Abstract

This paper provides a general description of the research project "CO2 Field Laboratory for Monitoring and Safety Assessment" (CO2FieldLab) including the objectives, activities performed to date and main conclusions. Although a well-chosen and well-designed storage site is not expected to leak, the issue of leakage has to be addressed. Therefore, this project comprises two controlled releases of CO2 in the shallow (approx. 100 m) and very shallow (20 m) subsurface onshore Norway. The very shallow controlled release of CO2 took place in September 2011. The CO2 displacement in the subsurface and at the surface has been monitored with an exhaustive set of techniques deployed by the different partners. This approach enables an evaluation of the sensitivity of monitoring systems to detect shallow CO2 migration and leakage at the surface. These results will be up-scaled to assess monitoring systems and requirements that will ensure safe CO2 storage. CO2FieldLab has also performed an exhaustive appraisal of the site that is briefly presented in this abstract. The work in this project will contribute to the development of a monitoring and certification protocol that would be a significant milestone in a standardization process. A short overview of the project work on the monitoring protocol is also provided. By using a range of complementary measurements it will be possible to test and calibrate the migration models in well controlled conditions. Finally, such a demonstration is an opportunity to inform the public about the safety of CO2 storage by showcasing the performance of monitoring systems.

1. Introduction

According to ZEP (2012), the critical role of CCS in meeting European Union (EU) and global climate targets is now indisputable: it can not only abate at least 90% of emissions from the world’s largest emitters, but complement the large-scale deployment of intermittent renewable energy sources with low-carbon base-load power generation and balancing capacity.

In the scenario analysis recently reported by IEA/OECD (2012), CCS accounts for slightly more than one-fifth of needed emissions reductions between 2015 and 2050 in order to reach a 2°C temperature increase.

1 Ph.D., Mechanical Engineer - SINTEF Petroleum Research, Norway
2 Ph.D., Environmental Geology – Norwegian Geotechnical Institute (NGI), Norway
3 Ph.D., Geologist – BRGM, France
4 Ph.D., Geologist – British Geological Survey (BGS), UK
5 Ph.D. – British Geological Survey (BGS), UK
6 Ph.D., Professor – CNRS, France
7 Ph.D., Scientific Advisor – imaGeau, France
8 Ph.D., Bureau Veritas, France
9 Ph.D., Geophysicist – SINTEF Petroleum Research, Norway
10 Ph.D., Physicist – SINTEF Petroleum Research, Norway
In the coming years, it is expected that CCS will go from the current technical demonstration phase to a commercial upscale. However, commercialization of CCS will only be possible when public acceptance is gained, probably on a case by case basis. The choice of storage site and the design of operations aim at a very low risk of loss of containment. However, mitigating such a risk includes deploying an appropriate monitoring plan.

The Carbon Capture and Storage Directive was approved by the European Parliament in December 2008 (EC a), mentioning the need for monitoring plans that enable the detection of significant irregularities, migration and leakage outside the storage complex. In addition, the European Trading Scheme Directive was amended so that CCS was included (EC b). The amendment implied that a standardized set of monitoring protocols will need to be defined to monetize carbon credits. This includes the capacity to detect and quantify leakage. If leakage occurs, emission credits must be surrendered.

Even though the detection of CO₂ outside the storage complex, and the quantification of CO₂ leaking at the surface are explicitly required by these two directives, protocols to perform such tasks are not mature yet. The absence of monitoring, measurement and verification protocols does not stem from the need for new technologies but rather from the lack of relevant field tests. Indeed, many techniques are potential candidates for leakage detection outside the storage complex. Some are inherited from the oil and gas industry (seismic, electromagnetic methods and sea-bed sensors), while others come from a water management context (water permanent monitoring, sampling and chemical analysis) and are expected to be sensitive to dissolved or gaseous CO₂ migrating to the surface.

However, the required spatial and temporal resolution of each of these techniques for detecting CO₂ leakage is not well understood, undoubtedly site specific and therefore this is a central element in this project.

