Adding geodetic strain rate data to seismogenic contexts in the Alps, Apennines and Central Europe

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Summary

In several seismic or potentially seismic areas deformation processes at moderate depth generate deformation at the surface, and the measurement of such surface deformation is an important boundary condition to models of the evolution of interacting blocks before, during and after earthquakes. The network of some 160 permanent GPS stations disseminated in Europe under the European Permanent Network of EUREF and the CERGOP 2 Project of the European Union, with additional local densification stations, provides a valuable contribution to the estimate of the average surface strain rate. The expected strain rate is of the order of 20 – 40 nanostrain per year, corresponding to a velocity change of a few mm/year over distances of some hundreds of km. Consequently, we require accuracies in the velocities of fractions of mm/year, and full control of systematic errors which may mask tectonic signals. Based on our systematic processing of GPS data from permanent European GPS stations covering nearly a decade (1995- 2005) we present the large scale velocity flow across most of continental Europe, and the associated horizontal gradient, or strain rate field. We focus on the Eastern Alps area, where the distribution of GPS stations is relatively dense, there exist a number of seismic and gravimetric profiles, and the Adria microplate is actively indenting northwards, into the stable European foreland. We present velocity profiles and estimate slip rates along the TRANSALP transect, which is already well constrained from seismic refraction experiments, gravity and geological survey. We further examine velocity profiles along the CROP03, CROP04, CROP 11 and CROP Western Alps, and obtain estimates of slip rates which can prove very useful in several fields, from active tectonics to seismic risk assessment.

Goals

- Distribution in space and time of strain rate in Italy and surrounding areas

Motivation

- A strain rate map is expected to correlate with the geometry and activity of seismogenic faults
- Changes of strain rate with time should affect the probability that a fault activates in the short term
- Post seismic creep should be visible by combining geodetic/GPS and D-InSAR data

Context

- CERGOP 2 (5. FP UE); INGV DPC project S2 Task 3

Data sources

SINEX files: typically represent a quantitative picture of a network at an epoch: coordinates, covariance, constraints

Some SINEX files are homogeneous and compatible as to data processing standards (IGS/EPN recommendations)

– EUREF (EUR<GPSwk>.SNX) from 860 to 1366 (~10 years)
– Italian network (UPA<GPSwk>.SNX) from 1000 to 1366 (~ 7 years)
– Austrian network (GP_<GPSwk>.SNX) from 995 to 1366 ~ 7 years)

SINEX data files from CEGRN/CERGOP Campaigns in Central Europe 1994 - 2003

Additional velocity estimates (values are given 'as such'):

- Epoch and permanent stations from Serpelloni McClusky - Hollenstein (particularly Central Southern Italy):

Data Analysis: weekly combination

Weekly combination with Program ADDNEQ of Bernese v. 4.2: EUREF+UPA+GP_ in a unique file. EUREF overweighted relative to UPA e GP_:

FILE	FILE NAME	RMS (SINGLE DIFFERENCE)
1	C:\STORICRD\OUT\EUR13667.NEQ	0.0020
2	C:\STORICRD\OUT\UPA13667.NEQ	0.0020
3	C:\STORICRD\OUT\GP_13667.NEQ	0.0012

Default weight in SINEX

FILE	FILE NAME	VALUE	RMS	GRP
1	C:\STORICRD\OUT\EUR13667.NEQ	1.0000	0.000000	EUR
2	C:\STORICRD\OUT\UPA13667.NEQ	0.0100	0.000000	UPA
3	C:\STORICRD\OUT\GP_13667.NEQ	0.0100	0.000000	GP_

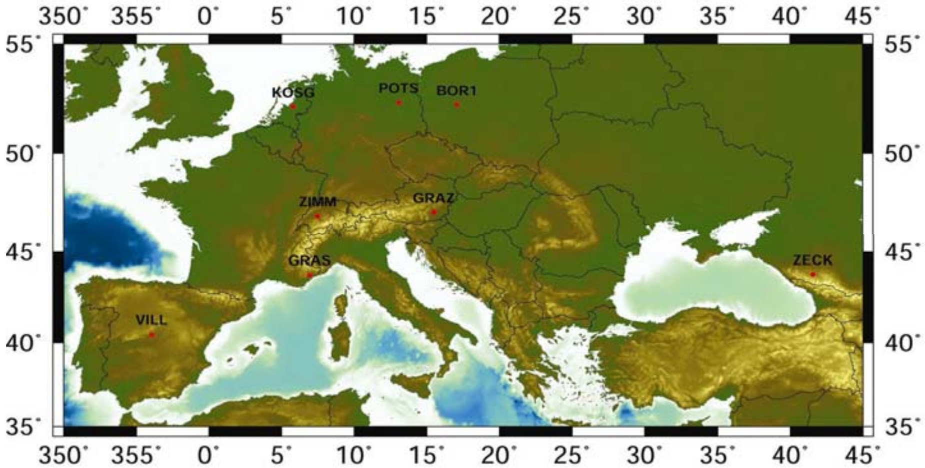
Relative weight assigned to each solution

TOTAL NUMBER OF STATIONS: 258			1	2	3
123 HFLK 11006S003 3	N	0.1	0.1	-0.1	0.0
	E	0.3	0.0	-0.2	0.3
	U	0.5	0.1	0.6	-0.4
802 RTMN 11037S001 2	N	0.2		-0.1	-0.2
	E	0.1		0.0	-0.1
	U	0.5		0.5	0.0

This site only in the regional solutions

Data Analysis: time series

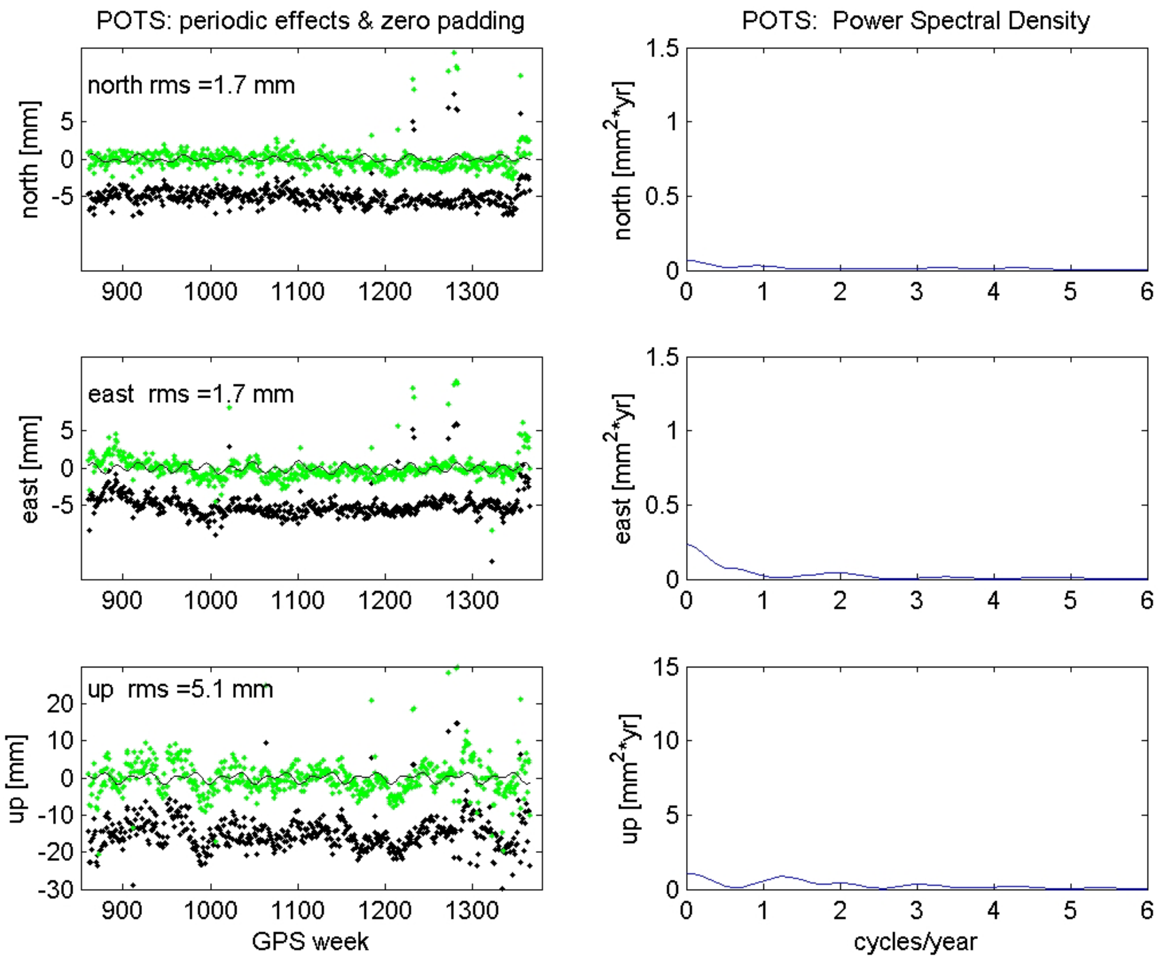
– Constraints to IGS/ITRF2000 values



•	BOR1 12205M002	POS	
•	KOSG 13504M003	POS	
•	ZIMM 14001M004	POS	VEL
•	POTS 14106M003	POS	VEL
•	GRAS 10002M006	POS	VEL
•	GRAZ 11001M002	POS	
•	VILL 13406M001		VEL
•	ZECK 12351M001		VEL

