MUDA: dynamic geophysical and geochemical MUltiparametric DAtabase

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Abstract

In this paper, the new dynamic geophysical and geochemical MUltiparametric DAtabase (MUDA) is presented. MUDA is a new infrastructure of the National Institute of Geophysics and Volcanology (INGV), published on-line in December 2023, with the aim of archiving and disseminating multiparametric data collected by multidisciplinary monitoring networks. MUDA is a *MySQL* relational database with a web interface developed in *php,* aimed at investigating in quasi real time possible correlations between seismic phenomena and variations in endogenous and environmental parameters. At present, MUDA collects data from different types of sensors such as hydrogeochemical probes for physical-chemical parameters in waters, meteorological stations, detectors of air Radon concentration, diffusive flux of carbon dioxide (CO_2) and seismometers belonging both to the National Seismic Network of INGV and to temporary networks installed in the framework of multidisciplinary research projects. MUDA daily publishes data updated to the previous day and offers the chance to view and download multiparametric time series selected for different time periods. The resultant dataset provides broad perspectives in the framework of future high frequency and continuous multiparametric monitoring as a starting point to identify possible seismic

precursors for short-term earthquake forecasting. MUDA is now quoted with the Digital Object Identifier https://doi.org/10.13127/muda (Massa et al., 2023).

Key words: multiparametric data, monitoring networks, dynamic data base, earthquakes forecasting

1 Introduction

Today, there is an increasing awareness of the role played by the interaction between tectonics and fluid dynamics in triggering seismicity. Yet, the simultaneous monitoring of the relevant key factors is still lacking, even though it could be crucial in recognizing precursory signals. Changes in water chemistry and levels, spring discharges, soil flux regimes (e.g. CO_2, CH_4, Radon) and compositions of dissolved gases in water are well-documented in the literature (e.g. Italiano et al., 2001, 2004; Chiodini et al., 2020; Gori and Barberio, 2022 and references therein), as being pre-, co- and post-seismic modifications as well as markers of the local tectonic stress acting in the crust. These recognized seismic-induced variations in groundwaters and springs led, in recent years, scientists to give more attention to the development of multiparametric monitoring, in order to capture the main evidences concerning abrupt changes in chemical and physical parameters recorded before (and also after) energetic seismic events (Rikitake and Hamada, 2003; Cicerone et al., 2009; Martinelli, 2018 and references therein). The ultimate goal is to find systematic signals that can be assumed as possible "precursors" or indicators that a seismogenetic process is ongoing (Hubbert and Rubey, 1959; Brauer et al., 2003; Miller et al., 2004; Chiarabba et al., 2009; Di Luccio et al., 2010; Malagnini et al., 2012; Keranen and Weingarten, 2018; Napolitano et al., 2020; De Matteis et al., 2021; Gabrielli et al., 2022, 2023; Ventura and Di Giovambattista, 2013). At the Italian scale, several studies have described the utility of groundwater and spring parameters and soil gas emissions to catch seismic-related signals as well. However, only a few studies reported a continuous, high-frequency monitoring, mainly of groundwater level or hydraulic pressure (De Gregorio et al., 2012; Barberio et al., 2017; De Luca et al., 2018), or as Gori and Barberio (2022) concerning spring monitoring (i.e. temperature, pH, electrical conductivity, dissolved oxygen and carbon dioxide) or D'Alessandro et al. (2020) on soil Radon emissions related to seismic activity.

MUDA (geophysical and geochemical MUltiparametric DAtabase), a new dynamic multiparametric database published on-line in December 2023 at the web site https://muda.mi.ingv.it (Figure 1), has been developed in such a framework. MUDA is a new infrastructure of the National Institute of Geophysics and Volcanology (INGV, www.ingv.it) devoted to archive daily and distribute quasi real time geophysical and geochemical multiparametric data recorded in continuous or near-continuous mode at selected sites installed at the most tectonically active Italian areas (Figure 2). MUDA was designed in the framework of INGV Dynamic Planet S2-project (i.e. 3D structure of Italy from multidata analysis. Passive/active seismic, magnetic, magnetotelluric, electrical, gravimetric prospecting, https://progetti.ingv.it/it/pian-din) and its development is ongoing in the framework of the INGV Dynamic Planet GEMME project (Integrated Geological, gEophysical and geocheMical approaches for 3D Modelling of complex seismic site Effects).

The need for an infrastructure capable of acquiring, storing, organising and publishing multiparameter data in near real time arose following the installation of the Garda multiparameter seismic network, PDnet (https://eida.ingv.it/it/networks/network/ZO), installed starting from 2021 as part of the Task-S2 of the INGV Dynamic Planet project (Massa et al., 2021; Ferrari et al., 2024). In this framework, MUDA collects information from different types of sensors, such as seismometers, accelerometers, hydrogeochemical for physical-chemical parameters in waters, geochemical for measuring the diffusive flux of carbon dioxide (CO_2) from the soil or detecting the air Radon concentration, and meteorological stations. The aim is to constraint the influence due to exogenous parameters in order to make potential correlations between seismic phenomena and variations concerning monitored parameters (i.e. groundwater level, temperature, electrical conductivity, CO_2 soil flux, air Radon concentration; Barberio et al., 2017; Chiodini et al., 2020; Mastrorillo et al., 2020).

The challenge of MUDA is to provide the end-user a high quality dynamic but also simultaneous and continuous monitoring of groundwater physical parameters, meteorological data and seismic signals, together with gas concentration such as Radon or soil CO_2-CH_4 fluxes (Figure 3). In order to furnish the main information for a detailed interpretation of local phenomena in the framework of multi-hazard assessment, the multiparametric data are provided together with all necessary stations and sites metadata, supplied with a complete geological and morphological description (Figure 4).

2 Seismotectonic framework and seismicity

The multiparametric sites now included in MUDA are located in five main target areas (Figure 2): Lake Garda, eastern Alps, Po alluvial basin, Northern and Central Apennine chains (Table 1). Concerning instrumental seismicity (http://terremoti.ingv.it/), in the last 40 years, thousands of small to moderate energy seismic events (Figure 2) occurred in Northern Italy. Despite the low-to-medium seismic hazard of the area (Stucchi et al., 2011), the high level of exposure (e.g. metropolitan areas, industrial plants etc.), the local geological condition and the proximity of active buried seismogenic structure (Burrato et al., 2012) make many portions of North Italy a medium to high seismic risk zone (Massa et al., 2022b, Lai et al., 2020).

In particular, the Garda region (Area 1, Figure 2) is characterized by low-to-moderate seismicity with the active tectonic regime located on the margin of the southern Alpine chain controlled by the Africa-Europe convergence. The main active faults affecting the area consist of mainly NNE-SSW trending thrusts (Galadini et al., 2001). For instance, the November 24, 2004, Vobarno M_w 4.8 earthquake (https://terremoti.ingv.it/event/1564989), generated maximum macroseismic intensities (Imax) of VII/VIII (https://emidius.mi.ingv.it/CPTI15-DBMI15/, Locati et al., 2022). It is worth noting that in the past the same area was struck by several powerful events, such as the October 30, 1901, Salò M_w=5.4 earthquake (https://emidius.mi.ingv.it/CPTI15-DBMI15/, Rovida et al., 2022).

Moving eastwards (Area 2, Figure 2), the highest rate of energetic events in Northern Italy is associated to the South-verging thrust faults typical of the central and East South Alpine Chain (Battaglia et al., 2004; Serpelloni et al., 2005; D'Agostino et al., 2008), due to the North-South convergence between the Adriatic microplate and the Alps. The most recent destructive earthquake occurred in Friuli, during the seismic sequence of May 6, 1976, with M_w= 6.5 (Pondrelli et al., 1999 and reference therein), whereas the largest historical event was the 1695 Asolo earthquake, with an estimated M_w=6.48 (https://emidius.mi.ingv.it/CPTI15-DBMI15/) broadly associated to the thrust system of the Montello area (Danesi et al., 2015).

South of the Alps, the Po alluvial plain (Area 3, Figure 2) represents a very deep foreland basin of two opposing verging fold-and-thrust belts developing in the framework of the African and European plates relative convergence (Pieri and Groppi, 1981; Bigi et al., 1990). Despite the flat morphology, the Po plain is far from being an undeformed domain, since the outermost and most recent thrust fronts of the two belts are buried by the Plio-Quaternary sedimentary sequence (Burrato et al., 2012). The historical and instrumental Italian seismic catalogues show that the southern Po plain is affected by low to moderate seismicity, with M_w up to 5.8 during the 2012 sequence (Luzi et al., 2013). Considering the historical seismicity (Rovida et al., 2020), the central part of the Po plain was struck by the more significant North Italy earthquake on January 3, 1117, with an estimated M_w=6.52.

Moving southwards, the Northern Apennines (Area 4, Figure 2) underwent the regional seismicity associated with the Apennine fronts defined by different arcs of blind, North-verging thrusts and folds (Mazzoli et al., 2015; Chiaraluce et al., 2017), capable of generating moderate energetic seismic events with a maximum magnitude around 6 (i.e. June 5, 1501, M_w 6.05, Rovida et al., 2022). In particular, this area hosts the Nirano site (Table 1), in the Regional Natural Reserve of Salse di Nirano (Giambastiani et al., 2024; Romano et al., 2023), an area lying upon an anticline structure of the North-East verging fold-and-thrust Apennine belt characterized by one of the largest mud volcano fields in Europe (Bonini, 2008; Castaldini et al., 2005) coupled to the emission of CH_4-dominated gases (e.g., Buttitta et al., 2020).

Finally, two stations included in MUDA, are installed in the surroundings of the Norcia alluvial basin (Area 5, Figure 2), an area characterized by high seismic hazard and seismicity rate due to dense extensional NW-SE active fault systems (e.g. Galadini et al., 1999, Brozzetti and Lavecchia, 1994) capable of generating high-magnitude earthquakes (Galli et al., 2018; 2019), such as the January 14, 1703, M_w=6.9, earthquake or other moderate events such as the 1328, M_w=6.3, the 1730, M_w=5.9, the 1859, M_w=5.5 and the 1979, M_w=5.8, earthquakes (Rovida et al, 2022). The recent instrumental seismicity highlights the two main events occurring on August 24, 2016 and on the October 30, 2016, with M_w 6.0 and 6.5 respectively, in an area a few kilometres of the Norcia plain (e.g. Improta et al., 2019 and reference therein).

3 State of the art

At present, in Italy and Europe, the seismological communities in general are fairly advanced in their running of both network data management and seismic data sharing. In Italy, the main seismic network is represented by the National Seismic Network (RSN, https://eida.ingv.it/it/networks/network/IV, Margheriti et al., 2020), managed by INGV and sometimes integrated for real time data exchange by many local or regional networks (Massa et al., 2022). The RSN permanent network is codified through the IV code assigned by the International Federation of Digital Seismograph Networks, FDSN (https://www.fdsn.org/). The RSN station codes are registered at International Seismological Center, ISC (http://www.isc.ac.uk/), while data, recorded following the SEED (Standard for the Exchange of Earthquake Data, http://www.fdsn.org/seed_manual/SEEDManual_V2.4.pdf) format, are shared (Danacek et al., 2022) through the EIDA-Italia node (European Integrated Data Archive, https://eida.ingv.it/it/). In Italy, INGV provides many websites and thematic databases for real time data quality and distribution, such as EIDA-Italia, ISMDq (INGV Strong Motion Data quality, https://ismd.mi.ingv.it , Massa et al., 2022), ITACA (ITalian Accelerometric Archive, https://itaca.mi.ingv.it, Pacor et al., 2011), ESM (Engineering Strong Motion database, https://esm-db.eu/, Luzi et al., 2016), BSI (Italian Seismic Bulletin, https://terremoti.ingv.it/bsi, Marchetti et al., 2016), TDMT (Time Domain Moment Tensor, https://terremoti.ingv.it/tdmt, Scognamiglio et al., 2009), ShakeMaps (https://shakemap.ingv.it/, Michelini et al., 2020), etc.

Differently, the geochemical community has still not developed a so capillary network of automatic stations for data acquisition, management and sharing, as the seismic community does. This mostly depends on the fact that only a few geochemical parameters/tracers can be measured directly in the field and in near real-time [e.g., diffusive flux of CO_2 from the soil through accumulation chamber method (Chiodini et al., 1998; Carapezza et al., 2004; Inguaggiato et al., 2011a; Rizzo et al., 2015), Radon concentration in atmosphere or from the soil with specific Geiger counters, concentration of H_2O, CO_2, SO_2, H_2S, CH_4, halogens in atmosphere through MULTIGAS sensors (Aiuppa et al., 2005; Shinohara et al., 2005) or FTIR technique (e.g., Allard et al., 2005), SO_2 flux in atmosphere by DOAS and UV techniques (Burton et al., 2009; Aiuppa et al., 2021)]. It must be also highlighted that most of the automatic measurements of geochemical parameters above reported were developed and applied in volcano monitoring, while only recently the geochemical community is moving to apply some of those tracers to seismic monitoring. In terms of hydrogeochemical monitoring, apart the physical-chemical parameters in water (e.g., temperature, water level, electric conductivity, and others such as pH and Eh but with less precision and accuracy) for which automatic sensors exist since long time, the automatic and high-frequency measurement of the water's composition is limited to a few sensors developed in the last decade or so, which mostly focus on the concentration of a few gas species dissolved in waters (e.g., CO_2, CH_4, total gas pressure; De Gregorio et al., 2005, Inguaggiato et al., 2011b). As for gas sensors, most of the automatic measurements of water's composition were developed for volcano monitoring applications.

