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# WP3

## HADES demonstrator report

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<b>RE</b>	Restricted to a group specified by the partners of the MoDeRn project	
<b>CO</b>	Confidential, only for MoDeRn partners	



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## **1 Summary**

This report documents the PRACLAY demonstration programme implemented in the HADES Underground Research Facility for the MoDeRn project. The main focus of the demonstration programme is the PRACLAY Gallery, where a long term heat experiment will be carried out to simulate a disposal gallery containing heat-generating, high-level radwaste.

The demonstrator part focuses on two instrumentation aspects related to repository monitoring conditions, namely: fibre-optic based sensing techniques and the long term micro-seismic monitoring of the Boom Clay.

The fibre-optic sensing techniques used are based on two principles: scattering (for distributed measurement of temperature), and interferometry (for strain measurement over long distances – up to 10 m). Specific issues related to this demonstrator project deal with the installation and operation of instrumentation in underground galleries as well as in boreholes located in the Boom clay.

The micro-seismic techniques included the development of a new seismic hammer to enhance the ability to generate shear (S) wave signals. The new hammer is necessary to improve the monitoring of S-waves in the near field. Signal processing was also improved to obtain more information from the measured signals, which included filtering out high frequency content from the data to improve the detection of S wave signals and the use of high frequency cut-off filters.

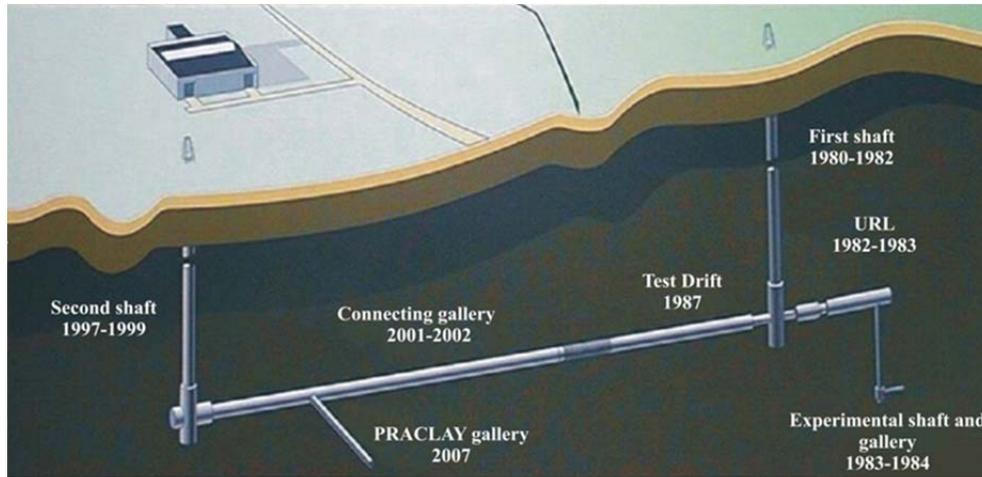
## **2 Objectives**

One of the objectives of the demonstrator project was to test the applicability in representative conditions (with the exception of radiation) of two types of fibre-optic sensors: (1) distributed sensing based on scattering (Brillouin and Raman) to monitor the thermal distribution along long (> 100 m) optical fibres, and (2) long-base (5 and 10 m) interferometric sensing to monitor the overall gallery expansion and the radial movement of the clay around the gallery.

S-waves are sensitive to structural changes in the clay and are, therefore, important to follow the evolution of the clay during the heat experiment. For example, they could provide information on the evolution of fractures and effective stress in the clay around the gallery during the heat experiment. The potential of micro-seismic techniques was also explored by: (1) monitoring the near-field (first few metres around the gallery) during different experimental phases (gallery excavation, ventilation, saturation, and heating); (2) enhancing the generation and interpretation of the S-wave signals; and (3) the construction of a new S-wave hammer to generate predominantly S-waves.

### 3 Introduction

The demonstrator site is the PRACLAY Gallery, shown in Figure 1, which is part of the HADES URL.



**Figure 1** The HADES URL showing the PRACLAY Gallery constructed in 2007 for the heat experiment.

The URL is situated at a depth of 223 m below surface, in the "Boom Clay" formation (from 190 to 290 m deep). Overlying the clay are water bearing sand layers extending to the surface. The clay has a water content of 35 to 40 % per volume and a pore water pressure of about 2.2 MPa.

Compared with older clays, the Boom Clay (Oligocene, 35 My old) is a relatively young, plastic clay. Due to its sedimentary origin, it exhibits a strongly anisotropic behaviour that can be observed e.g. in its stress state, hydraulic permeability, or thermal conductivity. The total stress is estimated at about 4.5 MPa. Geochemically, the clay acts as a reducing environment and is slightly alkaline (pH = 8.2; Eh = -0.250 V). The main component of the pore water is NaHCO<sub>3</sub> (at a concentration of about 1160 mg/l). The clay contains small amounts (1 to 5 %) of pyrite and organic matter. At distinct levels, concretions (septaria) are also present.

All major excavations, including shafts and galleries, in this type of clay require a structural lining for support. The galleries excavated in the last 10 years (Connecting Gallery in March 2002, PRACLAY Gallery in October 2007) have been lined with segments of unreinforced concrete. These consist of a wedge-block system with one or two key segments.

The PRACLAY Gallery, 40 m long, is lined with 30 cm thick segments and has an inside diameter of 1.90 m. At the beginning of 2010, a hydraulic seal was installed, at a distance of 10 m from the Connecting Gallery, to seal the PRACLAY heat experiment. The heat experiment consists of a 30-m long saturated and heated section of the PRACLAY gallery. At the location of the seal, the concrete lining has been removed and replaced by a cylindrical bentonite plug (Van Marcke et al., 2012).

The experimental part of the PRACLAY Gallery has been backfilled with sand<sup>1</sup> and saturated artificially to speed up the natural hydration by the clay. After saturation, and after the bentonite seal has developed sufficient pressure against the clay, which depends on the hydration and swelling of the bentonite, the heater will be switched on for a period of approximately 10 years. Due to the slow hydration of the seal, the switch-on has been postponed to 2014. The combined heating and saturation will generate expected temperatures of about 90 °C at the inside of the PRACLAY Gallery lining and 80 °C at the outside. The expected pore pressure increase will be up to 3 MPa as a result of thermal coupling and dilation of the pore water.