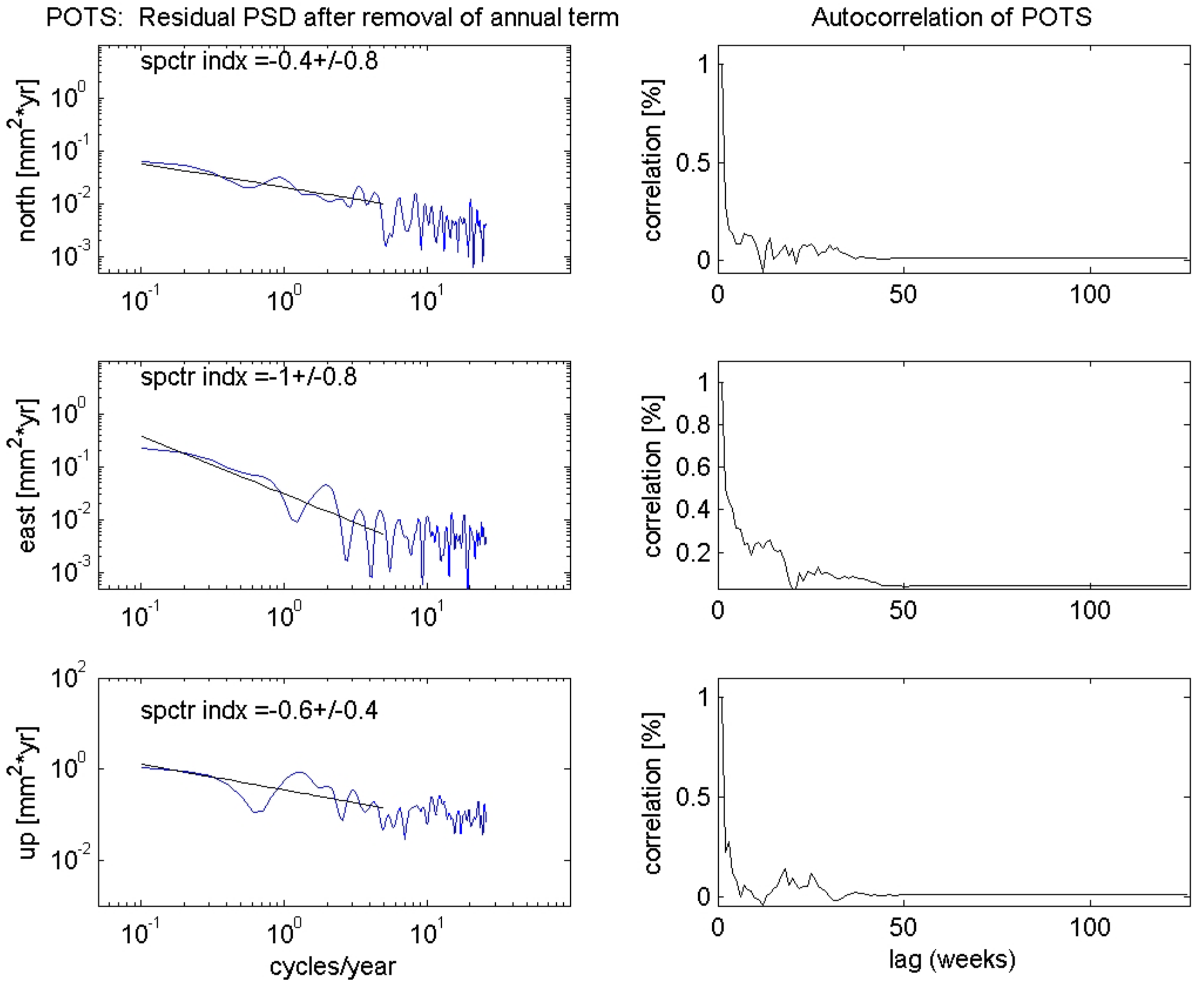
STATISTIC OF SOLVED FOR PARAMETERS	#PARAMETERS	#PRE-ELIMINATED
STATION COORDINATES	1116	2706 (BEFORE INV)
STATION VELOCITIES	1053	0
NUMBER OF SOLVE FOR PARAMETERS	2169	2706
TOTAL NUMBER OF PARAMETERS	: 35894517	
TOTAL NUMBER OF OBSERVATIONS	: > 53806263	
NUMBER OF SINGLE DIFF. FILES	: 34758	
A POSTERIORI SIGMA OF UNIT WEIGHT	: 0.0034 m	
TOTAL NUMBER OF STATIONS	: 372	

Statistical analysis on time series: 1. Identification of periodic signals



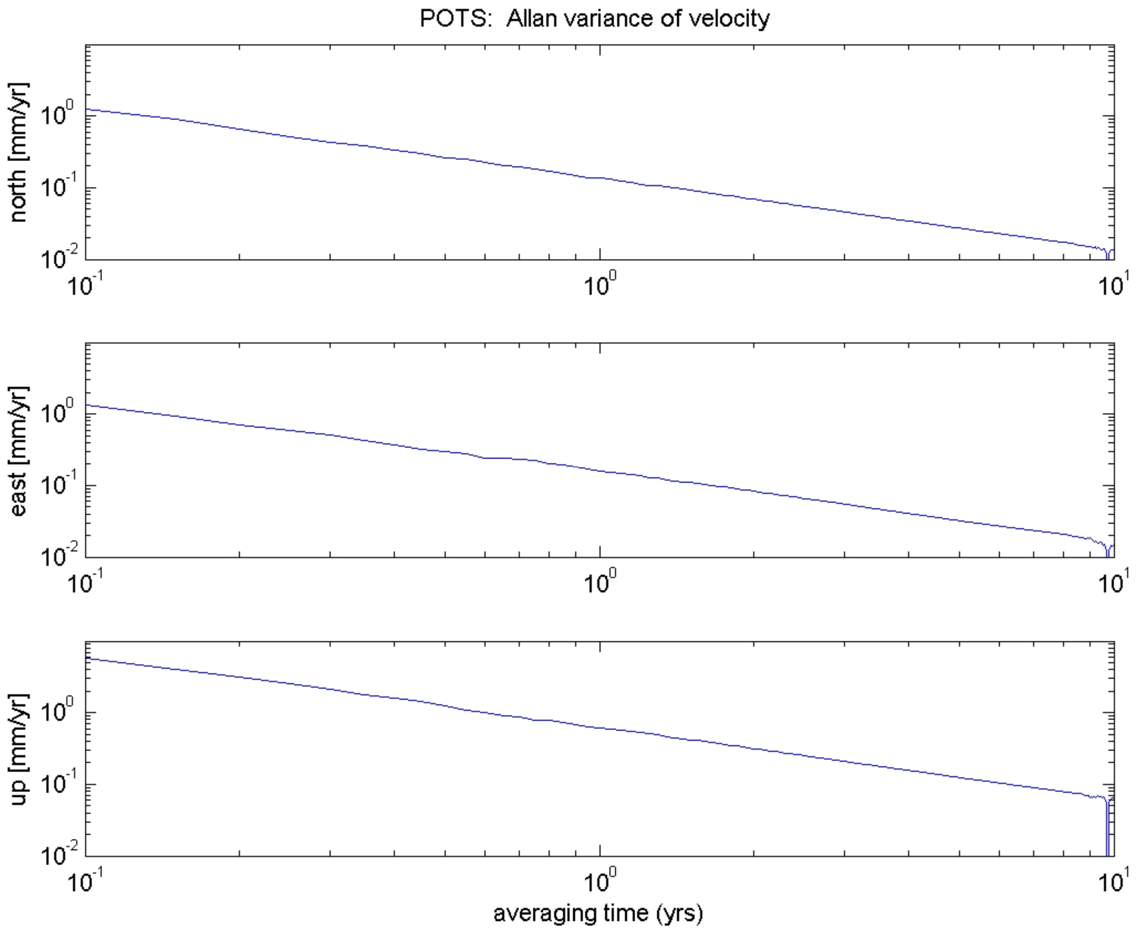
Statistical analysis on time series:

2. Noise profile and statistical independence of samples

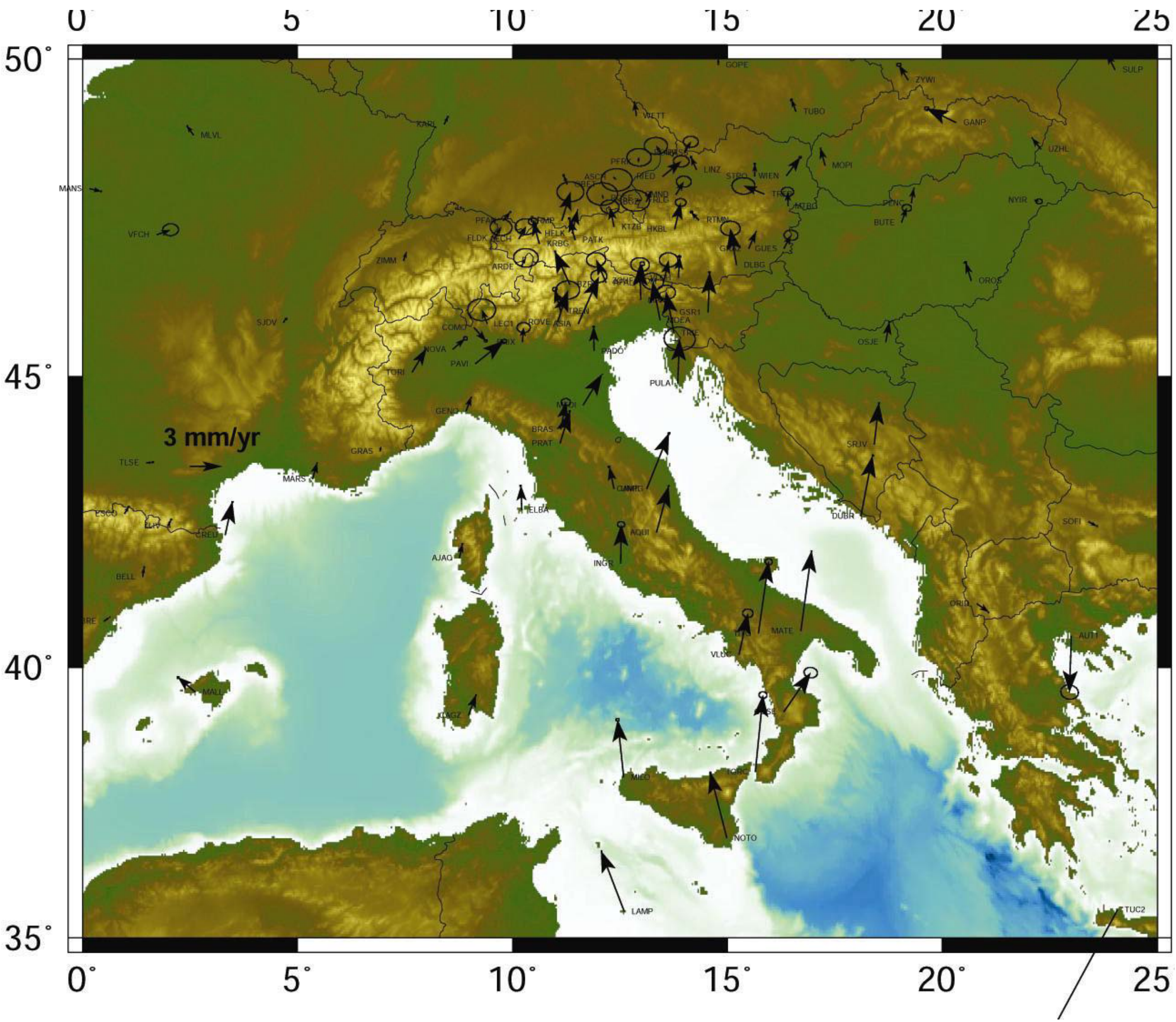


Statistical analysis on time series:

