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Earthquake Tectonics and Hazards on the Continents

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Italy-Adriatic tectonic and hazards

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Crustal deformation and geomorphology of normal faulting in the Apennines

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Trieste, June 2013

- Main features of normal faulting in the Apennines similar to Greece or Nevada
- Distinct features given by geomorphological interactions with regional uplift
- Good coverage of geodetic data and a rich historical earthquake catalogue constrain the rate and location of deformation
- The 2009 l'Aquila Mw 6.3 event provides the opportunity to study how these interactions operate at the scales (spatial and temporal) of a single seismic event

Topics

- Regional context (Eu-Nu plate boundary, Adria)
- Present-day geodetic deformation, strain rates, historical seismicity and earthquake recurrence
- Geomorphology of active normal faulting and interaction with mantle-driven regional uplift
- A well-recorded normal faulting earthquake:
  the 2009 April 6 L'Aquila (Mw 6.3) event

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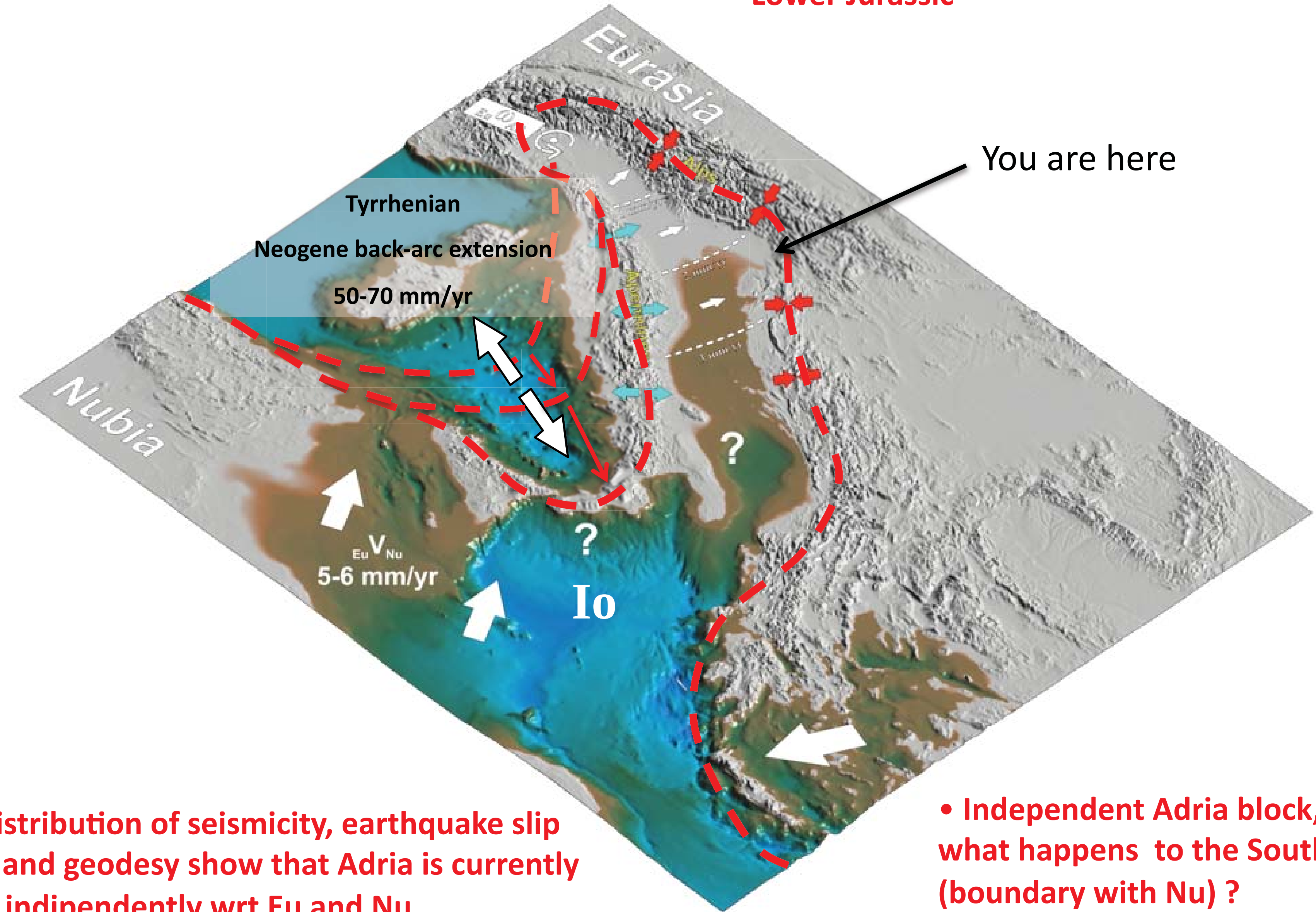
• The Adriatic region has been initially described as a rigid African promontory colliding with Eurasia

• Paleomagnetic data show the lack of differential rotation wrt Africa since the Lower Jurassic

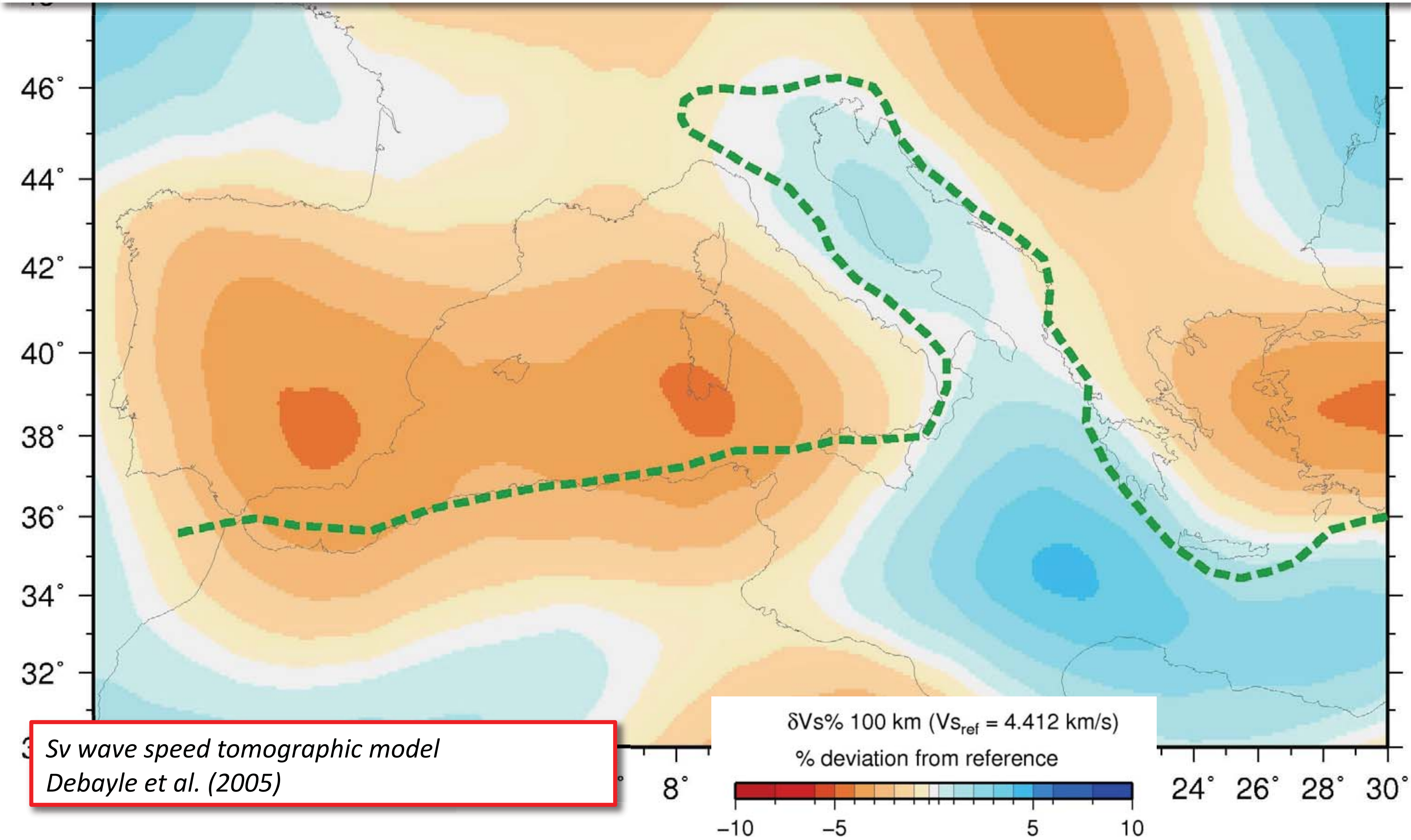


• The distribution of seismicity, earthquake slip vectors and geodesy show that Adria is currently moving indipendently wrt Eu and Nu

• Independent Adria block, but what happens to the South (boundary with Nu) ?

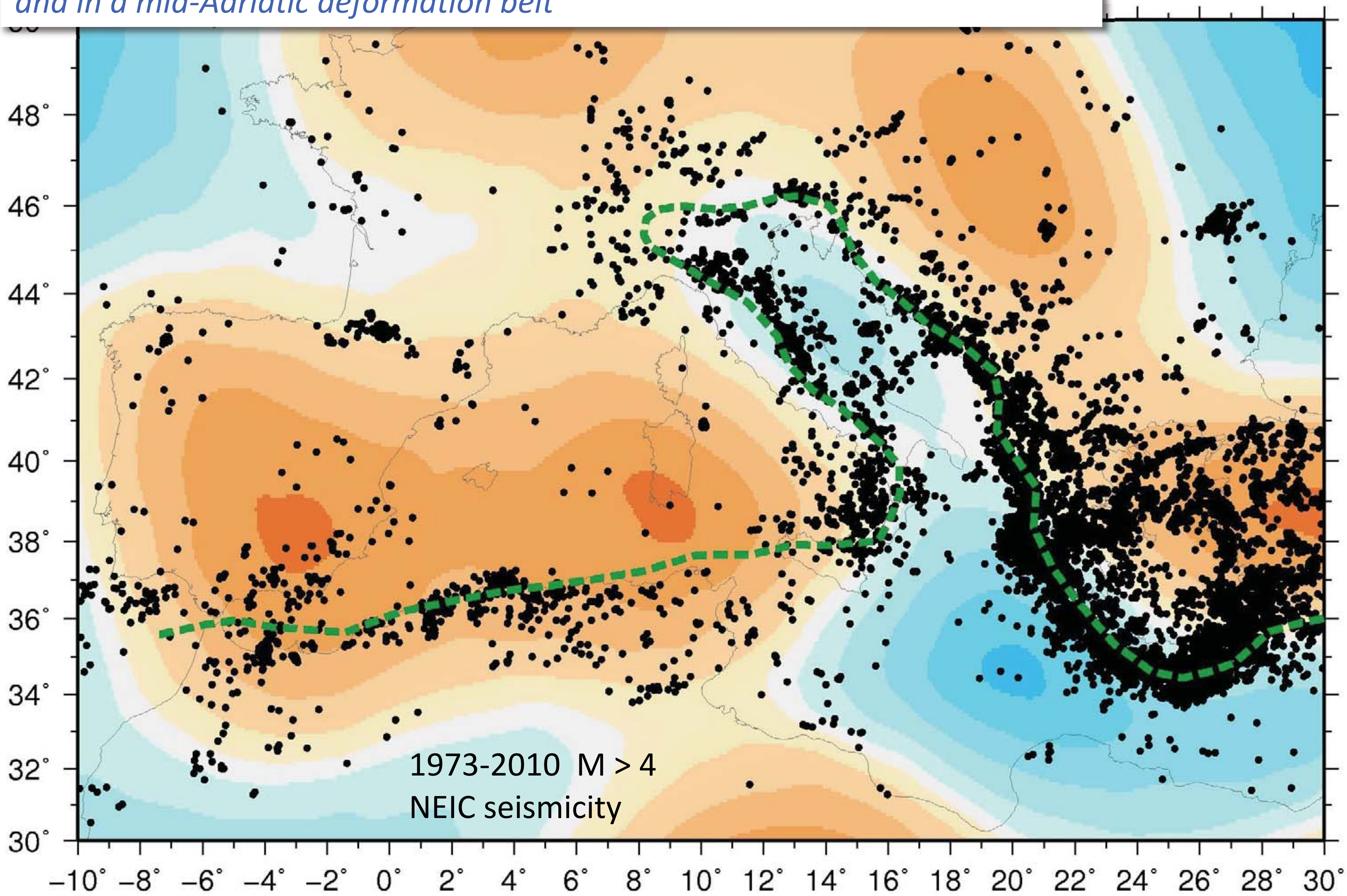
•Surface wave tomography (at 100 km depth) enphasizes the continuity of the Adriatic Promontory and the contrasts of lithospheric properties

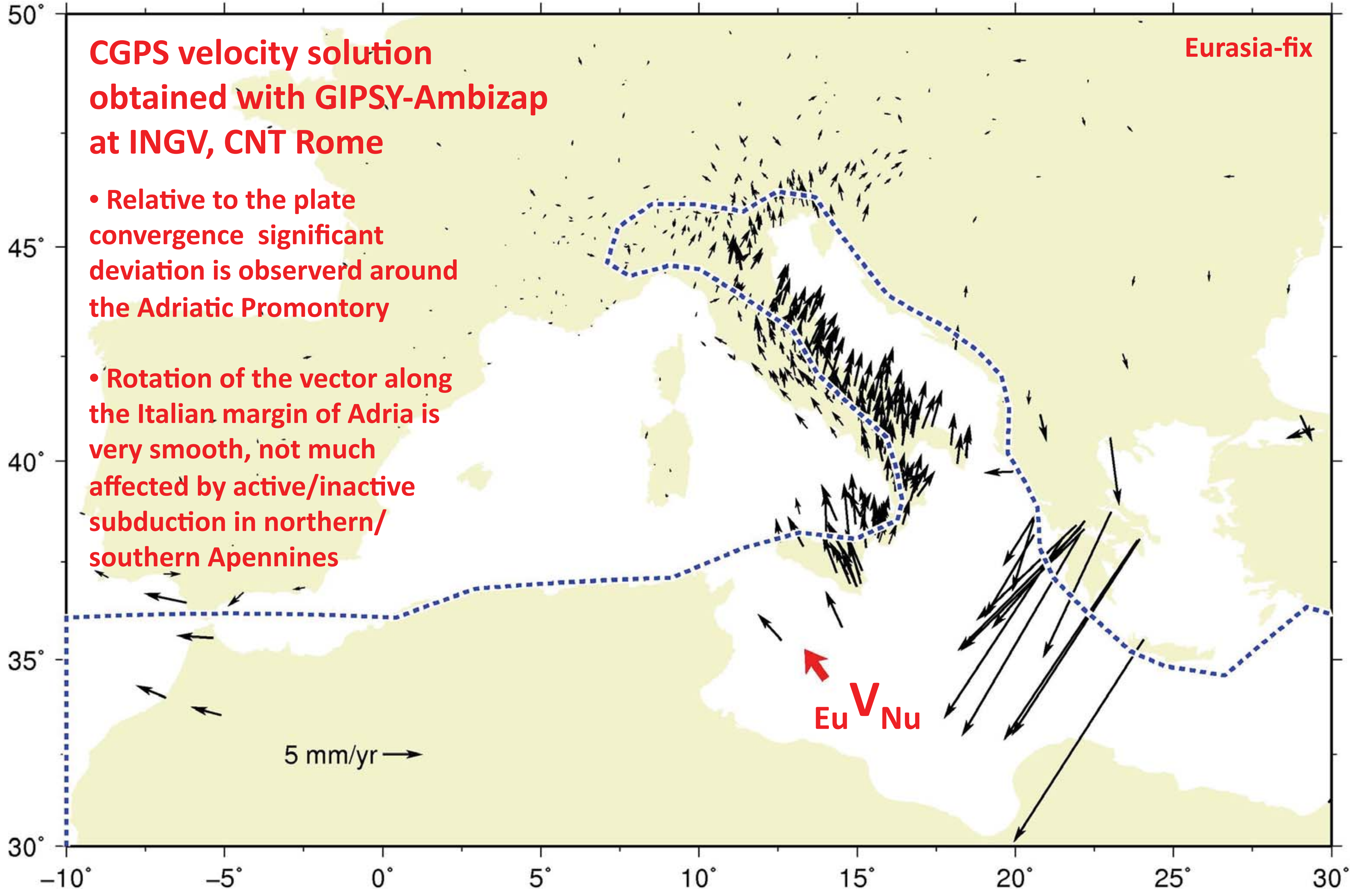
•Regions of recent crustal extension (Alboran, Tyrrhenian, Pannonian, Aegea) show slow velocities at 100 km depth

