Adding geodetic strain rate data to a seismogenic context: Theory and application

Alessandro Caporali, Università di Padova
EUREF Symposium 2005

Summary

- International context for monitoring present day velocities and strain rate: IGS, EUREF, GPSVEL, Global Strain Rate Map Project of the International Lithospheric Project
- Focus on the Alpine Mediterranean seismic area: permanent GPS stations, processing, combination with EUREF/IGS, alignement to ITRF
- From scattered velocities of permanent GPS stations, to a velocity field and strain rate
- Implications:
  - strain rate accumulation vs strain rate release in seismic areas: seismic efficency (not discussed here: see Caporali et al., GJI 2003)
  - How strain rate on the surface constrains stress at depth: a simple slider block model (new!)
- Conclusions

GPSvel, ILP e GSRM:

Kreemer, C., W.E. Holt, and A.J. Haines, A integrated global model of present-day plate motions and plate boundary deformation, *Geophys. J. Int.*, in press, 2003.

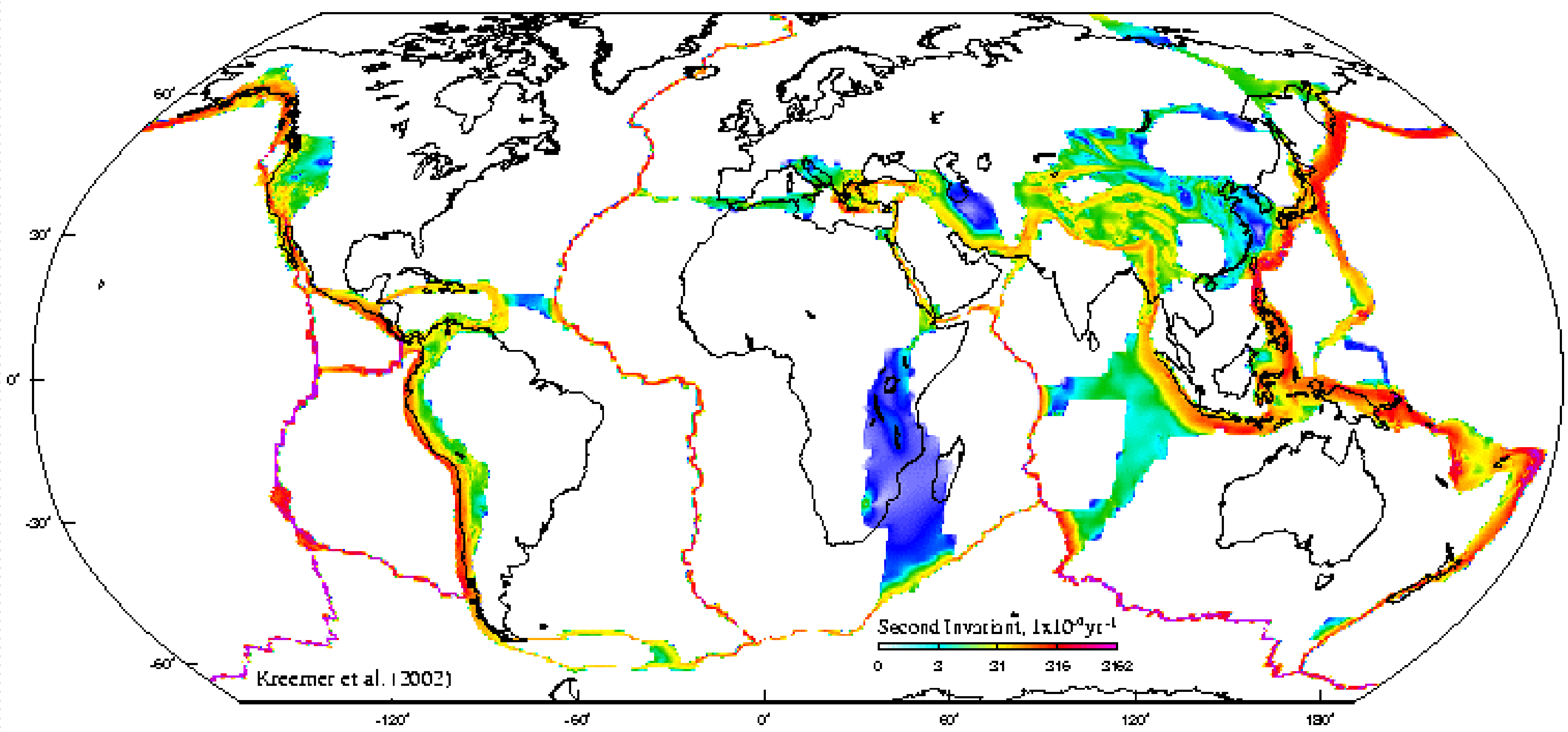
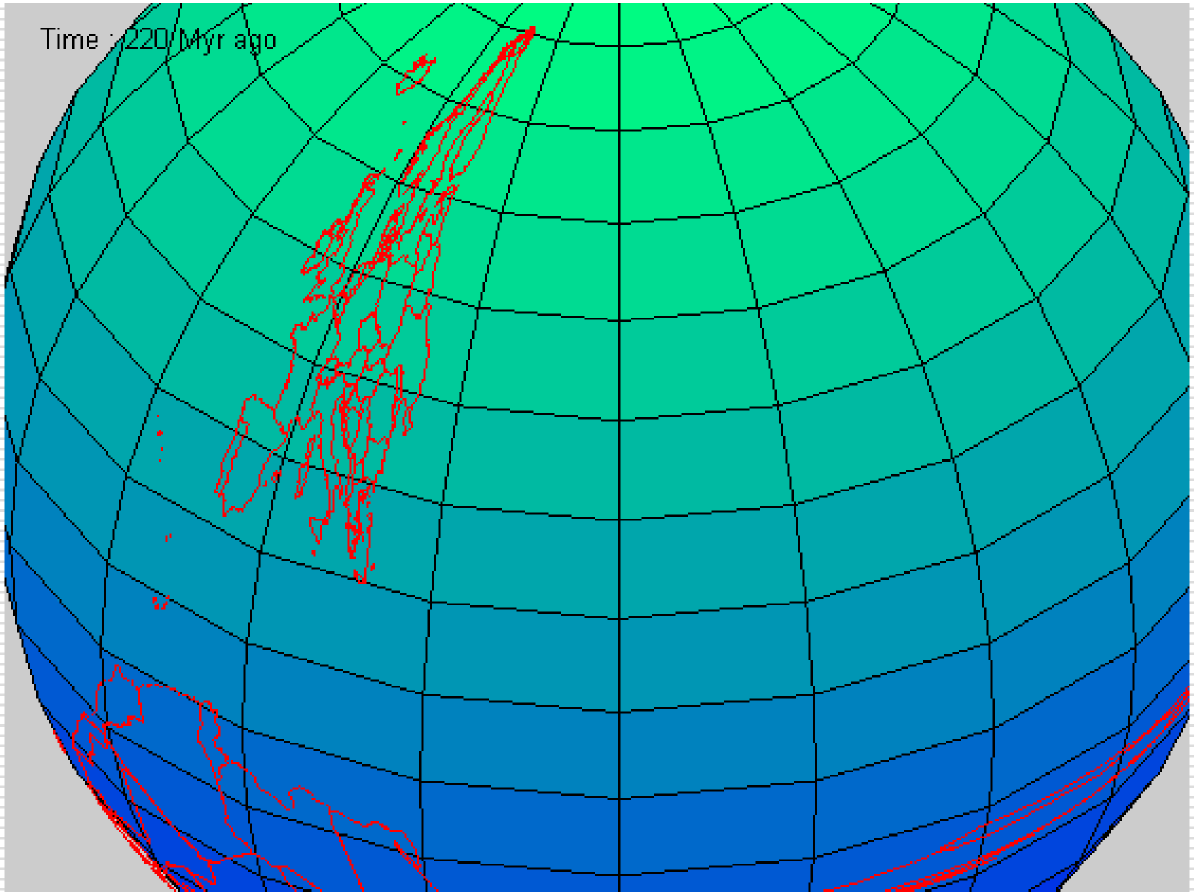
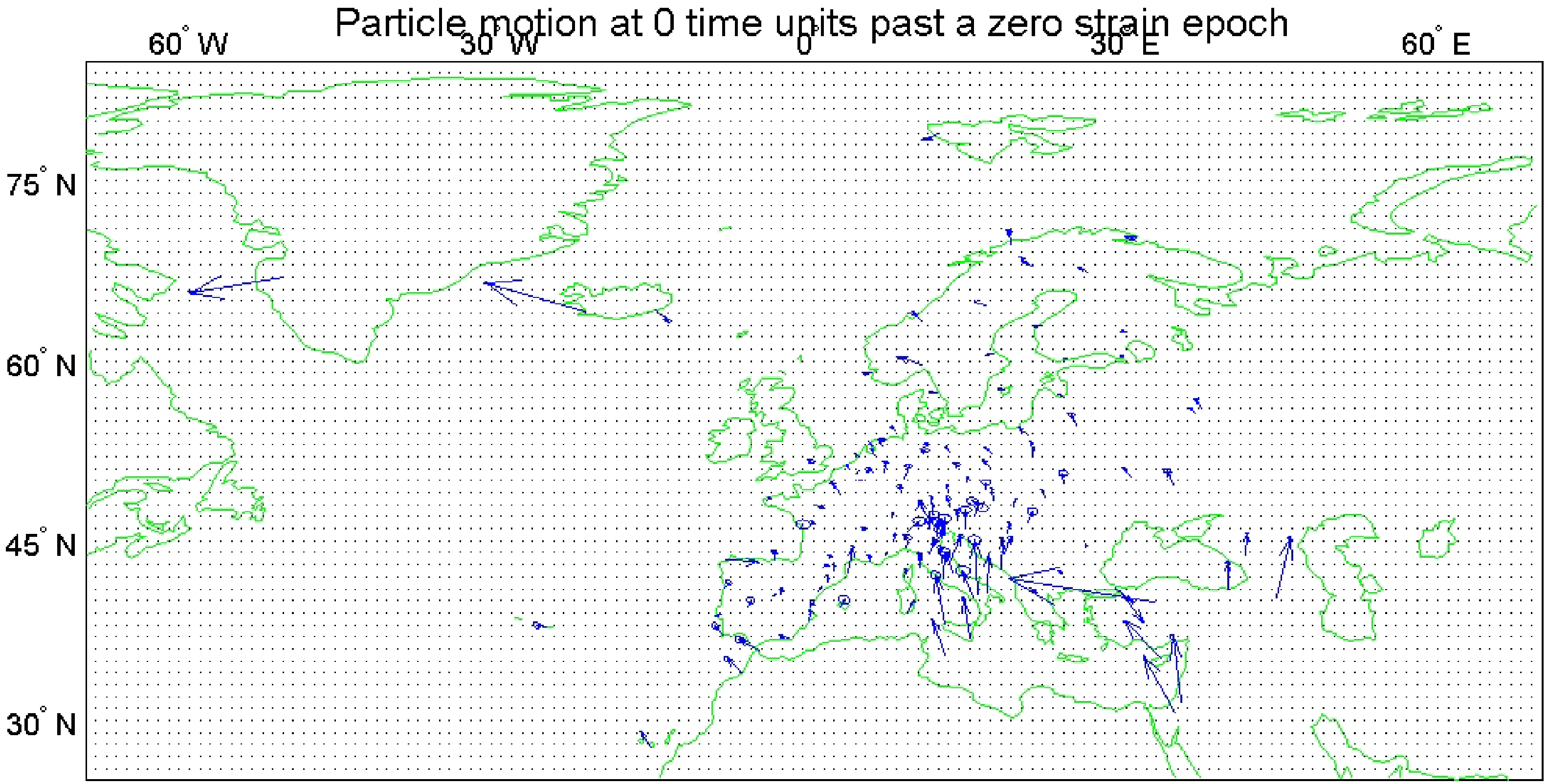