2. Project objectives

The CO₂FieldLab project aims at determining the sensitivity of monitoring systems to detect shallow CO₂ subsurface migration and seepage at the surface by means of controlled injection in shallow and very shallow subsurface of small amounts of CO₂ in permeable rocks in a well-controlled and well-characterised geological environment.

This type of controlled release experiment is unique at this stage and will fulfil four objectives: (i) determine the sensitivity of monitoring systems to detect shallow CO₂ migration and surface leakage, (ii) upscale these results to assess monitoring systems and requirements that will ensure safe CO₂ storage, (iii) test and calibrate migration models in well controlled conditions, and (iv) inform the public about the safety of CO₂ storage by showing the performance of monitoring systems.

Although several controlled releases are on-going at other sites (i.a. Postma, 2012, Lewicki 2009, Ginninderra (CO2CRC, Australia), the uniqueness of the project resides in the focus on detection limits and on the combination of monitoring tools and technologies. There is also an interest on finding repeatable and permanent networks.

2.1. Site description

The field laboratory is located at the Svelvik ridge at about 50 km south of Oslo (Norway) as illustrated in Figure 1. The formation is a heterogeneous glaciofluvial sand deposit formed during the last glacial age. The depth to the bedrock is between 300 and 400 m. The central part of the ridge is sub-aerially exposed with the top about 70 m above sea level. It forms a phreatic aquifer. In this part of the ridge, sand has been excavated since 1915. Further description of the site is given by Bakk et al. (2010).
This site was chosen as a field laboratory on the assumption that the sand ridge contains more or less homogeneous, unconsolidated, highly permeable sand, which offers well constrained conditions for controlled gas injection experiments. The appraisal work and the very shallow injection shows that the site has more complex bedding and channels and that contains poorly sorted coarse sand, abundant fines and pebbles.

3. Appraisal work

A series of surveys were conducted from November 2009 to December 2010 to characterize the site. This included:
- geophysical surveys including resistivity and seismic reflection profiles along two 2D lines and ground penetrating radar shallow profiles (February 2010)
- drilling, sampling and logging of a 333 m deep exploration well (June 2010)
- analysis of core and flow-line samples (July 2010)
- hydrodynamic, geochemical and soil gas surveys (August 2010).

Due to the risk involved in drilling in unconsolidated, highly permeable sand, reverse circulation method was used for the drilling of the exploration well. As a consequence, the depth reference and quality of the flow-line samples were very satisfactory. Therefore, the visual inspection of these samples in addition to well log data provides vital information about the sub-surface. The flow-line samples and cores show that the Svelvik ridge consists, as assumed, of permeable sand down to approximately 50 m. However, below 50 m results indicate layers or lenses of considerable vertical extent that consist of variable proportions of sand, silt and clay. Results also show that the sediment facies are dipping 10° North to South. Further information about the appraisal work is given by Bakk et al. (2010).

Prior to the very shallow injection, a more detailed feasibility study was carried out and the suitability of three different areas within the CO2FieldLab site was assessed with ground penetrating radar and surface gas measurements. Two areas were found to be unsuitable, due to either hard ground conditions which make gas sampling difficult, or due to the high water level (saturation at 25-65 cm depth). The third area did not have these problems. The surface gas measurements were used to assess baseline conditions. Soil gas concentrations and fluxes are low with CO2 concentrations mostly below 1.0 % and fluxes less than 8 g/m²d. This is consistent with the scarcity of vegetation. Chemical and environmental background data were also acquired in September 2010.

4. Very shallow injection monitoring

4.1. Objectives

During the very shallow injection experiment, small amounts of CO2 were injected at 20 m depth. The objectives were (i) to detect and, where possible, quantify migrated CO2 concentrations in soil and enabling a more accurate calibration of tool measurements, (ii) to evaluate the sensitivity of the deployed monitoring tools, (iii) to study the impact of the vadose zone on measurements and (iv) to rehearse and coordinate surface monitoring methods before
they are applied to monitoring the injection at approx. 100 m depth later in the project. A variety of monitoring methods were deployed for the field measurements, as presented in Table 1.