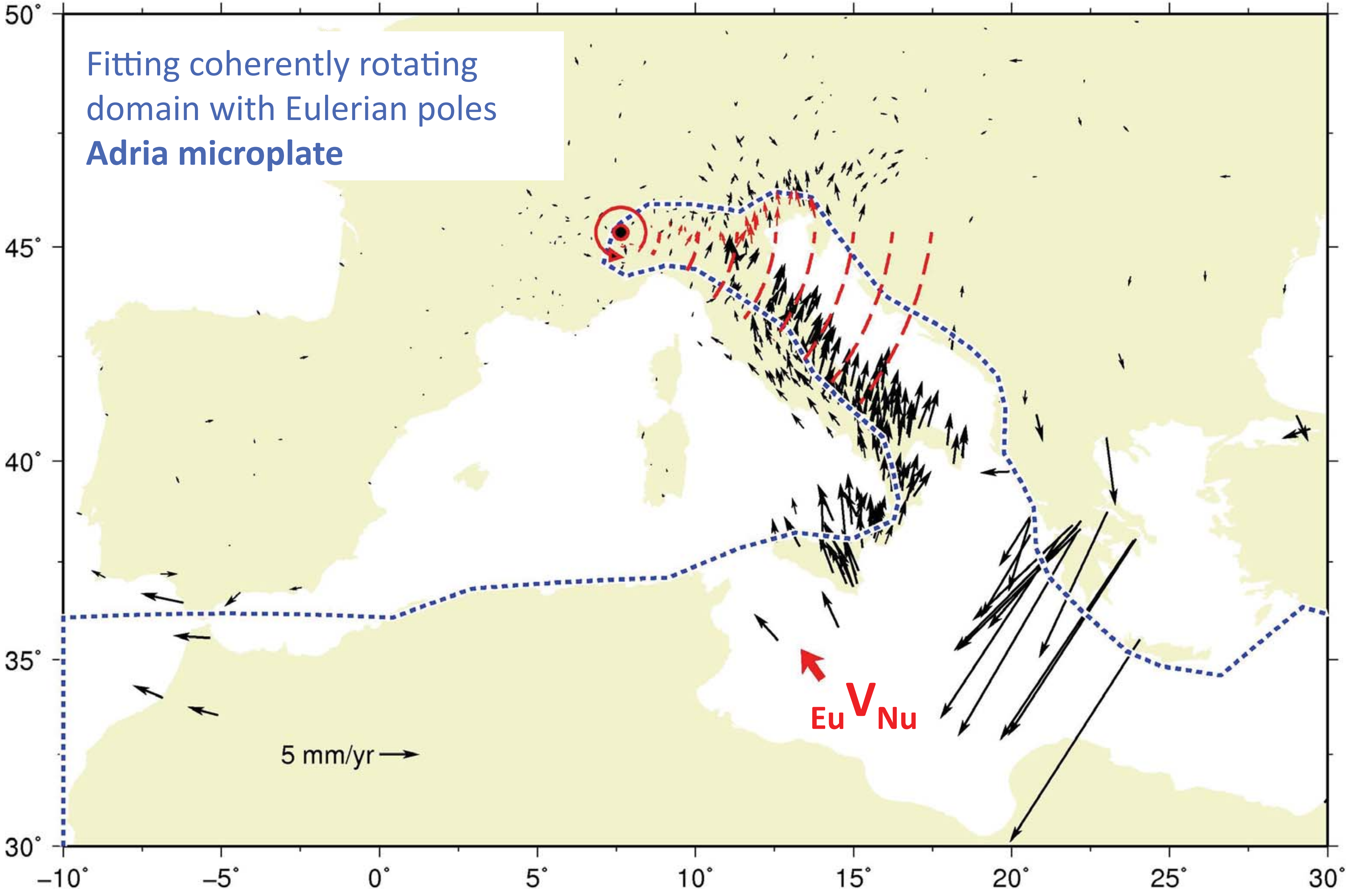


Sv wave speed tomographic model
Debayle et al. (2005)

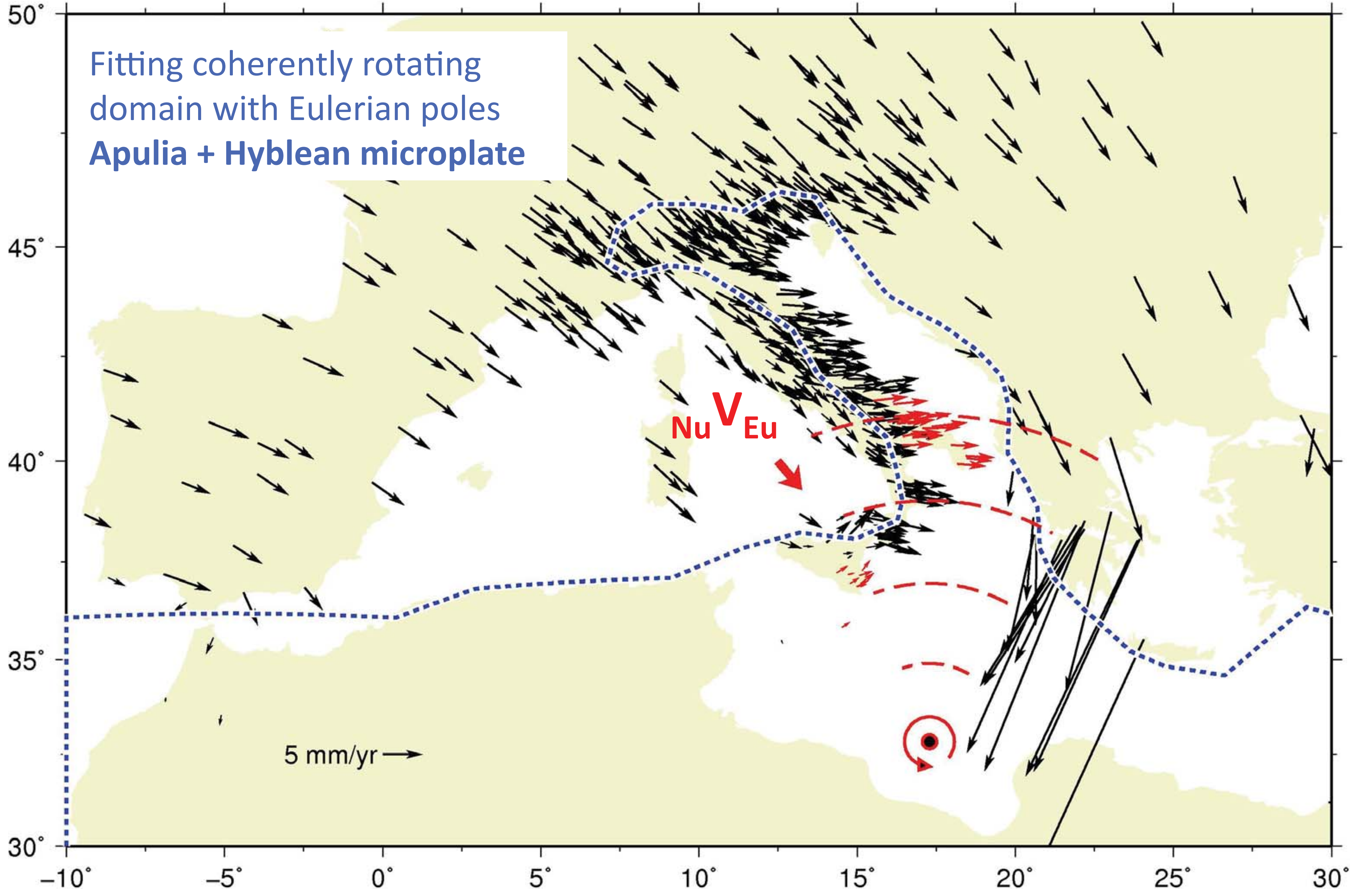
•Seismic activity concentrates at the boundaries of the Adriatic Promontory and in a mid-Adriatic deformation belt



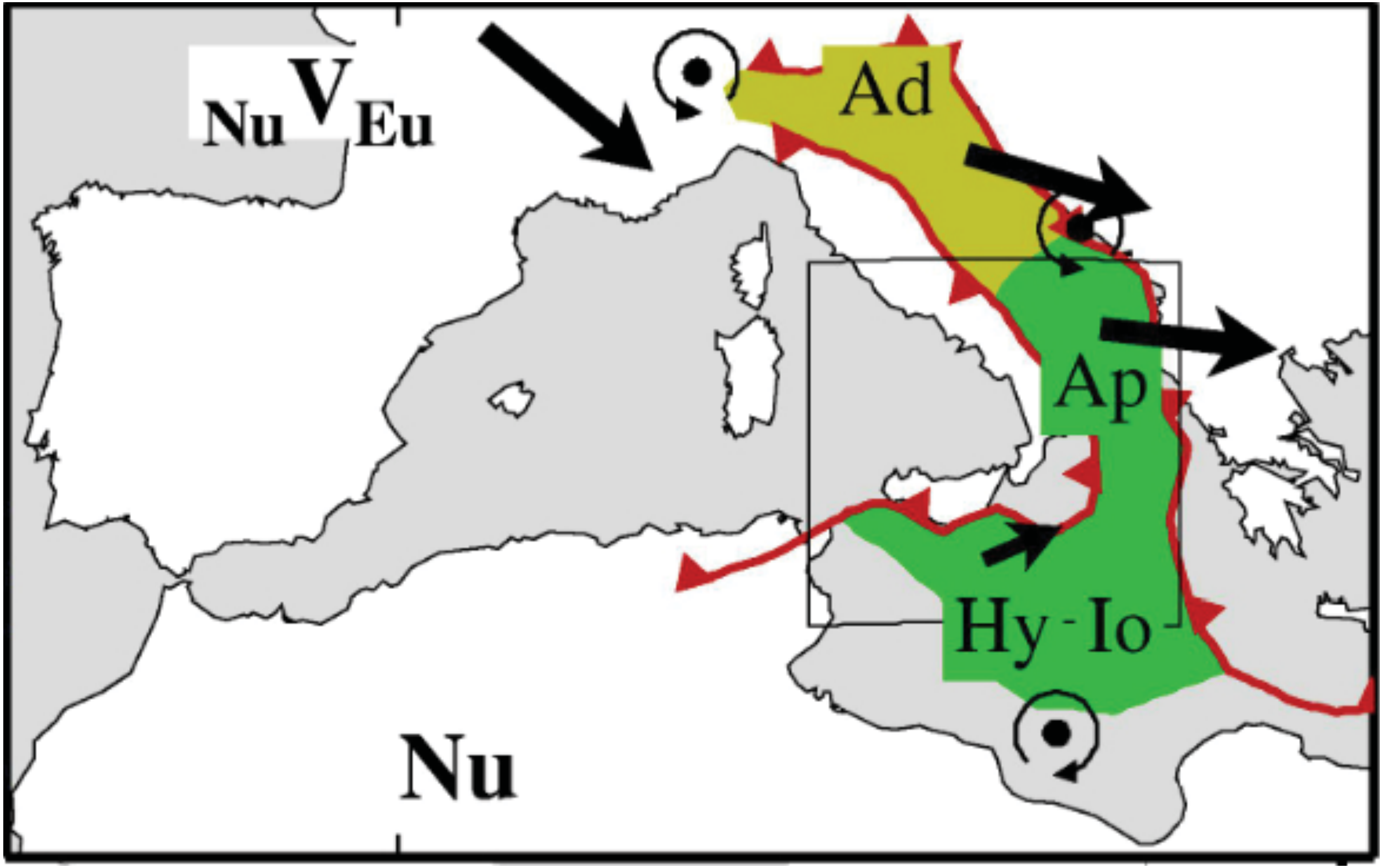

CGPS velocity solution obtained with GIPSY-Ambizap at INGV, CNT Rome
• Relative to the plate convergence significant deviation is observerd around the Adriatic Promontory
• Rotation of the vector along the Italian margin of Adria is very smooth, not much affected by active/inactive subduction in northern/southern Apennines
Eurasia-fix
$_{Eu}V_{Nu}$
5 mm/yr
50°
45°
40°
35°
30°
–10°
–5°
0°
5°
10°
15°
20°
25°
30°



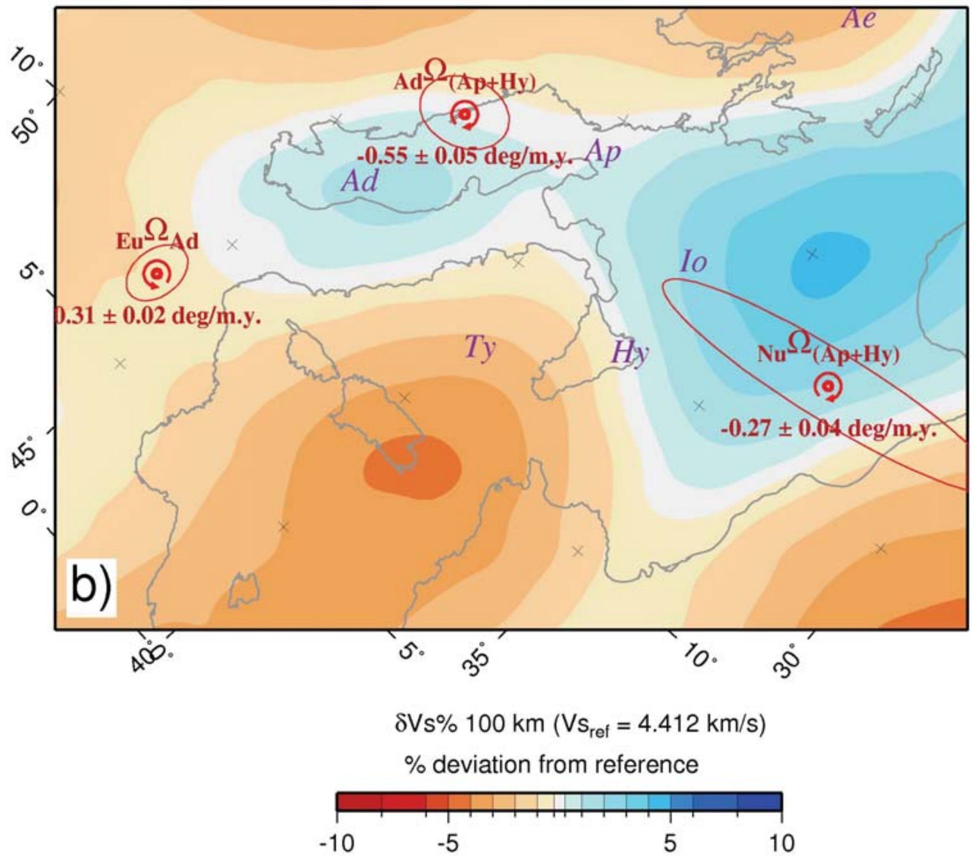
Fitting coherently rotating
domain with Eulerian poles
Adria microplate
5 mm/yr
EuVNu
50°
45°
40°
35°
30°
−10°
−5°
0°
5°
10°
15°
20°
25°
30°

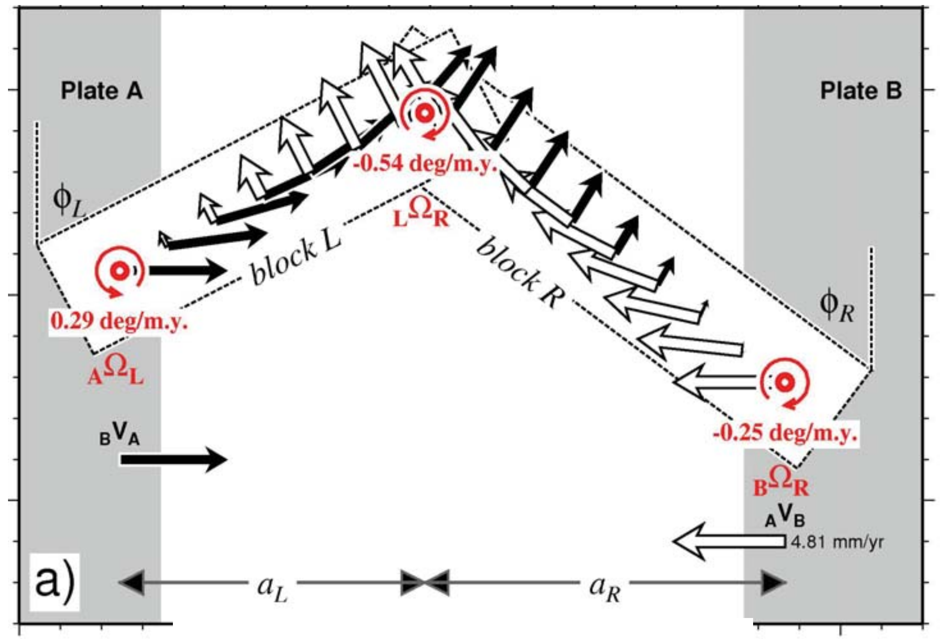


Fitting coherently rotating
domain with Eulerian poles
Apulia + Hyblean microplate
NuVEu
5 mm/yr
50°
45°
40°
35°
30°
−10°
−5°
0°
5°
10°
15°
20°
25°
30°



Nu V Eu
Ad
Ap
Hy - Io
Nu





$$\Omega_L = \frac{{}_AV_B}{a_L(cot\phi_L + cot\phi_R)} =_{EU} \Omega_{AD}$$

$$\Omega_R = -\Omega_L \frac{a_L}{a_R} =_{NU} \Omega_{AP}$$

Microplate rotation rates can be reproduced with a simple model in which blocks are strongly coupled to the nearby plate/microplate and rotate to accommodate the EuNu plate convergence

