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GNSS data provide unexpected insights in hydrogeologic processes

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ABSTRACT The analysis of long time series of Global Navigation Satellite System (GNSS) observations has recently evidenced that the slow tectonic processes are not the only ones producing the observed slow deformations, but the Earth's crust reacts also to stresses induced by pressure variations and water circulation. The basic mechanisms are substantially of two kinds: deformations induced by the elastic response of the loaded surface and deformations due to the poroelastic properties of the ground. These mechanisms are quite different, in the first case the water load causes subsidence, in the second uplift; both create horizontal deformations moving away from the centre of deformation. Under anisotropic conditions, water pressure changes in poroelastic soils can induce large horizontal deformations especially where highly fractured rocks may provide permeability for fluid flow. Both elastic and poroelastic phenomena are observable and measurable by continuous GNSS monitoring of ground deformations. Both can be triggered by periodical atmospheric processes but also by extreme events, like heavy rainfalls. We will show a few case studies, observed in the Italian area, that demonstrate how the deformation patterns, at different repeating periods, clearly correlate with groundwater circulation in different environmental condition.

Key words: GNSS time series, Italian area, hydrogeologic processes, deformation patterns.

1. Introduction

Physical processes capable to deform the Earth's crust could be roughly classified into three major categories, distinguished by different mechanisms: internal stress variations caused mainly by mantle convection and its interaction with the lower crust (i.e. tectonic source), gravity variations caused by astronomical bodies (i.e. Earth tides), and loading responses caused by external local or global sources (i.e. ocean, surface or groundwater and atmosphere loadings). In this work we discuss a few peculiar aspects of the crustal response to different loading processes as measured by Global Navigation Satellite System (GNSS) data in Italy. Past works on the elastic response of the Earth's crust were pioneered by George H. Darwin in late 1880, fifth child of the biologist Charles Darwin, mathematician and astronomer, who first investigated the effects caused by variations of pressure acting on an elastic surface such as water mass redistribution due to ocean tide loading (Darwin, 1882).

More recently, Karl Terzaghi, an Austrian geotechnical engineer, introduced the principle of the poroelastic effect of soils: it states that all the measurable effects of a stress change, such as compression, distortion, and change of shearing resistance, are due exclusively to changes in

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the effective stress. The effective stress σ' is related to total stress σ and pore pressure u by the simple relationship $\sigma' = \sigma - u$ (Terzaghi, 1943). Therefore, when a rock is subjected to a stress, it is opposed by the fluid pressure of pores in the rock.

Surface strain variations caused by hydrological processes have been measured thoroughly all over the world, using space geodetic data [GNSS, VLBI (Very Long Baseline Interferometry), and InSAR (Interferometric Synthetic Aperture Radar)]. Vertical displacements induced by seasonal variability in continental water storage have been first measured by van Dam *et al.* (2001) using Global Positioning System (GPS) data. The main component of vertical deformation is an annual oscillation with superimposed long-period variations capable to hide the long-term tectonic trends, if observed on a limited time span. The modelled amplitudes of vertical displacements range within 30 mm.

These findings show that the Earth's crust reacts to water circulation basically because of its weight and pressure variations. Water content variations cause time varying loadings on the Earth surface and cause time-varying elastic deformations of the solid Earth.

In elastic environments, the surface response to water and ice mass load change is primarily vertical, localised where the loading is concentrated (subsidence and uplift during loading-unloading conditions) and less important horizontal deformations occur that decrease moving away from the loading centre. In poroelastic environments, the response is quite different: if the porosity is isotropic, during water recharge the surface undergoes to uplift; whereas when the porosity is determined by systematic fractures, the medium is anisotropic and the surface deformation is mainly perpendicular to the fracture system (Fig. 1). Since the 1990s, both the elastic rebound caused by continental water loading and poroelastic deformation caused by water table variations are monitored by continuous GNSS networks and other space geodetic techniques (Schuh and Moehlmann, 1989; Ikehara and Phillips, 1994; van Dam *et al.*, 2001; Zerbini *et al.*, 2004; Tregoning *et al.*, 2009). Previously, these deformations had been known for decades through terrestrial geodetic observations as strain, tilt, and gravity observations (e.g. Kümpel, 1997; Kroner *et al.*, 2004).

