

# Preliminary results on the response of some springs of the Sibillini Mountains area to the 2016-2017 seismic sequence

## *Risultati preliminari sulla risposta di alcune sorgenti dell'area dei Monti Sibillini a seguito della sequenza sismica del 2016-2017*

D. Fronzi, F. Banzato, S. Caliro, C. Cambi, C. Cardellini, R. Checcucci, L. Mastrotrillo, F. Mirabella, M. Petitta, D. Valigi, A. Tazioli

**Riassunto:** La dinamica dei sistemi idrogeologici che alimentano le sorgenti dei Monti Sibillini è stata profondamente influenzata da nove eventi sismici di  $M_w$  5,0÷6,5 avvenuti nell'Italia centrale a partire da agosto 2016. Lo shock più forte si è verificato il 30 ottobre 2016 a circa 5 km a nord-est della città di Norcia, a 9 km di profondità, a seguito della fagliazione normale della crosta superiore sui quasi 30 km di lunghezza del sistema Mt. Vettore-Mt. Bove, avente direzione NW-SE, immersione SW. La faglia affiora sul versante occidentale del Monte Vettore, la vetta più alta dei Monti Sibillini. Poco dopo questo evento, è stato osservato un generale aumento della portata delle sorgenti, dei corsi d'acqua e dei livelli piezometrici sia nelle aree di Visso che di Norcia, a ovest dei Monti Sibillini. Mentre nell'area di Visso le variazioni idrogeologiche indotte dalla sequenza sismica si sono esaurite nel 2019, attualmente le portate e i livelli piezometrici nell'area di Norcia sono più alti rispetto alla fase precedente alla sequenza sismica.

I dati di portata delle principali sorgenti situate ad est, sud-est dei Monti Sibillini sono stati analizzati per verificare se l'aumento generale osservato sul lato occidentale fosse associato a una diminuzione nell'area orientale. I risultati dell'analisi mostrano che le sorgenti situate sul lato orientale e sud orientale del Mt

Vettore, hanno subito una significativa riduzione delle portate a lungo termine. In questo lavoro preliminare, l'analisi delle serie storiche di portata della sorgente di Pescara di Arquata (SE del Monte Vettore) e il suo rapporto con lo Standard Precipitation Index (SPI) mostra che i valori di portata molto bassi registrati nel periodo post terremoto non sono associati a valori di SPI così bassi come documentato in passato per portate simili. Inoltre, la composizione degli isotopi stabili dell'acqua della sorgente di Pescara di Arquata nel periodo post-sismico è leggermente differente rispetto a quella pre-sismica. Questo suggerisce un minore apporto di acque a contenuto isotopico del  $\delta^{18}O$  più arricchito e sembra indicare che la circolazione idrica sotterranea dell'area sud orientale dei Monti Sibillini abbia risentito della sequenza sismica del 2016-2017.

**Abstract:** *The dynamic of groundwater systems feeding several springs of the Sibillini Mountains was deeply affected by nine  $M_w$  5.0÷6.5 seismic events occurred in central Italy starting from August 2016.*

*The strongest shock occurred on October 30<sup>th</sup> 2016 about 5 km NNE of Norcia Town, 9 km below the surface, as a result of upper crust normal faulting on the nearly 30 km-long Mt Vettore - Mt Bove fault system, a NW-SE trending, SW-dipping fault system outcropping on the western slope of Mt Vettore, the highest peak of Sibillini Mountains.*

*Soon after this event, a general increase of springs and rivers discharge and groundwater levels was observed both in the Visso and Norcia areas, west of the Sibillini Mountains. In the Visso area the hydrogeological changes due to the seismic sequence exhausted in the 2019, while nowadays both discharges and groundwater levels are still higher than before in the Norcia area.*

*Discharge data of the main springs located east, south-east of the Sibillini Mountains were analysed to verify whether the general increase observed on the western side was associated to a decrease on the eastern and southern-east area. The results show that the springs located on the eastern side and southern-east side of Mt Vettore experienced a significant long-term discharge decrease.*