Table 4. Calculated and Observed Microplate Rotation Rates

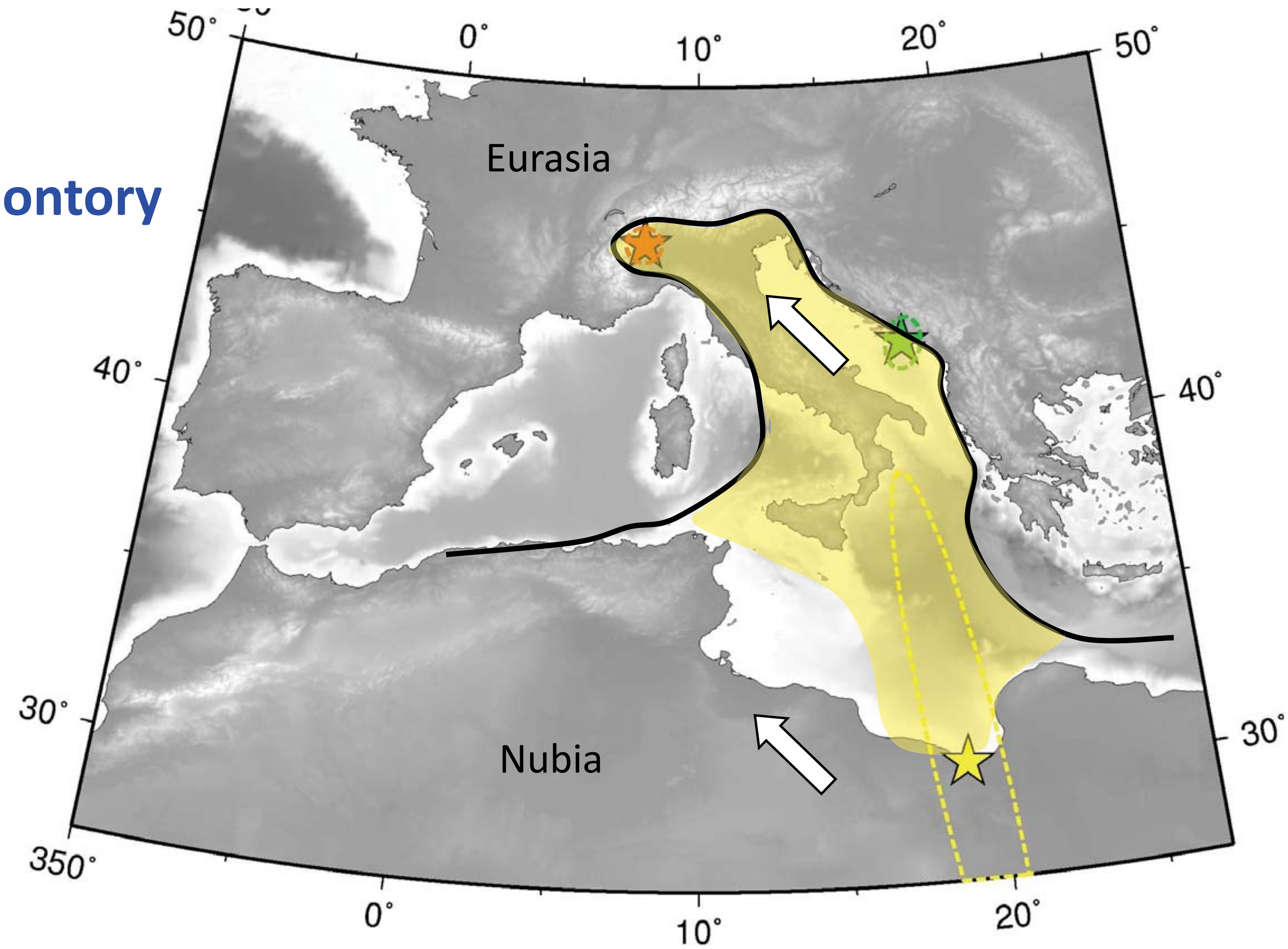
Pole	Calculated (deg/Ma)	Observed ± 1σ (deg/Ma)
${}_A\Omega_L$	0.29	0.31 ± 0.02 (${}_{Eu}\Omega_{Ad}$)
${}_B\Omega_R$	−0.25	−0.27 ± 0.04 (${}_{Nu}\Omega_{Ap+Hy}$)
${}_L\Omega_R$	−0.54	−0.55 ± 0.05 (${}_{Ad}\Omega_{Ap+Hy}$)

D'Agostino et al.,JGR2008

Reconciling the Adriatic Promontory and Adria

• Present-day configuration follows a recent plate boundary reorganization related to the narrowing of the Ionian "corridor"

Phase 1:
Adriatic Promontory



Reconciling the Adriatic Promontory and Adria

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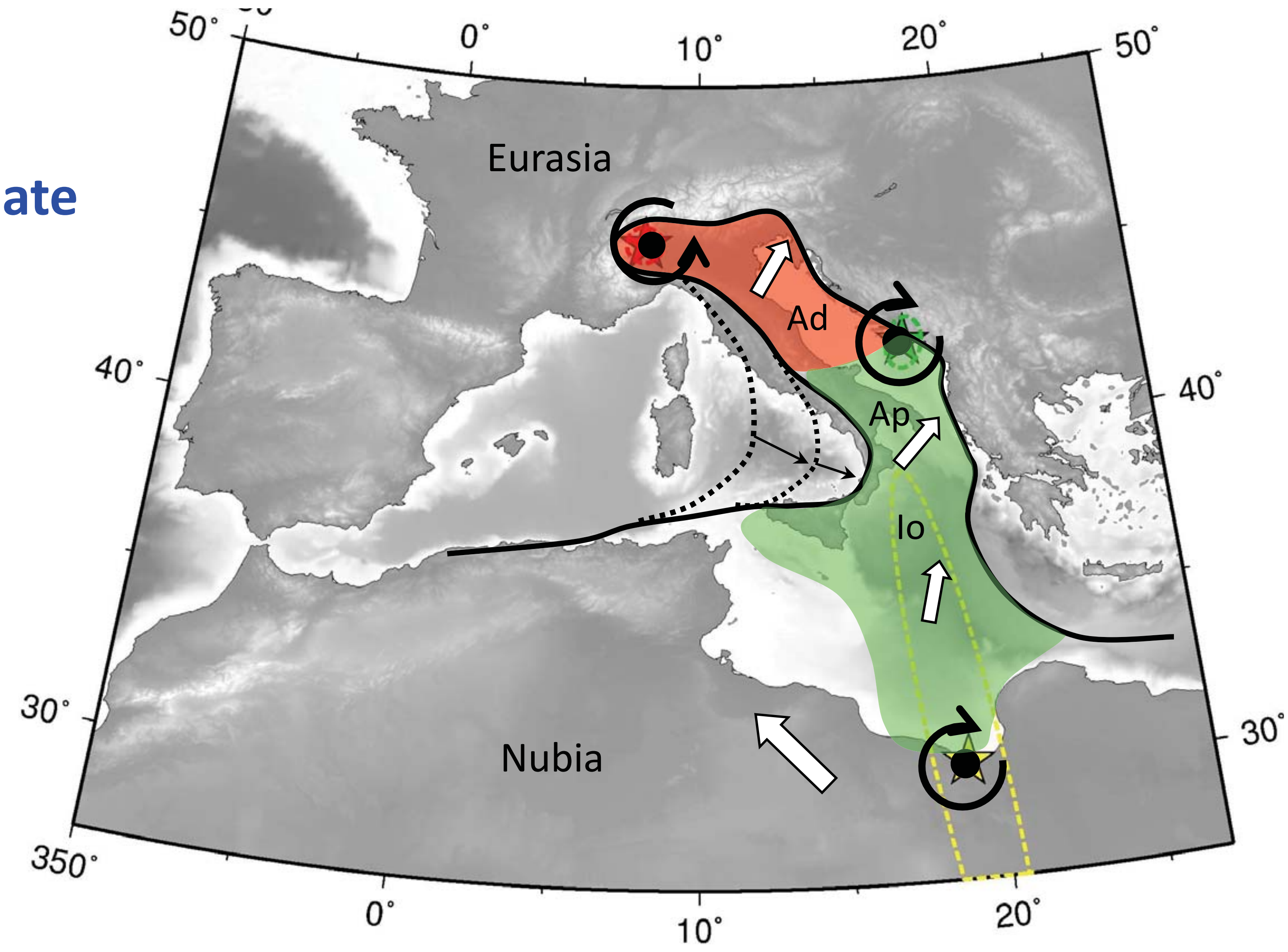
Phase 2:
Adria Microplate



Main deformation belts around the Adriatic:

Apennines

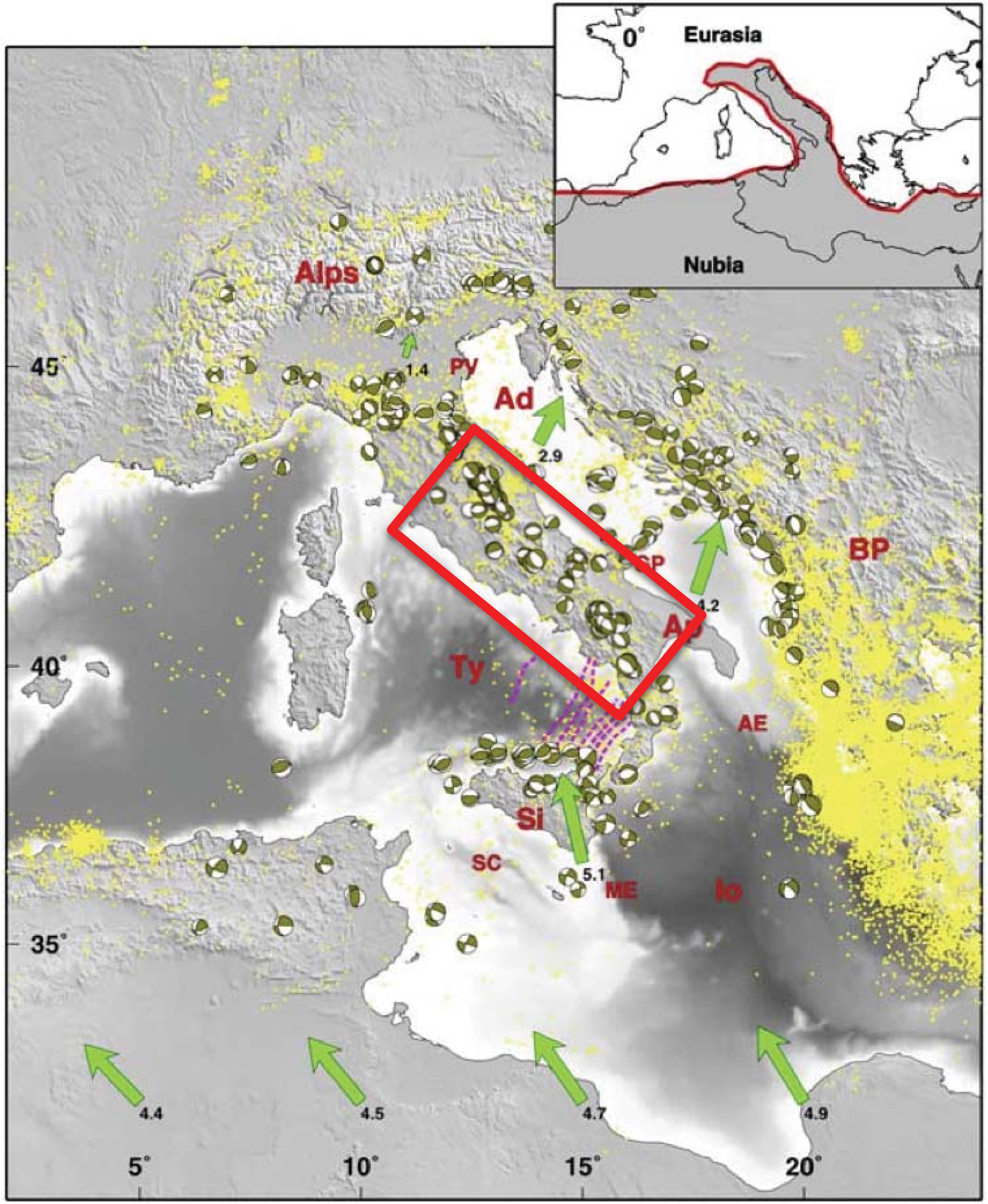
- Extension/shortening in the Northern Apennines
- Extension in the Centr.-South. Apennines (3 mm/yr)

Alps

Shortening along the South. Alps (< 2 mm/yr)

Dinarides

Shortening along the coast (2-4 mm/yr)



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Geodetic data

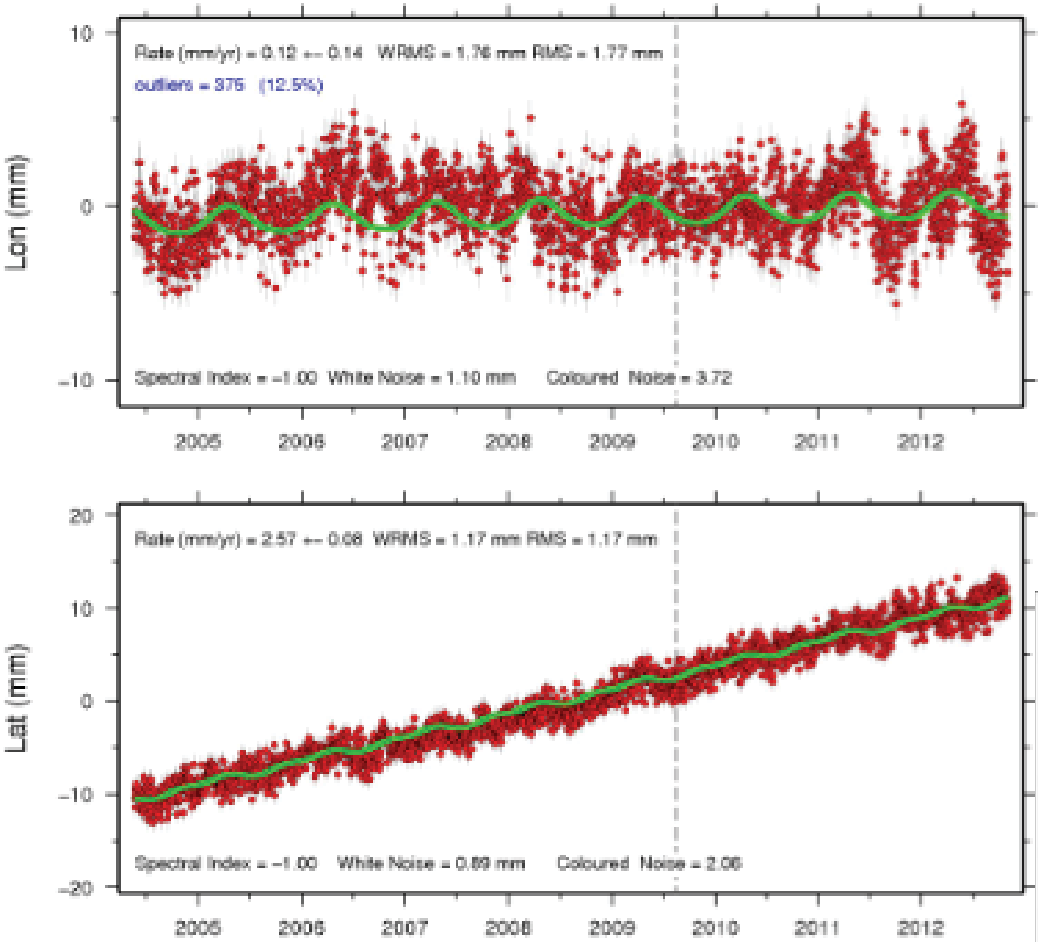
GPS:

- ~200 CGPS stations with > 2.5 years of data (included in a global processing routine > 1000 stations)
- (RING + ASI+Italpos + regional cadastral networks)
- Episodic campaigns in central/southern Apennines
- GIPSY-OASIS ppp + Ambizap + Eurasian frame alignment

GPS time serie

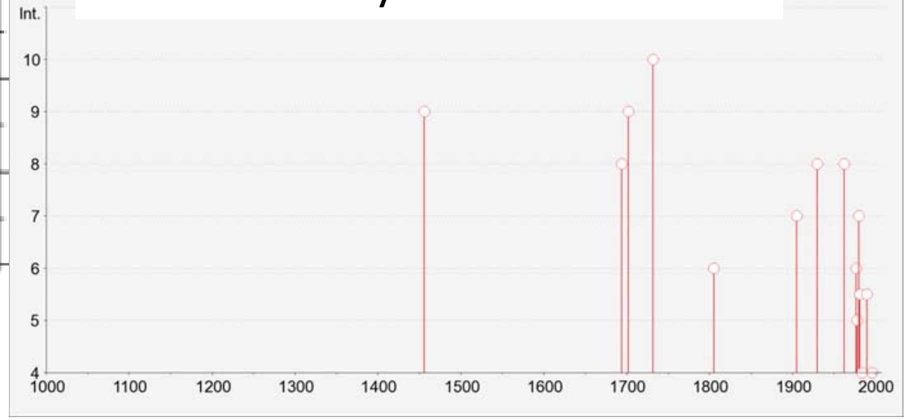
(Eurasian reference frame)

INGV station of Grottaminarda (southern Italy)
Installed on a XIIth century castle

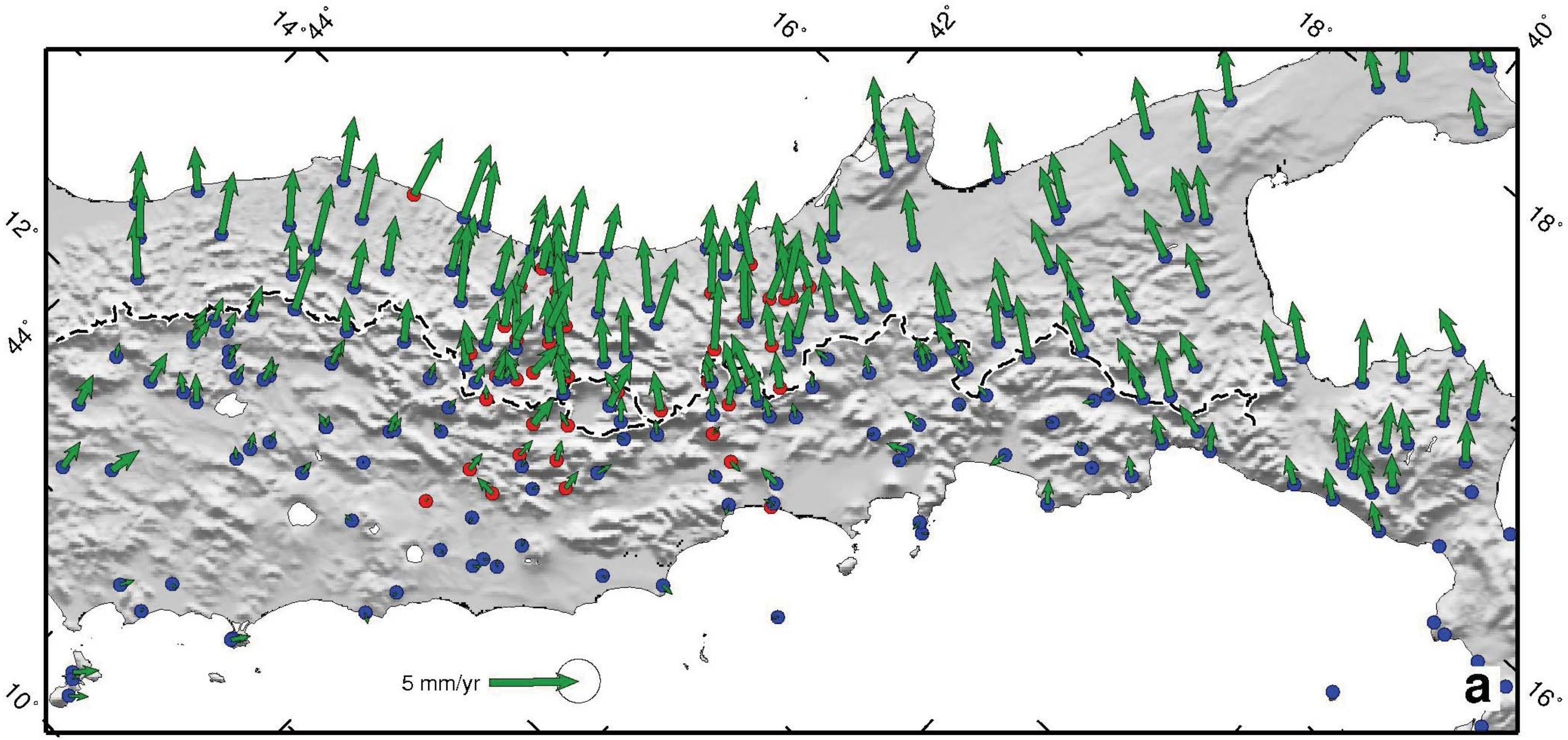


RMS of horizontal positions (1-2 mm)

