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Monitoring CO_2 migration in an injection well: evidence from MovECBM

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Abstract

Carbon dioxide (CO_2) geological storage relies on safe, long-term injection of large quantities of CO_2 in underground porous rocks. Wells, whether they are the conduit of the pumped fluid or are exposed to CO_2 in the storage reservoir (observation and old wells) are man-made disturbances to the geological storage complex, and are thus viewed by some as a possible risk factor to the containment of the injected CO_2.
Wells are composite structures, with an inner steel pipe separated from the borehole rock wall by a thin cement sheath (~2 cm) that prevents vertical fluid migration. Both carbon steel and cement react in the presence of CO_2, although evidence from production of CO_2-rich fluids in the oil and gas industry and from lab experiments suggests that competent, defect-free cement offers an effective barrier to CO_2 migration and leaks.
However, reactivity of cement and steel may result in CO_2 migration pathways degrading over time, thus in the leakage risk increasing during the life of the storage project. The issue then becomes how to best integrate preventive verification of zonal isolation/well integrity in the storage site monitoring plan. An analysis of the order of magnitude of possible CO_2 leaks, and of their path to potable aquifers or the atmosphere, is also necessary to optimize the assurance (mitigation) monitoring of the storage site.
Evidence gathered during the MovECBM project indicates that migration of small quantities of CO_2 happened during injection in a coal seam in Southwest Poland. The evidence, gathered from casing and cement logging as well as soil gas monitoring over a 3-year period, was coupled with laboratory testing and extensive modeling of the chemo-mechanical behavior of cement and steel to determine if CO_2 migration might have been responsible of the observed behavior.
The three lines of evidence were: the detection of very small CO_2 fluxes, coupled with less controversial helium concentration in soil; the occurrence of a thin pathway at the interface between cement and casing; and the change in mechanical properties of cement, suggestive of partial carbonation.
Whereas the observations suggest that limited CO_2 migration might have happened in the well, they are by no means proof that the migration did happen. Nonetheless, the integration of measurement and modeling yields important lessons for wellbore monitoring.
First, it puts a probable ceiling on the order of magnitude of expected leaks from reasonably well-cemented wells at around 100 metric tons per year (less than 0.05% of the injected mass in a well like Sleipner or In Salah). It also suggests that cement may be a very effective leak detector: exposure to CO_2 modifies its mechanical properties, which in turn can be detected using cement

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evaluation logs. Finally, coupling with dispersion modeling suggests the precision and accuracy required from soil gas and atmospheric monitoring, as well as the placement of sampling points; it also suggest that hysteresis, due to the accumulation in CO_2 in surface aquifers and to the time required for it to be transported to the survey points, may delay initial detection; the same hysteresis may at the same time prolong the occurrence of CO_2 shows long after the leak has stopped.

Keywords: CO_2 geological storage; containment; wellbore integrity; leak; migration; cement evaluation; monitoring

1. Introduction

The European projects RECOPOL and MovECBM studied the injection of carbon dioxide (CO_2) in a coal seam at the Kaniow site (Upper Silesian Basin, Poland, see Figure 1) during the period 2001-2008. CO_2 injected into coal can help release absorbed methane – hence the name enhanced coal-bed methane (ECBM) for the technique – and ends up being captured within the coal structure, making ECBM a potentially attractive prospect for CO_2 geological storage ([1], [2]).

Injection happened at depths of around 1000 m through the 7" (0.178 m diameter) casing of MS-3, a new well purpose-built in 2001. An existing well (MS-1) was used to produce methane during the RECOPOL project.

