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# Geophysical exploration case histories at the PITOP geophysical test site - A key facility in the ECCSEL-ERIC consortium: an overview

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***ABSTRACT*** PITOP is a geophysical test site, owned by OGS, located in Italy, designed and developed with the objective of providing a facility for the testing of drilling technologies, measurements, and diagnostics during drilling, geophysical methods while drilling, new technologies and borehole/surface tools under realistic conditions. Initially, four wells were available: of which two equipped with borehole sensors, with the possibility of drilling two additional wells to perform while-drilling experiments. Thanks to the PNRR funding, a new well, instrumented for geoelectrical surveys, was drilled in 2024. A new office/laboratory, built with eco-friendly materials, has improved the attractiveness of the site, where permanent laboratories already exist. Auxiliary borehole/surface seismic sources and sensors are available. Due to its characteristics, PITOP represents a unique scientific test site. PITOP is part of the European Research Infrastructure for Carbon Dioxide Capture, Utilisation, Transport and Storage and represents a resource that is available to the scientific and industrial community on request. The objective of this work is to provide a description of the infrastructure and an overview of the experiments already performed to broaden the range of potential stakeholders to promote research and technology development in the drilling/geophysics field, as well as to boost carbon dioxide capture and storage applications, including monitoring, for climate change mitigation purposes.

**Key words:** ECSSEL-ERIC, geophysical exploration, borehole and surface geophysics, DAS, instrumented wells, geoelectrical surveys, seismic surveys.

## 1. Introduction

The OGS test site for geophysical-drilling, PITOP (Fig. 1), located in the municipality of Travesio, province of Pordenone (north-eastern Italy), covers an area of approximately 22,000 m$^2$ and was set up with the purpose of providing a framework facility for studying and testing geophysical methods, new technologies and borehole/surface tools under realistic conditions. In the early 2000s, before the development of this site, testing well instrumentation under realistic conditions was almost impossible in the European scenario. PITOP filled this fundamental gap and, to date, represents a unique scientific test site in Italy. Permanent laboratories equipped with instrumentation for geophysical data recording, real time processing, and signal conditioning are present at the site. Auxiliary seismic sources and sensors are available both on the surface and downhole. OGS currently operates in this borehole facility for special testing of instrumentation and methodologies, also in cooperation with European research institutes and/

or industries in the framework of specific projects. The site is part of the European Research Infrastructure for Carbon Dioxide Capture, Utilisation, Transport and Storage (ECCSEL). ECCSEL, established as a European Research Infrastructure Consortium (ERIC) in June 2017, is the European Research Infrastructure for $CO_2$ Capture, Utilisation, Transport and Storage (CCUS). Its vision is to enable low to zero $CO_2$ emissions from industry and power generation to combat climate changes, enhancing European science, technology development, innovation, and education in the field of CCUS. Five countries are now part of ECCSEL (France, Italy, Norway, the Netherlands, and the United Kingdom), whose commitment is to continuously expand with new partners and research facilities. ECCSEL offers open access to over 100 world class CCUS research facilities across Europe and the PITOP site is part of the network (https://www.eccsel.org/catalogue/126).

In this work, the tools for geophysical exploration testing available at the PITOP site are presented, starting from the already drilled wells, and are followed by the description of the structural and geological setting of the site and well stratigraphy results derived from the detailed analysis of both cuttings and core sampled during drilling. Moreover, we present an overview of the most significant experiments and tests among the several ones hosted by PITOP over the years, both for theoretical and methodological studies and for instrument and prototype testing.

## 2. Wells and facilities

Fig. 1 shows the geographic location of the PITOP geophysical test site, details of the yard (Fig. 1a), and a picture (Fig. 1b) taken by the OGS drone. Fig. 1b is the three dimensional (3D) mesh generated by the photographic survey with the DJI Matrice 210 v2 drone and DJI X5S camera. The mesh was generated from the dense point cloud, extracted from the aerial images.

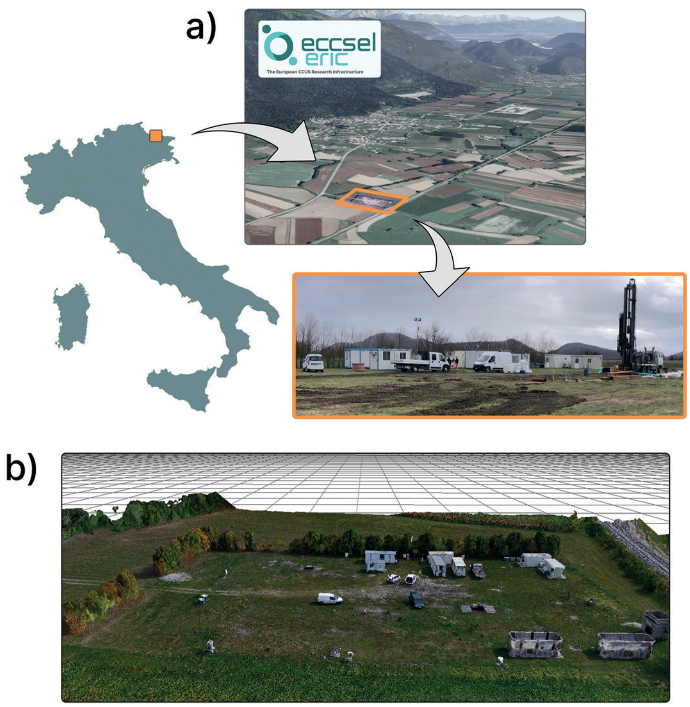



Fig. 1 - The PITOP geographic location and details of the yard (a) and a picture taken by the OGS drone (b).

Four wells, schematised in Fig. 2a, were drilled at the test site. PITOP1 is a 280-metre deep water well for Civil Protection purposes and Table 1 collects the positions of the water filters. Two additional wells, namely PITOP2 (drilled by OGS in 2004, equipped with 30 triaxial geophones at a depth of about 385 m) and PITOP3 (drilled by ENI in 2006 at a depth of about 423 m) were drilled as part of the geosteering project in which ENI and OGS were project partners. Geosteering used to drive the well path into the reservoir is one of the key road-ahead topics of the while-drilling measurements using different technologies. The study at the PITOP site focused on acoustic geosteering technology. For a description of the geosteering methods see Poletto and Miranda (2022). A fourth well (PITOP4) was drilled in 2014 and equipped with a string of optical fibre sensors [distributed acoustic sensing (DAS)] and a high-sensitivity seismometer at a depth of 150 m. In 2024, thanks to the PNRR (National Recovery and Resilience Plan) funding, the site was strengthened by drilling a new well (PITOP5, located SE from the PITOP1 well), which has been instrumented with electrodes for geoelectrical surveys, to be used with a new electric FullWaver for resistivity, induced polarisation, and self-potential measurements. Moreover, two fibre optic cables and an interrogator will improve the operational capacities of the site, as well as mobile equipment. Fig. 2b shows a top view of the site, the location of the wells, and their spacing.

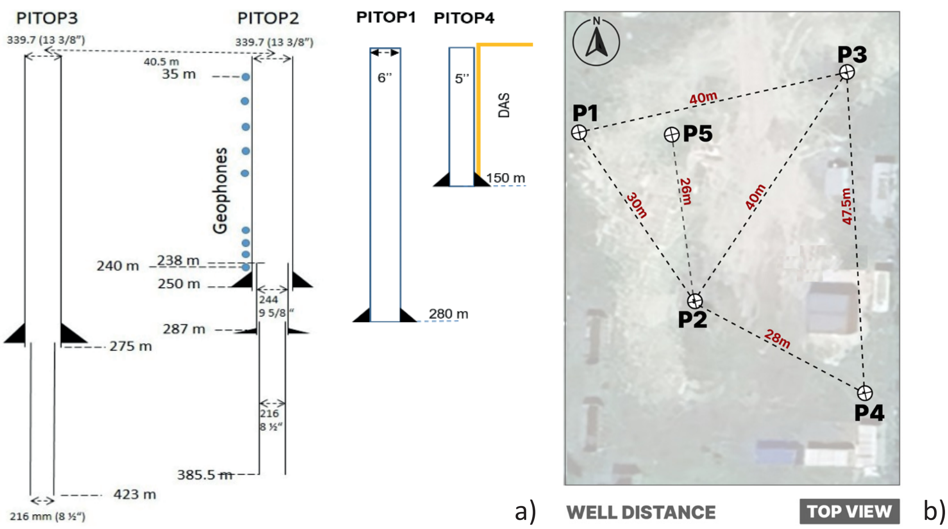



Fig. 2 - Scheme of the four wells at the PITOP site and of the facilities available in terms of geophones and DAS installed in the PITOP2 and in PITOP4 wells, respectively (a) and top view of the site, including the new PITOP5 well, and distances between the wells (b).

Table 1 - Water filters in PITOP1 (after Benedetti S.n.c.).

| PITOP1 filters | | |
|---|---|---|
| **Description** | **Start depth (m)** | **Stop depth (m)** |
| Filter 1 | 157.60 | 169.60 |
| Filter 2 | 181.60 | 193.60 |
| Filter 3 | 205.60 | 223.60 |
| Filter 4 | 235.60 | 253.60 |
| Filter 5 | 283.85 | 289.85 |

Several facilities and tools are available at the test site: two cabins for acquisition and processing (Fig. 3), two water deposits, parking space, night lighting. In 2024, thanks to the PNRR funding (ECCSELLENT Project), a new office housing built with cutting-edge sustainable materials improved the existing logistics.