## **4 Experimental set-up**

### **4.1 Fibre optic interferometric sensors**

The (mainly thermal) expansion of the PRACLAY Gallery is monitored by three interferometric sensors each measuring 10 m in length and placed in series to cover the 30-m long span of the heat experiment. The radial movement of the clay formation around the gallery is monitored by 9 extensometers installed in three boreholes (Figure 2). One of the boreholes is installed upward (PG40U), one downward (PG40D) and one horizontal (PG40S). The design consists of 20-m deep boreholes each with three sensors (two 5-m long sensors; and one 10-m long sensor installed at the far end of the borehole. The presence of a water bearing septaria in the upward borehole limited its length to 10 m.

The fibre optic sensors are based on the SOFO gauge system. A SOFO gauge consists of two fibres inside a protective tubing. One of the fibres is fixed at both ends by two anchor points. The other fibre has similar length but sits loose inside the tubing. It is expected that the length of the latter fibre will not be influenced by the change in length between the anchor points, but only by temperature, making the sensor inherently temperature compensated. The difference in strain measured along each fibre can then be calculated by interferometry. These optical fibre gauges were selected because of their resistance to high water pressure and temperature expected near the gallery wall, and as an alternative to conventional borehole extensometers, which tend to fail when installed in a plastic clay environment.

Two of the nine SOFO fibre optic interferometric sensors installed in the PRACLAY gallery failed before the start of initial testing. One of the sensors failed during installation, while another broke during works in the gallery. In both cases, the failure happened in the connecting part of the fibre and not in its measurement section. The installation of the sensors was carried out following in-house procedures developed for the test. This was necessary due to the lack of installation procedures available from the supplier for this type of application. In

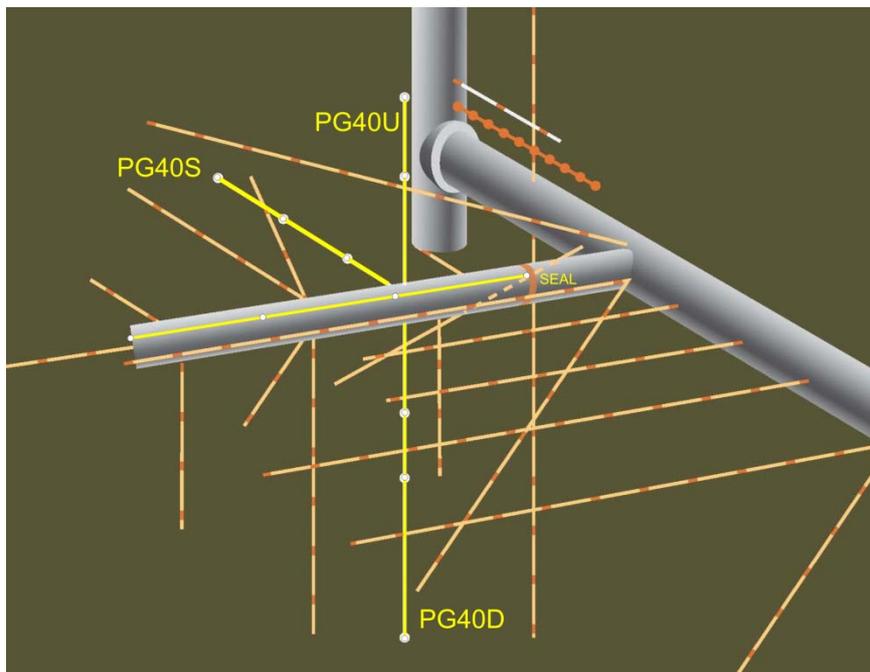
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<sup>1</sup> The underground PRACLAY test programme has been conceived as a generic experiment to investigate the effect of large-scale heating on the host rock, so concept-specific gallery design details such as backfill or the Supercontainer configuration are not dealt with in the underground heat test.

the future, generic installation procedures should be prepared to guarantee a better success rate for the installation of this type of novel sensor.

Data acquisition has been performed using a manually operated read-out system. The experimental conditions (installation conditions, water pressure and temperature) represent the main risks regarding the reliability of the sensors. For this reason, the most delicate parts (anchor points of the sensors) were installed with additional protection.

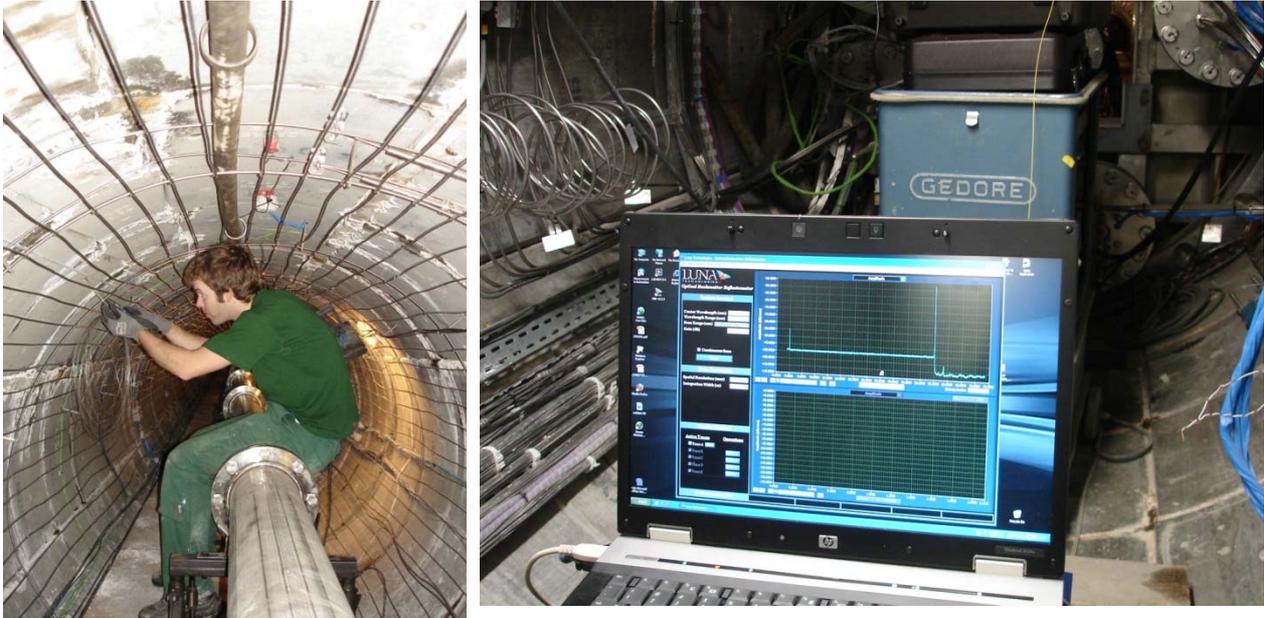
One of the aims of this work was to improve our understanding of the use of optical fibres for this type of monitoring and to propose adaptations to further enhance this technique.



