Analisi retrospettiva della fase precedente il terremoto di MD=5.1 di Bovec-Krn (2004).

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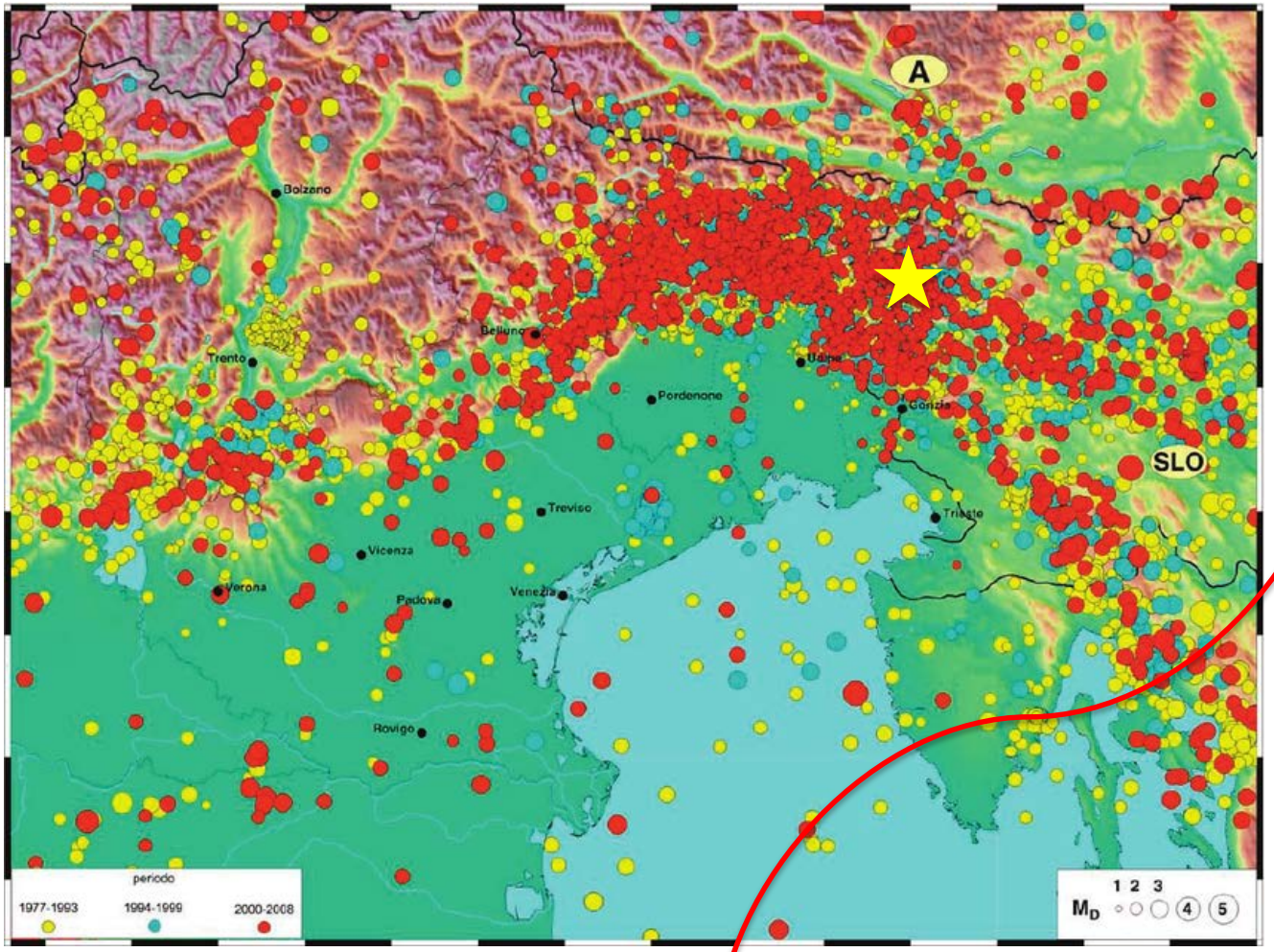
Northern Adria: the seismic activity



Bragato et al., 2011, Ann. Geofis.

In the last 40 years:

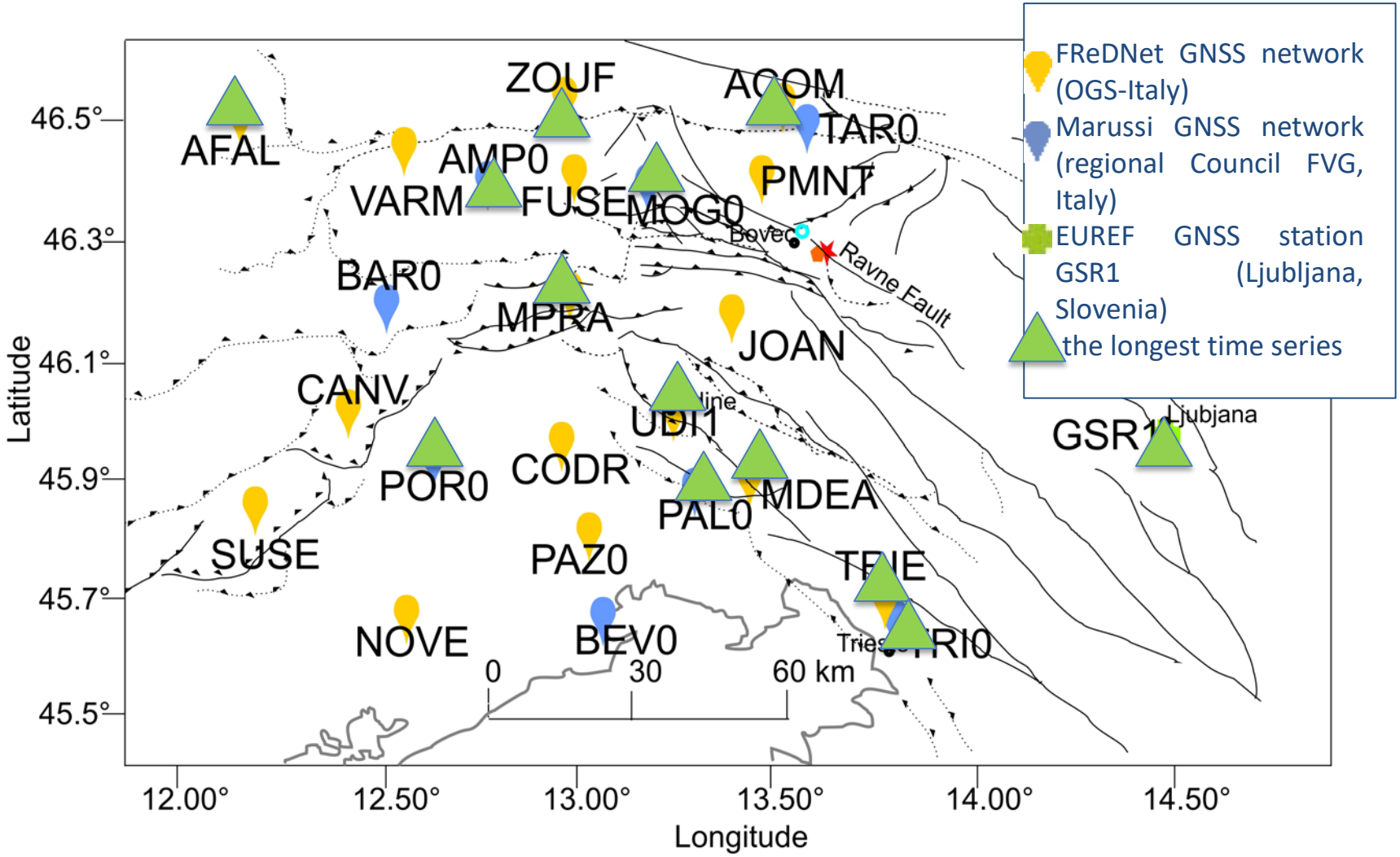
1976: M_w=6.4 and M_w=6.0 (Friuli, Italy)

1998: M_w=5.6 (Bovec-Krn, W Slovenia)

2004: M_w=5.2 (Bovec-Krn, W Slovenia)