At present, in Italy, hydrogeochemical and geochemical seismic monitoring is limited to selected areas or sites, and it is essentially performed by several departments of INGV in the framework of individual initiative such as the Alto Tiberina Near Fault Observatory (TABOO, https://ingv.it/en/monitoring-and-infrastructure-a/monitoring-networks/the-ingv-and-its-networks/taboo, Chiaraluce et al., 2014) or recent and on-going INGV projects such as the Dynamic Planet (https://progetti.ingv.it/it/pian-din), FURTHER (https://progetti.ingv.it/en/further), MYBURP (https://progetti.ingv.it/it/pian-din#myburp-modulation-of-hydrology-on-stress-buildup-on-the-irpinia-fault), Multiparametric Networks or Rebuilding Central Italy, DL50 and related tasks (e.g. Idro-DEEP CO_2, Idro-Calabria, Idro-Nord), concerning the groundwater continuous monitoring (e.g. springs and thermal waters) of different areas of mainly Central and Southern Italian Apennines (https://www.pa.ingv.it/index.php/progetti/) and Radon monitoring (IRON project, https://ingv.it/monitoraggio-e-infrastrutture/reti-di-monitoraggio/l-ingv-e-le-sue-reti/iron). In particular, the Alto Tiberina Near Fault Observatory is managed by EPOS (European Plate Observing System) research infrastructure (https://www.epos-eu.org/) of which the mission is to foster the integration of solid earth data and their by-products made by the entire European scientific community: in this case, seismological, geophysical, geodetic and geochemical data recorded by TABOO-Near Fault Observatory are accessible via the FRIDGE European web portal (https://fridge.ingv.it/index.php).

Further local monitoring initiatives are provided by other institutions or Universities through the installation of geochemical stations and probes in different parts of the national territory such as in Tus**ca**ny, by the IGG-CNR (Institute of Geoscience and Earth Resources, https://www.igg.cnr.it/en), in Southern Italy, by the IMAA CNR (Institute of methodologies for environmental analysis, https://www.cnr.it/en/institute/055/institute-of-methodologies-for-environmental-analysis-imaa) or Central Italy, by the Earth Sciences Department (DES, https://www.dst.uniroma1.it/en) of Sapienza University of Rome (Martinelli et al., 2021).

Consequently, at a national scale the hydrogeochemical and geochemical monitoring is not organized by using an ad hoc reference institutional database or web portal able to homogeneously archive and distribute high quality multiparametric data to the scientific community. At present and at the best of our knowledge, the only existent databases focus only on mapping gas emissions (e.g., MaGa, http://www.magadb.net/) or thermal springs, without archiving data from a regular monitoring. A first attempt was recently made in the framework of an agreement between the National Institute of Geophysics and Volcanology (INGV) and the National System for Environmental Protection (SNPA, https://www.snpambiente.it/, comprising the Regional Environmental Protection Agencies, ARPA, and the Italian Institute for Environmental Protection and Research, ISPRA, https://www.isprambiente.gov.it/), with the aim of sharing data from the continuous monitoring of water wells and springs, in particular the piezometric level, temperature, electrical conductivity, salinity and total dissolved solids (Comerci et al., 2019).

4 MUDA database

MUDA is a dynamic and relational multiparametric database designed and built using a table structure that can correlate data of a different nature (i.e. seismic, hydrogeochemical, geochemical, meteorological). It is adaptable to further types of data from other projects and capable of integrating perfectly with those already acquired via both real time and off-line transmission vectors (Figure 5). The MUDA database is based on MySQL (https://www.mysql.com/it/), a popular and efficient open-source relational database management system for handling large amounts of data. Particular attention has been paid to optimising and, above all, integrating all the different types of data taken from different sources while trying to maintain a certain structural uniformity, also open to possible future new implementation.

Data collection takes place separately for each type of monitoring station (Table 1), each according to its preferred channels (email, ftp system, Application Programming Interface API, Structured

Query Language SQL) with the effort to improve each procedure, avoid data loss and minimise the time taken to receive data.

Data are acquired and then archived on a centralised server from which all pre-processing procedures are then carried out to insert this data, after appropriate checks and automatic analysis, into the MUDA database (see next chapter for details). All data downloaded from the remote stations, after the check and processing phase are stored in files before the population of the MySQL database. This is also convenient to have a native and complete data backup, for future requirements.

The MUDA database is structured to consider all the different types of monitoring stations at the same multiparametric site through a univocal internal site code, linked to all different types of data. At the same time, however, the independence of the data of each different station is also maintained, as each individual site may have its own particular condition and metadata. For each type of monitoring station, the MUDA database includes 2 tables, one for the station metadata and the other for the recorded data, linked by a unique station id.

4.1 Processing of raw data

The MUDA project currently includes 5 types of data: hydrogeochemical, meteorological, Radon, CO_2. and seismic. All data are pre-processed to align each time series to the common UTC (Coordinated Universal Time) time. Hydrogeochemical, seismic, meteorological and Radon data are moreover resampled in order to have a representative data each few minutes (i.e. from 1 to 5), namely a good enough interval to see possible cross-correlation signals on different parameters. A data resample is a priori necessary in order to, at first, homogenize data for viewing and comparison, but also to allow the web page to have a fast response to any query involving long time periods (actually up to a maximum of 30 days) of continuous and high frequency multiparametric recordings. In particular, while hydrogeochemical, gas and meteorological data are uploaded into MUDA database as raw data with only a consistency check, the seismic data are pre-processed in order to obtain waveforms metadata to be included into MUDA database and to be easily comparable in terms of time series to the other parameters.

The processing of raw data for each of the 5 parameters included in MUDA is described in detail in the following.

The hydrogeochemical data are acquired by two different types of instrumentation, the first provided by Van Essen Instruments (https://www.vanessen.com/) and the second by STS-Italia S.r.l. (https://www.sts-italia.it/). Data recorded by Van Essen Instruments and STS-Italia are set to sample records everyone and ten minutes, respectively. In both cases, groundwater level (m), electrical conductivity (μS/cm), and temperature (C°) are achieved using probes (e.g. CTD-Diver®, https://www.vanessen.com/) installed in correspondence of wells or springs by using weir flowmeters; the recorded chemical and physical parameters are sent at defined time intervals to the remote company head offices and then to the INGV acquisition centre by proprietary API or email. At present, remote stations send data in ASCII format twice a day (i.e. 9 a.m. and 9 p.m., Central European Time, CET) as an email attachment or by ftp-protocol. Depending on the target instrumentation, before populating the MUDA database, a pre-processing is necessary: as an example, the Van Essen probes for water wells need a barometric compensation to account for atmospheric pressure variations in order to provide the corrected water level value (Ferrari et al., 2024). Automatic data acquiring and processing tools have been developed in Python (https://www.python.org/), while automatic tools for populating the MUDA database have been developed in PHP language (https://www.php.net).

The meteorological data included in MUDA are provided by Davis Vantage Vue® instrumentation (https://www.davisinstruments.com/). Each single meteorological station, placed near the water well, provides information on atmospheric pressure (mbar), temperature (C°), humidity (%), rainfall amount (mm), wind speed and direction. Also in this case, data take advantage of

GPRS/LTE technologies and are gathered by a dedicated WeatherLink Live cloud platform, making them available in real time on the dedicated website (https://www.weatherlink.com/). With samples every one minute, data are archived into the Davis server-cloud and then shared by payment to the end-users (e.g. INGV server) through proprietary Application Programming Interface (API) set into an automated ad-hoc developed python tool, suited for all the different kinds of meteorological instrumentation at each site. Just as for hydrogeochemical data, meteorological parameters are then automatically inserted into the MUDA database twice a day (i.e. 9 a.m. and 9 p.m. CET) using a procedure developed in PHP.

The Radon data are provided by the IRON network (Italian Radon mOnitoring Network, https://ingv.it/monitoraggio-e-infrastrutture/reti-di-monitoraggio/l-ingv-e-le-sue-reti/iron, Cannelli et al., 2018). Stations, placed next to the water well, measure the concentration of gas in the air using a photodiode detector (AER Plus, Algade), with a sensitivity of 15 Bq/m^3 by counts/hour. Data are measured and acquired every 4 hours together with temperature and humidity, Radon data are transmitted in real time by the Sigfox (https://www.sigfox.com) 0G-technology and archived at the Sigfox cloud, with the exception of particularly remote sites where a periodic local data downloading is also necessary. Radon data are provided in csv format, where the concentration is measured in Bq/m^3, and then uploaded into the MUDA database using an ad-hoc developed PHP tool. In this case, the procedure is manually started after each single data downloading.

The CO_2 soil flux measurements are acquired using an accumulation chamber provided by Thearen S.r.l (https://thearen.com/). The permanent stations have a no-stationary flux chamber and are equipped with an infrared analyser measuring CO_2 concentrations ($g \cdot m^{-2} \cdot d^{-1}$) in a time frame of three minutes. A single CO_2 flux measure is returned each hour already corrected for pressure (mbar) and temperature (C°) recorded inside the chamber. Soil temperature and humidity (%) and meteorological parameters (atmospheric pressure, temperature, humidity, rain, wind speed and direction) are acquired concurrently. Data are sent to the head company server-cloud through a dedicated modem with automatic data transmission. Data are acquired daily by the INGV acquisition centre through an ad-hoc server to server link using an internal INGV-VPN (Virtual Private Network) connection. Data provided in csv format, are then daily automatically inserted into the MUDA database by using an ad-hoc developed PHP tool.

The Seismic data are acquired by selected stations of the Italian National Seismic Network (RSN, https://eida.ingv.it/it/networks/network/IV) and the multiparametric network of Northern Italy (PDnet, https://eida.ingv.it/it/networks/network/ZO) placed near the water well used for hydrogeochemical data. Recorded data are codified following the international standard commonly used by the seismological community, namely the FDSN (https://www.fdsn.org/) network-station code and SEED (Standard for the Exchange of Earthquake Data, http://www.fdsn.org/seed_manual/SEEDManual_V2.4.pdf) format supported by European Integrated Data Archive, EIDA (https://eida.ingv.it/it/) and maintained by the FDSN. Data are transmitted by different technologies (LTE, satellite, etc.) to the INGV Milano acquisition centre where they are archived through a Seiscomp4 (https://www.seiscomp.de/doc/apps/seedlink.html) client to improve the SeedLink real time data acquisition protocol. Data are archived in the standard binary miniSEED format (http://ds.iris.edu/ds/nodes/dmc/data/formats/miniseed) and organized in a structured archive. Seismic data are pre-processed every night considering the 24 hours of all miniSEED files recorded by stations on the previous day and then checked for quality before being automatically included in the MUDA database by using an ad-hoc developed PHP tool.

In dependence of the adopted sampling rate (i.e. 100 Hz for seismometers and 200 Hz for accelerometers) the amount of continuous data stream per day, relative to a single channel at each single station, ranges between 6 and 10 Mbyte for seismometers and between 15 and 20 Mbyte for accelerometers. Considering many seismic stations, the result is a total daily archive in the order of Gigabytes, not easy to organize in the framework of a quasi-real time data distribution provided by a thematic web portal. In this framework, also considering the sampling rate of the other multiparametric instrumentation (i.e. spanning from one record per minute to one record every four hours), the continuous seismic data streams are processed in order to conform the contents to the web portal requirements before inclusion in the MUDA database. In particular, every night at 2 a.m. miniSEED files relative to the 24-hour recordings of the previous day are selected at each station and processed by using an ad-hoc procedure developed by merging the Bash and SAC (Seismic Analysis Code, https://ds.iris.edu/files/sac-manual/) scripting languages.

The processing scheme starts by downloading at each single recording station 24 hours of miniSEED files; data are then separated into 288 sub-windows, each one with length of 5 minutes starting from the origin time of each single miniSEED file (usually corresponding to the 00:00:00 UTC if the station works well). Then, for each 5-minute windows, raw data recorded in counts are converted to the proper unit of measurements (cm/s for seismometers and gal for accelerometers) and the sensor response curves are removed by deconvolution and finally filtered using a 4th order Butterworth filter in the range 0.1 - 20 Hz. For each single sub-window relative to a specific channel recorded by a specific station, the RMS (Root Mean Square, e.g. Goldstain et al., 2003), the maximum ground shaking in terms of velocity (cm/s), the mean amplitude value of the whole FFT (cm/s/Hz) (Fast Fourier Transform, e.g. Bormann 2012) and the maximum amplitude of the FFT for frequency interval spanning from 0.1 Hz to 20 Hz, are calculated, providing for each parameter 288 values per day, corresponding to the daily upload of hydrogeochemical and meteorological data. In particular, the RMS is calculated for the entire time windows using the following equation:

$$x_{RMS} = \sqrt{[1/n\,(x1^2 + x2^2 + \ldots + xn^2\,)]} \qquad (1)$$

where x is the amplitude of the single sample, and n the number of samples of the trace considered. Daily time series of RMS, PGV, FFT-mean and FFT*(f)* are finally uploaded into the MUDA database using an ad-hoc developed PHP tool.

4.2 Data availability and dissemination

MUDA publishes and shares the available data recorded at each site through a specific web interface developed in PHP (https://www.php.net/) to easily and effectively interact with MUDA SQL database, and using a responsive design in HTML5, capable of adapting automatically to any device on which it is displayed (i.e. PC, tablet, smartphone, etc.). As a final step, the data publication required assigning a regular DOI associated to the DB and provided by INGV data management office through a standard procedure. The final DOI of MUDA is https://doi.org/10.13127/SD/ku7Xm12Yy9. Data have been licensed using the Creative Commons License CC BY 4.0. MUDA web portal publishes multiparameter data daily and updated to the previous day. It offers the chance to view and download dynamic time series for all available data and for different time periods, up to a maximum of 30 days. In reference to longer periods, an e-mail request can be sent to: muda@ingv.it.

The web portal has a main page showing an interactive map of Northern and Central Italy, as at present MUDA acquires data from automatic stations located in this part of the Country, where the multiparametric stations are indicated by triangles with pop-ups showing the main features (i.e. coordinates and available instrumentation) of the target site, including the direct access to the dynamic data viewing (Figure 3) and to the single station page (Figure 4). The home page on the top right corner shows a pop-up menu with selectable thematic layers including the reference seismic hazard map of the national territory in terms of peak ground acceleration (MPS04 working group, http://zonesismiche.mi.ingv.it/, Stucchi et al., 2011), the seismogenic areas and the active faults taken from the Database of Individual Seismogenic Sources database (DISS, https://diss.ingv.it/, DISS working group 2021), recent (https://terremoti.ingv.it/) and historical (https://emidius.mi.ingv.it/CPTI15-DBMI15/) seismicity bulletins, and the location of seismic stations of the National Seismic Network (RSN, https://eida.ingv.it/it/networks/network/IV) managed by INGV.