**Figure 2** Location of fibre optic extensometers in and around the PRACLAY Gallery.

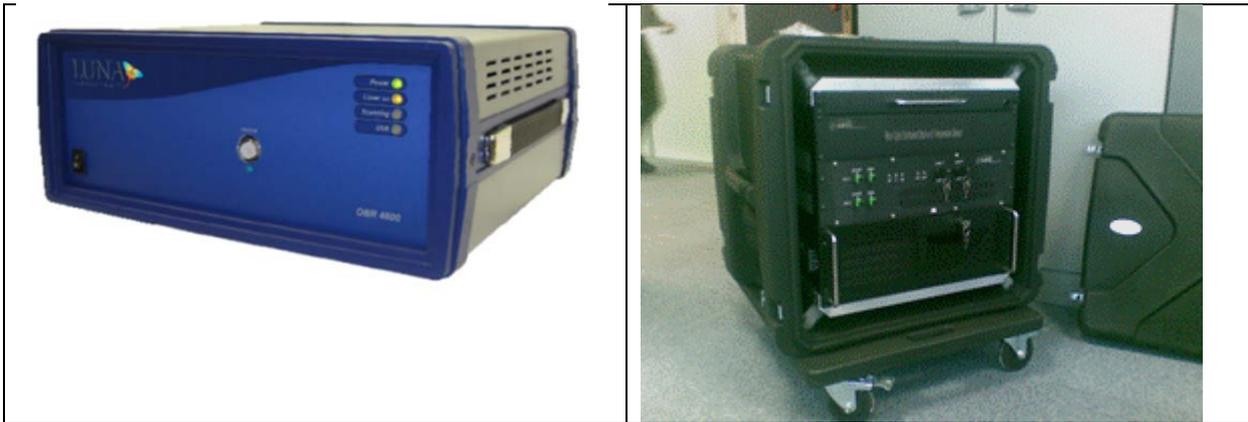
## **4.2 Distributed temperature monitoring**

A number of concrete liner segments in the PRACLAY gallery contain embedded temperature sensors. In addition, an optical fibre has been installed in the gallery to monitor the overall temperature field during the heat experiment (Figure 3). It consists of a single mode Draka optical fibre type SMF BBXS-PI with high-temperature polyimide coating. The fibre can be read using both Brillouin and Rayleigh scattering. The fibre has been installed in a capillary tube to provide additional protection during installation and to further minimize the interference caused by mechanical stresses due to the thermal response of the fibre.



**Figure 3 Installation of optical fibre for distributed temperature monitoring inside the PRACLAY Gallery[left]; and initial check of the optical signal using Rayleigh backscatter after installation [right].**

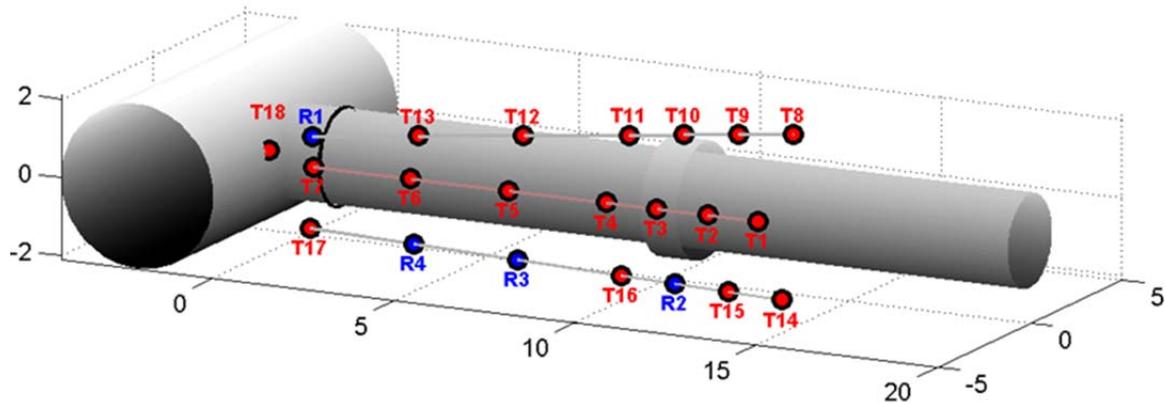
Data readout took place on an ad-hoc basis using read-out instruments (Figure 4) provided by the Nuclear Instrumentation department of SCK•CEN and ANDRA, as these types of instrument are quite expensive to purchase. Both the Rayleigh and the Brillouin backscatter methods have been tested. Rayleigh backscatter has been monitored with the Optical Backscattering Reflectometer (OBR) 4400, fabricated by Luna Innovations Ltd. It is an OFDR system with a spatial resolution of 10  $\mu\text{m}$  for the backscattering intensity measurements, and 1 cm for the temperature/strain. Figure 4 [right] also shows the Brillouin readout instrument used.



