monitoringnetworkand environmentalresearch network-combinedmeeting

Theme: Realistic Monitoring of CO_2 Migration from the Reservoir to the Surface

IEA GREENHOUSE GAS R&D PROGRAMME

International Energy Agency

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Front & back cover images: Andrew Feitz of Geoscience Australia showing the Ginninderra controlled release project; Cores from the CO2CRC Otway project site at the core store of Geoscience Australia; Geological heritage site at Parliament House showing normal and reverse faults and an unconformity; Attendees of the meeting

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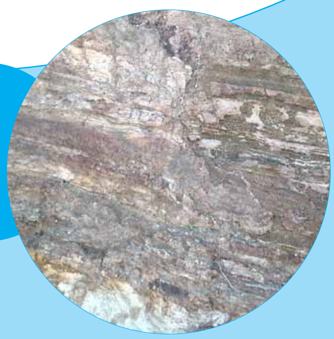


Sheraton Noosa Resort / Sheraton Noosa Resort (courtesy of http://2.bp.blogspot.com)

Introduction

IEAGHG supports and operates a number of international research networks. This report presents the results of a workshop held by two of these international research networks. The report was prepared by IEAGHG as a record of the events of that workshop.

The workshop on Monitoring and Environmental Research was organised by IEAGHG in co-operation with CO2CRC. The organisers acknowledge the financial support provided by CO2CRC, Global CCS Institute, anlecr&d, The CarbonNet Project, Chevron Australia, Geoscience Australia, and Shell for this meeting and the hospitality provided by the hosts at University House, Canberra.

Richard Aldous, CO2CRC and Tim Dixon, IEAGHG introduced the network meeting, which was the 8th meeting of the Monitoring Network and the 4th meeting of the Environmental Research Network. The theme of this meeting was to cover the realistic monitoring of CO_2 migration – from the reservoir to the surface. The meeting was attended by 80 delegates from 12 countries.

Session 2: Regulatory Environment

Summary

International work to standardise the framework for CCS is being developed, included the UNFCCC Clean Development Mechanism (CDM) and ISO TC 265. While regulations are important for commercial projects, the US EPS Class VI rule, could potentially have a negative effect on research projects and it may be necessary to adapt the rule in order to apply it to smaller research projects. Regulators should also understand what they will require, such as a comprehensive list of failures that could be caused by unexpected migration outside the confining zone or storage complex. Another important aspect in identifying leakage is the stage where the CO_2 is attributed to the storage project and it was suggested that this be included as an additional step in regulations and guidelines.

Terminology is important for comprehensive understand of regulations, e.g. when to use seepage or leakage. Scientific data sharing with industry could enhance accuracy of prediction models. Compliance efforts facilitate understanding of proposed projects and are important for public outreach. However, excessive regulations may be barrier to project development.

Overview and Update on ISO and CDM work; Tim Dixon, IEAGHG

At UNFCCC COP-17, in 2011 CCS Modalities and Procedures were agreed and adopted, which included assurance of environmental integrity and safety of a storage site, confirming containment and that the CO_2 behaves as predicted, determining GHG reductions and assessing remedial measures. IEAGHG Networks played a role in providing technical information to negotiators at a workshop in Abu Dhabi, including the 2011 meeting of the Monitoring Network which considered the specific issues which had been raised by UNFCCC. CDM project closure is when monitoring stops, which will not be less than 20 years after the last CDM crediting period. There is also the assumption of zero leakage, unless monitoring data suggests otherwise. In 2013 there was a consultation process on some specifics of operationalising CCS in the CDM, and IEAGHG provided further clarification on technical issues.

The process of determining international standards for CCS (ISO TC 265) started in 2011 with the aim to prepare standards for the design, construction, operation, environmental planning and management, risk management, quantification, monitoring and verification, and related activities in the field of CO_2 capture, transportation, and geological storage. ISO standards are not obligatory, but can be adopted within national regulation.

US Regulations, Class 6 Requirements; Lee Spangler, MSU

Class VI regulations were designed by US EPA to protect underground sources of drinking water (USDWs) and are to be applicable to commercial scale CCS projects. It is also to be applied to all new research CCS projects, which do not have an EOR component. Certain aspects were found to be potentially detrimental to research projects (as well as in some cases larger projects). This includes the post-injection site care (PISC), which is by default 50 years, this is flexible, but could be an issue for pilot projects; it also does not take injectivity tests into account. There is also likely to be less flexibility with plan changes under Class VI, which may be a problem with research projects, which are often opportunistic. The Kevin Dome site, which has safely stored natural CO_2 for 50 million years, was taken as an example. The aims of this project was to test monitoring technologies, mitigation methods, stacked storage and detection limits. As the storage formation is under pressures, this leads to a large area of review under the guidelines, which leads to an impact of costs, not only due to increased area, but also due depth of surface casing required. It will also not be possible to carry out a mitigation test, due to PISC implied liability. Because research projects do not have an economic driver, Class VI financial assurance requirements may also be a challenge.

Monitoring Protocols; Tim Dixon, IEAGHG

Detecting leakage emissions is challenging and quantification is very challenging as we need high sensitivities and low uncertainty. Current guidelines suggest monitoring to detect leakage, then more intensive monitoring for quantification of the leakage. However, it is suggested to have an intermediate step whereby the CO2 detected is attributed to the injected CO2. Methods that are available to do this include isotopic analysis, tracer gas signature and the process-based soil gas method, all of which have been used successfully at different times and discussed at IEAGHG Network meetings, so there is growing confidence in such 'attribution' monitoring.

Mapping the plume – What do Regulators Need to Require?; Sue Hovorka, BEG

It is important for regulators to understand when failure may occur and what to look out for to know when more information is needed. It is suggested that regulators should require a comprehensive list ofpossible failures of storage and for each case, the regulator should ask the project developer how they will know that this failure is not occurring and will not occur. To answer these questions there can be models created to illustrate failure cases and characterisation/ monitoring designed to disprove failure scenarios.

Most models look at the median, but when considering failure, we need to look at the outliers. It is also important to understand limits of measurement. Monitoring plans will be based on risk assessment, not models, as modelling cannot predict responses to unexpected parameters.

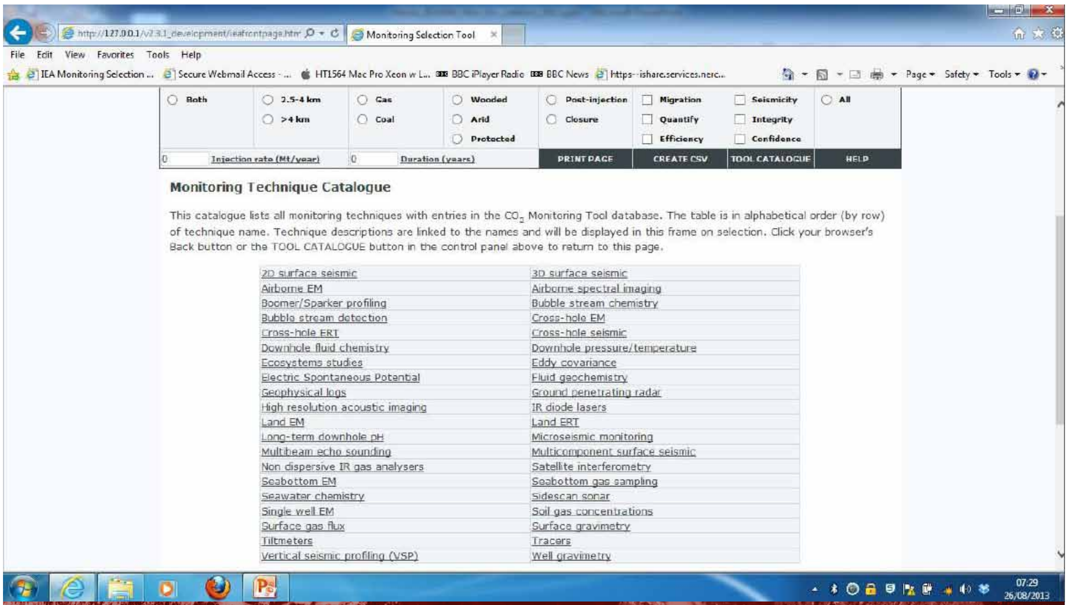
It is suggested that an inventory of failure scenarios are created, models of failure are created, conditions that precede failure are defined, then those conditions are characterised and monitored.

Comments after the talk included that the scenarios need to be credible, or there will be too much to consider. It is also important to understand if an unexpected migration is important – or is it still contained? Scenarios will also be project specific.

