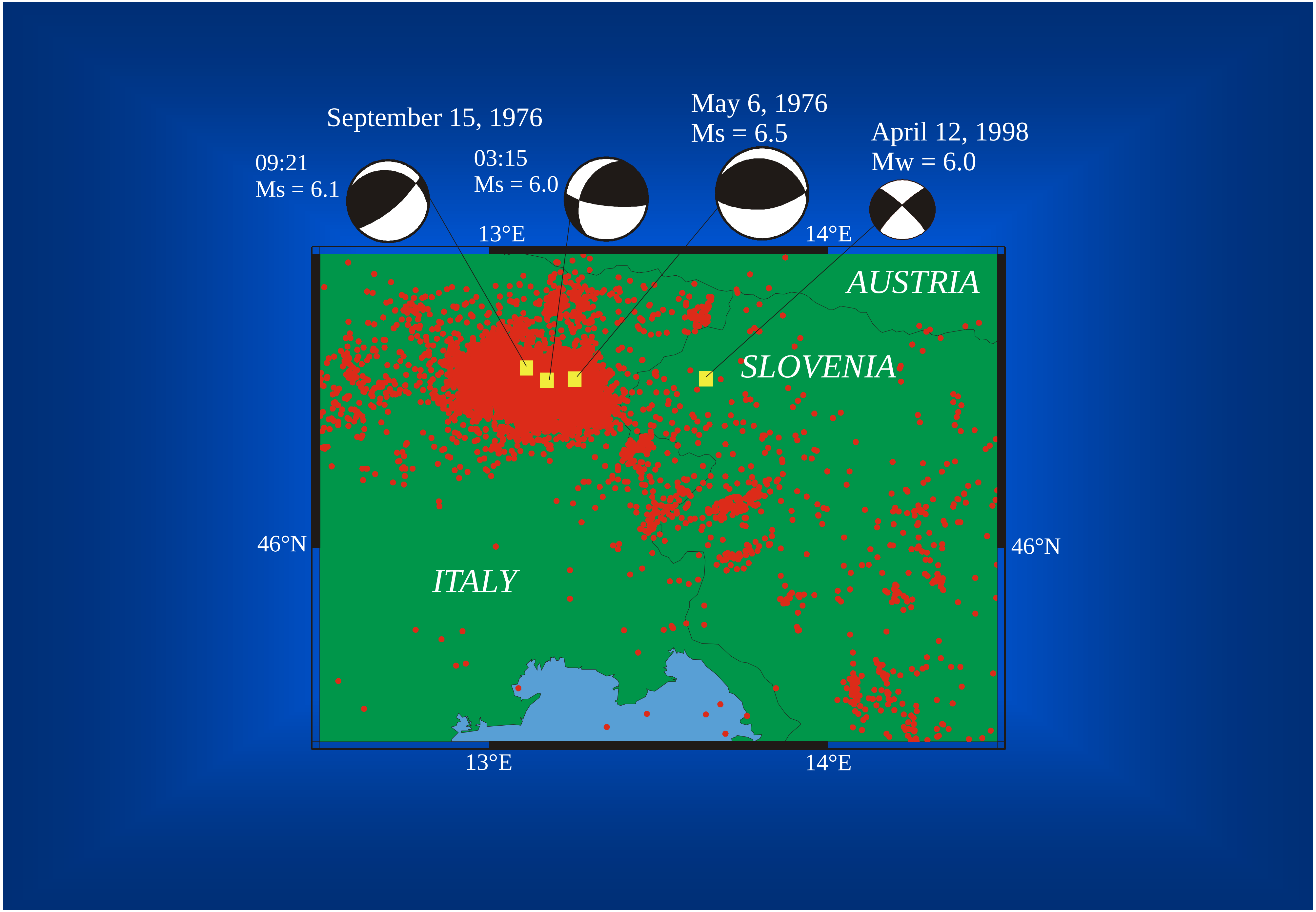
Source: Carlo Doglioni

EASTERN ALPS

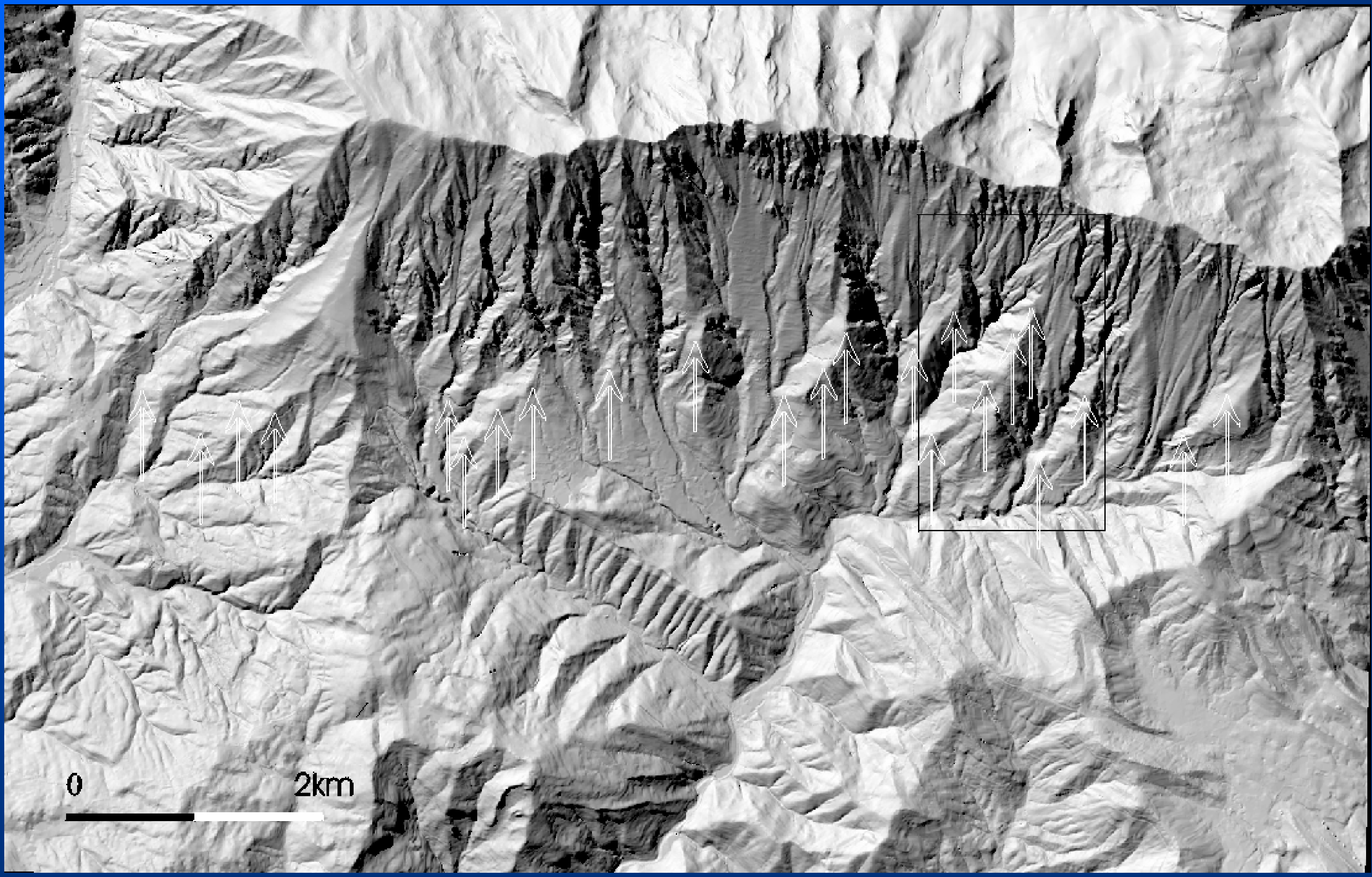


Panza et al., 2002

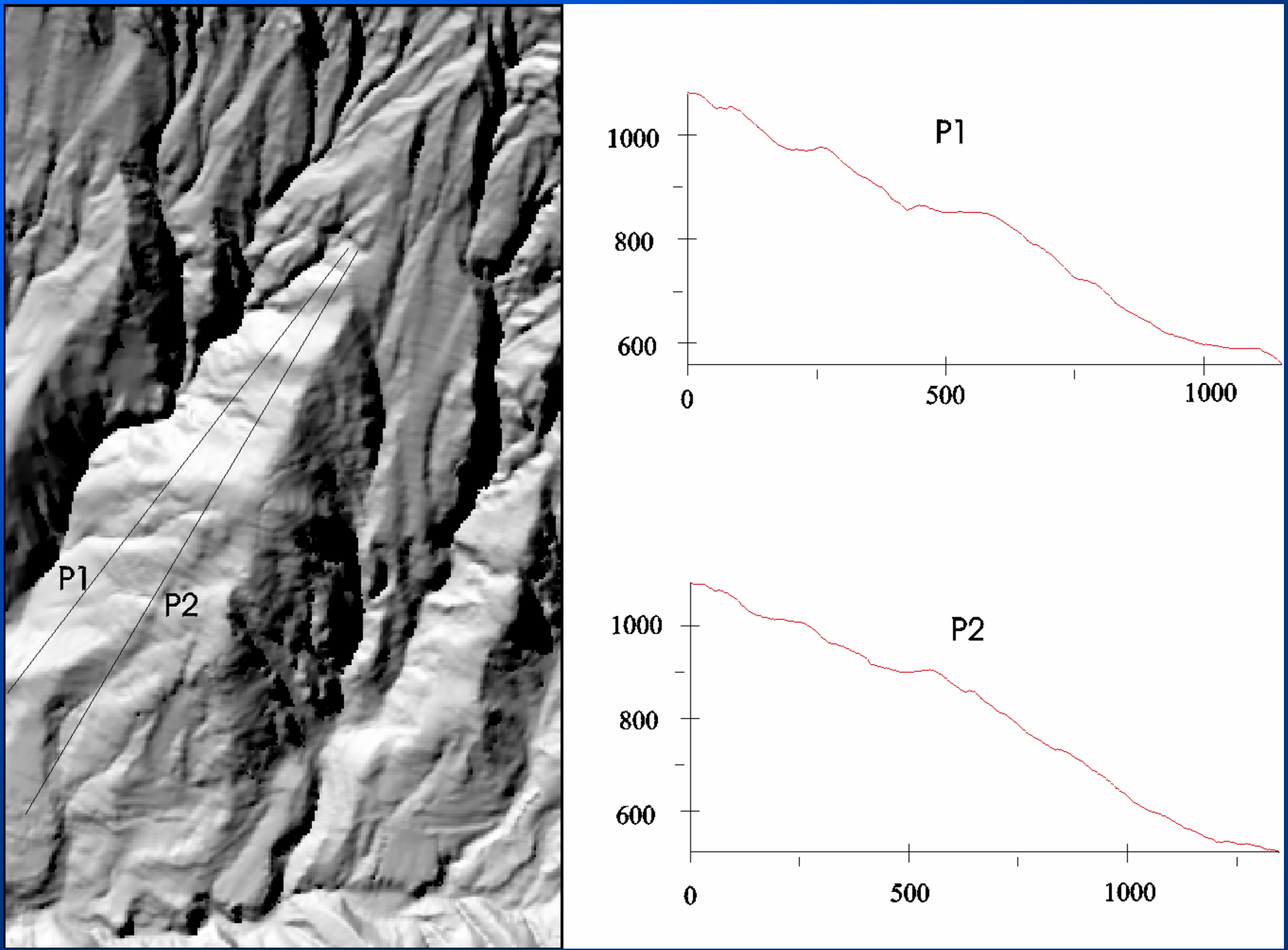

Forebelt
Alps
Retrobelt
Pannonian
backarc
Apennines
foreland
Dinarides
Forebelt
AUSTRIA
ITALY
SLOVENIA
ADRIATIC SEA
N


September 15, 1976
09:21
Ms = 6.1
03:15
Ms = 6.0
May 6, 1976
Ms = 6.5
April 12, 1998
Mw = 6.0
13°E
14°E
AUSTRIA
SLOVENIA
ITALY
46°N
46°N
13°E
14°E

