MONITORING TECHNOLOGIES USED AT SOME GEOLOGICAL CO_2 STORAGE SITES

Hannis S.[1]

1 British Geological Survey, Keyworth, Nottingham, NG12 5GG, UK, s.hannis@bgs.ac.uk , Telephone: (44) 115 936 3051, Fax: (44) 115 936 3446.

Carbon dioxide (CO_2) is being injected into geological storage sites around the world at both pilot and commercial scales. A variety of monitoring technologies are employed at these sites ultimately with the aim of demonstrating storage integrity both at the current time and also into the future. This paper reviews selected monitoring technologies employed at two pilot-scale and two commercial sites. At the pilot-scale CO_2 injection site at Ketzin (Germany), preliminary analysis of electrical resistivity measurements indicate the presence of injected CO_2 between the injection and monitoring wells. At Nagaoka, a pilot-scale CO_2 injection site in Japan, a suite of time-lapse wireline logs (including resistivity, neutron and sonic) were used to monitor injected CO_2. Resistivity readings increased in the injected formation and later decreased particularly in the layers below. This decrease was attributed to CO_2 dissolving in the formation water implying that the site is moving towards increased storage stability. Satellite-based monitoring is being used at the onshore commercial-scale CO_2 injection site at In Salah, Algeria, to monitor millimetre-scale ground displacement as a result of CO_2 injection. The displacement rates show a NW-SE trend, mirroring the known structure of the area, suggesting a structural control on the subsurface distribution of the CO_2. Sleipner is a commercial CO_2 injection site in the North Sea which has been in operation since 1996. Results of time-lapse (4D) seismic surveys over the site clearly show the migration of the CO_2 plume in the subsurface. The results add to the portfolio of successful 'fit for purpose' CO_2 storage monitoring techniques.

INTRODUCTION

Carbon dioxide (CO_2) is one of a number of greenhouse gases which contribute to climate change. In order to reduce anthropogenic emissions from large point sources, such as power stations, the CO_2 can be captured and stored underground in the pore space of geological formations. Very low permeability 'cap rocks' above the storage formation form a capillary seal and prevent the CO_2 returning to the surface. Monitoring of storage sites is necessary for a number of reasons including to demonstrate the site is behaving as predicted and to provide assurance that it is not leaking. In the unlikely event of leakage to surface, detecting any hazardous build up of CO_2 at or near the surface is of primary importance and any CO_2 escaping would require quantifying for emissions accounting. In the long term, it is likely that monitoring results will be a prime source of evidence that the site will continue to behave as predicted and is moving towards increased stability in order to facilitate site closure and transfer of responsibility from the operator to the State.

Geological storage of CO_2 is being demonstrated at several locations around the world both onshore and offshore and at pilot and commercial scales. The sites have a monitoring framework in place whereby multiple monitoring technologies are used in a complementary manner. The pilot-scale sites allow monitoring techniques to be developed and tested to further our understanding of CO_2 behaviour in different geological conditions and to help identify the most suitable technologies for large scale commercial storage. This paper reviews selected monitoring technologies at four different CO_2 storage sites (two pilot-scale and two commercial) on three continents. The monitoring results from these sites help to demonstrate the technological feasibility of geological storage of CO_2 (Michael et al., 2009).

CO_2 STORAGE SITES AND SELECTED MONITORING METHODS

Electrical resistivity tomography monitoring at Ketzin, Germany

The onshore pilot-scale CO_2 injection site near Ketzin is a former natural gas storage facility with storage in a sandstone at 250 - 400 m depth. Around 30 500 tonnes of CO_2 has been injected into a sandstone beneath this at a depth of 650 m. There are two monitoring wells about 50 to 100 metres from the injection well. All three wells are approximately 800 m deep and have permanent sensors cemented into the annular space behind the casing to monitor downhole pressure, temperature and for electrical resistivity tomography (ERT). Other monitoring technologies used at this site include wireline logs, tracers, surface and downhole seismic surveys and geochemical and microbial monitoring. The ERT method is described in more detail below.

The ERT measurements at Ketzin are taken using electrodes that are permanently installed behind the casing of the three wells and some measurements also use temporary surface electrodes. The resistivity of the formation between the electrodes is measured allowing the CO_2 plume to be tracked because CO_2 is more resistive than the saline formation fluids. Inversion modelling is used create a 3D image of sub-surface resistivity and hence CO_2 distribution. There are 15 electrodes at a 10 m spacing in each well between the depths of 590 – 735 m. These are known as Vertical Electrical Resistivity Arrays (VERA). Surface electrodes were also deployed for specific surface to downhole surveys in order to extend the area of investigation to a hemisphere about 3 km in diameter. Prior to injection, a baseline survey was carried out and continuous measurements have been acquired since the start of CO_2 injection. Each measurement cycle takes about one hour.

