# Groundwater changes affect crustal deformation, elastic properties and seismicity rates in the Southern Alps (Italy)

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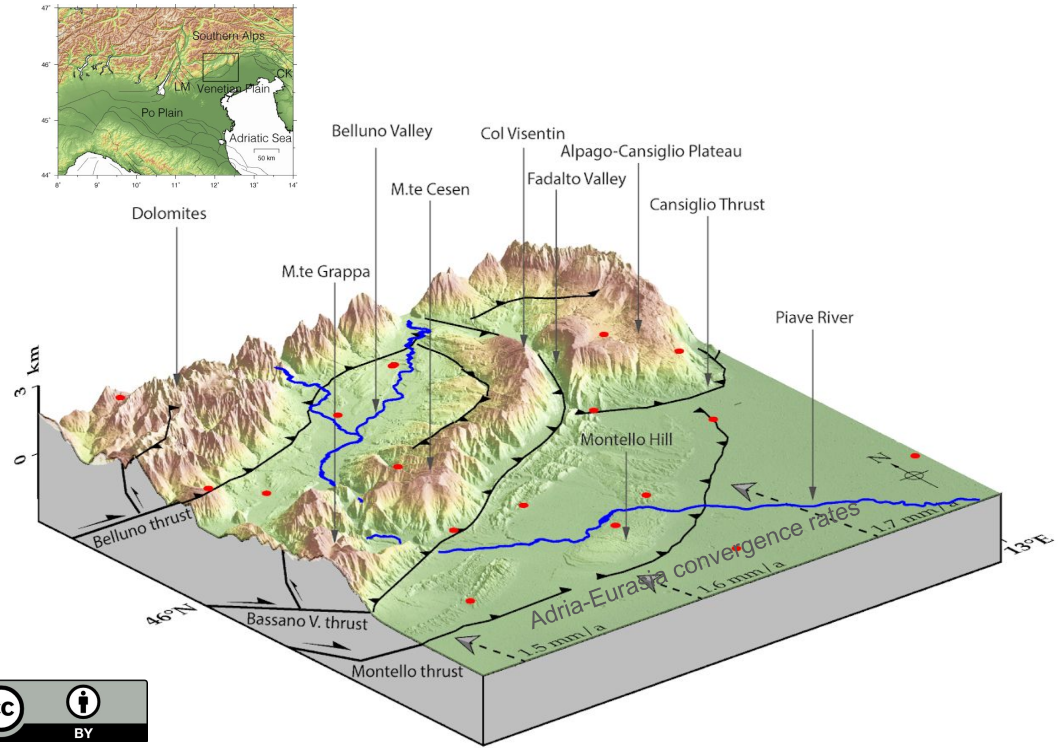



GPS show a **transient deformation signal**, occurring normal to the mountain chain, **causing a sequence of extensional and compressional deformation** (Serpelloni et al., JGR, 2018), superimposed on the long-term tectonic deformation (Serpelloni et al., Tectonophys., 2016)

**Total Water Storage (TWS) changes**, calculated from a lumped parameter hydrological model (GR5J), are **temporally correlated with the geodetic transient signal**.