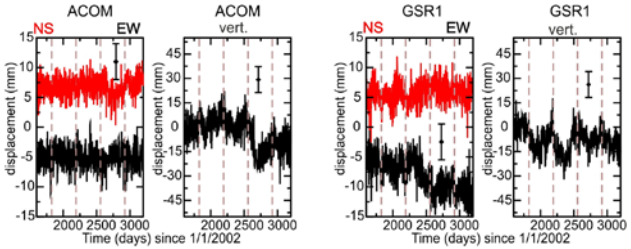
Ravne Fault

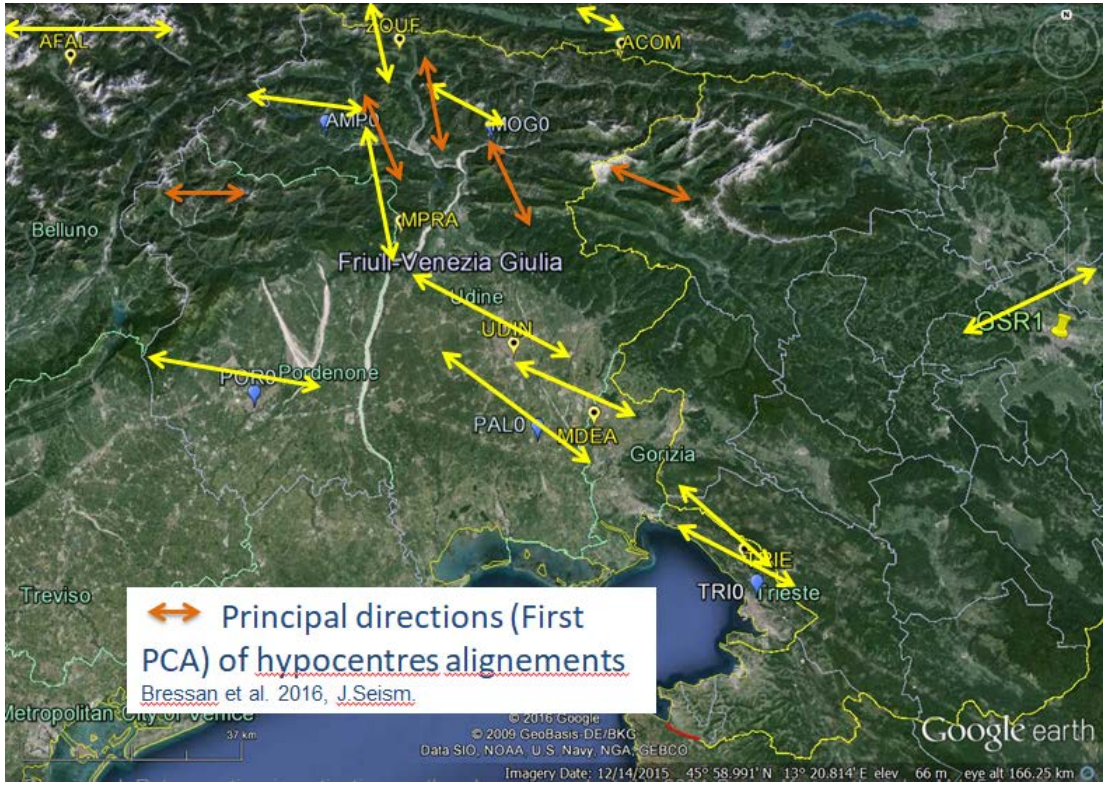
The GNSS monitoring networks operating in the area



Rossi et al. 2016; 2017; 2018

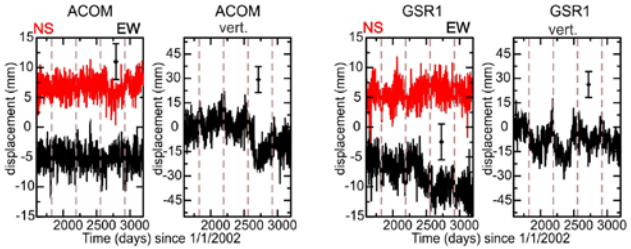
- Subtraction of the hydrological effect from the time series
- Recognition of a transient GNSS signal of apparent “period” of two years, causing an uplift and bending along the principal tectonic directions.

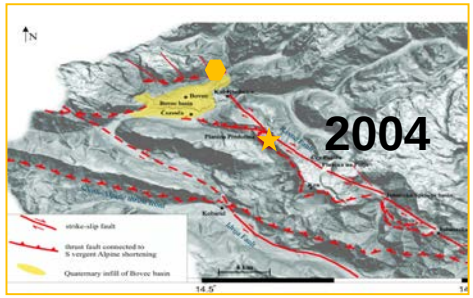


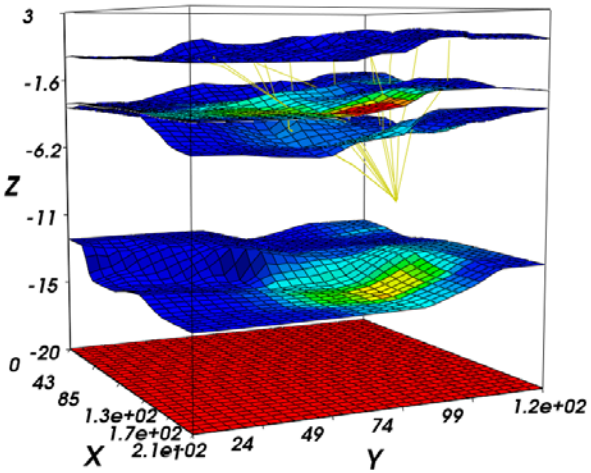


Rossi et al. 2016; 2017; 2018

- Subtraction of the hydrological effect from the time series
- Recognition of a transient GNSS signal of apparent “period” of two years, causing an uplift and bending along the principal tectonic directions.
- Location of its source through tomographic inversion at 9 km depth to the NW of Bovec-Krn 1998 and 2004 earthquakes, 3 months before 2004 event.
- The velocities are suggestive of fluid diffusion, and hydraulic diffusivity D_h obtained through hydraulic tomography is compatible with the lithologies of the region.

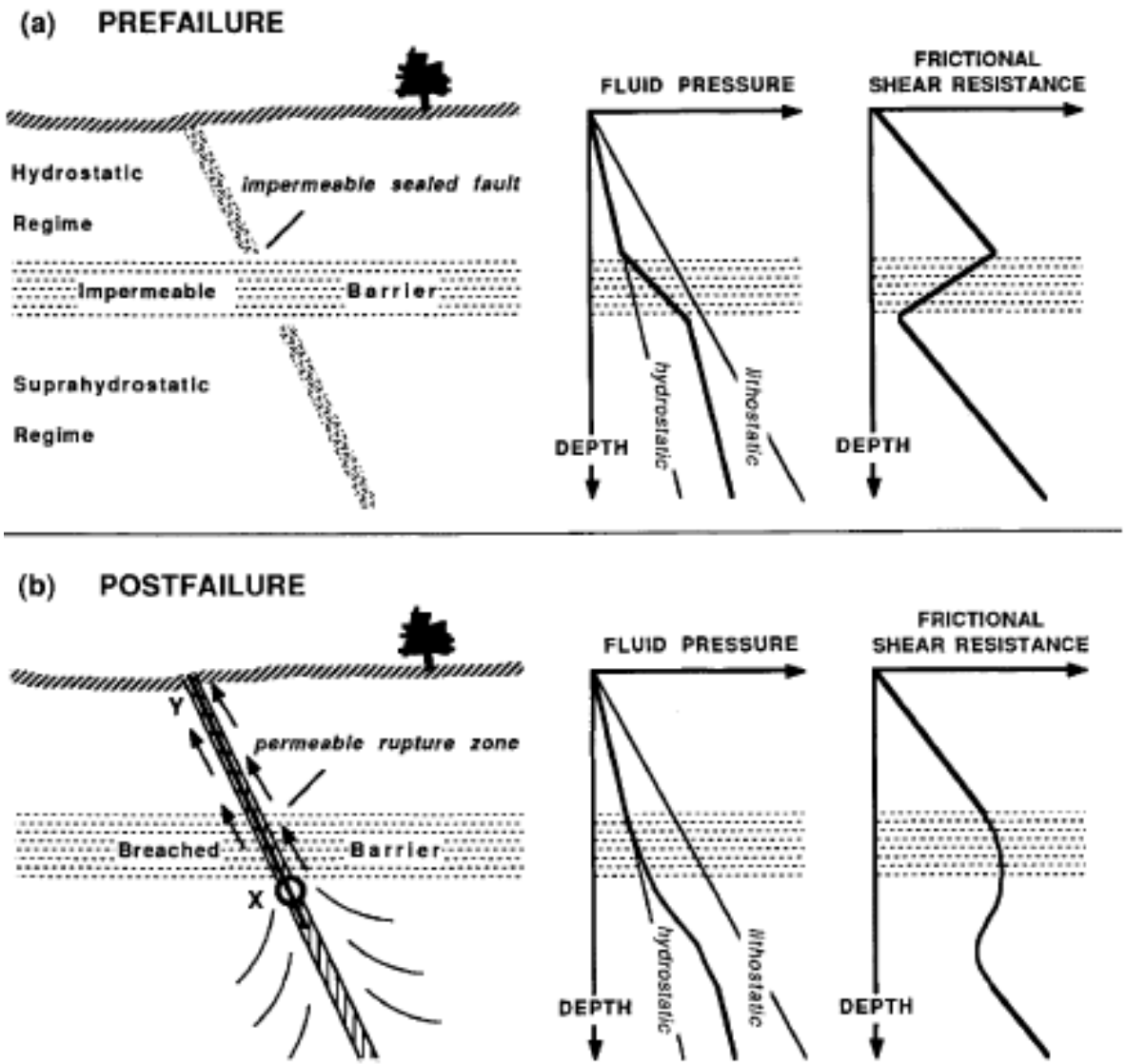






Fault valve behaviour (Sibson, 1992)

The origin could be a fault valve behavior (Sibson, 1992; Lucente et al., 2010; Fischer et al., 2015): in presence of supra-hydrostatic gradients in fluid pressure across an active fault the fluids migrate from the base of the seismogenic zone upward in the crust as porosity/solitary waves (Sibson, 1992; Rice, 1992; Connolly and Podladchikov, 2000; 2013; Revil and Cathles, 2002).