*In this preliminary work, the analysis of the historical discharge series of the Pescara di Arquata spring (SE of Mt Vettore), and its relationship with the Standard Precipitation Index (SPI) shows that the very low discharge values recorded during the post-seismic period are not associated with SPI as low as documented in the past for similar discharges. Moreover, the stable isotopic composition of Pescara di Arquata water during the post-earthquake period is slightly different from that measured before the seismic events; this suggests that a lower amount of water having more enriched isotopic  $\delta^{18}O$  content reaches the spring after the seismic sequence. These aspects seem to indicate that groundwater circulation in the southern-east area of Sibillini Mountains has been affected by the 2016-2017 seismic sequence.*

**Keywords:** *earthquake, hydrogeology, spring discharge, SPI, Central Italy.*

**Parole chiave:** terremoti, idrogeologia, portata delle sorgenti, SPI, Italia centrale.

Davide FRONZI ✉

Alberto TAZIOLI

Università Politecnica delle Marche - Dipartimento SIMAU.

Via Breccie bianche 12 - 60122 Ancona, IT

d.fronzi@pm.univpm.it; a.tazioli@staff.univpm.it

Costanza CAMBI, Carlo CARDELLINI

Francesco MIRABELLA, Daniela VALIGI

Università degli studi di Perugia, Dipartimento di Fisica e Geologia, Perugia IT

Francesca BANZATO, Marco PETITTA

Università di Roma La Sapienza, Dipartimento di Scienze della Terra, Roma IT

Stefano CALIRO

Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Napoli, IT

Roberto CHECCUCCI

Regione Umbria, Servizio Risorse Idriche e Rischio Idraulico, Perugia IT

Lucia MASTRORILLO

Università degli Studi Roma Tre - Dipartimento di Scienze, Roma IT

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## Introduction

Earthquakes effects on the hydrogeological systems are well known worldwide (Manga et al. 2003; Lai et al. 2004; Charmoille et al. 2005). In Italy these phenomena are documented by many Authors (Esposito et al. 2009; Amoruso et al. 2011; Barberio et al. 2017; Valigi et al. 2020). Sometimes the principal changes are related only to the geochemical aspects of groundwater (Skelton et al. 2014), sometimes earthquakes modify the hydrodynamics of the system (Montgomery 2003, Manga et al. 2003), but in general both effects are recognised during strong seismic events (Adinolfi Falcone et al. 2012).

Several seismic events occurred since August 2016 (Chiaraluce et al. 2017; Civico et al. 2018; Porreca et al. 2018; Brozzetti et al. 2019) affected the dynamic of groundwater systems in the Sibillini Mountains area, in which nine of these events displayed a magnitude ranging from 5.0 to 6.5  $M_w$ . In particular, a general increase of springs and rivers discharge was observed as a consequence of the main shock occurred on October 30<sup>th</sup> 2016 in the Visso and Norcia areas, that are located in the western portion of the Sibillini area (Petitta et al. 2018; Mastrotrillo et al. 2019; Valigi et al. 2019; Di Matteo et al. 2020). In addition, a general decrease of spring discharge occurred after this earthquake in the eastern and south-eastern part of the Sibillini Mountains area.

Due to the strategic role for human requirements of the main springs in the study area, where the protection of groundwater resources and of ecosystems is naturally safeguard by the Sibillini National Park (Mastrotrillo et al. 2012), a preliminary discharge analysis on one of a spring of the area, named Pescara di Arquata spring and its relationship with the Standard Precipitation Index (SPI), was conducted.

In addition, a preliminary evaluation of changes in the isotopic composition of the spring was performed and data were compared to pre-earthquakes ones to investigate if the general changes on the hydrodynamic system were related to the seismic sequence.

## Materials and methods

### Geological and hydrogeological setting

The study area is located in central Italy, between Marche, Umbria, Abruzzo and Lazio Regions. It involves the southern-east structure of Mt Sibillini Massif (Dragoni and Valigi 2003), where the Umbria-Marche succession crops out. The stratigraphic sequence is mostly composed by limestone deposited in a carbonate platform environment and overlaid by pelagic sequences (Pierantoni et al. 2013).

The area was subjected to a compressive tectonic stage (Late Miocene–Early Pliocene) generating a thrust and folds chain. The main compressional tectonic element is represented by the Sibillini Mountains thrust (Lavecchia and Jorio 1965). Extensional tectonic took place since Early Pliocene, with the consequent development of WSW-ESE normal faults, among which the ones responsible for the 2016–2017 seismic sequence (Porreca et al. 2018; Villani et al. 2018; Brozzetti et al. 2019).