The *View & Download DATA* web page, accessible from the horizontal tool bar of the home page, opens the dynamic data viewing (Figure 3). Users can select for each multiparameter site the time series to be displayed backwards in time (i.e. 1 day, 7 days, 15 days, 30 days) starting from a selected date. Once the site and period have been chosen, the available data automatically appear synchronised with respect to UTC (Coordinated Universal Time). From top to bottom, these are: hydrogeochemical data from well or spring sensors showing water temperature (°C), electrical conductivity (μS/cm) and the value of the water column (m) above the sensors; meteorological data showing air temperature (°C) and rainfall (mm); seismometric data showing the RMS, the maximum ground velocity values (cm/s), the average FFT amplitude values, the Fourier spectrum values for frequency bands selected in the interval 0.1 - 20 Hz; Radon gas emissions (Bq/m^3) and soil CO_2 flux ($g \cdot m^{-2} \cdot d^{-1}$). All interactive graphs can be zoomed with the left mouse button and they enable selecting individual functions using pop-up layers. In each graph, in the top right-hand corner, it is possible to view the individual image in full screen and download the selected data in csv (Comma Separated Values) format as well as the images in pdf (Portable Document Format), png (Portable Network Graphic), jpeg (Joint Photographic Experts Group), svg (Scalable Vector Graphics) formats. The last selectable item, on the right of this page, gives the possibility of viewing a single parameter, for a more detailed observation.

A further topic of the MUDA web portal is the single station web page (i.e. link *STATIONS*), also reachable from the horizontal tool bar. This web page is designed to provide a first and general geophysical and geochemical characterization of each multiparametric site. In particular, each single station web page shows, on the left, a thematic map indicating the location of the monitoring site. Below the map, the two links provide a geological and morphological setting of the area. For each recording site, a portion selected from the geological map at a 1:100,000 scale (Società Geologica Italiana, http://www.isprambiente.gov.it/it/cartografia/) is provided, with topographic base at 1:25,000 scale (Istituto Geografico Militare, http://www.igmi.org/prodotti/cartografia/carte_topografiche/). Concerning morphology, for each recording site, a topographic map (i.e. Slope and Ridge) is proposed by considering the available digital elevation model (ASTER GDEM with a cell size of 10 m, https://www.earthdata.nasa.gov/news/new-aster-gdem). Starting from the processed DEM, the slope map was constructed with three topographic classes (0°–15°, 15°-30°, and >30°), considering the break values defined in the current Italian seismic code (NTC, 2018). The ridgelines were extracted using the Topographic Position Index (TPI) algorithm (Weiss, 2001; Pessina and Fiorini, 2014). On the right, the web page shows thematic tables relative to the installed instrumentation. At each site, besides the general information on coordinates and technical features of the instruments, a geophysical characterization of the site is also provided in terms of polarized horizontal to vertical spectral ratio (HVSR) on ambient noise (Nakamura, 1989) and each single log performed in the wells regarding water electrical conductivity and temperature as a function of the available stratigraphy together with the main features of monitored well or spring. Finally, in each station web page, graphs relative to the whole hydrogeochemical time series are also downloadable.

5 Data Records

At present (i.e. March 31, 2024), MUDA includes data from 25 multiparametric sites (Table 1) located in Northern and Central Italy (Figure 2), both already monitored by permanent INGV infrastructures or installed in the framework of recent INGV research projects. It is worth mentioning that not all multiparametric sites are characterized by homogeneous multiparametric instrumentation (Figure 6). In any case, all available data are always sent in real time to the INGV acquisition centres. In particular, concerning seismic data, the multiparametric sites include 7 stations belonging to the permanent National Seismic Network (RSN, https://eida.ingv.it/it/networks/network/IV) and 12 stations belonging to the temporary multiparametric network of Northern Italy (PDnet, FDSN code ZO, https://eida.ingv.it/it/networks/network/ZO), installed in the framework of the INGV Dynamic Planet S2-project. These sites are located in Northern Italy, around the Lake Garda, at the southern limit of the Eastern Italian Alps and in the central portion of the Po Plain (Figure 2). Two further seismic stations (PDN11, PDN12, table 1) have recently been installed in the framework of the INGV Dynamic Planet GEMME (Integrated Geological, gEophysical and geocheMical approaches for 3D Modelling of complex seismic site Effects) project, in Norcia basin (Apennine chain in central Italy) and its surroundings (Figure 2). Finally, one seismic station (PDN10, table 1) has been installed in cooperation with the Dynamic Planet PROMUD (Definition of a multidisciplinary monitoring PROtocol for MUD volcanoes) project, in the Salse di Nirano Reserve (Italian Northern Apennines, Figure 2). In general, seismic stations are equipped with high dynamic 24-bit digital recording systems coupled to enlarged (5s owner period) or broadband (120s owner period) seismometers. In particular, at Oppeano multiparametric site (Table 1), borehole instrumentation is installed at 150 m depth. Even if in some cases accelerometer sensors are coupled to the target seismometer (velocimeter), MUDA includes only seismometric data due to their higher sensitivity and best resolution with respect to possible occurrences of natural phenomena such as micro seismicity, local weak motion earthquake occurrences and/or teleseisms or environmental modifications (i.e. landslides, low atmospheric pressure, tides etc.).

Hydrogeochemical data are recorded in all 25 multiparametric sites (Table 1), at both wells and springs set up in the framework of INGV Dynamic Planet projects (S2 and GEMME) and INGV Multiparametric Networks or the Rebuilt central Italy, DL50 project. The Toppo site (Table 1), installed in the eastern Alps in the framework of the Eccsel Eric consortium (https://www.eccsel.org/), is managed by OGS (National Institute of Oceanography and Applied geophysics, https://www.ogs.it/en) in cooperation with the University of Ferrara (Department of Physics and Earth Science, http://fst.unife.it/en) and the INGV. At present, data included in MUDA are recorded at 22 wells and 3 springs (Recoaro, Recoaro1, Feltre, see table 2). In general, wells have depths ranging from a few meters (< 10 m) to a maximum of 300 m for Toppo and Mirandola sites (Table 2). The instrumented wells have a mean depth between 5 and 150 m. Monitored sites are mainly characterized by cold waters whose average temperatures range from 10.3 to 17.4 °C, except for TRIPONZO site that owns thermal water (~ 30 °C; Table 2). A wide variety of water electrical conductivity values (~ 130-88000 μS/cm; Table 2) are illustrative of heterogeneous compositions and salt contents. Information on the presence of borehole pump (Table 2), frequency and intensity of water pumping were carefully collected from well owners. Water level, temperature and electrical conductivity changes are observed because of pumping for water chemical analysis (e.g., Balconi) or irrigation purposes (e.g., Norcia) or functioning of spa (e.g., Triponzo). These anthropogenic variations must be accounted for when analysing groundwater data. A comprehensive example of data-processing able to recognize in groundwater time series both natural phenomena and anthropogenic noise signals is reported in Ferrari et al. (2024) for the site of Balconi.

All sites monitored by hydrogeochemical instrumentation are also equipped with a meteorological station able to capture the main atmospheric variations. Four sites (i.e. Montelungo, Bondo, Norcia, Triponzo, table 1) are currently equipped with instrumentation able to record the Radon concentration in the air. Sensors for Radon monitoring are part of the IRON network (Italian Radon mOnitoring Network, https://ingv.it/monitoraggio-e-infrastrutture/reti-di-monitoraggio/l-ingv-e-le-sue-reti/iron) of INGV. Finally, just one site (i.e. Nirano, table 1) is equipped with instrumentation for Carbon Dioxide (CO_2) soil flux measurements.

In general, the multiparametric sites show co-located instrumentation, with a few exceptions due to logistic difficulties during the site installation or other technical problems (e.g. sites with a very high level of background seismic ambient noise or working pump installed in well). In all cases, the reference seismic station is installed in the same geological, morphological and hydrogeological context as the other instruments, possibly co-located or at least in the proximity. Hydrogeochemical stations installed in a narrow area (e.g., Bulgarelli, Medolla, Mirandola and Secchia sites, table 2) might refer to the same seismic station.

5.1 Data quality check

In order to verify the completeness and correctness of the recorded data, we carried out several checks.

Concerning seismic data included in MUDA, the results of the processing procedure to produce 5 minutes interval data are verified to check the capacity of the proposed processing scheme to represent a real marker to detect earthquakes or environmental phenomena. Figure 7 reports an exhaustive example at the Oppeano site for events recorded by the seismic station on December 29, 2020. Figure 7 shows in the panel *a* (top) the occurrences of subsequent events in a narrow time window spanning from 2020/12/29 14:02:40 to 15:36:57 UTC. The first evident transient is related to the regional M_w=6.3 Croatia earthquake on 2020/12/29 at 12:19:54 UTC (https://terremoti.ingv.it/event/25870121). A few hours later, a small sequence of three local weak motion was recorded 12 km South West of Oppeano and localised by the INGV bulletin at 2020/12/19 14:02:40, 14:44:51 and 15:36:47 UTC with magnitudes of M_L=3.4, M_L=2.8 and M_w=3.9, respectively (https://terremoti.ingv.it/event/25871441). In the bottom of panel *a* the results of our detector procedure in terms of FFT interval is shown for the 288 data points of the 2020/12/29. It is evident how all transients have been clearly recognized by marked peaks: in particular, the regional event, occurring about 400 km East of the Oppeano well highlights a notable contribution at low frequency, showing a clear peak for the FFT around 0.1 Hz. On the contrary, the local seismicity is well described by peaks detected at higher frequency content, in particular ranging from 1 to 10 Hz. In this case, it is worth noting how the high frequency content of FFTs also highlight variations in ambient noise level between night and day. In the panel *b* of figure 7, the results of the detection procedure are presented in terms of relative RMS, ground motion velocity and averaged FFTs (from top to bottom).

In order to publish reliable results, all continuous seismic data streams for all seismic stations are checked daily for quality by the interoperability between MUDA and ISMDq (INGV Strong Motion Data quality, http://ismd.mi.ingv.it, Massa et al., 2022). In this way all seismic stations included in MUDA are checked for gaps (%), availability (%) and ambient noise level variation in terms of PSD (Power Spectral Density) and PDF (Probability Density Function), in dB, as calculated by McNamara and Buland (2004). Through ISMDq, it is possible to build temporal time series with a maximum time length of up to 2 years for all stations included in MUDA in order to check at first the correct functioning of the stations, the accuracy of used metadata, daily and seasonal variations of ambient noise level and transient or permanent anthropic disturbances. In particular, in case of failure in data transmission, the continuous monitoring of data gaps and availability allow us to retrieve data directly from station memories thereby avoiding important gaps in the data.

Hydrogeochemical and geochemical data are checked daily for availability and gaps usually due to a temporary lack of data transmission platforms (i.e. cellular line or satellite), in particular during rainy and stormy days or more rarely due to malfunctioning of the instrumentation. In the first case, the recorders, thanks to their internal memory and datalogging capacity, are able to archive data up to a maximum of 30 days. If needed, the recovery of data is possible through a manual download. Subsequently data are uploaded into the MUDA database by calling the same ad-hoc developed tools for populating the database for each parameter, with appropriate flags. In some cases, water level time series show unusual abrupt peaks (i.e. spurious spikes that are filtered) due to some problems during the compensation of atmospheric pressure performed by the recording system in order to obtain the correct values of water level: in general, misalignments in pressure compensation lead to wrong water level values, usually with differences of ~ 10 m, as a consequence of the measured atmospheric pressure usually around or slightly above 1000 mbar, considering that all the stations are within a few hundred meters above sea level.

Other data included in MUDA (i.e. meteorological, Radon, CO_2 flux) do not need particular processing. In any case, for all meteorological, Radon and CO_2 measurements, data are always checked for gaps and possible spurious peaks that are deleted. In particular, meteorological data regarding the pluviometry are archived and uploaded into MUDA as a single sample recorded each minute, or even better, in some cases, at each individual movement of the rain gauge's tipping bucket

(0.2 mm every time). In these cases, before publishing the rain values on the web site, data are cumulated in intervals of 1 hour directly in the SQL query made by the web portal, in order to better highlight heavy storms or other particular meteorological phenomena.

6 Multiparametric monitoring

In this section, some examples of comparison among multiparametric data are presented and discussed in the framework of their possible applications for research and services devoted to natural hazard risk reduction.

An interesting example of multiparametric monitoring, concerning groundwater level variation presumably related to large landslide phenomena has been collected at the Bondo (Table 1) site and aquifer (Lake Garda area, Figure 2), where on the November 1, 2023, the water column above the sensor in the well abruptly increased by ~ 20 m. This significant modification, also combined with the diminishing temperature and electrical conductivity (Figure 8, panel *a*), happened as a consequence of 2 days of intense rainfall with measured values of precipitation up to 400 mm in a narrow area surrounding Bondo. It is important to highlight that the stratigraphy below Bondo is mostly made of fractured-carsified limestones belonging to the Dolomia Principale formation (Upper Triassic). To explain such a notable groundwater level variation, additional and contemporary natural phenomena should be hypothesized; on the base of the information provided by the local media, in the same period the area was affected by diffuse landslides. In particular, between October 31 and November 1, 2023, a clear seismic transient (Figure 8, panel *b*) was recorded on all 3 components of ZO.PDN3 station (Table 2), characterized by very long duration (i.e. some hours), higher amplitudes with respect to the local ambient noise level (i.e. the Peak Ground Velocity, PGV was equal to 0.01 cm/s, comparable to a local earthquake with magnitude ranging from 2.5 and 3.0), prevalent high frequency content (~ 5-30 Hz) and a strong polarisation with preferential amplification of motion along the NS direction (Figure 8, panel *c*). In this case, the recorded transient at ZO.PDN3 could in fact be attributable to local and diffuse landslides that could have modified the volume and/or the extent of the aquifer and eventually the water flow infiltration and circulation through the rock fractures by influencing the water level and leading the aquifer to be more sensitive to meteorological events.

Meteorological events, in particular the intense rainfall period, also seem to have a strong influence on Radon emission measurements, usually adopted as a possible marker in case of a tectonic event. An example can be observed considering the complete Radon time series at the Bondo site where data highlight a positive correlation with the seasonality, with increasing values in summer and decreasing values in winter, following the trend of both atmospheric pressure and temperature. At least during the monitored period, at the Bondo site no correlation with local seismicity appears to be noticeable, while clear correlations between Radon outliers and the rainfall period are evident (Figure 9, panel *a*). It is worth mentioning how not all Radon sensors show the same behaviour with respect to the season. At the Montelungo site (Table 1), for instance, data show a complete anti-correlation with the seasons (Figure 9, panel *b*), with lower values in summer and higher values in winter, probably as a consequence of the different local geological and morphological setting.

