A shallow experimental site for integrated, multi-method hydrogeophysical monitoring.

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An experimental setup for shallow subsurface hydrogeophysical monitoring has been installed at the Maguelone site, located along the Mediterranean lido of the Gulf of Lions near Montpellier, France. The objective of the experiment is to to test in an integrated manner a full suite of coordinated monitoring techniques, either from surface or downhole. The field spread includes the injection hole, a logging hole, downhole electrical observatories at variable distance from the injection point, a downhole hydrodynamic observatory based on a pore fluid sampling completion from WestBay (SWS), a downhole seismic observatory, plus surface electrical and seismic observatories. This coordinated set of observatories should lead to the design of integrated sensors and methods for water management in a variety of hydrogeological settings, as well as for the monitoring of gas injection in deeper reservoirs.

Keywords: hydrogeophysics, monitoring, gas injection experiment.

Introduction

Geological storage of CO2 is still a new technology and many questions still remain open. This is in particular the case for the study of saline formations. These reservoirs have not been as thoroughly investigated in the past, mostly due to the lack of financial value. Detailed monitoring techniques to follow either the CO2 injection process or the long-term sustainability of subsurface storage are needed.

One of our key objectives in this work is to develop and disseminate a comprehensive set of generic tools and methodologies for the identification, assessment, characterization and evaluation of deep saline aquifers for CO2 storage. In order to achieve this overall objective, a number of technical issues must be addressed. First, the needs for monitoring must be identified in terms of relevant parameters, extent, vertical and horizontal resolution, time span and frequency of measurements.

On the basis of field characterization methods beyond classical methods (geophysical surveys, well logging, core analyses, interference well tests and tracer tests), the objective is to provide innovative and CCS (carbon capture and storage) adapted characterization techniques to assess sustainability and safety of the storage process. To achieve this objective, a “Shallow Injection Monitoring Experiment” (“SIMEx”) was designed and planned for deployment at the Maguelone experimental site located south of Montpellier along the Mediterranean coast. This shallow depth (< 25 m) monitoring experiment will permit to associate and deploy, from surface and downhole, a multi-methods approach in order to propose strategies to be implemented later at a greater depth, keeping the experiment at a reasonable cost.

In-situ monitoring based on geophysical probing from permanent and autonomous observatories shall provide means to :

- (1) monitor the injection process in terms of pore space saturation,
- (2) validate the stability of the reservoir storage (over long periods of time),
- (3) evaluate the sealing capacity of the cap rock (over long periods of time).

In this paper, the Maguelone experimental site is presented first of all with an historical perspective on regional investigations. The SIMEx experiment is described in a second phase; new field spread, drilling and completion of the downhole instrumentation are outlined. In the next sections, the pre-injection site monitoring results are detailed for borehole surveys (electrical, acoustical, time-lapse logging), followed by a surface (electrical and seismic tomography) and surface-to–borehole (seismic) surveys. Finally, a discussion on present results is given together with a general strategy for future works.

The Maguelone experimental site (Languedoc, France)

The Maguelone experimental site is located along the Mediterranean lido of the Gulf of Lions passive margin, 10 km to the south of Montpellier. Limited to the north by the Prevost coastal lagoon and to the south by the Mediterranean Sea (Fig. 1), this site offers a natural laboratory to study porous coastal reservoirs in a clastic and clay-rich context saturated mostly with saline fluids. The site geological context and cross-section are given in figures 2 and 3, respectively.

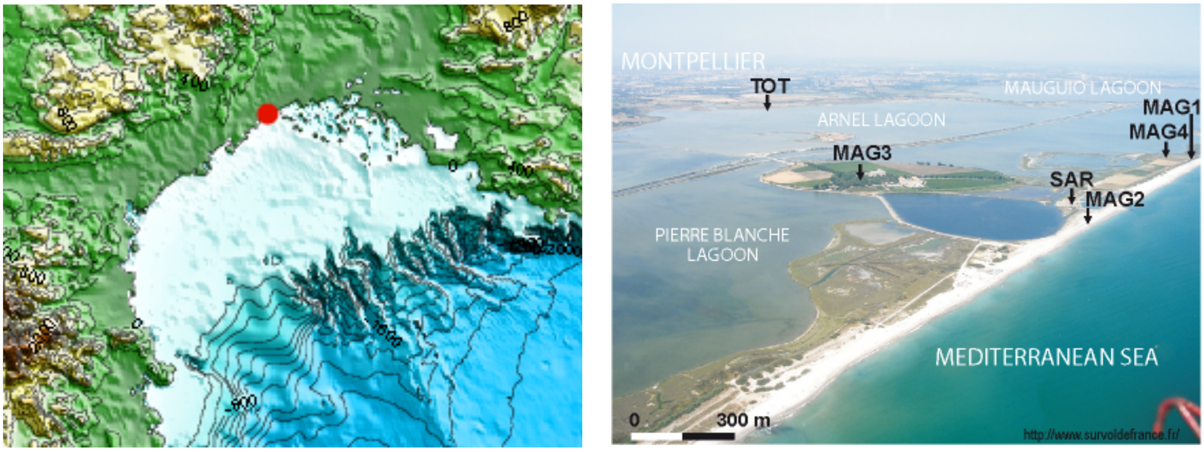

Figure 1. *Geographical location (left) and aerial photograph (right) of the Maguelone experimental site located to the NW of the photograph (with the MAG1 and MAG4 boreholes) and one km to the east of the Maguelone island (with the MAG3 borehole).*

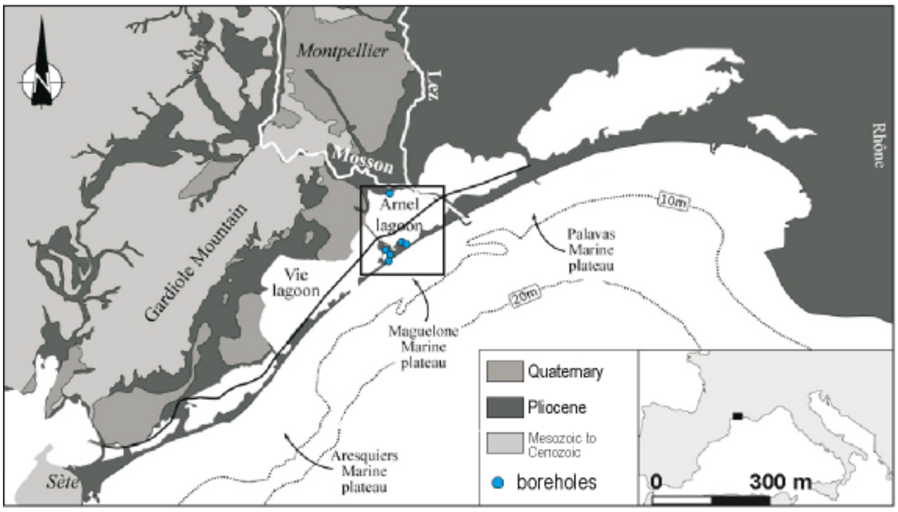

Figure 2. *Simplified geological context for the Maguelone site, located on a Lido limited to the northwest by lagoons and to the southeast by the Mediterranean sea. To the west of the study area, the Gardiole mountain forms a calcareous topographic high that prevented the Lower Pliocene deposits from erosion during the Quaternary (modified from Raynal et al., 2009).*