The hydrogeological setting depends on stratigraphic and structural features of the Umbria-Marche domain (Fig. 1). The main aquifers are located in the Calcarea Massiccio and Corniola formations, and in the Maiolica formation. These two aquifers are independent at a local scale, where they are stratigraphically separated from each other by a Jurassic sequence, mostly composed of siliceous and marly formations, acting as an aquitard. Conversely, in areas where these

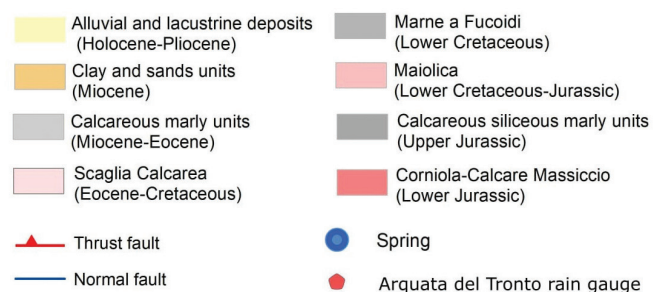
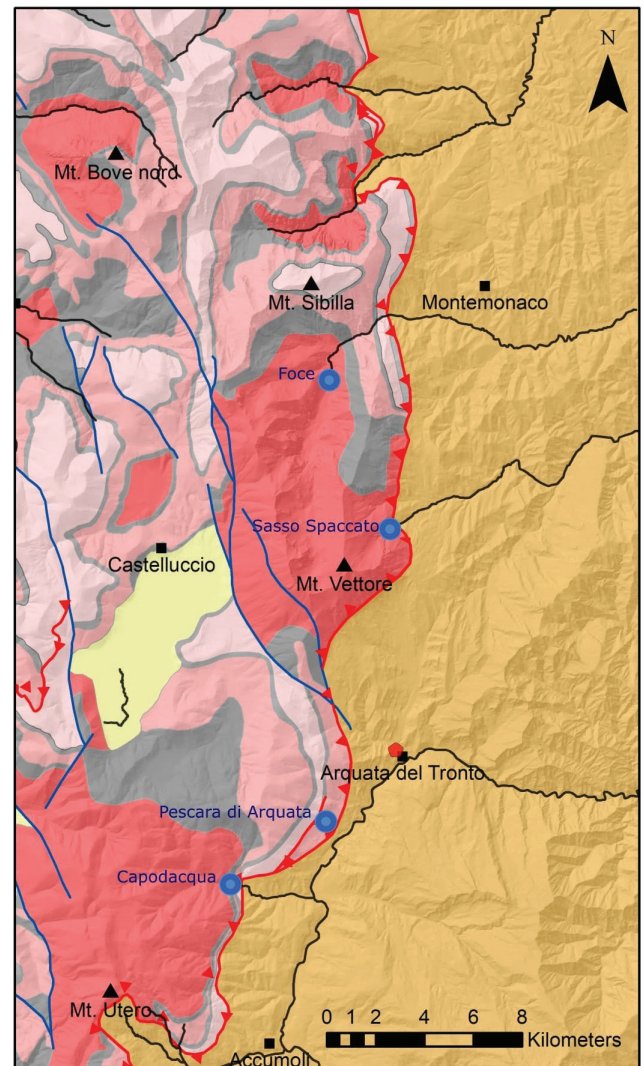


Fig. 1 - Geological sketch of the study area and location of the main springs of eastern/south-eastern area of Sibillini Mountains.

Fig. 1 - Schema geologico dell'area di studio e ubicazione delle principali sorgenti ad est/sud-est dei Monti Sibillini.

formations are thin or missing a single aquifer (Basal aquifer) including the above mentioned ones can be recognized (Boni et al. 2010; Valigi et al. 2020).

Above these two aquifers, other upper ones are located within the Scaglia Bianca and Scaglia Rossa formations (Calcareous Scaglia, late Cretaceous - middle Eocene), made of thin to medium-layered pelagic limestones. The Marne a Fucoidi (middle -Cretaceous) represents the aquiclude dividing the Basal and Scaglia aquifers.