A further example regards the CO_2 flux variation, measured at the Nirano site (Table 1) in October 2023 (Figure 10, panel *a*) during an intense period of weak motion earthquakes localized very close to ZO.PDN10 station, installed in the area of the Salse di Nirano regional park. Starting from June 2023, the area of Nirano showed an increase in the local seismicity. In the period 2023/06/01 to 2023/11/15, 32 earthquakes with local magnitude (M_L) in the range 2.0-3.5 were recorded with a maximum epicentral distance from Nirano of 30 km. In particular, the strong events with M_L=3.5 occurred on October 30, 2023 (04:25:53 UTC). Considering the CO_2 time series recorded at Nirano and a time period spanning from October 15 to November 15, 2023, it is possible to highlight the presence of many CO_2 data points with values exceeding the limit of +1 standard deviation (Figure 10, panel *b*), with respect to the average values of the period. Many outliers were recorded just before and also soon after the M_L=3.5 target earthquake. It worth noting that this evidence should be carefully evaluated also considering other parameters (for instance, atmospheric pressure, soil moisture and temperature), even though no relevant rainfall episodes occurred in that period.

Further case studies concern the correlation between meteorological (i.e. temperature and rainfall) and groundwater parameters. Understanding water level fluctuation patterns is one of the pillars for designing adaptive management practices that can mitigate the impacts of extreme water levels on infrastructure and associated economic activities (e.g. Gerten et al., 2013, Alley et al., 2002, Taylor et al., 2009; Russo and Lall, 2017). Groundwater recharge is difficult to estimate, especially in fractured aquifers, because of the spatial variability of the soil properties and because of the lack of data at basin scale. A possible solution consists in inferring recharge directly from the observation in boreholes (Guillaumot et al., 2022), even if the direct measures in wells overlook the impact of lateral groundwater redistribution in the aquifer. When evaluating the effect of exogenous parameters on groundwaters, rainfall is the main factor in promptly influencing all monitored groundwater parameters (e.g. Mancini et al., 2022, Guillaumot et al., 2022), with a variable aquifer response with respect comparable amounts of precipitation in the same period. Figure 11 shows an example of groundwater recordings related to the meteorological event of October 2023 at Volargne and Fonte sites (table 1). It is worth noting how in the first site (Figure 11, panel *a*) a gradual and moderate rise in water level is contrasted by a faster and larger (less than 2 hours) increase in water level at the Fonte site (Figure 11, panel *b*), which shows an intense influence of the rainfall, also proved by the extremely variable temperature and conductivity records not observed in the other sites (Ferrari et al., 2024). The light grey box in Figure 11 highlights another instant response of Fonte groundwater to precipitation which is even more sharper than the one described above and also involves electrical conductivity decrease and temperature increase.

The atmospheric temperature is moreover proven to affect groundwater temperature, especially in aquifers down to ~ 20 m depth (e.g. Lee and Hahn, 2006, 2021; Taylor and Stefan, 2009; Menberg et al., 2014). Monitoring sites having at least 1 year of recordings are taken into account to analyse groundwater temperature seasonal oscillations and correlations to air temperature. In our case, the absence of seasonality is detected at the Bondo, Montelungo and Volargne sites (Table 1) where the constant groundwater temperatures could be explained by the aquifer depth (~ 50 m). In other cases, such as the Casaglia site (Table 1), despite the depth of aquifer of a few meters below ground level, the relevant water (~ 40 m) column above the hydrogeochemical sensor dampened possible temperature fluctuations (Bucci et al., 2020; Egidio et al., 2022). On the contrary, at the Balconi site (Table1), despite the aquifer depth is greater than 50 m, a nearly seasonal variation characterized by maximum values reached in summer and minima in winter, is observed, in agreement with the measured air temperature periodicity (Ferrari et al., 2024). However, it should be evaluated whether this temperature variation in specific seasons is directly attributable to meteorological reasons or to anthropogenic causes, due to intense irrigation occurring in the area of Balconi during the most dry and hot months of the year.

7 Usage Notes and conclusions

The technical validation allowed us to obtain a reliable and homogenous dataset of continuous multiparametric time series and associated metadata. For hydrogeochemical, meteorological, Radon and CO_2, data are published in a raw format after a pre-processing whose main scope was just to detect gaps and spurious peaks to be deleted from the time series. Seismic data are published after applying a 5-minute resampling to the raw miniseed 24-hour continuous data and then by converting the velocity ground motion (cm/s) in RMS and FFT discrete time series. The raw seismic waveforms are however downloadable from the EIDA-Italia webservice (https://eida.ingv.it/it/).

For the first time, at least in Italy, high frequency and continuous multiparametric data are dynamically updated daily and published soon after for end users. Data can be used for different purposes, ranging from i) information regarding environmental and meteorological temporal trends with respect the global climate change problematic; ii) details on local aquifer features and seismicity;

iii) recommendations for the civil protection; iv) multiparametric geophysical, environmental and geochemical data for research studies. In particular, all seismic stations included in MUDA-db with code ZO (PDnet, https://eida.ingv.it/it/networks/network/ZO) contribute with the national seismic monitoring by sharing a continuous data stream in real time to the INGV National Seismic Network (https://eida.ingv.it/it/networks/network/IV). In addition, the dense ZO network installed around Lake Garda contribute significantly to improving the minimum magnitude threshold detection of the area as reported in Ferrari et al. (2024).

Seismic data, together with all geological, morphological and geophysical information collected at each site included in MUDA, can moreover be used to investigate the site response in terms of seismic amplification, in particular for sites installed in the central part of the Po Plain, a deep basin characterized by a significant thickness of incoherent alluvial deposits. Seismic events recorded at each station can also be used for local investigations into the micro seismicity of the area, seismic source recognition or to improve the available seismic velocity models at a local scale.

Hydrogeochemical and geochemical data will be used in the framework of a recent agreement between the National Institute of Geophysics and Volcanology (INGV) and the National System for Environmental Protection (SNPA, comprising the Regional Environmental Protection Agencies - ARPA and ISPRA), aimed at gathering information on seismic activity and aquifer/spring status from various acquisition sources, in some cases reaching a near real time monitoring through the SINAnet facility (https://www.snpambiente.it/attivita/sistema-informativo-nazionale-ambientale/).

In general, the multiparametric monitoring is the basis by which to understand and identify possible seismic precursors, an objective not yet achieved in earthquake studies. In particular, the short-term earthquake forecasting, remains elusive and largely unattained. An effective solution for such a major issue might be found, in the future, in systematic high frequency and continuous measurements with multiparametric networks operating over the long term. Owing to the influx from deep crustal fluids in active tectonic areas, groundwater monitoring may especially be considered a fundamental tool for investigating pre-seismic signals of rocks undergoing accelerated strain (e.g. King, 1986; Skelton, A. et al. 2014, Barberio et al., 2017).

8 Data Availability

Data and metadata presented and described in this manuscript can be accessed under https://doi.org/10.13127/muda (Massa et al., 2023).

9 Code Availability

All the procedures to acquire and process data coming from multiparametric remote stations have been specifically developed for the MUDA project in Bash scripting language, Python and PHP language, using, when necessary, proprietary API taken from the manufacturers of the installed remote instrumentation, as detailed in the text. Seismic data are acquired and archived through a Seiscomp4 (https://www.seiscomp.de/doc/apps/seedlink.html) client, thereby improving the SeedLink real time data acquisition protocol. Some processing steps on the seismic data are undertaken using the Seismic Analysis Code (SAC, https://ds.iris.edu/ds/nodes/dmc/software/downloads/sac/), a software designed for both real time and off-line seismological analyses of time series data. The MUDA database is developed with MySQL open source software. The MUDA web portal is developed in PHP and HTML5 languages, and all data are published under the Creative Commons License CC BY 4.0 licence.

Team list

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Author contributions

This study started from an original idea by MM and ALR. MM, ALR, EF and SL contributed to all phases of site installations, data acquisition, processing and archiving. DS developed MySQL-Db and the associated web page, as well as the procedures to upload data into MUDA-db. SL and EF contributed to organising the technical data sheet related to each multiparametric site now available at each single station web page. MM developed the procedures for multiparametric data pre-processing and seismic data post processing. All authors participated in the preparation of the manuscript draft and in the phases of revision.

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Figure Captions

Figure 1 - MUDA home page: https://muda.mi.ingv.it. Examples of interactive pop-ups are reported in map indicating the available main options concerning stations data and metadata, Italian seismic hazard (Stucchi et al., 2011), seismicity rate and both composite and single seismogenic sources (DISS database, DISS Working Group 2021). The base map is provided by ©OpenStreetMap contributors 2024. Distributed under the Open Data Commons Open Database License (ODbL) v1.0.

Figure 2 - Target areas and relative multiparametric sites. Each panel indicates the multiparametric site (yellow triangles), the Italian seismic hazard map in terms of horizontal peak ground acceleration (PGA) with 10% probability of exceedance in 50 years on hard ground (Stucchi et al., 2011), the instrumental seismicity from 1985 (black circles, https://terremoti.ingv.it), the historical seismicity (red circles, CPTI database, Rovida et al., 2020) and the seismogenic sources (CSS-DISS database, DISS Working Group 2021). The base maps are provided by ©OpenStreetMap contributors 2024. Distributed under the Open Data Commons Open Database License (ODbL) v1.0.

Figure 3 - Dynamic multiparametric data web page: https://muda.mi.ingv.it/dat.php. From top to bottom: hydrogeochemical data (light blue panels: water level, m; water electrical conductivity, μS/cm; water temperature, °C), meteorological data (green panel: soil temperature, °C; rain, mm), seismic data (light brown panels: RMS, ground motion velocity, cm/s; FFT, cm/s/Hz; FFT(*f*), cm/s/Hz), CO_2 data (grey panels: soil flux, $g*m^{-2}*d^{-1}$; humidity, %; soil temperature, °C), Radon data on air (yellow panel: Bq/m^3). All time series (*csv* format) and each single graph (*pdf*, *png* formats) are downloadable by using the menu available in the top right corner of each panel.

Figure 4 - Multiparametric site web page: https://muda.mi.ingv.it/stazione.php. The single site web page indicates the main features of both instrumentation and installation, downloadable thematic maps such as the geological map (1:100.000, Società Geologica Italiana http://www.isprambiente.gov.it/it/cartografia/), the topographic map (base at 1:25.000, Istituto Geografico Militare, http://www.igmi.org/prodotti/cartografia/carte_topografiche/), log and stratigraphy concerning the available wells for water, a preliminary geophysical soil characterization in term of horizontal to vertical spectral ratio performed on ambient seismic noise and the complete time hydrogeochemical time series. Sources for base maps: Esri, DigitalGlobe, GeoEye, i-cubed, USDA FSA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community.

Figure 5 - MUDA data base scheme and processing flow chart.

Figure 6 - Single station data set for multiparametric sites having at least 6 months of data and three different types of acquisition. S: seismic data (red); Id: hydrogeochemical data (blue); M: meteorological data (green); R: Radon data (grey); C: CO_2 data (yellow). Yellow and orange stars indicate recorded earthquakes at each site with magnitude (Moment or Local) lower and higher then 4, respectively.

Figure 7 - Quality check of seismic data at Oppeano site (table 1).

Panel *a* (top): timeseries recorded on December, 29, 2020, by IV.OPPE station (https://terremoti.ingv.it/instruments/station/OPPE) showing consecutive earthquakes: the first, with M_w=6.3, occurred in Croatia land (https://terremoti.ingv.it/event/25870121) 450 km East of IV.OPPE and the others with epicentres 11 km South-West of IV.OPPE with maximum M_w=3.9

(https://terremoti.ingv.it/event/25871441). Earthquakes origin times (UTC) are reported in the top panel *a*).

The bottom panel *a*) shows the FFT functions calculated considering 15 frequency intervals from 0.1 to 20 Hz, considering 288 consecutive 5 minutes-time windows (i.e. 24 hours) selected on the vertical component of motion.

Panel *b*: from top to bottom, the RMS, the ground motion velocity and the mean FFT calculated for 288 consecutive time windows with duration of 5 minutes. Red, blue and green indicate the vertical, the North-South and the East-West horizontal components of motion. The black solid lines indicate the cumulative functions.

Figure 8 - Example of multiparametric data recorded at Bondo site (table 1). Panel *a* shows the hydrogeochemical data recorded in the time period from October 15 to November 15, 2023: black, red and green solid lines indicate the water level (m), the electrical conductivity (µS/cm) and the water temperature (°C) variations, respectively.

The panel *b* shows the seismic data recorded at ZO.PDN3 station (table 2) on October, 31 and November, 1, 2023, while the panel *c* shows the polarization analysis in terms of rotated horizontal to vertical spectral ratio.

Figure 9 - Radon time series (Bq/m^3, black lines) recorded at Bondo (panel *a*) and Montelungo (panel *b*) multiparametric sites. Soil temperature (°C, green lines) and rain (mm, light blue lines) are also indicated. At the top of each panel seasons are indicated (Aut=Autumn, Win=Winter, Spr=Spring, Sum=Summer).

Figure 10 - Panel *a*: CO_2 flux (g*m^{-2}*d^{-1}, black line) recorded at NIRANO multiparametric site. Red and green solid lines indicate the smoothing function of CO_2 flux and the temperature (°C), respectively. The orange box indicates the time window represented in the bottom panel.

Panel *b*: detailed monitoring for period October 25 to November 15, 2023, where a seismic sequence, with maximum local magnitude of 3.5 (vertical yellow dashed lines) occurred in correspondence of the Nirano's Mud-Volcanoes. Dotted and dashed orange lines indicate the mean values +/- 1-standard deviation of CO_2 flux recorded during the analysed time period. Rain values (mm, light blue) and soil temperature (°C) are also indicated. Black dots indicate the CO_2 measures ($g*m^{-2}*d^{-1}$).