Preliminary ERT inversion results show the CO_2 plume between wells within the injected formation (Giese et al., 2009). ERT is well suited to this site as the saline formation water has a good contrast with the more resistive CO_2 and there are two monitoring wells arranged close by with electrodes installed. However the technique is quite low resolution, although it may prove to have a better sensitivity to CO_2 saturation changes at higher gas saturations (>20%) compared to seismic methods (Kiessling et al., 2009). A limitation of this technique is the necessity of having monitoring wells near the injection site. Additionally, if the sites also contain hydrocarbons, which also have high resistivity, interpretation is likely to be difficult. However at Ketzin, ERT has been successful at tracking the CO_2 plume between monitoring wells and so far all monitoring techniques show the CO_2 remaining in the reservoir.

Wireline log monitoring at Nagaoka, Japan

In total 10 400 tonnes of CO_2 was injected into a 60 m sandstone saline aquifer at 1100 m depth at the onshore Nagaoka pilot-scale site between 2003 and 2005. The injection well is surrounded by three monitoring wells, between 40m and 120m away. A variety of primarily well-based monitoring methods were deployed, including continuous temperature and pressure measurements, time-lapse geophysical well logging, *in situ* fluid sampling and cross-well seismic methods. The geophysical logging results are discussed in more detail below.

Fibreglass casing was used in the monitoring wells to enable use of standard (dual induction) resistivity tools. Sonic velocity and neutron porosity logs were also acquired. Geophysical logs such as these are routinely run in oilfields to determine the location and saturation of hydrocarbons. Laboratory experiments on rock samples indicated that a decrease in sonic velocity could be expected when CO_2 reached the monitoring wells (acoustic waves travel slower through CO_2). An increase in resistivity (CO_2 is more resistive than the saline formation fluid) and a decrease in the neutron porosity readings (the tool measures hydrogen, primarily found in the pore fluid which was expected to be displaced by the CO_2) was also predicted. Baseline logs were run prior to injection and 23 logging runs were conducted during injection followed by 13 post injection surveys (to June 2009).

Time-lapse wireline logging surveys at Nagaoka indicated the presence of CO_2 in the injected formation. CO_2 breakthrough was detected in two of the three observation wells by an increase in resistivity from 5 Ωm to 5.5 Ωm, a decrease in neutron porosity readings from 24 % to 14 %, and a decrease in sonic p-wave velocity from 2.54 km s^{-1} to 1.86 km s^{-1} as predicted. Resistivity later increased up to a maximum of 6.38 Ωm, as more CO_2 replaced the relatively conductive formation water (Sato et al., 2009). Post injection monitoring results showed a decrease in both the resistivity readings and the CO_2 saturations (calculated using the neutron porosity and the sonic velocity), particularly in the lower layers. These results were interpreted to be due to CO_2 dissolving into the formation water and sinking and free CO_2 migrating updip. This was verified using downhole geochemical sampling and suggests increasing stability of the storage as the CO_2 moves from structural to dissolution trapping (Xue et al., 2009). The very low salinity of the formation makes this site suitable for monitoring with resistivity tools. No signs of leakage have been detected.

Remote sensing (DInSAR) monitoring at In Salah, Algeria

At the In Salah natural gas field, CO_2 is separated from the gas stream at the surface and re-injected through 3 wells into the same reservoir dowdip of the gas field itself, below the gas column. More than 3 million tonnes of CO_2 has been injected into the 20 m thick sandstone, which is 1900 m deep and is overlain by a thin anhydrite seal and a thick sequence of low permeability mudstones. Various monitoring techniques are being used including geophysical logging, tracers, tiltmeters, microseismic, time-lapse 3D seismic, surface gas flux and satellite interferometry. The remote sensing methods are discussed in more detail here.

Differential satellite interferometry (DInSAR) uses multiple synthetic aperture radar images gathered from satellites to monitor for millimetre-scale ground displacements. Processing the images to measure the phase differences between images taken at different times over the same area allows ground displacements to be mapped through time. Repeat InSAR images of 36 scenes of C Band (5.6 cm wavelength) data were collected between July 2003 and March 2009. Images were processed (paired, filtered and stacked for noise-removal and to derive phase difference) to show displacement history over the area at a pixel size of 80m.