3. Evolution of velocity uncertainty in the sense of Allan variance

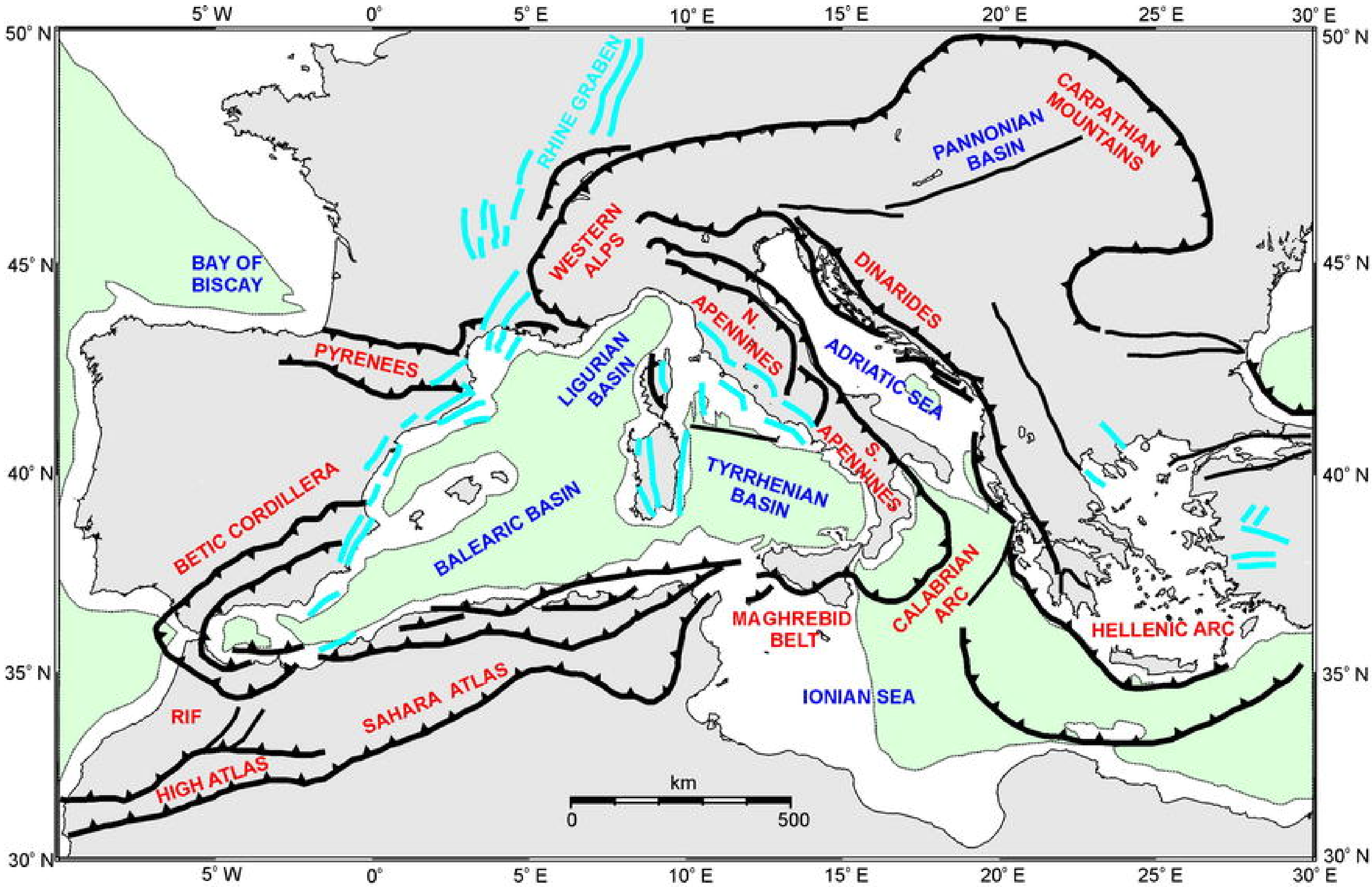


The resulting velocities relative to NUVEL1A NNR



Structural setting and active tectonics

after Jolivet, L., and Faccenna, C., 2000, Mediterranean extension and the Africa-Eurasia collision: Tectonics, 19, 1095–1106.

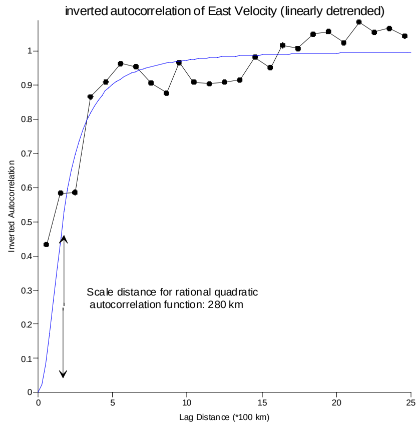


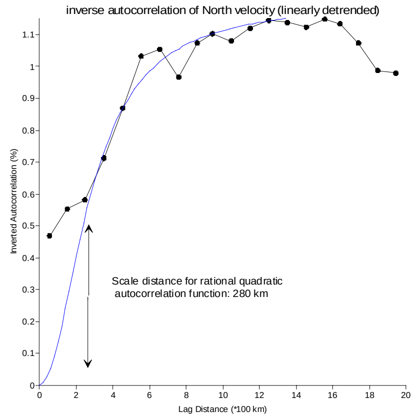
Interpolation of velocity vectors with least squares collocation, a minimum variance algorithm

- Variogram analysis: length of decorrelation d_0 =290 km (correlation drop of 50%)
- Isotropic correlation function defined consistently:

$$C_{ij}(d) = \frac{C_{ij}(0)}{1+\left(d/d_0\right)^2} \qquad i,j = e(ast), n(orth);$$

$$C(d) = \begin{bmatrix} C_{nn} & C_{en} \\ C_{en} & C_{ee} \end{bmatrix}$$





$$\begin{bmatrix} v_n \\ v_e \end{bmatrix}_{grid-node} = \sum_s C(d_{grid-node,s}) \sum_{s'} C^{-1}(d_{s,s'}) \begin{bmatrix} v_n \\ v_e \end{bmatrix}_{s'} \qquad s, s' = station \quad indeces$$

$$\begin{bmatrix} \sigma_{nn} \\ \sigma_{ee} \end{bmatrix}_{grid-node} = \left\{ \left[\sum_s C(d_{grid-node,s}) \sum_{s'} C^{-1}(d_{s,s'}) \right]^T E^{-1}{}_{s's'} \left[\sum_s C(d_{grid-node,s}) \sum_{s'} C^{-1}(d_{s,s'}) \right] \right\}^{-1}$$

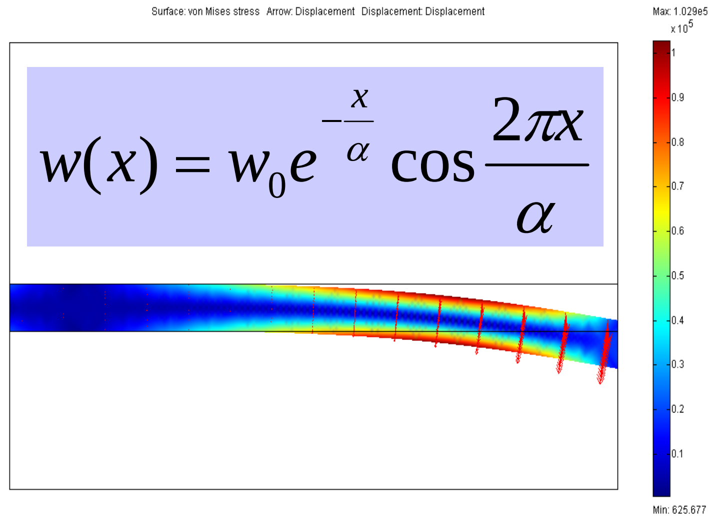
- E is a diagonal matrix with elements equal to the variance of each velocity component, e.g. in the sense of Allan variance.

Why 290 km? Possible interpretation using an isostatic flexural model of an elastic plate

$$D\frac{d^4 w}{dx^4} + (\rho_m - \rho_c) g w = 0$$

$$D = \frac{Eh^3}{12(1-\nu^2)} \qquad \alpha = \left[\frac{4D}{(\rho_m - \rho_c) g}\right]^{1/4}$$

$$w(x) = w_0 e^{-\frac{x}{\alpha}} \cos\frac{2\pi x}{\alpha}$$



- If E=70 Gpa, ν=0.25, density contrast 600 kg/m^3 and plate thickness ~ 27 km, then the flexural parameter α ~ 290 km

From velocity to horizontal strain rate

Eigenvectors of the 2D strain rate tensor are computed at those permanent GPS sites such that there exist at least 4 other stations in the four quadrants within d_0 (= 290 km)

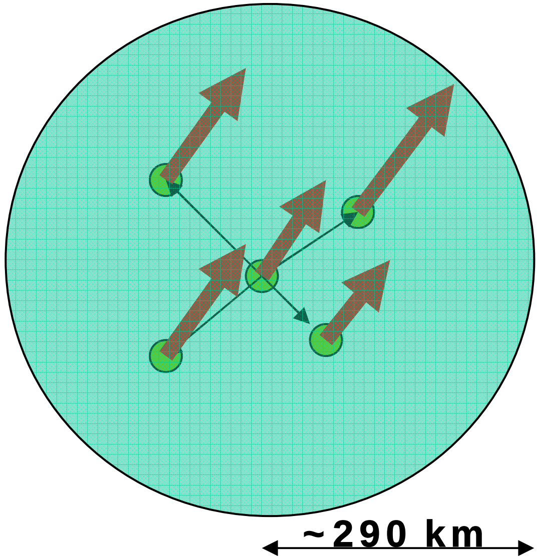
$$\begin{bmatrix} v_{n,n} & v_{n,e} \\ v_{e,n} & v_{e,e} \end{bmatrix}_P = \sum_s \begin{bmatrix} \frac{\partial C}{\partial n} & \frac{\partial C}{\partial e} \\ \frac{\partial C}{\partial n} & \frac{\partial C}{\partial e} \end{bmatrix}_{P,s} \sum_{s'} \left[C(d_{s,s'}) + W_{ss'}\right]^{-1} \cdot \begin{bmatrix} v_n \\ v_e \end{bmatrix}_{s'} \qquad s, s' = station \quad indeces$$

$$\varepsilon_1 = \frac{v_{n,n} + v_{e,e}}{2} + \sqrt{\left(\frac{v_{e,e} - v_{n,n}}{2}\right)^2 + \left(\frac{v_{e,n} + v_{n,e}}{2}\right)^2}$$

$$\varepsilon_2 = \frac{v_{n,n} + v_{e,e}}{2} - \sqrt{\left(\frac{v_{e,e} - v_{n,n}}{2}\right)^2 + \left(\frac{v_{e,n} + v_{n,e}}{2}\right)^2}$$

$$\sin 2\theta = \frac{v_{e,n} + v_{n,e}}{\varepsilon_2 - \varepsilon_1}; \cos 2\theta = \frac{v_{e,e} - v_{n,n}}{\varepsilon_1 - \varepsilon_2}$$

- Link to strain rate map for North Center Italy (EUR+UPA+GP_ combination)
- Link to strain rate for Center South Italy (data base of E. Serpelloni)
- Comparison of the two velocity data base



Estimating a formal strain rate uncertainty

Step 1: Mapping by collocation the velocity uncertainties into strain rate uncertainties, expressed in geographical coordinates

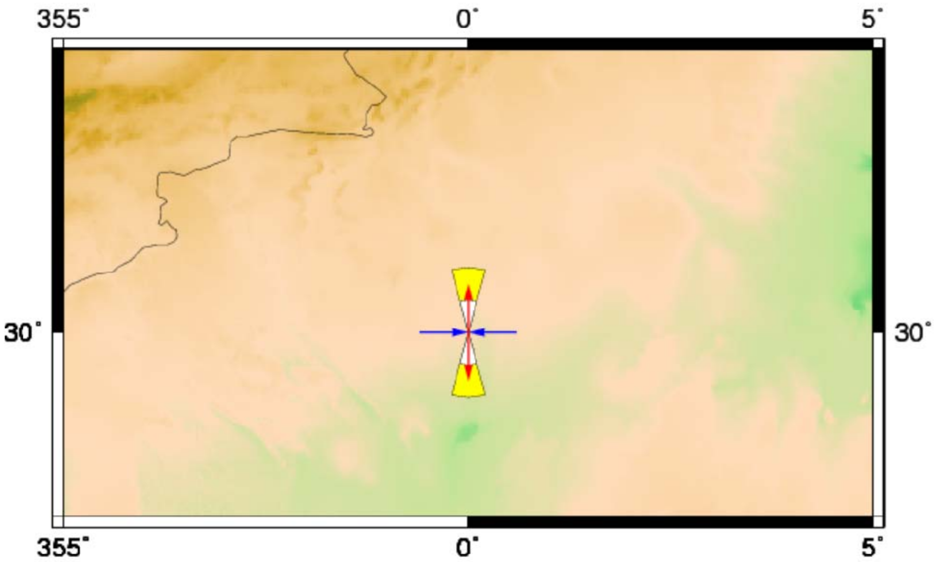
$$\begin{bmatrix} dv_{n,n} & dv_{n,e} \\ dv_{e,n} & dv_{e,e} \end{bmatrix}_P = \sum_s \begin{bmatrix} \frac{\partial C}{\partial n} & \frac{\partial C}{\partial e} \\ \frac{\partial C}{\partial n} & \frac{\partial C}{\partial e} \end{bmatrix}_{P,s} \sum_{s'} \left[C(d_{s,s'}) + W_{ss'}\right]^{-1} \cdot \begin{bmatrix} \sigma_n \\ \sigma_e \end{bmatrix}_{s'} \qquad s, s' = station \quad indeces$$