### Discharge and climatic setting

A preliminary discharge analysis was conducted on Foce, Sasso Spaccato, Capodacqua and Pescara di Arquata springs for which the data were provided by C.I.I.P. Servizio Idrico Integrato.

In this work a focus was dedicated to Pescara di Arquata spring discharge and its relationship with the Standard Precipitation Index (SPI) (McKee et al. 1993).

SPI values, at a time scale from 1 to 24 months, were calculated for the Arquata del Tronto rainfall station managed from Civil Protection Agency of Marche Region. For this station, located nearby the spring recharge area, a representative set of data is available. The rainfall station is located at an altitude lower than the spring mean recharge area. Nonetheless, although it could not be used as it is to estimate water balance, it seems that it can be conveniently used to determine the relation between mean monthly discharge values and SPI values before and after the seismic sequence.

The SPI is the number of standard deviations that the observed value would deviate from the long-term mean, for a normally distributed random variable. In the SPI computation, cumulated rainfalls over different time scales (1, 2, 3 ... n months) were fitted to a gamma probability distribution and then transformed into a normal distribution. For a given data time series of precipitation  $x_i$  as  $x_1, x_2 \dots x_n$ , the SPI is defined by the equation:

$$SPI = \frac{x_i - \bar{x}}{\sigma_x}$$

where  $\bar{x}$  is the arithmetic mean of rainfall and  $\sigma_x$  is the standard deviation.

For a defined timescale, SPI equal to 0 implies that there is no deviation from the mean. Positive values of SPI indicate wet periods, while negative values indicate dry periods. The severity of drought events increases when SPI values are highly negative. Table 1 shows the classification of drought severity based on the SPI values.

### Isotopic analysis

In order to investigate if any change on the recharge area or aquifer geometry of the southern-east sector of Sibillini Mts occurred after the seismic sequence, a preliminary isotopic analysis on  $\delta^{18}\text{O}$  content was conducted in several springs of the area.

Tab. 1 - Classification of drought conditions based on the SPI values (McKee et al. 1993).

Tab. 1 - Classificazione delle condizioni di siccità basate sui valori dell'SPI (McKee et al. 1993).

Condition	Range
Extremely wet	$SPI \geq 2.0$
Very wet	$1.5 \leq SPI < 2.0$
Moderately wet	$1.0 \leq SPI < 1.5$
Near normal	$-1.0 < SPI < 1.0$
Moderately dry	$-1.5 < SPI \leq -1.0$
Severely dry	$-2.0 < SPI \leq -1.5$
Extremely dry	$SPI \leq -2.0$

At first we determined the isotopic altitude gradient of  $\delta^{18}\text{O}$  in the study area with rain gauges and shallow springs, used to integrate the rain data. In fact, due to the relatively short flowpath between recharge area and discharge point, the minor springs can be considered as meteoric water collectors (Tazioli et al. 2019). A second analysis on  $\delta^{18}\text{O}$  content was performed between 2016-2019 on the Pescara di Arquata spring, on the water of which a previous collection campaign was conducted between 2002 and 2009. Samples for isotopes analysis were collected in 50mL high-density polyethylene bottles sealed by plastic inserts to avoid water evaporation. Isotopic analysis of  $\delta^{18}\text{O}$  were performed by using standard mass spectrometry techniques with an analytical error of  $\pm 0.08\%$ . A statistical analysis (performed in MATLAB®) based on moving mean (window length equal to 7) was applied to the Pescara di Arquata  $\delta^{18}\text{O}$  isotopic data in order to detect abrupt changes in the signal.

### Results and discussion

After the 2016-2017 seismic sequence, the discharge of the Foce and Sasso Spaccato springs, both fed by the Basal aquifer significantly decreased in the long term (Fig. 2). As regards the Foce spring, the mean discharge calculated for the period 2014-2016 was about 500 L/s, whereas after the seismic sequence the mean discharge value was about 300 L/s. At the end of 2019 recession period, the mean monthly discharge reached a value lower than 200 L/s. The Sasso Spaccato spring mean discharge, calculated for the period 2014-2016, was about 70 L/s, whereas after the seismic sequence the mean discharge value was about 30 L/s. On the contrary, the Capodacqua spring, also fed mainly by the Basal aquifer, do not show an evident long lasting decrease of average discharge after the seismic sequence. The mean monthly discharge before (2004-2016) and after the seismic sequence has a value of about 400 L/s. In the Pescara di Arquata spring, fed mainly by Maiolica and Scaglia aquifers, it was observed that in 2017, 2018 and 2019 the minimum discharge values at the end of the depletion periods were about 30 L/s.