**Figure 4 Luna OFDR device used for the Rayleigh backscatter [left] and Brillouin backscatter readout device [right].**

### 4.3 Micro-seismic monitoring

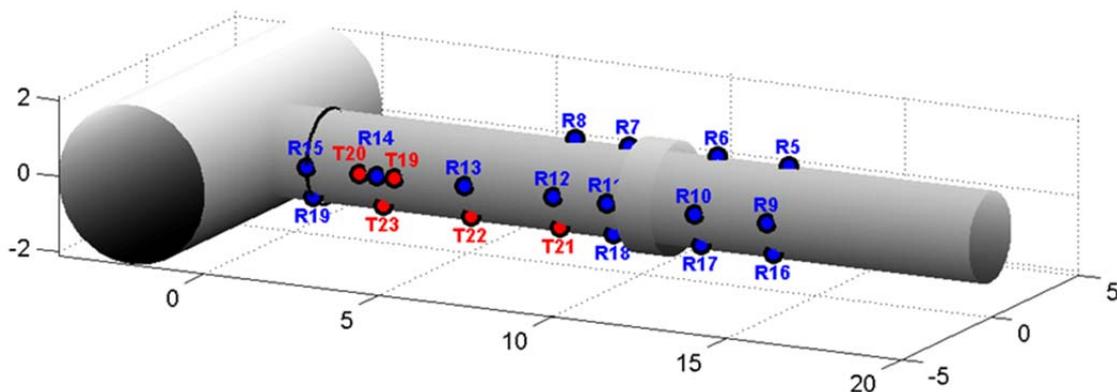
The micro-seismic installation consists of a conventional network of micro-seismic receivers and transmitters. Both are piezo-electric ceramic sensors, configured as a transmitter (driven by high-voltage signals) or as a receiver. The system has been installed in two phases. The first phase was installed in 2006, prior to the excavation of the PRACLAY gallery, and consisted of three boreholes located around the gallery to monitor the excavation works (Figure 5).



**Figure 5** Transmitters (T) and receivers (R) installed in 2006 in three boreholes around the PRACLAY gallery.

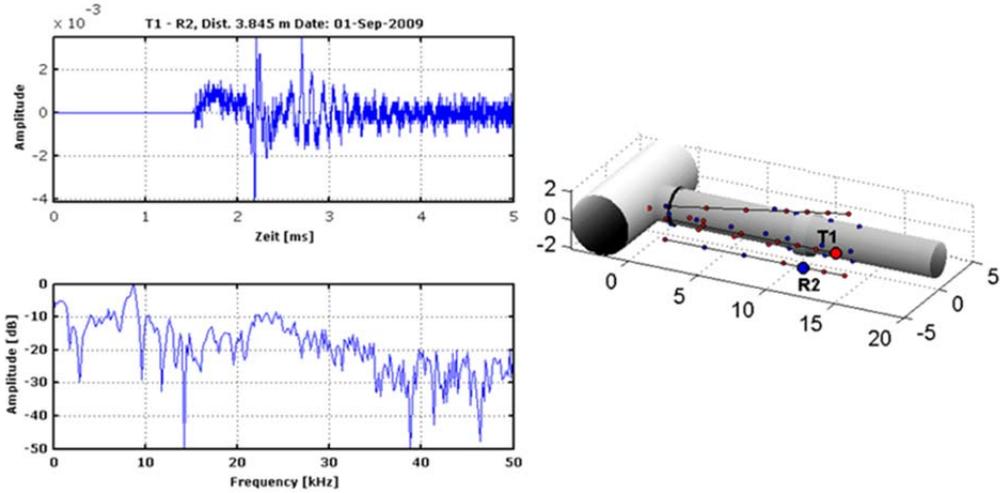
The second phase of the installation was carried out after the construction of the PRACLAY Gallery in 2007. This installation added additional sensors to the interface between the gallery lining and the clay, as shown in Figure 6.

The installation has been generating and recording microseismic signals on a daily basis since its initial installation in 2006. The system operates fully automatically in both active mode (signals are generated by transmitters) as well as in passive mode for the measurement of acoustic signals generated in the clay.



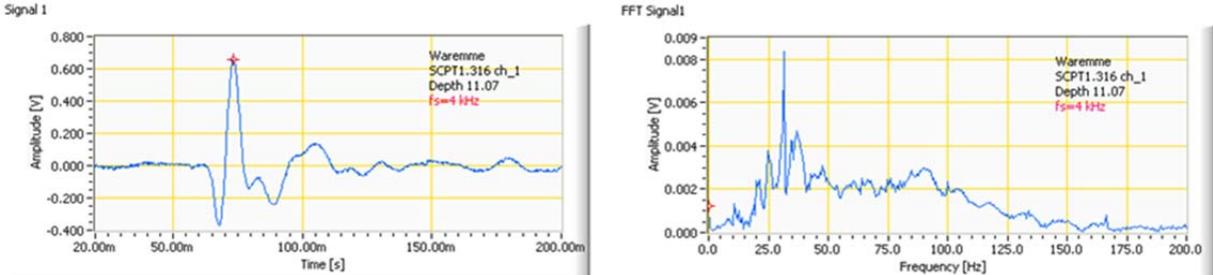
**Figure 6** Transmitters (T) and receivers (R) installed after the PRACLAY gallery excavation in 2007 at the interface between the Boom Clay and the concrete lining.

These micro-seismic sensors operate best at high frequencies, above 5 kHz, because of their inherent high background noise at frequencies below 5 kHz. These frequencies are quite suitable to generate primary or compression (P) waves in the Boom clay. Figure 7 shows typical P-wave signals generated between transmitter T1 and receiver R2. However, identifying shear (S) waves, which propagate predominantly in the frequency range between 0 and 5000 Hz, from the high frequency measurements requires special post-signal analysis to filter out the higher frequencies. Better still, is the installation of low-pass filters in the data acquisition (DAQ) system prior to signal generation.



**Figure 7 Typical time series [top]; and frequency spectra [bottom] obtained with micro-seismic installation in HADES between transmitter T1 and receiver R2.**

S waves in the Boom Clay are known to propagate predominantly in the frequency range between 1 and 1000 Hz (Figure 8). S waves are sensitive to changes in physical properties of the clay and will help assessing the mechanical response of the excavation damage zone (EDZ) around the PRACLAY gallery during the heat experiment. For this reason, attempts have been made to recover S waves from the signals currently measured by the micro-seismic installation, as much as possible. This consisted mainly in filtering out the higher frequencies during post-signal analysis and installing low-pass filters in the DAQ system prior to recording the signals.