Step 2: Linear propagation of the strain rate uncertainty from geographical axes to principal axes:

$$\varepsilon_1 = \frac{v_{n,n} + v_{e,e}}{2} + \sqrt{\left(\frac{v_{e,e} - v_{n,n}}{2}\right)^2 + \left(\frac{v_{e,n} + v_{n,e}}{2}\right)^2}$$

$$\varepsilon_2 = \frac{v_{n,n} + v_{e,e}}{2} - \sqrt{\left(\frac{v_{e,e} - v_{n,n}}{2}\right)^2 + \left(\frac{v_{e,n} + v_{n,e}}{2}\right)^2}$$

$$\sin 2\theta = \frac{v_{e,n} + v_{n,e}}{\varepsilon_2 - \varepsilon_1}; \cos 2\theta = \frac{v_{e,e} - v_{n,n}}{\varepsilon_1 - \varepsilon_2}$$

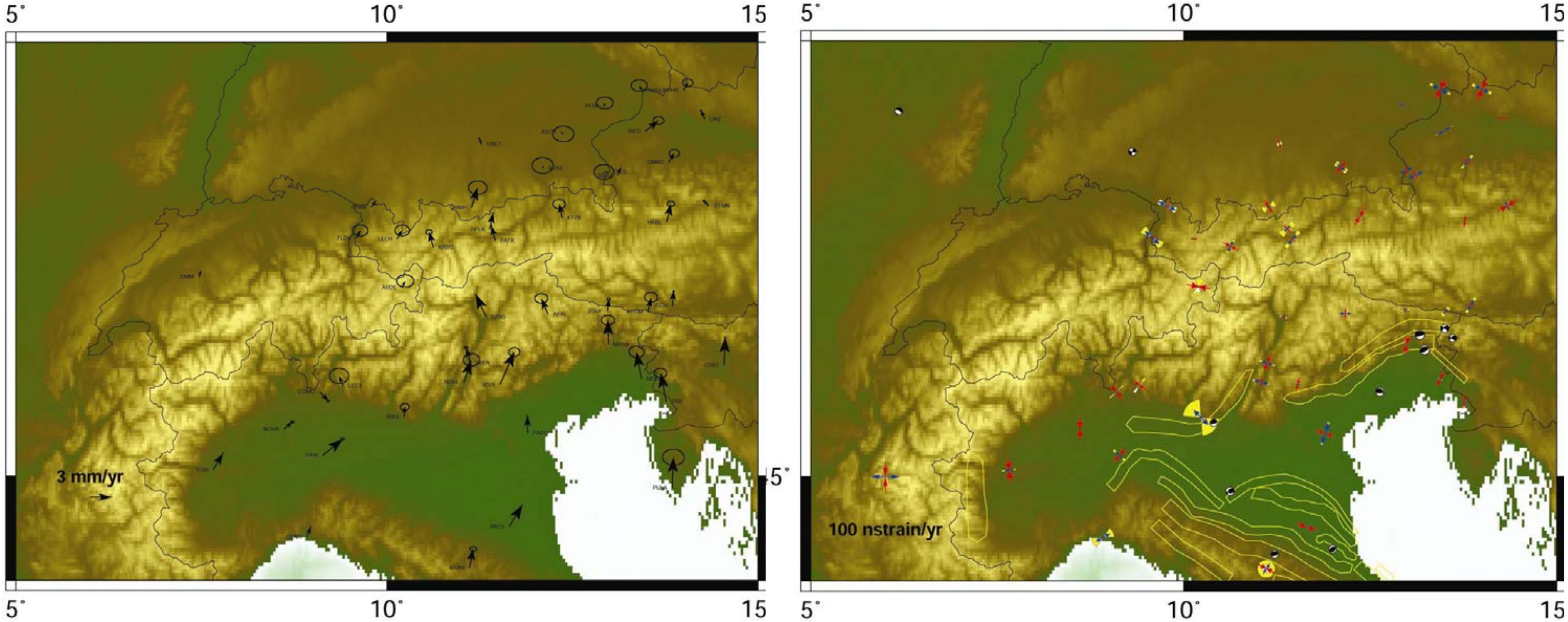


$$d\varepsilon_{1,2} = \frac{dv_{n,n} + dv_{e,e}}{2} \pm \frac{\frac{\left(v_{e,e} - v_{n,n}\right)\left(dv_{e,e} - dv_{n,n}\right)}{2} + 2\varepsilon_{e,n} d\varepsilon_{e,n}}{2\sqrt{\left(\frac{v_{e,e} - v_{n,n}}{2}\right)^2 + \left(\varepsilon_{e,n}\right)^2}}$$

$$d\theta = \cos^2 2\theta \left[\frac{d\varepsilon_{e,n}}{v_{e,e} - v_{n,n}}\right] - \frac{\varepsilon_{e,n}\left(dv_{e,e} - dv_{n,n}\right)}{\left(v_{e,e} - v_{n,n}\right)^2}$$

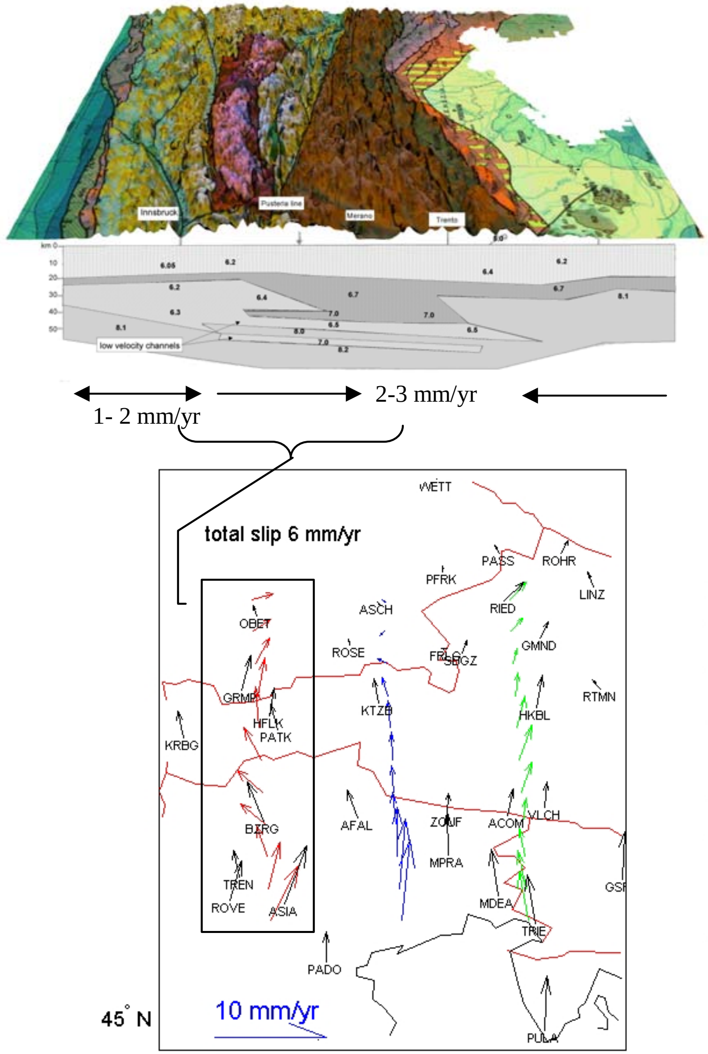
Velocity relative to NUVEL 1A NNR and strain rate at selected sites

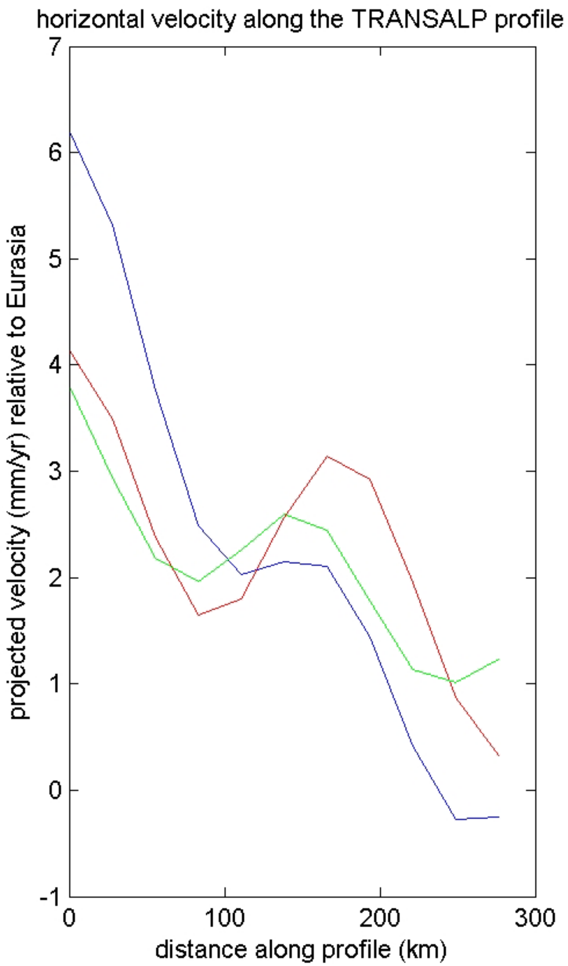
Alps



Error ellipses and strain rate uncertainties are at 3 σ; CMT's from Harvard Catalog; Seismogenic zones from DISS 3.0

Slip Profiles in the Eastern Alps

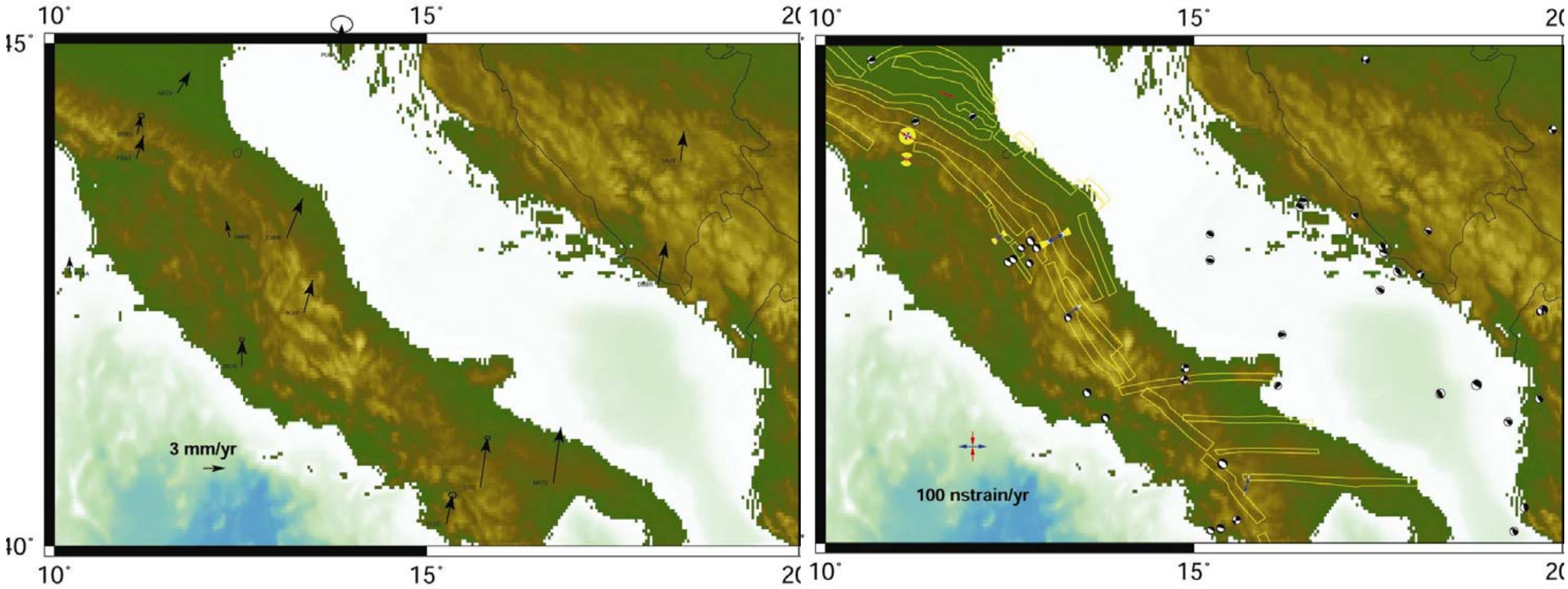




- Velocities are interpolated to a profile (left) and their projection onto the profile is plotted against space (right)
- A shortening of up to ~ 6 mm/yr is implied across the 300 km profile, or 20 nstrain/year. Locally can be higher, to ~ 40 nstrain /yr
- Divergent pattern in parallel profiles across the Tauern window may imply a squeezing and hence lateral extrusion