Digital elevation modeling

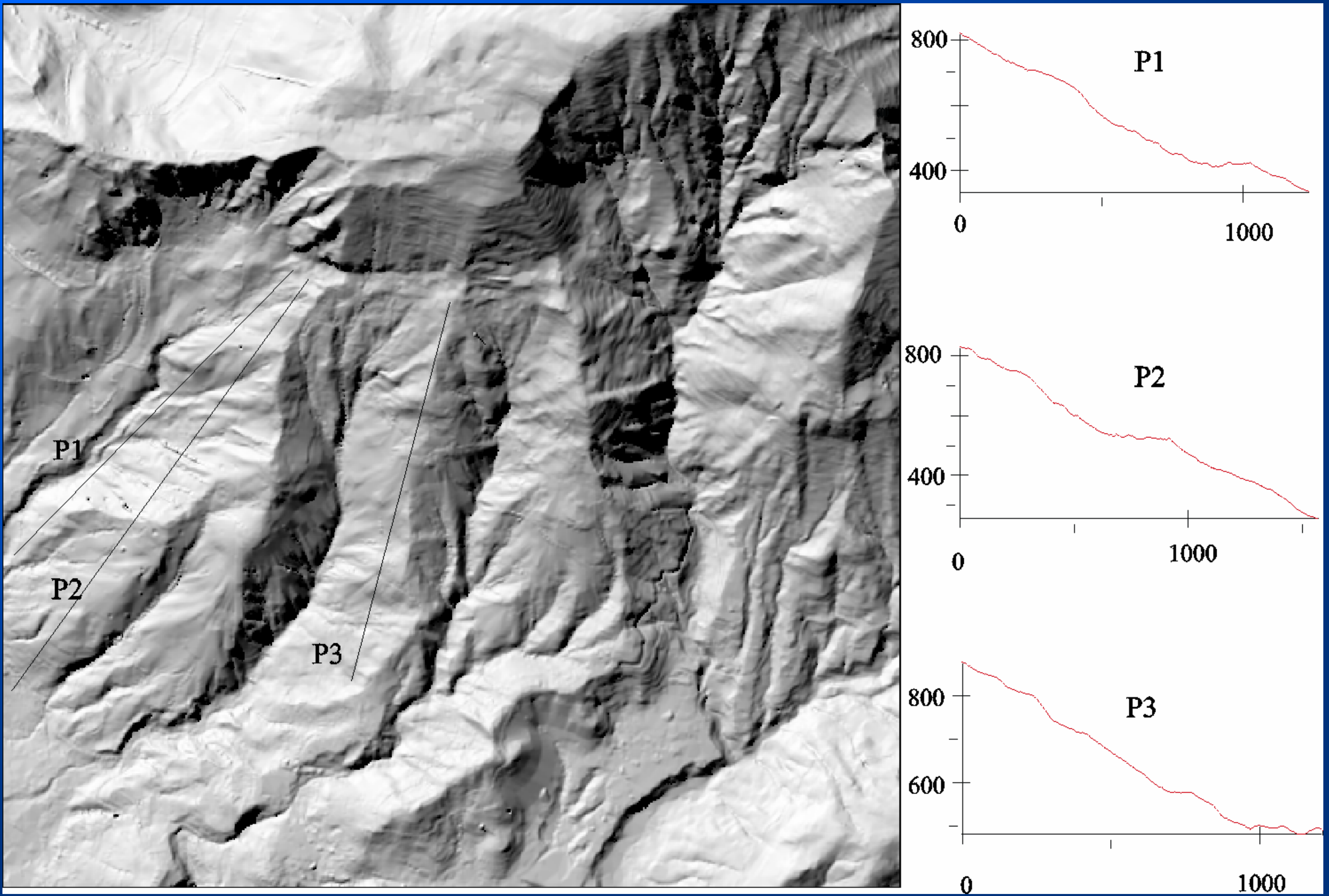


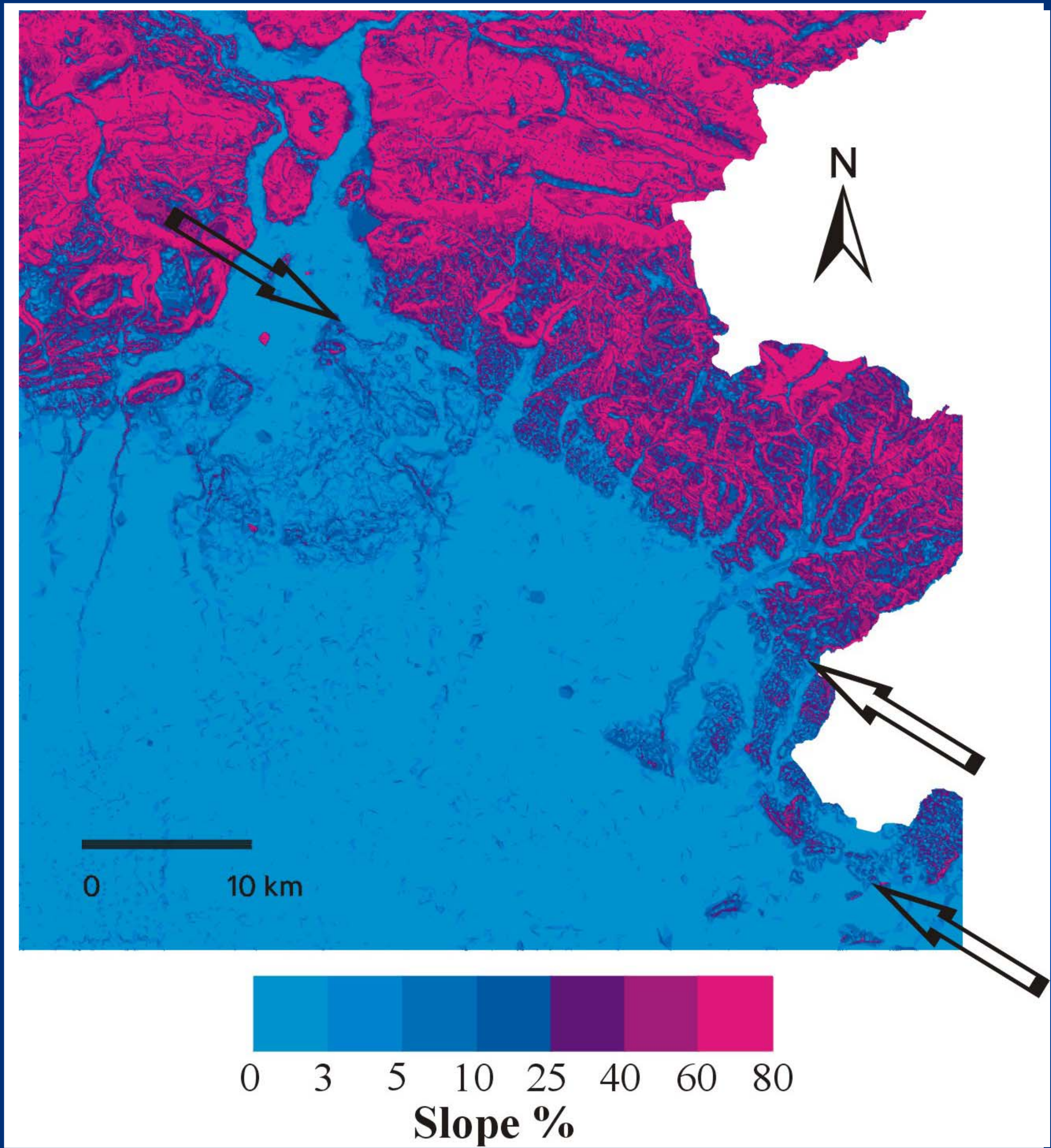
Digital elevation modeling



Digital elevation modeling

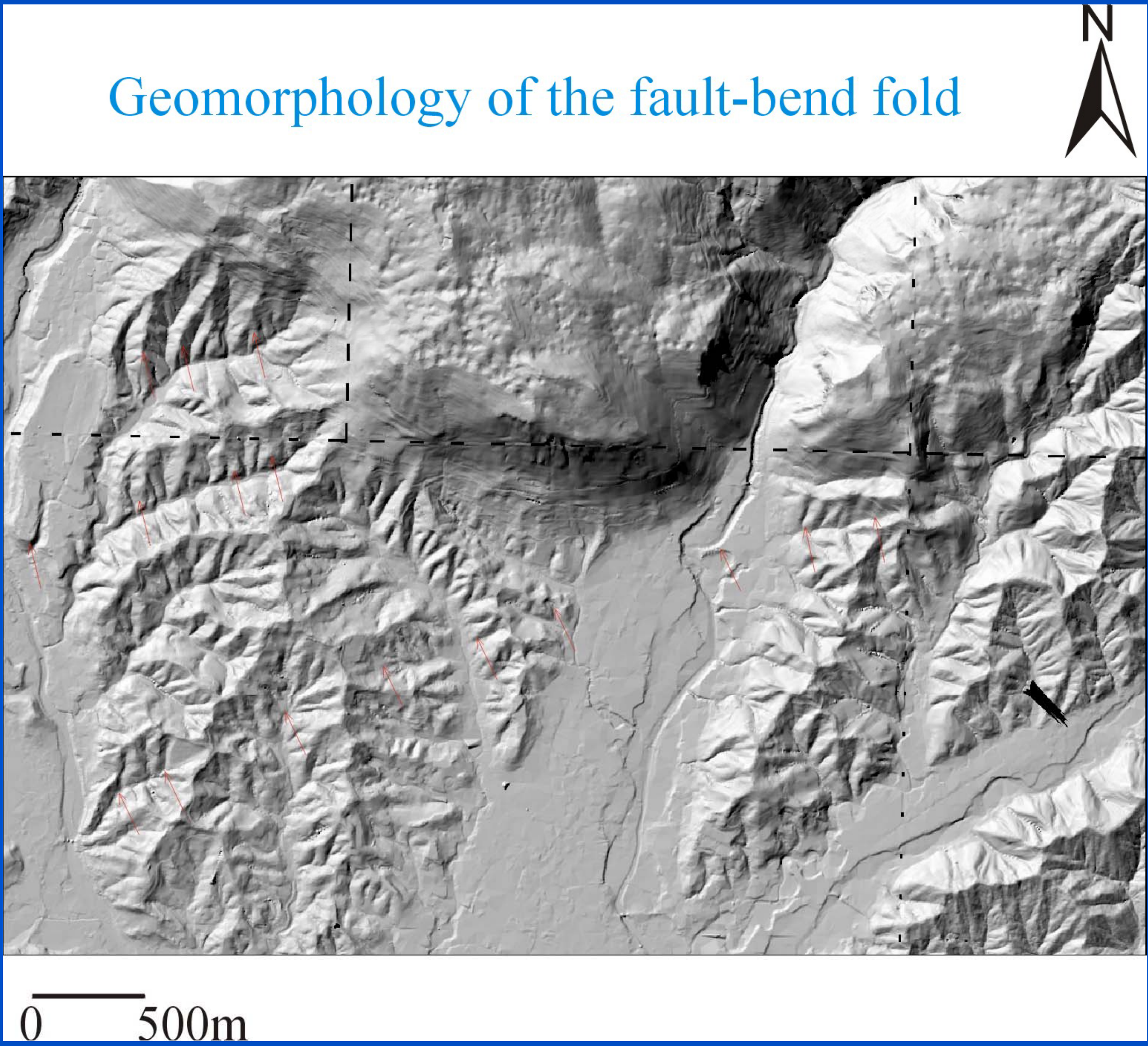
Digital elevation modeling

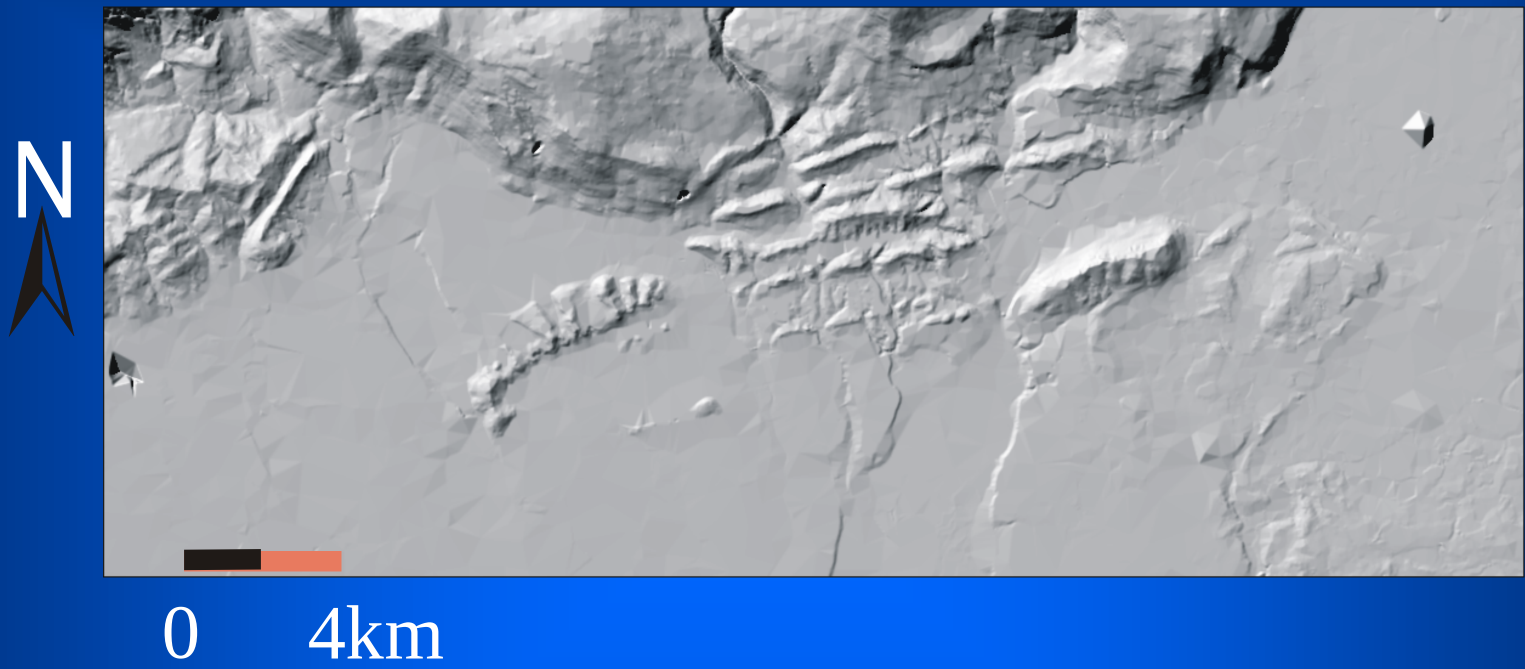


