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Dossier

CO_2 Storage in the Struggle against Climate Change
Le stockage du CO_2 au service de la lutte contre le changement climatique

The Géocarbone-Monitoring Project: Main Results and Recommendations for Monitoring Deep Geological CO_2 Storage in the Paris Basin

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Résumé — Le projet de recherche Géocarbone-Monitoring : principaux résultats et recommandations pour le monitoring des stockages géologiques profonds de CO_2 dans le bassin Parisien — Le projet de recherche Géocarbone-Monitoring avait pour but principal d'évaluer et de tester, le cas échéant, les différentes méthodes de surveillance qui pourraient être appliquées au contexte géologique spécifique du Bassin Parisien. Les objectifs principaux de celles-ci sont de :

– détecter et cartographier le CO_2 dans le réservoir ;
– détecter les fuites éventuelles entre le réservoir et la surface et être en mesure de les quantifier.

Les recherches et les réflexions menées par les partenaires sur les méthodes de surveillance et de monitoring ont permis de dresser une vision critique des méthodologies existantes et de proposer des pistes de progrès. À l'issue du projet, des recommandations ont été rédigées à l'intention des parties prenantes du stockage de CO_2 (administration chargée de mettre en œuvre la réglementation des stockages, décideurs et futurs opérateurs de site) et un schéma général pour la conception et la mise en œuvre d'un programme de monitoring pour un test d'injection dans le Bassin Parisien en réservoir déplété ou en aquifère profond a été proposé.

Abstract — The Géocarbone-Monitoring Project: Main Results and Recommendations for Monitoring Deep Geological CO_2 Storage in the Paris Basin — *The aim of the Géocarbone-Monitoring research project was the evaluation and testing, as far as possible, of the different monitoring methods that might be applied in the specific context of the Paris Basin. Their main objectives are to:*

– *detect and map CO_2 in the reservoir rocks;*
– *detect and quantify possible leaks between the reservoir and the surface.*

The partners developed several thoughts and research concerning the various monitoring methods. This enabled drawing up a critical overview of existing methods and proposing leads for further work. At the end of the project, recommendations were made for the stakeholders of CO_2 storage, i.e. the government departments regulating storage, decision-makers, and future site operators. In addition, a proposal was made for the general design and implementation of a monitoring programme of an injection test in the Paris Basin, within a depleted reservoir or a deep aquifer.

INTRODUCTION

Monitoring is an essential aspect of the geological storage of CO_2, as we need real-time data on the evolution of a CO_2 plume and on any potential leaks (IPCC, 2005). In the case where a leak is detected, this should trigger any safety actions and corrective measures to stop the CO_2 from arriving at the surface. Surveillance is the backbone of a monitoring programme that, from the design phase onward, is based on risk analysis and is an integral component of risk management.

The main aim of the Géocarbone-Monitoring research project, funded by the French National Research Agency (ANR), was the evaluation and testing, as far as possible, of the different monitoring methods that might apply to the specific geological setting of the Paris Basin. Here, the potential reservoirs are either depleted hydrocarbon reservoirs in Dogger carbonate rocks at depths from 1 500 to 1 800 m, or deep aquifers in Triassic claystone-sandstone formations (depths from 2 000 to 2 500 m). The main objectives of the project were to evaluate the methods that can:
- detect and map CO_2 in a reservoir;
- detect and quantify possible leaks between the reservoir and the surface.

The project followed two complementary approaches: simulations on a numerical model, and full-scale field studies on sites of seasonal gas storage and natural analogue sites. Specific tools were developed as well; for instance, for gas sampling in wells. The partners drew up a critical overview of existing monitoring methods and further work, based on research and discussions. At the end of the project, recommendations were made for the parties involved in CO_2 storage, such as government departments in charge of drawing up regulations for storage, decision-makers, and future site operators. A general outline was proposed for the design and implementation of a monitoring programme on a test site in the Paris Basin, whether in a depleted hydrocarbon reservoir or in a deep aquifer. These recommendations are a useful complement to the Annexes of the European Directive on CO_2 storage, which concern risk management and monitoring.