Seismic history of Grottaminarda



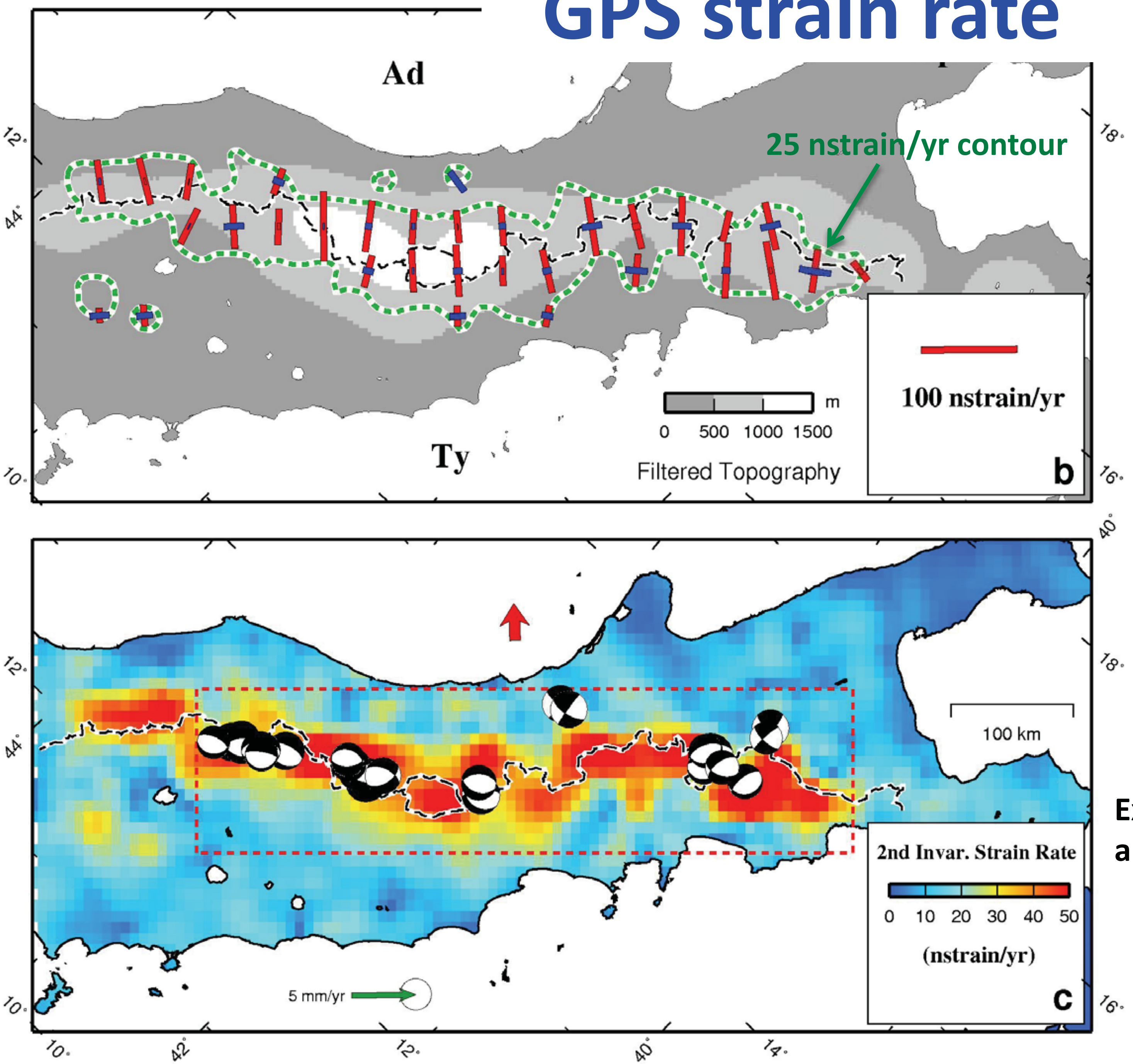
GPS velocity field



- Velocities in a Tyrrhenian reference (RMS 0.3 mm/yr)
- CGPS (blu circles)+Episodic GPS (red circles)
- ΔT > 2.5 years
- 95% CI errors 0.1-0.6 mm/yr

D'Agostino, in prep.

GPS strain rate



Strain rates obtained using bicubic spline interpolation technique (Beavan and Haines, 2001).

Continuous band of ~50 nstrain/yr along the crest of Apennines.

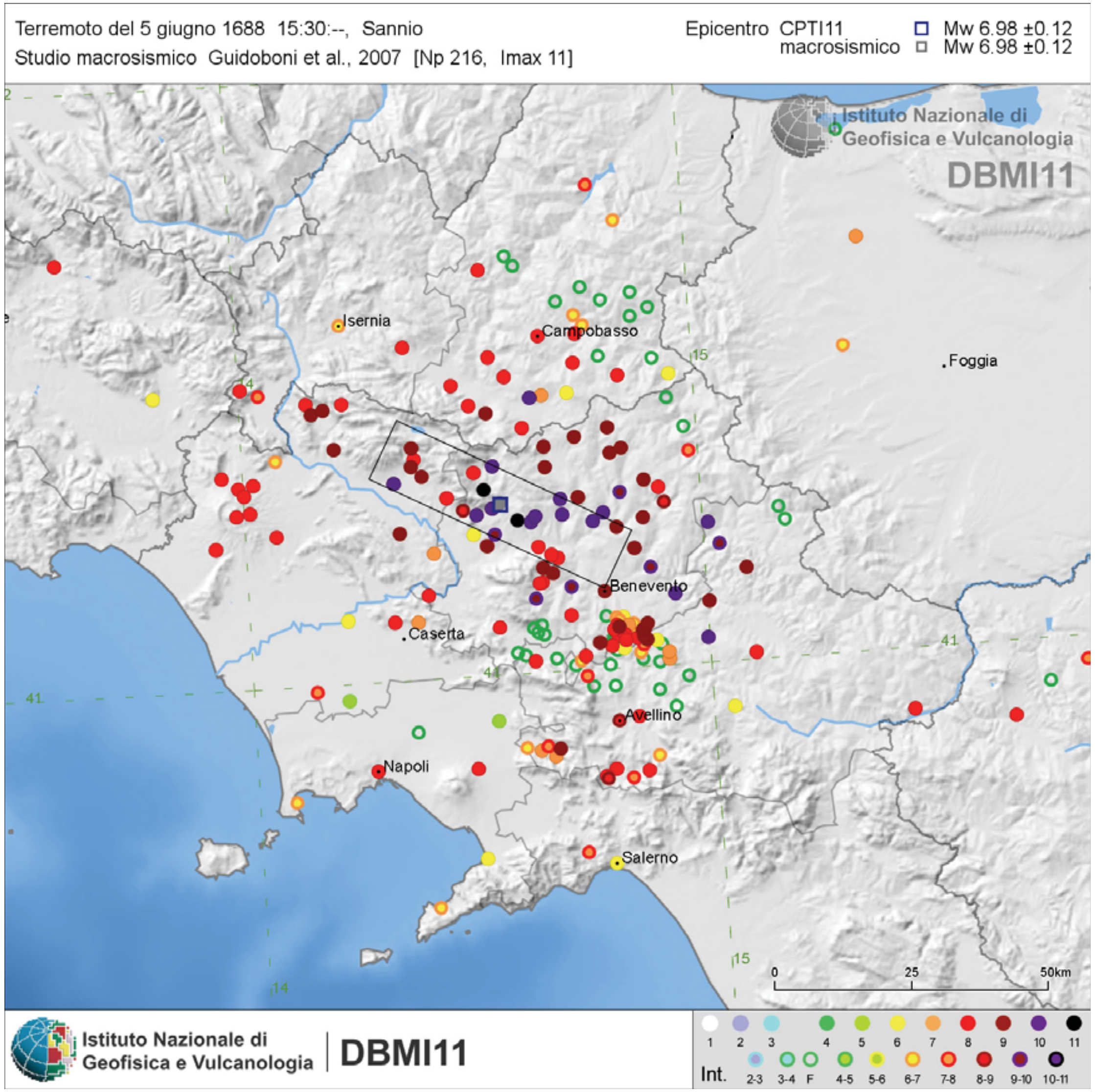
Average within the box is 25 nstrain/yr

Almost uniaxial NE-SW extension coherent with seismic moment tensors

Extension varies smoothly along strike (2.5-3.0 mm/yr)

D'Agostino, in prep.

Historical earthquake catalogue



Historical seismicity:

1600-2010 seismicity from CPTI11 (nominally complete for Mw > 6) (Stucchi et al.,2011; emidius.mi.ingv.it/CPTI11)

Each event in the CPTI11 catalogue has an estimate of Mw obtained by regressions calibrated using intensity/instrumental data available for recent earthquakes (Gasperini et al. 1999)

Seismic moment M_0 calculated using Hanks and Kanamori (1979):

$Mw = 2/3\log_{10}M_0 + 9.05$

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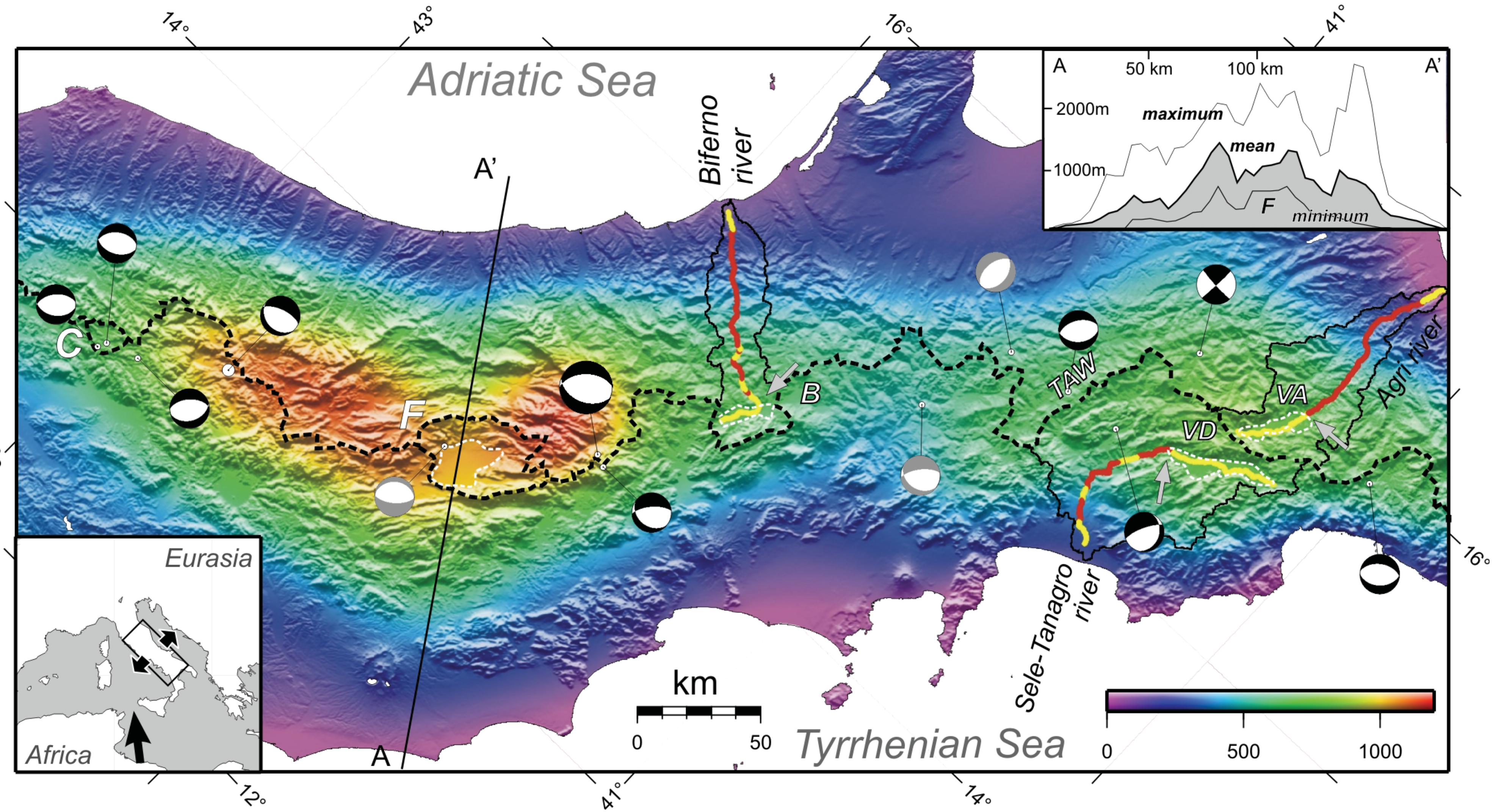
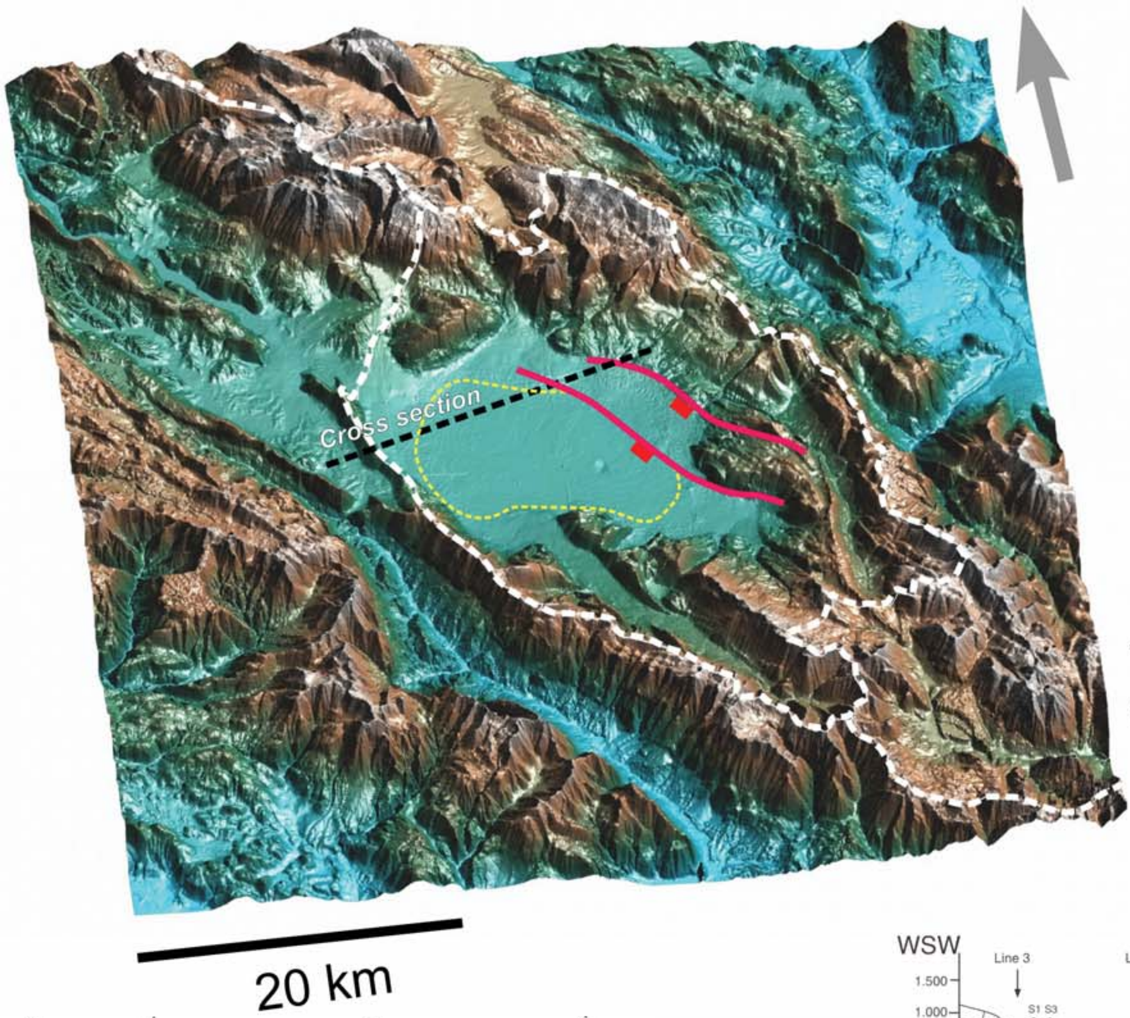
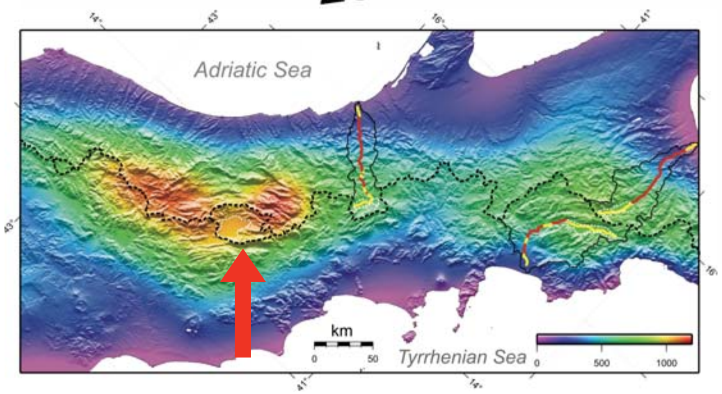
Drainage network and basin evolution in the Apeninnes

