Adding geodetic data to a seismogenic context: the study case of the Adria indenter

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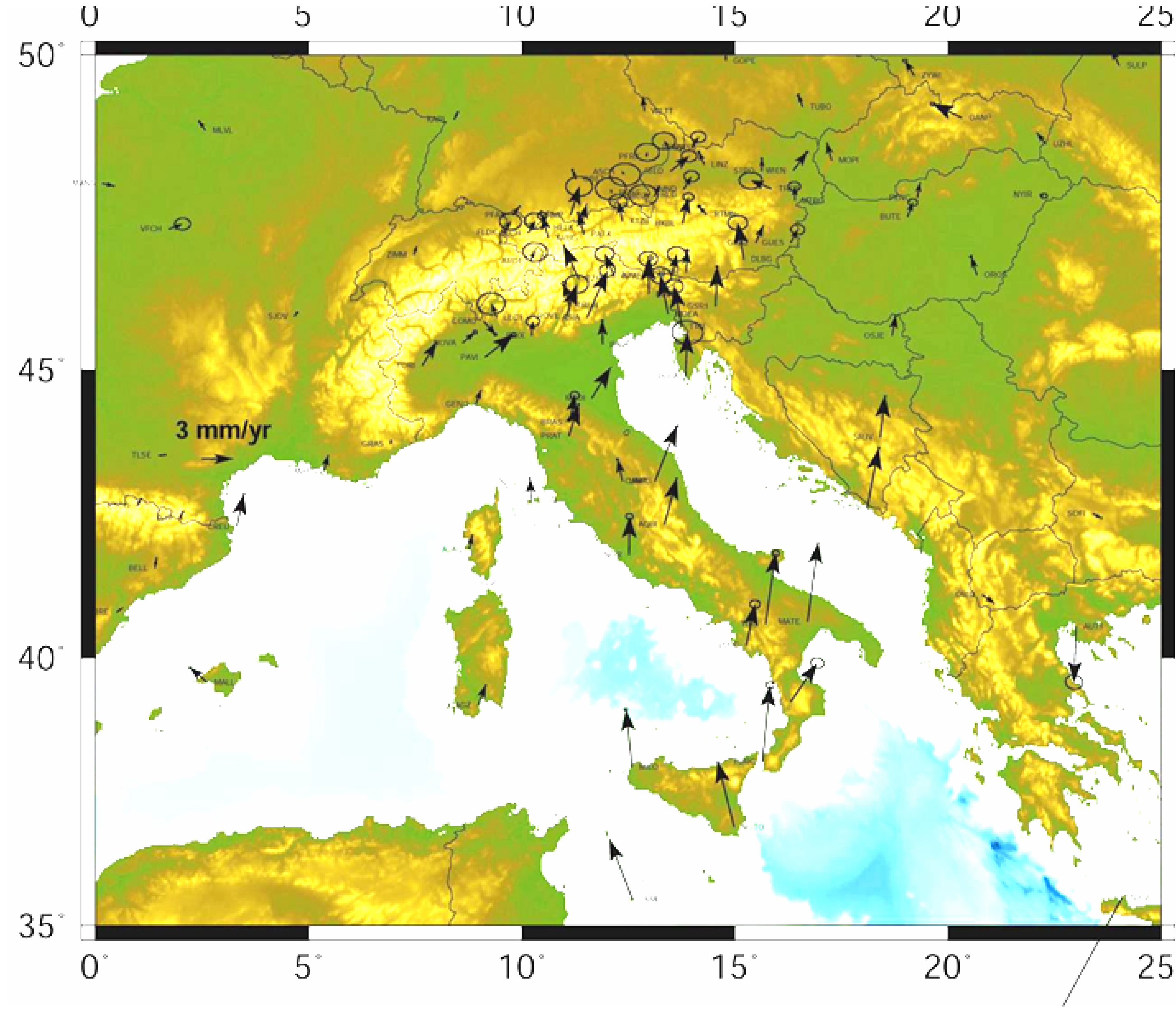
Outlook

