GEOLOGICAL CONTROL OF HYDROLOGICAL TRANSIENT DEFORMATION IN VENETIAN SOUTHERN ALPS

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The increased availability of precise Global Positioning System (GPS) data, or more generally Global Navigation Satellite System (GNSS), that are dense in both space and time is transforming how scientists measure and visualize active Earth's processes on land, water, ice and in the atmosphere.

The Euro-Mediterranean region is now monitored by thousands of continuously operating GPS stations, providing increasingly detailed measurements of interseismic, coseismic and postseismic deformation occurring at plate boundaries. At the same time, the availability of continuous ground displacement monitoring enables the study of transient deformation processes of different origin. The study of transient deformation signals is of global interest, since transient processes, of both tectonic and non-tectonic origin, can play an important role during the earthquake cycle, increasing/decreasing the seismicity rates or anticipating or

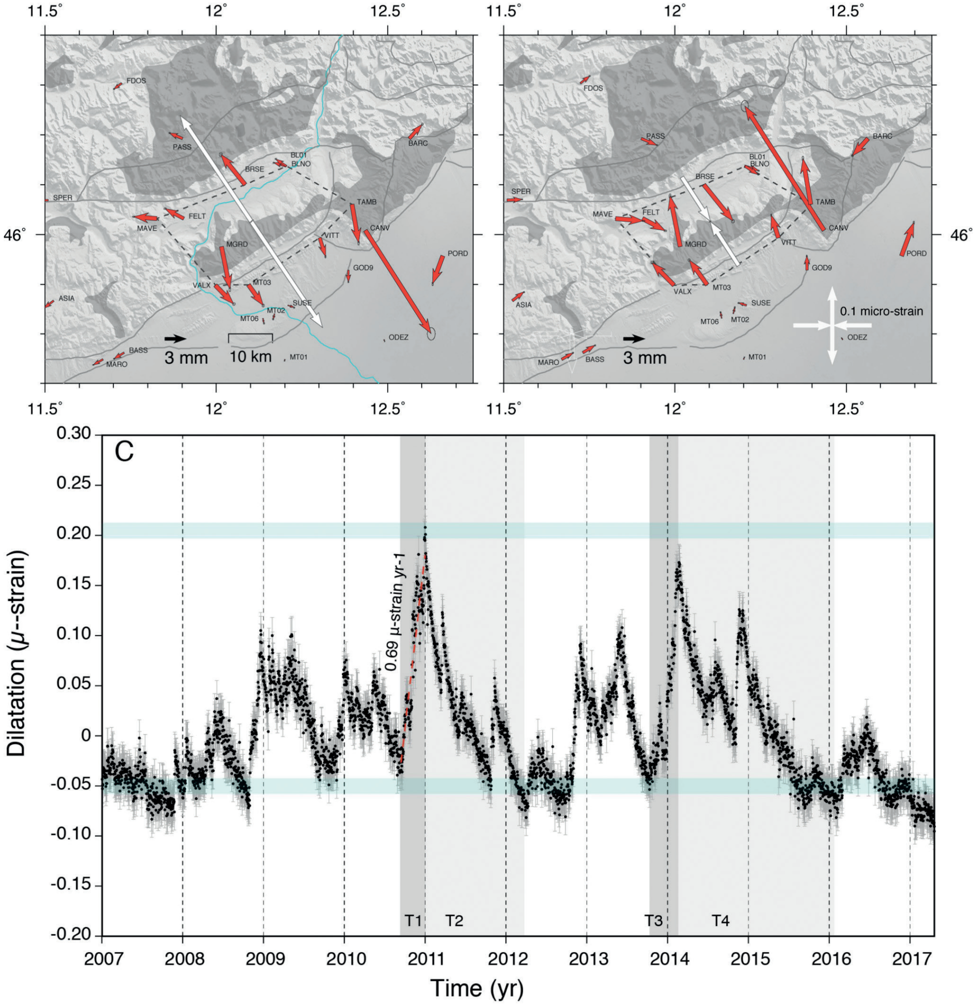

Fig 1 - Top: Horizontal displacements (red arrows) associated with the IC2 signal in the two time intervals T1 (mid-September to December 2010, top left figure, extensional phase) and T2 (January 2011 to April 2012, top right figure, compressional phase). White arrows represent horizontal principal strain axes, obtained from the displacement time series associated with IC2 of stations included in the black dashed polygon. The dark and light gray areas represent "highly productive fissured karst aquifers" and "low and moderately productive fissured karst aquifers" from the International Hydrogeological Map of Europe 1:1,500,000 (http://www.bgr.bund.de/ihme1500). Bottom: Time series of the dilatational strain. Two time intervals (T1, T3) representing extensional deformation are highlighted in dark gray, while in light gray two time intervals (T2, T4) associated to contractions.

delaying the occurrence of large earthquakes. Among all the possible natural processes that cause the Earth's surface to deform, there is an increasing interest in using geodetic observations to study hydrological processes at global to local spatial scales.