The Standardized Precipitation Index, calculated for the Arquata del Tronto rainfall station in October 1985 - September 2019 interval allowed to understand if these circumstances of low discharge values were related to long lasting extreme droughts.

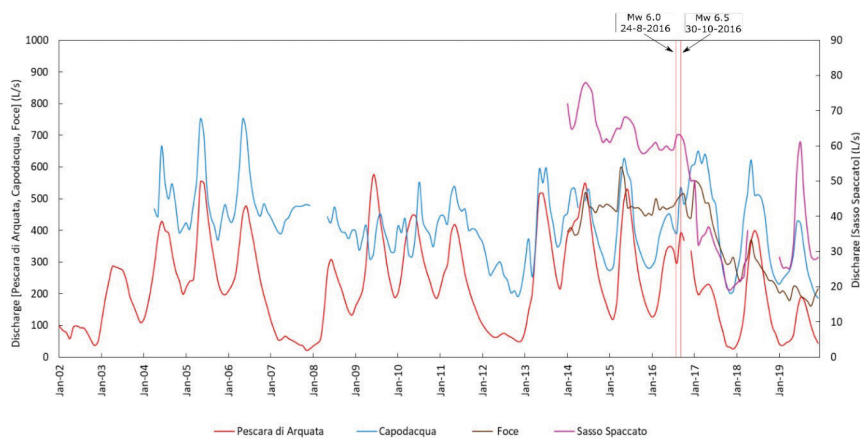


Fig. 2 - Mean monthly discharge data of the main springs of eastern/south-eastern area of Sibillini Mountains, until December 2019. The red lines represent the  $M_w$  6.0 earthquake occurred on August 24<sup>th</sup> and the  $M_w$  6.5 earthquake occurred on October 30<sup>th</sup>, 2016.

Fig. 2 - Portate medie mensili delle principali sorgenti ad est/sud-est dei Monti Sibillini, fino a dicembre 2019. Le linee rosse rappresentano gli eventi sismici di  $M_w$  6.0 del 24 agosto e quello di  $M_w$  6.5 del 30 ottobre 2016.

The best correlation was found for SPI calculated at a time scale of 12 months (SPI-12) ( $R=0.60$ ). Only six times (1990, 2002, 2007, 2012, 2017 and 2019) the discharge has fallen below 50 L/s (Fig. 3). In all these periods except in 2017 and 2018-2019, the very low discharge values have corresponded to SPI-12 values lower than, or very close to, -2. In 2017 only, SPI-12 values between -1 and -1.5 (moderately dry) for just a one month (October 2017) have corresponded to a discharge even lower than 30 L/s. Starting from October 2017, the SPI-12 ranges between -1.47 to 1.59 which corresponds to a moderately dry to a very wet period. These considerations suggest that the very low discharges recorded in 2017 and 2018-2019 could be linked to the earthquake

Our results are in accordance with the higher Maillet depletion coefficient ( $\alpha$ ) (Maillet 1905) values determined for the post-earthquake recession periods, with respect to those calculated before October 30<sup>th</sup>, 2016 earthquake. The average value of  $\alpha$  coefficient before and after the  $M_w$  6.5 earthquake are  $6.35 \cdot 10^{-3} \text{ day}^{-1}$  and  $1.27 \cdot 10^{-2} \text{ day}^{-1}$  respectively. The aquifer feeding the Pescara di Arquata spring emptied faster than it did before (Valigi et al. 2020).

The  $\delta^{18}\text{O}$  altitude gradient calculated in this area in the studied period is about 0.28 ‰/100 m, similar to other values determined for the same area in previous studies (Tarragoni 2006; Nanni and Tazioli 2013; Giustini et al. 2016; Mussi et al. 2017).

