Constraining the seismic budget of Adria indentation and the dynamics of fault interaction with geodetic strain rate data

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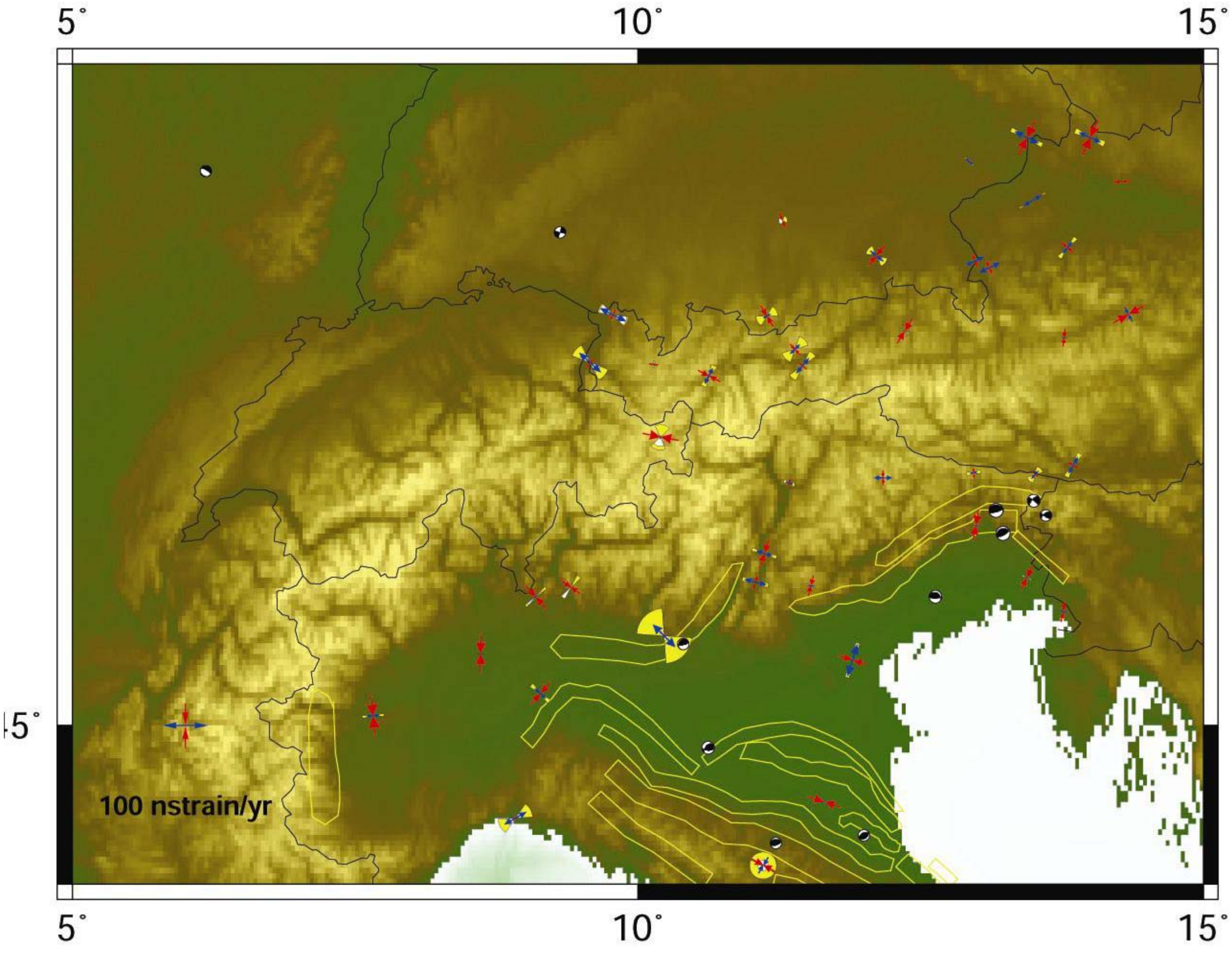
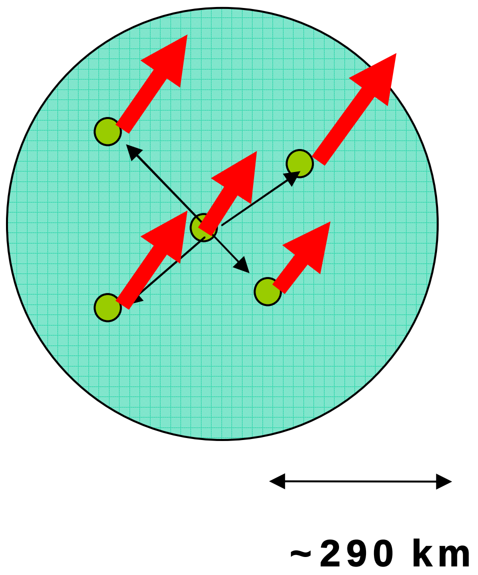
Geodetic strain rate, CMT and seismogenic sources