**Figure 8 Typical time series [left]; and frequency spectra [right] obtained in the Boom Clay with an impact hammer similar to the one developed for the new S-wave hammer.**

Another attempt centred on the design of a new S-wave hammer to generate predominantly S waves. A prototype of the hammer appears in Figure 9. The hammer fits in a borehole with a minimum internal diameter of 95 mm. The hammer can be installed in any direction in the borehole in order to optimise the generation of S wave signals. A built-in anvil-and-piston system generates predominantly low frequency, S waves.

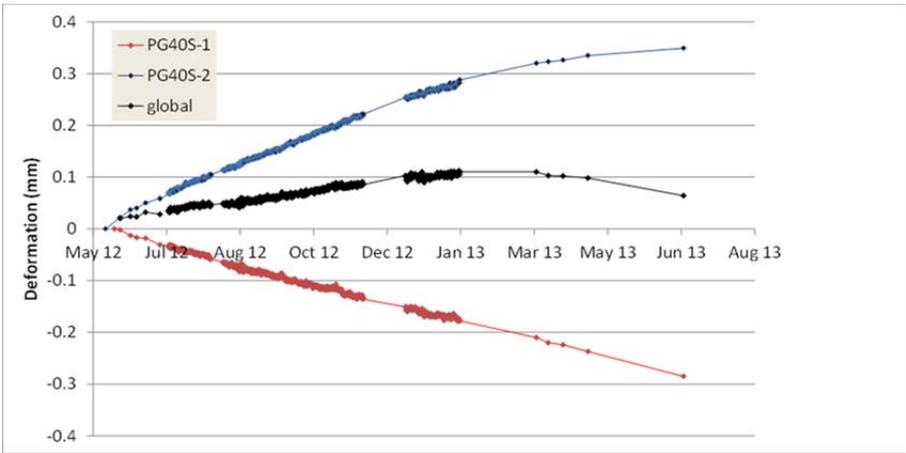


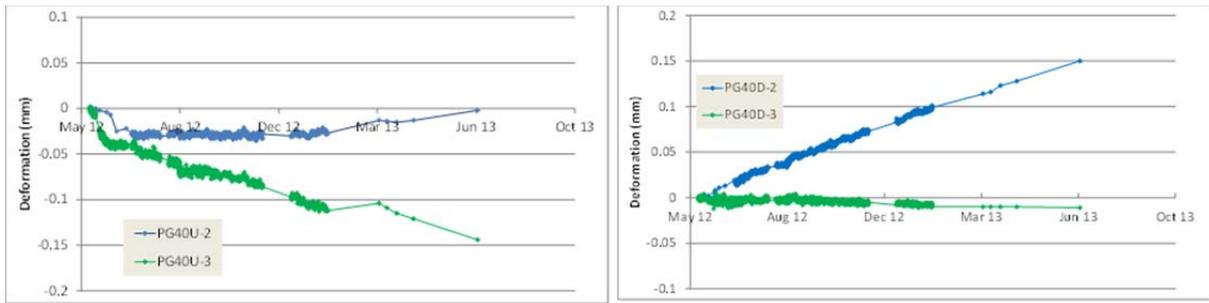
**Figure 9 [Left] 3-D design model; and [right] prototype of new seismic hammer designed to enhance the generation of S waves.**

### 5 Experimental results

The rate of hydration of the bentonite seal, installed in the PRACLAY gallery for the heating test, is slower than originally estimated. This has delayed the start of the PRACLAY test until 2014. Therefore, the results presented here are those obtained during initial control tests carried out at ambient temperature conditions.

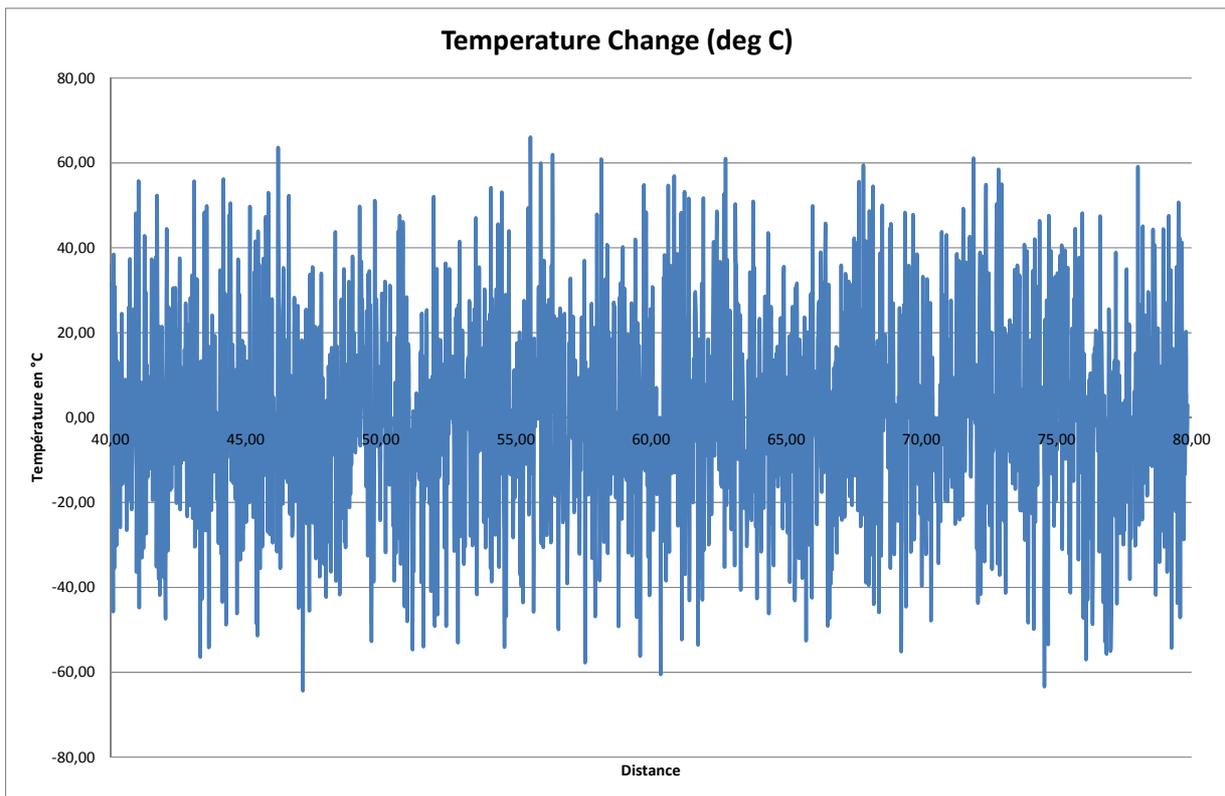
Typical measurements obtained with the fibre optic interferometric sensors appear in Figure 10. The sensors have a resolution of 1  $\mu\text{m}$  and an estimated overall accuracy of about 10  $\mu\text{m}$  over long periods of time, ranging from months to years. This allows the monitoring of strain with sufficient accuracy for use in repository monitoring. The results demonstrate the suitability of the SOFO sensors to monitor small, low-strain rates or deformation in a repository. Since the heat experiment has not started yet, their performance in a higher temperature environment, which could reach 100  $^{\circ}\text{C}$  or more, still has to be confirmed.