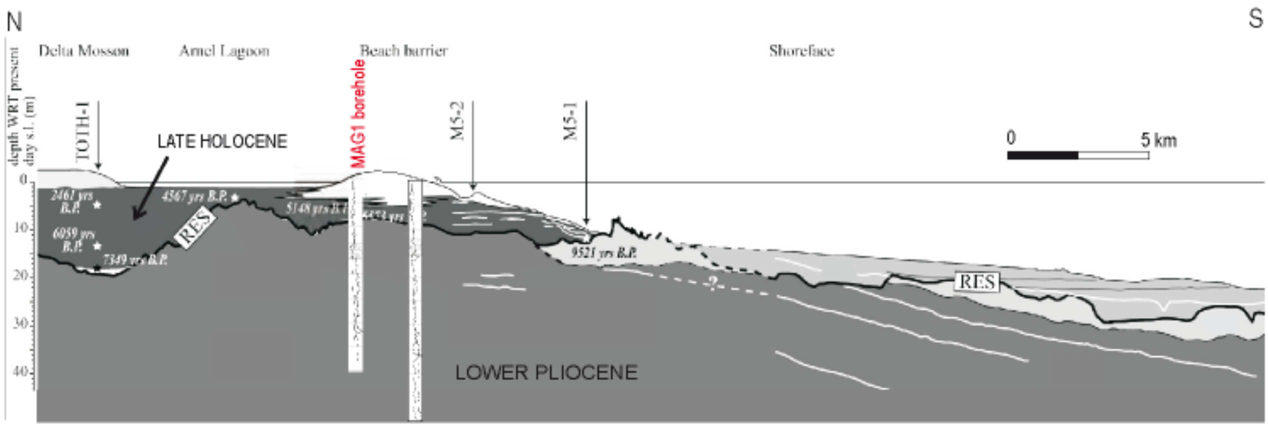

Figure 3. *Dip line drawing across the Maguelone area. The Lower Pliocene sequence outcrops on the Maguelone island at +11m (Figure 1), and offshore on the Aresquiers plateau (Figure 2). Eastward, those deposits have been deeply incised during successive lowstand phases (modified from Raynal et al., 2009).*

Five shallow boreholes (12 to 60 m deep) have been drilled from 2003 to 2004 at Maguelone over 5 km^2 for geological, hydrological and instrumental reasons in the framework of EC “ALIANCE” project (Fig. 1). This FP5 project was dealing with the development and testing of new geophysical methods and instruments to document salt-water intrusion in porous coastal aquifers. For this, one of the boreholes (MAG4) allowed the deployment of the first in-situ observatory of electrical resistivity. This observatory provides daily and m-scale downhole resistivity profiles. It allows following the vertical and temporal high-resolution evolution of the salinity of the fluids that saturate porous environment.

Subsurface stratigraphy at Maguelone

Continuous geological samples (from MAG1) and geophysical data from shallow boreholes allowed to evidence two distinct depositional sequences (Fig. 4):

- Near the ground surface (0-9 m), a thin Late-Holocene sequence (< 5000 yrs B.P.) is constituted with lagoon sediments with impermeable dark green clays topped by grey shelly beach sands. This sequence forms an impermeable seal overlying the Pliocene sequence with an unconformity.
- Pliocene sequence, from 9 m to the base of MAG1 (60 m). This sequence consists mainly in relatively homogeneous fine grained continental deposits (clays, silts, and clayey silts). Locally, some marine incursions (grey clays) and lacustrine levels (white carbonates clays) are visible. The clayey fraction is relatively high all along the sequence, making those deposits relatively poorly permeable.

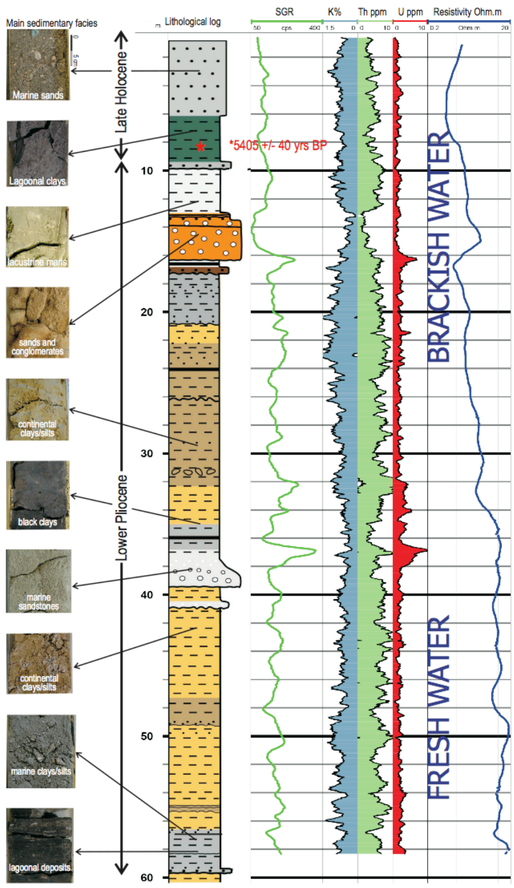

Figure 4. *Sedimentological sequence and geophysical logs from the MAG1 hole at Maguelone.*

In this sequence, a single remarkable depositional unit is located from about 12 to 16 m depth and consists in a porous and permeable conglomerates and sands interpreted as fluvial deposits. The conglomerates, clearly identified downhole from low natural gamma radioactivity values, can be correlated laterally with boreholes located at a km distance, showing the lateral extension of this unit. Sedimentary facies and geophysical measurements suggest a high permeability and porosity for these conglomerates, also bounded above and below by clay-rich horizons. Also, hydrogen sulphite (H_2S) was encountered during drilling operations when the drill went through this horizon. The possibility of the conglomerate forming a 3 m-thick gas-rich reservoir may consequently be envisaged, this anomaly resulting from lagoonal organic matter decomposition. This hypothesis is supported by the downhole profile of electrical resistivity, showing an increase which may correspond to pore space desaturation associated with the presence of gas, and coincides in space with the low gamma values.

From a hydrological point of view, the electrical resistivity data show that the sedimentary column is saturated with seawater to brackish water from surface down to 32 m. Below this, a gradual increases in electrical resistivity can only be explained by a gradual freshening in pore fluid. Below 40 m, values as high as 8.0 Ω.m and above are reached. During drilling, these horizons were found to be artesian for about 30 minutes, with an initial fountain a few meters high. The hole is now equipped with a PVC casing perforated at the base only (from 59 to 62 m). It has been producing fresh water (1200 μS/cm) at a very slow rate for the past 7 years. In addition, the in situ geophysical observatory evidenced temporal changes in electrical resistivity in front of the conglomerates, thereby illustrating the dynamics of the system from a hydrological point of view.

Site drilling and instrumentation

With SIMEx, the field objectives are expanded to test the new electrical downhole instruments (designed by imaGeau) for deep deployment in combination with a large number of surface and downhole arrays. While gas injection hole is restricted to the reservoir located from about 12-16 m in MAG1, all new holes were drilled down to 20 m depth (MAG 6-9) and 50 m (MAG 5) and instrumented over their entire length *(Fig.5. & Table 1)*. MAG5 and MAG6 were fully cored for lithological study and lab analyses. Continuous geological samples (from MAG5 & MAG6) and geophysical data from shallow boreholes allow detailing geological knowledge at the site in order to prepare most relevant geophysical monitoring.

The new downhole field spread (*Figure 5 & Table 1*) includes, along with previously existing holes (MAG4 resistivity observatory and MAG1 PVC hole), a total of 7 nearby holes located within a maximum of 50 meters lateral distance from each other, as follows.