1 GENERAL STRATEGY FOR MONITORING A CO_2 STORAGE SITE

The main objective of monitoring is the demonstration of safety, according to existing regulations. Demonstration of safety will be based on the lack of leakage from the reservoir and a good match between predictive modelling of the CO_2 plume behaviour and observations from monitoring. Monitoring will cover three main areas: control of containment integrity (well, reservoir and seal), behaviour and extension of the injected CO_2 flux, and leakage detection and mapping. The monitoring plan will be designed according to risk and environmental impact assessment and the results of the public hearings.

Monitoring will span the lifecycle of a CO_2 storage site. The pre-injection phase takes up to 5 years, the injection phase a few decades based on the site and the quantity captured, and the post-injection phase can last 50 years or more, including up to final closure of the site and the transfer of liability to the State. Figure 1 modifies an earlier diagram by the BGS (DTI, 2005).

Baselines will be acquired during the pre-injection period and should take into account the long-term monitoring requirements, in order to prevent massive or diffuse leaks. The operator ensures monitoring of the natural seismicity of the site by means of a micro-seismic data-acquisition network covering the injection area, and using dedicated observation wells. The adjacent or overlying aquifers are monitored through regular measurements including pH, alkalinity, dissolved gases, trace-element chemistry, water isotopes and redox potential, and by *in situ* sampling or measurements. Existing or new wells are checked for the condition of technical equipment and scaling. Soil gases are analysed at suitable intervals for flux and concentration through a suitably spaced network that takes into account the impact of biological activity. The condition of the biosphere (diversity, locations) is checked, in particular when the injected gases contain potentially noxious sulphur compounds. Finally, the lower atmosphere is characterised from a dynamic viewpoint, in order to assess the relative contributions of natural and anthropogenic CO_2. The objective of this check is to establish propagation models of CO_2 and associated gases in case of massive leaks, ensuring a monitoring of air quality above the site.

During injection, monitoring is either continuous or takes place during measurement campaigns designed around the specifics of the techniques used during the injection period. If no leaks are detected on the surface or in the aquifers, the monitored distribution of CO_2 is compared with the simulated predictions in order to validate, or not, the estimated sequestration capacity. In the case of disagreement, the geological model and the predictive simulations developed during the pre-injection period are updated by history matching.