Plate kinematics in the Alpine Mediterranean area

- **Absolute horizontal velocities of the order of ~1-3 cm/yr**
- **Stations in Africa, Turkey, Europe, are differently affected because of different Eulerian poles**
- **Reference systems, e.g. ETRS89, attempt to model the displacements of strictly European stations in terms of a rigid transformation**
- **Residual velocities do exist, especially for non Eurasian stations**
- **Implications of residual velocities for strain and seismicity are potentially significant (geodetic networks, seismic risk..)**

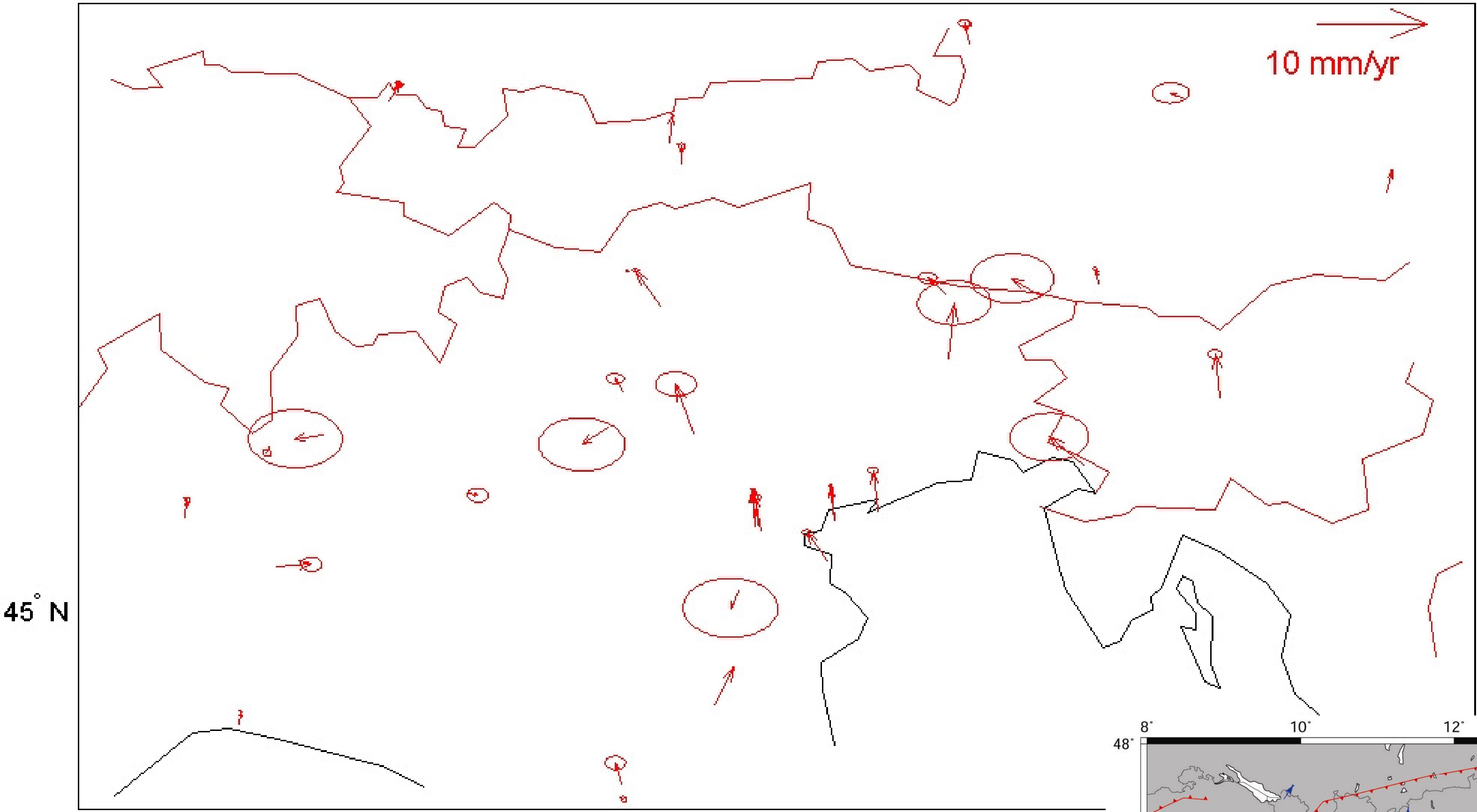


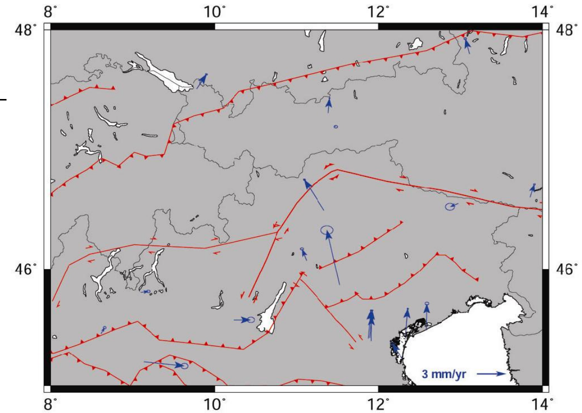
How a regular grid is strained by residual velocities relatively to a rigidly rotating Eurasia?



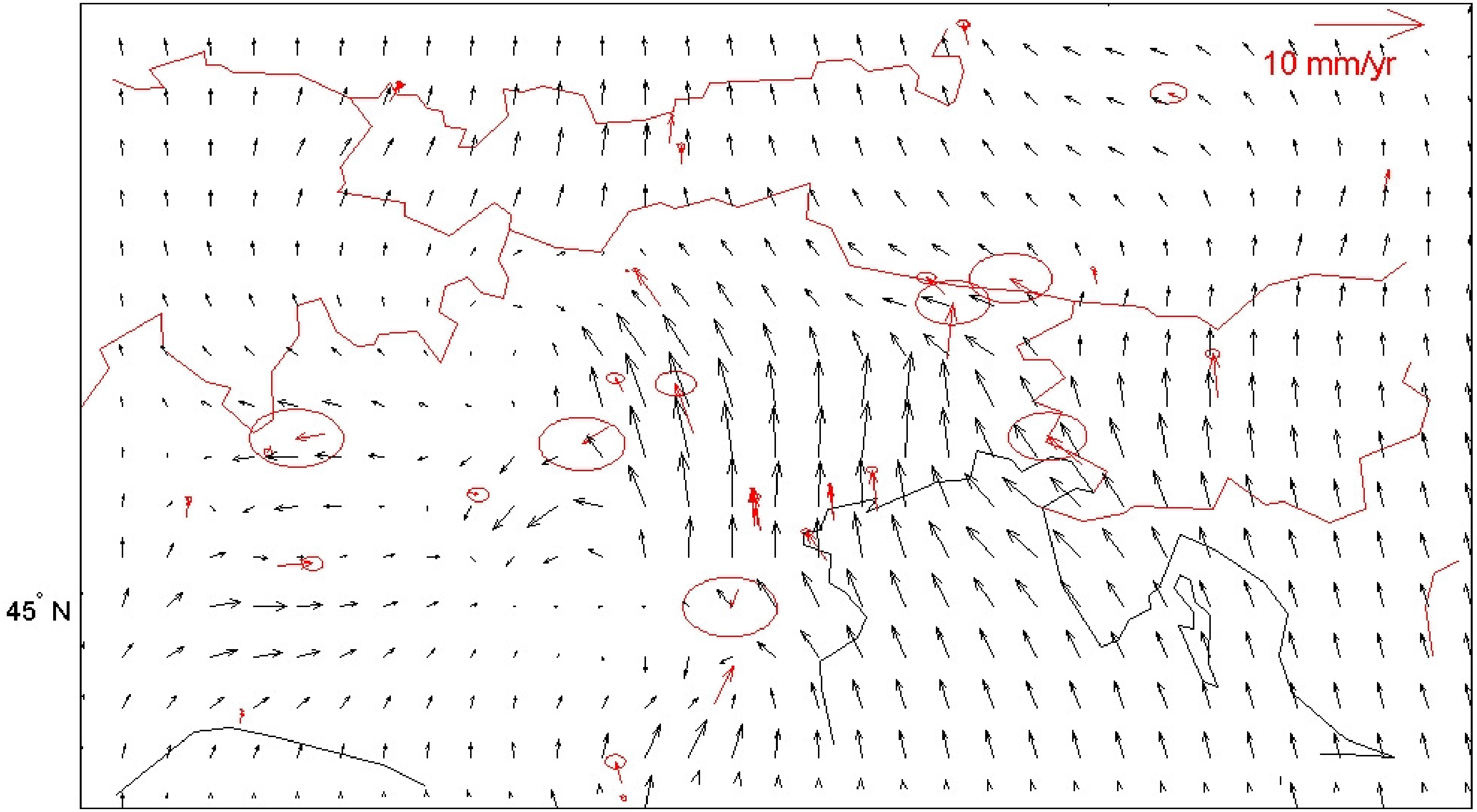
Velocities are interpolated to a regular grid and the coordinates of the nodes are time-propagated to realize the strain.