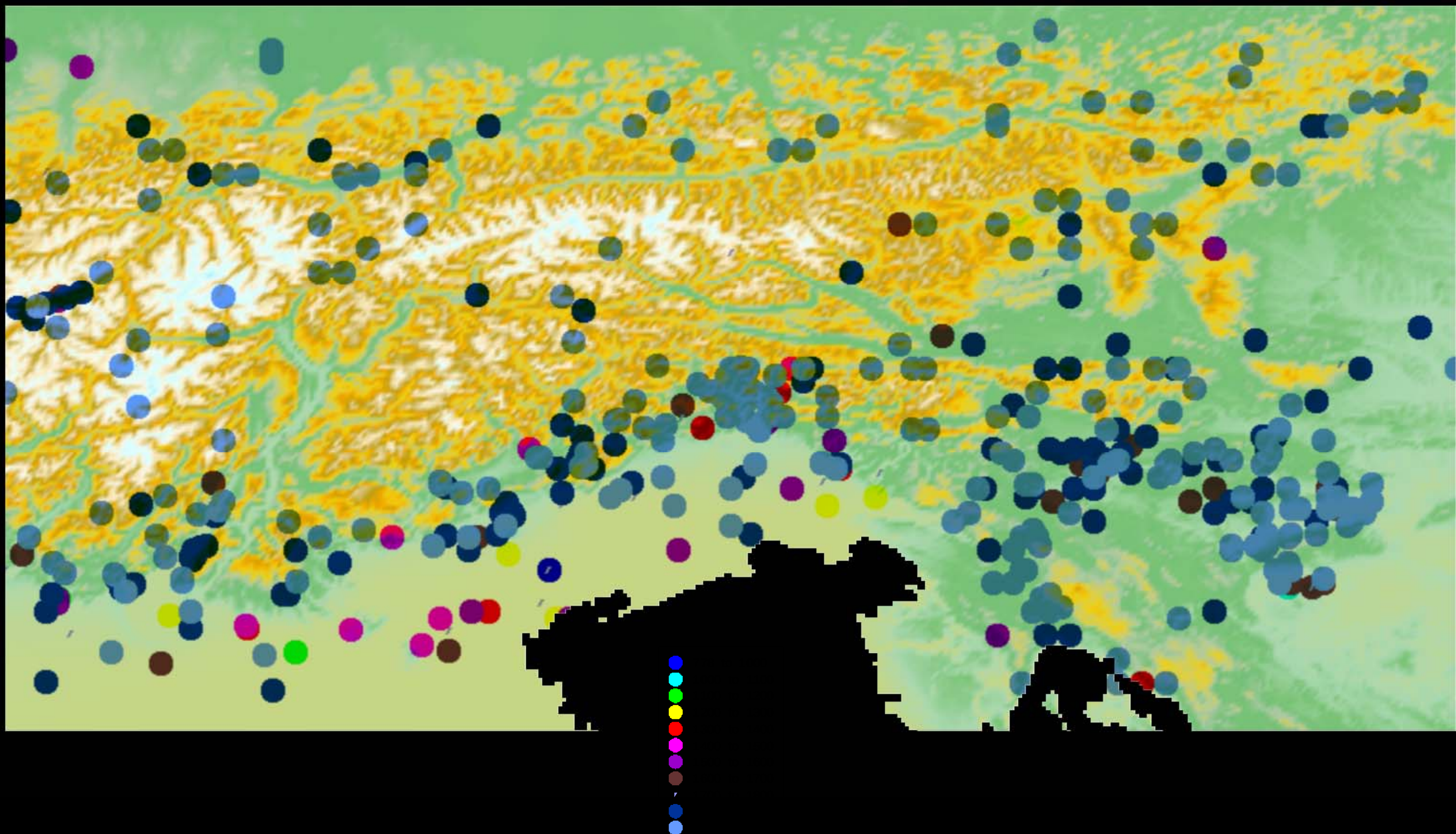
Moderate (~30 –50 nstrain/yr) are estimated wherever sufficient data are available