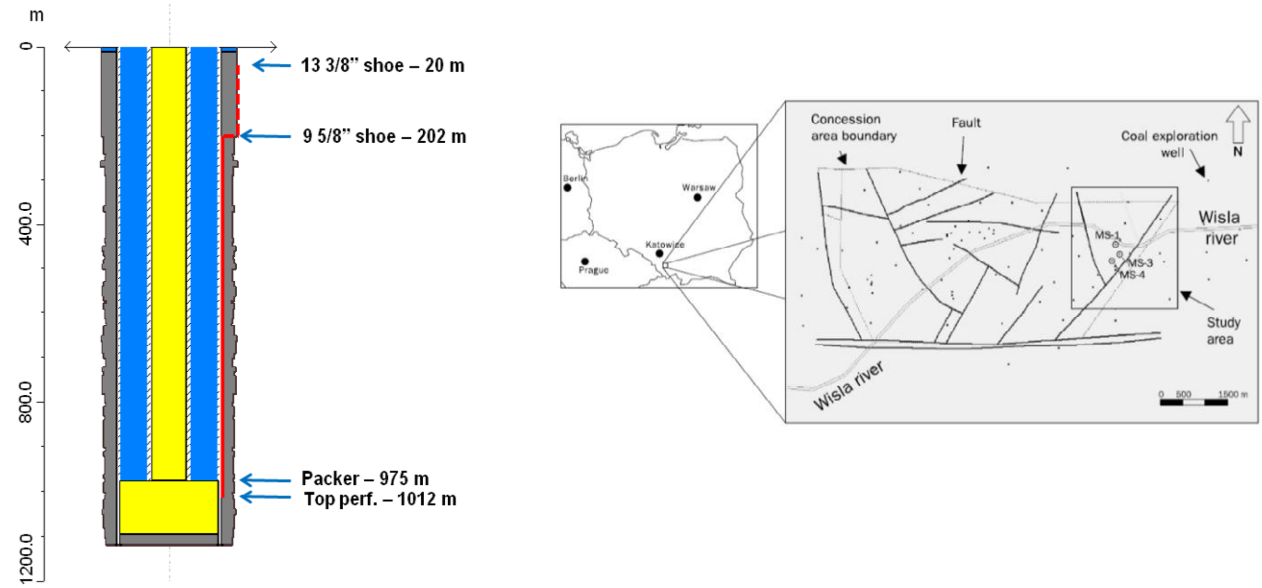

Figure 1 Well schematic on the left (in red the supposed path of the microannulus); on the right the position of the MS-3 wells with respect to local faults (from [1])

Before injection started in the MS-3 well, a Cement Bond Log (CBL, a type of sonic cement evaluation log) was run on 2003 Sep 12. Injection was carried out from Aug 2004 to Jun 2005, for a total of 308 days (see Figure 2 for a timeline). Even though the pressure at surface had been increased from 9 MPa to 14 MPa in Dec 2004, continuous injection could not be established. For this reason a hydraulic fracture job was performed in Apr 2005, after which CO_2 could be injected continuously. 80% of the total CO_2 was thus injected during the last 38 days of the operation at a surface pressure of 14 MPa.

After the injection was completed, two cement evaluation log suites were run at 512 days' interval. A soil gas survey was also run in May 2007, ~720 days after the end of the injection.

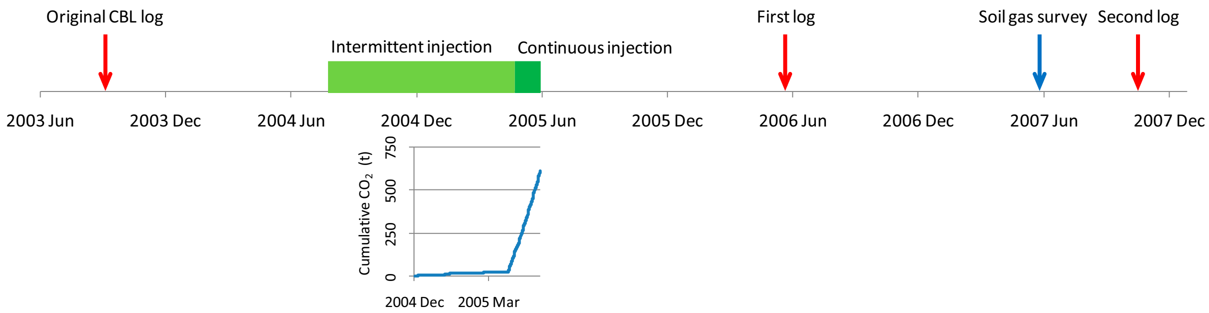

Figure 2 Timeline of CO_2 injection, cement evaluation logging and soil gas surveying for MS-3. The graph shows the cumulative CO_2 mass injected for the period during which detailed data are available.