Focus on Adria plate, Eastern Alps: <u>Kinematics</u>

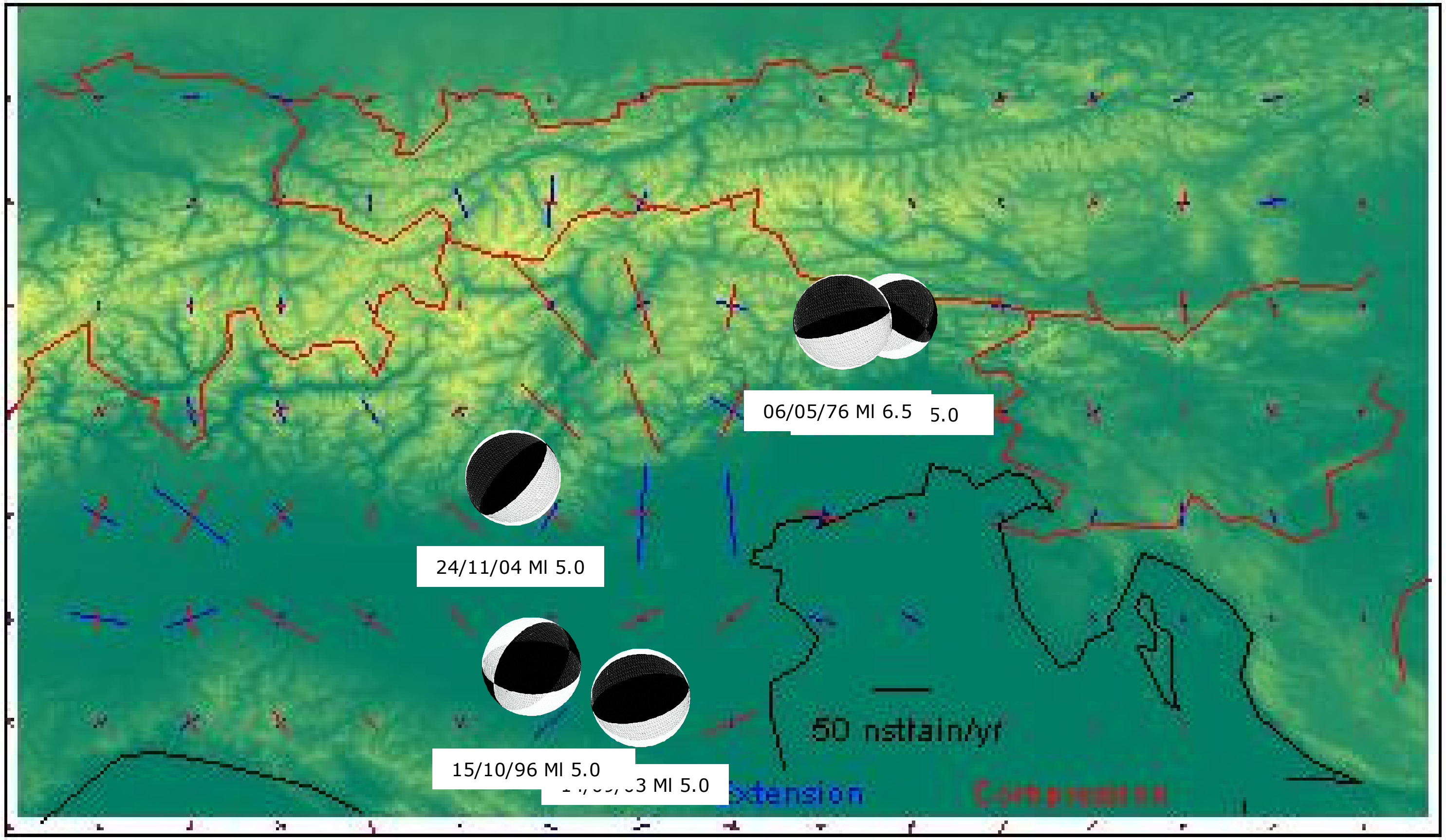




Focus on Adria plate, Eastern Alps: Velocity field

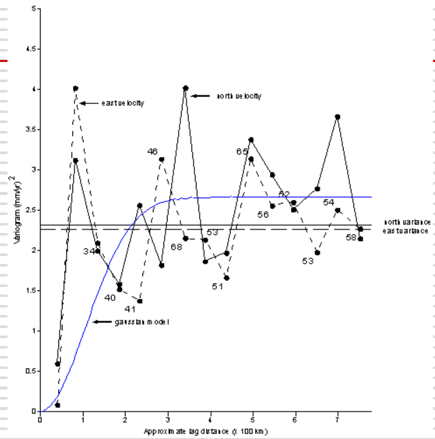


Focus on Adria plate, Eastern Alps: <u>strain rate eigenvectors vs. recent Centroid Moment Tensor solutions</u>



Interpolazione delle velocità mediante collocazione

- Velocità de-correlano a una distanza d_0 =350 km, come da variogramma →
- Funzione di correlazione isotropa:



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

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

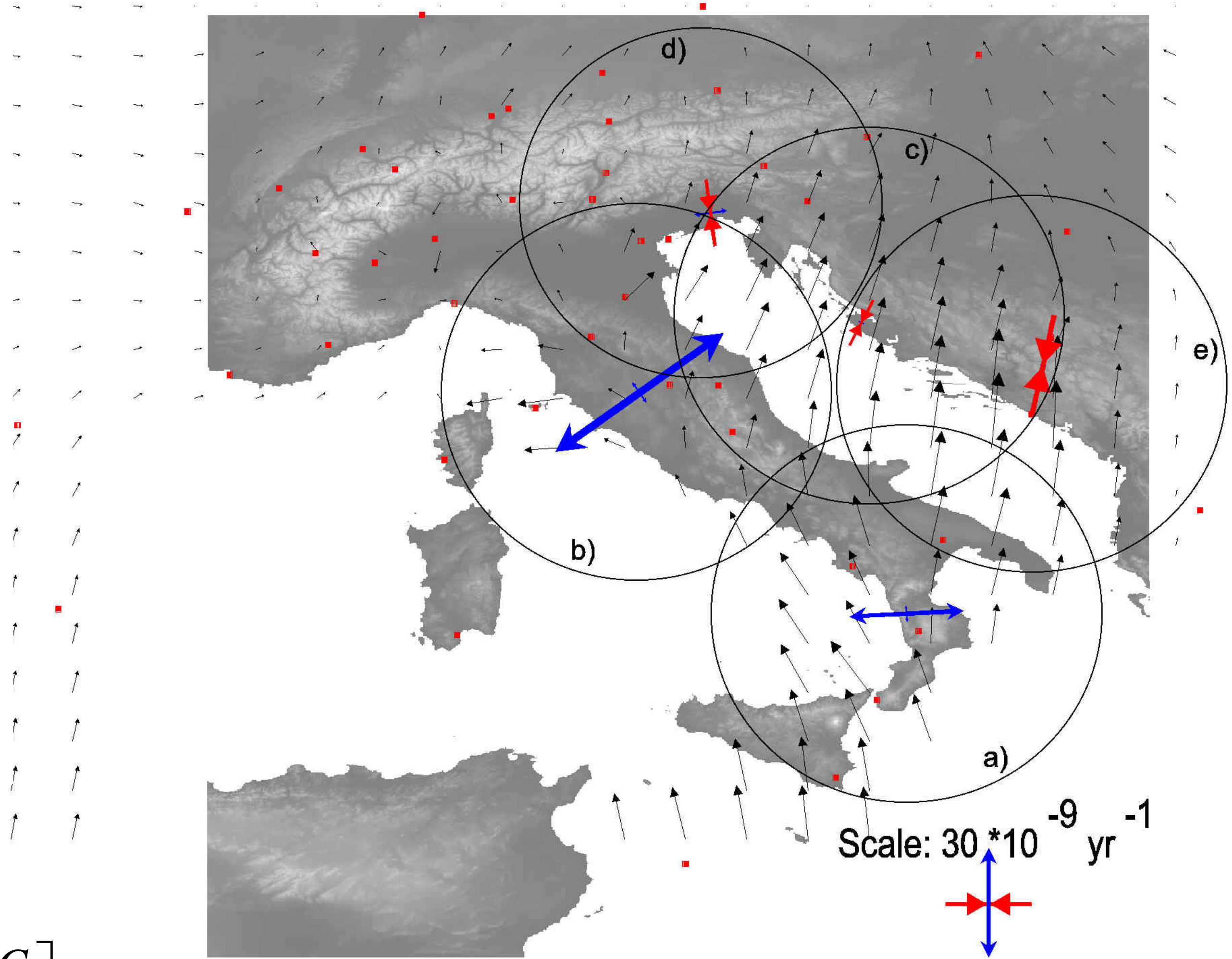
$$\begin{bmatrix} v_n \\ v_e \end{bmatrix}_{grid-node} = \sum_s C(d_{grid-node,s}) \sum_{s'} C^{-1}(d_{s,s'}) \begin{bmatrix} v_n \\ v_e \end{bmatrix}_{s'} \qquad s,s' = station \quad indeces$$

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

- E è una matrice diagonale i cui elementi sono le varianza di Allan delle velocità delle singole stazioni.