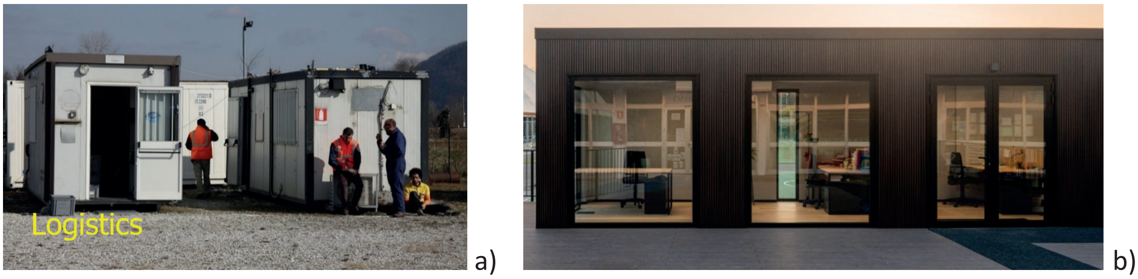



Fig. 3 - Current laboratories (a) and the permanent office installed in 2024 (b).

The sensor installations available at the site are described hereafter:

- PITOP2 and PITOP4 are instrumented with geophones and optical fibre cables for DAS measurements, respectively (Fig. 2a);
- a ground force station with four load cells and three accelerometers (Figs. 4a and 4b);
- a cross of two lines of recording sensors, geophones (yellow dots) and DAS (green lines), are buried in shallow trenches (Fig. 4a);
- a Davis Vantage Vue weather station for real-time weather information (temperature, humidity, barometric pressure, wind speed and direction, rainfall, dew point, wind chill, forecast, and moon phase).

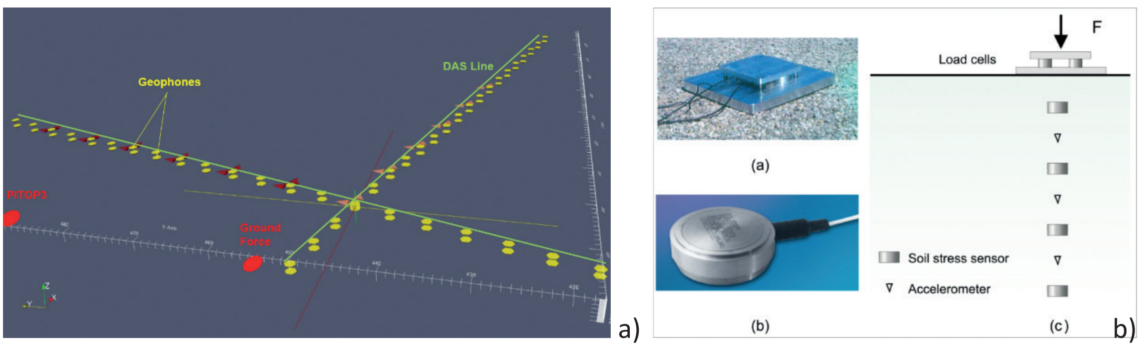



Fig. 4 - PITOP installations: a) external test line: geophones (yellow), DAS line (green), and ground force installation (red dot); b) details of the ground force installation (load cells, soil stress sensors, and accelerometers).

In 2021, in collaboration with the University of Ferrara, INGV, ENEA, and NUVAP, the site hosted an experiment including a chamber for gas (e.g. $CO_2$, radon, etc.) measurements, located in well PITOP3.

To investigate soil-structure interaction for civil engineering purposes, a full-scale prototype structure [EuroMASS: Sklodowska *et al.* (2024)] was erected in the north-western section of the PITOP test site. The structure comprises a shallow square concrete foundation (2×2 $m^2$, 0.3 m deep) supporting a hollow steel column with quadratic profiles (250×250 $mm^2$, 10 mm deep), topped by a similar concrete slab (2×2 $m^2$, 0.5 m deep). Standing at a total height of 2.5 m and with dimensions of 2×2 $m^2$, its symmetrical design ensures uniform bending stiffness in both orthogonal directions. Notably, the higher mass of the top slab (approximately 5 t) compared to the bottom (approximately 3 t) shifts the system's centre of gravity closer to the top, resembling the structural behaviour of a single-degree-of-freedom system (Skłodowska *et al.*, 2024). The structure exhibits a fundamental frequency of 5.0 Hz, determined using SAP2000 software (www.csiamerica.com/products/sap2000).

## 3. Geological overview

Piana di Toppo is an alluvial plain located between the Eastern Southalpine Chain (ESC) and the High Friulian Plain. More in detail, it is bordered to the north by the Mesozoic carbonatic sequence of Mount Ciaurlec and to the south by the Quaternary alluvial fan and Neogenic reliefs of Sequals.

The ESC is one of the most seismically active zones of the central Mediterranean region. In particular, the Friuli area is characterised by a considerable number of instrumental and historical $M>6$ earthquakes, as shown by the red dots in Fig. 5 (Marchesini *et al.*, 2021). In the same figure, the main seismogenic sources for earthquakes greater than $M>5.5$ are also reported, as indicated in the Database of Individual Seismogenic Sources version 3 [DISS3: DISS Working Group (2021)].

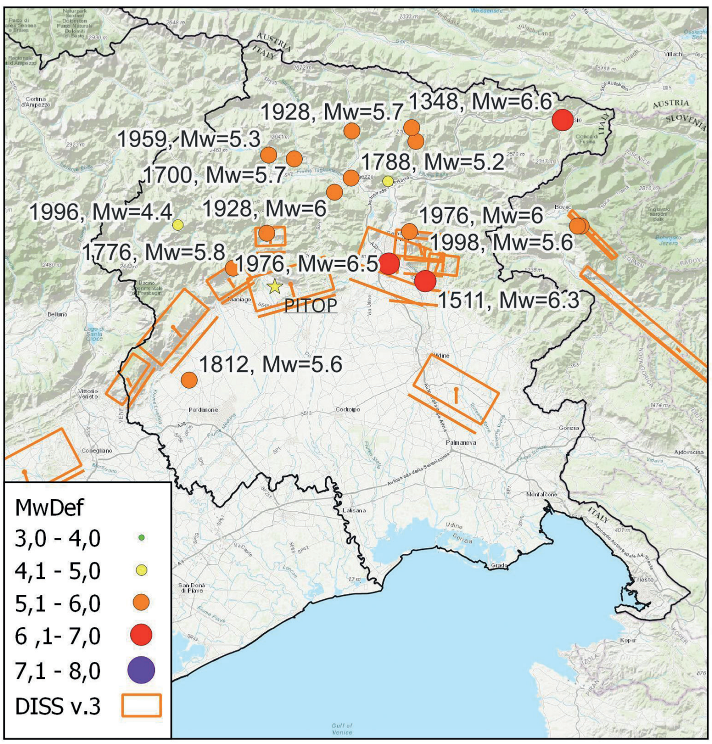



Fig. 5 - Epicentral location of the main historical and instrumental seismic events in Friuli-Venezia Giulia modified after Marchesini *et al.* (2021) and seismogenic sources from the DISS3 database in orange rectangles (DISS Working Group, 2021).

Historically, the area of Piana di Toppo suffered the strong $M$ = 5.8 earthquake of 7 October 1776, generated by the Maniago source, and the $M$ = 5.96 earthquake of 7 June 1794 generated by the Tramonti source.

From a structural point of view, the PITOP area is characterised by a system of thrusts as shown in Fig. 6, the northern part is delimited by the Mount Jouf and Maniago thrusts, while the southern part is interested by a series of subparallel thrusts, Solimbergo, Travesio, Sequals, Pinzano, and Arba-Ragogna, caused by the neo-Alpine tectonic movements, which continued until the Quaternary. Furthermore, the north-eastern side of the PITOP site is delimited by the Mount Ciaurlec fault.