The isotopic analysis (between September 2002 and September 2009) of the Pescara di Arquata spring shows that the average value of  $\delta^{18}\text{O}$  content is -9.91 ‰ with a standard deviation of  $\pm 0.39$  ‰. The maximum value of  $\delta^{18}\text{O}$  reached before the seismic sequence is -8.51 ‰ in July 2004, the minimum value is -10.5 ‰ reached in September 2009. All the water samples collected after the earthquake are characterized by a  $\delta^{18}\text{O}$  content lower than the average value recorded for the period 2002-2009 (Fig. 4a). The more limited variability of  $\delta^{18}\text{O}$  content and the general slight decreasing of  $\delta^{18}\text{O}$  values after the seismic sequence could be attributable to a low number of samples so far collected, but a contribution to spring discharge of waters more enriched in  $\delta^{18}\text{O}$  slightly lowered with respects to pre-seismic conditions, cannot be excluded.

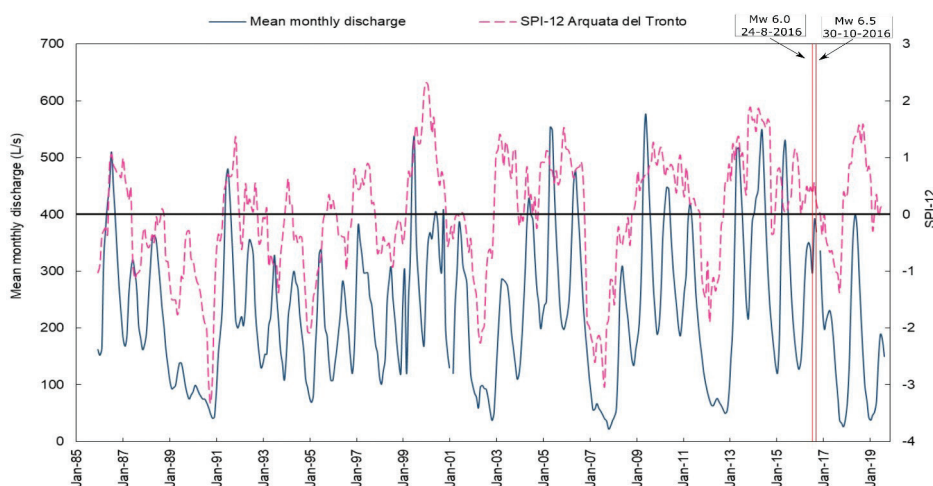


Fig. 3 - SPI-12 values from October 1985 to September 2019 for Arquata del Tronto rainfall station vs mean monthly discharge values of Pescara di Arquata spring.

Fig. 3 - Valori dell'SPI-12 per la stazione pluviometrica di Arquata del Tronto calcolati tra ottobre 1985 e settembre 2019 vs le portate medie mensili della sorgente di Pescara di Arquata.