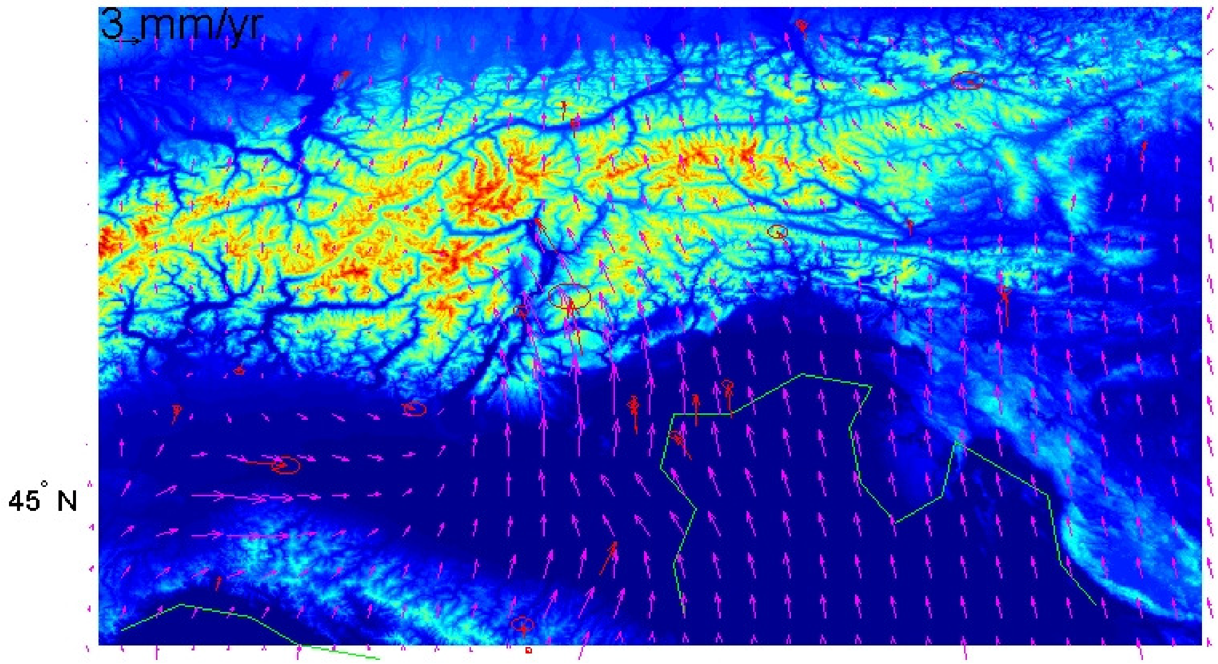
- Lo strain rate viene calcolato per collocazione in punti baricentrici ad aree con >4 stazioni GPS permanenti

- Autovalori e azimut delle direzioni principali



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

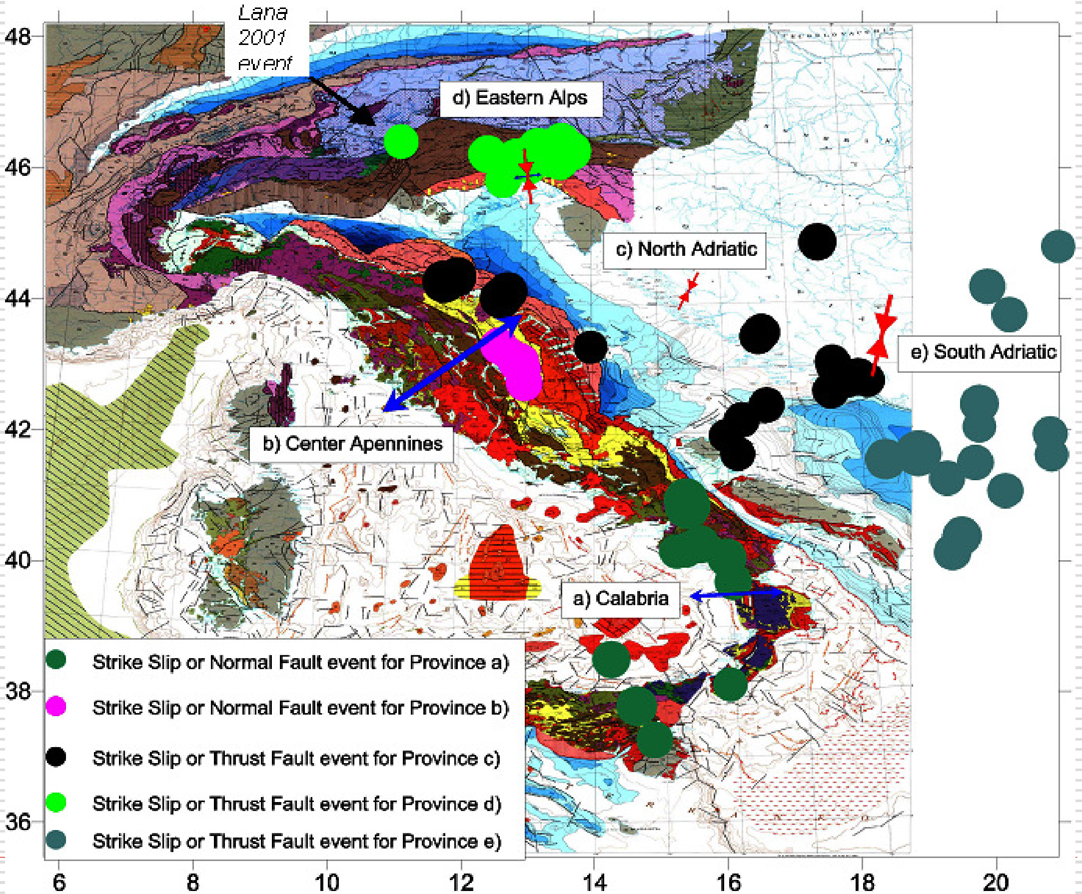
Ultima soluzione (Marzo 2005) per Nord Italia



Confronto strain rate geodetico/strain rate sismico

Vengono identificate 5 Province con terremoti omogenei e di momento sismico noto, negli ultimi 30 anni

Per ogni provincia viene calcolato il momento sismico rilasciato nell'area coperta dagli epicentri, con profondità media ipocentrale ~15 km



Esempio di calcolo dello strain rate cosismico per eventi M>5 (secondo Kostrov, e Savage&Simpson)

Province b) Center Apennines

Reference	date	lon	lat	Mag	M_0	Depth	
	1979.8	12.95	42.70	5.5	0.2	10	
M20	1984.3	12.57	43.27	5.6	0.3	14	
M30	1997.8	12.89	43.02	5.7	0.4	10	
M31	1997.8	12.85	43.03	6.0	1.1	10	
M34	1997.8	12.84	43.03	5.2	0.1	10	
M36	1997.8	12.84	43.02	5.4	0.1	10	
M39	1997.8	12.94	42.91	5.2	0.1	10	
M40	1997.8	12.90	43.00	5.4	0.1	10	
M43	1998.8	12.70	43.16	5.1	0.1	10	
	19	31	63		2.5	10	114
	t	Δeast	Δnorth		M_{0tot}	Mean	Coseismic strain rate