**Figure 10** Typical deformation measurements obtained using SOFO sensors installed in three boreholes around the PRACLAY gallery.

Two distributed temperature measurement campaigns were carried out in the PRACLAY gallery. Typical Rayleigh backscattered raw signals measured in the PRACLAY gallery appear in Figure 11. It is clear that the raw measurements do not provide a direct temperature profile of the gallery. In fact, the backscattered signal is influenced by many factors including the type of fibre (type/quality and dimensions of glass, cladding and coating), the installation characteristics (splices, connectors and type of fixation) and the experimental parameters being monitored, such as temperature and strain.



**Figure 91** Typical Rayleigh backscatter raw signal measured in the PRACLAY Gallery.

Similar measurements were obtained when using the Brillouin backscatter method. A fibre installed in 2005 along two boreholes of the ATLAS experiment in HADES (Figure 102) has been measured in 2006 and in 2013 (Figure 13). Although the actual temperature variation within the fibre, inferred from measurements made using thermocouples installed in the gallery next to the fibres, was less than  $\pm 2.5$  °C, which is also the global temperature variation

in HADES, the apparent temperature variations measured by the “stress-free” fibres exceeded 20 °C, as shown. The variations are most probably due to the residual stresses that resulted from the installation of the fibre. The peaks and valleys in Figure 13 can easily be linked to the double loop configuration of the fibre, as shown in Figure 12.

The measured frequencies shown in Figure 13 indicate that the strain can reach values up to several hundreds of a  $\mu$ strain. A variation of 20  $\mu$ strain corresponds approximately with a frequency shift of 1 MHz or a temperature variation of 1 °C. The Brillouin measurements shown in Figure 13 show a good repeatability between the two readout methods.

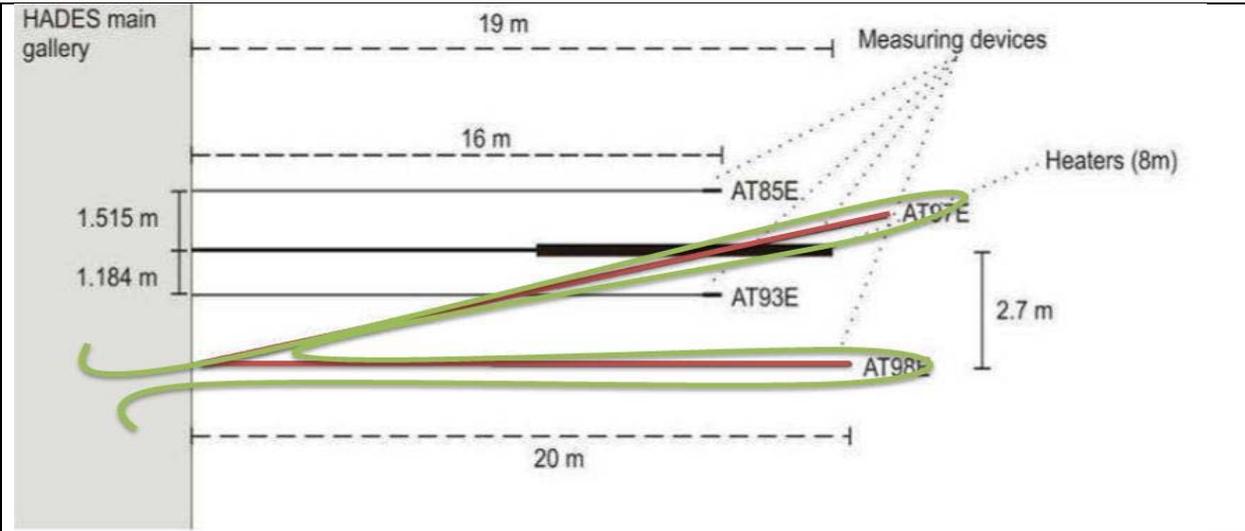


Figure 102 Plan view of the ATLAS experimental set-up in HADES showing one optical fibre running along instrumented boreholes AT97E and AT98E.

