Continuous monitoring of physical parameters (temperature, electrical conductivity, water pressure) in a karst aquifer of central Italy (Venafro Mts., Molise): first results in a seismically active region.

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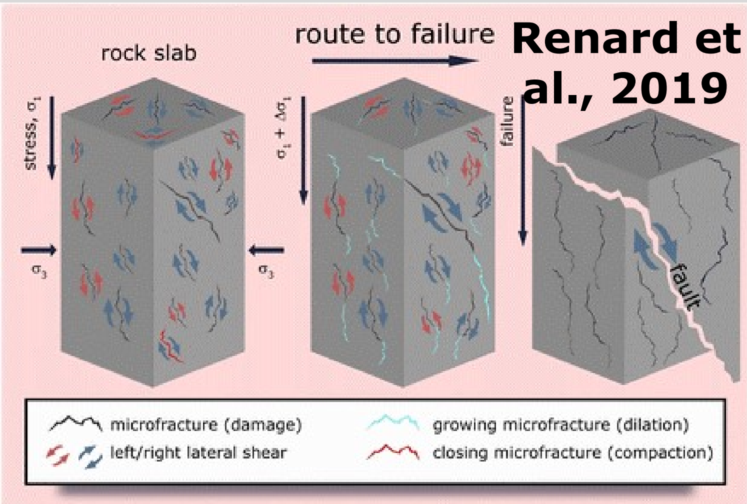
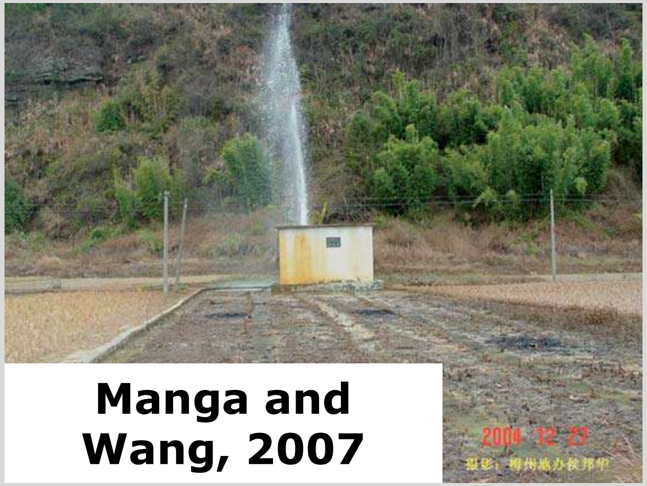
The seismic cycle is accompanied by stress perturbations that possibly accelerate at the end of the interseismic period, just before the earthquake; stress modification can determine fluids migration (dilatancy model, Nur, 1972; Scholz et al., 1973). Therefore, changes in the flow and geochemistry of groundwater prior to an earthquake may be expected (e.g. King and Muir-Wood, 1993; Skelton et al., 2014; Wang et Manga, 2015). In fact, hydrologic effects of strain during and after an earthquake have been abundantly documented worldwide.

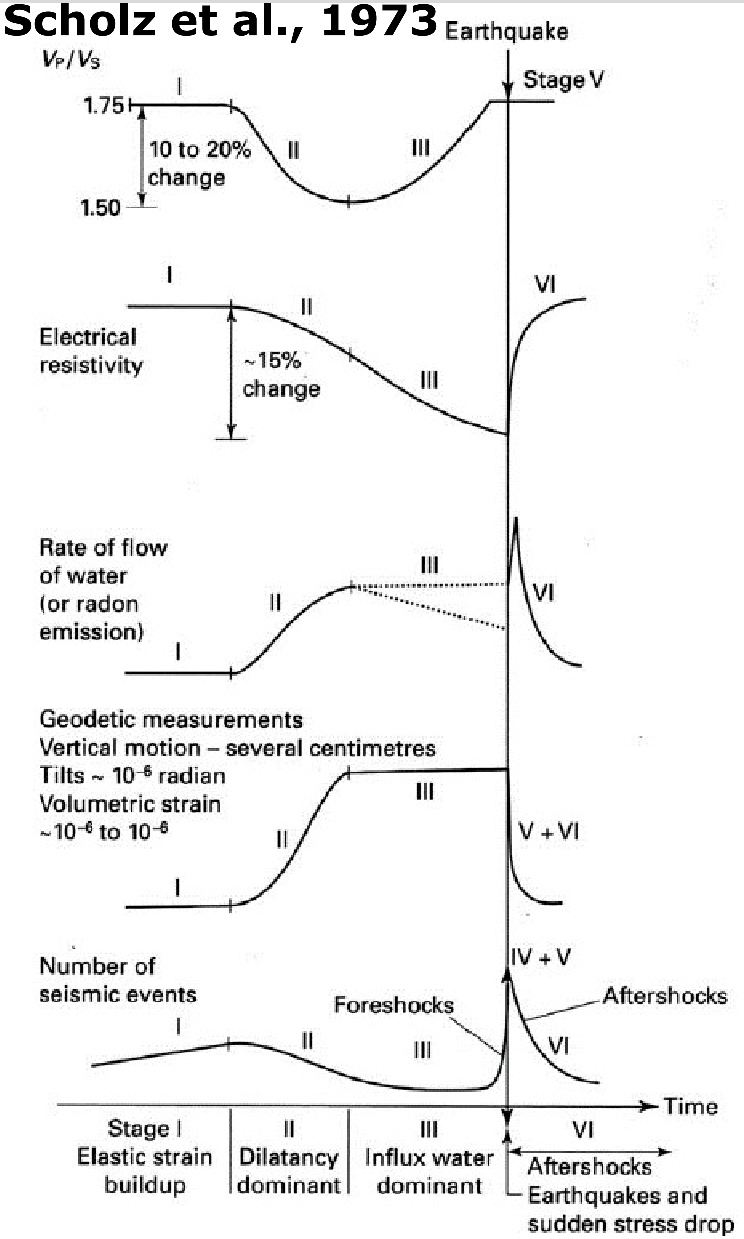


Renard et al., 2019

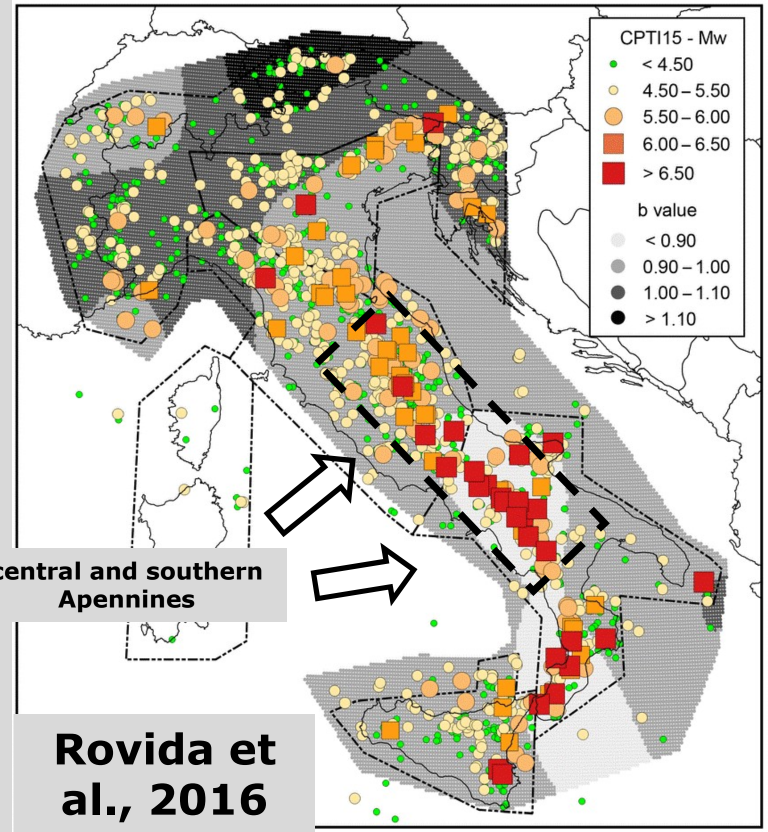


Manga and Wang, 2007

Scholz et al., 1973



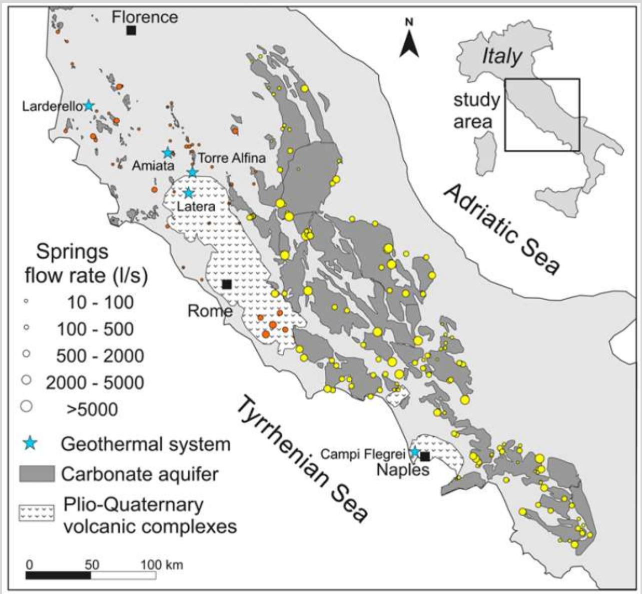
In Italy, central and southern Apennines show a diffuse and highly energetic seismic activity (CPTI15, M_{max}=7.0). Carbonate mountain ranges host huge water (karst) and (spotty) CO_2 circulation at depth (e.g. Chiodini et al., 2004; Frondini et al., 2018), making studies on the relationship between fluids and earthquakes particularly stimulating and, hopefully, effective.



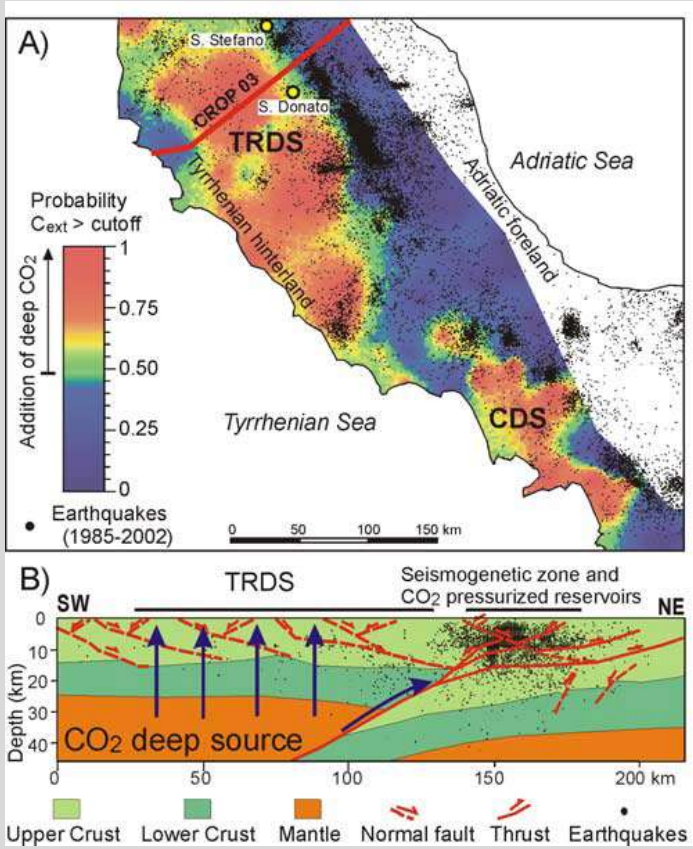
central and southern Apennines

Rovida et al., 2016

Frondini et al., 2018

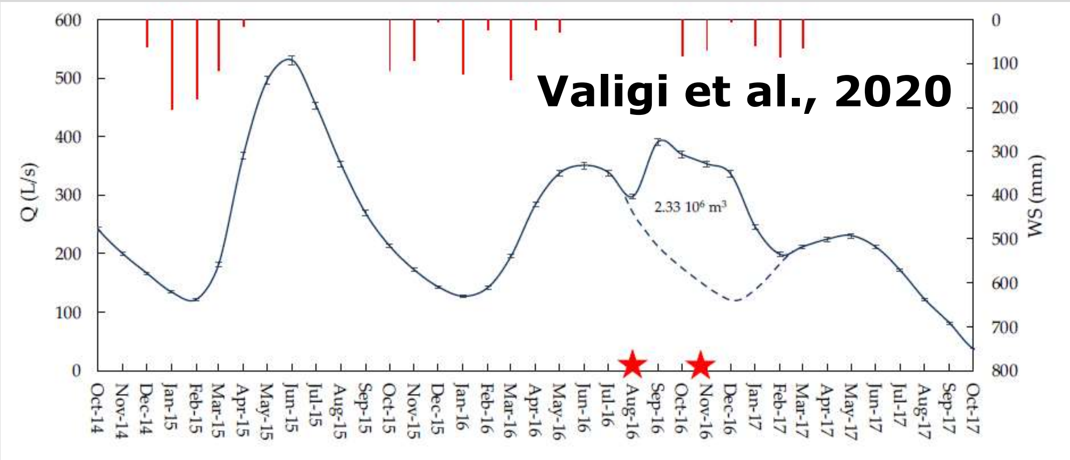


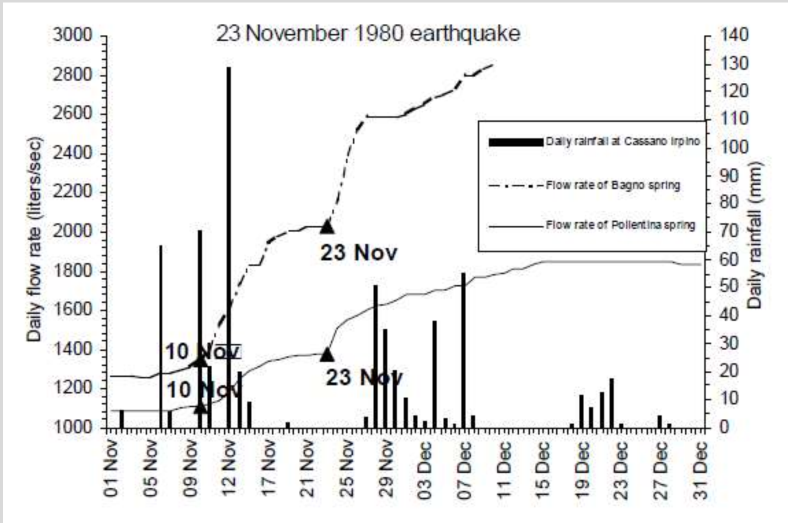
Chiodini et al., 2014



The effects of past earthquakes on groundwater in the central and southern Apennine belt of Italy have been described by some papers:

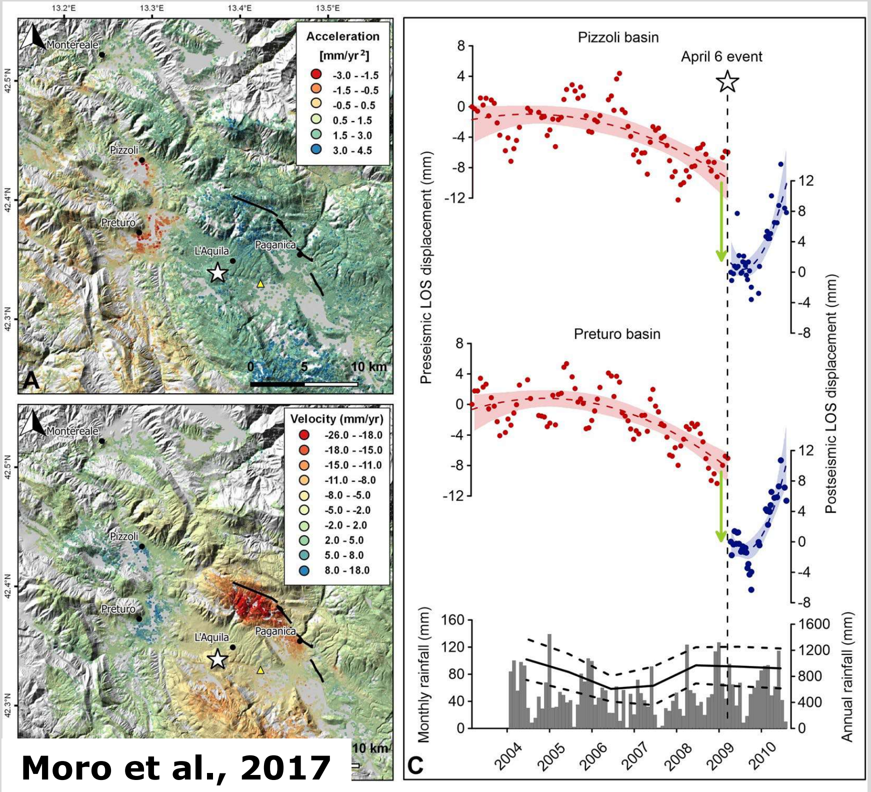
- **Celico (1981); Celico et al. (1981); Esposito et al. (2009, 2011): four earthquakes in southern Apennines, including the Mw 6.9 1980 Irpinia earthquake;**
- **Carro et al. (2005): 1997-1998 Umbria-Marche seismic sequence;**
- **Amoruso et al. (2011); Adinolfi Falcone et al. 2012; Galassi et al. 2014: L'Aquila 2009 earthquake;**
- **Barberio et al. (2017); Maestrelli et al. (2017); De Luca et al. (2016, 2018); Petitta et al. (2018); Mastrorillo et al. (2020); Barbieri et al., 2020; Fronzi et al. (2020); Valigi et al. (2020): 2016-2017 central Italy seismic sequence.**



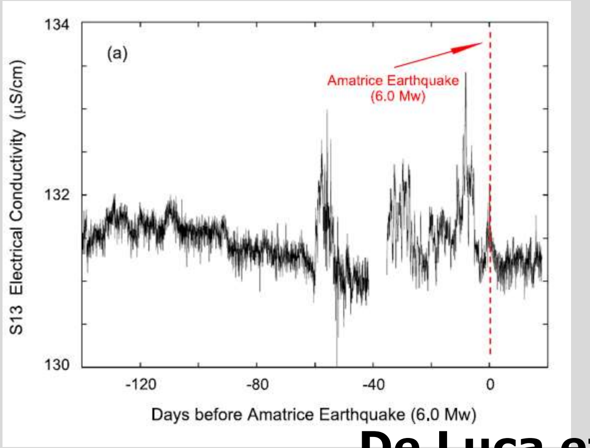


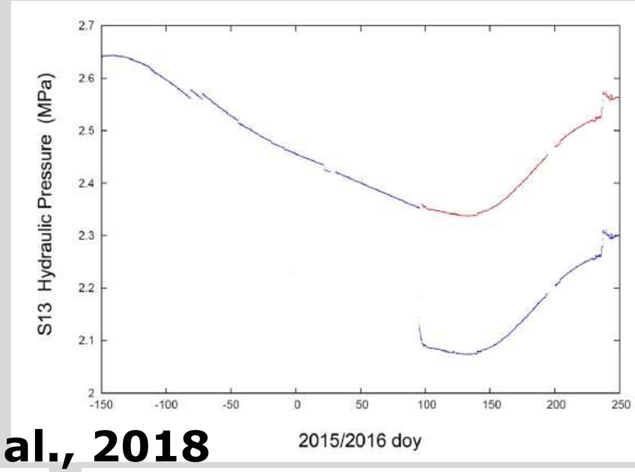
Esposito et al., 2011

Changes were observed mainly in the co and post-seismic phase and only a few short and long-term pre-seismic signals were recorded (Esposito et al., 2001; De Luca et al., 2016, 2018; Moro et al., 2017). Some geological models (e.g. by Doglioni et al., 2014) were proposed to explain the mechanisms that can generate these hydrological anomalies both in extensional and compressional tectonics.

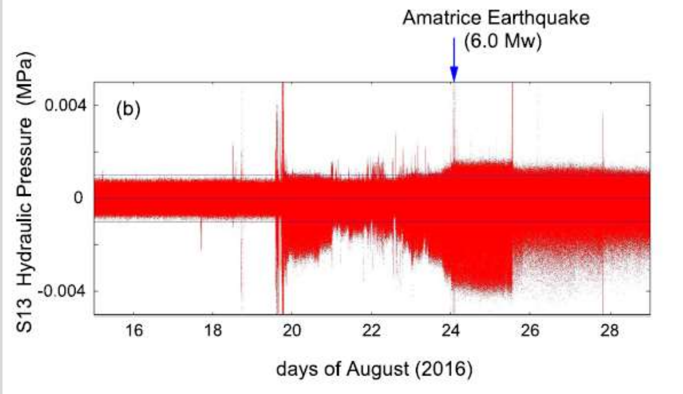


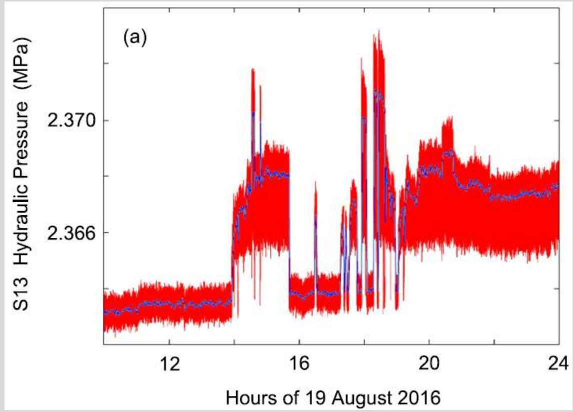
Moro et al., 2017





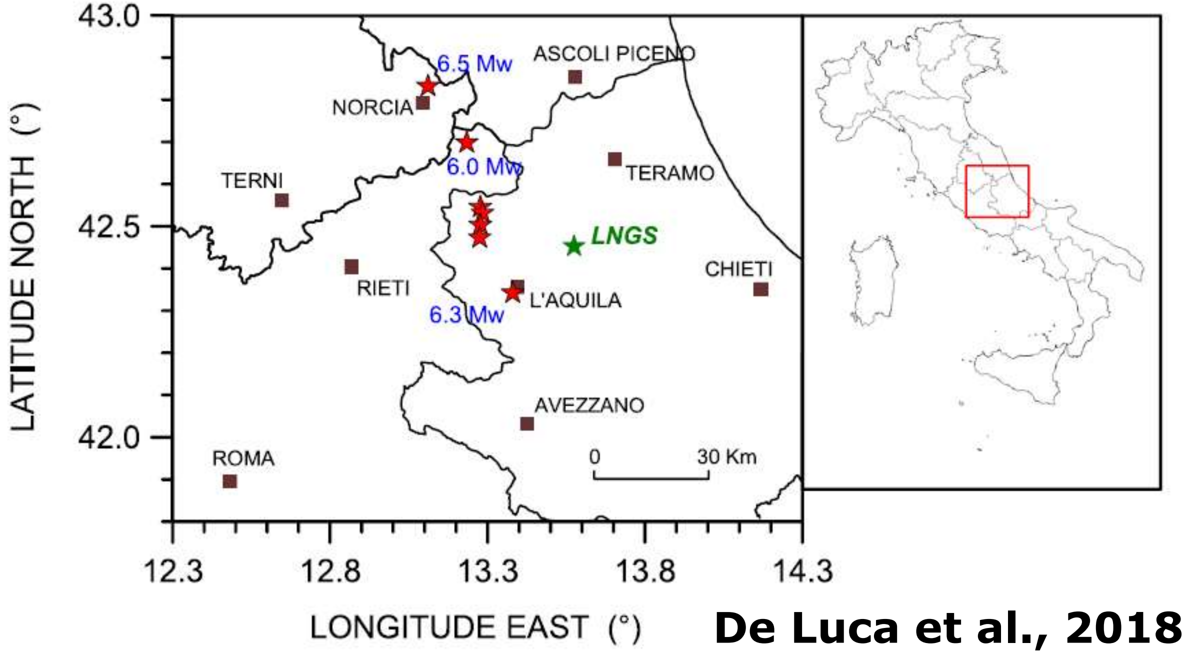
De Luca et al., 2018



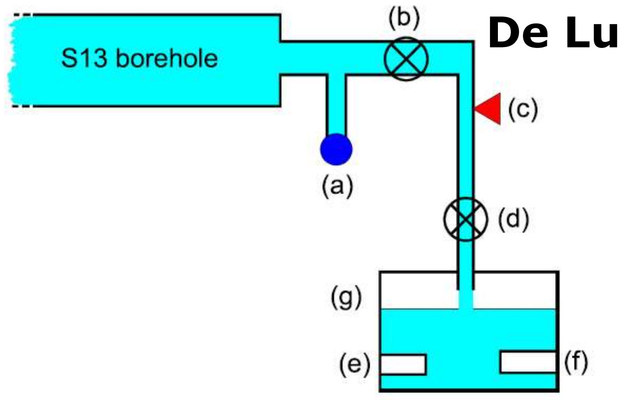


Sampling rate spans from weeks to months, but higher frequency of data collection is needed to study crustal deformation processes (stress and volumetric strain) during the earthquake cycle.

Since 2015, De Luca et al. (2016, 2018) have been performing high frequency (up to 20 samples per second) continuous monitoring of temperature, hydraulic pressure, and electrical conductivity in the Gran Sasso aquifer (LNGS, central Italy). They recorded unambiguous long-term (days to months) pre-August 24, 2016 earthquake (M_w=6.0) anomalies in both hydraulic pressure and electrical conductivity, related to its preparation stage.