$$\varepsilon_s = \frac{M_{0,tot}}{2\mu H A t}$$

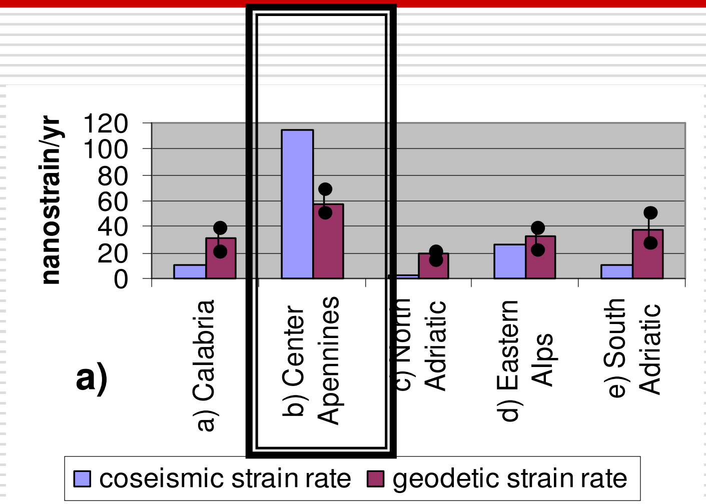
Province	lon (deg)	lat (deg)	ε_1	ε_2	ε_1-ε_2	2nd invariant	uncertainty
a) Calabria	16.12	39.48	31	-4	27	32	11
b) Center Apennines	11.87	43.00	57	-6	50	57	13
c) North Adriatic	15.40	44.11	2	18	-16	18	3
d) Eastern Alps	13.00	45.86	9	23	-14	25	8
e) South Adriatic	18.29	43.43	2	36	-34	36	7

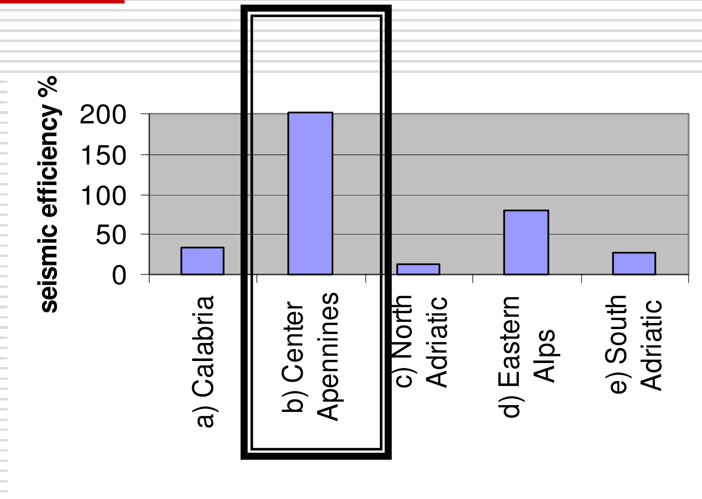
Nota: la distribuzione spaziale e temporale degli eventi è fortemente **non uniforme:** le stime dello strain rate cosismico dipendono fortemente dal data set

Viene dissipato sismicamente ~ il doppio (114/57) dello strain rate geodetico

Corrispondente strain rate **geodetico**

Bilancio ed efficienza sismica di ciascuna provincia



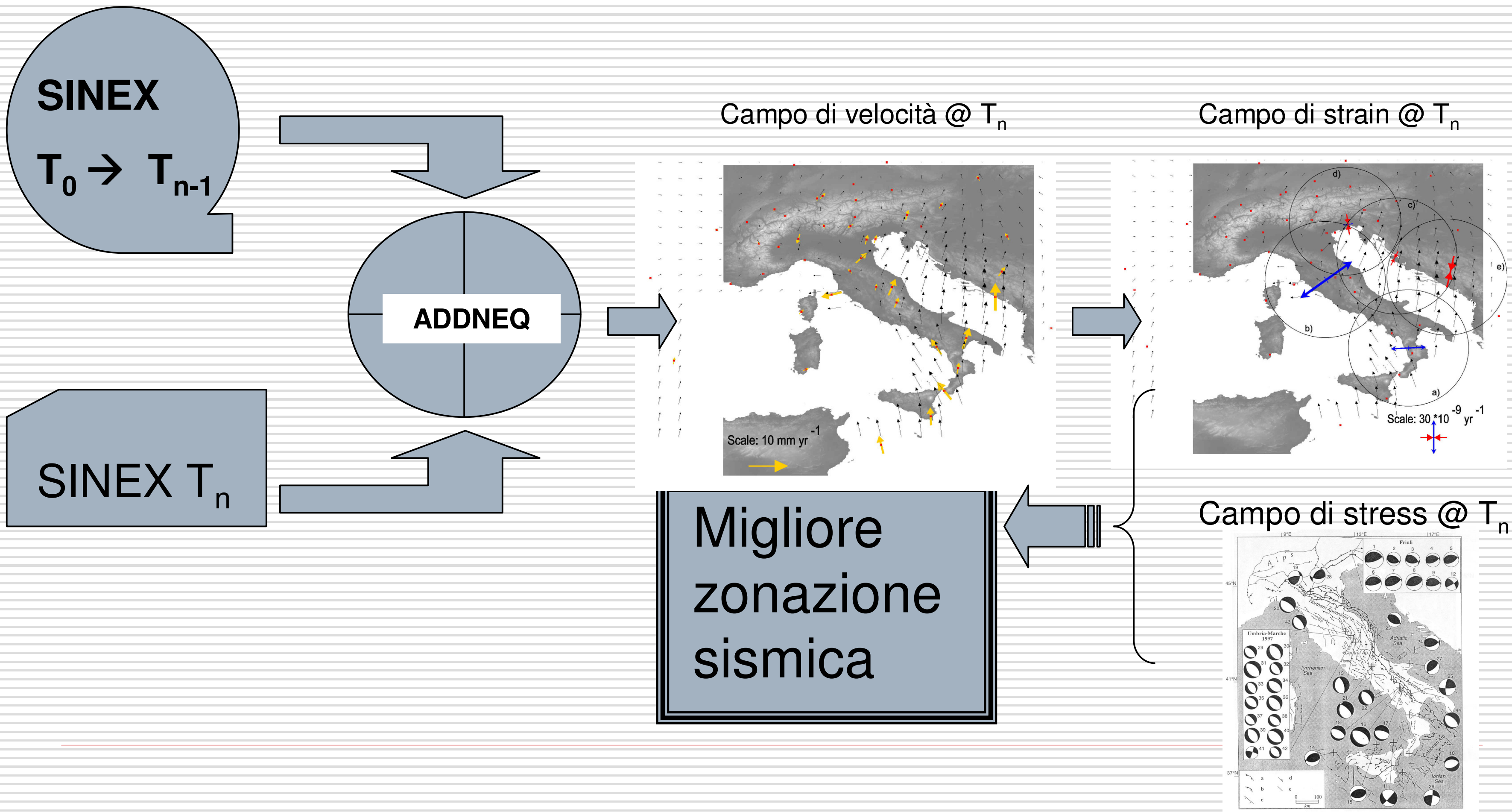


Raffronto strain rate cosismico- strain rate geodetico in termini assoluti

Raffronto strain rate cosismico- strain rate geodetico in termini percentuali

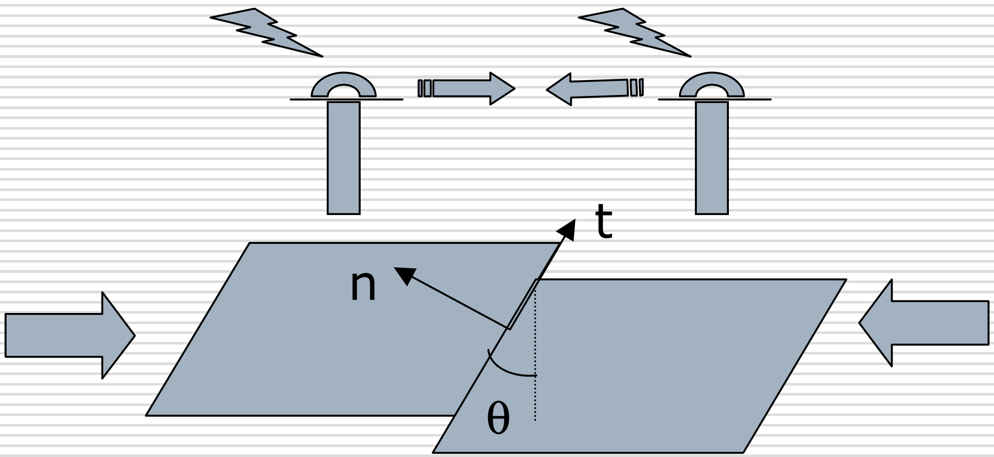
Mediando sulle 5 province troviamo che 70-100% dello strain rate geodetico è rilasciato sismicamente negli ultimi 30 anni. Tuttavia la dispersione per provincia è notevolmente elevata

Verso un nuovo tematismo cartografico: la deformazione di superficie



How can GPS geodesy constrain (simple) dynamic models?