### Table 1. Monitoring methods applied during the very shallow injection in September 2011.

(*: Tubing connected to ALERT boreholes)

<table>
<thead>
<tr>
<th>Tool</th>
<th>Depth</th>
<th>Deployment</th>
<th>Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>GAS</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gas monitor station</td>
<td>c. 1 m</td>
<td>Fixed</td>
<td>Continuous</td>
</tr>
<tr>
<td>Flux station</td>
<td>Surface</td>
<td>Fixed</td>
<td>Continuous</td>
</tr>
<tr>
<td>Eddy covariance</td>
<td>Surface</td>
<td>Fixed</td>
<td>Continuous</td>
</tr>
<tr>
<td>Mobile laser</td>
<td>Surface</td>
<td>Mobile</td>
<td>Intermittent</td>
</tr>
<tr>
<td>Flux</td>
<td>Surface</td>
<td>Point (not fixed)</td>
<td>Intermittent</td>
</tr>
<tr>
<td>Radon/CO₂ monitoring probes</td>
<td>0.8 m</td>
<td>Fixed</td>
<td>Continuous</td>
</tr>
<tr>
<td>CO₂, O₂ and CH₄ monitoring (soil gas)</td>
<td>1 m</td>
<td>Fixed/mobile</td>
<td>Intermittent</td>
</tr>
<tr>
<td>Portable GC</td>
<td>Surface</td>
<td>Fixed</td>
<td>Intermittent</td>
</tr>
<tr>
<td><strong>WATER</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Sampling for chemistry and isotopes (using peristaltic pumps)</em></td>
<td>5,10 &amp; 15m</td>
<td>Fixed</td>
<td>Intermittent</td>
</tr>
<tr>
<td><em>Idronaut probe (piezometer)</em></td>
<td>2m</td>
<td>Fixed</td>
<td>Intermittent</td>
</tr>
<tr>
<td>Water sampling with West-bay completion</td>
<td>Several depth levels 1-20 m</td>
<td>Fixed</td>
<td>Continuous</td>
</tr>
<tr>
<td><strong>Borehole GEOPHYSICS</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4D cross-borehole resistivity</td>
<td>0 – 20 m</td>
<td>fixed</td>
<td>Automatic repeat</td>
</tr>
<tr>
<td>tomography ALERT</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2D resistivity observatory IMAGEAU</td>
<td>0 – 20 m</td>
<td>fixed</td>
<td>Automatic repeat</td>
</tr>
<tr>
<td>Logging (resistivity, gamma-ray,</td>
<td>0 – 20 m</td>
<td>fixed</td>
<td>Intermittent</td>
</tr>
<tr>
<td>sonic)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Crosswell radar (GPR) tomography</td>
<td>0 – 13 m</td>
<td>fixed</td>
<td>Intermittent</td>
</tr>
<tr>
<td>Pressure, conductivity monitoring</td>
<td>0 – 20 m</td>
<td>Fixed</td>
<td>Continuous</td>
</tr>
<tr>
<td>in West-bay well</td>
<td></td>
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</tbody>
</table>

A total of 1.7 ton CO₂ was injected at 20 m depth through a 45° inclined injection well between 7th and 13th September 2011. Figure 2 illustrates the drilling of the injection well while Figure 3 illustrates the site during operation.

Figure 2. Drilling of the injection well for the very shallow injection. August 2011.
4.2. Results

Surface gas monitoring was detected CO$_2$ seepage near the injection well head one day after injection. Another seep was found to the North-East three days later and another 2 days after (Figure 4). While the fluxes declined immediately after injection ceased, the water sampling system detected CO$_2$ close to the injection point during and after injection had stopped. Gas bubbling was observed in a 6 meter deep well to the north of the observed surface seeps.

Figure 3. The CO$_2$FieldLab site during the very shallow injection, September 2011. The CO$_2$ tank on the right provides gas through a 45º inclined well with injection at 20 m depth midway between the tank and the blue portacabin.