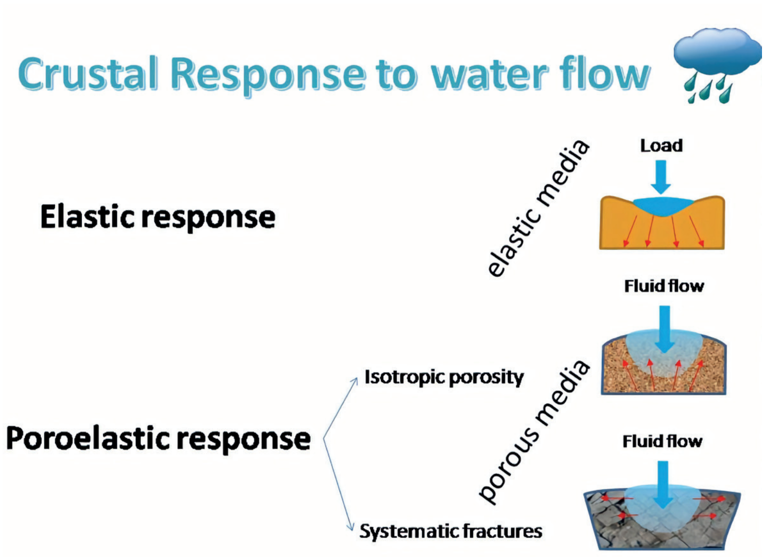

Fig. 1 - Sketch showing the different response to water flow in elastic and poroelastic media.

The recent deployment of many permanent GNSS networks in Italy has significantly improved the spatial and temporal resolution of the deformation patterns. At present, at least 30 GNSS networks maintained by different institutions constitute the grid of monitoring sites that includes over 1000 permanent stations, mainly devoted to real-time positioning services but that has proven to be suitable also to detect slow deformations (Devoti *et al.*, 2017).

Recent studies have shown that heavy rainfall or water level variations in confined aquifers, are able to induce significant transients or long-term periodical deformations especially in karstic areas (e.g. D'Agostino *et al.*, 2018; Devoti *et al.*, 2018; Serpelloni *et al.*, 2018; Braitenberg *et al.*, 2019; Silverii *et al.*, 2019).

We will show a few case studies, based on the analysis of GNSS time series, observed in the Alps and in the Apennines that demonstrate repeating extension-contraction deformation pattern occurring in different areas, but sharing similar geohydrologic conditions and responding to rainfall variations at different time scales: episodic, seasonal, and multi-year rainfall variations. In particular, we show two kinds of hydrologic driven deformations. First a loading response, due to seasonal oscillations at regional scale in the Italian peninsula, by comparing the GPS velocity variations during one annual cycle with the variations of equivalent water height retrieved by Gravity Recovery and Climate Experiment (GRACE) observations. Second, a fractured carbonates response occurring at two different time scales: short-term transients observed on the Cansiglio Plateau [(CP) south-eastern Alps] during rainwater recharge and discharge; and long-term oscillations in the Aterno Valley (central Apennines) caused by groundwater storage variations. These hydrologic-induced deformations both share the cause (groundwater) responsible of the observed effect, in which the interaction of shallow rainfall drainage (short-term effects) and deep groundwater level variations (long-term effects) take place in a matrix of fractured rock. These deformations are possibly correlated with multi-annual climatic changes and would represent a first order noise source in the GNSS time series and in the studies that aim to isolate slow drifting tectonic processes.