Here we focus on the Eastern Southern Alps, a region where large part of the Adria-Eurasia convergence is accommodated (Serpelloni *et al.*, 2016), through large past earthquakes, and now precisely measured by a dense network of continuous GPS stations, managed by several private and public institutions.

GPS horizontal velocities (Cheloni *et al.*, 2014; Serpelloni *et al.*, 2016) show that the highest horizontal deformation rates are localized along the South Alpine mountain front in Veneto and Friuli. Here GPS stations provide a (improvable) measure of the interseismic coupling, showing that for some segments of the Adria-Eurasia boundary aseismic deformation is likely. Moreover, Devoti *et al*. (2015) found that the same area, and in particular the Cansiglio plateau, is affected by deformation processes associated with the hydrological cycle in karsts.

Serpelloni *et al*. (2018) studied GPS displacement time-series in an area encompassing the Veneto-Friuli Eastern Southern Alps and the Northern Dinarides by using the Variational Bayesian Independent Component Analysis (vbICA) (Gualandi *et al*., 2016), a multivariate statistical analysis based on the solution of blind source separation problems. This method allows separating statistically independent signals, named independent components (ICs), characterized by different spatial and temporal features affecting GPS time series.

The results of this analysis highlight two annual components (IC1 and IC3), interpreted as horizontal and vertical displacements associated with continental-scale surface hydrological loading, and a time-variable, non-cyclic signal (IC2). The horizontal displacements associated to this component are larger than the vertical ones, which are almost always below the noise level. Furthermore, the largest amplitudes are recorded in three karst areas of the study region, which are the Lessini Mountains, Val Belluna-Montello-Cansiglio and Northern Dinarides. The GPS stations respond to this signal by moving in opposite directions, reversing the sense of movement in time, implying a succession of extensional/compressional strains (Fig. 1), with variable amplitudes through time, oriented normal to rock fractures.

The temporal evolution of IC2 is correlated with the history of cumulated precipitations at monthly time scales, and it can be explained by pressure changes associated with variable water levels within vertical fractures in the vadose zones of karst systems, as found for the Southern Apennines by Silverii *et al*. (2016).

In this work, we tried to constrain the physical process causing this signal, testing if it is associated with water flow and changes in water storage in karst systems and linking it to the geological features of the area. Quantifying water storage variations cannot be done by using GRACE measurements, because of their limited spatial resolution at the Earth's surface (200x200 km grids); we then decided to represent dynamic of hydrological basins, i.e. areas drained by a river, by means of rainfall-runoff models. These models describe how the rainfall over a basin turns into river flow once given as input rainfall and potential evapotranspiration. Among the outputs of such models, the temporal evolution of the amount of water stored within the basin (water storage variations) is exactly our target.

We focused on the Val Belluna (i.e. Piave river basin) and the pedemountain front of the Venetian Southern Alps, because of the availability of both dense geodetic and hydrological data. In particular, we considered the hydrological basins defined by the Cordevole River at Ponte Mas and by Piave River at Belluno and Segusino (Fig. 2). The hydrological model that best reproduces the observed river flows is called GR5J, which is slightly differs from GR4J (modèle du Génie Rural à 4 paramétres Journalier), described in Perrin *et al*. (2003).

We compared the time evolution of the model total water storage with the temporal evolution of IC2. The correlation between these two quantities is high (Fig. 2): 0.89/0.91 when considering the Piave basin at Belluno/Segusino and 0.78 considering the Cordevole basin at Ponte Mas.

We built a bi-dimensional numerical model with the goal of understanding how water level variations in karst aquifers, rock fractures or fault zones can generate the displacements shown in Fig. 1. In order to take into account the topography and the geological features of Val Belluna and M.te Grappa-M.te Cesen mountain chain, we implemented in the numerical model a geological profile of the Foglio Belluno of the Carta Geologica d'Italia (Fig. 3). We tested different sources of deformation in order to find the one that best reproduces the displacements obtained from the geodetic analysis, finding that it is the backthrust of the Bassano-Valdobbiadene thrust fault. Since M.te Grappa-M.te Cesen mountain chain is karstified and corresponds to an anticline, the top of it is characterized by a distension regime that generates sub-vertical fractures. We made the hypothesis that the meteoric water penetrates through the fractures and flow along an impermeable formation, converging to a sub-vertical fracture, the backthrust of