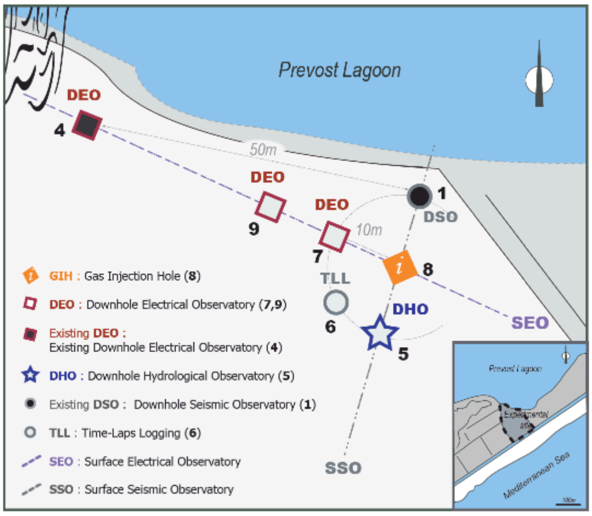

Figure 5. *Field spread at the Maguelone experimental site for the SIMEx integrated monitoring experiment. A set of 5 boreholes was added in 2010 to existing ones (MAG1, MAG4), with core taken in MAG5 and MAG6, and destructive hole for the other holes. Surface monitoring arrays was deployed in order to complement downhole approaches at larger scale.*

Table 1. *Technical description of the set of new boreholes drilled in May-June 2010.*

Borehole	Open-hole		Cased-hole			Cementation
	Depth (m)	Diameter (mm)	Depth (m)	Diameter (mm)	Casing	Depth (m)
MAG 5 *(DHO)* fully cored	80	104/113	50	55/90	SWS MP55 (7 zones for fluid sampling)	50-80
MAG 6 *(TLL)* fully cored	20	134/143	20	112/125	PVC perforated (0.05m) from 10 to 20 m	
MAG 7 *(DEO)* destructive	20	134/143	20	112/125	Downhole Electrical Observatory (IMAGEAU)	
MAG 8 *(GIH)* destructive	19	134/143	16	112/125	PVC perforated for injection at ~16-19 m	
MAG 9 *(DEO)* destructive	20	134/143	20	112/125	Downhole Electrical Observatory (IMAGEAU)	

Downhole experimental set-up *(for acronyms terminology, see Figure 5):*

- **Existing DSO (MAG1)**: the first hole drilled and fully cored in 2003 to a depth of 60 m was equiped with a PVC liner down to 59 m, and with a slotted PVC liner from 59 to 63 m. However, the bottom 4 meters of the hole were found to be obstructed by fine grain sediments only a few meters after drilling, yielding a total depth of 59 m which has remained unchanged since drilling. Open at the base and artesian for a few tens of minutes from about 40 m depth, the hole has been producing water from its base since initial drilling, and with an electrical resistivity of 8.0 Ω.m (or 1250 µS/cm of fluid conductivity, equating to a pore fluid salinity of about one g/l). In the new SIMEX spread, MAG1 is used to install a downhole seismic observatory in order to complete the overall geophysical strategy and study how different methods might be combined for a more efficient description of the saturation/desaturation process associated with gas injection in the conglomeratic reservoir.

- **Existing DEO (MAG4):** The first resistivity observatory prototype was constructed and set-up in June 2004 in a borehole (MAG4) located 50 m to the NW of MAG1. The observatory was equipped from surface to 41 m depth with permanent electrodes with a spacing of one meter. It was tested in Wenner, dipole-pole and dipole-dipole modes, and calibrated against induction resistivity logs recorded in MAG1. A good coherency between dipole-dipole data and medium induction resistivity (*Figure 6*) was found, both probing the electrical resisitivity of the formation at meter scale. Time-lapse resistivity measurements were made automatic from 28 to 40 m in 2006, showing very gradual but continuous changes over time in electrical resistivity at the base of the hole.

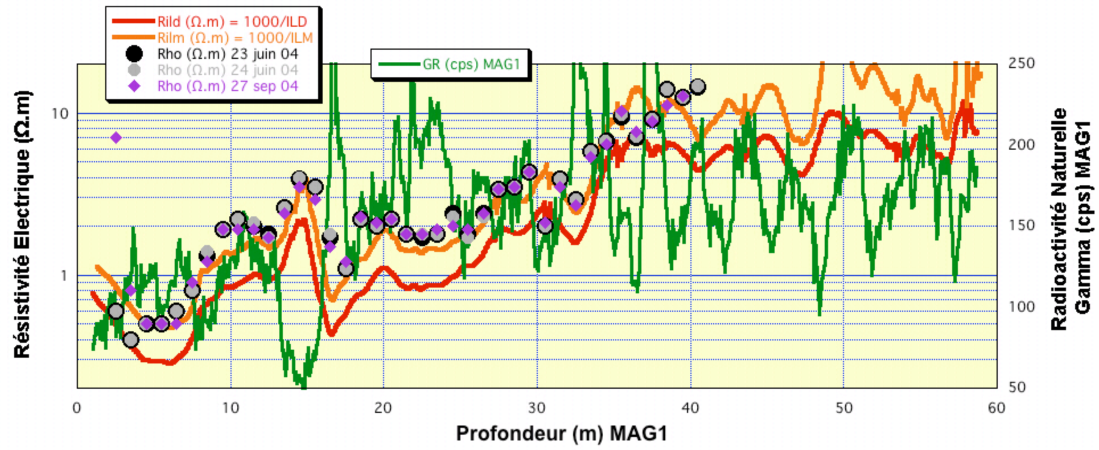

Figure 6. *Calibration of electrical resisitivity data recorded in 2003 in MAG4 in a dipole-dipole mode from induction resistivity logs recorded through PVC liner in MAG1. Downhole observatory data are presented with black (June 23rd), grey (June 24th) and purple dots (September 27th), while medium (orange) and deep (red) induction logs appear as continuous traces. A downhole gamma radioactivity profile is also included (green curve) for lithological reference to underline the presence of clays and the conglomeratic reservoir at 15 m depth. Excellent repeatability is demonstrated for the entire observatory by measurements recorded during successive days in June. The profile recorded in September is very similar to the previous ones in front of clay-rich horizons, with departures in the conglomeratic layer, some sand-rich layers, and close to surface due to desaturation from surface during summer.*

- **New GIH (MAG8)**: an injection hole perforated over the 3 m along interval corresponding to the conglomeratic layer was firmly cemented above and below the target reservoir in order to allow for gas injection in the future. Prior to gas injection, this hole will be tested first with water in pumping and injection modes.

- **New DEO's (MAG7 & MAG9):** additional downhole electrical observatories (MAG7 & MAG9) were installed at respectively 10 m and 20 m from the injection hole (MAG8 or "GIH"). To the new "double cask" downhole technology jointly developed by imaGeau and installed in MAG7, a second observatory was installed in MAG9 to allow for cross-hole and surface-to-hole tomography between the two holes. Both holes were equipped down to 21 m with an array of electrodes with 35 cm spacing. The new "double cask" electrical observatory developed by imaGeau and installed in MAG7 is adapted to resist the aggressive conditions encountered in CO_2 underground storage, (using high grade, double shell PVC tubing with dedicated gold-plated electrodes), and pressure conditions down to 1500 m depth.

- **New DHO (MAG5):** a downhole hydrodynamic observatory based on a multi-packer completion from WestBay (SWS), including packers in order to provide fluid samples, temperature and pressure records during injection and thereby time/space calibration points from tracers (i.e. precise boundary conditions) to numerical modelers. Eight zones were equipped for fluid sampling and monitoring down to a depth of 49 m. For experimental purpose as part of SIMEx, two of these zones were located within the reservoir (at 13.9 and 15.5 m), one was located above (at 7.9 m) and a fourth one below (24.9 m). For long-term survey of underlying groundwater, another set of four sampling zones was installed in front of sand-rich layers (Figure 6) to allow probing at 32.1, 36.7, 39.8 and 49.0 m.

- **New TLL (MAG6)**: a single hole cased with thin PVC for rapid time-lapse logging measurements (whether electrical, sonic, neutron) dedicated to the calibration of timely continuous monitoring techniques during gas injection experiments.

Surface experimental set-up *(for acronyms terminology, see Figure 5):*

- Surface electrical observatory **(SEO)** and seismic observatory **(SSO)** with permanent flutes during the injection period in order to study how surface and downhole monitoring strategies shall complement each other, looking at different volumes, with possible surface/downhole tomographic approaches.

Pre-injection site calibration & reference

Prior to injection experiments in 2011, a series of preliminary geophysical measurements and experiments have been conducted in 2010 to prepare, test, and calibrate the Maguelone site for later experiments. Also, these preliminary surveys permitted to better characterize site geology and reservoir characteristics. Downhole geophysical measurements (gamma ray, electrical and acoustical logging) are detailed below, followed by surface (electrical and seismic tomography) and surface-to–borehole (seismic) preliminary surveys.