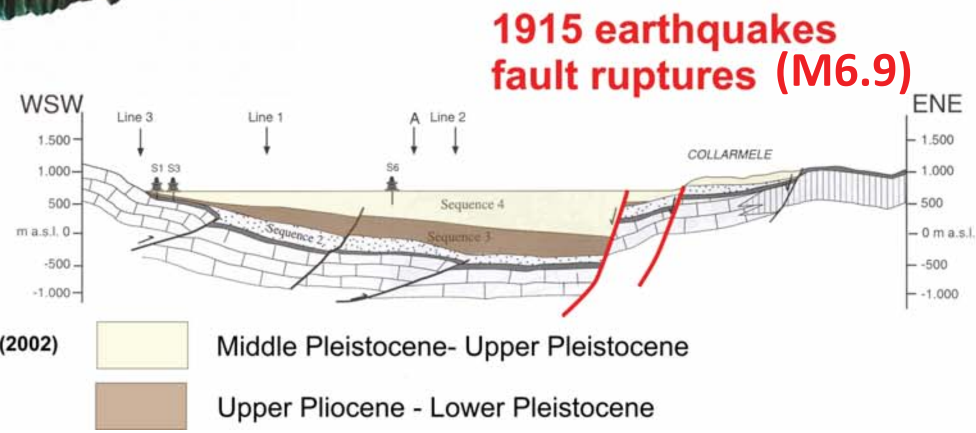


- Black focal mechanisms, CMT
- Grey focal mechanisms, first-motion or modelled from geodetic levelling
- Colour scale represents regionally filtered topography (>150 km)

FUCINO BASIN







From Cavinato et al (2002)

Continuous lacustrine sequence from Pliocene to 19th century (artificial external drainage)

Surface faulting of the 1915 Ms 6.9 Avezzano earthquake

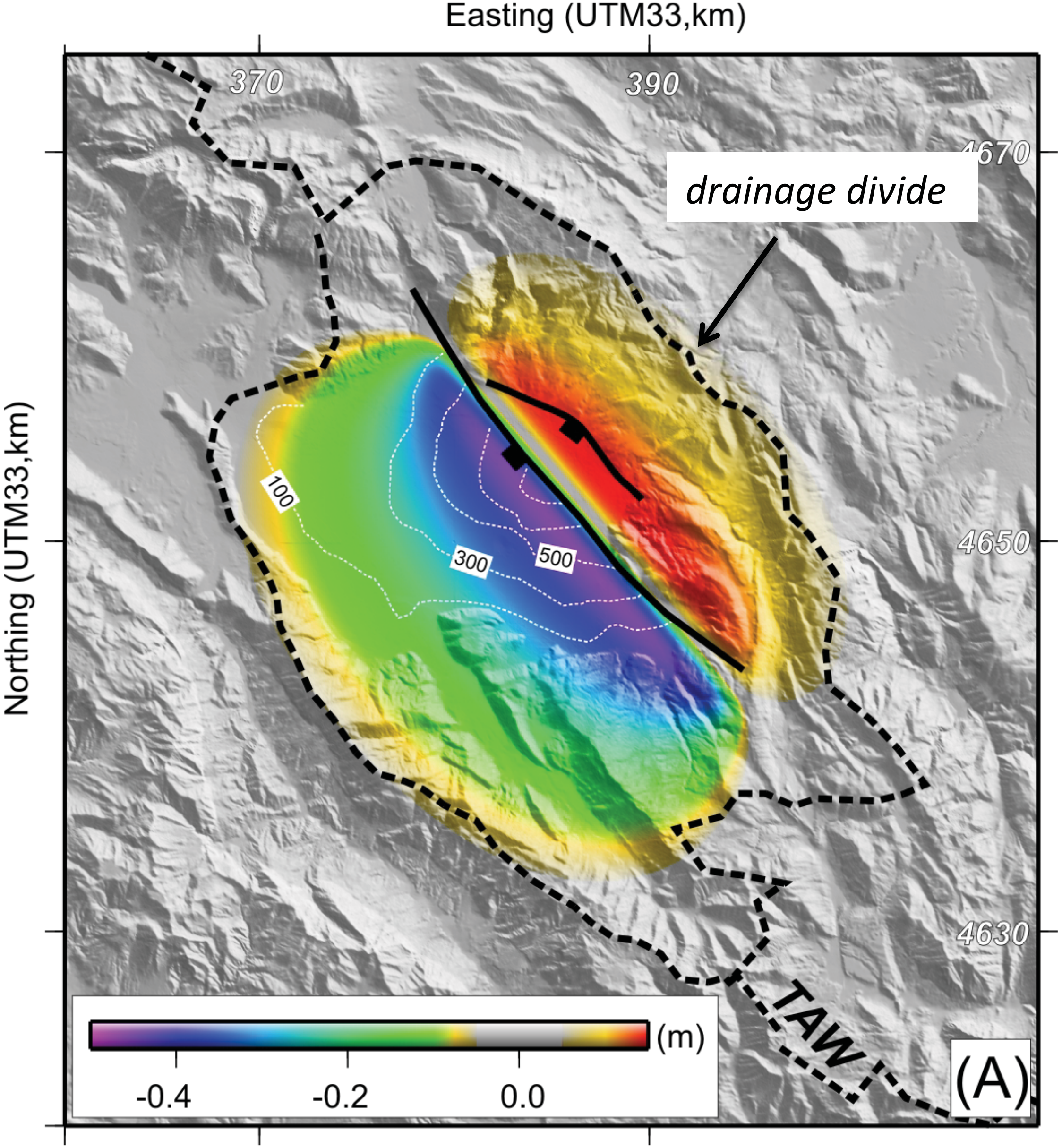
Coseismic vertical deformation of the 1915 Avezzano M 6.9 earthquake

Fault parameters from surface faulting and geodetic levelling (Ward and Valenisise, 1989)

White dashed lines = basin fill isochron contours (ms TWT) (Cavinato et al., 2002)

Limit of internal drainage correlates with coseismic vertical deformation

The fault keeps the basin internally-drained ?



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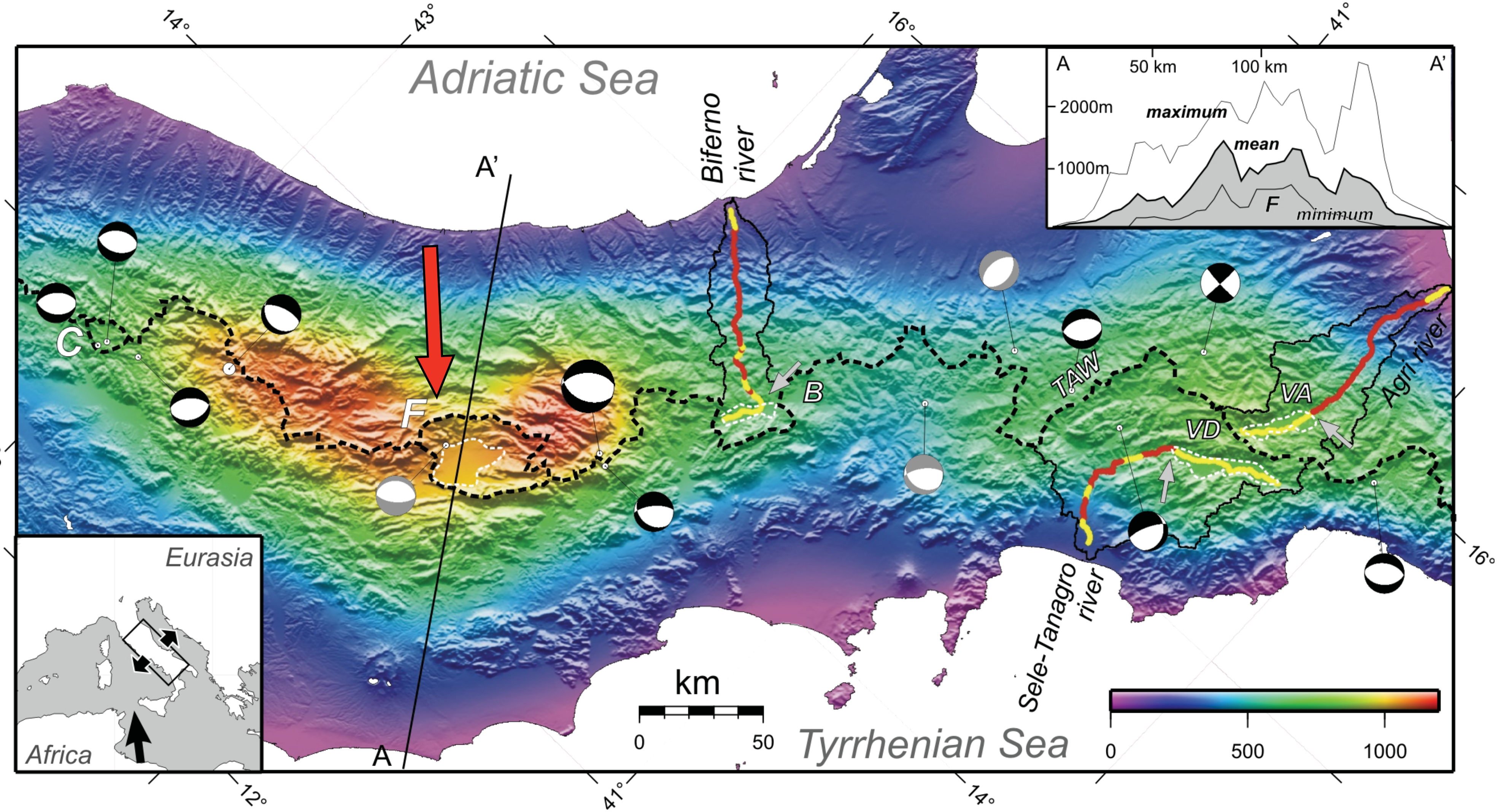

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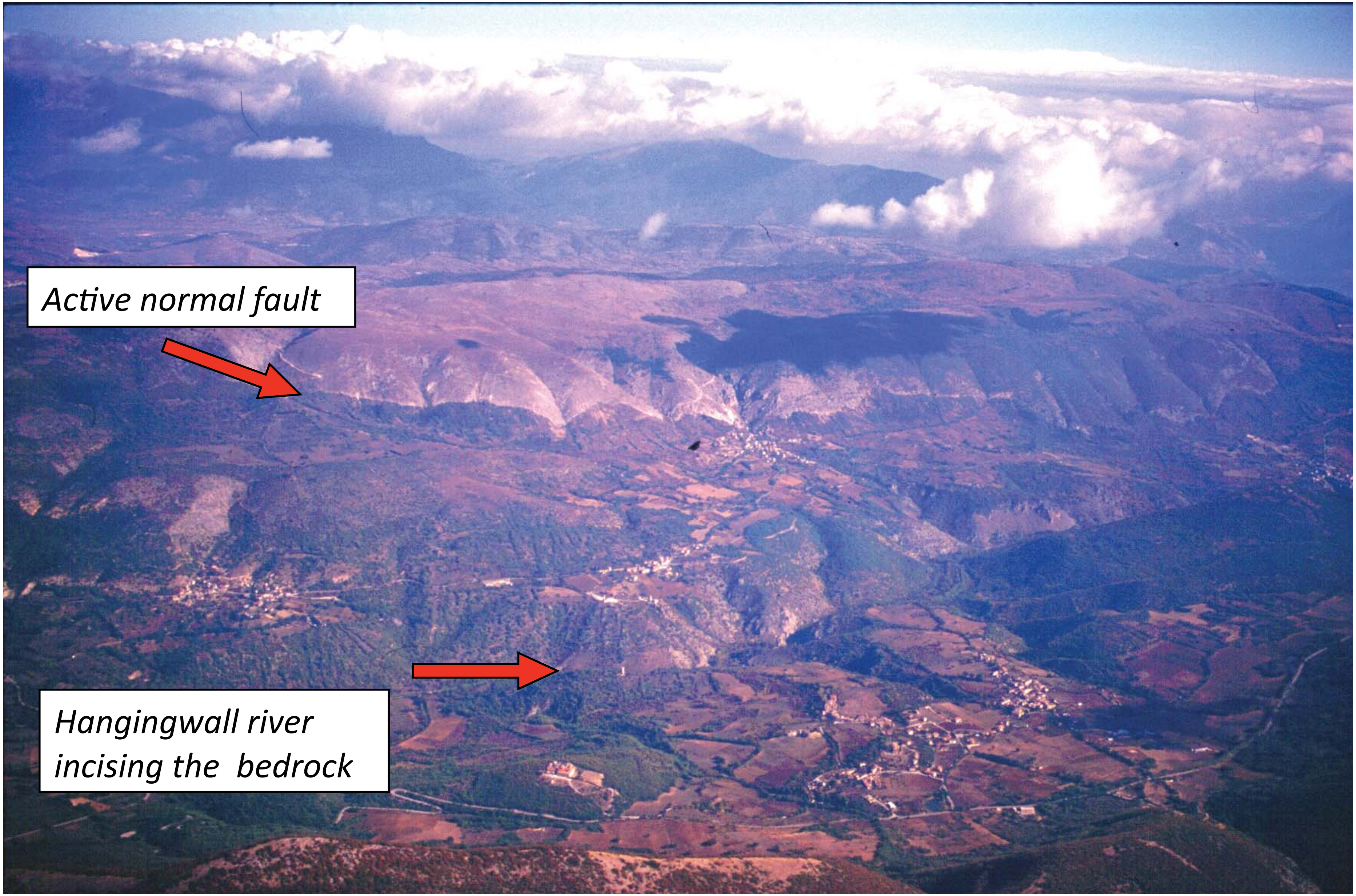
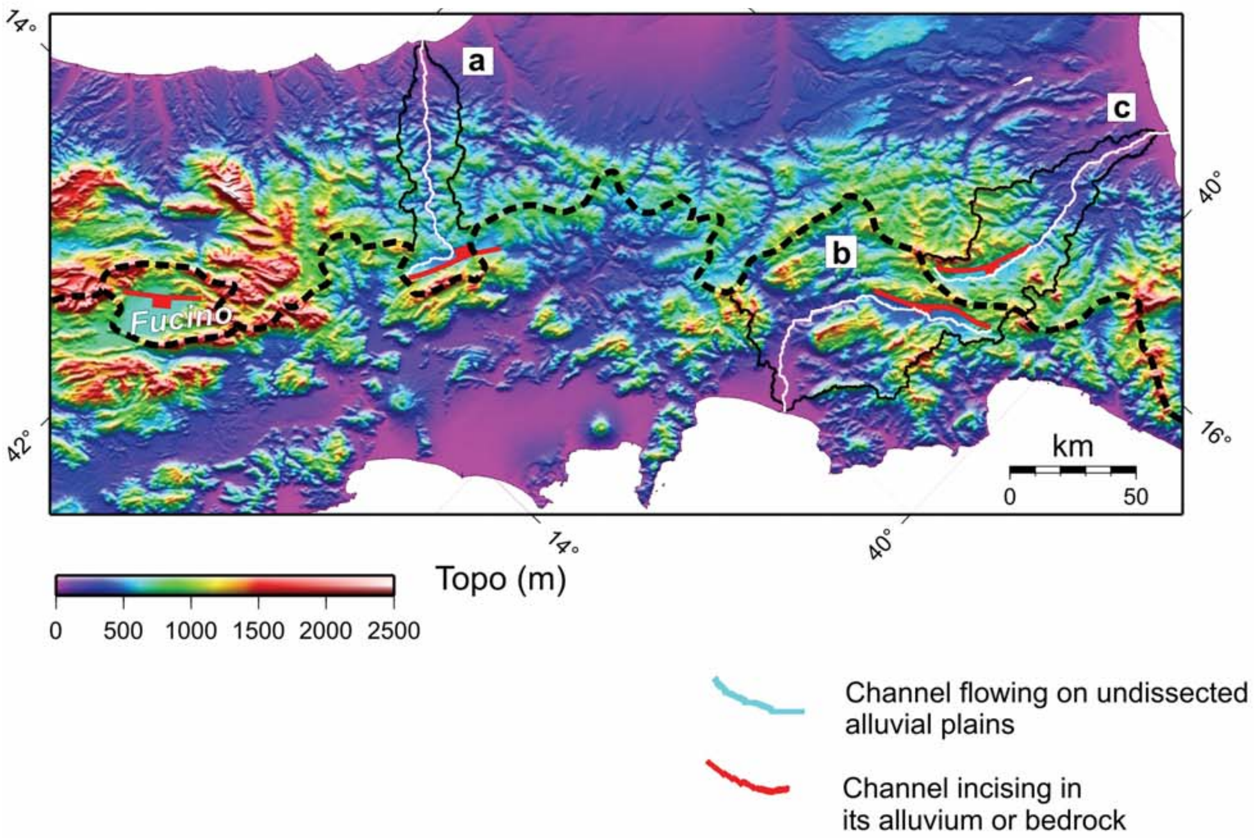
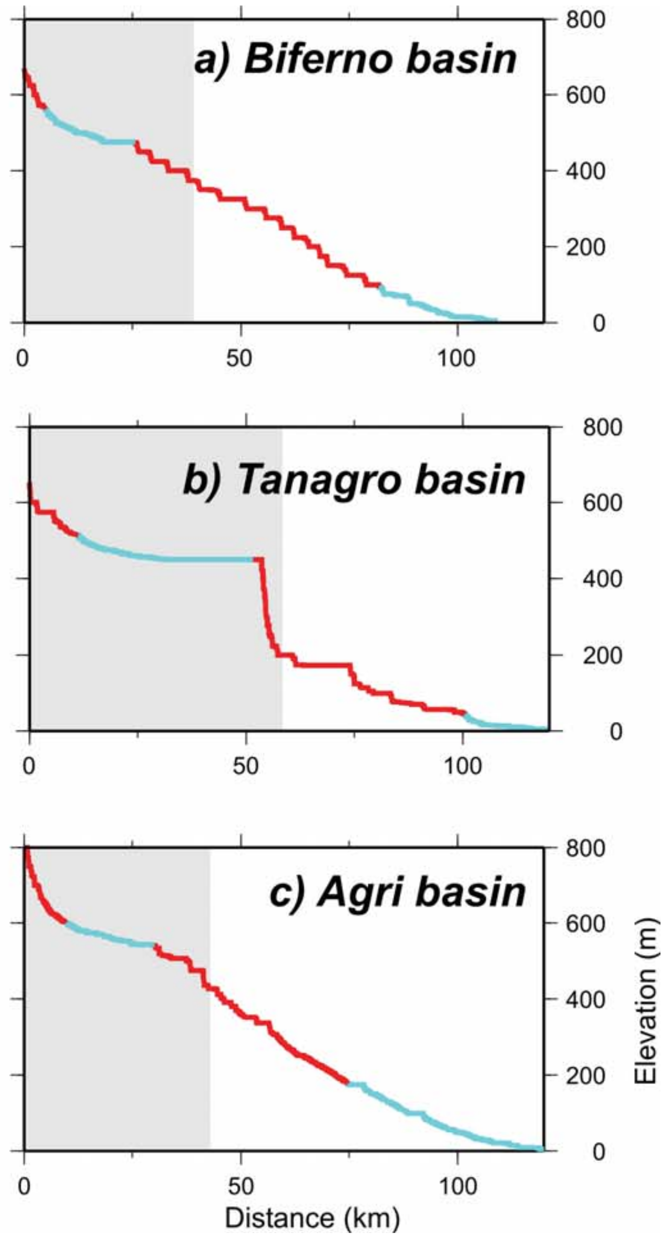
Drainage integration and basin incision in off-watershed basins