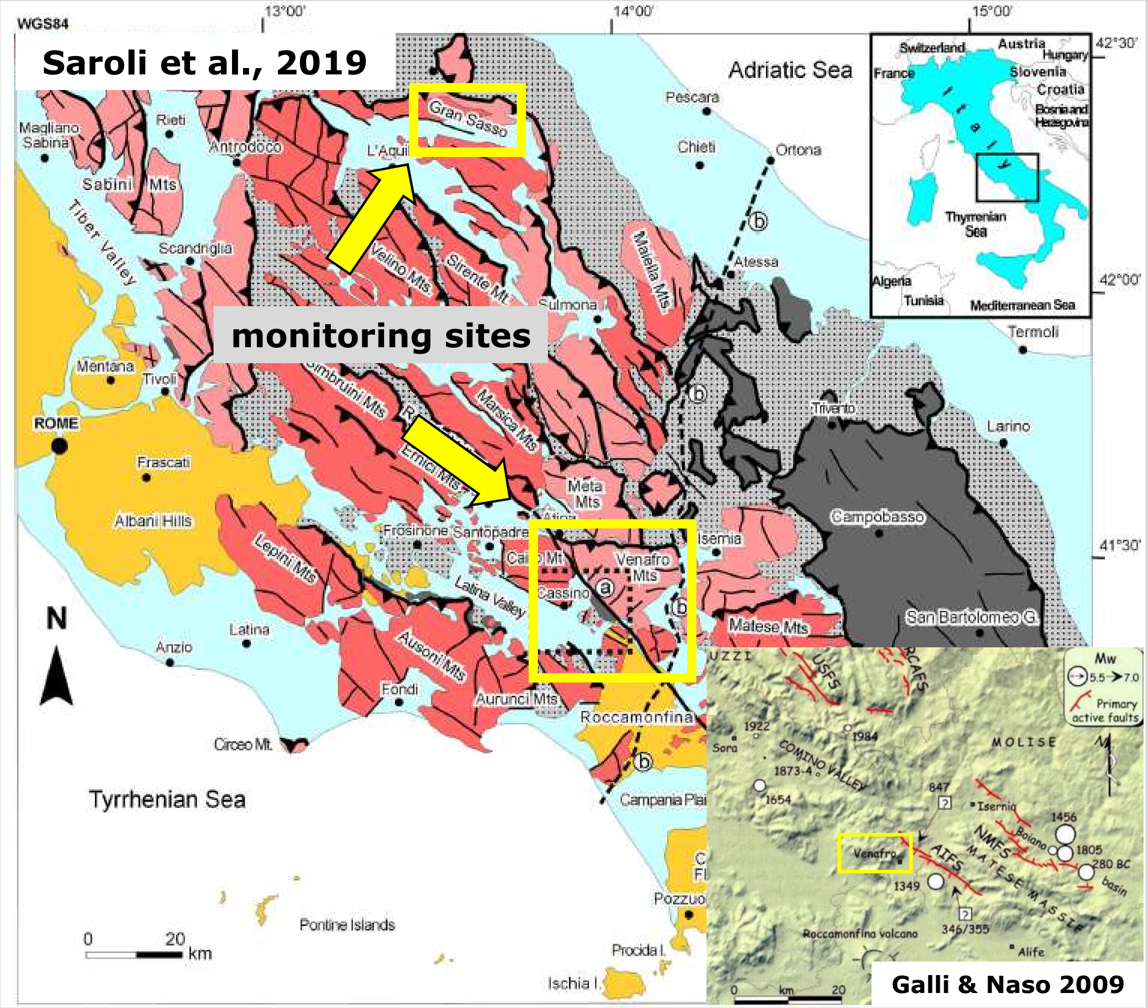
De Luca et al., 2018

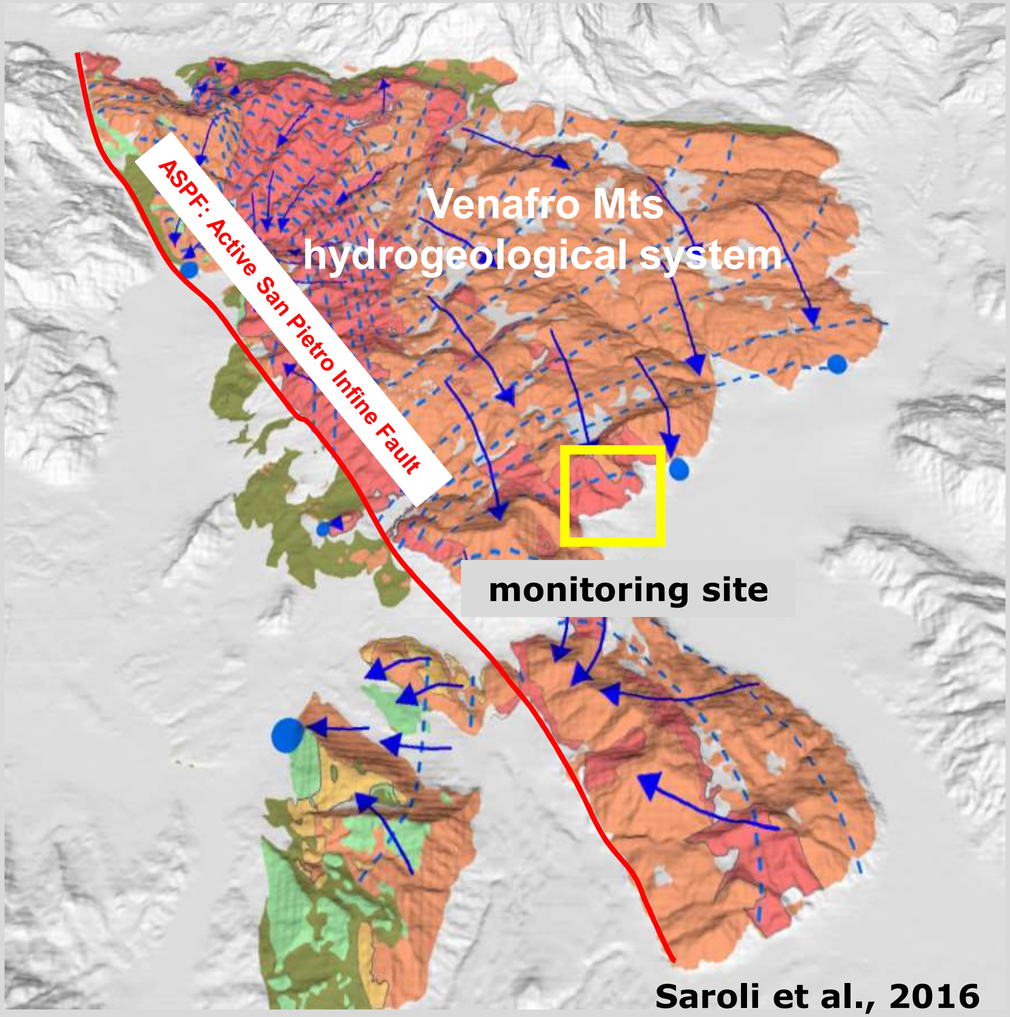


De Luca et al., 2018

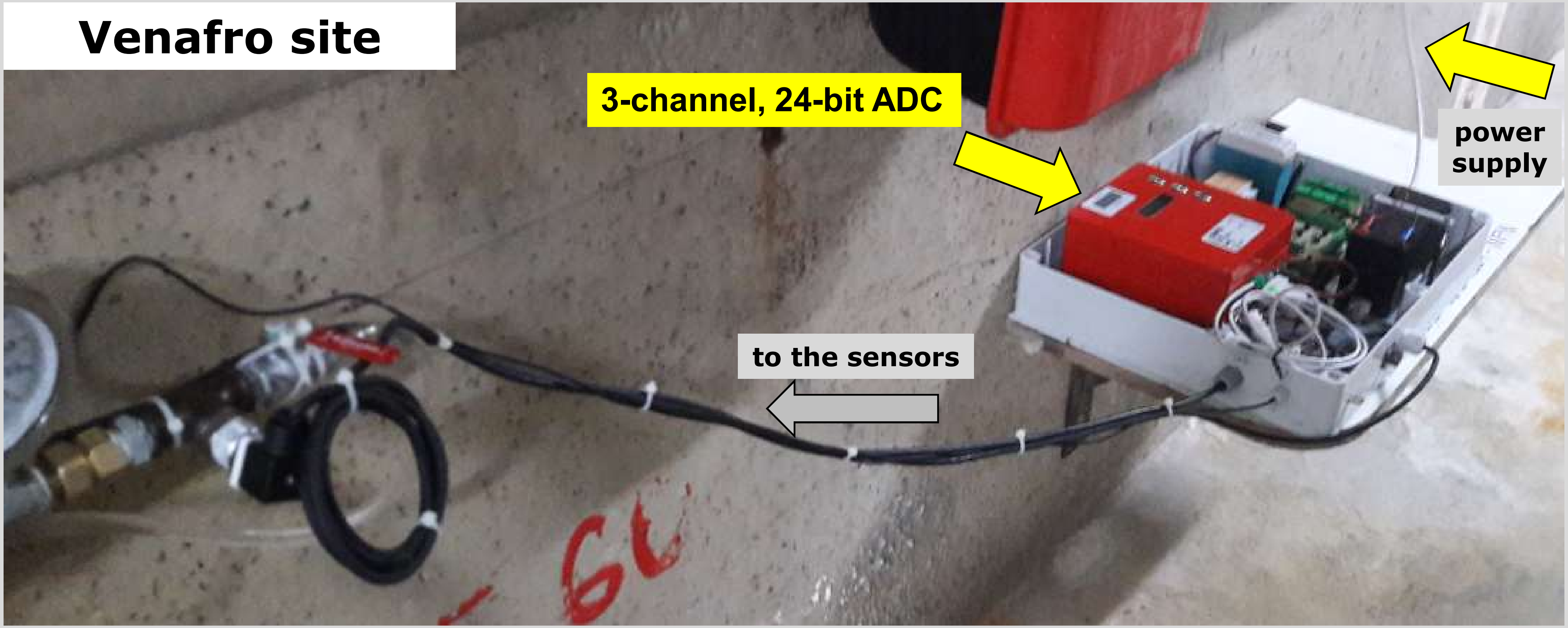
Figure 5. Hydraulic scheme (not in scale) of the experimental apparatus. The length of the S13 horizontal borehole is 190 m. (**a**) old analogic manometer; (**b**) hydraulic valve that is always open during the data acquisition periods; (**c**) hydraulic pressure sensor; (**d**) hydraulic valve not completely close to enable the measurement of temperature and electrical conductivity in the box (**g**); (**e**) temperature sensor; (**f**) electrical conductivity sensor; (**g**) transparent plastic container housing the temperature and electrical conductivity sensors; water is expelled when reaching about three quarters of the volume of the container.

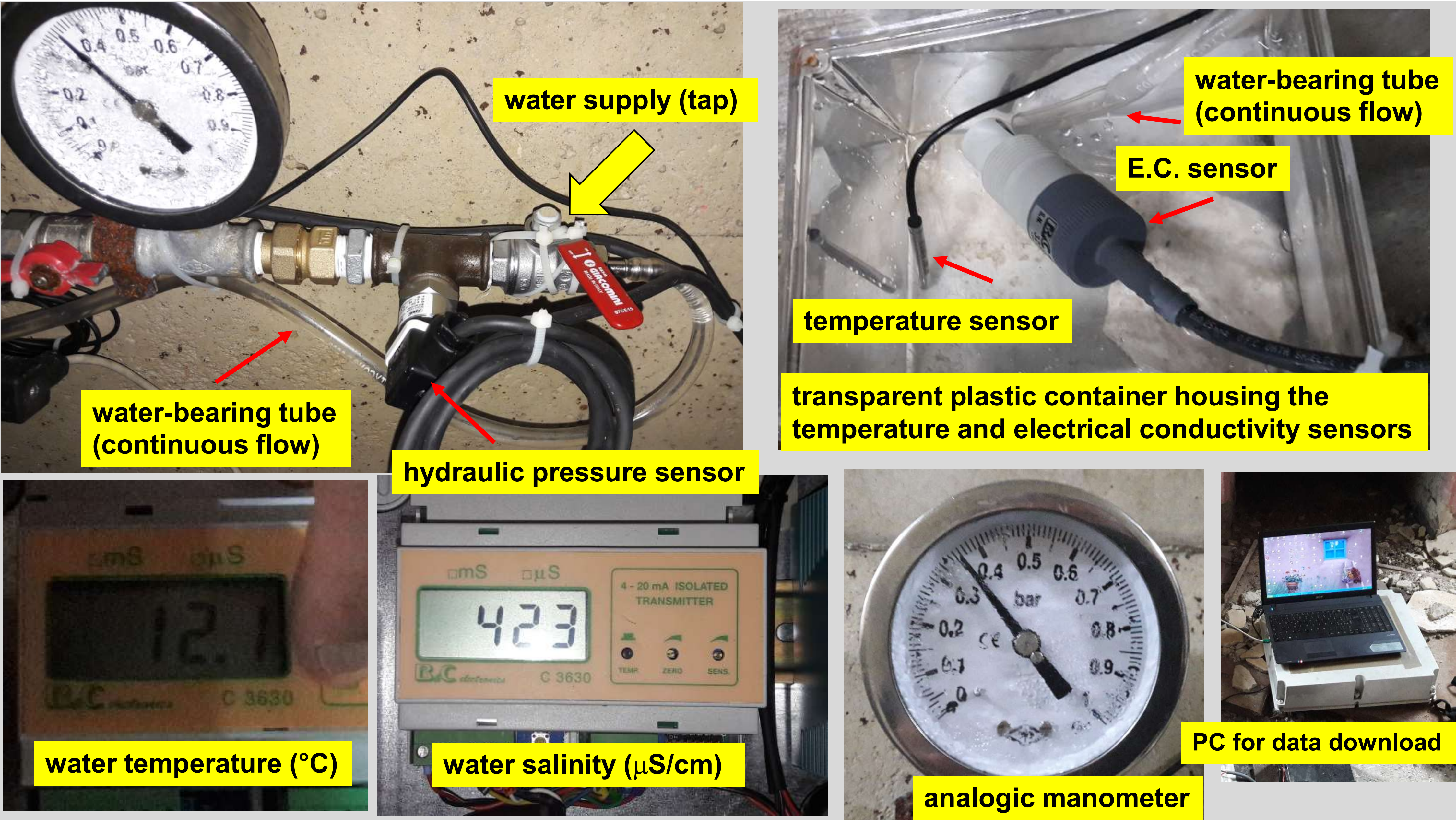
Within this context, we decided to duplicate the equipment presently working in the Gran Sasso aquifer in a site with a similar hydrological setting: the Venafro carbonate hydrostructure (Molise, Saroli et al., 2019). The site we chose is located in one of the most seismically active sectors of central-southern Apennine belt, repeatedly hit in the past by large magnitude earthquakes and crossed by up to 20 km-long extensional fault systems (e.g. Galli & Naso, 2009; Saroli et al., 2016, 2019, 2020).





Our experimental equipment includes a 3-channels 24-bit ADC set up for continuous local recording in groundwater (De Luca et al., 2016, 2018) in a horizontal borehole located in the drainage gallery "San Bartolomeo", managed by Campania Aqueduct company. We started data acquisition in May 2019 by high-frequency continuous sampling (20 Hz for each channel) of physical parameters such as groundwater temperature, electrical conductivity and hydraulic pressure.




water supply (tap)
water-bearing tube (continuous flow)
hydraulic pressure sensor
water-bearing tube (continuous flow)
E.C. sensor
temperature sensor
transparent plastic container housing the temperature and electrical conductivity sensors
water temperature (°C)
water salinity (µS/cm)
analogic manometer
PC for data download

The main goals of our research are:

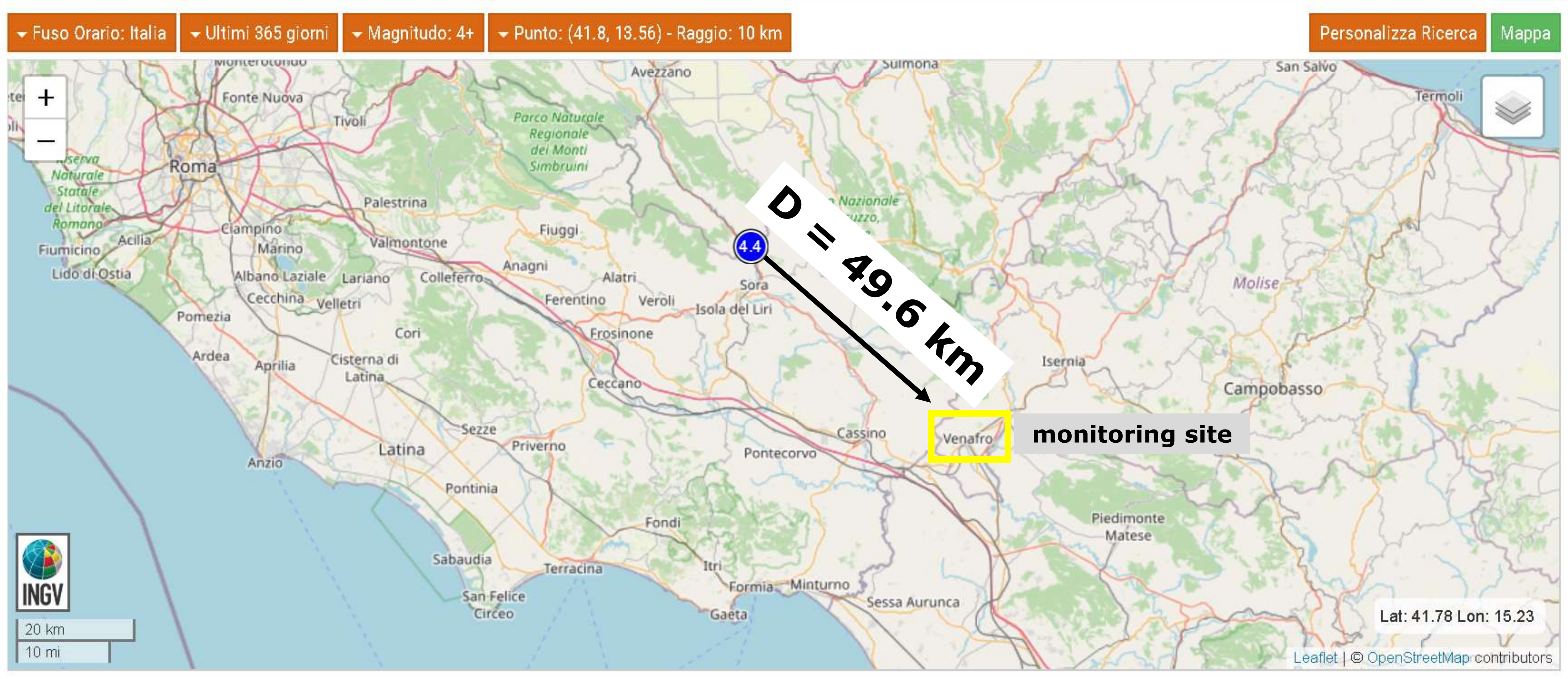
i)measuring and understanding the dynamics of the carbonate aquifer (i.e. seasonal effect of loading and unloading) through the analysis of rainfall;

ii) deepening the relationships between aquifer behavior and earthquakes;

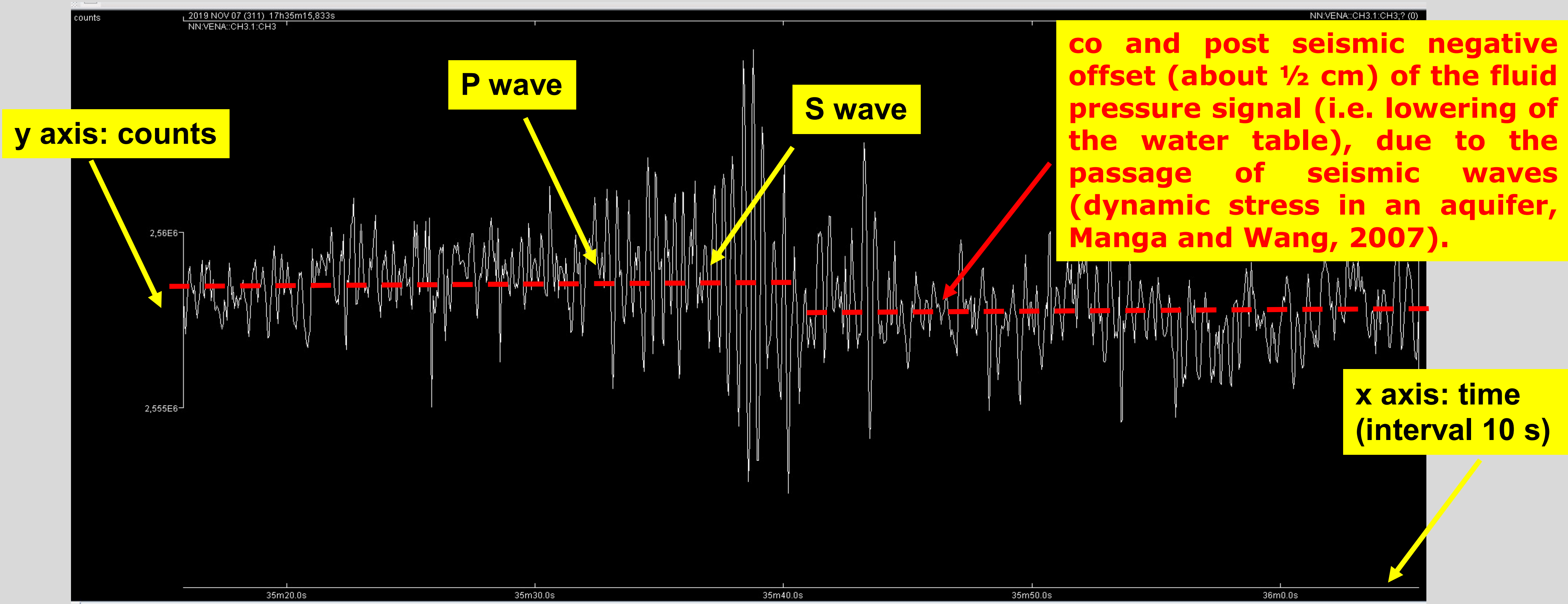
iii) to widen the monitored areas through the Apennine belt;

iv) to compare seismic activity and the "response" of physical signals (shape, amplitude, time of occurrence) both in the Gran Sasso and Venafro monitored aquifers.