Downhole geophysical surveys

Downhole geophysical measurements (gamma ray, electrical and acoustical logging) were made in MAG1, MAG5 and MAG6 in June 2010 (*Table 2, Figures 7, 8 & 9*). There was no measurement recorded in the other three holes due to the large number of data already available at the site and to operational constraints related to installing the DHO and DEO's immediately after drilling.

Gamma ray (GR): measures naturally occurring gamma radiations in boreholes to characterize the surrounding rock or sediment. This measurement provides lithological information related to the presence of clays (high gamma radioactivity), which often form the boundaries of reservoirs. As such, the natural gamma record can lead to estimate the percentage of clay in sandy formations. It might be used either in open or PVC cased holes. From spectral analysis at each level, GR logging permits the determination of the concentrations of radioactive elements (potassium, uranium, and thorium) in the formation.

Dual induction laterolog (DIL): uses 20 kHz currents in transmitter coils to set up an alternating magnetic field in the surrounding conductive formation. Two resistivity measurements are made at different depths of investigation from different sets of coils, yielding so-called "deep" and "medium" induction curves at each depth. Due to the electromagnetic nature of the measurement, the tool might be deployed in air-filled or PVC-cased boreholes.

Full Waveform Sonic (FWS): a geophysical measurement of sound properties (formation's capacity to transmit sound waves) in a fluid filled borehole. FWS logs are used for fracture identification, lithological determination, waveforms analysis, rock properties analysis such as porosity, competency, and strength.

Table 2. Downhole geophysical measurements recorded in MAG1, MAG5 and MAG6.

Logging tools	**Correlation and Uses**	**MAG1** *(DSO)*	**MAG 5** *(DHO)*	**MAG 6** *(TLL)*
Gamma ray **(GR)**	Radioactivity associated with shaliness	Yes	Yes	Yes
Dual induction laterolog **(DIL)**	Variations of water content (and salinity) in bed with non conductive matrix Correlation in low-resistivity sections (shales)	Yes	Yes	Yes
Acoustic borehole imaging **(ABI)**	Imaging tool	Yes	-	Yes
Full wave sonic **(FWS)**	Travel time depending on lithology, rock texture and porosity	Monopole, dipole at 5, 10, 20 kHz	-	Monopole, dipole at 5, 10, 20 kHz

Acoustic Borehole Imager tool (ABI): produced images of the borehole surface from the reflection of a 500 kHz acoustic signal to image the borehole surface. ABI is a multi-echo system that gives optimum performance under a wide range of borehole conditions (from 60 to 150 mm in diameter). The principle of the multi-echo system is the digital recording of each reflected acoustic wave train. In all, two images are produced from this acoustic probing (amplitude and traveltime).

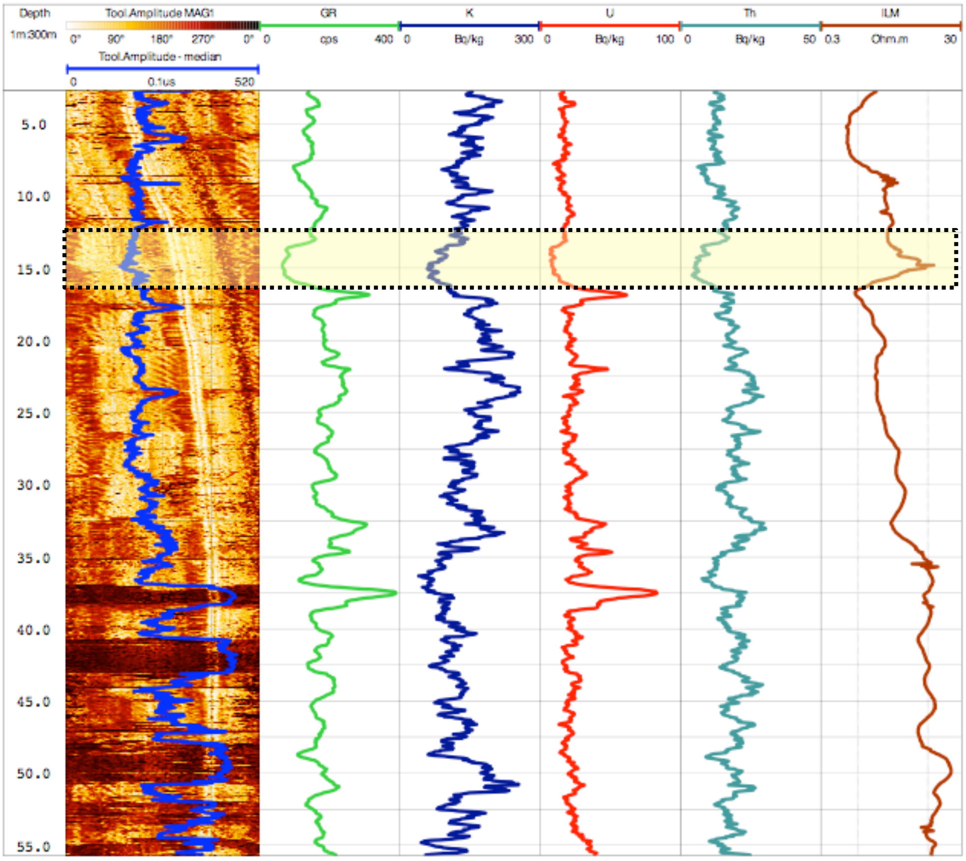

Figure 7. *Downhole geophysical measurements from the MAG1 hole. From left to right*: *acoustic borehole imaging (ABI), spectral gamma ray (U, Th, K) and induction electrical resistivity logs, at 0.05 m spacing. Location of the 3 m thick conglomeratic reservoir is outlined in yellow.*

Continuous geological sampling (from MAG5 & MAG6) and geophysical data from theses (*Fig. 7, 8 & 9)* holes confirm the lithological description obtained from the MAG1 core (*Figure 4*). Two main geological formations are distinguished: near surface (0-9 m), a thin Late Holocene sequence (lagoonal sediments made of dark green clays topped by grey shelly beach sands) forms an impermeable seal overlaying a Pliocene sequence with continental deposits (clays, silts, and clayey silts). In this sequence, a single remarkable depositional unit is located from 13 to 16 m. It consists in a porous and permeable conglomerates and sands interpreted as fluvial deposits. The conglomerates, clearly identified downhole from low natural gamma radioactivity values, can be correlated laterally with nearby boreholes, showing lateral extension of this unit. Sedimentary facies and geophysical measurements suggest a high permeability. This hypothesis is supported by the downhole profile of induction electrical resistivity in MAG1 and MAG6 *(Fig. 7 & 9)*, showing an increase in this reservoir with respect to the surrounding, which coincides in space with low gamma values. Figure 10 illustrates a full-waveform dual-sensor sonic well log (20 kHz) recorded in MAG1 at 5 cm spacing with V_p determined from first arrival pick-up, clay index and sonic porosity obtained from Wyllie's formula (Wyllie et al., 1956).