This work aims to further validate this hypothesis by:

- Calculating the permeability values for the principal rock formations;
- Calculating the state of pore pressure when the transient was originated;
- Verifying the compatibility of seismic activity with the overpressure state and the fluid diffusion.

Permeability

$$permeability\ k = D_h \eta_f \left[\varphi \beta_f + (1-\varphi)\beta_r\right]$$

Talwani et al. 1999, JGR.

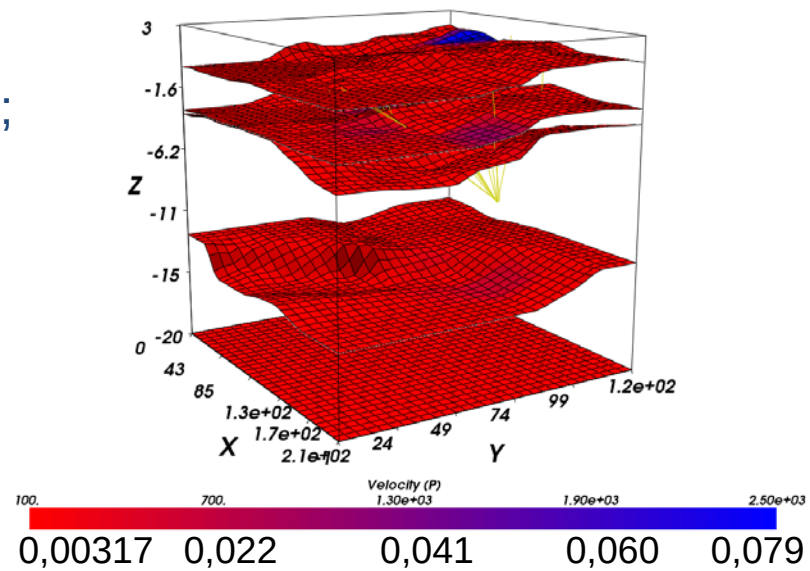
φ = porosity (data from Faccenda et al., 2007, Tectonophysics)

η_f = fluid dynamic-viscosity = $8.90 \cdot 10^{-04}$ Pa s;

β_f = fluid compressibility = $4.6 * 10^{-10}$ Pa^{-1};

β_r = rock compressibility$_r$ = $2 \cdot 10^{-11}$ Pa^{-1} ;

D_h = hydraulic diffusivity (data from Rossi et al., 2016;2017, Tectonophysics).



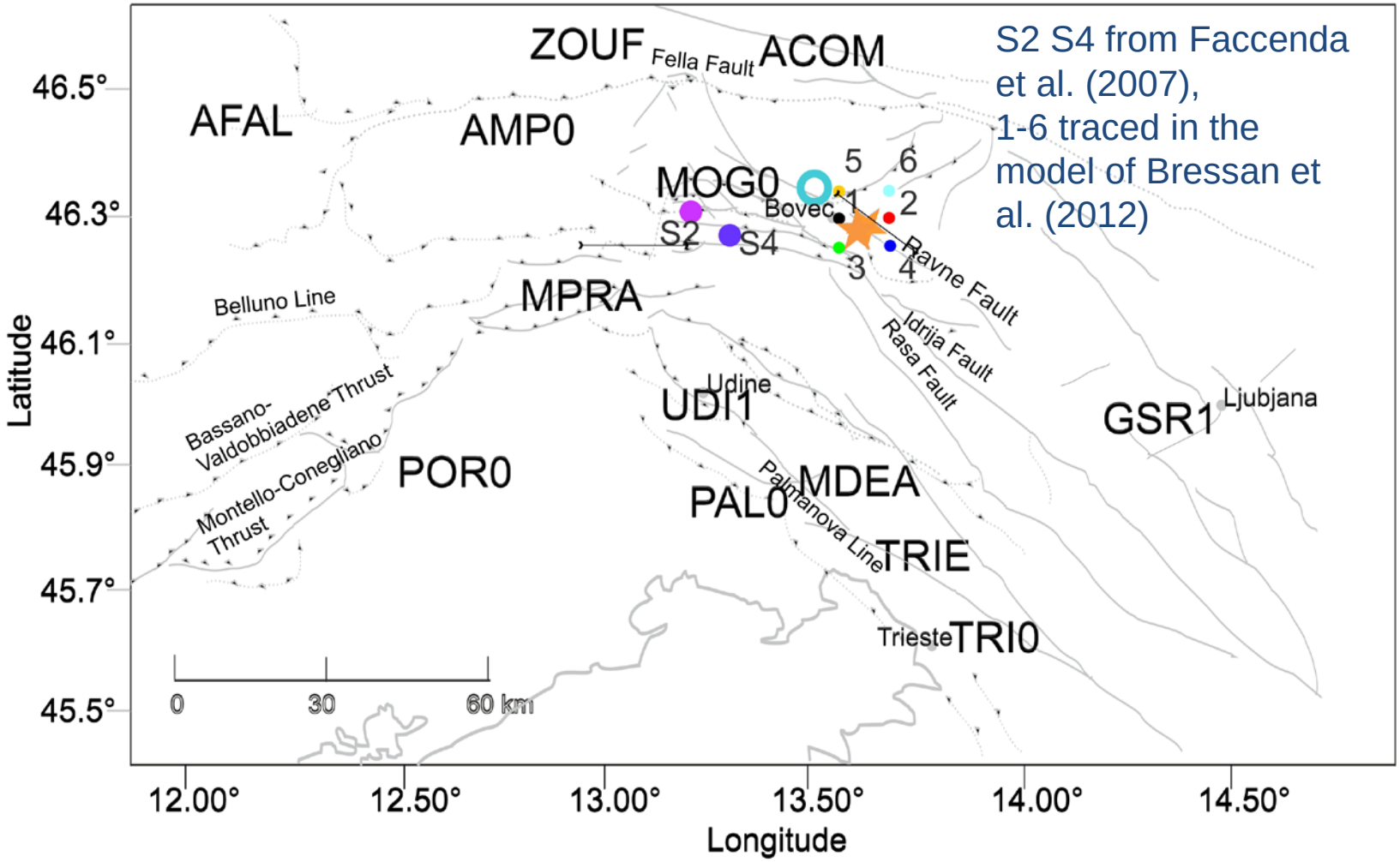
0,00317 0,022 0,041 0,060 0,079

Hydraulic diffusivity m^2/s

Lithology	k (m^2)
Triassic "Dolomia Principale"	$2.87 \cdot 10^{-15}$ $\pm 4{,}61 \cdot 10^{-17}$
Cenozoic flysch	$6.65 \cdot 10^{-16}$ $\pm 1{,}52 \cdot 10^{-17}$
Jurassic limestone	$5.22 \cdot 10^{-17}$ $\pm 1{,}16 \cdot 10^{-19}$
Paleozoic sandstone	$7.60 \cdot 10^{-17}$ $\pm 1{,}11 \cdot 10^{-19}$

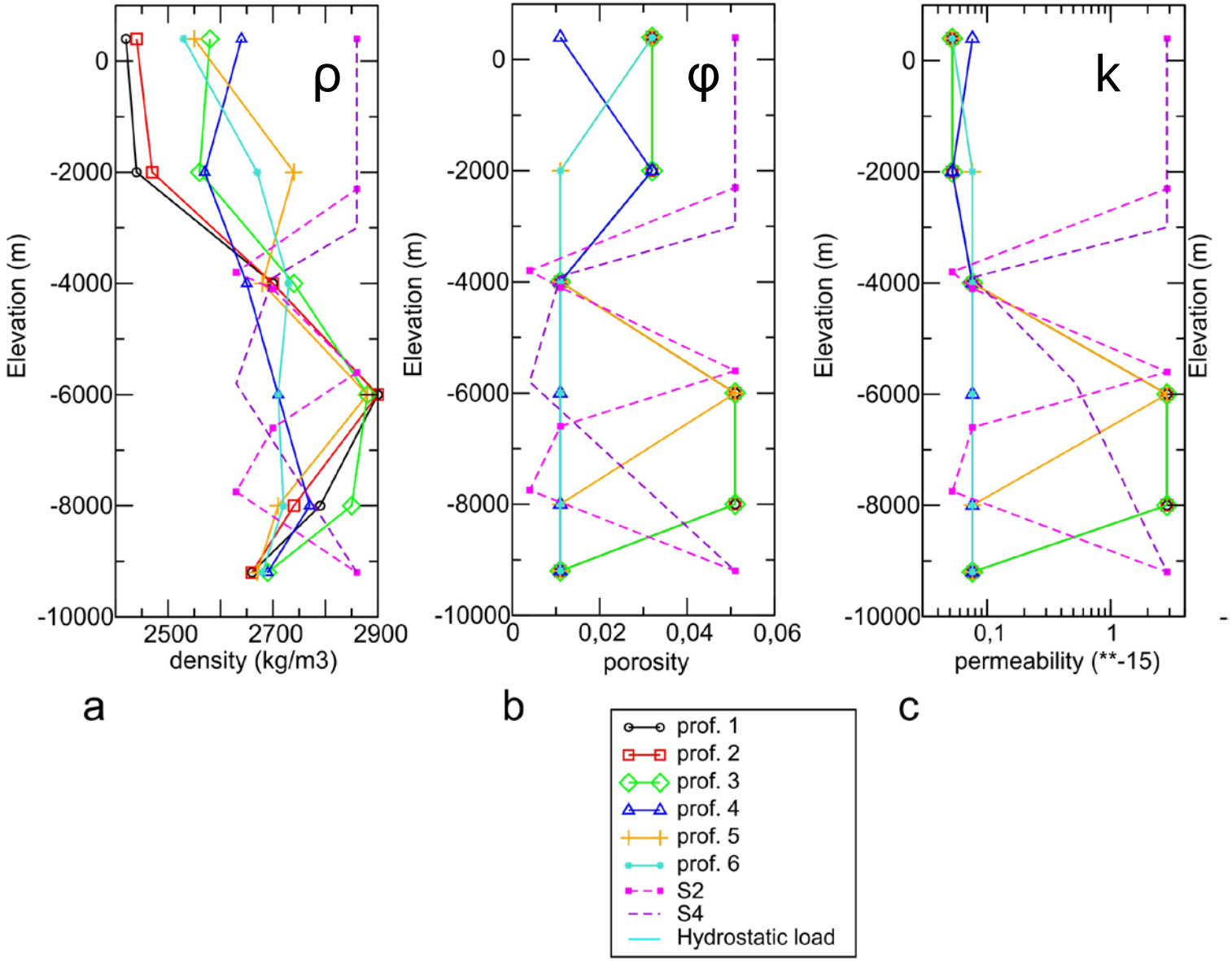
Agreement with Hawle et al. (1967) Petrol.Congress; Sibson and Rowland (2003), GJI; Giorgioni et al., (2010), Mar.Petr. Geology.