- Velocities and strain rates from multi (3 – 10 yrs of continuous tracking) year solutions with permanent GPS stations: data, algorithms, uncertainty estimates
- Attempting a seismic budget: strain accumulated (measured geodetically) vs. strain released (measured from earthquakes)
- Yield stress and fault reactivation time as a function of local strain rate, friction coefficients, dip angle, lithostatic load, previous load.
- Velocity pattern on the surface as a boundary condition for dynamic stick slip models of earthquake triggering

Reference Project: INGV – DPC S2 on the seismic risk in Italy in the next 30 years, coordinated by D.Slejko and G. Valensise, Task 3.

Velocities of permanent GPS stations relative to a paleomagnetic kinematic model NUVEL1A NNR of Eurasia

- Time interval for GPS: 1995-2006
- Solution obtained from normal equation stacking of EUREF, Italian and Austrian GPS stations with >3yrs of data
- Full compliance with IGS/EUREF processing standards
- Uncertainty <0.5 mm/yr (1σ)

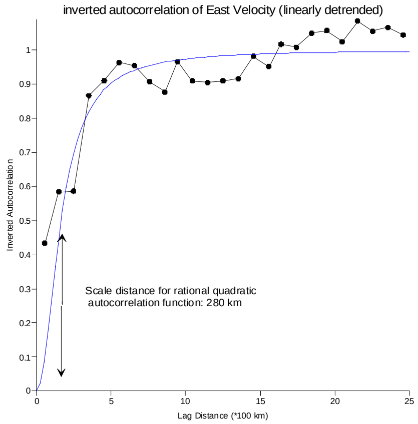


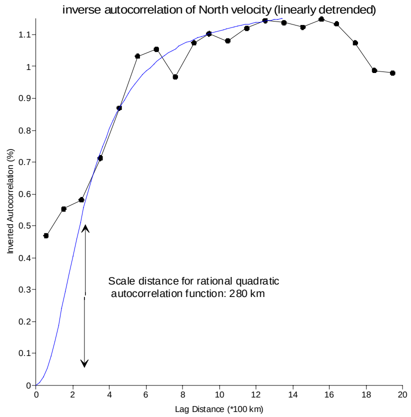
Interpolation of velocity vectors with least squares collocation, a minimum variance algorithm

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

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

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





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

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

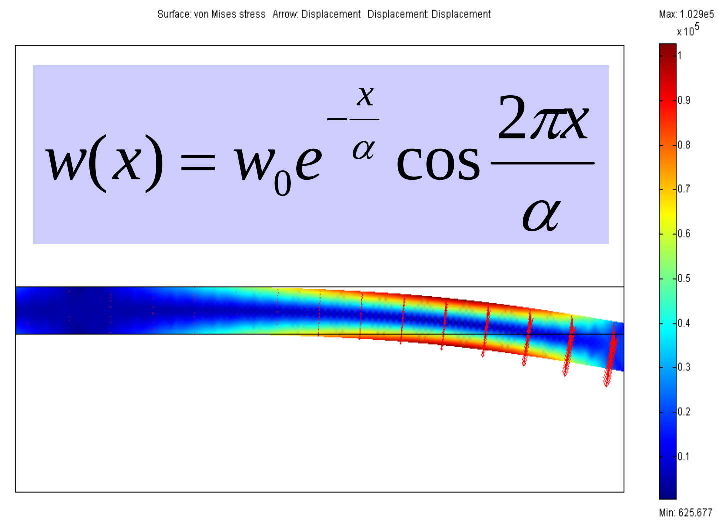
- E is a diagonal matrix with elements equal to the variance of each velocity component, e.g. in the sense of Allan variance.
- The choice of d_0 discriminates between 'signal' and 'noise': other choices typically determine a higher (small d_0) or smaller (large d_0) scale change of the interpolated variable, as can be expected

Why 290 km? Examine typical deformation wavelength in an isostatic flexural model of an elastic, continuous and semi-infinite 2D plate, loaded at one end