Surface geophysical surveys

Electrical resistivity tomography

Over the past decades, electrical methods have been increasingly used for the investigation of shallow subsurface structures. In particular, electrical resistivity tomography (ERT) has been reported to be one of the most effective non-invasive and spatially integrative prospecting technique. The ERT method provides significant improvements, with the developments of new inversion algorithms, and the increasing efficiency of data collection techniques. Multichannel technology and powerful computers allow collecting and proces-

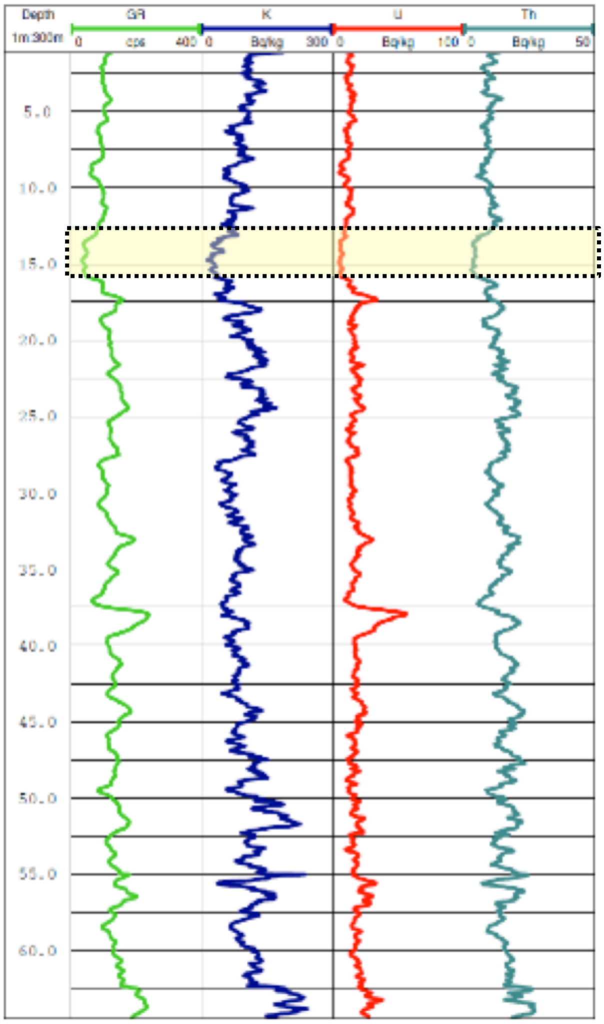

Figure 8. *Downhole geophysical measurements from MAG 5: spectral gamma ray (U, Th, K) recorded with a 5 cm sampling rate. Location of the 3 m thick conglomeratic reservoir outlined in yellow.*

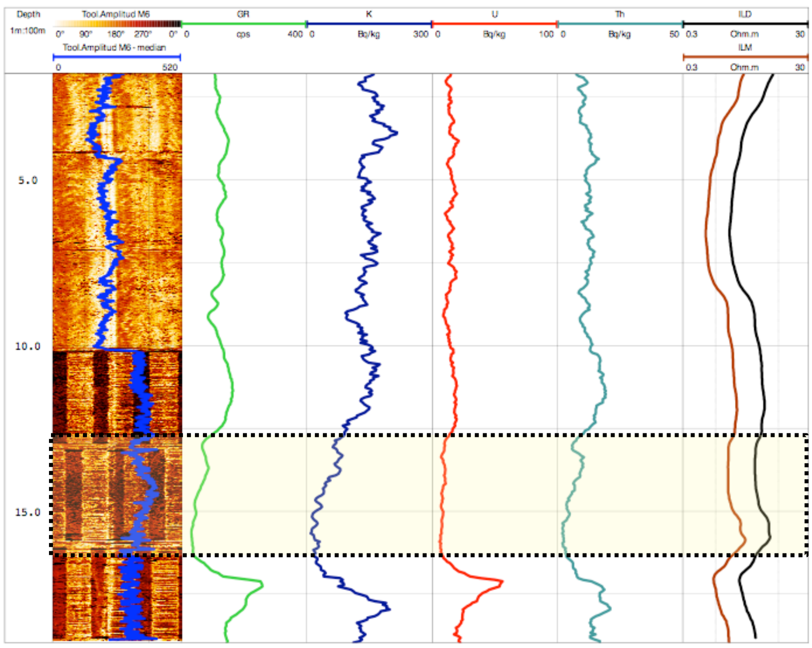

Figure 9. *Downhole geophysical measurements from the MAG6 hole*: *acoustic borehole imaging (ABI), spectral gamma ray (U, Th, K) and induction electrical resistivity logs, at 5 cm spacing*. *Location of the 3 m thick conglomeratic reservoir outlined in yellow.*

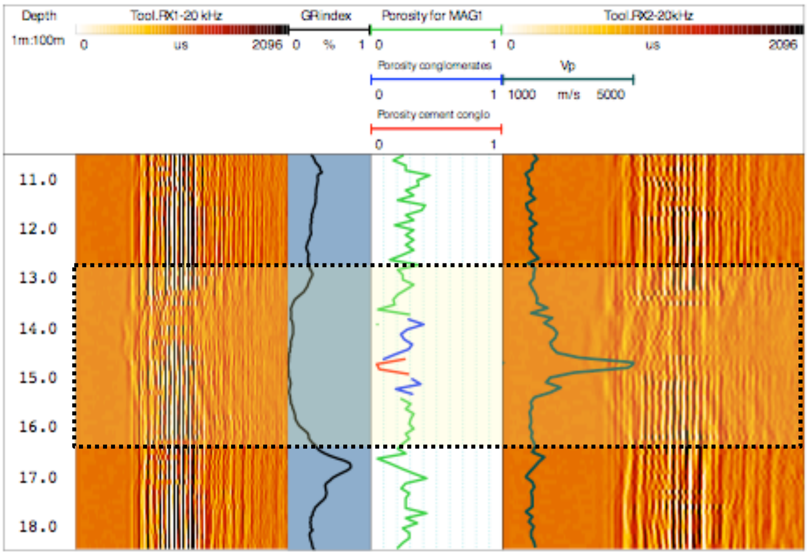

Figure 10. *Downhole geophysical measurements from the MAG1 hole: full-waveform dual-sensor sonic well log (20 kHz) at 5 cm spacing, V_p determined from first arrival pick-up, GR index (amount of clay from 0 to 100 %), with sonic porosity estimate obtained from Wyllie's formula. Location of the 3 m thick conglomeratic reservoir outlined in yellow.*

sing resistivity data within few hours. Application domains are numerous, from geology to hydrogeology, and environmental studies. In particular, electrical methods are commonly used to detect reservoir structures and to map fluid mixing properties.

Many different electrode arrays have been used in geoelectrical technique. Each spread has advantages depending on depth of investigation, sensitivity to horizontal and vertical changes, and signal strength. Multiple studies have been realized to determine which electrode configuration will respond best to a given problem. This choice depends mainly on the subsurface properties (White, 1994; Chambers et al., 2002; Zhou et al., 2002; Dahlin and Zhou, 2004).

For surface imaging, the traditional four-electrode arrays (i.e. Wenner, Schlumberger) were not considered here. These electrode configurations are poorly suited for multi-channel imaging measurements because of the limited number of channels that can be used (leading to very significant acquisition times), low data coverage and shallow investigation depth. A dipole-dipole array was also not considered because of singularity in some potential differences and the low signal-to-noise ratio. Pole-pole and pole-dipole arrays only were considered in this preliminary study.

In designing the electrical measurement sequence, a large spacing for a and n (*Fig.11*) provides relatively deep information about the subsurface structure, while a small spacing for a or n gives a relatively good horizontal resolution at shallow depth. Pole-pole and pole-dipole arrays have a larger depth of investigation than the traditional four-electrode arrays, but these arrays can be sensitive to noise because of the use of a remote electrode(s). The investigation depth of pole-dipole array is lower than that of the pole-pole. These arrays are commonly used for monitoring surveys because they allow a larger number of measurements to be collected and reduced acquisition time compared with other arrays.

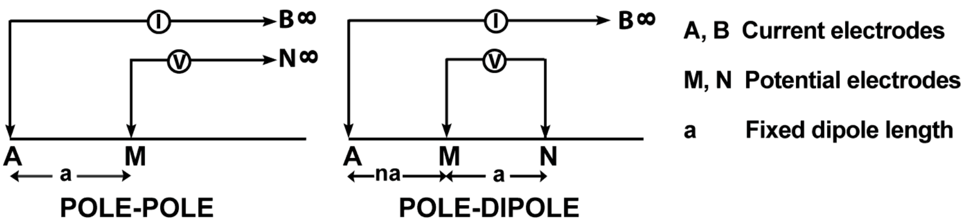

Figure 11. *Pole-pole and pole-dipole electrode arrays used in this preliminary survey.*

In parallel to field investigations, a numerical study was carried out to identify the most appropriate array to localize fluid movements in the subsurface. To assess the reliability of the monitoring technique, the results of this numerical study were confronted to field data.