The processed, interpreted satellite interferometry data from the In Salah site shows surface displacement relating to subsurface pressure increase due to CO_2 injection. Surface uplift rates of up to 14 mm/yr around CO_2 injection wells and a 2 mm/yr subsidence around the gas producing wells were detected (Figure 1). Detailed analysis of the displacement time series shows close correlation with the injection history at each well. For example, there was no initial uplift around KB-502, because of an eight month delay in CO_2 injection and there was subsidence around the same well after a mid-2007 shutdown (Onuma and Ohkawa, 2009). The displacement shows a NW-SE trending prominence, suggesting a deep structural control on the underground CO_2 distribution (Vasco et al., 2008). The rocky desert at In Salah has a high image signal coherency which makes the site particularly suitable for the DInSAR monitoring technique. The surface displacement data relating to CO_2 injection is being integrated with numerical and geomechanical models of underground CO_2 distribution.

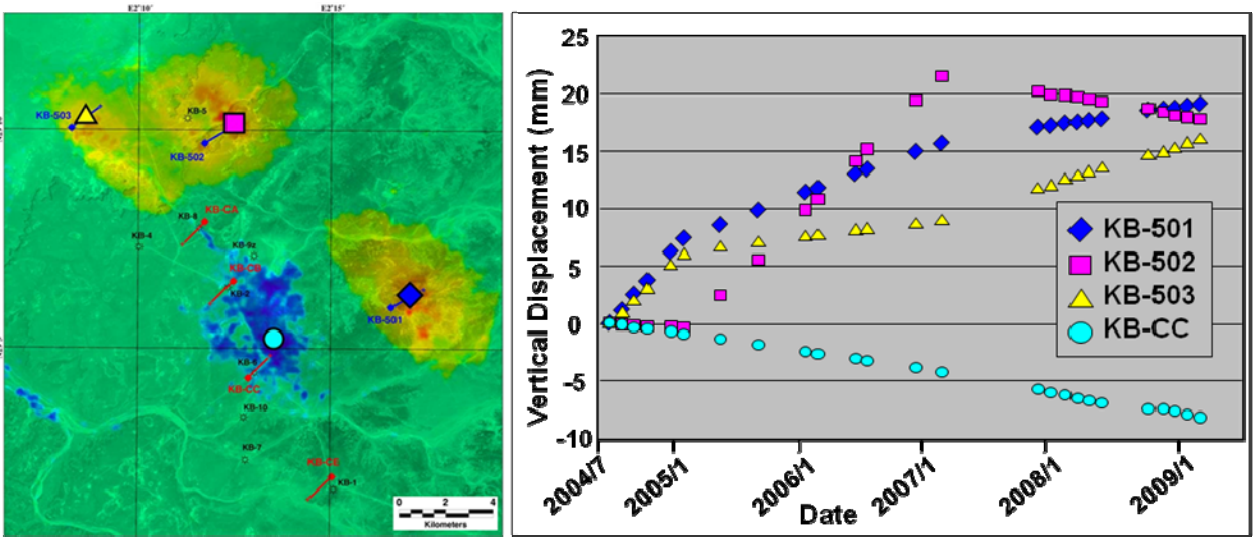

Figure 1: Satellite interferometry data from In Salah, Algeria. Left: Displacement from baseline over the injection period. Uplifted areas are yellow, areas of subsidence are blue. Right: Displacement history around three injection wells (KB-501 to 503) and a gas producing well (KB-CC). Locations are marked on the map (left) (courtesy of Onuma et al, 2009).

Time-lapse seismic monitoring at Sleipner, North Sea (Norway)

CO_2 has been injected at the Sleipner site in the North Sea since 1996. The CO_2 is separated from the extracted natural gas on site and then reinjected into a sandstone saline aquifer capped by mudstones at a depth of about 1000 m and approximately 12 million tonnes has been injected to date. No monitoring wells exist at this site, but temperature and pressure are monitored at the injection wellhead and non-invasive imaging surveys are used including

4D surface seismic, 2D high resolution seismic, seabed gravity, controlled source electromagnetic and seabed imaging surveys. The 4D seismic is discussed in more detail here.

Seismic surveys are acquired using an acoustic source which creates pressure waves that are reflected back off layers in the rocks that have different acoustic impedances. The returning waves are received by a series of hydrophones towed behind a ship. The recorded waveforms are processed to give an image of the subsurface. Seismic surveys are routinely run in oilfields to detect hydrocarbons. Gases and supercritical CO_2 appear as a 'bright spot' on seismic sections because the difference in acoustic impedance creates a strong reflection. At Sleipner, a baseline seismic survey was acquired in 1994 before injection and since then there have been six surveys, in 1999, 2001, 2002, 2004, 2006, 2008, with the aims of imaging the plume to track the migration of CO_2 and to demonstrate that no CO_2 has migrated out of the storage reservoir.