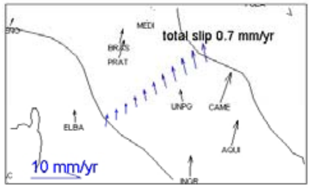
Velocity relative to NUVEL 1A NNR and strain rate at selected sites

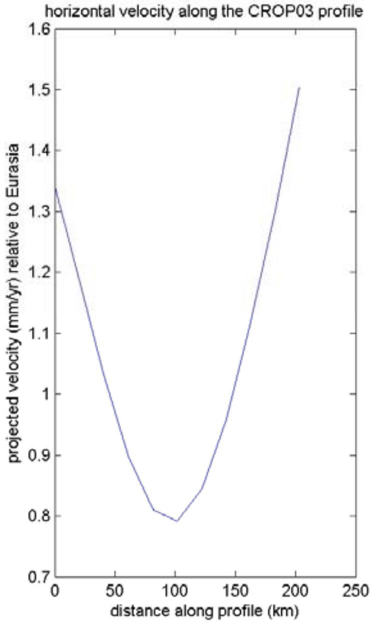
Apennines

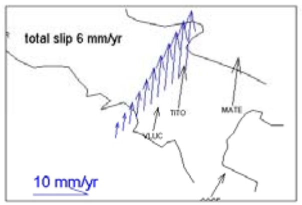


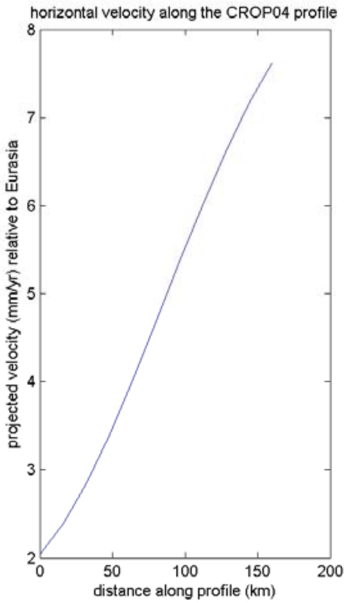
Error ellipses and strain rate uncertainties are at 3 σ; CMT's from Harvard Catalog; Seismogenic zones from DISS 3.0

Slip Profiles in the Apennines









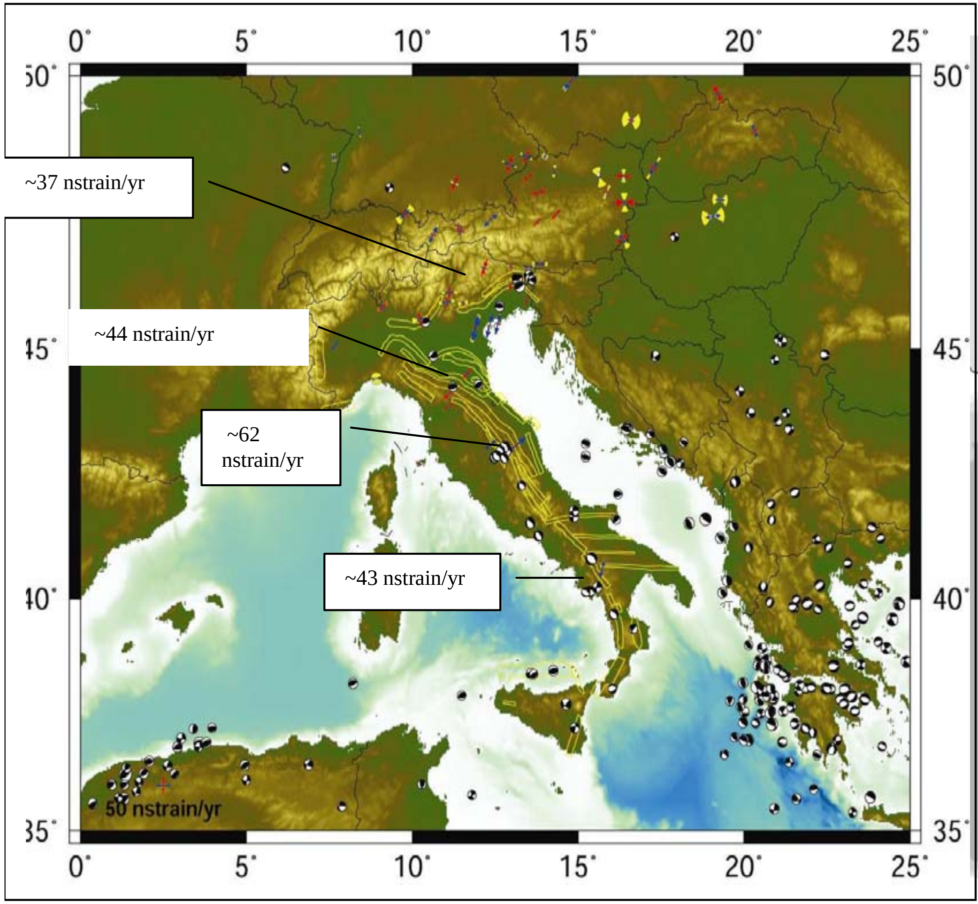
Velocities are interpolated to a profile (left) and their projection onto the profile is plotted against space (right)

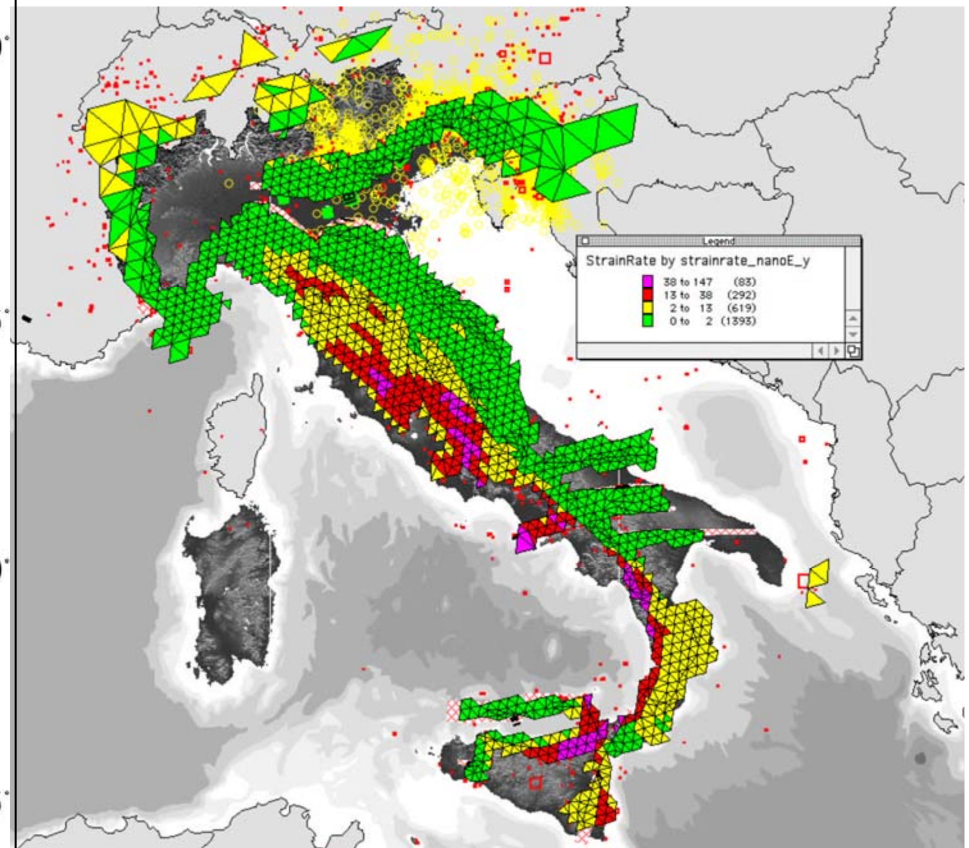
A streching of ~ 0.7 mm/yr is implied across the East150 km profile, or 5 nstrain/year. (CROP03)

A streching of ~ 6 mm/yr is implied across the 150 km profile, or 53 nstrain/year. (CROP04)

Hence deformation rate is ~ an order of magnitude larger in the Irpinia area than in Umbria