Depth variation of the physical properties



S2 S4 from Faccenda et al. (2007), 1-6 traced in the model of Bressan et al. (2012)

Density, porosity, and permeability vs depth



Pore pressure?

Rossi et al. (2016) calculated the effective stress σ_0, which generated the observed wave (23 MPa).

Following Terzaghi, K. (1923)

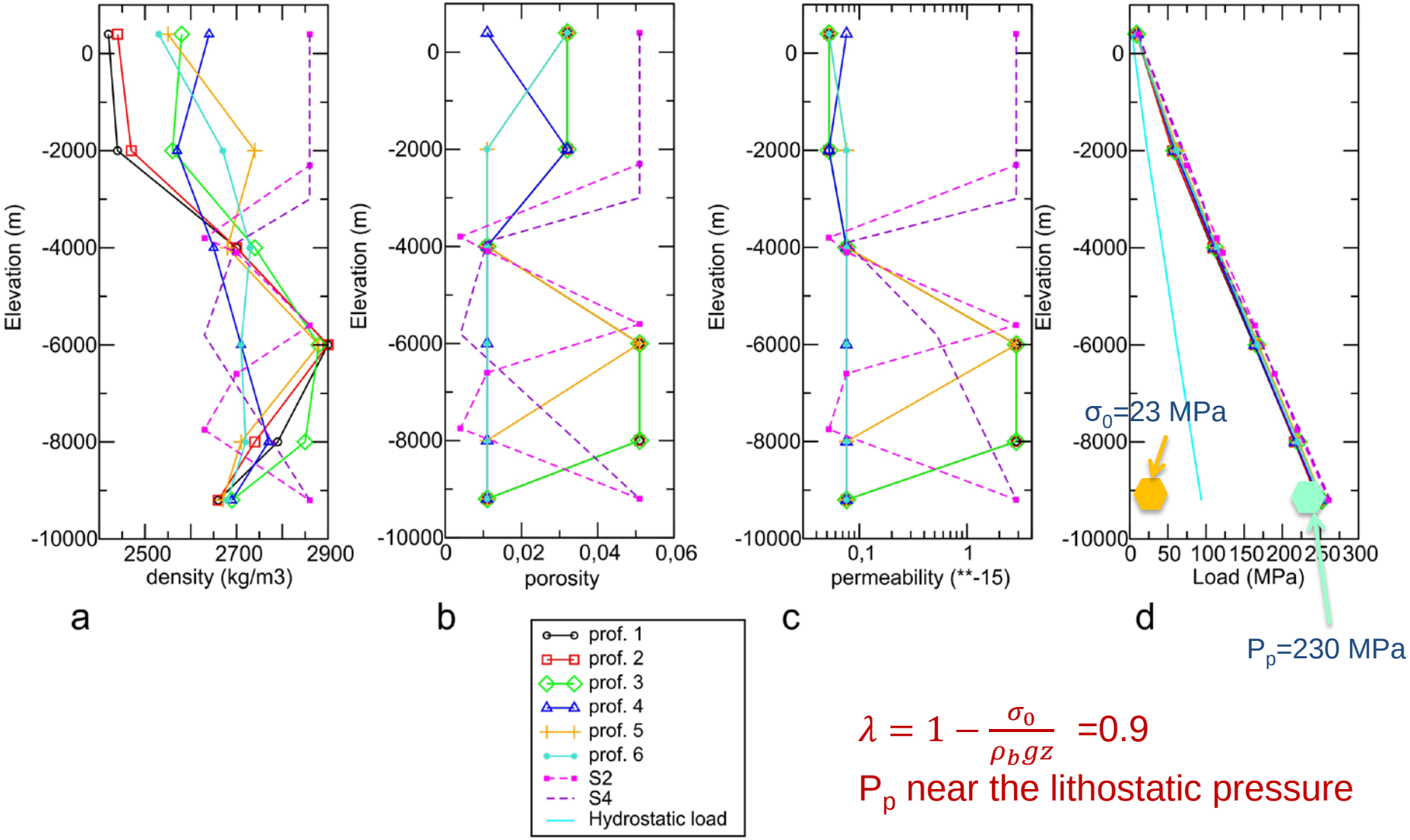
$\sigma_v = \rho_b g z - P_p = (1-\lambda)\rho_b g z$ where $\rho_b = \varphi\rho_f + (1-\varphi)\rho_g$

P_p=pore pressure,
ρ_b=bulk density of sediment
ρ_g: grain density
ρ_f: water density

