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# Long-term strain oscillations related to the hydrological interaction between aquifers in intra-mountain basins: A case study from Apennines chain (Italy)

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ABSTRACT

We analyze the multiyear strain cycle of a network of continuous GPS stations in the L'Aquila intra-mountain basin in Central Apennines, Italy. The basin is bounded by two aquifers (Nuria-Velino and Gran Sasso) hosted in two tectonically active mountain ranges. All stations show coherent displacements, mostly in the horizontal plane and orthogonal to the normal fault zones of the Apennine mountain range. The displacement repeats back and forth, roughly every 4–5 years with elongation up to 6 mm. The deformation occurs in the region bounded by the two aquifers and the displacement amplitude decreases with distance as predicted by two tensile sources acting in an elastic medium. We interpret this type of deformation as induced by the opening of pre-existing fractures related to two different fault systems as a response to hydrostatic pressure variations. The strain cycle follows the average multiyear rainfall cycle and foresees a dilatation phase during high rainy seasons and a contraction during drier periods. The estimated depth of the equivalent tensile sources ranges from 1.2 to 1.5 km affecting stations at distances up to 20 km away. GPS data show the cumulated movement induced by the two nearby aquifers and suggest a mutual interaction in the elastic space related to the different average annual rainfall and effective infiltration. We fit two tensile sources located along the main faults affecting the aquifers. The eastern source corresponds to the major active fault system affecting the Gran Sasso Range, while the western one includes the sub-parallel active faults of the Mt. Ocre in the Nuria-Velino Range, where carbonate rocks show a higher structural permeability and effective infiltration. These fault systems affect Jurassic-Miocene limestones and dolomites inducing parallel fracturation style of the rock matrix and favoring a strong anisotropy allowing a prevalent lateral expansion as a reaction to pore pressure variations. The recorded hydrological signal may hamper other geophysical signals in GPS time series, thus the measure of tectonic strains requires a careful mapping and modeling of major aquifers.



## 1. Introduction

In the last two decades an increasing effort has been devolved in measuring the deformations caused by hydrological processes, mainly due to the increasing accuracy of GNSS and InSAR techniques. An obvious effect is produced by temporary loading the Earth's surface, causing the crust to react elastically downwards (Farrell, 1972). Vertical surface strain variations due to continental water loading were first observed by van Dam et al., 2001 and confirmed in successive investigations in different geological settings (van Dam et al., 2007; Wahr et al., 2013; Hao et al., 2016). The crustal response to external loading forces may be predicted using Farrel's loading model, in which the crust acts as a purely elastic medium. Instead, to represent the deformation experienced by porous media, subject to water inflow – e.g. intergranular aquifers formed by unconsolidated sediments and aquifers hosted in fractured rocks – a more complex theory is needed. Such deformations are modeled by poroelastic theory in which fluid flow affects the deformation of the porous medium and vice versa, the medium alters the fluid flow. As an example, the water table increase in these model aquifers causes uplift of the soil, contrary to what happens in pure elastic loading. Strain variations caused by water table recharge and discharge has been widely observed around the world (Bawden et al., 2001; Watson et al., 2002; Schmidt and Bürgmann, 2003; Lanari et al., 2004; Argus et al., 2005; King et al., 2007; Ji and Herring, 2012; Preisig et al., 2014; Tung et al., 2016; Argus et al., 2017). A quite

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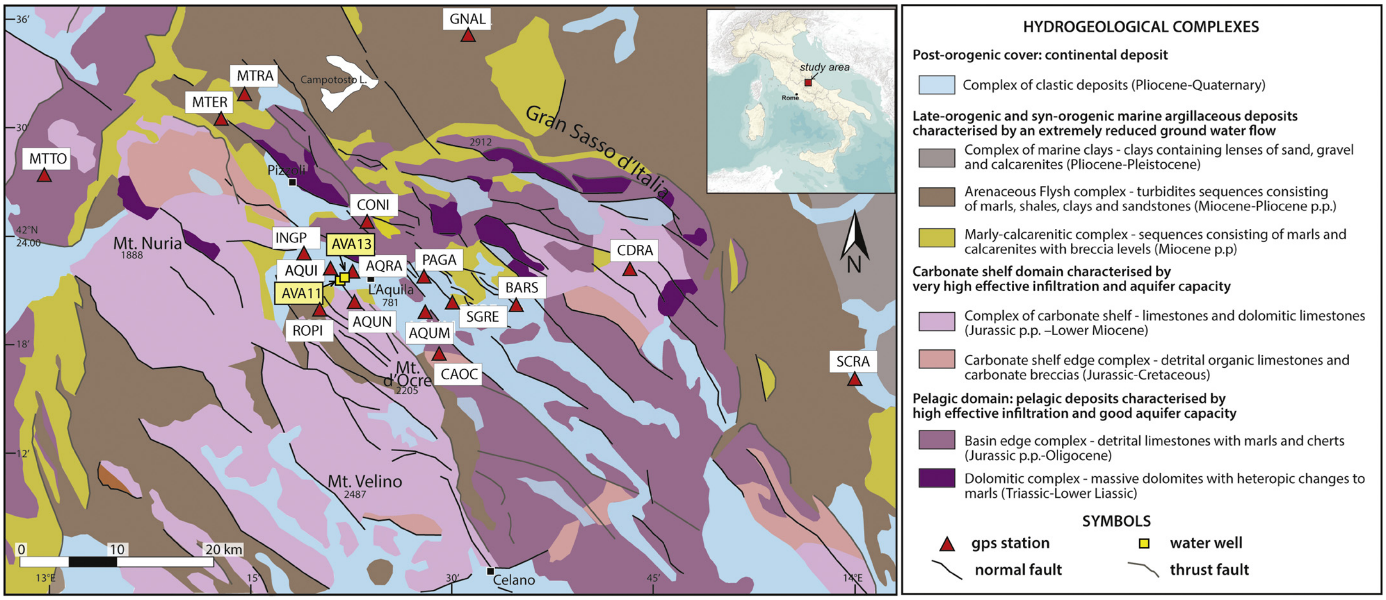