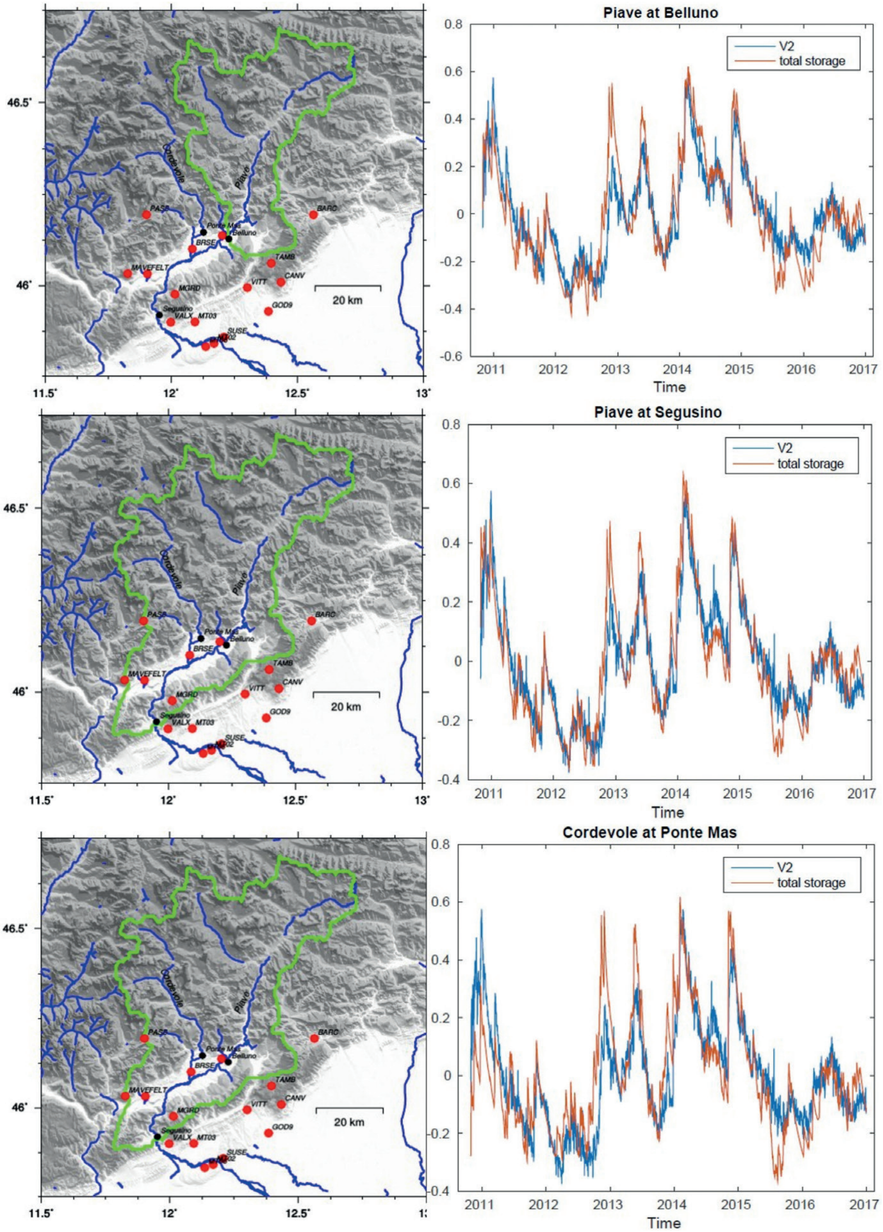

Fig 2 - Top: Piave at Belluno basin; Center: Piave at Segusino basin; Bottom: Cordevole at Ponte Mas basin. Left: The green lines represent the hydrological basins defined in Val Belluna-Montello-Cansiglio area, the red dots the GPS stations position and in blue the rivers. Right: Comparison between temporal evolution of IC2 (blue) and water storage variations (red) in each hydrological basin.

the Bassano-Valdobbiadene thrust fault (Fig. 3). Here, the water accumulates because of the larger permeability of the fractured rock faults, varying its level up to tens of meter and then generating pressure changes that cause the displacements reconstructed by IC2 (Fig. 1).