2. Annual loading response at local and regional scale

Elastic deformation of the Earth's crust caused by continental water load has been proven by geodetic data since many years (e.g. Tregoning *et al.*, 2009). One striking evidence of the water loading effect is represented by the style of deformation at annual frequency of the L'Aquila GNSS (AQUI) station, located on the roof of the Science Faculty of the L'Aquila University, in central Italy. Fig. 2 shows the detrended and low-pass filtered GPS height variations compared with the rainfall excess measured at the nearby weather station (Center of Excellence Telesensing of Environment and Model Prediction of Severe events, http://cetemps.aquila.infn.it/). The two quantities are clearly anti-correlated in the annual frequency bandwidth, so that an excess of rainfall causes a lowering of the GPS station position and vice versa. Thus, most of the annual height variations at AQUI, of the order of 1-2 mm, may be ascribed to the loading effect of the land water content, modulated by the rainfall recharge in the L'Aquila basin.

At more regional scale, the water mass loading effect is also evident comparing GRACE data with GPS time series. Here, the horizontal GPS displacements during one annual cycle are compared with the variations of equivalent water height (EWH) retrieved by GRACE data (www2.csr.utexas.edu/grace; Save *et al.*, 2016). Even if the spatial grid of EWH is large (1º×1º), a regional seasonal oscillation is observed in EWH data and the Apennines chain seems to be a nodal line of the oscillation. The increase in EWH anticipates the GPS displacements (Movie 1 in

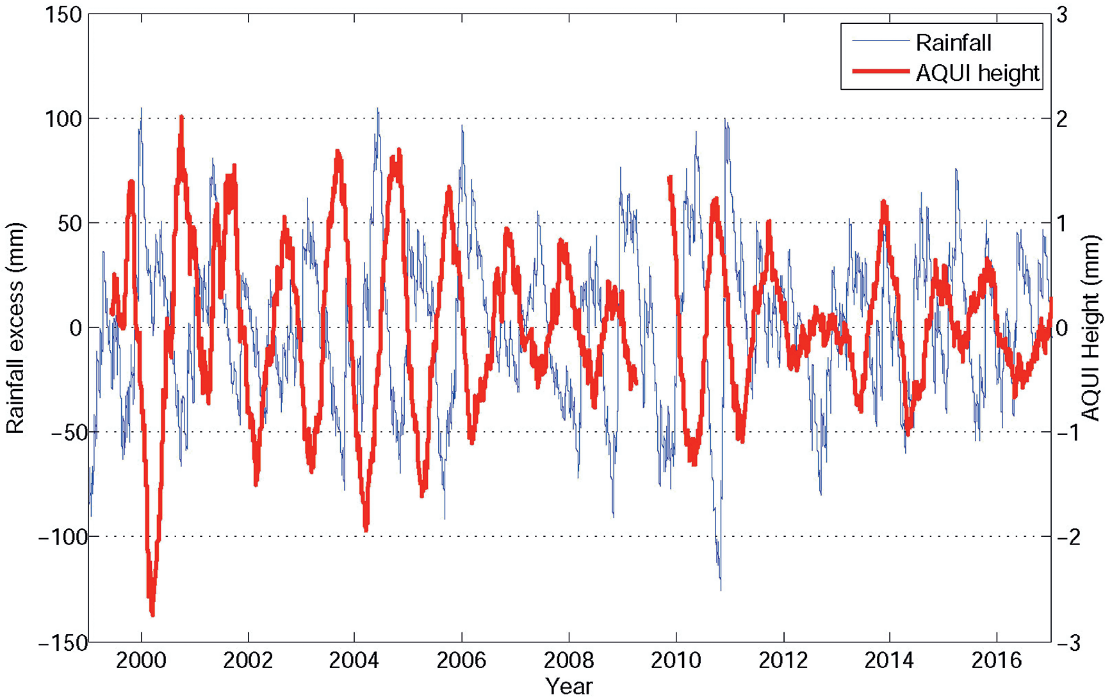

Fig. 2 - Time series of GPS height variations of AQUI (red line) and excess of rainfall (blue line). The time series are detrended and filtered from low frequencies (periods greater than 1 year), the left axis shows the rainfall excess (millimetres in excess from average rainfall rate in the 2006-2018 period) and on the right axis the GNSS annual deformation expressed in millimetres.

Supplementary material). On the contrary, the vertical displacements are synchronous with the GRACE gravity changes: at increasing amounts of EWH, the GPS sites display subsidence and with decreasing EWH, the GPS show uplift (Movie 2 in Supplementary material).

