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Hydrologically induced slope deformations detected by GPS and clinometric surveys in the Cansiglio Plateau, southern Alps

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ABSTRACT

Changes in groundwater or surface water level may cause observable deformation of the drainage basins in different ways. We describe an active slope deformation monitored with GPS and tiltmeter stations in a karstic limestone plateau in southeastern Alps (Cansiglio Plateau). The observed transient GPS deformation clearly correlates with the rainfall. Both GPS and tiltmeter equipments react instantly to heavy rains displaying abrupt offsets, but with different time constants, demonstrating the response to different catchment volumes. The GPS movement is mostly confined in the horizontal plane (SSW direction) showing a systematic tendency to rebound in the weeks following the rain. Four GPS stations concur to define a coherent deformation pattern of a wide area (12×5 km^2), concerning the whole southeastern slope of the plateau. The plateau expands and rebounds radially after rain by an amount up to a few centimeters and causing only small vertical deformation. The effect is largest where karstic features are mostly developed, at the margin of the plateau where a thick succession of Cretaceous peritidal carbonates faces the Venetian lowland. A couple of tiltmeters installed in a cave at the top of the plateau, detect a much faster deformation, that has the tendency to rebound in less than 6 h. The correlation to rainfall is less straightforward, and shows a more complex behavior during rainy weather. The different responses demonstrate a fast hydrologic flow in the more permeable epikarst for the tiltmeters, drained by open fractures and fissures in the neighborhood of the cave, and a rapid tensile dislocation of the bedrock measured at the GPS stations that affect the whole slope of the mountain. In the days following the rain, both tiltmeter and GPS data show a tendency to retrieve the displacement which is consistent with the phreatic discharge curve. We propose that hydrologically active fractures recharged by rainfall are the most likely features capable to induce the observed strain variations.

1. Introduction

In the last decade, surface deformation attributed to hydrological processes has been observed with InSAR and GPS techniques in different aquifer systems. A number of papers reported measurable effects in response to groundwater level changes in different geographical areas (Bawden et al., 2001; Lanari et al., 2004; Argus et al., 2005). The San Gabriel Valley basin (Los Angeles, California) experienced an expansion of about 1 cm and an uplift of nearly 5 cm due to a heavy rainfall during winter 2004–2005 (King et al., 2007; Ji and Herring, 2012). Recently Diaz et al. (2014) detected an unusual spectral signature in seismic data, recorded also as local strain variations, that were related to the discharge of the Aragon River in the southern Pyrenees (Spain). Rainfall and snowmelt episodes were identified to cause distinctive signatures in the seismic and strain measurements throughout the discharge phase in porous and fractured media.

Also tilt measurements have been long known to be affected by various hydrologic processes at the level of few micro-radians (μrad). One of the first works in Italy that claim for "micro-movements" caused by local rainfall was carried out by Caloi and Migani (1972), in which a couple of clinographs revealed a tilt towards SSE in correspondence of rain, in an area not far from our study region (70 km NE of the Cansiglio Plateau). The hydrologic induced deformation could also be linked to the seasonal modulation of the regional shallow seismicity in the southeastern Alps (Braitenberg, 2000).

Similar studies in different environments revealed the effect of groundwater on tiltmeter measurements (e.g. Edge et al., 1981;

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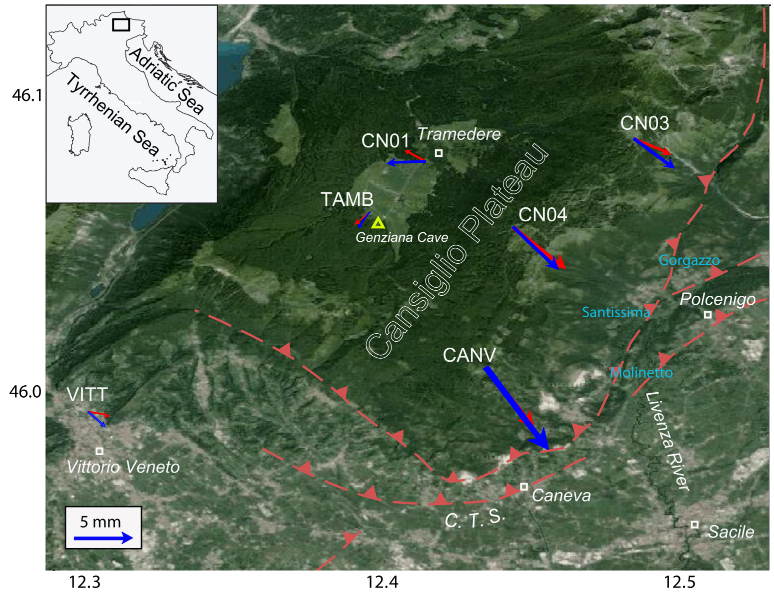