Central Italy earthquake: November 7th, 2019. M_w=4.4, 17:35 UTC



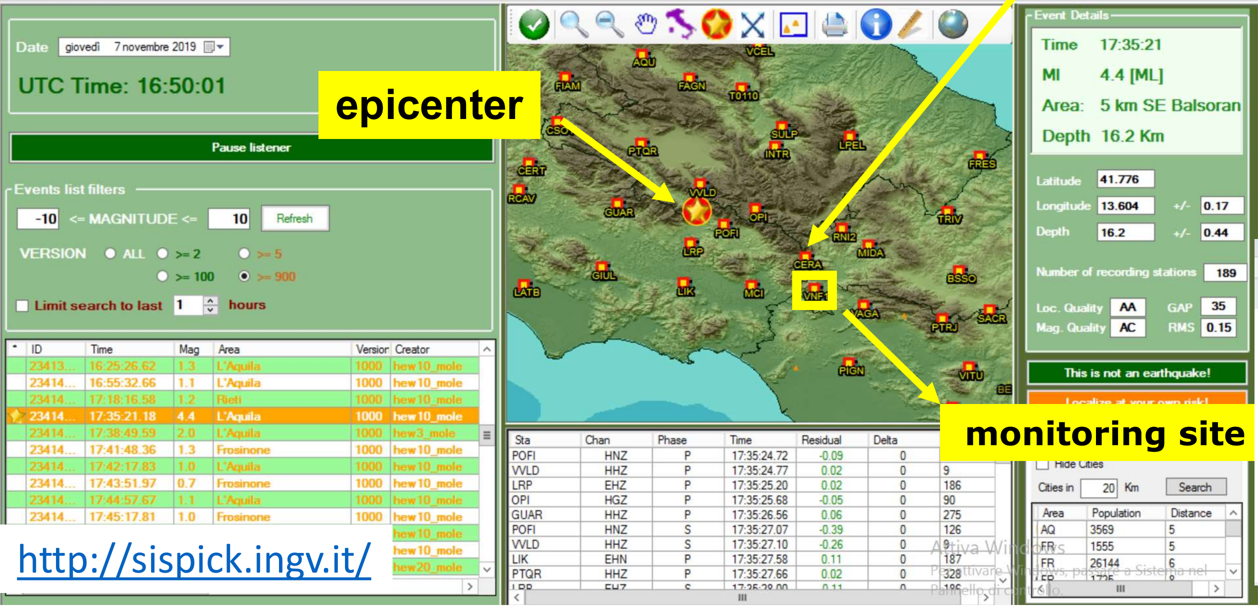
Hydroseismograph of the November 7th, 2019 earthquake. M_w=4.4, 17.35 UTC



P and S waves appearing on the hydrograph are those that travel across the mountain hosting the aquifer. The shaking of the mountain is transferred to the fluid phase, affecting the hydraulic pressure signal.

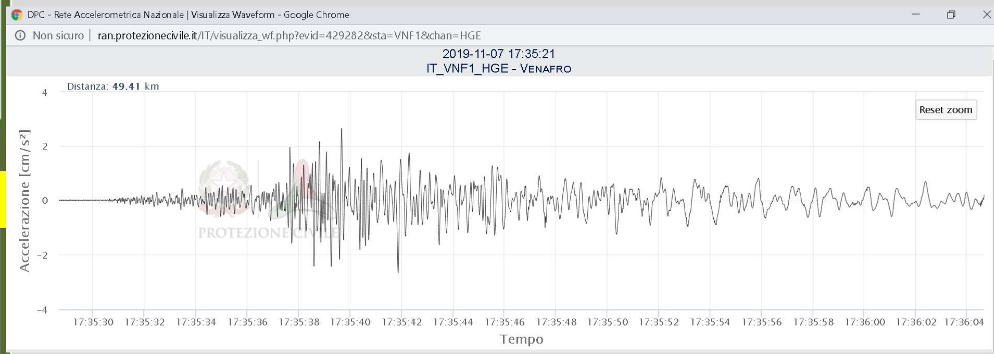
Arrival times of P and S waves in the hydroseismograph are compatible with those recorded by the closest seismometer (around 11 km from the monitoring site) of the Italian Seismic Network (acronym CERA).
Revised earthquake location was provided by the Italian Seismic Bulletin at http://terremoti.ingv.it/BSI

The software utilised to show waveforms can be found at: sispick.ingv.it.

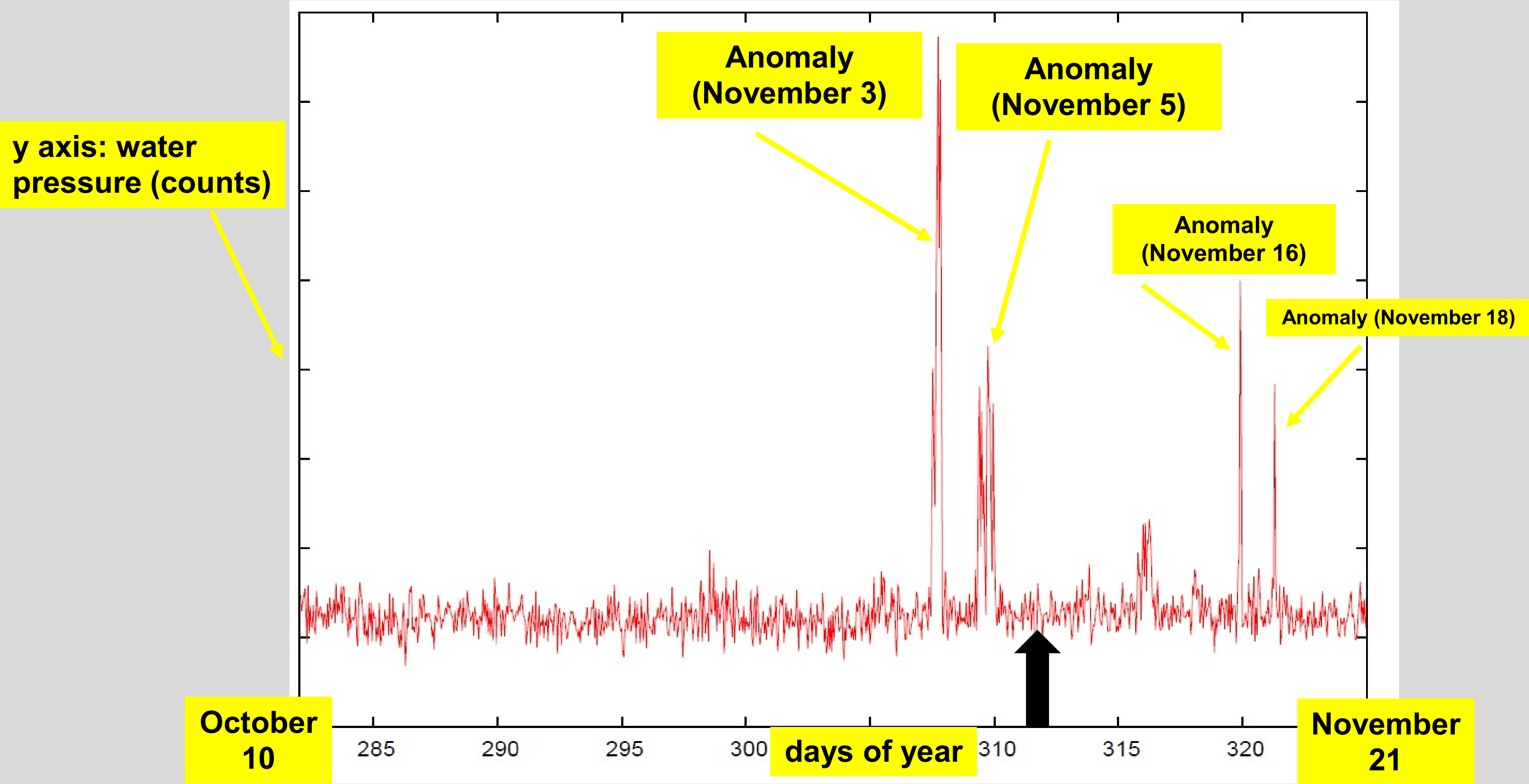


http://sispick.ingv.it/

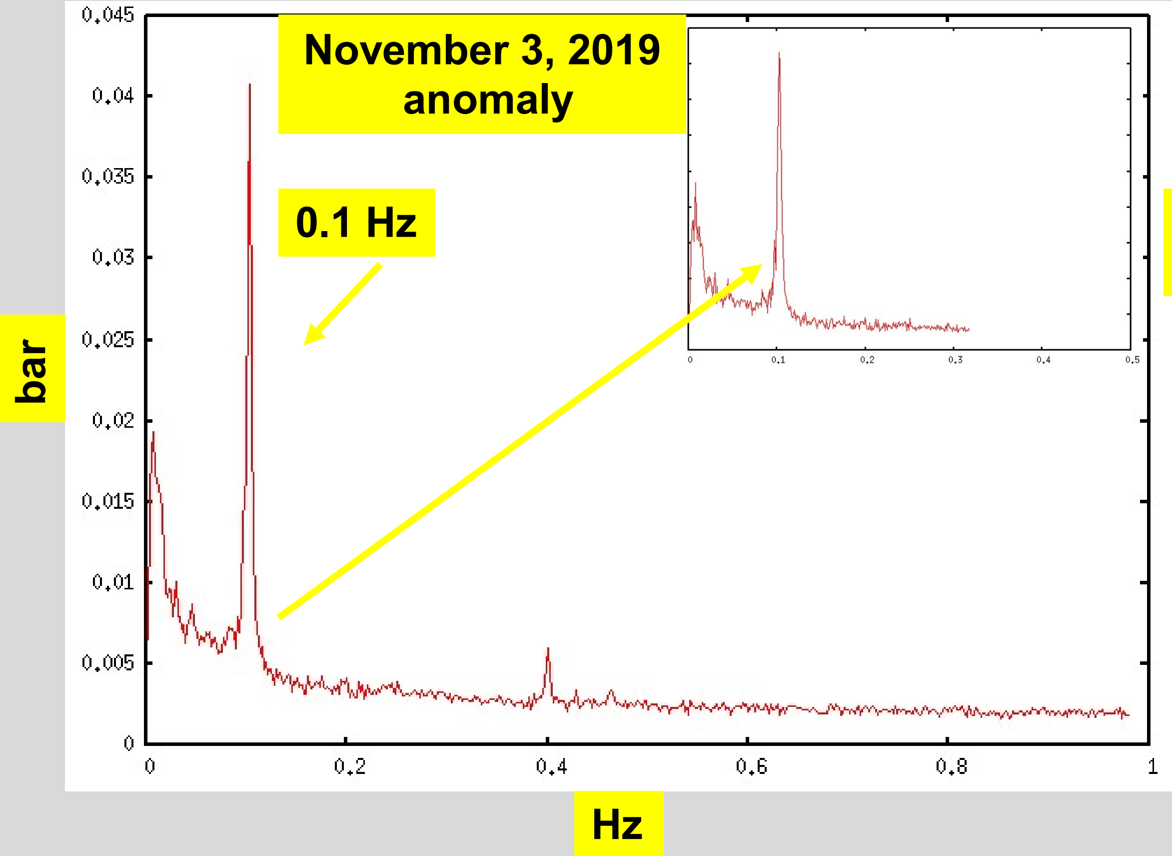
Italian Strong Motion Network (RAN): Venafro station (accelerometer)

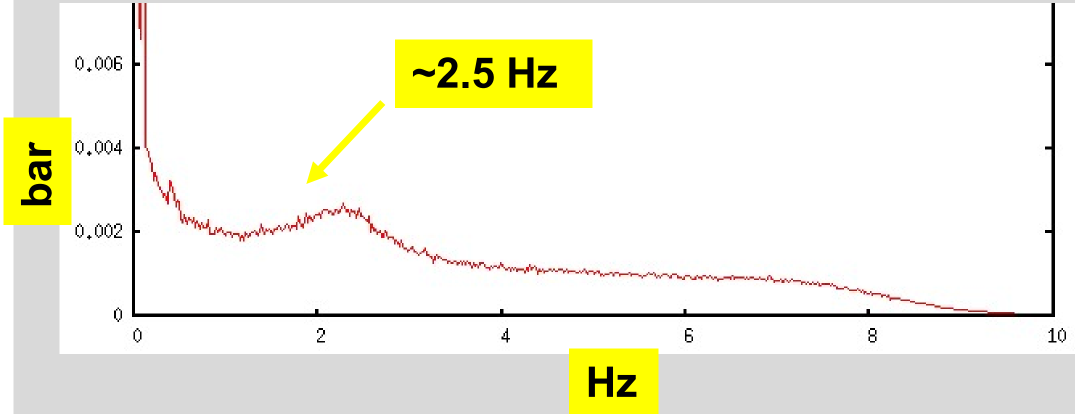


Statistical analysis (variance) of the hydraulic pressure from October 10 to November 21, 2019 (black arrow, M_w = 4.4, 17:35 UTC)