3. Short-term deformations due to extreme rainfall events

Short-term transients caused by rainfall have been observed on the CP, south-eastern Alps, during rainwater events (Devoti *et al.*, 2015; Grillo *et al.*, 2018). The CP rises steeply from the underlying Veneto-Friuli Plain to over 1000 m of altitude and is bounded on the W-SE sides by a ridge of super elevated hills reaching up to 1500 m above sea level. The whole CP is a limestone plateau with extensive karstic epigenic and hypogenic features typical of a mature karst system, dolines are the most remarkable landscape features, both of dissolution and collapse origin, and hundreds of caves and sinkholes have been identified, a few of them several hundred metres deep. On the surface, there is a fracture system oriented perpendicularly to the long-term tectonic compression direction and connected to the karst system, and deep caves that under rainfall conditions work like pressurised reservoirs. Fig. 3 shows the strong correlation among the GPS position at CANV (Caneva) station in response to the rainfall events (black bars) (Devoti *et al.*, 2015; Grillo *et al.*, 2018). The deformation occurs mostly in the horizontal (S-SE direction): it takes place in a few hours following the rainfall and tends to rebound during the

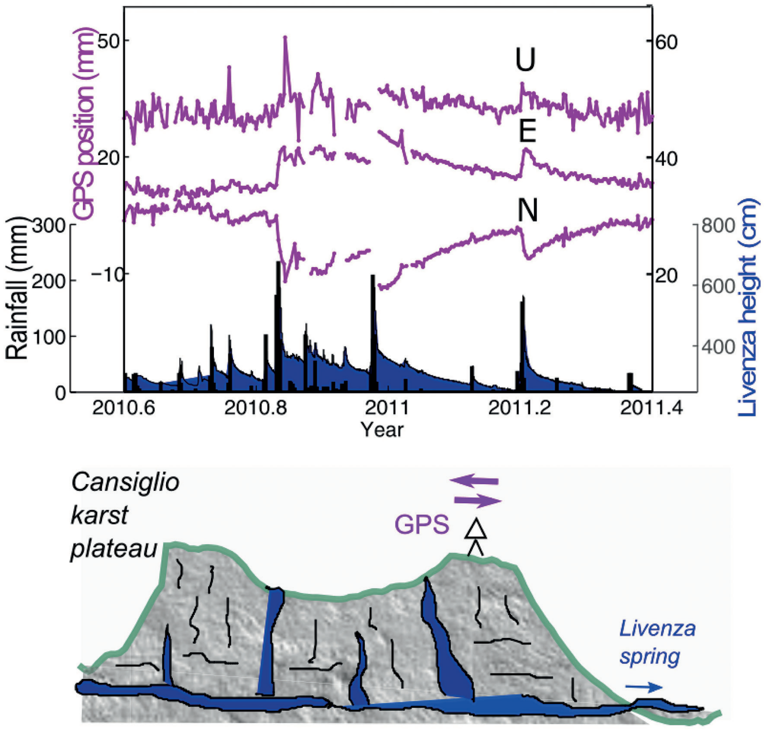

Fig. 3 - Example of short-term deformation after heavy rainfall episodes: the Cansiglio Plateau. Upper panel, time series of horizontal deformations from GPS and rainfall (Devoti *et al.*, 2015; Grillo *et al.*, 2018) showing the correlated behaviours; lower panel, topographic cross-section (from SRTM grid) along a profile parallel to the maximum deformation direction; the texture indicates roughly the karstic features of the plateau and the location of the Livenza River spring.

weeks following the rain. Devoti *et al.* (2015), analysing a series of rainfall events, observed a horizontal displacement proportional to the amount of rainfall, being about 3 mm displacement every 100 mm of rain. This particular response is noteworthy, because it cannot be explained by an elastic loading effect, since a load should contract the surface towards the loading centre. In this case the opposite occurs, the plateau experiences an extension proportional to the rainfall amount, whereas the vertical movement is barely measurable. The phenomenon has been interpreted as a poroelastic effect, taking place in the fractured limestone in the vadose zone of the epikarst (Devoti *et al.*, 2015) and correlated to similar findings detected in different Alpine areas (Longuevergne *et al.*, 2009; Jacob *et al.*, 2010).