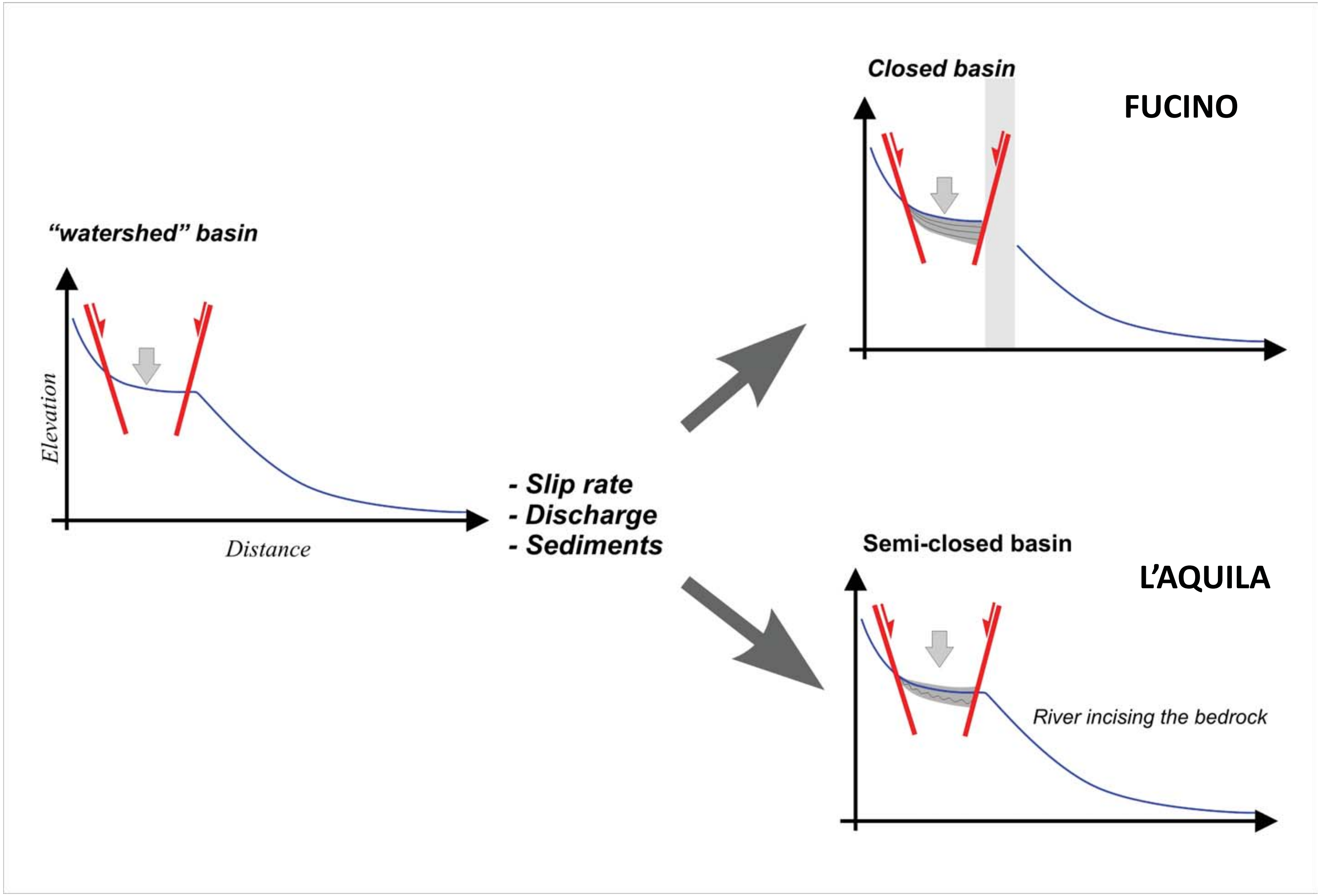
“Watershed” basins and river longitudinal profiles

Most of the rivers draining from the Apennines divide originate in normal fault-controlled intermontane basins and display a characteristic double concavity in their longitudinal profiles



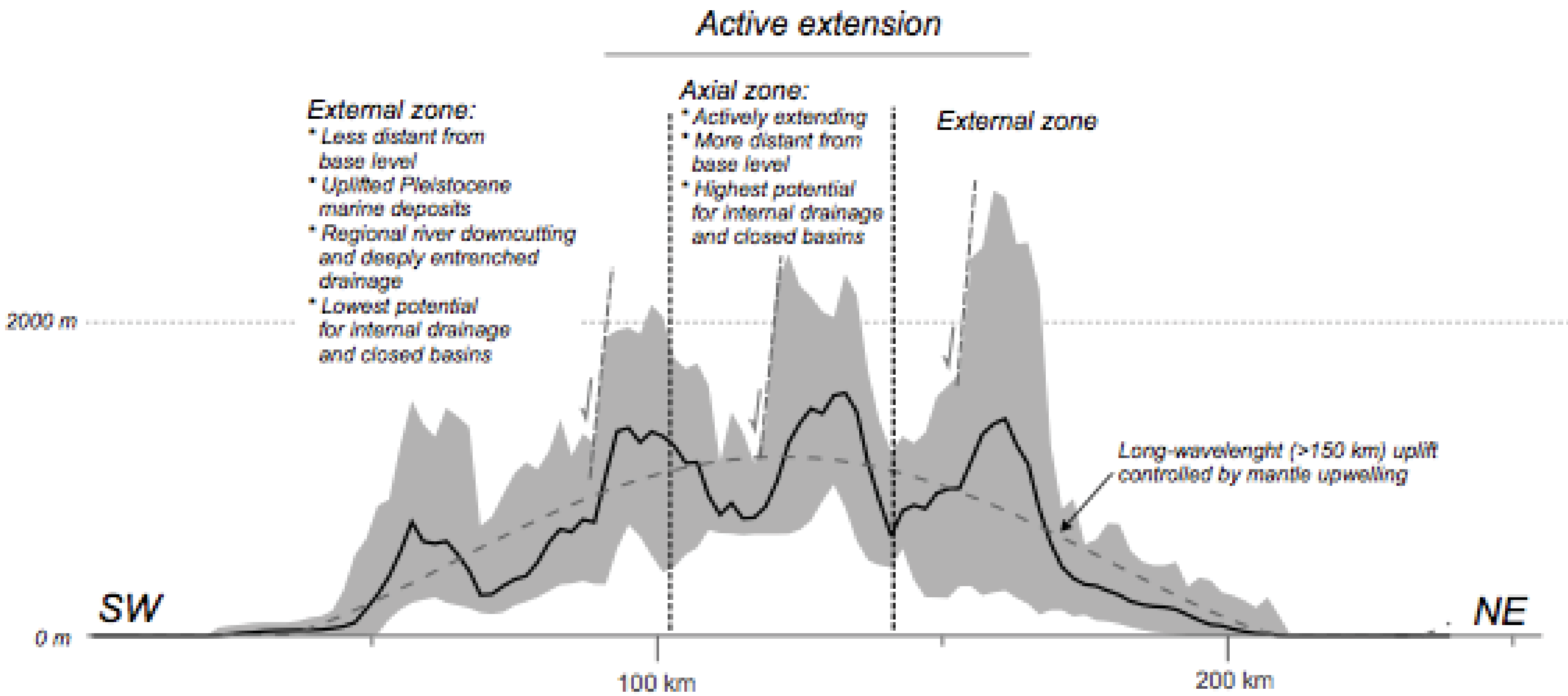


Conceptual model for river longitudinal profiles in the Apennines



Topography is the sum of two contributions:

- short-wavelength → normal faulting
- long-wavelength (> 150 km) → driven by mantle upwelling



D'Agostino et al. (2001)

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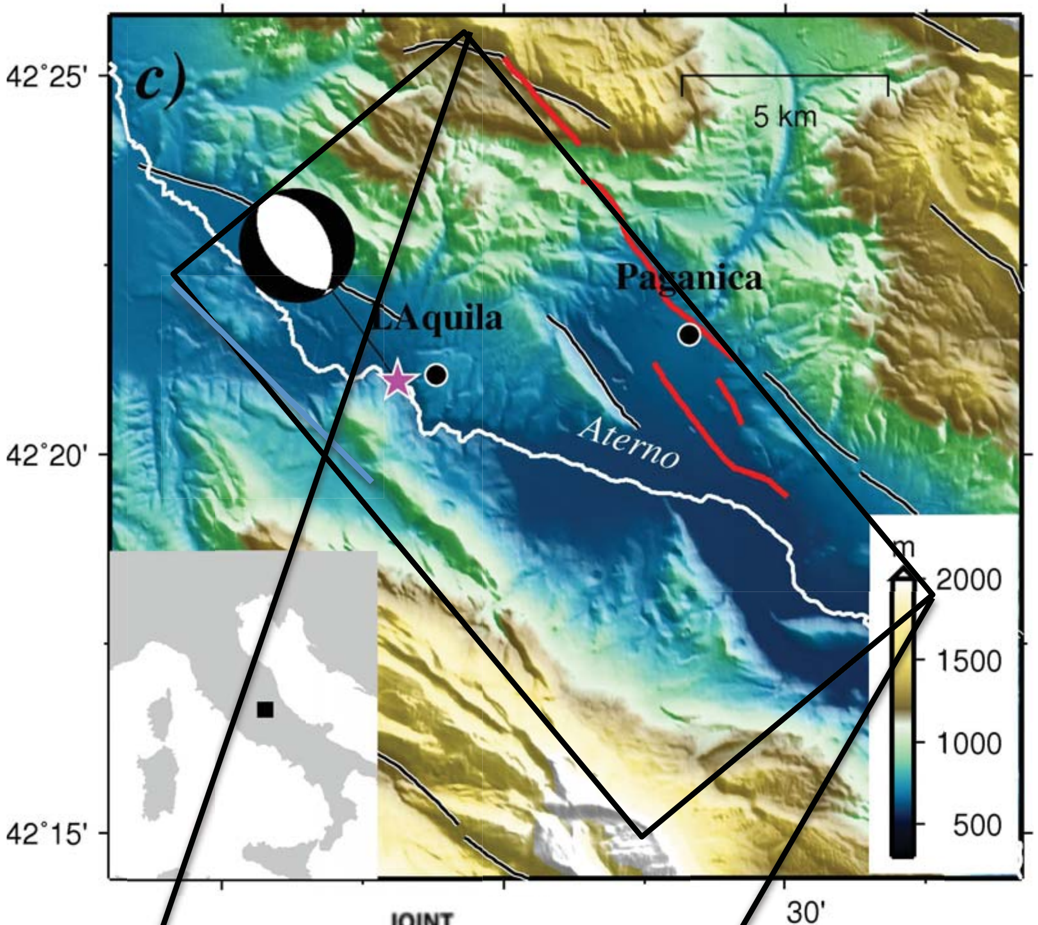
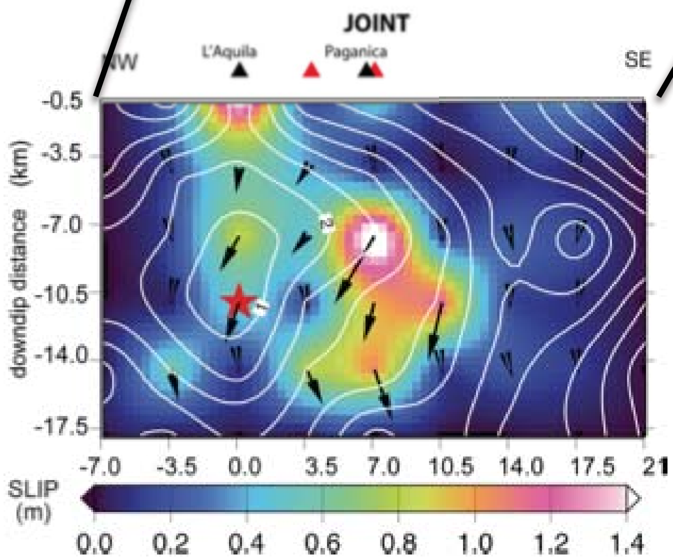
Questions posed by the 2009 Mw 6.3 L'Aquila event

- Geomorphological effects of repeated ruptures
- Do seismic events repeat similarly (same magnitude) on the same fault ?
- Postseismic slip contributes significantly to seismic moment release ?





Joint inversion of InSAR, GPS and strong motion
(Cirella et al., GJI 2012)

The Mw 6.3 april 2009 L'Aquila earthquake

A normal faulting event preceded by a long foreshock sequence

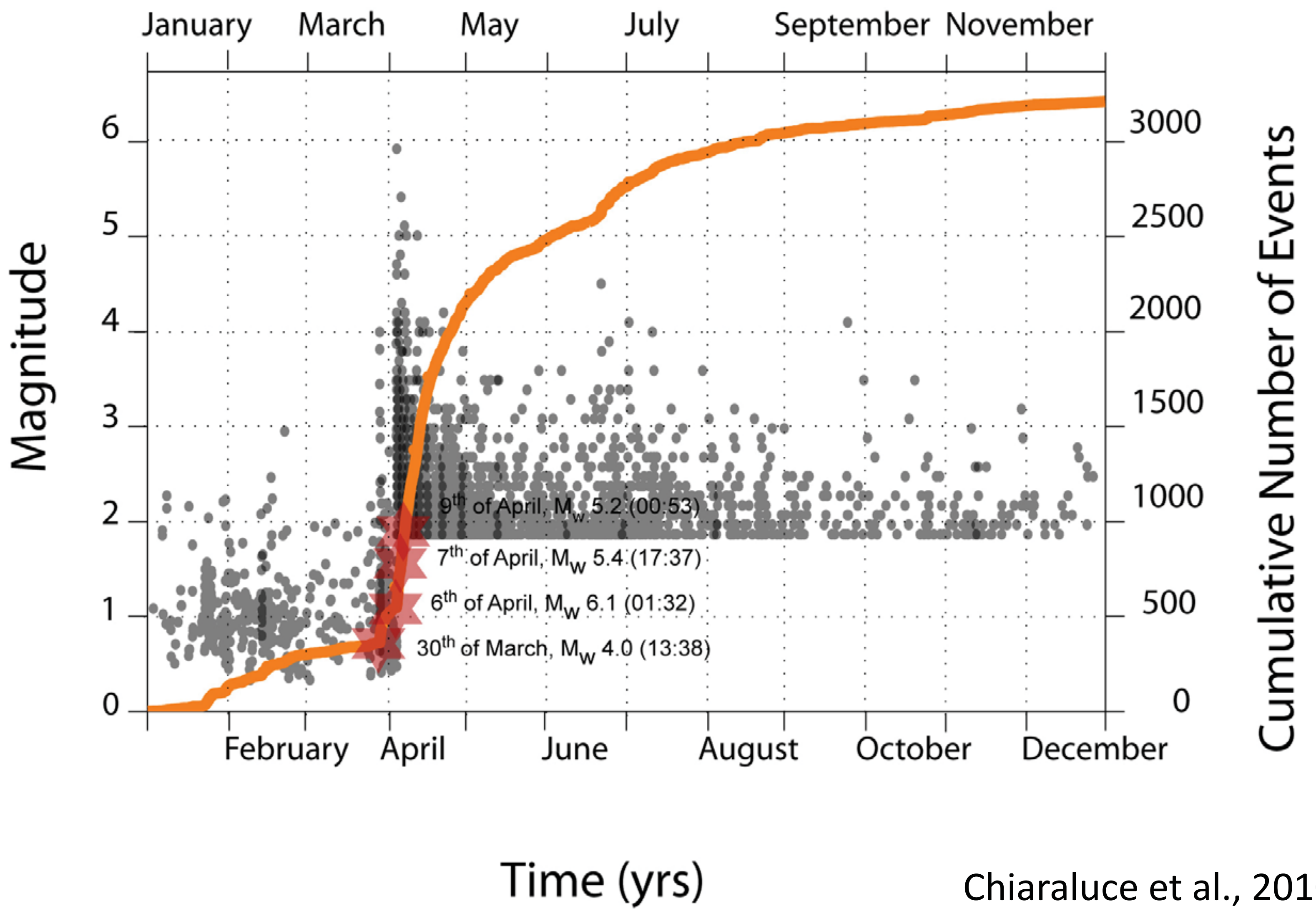
Significant fault slip (0.5 m) beneath the town of L'Aquila (popul. 70,000)