Issues related to the knowledge of strain rate in a seismic province

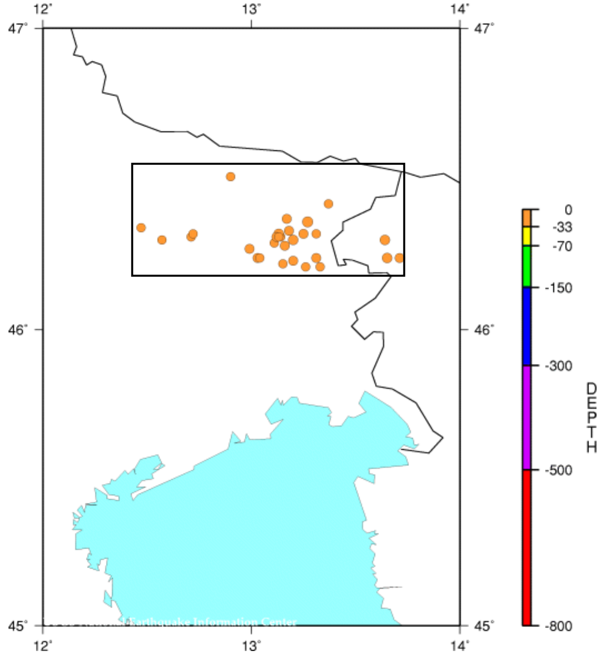
- seismic efficiency: how does the strain rate released seismically (Kostrov) relate to geodetic strain rate?
- When is a fault going to fail, depending on fault geometry and friction coefficients, and how does this epoch depend on the previous failure history, both locally and in the neighbourhood?
- How is the spatial distribution of geodetic strain related to the epicenter location?

Historical seismicity from CPTI 2.0



Past 30 years: Kostrov strain rate in Friuli ~ 400 nstrain/yr, that is nearly 8 times the geodetic strain rate

Year	Month	Day	North Lat	East Long	M	depth (km)	Area (km^2)	M0*10^18 Nm	Volume (km^3)	
1976	5	6	46.36	13.27	6.5	9	447	5.62	4020	
1976	5	9	46.24	13.31	5.1	14	25	0.04	344	
1976	5	11	46.51	12.90	4.7	15	11	0.01	161	
1976	5	11	46.27	12.99	5.2	11	30	0.06	332	
1976	9	6	46.24	13.03	5.2	5	30	0.06	151	
1976	9	11	46.28	13.16	5.5	16	56	0.18	900	
1976	9	11	46.30	13.20	5.4	20	46	0.13	914	
1976	9	11	46.23	13.20	5.1	10	25	0.04	245	
1976	9	12	46.22	13.15	4.6	3	9	0.01	26	
1976	9	15	46.30	13.20	6.3	10	295	2.82	2951	
1976	9	15	46.31	13.14	4.9	10	16	0.02	162	
1976	9	15	46.29	13.11	4.5	8	7	0.01	57	
1976	9	15	46.32	13.13	5.9	17	129	0.71	2190	
1976	9	15	46.33	13.18	5.0	10	20	0.03	200	
1976	9	17	46.42	13.37	4.9	10	16	0.02	162	
1978	12	12	46.31	12.71	4.5	10	7	0.01	71	
1979	4	18	46.32	13.25	5.1	11	25	0.04	270	
1981	8	30	46.32	13.31	4.9	10	16	0.02	162	
1981	12	5	46.32	12.72	4.7	10	11	0.01	107	
1983	2	10	46.21	13.33	4.9	10	16	0.02	162	
1986	8	29	46.34	12.47	4.8	10	13	0.02	132	
1988	2	1	46.31	13.12	5.4	8	46	0.13	366	
1988	2	4	46.31	13.13	4.6	15	9	0.01	131	
1991	10	5	46.21	13.26	4.5	10	7	0.01	71	
1994	4	20	46.30	12.57	4.8	10	13	0.02	132	
1998	4	12	46.24	13.65	6.0	10	158	1.00	1585	
1998	5	6	46.24	13.71	5.1	10	25	0.04	245	
1998	5	28	46.24	13.04	4.5	10	7	0.01	71	
2002	2	14	46.37	13.17	5.3	10	37	0.09	372	
2004	7	12	46.30	13.64	5.7	7	85	0.35	596	
28			33	98			1636	12	17287	397
yrs			North boxsize km	East boxsize km			3258	(M0)total		Kostrov (nstrain/yr)
							box(km^2)		μ=	30
									(Gpa)	