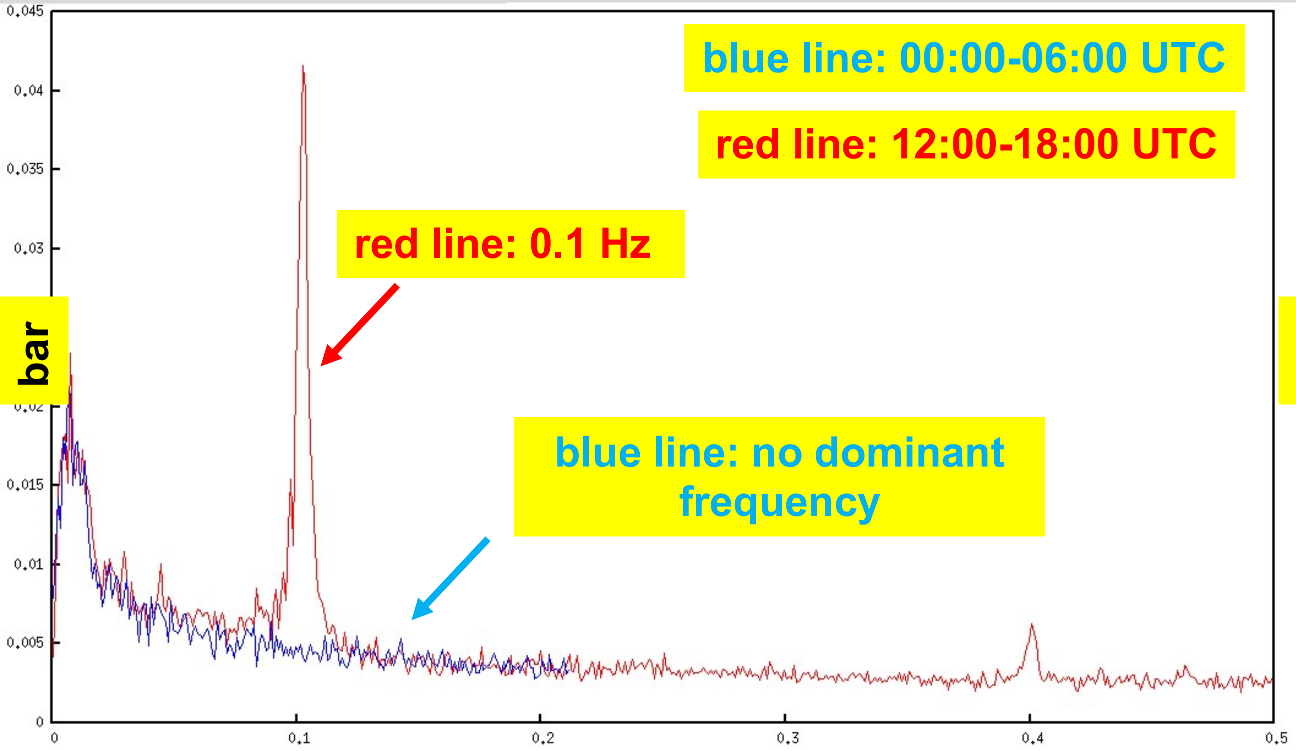


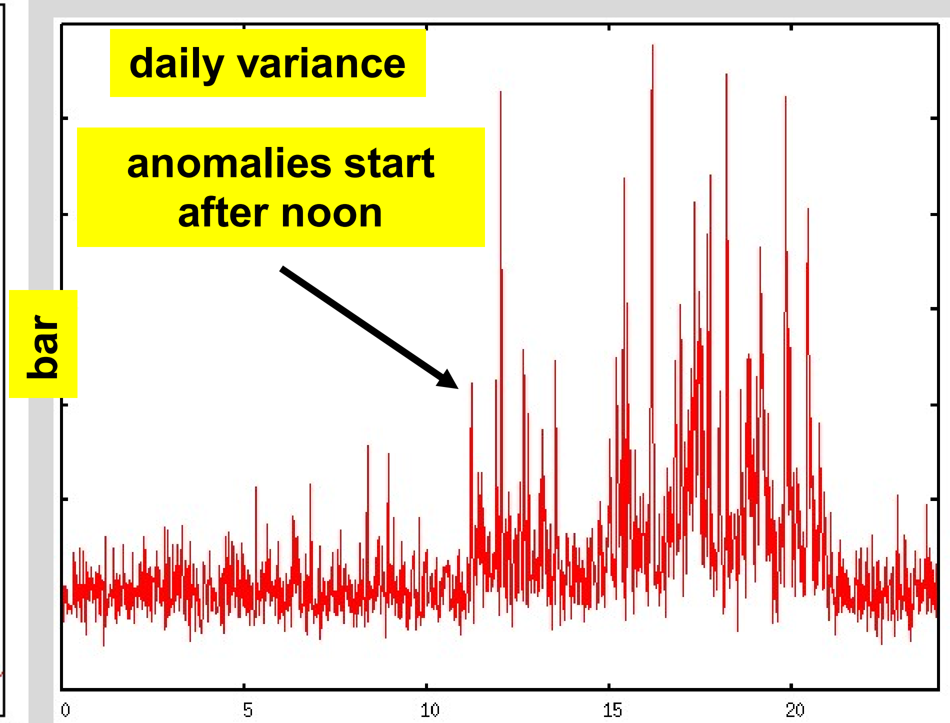
Spectral analysis at different Hz intervals: 0-0.5, 0-1 and 0-10 of the hydraulic pressure referred to November 03, 2019 (the day of the most noticeable anomaly) in the time span 12:00-18:00 UTC. Peaks at 0.1 Hz and about 2.5 Hz were found.



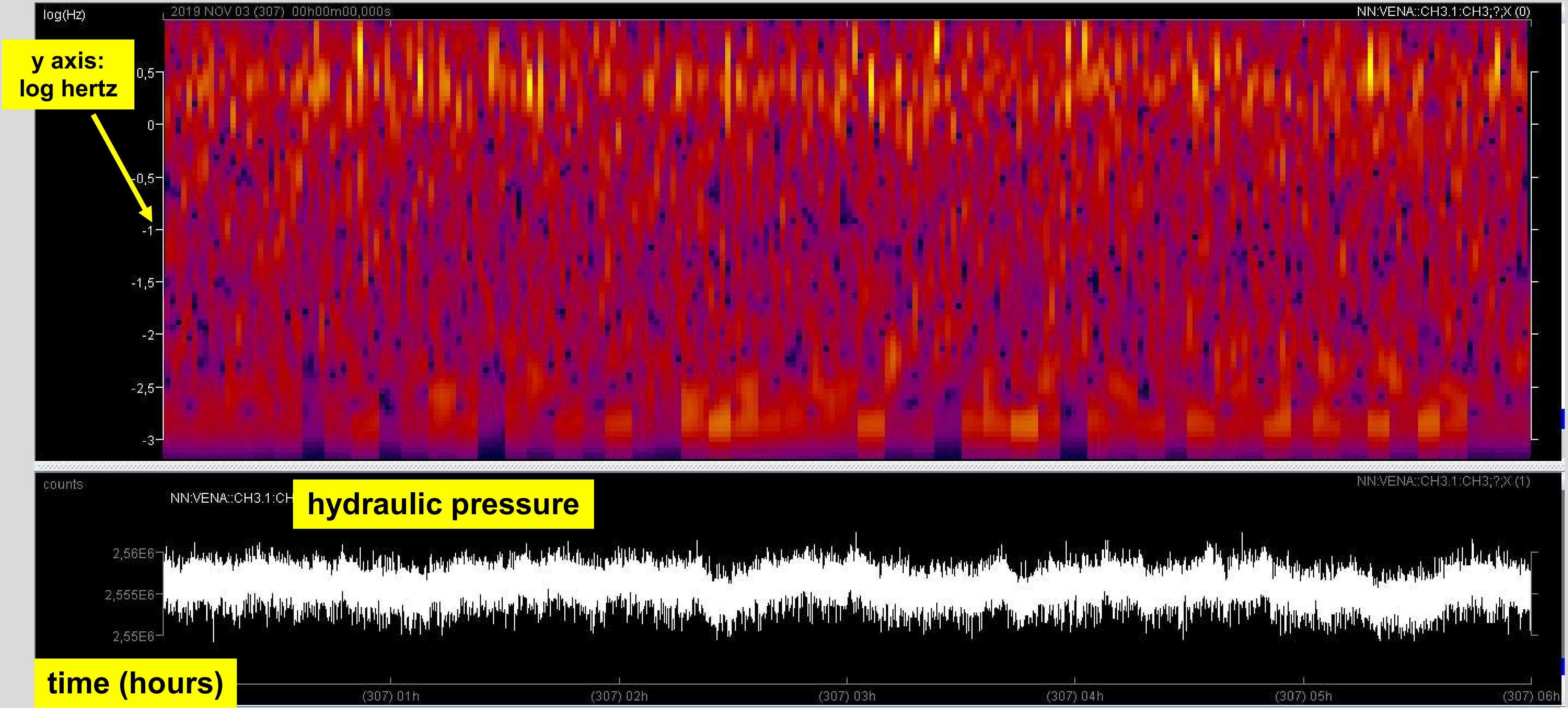


Spectral analysis of the hydraulic pressure referred to November 03, 2019 (the day of the most noticeable anomaly). Analysis refers to two time windows of the day: 00:00-06:00 and 12:00-18:00 UTC.

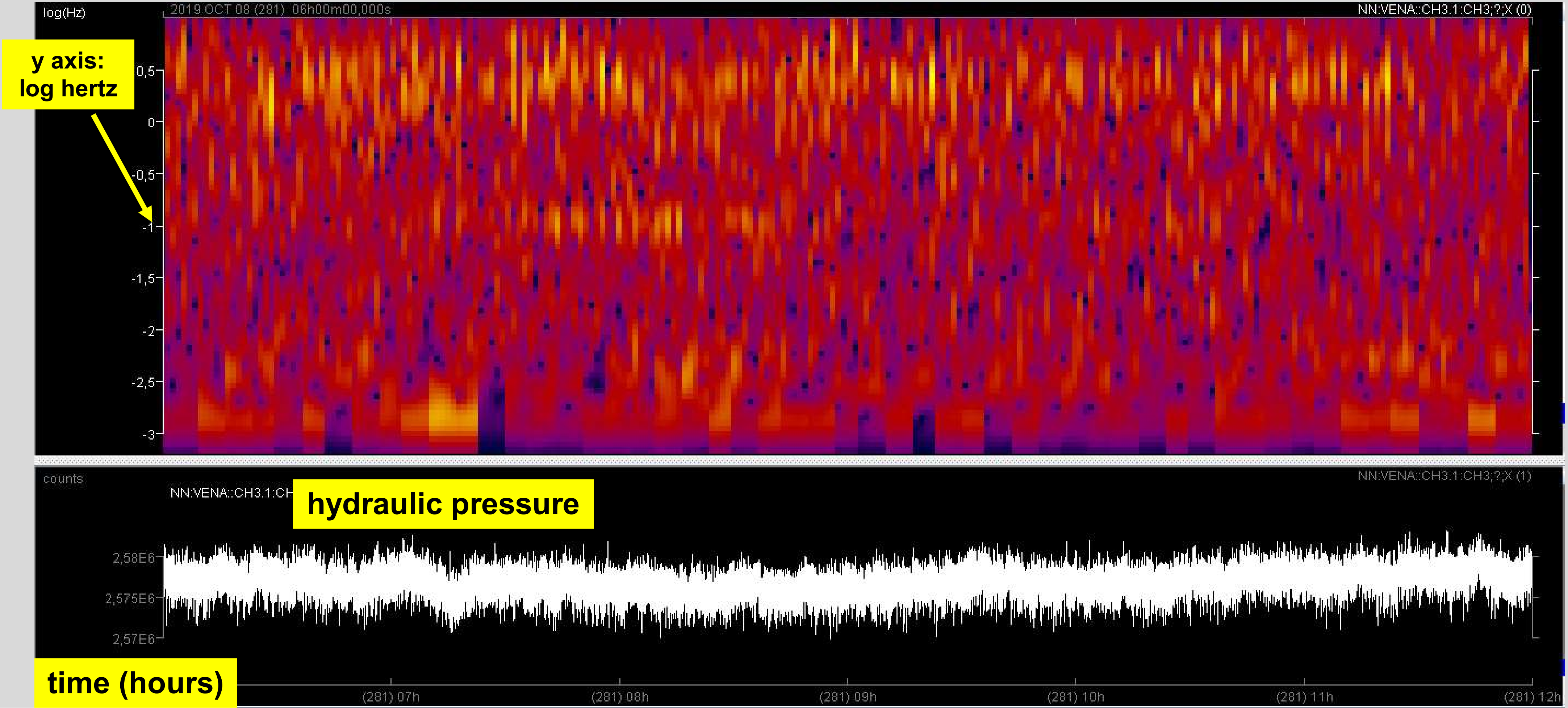




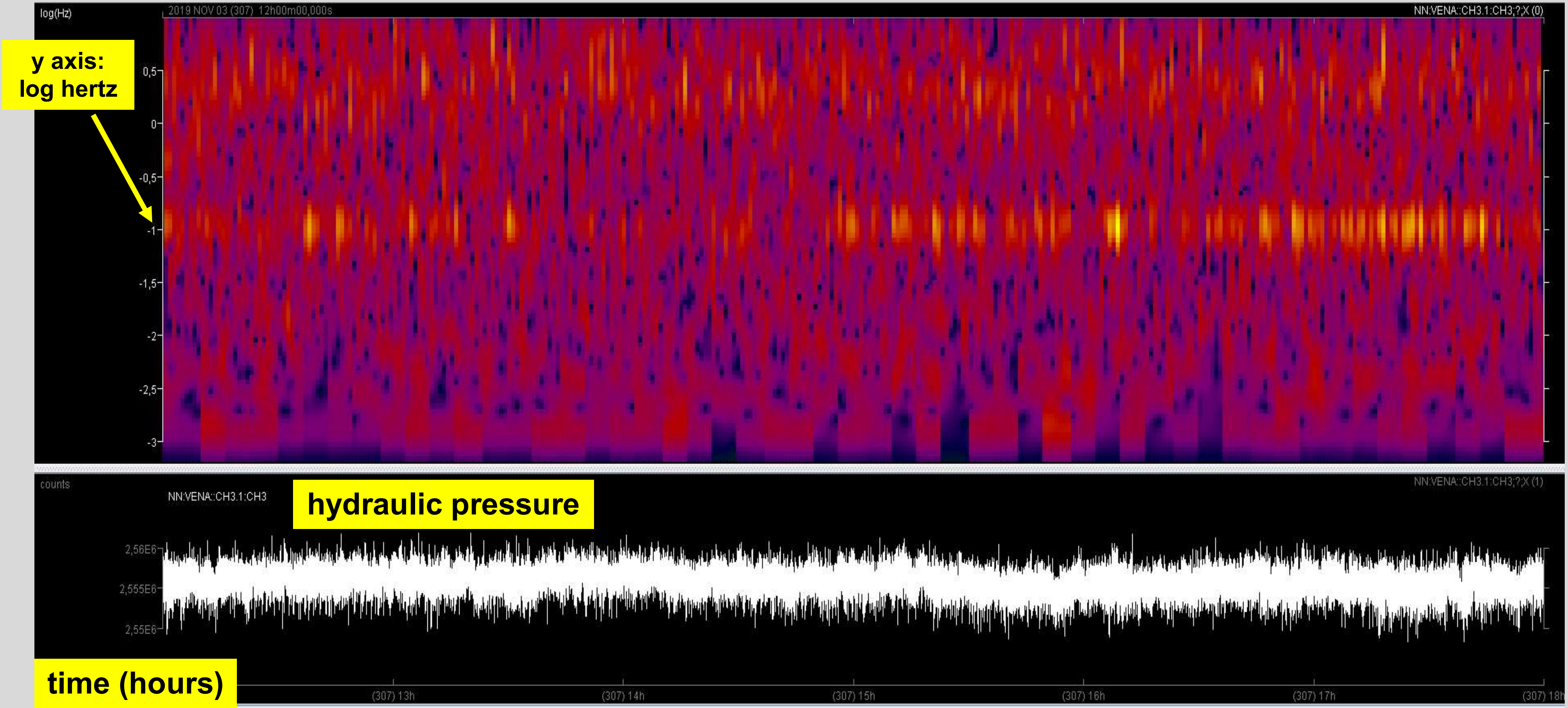
Spectral analysis of the hydraulic pressure signal: November 3 (the day of the most noticeable anomaly), from 00:00 to 06:00 UTC. One dominant frequency is highlighted at around 2.5 Hz.