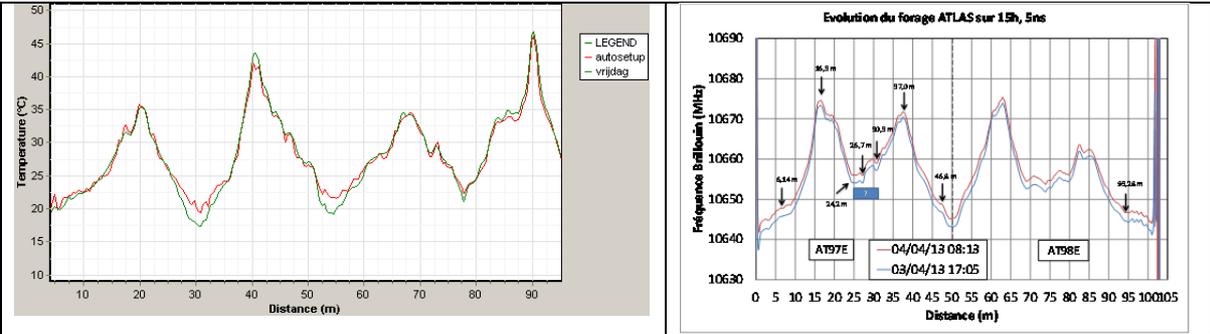
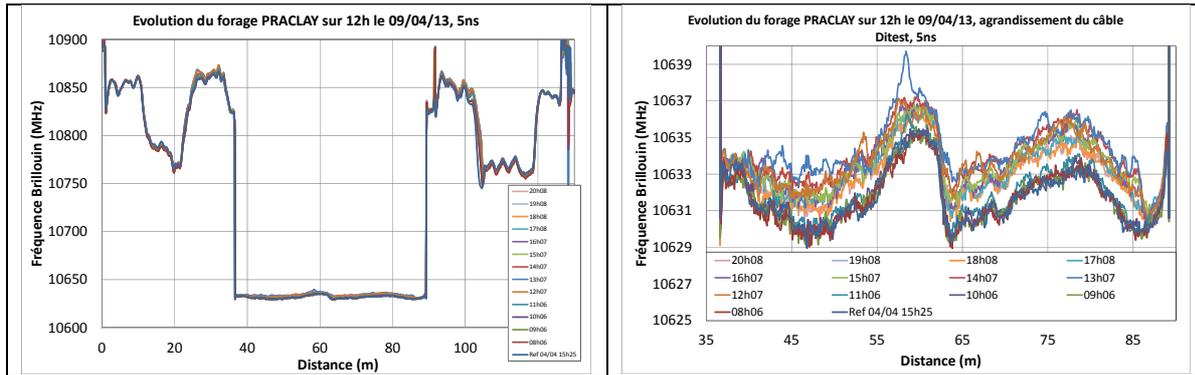


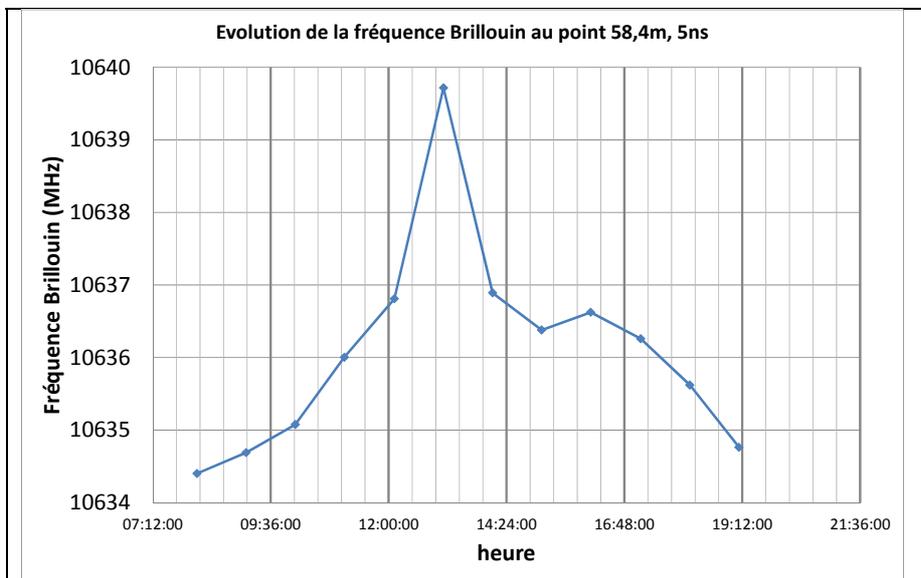
Figure 113 Brillouin measurements for the ATLAS experiment using two types of readout equipment performed on 2 June 2006 [left] and 4 April 2013 [right].

The Brillouin frequency measured in the fibre installed inside the PRACLAY Gallery, given in Figure 124, shows a smaller variation along the fibre (< 8 °C). This is still larger than the actual conditions, which are almost isothermal.



**Figure 124 Brillouin backscatter measurements for optical fibre installed in the PRACLAY Gallery: [left] overall fibre measurements including extensions, [right] detail measurements of the fibre in the gallery.**

Figure 135 shows the Brillouin frequency measured during a control test of the heater system, while the heater was switched on during a few hours.



**Figure 135 Evolution of the Brillouin frequency during a short heater test on 9<sup>th</sup> of April 2013.**

The interpretation of data acquired using optical fibres requires an elaborate calibration of the fibre's response against known parameter measurements. This is usually performed by adding classical temperature sensors, such as thermocouples, next to the fibre at specific locations to provide reference of the temperature measurements.

Calibration requires determining optical fibre characteristics, such as shifts in the intensity and frequency of the light as a function of change in temperature and strain; and an assessment of installation-related effects. Each installation has its own characteristics, such as the way the fibre is fixed, the number and quality of splices and connections, and the type of connectors installed. Part of the calibration can be performed by the manufacturer. However, to achieve maximum accuracy, an *in-situ* calibration is recommended.

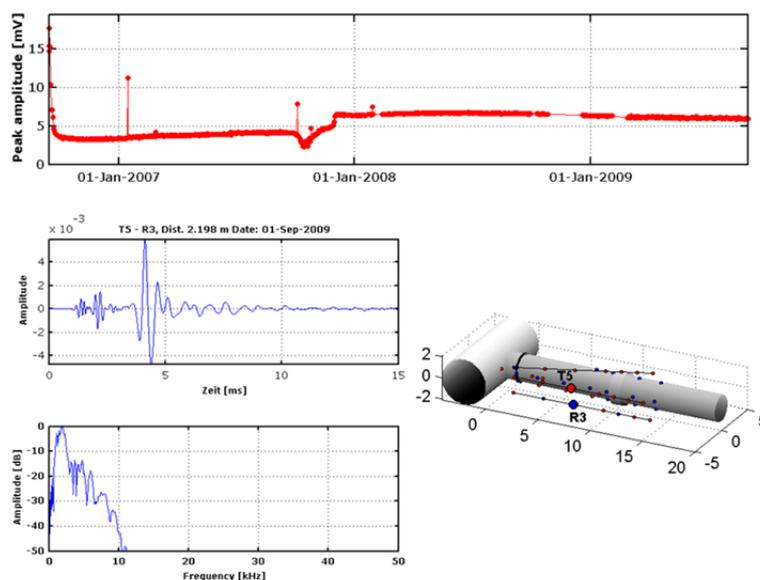
In theory, high accuracies with elevated spatial resolution (typically better than a metre) can be obtained, but this requires a comprehensive knowledge of processes that affect the

response of the fibre to the targeted parameter. For the measurement of strain and temperature, distinguishing between both parameters can be problematic, as a stress-free installation usually cannot be guaranteed.