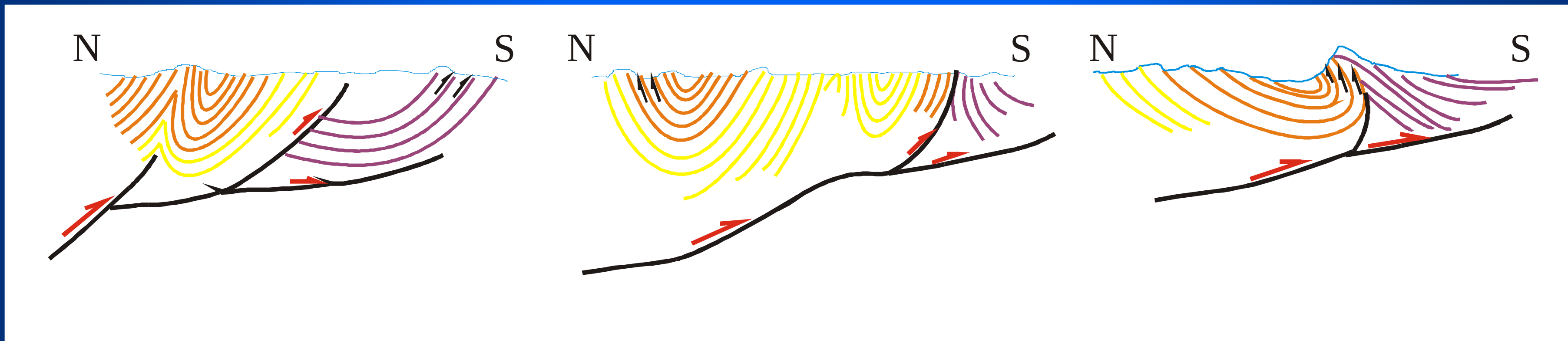


Digital elevation models and GIS-based analysis

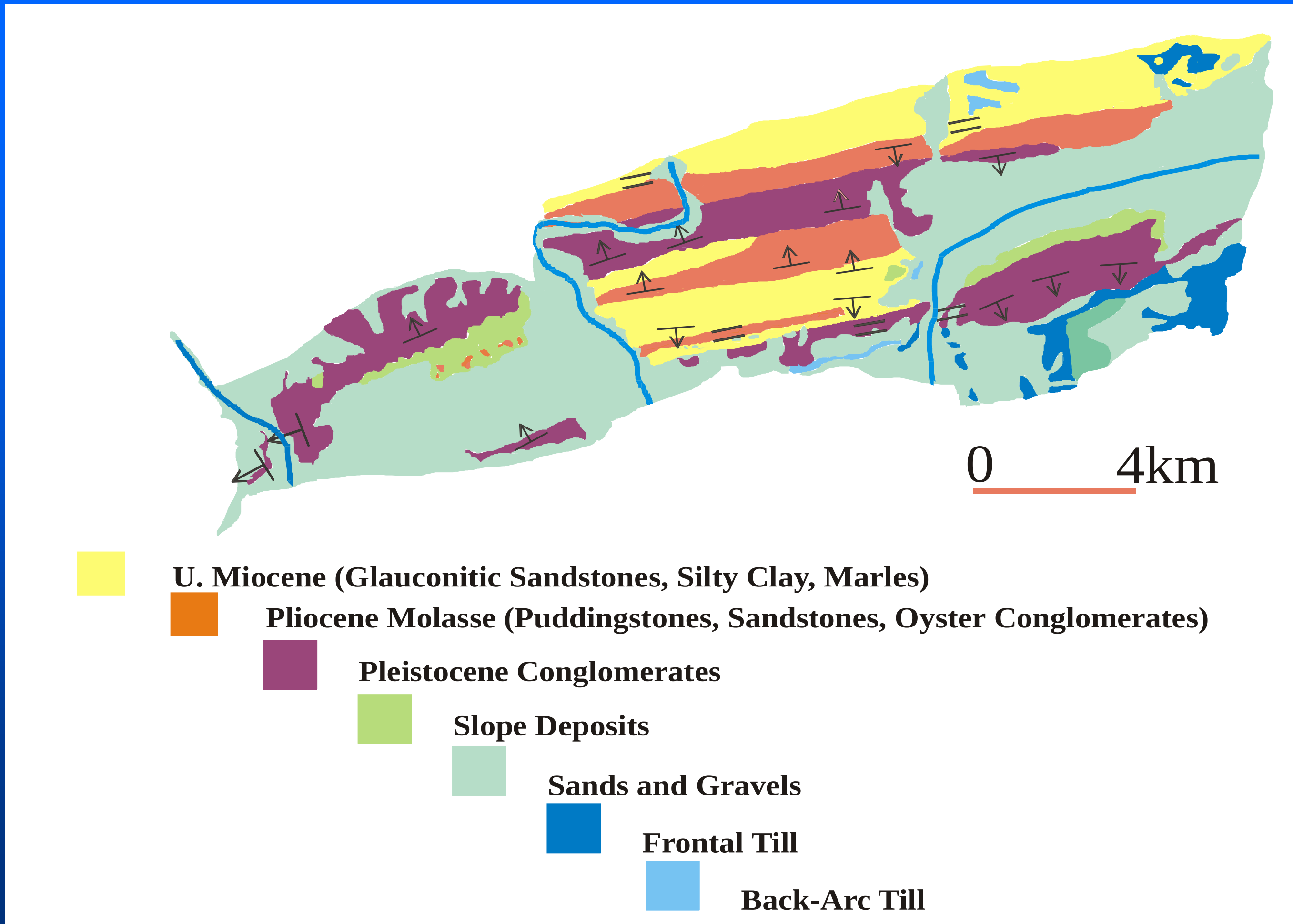
Geomorphology of the fault-bend fold



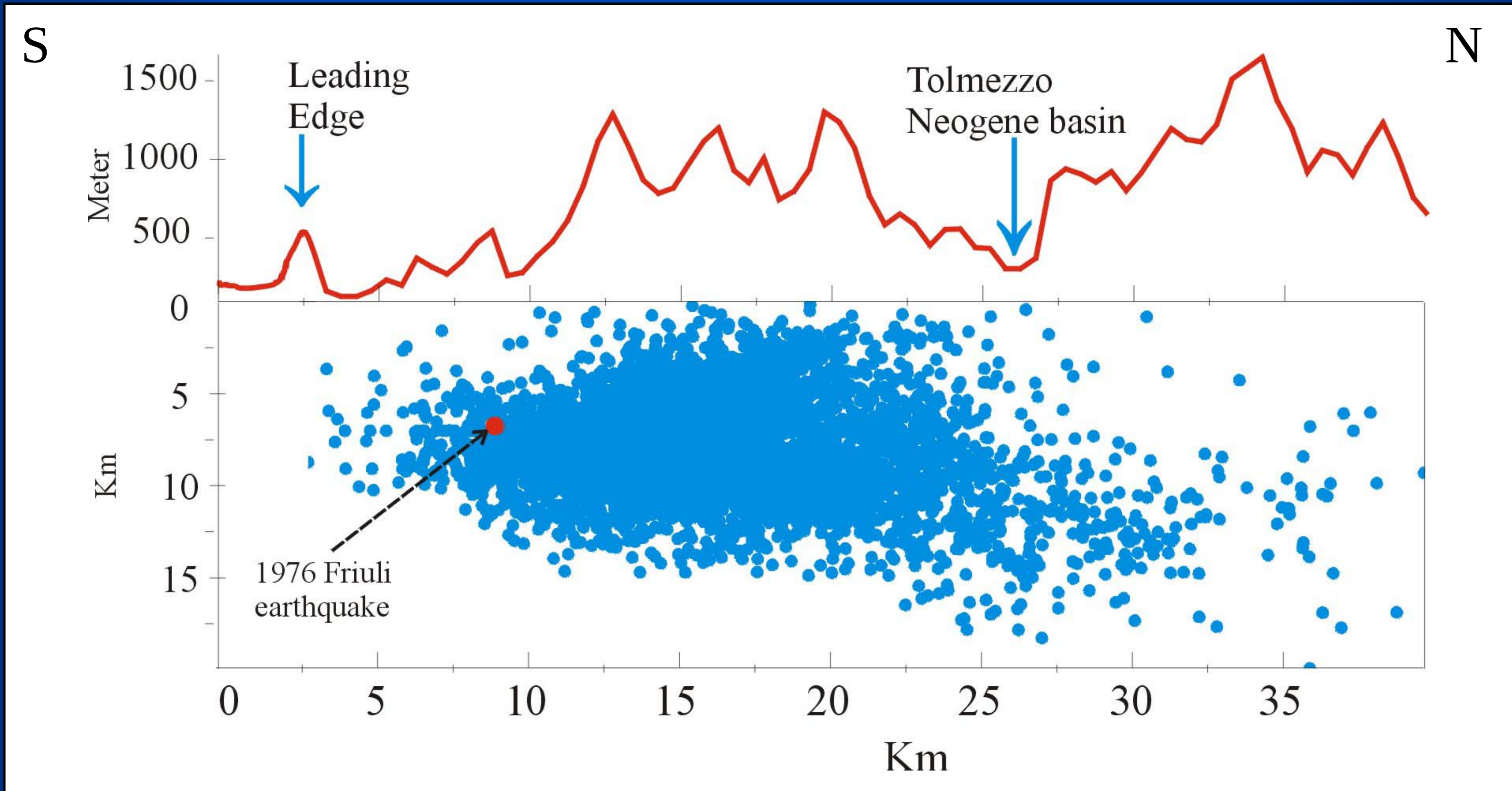

N
0
4km


N
S
N
S
N
S

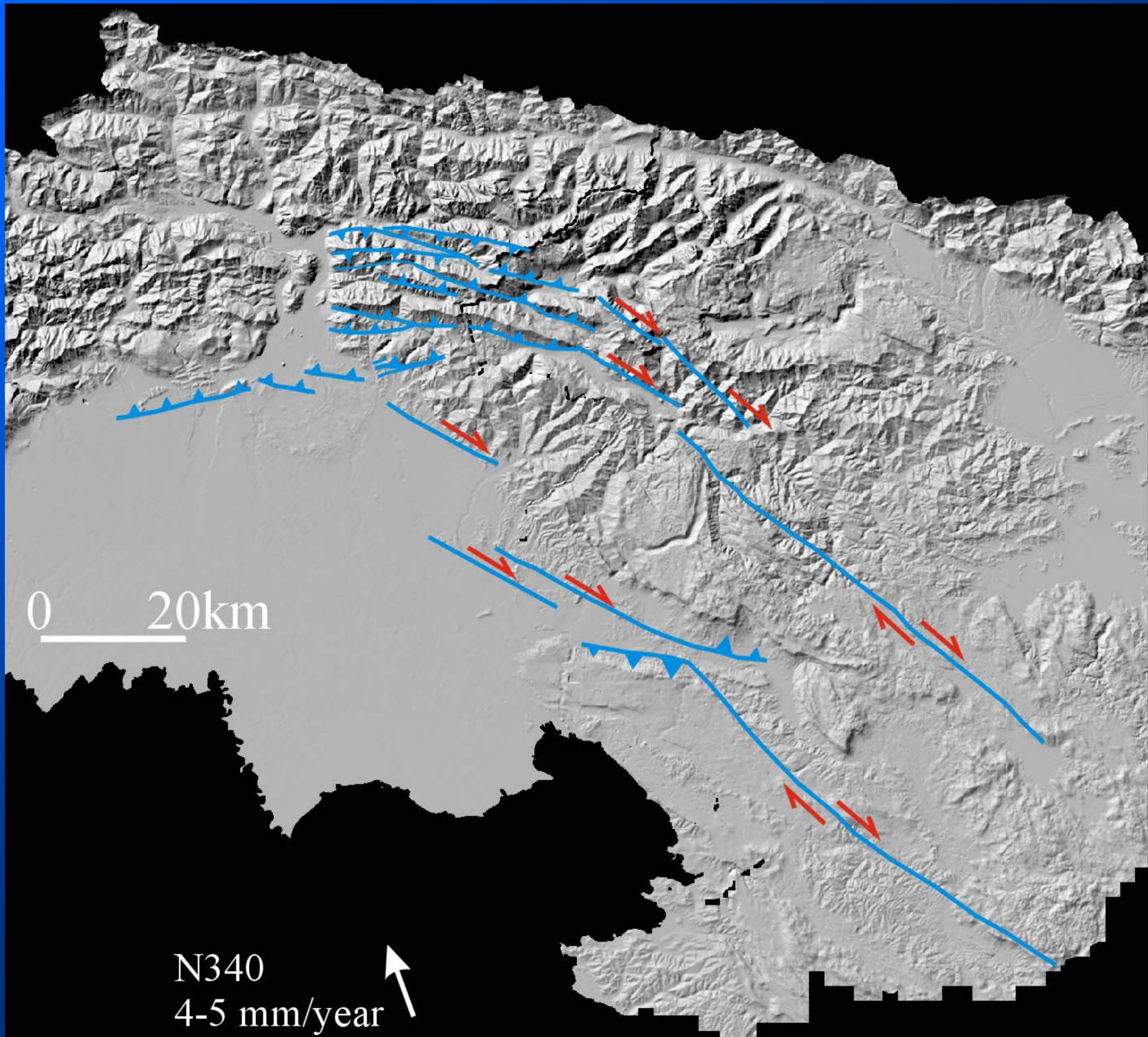
Geology of the Leading Edge