Figure 4. Soil gas CO$_2$ concentration (%) at 50 cm depth after 24, 72 and 120 hours of injection. Injection point is located at coordinate 15/10 (green star).
The following figures illustrate how the different monitoring methods detected the presence of CO₂ during the controlled release. Figure 5 illustrates the effect that CO₂ injection has on the Ground Penetrating Radar (GPR) 2D tomography measurements, showing evolution from baseline (left side) to post-injection – Day 8 (right side). The top figures show the velocity distribution and the figures below the corresponding time-lapse relative variation in percentage. This figure illustrates the effect that CO₂ injection has on GPR velocities.

![Ground Penetrating Radar (GPR) 2D tomographies.](image)

Figure 5. Ground Penetrating Radar (GPR) 2D tomographies.

Figure 6 compares the variation over time of the resistivity-depth profile due to CO₂ injection measured between the measurements of the 2D resistivity observatory imaGeau system and the 4D cross-borehole resistivity tomography ALERT system. The measurements are extracted at the same location, for comparison purposes.

![Variation over time of the resistivity-depth profile due to CO₂ injection measured with a) the imaGeau system (left) and b) the BGS ALERT system (right).](image)

Figure 6. Variation over time of the resistivity-depth profile due to CO₂ injection measured with a) the imaGeau system (left) and b) the BGS ALERT system (right).
Figure 7 shows electrical resistivity tomograms (measured by 4-borehole ALERT tomographic array) on day zero, four and eight after injection began. The transparent cubes on the left reflect the relative changes in resistivity compared to day 0. The images on the right display the absolute resistivity.

Figure 7. Electrical resistivity tomograms (measured by 4-borehole ALERT tomographic array).

The analysis of the monitoring data show that little CO$_2$ migrated vertically from the injection point and that most of it moved towards the East and North East. Geophysical results and water chemistry, in agreement with the surface flux measurements, further suggest that a considerable amount of the CO$_2$ remained dissolved in the pore water and did not migrate to the surface.

5. Development of monitoring protocol

A Monitoring Protocol is an agreed standardized method of installing equipment, performing measurements and interpreting the results. The measurements must be repeatable and reproducible. It covers all the phases of the CO$_2$ storage project: Preparation, Baseline monitoring, Operations monitoring and Post-Closure monitoring. The scheme of certification would verify that the successive steps are in compliance with the Monitoring Protocol. The Certification itself is a document that ensures that the Monitoring Protocol has been applied correctly.

The need for a monitoring protocol relies on the need to provide a key component of quality assurance and to ensure that the changes detected through monitoring are actual and not the result of differing equipment calibration, methods or skills. The monitoring protocol will enable consistent detection and quantification of CO$_2$ leakage – or lack thereof.

A monitoring protocol is under development as part of the CO2FieldLab project. The focus of the implemented version has been on the glossary, the risk analyses, the operation phase monitoring, the lessons learned and the update of the site instrumentation plan.

6. Conclusions and further work

The very shallow CO$_2$ injection performed in September 2011 in the CO2FieldLab project has provided valuable information regarding the behaviour of CO$_2$ and the effectiveness of the monitoring techniques. Even if the CO$_2$ did not migrate vertically from the injection point, most monitoring techniques showed sufficient sensitivity to the presence of CO$_2$ in the shallow subsurface. In particular, the CO$_2$ injection has resulted in a complex pattern of changes in electrical properties. Correlation has been observed between resistivity measurements derived from the ALERT models, the imaGeau electrical observatory and the wire line induction logging. Larger arrays covering a wider area would be required to achieve a more complete monitoring coverage. The majority of the changes observed is consistent with and are explained by simultaneous changes in pore water properties (EC, pH, alkalinity) observed by direct sampling.

The results indicate that the heterogeneity in the sand deposit may have caused the deviation of the plume path. This heterogeneity was not predicted based upon analysis of data from non-invasive methods prior to injection. Thus, post injection data, sand samples taken at depth and the characterization data are currently being used to build a reliable geological model that can explain both location and timing of the observed surface seepage and other
Further characterization of the layers at around 100 meter deep is on-going, preparing for a new semi-shallow CO₂ injection in the near future.

7. Acknowledgements

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