Flexural equation:

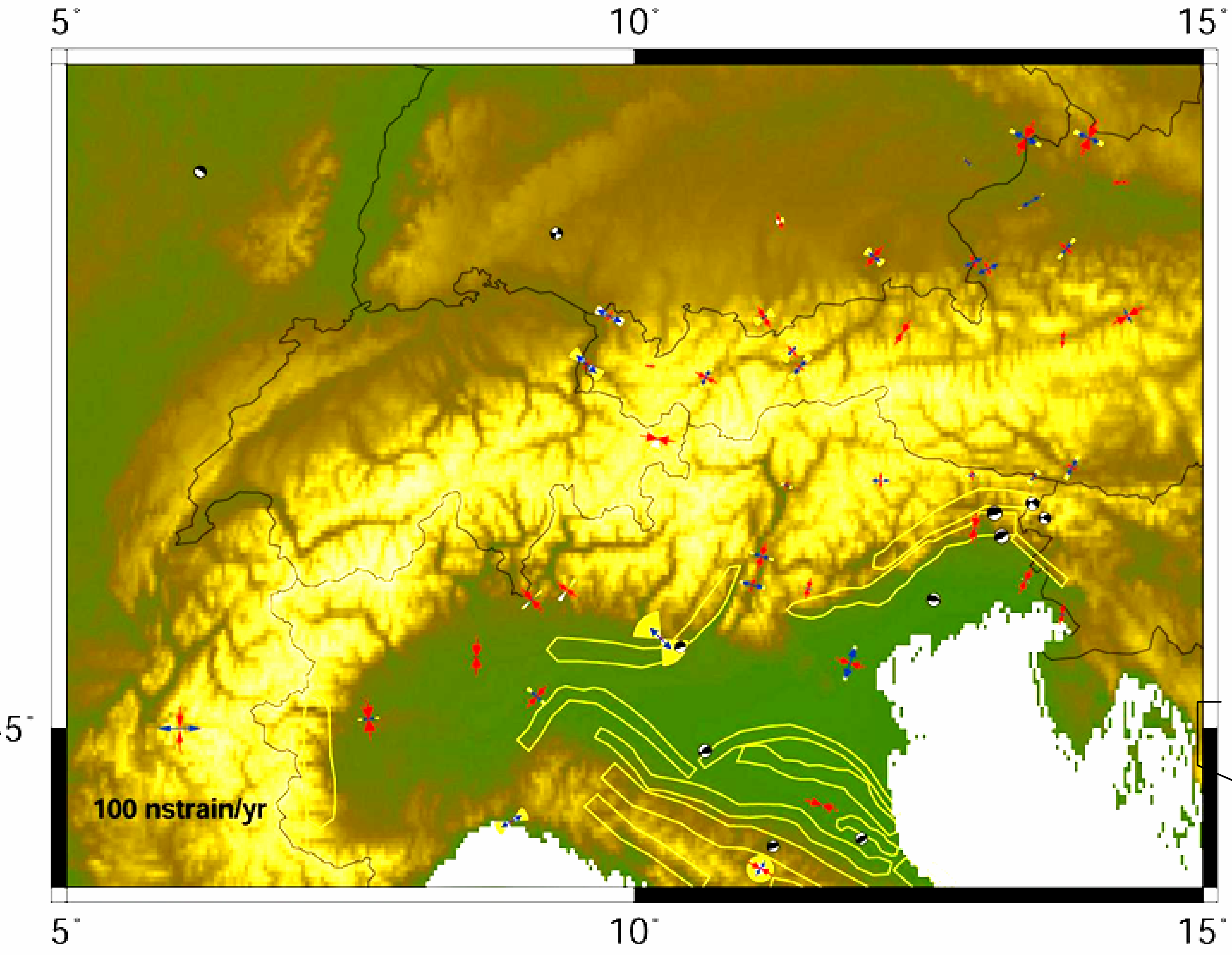
$$D\frac{d^4 w}{dx^4} + (\rho_m - \rho_c) g w = 0$$