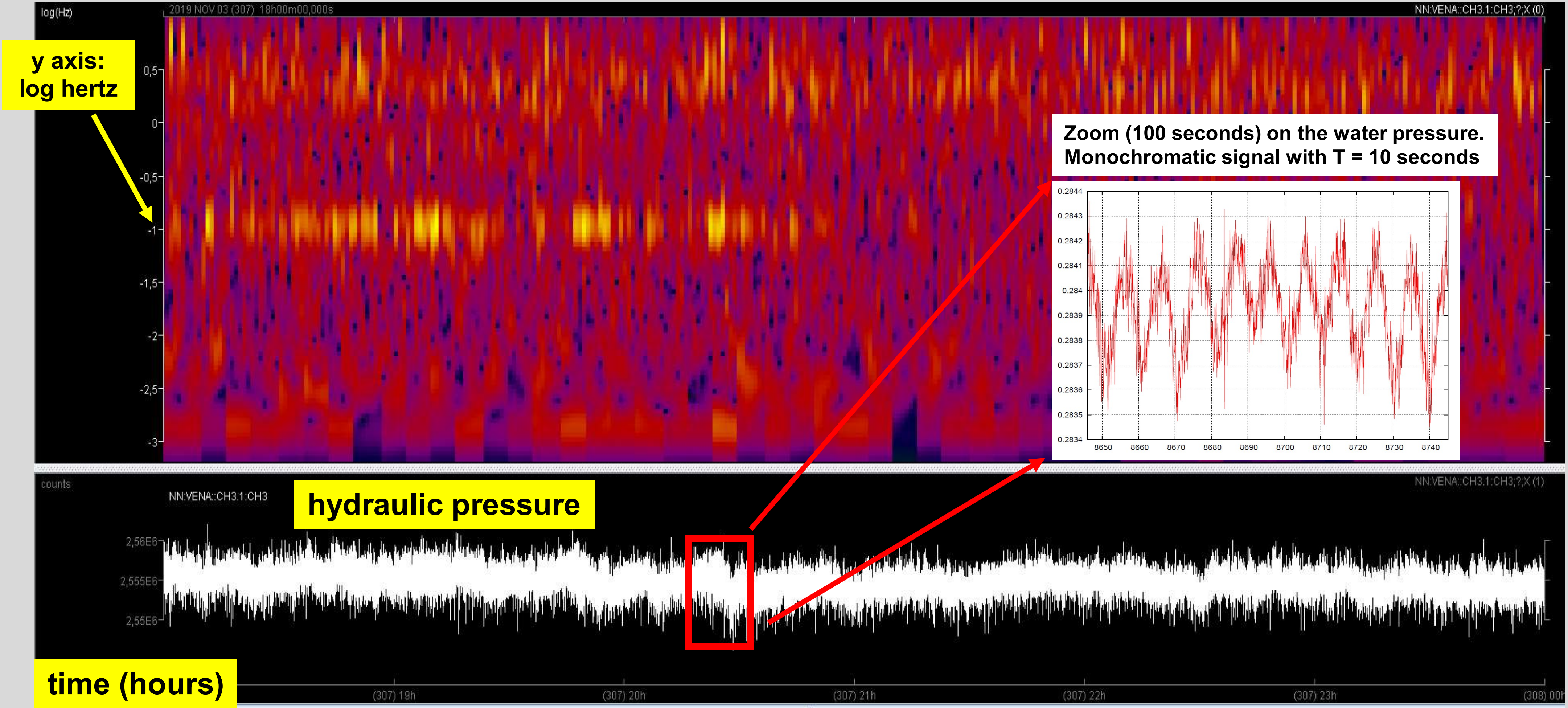
Spectral analysis of the hydraulic pressure signal: November 3 (the day of the most noticeable anomaly), from 06:00 to 12:00 UTC. One dominant frequency is highlighted at about 2.5 Hz. A weak 0.1Hz frequency is also visible.



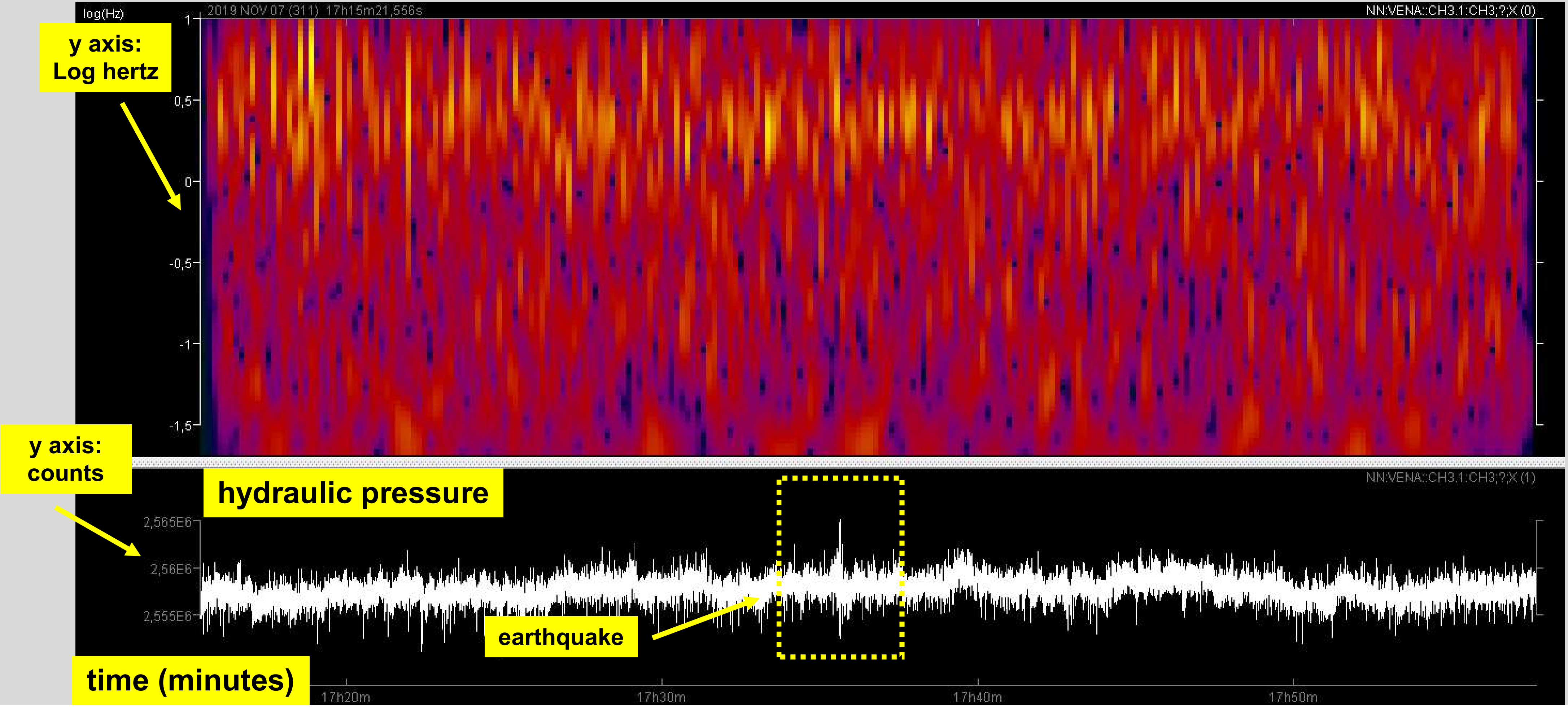
Spectral analysis of the hydraulic pressure signal: November 3 (the day of the most noticeable anomaly), from 12:00 to 18:00 UTC. Two dominant frequencies are highlighted: 0.1 and about 2.5 Hz.



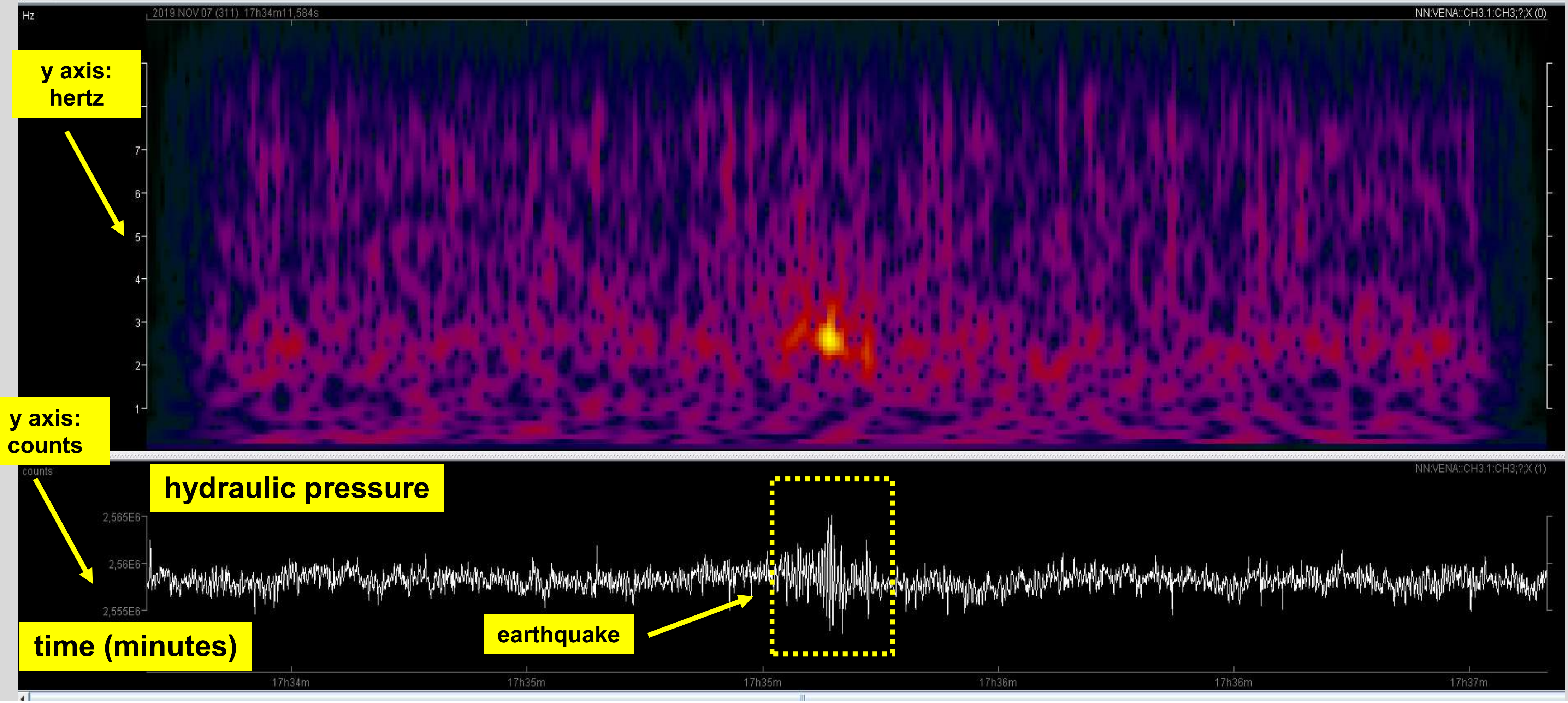
Spectral analysis of the hydraulic pressure signal: November 3 (the day of the most noticeable anomaly), from 18:00 to 00:00 UTC. Two dominant frequencies are highlighted: 0.1 (up to 20:30 UTC) and ~ 2.5 Hz.



Spectral analysis of the hydraulic pressure signal: November 7 (the day of the M_w 4.4. earthquake, 17:35 UTC), from 17:15 to 17:55 UTC. One dominant frequency at ~2.5 Hz appears. Any 0.1 Hz frequency is evidenced.



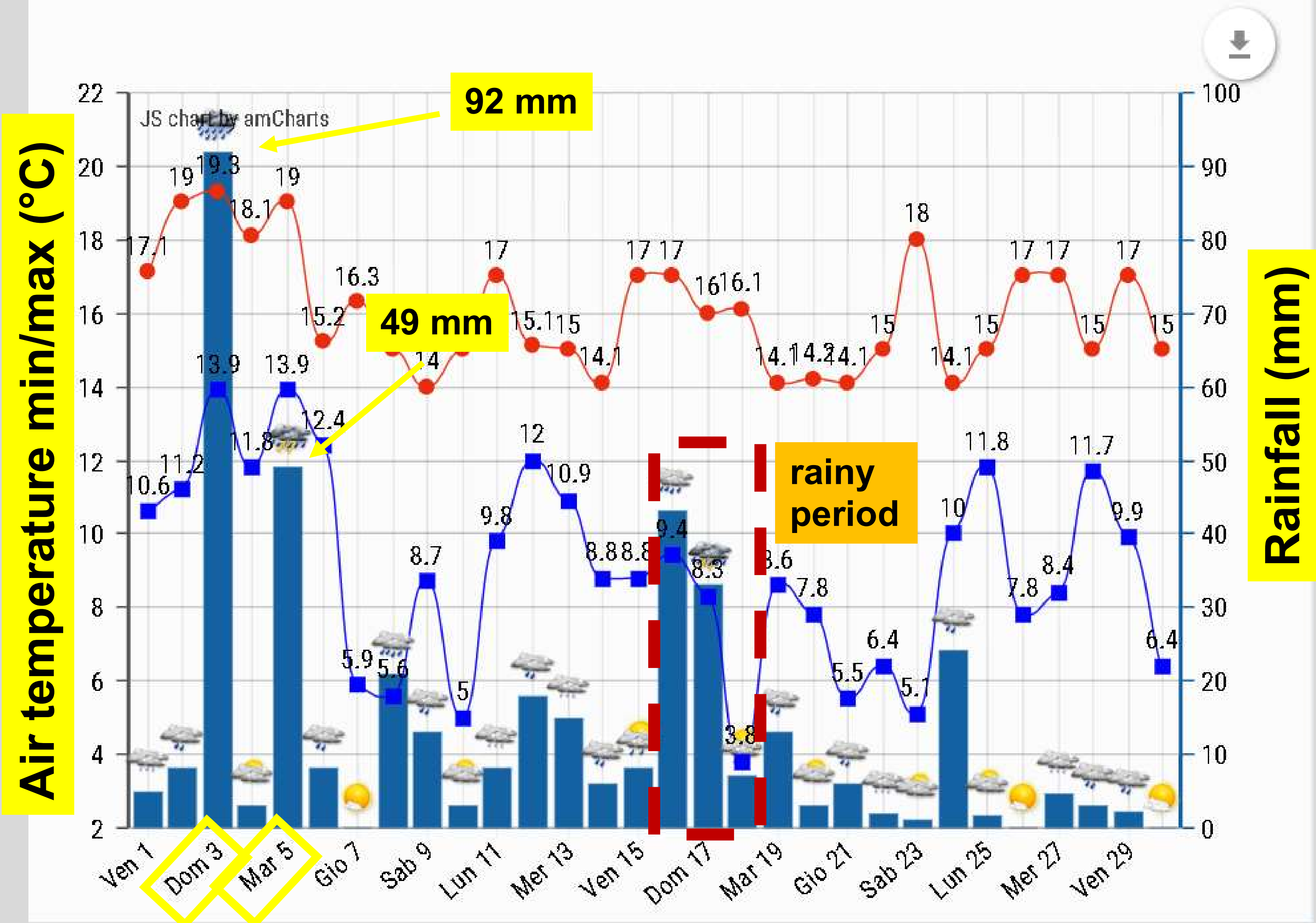
Zoom on the spectral analysis of the hydraulic pressure signal: November 7 (the day of the M_w 4.4. earthquake, 17:35 UTC), from 17:33 to 17:38 UTC. One frequency appears at ~2.5 Hz when earthquake takes place.