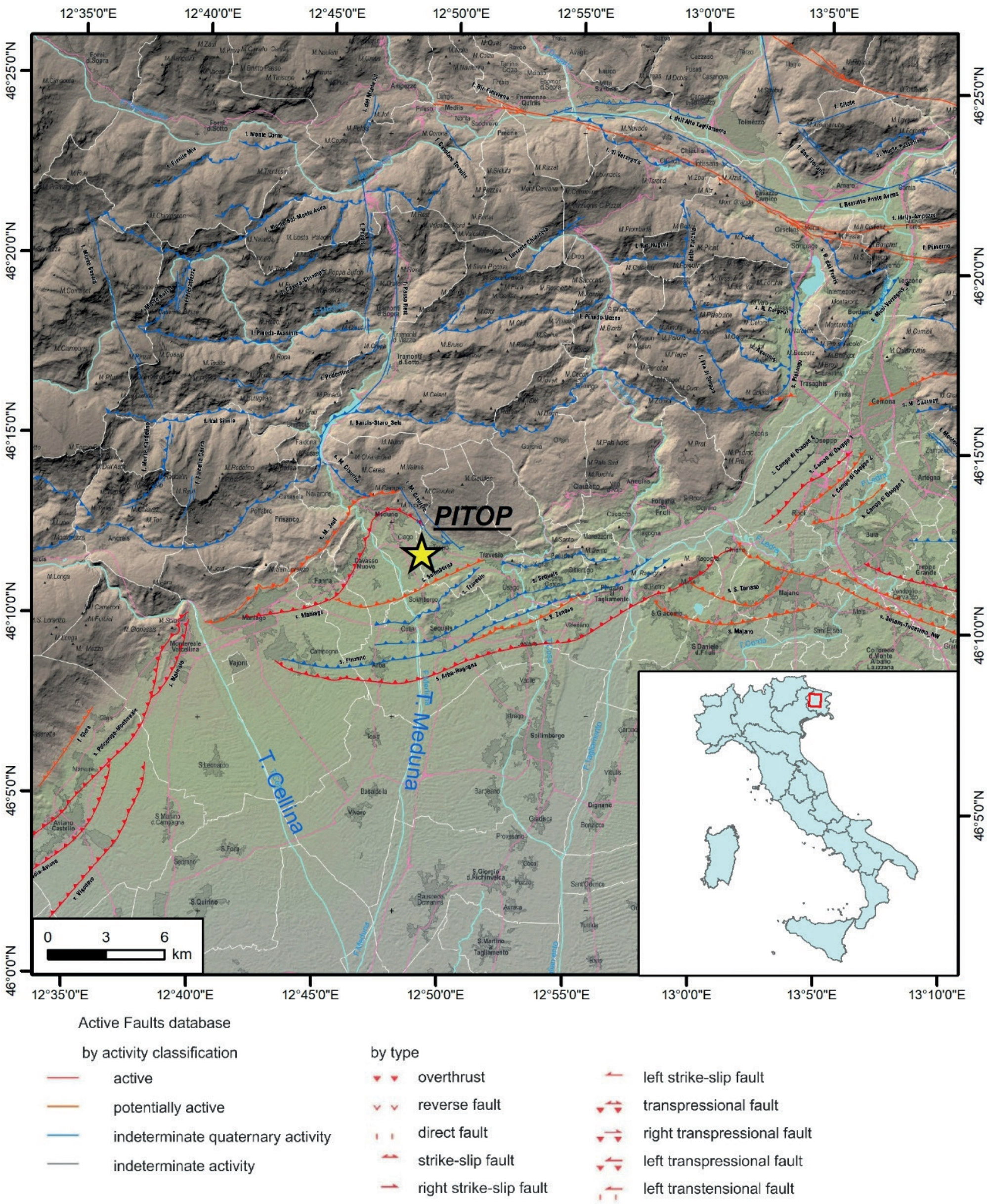



Fig. 6 - Structural map of the PITOP area (modified after Marchesini *et al.*, 2021).

## 4. Well stratigraphy

The detailed analysis of both cuttings and core, sampled during drilling, enables reconstructing the stratigraphy of the site. The PITOP2 well has the greatest and most complete data of the site, acquired during $12^{1/4''}$ and $8^{1/2''}$ phases (from 42 to 282 m and from 282 to 385.5 m, respectively). During the drilling of the PITOP2 well, Baker Hughes Inteq, a mudlogging company, sampled cuttings from depths ranging from 44 to 385.5 m, which provided a detailed lithological description (masterlog). Gravels and lightly cemented conglomerates with limestone and dolomitic clasts are alternated to soft and plastic brown ocher clay until the first 180 m. The same lithologies, but with a greater cementation of the conglomerates and different coloured (beige-brown-grey) clay that is silty at times, are found up to the bottom of the well.

Furthermore, Schlumberger Limited acquired several electric logs in the PITOP2 well after both phases ($12^{1/4''}$ and $8^{1/2''}$) and in the PITOP3 well only after the $8^{1/2''}$ phase. The recorded well logs are listed in Table 2.

Table 2 - Well logs performed in wells PITOP2 and PITOP3 [dipole shear imaging (DSI), gamma ray (GR), environment measurement sonde (EMS) ultra sonic imager tool (USIT), cement bond logging tool (CBL)].

| Well | Run | Logs | Interval (m) |
|---|---|---|---|
| PITOP2 | 1 | DSI – GR - EMS | 246.0 - 41.5 |
| PITOP2 | 2 | DSI – GR - EMS | 387.5 - 250.0 |
| PITOP2 | 3 | USIT - CBL | 250.0 - 41.0 |
| PITOP2 | 4 | Gyro survey | 387.5 - 0.0 |
| PITOP3 | 1 | DSI – GR - EMS | 426.0 - 97.6 |
| PITOP3 | 2 | DSI – GR - EMS | 333.0 - 253.7 |

The analysis of the data (master log and electric logs) acquired in the wells at the PITOP site, together with the 1:150,000 geological map (Carulli, 2006), enables highlighting the Quaternary alluvial sediments (gravels and clays) and Upper Miocene Montello conglomerate.

The Montello conglomerate, approximately 900-metres thick, is mainly characterised by polygenic and heterometric conglomerates with carbonate clasts and subordinate siltstones and sandstones, initially marine and, then, continental (Carulli, 2006).

In particular, at the PITOP site, only the upper member of the Montello conglomerate is in layers several metres thick. It is characterised by limestone and dolomitic clasts and intercalations of beige-brown-grey clays, at times silty. The clasts are sub-rounded to sub-angular, centimetre to decimetre in size, and sometimes well cemented with calcareous cement.

The interface between the Quaternary sediments and Neogenic formations is not well identified in Piana di Toppo, due to lack of biostratigraphic analysis.

Fig. 7 shows the stratigraphic correlation between the three wells, PITOP1 (P1), PITOP2 (P2), and PITOP3 (P3). For the PITOP1 well, the stratigraphy is based on the lithological description provided by the drilling company in agreement with the Regional Directorate of Civil Protection (Giorgi and Pinna, 2005).

The layers are mainly sub-horizontal but with a certain inclination from 275 m to the bottom of the wells that results from the interpretation of the PITOP2 and PITOP3 electric logs. The different thickness of the conglomerate layers reflects the continental depositional environment characterised by the terrigenous sedimentation within an alluvial fan or plain linked to the Meduna and Cellina Streams.

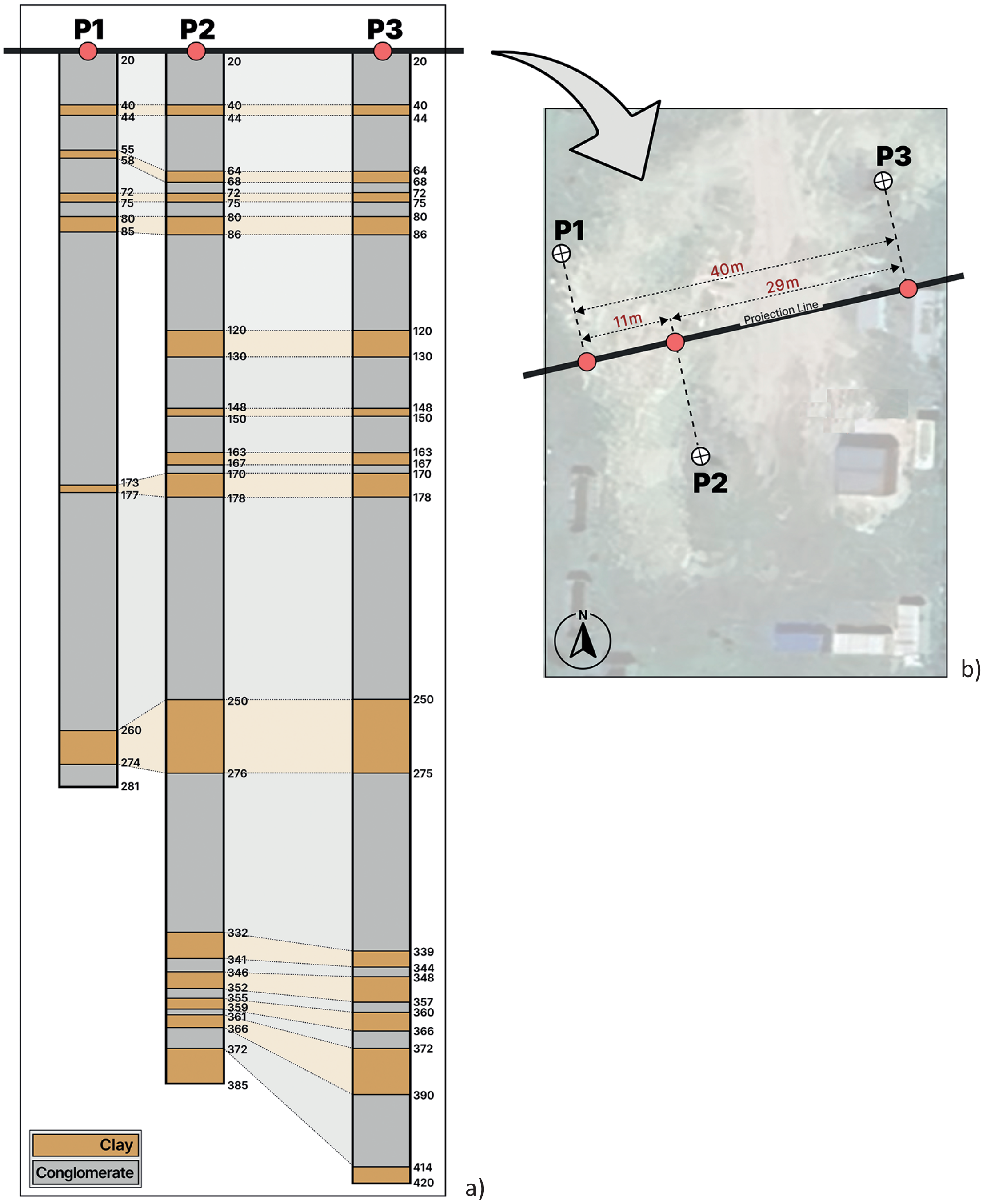



Fig. 7 - a) Stratigraphic correlation between the PITOP1 (P1), PITOP2 (P2) and PITOP3 (P3) wells at the PITOP site. The ocher colour denotes clay and grey denotes conglomerate. b) Top view of the site where the distances between the wells are projected on an arbitrary line that is parallel to the segment from P1 to P3.