4. Long-term horizontal deformations caused by groundwater storage

There are some particular sectors of the Italian area where long-period deformations have been observed through the analysis of long GPS time series. Multi-annual oscillations of the surface deformation are evidenced in different places in the Apennines and Alps (e.g. Devoti *et al.*, 2018; Serpelloni *et al.*, 2018; Silverii *et al.*, 2019). To characterise the extent of variable deformations in Italy, we evaluate the time variability of the velocity vector computing time series of velocities. The amplitude and impact of these oscillations are, then, assessed computing a velocity variability index. The velocity time series is obtained applying a sliding window of $t_j - t_i$

equal to 3 years and computing a linear velocity v_i in each window using the MIDAS estimator (Blewitt *et al.*, 2016). Fig. 4 shows two end-member examples of velocity time series, a well-established velocity oscillation at AQUI with velocity variations exceeding 2 mm/y, whereas a rather stable velocity time series at GRAS (Caussols, France) showing moderate velocity variations below 1 mm/yr. It is worth noting that the 3-year sliding window will filter out any annual or sub-annual signature in the velocity time series, emphasising the multi-annual velocity variability. A robust estimator of velocity dispersion is the MAD_{vel} = median $|v_i - v_m|$, where MAD_{vel} is the median of absolute deviations and v_m is the median of the velocity time series. Therefore, a useful indicator of the velocity variability is the ratio between the MAD and the noise level of the velocities computed in the running window. We, thus, define the V_{index} as follows:

$$V_{index} = \mathrm{MAD}vel/(\sigma_v\sqrt{\frac{N_{tot}}{N_{win}}})$$

where σ_v is the velocity root mean square, N_{tot} and N_{win} are the total number and the sliding window number of velocity points.