Figure 11 - Groundwater recharge at Volargne (panel *a*) and Fonte (panel *b*) sites (table 1) recorded on October 30, 2023. In both panels, black, red and green solid lines indicate the water level (m), the electrical conductivity (μS/cm) and the water temperature (°C) variations, respectively, while the blue solid lines indicate the cumulative rain.

Table captions

Table 1 - Monitoring multiparametric sites at present include in MUDA.

Table 2 - Main features of hydrogeochemical probes and seismic monitoring stations. Grey cells indicate well with thermalism (i.e. Triponzo site), while the black cells indicate the borehole seismic sensor installed 150 m depth at Oppeano site.

In detail,

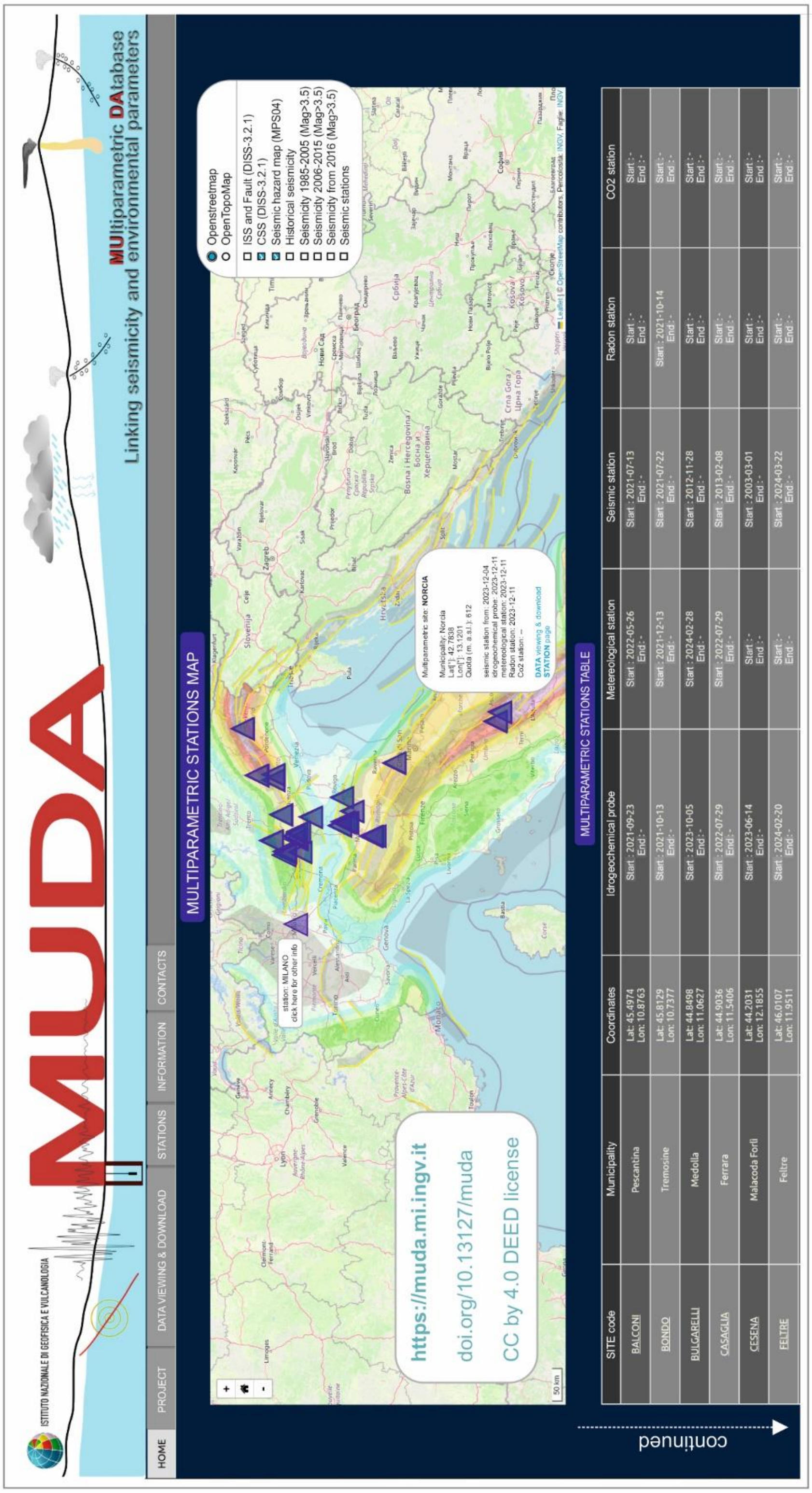
water level: water depth below ground level at the time of installation;

water column: water column above the sensor at the time of installation;

water temperature: average values of water temperature and specific electrical conductivity. It is worth noting that for some sites the averages are merely indicative as they refer to short recording intervals (see Table 1 for installation dates). Specific electrical conductivity is recalculated at 25 °C.

water pump: absence (0) or presence (1) of water pump.

1234



1235

1236 Figure 1

1237

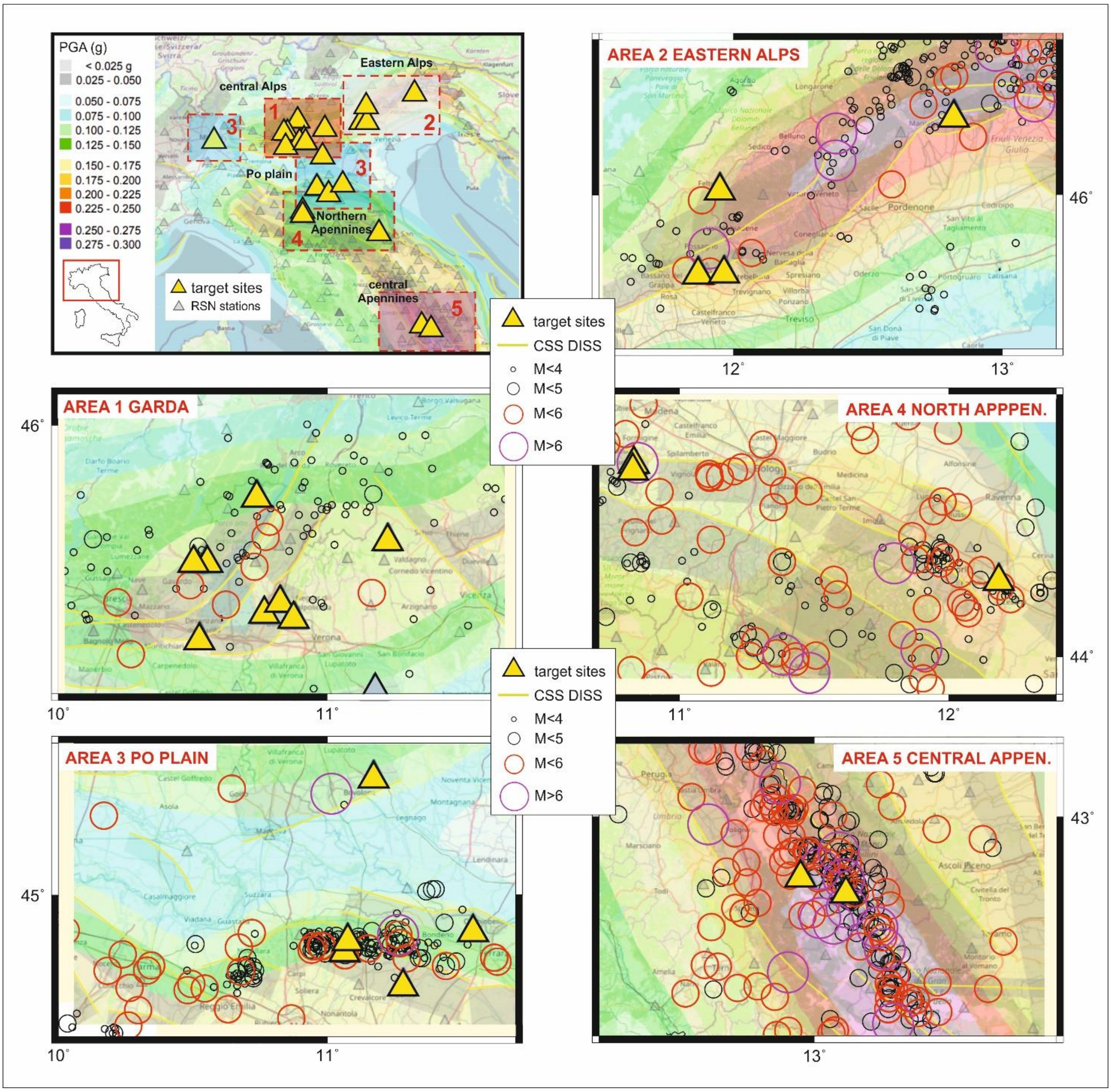

PGA (g)
< 0.025 g
0.025 - 0.050
0.050 - 0.075
0.075 - 0.100
0.100 - 0.125
0.125 - 0.150
0.150 - 0.175
0.175 - 0.200
0.200 - 0.225
0.225 - 0.250
0.250 - 0.275
0.275 - 0.300
central Alps
Eastern Alps
Po plain
Northern Apennines
central Apennines
1
2
3
3
4
5
target sites
RSN stations
AREA 2 EASTERN ALPS
AREA 1 GARDA
AREA 4 NORTH APPPEN.
AREA 3 PO PLAIN
AREA 5 CENTRAL APPEN.
target sites
CSS DISS
M<4
M<5
M<6
M>6
target sites
CSS DISS
M<4
M<5
M<6
M>6
10˚
11˚
12˚
13˚
43˚
44˚
45˚
46˚

Figure 2

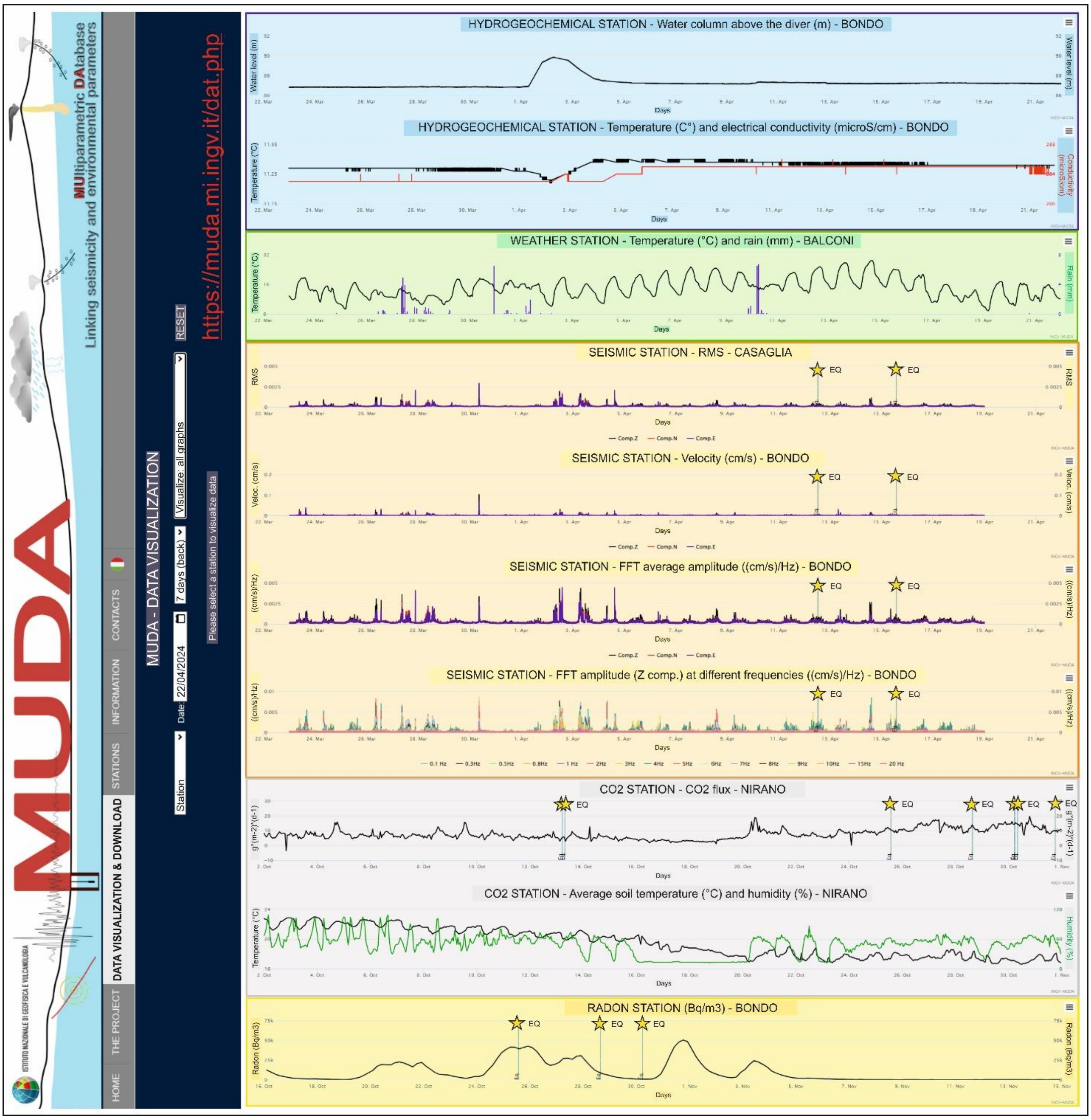

HYDROGEOCHEMICAL STATION - Water column above the diver (m) - BONDO
HYDROGEOCHEMICAL STATION - Temperature (C°) and electrical conductivity (microS/cm) - BONDO
WEATHER STATION - Temperature (°C) and rain (mm) - BALCONI
SEISMIC STATION - RMS - CASAGLIA
SEISMIC STATION - Velocity (cm/s) - BONDO
SEISMIC STATION - FFT average amplitude ((cm/s)/Hz) - BONDO
SEISMIC STATION - FFT amplitude (Z comp.) at different frequencies ((cm/s)/Hz) - BONDO
CO2 STATION - CO2 flux - NIRANO
CO2 STATION - Average soil temperature (°C) and humidity (%) - NIRANO
RADON STATION (Bq/m3) - BONDO
EQ
Days