## 5. Methods and results of the scientific experiments at the PITOP site

Over the years, the scientific PITOP test site hosted several tests and experiments, both for theoretical and methodological studies and for instrument and prototype tests. In the following paragraphs, only a brief description of the main experiments is provided. For further details about the tests, reference should be made to the specific references cited in the text. The aim is to illustrate the variety of experiments that can be carried out at the site (e.g. by using test drilling and geophysical technologies, methodologies, and instruments) and to highlight the opportunity to design and carry out innovative experiments in an equipped facility with scientific and technical staff support.

To provide a comprehensive view, Fig. 8 summarises the main instrumental installations at the PITOP site. Fig. 8a shows a top view of the site and the location of the wells and instrumentation, while Fig. 8b provides a 3D image of the wells, their depth, and the borehole tools inside the wells.

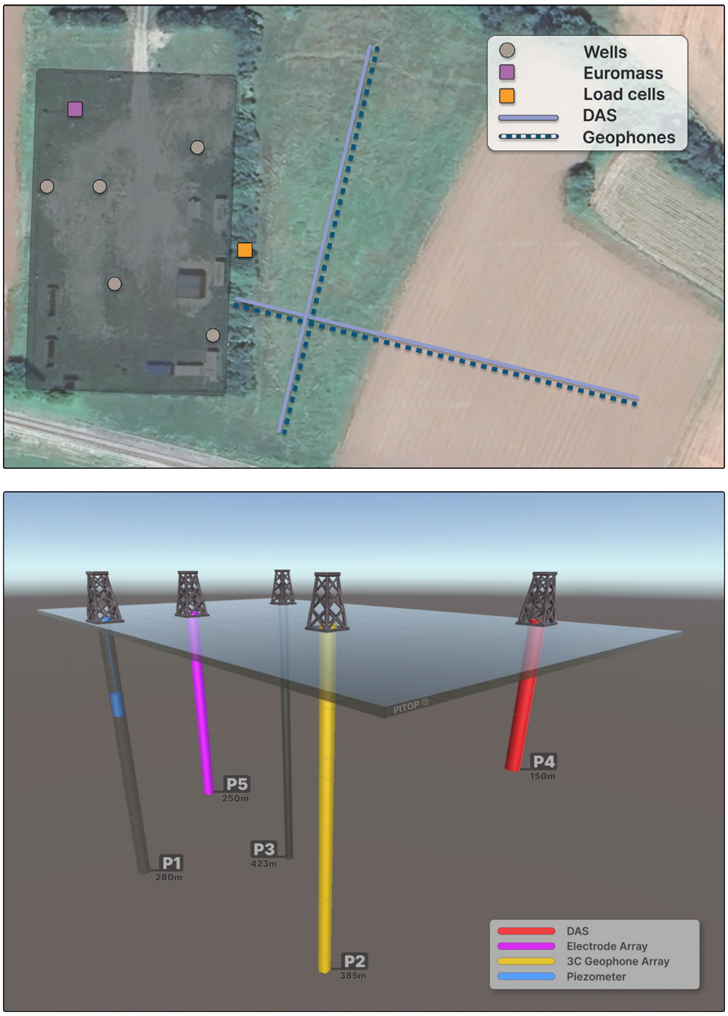



Fig. 8 - Top view of the site with the location of the wells and instrument (a) and a 3D image (b) of the wells, their depth, and borehole instrument.

## *5.1. Drill-bit seismic monitoring while drilling*

This seismic while-drilling (SWD) crosswell experiment was performed during the drilling of the PITOP3 well (well 2 in Fig. 9), using the drill bit as a seismic source and a three-component (3C) geophone array installed in the nearby PITOP2 well (well 1 in Fig. 9) (Poletto *et al.*, 2014b). The experiment aimed at testing drill pipes equipped with a wired-pipe communication system from the bottom hole to the surface as an instrument to improve SWD monitoring. In fact, SWD is based on the recording of reference (pilot) signals, which enable to recognise and process the signal from the downhole drill-bit source, thus obtaining impulsive seismograms after the cross-correlation and deconvolution of the pilot signals and the seismic data recorded by surface or crosswell geophones. An issue in the application of this methodology is the loss of the transmitted energy for the reference signal propagating from the bit to the surface through the drill string, when the pilot signals are recorded at the surface (at the top of the drill string). A solution to improve the drill-bit SWD method is to record the reference signal in proximity of the bit source, using downhole near-bit tools to obtain good-quality measurements of the pilot signal. In the reported crosswell SWD test, a downhole tool with wired-pipes, for high-rate communication from bottom hole to the surface, was used under realistic and controlled conditions. The downhole recording tool was equipped with axial and torsional vibration and pilot sensors for the downhole characterisation of the drilling process (Poletto *et al.*, 2004; Poletto and Bellezza, 2006). The results demonstrated the applicability of this integrated approach as a standard procedure, and pointed out the advantage of providing real-time synchronised reverse vertical seismic profiles, as well as high-resolution and good-quality data in terms of signal-to-noise ratio (S/N) and high-frequency content. The method improved the use of the working drill bit as a downhole seismic source with different types of bits and drilling (Poletto *et al.*, 2003, 2014b).

A vertical seismic profile (VSP) was acquired after the drilling phase, using a surface vibrator as source (Fig. 9) and the 3C geophones installed in the PITOP2 well as recording sensors. Fig. 10 shows a comparison between the borehole signals recorded using the drill-bit source (Fig. 10a) and the surface vibrator source (Fig. 10b).

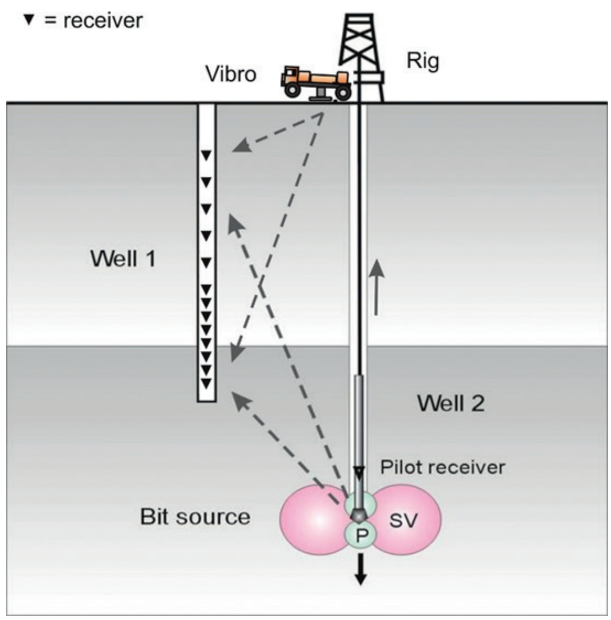



Fig. 9 - Geometry of the SWD crosswell and VSP surveys. This geometry was also used for the comparison of wave fields from drill-bit and surface vibrator sources (not to scale) (Poletto *et al.*, 2014b).

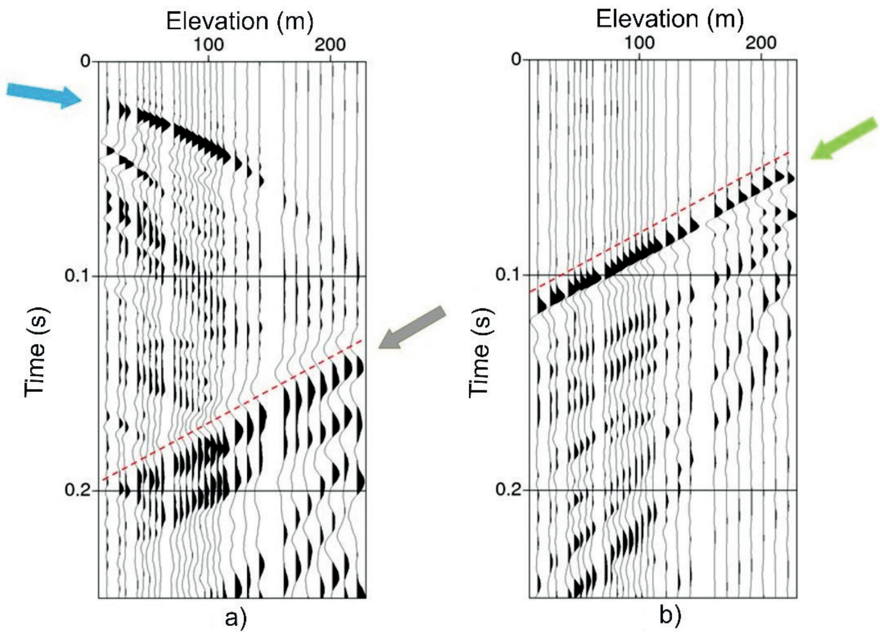



Fig. 10 - Comparison between the borehole signal of the casing geophone array (vertical Z component) obtained using the drill-bit source at 284 m of depth (a) and that obtained using a surface-vibrator seismic source offset 35 m from the receiver well (b), as sketched in Fig. 9 (Poletto *et al.*, 2014b). The blue arrow in panel a indicates the drill-bit arrivals from below and the green arrow in panel b indicates the vibrator first arrivals from the surface. The grey arrow in panel a points at the rig-radiated noise in the SWD data and it has a similar trend with direct arrivals from the surface vibrator source.