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



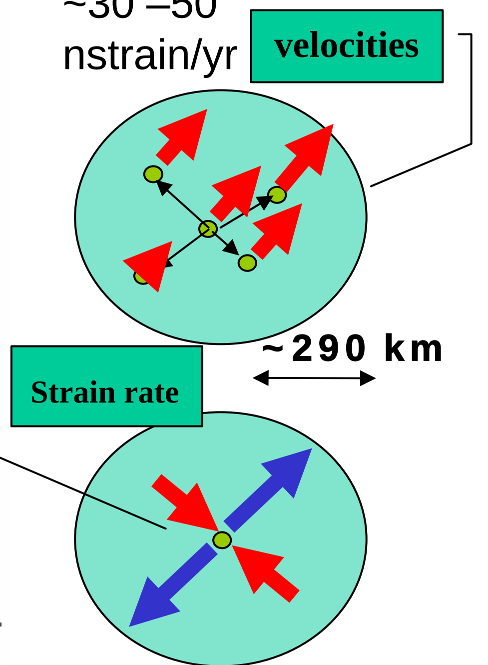
- If E=70 Gpa, ν=0.25, density contrast 600 kg/m^3 and plate thickness h ~ 27 km, then the flexural parameter α ~ 290 km
- **Conclusion**: 290 km is the typical horizontal scale of elastic deformation, and the statistics of our velocities agree with this estimate

Geodetic strain rate from GPS velocities, CMT and seismogenic sources from DISS 3.0



Strain rates are computed by numerically differentiating velocities in a neighbourhood of a GPS station

Moderate values: ~30 –50 nstrain/yr



Estimating a formal strain rate uncertainty

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

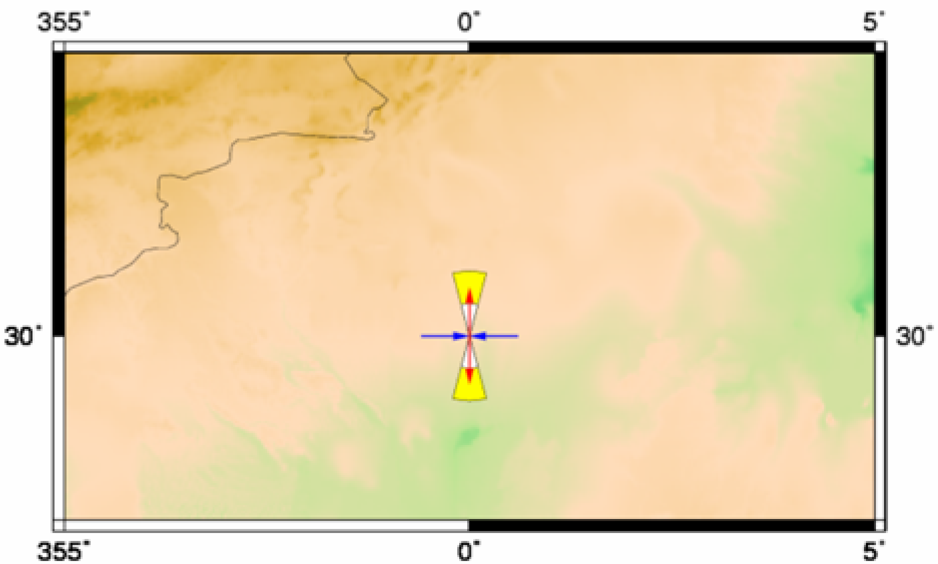
$$\begin{bmatrix} dv_{n,n} & dv_{n,e} \\ dv_{e,n} & dv_{e,e} \end{bmatrix}_P = \sum_s \begin{bmatrix} \frac{\partial C}{\partial n} & \frac{\partial C}{\partial e} \\ \frac{\partial C}{\partial n} & \frac{\partial C}{\partial e} \end{bmatrix}_{P,s} \sum_{s'} \left[C(d_{s,s'}) + W_{ss'} \right]^{-1} \cdot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