Figure 3

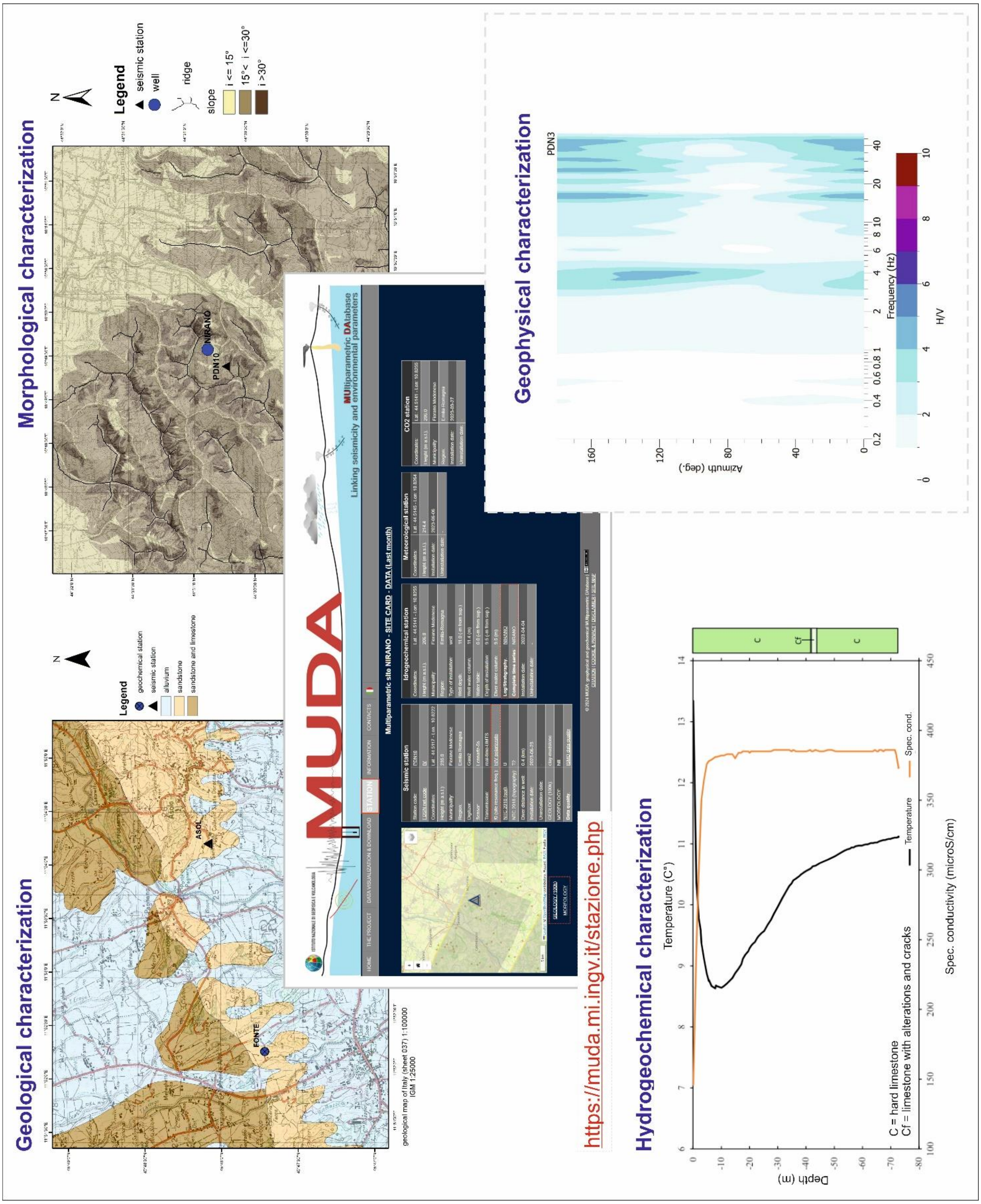
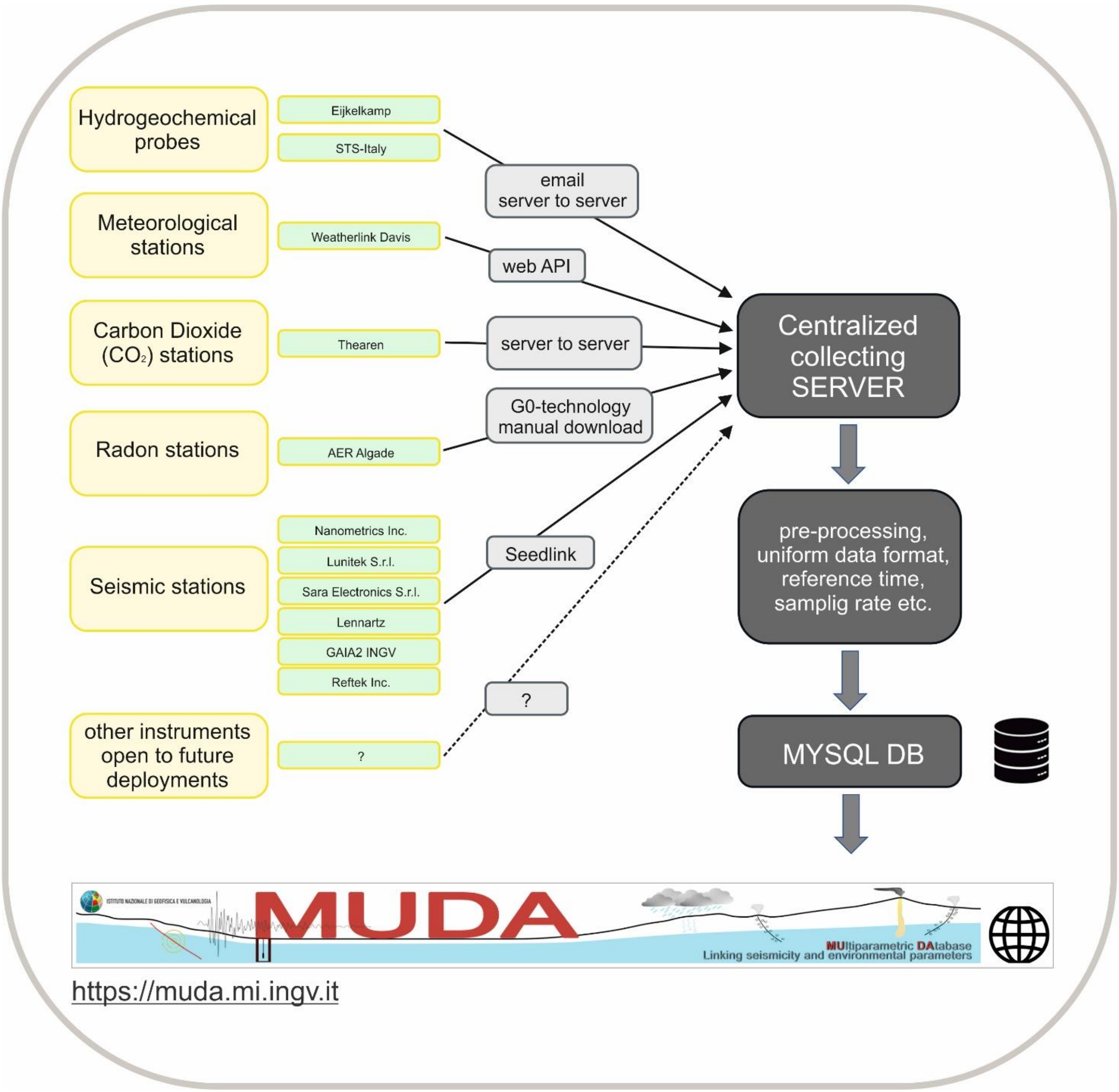

Geological characterization
Morphological characterization
Geophysical characterization
Hydrogeochemical characterization
MUDA
https://muda.mi.ingv.it/stazione.php

Figure 4



Hydrogeochemical probes
Eijkelkamp
STS-Italy
email server to server
Meteorological stations
Weatherlink Davis
web API
Carbon Dioxide (CO_2) stations
Thearen
server to server
Radon stations
AER Algade
G0-technology manual download
Seismic stations
Nanometrics Inc.
Lunitek S.r.l.
Sara Electronics S.r.l.
Lennartz
GAIA2 INGV
Reftek Inc.
Seedlink
?
other instruments open to future deployments
?
Centralized collecting SERVER
pre-processing, uniform data format, reference time, samplig rate etc.
MYSQL DB
MUDA
MUltiparametric DAtabase
Linking seismicity and environmental parameters
https://muda.mi.ingv.it

Figure 5

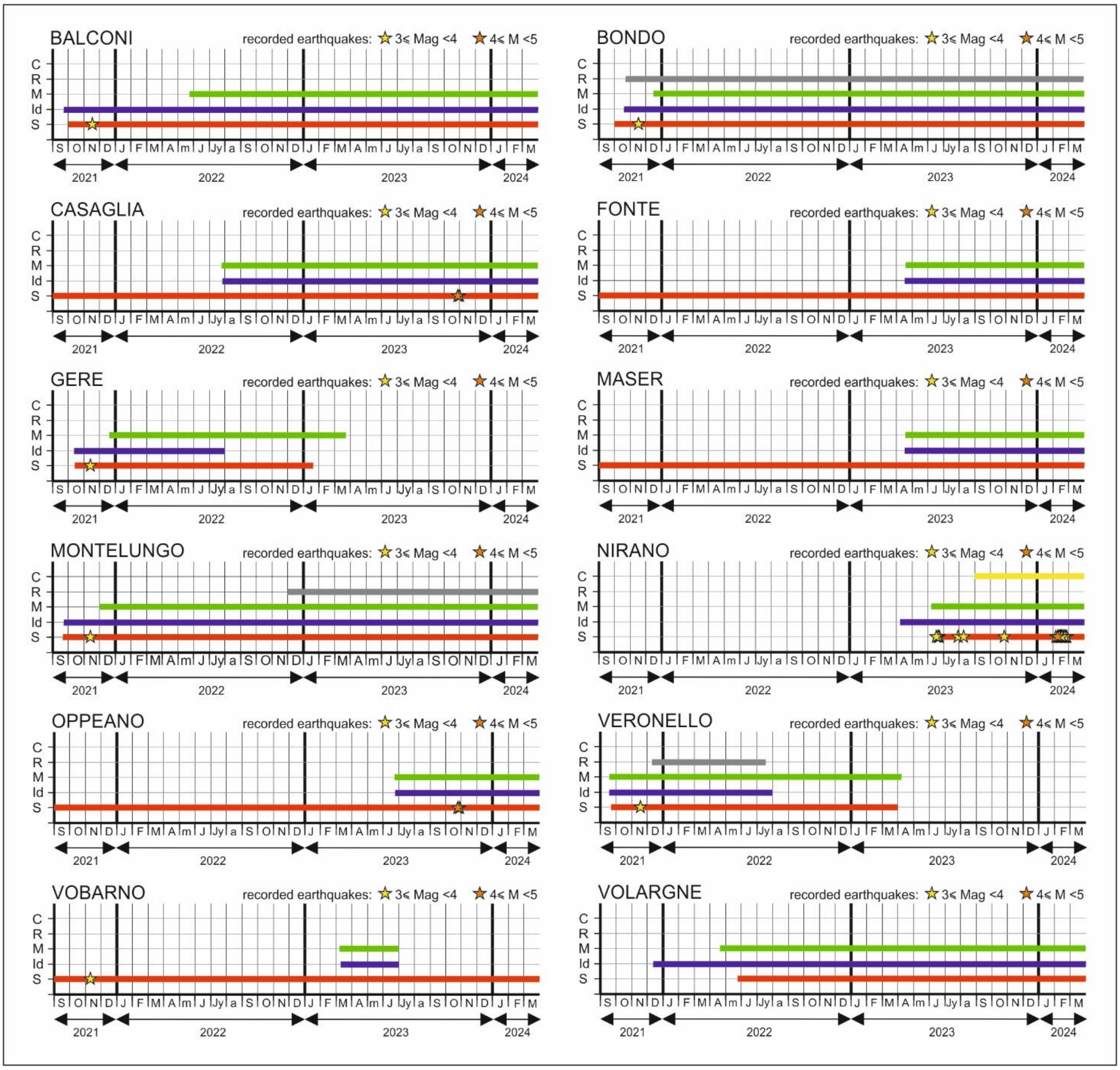
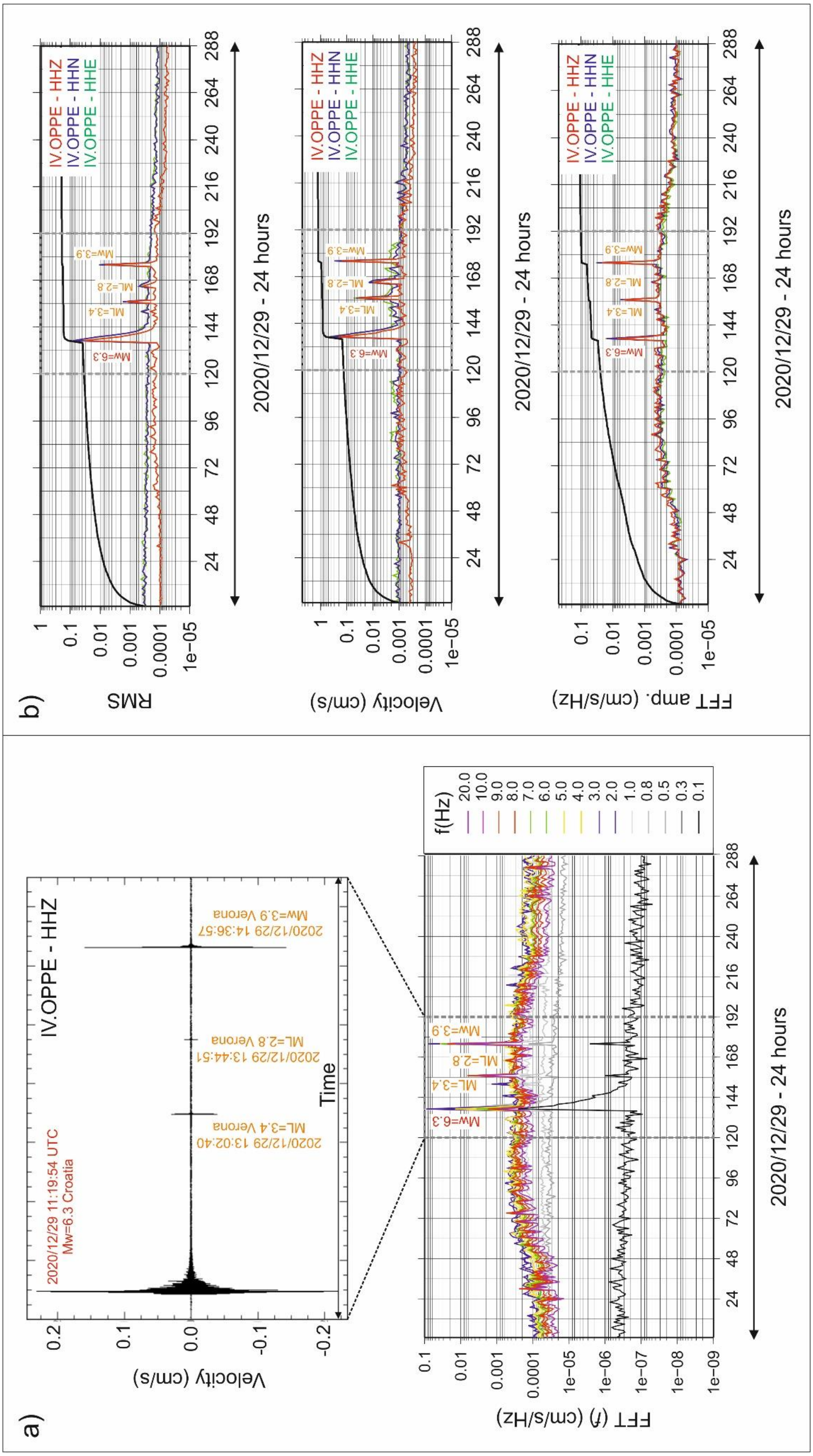
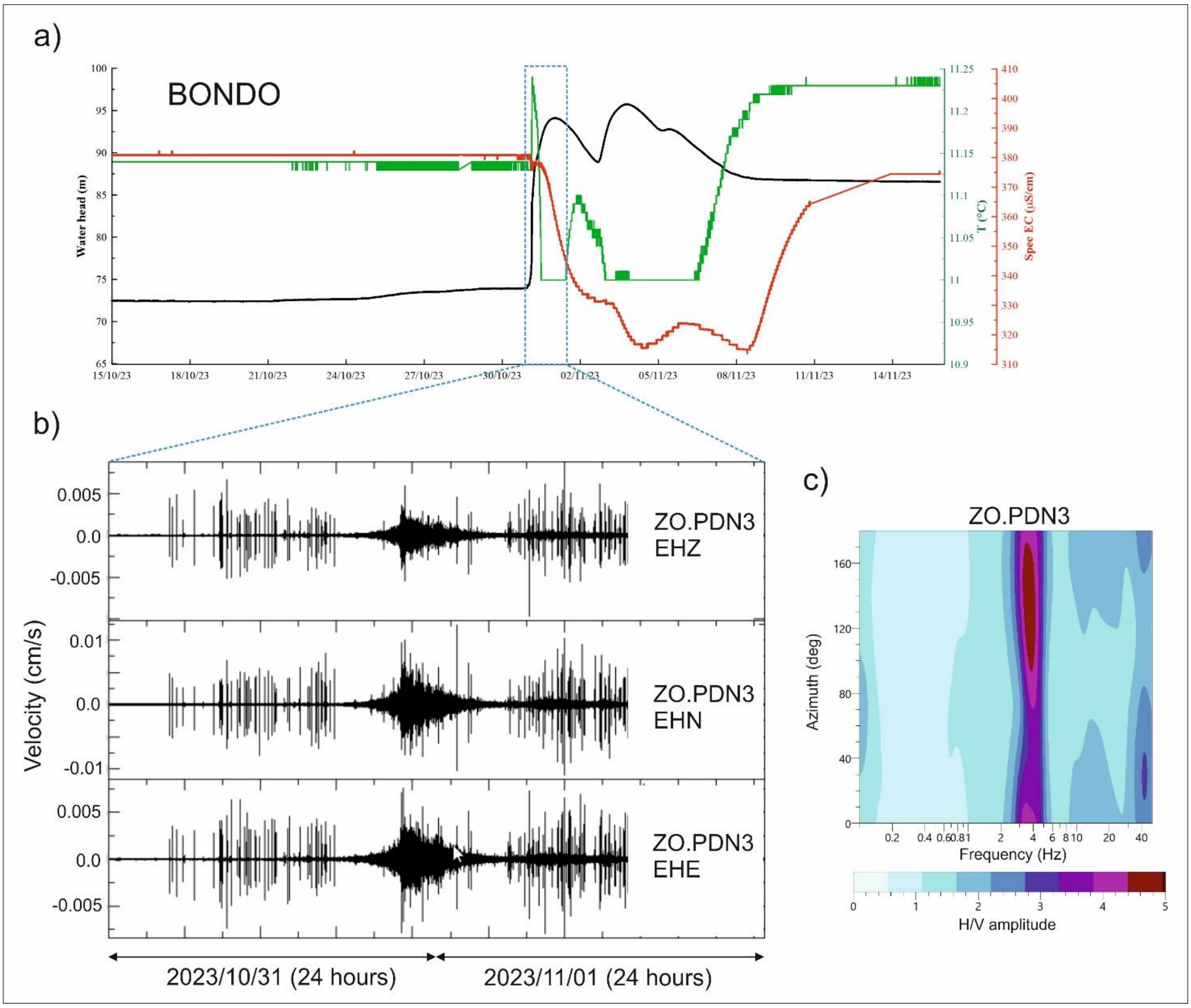