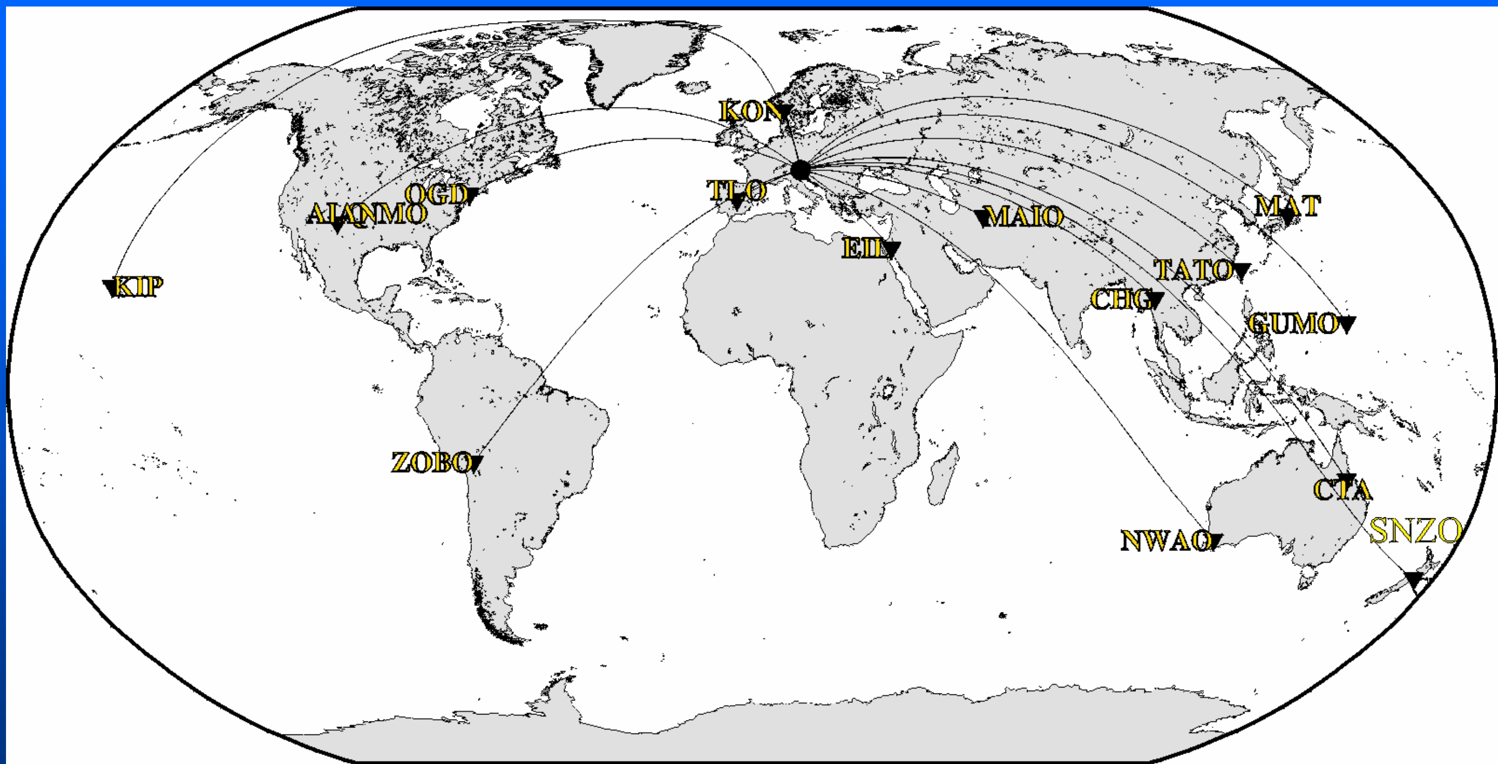
Cross-section: Topography & seismicity



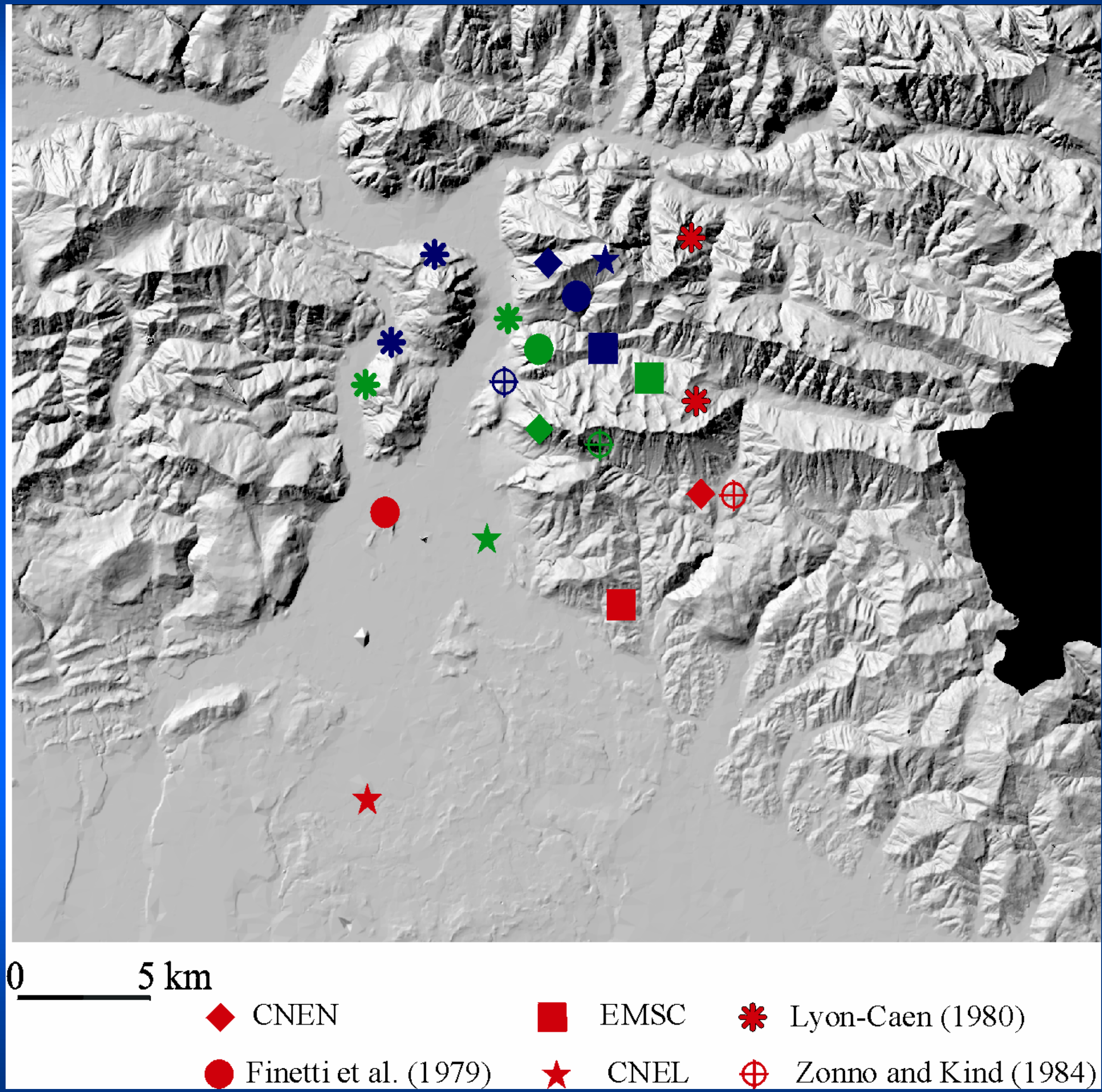
Active deformation: Geometry of the structures



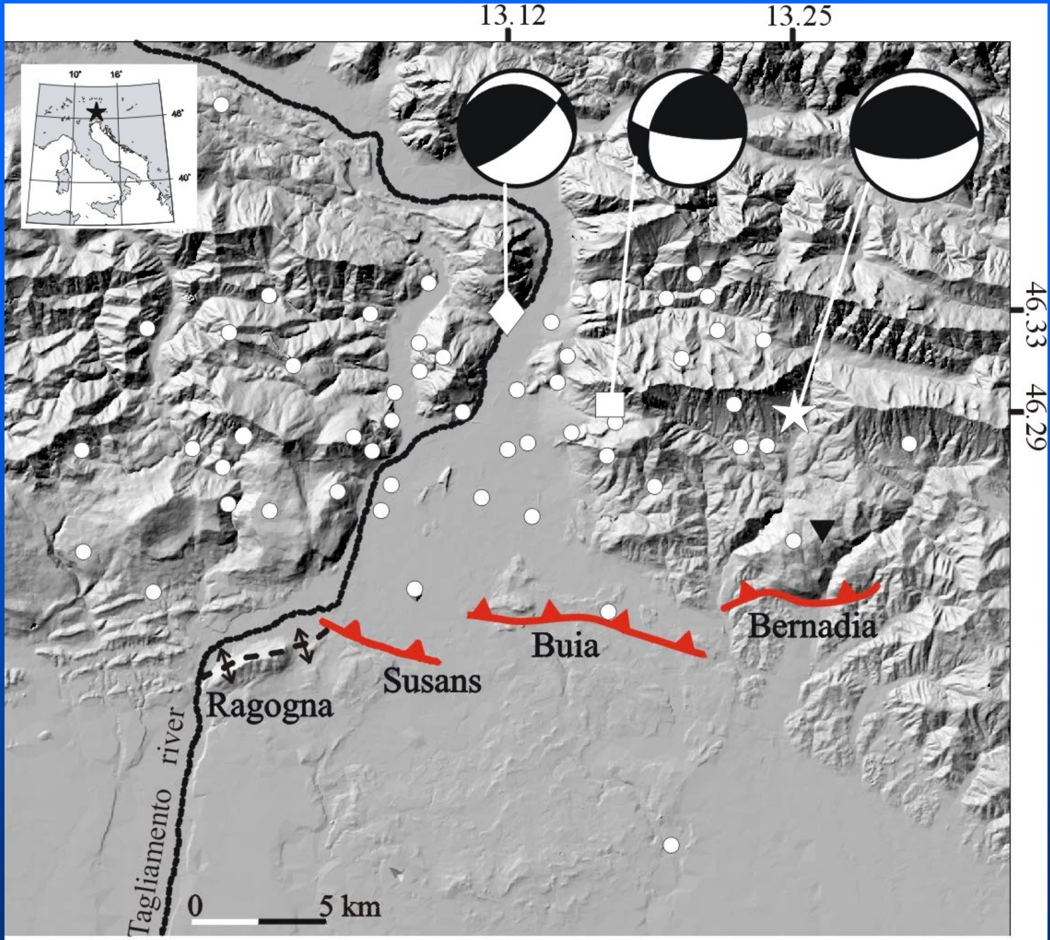
HGLP and GDSN stations that recorded the 1976 Friuli sequence