Geodetic/seismic inversions indicate max ~1 m coseismic slip

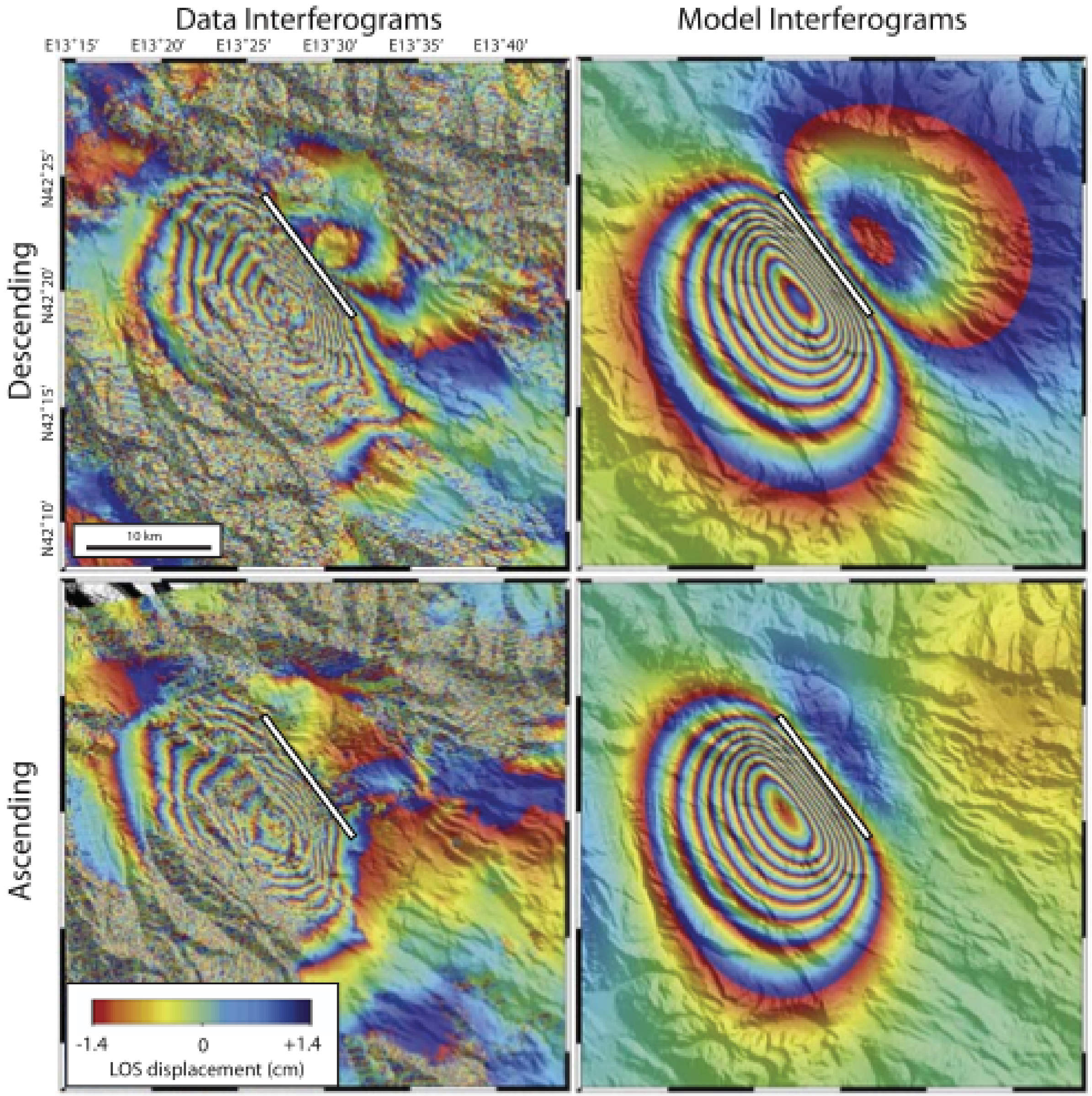
Only small coseismic ruptures (1-10 cm) observed along the PF (in red)

Afterslip observed by:
- InSAR, GPS, Increasing offsets of surface ruptures, Strainmeters, Levelling, LIDAR studies

The foreshock/aftershock sequence



Chiaraluce et al., 2010



Envisat coseismic interferograms

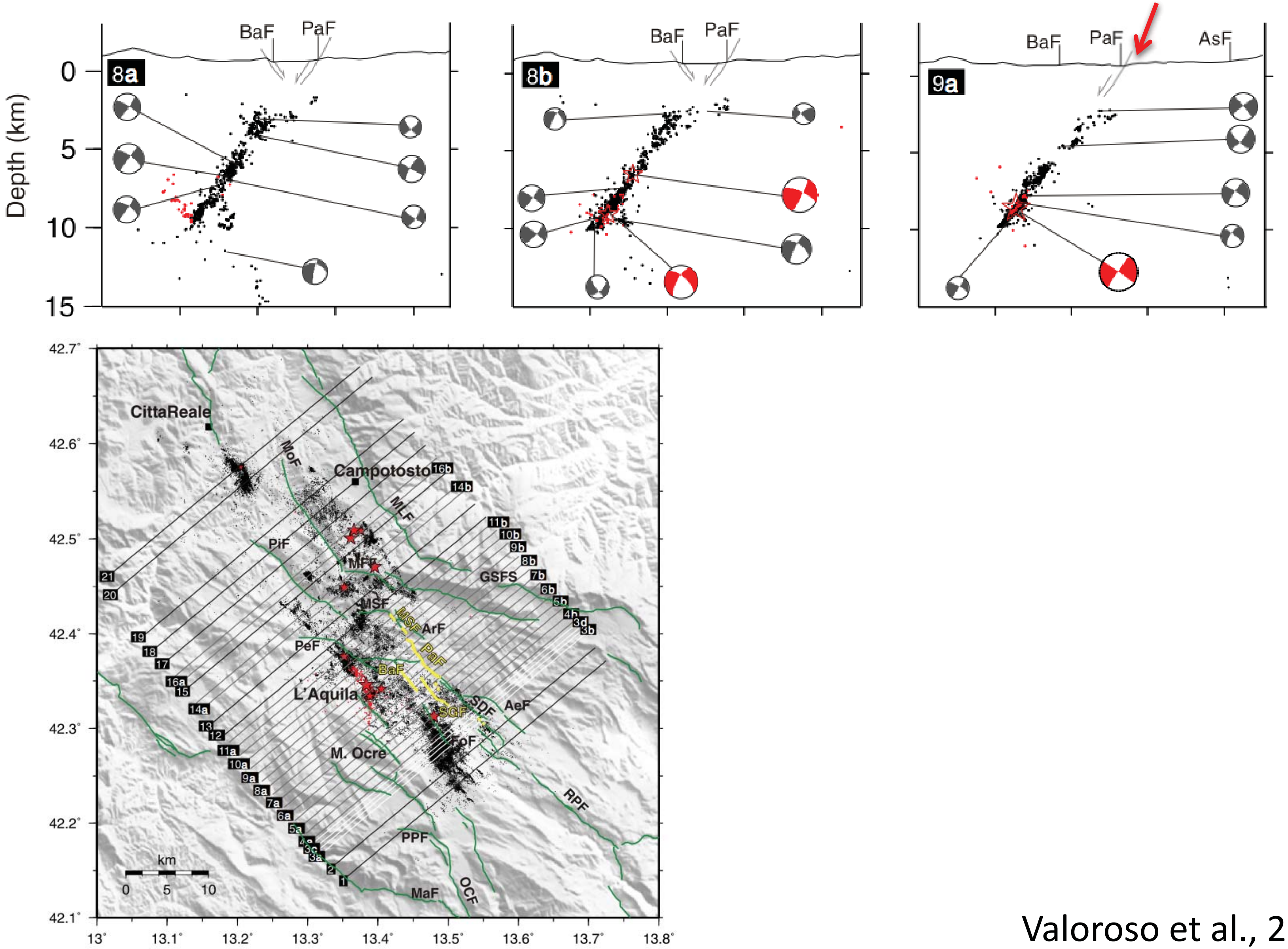
Main pattern well reproduced by a constant-slip fault patch

Fringes are continuous. Coseismic slip did not fully reached the surface

Walters et al., GRL 2009

Aftershocks and fault geometry

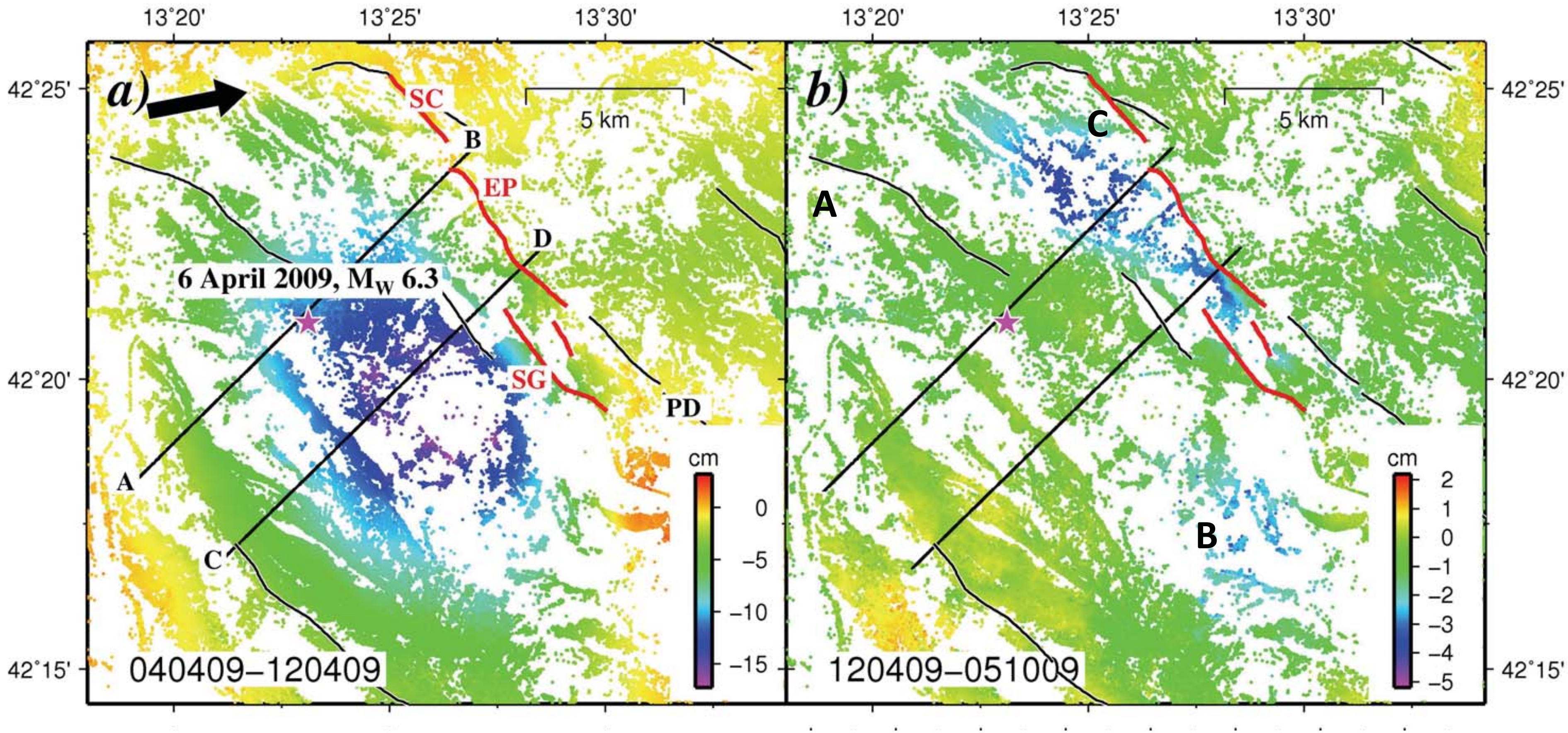
Small ruptures on Paganica fault



Valoroso et al., 2013

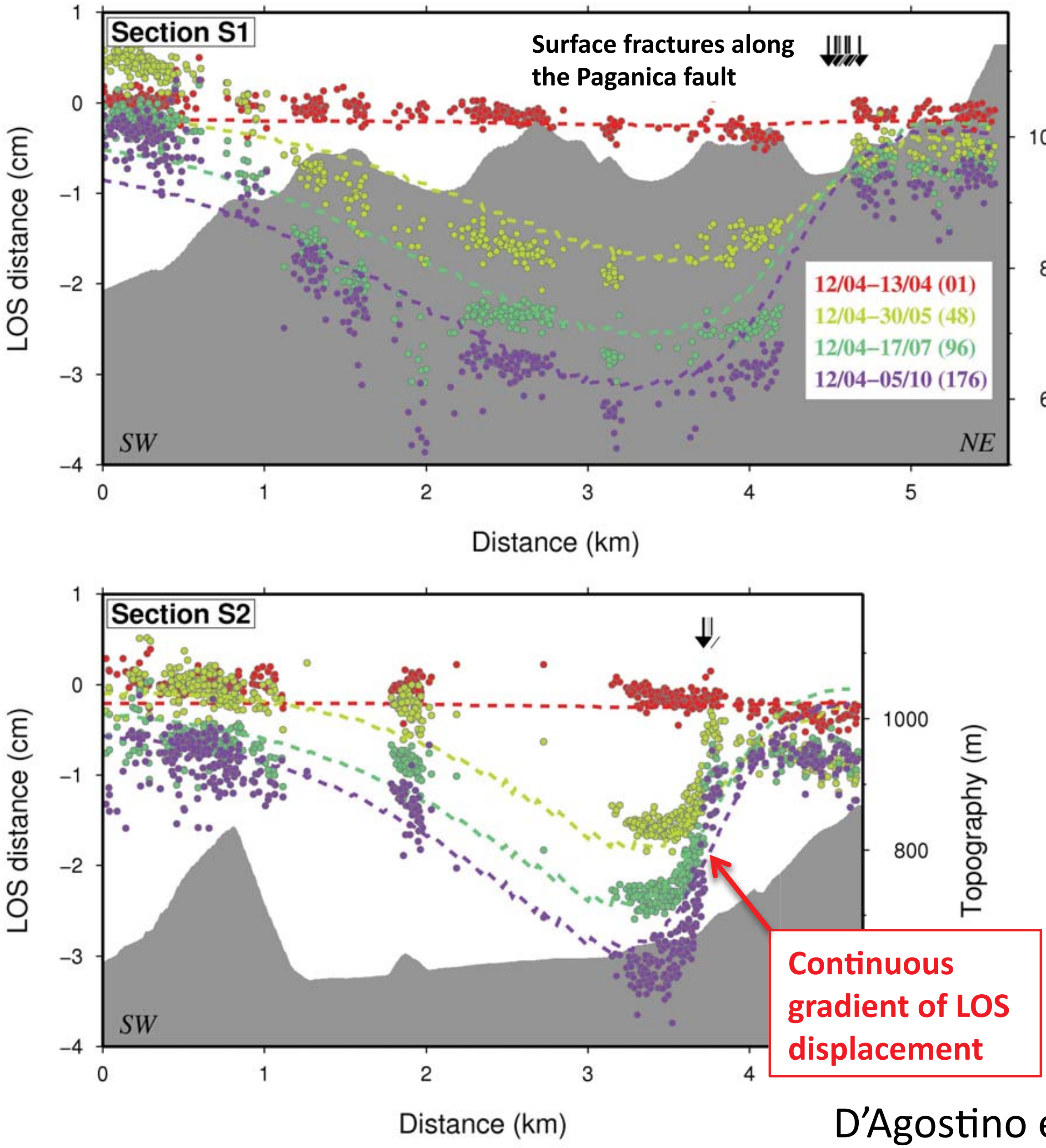
Coseismic and postseismic LOS displacements are spatially complementary (Cosmo Sky-Med)

Coseismic (-2/+6 days) Postseismic (+6/+180 days)



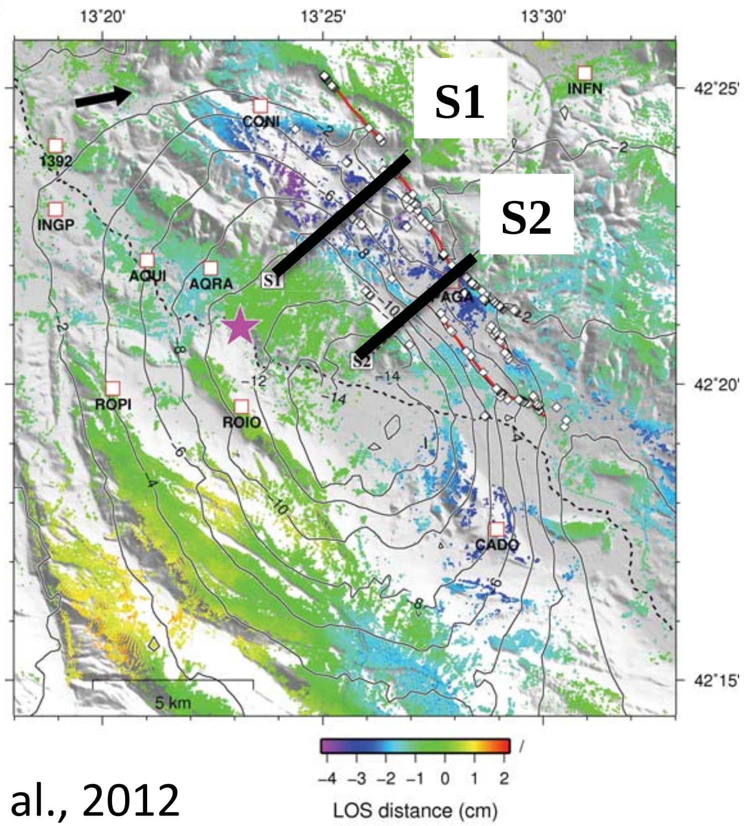
D'Agostino et al., 2012

Postseismic evolution of near-fault LOS displacements along the PF for 1/48/96/176 days intervals