The identification and characterization, both in space and time, of transient deformation signals is crucial in interpreting active tectonic processes. This is twofold; first because thanks to a proper modeling of non-seasonal transient deformation we can improve the accuracy of

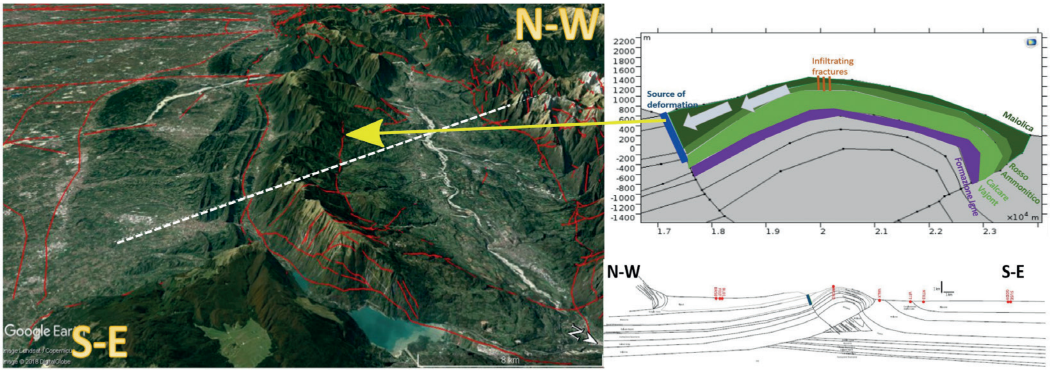

Fig 3 - Left: 3-D view of Val Belluna-Montello-Cansiglio area. The red lines represent the faults, the yellow arrow points the backthust of the Bassano-Valdobbiadene thrust fault, chosen as source of deformation for our model. The cross section of this area along the dashed white line, modified from Carta Geologica d'Italia, Foglio Belluno, is presented in the bottom right figure, where the chosen source of deformation is highlighted in blue and the positions of the GPS stations along this profile, implemented in the COMSOL software for displacements computations are in red. Top right: Process driving to the hydrological transient deformation. In green permeable layers, while in purple the impermeable one.

long-term tectonic rates from geodetic data, second because if transient processes can perturb crustal stress at seismogenic depths, they can affect background seismicity rates or the seismic cycle. In the area under analysis several studies suggest that the Bassano-Valdobbiadene thrust is active and elastically locked, pointing toward a significant seismic potential of this fault. The hydrological deformation discussed in this work is occurring within the anticline associated with this thrust fault. Future studies will include the analysis of seismic velocity changes from ambient seismic noise analyses, the improvement of the GPS network and the analysis of SAR data in order to detect vertical deformation associated with groundwater changes, for which GPS is less sensitive.

A second, but not less important implication of this study is that precise and accurate geodetic data as GPS observations are, can provide an indirect measurements of fresh water resources, such as those in karst aquifers, which is very important considering that more than 25% of the world's population either live on or obtain water from karst aquifers.

References

Cheloni, D., D'Agostino, N. and Selvaggi, G.; 2014: *Interseismic coupling, seismic potential, and earthquake recurrence on the southern front of the Eastern Alps (NE Italy)*. Journal of Geophysical Research: Solid Earth, 119, 4448–4468. https://doi.org/10.1002/2014JB010954.

Devoti, R., Zuliani, D., Braitenberg, C., Fabris, P. and Grillo, B.; 2015: *Hydrologically induced slope deformations detected by GPS and clinometric surveys in the Cansiglio Plateau, Southern Alps*. Earth and Planetary Science Letters, 419, 134–142. https://doi.org/10.1016/j.epsl.2015.03.023.

Gualandi, A., Serpelloni, E. and Belardinelli, M. E.; 2016: *Blind source separation problem in GPS time series*. Journal of Geodesy, 90(4), 323–341. https://doi.org/10.1007/s00190-015-0875-4.

Perrin, C., Michel, C., & Andréassian, V.; 2003: *Improvement of a parsimonious model for stream flow simulation*, Journal of Hydrology, 279(1-4), 275-289.

Serpelloni, E., Vannucci, G., Anderlini, L. and Bennett, R. A.; 2016: *Kinematics, seismotectonics and seismic potential of the eastern sector of the European Alps from GPS and seismic deformation data*. Tectonophysics, 688, 157–181. https://doi.org/10.1016/j.tecto.2016.09.026.

Serpelloni, E., Pintori, F., Gualandi, A., Scoccimarro, E., Cavaliere, A., Anderlini, L., Belardinelli, M. E. and Todesco, M; 2018: *Hydrologically induced karst deformation: Insights from GPS measurements in the Adria-Eurasia plate boundary zone*. Journal of Geophysical Research: Solid Earth, 123. https://doi.org/10.1002/2017JB015252.

Silverii, F., D'Agostino, N. and Métois, M.; 2016: *Transient deformation of karst aquifers due to seasonal and multiyear groundwater variations observed by GPS in southern Apennines (Italy)*. Journal of Geophysical Research: Solid Earth, 121, 8315–8337. https://doi.org/10.1002/2016JB013361.