BALCONI
BONDO
CASAGLIA
FONTE
GERE
MASER
MONTELUNGO
NIRANO
OPPEANO
VERONELLO
VOBARNO
VOLARGNE
recorded earthquakes: 3≤ Mag <4 4≤ M <5
C
R
M
Id
S
S O N D J F M A m J Jy a S O N D J F M A m J Jy a S O N D J F M
2021
2022
2023
2024

Figure 6



a)
IV.OPPE - HHZ
2020/12/29 11:19:54 UTC
Mw=6.3 Croatia
2020/12/29 13:02:40
ML=3.4 Verona
2020/12/29 13:44:51
ML=2.8 Verona
2020/12/29 14:36:57
Mw=3.9 Verona
Time
Velocity (cm/s)
FFT (f) (cm/s/Hz)
f(Hz)
2020/12/29 - 24 hours
b)
RMS
Velocity (cm/s)
FFT amp. (cm/s/Hz)
IV.OPPE - HHZ
IV.OPPE - HHN
IV.OPPE - HHE
Mw=6.3
ML=3.4
ML=2.8
Mw=3.9

Figure 7



a)
BONDO
Water head (m)
T (°C)
Spec EC (µS/cm)
15/10/23
18/10/23
21/10/23
24/10/23
27/10/23
30/10/23
02/11/23
05/11/23
08/11/23
11/11/23
14/11/23
b)
Velocity (cm/s)
ZO.PDN3
EHZ
ZO.PDN3
EHN
ZO.PDN3
EHE
2023/10/31 (24 hours)
2023/11/01 (24 hours)
c)
ZO.PDN3
Azimuth (deg)
Frequency (Hz)
H/V amplitude

Figure 8

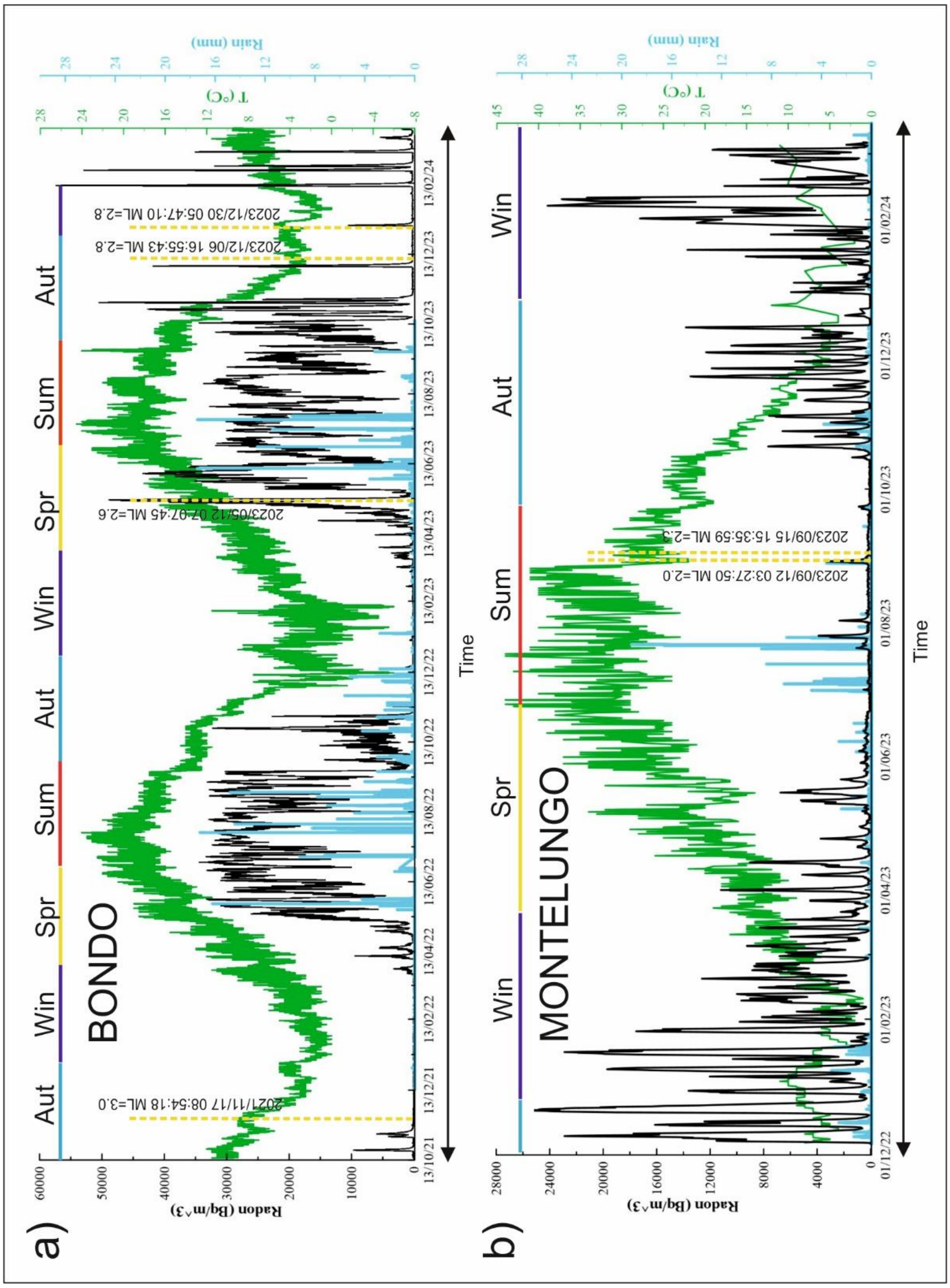

a)
BONDO
Radon (Bq/m^3)
T (°C)
Rain (mm)
Aut
Win
Spr
Sum
Aut
Win
Spr
Sum
Aut
2021/11/17 08:54:18 ML=3.0
2023/05/12 07:07:45 ML=2.6
2023/12/06 16:55:43 ML=2.8
2023/12/30 05:47:10 ML=2.8
Time
b)
MONTELUNGO
Win
Spr
Sum
Aut
Win
2023/09/12 03:27:50 ML=2.0
2023/09/15 15:35:59 ML=2.3
Time

Figure 9

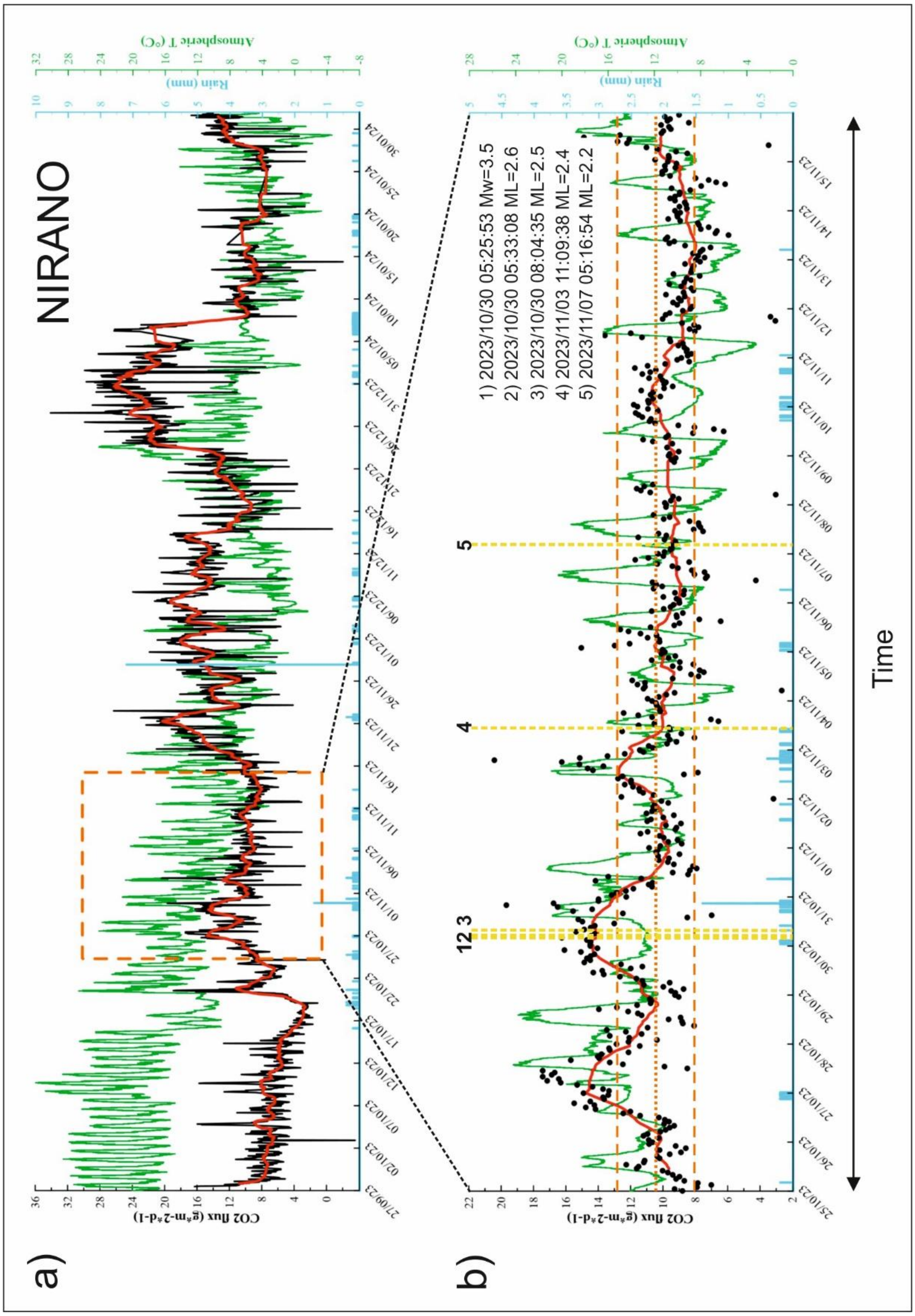

a)
NIRANO
b)
1) 2023/10/30 05:25:53 Mw=3.5
2) 2023/10/30 05:33:08 ML=2.6
3) 2023/10/30 08:04:35 ML=2.5
4) 2023/11/03 11:09:38 ML=2.4
5) 2023/11/07 05:16:54 ML=2.2
Time
CO2 flux (g*m-2*d-1)
Rain (mm)
Atmospheric T (°C)