$$\log A = -3.42 + 0.9M$$

$$\log M_0 = 1.5M + 9$$

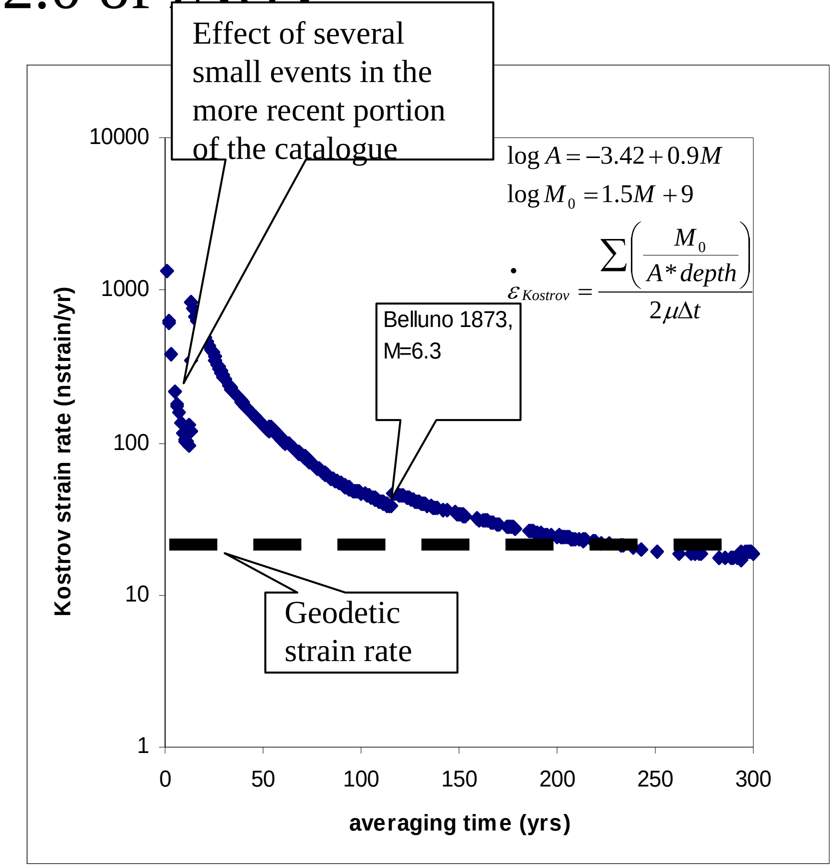
$$\dot{\varepsilon}_{Kostrov} = \frac{\sum \left(\frac{M_0}{A * depth} \right)}{2\mu \Delta t}$$

Two opposite interpretations are in principle possible:

- **active deformation is slowing down (→ less hazard)**
- **end of seismic cycle (→ greater hazard)**
- **or: still settling from the 1976 M=6.5 event -> need longer averaging time**

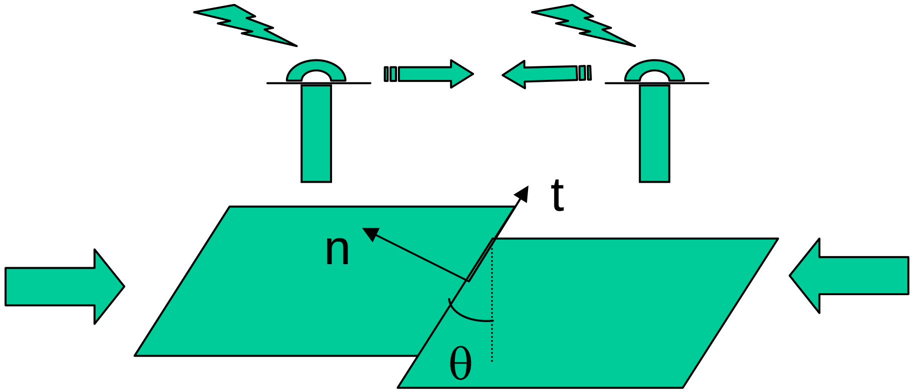
Analysis of the Parametric Catalogue of Historical Earthquakes CPTI 2.0 of INGV

- Criteria of analysis:
  - Select a location where geodetic strain rate could reliably be computed
  - Compute slip area and seismic moment from magnitudo by means of statistical formula, for earthquakes within 290 km from selected location
  - Sum equivalent Kostrov strain rates and divide by time interval
- Results:
  - 555 events from 778 (Treviso) till 1998 (Bovec) spanning 1220 years
  - Max M=6.5
  - Average strain rate: 7 - 10 nstrain/yr
  - Average strain rate equals geodetic strain rate after ca. 300 yrs



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

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:

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

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

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

Yield deviatoric stress non tectonically driven

- One way is to decrease the yield deviatoric stress by increasing the **pore fluid pressure**

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

- Alternatively, we can imagine that hydraulic heads triggered by a major earthquake generate the necessary deviatoric stress at nearby locations and later times
- This could be in principle achieved by diffusion, in a neighbourhood of a preceeding earthquake
- In such case, events following a major (M>6) earthquake should correlate according to the dimensionless variable

$$\xi = \frac{d}{2\sqrt{\kappa t}}$$

Where d is the distance from the major event, t is the time since the major event and κ is the diffusion coefficient