The cement evaluation logs suggested that cement mechanical properties had changed between 2006 and 2007 ([3]) and the soil gas surveys showed anomalies in CO_2 and He concentrations and CO_2 fluxes. Due to time constraints in the European projects, the discrepancies could only be analyzed in detail in 2009-10 to evaluate possible causes. An intriguing scenario that could explain both sets of observations is that the injection of CO_2 caused a microannulus[2] between casing and cement, which migrated to the outer cement-formation interface at the previous casing shoe. Three separate lines of evidence that support this scenario will be described in detail.

2. First line of evidence: cement evaluation logs indicate a fluid-filled microannulus

CBL logs are overwhelmingly sensitive to shear-bonding[3]. Whereas this makes them poorly adapted to evaluating cement, it does make them invaluable to detecting the presence of microannuli; ultrasonic cement evaluation logs can then easily confirm whether they are fluid- or gas-filled. In the MS-3 well, CBL logs before and after the injection show an increase in amplitude (decrease in shear-bonding), mostly below 200 m. High CBL amplitude can denote channeling as well as a microannulus – even cement contamination in extreme cases. In the MS-3 wells, ultrasonic logs were crucial in ruling out these alternative hypotheses.

Quantitative evaluation of CBL logs requires assessing amplitudes for free pipe, fully bonded and fully debonded conditions[4]. Whereas the free-pipe CBL amplitude is a generally well known calibration factor, the other two are more fraught with uncertainty, and can be obtained from either approximate models or by picking the limits of the CBL amplitude distribution. The microannulus azimuthal coverage is linearly proportional to the attenuation of the extensional mode excited by the tool. Since attenuation is proportional to the logarithm of the amplitude, relatively small errors on the fully bonded (low) amplitude amplify into large differences at the low end of the scale, as can be observed in Figure 3. It should be stressed that sonic tools that measure attenuation directly with multiple receivers are somewhat less sensitive to calibration uncertainties.

In spite of some uncertainty in the calibration values[5], the microannulus coverage thus calculated confirms the qualitative trend from the amplitude logs, namely that the microannulus cover increased during the injection period, particularly between 1000 m (top of perforations) and 200 m (bottom of previous casing). Azimuthal coverage values cluster between 20% and 50% of the circumference (70° to 180°).

Under certain assumptions, ultrasonic azimuthal logs can also yield independent estimates of microannulus cover. An example of these ultrasonic estimates is given in [3]. Ultrasonic estimates follow the same trend as the sonic

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[2] A "microannulus" is a partial or total debonding at the interface between two materials (casing-cement, cement-formation) with a width of the order of 10-100 micrometers. The gap can be filled with fluid or gas. Gas-filled microannuli are a bane of ultrasonic cement evaluation logs: due to the very strong impedance contrast between steel and gas, energy cannot propagate behind them to investigate the annular material.

[3] "Shear-bonding" is the ability to transmit shear stress to the annular material. This requires both a solid material in the annulus and continuity of shear stress and strain at the interface.

[4] These are, respectively, the log response to an annulus full of fluid, full of cement shear-bonded to the casing or full of cement with a microannulus covering the whole casing circumference.

[5] Models suggest a fully-bonded amplitude of 3.5 mV and a fully-debonded value of 56.3 mV. The logs seem to support 2 mV and 45 mV respectively. The log limit values were used in the rest of the processing.

ones, but suggest slightly larger microannulus cover (between 45% and 75% of circumference). The agreement between both sets of logs confirms that a fluid-filled microannulus is present from the perforations to the previous casing shoe, that it covers around 50% of the pipe and that it was likely formed at some point during the injection period.