IEAGHG Monitoring Tool Update; Sarah Hannis, BGS

The Monitoring Tool was created and maintained by BGS for IEAGHG and has been on the IEAGHG website since 2006, though there have been several updates. It contained >40 monitoring techniques, which are selected and rated based on a user defined scenario. It is a decision support tool, which aims to identify and prioritise monitoring techniques that could form part of a monitoring programme from site characterisation through to post-closure.

The tool is updated from information from experts, new articles, papers and reports. New planned and possible updates to the tool are: inclusion of unranked tools; a benchmarking study using an existing site; further cost information (though this will not be used in the ranking system). User data is logged and there were 400 visits to the tool over a 6 month period. Feedback from participants included a suggested colour scheme change as the current traffic light colours may be considered 'backwards'. It could be tested with first time users for ease of useability, it could be made clearer that it is not necessary to log in to use the tool, it was suggested that the ratings system could be more transparent and it was also suggested that porosity and permeability could be included. It was also commented that the tool is useful as a starting point for discussions by regulators.



IEAGHG's online Monitoring Selection Tool

Session 3: Monitoring Migration from the Reservoir

Summary

This session covered deep subsurface monitoring techniques. An innovative experiment at Otway injected a small mass of CO_2 and then documented stabilization induced by water flooding, monitored by time lapse pulsed neutron logging and downhole pressure gauges at different depths.

Methane leakage over geologic time from the Baracouta structure, Gibbsland basin was illustrated with geological data. At the SECARB "anthropogenic test", under funding from CCP, LBNL designed a new multi-tool package, Modular Borehole Monitoring , allowing better deployment of complementary tools. The utility of the package was demonstrated during diagnosis of a well completion problem. A permanent seismic receiver array at the Ketzin project was described. Some microseismic events were identified and the utility of the array for detection of changes in pressure at the reservoir level. Seismic detectability of CO_2 migration from the reservoir was evaluated in light of the need for climate change mitigation of a high storage retention standard and found that sensitivity to shallow accumulations in low noise settings is adequate to detect the relevant leakage.

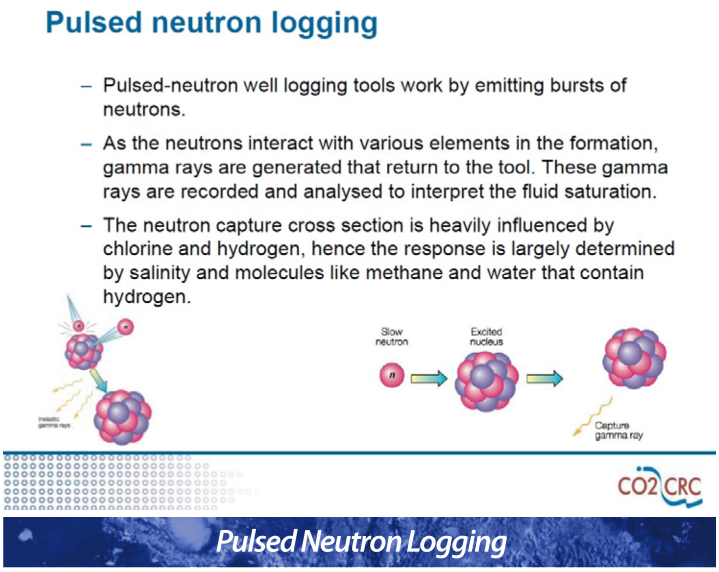
An overview was given of a recent review paper prepared for IEAGHG on induced seismicity and its implications for geologic storage, using literature reports of induced events at 100 locations of large scale injection and withdrawal. A need for additional data for CCS was noted.

Otway Injection Experiment; Lincoln Paterson, CSIRO and CO2CRC

A small mass of CO_2 was injected, followed by water flooding. This was monitored using a wide variety of techniques, though this presentation focused on downhole pressure and pulsed neutron logging.

For downhole pressure measurements, there were two gauges above the perforation and two below. Water gave a greater pressure difference than CO_2, which is useful to tell which fluid is present. Downhole pressure was found to be very accurate, fast, continuous and inexpensive, but cannot give directional information. A fault which was around one kilometre away was able to be identified using Horner plots, but it is not possible to tell which direction it was using this method alone.

Pulsed neutron logging can be used to determine thickness and variability of saturation from an injected CO_2 plume with limited surface disturbance, however there is a very limited depth of penetration into the formation and it needs calibration. At Otway this was conducted at full water saturation, after CO_2 injection and after water injection to drive CO_2 to residual saturation. The saturation profiles show that the CO_2 has tended to migrate to the top of the injection interval under buoyancy, and that the average residual saturation is around 20% with some uncertainty arising from the calibration.



Evidence for Slow Migration of Fluids over Geologic Time Through the Cover Sequence in the Gippsland Basin; Nick Hoffman, CarbonNet

This area is very data rich, with wall to wall seismic and many wells. There are several oil and gas accumulations, which are all thought to be fill to spill, and so there may be seepage concerns where there are lower accumulations in a large closure. There is also a more recent low salinity wedge, which has caused biodegradation and water-washing of the hydrocarbons. The Lakes Entrance Formation acts as a regional seal and weak points related to Miocene channels have been identified. Some wells show a small amount of hydrocarbon above the seal, and seismic anomalies can be mapped as clusters – these show that fluids have moved 30km laterally through the overburden. It is suggested that there is 2 way pressure communication and that the fresh water can migrate and the path can be seen through dolomitisation.

The duration of fluid movements in the cover may extend to tens or hundreds of Ka – perhaps beyond human timeframes of MMV. The direction of movement of buoyant fluids can be predicted from the dip of the overlying strata. The area required for MMV can be mapped-out using predicted fluid paths in the cover sequence. Structures with dip closure in the cover sequence have a natural ability to constrain buoyant fluids, and smaller required areas for MMV, which may limit the opportunity for geochemical reactivity. Conversely, structures with gentle but open dips allow long-distance migration of fluids and ample opportunity for geochemical reactivity, but are more challenging for MMV.

Modular Borehole Monitoring (MBM) at Citronelle and Project Update: SECARB's Integrated Anthropogenic CCS Pilot; Tom Daley, LBNL

CO_2 captured from a 25MW coal fired boiler at Southern Company's Plant Barry, is shipped by pipeline to the injection site in the saline Paluxy reservoir at Citronelle oilfield. Under funding from CCP, LBNL designed a new multi-tool package, Modular Borehole Monitoring, in order to allow better deployment of complementary tools and to maximize the efficient use of available wellbores for semi-permanent monitoring. The tool includes P/T gauges, U-tube fluid sampling, hydraulic clamping geophones, fiber optic temperature and heat pulse.

Initial testing of the MBM system was successful and useful in understanding well completion. MBM Fiber-optic seismic acquisition was tested and is very promising. Monitoring using the MBM system is continuing.

Four Years' Experience with Testing Continuous Seismic Monitoring at Ketzin; Rob Arts, TNO

The permanent seismic array is in boreholes 50 m deep and has been operational for almost 4 years continuously. Though a 3D layout is preferred, this was not feasible at Ketzin. Seismic data was recorded in 89 channels and sampled at 2 ms interval (16GB/day), which was increased to 0,5 ms when appropriate (68GB/day). There has been a huge amount of data including lots of noise and a lot of work has gone into determining data from the subsurface and filtering out surface noise; in this respect it was found to be useful to focus on events out of working hours. The signal to noise ratio was improved when burying the receivers at depths of >20-30m. There is still limited understanding of variable data quality (spectrogram plots), the existing algorithm is able to detect upgoing events automatically, improvements for localization and magnitude estimation of events is ongoing.

A low frequency vibrator was installed relatively close to the permanent array, where there was almost daily monitoring over a 1 month period. A combination of permanent source and permanent receivers has the potential for increased repeatability and signal to noise ratio. There was good repeatability of shots, though some issues remain (being resolved now), changes are observed, but due to the HAN no clear conclusions can be drawn yet. Injection stops on 29th August 2013: Experiment is currently being repeated, unfortunately not with the permanent source, but with accelerated weight drop.

Induced Seismicity in Global Injection Projects and the Implications for CCS; Matt Gerstenberger, GNS

Induced seismicity has been observed in injection and extraction sites related to hydrocarbon production, geothermal activity and waste water disposal. Information has been taken from these sites to attempt to consider the potential risk at CO_2 storage sites. Some key questions considered are what magnitudes, rates, timing and locations of induced earthquakes can be expected; what don't we know about induced seismicity and how can these knowledge gaps be closed; what are the risks and can these be quantified; and how do we best reduce and mitigate the risks.