Assume isotropic diffusion, i.e. not channeled along preferred directions

Example: Friuli (1976) and Bovec (1998) seismic ‘*diffusion sequences*’

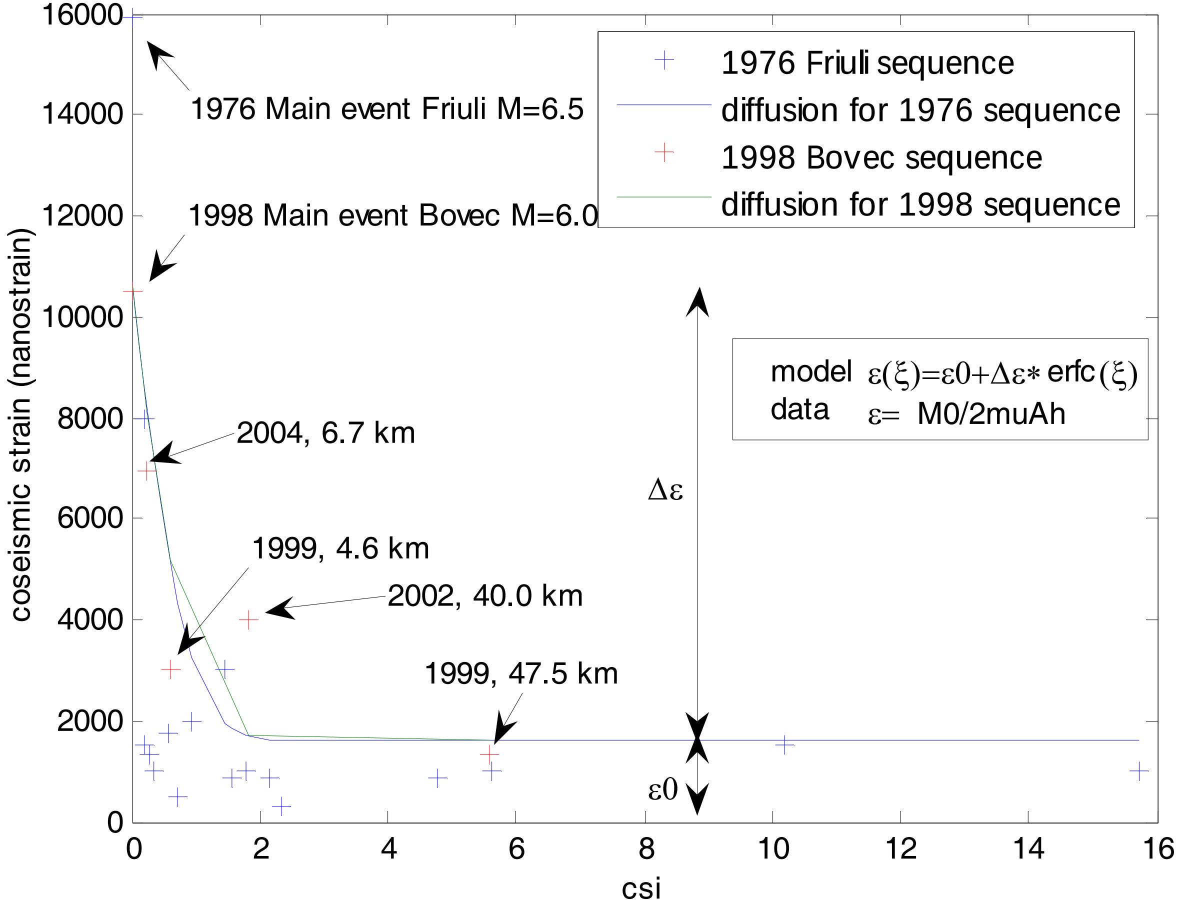
Method:

- Compute coseismic strain ε for each event
- Plot against similarity variable

$$\xi = \frac{d}{2\sqrt{\kappa t}}$$

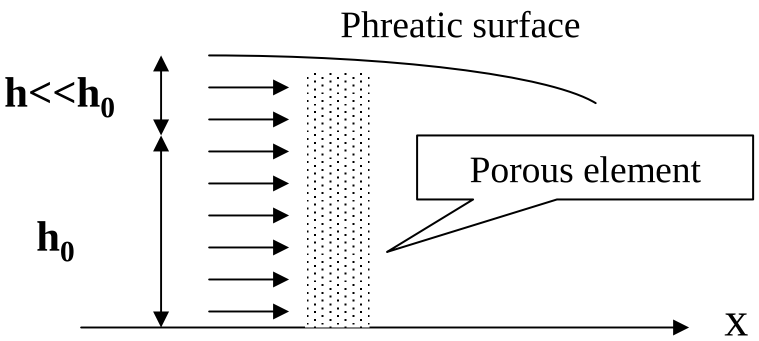
- Find diffusion coefficient κ such that diffusion model fits the data