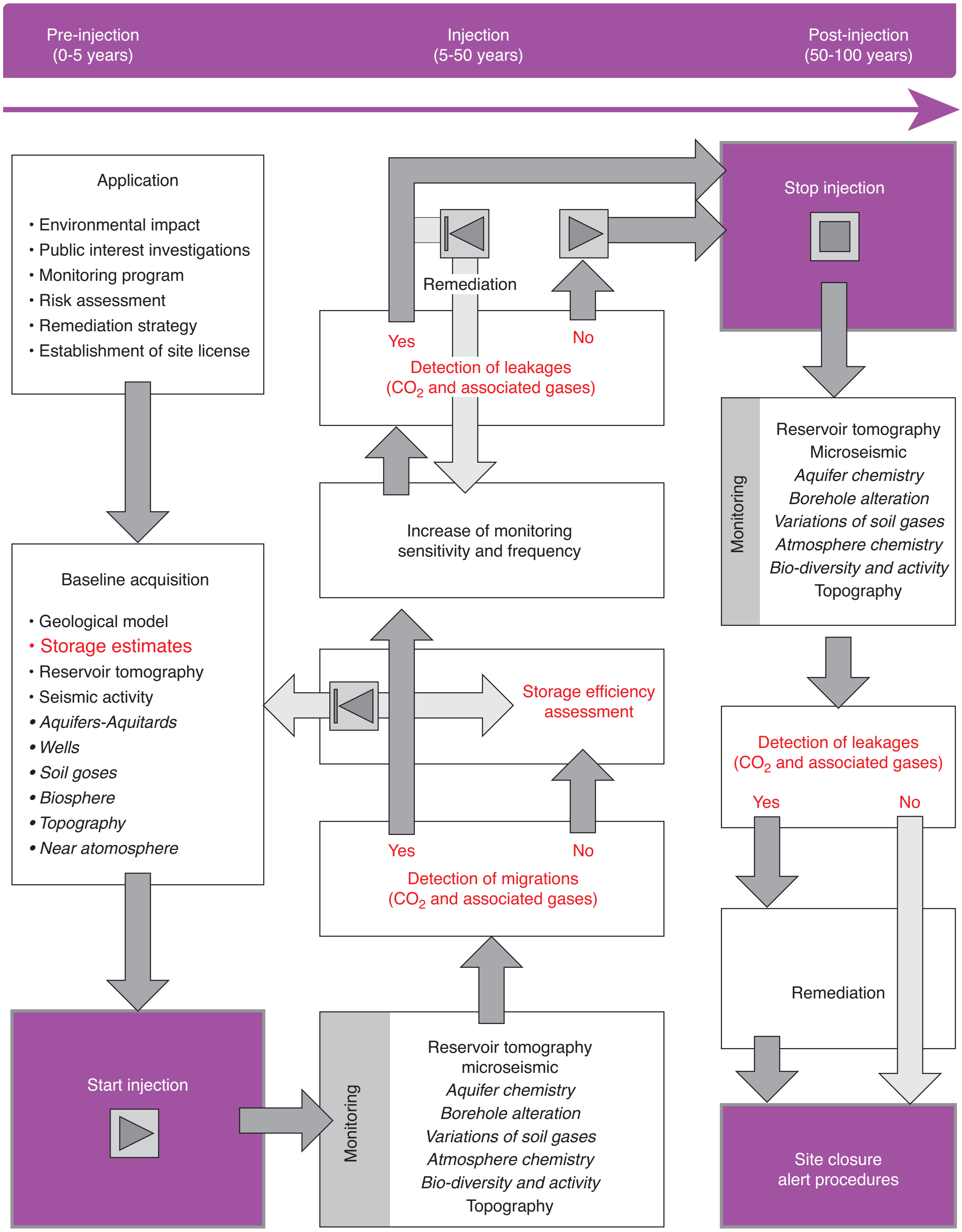

Figure 1

Synoptic diagram of the different steps in monitoring a CO_2 storage site.

Feedback into predictive simulations is carried out at all moments of the procedure until the end of the injection period.

In the case where a CO_2 leak is detected, the monitoring plan is updated and checks are intensified in sensitivity and/or frequency. When a leak is confirmed, the injection may be halted and the remediation strategy defined during the pre-injection phase will be implemented. If the repair succeeds, the injection may resume; if not, a definitive halt of the injection may be necessary.

When the sequestration capacity is reached, the injection phase is halted but monitoring continues throughout the post-injection period. If the system remains stable over at least 20 years (in the UE Directive), transfer to the State can be envisaged. Transfer implies changing the above-defined monitoring procedures for lighter procedures based on restricted warning devices. In the case where the system is considered as not stable and should a leak occur, the remediation procedures are implemented and the monitoring period is extended.

2 SPECIFIC CONTRIBUTIONS OF THE GÉOCARBONE-MONITORING PROJECT

In order to propose recommendations for monitoring in the specific case of the Paris Basin, the Géocarbone-Monitoring project group gained experience from numerical simulations and field work, on both seasonal gas-storage sites and natural analogues.

Concerning the ability of geophysical methods for detecting CO_2, modelling covered active seismics and electrical resistivity. The Saint-Martin-de-Bossenay site in France was selected for numerical modelling of 4D seismics (*i.e.* repetitive active seismics) as logging data were available (see Becquey *et al*., this issue). The modelling results indicate that an increase in *Dt* (transit time), corresponding to a lowering of *P*-wave propagation velocity, could be detected. This lowering is caused by a compressibility difference between the injected CO_2 and the *in situ* fluids. The expected reflection amplitude variations, around 4 to 6%, are below the detection threshold of classic seismics. Although the model can be improved by taking fracturing into account, the acquisition of new data (*i.e.* 2D or 3D seismic surveys, VSP, well logging, cores, etc.) remains indispensable in the case of full-size monitoring, thus allowing truly significant data processing and interpretation.

The use of electrical-resistivity imagery methods is based on the existing resistivity contrast between the resistant supercritical CO_2 and the conductive brine in place. The modelling developed for Géocarbone-Monitoring showed that with the selected model of electrical-resistivity distribution in the Paris Basin, the resistivity contrast between CO_2 and brine was insufficient for creating a signal that can be detected at the surface (see Bourgeois *et al*., this issue). This implies further work on refining the electrical model and selecting more favourable configurations (possibly selective injection of current into the reservoir through an *ad hoc* logging cable).