we calculated : λ =pore fluid ratio

where $\lambda = 1 - \frac{\sigma_0}{\rho_b g z}$

Density, porosity, permeability and lithostatic load vs depth

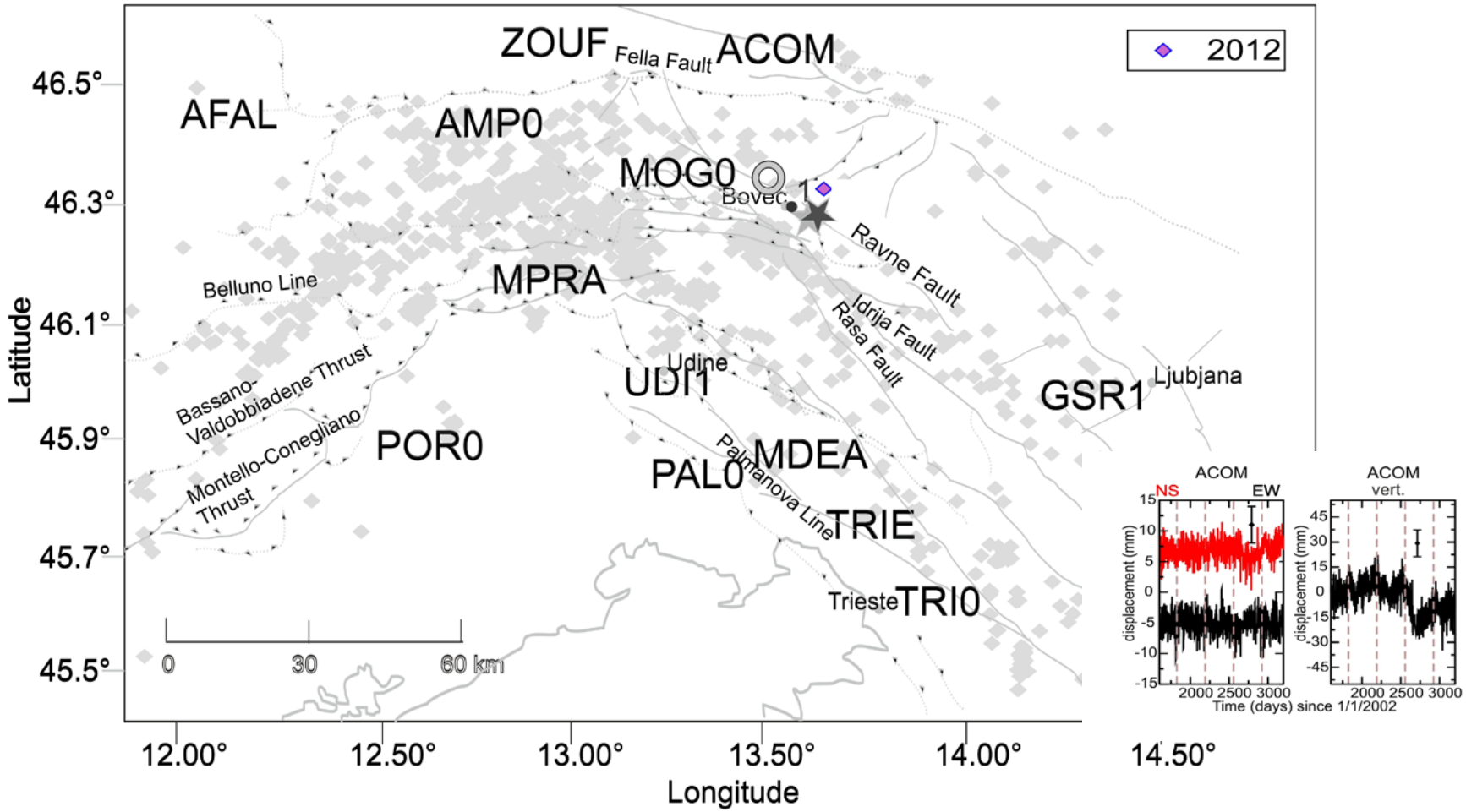


$$\lambda = 1 - \frac{\sigma_0}{\rho_b g z} = 0.9$$

P_p near the lithostatic pressure

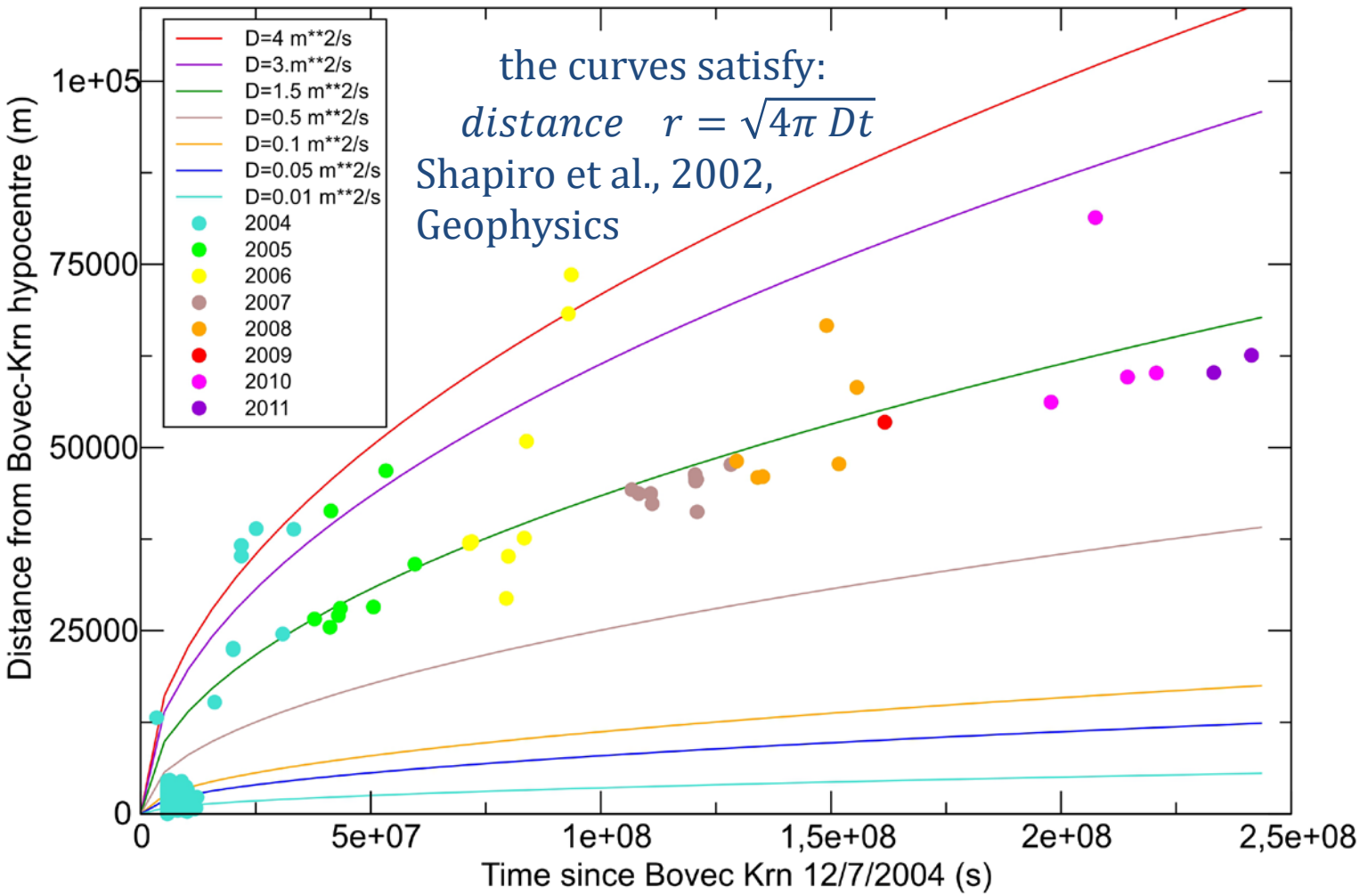
Diffusion as an additional mechanism in the Bovec sequence

2004-2012

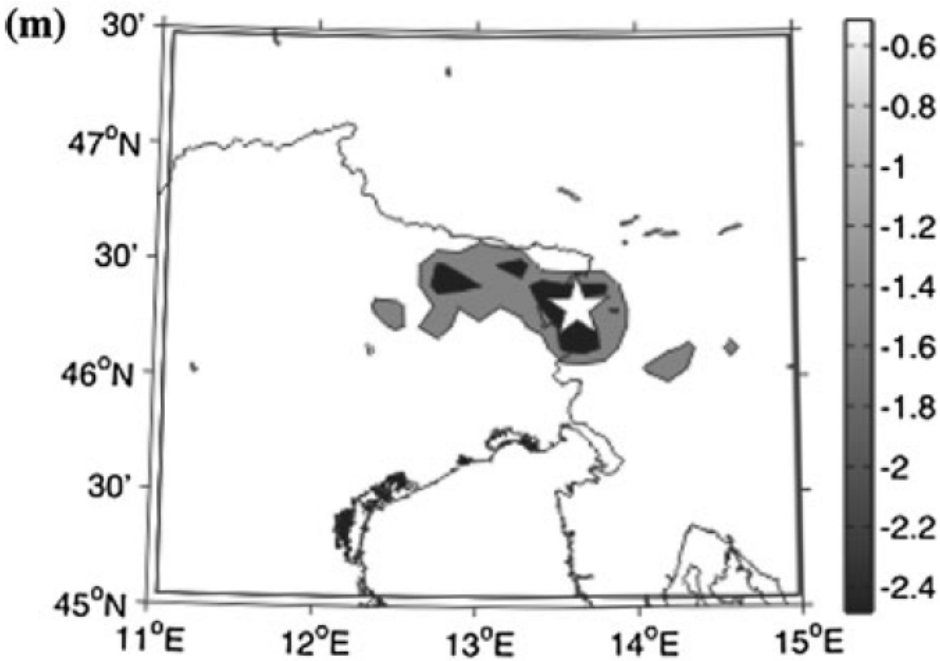


Rossi et al. **Analisi retrospettiva della fase precedente il terremoto di M_D=5.1 di Bovec-Krn (2004).**

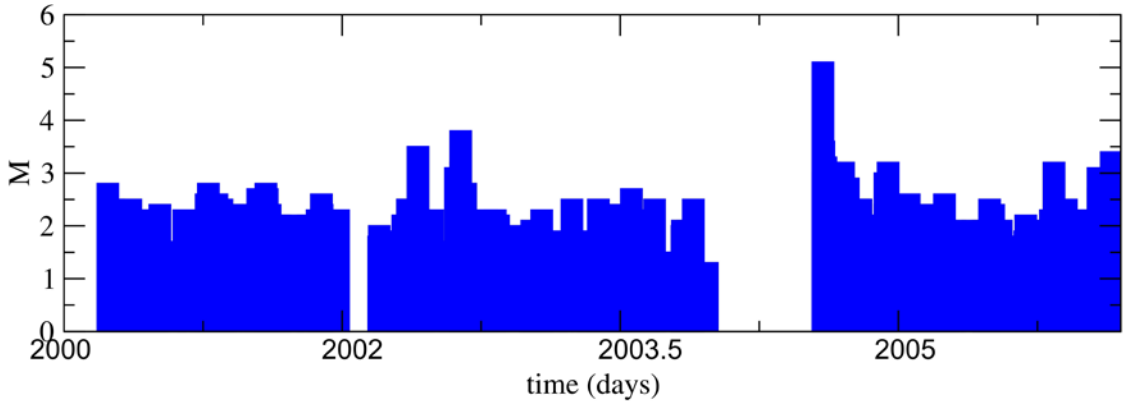
Diffusion as an additional mechanism in the Bovec sequence and in the following



But what occurred BEFORE the 2004 Bovec-Krn earthquake?



A quiescence is observed before the main shock from RTL analysis (Gentili, 2010, PAGEOPH). Earthquakes are precluded under conditions of fluid overpressure (Townend and Zoback 2000, Geology)



CONCLUSIONS

- The permeability values for the four main rock formations in the region are consistent with independent observations for similar lithotypes.
- The ratio between the effective stress and lithostatic load for different vertical profiles in the Bovec area indicated a state of overpressure, with pore-pressure close to the value of the lithostatic load.
- Some of the earthquakes following the Bovec-Krn 2004 earthquake are compatible with a mechanism of fluid diffusion, and their locations are consistent with the transient.
- A quiescence has been observed in the months preceding the Bovec-Krn 2004 earthquake, compatible with the overpressure state precluding earthquakes.
- The valve behavior of the Ravne fault is, hence, compatible with the seismicity characteristics.