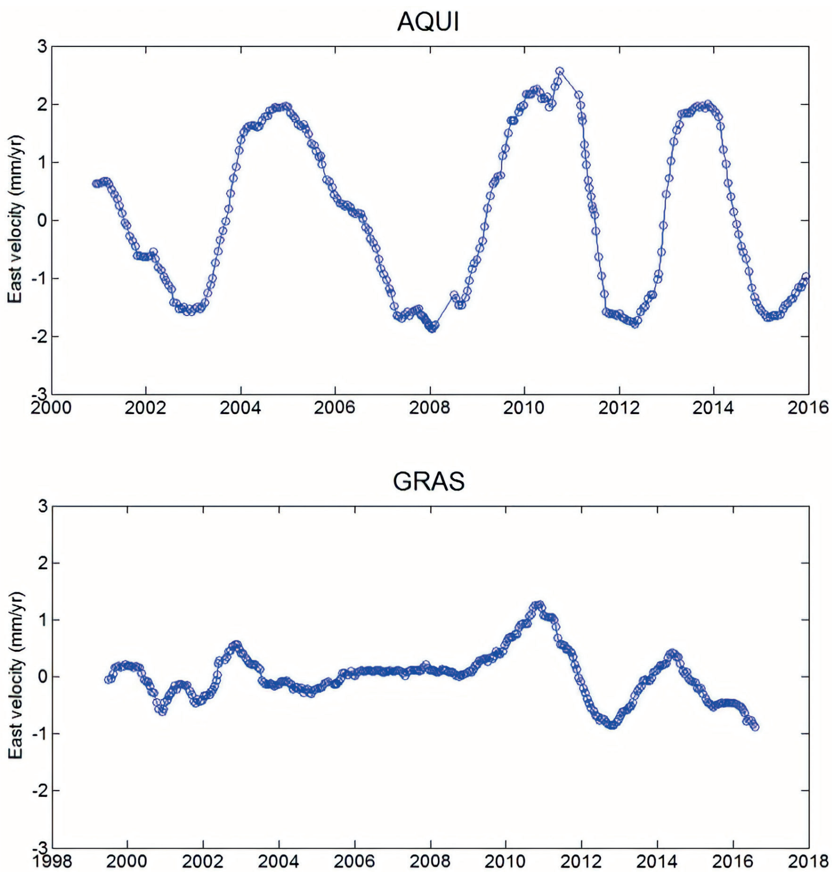

Fig. 4 - The multi-annual signal is not a signature occurring in all the velocity time series, here the filtered AQUI and GRAS east velocity components display a very different behaviour. The time series of velocity are obtained applying a 3-year sliding window and computing a linear velocity in each window using the MIDAS estimator.

In Fig. 5 we show the horizontal velocity index (V_{index}) as estimated from all the permanent GPS stations in Italy (black dots on the map), the horizontal velocity demonstrate long-term oscillations (> 3 years) mostly along the Apennines chain and in a few areas where the $V_{index} > 2$. It is important to remind that, in this analysis, any annual signature in the GPS velocities is filtered out by the 3-year window, and the V_{index} here emphasises only the long-term variability of the GPS time series.