The feasibility of gravimetry in the Paris Basin was evaluated by means of repetitive measurements on the seasonal gas-storage site in Chémery (Loir-et-Cher Dept.). This showed reliable variations over time of the gravimetric signal that are partly related to shallow hydrological effects such as aquifer-level variations and soil humidity. Nevertheless, the results obtained by inversion with the compact-body method allow proposing an evolution scenario of the water level within the reservoir and of its migration, which agrees with the available data on the injection/recovery activities and the supposed reservoir geometry.

Satellite inferometry (InSAR) can detect surface deformation related to geomechanical changes in the reservoir or the overlying rocks. In the case of seasonal natural gas storage, despite the fact that operators are usually reluctant to publish data about the uplift or subsidence of ground level above these sites, it should normally be expected that the ground surface is affected by slight seasonal movements. InSAR was tested on the Chémery site, using satellite images from the period July 1995-March 1997. No significant changes were detected during this period, either with the standard method, that gives a precision of around 1 cm, or with the Permanent Scatterers (PS) method, that has a precision of around 1 mm. The latter result may be explained by the thickness of plant cover, the low density of PS measurements, or the short interval of only 70 days between the two PS-image couples.

As far as the sampling and analysis methods of gases and fluids are concerned, specific tools were developed and tested for CO_2 sampling in intermediate aquifers, *i.e.* down to 1 000 m depth (see Pokriszka, *et al*., this issue). The first results show that very low CO_2 concentrations can be detected. For surface measurements, accumulation chambers were adapted for low to very low flux measurements (0.05 to 2 $cm^3.min^{-1}.m^{-2}$). A continuous near-surface CO_2 measuring device based on FT-IR spectrometry was developed as well.

The Géocarbone-Monitoring project attached particular importance to measuring methods for gas in soil and at the soil-air interface, in order to quantify leaks in the shallow subsurface and on the surface, and for evaluating their impact on humans and the environment. Four project partners compared their tools and methods on two natural analogue sites in France, the natural CO_2 reservoir of Montmiral, active since 1990 (see Gal *et al*., this issue), and the volcano-sedimentary site of Sainte-Marguerite (see Batani *et al*., this issue). Three types of test were carried out in two successive years:

– continuous measurements with the above-mentioned FT-IR spectrometer;

- analyses of different soil gases (CO_2, CH_4, O_2, Rn and He);
- flux measurements with accumulation chambers, or specifically for radon rise using BARASOL™ sensors. The different measurements agree where they show abnormal CO_2 and radon gas-concentration values in space and time. Strong spatial variabilities are either related to regional tectonic lineaments (*e.g*. Sainte Marguerite), or have no apparent link with geological features (Montmiral). Strong variations over time (doubling of values) are explained by variations in permeability to soil gas due to seasonal variations. As mentioned in Section 1, it is thus indispensable to draw up a baseline covering at least a full year before starting any injection project, so as to define the presence of gases and their natural fluctuations.

Finally, an airborne survey of hyperspectral measurements was carried out over the two sites, to detect stress areas in the vegetation related to high CO_2 concentrations. In the absence of associated noxious gases such as H_2S or SO_x, the CO_2 does not seem to harm the vegetation cover, except in the case of high concentrations such as in Sainte Marguerite. In addition, two microbiological studies were carried out on two other natural analogue sites: Latera, in Italy, and Laacher See, in Germany. The impact of CO_2 leaks on soil micro-flora was evaluated and quantified by studying the bacterial populations and activities that might develop, or disappear, in the immediate vicinity of such leakage areas. This work showed that it will be possible to determine potential microbial indicators for CO_2 leaks.

3 RECOMMENDATIONS FOR MONITORING CO_2 STORAGE IN THE PARIS BASIN

As far as it has been evaluated through the Géocarbone-PICOREF and previous projects, the main characteristics of the potential reservoirs of the Paris Basin (see Brosse *et al*., this issue) are: depleted oil reservoirs and saline aquifers in Dogger carbonates or in Triassic sandstones, with permeabilities ranging from 0.1 to a few hundred mD, and salinities from 15-20 g/L to more than 200 g/L. The Dogger formation is relatively well known thanks to an extensive seismic coverage for oil exploration, many wells either for petroleum E&P or for geothermal fluid exploitation, and a few small oil fields still in exploitation. The Triassic aquifers are much less known, as they lie much deeper; acquisition parameters for seismics were optimised for Dogger, and only a few wells were drilled, mainly focused on a limited number of oil fields. Because of the extensive seismic coverage and well information, the structural geology of the Paris Basin is relatively well known with gently deepening layers towards the centre of the Basin and some faulted areas with throws not larger than a few tens of m. One important aspect of the Paris Basin is the presence of several aquifers of drinkable water in the overburden (*e.g*. the Albian aquifer, at 900 m depth, and the Neocomian at 700 m depth). Both are considered as strategic reserves and must be protected. The design of a specific monitoring plan will be based on the general strategy described in Section 1, the specific characteristics of the selected site and the main results of the Géocarbone-Monitoring project described in Section 2.