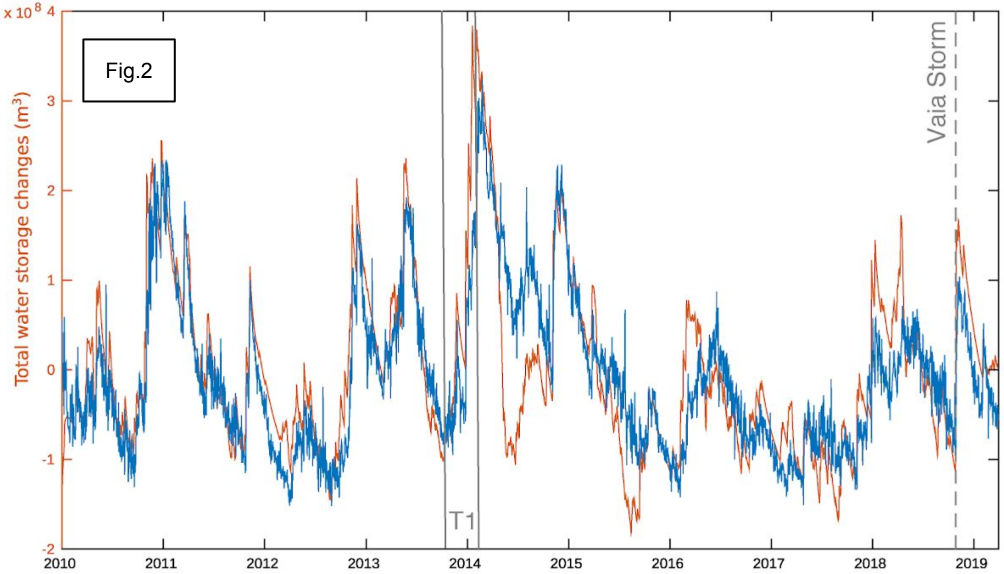
**Background seismicity rates**, from a local high-resolution seismic network, are also **temporally correlated with TWS changes**.

Numerical geomechanical modelling suggests a **sub-vertical hydrologically-active fracture**, associated with the Bassano-Valdobbiadene backthrust, as **the deformation source**, implying **stress changes up to 25 KPa at seismogenic depths** (4-13 km).

**Changes in the medium properties**, calculated from analysis of the ambient **seismic noise cross-correlation**, are **temporally (anti-) correlated with TWS changes**.

# Correlation with hydrology

We estimate Total Water Storage (TWS) variations in the hydrological basins of the Piave river (Fig. 1) using the GR5J hydrological model, constrained by precipitation, temperature, evapotranspiration and river discharge measurements. TWS changes for the Belluno Valley basin are temporally correlated with the geodetic transient signal detected in Serpelloni et al. (JGR, 2018) obtained from the application of a variational Bayesian Independent Component Analysis method (Gualandi et al., J. Geodesy, 2016) to the GPS displacement time-series (Fig. 2).