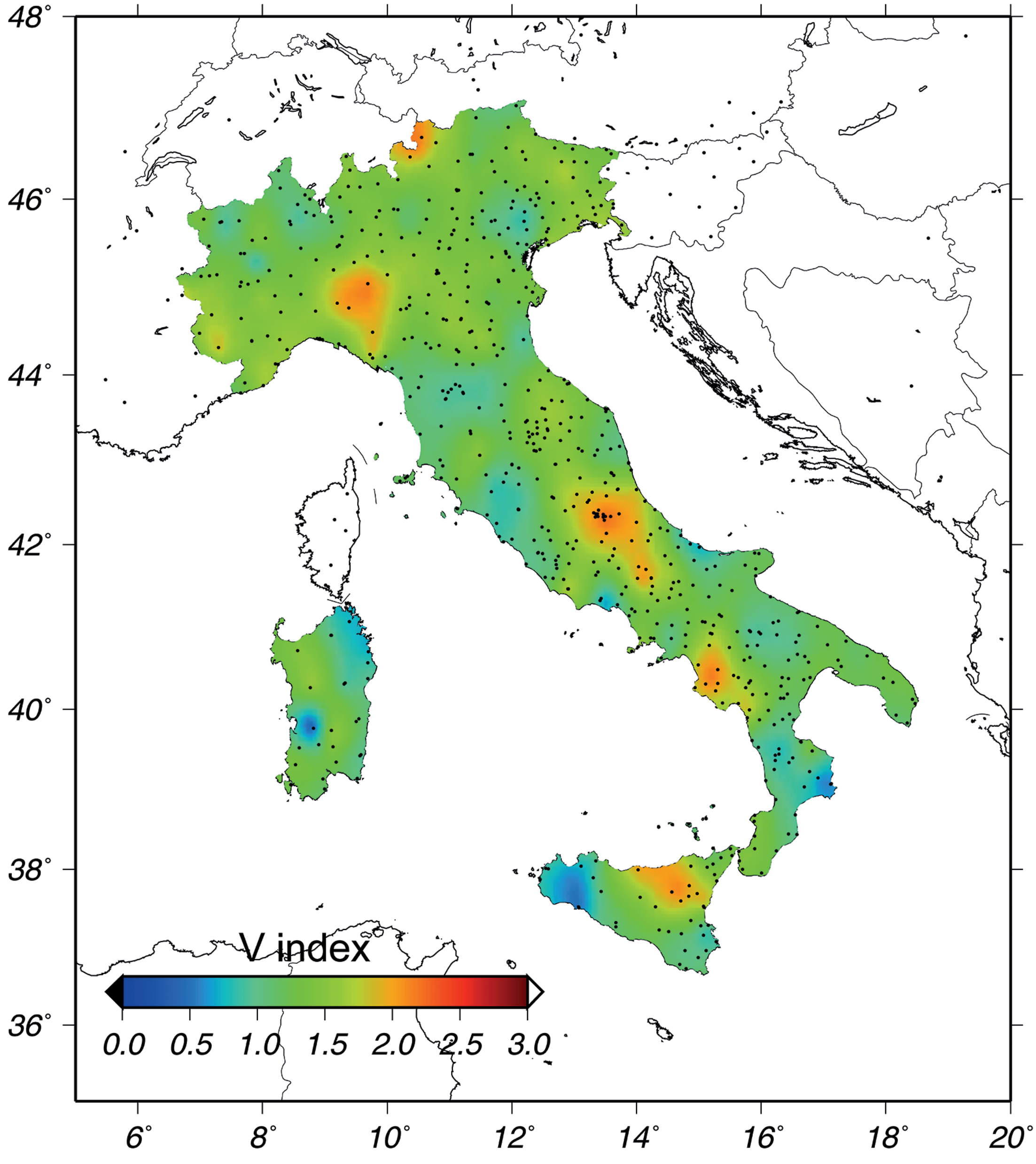

Fig. 5 - Map of the velocity variability index (V_{index}) in the Italian area, obtained after filtering out any annual or sub-annual signature in the velocity time series, to emphasise the multi-annual velocity variability. The index is dimensionless and computed at each GNSS station (black dots). The map is obtained after spatial interpolation of index values by GMT software (Wessel and Smith, 1998). High variability is indicated from orange to red.

The most interesting area, where a dense network of stations catches a long-term horizontal deformation is the central Apennines area close to the city of L’Aquila. There, the GPS velocity time series, exhibit an oscillatory behaviour with an amplitude of a few millimetres, mostly in the horizontal components. The AQUI oscillation seems opposite to that of the westerly stations, i.e. the whole region oscillates between extension and contraction phases with a period of roughly 4.5 years (Fig. 6). The L’Aquila area is bordered by two main aquifers: the Gran Sasso aquifer (to the east) and the Nuria - Velino aquifer (to the west), hosted in carbonate rocks. Cyclic displacements up to 10 mm repeat every 4-5 years along a direction orthogonal to the ground

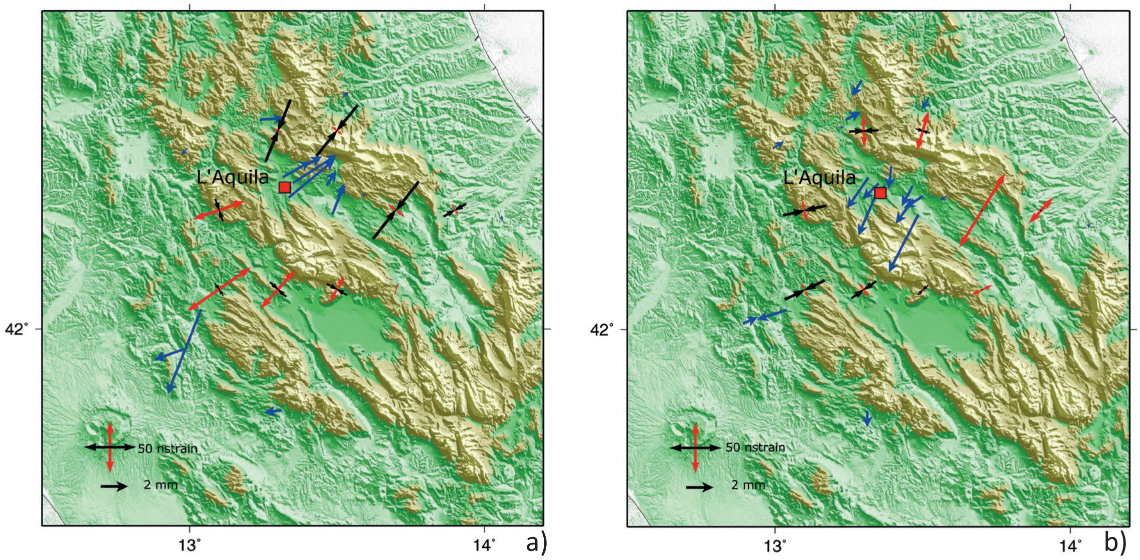

Fig. 6 - Maps showing the long-term dilation-compression phases in the Aterno Valley area: a) June 2011; b) January 2013. The strain rate axes are computed by *visr* software (Shen *et al.*, 2015); map obtained by GMT software (Wessel and Smith, 1998).