THANKS!

J.Brauer https://www.mountainphotography.com/gallery/earthquake-in-julian-alps/

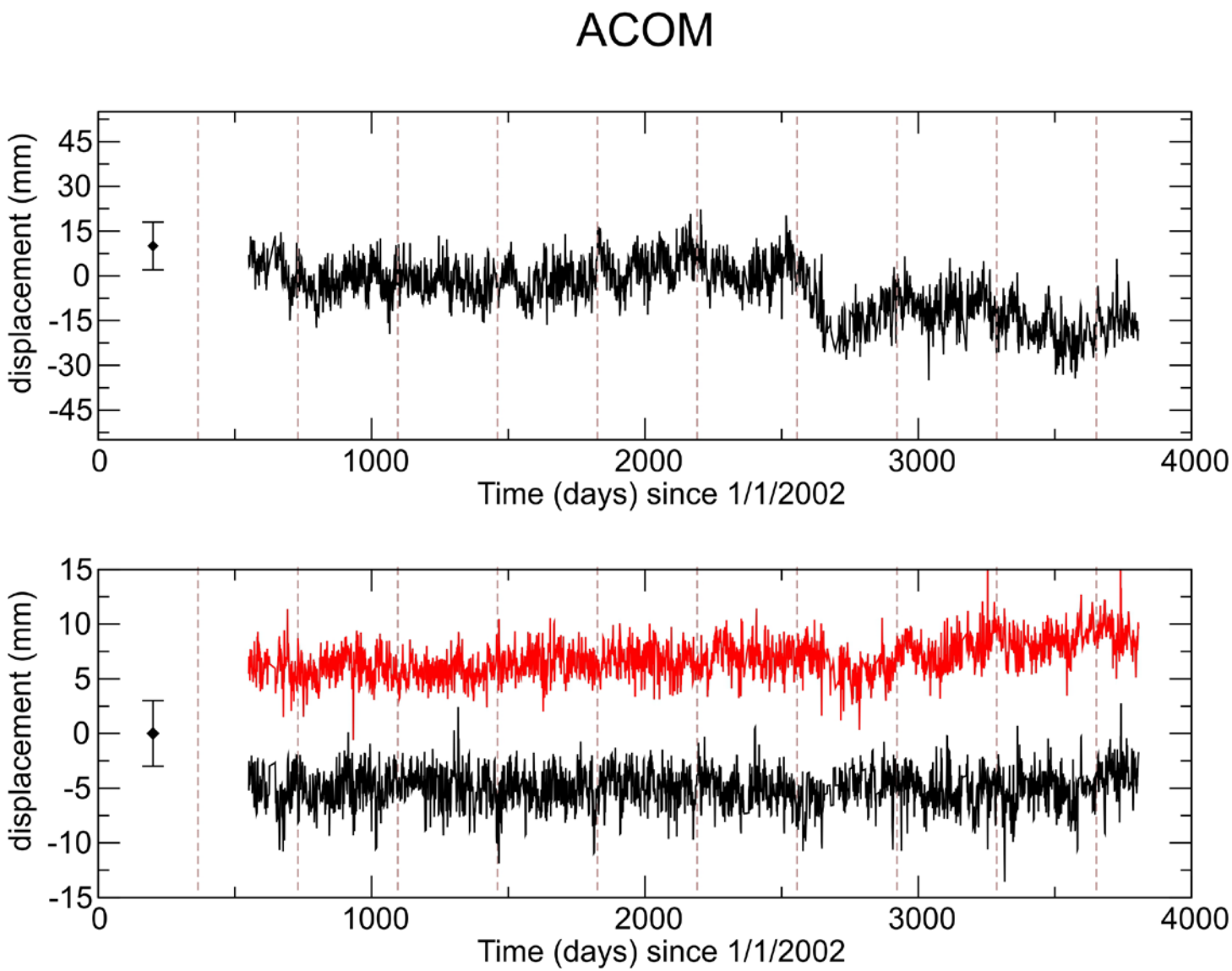
More details in

Rossi, G., Fabris, P., Zuliani, D., 2018. Pure and Applied Geophysics, 175, 1869-1888, doi: 10.1007/s00024-017-1712-x.

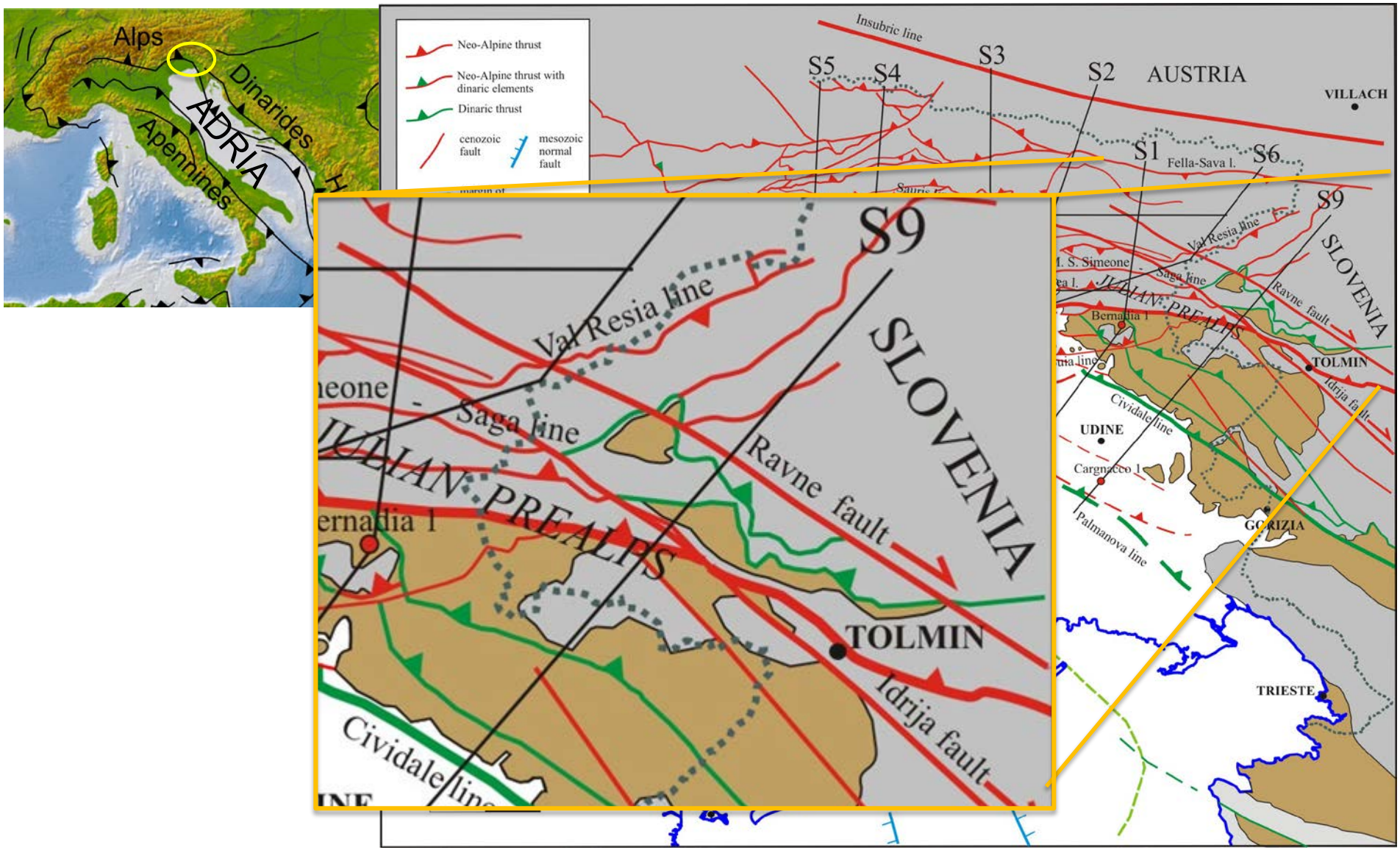
The seismometric network and FReDNet are managed by OGS with the support of the Friuli Venezia Giulia Regional Civil Protection. We thank ARSO for data sharing, all the colleagues managing the OGS seismometric network, and G. Bressan, and G. Bohm, for the suggestions and comments.

Materiale supplementare

Analysis and correction for the hydrological and seasonal effects



Northern Adria: the tectonics



Bressan G., et al. 2016. J. of Seismology, 20, I2, 511–534, DOI: 10.1007/s10950-015-9541-9.