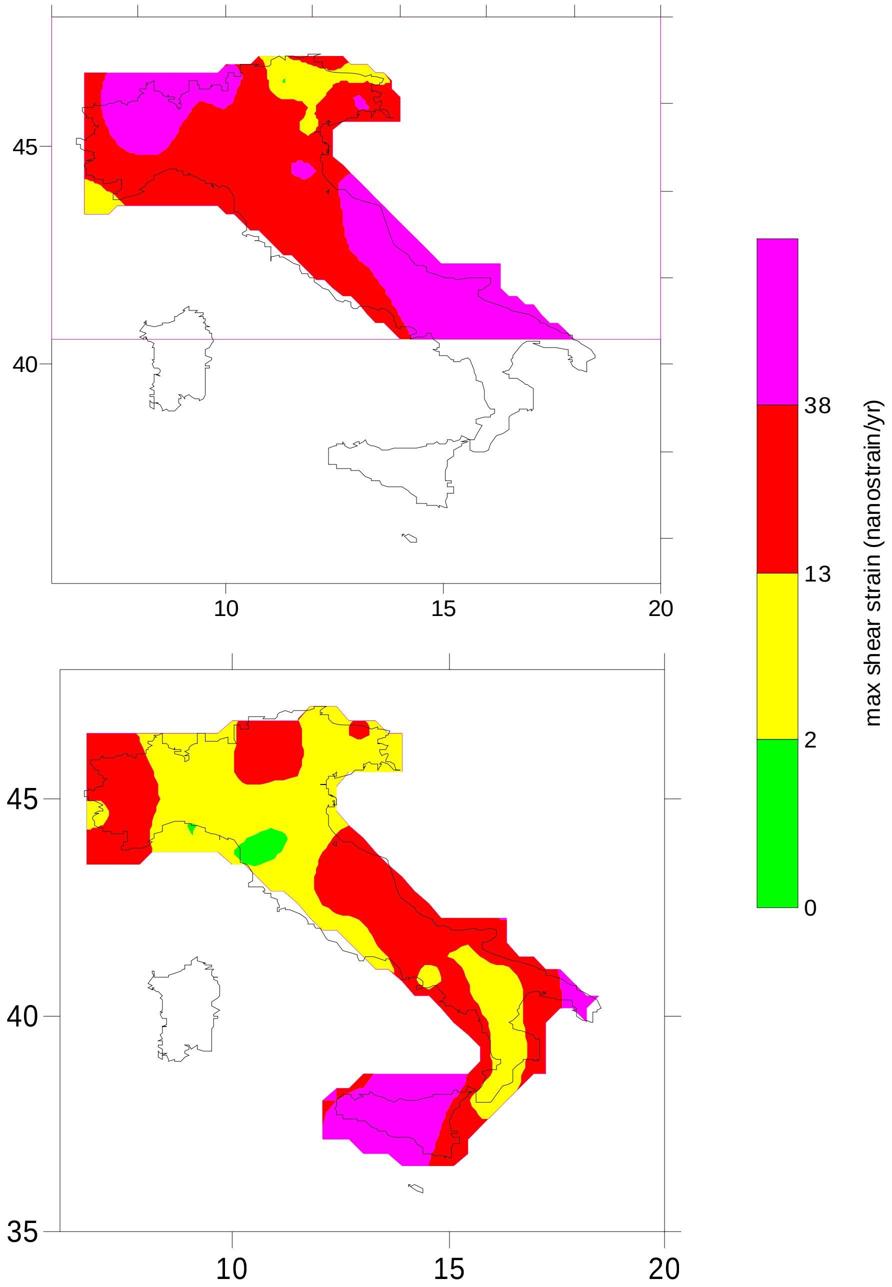
Strain rate from geodetic data and numerical modeling (Barba and Basili, private communication, May 2006)

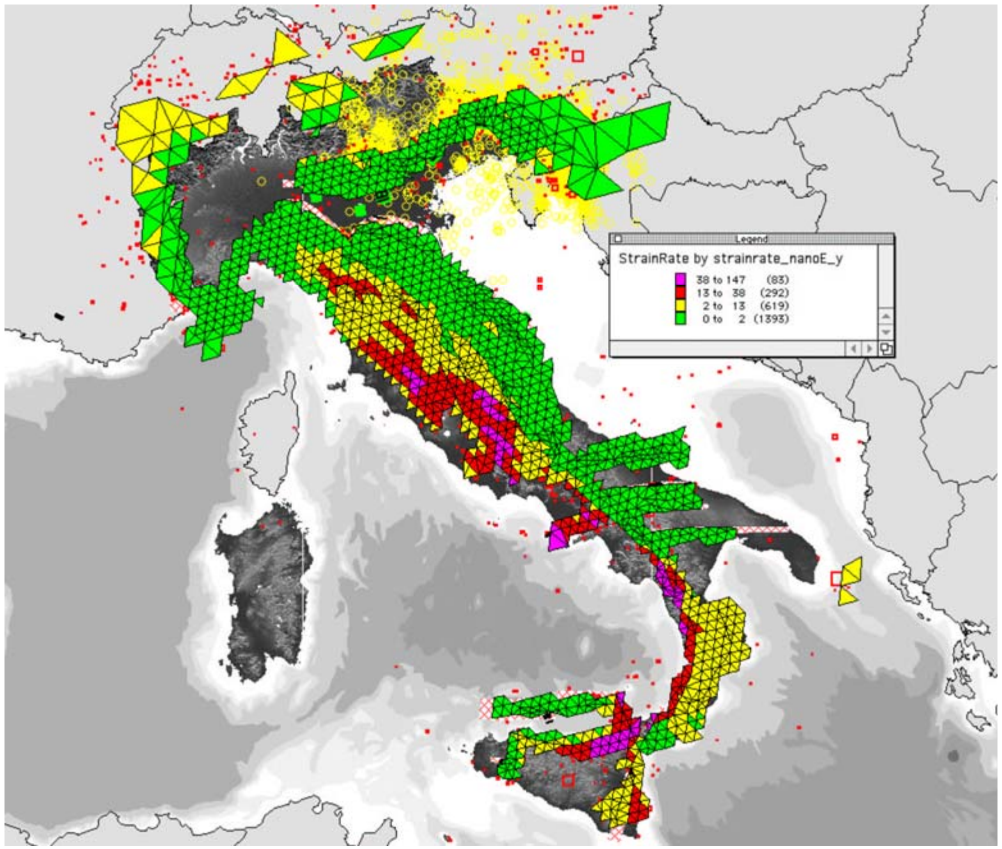




Numerically modeled vs. geodetic shear strain: different data bases

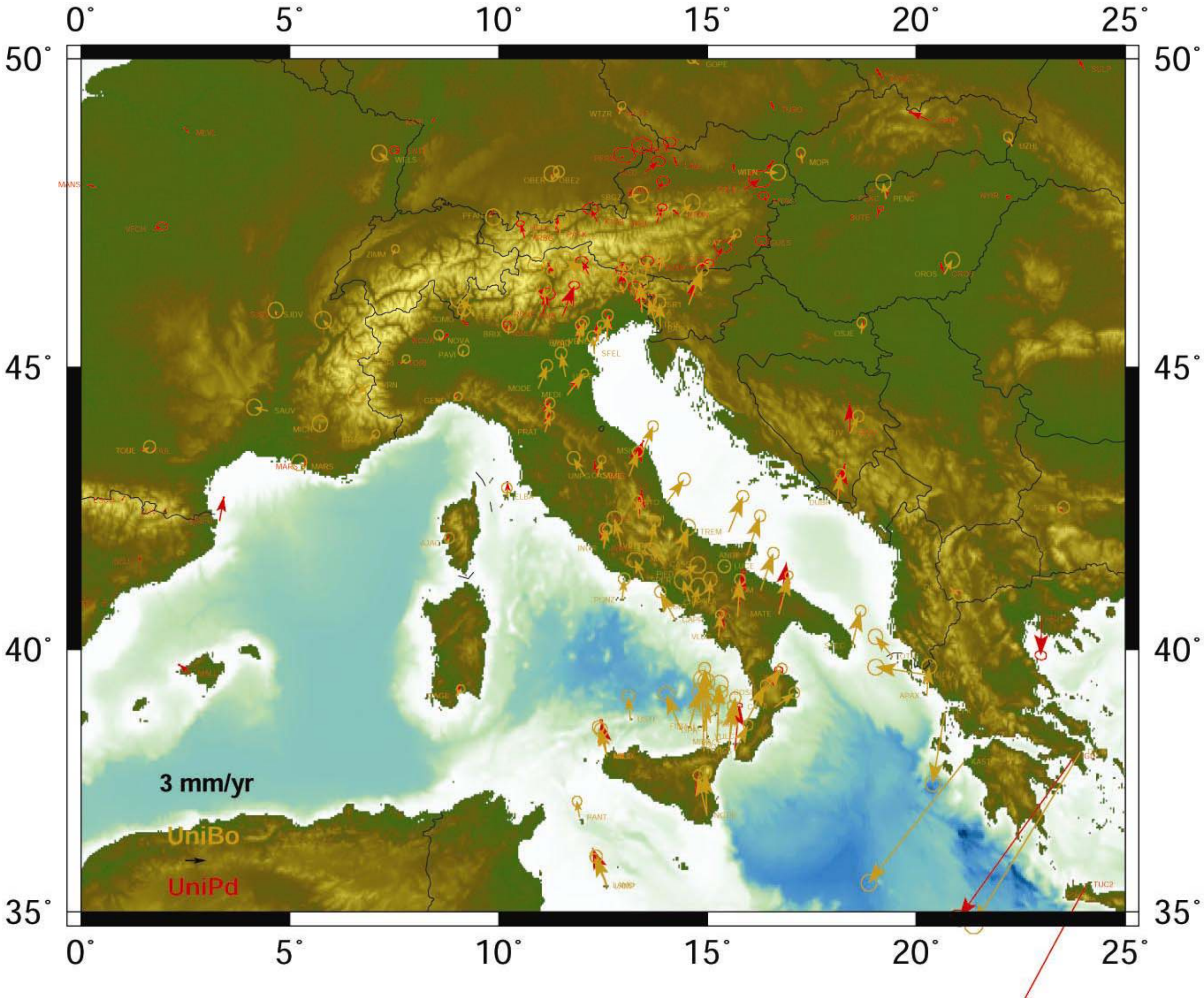
‘Permanent only’ data base (top left) gives systematically higher strain rates than the ‘permanent & campaign’ data base (lower left) ; geodetic data sets predict higher rates than the numerical model





Additional analysis with an independent velocity set

(Serpelloni, private communication Jan. 2006)

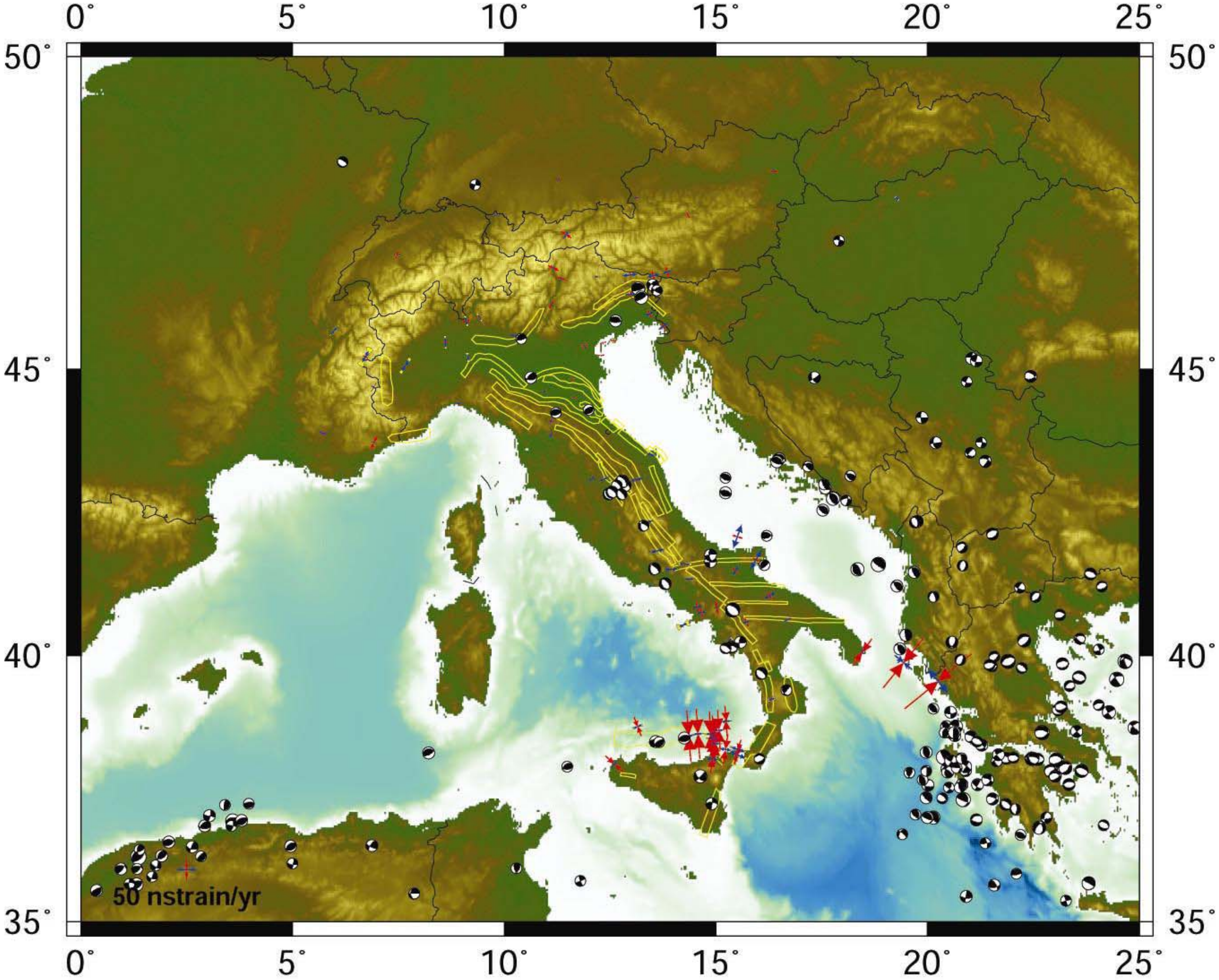


A posteriori validation of the velocities (brown), after removal of a rigid rotation, against EPN velocities (red) at common sites