**Fig. 1.** Map of the hydrogeological complexes and tectonic setting of the study area (modified from Boni et al., 1986). The network of the analyzed GPS stations (acronyms in white capital letters) is mostly located in the L'Aquila basin and surrounding carbonate reliefs of the Gran Sasso and Nuria-Velino aquifers. Location of two water wells for which water table data are available also reported (see also Fig. 3). (For interpretation of the colors in the figure(s), the reader is referred to the web version of this article.)

peculiar hydromechanical coupling occurs in karst aquifers, i.e. fractured rock aquifers in which carbonate dissolution or tectonically related fractures and faults significantly increase the size of the systematic fractures enhancing secondary porosity and forming a network of fissures, caves and conduits of prevalent subvertical growth. Flow paths are controlled by discrete fracture sets in zones of high fracture density and connectivity (e.g. joints, fractures, shear zones). Distinctive deformations of karst aquifers have been recently observed and have been ascribed to hydrologically active fractures that expand and contract laterally as water flows in and out, elastically deforming the surrounding rock matrix. The repeat time of such displacements range from intermittent and irregular events modulated by rainfall (Diaz et al., 2014; Devoti et al., 2015) to seasonal and multiannual variations driven by the hydrological cycle (Longuevergne et al., 2009; Jacob et al., 2010; Amoruso et al., 2014; Silverii et al., 2016; Argus et al., 2017). In this work, we analyze the multiyear strain cycle of karst aquifers in an intra-mountain basin of Central Apennines in Italy. This basin is bounded by two mountain ranges affected by active, seismogenic faults, and hosting two of the major aquifers of the whole Apennine chain. We observe multiyear peak-to-peak horizontal oscillations up to 12 mm that, if not correctly modeled, could be a concern for the detection of tectonic signatures (inter-, pre-, co- and post-seismic) in continuously recording GNSS stations. We model the mutual interaction among the aquifers in terms of their elastic induced strains. We also discuss the role played by the faults and fractures as water infiltration pathways and the resulting strain pattern, which is also related to the interaction between the two aquifers.

## 2. Geological setting

The Apenninic thrust belt is a part of the accretionary wedge raised by the rollback of the Adriatic subduction towards the east (Doglioni et al., 1998). The Quaternary-Neogene normal faults, formed by the subsequent west-to-east migration of the extensional regime, guide the Apennine intra-mountain basin evolution and its filling through continental clastic deposits such as those of the L'Aquila basin (Cavinato and De Celles, 1999). The intra-mountain basin of L'Aquila is located between the Gran Sasso Range to the East and the Mts. Velino-Nuria Range to the West. The basin is part of the axial zone of the Apennine belt that is characterized by a network of prevalently NW-SE to minor WNW-ESE striking normal faults (e.g. Ghisetti and Vezzani, 2002; Fig. 1). These active faults are responsible for the historical (e.g. Mw 6.8, 1703 Norcia, Mw 7.1, 1915 Fucino) and recent (Mw 6.3, 2009 L'Aquila and Mw 6.5, 2016 Norcia) destructive earthquakes with intensity $I_0$ up to XI and $M_W \geq 6$ (https://emidius.mi.ingv.it/CPTI; http://iside.rm.ingv.it/). The area is characterized by structural units deeply involved in the Apennines building and includes deposits from marine carbonate shelf to foredeep environments. The L'Aquila basin consists of low-permeability Plio-Quaternary conglomerates and detritic sands and Quaternary alluvial deposits (Boni et al., 1986; Fig. 1). The basin and its filling deposits are surrounded by the two main carbonate mountain ranges of Gran Sasso and Mts. Velino-Nuria. The Gran Sasso Range consists of Jurassic-Oligocene detritic limestones with marls and cherts, and subordinated Jurassic-Miocene massive dolomites belonging to a continental shelf domain, while the Mts. Velino-Nuria Range mainly consists of Jurassic-Miocene pelagic limestones and dolomites (Fig. 1). These two mountain ranges include two of the major hydrological complexes of the Central Apennines. The carbonatic rocks show a high structural permeability related to the occurrence of NW-SE striking faults and joints, and to karst dissolution of the carbonates by infiltrating water. The major groundwater flow lines follow a prevailing NW-SE strike suggesting that these faults control the distribution of water within the aquifers (Fig. 2). The connected porosity and permeability of the limestone rocks with joints measured in the laboratory are 3% and $7.7 \cdot 10^{-14}$ m$^2$, respectively; these values are significantly higher of that of intact limestone (porosity = 0.8%; permeability = $6.8 \cdot 10^{-19}$ m$^2$) of this area (Agosta et al., 2007). The Mts. Velino-Nuria Range hydrological complex is classified, in the Apennines, as a high infiltration aquifer with an average effective infiltration >900 mm/yr, while the values of Gran Sasso Range are lower, i.e. between 700 and 900 mm/yr (Fig. 2). Also, the Mts. Velino-Nuria Range shows a basal flow index >0.75, while the values of this index are between 0.6 and 0.75 in the Gran Sasso Range. Finally, the mean annual rainfall of Velino-Nuria Range is 1115 mm/yr, and 947 mm/yr in