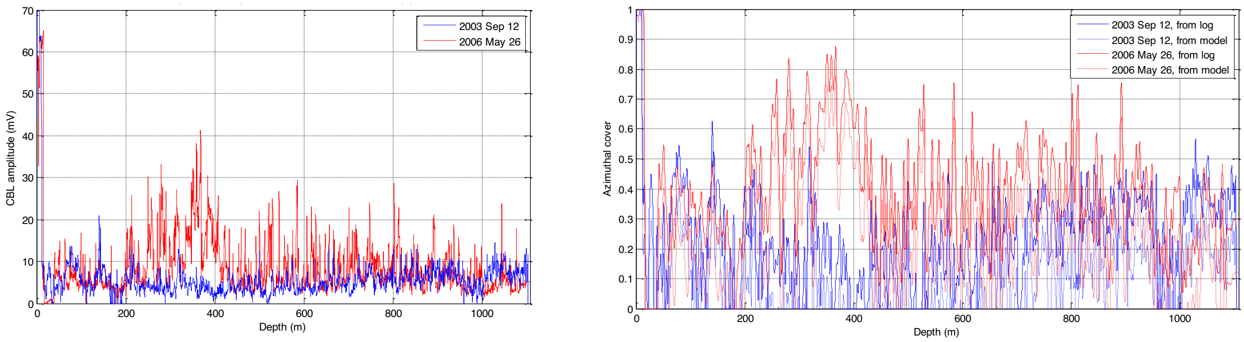

Figure 3 Time-lapse CBL amplitudes normalized to 63 mV free pipe (left), and the resulting computed azimuthal coverage of the mircoannulus, low-pass filtered at 6 m (right)

To investigate possible cause of microannulus formation, a mechanical model of the system casing-cement-formation was built. Mechanical properties of the rocks were taken from open-hole acoustic and nuclear logs and used to build a one-dimensional Mechanical Earth Model (1-D MEM). For cement, estimates independent from the logs[6] were obtained from monitoring compressional wavespeed evolution during setting and from micro-mechanical cement models that can very well reproduce cement mechanical properties during hydration.

Buoyancy-driven[7] delamination of the casing-cement or cement-formation interface was selected as the mechanism of microannulus propagation, under the high CO_2 injection pressure. Although a radially-symmetrical model was used to simulate the microannulus origin, 2-D studies and 3-D experiments ([4]) suggest that the viscous pressure drop and average microannulus width calculated by the 1-D model are reasonably correct.

The mechanical model predicts that microannulus width is a linear function of casing and microannulus pressures but, obviously for a 1-D model, it doesn't predict microannulus azimuthal coverage – which is instead measured by the CBL tool. Nonetheless, some initial results seem to suggest the average width and the coverage are correlated. In MS-3, the 1-D microannulus compliance shows a correlation coefficient with the microannulus coverage of 0.363, which is a fairly high figure given the inherent variability of logs and the simplified hypothesis used in the derivation.

A parallel series of models targeted the localization of the microannulus when multiple interfaces are present, and it helped shed light on the fate of the delamination at the 9⅝" casing shoe (202 m below surface).

The so-called "rat-hole", in this case the portion of 12¼" open-hole below the 9⅝" casing shoe, is normally a weak point in cement integrity because of the sudden annular enlargement. Considering this rat-hole as a chamber at constant pressure a first model looked at the energy release due to fracture propagation at each of the four interfaces; the outermost microannulus (between formation and 9⅝" cement) shows the highest energy release rate both for soft and hard formations. A second model, looking at dynamic localization, computed the distribution of flowrate and microannulus width between all four interfaces, assuming all of them are debonded. In this case as well the flow (proportional to the third power of the width) is at least two orders of magnitude greater in the outermost microannulus than in either of the others.

Models thus suggest that cement-casing delamination during CO_2 injection could be the cause of the fluid-filled microannulus observed by the cement evaluation tools. The microannulus width would increase with depth between

[6] Since, as will be described, cement mechanical properties may have evolved between microannulus formation and the ultrasonic logs because of exposure to CO_2, and the resulting material layering in the annulus would have made log interpretation harder, an independent estimate was sought.

[7] CO_2 is lighter than the water present in the annular gap between the injection tubing and the 7" casing. The resulting CO_2 buoyancy forces cause CO_2 pressure to decrease more slowly than water pressure, favoring the propagation of the delamination fracture, not unlike the mechanisms of gas kicks in wells.

approximately 100 and 250 μm. Models also suggest that the microannulus switched to the outermost interface at the 9⅝” casing shoe, and may have switched interface again at the 13⅜” casing shoe at 20 m depth.