Fig. 1. Map of the Cansiglio Plateau area showing the Cansiglio Thrust System (C.T.S.) bordering the southeastern flanks of the Plateau. The four letter words represent the GPS station ID considered in this study, the red and blue arrows represent the displacements measured after two rain events in autumn 2011 (see text for more details). (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

Evans and Wyatt, 1984; Kümpel et al., 1988; Takemoto, 1995; Dal Moro and Zadro, 1998; Braitenberg, 1999a; Jahr et al., 2008). More recently Longuevergne et al. (2009), Jacob et al. (2010) and Tenze et al. (2012) have successfully measured rock deformations induced by hydrological processes in different karst systems (respectively Vosges mountains, southern French Massif Central and classical Trieste karst). The first two investigations demonstrate that the observed karstic media deformations are likely due to water pressure changes in nearby fractures. Strain variations due to pumping experiments have been recently studied in California to constrain material properties of rock using the Darcy flow approximation (Barbour and Wyatt, 2014).

In this study, we test the hypothesis of hydrologic induced strain observed using both GPS and tiltmeter data in a karst system located in the southeastern Alps, the Cansiglio Plateau (CP), Italy (see Fig. 1 for location). Previous works in similar environments suggest that the occurrence of such phenomenon is not isolated and uncommon, but could be recurrent especially in karst areas providing new insights into hydrologic karst processes (Longuevergne et al., 2009; Jacob et al., 2010; Tenze et al., 2012; Diaz et al., 2014).

The CP is an extensive polje located in the southeastern Alps halfway between the Veneto and Friuli districts in Northeastern Italy. Its average height is about 1000 m above sea level (asl), bounded on the W–SE sides by a ridge of super elevated hills up to 1500 m asl. 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 dissolutional and collapse origin, and hundreds of caves have been identified, a few of them several hundred meters deep. The most sizable ones are: *Bus de la Genziana* 590 m depth, and *Abisso Col della Rizza*, reaching 800 m depth, both of them are regularly inspected by speleological expeditions. The southeastern slope of the CP is characterized by a thick succession of Cretaceous peritidal carbonates, while the central-western part is characterized by slope breccia deposits, all capped by basinal marly carbonates (Cancian et al., 1985). The surficial hydrography of CP is only modest and a deep aquifer, several hundreds of meters below the top of the CP, is supplied by infiltration of meteoric precipitation (up to 1800 mm/yr) through, dolines, sinkholes and conduits of prevalent vertical development. The aquifer yields significant quantities of water to springs at the lower limb of the anticline, where the tectonized Mesozoic limestones are in contact with the Cenozoic and Quaternary impermeable units of the footwall. Three main springs at the foothills drain most of the CP water forming the Livenza River: Gorgazzo, Santissima and Molinetto, each bearing an average flow of 2–6 m^3/s, yielding a total flow of about 11 m^3/s (Vincenzi et al., 2011).

The Gorgazzo spring is a typical Vauclusian spring that originates from a shaft, a few meters of diameter, with the water running upwards. Occasionally, over periods of persisting drought, the piezometric surface is lowered below the outlet elevation and the spring dries up. Since no piezometric data are available, we presume that the springs at the foothills are located in a zone of intermittent saturation. A quantitative model of the hydrology of the CP has not been developed up to now and is therefore unavailable. In general, karst hydrology is complicated by the fact that the hydraulic conductivity is inhomogeneous and anisotropic due to the presence of fractures and shafts. Groundwater flows in the rock matrix, fractures and in conduits, where the conduit component (cave-like tubes) is significant.

Although matrix porosity has been shown to be important in providing storage capacity, the secondary porosity (conduits and fractures) dominates the pathways for groundwater flow (Ford and Williams, 2007, p. 104). In our case the rainfall response (input–output) relationships are the only means to treat the hydrologic system, as pumping experiments are not known to us. The latter are probably very difficult to accomplish, as the watertable is many hundreds meters below the surface. In the location of the tiltmeter the cave has been explored 600 m below surface before reaching the ground water level. Relying only on the rainfall response of the springs, the hydrologic system cannot be reliably parameterized. Parameters which could possibly be estimated and which contribute to drainage are gross specific yields and continuum transmissivity for the different portions of the aquifer (Shevenell, 2007). In order to accurately assess the deformation processes of karstified aquifers a detailed hydrologic study is necessary, due to the presence of well developed secondary porosity (fractures and fissures) and large conduits channeling most of the turbulent flow. Our study is focused on geodetic movements and inclinations of the CP karst plateau, and currently an accurate modeling of the