3.1 Controlling the Site Integrity

As for every storage site, control of the site integrity includes the monitoring of:

- injection pressure in order to not exceed the fracturation pressure of the seal;
- well integrity, measuring annulus pressures and possibly using wirelogging of the injection well(s) and the observation wells, if any. Up to now, observation wells have not been compulsory but the requirement for maximum security from the administration and the public will impose them. In the case of the Paris Basin, where using 4D seismic or other geophysical methods will not be straightforward (see *Sect. 3.2* and Becquey *et al*. and Bourgeois *et al*., this issue), observation wells are strongly recommended, at least for the future pilot projects;
- variations in the stress field: induced microseismicity and ground deformations are good indicators of significant changes in the local stress field. Monitoring with passive seismic and with tiltmeters and remote-sensing methods (Differential InSAR and PS InSAR) may be applied. As the Paris Basin is a relatively urbanised area, background noise could be high: therefore a permanent downhole array of geophones (in the observation wells and, if possible, in the injection wells) and dedicated corner reflectors for PS InSAR will be necessary *(see Sect. 2)*.

During the injection and post-closure phases, density of sensors of both methods could be modified, depending on the evolution of the storage.

3.2 Monitoring of the CO_2 Plume

The behaviour of the CO_2 plume can be monitored by measuring, directly in the wells:

- at the wellhead of the injection well, the injected quantity and the CO_2 flux composition;
- in the wells, the CO_2 saturation *in situ* and the depth of the Gas Water Contact (GWC), using wireline logging;
- pressure, temperature, conductivity, Redox potential, or even the dissolved CO_2 concentration using a multiparameter tool, that can be installed permanently in an observation well;
- geochemical composition of fluids sampled either in the reservoir or in the overlying aquifer will allow one to characterise finely the chemical processes occurring in the reservoir;

– active seismic measurement in wells: VSP and Walkaway, which are much more precise than simple surface 3D seismic.

Surface measurements give much broader information than measurements in wells, which are obviously too limited. The advance of the injected gas will be revealed by 4D seismic and the comparison between successive seismic images (2D or 3D) and the baseline. This is particularly true for the Paris Basin, where the layers likely to be used as reservoirs for CO_2 storage are deep (from 1 500 to 2 500 m) and, often, with relatively low porosity and not very compressible (Becquey *et al*., this issue). To be interpreted properly and be able to detect changes in CO_2 content with a resolution of the order of some tens of thousands of tons, the seismic image should be completed by well information: sonic logs in particular, lithology and well seismics *(see Sect. 3.1)*. In the case where the storage reservoir is limited to a geological structure, the emitting and receiving array should cover all of the structure with a margin of the order of one kilometre, allowing visualising the structure at depth. This survey should be repeated, for example, every two years during the injection period. Coverage and the rate of repetition may change depending on the displacement of the CO_2 plume.

Monitoring by gravity and electrical measurements was tested in Géocarbone-Monitoring. Gravity will provide valuable information about changes in density in the reservoir and then constrain 4D seismic interpretation, when the injected quantity exceeds several millions of tons. A strong control on near-surface-induced variations will be necessary as well as a precise description of density distribution in the reservoir and its overburden. In the case of storage in high salinity aquifers, electrical resistivity measurements could be combined with seismic measurements, allowing a better mapping of the CO_2 plume and saturation estimations where well information is not available. Results of modelling in the particular case of the Dogger Formation of the Paris Basin show that applying this method will be very site-dependent (Bourgeois *et al*. this issue).

As mentioned in Section 3.1, monitoring ground deformation generated by pressure variations in the reservoir and the overburden may be used as well to constrain mapping the CO_2 plume extension.