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

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

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

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

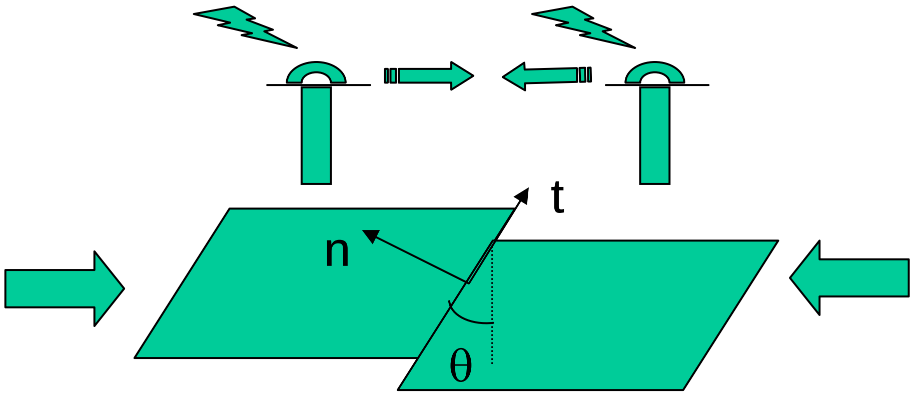


$$d\varepsilon_{1,2} = \frac{dv_{n,n} + dv_{e,e}}{2} \pm \frac{\frac{(v_{e,e} - v_{n,n})(dv_{e,e} - dv_{n,n})}{2} + 2\varepsilon_{e,n} d\varepsilon_{e,n}}{2\sqrt{\left(\frac{v_{e,e} - v_{n,n}}{2}\right)^2 + (\varepsilon_{e,n})^2}}$$

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

Deviatoric stress $\Delta\sigma_{xx}$ at yield point

Theory of Anderson :



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

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

Amonton law: static limit to the deviatoric stress

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

Recurrence time Δt under a perfectly elastic, plain stress hypothesis : it depends on strain rate and preexistent deviatoric stress in the rocks:

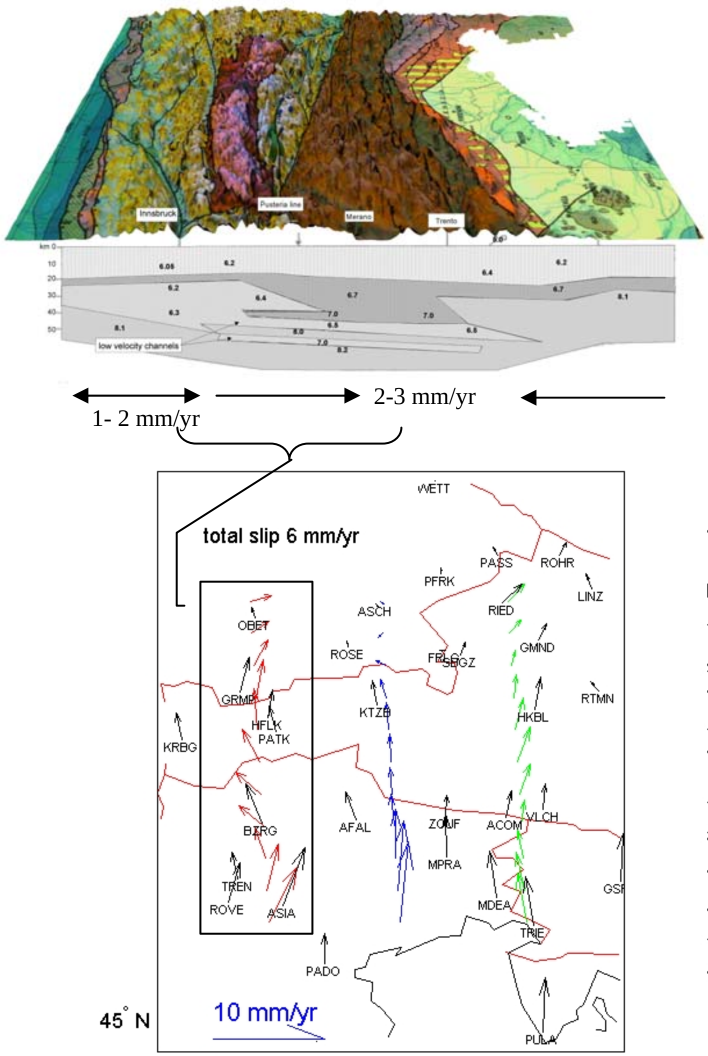
$$\Delta\sigma_{xx} = \frac{E\,\dot{\varepsilon}_{xx}\,\Delta t}{1-\nu^2} + \sigma_{xx}^{(o)}$$