Complete monitoring down to small events is key to better understand the behaviour of induced earthquakes and to understand the behaviour of a particular reservoir. Few earthquakes have occurred at CCS sites, but there are generally small volumes of injected CO_2 and only a few sites. Observed empirical data show some relationships, most notably between maximum magnitude and total volume injected/injection rate. Physical and statistical models are in relatively early stages of development, though statistical models are better established. Risks can be reduced and mitigated using a systematic and structured risk management programme.

Spatial Monitoring in the Overburden: Detection Limits in 3-Dimensional Volumes; Andy Chadwick, BGS

Seismic detectability of CO_2 was evaluated in light of the climate change mitigation needs of a high storage retention standard. It may be difficult to detect a leakage in 1D and 2D, depending on the sample spacing, and though 3D seismic may have full coverage, there will still be detection limits. The Sleipner dataset was used as an example and a difference map of the first repeat survey shows some quiet areas and some not so quiet areas. Noisier data will have lower detection ability and it is one of the quiet areas above the storage formation that would be most suitable to monitor for leakage.
The detection limits at the top of the Utsira were determined by spatial wavelet decomposition. The method accurately extracts known CO_2 accumulations on synthetic data, though detection will depend on the thickness and the area (if the plume is too thin it will not be detected). It is therefore possible to say whether or not a site is leaking with respect to acceptable levels.

In conclusion, it can be said that detection limits are statistically manageable and allow comparison with performance acceptance criteria. The 'No detected leakage' requirement might be considered fulfilled if the monitoring system has detection capability sufficient to assure effective greenhouse mitigation performance.

In discussion on what a leak would look like, it was thought that somewhere in the overburden there would be pooling of CO_2 sufficient to be detected.

Session 4: Migration of Fluids through the Overburden

Summary

Understanding the overburden is crucial to understanding leakage. We need to know how much CO_2 will be emitted at the surface if there is leakage from the reservoir, how long does it take to get there, where will it occur and how reservoir changes affect flow in the overburden, as well as the best way to monitor this.

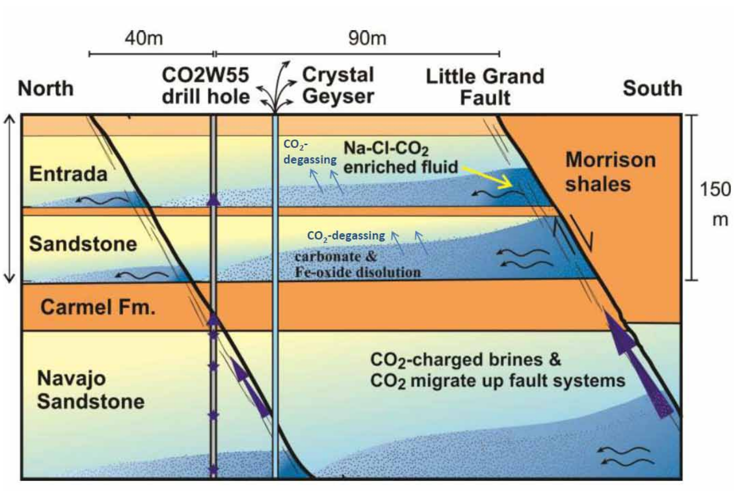
There is evidence of major relatively recent dynamic flows in the overburden. It can also be seen how CO_2 – brine – rock interactions work on geological time-scales, migration up faults and within aquifers are key insights into this potential journey of CO_2 from reservoir to surface. Pressure propagates much quicker than fluid particles - influences monitoring preferences for rapid response. Reservoir pressure changes induce tiny geomechanical volume changes in the overburden pore-space can 'switch on' and 'switch off' the background flux.

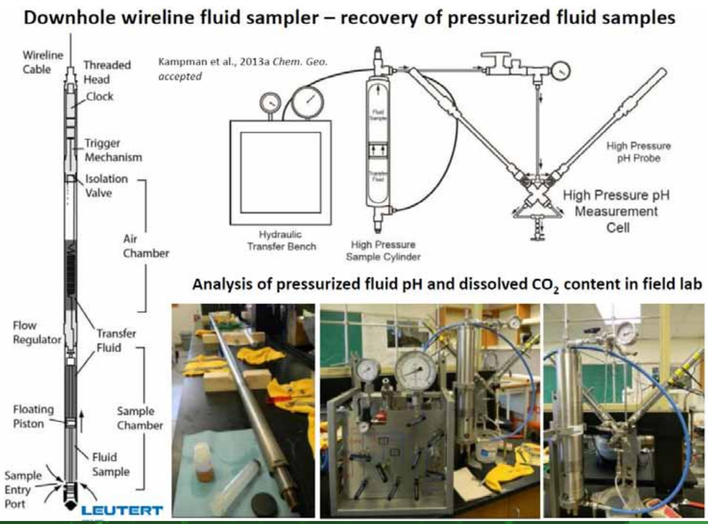
Fluid Migration in CO_2 Reservoirs and Faults: Constraints from the Green River Storage Site Analogue; Niko Kampman, University of Cambridge

At this site CO_2 has migrated through 100m of overburden. CO_2/ CO_2-charged brines mainly migrate up fault zones and rock core across the fault was sampled. Downhole wireline fluid sampling was used to recover pressurised fluid samples. At depth, the brines are CO_2 saturated and at shallower depths become undersaturated; it appears that CO_2 is degassing at a depth of 50m, though it is difficult to know the total amount of degassing as it may not be preserved in the rock record.

Some conclusions from this study are that thin siltstones form surprisingly impermeable caprocks; fluid-rock reactions strongly retard CO_2-transport & buffer fluid reactivity; the mineral dissolution front is only ~10cm thick after 100,000's of years of exposure; and carbonate dissolution/reprecipitation occurs with net dissolution in caprocks adjacent to the reservoir and net precipitation within the reservoir.

Natural systems have been shown to be useful for: testing theory, models and assumptions about coupling of fluid flow and brine-rock interactions along flow-paths where reaction fronts are preserved in the rock (also trace metal mobilization and biogeochemistry); two-phase CO_2-gas and brine migration in faults; and as test sites for subsurface monitoring and sampling equipment. They have not yet been found useful for understanding dynamic two- phase flow in storage reservoirs.

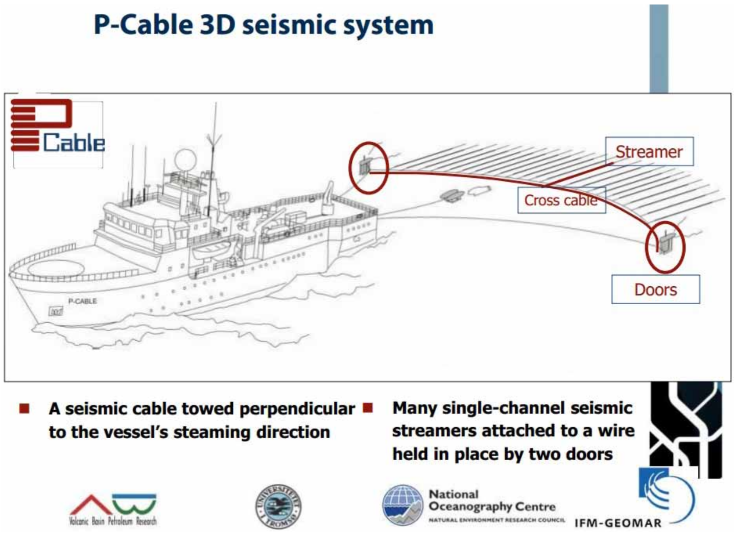




Green River Natural CO_2 Seeps

Fluid Migration Systems and Leakage Assessment in the Shallow Subsurface; Stefan Buenz, UIT

This assessment is part of work package 2 of the ECO_2 project and involves looking at flow features between the potential caprock and the seafloor in the North Sea. Different types of fluid flow are observed through pipes/ chimneys and along strata and are often seen in conjunction with gas hydrates. In the Barents sea gas chimneys are seen as bright spots on seismic. Faults can be identified, and there are indications of gas along faults. The origins of the observed features are thought to be from uplift and erosion from glaciation. A basin scale approach is needed to understand governing controls which impact leakage scenarios and risk assessment. It is also necessary to appreciate the varied dimension of fluid flow features and that their detectability hinges on suitable high-resolution approaches, particularly in detecting CO_2 leakage along these features.