Once the microannulus mechanical properties were established, flow of CO_2 in the pathway could also be simulated, together with cement reaction to it. The simulation considered a piecewise-constant injection pressure, computed from the measured surface pressure, and an imposed geothermal temperature profile[8]. Multiphase flow was considered since it was found that CO_2 saturates with water (produced by the carbonation of cement) very soon, within the first week from the start of injection. The cement reaction model was calibrated with lab tests, measuring the progression of the carbonation front in a cement “puck” exposed to water-saturated CO_2.

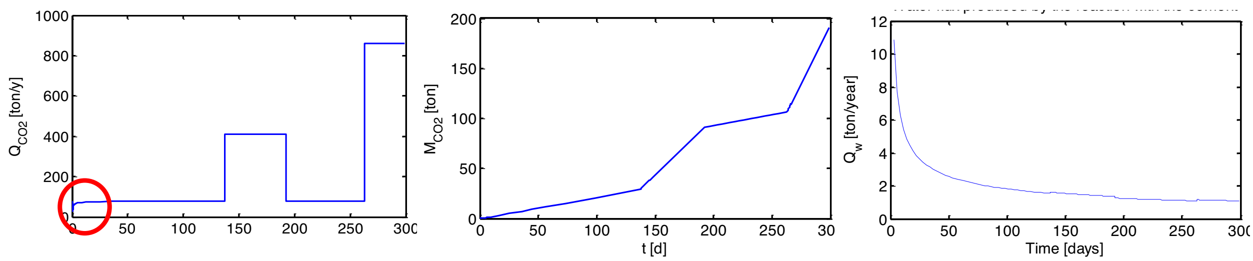

Figure 4 CO_2 mass flowrate as a function of time (left, the red circle highlights the initial transient); cumulative CO_2 mass as a function of time (middle) and total water flowrate produced by cement as a consequence of carbonation (right). The difference in flowrate between the first plateau around 150 days and the final one is due to the intermittent injection during the former: average surface pressure was used in the simulation, resulting in a value lower than the 14 MPa peak surface pressure.

Since the computed flowrate in the microannulus only depends on the pressure at the inlet, consistency of the results can be checked by comparing it to the injected mass of CO_2 recorded at the pump. For the period 2005 Feb 2-7, 180 to 186 days after the start of injection and during the intermittent phase, the pump recorded an average injected mass of 354 metric tons per year (t/y, 1 t/y=$3.17\cdot10^{-2}$ g/s), whereas the model predicts an outflow of 410 t/y. During the final continuous injection phase, on 2005 Apr 29-May 29 (266 to 296 days after the start of injection), the pump recorded an average mass flowrate of 5,452 t/y injected in the well and the model predicts an instantaneous flowrate out of the microannulus of 861 t/y, 16% of the inflow. Of course, flowrates through the microannulus should be considered more like order-of-magnitude estimates than exact predictions.

The above comparison shows that the hypothesis of a microannulus is consistent with the acquired flowrate, and suggests that during the initial intermittent injection phase, a sizeable share of the CO_2 may not have gotten into the coal seams, but rather migrated up the annulus.

There is also the possibility that the microannulus was created during the hydraulic fracturing job or the later continuous injection phase. Continuous pumping in particular adds another stress to the casing-cement system because of the large drop in temperature caused by the injection of liquid CO_2. A later microannulus opening would halve the total CO_2 flow from around 190 t to 90 t. Temperature simulation of the injection could help quantify the additional stresses on the system – and thus whether the likelihood of debonding increased substantially during the continuous injection phase.

Analysis of cement reaction under CO_2 exposure allows an estimate of the progression of the carbonation front[9]. A source of uncertainty for this prediction was the evolution of pressure in the microannulus after the end of injection[10]. However, because of the relatively large residual mass of CO_2 left in the microannulus with respect to the mass lost to cement carbonation, the front evolution didn’t change appreciably between the two limiting hypotheses. At the time of the second log, the model predicted that more than half of the cement sheath had already

[8] Dimensional analysis suggested that for the very small mass flowrate in the microannulus, temperature in the flowing CO_2 would be almost everywhere in equilibrium with the formation. This is not the case in the upmost ~100 m of the 1000 m pathway; there, phase transition to vapor would introduce latent heat of vaporization, high velocity and multiphase flow. A robust flash simulator would be needed to characterize in detail behavior in this (narrow) zone, but it was felt that the added complications would not contradict the basic conclusions of this study.