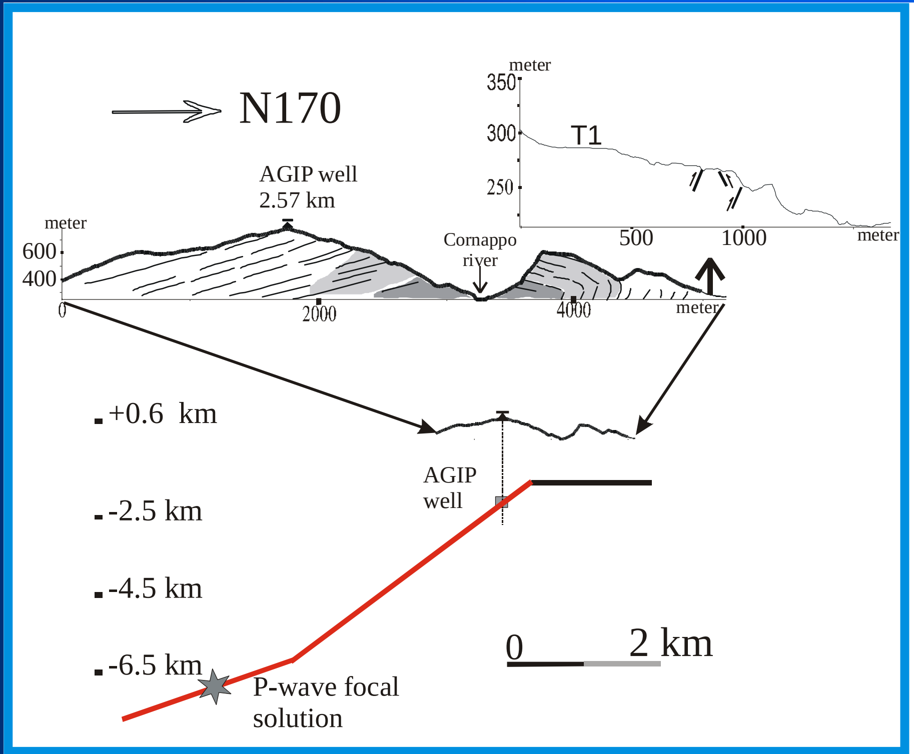
Epicentral locations of the 1976 earthquake sequence

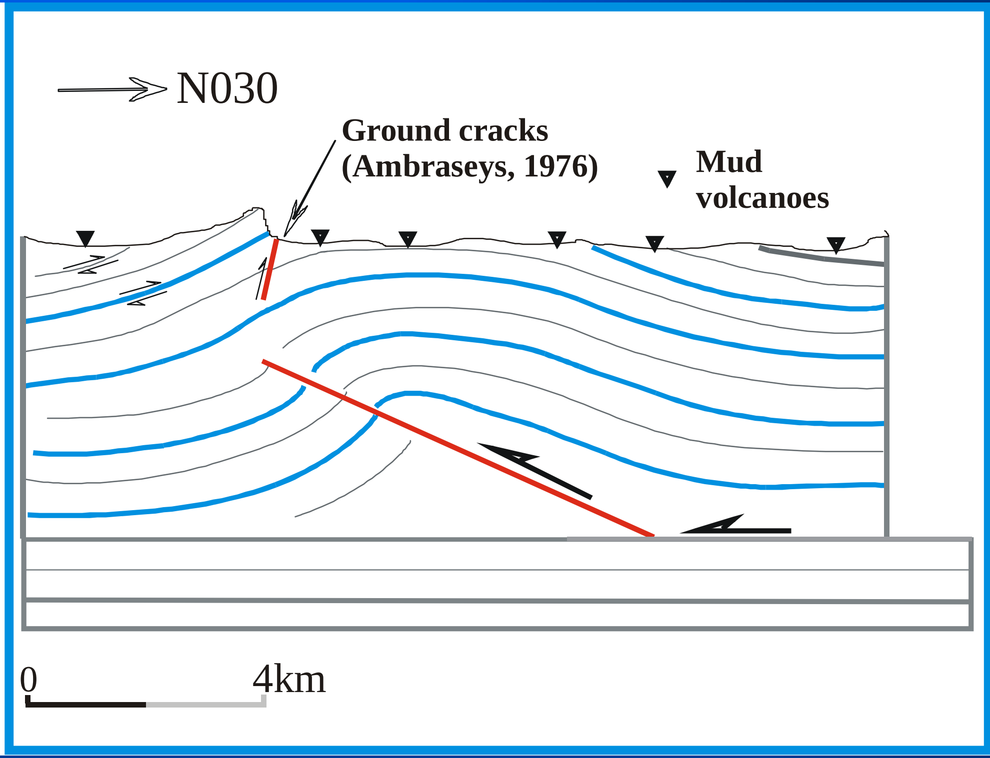


The 1976 Friuli thrust fault and related earthquake sequence

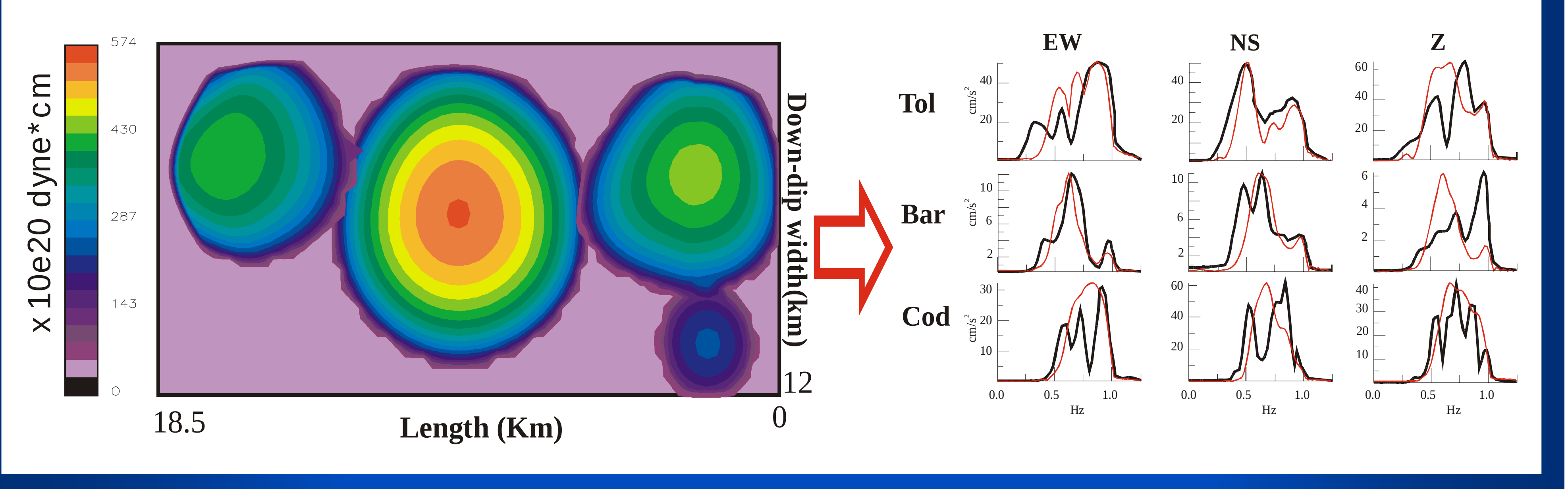


Fault-bend and fault-propagation folds reactivated during the 1976 Friuli earthquake





The 1976 Friuli thrust faulting Earthquake: Forward modeling

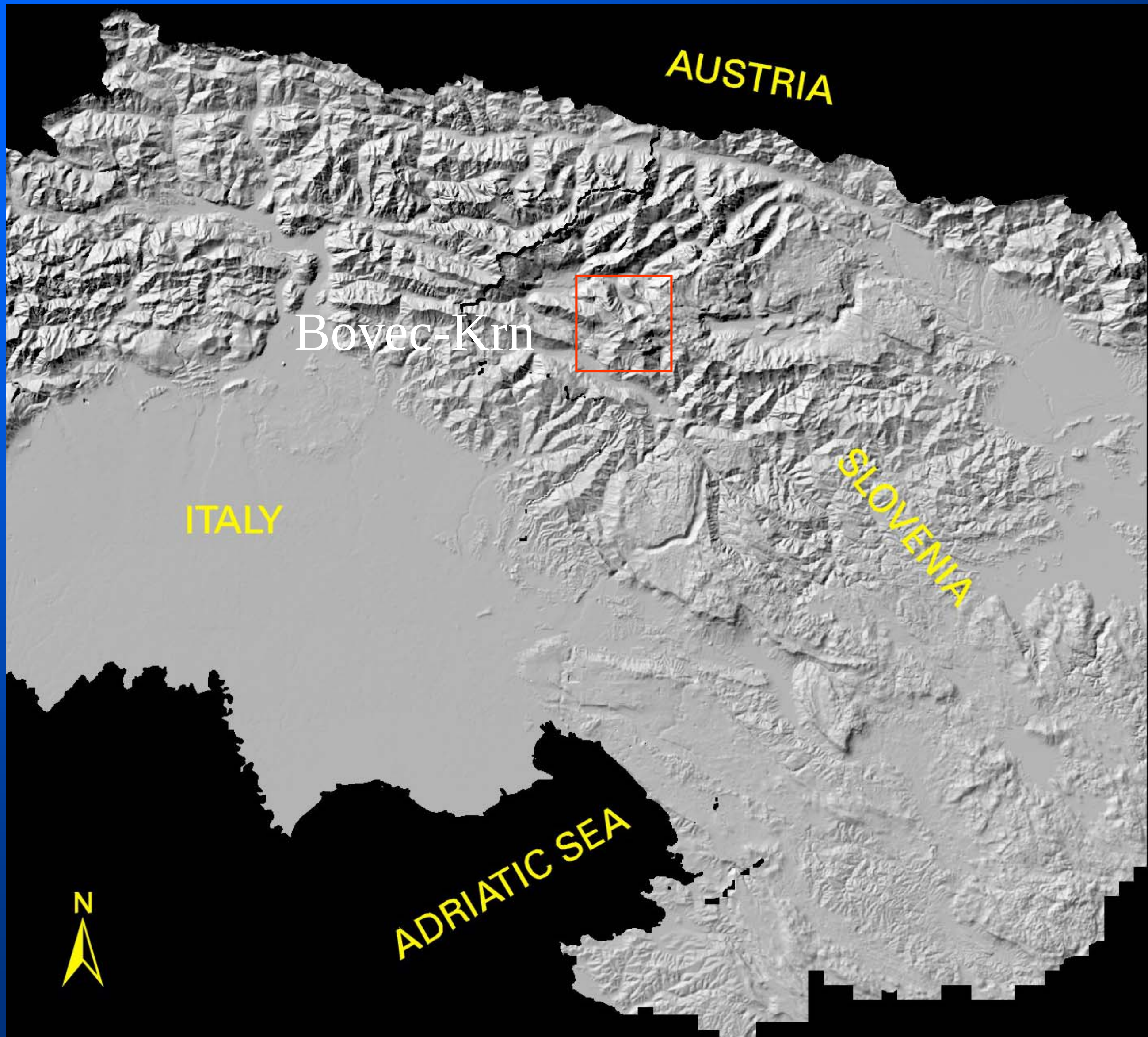


Why do "thrust faulting" earthquakes stop?