Result: $\kappa = 0.1\ m^2/sec$



Interpretation of κ for isotropic flow in a porous medium

- Linearized Boussinesq equation describes the height of the phreatic surface in the one-dimensional flow through an unconfined aquifer:

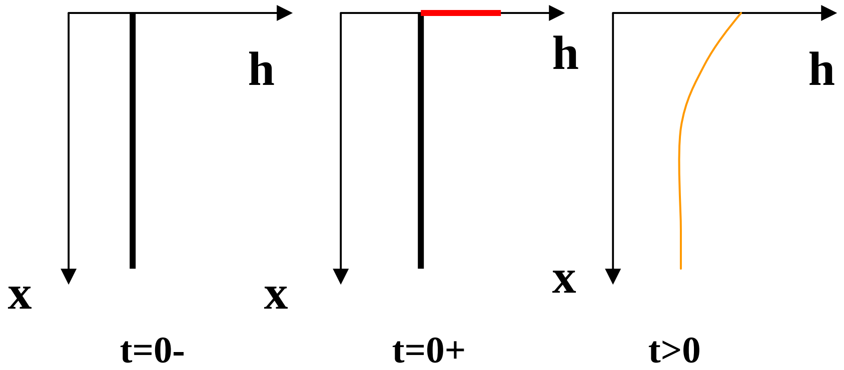


$$\frac{\partial h}{\partial t} = \kappa \frac{\partial^2 h}{\partial x^2}, \text{ where } \kappa = \frac{k\rho_w g h_0}{\eta\phi}$$

<u>Variables and constants:</u>

- **k permeability (10^{-11} to 10^{-12} m^2)**
- **ϕ porosity (0 to 1)**
- **η viscosity (0.001 Pa sec)**
- **h_0 undisturbed height**
- **ρ_w water density (1000 kg/m^3)**
- **g gravity accel. (9.8 m/sec^2)**