No scale or orientation systematics result to be statistically significant, to within a fraction of mm/yr

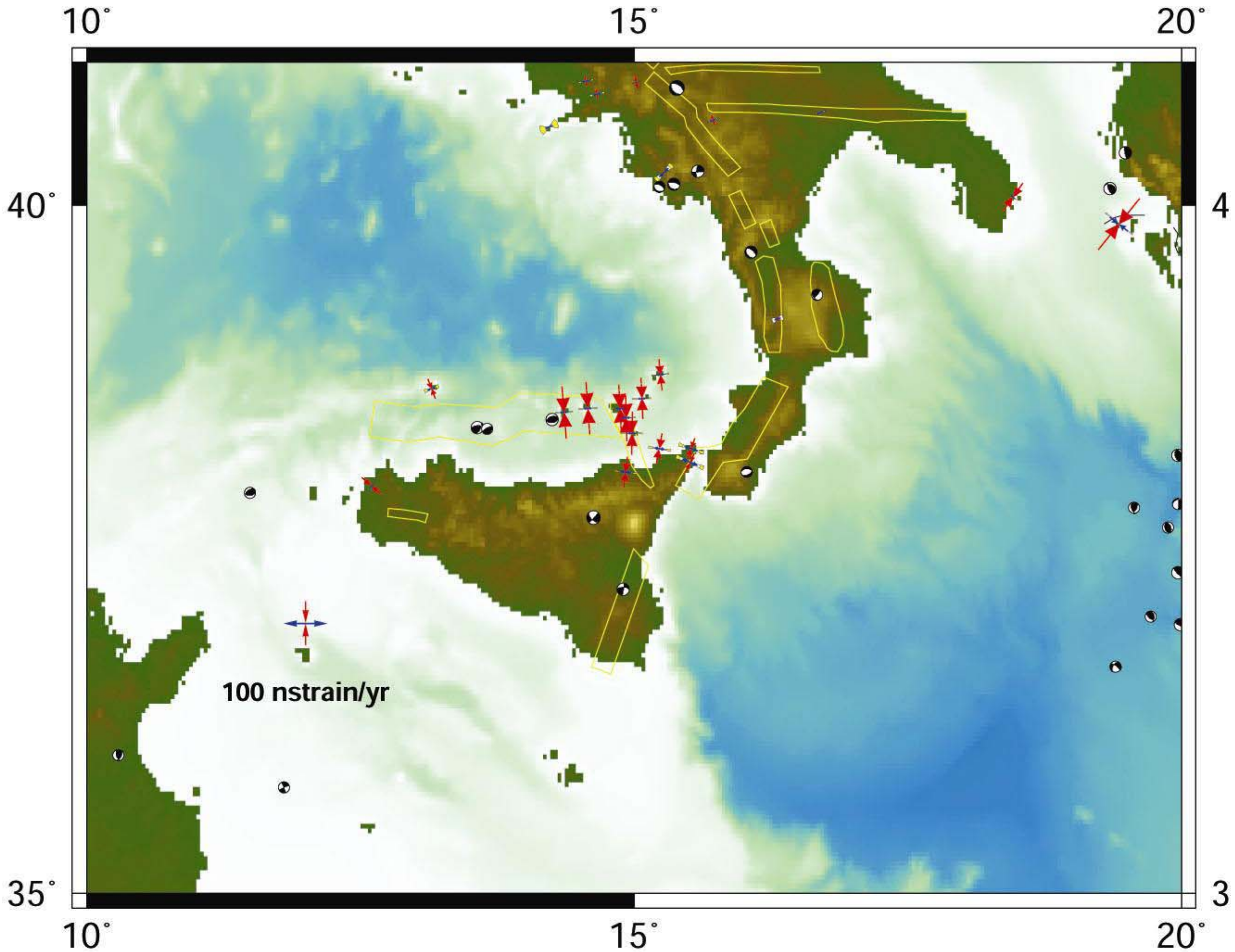
Data set is particularly dense in the Southern Apennines and Sicily

Implied strain rate field computed with the same algorithm as before



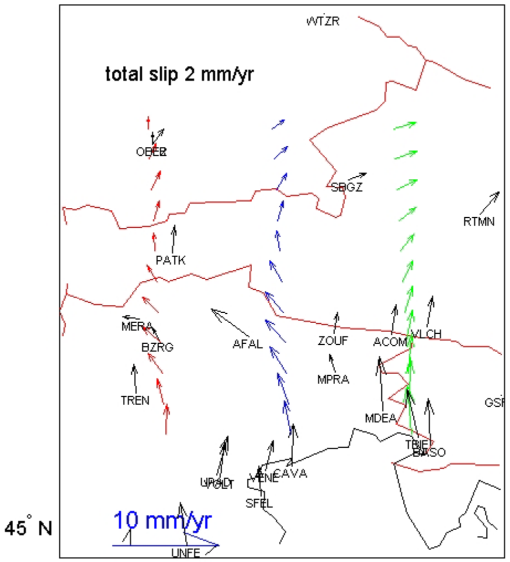
- High strain rates in northern Sicily and Kefalonia
- Excellent agreement with CMT’s as to style of tectonic deformation

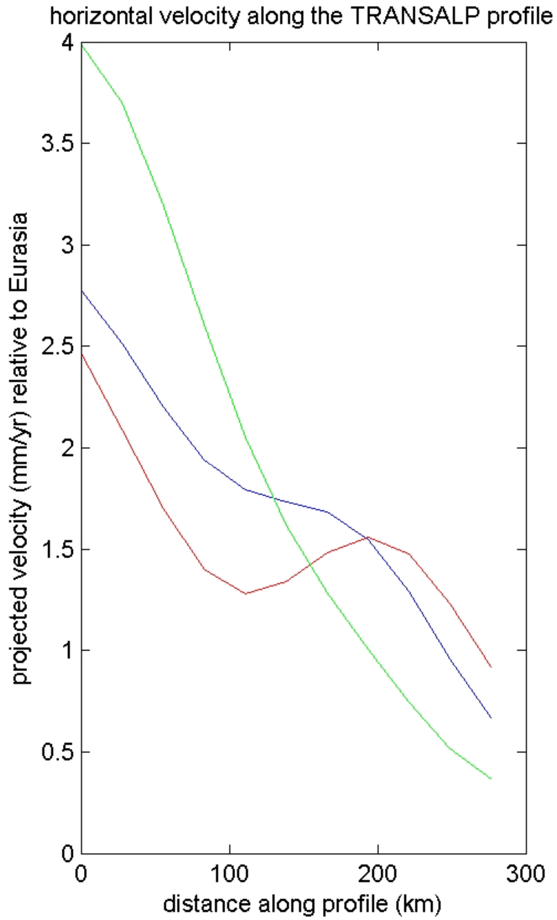
Strain rate in Northern Sicily



- Relatively high (>100 nstrain/yr) result from the Sicilian stations
- Perfect agreement of deformation style with CMT's

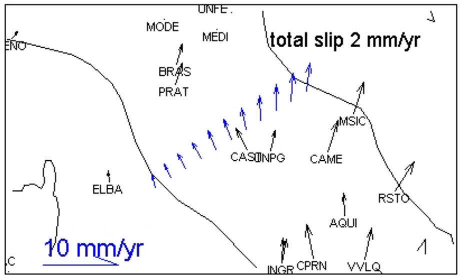
Eastern Alps

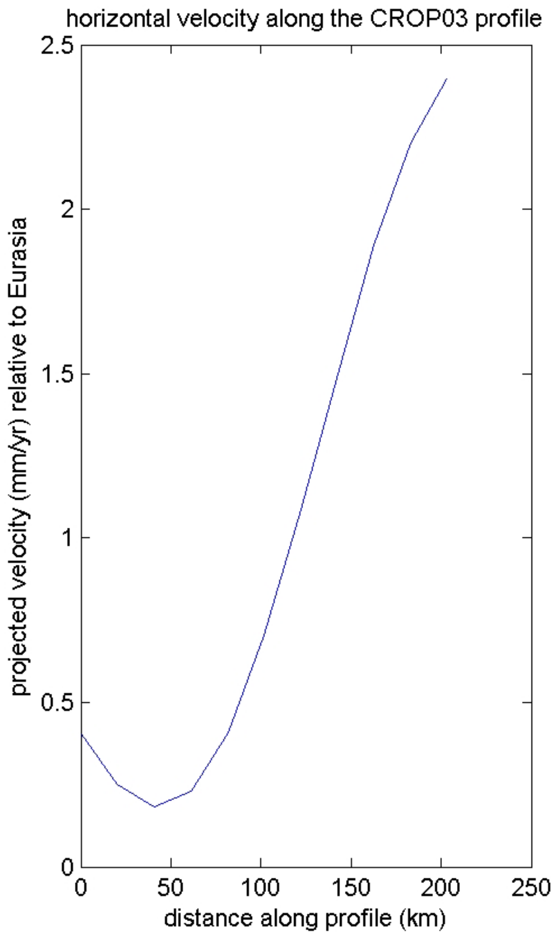




- Small number of Austrian stations
- Slip rate is 2 mm/yr, or 33% the value with the permanent stations only
- Estimated slip agrees with D'Agostino et al. (2005)
- Probably more interesting are Central and SouthernApennines

CROP 03



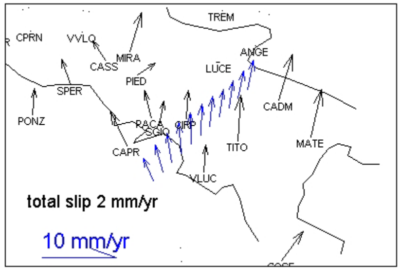


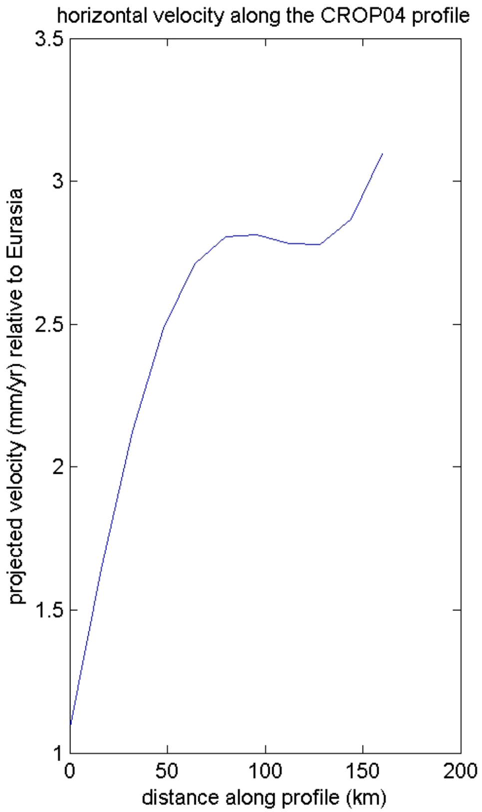
Relative to the 'permanent only' velocity set:

- Larger number of stations to the south
- Larger slip rate and strain rate (~ a factor of 2)

However the strain rate is in both cases small in this profile

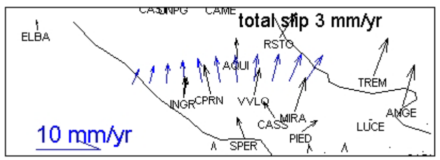
CROP 04

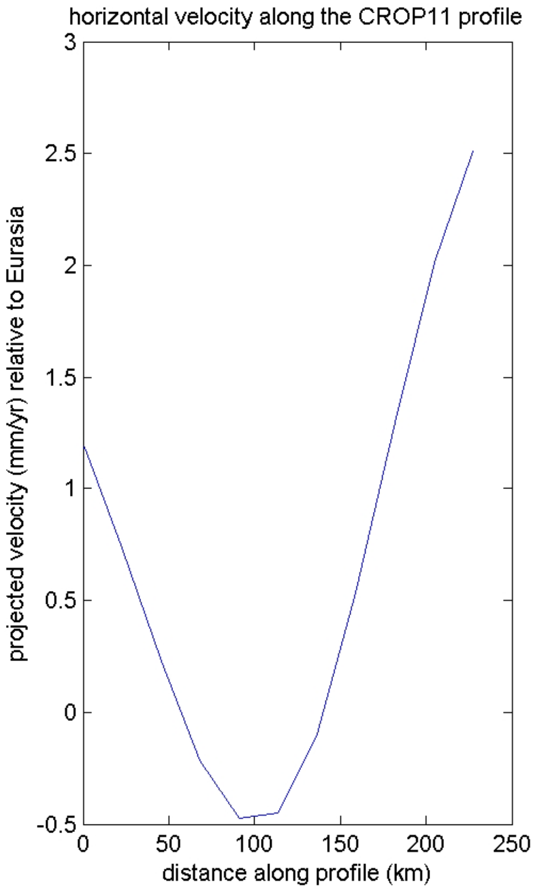




- This profile is better constrained by this data set than by the 'perm only' data set
- Extension is ~ 1.8 mm/yr in the first 100 km, implying ~ 20 nstrain/yr
- This is again ~30% the value observed with the 'perm only' data set

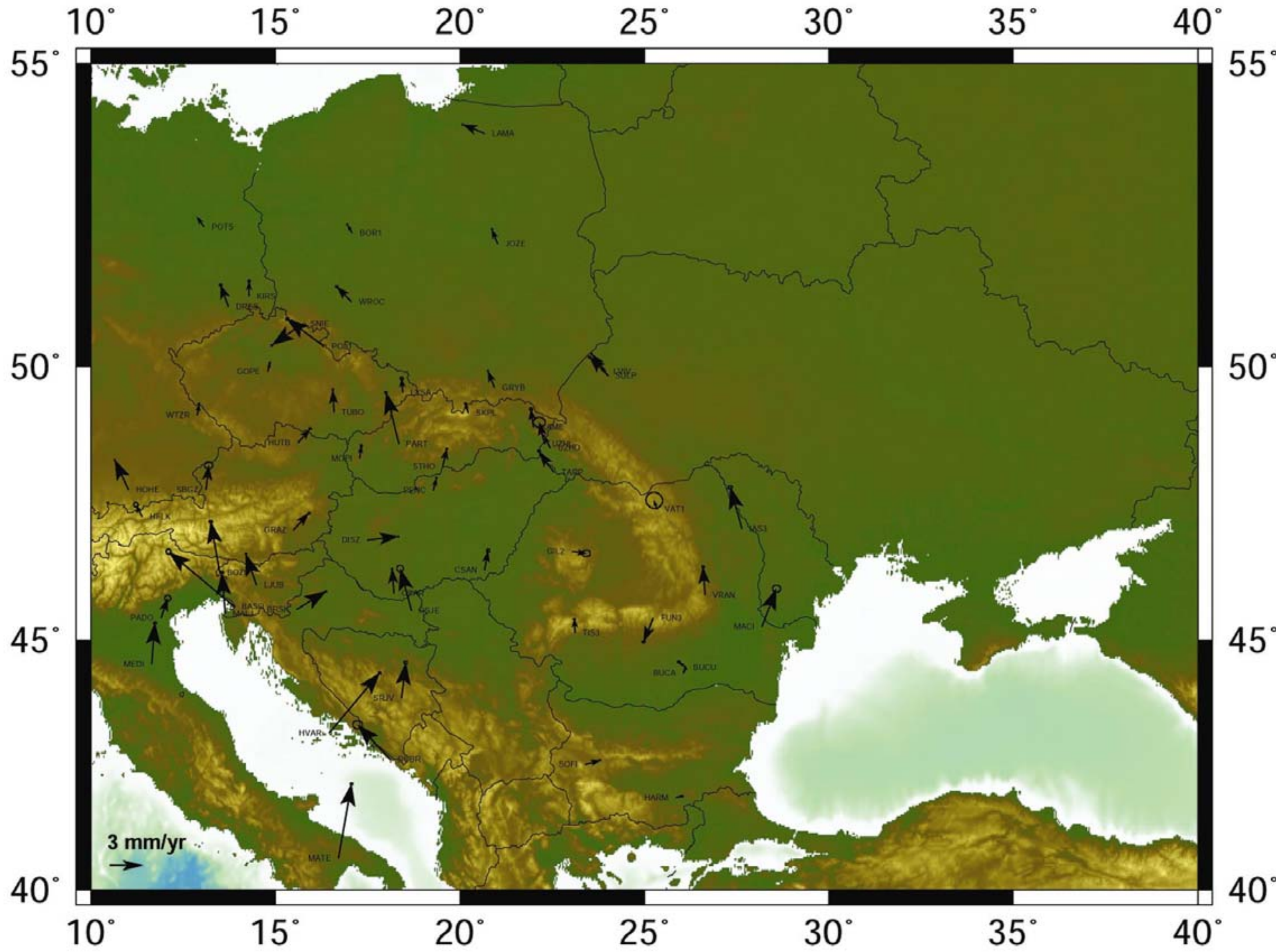
CROP 11





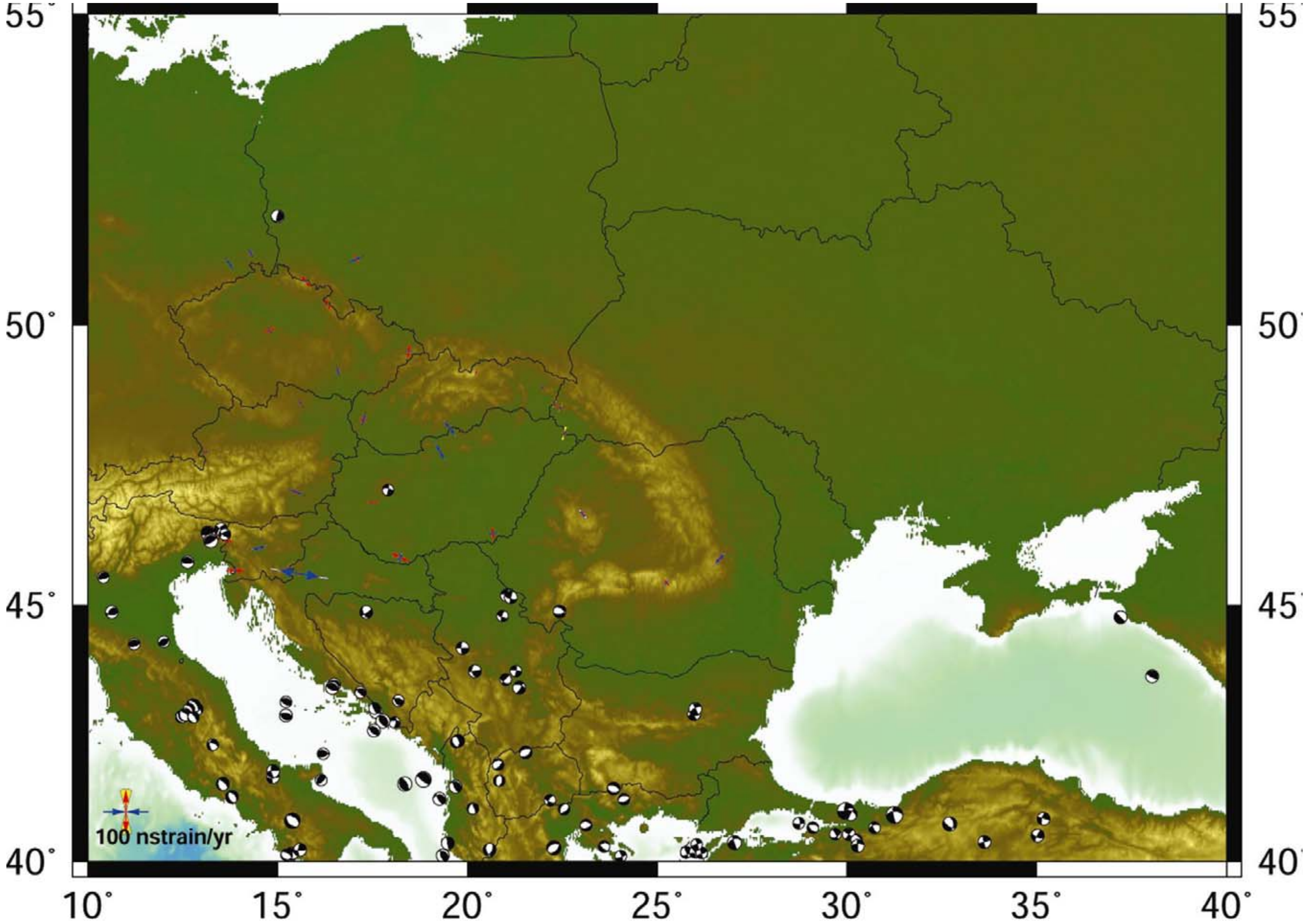
This is another well constrained profile in the Central Apennines

Strain rate is ~23 nstrain /yr concentrated in the Eastern part of the profile



Velocity in Central Europe (CERGOP data set)

Strain rate in Central Europe (CERGOP data set)



Conclusions

- We have presented a systematic analysis of time series of coordinates of permanent, high quality GPS stations belonging to the EPN and national networks, spanning up to 10 years
- Velocities have been computed rigorously by staking the normal equation of the merged networks. Rigorous noise analysis and estimate of velocity uncertainty. Statistical analysis of the ensemble of velocities yields a correlation length of 290 km
- Strain rates and interpolated velocities along seismic profiles have been computed by least squares collocation
- We find slip rates of up to 6 mm/yr in the Eastern Alps (TRANSALP) and Southern Apennines (CROP04) with strain rates of the order of 40-50 nstrain /yr. An independent data set by Serpelloni, with more stations but including velocities from campaigns, yields consistently smaller slip and strain rates by a factor of 2 to 3.
- The Italian region subject to the largest deformation appears, on the basis of one data set only, to be the northern coast of Sicily with strain rates exceeding 100 nstrain/yr
- Data in Central Europe are very sparse. Strain rate appears to be very small wherever it can be computed with the chosen reliability standards