The second Supercontainer half-scale test performed in 2014 made extensive use of fibre optics to measure strain and temperature in the three orthogonal directions. The test is part of an experimental program to demonstrate the construction feasibility of the Belgian Supercontainer. The results obtained with the use of different optical fibre techniques, which appear in a separate MoDeRn report, further demonstrate the potential of optical fibre technology for use in in-situ monitoring. In particular, optical fibres provide both high measurement sensitivity and low intrusiveness to the environment being monitored. At the moment, the fibres need to penetrate the engineered barriers in order to connect to the readout equipment, a condition that could limit its applicability as a monitoring technology suitable for use in a deep geological repository.

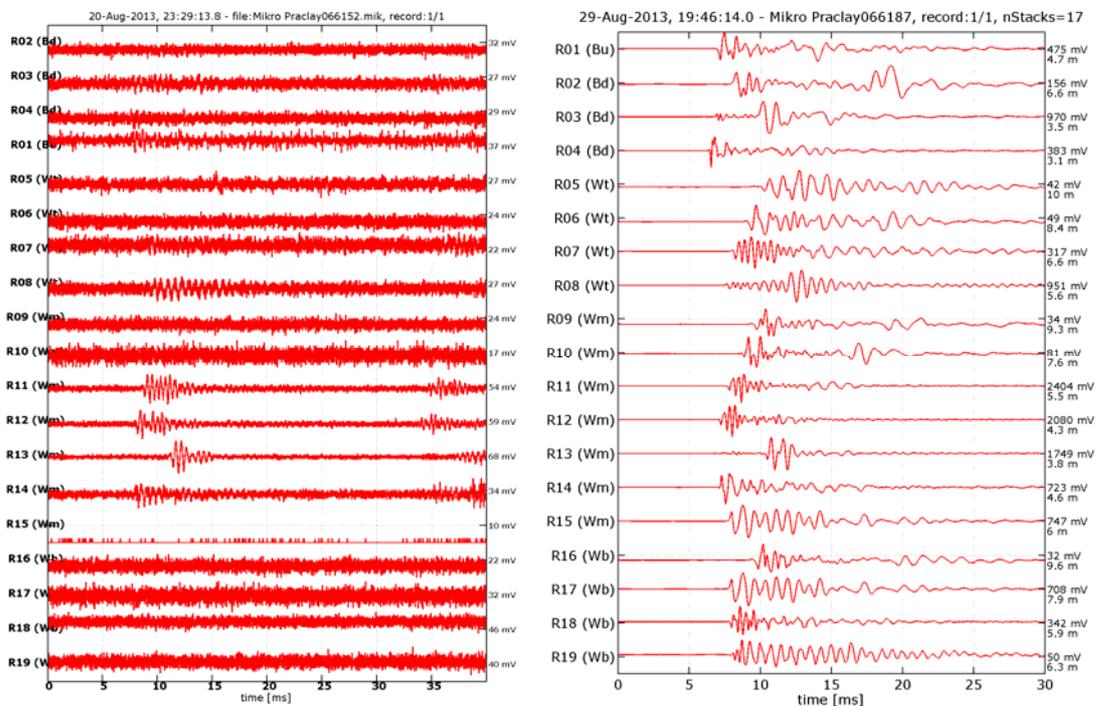
Although optical fibre technology can be considered as mature and fibres are now omnipresent in many uses, their application for monitoring purposes requires further development. In particular, calibration is a subject that requires further research and development. Finally, additional knowledge of cross sensitivity and other factors that influence the response of optical fibres is also required.

Analysis and interpretation methods of the existing micro-seismic installation data recorded in HADES have been modified (Areias *et al.*, 2012) to improve the detection of S waves. Part of the improvement comes from lowering the high-pass frequency from 5000 to 1000 Hz during post-signal analysis, which significantly improves the detection of S-waves. Another method that showed an improvement in the detection of S waves resulted from the installation of a low-pass 5 kHz filter in the DAQ system. The results, shown in Figure 16 for transmitter T5 and receiver R3, clearly show the detection of S waves after the installation of a low-pass 5 kHz filter.



**Figure 16. Evolution of S-wave signals between T5 and R3 from 2006 to 2009, low-pass filter 5 kHz, (Areias et al., 2012).**

Results of two tests performed in HADES with the prototype hammer appear in Figure 17. The prototype hammer was installed in a cased borehole, located next to the PRACLAY gallery. The first test campaign carried out on August 20<sup>th</sup>, 2013 (Figure 17, left) shows a significant amount of noise in most of the signals. After this test, improvements to the hydraulic system of the hammer were made before repeating the tests on the 29<sup>th</sup> of August, 2013. The signals generated during the second test (Figure 17, right) show a significant improvement in the S wave signals in comparison with the results of the first test campaign. Besides improvements to the hydraulic system, the signals in the second test campaign have been stacked, which further reduces background noise and improves the quality of the signals.



**Figure 17 Signals generated with prototype of new seismic hammer [left] showing first tests on 20<sup>th</sup> August 2013; and [right] after improvements to hydraulic system and stacking.**

Testing is on-going to further improve the quality and performance of the new S-wave hammer. When completed, the hammer will enhance the ability to generate S-wave signals and thereby to improve S-wave monitoring of the near field around the PRACLAY gallery during the heat experiment.

## 6 References

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Van Marcke Ph., Li X., Chen G., Verstricht J., Bastiaens W. and Sillen X. (2012). The PRACLAY experiment, Clays in Natural and Engineered Barriers for Radioactive Waste Confinement. Montpellier, France 22-25 October.