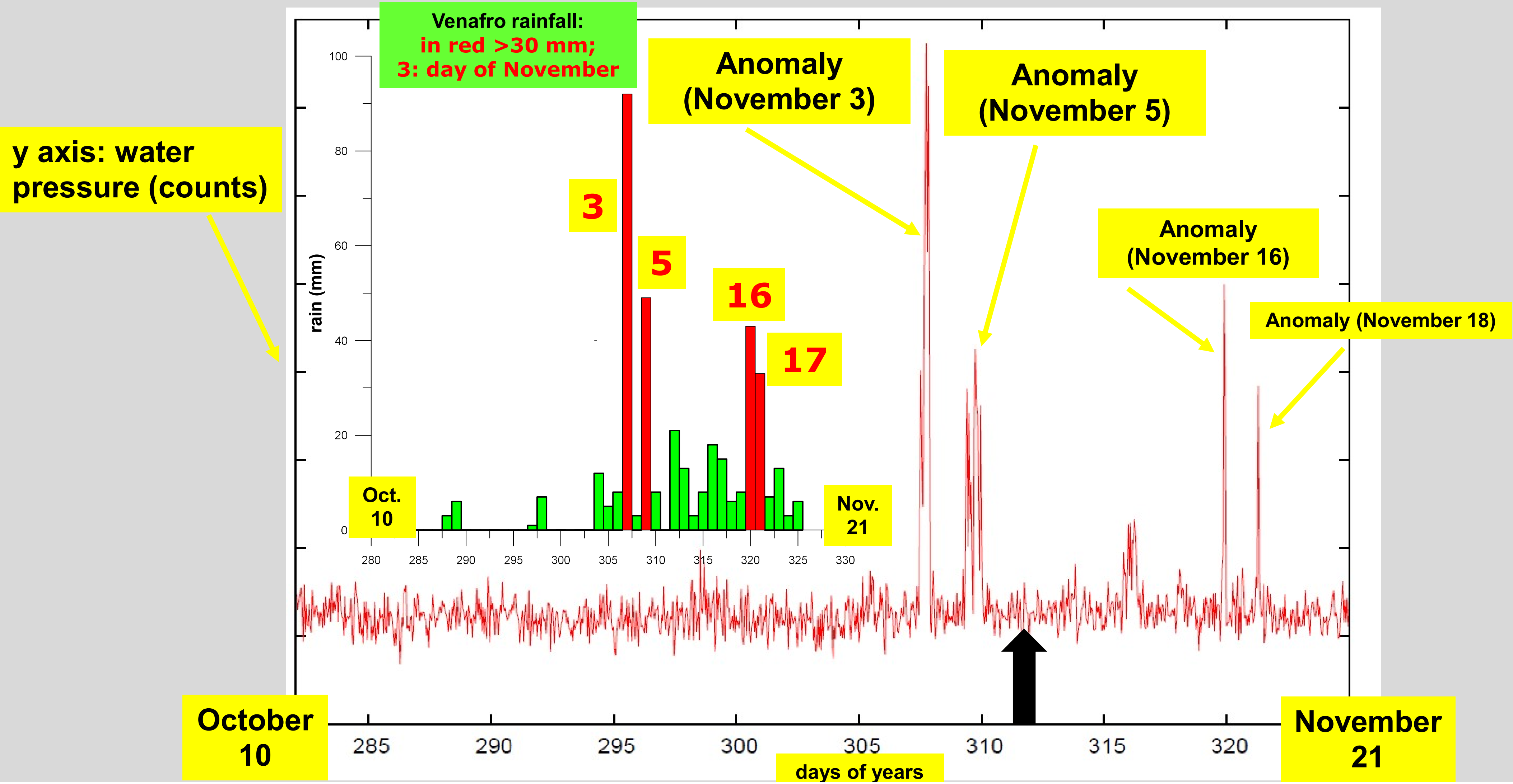
Open questions:

- **Which are the source(s) of statistical anomalies and frequency content of hydraulic pressure signals recorded on November 3, 2019?**
- **Are they linked to the November 7 earthquake?**
- **What happened in the different time windows we investigated?**
- **What happened in terms of excited frequency when the M_w 4.4 earthquake took place?**
- **Is frequency domain dependent from other source(s) besides (possible) endogenous ones?**

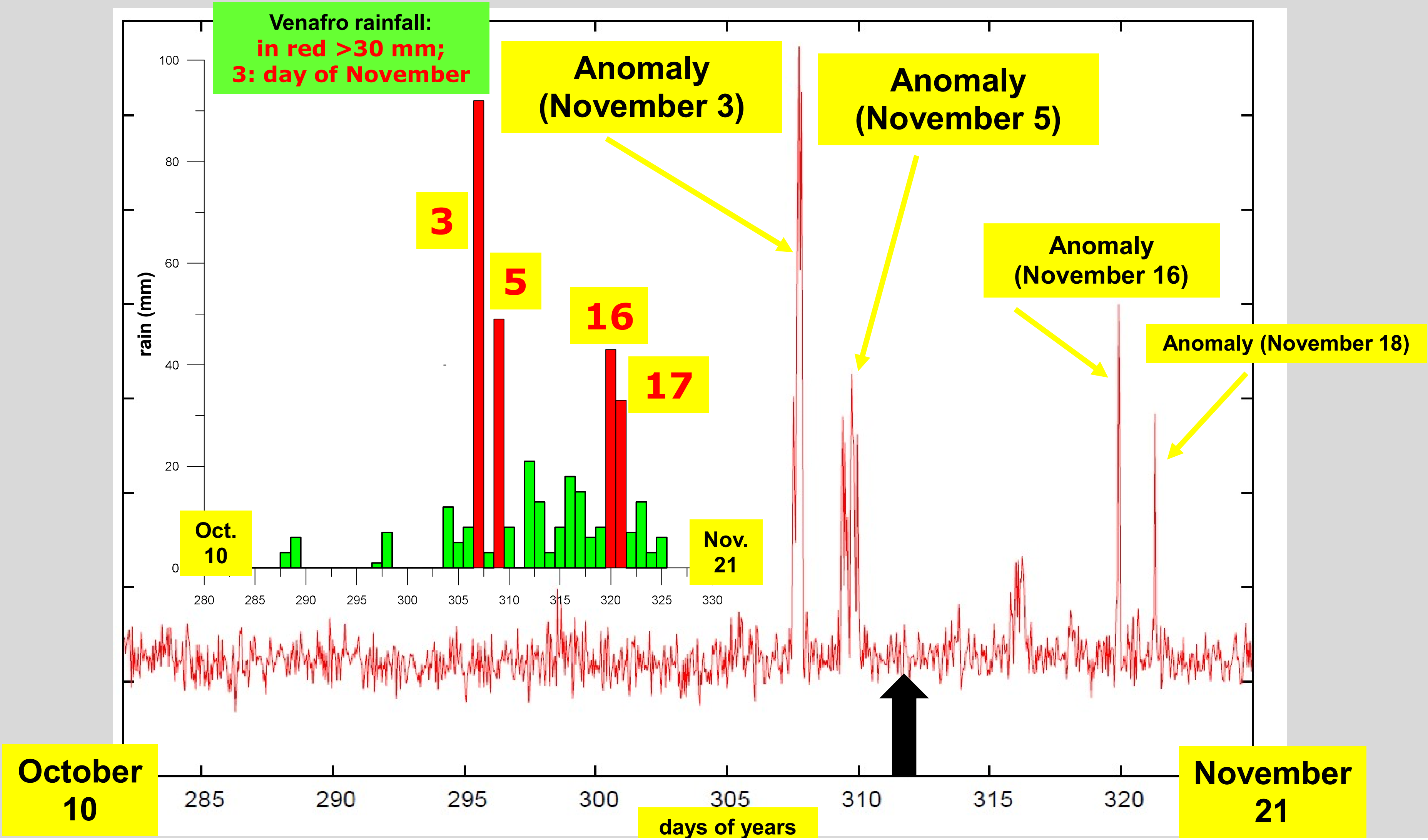
If we consider the daily rainfall at the Venafro site on November 2019, it results that high amount of rain (~ 100 and 50 mm) fell on days 3 and 5, respectively. The other two rainiest period of the month was 16 through 18 (83 mm).



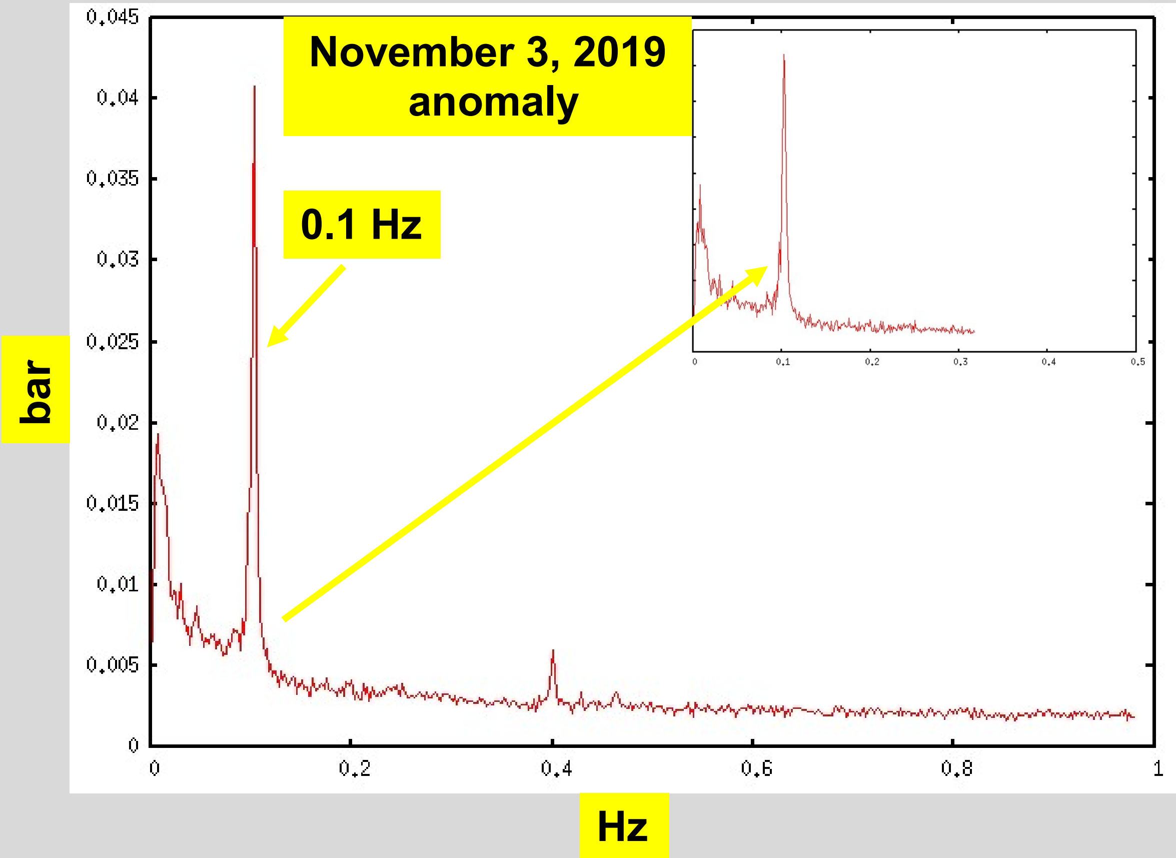
Statistical analysis (variance) of the hydraulic pressure from October 10 to November 21, 2019 (black arrow, M_w = 4.4) *vs* rainfall.



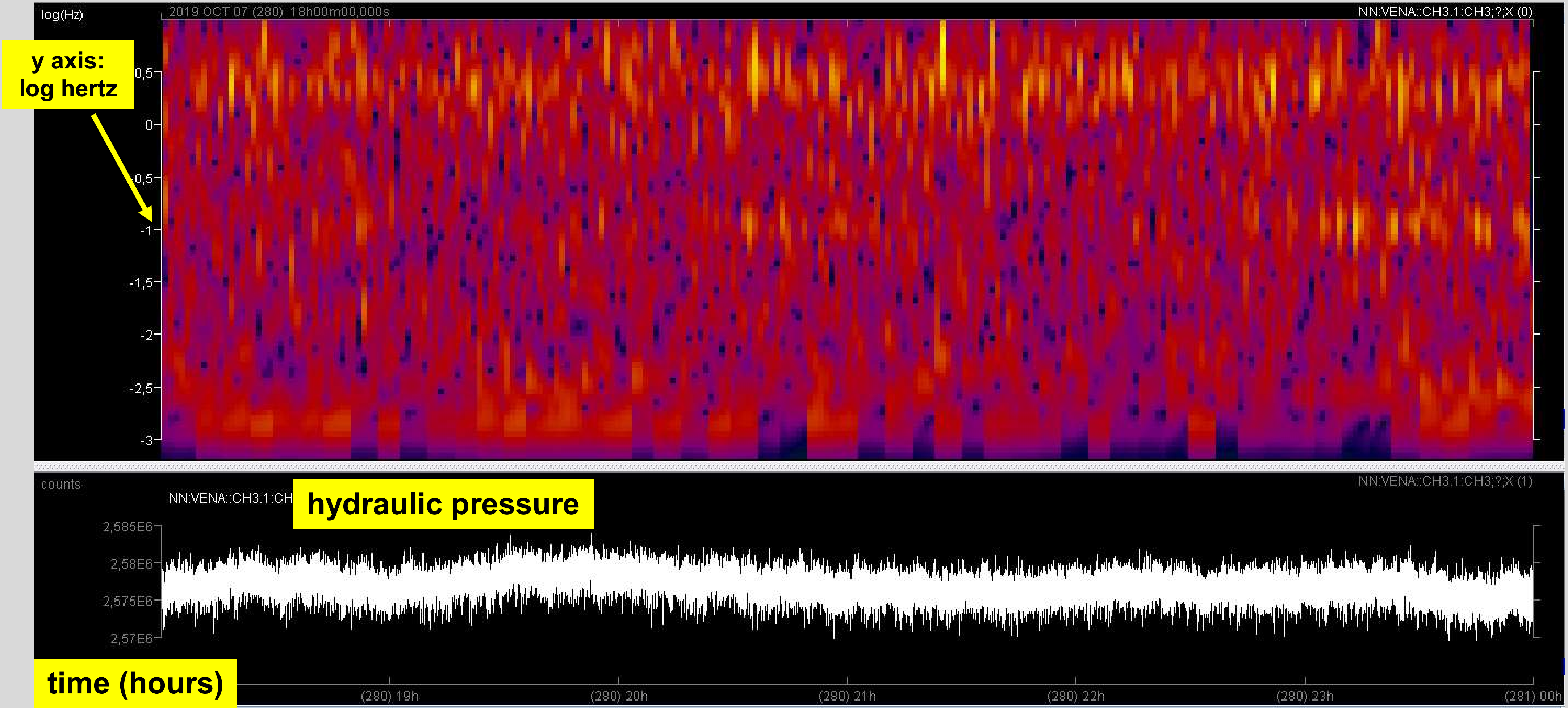
Statistical anomalies of the hydraulic pressure from October 10 to November 21, 2019 (black arrow, M_w=4.4) coincide exactly with the rainiest days/period.