A set of two nearly orthogonal 2D electrical tomography profiles *(Fig. 5)* was recorded on June 15-16, 2010, with a multi-electrodes system:

- NW-SE pole-dipole and pole-pole arrays profile (142.5 m in length, with 1.5 m inter-electrode spacing, *Figures 12,13 & 15)*
- a NE-SW pole-pole array profile (47 m in length, with 1.0 m inter-electrode spacing, *Figure 14*) parallel to seismic surface survey.

The field results show that a pole-dipole array tends to have a better resolution than a pole-pole array. However, the pole-dipole array is affected by position of remote electrode: when a remote electrode is placed 250 m away to the east of profile, a resistivity anomaly appears in the east part of the 2D electrical cross-section *(Figure 12)*. When a remote electrode is placed 350 m away to the west the of profile, a resistivity anomaly appears in the west part of the electrical tomography profile *(Figure 13).* Also the acquisition time of measurement sequence used for monitoring (about 1300 measurement points) is smaller for pole-pole arrays (about 6 minutes for each sequence) than for pole-dipole arrays (about 12 minutes). Therefore a pole-pole array is more appropriate for this electrical tomography monitoring survey which will need to be repeated at a high frequency during injection experiments.

The range of the resistivity measured in the field (from 1.0 to 5.0 Ω.m) corresponds to the data obtained from induction resistivity logging in MAG1 *(Fig. 7)*. As for the logging data we remark an increase of the surface resistivity values with depth. However, the resolution of the surface resistivity measurements decreases with depth, what makes difficult to distinguish thin layers as a dark clay 1meter layer at the depth about of 16 m visible with resistivity logging *(Fig. 6 & 7)*. In order to improve this limitation we consider using a combination of surface–to-borehole resistivity measurements for the next stage of the project.

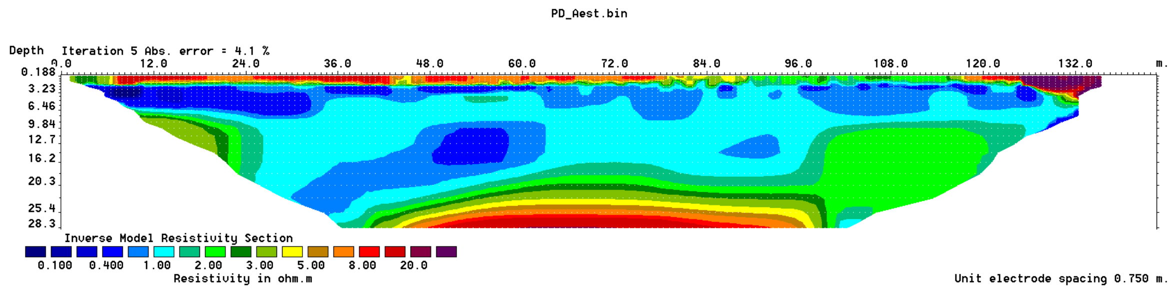

Figure 12. *NW-SE electrical tomography profile with a pole-dipole array (orthogonal to coastline). Inverse 2D model of field data with a remote electrode placed 250 m away to the east. The low resistivity (dark blue) patch located at depth of the target reservoir appears to be an artifact coming from the location of the remote electrode.*

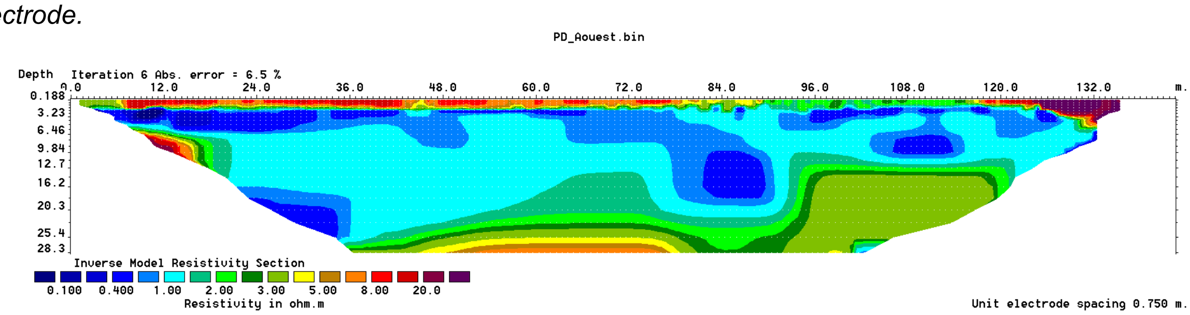

Figure 13. *NW-SE electrical tomography profile with a pole-dipole array (orthogonal to coastline). Inverse 2D model of field data with a remote electrode placed 350 m away to the west. The low resistivity (dark blue) patch located at depth of the target reservoir appears to be an artifact coming from the location of the remote electrode. It is somewhat symmetrical to the previous, with a remote electrode located to the west.*

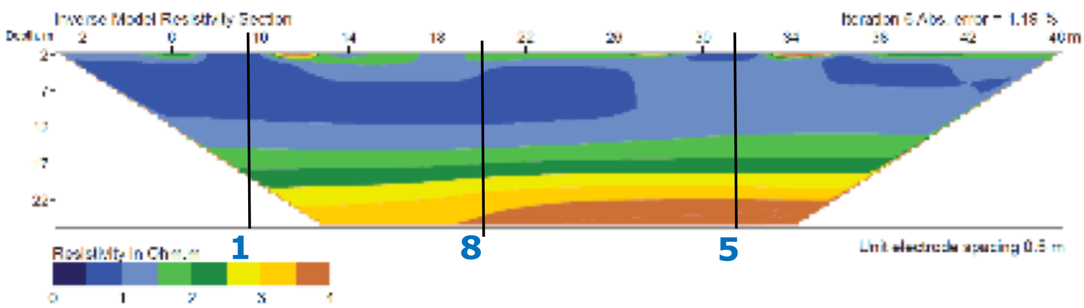

Figure 14. *Inverse 2D model of field data in a pole-pole mode along the NE-SW direction (along coastline). Position of MAG1, MAG8 and MAG5 are indicated.*

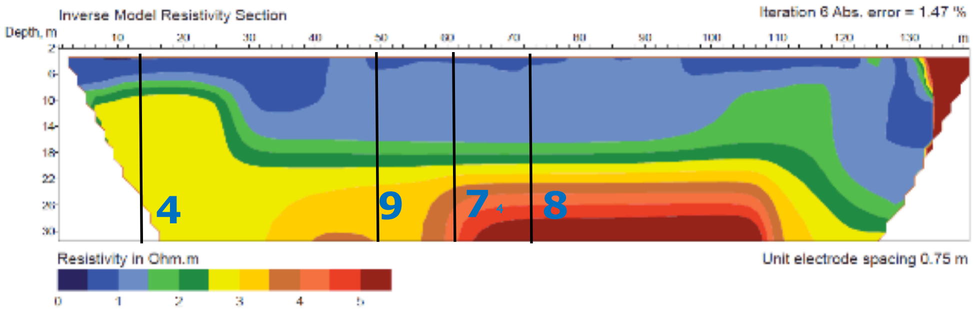

Figure 15. Inverse 2D model of field data in a pole-pole mode along the NW-SE direction (orthogonal to coastline). Position of MAG4, MAG7, MAG8 and MAG9 are indicated.

Surface and downhole seismic surveys

The physical properties of the reservoir layer, as well as the presence of a lithographical unconformity in the sedimentary sequence or the evidences from well logs, suggest that acoustical impedance contrasts may exist at shallow depth, allowing a seismic monitoring of the proposed experiment. Furthermore, desaturation induced by the gas injection could also significantly affect both density and seismic velocity of the reservoir layer. For these reasons, different seismic survey configurations were tested, both at the surface or using boreholes. However, it should be reminded that the thickness of the reservoir layer is only a few meters, so very high seismic resolution and sophisticated processing are required.