Hydraulic tomography

If it is a porosity wave, with fluid-filled cracks, it can be inverted through hydraulic tomography, the main equation being:

$$t(x_r) = \frac{1}{\sqrt{6}} \int_{x_s}^{x_r} \frac{ds}{\sqrt{D_h(s)}}$$

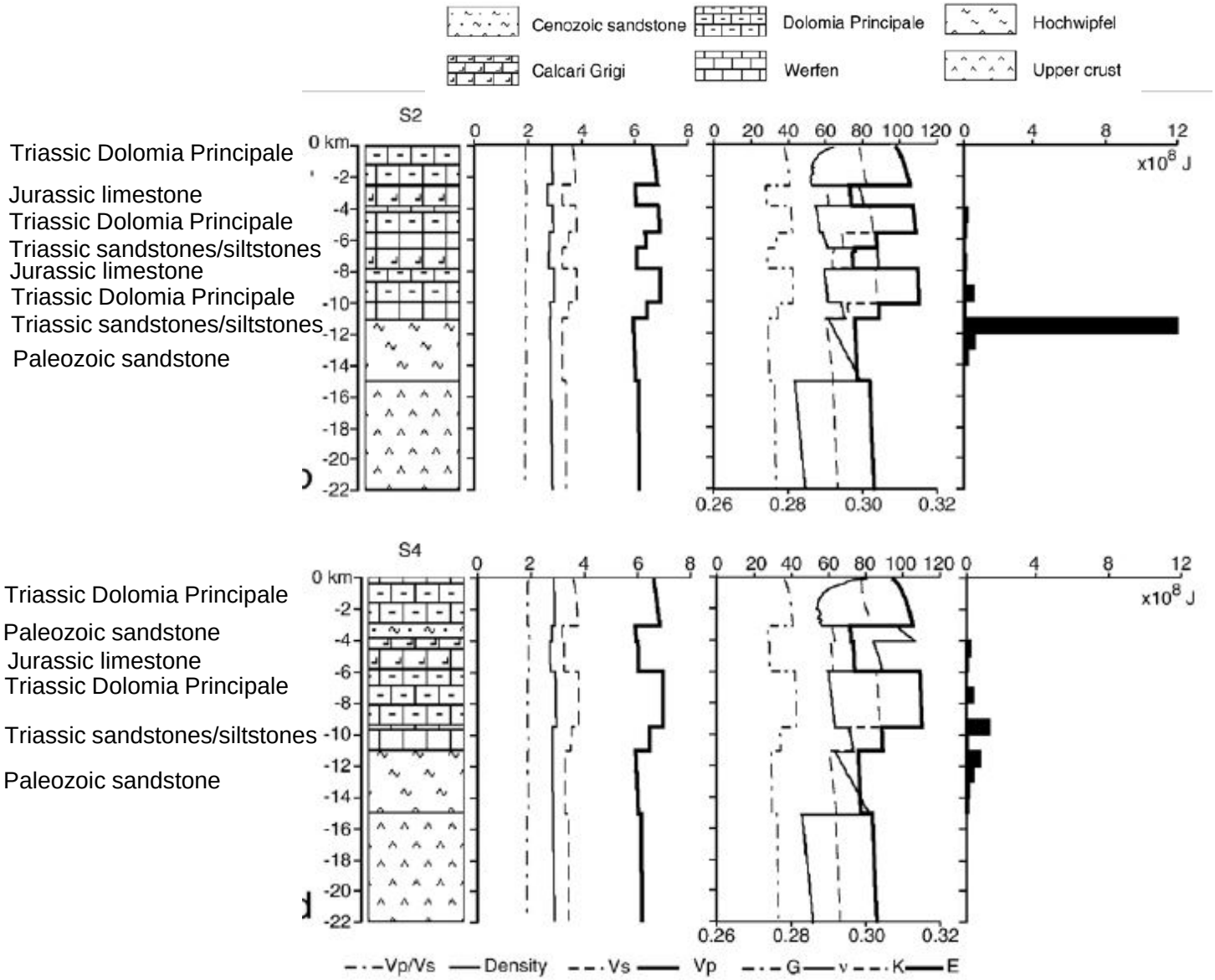
t is the observed arrival time of a signal from the source s to the receiver r and D_h is the diffusivity as function of the path s (Brauchler et al, 2013).

Hydraulic diffusivity is:

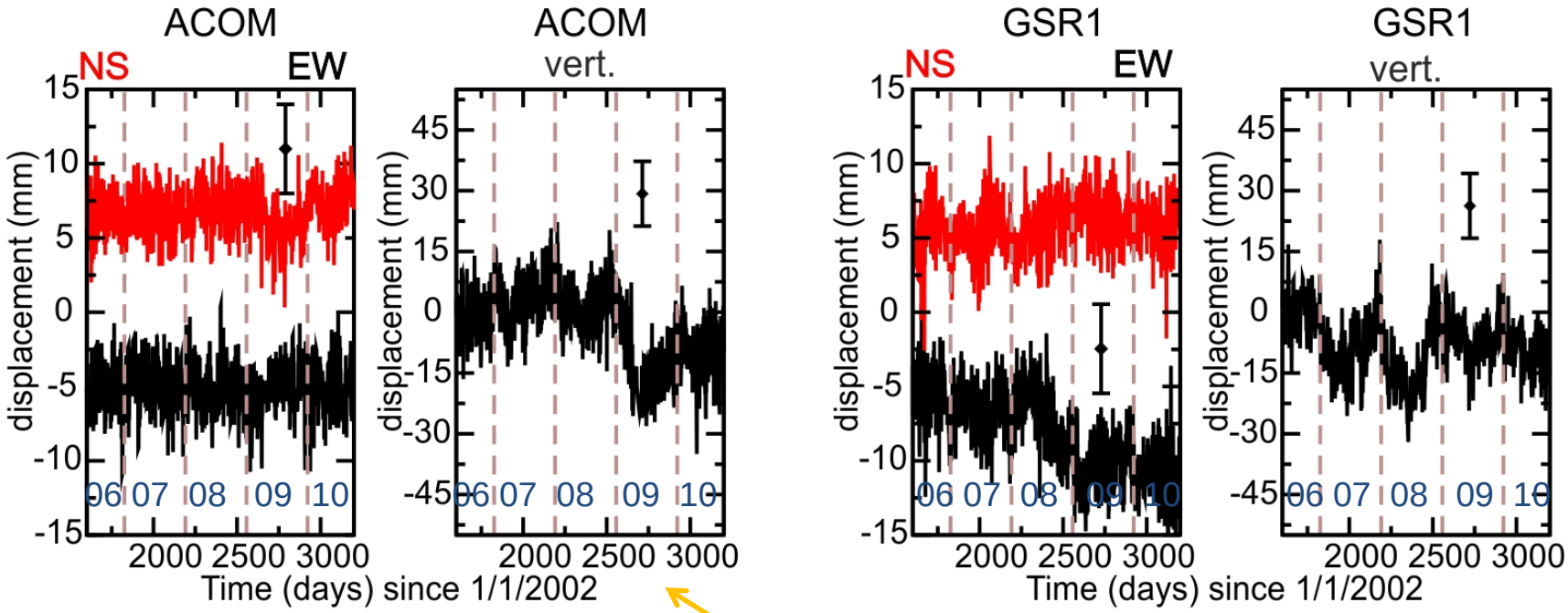
$$D_h = \frac{k}{\eta_f \beta}$$

where η_f is the fluid viscosity, k the permeability and β the compressibility.