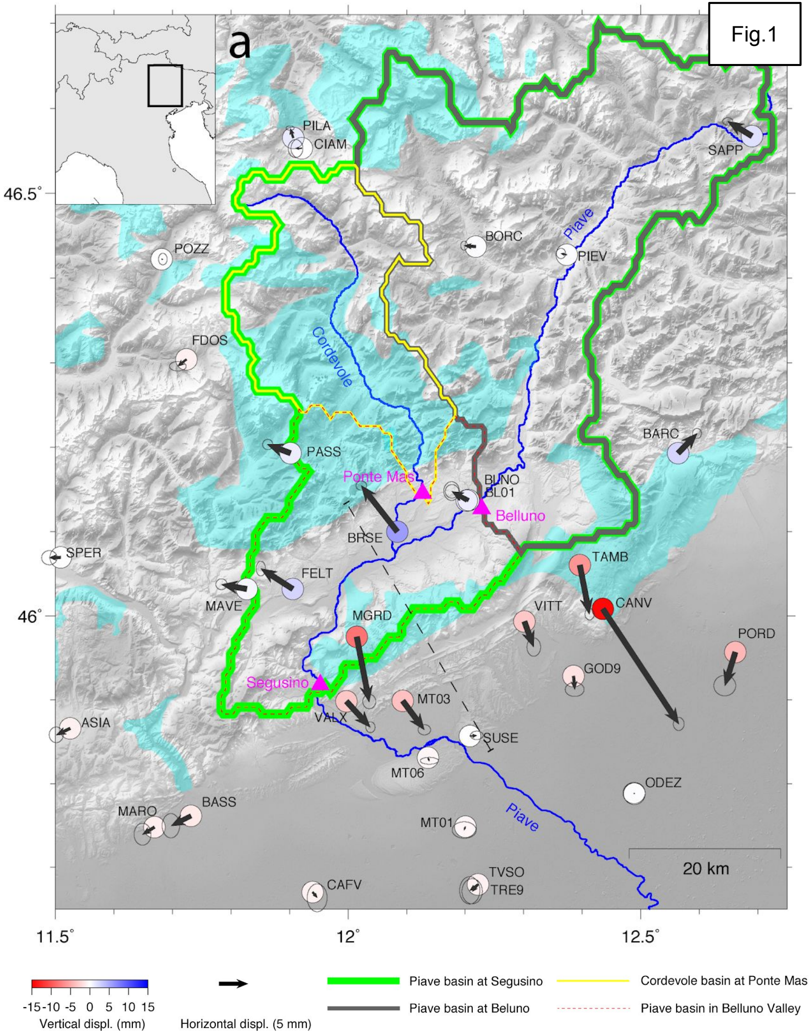




*Fig. 1 - Hydrological basins and displacements of GPS stations during T1 (Fig. 2 and Serpelloni et al., JGR, 2018 for more details on the vbICA analysis).*

*Fig. 2 - Temporal evolution of the TWS changes in the Belluno Valley (orange) and the geodetic transient deformation signal component (blue). Note the rapid response to the October, 2019 Vaia storm (dashed line).*

# Correlation with seismicity

Background seismicity, obtained from ETAS modeling of a high-resolution earthquake catalogue (Romano et al., SRL, 2019), has been analyzed looking for temporal correlations with the geodetic and hydrological signals.

We use a covariate model (Garcia-Aristizabal, GJI, 2018) in order to provide a robust statistical evaluation of possible relationships between TWS changes and background seismicity rates. Using this approach we test two competing models: a constant rate (i.e. stationary, with no dependence between seismicity and TWS) and a log-linear relationship between seismicity rates and TWS changes. The model selection is based on Bayes factor calculations (see Garcia-Aristizabal, GJI, 2018 for more details).

We identified two spatial clusters (A and B in Fig. 3) using K-means. Seismicity rates in cluster A change in agreement with TWS changes (Fig. 4c), whereas a somehow opposite trend is observed for cluster B (Fig. 5e). The results obtained with the covariate approach confirm this observation (Fig. 4d and 5f).