The drill-bit and the vibrator arrivals from below (blue arrow) and from the surface above (green arrow), respectively, have opposite trends. The SWD and vibrator direct signals show similarities in quality and S/N. The similar trends (red dashed line) and patterns of the vibrator direct arrivals (green arrow) and of the rig-radiated noise in the SWD data (grey arrow) can be observed (Poletto *et al.*, 2014b).

## *5.2. Borehole seismic interferometry in a single well*

Seismic interferometry, sometimes known as virtual source, is a relatively recent method applied with different variants to redatum the source position at a receiver (virtual source). This method enables to use sources in wells in receiver positions where the use of active sources is more difficult than the installation of borehole receivers, or not possible. The method improves seismic illumination provided that a suitable illumination from field active or passive sources is achieved to obtain stationarity conditions for the redatuming equations. The method does not create new information but utilises and remaps the information already contained in the data. A great advantage of this redatuming method is that it is data based, i.e. it does not require any knowledge on the arbitrary subsurface model. Another advantage of the method based on cross-correlation is to remove the real source wavelet, with advantages for time-lapse monitoring. A seismic interferometry experiment, in a shallow cased borehole, was performed in the PITOP2 well (Poletto *et al.*, 2011). The purpose of this application is to improve the knowledge of the reflectivity sequence and verify the potential of the seismic interferometry approach to retrieve high-frequency signals in the single well geometry, overcoming the loss and attenuation effects introduced by the overburden. To this end, Poletto *et al.* (2011) described the use of a walkaway VSP geometry with a seismic vibrator to generate polarised vertical and horizontal components along a surface seismic line and a 3C geophone array cemented outside the casing of well PITOP2, as displayed in Fig. 11. The recorded traces were processed to obtain virtual sources in the borehole and to simulate single-well gathers with a variable source-receiver offset in the vertical array. The results obtained by processing the field data were compared with the synthetic signals calculated by means of numerical simulation, while signal bandwidth and amplitude versus offset were analysed to evaluate near-field effects in the virtual signals. The application was shown to provide direct and reflected signals with improved bandwidth after vibrator signal deconvolution (Fig. 12). Clear reflections were detected in the virtual seismic sections (Fig. 12e) in agreement with the geology (Fig. 12c) and other surface and borehole seismic data (Figs. 12a, 12b, 12d) recorded with conventional seismic exploration techniques (Poletto *et al.*, 2011).

In many applications, the seismic interferometry method uses cross-correlation and or

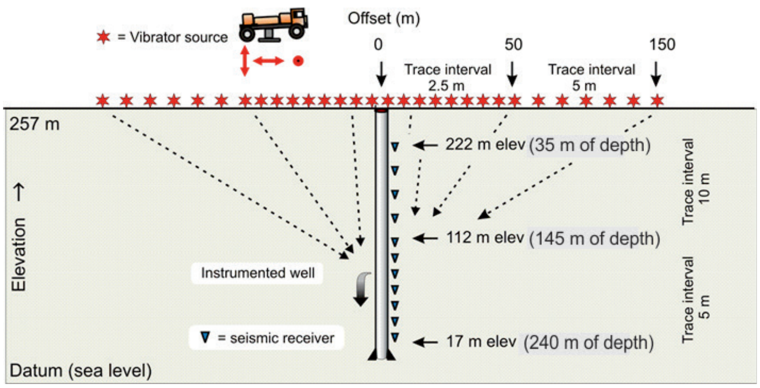



Fig. 11 - Schematic layout of the single well interferometry test (not to scale) (Poletto *et al.*, 2011).

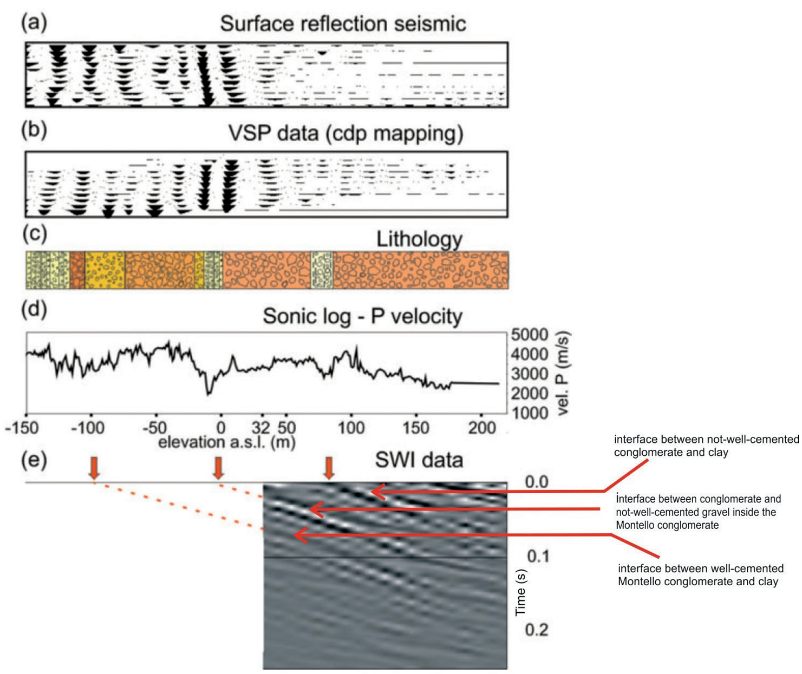



Fig. 12 - Comparison of P-wave virtual single-well imaging (SWI) upgoing wavefield (e) with sonic log data (d), lithology obtained by the well master log (c), the seismic section obtained by common depth point (CDP) mapping of borehole data (b), and surface seismic data (a) (Poletto *et al.*, 2011). The events in the seismic data have been associated with the changes in the lithology.

deconvolution between real traces. Using vibroseis or equivalent drill-bit pilot data from a conceptual point of view, seismic interferometry can be applied starting from uncorrelated field signals from correlated field signals, with advantages for the noise selection and removal in the second case. The PITOP site offered an important opportunity to test the methods with the drill-bit source during a drilling test. In the framework of the interferometry studies, an interesting methodological investigation was performed at the PITOP test site during the acquisition phase of a cross-hole drill-bit seismic while-drilling experiment, comparing both the drill-bit interferometry methods, with and without a drill-string pilot signal, in an experiment with two boreholes (PITOP2 and PITOP3) and a surface seismic line (Poletto *et al.*, 2010). The analysis showed that the use of the reference pilot signal improves the quality of the drill-bit wavefields redatumed by the interferometry method. An example of an offshore seismic while-drilling application without rig-pilot signal is described in Poletto *et al.* (2022).

## *5.3. Experiments in the framework of the $Co_2$ monitor project*

### 5.3.1. Crosswell survey

Different seismic methods are useable to monitor $CO_2$ injection. These include surface seismic VSP, with direct measurements at the depth of the seismic waves with higher resolution, and crosswell surveys, with an even greater seismic resolution and high-frequency content. While a key role of VSP is to calibrate the surface seismic in depth, and link the seismic results to the well logs, the use of crosswell surveys enables to illuminate in detail the interwell reservoir. Benefits and quality of the crosswell results, in relation to the well conditions, are important aspects. In the framework of the $CO_2$ Monitor Project (2013), funded by the Italian Government (Progetto Premiale 2013, Art. 4 para. 2 of Legislative Decree no. 213/2009), which aimed to study the benefits of the application of different methodologies in CCS site identification and management, a crosswell survey (Fig. 13) was performed between the PITOP2 well (in which a permanent array of geophones is installed) and the PITOP3 well (in which the source was located). Different sources (i.e. sparker and airgun) were tested, allowing comparisons between synthetic and acquired seismic data and log results (Figs. 14 and 15) (Poletto *et al.*, 2015).

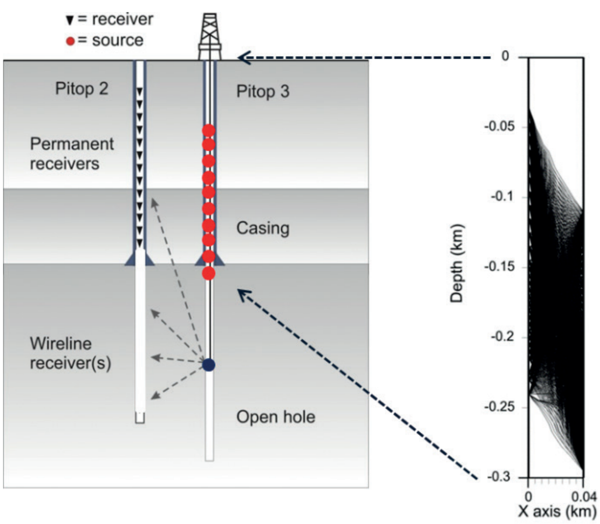



Fig. 13 - Crosswell seismic survey and ray tracing diagram.