A seismic surface survey at 1m trace interval (77 shots, 32 receivers), parallel to the NE-SW electrical resistivity tomography profile (Fig. 5), was carried out on June 15-16, 2010. The data processing was achieved using the new CRS stack method (Jager et al., 2001), followed by depth migration. Figures 16 illustrates the field results, where only events passing reliability criteria based on data coherency are shown. The traveltimes of the most superficial events that were recovered (0.015 to 0.04 s) correspond to the holocene-pleistocene unconformity to bottom of reservoir layer depth range (9 to 16 m), albeit the limited seismic resolution. This result confirms the potential of the seismic method for the geophysical monitoring of the injection experiment. However, the amount of time required for the acquisition and processing of this dataset makes this setup inadequate for real-time monitoring, so other configurations, including both surface and downhole receivers, were investigated.

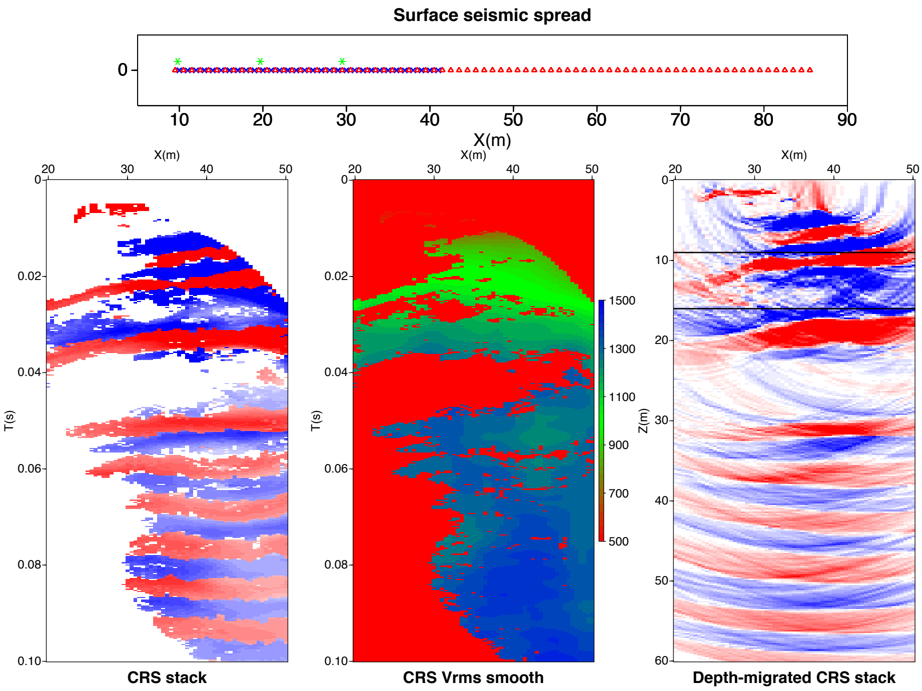

Figure 16. *CRS stack processing method* ***A.*** *Surface seismic spread: in red – seismic surface sources with 1m interval, in blue – surface geophones, in green – position of holes (from left to right: MAG1, MAG8 and MAG5).* ***B.*** *CRS stack processing: CRS stack section, RMS Velocity and CRS stack migrated to depth.*

A VSP-type experiment has been made in well MAG1, with a hammer source at 0.7 m from the well top, and receivers every 5m downhole, until 50m depth (*Fig. 17A*). First-break picks along this VSP profile were converted into 5m-interval velocities, showing values close to 2000 m/s, with a peak in the interval 15-20m, which could be at the origin of the reflection event starting around 0.032 s (two-way traveltime). The Vrms velocities derived from these picks are also very similar to those recovered by the CRS stack (*Fig. 16B*).

As an alternative to the VSP, which requires time-consuming receivers manipulations, a walkaway experiment has also been acquired, with a fixed receiver in the well, and moving shots away from the well at the surface, up to 40 m. This setup is reciprocal for a fixed shot in the well, and an array of receivers at the surface, which can be obtained very quickly, and therefore seems quite adapted for monitoring purposes, if a well seismic source is available. The corresponding profile is shown in figure *17B*, for a receiver at depth 15 m, that is within the reservoir layer. It reveals a more complex behavior in the short offset range, but a very clear linear trend for offsets greater than 25 m, whose slope correspond to a horizontal velocity around 2000 m/s within the reservoir layer.

Finally, a combination of both experiment types was obtained as an oblique multi-component profile, including a single shot at offset 24.5 m from MAG1, and three 3-components geophones at depths 10, 20 and 30 m within the well, in order to combine their advantages. The corresponding profile is shown in figure *17C*, with a single first-break pick obtained for each group of 3 traces (X, Y, and Z components). An interesting feature can be seen on the Z component (every 3rd trace), since a polarity change occurs between depth 10 and 20 m, that we interpret as an evidence for the record of an up-going wave (negative polarity) at depth 10m, while down-going waves (positive polarity) are recorded at depth 20 and 30 m. It means it exists a seismic reflector in the 10-20 m depth range, where our reservoir lies, as was already suggested by previous surface and VSP surveys. It therefore provides a very good opportunity for the seismic monitoring of the planned injection experiment.

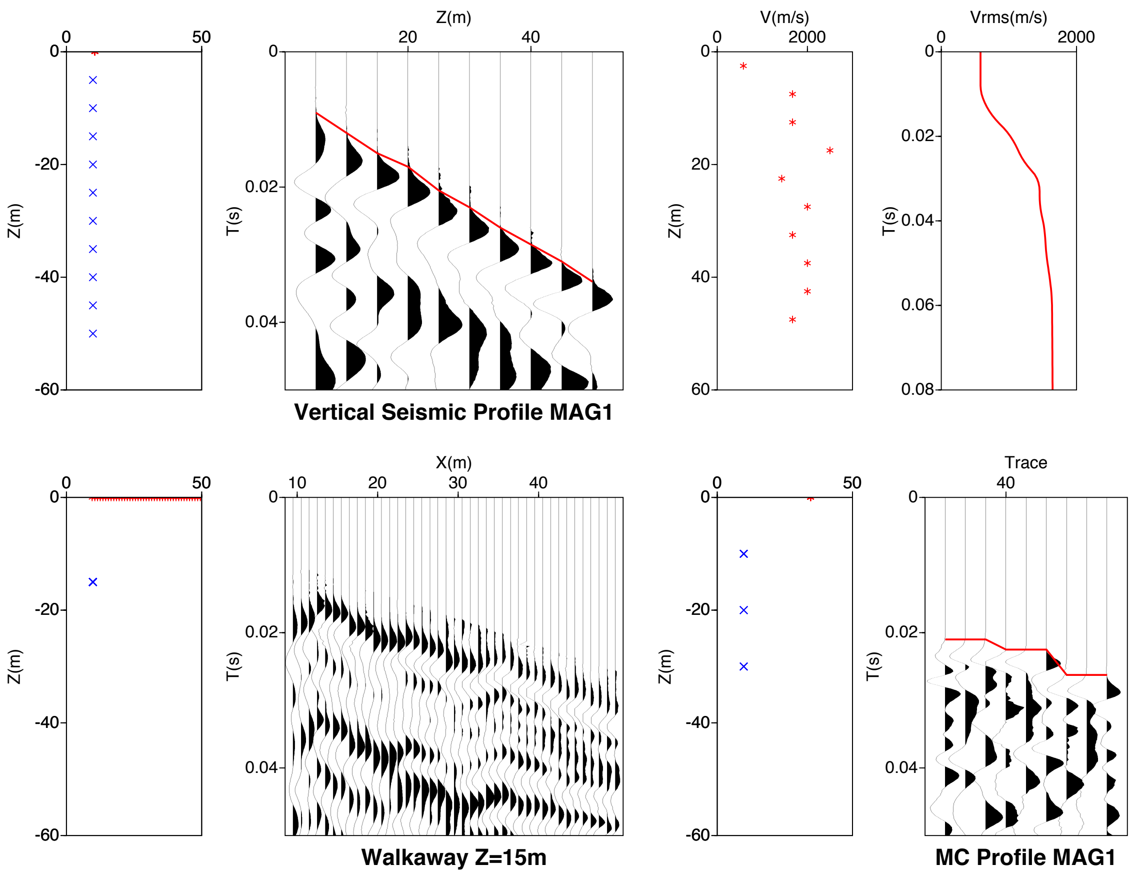

Figure 17. ***A. Vertical seismic profiling****. Set-up: seismic surface source (in red) and well geophones (in blue). VSP data recording with first arrival pick-up. Interval velocity model. RMS velocity calculated from interval velocity.* ***B. Seismic walkaway****. Set-up: seismic surface sources (in red), well geophone (in blue). Data recording for 15m depth geophone.* ***C. Oblique Multi-Component profiling****. Set-up: surface seismic source (in red), well geophones (in blue). Oblique MC data recording with one first arrival pick-up for each 3C geophone position.*