Fig.3

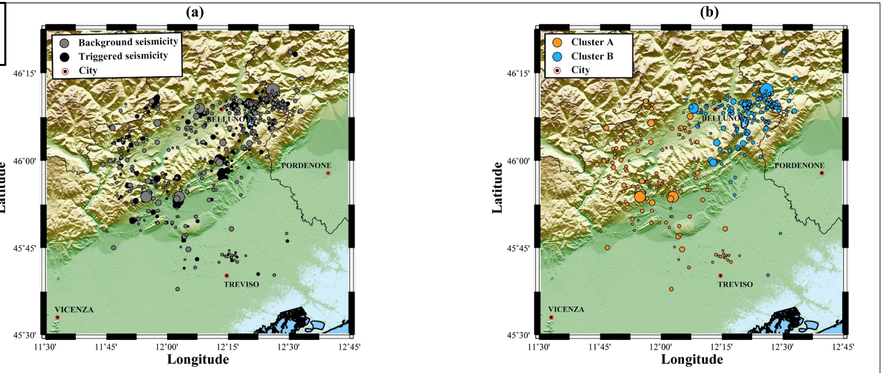



Fig.4

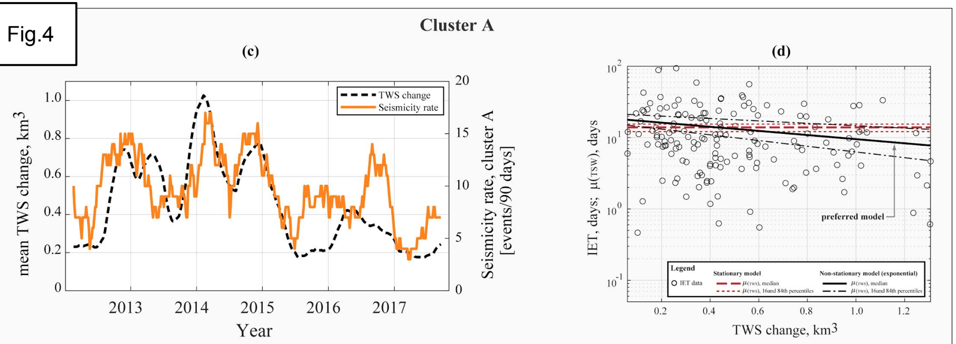



Fig.5

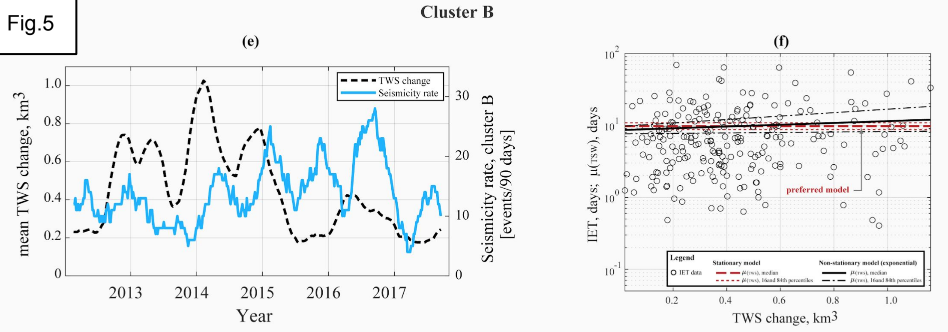



*Fig. 3 - (a) Background (grey circles) and triggered (black circles) seismicity. (b) Spatial clusters (A and B) of background seismicity identified using K-means.*

*Fig. 4 - (c) Moving average of TWS changes (dashed black) and rate of seismic events (orange) in cluster A calculated in 90-days length time windows sliding at increments of 1 day. (d) plot of inter-event times (IET) against TWS changes in cluster A and results for the stationary (red) and Log-linear (black) models.*

*Fig. 5 - (e) Moving average of TWS changes (dashed black) and rate of seismic events (blue) in cluster B calculated in 90-days length time windows sliding at increments of 1 day. (f) plot of inter-event times (IET) against TWS changes in cluster B and results for the stationary (red) and Log-linear (black) models.*

# Inferring the deformation source

A 2D numerical model, constrained by subsurface geological and geophysical information (Fig. 6a), is used to test different sources of deformation potentially able to "accommodate" groundwater level changes (Fig. 2 slide 1) while explaining the observed ground displacements (Fig. 1 slide 1).

The preferred source is the network of damage-zone faults associated with the Bassano-Valdobbiadene backthrust (Fig. 6b), which is simulated through an open fracture. We assume that the water level in the fracture varies as the TWS, causing pressure changes orthogonal to fracture walls.

Stress perturbations associated with this source are shown in Fig. 7a for faults parallel to the Montello decollement (red line). However, faulting mechanisms of background seismicity are heterogeneous (Romano et al., SRL, 2019), responding to a highly deformed upper crust inherited by the complex tectonic evolution of the Southern Alps. For this reason a spatial correlation between seismicity and regions of stress increase is difficult to find.

The amplitude of the CFF changes (Fig. 7a) is much larger than the one generated by the annual surface hydrological mass loading (Fig. 7b).