<u>κ=0.1 m^2/sec is consistent with these values</u>

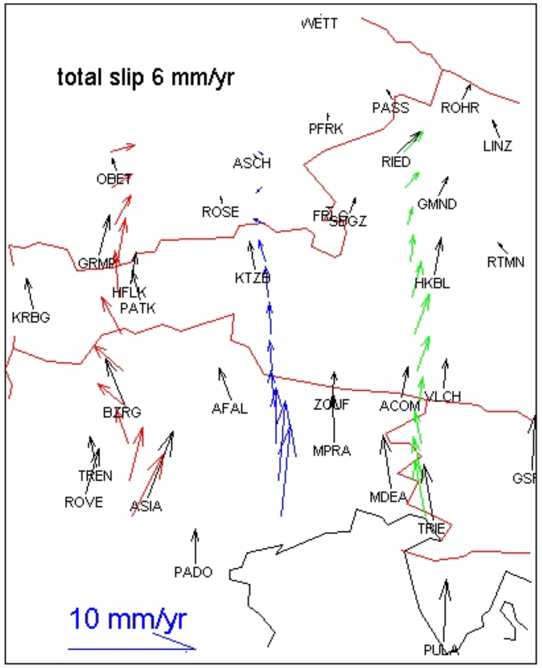


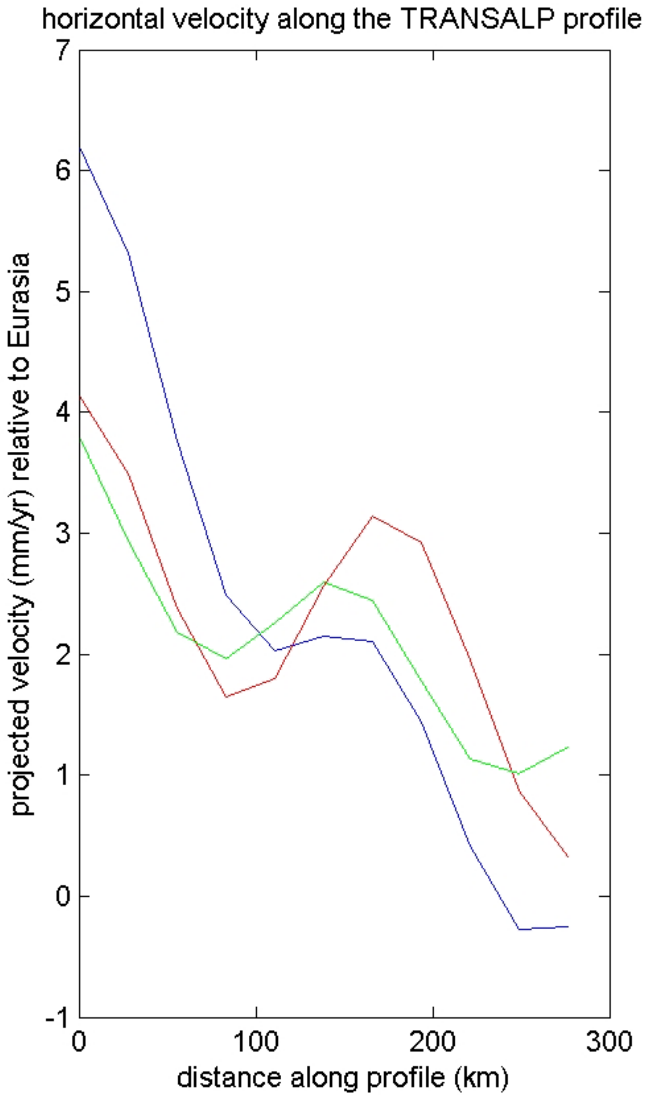
Boundary conditions

Can earthquakes trigger other smaller earthquakes nearby?

- The two examples of Bovec and Friuli seem consistent with a model in which the main event triggers a hydraulic head which propagates by diffusion with a coefficient **$k=0.1\ m^2/sec$**
- If this is true, then following a major event, one would be able to predict at each point the probability of an event of given Magnitude

Slip Profiles in the Eastern Alps





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

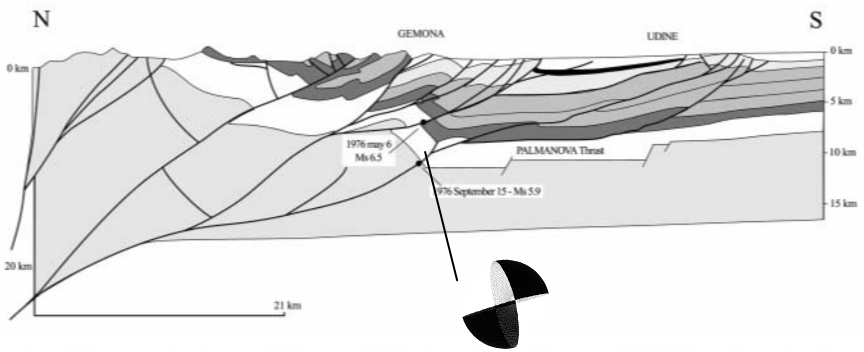
A shortening of up to ~ 6 mm/yr is implied across the 300 km profile, or 20 nstrain/year. Locally can be higher, to ~ 40 nstrain /yr

Divergent pattern in parallel profiles across the Tauern window may imply a squeezing and hence lateral extrusion

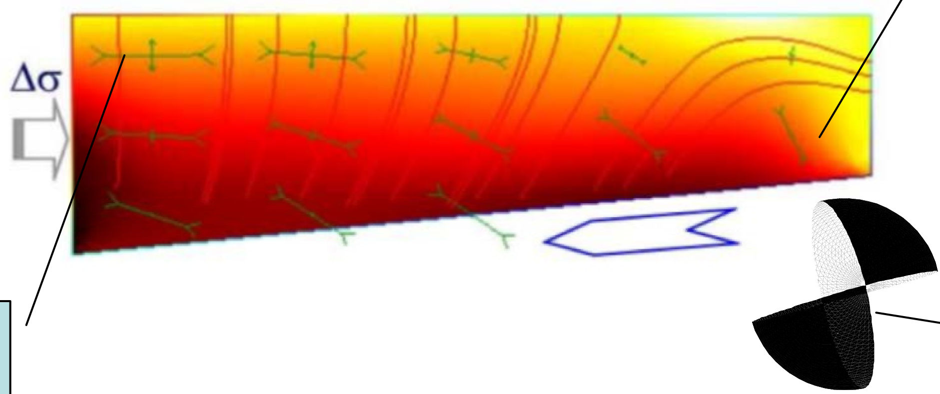
Strain rate profile and hypocenter location

Structural model:

(Galadini et al. 2005)



Idealized model(FEM)