- Fault bends (King & Nabalek, 1985)
- Shear strength ↗ along the fault ends in order to ↘ K_{II} (Cowie & Scholz, 1992; Rundle, 1996)
- Flexural-slip folding

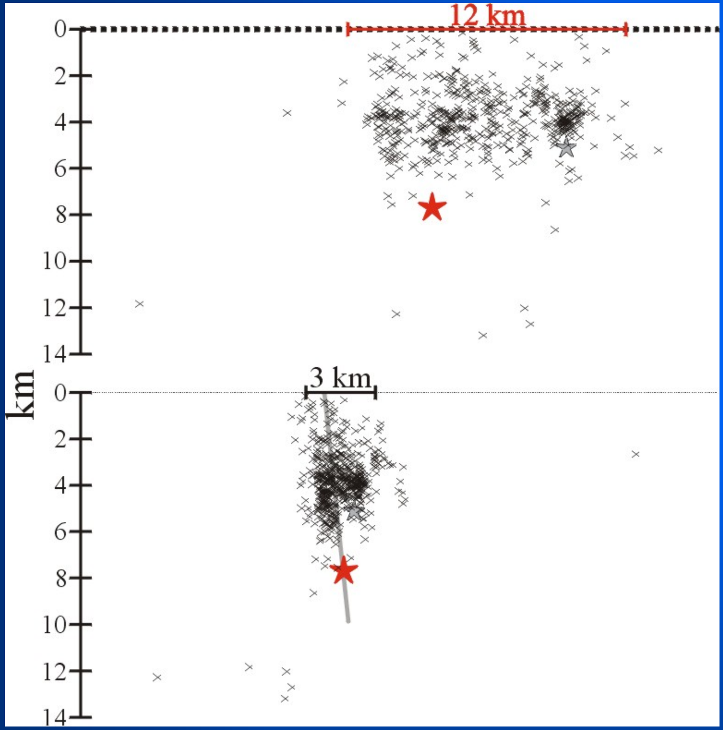
  Up-dip bedding planes
  Along-strike bedding planes } Wide Shear Zones

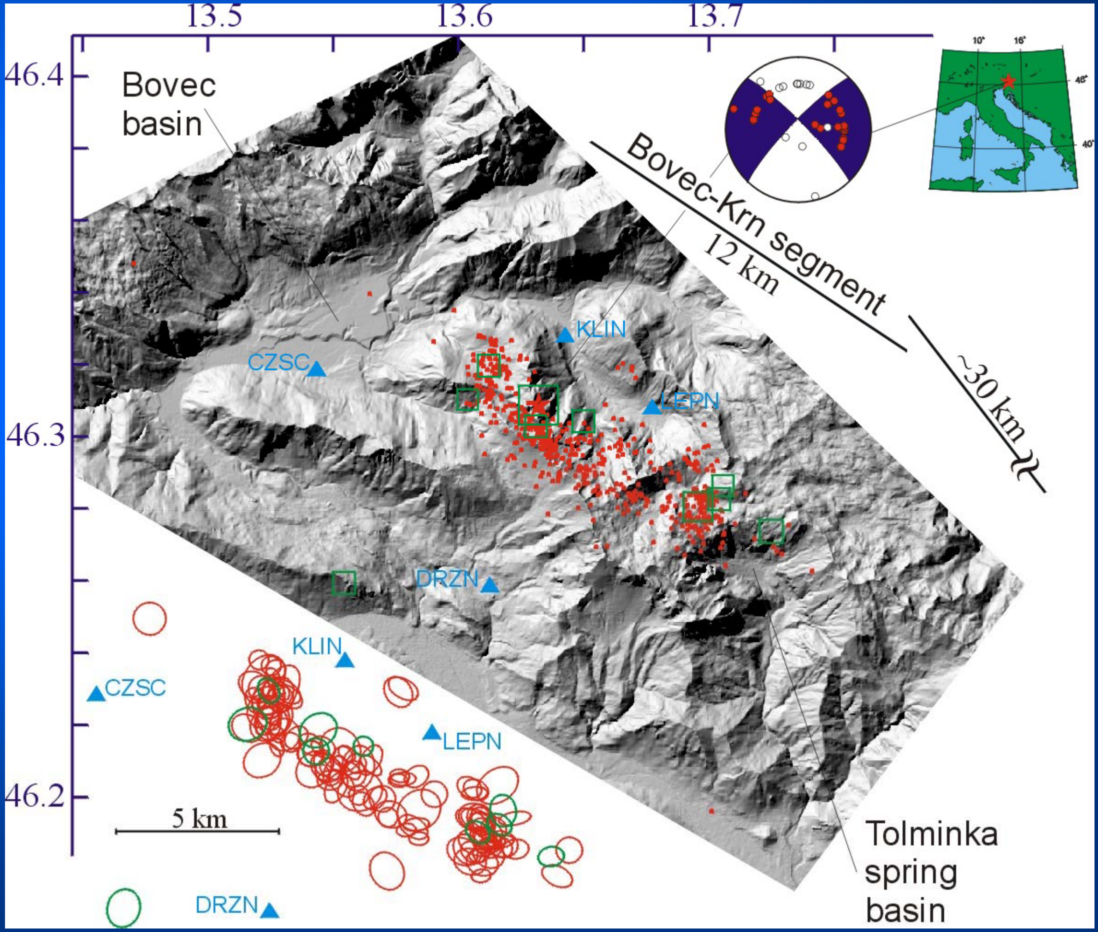
  from a single shear to a multiple shear



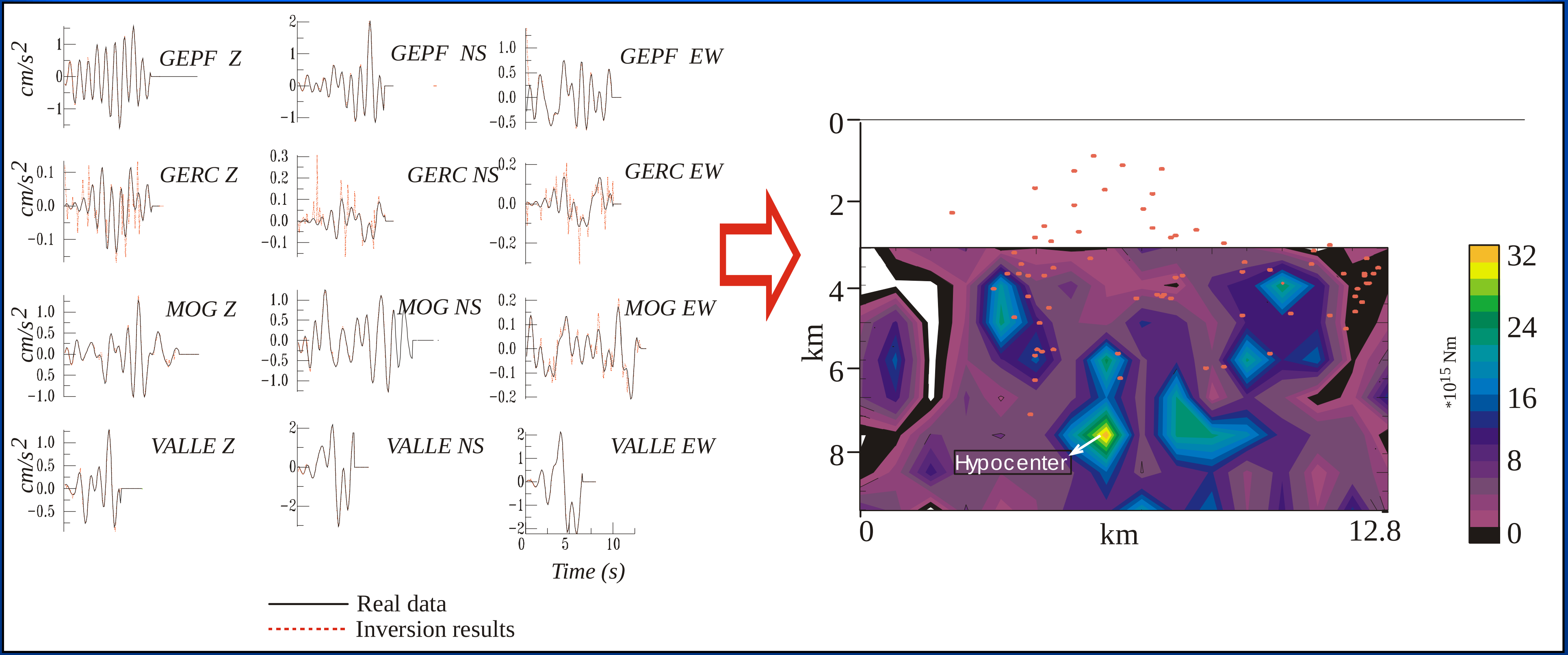
AUSTRIA
Bovec-Krn
ITALY
SLOVENIA
ADRIATIC SEA
N