Fig.6

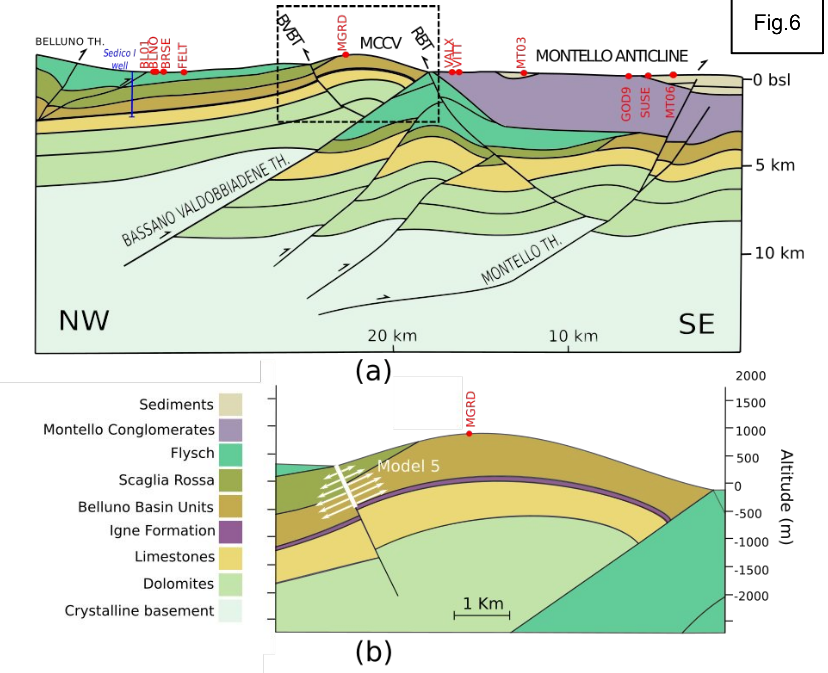



*Fig. 6 - (a) Geological cross section of the study area; red dots: position of the GPS stations projected along this NW-SE profile. RBT: Revine backthrust; BVBT: Bassano-Valdobbiadene back thrust. (b) zoom on the hydrologically-active BVBT and associated pressure profile (white arrows).*

Fig.7

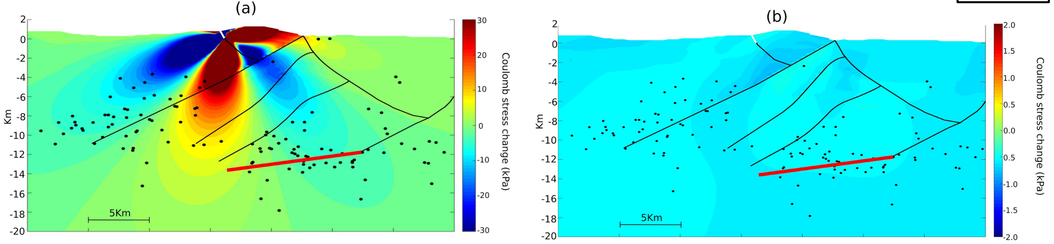
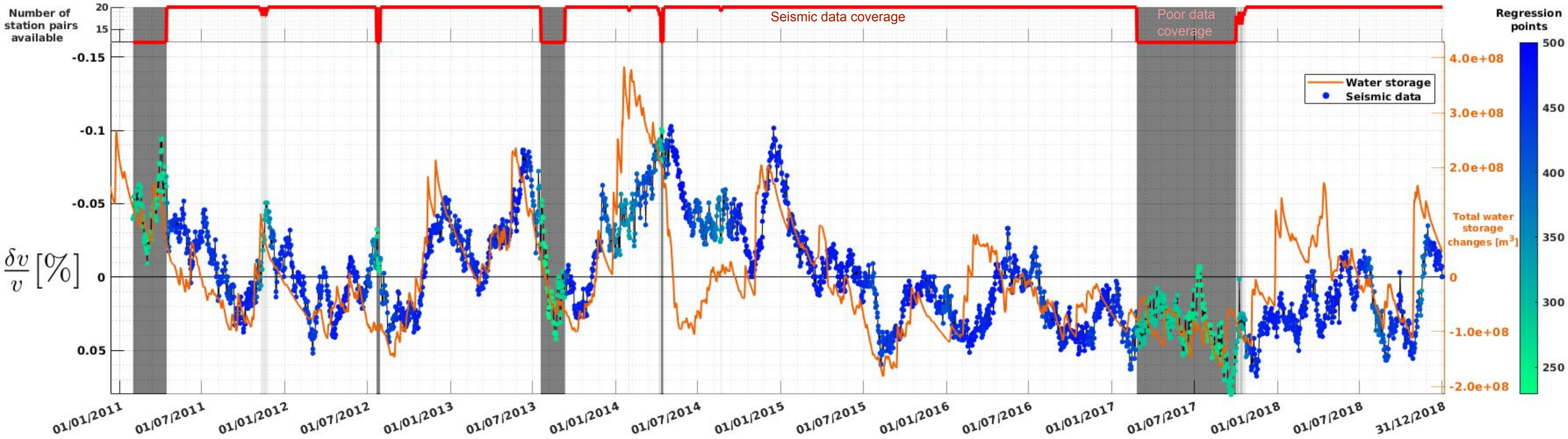