[9] Portland cement is produced by calcinating limestone. Calcium hydrates produced during cement setting – $Ca(OH)_2$, portlandite, and C-S-H gel – react to calcium carbonate, $CaCO_3$, and water when exposed to CO_2.

[10] Pressure may have been trapped in the microannulus, leading to an injection pressure Boundary Condition at the inlet, or may have bled down to hydrostatic pressure. In reality pressure would likely decrease from injection to hydrostatic over an unknown relaxation time.

been carbonated. Analysis of water production due to cement carbonation shows that CO_2 (which was injected dry) would have been water-saturated throughout the carbonation process. This in turn would delay the onset of drying-out, in which cement pore water evaporates in the dry CO_2 flow. The important water production could also help explain why the microannulus was fluid-filled at the time of the two ultrasonic logs.

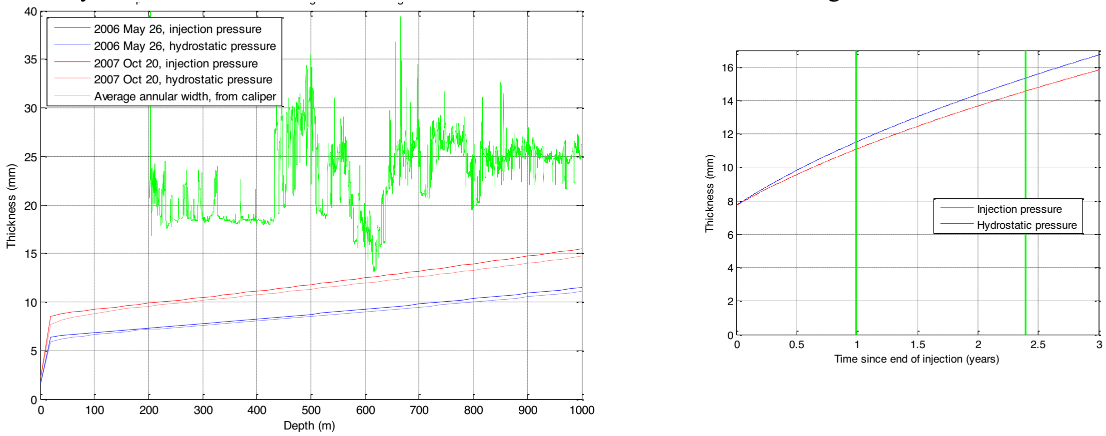

Figure 5 Comparison of predicted carbonation front thickness at the time of the two ultrasonic logs with the average annulus thickness (left) and comparison of the thickness of the carbonation front predicted at 1000 m versus time under the two limit boundary conditions (right, green lines denote ultrasonic logs times).

3. Second line of evidence: soil-gas survey

A comprehensive soil-gas survey was carried out in the Kaniow area in May 2007, with 150 samples being tested for selected gases (CO_2, light hydrocarbons, N_2, He, O_2) and the same number of CO_2 flow measurement being recorded. The majority of measure points were concentrated around the two wells (MS-3 and MS-1).

A subset of 47 sample points was selected within a radius of 350 m from the MS-3 injection well for further analysis. The sampled area was divided into 50 meter-side cells, and a concentration map was re-sampled. As a further step, the median cell value was chosen for each of the 32,000 m^2 slices into which the smaller area was subdivided. The resulting pie chart shows an anomaly in CO_2 concentrations north-west of the MS-3 well, in the direction of the nearby Wisla River (see Figure 6). Helium concentrations show a similar anomaly which, unlike the one for CO_2, cannot be attributed to a biological origin.