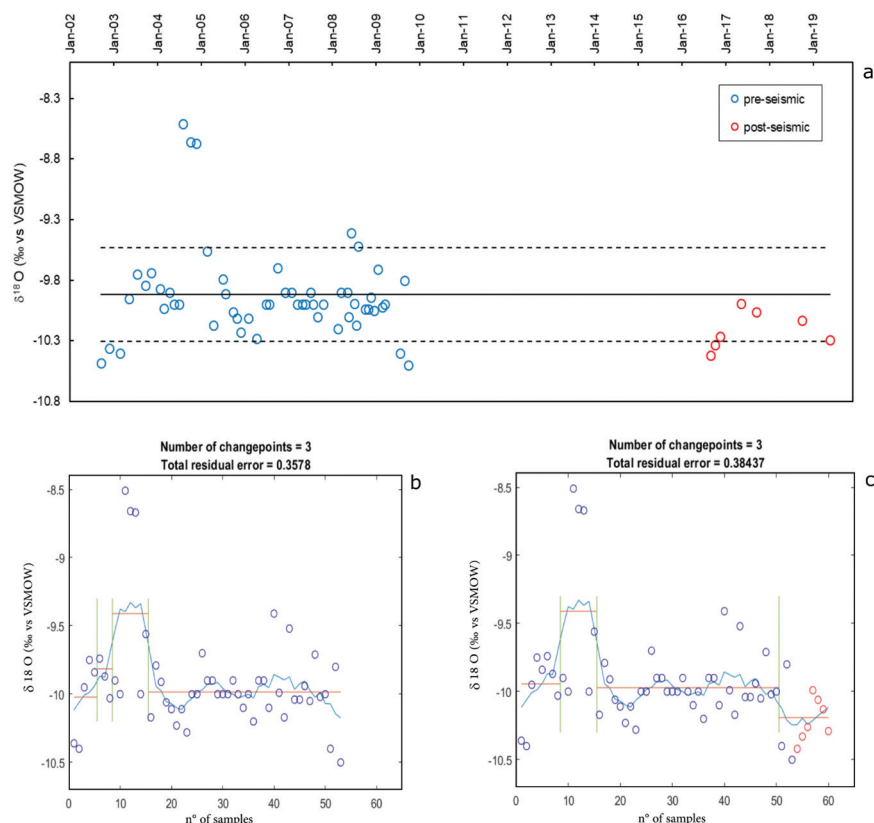


Fig. 4 - a)  $\delta^{18}\text{O}$  content of the Pescara di Arquata spring before and after the seismic sequence. The black solid line shows the average value of  $\delta^{18}\text{O}$  content recorded between 2002 and 2009, the dashed lines show the standard deviation from the average value.

b-c) the red horizontal lines represent the mean  $\delta^{18}\text{O}$  values associated to each of the periods delimited by abrupt changes with just the data collected before the seismic sequence (b) and per tutto il set di dati (c).

Fig. 4 - a) contenuto isotopico del  $\delta^{18}\text{O}$  per la sorgente di Pescara di Arquata, prima e dopo la sequenza sismica. La linea nera continua mostra la media del contenuto isotopico registrato tra il 2002 e il 2009, le linee tratteggiate mostrano la deviazione standard dei valori rispetto alla media. b-c) le linee rosse orizzontali rappresentano i valori medi del  $\delta^{18}\text{O}$  associati ad ogni periodo delimitato da bruschi cambiamenti, per i dati prima della sequenza sismica (b) e per tutto il set di dati (c).

## Conclusions

The results show that the springs of the Sibillini area analysed in this preliminary work behaved different from each other in response to the 2016–2017 seismic sequence. The Foce and the Sasso Spaccato springs, both fed by the basal aquifer of the Mt Vettore Massif, experienced a significant long term discharge decrease. In particular, the discharge of Foce spring, is still presently much lower with respect to the pre-seismic value. The discharge of Capodacqua spring, fed mainly by the basal aquifer of Mt Utero Massif, is the only one which did not change significantly after the earthquakes. The discharge reduction recorded in Foce and Sasso Spaccato springs could be related to the fact that the Basal aquifer of the Mt Vettore Massif was affected by significant dislocations as a consequence of the activation of the Mt Vettore - Mt Bove fault system during the 2016–2017 seismic sequence. This could have caused a connection between the Mt Vettore Basal aquifer and the groundwater bodies located west of the Sibillini chain. Part of the groundwater previously feeding the springs east of Mt Vettore Massif could have therefore diverted westward, increasing the discharge of western groundwater systems in Norcia and Visso areas (Petitta et al. 2018; Mastrorillo et al. 2019; Valigi et al. 2019; Di Matteo et al. 2020).

The Pescara di Arquata spring is the only one among those analysed which is mainly fed by an upper aquifer hosted in Maiolica and Scaglia formations (Valigi et al. 2020).

The analysis of the relationship between Pescara di Arquata spring discharges and climatic conditions of the area

shows that, after the seismic sequence, at the end of recession periods very low discharge values were reached, which cannot be justified only by climatic conditions. This suggests that the system was affected by modifications related to the 2016–2017 seismic sequence.

Although isotopic data presently available are still not enough to certainly define the changes occurred in the Pescara di Arquata spring system, the  $\delta^{18}\text{O}$  content of the seven water samples so far collected, might indicate that the contribution of water coming from lower altitudes has decreased after the seismic sequence.

New data will hopefully allow to confirm the preliminary isotopic results and to better define the mechanisms which could have modified the groundwater flowpaths determining significant discharge changes both west and east of the Sibillini Mountains.

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