The time-lapse seismic data from Sleipner clearly shows the CO_2 plume development by the growth of high amplitude (bright) reflections. The CO_2 is injected near the base of the reservoir and it has migrated upwards and outwards from the point of injection. The 2008 survey shows the plume to be approximately 200m high and over 3000m long (along the long axis) (Figure 2). The stacked, roughly horizontal reflectors are interpreted to be the CO_2 spreading out under very thin mudstones within the sandstone. The CO_2 is now spreading out under the mudstone caprock where its distribution is being controlled by the topography and structure of that surface (Chadwick et al., 2009). Analysis of the velocity pushdown in 1995 (due to the decrease in velocity of the acoustic wave through the lower density CO_2) accounted for about 85% of the injected CO_2 (Chadwick et al., 2005) which is considered to be a satisfactory match given the uncertainties.

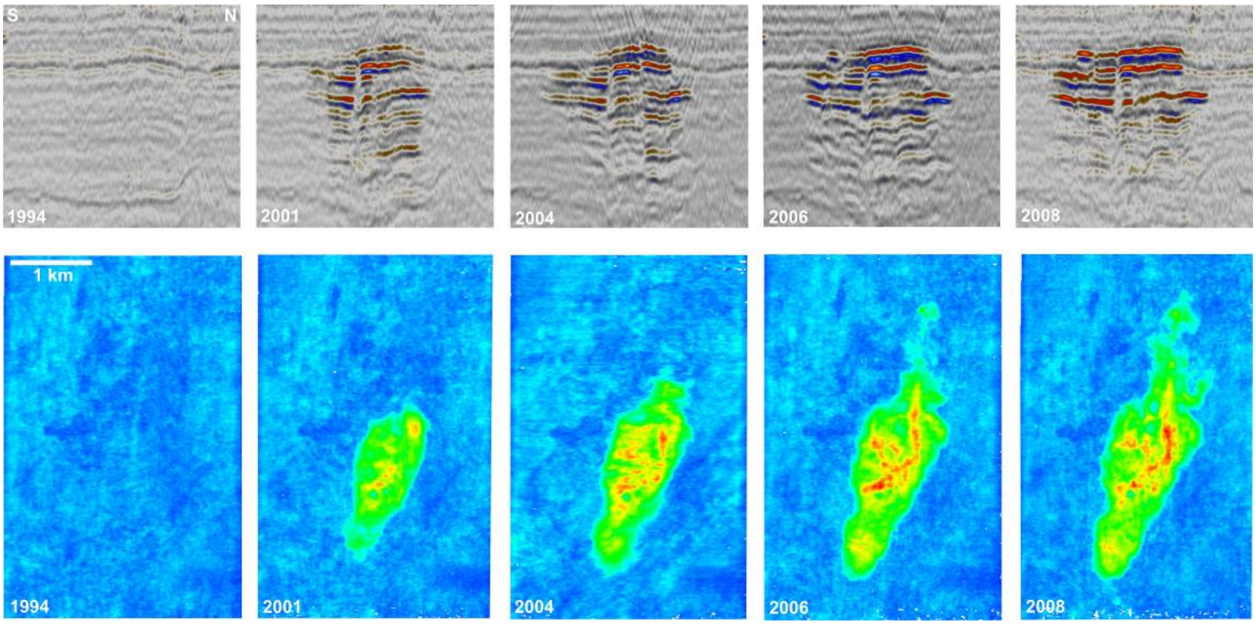

Figure 2. Time-lapse 3D seismic surveys of the CO_2 plume at Sleipner (baseline survey on the left). Top: 2D cross-sections. Bottom: plan view (courtesy of Chadwick et al, 2009).

DISCUSSION AND CONCLUSIONS

A variety of monitoring technologies are being applied at CO_2 storage sites around the world. Examples of effective 'fit monitoring deployments from four CO_2 storage site were examined in this study. The monitoring technologies and sites discussed in this paper were chosen because they cover a range of storage scenarios and the results at those sites demonstrate the technique particularly well. The results highlight that useful monitoring techniques are often site specific. For example using 4D seismic to monitor CO_2 has been shown to work very well at Sleipner where CO_2 is injected into a saline aquifer, but may give less information where CO_2 is injected into a depleted gas field, because of the likely difficulty in distinguishing between CO_2 and residual hydrocarbons. Certain monitoring techniques are likely to be required at all sites, for example the monitoring of wellhead or downhole pressure and temperature. The results add to the portfolio of successful CO_2 storage monitoring techniques and will help to improve public and regulator confidence in geological storage of CO_2.

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