ECO2 Project's Offshore Monitoring of Shallow Subsurface

Insights into CO_2 Migration from Non-CCS Perspectives; Katherine Romanak, BEG

One of the challenges to understanding migration through the overburden is that it may occur over long timescales that are difficult to directly observe. Industrial analogues give us time scales of observation on the order of about 40 years (such as at the SACROC oilfield, Texas, USA where CO_2 injection for EOR has occurred since 1972) and natural systems which are 100,000s of years old. Reactions and migration processes that may occur over the time period of interest for a CO_2 storage project (1000 years) are therefore difficult to discern. When using natural systems as analogues for engineered storage sites, it is important to consider what aspects of the natural system are important and relevant to CO_2 storage sites, and how these systems can be used to predict the range of possible surface impacts that could result. Natural sites should be used cautiously with a detailed understanding of geological similarities and differences.

Whereas it is generally widely believed that macro-seepage along faults or wells would be the dominant mechanism for CO_2 migration in the overburden, there is some indication that micro-seepage may be important. In some cases micro-seepage appears to be rapid and therefore should be addressed by the CCS community. Cases considered included a Gulf Coast oilfield where after 30 years of decreasing pressure from oil production there was a disappearance of seepage signals at the surface. Lateral seepage is also possible, so it is very important to understand the geology to be able to predict CO_2 migrations rates, surface flux rates, surface location and impacts. Because CO_2 is reactive, a release from a storage formation may never reach the surface, so understanding CO_2-brine-rock interactions is important.

There was discussion about the mechanisms of surface micro-seepage and explanations as to how this can be switched on and off by pressure changes at reservoir level, pressure moving much faster than fluids, without an implication that this would mean that leakage of the CO_2 injected into the reservoir would occur.

Monitoring in the Overburden: Is Pressure or Geochemistry a Better Indicator of Leakage?; Sean Porse, BEG

The Hastings oil field was used as a case study to consider pressure and geochemical monitoring in determining leakage. There are hydrocarbon accumulations around edge of the field and logs show a lack of continuity especially at a shallow level. It is thought that pressure monitoring may be more suitable due to the faster response to changes in subsurface conditions, though both methods could be used in concert to comprehensively to monitor for brine (and CO_2) migration into shallower aquifers over longer time frames.

Pressure monitoring at the Hastings field can work in all Miocene formations and geochemical monitoring works best in deep Miocene formations at monitoring points closest to the fault. t Geochemistry can provide secondary information over longer monitoring periods. Understanding the hydraulic parameters of both formations and migration pathways are critical towards assessing the potential risk of fluid migration at a project. The probability that a monitoring technique will detect adverse leakage should be the driving factor in developing a subsurface monitoring network.

Geochemical monitoring is necessary to analyse effects on drinking water, but pressure can be considered as a pre indicator and if only geochemistry is used, it may be too late to protect drinking water as it may mean leakage has already occurred.

Session 5: Detection of Leakage into Shallow Groundwater

Summary

Groundwater monitoring can be conducted for different purposes (e.g., characterisation, regulatory compliance, research), and it is important to establish the goals of each of those purposes before a network is constructed and monitoring is initiated. Having more wells or sampling more frequently (i.e., increasing data density) can help address uncertainties in data interpretation, but is more costly. Regulators may not be completely familiar with monitoring needs and can benefit from project specific input and guidance. It is also important to understand the time scales, spatial scales and mechanisms of metal mobilisation in groundwater. Work is being carried out assessing the use of remote sensing for groundwater quality monitoring. As CCS projects move from the research and demonstration -scale with relatively small injected masses of CO_2 and high-intensity monitoring strategies, commercial-scale projects will seek cost-effective, lower intensity monitoring programs to meet regulatory monitoring requirements.

Experiences from the Illinois Basin – Decatur Project Groundwater Monitoring Program; Randy Locke, ISGS

For shallow (<100 m) groundwater assurance monitoring, primary goals for the Illinois Basin – Decatur Project (IBDP) include demonstrating that project activities are protective of human health and the environment. In particular, monitoring is documenting that there have not been project impacts to potable water supplies. Four regulatory compliance wells have been sampled quarterly for 11 indicator parameters to meet current injection permit conditions. To ensure spatial and temporal variability of groundwater quality is fully understood, the project operates 13 additional wells and samples more frequently than required by permit. There are more than 2 years of monthly baseline data for all 17 monitoring wells. The IBDP site has a relatively high intensity monitoring program in comparison with what may be implemented for larger, commercial-scale projects. The monitoring network for the adjacent Illinois Industrial CCS project (which will inject at up to 2,500 tpd or 2.5 times the IBDP rate) is more focused on optimizing monitoring intensity and regulatory requirements.

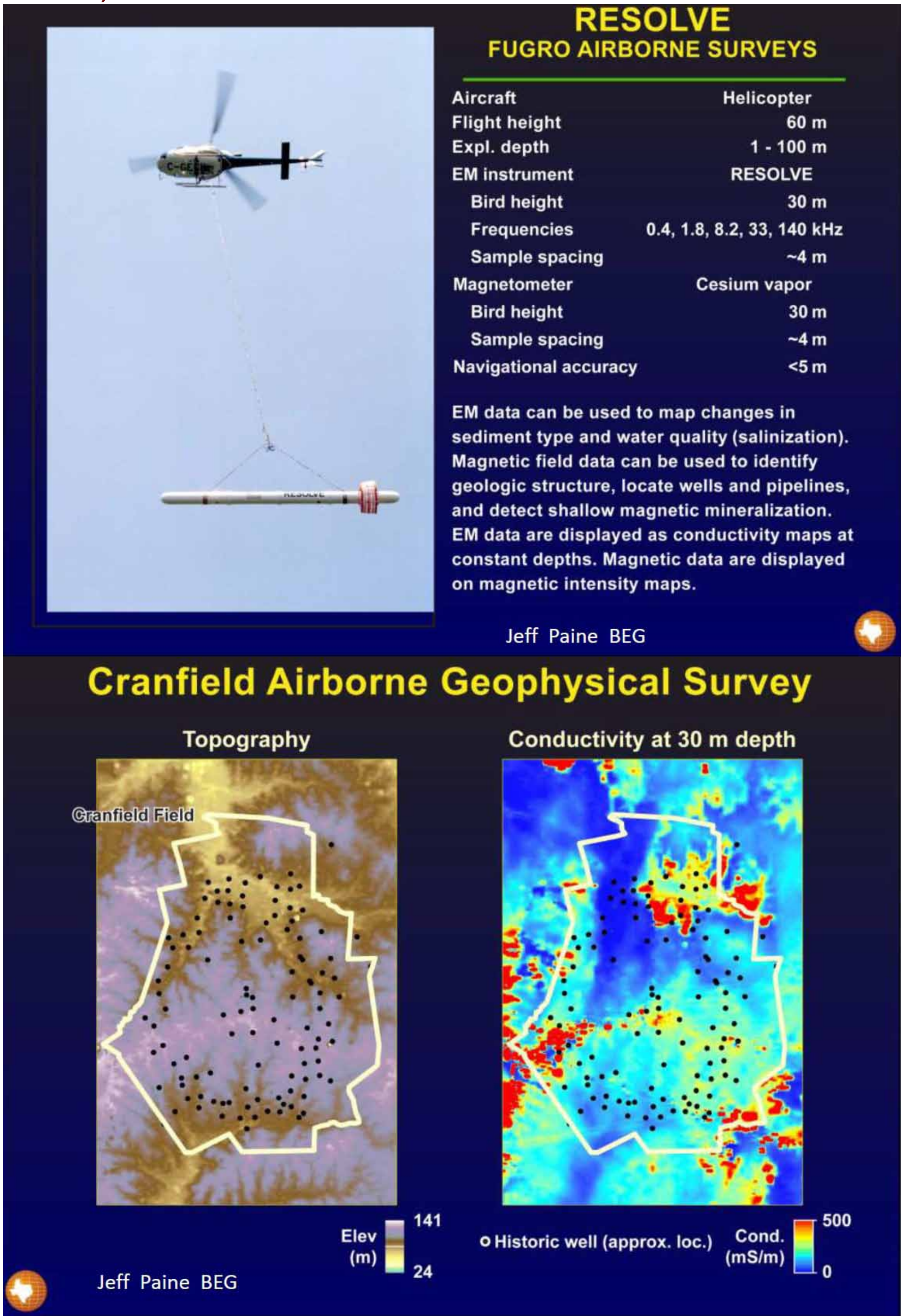
In a non-regulatory well about 560m from the injection well, increases in calcium, magnesium, and potassium concentrations were observed. This case illustrated how different durations of pre-injection data could lead to different conclusions about the causes of cation variability. The cation increases were attributed to multiple factors including 1) natural variability as was observed in the baseline record and 2) oxygenated water interacting with naturally occurring pyrite in the carbonate-rich, unconsolidated aquifer. This new information was useful in revising the hydrogeological conceptual model, showing more interaction between aquifers. The baseline data were also important, because they included the 3rd most severe local drought on record and showed shallow groundwater responses to a wide range of moisture conditions. Statistical assessments of IBDP groundwater data are based on the 2009 USEPA Unified Guidance, "Statistical Analysis of Groundwater Monitoring Data at RCRA Facilities" as developed under the U.S. Resource Conservation and Recovery Act.