Seismic monitoring

As seen above, the oblique multi-component profile seems a good compromise for the seismic monitoring, and furthermore, an array of surface geophones can be added up to the configuration in order to complement the seismic record, at no cost. An example of the corresponding oblique surface-to-borehole seismic survey is shown at figure *18*. The raw shot record from the surface geophones array reveals the different waves involved, direct, refracted and reflected, which largely interferes with each other. In order to recognize the events of interest, reflection hyperbolas corresponding to the two superficial events, as obtained from the CRS stack image, were superposed on the shot record (*Fig. 18*). This allows to identify the best offset range, and corresponding reflection time, where these events can be easily monitored. For the first event, this range is achieved at geophone position 24 m (offset -10.5 m) and start time around 0.021 s. For the second, it is geophone position 14 m (offset -20.5 m) and start time around 0.032 s. These two events could then be monitored with time using these two receivers, and the corresponding time interval.

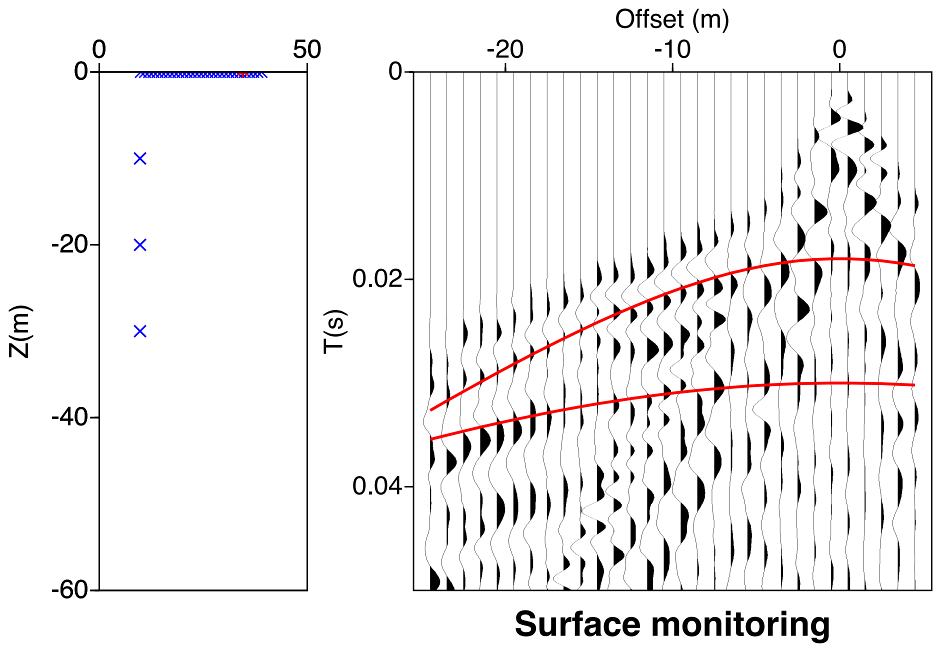

Figure 18. *Surface-to-borehole seismic survey. At left: Set-up geometry, surface seismic source (in red), surface and well geophones (in blue). At right: Data recording with reflection hyperbolas.*

Preliminary monitoring experiments were conducted with the oblique surface-to borehole configuration, involving repeated shots every minute during one hour, in order to verify the experimental setup and data stability prior to injection. Two types of sources were tested, hammer blows or weight drops, the latter being discarded due to triggering issues. Figure 19 shows the monitoring from one 3-components well geophone at depth 20 m, together with the monitoring from the selected surface geophones at position 14 and 24 m (for which the events starts are shown as black horizontal lines). In all cases, the data stability is quite satisfying, all events appearing as horizontal stripes (no time changes). However, a closer look reveals small time perturbations, probably related to the seismic triggering, and a very light and progressive color (or amplitude) shift, that could be related either to A/D converter instrumental drift, or to soil conditions due to the repeated hammer blows. Further experiments using a stable seismic source setup will be necessary to investigate the reality and nature of such changes, in order to not confuse them with changes linked with the gas injection.

Conclusion

A whole set of pre-injection experiments have been conducted at the Maguelon site, including well logs, electrical surveys, surface and well seismic acquisitions. The initial physical properties of the reservoir layer have been successfully characterized, with the exception of the electrical resistivity which cannot be accurately recovered from surface experiment only. Combined surface to well electrical surveys will therefore be tested when the electrical downhole observatories are available. Further pre-injection seismic monitoring experiments with a stable source configuration, as well as further injection simulations, will also be conducted in the near future, before actual injection could be performed.

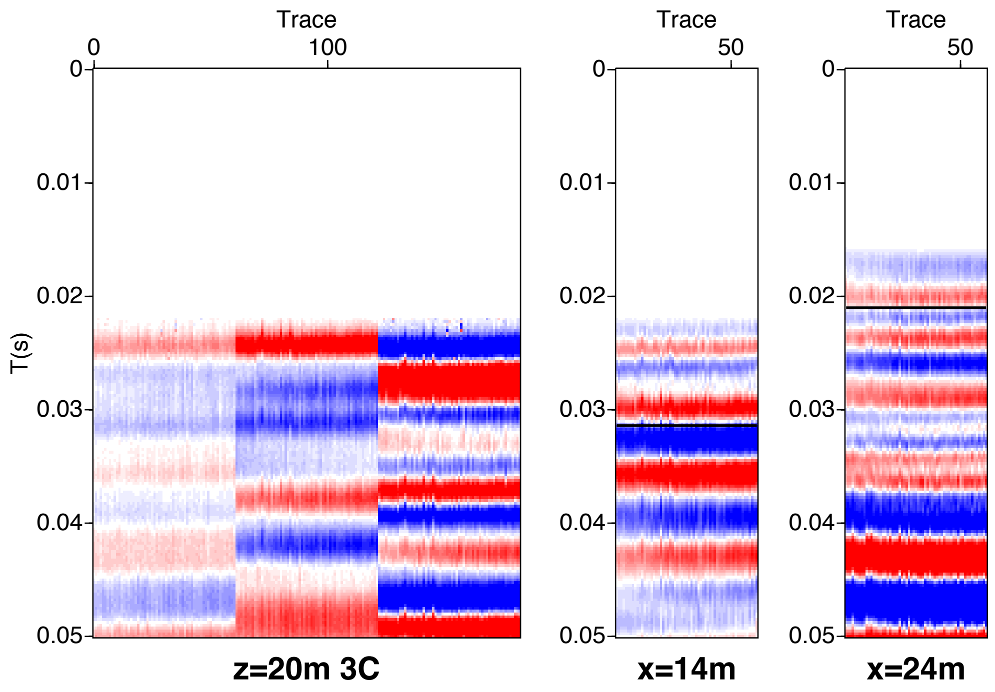

Figure 19. *Time-lapse seismic monitoring with a 3-Components geophone installed at 20 m depth into MAG1, and surface receivers at positions14 and 24 m, respectively (source located at 34.5 m).*

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