3.3 Detecting Leakage from the Reservoir

Concerning leakage of CO_2 into the overburden, this will imply deploying a specific monitoring strategy, in order to detect it as early as possible:

– CO_2 concentration in the overlying aquifers will be controlled permanently with observation wells, at least in one of the aquifers located between the reservoir and the deepest aquifer of fresh water (which could be at the top of the Dogger) and in the deepest fresh water aquifers (Albien and Néocomien). It is also recommended to control the aquifers used for other purposes: geothermal energy and oil extraction. Interference with other users of the aquifers will depend on the maximum extension of the CO_2 plume, and consequently, on the size of the project;
– tracers, which are much more volatile than CO_2 and likely to precede the inflow of leaking CO_2, could be added to the injected flux, on condition they are environmentally harmless;
– gas and fluid sampling and control of the water level in the shallow wells could be carried out on a regular basis (*e.g*. once or twice a year);
– concentration and fluxes of CO_2 should be controlled in the soil and atmosphere on a regular basis. Two baseline surveys should be carried out before beginning of injection, one during the “active” season of vegetation and the other one during the “passive” season of vegetation. A careful mapping of the natural fluxes should be set up all over the area of maximum extension of the plume, with particular attention paid to abandoned wells, faulted areas, and depressed or inhabited areas. After the pre-injection phase, the regularity of such measurements will be of the order of once a year. Frequency of surface measurements could increase, in particular around the areas with higher leaking susceptibility. Soil gas should be sampled as well in some points located out of the maximum CO_2 plume extension, in order to have references of natural emissions, varying with time and climate evolution and not affected by possible leakages.

4 CONCLUSION: GAPS OF KNOWLEDGE AND AVENUES FOR FUTURE RESEARCH

As a general comment about monitoring CO_2 geological storage, it is fundamental to note that CCS (Carbon Capture and Storage) is still in its infancy. At present, it is mainly based on the accumulated experience of the oil and gas industry. This means that the input from research and industrial-scale projects in the coming decade will probably modify the entire present-day methodological framework. Such research should be carried out in close cooperation with the government bodies in charge of regulations, with the standardisation organisations for safety and quality, and with the teams working on risk evaluation.

As seen in Section 2, many ways exist for improving geophysical methods. They mainly concern the *in situ* detection and quantification of CO_2 (evaluation of saturation). This in particular requires an integrated approach combining seismics, gravimetry, and electrical-electromagnetic or other methods enabling a proper quantification of the injected volumes.

The present difficulties of surface geophysical methods and logging tools for a precise definition of the presence of CO_2 reside in:

– a lack of sensitivity in the case of diffuse leaks;

- the impossibility of detecting dissolved CO_2 in water;
- the difficulty of detecting CO_2 leaks in sub-vertical faults and fractures, either because the volumes are too small, or because the methods are unsuitable for such structures, as is the case of seismic reflection;
- the general lack of resolution of geophysical methods at great depths, *i.e.* the incapacity to detect small volumes.

Among the possible fields of progress we can thus mention:

- more laboratory measurements are needed for defining the evolution over time of the physical properties of different rocks in the presence of CO_2, and under different pressure and temperature conditions. Ideally, one should have databases that can serve as reference for the interpretation of *in situ* measurements;
- the further development of permanent sensors in observation wells, or directly in contact with the storage reservoir:
  - increasing their life span that at present is limited to a few years;
  - minimising the increased risk of leaks from wells due to the presence of sensors and cables for power supply and data recovery;
- the application of airborne and satellite techniques, today still in the R&D phase:
  - airborne gravimetry, in particular gradiometry;
  - airborne hyperspectral and EM methods for detecting CO_2 near the surface;
  - radar interferometry (InSAR) for detecting vertical deformation of the order of a few millimetres, using the PS (Permanent Scatterers) method.

In geochemistry, the potential fields for progress in monitoring methods are:

- selection or development of appropriate technology, validated during field studies on pilot sites for CO_2 injection, or during bench studies in the laboratory;
- understanding the processes related to the presence of CO_2 in geological formations. To be efficient, the monitoring should be based on the inventory and modelling of the different processes that might be generated by the geological storage of CO_2;
- confrontation of geochemical data (*i.e.* gas content in soils and fluids) with geological data and geophysical measurements;
- calculation of tracer quantities to be injected;
- testing and improvement of isotopic methods (rare gases and carbon).

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