*Fig.7 - (a) Coulomb stress change during a phase of TWS increase (see Fig. 2, slide 1) caused by the source of deformation considering planes parallel to the Montello decollement, highlighted in red. (b) Coulomb stress change calculated on the same dipping planes considering as source of deformation a 1 kPa uniform load on the free surface, representing the large scale superficial loading. The black dots represent the background seismicity of cluster A (Fig.3b slide 3).*

The background seismicity rates are correlated, without evident temporal delay, with the terrestrial water content. Being independent from hydraulic diffusivity, seismicity modulation is likely affected by direct stress changes on faults planes.

# Seismic noise-based monitoring

Fig.8



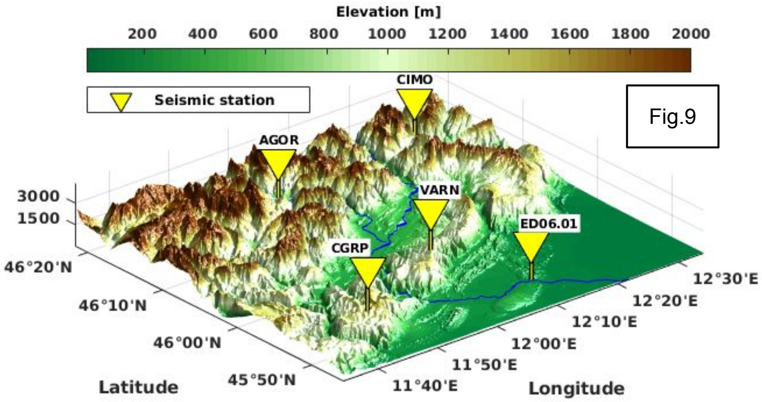

Ambient seismic noise cross-correlation (CC) analysis from the recordings of 5 OGS seismic stations (Fig. 9) allows us to estimate the relative velocity variations (dv/v) undergone in the Earth crust (Fig. 8). We apply moving-window cross-spectral analysis (Clarke et al., GJI, 2011) to the ambient noise cross-correlations at the frequency band dominated by oceanic microseisms (from 0.1 to 0.9 Hz), and measure variations in the propagation velocity of scattered seismic waves.

We interpret changes in dv/v with variable fluid content: negative perturbations are due to an increased amount of fluids in the medium, while positive dv/v to decreasing fluid content.

*Fig. 8 - Comparison between Total water storage (orange) with seismic velocity perturbations, the latter are displayed with reversed sign.*
*Observations from seismic-noise CC show a time delay of ~15 days.*

*Fig. 9 - Location of the seismic stations employed in the analysis at the study site, they are part of the OGS seismic network.*

Fig.9



# Conclusions

1) Hydrologically-active and seismically-active faults can be totally disconnected, and that triggering of seismicity down to depths of 10s of kilometers is mostly related to elastic stress transfer from shallower hydrologically active structures.

2) Hydraulic pressure changes in a shallow fault (<1 km) can generate large shears (~10 kPa) in faults oriented orthogonally at distances of the order of ~10 km (horizontally and vertically).

3) The link between hydrology and seismicity is favoured by 1) the existence of a hydrologically-active fault connected to the surface and an orthogonal seismically active structure (such as a classical thrust/backthrust couple) and 2) water convergence from a watershed/river basin towards the hydrologically active fault, leading to large water storage (so water pressure) changes.

4) Horizontal deformation is best suited to highlight physical links between surface and depth.

5) Ambient seismic noise cross-correlation analysis proves to be an ideal monitoring tool for tracking crustal seismic velocity variations. In the Southern Alps we found a dv/v trend anti-correlated with the upper-crustal deformation due to hydrological cycles, thus showing how these kind of deformations affects also the first few km of Earth crust, also reinforcing the possible link found at point 3) between hydrological variations and seismicity rates.