CO_2 Field Lab and CIPRES Experiments; Frédéric Gal, BRGM

The main objectives of the 2 projects differ slightly. For CO_2FieldLab the objectives were to obtain knowledge about monitoring of CO_2 migration and enable early detection of possible CO_2 leakage, as well as to provide guidelines to regulators, operators and technology providers. 1.7tonnes of gaseous CO_2 was injected into fluvio-glacial deposits at 20m depth through a deviated injection borehole.

The objectives of CIPRES are the quantification of the biogeochemical reactivity of CO_2 to estimate impacts on water quality and potential associated risks and to establish methodological guidelines and recommendations for monitoring programs (Drinking Water Standards). It involved an Injection of 10m^3 of water saturated in CO_2 in shallow aquifer in between 12 and 20m depth in chalk aquifer.

There were strong effects on soil gas even if the CO_2 is injected in water. Channelling in heterogeneous formations can lead to adverse effects even in near surface formations. Extensive site characterisation is required. Basic characterisation of the water (e.g. pH, electrical conductivity…) is sufficient to account for leakage, but there is a need of using more complex systematics (isotopes) to account for more complex phenomena (mixing). Water/rock interaction processes may have rapid kinetics that strongly affects water chemistry (or quality considering trace metal elements); good from a monitoring point of view, but critical from a water management point of view.



Cranfield Airborne Geophysical Survey

Value of Airborne Conductivity and Magnetics for CCS: Test Xase at Cranfield; Sue Hovorka, BEG

It may be necessary to be able to detect and characterise over a large area. Using ground methods it is not possible to monitor everywhere, so it is helpful to be able to determine the best places to monitor. Future leakage may follow the path of other previous gases, e.g. methane, therefore understanding past gas migration is useful in deciding the monitoring plan. To characterise previous pathways, methane may be detected, or methane impacts through iron mobilisation and mineralisation, which could produce a detectable magnetic signal.

At the Cranfield site, the survey was flown in April 2013 and initial EM and magnetic processing is completed. Known wells have associated magnetic anomalies that were detected by the survey. Additional magnetic anomalies may represent additional wells and possible preferred pathways. Shallow and moderate depth conductivity images indicate possible pre-existing salinisation of soil and groundwater. Processing, analysis and interpretation have just begun.

Session 6: Terrestrial Detection Monitoring and Environmental Impacts

Summary

The discussion focused on finding leaks, attributing Leaks to sources, quantifying Leaks and assessing Impacts of leaks. The technologies for these tasks vary. Hyperspectral analysis shows some promise for wide area detection, but is an indirect method. Improvements in processing and analysis are reducing the number of false positives and negatives. Wide area detection still remains a target for improved technologies. Process based methods and isotopic analysis show promise as methods to attribute the source of CO_2. Atmospheric methods have potential for leakage quantification but are not as well suited for locating leaks. Surface flux is patchy and flux areas do not necessarily match vadose zone elevated CO_2 in the soil gas. Natural leaks and controlled release sites both indicate that surface impacts are likely confined to relatively small areas. Plant response can potentially be used as a semi-quantitative measure of CO_2 soil gas concentration.

Remote Leakage Detection Methods; Anna Korre, Imperial College

Indirect detection methods have been used at the Latera and Laacher See natural release sites. The Latera site has used hyperspectral and multispectral remote sensing analysis and validation of leakage locations with gas flux measurements. In Laacher See, hyperspectral remote sensing analysis has been compared with open path mobile laser measurements.

Direct and indirect measurements need to be combined and it is necessary to be able to distinguish a leakage target from the background as false alarms are possible.

Detection of leakage by monitoring inevitably involves statistical analysis – detecting the leakage signal above noise and dealing with missing signals in monitoring data. Different monitoring datasets may refer to different spatial and temporal domains and may refer to open systems, affected by varying factors outside monitoring control, which may also be unknown or not recorded. Joining up different monitored data analysis in a statistical framework allows improvement of leakage detection and reduces vulnerability to false alarms and handles data uncertainty.

Detection of leakage pathways is feasible and benefits from the use of independent datasets to corroborate detection. Common to all broad categories of detection is the need for detailed information in the statistical structure of the data and the uncertainties in that knowledge. Accumulation of enough background data may be impractical. However, many statistical techniques are available when dealing with uncertainties.

Further work is planned on also considering false negatives using the same method.

Synthesis of RISCS Results: (Near Surface) Terrestrial Impacts; Dave Jones, BGS

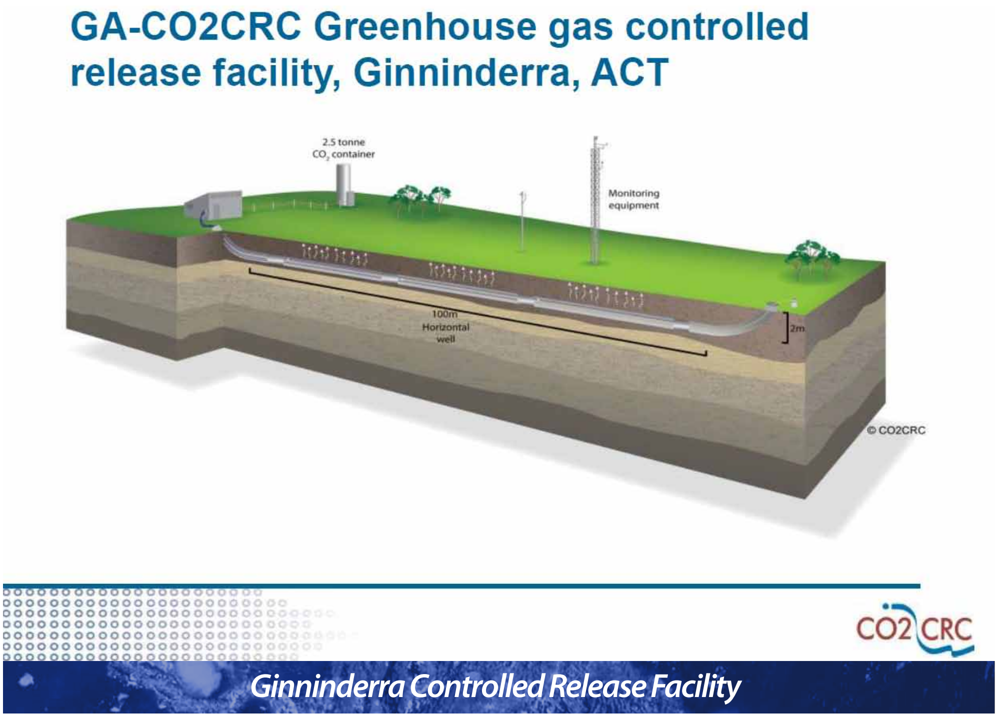
The RISCS project has been running for 4 years and is due to end this year; its aim was to research onshore and marine impacts of leakage from CCS. This involved scenario and reference environment development, studies at experimental sites, lab experiments, field observations, comparisons with previous studies, results from other projects and modelling.

Experiments on the effect of CO_2 on plants showed that below 10% CO_2 concentration at 20cm injection depth is the threshold for observing changes in plant coverage. Between 10 and 50% monocotyledenous (grasses) plants dominate and above 50%, there is a rapid decrease in plant coverage. Raised CO_2 may be a benefit to cereal crops. Bioindicator species were also identified. Microbial activity was studied and found to have a very complex relationship to soil CO_2 concentrations . CO_2 concentrations above 15-20% seem to be threshold for microbiological changes. At natural sites the microbial community has adapted to increased CO_2 concentrations, there has been a shift to anaerobic and acidotolerant/philic species (Archaea or SRB) and anaerobic methane generation observed.

Overall conclusions of the project are that impacts are spatially limited – there is a small effect on overall yield with implications for monitoring; some fertilisation effects counteracting negative impacts; limited to soil gas effects (rapid dispersal of CO_2 in the atmosphere); only occur above ~ 10% CO_2 at 20cm, effects are rapid (1 - 4 weeks), recovery and impact on long-term fertility is less clear, with different species sensitivity (better bioindicators or indicator species), plant development stage and timing of exposure are important; effects are blurred by seasonal/annual factors; effects can be used for monitoring (with some limitations – they are seasonal and not necessarily CO_2-specific); impacts appear to be manageable – they are small compared with the effects of other climatic/meteorological factors or pests.