water fluxes, and to the Apennine normal fault system. The long-term ground deformation is correlated with rainfall excess and has been interpreted as the response of karstic limestones to the variations of groundwater level in the aquifers (Devoti *et al.*, 2018). Fig. 7 shows the GPS displacements in the Aterno Valley (different colours), the rainfall excess (blue) and the GRACE long-term gravity change (cyan) expressed as Equivalent-Water-Height (EWH). The GRACE time series has been extracted from the CSR-RL05, 1°×1° grid solution (https://grace.jpl.nasa.gov/), centred on the 42.5°N, 13.5°E bin position and low-pass filtered to enhance the long-term pattern. The correlation among the ground deformation and land water content is outstanding (0.65 between EWH and GPS, in normalised units). The cross-correlation analysis based on the 2 long-lasting GPS stations (AQUI and INGP) shows a variable phase lag of 6-11 months between GPS and EWH signals and of 2-7 months between GPS and rain excess. Thus, the ground deformation lags the land water variation by at least 2-11 months. These differences in the time lags are not surprising, since the EWH is evaluated on a wide geographic area and represents a regional smoothed signal, whereas the rain excess is computed from a single station that may not properly catch the long-term average signal. Although the two water storage proxies do not sample the same quantities, both suggest a time lag of several months, between the rising (or lowering) of land water storage and the extension (or contraction) of the Earth’s surface. This

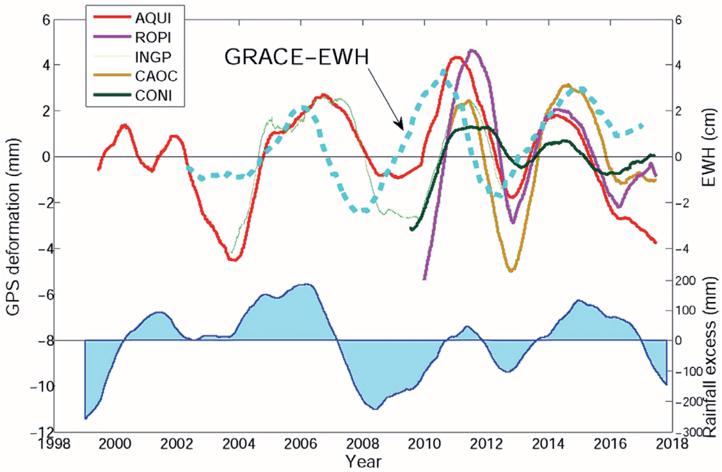

Fig. 7 - Maximum elongation of the GPS horizontal displacements (colours in legend) compared with rainfall excess (i.e. with respect to the average rain, blue line). GRACE long-term gravity change (cyan) in central Apennines is synchronous with the GPS displacements.

time lag is consistent with the low permeability associated with a diffuse flow system in the saturated zone. We interpret this time lag as the delay required by the diffuse water flow in the phreatic zone to get the long-term equilibrium of the water table.

5. Conclusions

The analysis of long-term GPS time series has allowed us to identify different processes related to water circulation in bedrock fractures at different time scales. Episodic rainfall causes short-term deformation transients whereas groundwater variations induce annual and long-term deformations. All deformations share a common characteristic pattern of repeating extension-contraction phases, mostly in the horizontal plane. They occur in different tectonic settings, associated both with surface water circulation and with large aquifer oscillations, in areas where carbonate dissolution, tectonically related fractures, and faults may represent pathways for groundwater flow and pore pressure build-up. Thus, there seems to be an interconnection between water circulation and crustal tectonic processes, worth of more detailed analyses such as the possible interactions between slow slip events and even earthquakes with such hydrologic induced deformations.

Supplementary material related to this article is available online at the BGO website www.bgta.eu.

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