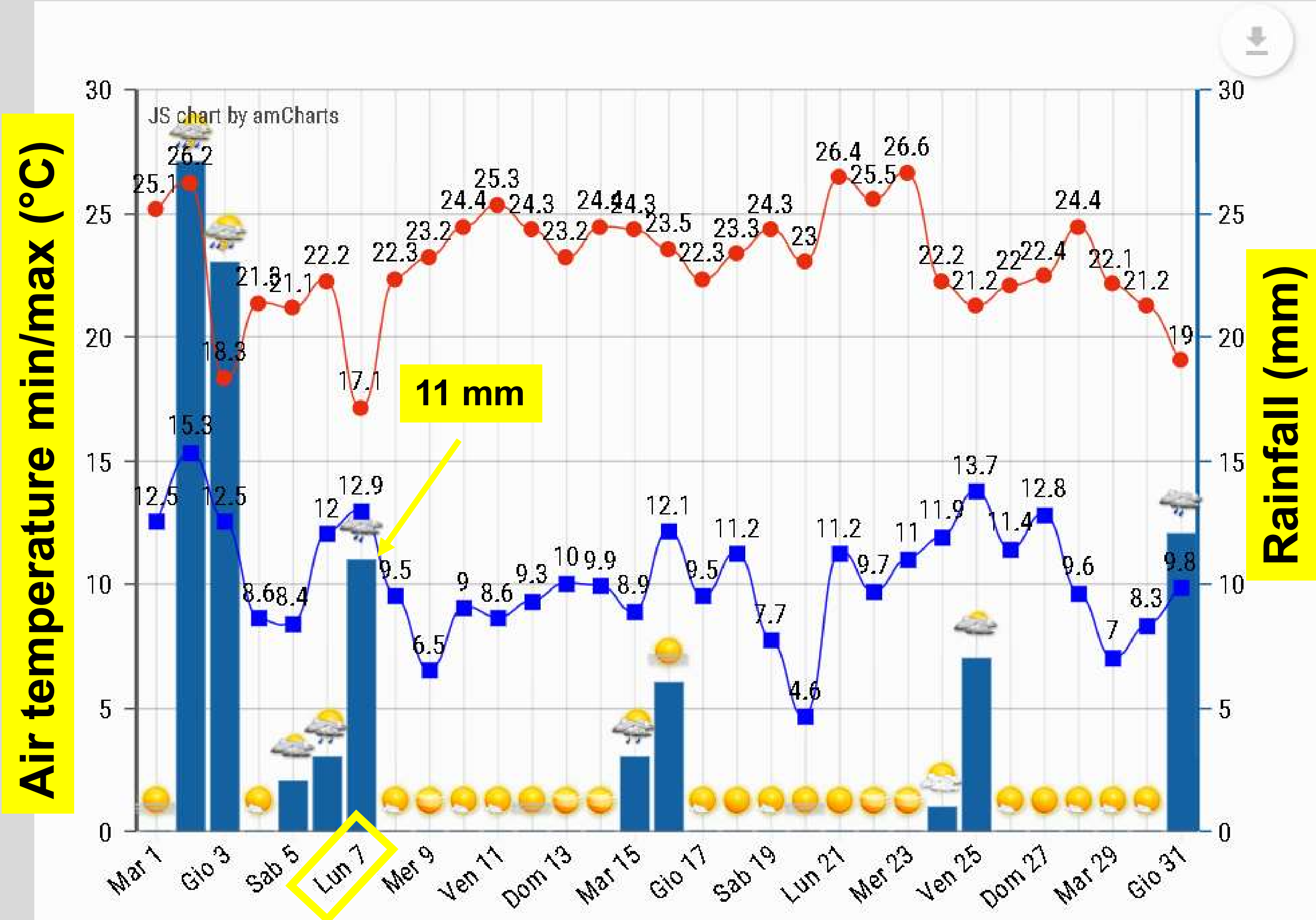
In particular, a detailed study on the frequency content of the hydraulic pressure referred to November 03, 2019 reveals that the dominant peak was found at 0.1 Hz. Therefore, we can assume it as the typical frequency response of the Venafro aquifer in case of moderate-to high rain episodes (> 50 mm).



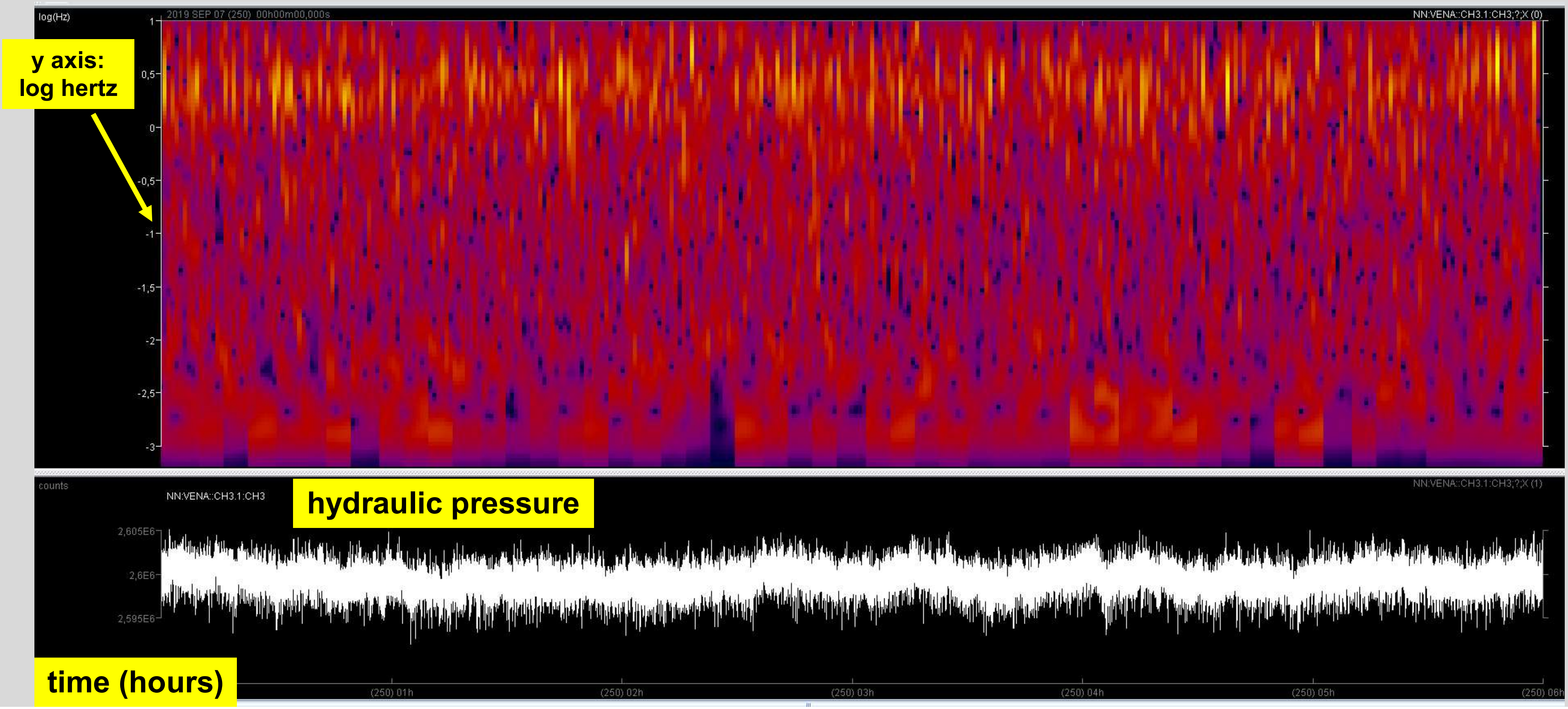
If we analyse the frequency content of the hydraulic pressure in a day with minor rain (example October 7, 11 mm cumulated), only a vey weak signal at 0.1 Hz appears. Furthermore, all dry days don't show that frequency.



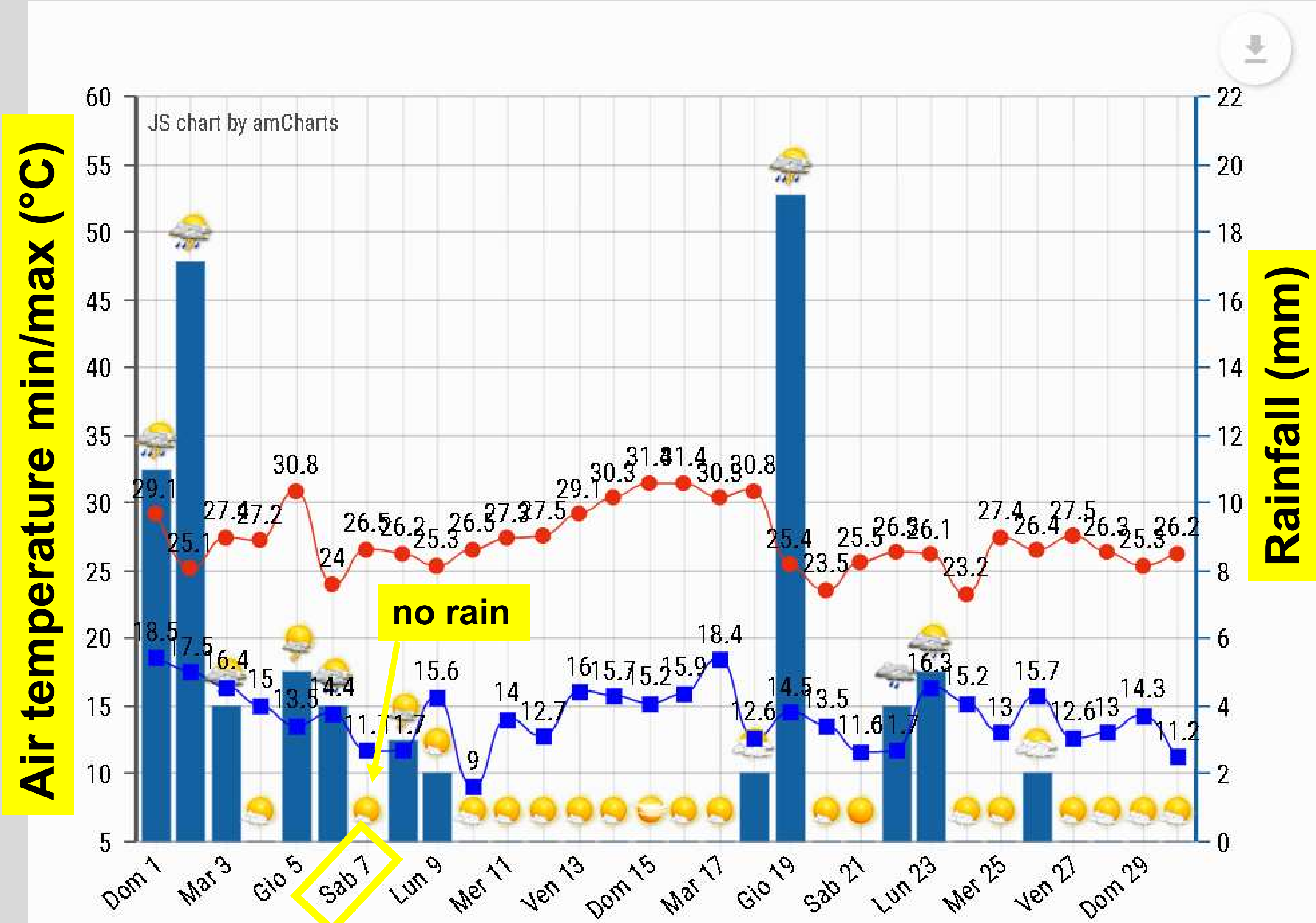
Daily rainfall at the Venafro site in October 2019



In all spectrograms (irrespective of rain/no rain) the hydraulic pressure signal shows a permanent frequency of ~ 2.5 Hz.
In case of dry days/periods, the 0.1 Hz frequency doesn’t appear.
The example refers to September 7, 2019 (00:00 to 06:00 UTC).



Daily rainfall at the Venafro site in September 2019



So, we can move to the preliminary conclusions of our study and answer some questions (part I):

a) We found two main frequencies in the hydraulic pressure recorded at the Venafro aquifer:

1) temporary 0.1 Hz, due to moderate to high rainy episodes. It can be due to the quick inflow of rain water into the karst conduits of the Venafro hydrostructure;

2) permanent ~ 2.5 Hz, probably due to the water intake structures of the aqueduct. This frequency also appeared when the M_w=4.4. magnitude earthquake occurred (resonance of the aquifer).

So, we can move to the preliminary conclusions of our study and answer some questions (part II):

b) Anomalies of days 3 and 5 are likely not linked to the November 7, M_w 4.4 earthquake;

c) We recorded co and post seismic negative offset (about ½ cm) of the fluid pressure (i.e. lowering of the water table), due to the passage of seismic waves (dynamic stress in an aquifer);

d) We highlighted the importance of performing a very high-rate water sampling, coupled with: i) detailed data statistical analysis; ii) the study of the time-series frequency domains and iii) rainfall data (possibly hourly) analysis.

Future developments:

a) **Going on with the acquisition of continuous physical parameters in the Venafro aquifer (T, E.C. and water pressure), by comparing time-series with local/regional seismicity and rainfall;**
b) **To widen the monitored sectors through the southern Apennine belt by installing a third monitoring station in a selected well located in the seismically active area of the Matese mountains (Campania region);**
c) **Coupling the continuous monitoring of physical parameters with a discrete (sampling every 1 week) hydrochemical data acquisition at both Gran Sasso and Venafro sites;**

Future developments:

d) Statistical and spectral analyses of both temperature and waters salinity time-series;

e) Installation of a GPS station at Venafro site to compare aquifer behaviour (in terms of seasonal loading/unloading, pre-co and post-seismic response; heavy rainfall episodes in a short time span, prolonged drought periods) and horizontal/vertical deformation of the karst hydrostructure.