CO_2 Leak Detection at the Ginninderra Controlled Release Facility; Andrew Feitz, Geoscience Australia

The Ginninderra site is situated in 800 hectares of cropping/ grazing land, 10km from the centre of Canberra. It is a similar setup to the ZERT site, though there are different soil types. Several techniques have been tested.



Ginninderra Controlled Release Facility

The CO_2 was released along a pipe, but mostly came out at a particular point, due to strong lateral migration, thought to be due to clay layers. Atmospheric monitoring methods used were Eddy covariance and atmospheric tomography. Detection with eddy covariance was seen to work, but it was difficult to know where the leak was. Detection is only up to 200m and quantification is problematic. Leaks are patchy, not diffuse. There are issues with eddy covariance due to the horizontal component of flow. Atmospheric tomography (bayesian inversion) looks at the CO_2 gradient difference and worked well. The CO_2 emission rate was determined to within 3%, however, tubes were needed all over the site. Sensor arrays were tried instead and while there were accuracy issues, this may be a more practical method.

Much of the challenge is locating a leak, for which atmospheric techniques may not be good, but once the leak location is known, it can be quantified.

In summary CO_2 surface expression is less than sub-surface footprint (no "V"); quantification techniques still require work; finding small surface leaks over large areas remains the greatest challenge; and cross calibration of techniques is important.

Detection of Signal Over Hydrocarbon-Induced Noise at Cranfield; Katherine Romanak, BEG

A method for near-surface leakage assessment and its use at the Cranfield site was presented. The leakage assessment method consists of locating an anomaly and then attributing its source as either in-situ or exogenous. If exogenous, the gas is then assessed as either originating from an intermediate gas-producing zone or from within the reservoir. If a soil gas signal is from the reservoir, leakage may be indicated and migration mechanism and leakage flux should be determined.

A near-surface anomaly discovered at the Cranfield site was determined to be exogenous using the process-based soil gas method and was then determined by an isotopic analysis to be from the Tuscaloosa formation (the storage reservoir) and not the intermediate Wilcox Formation. This anomaly represented an active migration pathway from the reservoir to the surface. At the time of its discovery, the anomaly contained only gases from the reservoir without injected CO_2. The anomaly was located 10s of feet from a plugged and abandoned well that was re-entered in 2010 to become a producer. Shortly after injected CO_2 flooded the area, both a process-based analysis and isotopes confirmed that injectate CO_2 had reached the surface within the anomaly. The leakage signal was transient over time. The migration mechanism is currently being investigated.

Session 7: Marine Detection Monitoring and Environmental Impacts

Summary

Potential leakage sites are large and leakage could be point source or dispersed. Leakage plumes will be dynamic and complex. There are various detection methods, geophysics, acoustics, chemical, and which a mix will likely be required. Sensors exist and accuracy is adequate, deployment can be via fixed platform and roving AUVs. Various modelling techniques can improve monitoring strategies but these will be site specific. Much improved baseline data is needed to evaluate and tune these models. The baseline needs both spatial (topography) and temporal (seasonal – inter-annual) content. The sea floor gives the best opportunity for quantification and will need spatial and temporal resolution. Quantification will still be difficult, given the observed lateral spread within sediments. Shallow movement of gas plumes is greatly influenced by stratigraphy and sediment type. Chemical transformations are complex and will be sediment specific. Biological monitoring addresses scale and impact, but may not be useful for detection.

The Future of Water-Column and Shallow Sub-Seafloor Monitoring of Offshore CCS sites; Ian Wright, NOC

Tools are able to detect both gas and dissolved phase. Physical detection of bubbles can be done through hydrophones and quantification can be with passive and active systems. Active sonar can sit on the seafloor and be used to image bubble plumes and passive sonar can be mounted on gliders or AUVs. Forward reactive chemistry modelling can be used to test what can be detected. There area range of pH monitoring tools available and methane sensors can possibly be extended for use with other gases.

CCS sites with large spatial seafloor extent and overlying ocean volumes (with potentially dispersed and localised emission sources) provide a monitoring challenge. Essential rationale for monitoring will be baseline studies, leakage detection, and flux emission quantification. Potential CO_2 leakage may have precursor fluid release of reducing sediment pore fluids ± aquifer brines (each of which has a unique chemical signature). Shallow sub-seafloor geophysics can detect gas leakage as low as 85 kgs day-1. New marine sensor and underwater platform technology is developing to deploy long-term point observing and remotely surveyed monitoring of the critical fluid parameters at the necessary sensitivity and spatial scales for CCS sites (and at relative low cost). Seafloor / ocean monitoring can detect both dissolved phase (using chemical detection) and gas phase (using passive and active sonar), but is not yet commercially deployable. Chemical and sonar monitoring systems may provide a tractable and robust method for quantifying leakage loss beyond just detection.

Fate of Emitted CO_2; Guttorm Alendal, UIB

Once CO_2 leaks to the seabed, the current governs its movement and waves cause turbulence, which results in mixing of the CO_2. Spatial resolution is very dependent on topography.

Predicting dynamic systems is very difficult, particularly when looking at longer than a few days. There are some systems where flows come together and some where they diverge, if it can be understood what flow is most likely, then it can be understood where is the best place for the monitoring equipment.

If there is a leak, we can look at expected concentration and can calculate the probability of detecting this from a certain place and from this where to monitor.

Modelling Approaches to Assess CO_2 Leakage; Keisuke Uchimoto, RITE

If CO_2 leaks to the seabed, the distribution is influenced by ocean dynamics and the leaked CO_2 is likely to be mainly bubbles. Modelling efforts have couple the MEC model – ocean physical model and a CO_2 2 phase flow model, to calculate bubble dissolution. Leaked CO_2 simulations were conducted in Ise Bay in Japan using this model. It shows strong stratification near the surface and weak in the deeper layers.

Distributions of simulated ΔpCO_2 provide information on the monitoring area to be investigated, and potential impacts on organisms based on a biological impacts database. In the simulations, a leakage rate of 3,800 t/y (based on data from an EOR site) makes just a small increase of TCO_2 and pCO_2. A leakage rate of 38,000 t/y (the same order as a natural analogue site) may impact organisms, but the area is limited to above the leakage area.

Effects of CO_2 Leakage on Benthic Biogeochemistry: Findings from the QICS in Situ Release Experiment; Henrik Stahl, SAMS

The geochemical objectives of this project are to: determine geochemical properties of water column and sediments before, during and after the release; monitor the fate of carbonate system parameters (DIC, TA, δ13CDIC, pH) in sediment and water column – spatial and temporal dynamics; detect and quantify mineral transformation and possible release of toxic components (metals); and to quantify fluxes of DIC, O_2 and metals across the sediment-water interface.

CO_2 bubbles were seen in the water column within hours of injection. Gas chimneys and pock marks could be observed in sub-surface/surface sediments by seismic profiling and multibeam. Up to 35 distinct bubble streams were observed, with flow rates affected by tidal phase and >10% of injected gas escaping as bubbles at low tide. Elevated pCO_2 values where observed in bottom water at release site, which varied with tidal phase and injection rate. Significant changes in carbonate parameters were observed in sediments and water column at the release site. $CaCO_3$ dissolution had a buffering effect on the dissolved CO_2. There was no evidence of elevated 'dissolved' flux of DIC. Impacts were spatially restricted and recovery to background values occurred within a month after terminating the gas release.

Biological Impacts of CCS Leakage, Monitoring Opportunities; Steve Widdicombe, PML

The effect of CO_2 is very dependent on the nature of the habitat, for example, what is the chemical buffering potential of the sediment. At the QICS site on injection of CO_2 there was seen to be a decrease in species, though there was an increase at the control site due to natural seasonal changes. After injection there was a decrease at both sites, due to a storm and after 12 months there was a return to the initial state. This all shows the importance of understanding the natural cycles within the system and other environmental drivers that might affect the fauna.