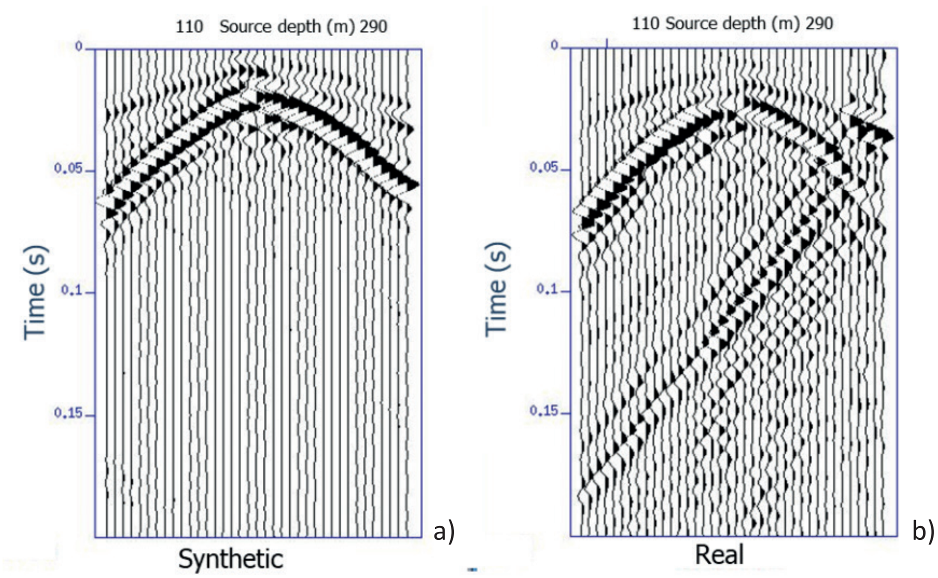



Fig. 14 - Crosswell synthetic (left) and real data (right) comparison.

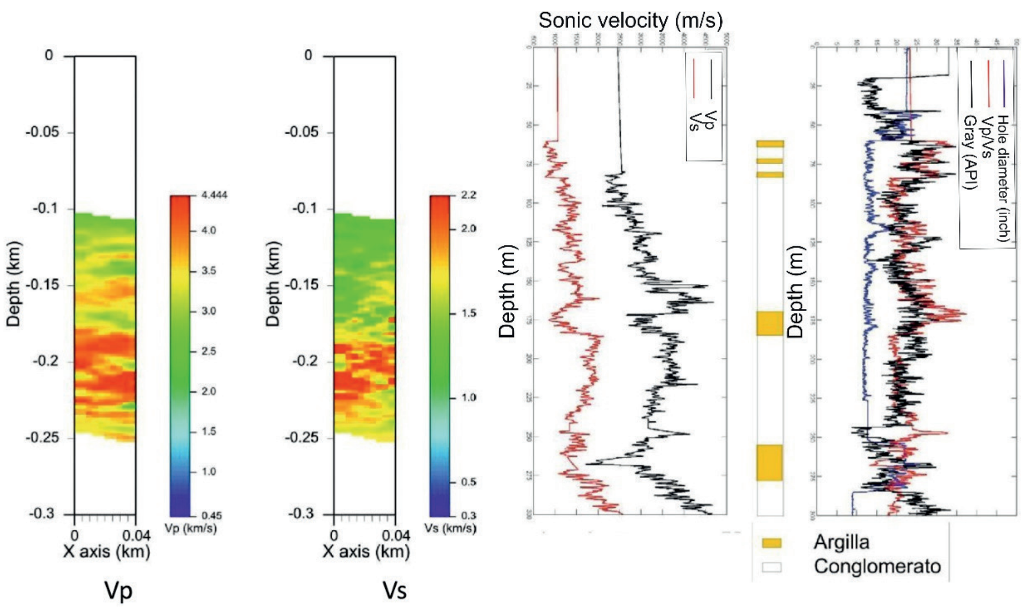



Fig. 15 - Crosswell tomographic inversion for P and S waves (a) and comparison with well logs (b).

## 5.3.2. Geoelectrical and electromagnetic survey

In geophysical and geological investigations, the integrated use of different types of data is an important aspect to improve the characterisation of the subsurface. In addition to the seismic methods, electromagnetic (EM) surveys provide information to discriminate fluids and are important for $CO_2$ monitoring as well. In the framework of the $CO_2$ Monitor Project (2013), OGS performed an Electric Resistivity (ER) log in well PITOP2 and in well PITOP3, an ER cross-hole and a time-domain EM (TDEM) survey, which also covered the area around the yard (Fig. 16). Both PITOP2 and PITOP3 wells were completed with an open hole section below the casing enabling electric and EM measurements in the lower part of the wells.

The results from the ER and TDEM surveys enabled to characterise the well test site and were useful for $CO_2$ monitoring model calibration and numerical modelling simulation. Moreover, they provided useful near-well information to be subsequently used for following geophysical acquisition at the site (Poletto *et al.*, 2015).

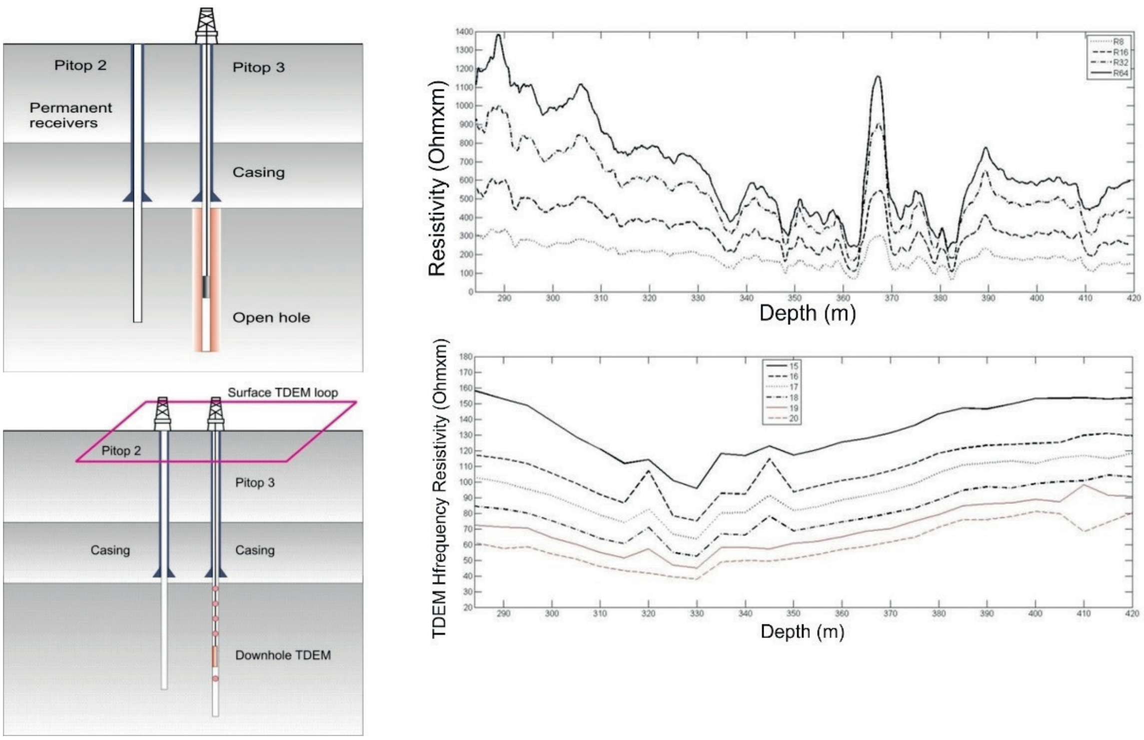



Fig. 16 - Schematic description (a) of the electric log (top) and TDEM survey (bottom) and corresponding resistivity data results for different configurations (b).

## *5.4. Ground force studies with analyses of near and far fields*

The characterisation of the radiation properties of surface vibrator sources is an important aspect in the processing of seismic data. Vibrations recorded in proximity of the source are dominated and affected by near-field effects, i.e. vibrations due to local source-ground coupling effects. Conversely, one key aspect is the obtainment of a reliable estimation or, better, measurement of the ground force below the source. In fact, the signature of the radiated waves in the far field is obtained by means of the time deconvolution of the ground force signal. The PITOP site offered a unique opportunity to test the use of a new assembly of permanent and non-permanent ground force sensors below the source. The PITOP site hosted an experiment performed using different impulsive and non-impulsive surface seismic sources along with ground-force reference measurements obtained with baseplate load cells and a shallow assembly of buried stress sensors. The aim was to obtain appropriate deconvolution operators to remove the individual source signatures in the seismic signals, in order to improve signature removal and seismic data resolution. The experiment demonstrated the high repeatability of the signals obtained with a standard seismic vibrator source, percussion tool used for civil works, and dropping mass. The experiment with these different tools demonstrated that the use of arbitrary injection sources can be equivalent if appropriate ground-force measurements are performed. An analysis with VSP signals, recorded by an array of permanent 3C geophones in the shallow PITOP2 instrumented well, was performed (Fig. 17). The test highlighted a significant improvement in the signal using the ground force as a deconvolution operator (Fig. 18) stating the potentiality of the direct ground-force measurement approach to effectively remove the far-field source signature in VSP onshore data and to increase the performance of permanent acquisition installations for time-lapse application purposes (Poletto *et al.*, 2016b). Moreover, the results obtained by using different sources displayed negligible differences.

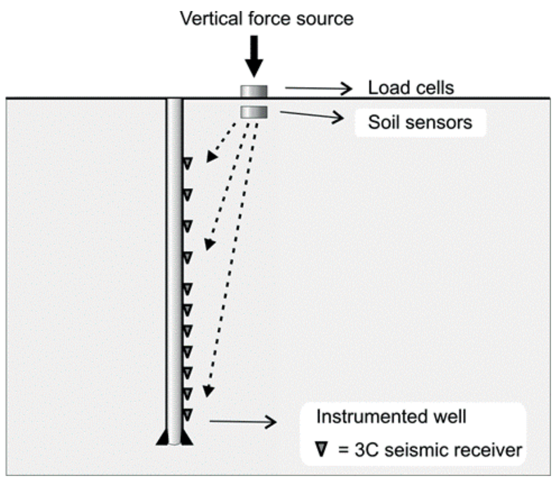



Fig. 17 - Shallow near-field ground-force and acceleration sensors, and far-field downhole wavefields recorded by 3C borehole geophones (Poletto *et al.*, 2016b).

