DIPARTIMENTO
DI SCIENZE DELLA TERRA

SAPIENZA
UNIVERSITÀ DI ROMA

DOTTORATO DI RICERCA
IN SCIENZE DELLA TERRA

Research activity

Groundwater and seismicity relationship: hydrogeological monitoring to identify hydrosensitive sites in central-southern Italy

General objective: Hydrogeological and hydrogeochemical characterization of the main springs in central-southern Apennines in order to identify specific sites for a potential future national monitoring network.

Specific objective: Expanding our understanding of the cause-effect relationship between groundwater and seismicity to define "hydrosensitive" sites in central-southern Italy.

State of the art: Earthquake-induced groundwater and gas changes have been widely documented in seismogenic areas worldwide. Several studies have highlighted the sensitivity of fluid behaviour related to the seismic cycle both in terms of hydrogeological and hydrogeochemical anomalies[1-3]. In detail, variations, including changes in isotopic ratios[4], pH values and electrical conductivity[5], temperature[6], gas geochemistry[7], ion concentrations in solution[8], trace elements[9] and piezometric level[10], have been observed in sensitive monitoring sites at different distances from epicentres. In literature, various mechanisms have been proposed to explain groundwater level and discharge changes such as: pore-pressure response to crustal elastic strain[11], permeability changes caused by seismic waves[12] and fluid migration along dilatant cracks or deep crustal fractures[13]. Besides, variations in geochemistry and isotopic signature of groundwater have been also defined as the results of the following processes: deep and hydrothermal fluid injection[14], mixing of waters from different aquifers and rock weathering enhancement in new rupturing[15]. Previous studies carried out by international research teams show that focusing on hydrogeological and hydrogeochemical earthquakes-related effects is a promising target for the seismic investigation. For example, a progressive increase in radon concentrations some months prior to the M_w 7.2 Kobe earthquake in Japan (1995) was pointed out and then a drastic decrease immediately after[16]. In Taiwan, three phases of groundwater level in connection with fracture opening and permeability changes were recorded since 230 days before the M_w 7.6 Chi-Chi earthquake[17]. In China, hydrogeochemical changes in three hot springs were found by following three large near-field earthquakes (M_w 8.0 Wenchuan earthquake in 2008, M_w 7.0 Lushan earthquake in 2013 and M_w 6.3 Kangding earthquake in 2014)[18]. Furthermore, spatial-temporal variations of $^3He/^4He$ and $\delta^{13}C_{CO2}$ appeared to be related with seismic activity. Indeed, increasing upwellings of deep fluids presumably due to development of higher permeability pathways were also recorded along active fault zones[19]. In central Italy as well, during the Amatrice-Norcia seismic sequence, geochemical anomalies and pH changes have been detected four months before the onset of the seismic swarm[20]. Thus, given these previous results and taking into account hydrogeological and seismological constrains, the central-southern Apennines represent a natural promising laboratory for monitoring geofluids as markers of active seismogenic processes, owing to the great abundance of groundwater resources and the nature of the regional aquifers hosted by fractured Meso-Cenozoic carbonates that enhances the response to deep fluids uplift, allowing fast and concentrate changes in groundwater close to tectonic lines. Additionally, the intense seismic activity, which affects the study area, confirms the importance of deepening the knowledge about the groundwater-seismicity relationship. Therefore, this PhD project has the dual purpose of identifying potential earthquake-induced groundwater and gas changes and focusing on the hydrodynamic modifications that fractured aquifers undergo. Some recent earthquakes occurred in the study area are reported below: Molise earthquake in 1805 (M_w 6.6), Basilicata earthquake 1857 (M_w 7.1), Irpinia-Vulture earthquake in 1930 (M_w 6.7), Irpinia earthquake in 1980 (M_w 6.9), Campobasso earthquake in 2002 (M_w 6.0), Sannio-Matese earthquake in 2013 (M_w 5.0).