Marine organisms are used to natural changes in CO_2 and pH so many have developed physiological mechanisms to cope with short term fluctuations. These mechanisms will require energy which may be provided by increased feeding and/ or reduced growth and reproduction. In the short term this may be a suitable solution but in the long term this may not be sustainable so with leakage it is important to consider not only the magnitude of the leak but also how long it persists. There may also be a behavioural response, such as coming to the surface. Another indicator could be microbial mats, where cyanobacteria bloom in the presence of CO_2, though they will only exist in shallow areas with lots of light. Biological monitoring can integrate the impacts of periodic or stochastic events; quantify the severity and spatial extent of damage caused by CO_2 leakage on organisms, communities, processes and ecosystem services; track recovery of the marine system following a leakage; some behavioural or microbial responses may illustrate visually areas where

CO_2 (or other pollutants) may be leaking to the sediment surface or altering pore water chemistry; provide assurance that marine ecosystems are not being impacted by CCS activities; and describe natural cycles to differentiate between natural and CO_2 induced changes.

One area of impact that has received little study so far is the potential impact of displaced formation water on marine organisms.

Accounting for Environmental Variability in Monitoring Design and Leak Detection in Bass Strait; Nick Hardman-Mountford, CSIRO

A leak plume was simulated, forced by measured current velocities. The source of the plume was varied randomly (1000 iterations) and the results were analysed to assess monitoring strategies for such a dynamic marine system. The oscillating flow caused an intermittent plume, which may be more difficult to detect. Using the model to evaluate optimal placement of sensors suggested that the first sensor should be placed where the CO_2 is most likely to flow according to the modelling results, the second sensor where the first sensor is least able to detect and so on, to increase total coverage. Increasing the number of sampling locations would decrease the rate of leakage by increasing detectability, but with diminishing returns as more sampling locations are added. Consideration of natural environmental variability from background marine CO_2 monitoring showed this to be 6-20x the state of the art detection limit, thus limiting the detectability of the plume more than sensor/method sensitivity constraints.

Preliminary conclusions from this study are that the plume is potentially mappable; the baseline environmental variability overwhelms measurement sensitivity; a few fixed monitoring sites are unlikely to distinguish the plume from background environmental variability, except for large leaks; and large area monitoring is needed to identify the plume above background variability, i.e. reduce the detection threshold towards sampling / sensor limits.

Session 8: Complexity of the Natural System and Implications for Quantification

Summary

For terrestrial baselines, atmospheric monitoring is more sensitive close to the ground, wide-area coverage is needed and leaks may be small; it is important to understand baselines and 'baseline functions' and what the influencing parameters are. Marine systems are complex, though detection will be better closer to the seabed. There is much model based work and real data is needed. Understanding the system will better enable understanding of false alarms. It is important to understand the reality and site specificity, and what questions to ask. This understanding can be increased through the use of controlled release projects.

Natural Variability in Onshore Baselines; Dave Jones, BGS

Case studies of Weyburn, CO_2FieldLab and ASGARD are used to demonstrate the usefulness of different soil gas, flux and atmospheric monitoring approaches. There are clear seasonal and year on year effects at Weyburn with variation related to rainfall and temperature. Season effects are also seen in continuous monitoring at Weyburn; soil gas measurements broadly follow temperature with a slight lag. Short term increases of CO_2 found with eddy covariance, during the working day, were found to be from human activity at a nearby well.

At both ASGARD and CO_2FieldLab eddy covariance and soil gas and flux methods were used. Atmospheric methods like Eddy covariance are affected greatly by the wind speed and direction. At this site there was a low background CO_2 flux and seepage was therefore easily distinguishable.

Monitoring needs to take account of background variation; some experiments have given a clear cut difference above the baseline, but at another site, this could theoretically fall into the background. Baselines are site specific depending on location, soil and vegetation characteristics, climate and weather (T, P, rain, wind). Gas concentrations and fluxes vary diurnally, over days to weeks, seasonally and from year to year. Monitoring needs to take account of these changes (done for continuous monitoring). Soil gas is generally best measured in the autumn/winter, when there is low biological activity. Leakage signals can give clear cut anomalies, but at very low levels could disappear into the background noise. Atmospheric monitoring is more sensitive close to the ground with higher leakage detection capability at low wind speeds.

Permanent Soil Gas Monitoring; Franz May, BGR

Due to temporal variability of soil CO_2, caused by numerous controls, including amongst others land use, weather, soil type, temperature, water flux and microbial activity; site specific understanding is necessary. The concept of 'baseline functions' was introduced, describing the complexity of interactions behind baselines.

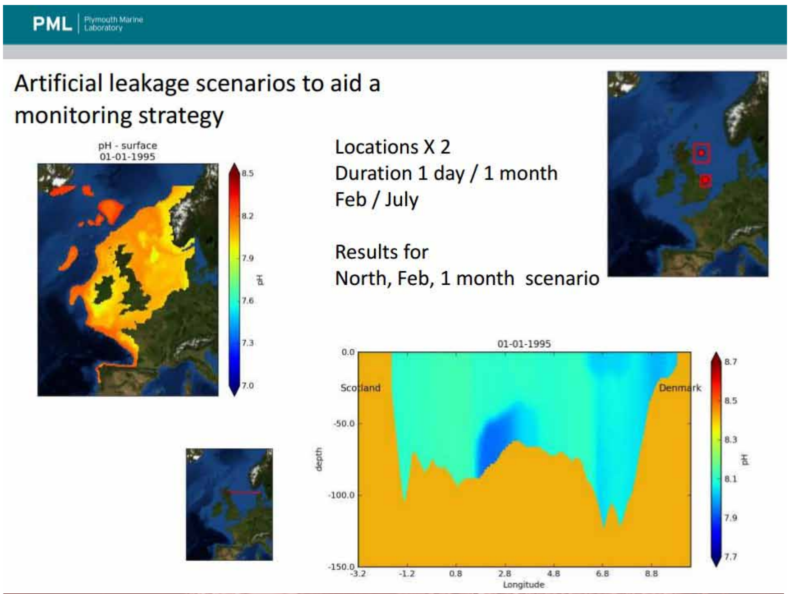
Examples from the Altmark natural gas field were presented for locations and periods where temperature and soil gas CO_2 concentrations follow each other, but in the summer the CO_2 decreases, due to the land becoming very dry. Other examples illustrate a trend with barometric pressure, but with a 20 hour time shift.

Challenges to soil gas monitoring include spacing and frequency of sampling points and formulation of baseline functions from sparse data, as well as issues of quantifying diffuse flux. Wet lowland sites, cause particular issues with ponding water, whereby the CO_2 level drops close to zero at a critical water level. Condensation and freezing can cause technical issues with the equipment, and while there are technical solutions, these can be very expensive.

It is recommended that site characterisation is always done prior to installation; where possible avoid wet, disturbed or soils rich in organic matter; to abandon and replace unsuitable sites early; recording of technical and environmental parameters is essential for process understanding and data interpretation; monitoring concentration (gradients) below top soil (more sensitive than surface fluxes); process simulations can supplement baseline measurements and can be used to establish calibrated baseline functions.

Natural Variability in Marine Baselines; Jerry Blackford, PML

This study was carried out using model based data, which a range of influences, including the buffering effect of the carbonate system, release chemical species, temperature, pH, effect on nutrients and bacterial effects. The carbonate system is very complex, DIC (dissolved inorganic carbon) is a good indicator, but is difficult to measure. pCO_2 and pH are easier to measure, but more understanding of the system is needed.



Modelled pH baselines to assess leakage monitoring

There is much variability in temperature, which will affect pCO_2, the biological variation changes pH – the variation is around 4 pH points. Real data shows great variability.

The nature of the leakage plume is that there will be a small region where there is a large difference and around that there will be smaller differences, which will be harder to determine and further away than that we will not able to detect, but the effects will be small/ none. However, it is not so simple as there will be an initial buoyant plume, but as dissolution of CO_2 takes place, there will be lateral migration and there is also the tidal effect

Covariance of ph with oxygen/ temperature can be used to aid a monitoring system, but to take out the biological effects, very site specific data is needed.

In summary the marine system is highly dynamic in space and time, at multiple scales, especially in regions favoured for European CS; pH etc similarly vary with multiple drivers; a leakage plume is dynamic affected by tidal mixing and seasonal stratification; the most detectable signal will be close to the epicentre. The relatively larger area of slightly increased CO_2 may be hard to distinguish from the background variability. Spatial resolution is critical; covariance with O_2 & T shows some promise, but natural signals are also variable; algorithms, if useful, will need to be site and season specific.

There is a need for extensive baseline data including carbonate chemistry, sediment carbonate concentration and biological proxies.

Variability of Monitoring Measurements – How do we Monitor "Nothing"?; Charles Jenkins, CSIRO/ CO2CRC

At the Otway site, soil gas was monitored through annual surveys, largely due to access issues, as much of the area is agricultural – there are 6 years of data. The CO_2 source is magmatic and so the C13 works as a good tracer. There is a large spread of data and the median CO_2 has decreased over time. This change is all due to weather changes, as this area has come out of a very long drought, then been subjected to flooding. Which emphasises the need to understand the background CO_2.