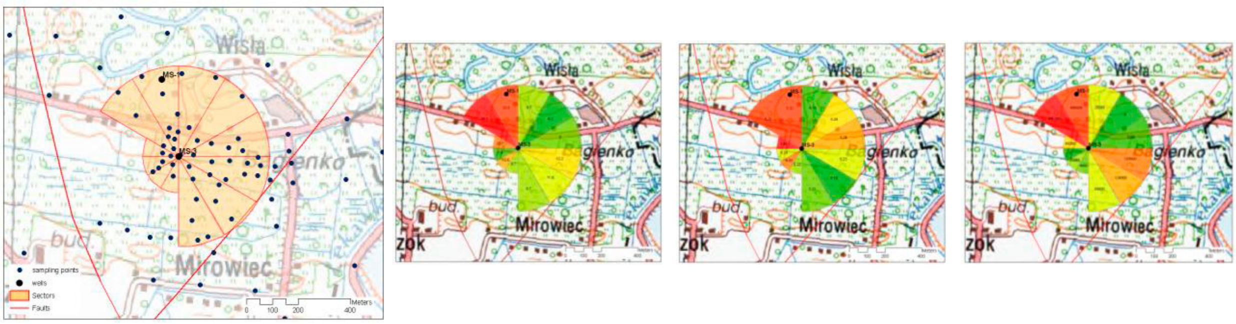

Figure 6 Soil-gas survey points (left), and processing results for CO_2 concentrations (second from left), He concentrations (third from left) and CO_2 flow (right).

A similar processing was applied to CO_2 flux, subtracting the median background value. The results show an anomaly in the direction SE-NW, consistent with the concentration results. Adding flux values for each of the pie slices gives a total value of 584 t/y (~20 g/m^2/day), a very small quantity of the order of background CO_2 flux, that may have been classified as noise were it not for the similar He anomaly.

If the anomalies are indeed caused by CO_2 migration through a microannulus, some questions are still left unanswered. The possible scenario is that CO_2 flowed during the active injection phase into the surface aquifer outside of the surface 13⅜" casing; the aquifer would then slowly de-gas CO_2 and He over the course of months. The first question is whether it is possible to record an instantaneous flux of the order of 500 t/y 720 days after the end of injection (with a peak flowrate into the aquifer of ~1,000 t/y). Better statistical analysis of the data together with aquifer modeling could help shed light on this.

The second question concerns He, which must originate from the coal. Most CO_2 would have flowed only during the active injection phase, with only marginal quantities released during the microannulus bleed-down after injection stopped. Whereas it is very unlikely that He could diffuse into the flow during the continuous injection phase, it might have done so during the breaks in the long intermittent injection phase. Some of it may also have been transported during the bleed-down period. None of these possible explanations has been yet tested with models or experiments.

4. Third line of evidence: changes in cement log response

Changes in log response have been flagged as an unexplained anomaly in [3]. The models used in this study helped assess whether the increase in cement carbonation caused by CO_2 trapped in the microannulus could explain the anomaly.

Under the assumption that the original cement had statistically uniform properties, different log readings can be attributed to different local microannulus thickness[11]. This allows a prediction of changes in acoustic impedance (Z) and flexural attenuation (α) between the two logs as a function of Z and α in the first log.

The more detailed, model-based analysis predicts a slightly more complex pattern than the simpler dZ/dα discussed in [3]. A characteristic signature predicted by the model is a sinusoidal variation in ΔZ with depth, caused by the linearly increasing thickness of the carbonated layer. An oscillation with similar phase and amplitude can be observed in the logs (see Figure 7), especially for the Z bin around 5.8 MRayl (corresponding to thin or no microannulus). The match is also fair for Δα, especially as far as phase is concerned[12].