- Goal: combine strain rate data with e.g. an elastic frictional model (Anderson theory)



$$\sigma_n = \rho g h - p_w + \frac{\Delta\sigma_{xx}}{2}(1 + \cos 2\theta)$$

$$\tau = \pm \frac{\Delta\sigma_{xx}}{2} \sin 2\theta$$

Pore fluid pressure

Amonton law (Coulomb yield criterion): static limit to the horizontal deviatoric stress

$$\tau = f_s \sigma_n \Rightarrow \quad \Delta\sigma_{xx} = \frac{2 f_s(\rho g h - p_w)}{\pm \sin 2\theta - f_s(1 + \cos 2\theta)}$$

Static frictional coeff.

Coseismic rebound: simple model

- Assume elastic model of shear stress along the fault plane:

$$\tau = \mp \frac{\mu u}{2\sqrt{A}}$$

μ = shear modulus
A = rupture area
u = in − plane dislocation

- Amonton law: maximum dislocation corresponding to yield point:

$$\mp u_s = \frac{2\sqrt{A} f_s \sigma_n}{\mu} = \frac{\sqrt{A}\Delta\sigma_{xx} \sin 2\theta}{\mu}$$

Equation of motion of coseismic rebound

Constant frictional force opposing the rebound

Relative acceleration of the rebounding block

$$\rho A^{3/2}\frac{d^2u}{dt^2}+\frac{\mu A^{1/2}u}{2}=f_d\sigma_n A$$

Elastic shear force

- Analytic solution satisfying the boundary conditions u(0)=u_s, u'(0)=0

$$u(t)=a\cos\omega t+b,\quad with\quad \omega=\sqrt{\frac{\mu}{2\rho A}};\quad b=\frac{2f_d\sigma_n\sqrt{A}}{\mu}$$

$$a=\frac{2(f_s-f_d)\sigma_n\sqrt{A}}{\mu}$$

Final status (no aftershocks!)

- Dislocation and rebound time (A=rupture area on the fault plane):

$$\Delta u = 2u_s\left(1 - \frac{f_d}{f_s}\right) \qquad t = \pi\sqrt{\frac{2\rho A}{\mu}}$$

- Corresponding scalar seismic moment released with the rebound (measurable quantity):

$$M_0 = \mu A \Delta u$$

Residual shear and deviatoric stress in the rocks, and 'recurrence time'

- Shear stress drop

$$\Delta\tau = \frac{\mu \Delta u}{2\sqrt{A}} = 2 f_s \sigma_n \left(1 - \frac{f_d}{f_s}\right)$$

- Residual shear stress

$$\tau^{(0)} = \tau(u_s) - \Delta\tau = \frac{\mu u_s A - M_0}{2A^{3/2}}$$

- Residual deviatoric stress

$$\sigma_{xx}^{(0)} = \frac{2\tau^{(0)}}{\sin 2\theta} = \frac{2 f_s \sigma_n \left(2\frac{f_d}{f_s} - 1\right)}{\sin 2\theta}$$

- Recurrence time Δt: strongly depends on the residual stress in the rocks!

$$\Delta\sigma_{xx} = \frac{E \dot{\varepsilon}_{xx} \Delta t}{1-\nu^2} + \sigma_{xx}^{(o)}$$

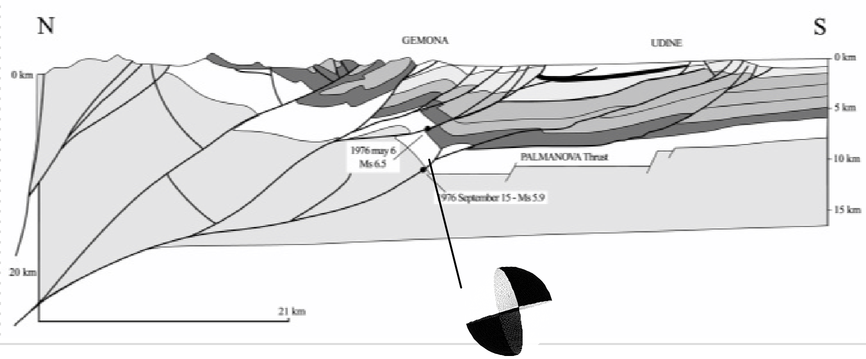
Initial stress depends on ratio of dynamic and static friction coefficients

~6MPa

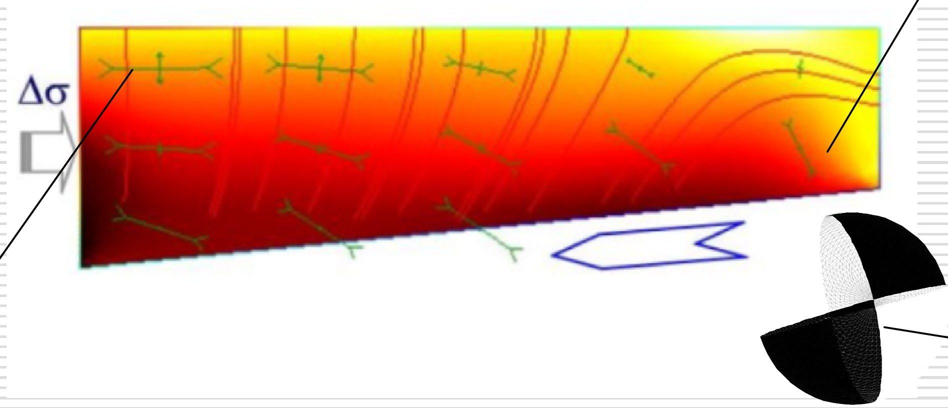
$$\frac{(30 \bullet 10^{-9}) \bullet (70 \bullet 10^{9})}{1 - 0.25^2} \Delta t \approx 0.002 \frac{MPa}{yr} \Delta t$$

Vertical section of seismogenic area (Friuli 1976 earthquake) (Galadini, Poli e Zanferrari, GJI 2005)

Observation:



Idealized model:

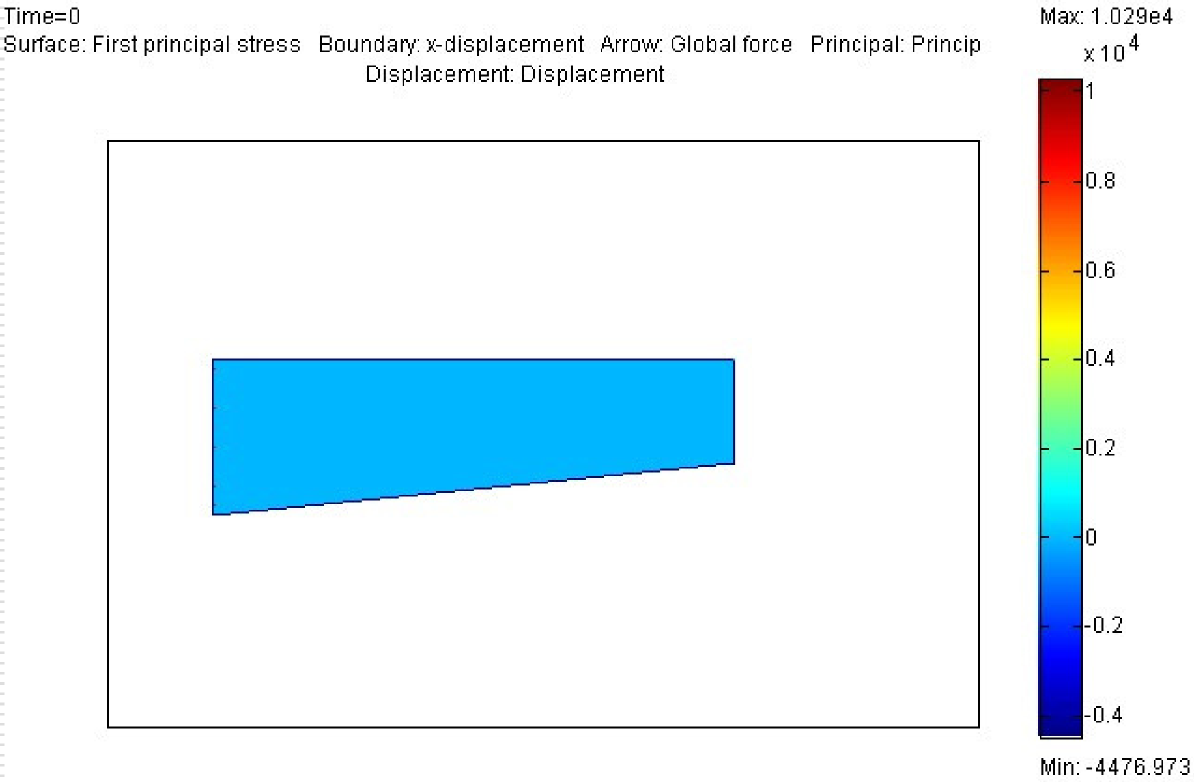


Maximum shear stress and probable rupture point

Horizontal surface strain observed by GPS

Plane of maximum strain (depends on frictional coupling of hanging and foot walls)

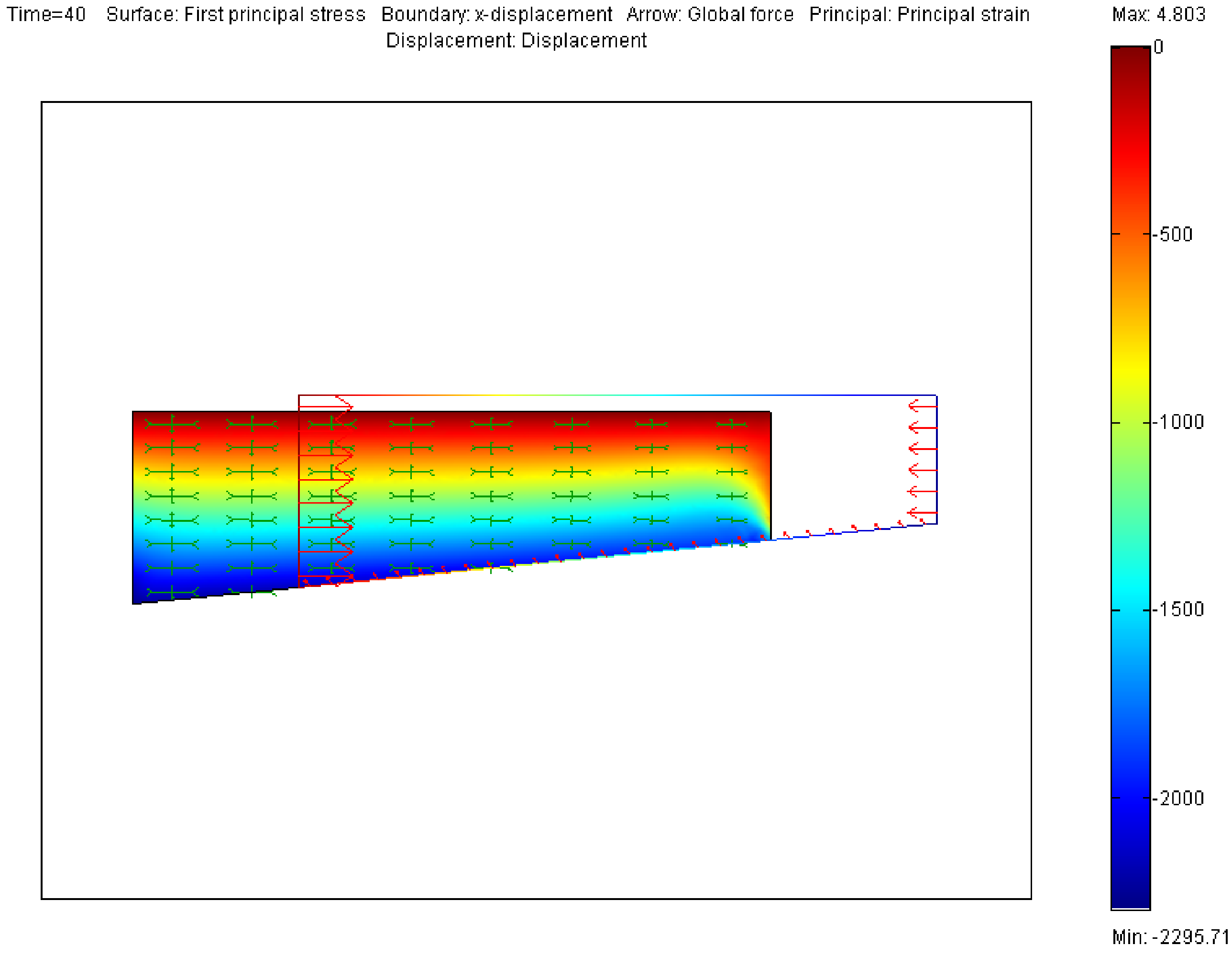
Finite elements simulation of sliding wedge 'stick/slip'



Boundary Conditions:

- North side: southwards surface force linearly increasing with time
- Bottom: stick/slip model (tangential); penalty stiffness (normal)
- South side: small horizontal penalty stiffness (required for numerical stability)
- Top: free

Final stress during slip phase



Conclusions

- Combining NEQ's (NQ0's) EPN + local permanent stations enables that densification which is needed for deformation studies
- Intraplate surface motion on a large scale is clear, less clear are the details on smaller scales, but will improve with time!
- In the Eastern Alps region, large deformation seems to be taking place along the Giudicarie more than the Insubric line
- New Friuli stations near the Insubric line seem moving West: need opposite motion for Austrian stations north of the line, to describe the Tauern eastwards extrusion towards the Pannonian basin
- Good agreement between recent (>1976) CMT's and eigenvectors of the strain rate tensor
- Stick slip behavior of reverse faults in Friuli: recurrence times may be constrained, but we need information on initial deviatoric stress in the rocks (i.e. since the last earthquake)
- Not known: triggering from nearby earthquakes (not on the same fault)? Identification of predecessor of a recent earthquake on same fault??