Activity and workplan: This research is included in the GRINT-PON project (INGV hydrogeochemical monitoring) that had already pre-selected some potential monitoring points in Molise, Campania and Basilicata. Hydrogeological and hydrogeochemical parameters potentially influenced by the seismic cycle will be investigated to verify the existence and modalities of the cause-effect relationship between the hydrogeological and hydrogeochemical signals with the seismic and geodetic ones. In detail, in the first year of the PhD, in order to deepen my knowledge about all the geological features of the study area, firstly I focused my study on the geological and hydrogeological setting and on the seismicity of central-southern Apennines with the main aim to select a smaller group of springs to achieve the project goals. By considering both logistic conditions and hydrogeological characteristics, about 10 among the most representative springs with different geochemical features (e.g., from low to high mineralization, abundance or absence of free gases) of the main carbonate aquifer systems were selected. Chemical-physical parameters (temperature, pH and electrical conductivity) were measured on-site, samples for the determination of major (anions and cations) and trace element concentration were analyzed by using the anionic and cationic chromatograph, and the ICP-MS spectrometer at the Geochemistry Laboratory of Earth Sciences Department of Sapienza University of Rome. Samples for analysis of the stable isotope of water ($\delta^{18}O$ and δD), dissolved and free gases (He, CO_2, H_2, N_2, O_2, CH_4) and isotopic ratio ($^3He/^4He$, $\delta^{13}C$) were collected and sent to the laboratories of isotopic geochemistry of the University of Parma and to ones of the National Institute of Geophysics and Volcanology, section of Palermo. On the basis of the results of the first year of research, respect with the entire study area, a smaller area characterized by an optimal condition of water-gas system will be selected. For this reason, in the second year I will focus the study mainly on one or two hydrogeological unit(s) among the previously investigated, where deep fluid contributions are more evident. Attempts to build a detailed deep circulation conceptual model, defining mixing extents of deep and shallow fluids, through a multidisciplinary approach will be carried out in some of the hydrogeological basins. Thus, in the first months of the second year, I will identify some specific sites among those previously selected, for which the installation of automatic stations for continuous multi-parameter monitoring is planned. The stations will be equipped with sensors to measure the main chemical-physical parameters of groundwater, electrodes for the measurement of specific ions, and spectrometer and probes for monitoring the concentrations of free and dissolved gases, such as Rn, He and CO_2 which have shown greater sensitivity to the seismic activity. This type of investigation represents the innovation of this project that is based on the multiparametric monitoring in different sites and on data cross analysis. For the first time, typical lab analyses will be carried on field and, through high frequency data, dynamics and time evolution of processes in relation to seismicity of the central-southern Apennines region will be characterized. Besides, in collaboration with the INGV, I will contribute to the elaboration of specific GPS data sequences related to short time intervals for the study of correlations between transient signals of potential significant nearby earthquakes and potential hydrogeological anomalies. For seismic investigation, I will consider earthquakes of different magnitudes (recorded by the National Seismic Network) for different epicentral distances from the monitoring site. I will make all the time series suitable for comparison to point out correlations and/or interactions between the parameters (i.e., potential characteristic trends that occur in relation to crustal strain) and also to identify periodicity, trends and relations with local, seasonal and anthropic conditions. During the last year, I will focus on the processing, comparison and interpretation of data acquired from the monitoring networks. On the basis of obtained results, the influence of seismic cycle on chemical-physical characteristics of water will be verified and the potential variations in the time series will be detected. In the last months of the third year, I will write the PhD thesis.

References:

1. Montgomery & Manga (2003). *Science* 300, 2047-2049. **2.** Doglioni et al. (2014). *Geosci. Front.* 5, 767-780. **3.** Manga & Wang (2015). *Treatise on geophysics* 305-328. **4.** Sano et al. (2016). *Sci. Rep.* 6, 37939. **5.** Malakootian, M., & Nouri, J. (2010). *Int. J. Environ. Res.* 4, 443-454 **6.** He & Singh (2020). *Pure Appl. Geophys.* 177, 109-120. **7.** Caracausi & Paternoster (2015). *J. Geophys. Res. Solid Earth* 120, 2200-2211. **8.** Onda et al. (2018). *Sci. Rep.* 8, 4800. **9.** Shi et al. (2020). *J. Hydrol.* 581, 124424. **10.** Petitta et al. (2018). *Hydrogeol. J.* 26, 1009-1026. **11.** Jónsson et al. (2003). *Nature* 424, 179. **12.** Elkhoury et al. (2006). *Nature* 441, 1135-1138. **13.** Tsunogai & Wakita (1995). *Science* 269, 61-63. **14.** Hosono et al. (2018). *Sci. Rep.* 8, 14809. **15.** Claesson et al. (2004). *Geology* 32, 641-644. **16.** Ingebritsen & Manga (2014). *Nat. Geosci.* 7, 697-698. **17.** Chen et al. (2015). *J. Hydrol.* 524, 378-384. **18.** Li et al. (2019). *J. Hydrol.* 579, 124175. **19.** Lee et al. (2019). *Sci. Rep.* 9, 1-9. **20.** Barberio et al. (2017). *Sci. Rep.* 7, 1-12.