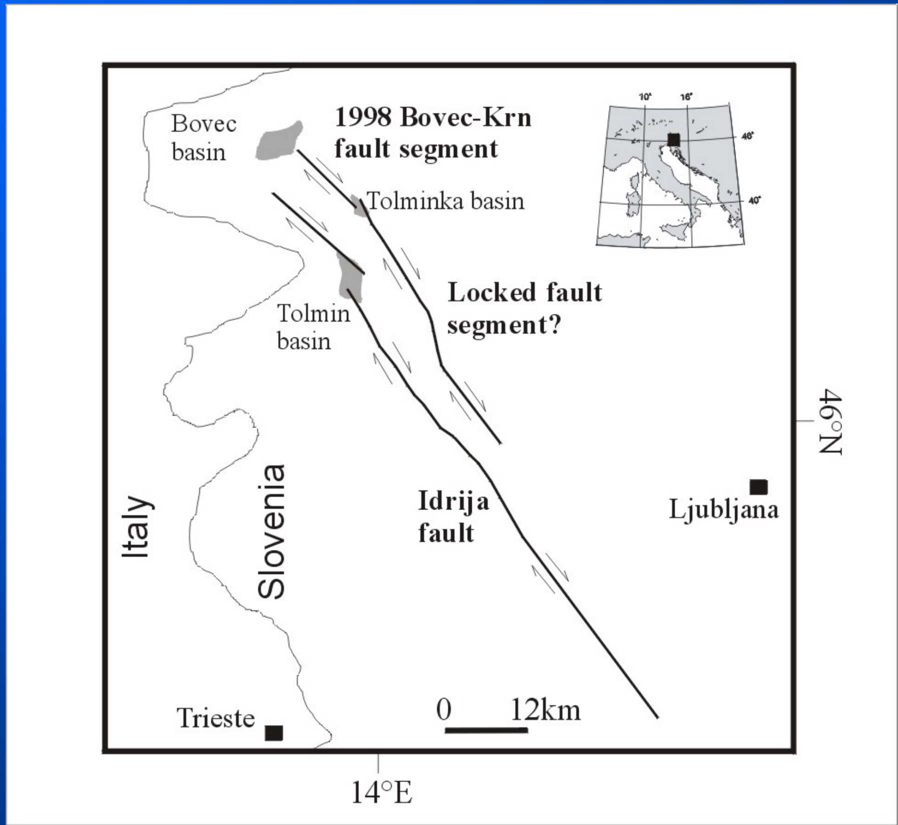
The 1998 Bovec earthquake sequence





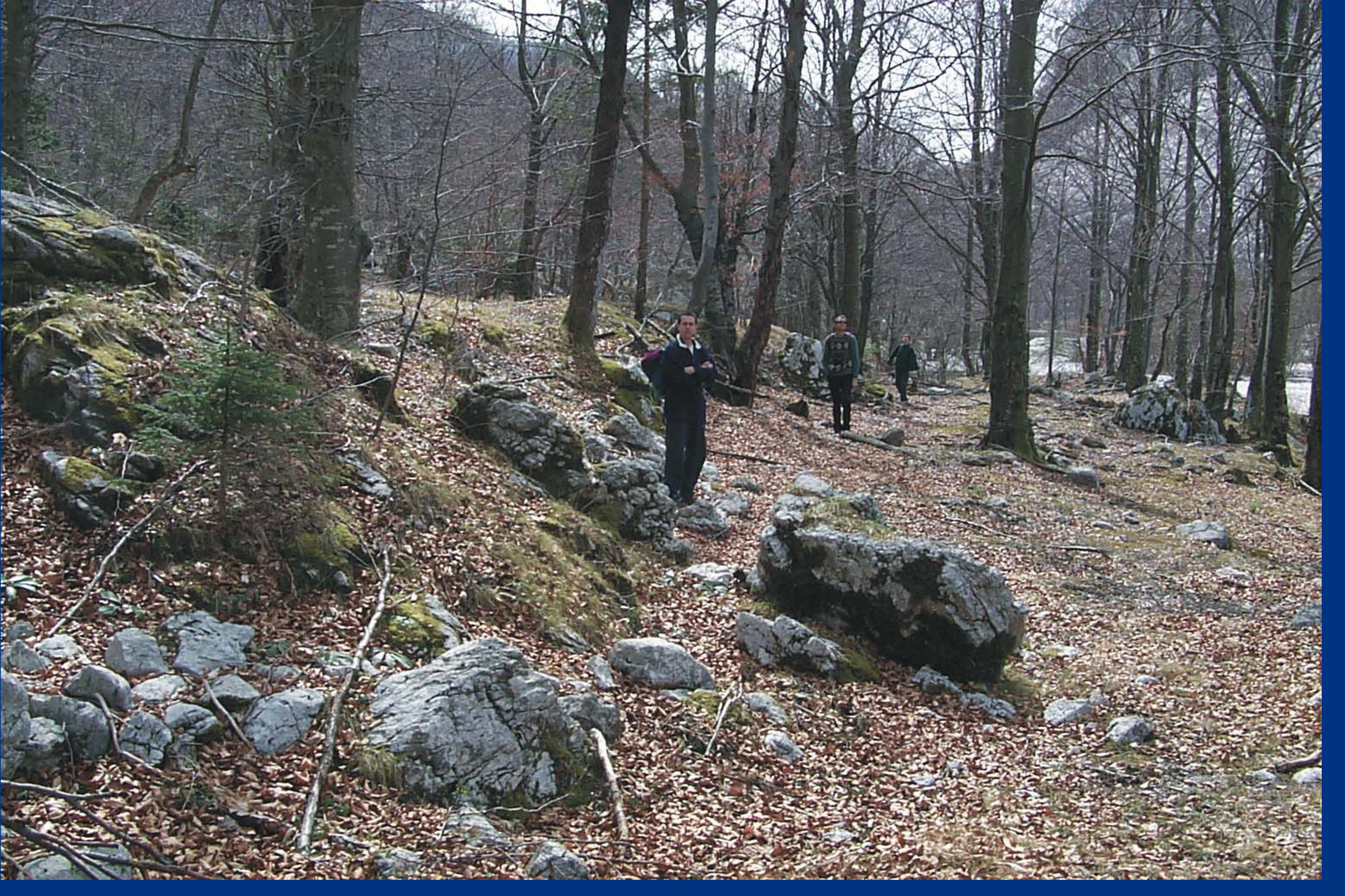
The 1998 Bovec strike-slip faulting Earthquake: Inverse modeling



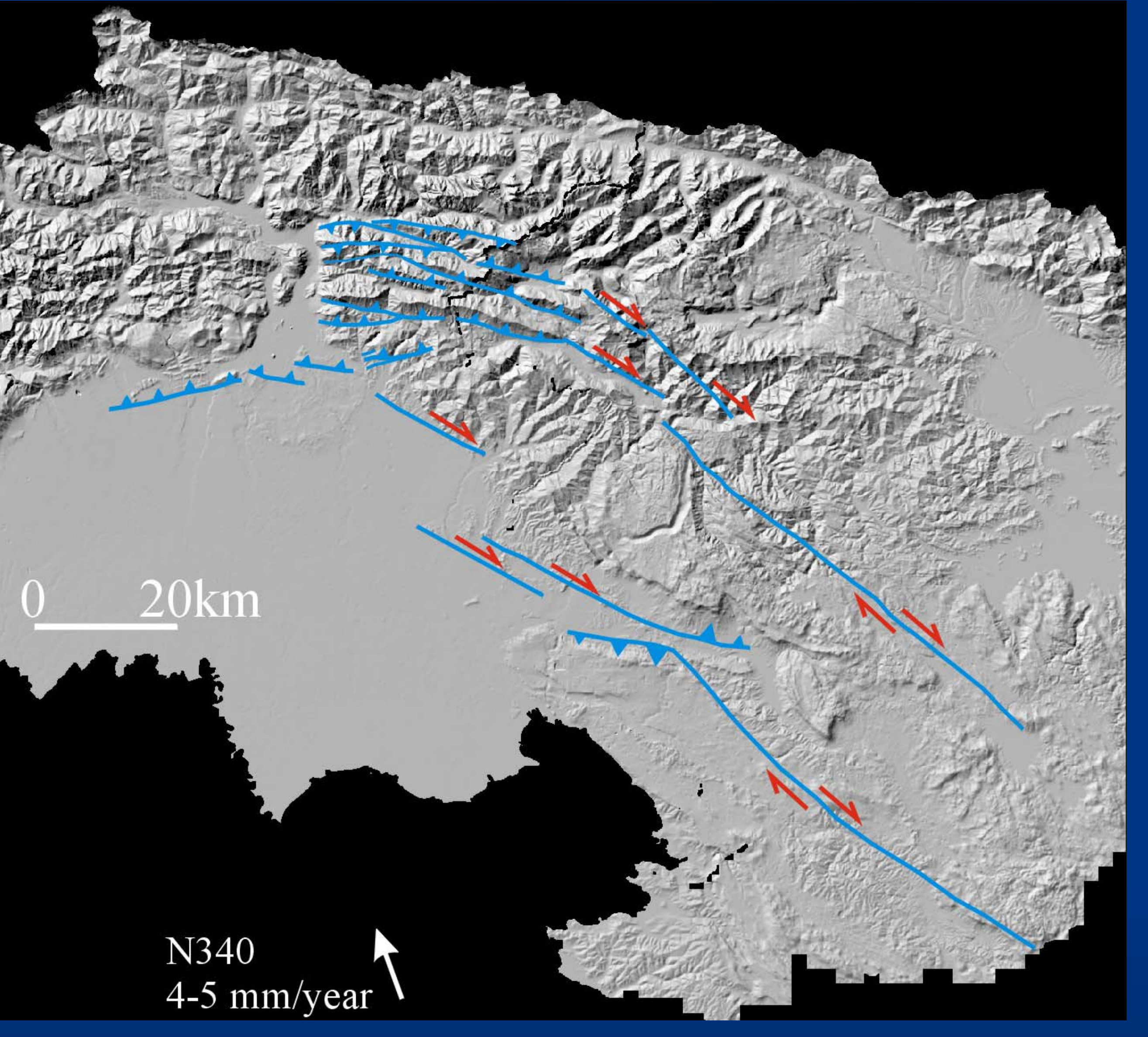

Bovec
basin
1998 Bovec-Krn
fault segment
Tolminka basin
Tolmin
basin
Locked fault
segment?
Idrija
fault
Ljubljana
Italy
Slovenia
Trieste
0 12km
46°N
14°E