Figure 10

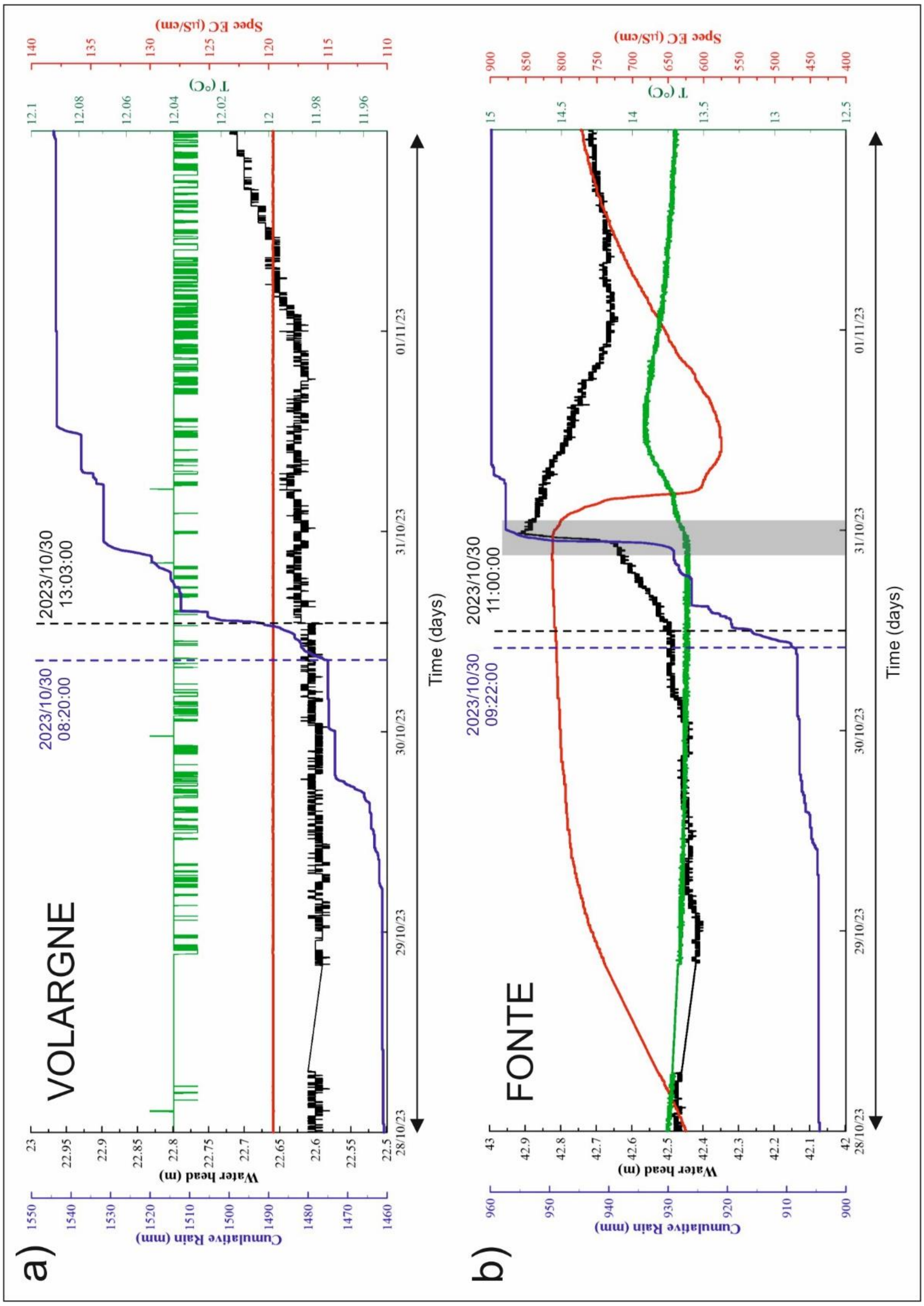

a)
VOLARGNE
2023/10/30
08:20:00
2023/10/30
13:03:00
Time (days)
Cumulative Rain (mm)
Water head (m)
T (°C)
Spec EC (µS/cm)
b)
FONTE
2023/10/30
09:22:00
2023/10/30
11:00:00
Time (days)
Cumulative Rain (mm)
Water head (m)
T (°C)
Spec EC (µS/cm)

Figure 11

Table 1

CODE	Municipality	AREA	LAT [°]	LON [°]	idro-geochemical	weather	seismic	Radon	CO2
BALCONI	Pescantina	1	45.4974	10.8763	start 2021-09-23	start 2022-05-26	start 2021-07-13	/	/
BONDO	Tremosine	1	45.8129	10.7377	start 2021-10-13	start 2021-12-13	start 2021-07-22	start 2021-10-14	/
BULGARELLI	Medolla	3	44.8498	11.0627	start 2024-02-28	start 2024-02-28	start 2012-11-28	/	/
CASAGLIA	Ferrara	3	44.9036	11.5406	start 2022-07-29	start 2022-07-29	start 2013-02-08	/	/
CESENA	Malacoda Forlì	4	44.2031	12.1855	start 2024-02-20	/	start 2003-03-01	/	/
FELTRE	Feltre	2	46.0107	11.9511	start 2024-02-20	/	/	/	/
FONTE	Fonte	2	45.7949	11.8697	start 2023-04-18	start 2023-04-17	start 2011-11-17	/	/
GERE	Gardone Riviera	1	45.6422	10.5484	start 2021-10-12 - end 2022-07-30	start 2021-12-02 - end 2023-03-25	start 2021-10-12 - 2023-01-18	/	/
MASER	Maser	2	45.7969	11.9658	start 2023-04-17	start 2023-04-17	start 2011-11-17	/	/
MEDOLLA	Medolla	3	44.8492	11.0734	start 2024-02-20	start 2024-02-28	start 2012-11-28	/	/
MILANO	Milano	3	45.4972	9.1812	start 2024-03-12	start 2024-03-12	start 2012-01-27	/	/
MIRANDOLA	Mirandola	3	44.8812	11.0782	start 2024-02-23	start 2024-02-23	start 2012-11-28	/	/
MONTELUNGO	Desenzano del Garda	1	45.4429	10.5256	start 2021-09-14	start 2021-11-30	start 2021-07-30	start 2022-12-06	/
NIRANO	Fiorano Modenese	4	44.5141	10.8255	start 2023-04-04	start 2023-06-06	start 2023-06-23	/	start 2023-09-27
NIRANO1	Fiorano Modenese	4	44.5002	10.8163	start 2024-02-20	start 2024-02-20	start 2023-06-23	/	/
NORCIA	Norcia	5	42.7838	13.1201	start 2023-12-11	start 2023-12-11	start 2023-12-04	start 2023-12-11	/
OPPEANO	Oppeano	3	45.3082	11.1723	start 2023-06-29	start 2023-06-21	start 2023-02-16	/	/
RECOARO	Recoaro Terme	1	45.6998	11.2217	start 2024-01-30	start 2024-01-30	/	/	/
RECOARO1	Recoaro Terme	1	45.7005	11.2215	start 2024-01-30	start 2024-01-30	/	/	/
RENAZZO	Renazzo	3	44.7624	11.2836	start 2024-02-20	/	start 2003-10-11	/	/
SECCHIA	Concordia Secchia	3	44.9245	11.0183	start 2024-03-14	start 2024-03-20	start 2012-11-28	/	/
TOPPO	Toppo di Travesio	2	46.1985	12.8171	start 2024-02-25	/	/	/	/
TRIPONZO	Triponzo	5	42.8400	12.9480	start 2023-12-12	start 2023-12-12	start 2023-12-04	start 2023-12-12	/
VERONELLO	Bardolino	1	45.5098	10.7645	start 2021-09-14 - end 2022-08-01	start 2021-10-19 - end 2023-04-07	start 2021-07-08 - end 2023-04-07	start 2021-12-17 - end 2022-07-08	/
VOBARNO	Vobarno	1	45.6428	10.5035	start 2023-03-10 - end 2023-06-21	start 2023-03-10 - end 2023-06-21	start 2021-07-08	/	/
VOLARGNE	Dolcè	1	45.5397	10.8235	start 2021-12-16	start 2022-05-20	start 2022-04-12	/	/

CODE	AREA	Geology (100k)	Topography	SITE TYPE	WELL DEPTH (m)	WATER LEVEL (m)	WATER COLUMN (m)	WATER TEMPERATURE (°C)	WATER SPECIFIC EC (μS/cm)	WATER PUMP	SEISMIC NET	SEISMIC CODE	RECORDER	SENSOR
BALCONI	1	fluvio-glacial deposits	plain	well	100	53.3	46.7	14.1	873	1	ZO	PDN2	Lunitek ATLAS	TELLUS-5s
BONDO	1	alluvial deposits	valley	well	180	44	136	11.1	377	0	ZO	PDN3	Reftek-130	LENNARTZ-5s
BULGARELLI	3	alluvial deposits	plain	well	8	1.5	6.5	14.5	2639	1	IV	CAVE	GAIA2	TRILLIUM-120s
CASAGLIA	3	alluvial deposits	plain	well	130	3.5	126.5	17.2	3616	0	IV	FERS	GAIA2	TELLUS-5s
CESENA	4	alluvial deposits	plain	well	8.3	3.1	5.2	16.0	1338	0	IV	BRSN	GAIA2	LENNARTZ-1s
FELTRE	2	limestone	relief	spring	/	/	/	13.4	488	0	/	/	/	/
FONTE	2	sandstone	relief	well	120	7.7	112.3	13.5	840	0	IV	ASOL	Lunitek ATLAS	TELLUS-5s
GERE	1	fluvio-glacial deposits	valley	well	60	31.3	28.7	10.3	406	1	ZO	PDN6	Lunitek ATLAS	TELLUS-5s
MASER	2	sandstone	relief	well	157	71.3	85.7	13.2	511	0	IV	ASOL	Lunitek ATLAS	TELLUS-5s
MEDOLLA	3	alluvial deposits	plain	well	50	3	47	15.3	5190	0	IV	CAVE	GAIA2	TRILLIUM-120s
MILANO	3	alluvial deposits	plain	well	152	18	135	14.0	250	0	IV	MILN	GAIA2	TRILLIUM-40s
MIRANDOLA	3	alluvial deposits	plain	well	300	5.4	294.6	17.2	87864	1	IV	CAVE	GAIA2	TRILLIUM-120s
MONTELUNGO	1	morainic deposits	hill	well	150	52.8	97.2	15.3	885	0	ZO	PDN4	Reftek-130	LENNARTZ-5s
NIRANO	4	mudstone	hill	mudhole	11	0	11	16.2	12024	0	ZO	PDN10	GAIA2	LENNARTZ-5s
NIRANO1	4	mudstone	hill	mudhole	11	0	11	14.8	2873	0	ZO	PDN10	GAIA2	LENNARTZ-5s
NORCIA	5	alluvial deposits	valley	well	64	30	34	12.0	535	1	ZO	PDN11	Reftek-130	LENNARTZ-5s
OPPEANO	3	alluvial deposits	plain	well	60	4.6	55.4	13.9	607	0	ZO	PDN9	SARA-SL06	SARA-SS08-120s
RECOARO	1	sandstone	relief	spring	/	/	/	11.4	2148	0	ZO	PDN13	Lunitek ATLAS	TELLUS-5s
RECOARO1	1	sandstone	relief	spring	/	/	/	11.3	3724	0	ZO	PDN13	Lunitek ATLAS	TELLUS-5s
RENAZZO	3	alluvial deposits	plain	well	6	1.5	4.5	17.4	1193	0	IV	RAVA	GAIA2	LENNARTZ-5s
SECCHIA	3	alluvial deposits	plain	mudhole	1	0	1	17.5	2343	0	IV	CAVE	GAIA2	TRILLIUM-120s
TOPPO	2	alluvial deposits	valley	well	300	114	186	12.7	591	0	/	/	/	/
TRIPONZO	5	limestone	crest	well	53	3.1	49.9	29.7	2487	1	ZO	PDN12	Reftek-130	LENNARTZ-5s
VERONELLO	1	fluvio-glacial deposits	hill	well	198	90	108	14.0	703	0	ZO	PDN1	Lunitek ATLAS	TELLUS-5s
VOBARNO	1	alluvial deposits	valley	well	36	11.2	24.8	13.3	240	0	IV	VOBA	Lunitek ATLAS	TELLUS-5s
VOLARGNE	1	fluvio-glacial deposits	valley	well	99	50	49	12.0	129	0	ZO	PDN8	Reftek-130	LENNARTZ-5s

Table 2