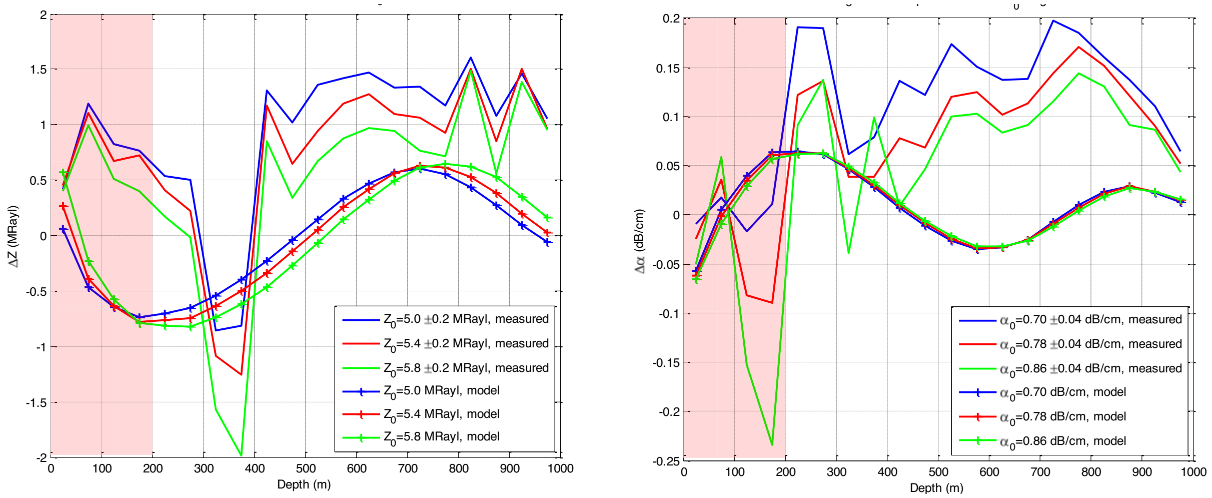

Figure 7 Difference in log readings between first and second log vs. depth for selected bins of first-log readings, ΔZ to the left and Δα to the right (pink bands denote the portion of microannulus that likely switched to the outermost interface, not covered by the log.

[11] Interestingly, supposing that low acoustic impedance readings in the first log are caused by carbonated cement behind a water microannulus, values of Z around 4 MRayl (at the low end of the observed distribution) would be explained by a microannulus width of ~150 µm, consistent with the width predicted by the mechanical model.

[12] The response of flexural attenuation to microannulus and carbonation is more complex than for acoustic impedance, increasing the possibility of error amplification and possibly affecting the quality of the match.

5. Conclusions and implication for wellbore leakage monitoring

The three lines of evidence outlined above indicate that it is possible that in the Kaniow MS-3 well CO_2 migrated to the surface aquifer through a microannulus, itself caused by the CO_2 injection pressure.

It must be stressed that there was no increase in pressure at the wellhead during injection, nor was there a localized important leak in the vicinity of the well. However, as reported in [5], not all leakage pathways from hydrocarbon wells end at the wellhead; mechanical analysis of the well system also seems to support this observation – at least for microannuli.

Because of the very high injection pressure, in turn caused by the very low permeability of coal, the amount of CO_2 that may have leaked from MS-3 should be considered at the high end of the expected range for CO_2 injection wells. A median value would thus be closer to 100 metric tons per year, less than 0.05% of the mass injected in a well like Sleipner or In Salah.

Furthermore, since flowrate grows like the third power of pressure, a microannulus is almost exclusively active during the injection phase. Creep, swelling or simple elasticity in the caprock can then effectively seal the pathway after the injection is over (on MS-3, thin coal seams have shut the microannulus in places). For this reason, the long-term post-closure risk of leakage from a microannulus seems to be low.

If the migrating CO_2 accumulates in a deep or surface aquifer, effective dispersion can spread the plume over a large surface. Distributed de-gassing can then quickly reduce the CO_2 flux to below the background noise, as in this case where a flux of ~1,000 t/y could be easily be dismissed as measurement error. Accumulation and dispersion in an aquifer could delay the initial detection, but it could also prolong the de-gassing long after the leak ends. This hysteresis should be taken into account when the response to leaks is planned or carried out.

Finally, the large, easily detectable changes in cement properties due to the exposure to relatively limited quantities of CO_2 suggest that cement could be used as a leak detector, akin to a bubble chamber. The advantages of such a method would be its sensitivity to the cumulated (and not instantaneous) leaked mass and the availability of non-destructive ultrasonic testing to probe the mechanical properties of cement behind casing. A draw-back is that only the innermost cement sheath can be monitored with ultrasonic logging tool, although wells can be designed to ensure "loggability" of cement that would be in the path of leaking CO_2. Other monitoring methods sensitive to the cumulative flow, such as pressure, can be used together with cement changes; the development of novel ways to measure CO_2 flowrate directly would also be a very welcome addition to the leakage monitoring technique portfolio.

Acknowledgements

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