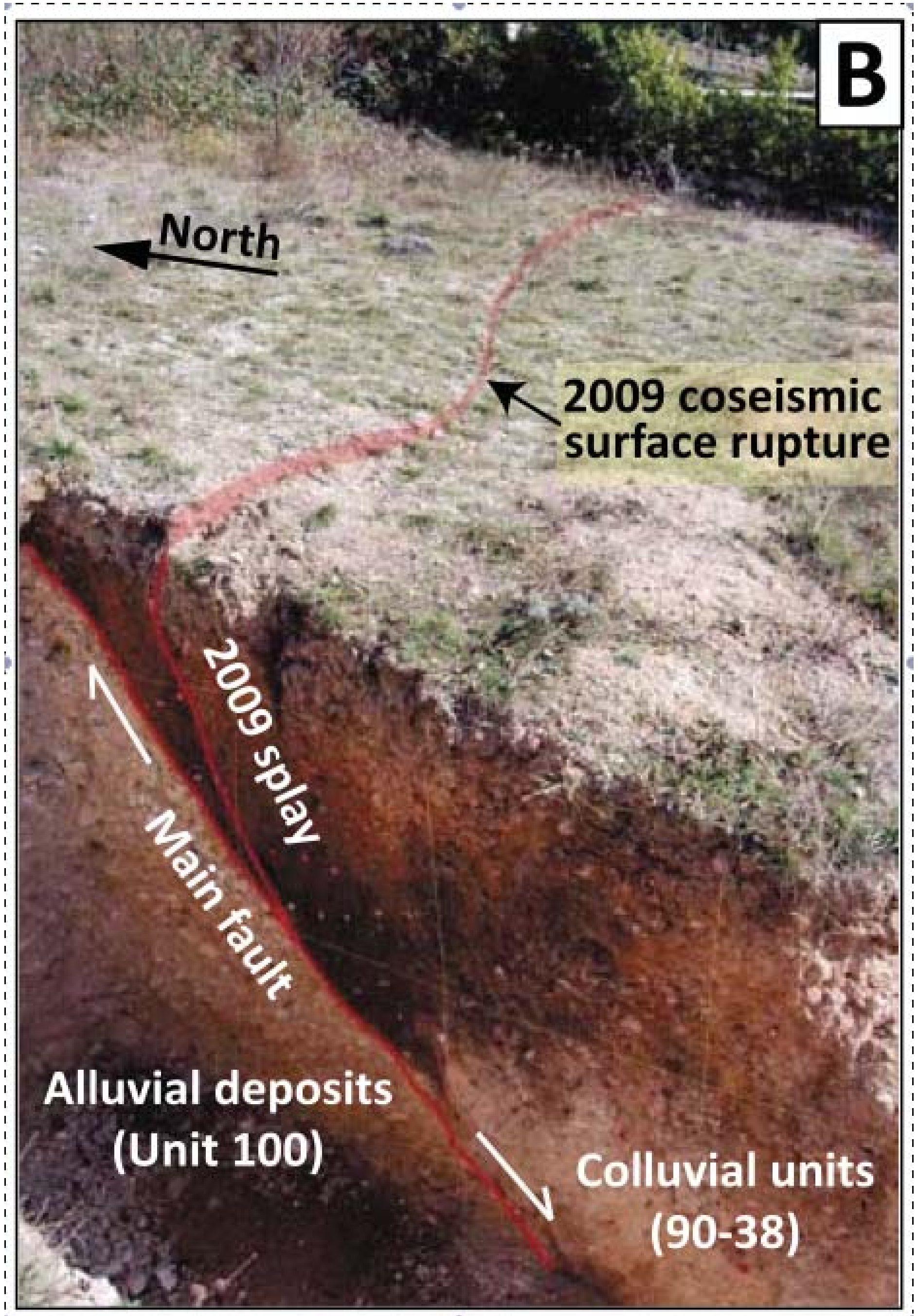
Consistent with afterslip at shallow depth along the PF but <u>not</u> full propagation to the surface

Observed postseismic fracture growth driven by continuing slip at shallow depth



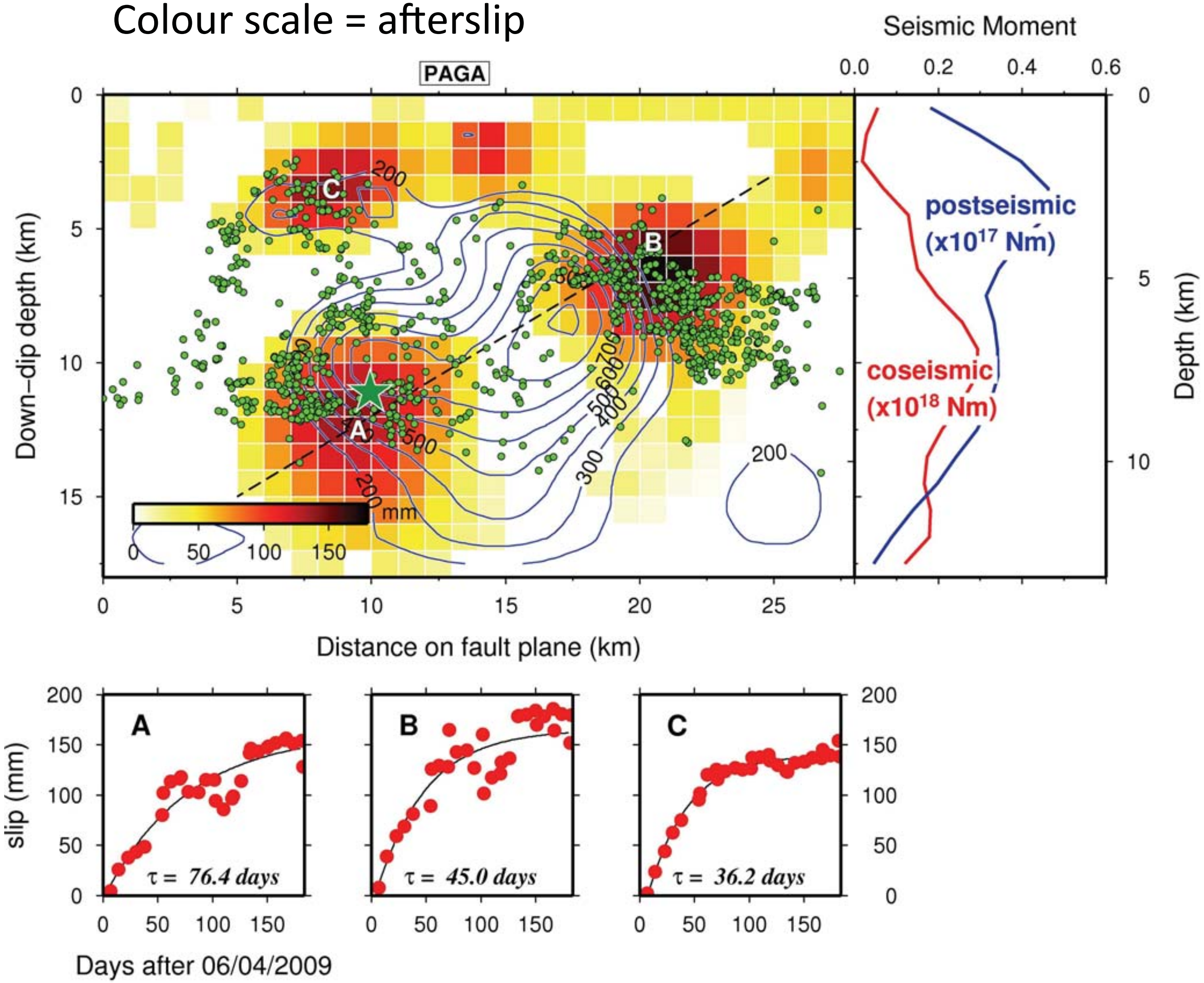
D'Agostino et al., 2012


fault scarp


B
North
2009 coseismic
surface rupture
2009 splay
Main fault
Alluvial deposits
(Unit 100)
Colluvial units
(90-38)

Distribution of coseismic and postseismic slip

Contours = coseismic slip
Colour scale = afterslip



Max coseismic slip ~ 1 m concentrated in a single patch

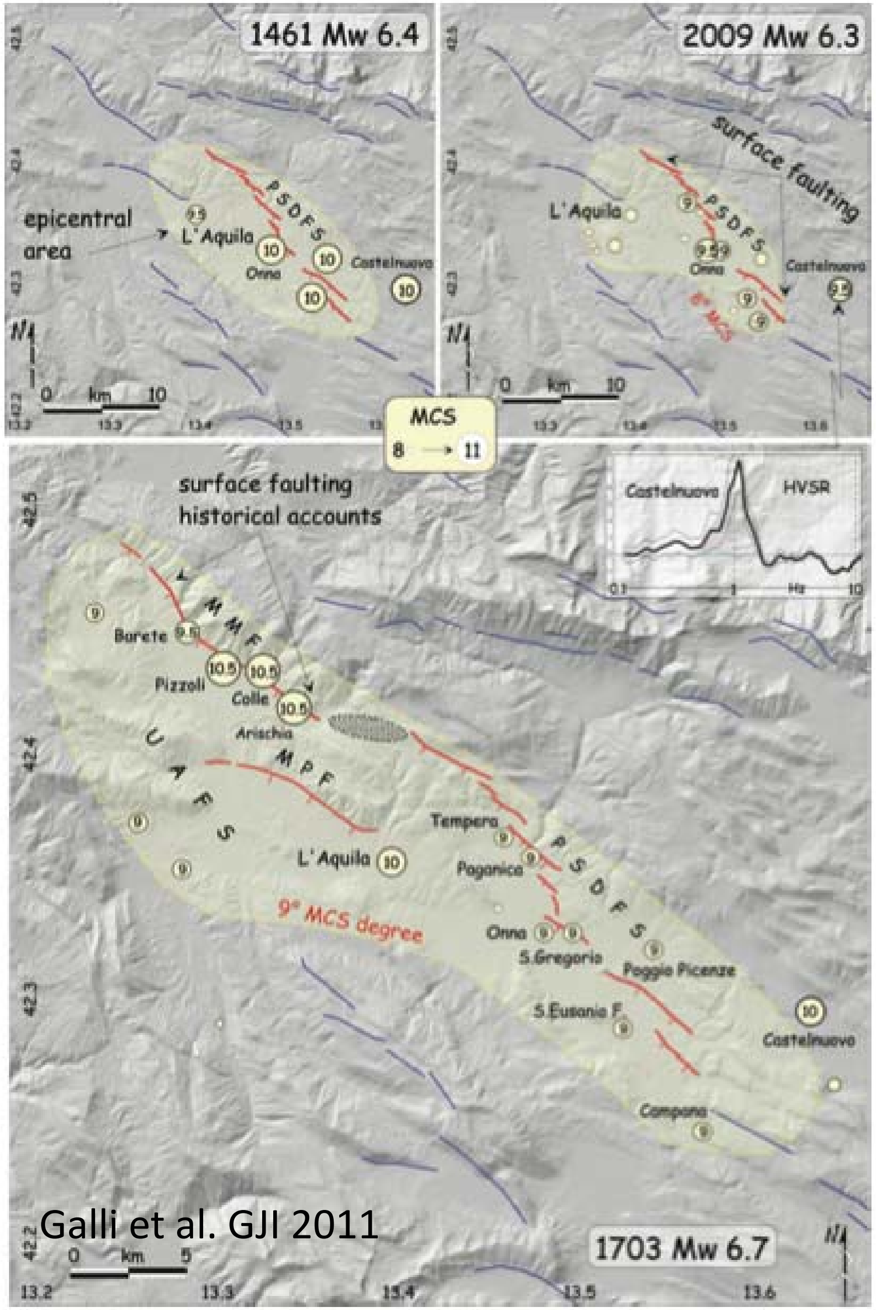
Postseismic moment (+6/+180 days): 0.51×10^{18} N m (Mw 5.8) 18% of coseismic

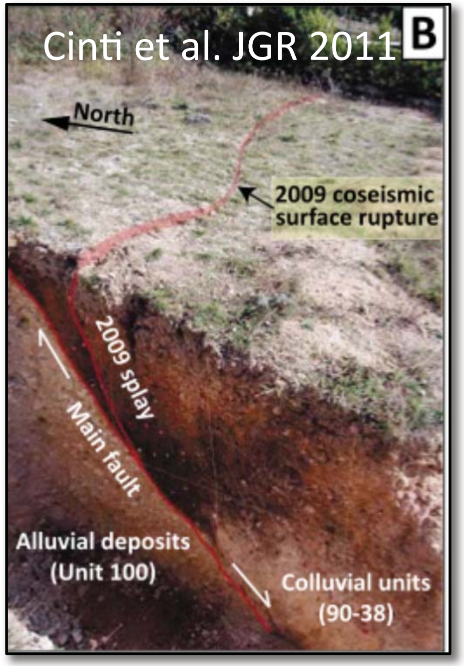
Afterslip (complementary with coseismic slip) not confined at shallow depth but distributed on the entire upper 10 km

Patch A falls in a poorly resolved region bur appears to be required by both GPS and InSAR

Postseismic patch B and C do not fully reach the surface

Paleoseismological studies



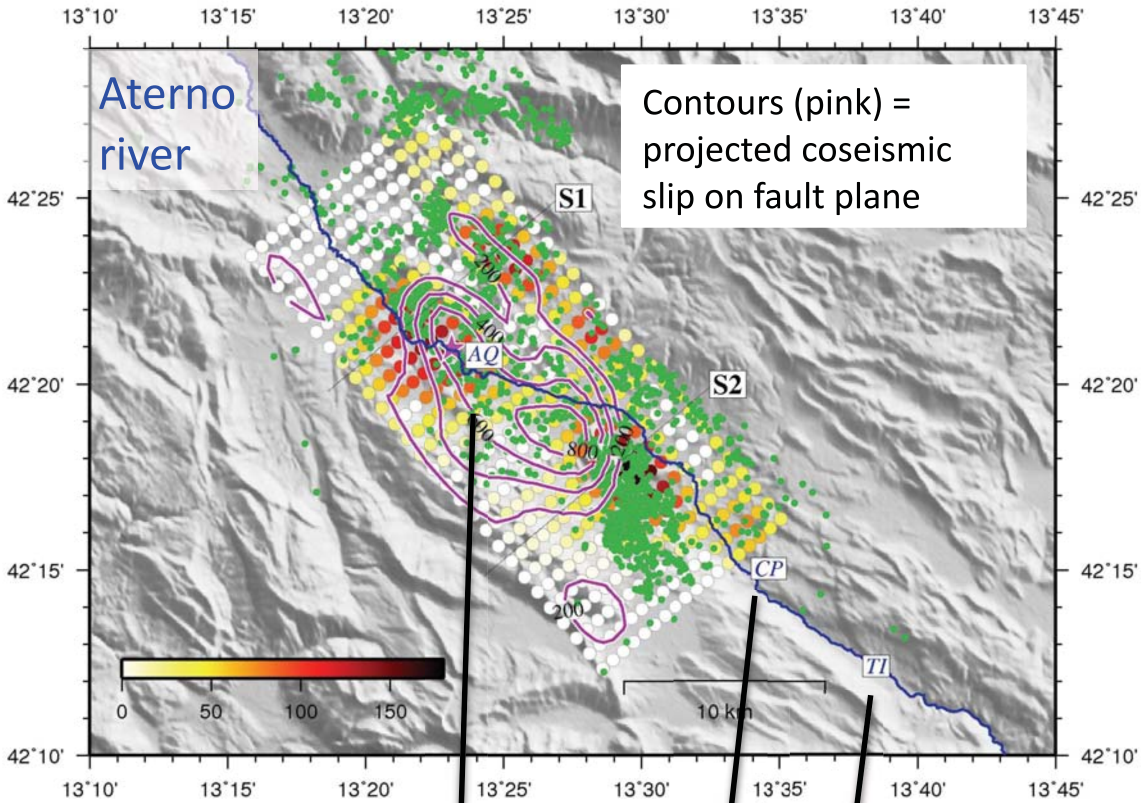


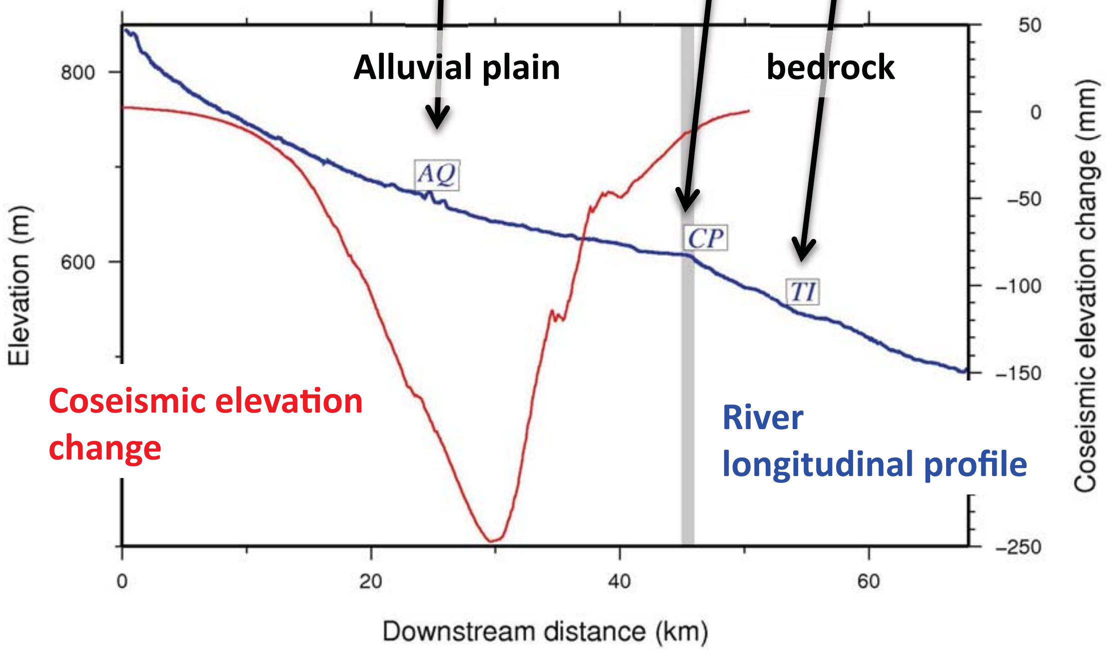
Trenching along the Paganica fault documents variable seismic behaviour (not characteristic):

- 2009-type Mw < 6.3 events producing small (1-10 cm) fractures (e.g. 1461, 2009) $T_{rec} \approx 500$ years

- Mw > 6.5 events (e.g. 1703) rupturing conterminous segments producing > 0.5 m surface fault scarps $T_{rec} > 1000\text{-}2000$ years

Effect of fault activity on river longitudinal profile





Coseismic vertical defomation correlates with the river profile concavity