Idrija fault

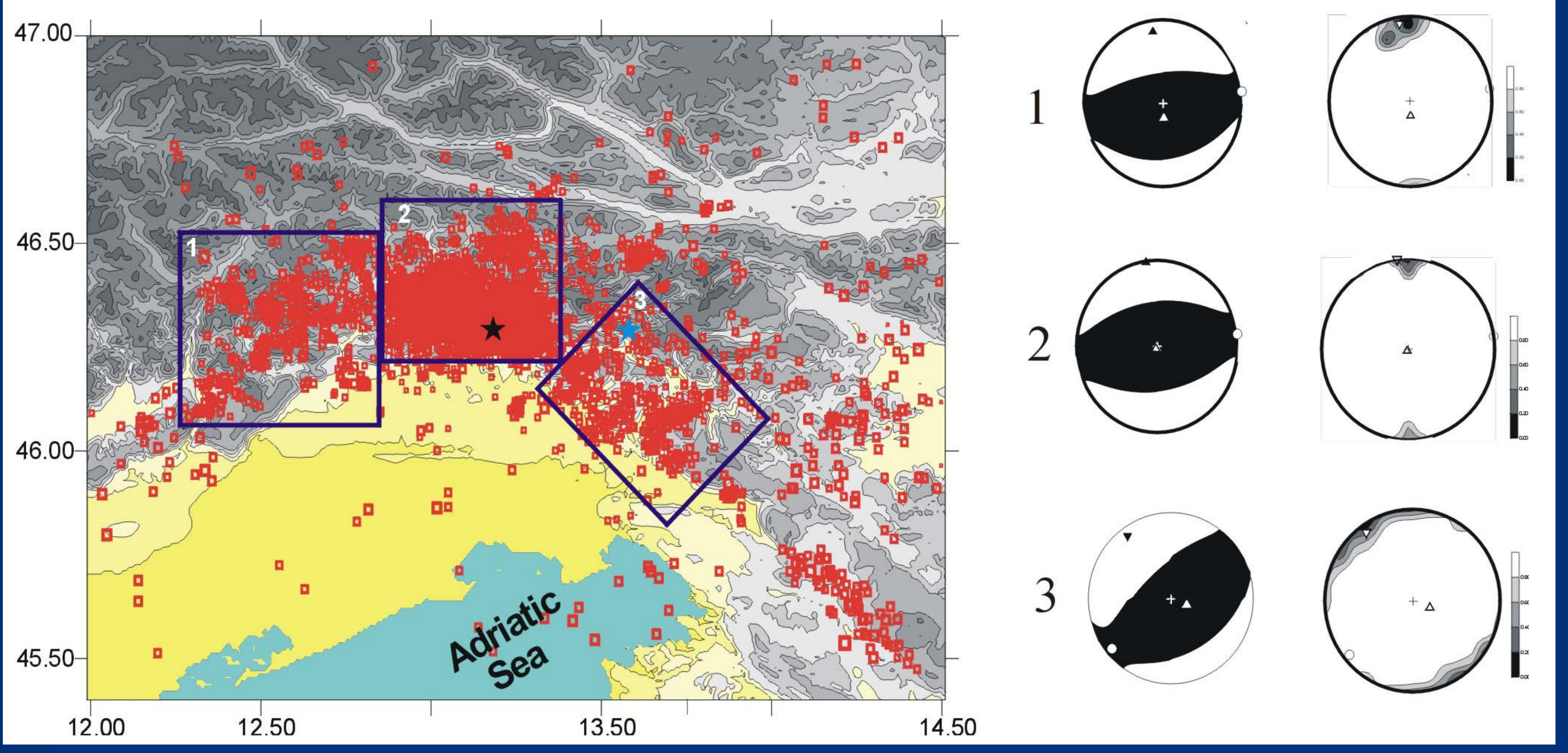
Tolminka fault scarp



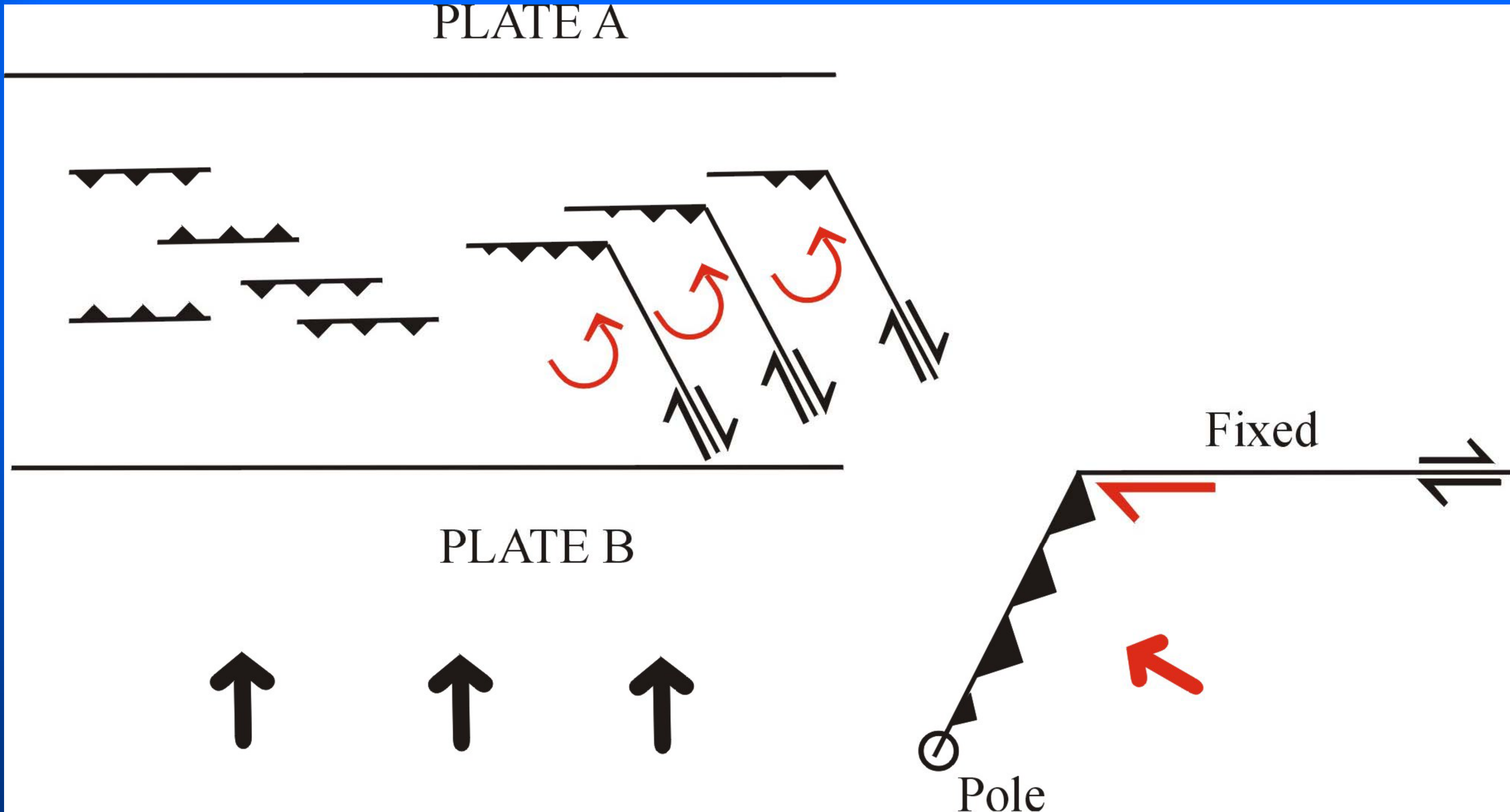
Active deformation: Geometry of the structures



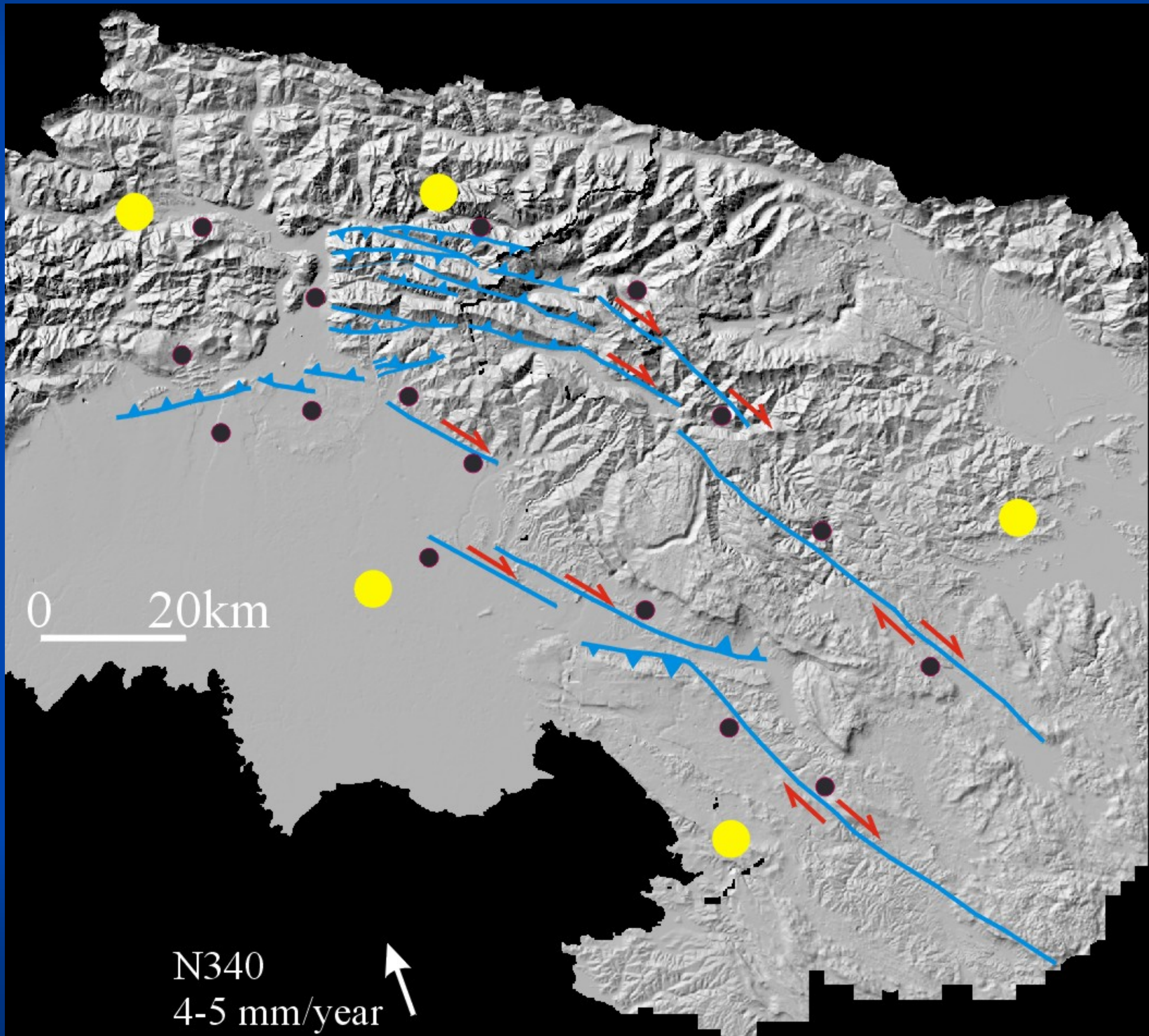
Bayesian reconstruction of the stress tensor from P-wave polarity data



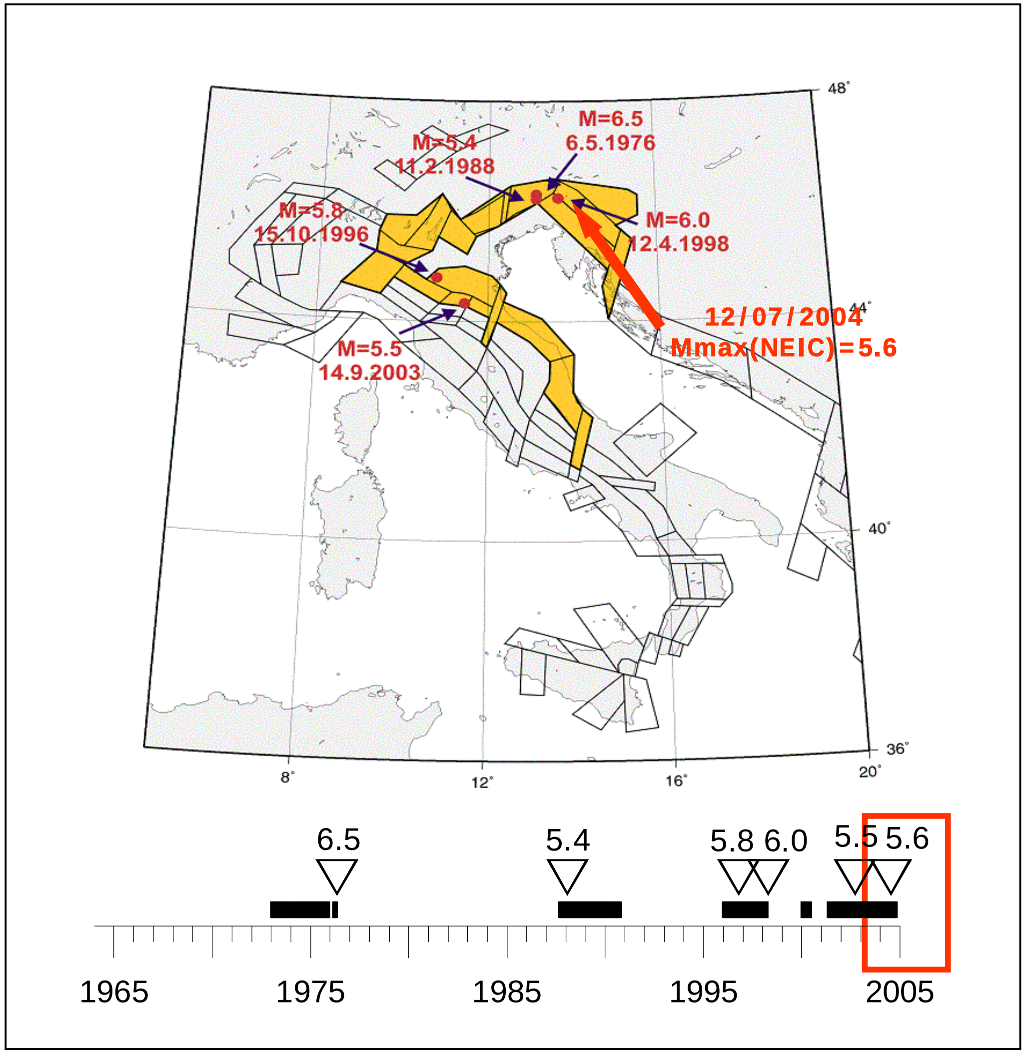
A possible Kinematic Model of Deformation



Active deformation: Geometry of the structures and GPS sites

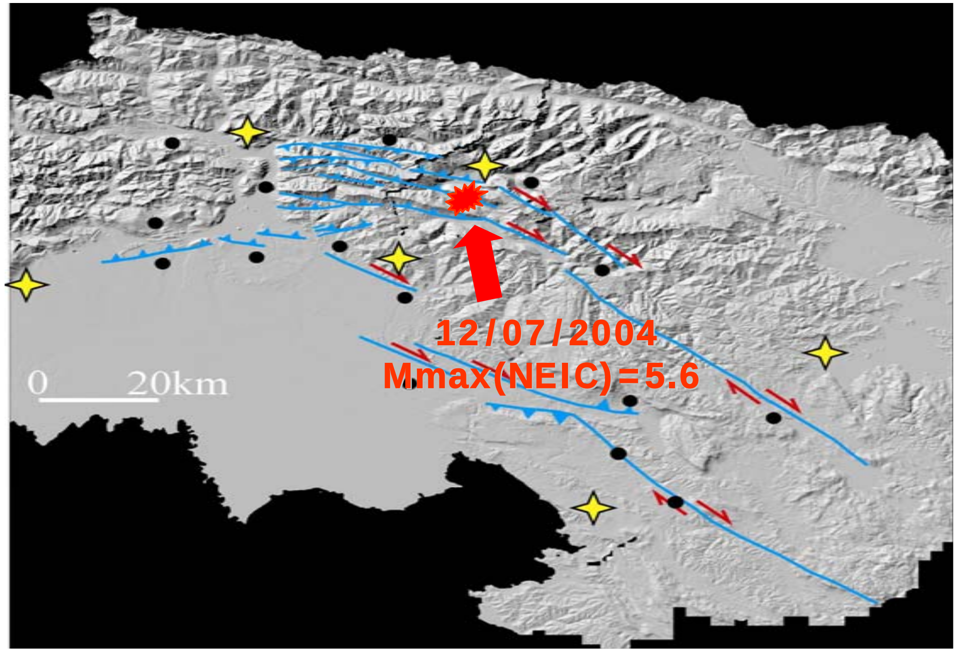


The recent Slovenia earthquake, July 12 2004



Alarmed area for M≥5.4
by CN algorithm (Peresan et al., 2004)
(As on 1 July 2004)

Southeastern Alps – External Dinarides
InSAR - CGPS - Campaign GPS monitoring



2004 Western Slovenia earthquake:

Campaign GPS monitoring before - after the earthquake and modeling