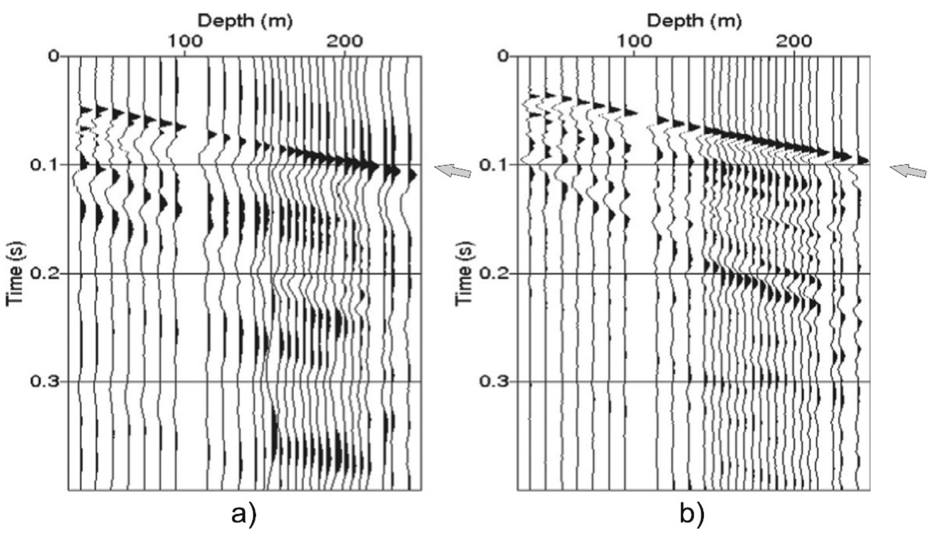



Fig. 18 - VSP signals of the seismic vibrator source, traces of vertical geophone component after reference deconvolution: a) signal obtained by reference soil-acceleration deconvolution; b) signal obtained by reference soil-ground-force deconvolution providing improved resolution. The arrows indicate the direct arrivals (Poletto *et al.*, 2016b).

### *5.5. Dual field studies by means of a reciprocal experiment*

Dual sensor measurements are widely used to separate seismic wavefield components in offshore surveys. To design an onshore experiment, we invoked source-receiver reciprocity. A reciprocal experiment was planned and carried out at the PITOP site for the analysis of seismic wavefields acquired by dual sensors. The method of separating upgoing and downgoing waves in signals recorded by dual pressure (hydrophone) and particle-velocity (geophone) transducers is well known, and commonly used to improve marine seismic data. A similar application is more difficult onshore, where pressure transducers are typically not available at surface. Nevertheless, the advantage of using dual recordings presents aspects of potential interest for near-surface signal analysis. The test performed included the study of the signals recorded by surface geophones and an assembly of acceleration and stress sensors buried at shallow depth in a fixed position. The field data were obtained through reciprocal geometry with respect to that of a conventional shot, by moving a surface seismic source at different offsets from the receiver location (Fig. 19). The analysis showed that combining the signals obtained at the fixed recording position enables separate first arrivals (direct and refracted) and surface-wave propagation along the seismic line (Poletto *et al.*, 2012).

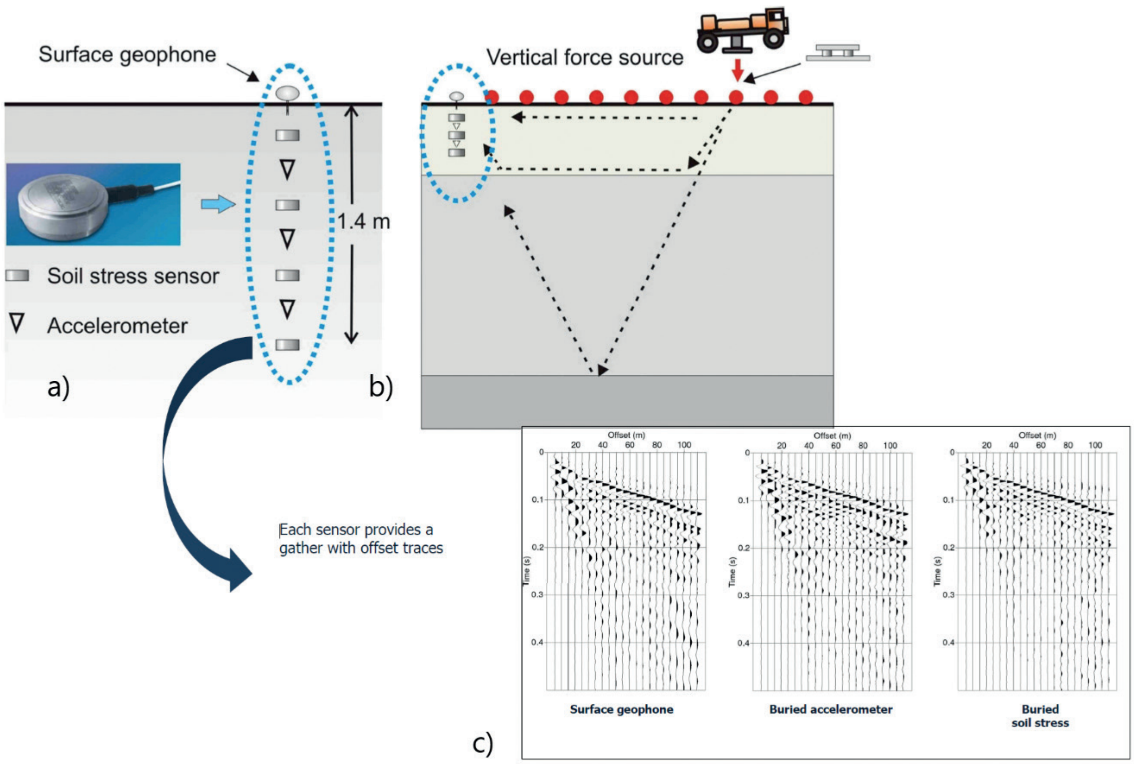



Fig. 19 - Layout of the soil-sensor permanent installation, with buried soil stress sensor, acceleration transducers, and surface geophone (a); onshore reciprocal acquisition geometry (not to scale) obtained using the permanent-receiver installation and moving a seismic source along the offset (b); and c) from left to right: shot gathers obtained by the surface geophone (vertical component), the buried acceleration sensor (averaged signal), and the buried soil-stress transducer (averaged signal) (Poletto *et al.*, 2012).

### *5.6. Dual wavefield application from DAS measurements*

DAS using fibre optic cables is an emerging seismic acquisition technology for the oil and gas industry, geothermal resource exploration, and underground fluid-storage monitoring (Bellezza *et al.*, 2024). This technology offers the advantage of improving seismic acquisition by enabling massive arrays for the monitoring of seismic wavefields at reduced costs with respect to conventional methods (Meneghini *et al.*, 2024). In general, it is accepted that this method provides acoustic signals comparable with conventional seismic data, although without the multicomponent directional information typical of geophones. A DAS cable was temporarily lowered in the PITOP2 well to perform an experiment that developed a modified data extraction method and pointed out that, as a result of the dense spatial distribution of recording points along the optic cable, DAS can provide two linked wavefield components in the axial direction, even when using a single one dimensional cable line (Poletto *et al.*, 2016a). These signal pairs consist of dual components that are related to native strain rate (or strain) and particle acceleration (or velocity) fields at a given recording location. These dual signals are easily usable for wavefield separation purposes by simply performing a trace-by-trace combination with an appropriate scaling coefficient (Poletto *et al.*, 2016a). Figs. 20a and 20b) show the VSP total wavefield acquired by the DAS measurements and the total field calculated through the developed method; the dual signals show higher contribution of downgoing waves and look very similar, however, with opposite upgoing reflection signals (weak in the figure). Following the wavefield combination by trace-by-trace summation and subtraction using a scaling coefficient, the separated downgoing and upgoing signals are obtained. The method does not require the picking of the first arrivals. This aspect is an advantage in DAS 3D VSP surveys. A representative sketch of the experiment is shown in Fig. 20c.

In 2013, Silixa Ltd., in collaboration with OGS, investigated the behaviour of iDAS™ sensors (Farhadiroushan *et al*., 2009), an innovative technology at the time (Fig. 21). The experiment consisted of borehole (multi-offset and multi-azimuth VSP) and surface acquisitions with both iDAS™ sensors and co-located single- and multi-component geophones with the aim of

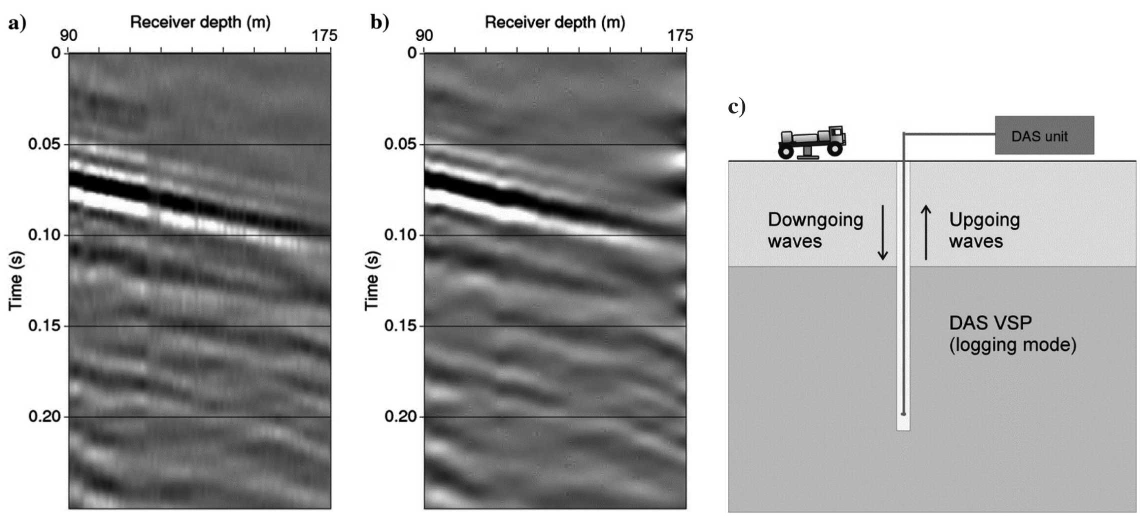



Fig. 20 - VSP total seismic field of the strain rate (a); corresponding dual particle acceleration (negative polarity plot) calculated in the same depth interval (b); sketch of the fibre optic folded (summation of direct and return) cable line used by the logging mode into the borehole to record the seismic waves from a surface vibrator (c); the folded array records downgoing and upgoing wavefields in the borehole (Poletto *et al.*, 2016a).

calibrating the iDAS™ cable and performing a comparison between the S/N and directional response assessment of the iDAS™ receivers and standard 3C geophones.