Gantt chart

PhD activity	First year		Second year		Third year	
	First semester	Second semester	First semester	Second semester	First semester	Second semester
University courses	X	X	X	X		
Bibliographic study	X	X	X	X	X	X
Monitoring and processing	X	X	X	X	X	X
Screening of the main springs (PON)	X	X				
Sites selection and station installation		X	X			
Training period abroad				X		
Analysis and comparison of processed data				X	X	
Data interpretation					X	X
Publications		X		X		X
Seminars and conference	X		X		X	
Thesis						X

Research products

a) Publications (ISI journals)

- Barberio, M. D., **Gori, F.,** Barbieri, M., Billi, A., Caracausi, A., De Luca, G., Franchini, S., Petitta, M., & Doglioni, C. (2020). New observations in Central Italy of groundwater responses to the worldwide seismicity. *Scientific Reports* 10, 17850.
- Barberio, M. D., **Gori, F.**, Barbieri, M., Billi, A., Casalati, F., Franchini, S., Lorenzetti, L., & Petitta, M. (2020). Optimization of dissolved Radon monitoring in groundwater to contribute to the evaluation of the seismic activity: an experience in central-southern Italy. *SN Applied Sciences*, 2(8), 1-12.
- Barberio, M.D., **Gori, F.**, Barbieri, M., Billi, A., Devoti, R., Doglioni, C., Petitta, M., Riguzzi, F., & Rusi, S. (2018). Diurnal and Semidiurnal Cyclicity of Radon (^{222}Rn) in Groundwater, Giardino Spring, Central Apennines, Italy. *Water*, 10, 1276.

b) Publications (NON ISI journals)

c) Manuscripts (submitted, in press)

- Barberio, M. D., **Gori, F.,** Barbieri, M., Boschetti, T., Caracausi, A., Cardello, G. L., & Petitta, M. Understanding origin and mixing of deep fluids in shallow aquifers and possible implications for crustal deformation studies: San Vittorino Plain, Central Apennines. *(submitted)*

d) Abstracts

- **Gori, F.**, Petitta, M., Barberio, M. D., Doglioni, C., & Caracausi, A. Groundwater and seismicity relationship: hydrogeological monitoring to identify "hydrosensitive sites" in central-southern Italy. *Roma chiama Roma 2020.* Earth Science Department of Roma Tre University. *Rome, 29-30 January*
- Barberio, M. D., **Gori, F.**, Barbieri, M., Billi, A., Franchini, S., Petitta, M., & Doglioni, C. (2020, May). First observation of multi-groundwater level responses to the strongest worldwide seismicity in Central Apennines (Central Italy). *In EGU General Assembly Conference Abstracts* (p. 5659).
- Barberio, M. D., Barbieri, M., Billi, A., Boschetti, T., Caracausi, A., Doglioni, C., Franchini, S., **Gori, F.**, & Petitta, M. Deep fluid source contribution to groundwater in Central Apennine: from regional to local scale. *MinWat 2020*
- Barberio, M.D., Barbieri, M., Billi, A., Doglioni, C., Gallo, T., **Gori, F.**, Franchini, S., Lacchini, A., Mariani, J., Petitta, M., & Rusi, S. Monitoring groundwater and earthquake relationships: "hydrosensitive zone" concept and experiences from Central Italy. – *45th IAH congress. Korea 9-14 September 2018*