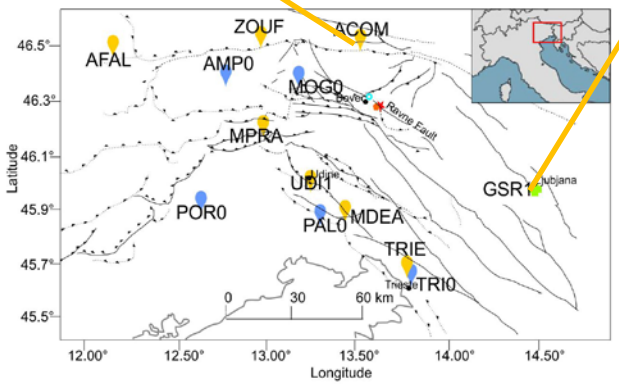
Stratigraphy in the region



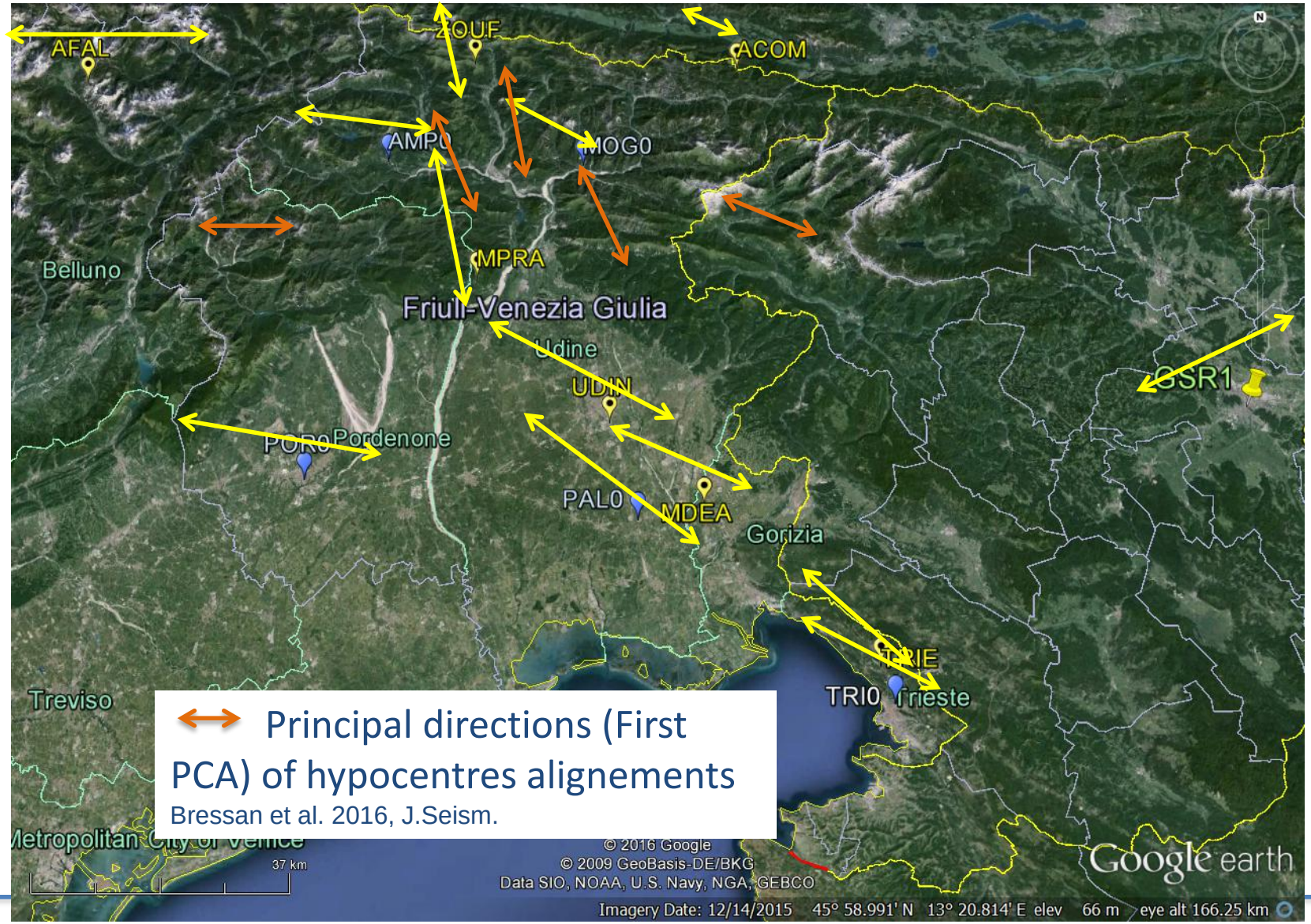
The transient signal after correction from the hydrological and seasonal effects



Rossi G., Zuliani D., Fabris P., 2016. Tectonophysics, 690,142–159,
Rossi G., Zuliani D., Fabris P., 2017. Tectonophysics, 694, 486–487.
Rossi, G., Fabris, P., Zuliani, D., 2018., Pure and Applied Geophysics, 175, 1869-1888.

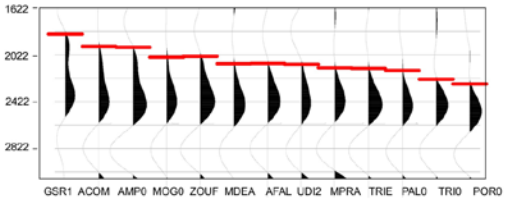


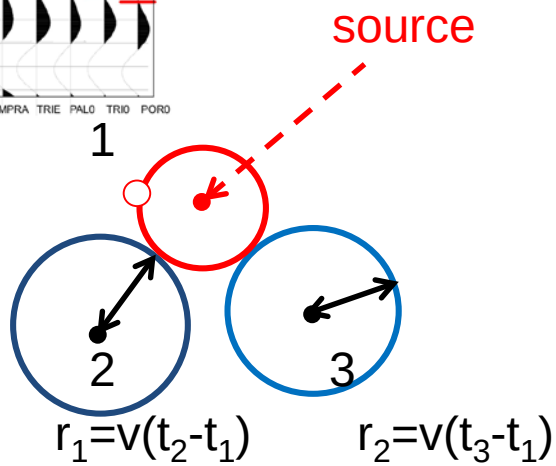
Rossi et al. ESC 2016
Tilting directions



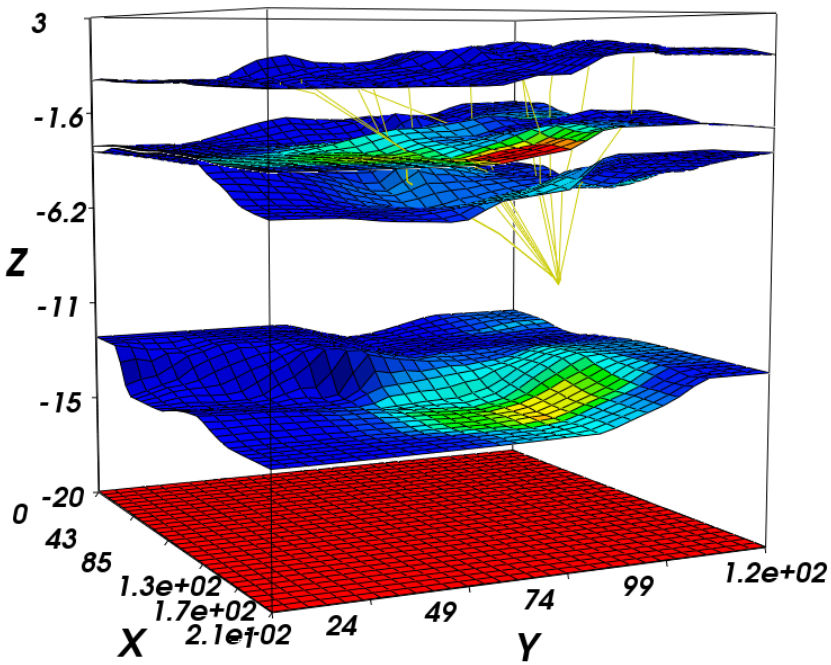
↔ Principal directions (First PCA) of hypocentres alignements

Bressan et al. 2016, J.Seism.

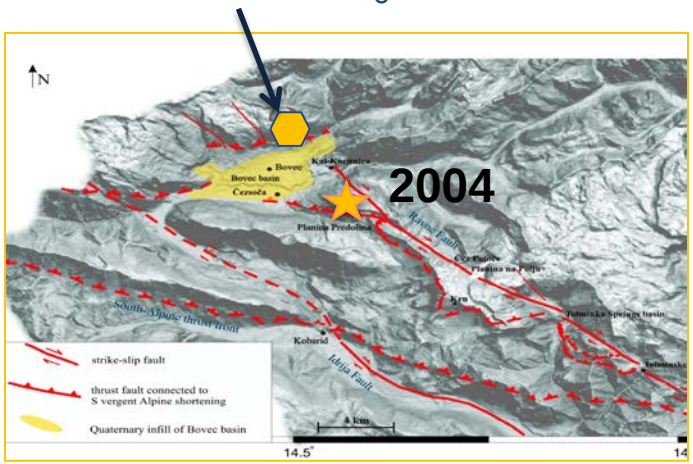




Velocity
7-40 km/yr



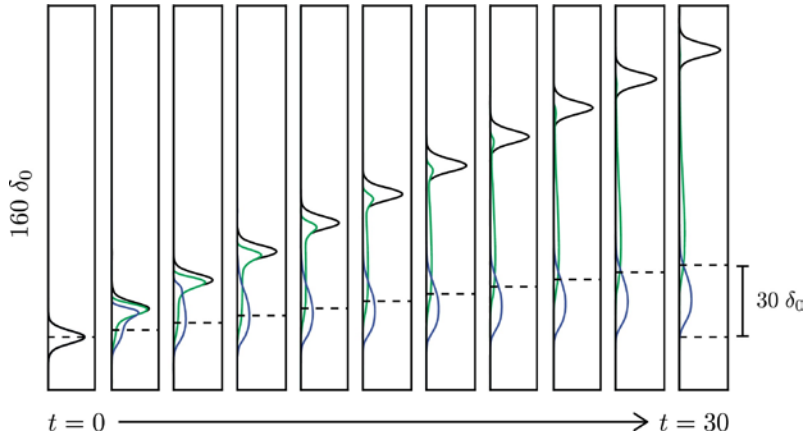
Transient source t_0= March, 27th 2004



Kastelic et al., 2008 J. Struct. Geol.

Porosity waves

- **Porosity are packets of fluid-filled, hydraulically connected cracks** that **self-propagate** within a ductile matrix **following the pressure gradient** (Rice, 1992; Connolly and Podladchikov, 2000; 2013; Revil and Cathles, 2002).
- The porosity waves break up into **spherically symmetric 3D solitary wa**ves, since the 1D solution is unstable. In heterogeneous media, **the wavefront changes shape, following permeability variations** to achieve more efficient transport (Wiggins and Spiegelman, 1995).
- There is compaction at the base of the affected rocks and dilation at the top with an **upward propagation of the porosity wave** (Connolly and Podladchikov, 2013), and in the direction of the minimum horizontal stress.



Jordan et al., EPSL, 2018

Is this plausible?
Relationship between the horizontal and the vertical motion

Skarbek, R.M. & Rempel, A.W. (2016). *G-cubed*