The results of the experiment showed a good correlation between the iDAS™ and standard geophone acquisitions, although with differences in the acquired seismic wavefields, confirming the quality of the iDAS™ signals (Poletto *et al.*, 2014a).

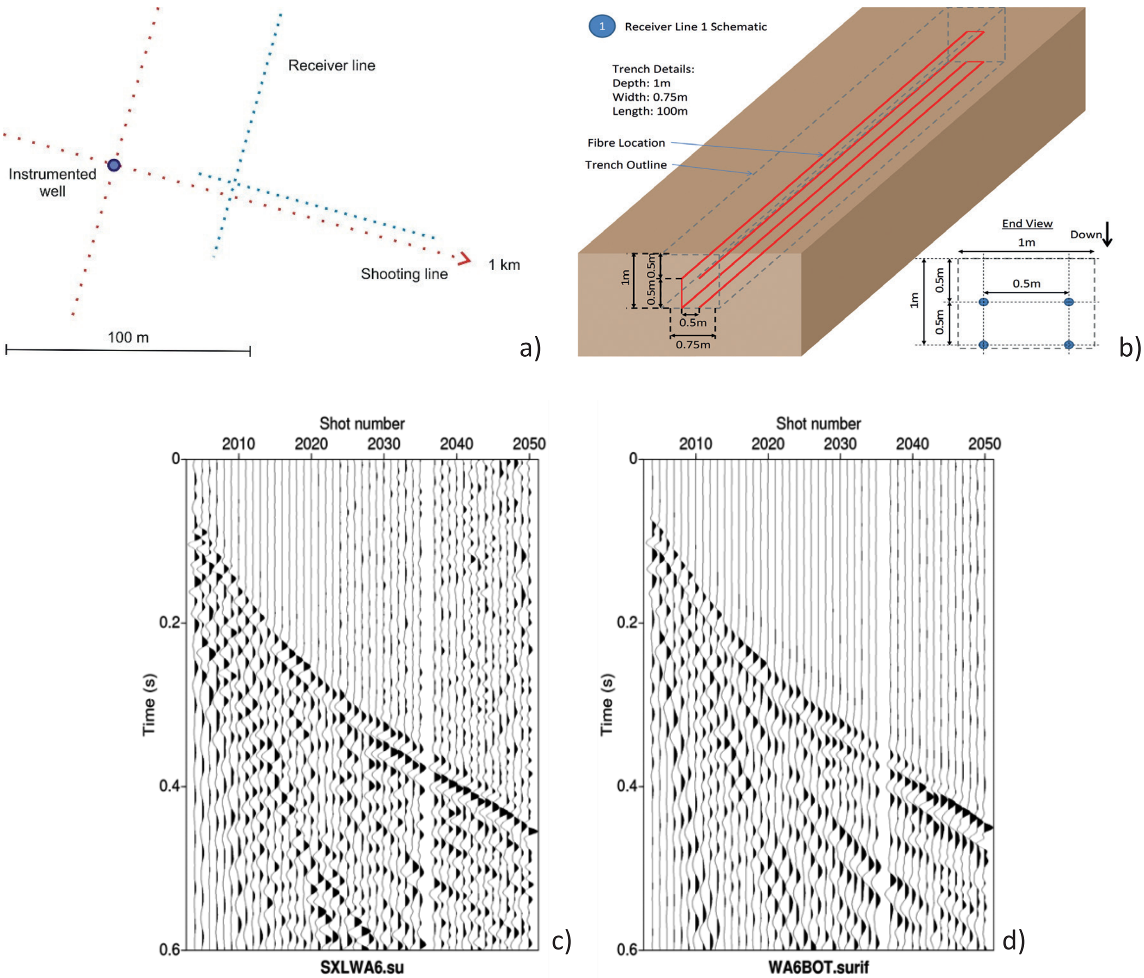


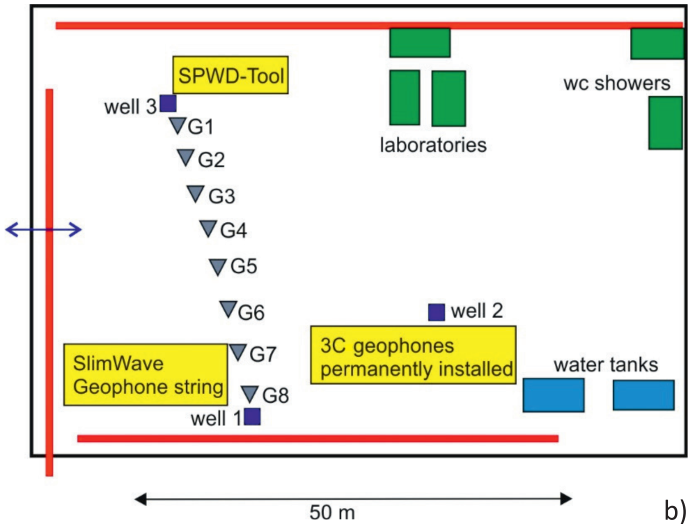

Fig. 21 - Surface recording layout (a) and layout of one of the two instrumented trenches prepared for the calibration experiment (b). The trench was instrumented with iDAS™ cables and geophones at corresponding positions. The other trench, 100 m in length, was perpendicular to this one: iDAS™ (c) and corresponding geophone signals acquired at a one-metre depth in one of the shallow-ground trenches (d). Shot trace #2050 corresponds to offset 920 m (Poletto *et al.*, 2014a).

## *5.7. Studies on innovative borehole sources*

This collaborative study was performed for the scopes of the seismic while-drilling and geosteering applications (Poletto and Miranda, 2022). Over the years, the infrastructures and instrumentation of the PITOP test site offered research institutes and companies, such as the Helmholtz Centre Potsdam - GFZ German Research Centre for Geosciences (GFZ) and Silixa Ltd., the opportunity to in-field test their prototypes and sensors under controlled conditions.

In 2014, GFZ successfully tested their newly developed instrumentation, the Seismic Prediction While-Drilling (SPWD)-wireline borehole prototype. The aims were to verify the applicability of the instrument, to calibrate it in sedimentary rocks, and evaluate its exploration range. The SPWD-wireline prototype was arranged in well PITOP 3 (well 3 in Fig. 22b) and both single-frequency or broadband sweep signals were emitted and registered in well PITOP 1 (well 1 in Fig. 22b) instrumented with six 3C geophones at 10-metre intervals (Sercel SlimWave tool string) and in well PITOP 2 (well 2 in Fig. 22b) instrumented with 13 permanently installed 3C geophones and eight 28-Hz 3C surface geophones (G1 to G8 in Fig. 22b) (Giese *et al.*, 2017).

a)




b)

Fig. 22 - The GFZ SPWD-wireline prototype test in well PITOP3, with recording in well PITOP2 and well PITOP1 (a) and base map of GFZ tests (modified after Giese *et al.*, 2017); red lines mark the power lines (b).

## 6. Conclusions

Acting also as a drilling facility, the PITOP geophysical test site (Travesio, Italy) offers extraordinary opportunities to perform borehole geophysics, surface seismic tests, crosswell surveys, and geoelectrical surveys both in borehole and at surface, using cutting-edge instrumentation provided, in part, by PNRR funding and by continuous technological upgrades to accomplish the ECCSEL implementation strategy.

This facility, being part of the ECCSEL-ERIC European infrastructure, is open to both scientific and industrial communities in order to boost research and collaborations in the geophysics field, with particular focus on CCS applications.

In this work, an overview of the PITOP facility was provided by describing its main current instrumentation and highlighting its potential for geophysical studies, as well as the geological framework of the area in which it is located.

The availability of different types of sensors (geophones, accelerometers, fibre optic cables (i.e. DAS), loading cells, electrodes) and borehole/surface sources offers a unique opportunity to carry out a wide range of geophysical experiments with logistics and personnel support.

Over the years, several experiments of different types performed have increased the knowledge of the site itself and improved the geophysical exploration methodologies studied. In this work we summed up only the main experiments performed at the PITOP site in the past years to highlight the different kinds of possible tests that can be designed and carried out in the field of geophysics with the aim to promote a broader use of this facility, thus, assuring its long-term sustainability and, in a wider strategic vision, the ECCSEL Research Infrastructure impact.

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