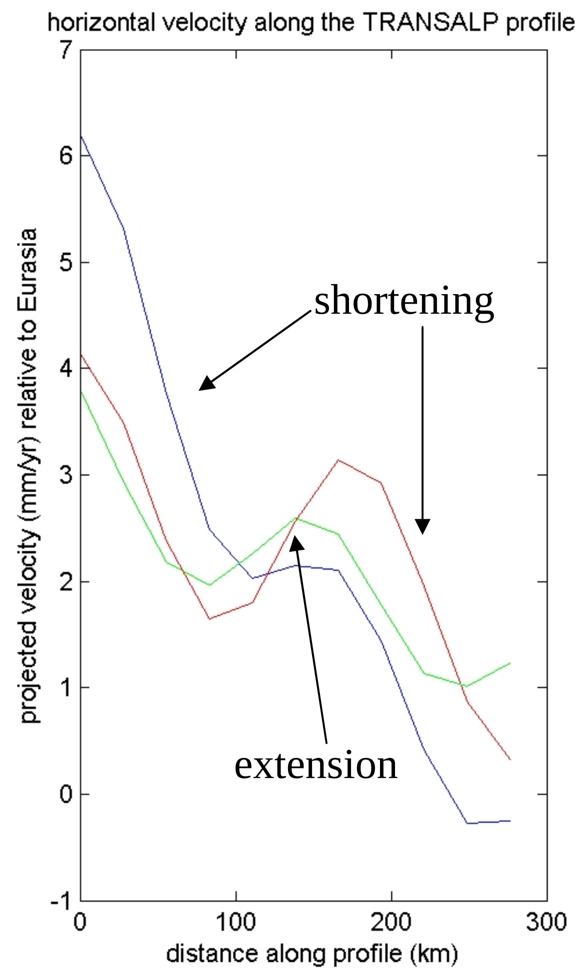
$$\boxed{\frac{\left(30\bullet 10^{-9}\right)\bullet\left(70\bullet 10^{9}\right)}{1-0.25^2}\Delta t \approx 0.002\frac{MPa}{yr}\Delta t}$$

In 100 years tectonics accounts for 0.2 MPa, if the strain rate is 30 nstrain/yr

If the yield deviatoric stress is of some MPa, for M>5.5 typically, ***f*$_s$ must be of the order of 0.01** and the starting stress must also be of the order of 1 MPa

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

Conclusions, and some open questions

- **The Adria/East Alps deformation zone is well constrained kinematically by permanent GPS stations: strain accumulation can be estimated in seismogenic areas; eigenvectors of the strain rate tensor are in excellent agreement with P-T axes of fault plane solutions.**
- **Geodetic data in Friuli indicate a shortening of 4 – 6 mm/yr, with inversion in Tirol: possible kinematic evidence of lateral extrusion of the Tauern window, with the Pannonian basin acting as stress sink?**
- **Yield stress corresponding to a stick/slip transition depends on friction coefficient, pore fluid pressure, dip angle, reverse/direct faulting...These dynamical parameters can be constrained with geodetic strain rates measured at the surface.**
- **To predict a reactivation time, the knowledge of the friction coefficient and of the pre-existing stress is crucial**