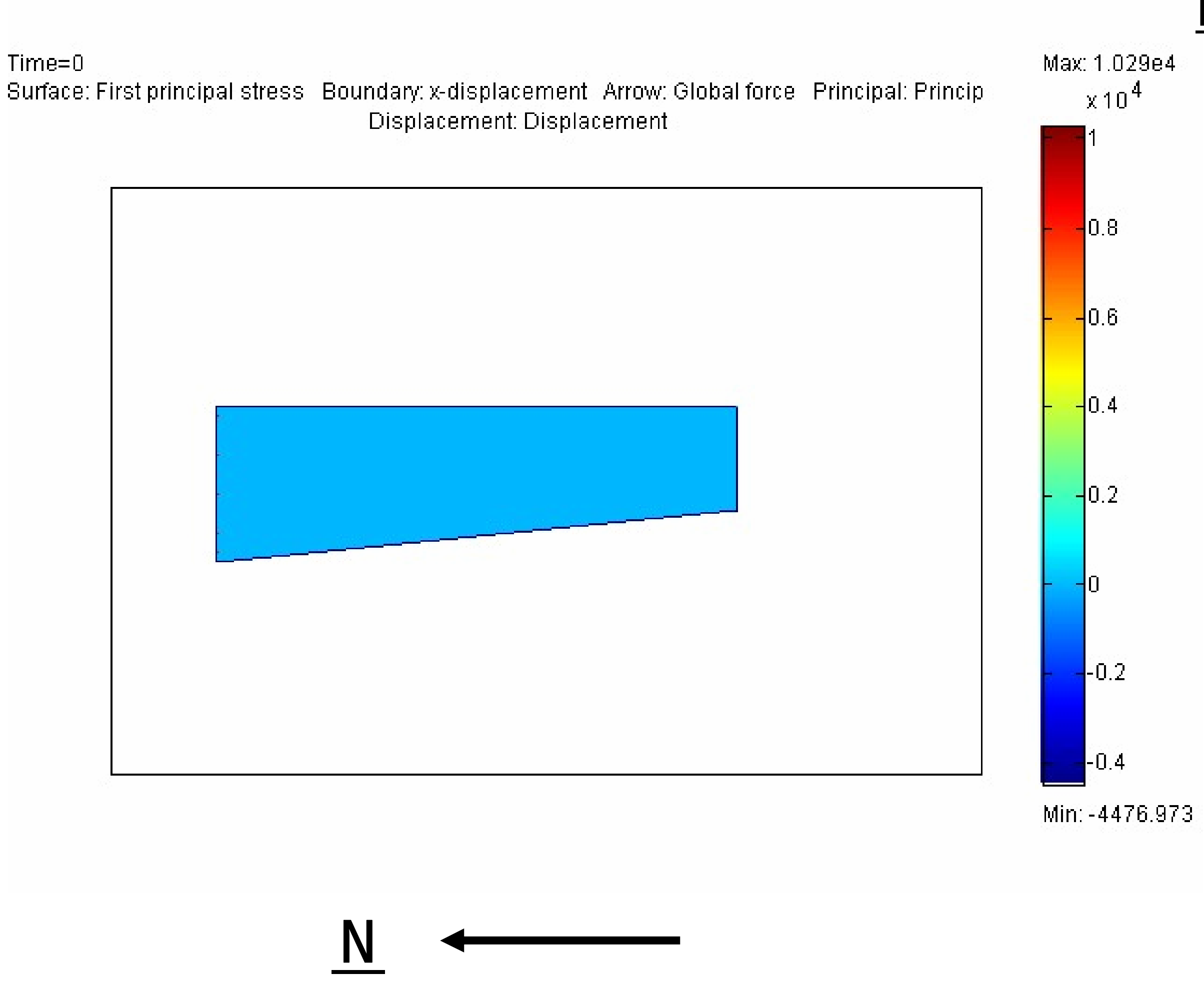


Maximum shear stress and probable slip point

Horizontal strain at the surface is observed by GPS: we expect it a minimum near the epicenter (max vertical)

Inclination of the strain eigenvector depends on frictional coupling of hanging and foot wall

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

Conclusions

- Geodetic data in Friuli indicate a shortening of 4 – 6 mm/yr, with inversion in Tirol: possible kinematic evidence of the extrusion of the Tauern window
- The pattern of the horizontal strain rate measured by GPS can be used to constrain the most probable epicenter location
- The earthquake activity is such that the Kostrov strain rate (i.e. average strain released by earthquake during a time) drops to the geodetic value of 30 nstrain/yr after no less than 300 yrs. During this interval rocks are loaded by 0.6 MPa
- Yield stress corresponding to a stick/slip transition depends on friction coefficient, pore fluid pressure, dip angle, reverse/direct faulting...
- A linearly increasing load can bring a sticking fault to slip after a time which depends also on initial load on the rocks
- Earthquakes of decreasing intensity can be related to a major event if it triggers an hydraulic head which propagates through a porous medium with diffusion coefficient 0.1 m^2/sec
- Evidence has been provided for the Bovec and Friuli sequences. Previous data in the CPTI catalogue are probably unsufficiently detailed
- If this model is true, it can prove a valuable method in seismic risk prediction, after a major event