In the Bass Strait there is a reasonable idea of variability of DIC, but more information is necessary to model the plume as it is important to keep the false alarm rate low. Real data is needed to put into the statistical model and it is necessary to understand the physical processes and set an appropriate threshold. We need to have models of what happens when a leak occurs, in order to understand when we are measuring something and not nothing.

If the only model of the data is that there is nothing there, then the data will never match perfectly and in fact they often will not match very well. So we need to understand what does match better, or, are the models you are worried about plainly a worse match. We are in the business of making decisions with data and to do this we have to choose between nothing and something.

Study of Site Specific Tool Sensitivity; Sue Hovorka, BEG

When selecting a tool, it is important to consider, not just what is being detected, but whether that tool is fit for purpose for that particular site. Several parameters have been reviewed including groundwater geochemistry, pressure, thermal and seismic sensitivity. Freshwater geochemical sensitivity will depend on groundwater composition and what would change were there to be leakage and what can be measured. When measuring AZMI (above zone monitoring interval) pressure, the pressure increase will depend on the boundary conditions and well spacing. For seismic sensitivity, a stronger 4D signal will results from higher rock compressibility and higher fluid compressibility contrast. Other sensitivities are the thickness of the layer and depth. When several experts used data from Cranfield, they put the plume in different places, which can make it difficult for regulators to assess the situation, but what the regulators need to know is when to ask questions about the data, and understanding different sensitivities and basic principles can help.

The next steps of the project are to add pulsed neutron sensitivity and try to frame more near-surface tools.

DOE Carbon Storage Goals and Supporting Research; George Guthrie, NETL; and Discussion Session

The main aim of the US DOEs carbon storage programme is to develop effective and economically viable enabling technologies — then validate them in small- and large-scale (extensive monitoring) field projects to ensure safe and permanent storage of CO_2 from power and industrial sources.

The 99% storage research goal was originally derived from the IPCC Special Report's policy summary, though this has evolved through time to now being to develop technologies to measure and account for 99% of injected CO_2. Other goals are to predict storage capacity to within +- 30%, to improve storage reservoir efficiency, and to develop best practice manuals.

Topics were given for the meeting to discuss:

- How do the CCS goals compare internationally?

In the EU, a project will only be permitted if no leakage is expected; there is then a zero leakage assumption, though leakage must be monitored for. It is only if the CO_2 reaches the surface that emissions need to be paid for. The US is partly similar, with the clean air act, whereby emissions need to be accounted for, though there is not an emissions trading system that there is in the EU.

No other country has specified numbers in measuring CO_2 retained in the ground. Only to quantify CO_2 leaked into the atmosphere or water column.

In the EU mitigation and testing corrective measures are high on the agenda.

In Australia the goals and regulations are not based so much on the IPCC Special Report, but on potential significant impacts on the environment and petroleum resources. It also needs to be shown that the reservoir is acting as predicted.

- Are the drivers for goals similar or different?

In the US, current regulatory drivers are protection of USDWs.

- Have the drivers changed over time?

The drivers are moving from just storage performance to include accounting.

- Is there agreement on the technical justification for goals, how far can we advance these technologies?

The most sensitive meters in pipelines have a 1% uncertainty, therefore it is extremely unlikely that techniques measuring in the deep subsurface, will ever be able to obtain the same accuracy. It is useful to know how much CO_2 can be quantified, but 99% is too high for in-situ storage.

Goal should be for 100% retention, but this may never be able to be quantified exactly.

The goals could also be related to the power plant capture rate. Is it acceptable for this to change, but not acceptable to the storage retention to go below 100%. The full chain must be considered.

- Can goals be modified based on knowledge gained to date for future revisions?

A reasonable goal might be to look at what is expected to be monitored for other fluid injection (e.g. waste water/ gas storage).

The goal was set before there was a regulatory environment, so an idea could be to step back and completely update the goals with this is mind and try not to set numbers, which may not be a good idea with respect to public perception. A suggestion is to identify leak sources and if a leak were to reach a sensitive zone, be able to carry out conformance and containment monitoring. This is not to say that a site should be permitted if leakage is expected, but that this needs to be part of the risk assessment. There should be objective based regulations, so if looking at safety, to have risk as low as is reasonably practicable. It can be shown quantitatively what the lower detection limit is.

A research goal could be to show if that the site is acting as expected and if not, whether there is any significant environmental impact.

Goals could also be to incentivise research in area where it is needed, such as:

- Controlled release experiments
- Understanding the intermediate zone between the reservoir and the surface (overburden)
- Fault transmissivity and fault detection

There could be rankings on key uncertainties for which there is not sufficient investment.

It was suggested that goals be differentiated more clearly into objective for research, objectives for regulators and objectives for accounting conventions. All three are different, so it might help to separate them.

Session 9: Discussion Session – Realistic Monitoring of CO_2 Migration from the reservoir to the Surface

Discussion points:

- What is "realistic" to monitor? (e.g. very small diffuse leakage)
- How to monitor wide areas esp. USDW
- Missing methods of monitoring?
- Mechanisms of migration in overburden – what does it look like?
- Are we thinking enough about consequences ("so what")
- Do we adequately convey the limitations on what we can do to the relevant stakeholders?

The theme of the meeting was to consider realistic monitoring, which includes understanding what is being monitored and what is significant.

It is necessary to see the CO_2 during injection as if the first time it is seen is when leakage is occurring, it may already be too late. Monitoring needs to be done early and cost effectively. Some key questions are; where will the CO_2 go? How quickly will it get there? Will it cause a significant problem, ie 'so what?'.

In general, it seems that offshore monitoring is much easier than onshore, for example because of poorer repeatability of seismic onshore, land-owner access issues, and background variability and complexity. It is useful to think in terms of detection limits, especially in a complex system. It may also be useful to think about how simple the system can be made.

Considering the Lindeberg leakage rates (from Andy Chadwick's presentation), it might help to think statistically about how many bad sites can be afforded.

Diffuse and focussed flow was discussed, what is more likely? What can be detected? From results of projects, diffuse leakage is looking less likely, especially offshore because it does not have a vadose zone for atmospheric mixing, and any leakage offshore is likely to be in the form of bubbles, which can be detected. This may be a useful focus. However, diffuse leakage could occur if there is lateral spread before the CO_2 reaches the surface (which has been seen in experiments) and would be harder to detect, but its extent and importance (in terms of the total leakage) has not been evaluated so it isn't known if it is significant or not. It might be useful to look for diffuse halos around anomalies, in order to discover the best detection method, though this may be buried in noise.

As the seafloor is heterogeneous, it is thought likely to be a more focussed flow. From modelling it can be seen that there is strong fingering if there is heterogeneity.

The type of flow will depend on processes, it can be driven by preferential pathways, or buoyancy/relative permeability effect. Onshore, it can get more complicated, due to soil etc. and can potentially be diffuse. It can be focussed at depth, spread laterally and become more diffuse, then appear at the surface as smaller point sources.

As everything on seafloor is saturated, flow will be through capillary pressures - focused flow. At terrestrial sites, diffuse flow may be more possible if the soil is well mixed with atmosphere. It wouldn't be focused where there is not a capillary barrier.

Monitoring for leakage was discussed.

Most monitoring is at wells and there are other wide area methods at the reservoir (seismic). At the surface there are other wide area methods, such as using AUVs. However there is a shortage of techniques for the overburden.

Some sites will use tracers, while others may not. Tracers may be useful, but consideration has to be given to how they are deployed. The right partitioning coefficient is needed as partitioning onto mineral phases needs to be understood. It is also possible that the tracer may reach the surface while the CO_2 has already reacted on the way up. Great care needs to be exercised in the use of tracers as any near surface spillage will limit their usefulness.

Pressure may be the most useful method for understanding what is occurring in the overburden, though there needs to be more work separating out the geomechanics. The expectation will be for projects to monitor the overburden and Gorgon and Quest will have downhole pressure gauges to do this. However, this may not be necessary in confined aquifers, e.g. the ROAD project.

There is also the potential to utilise passive seismic methods more as ambient noise can be used as the source, which will propagate through the subsurface and reflect back. Different noise levels will give more information.

Session 10: Conclusions

To draw the meeting to a close, the overall gaps, conclusions and recommendations were agreed.

Gaps in knowledge exist for the overburden, in terms of understanding mechanisms of transmission of CO_2 and monitoring. There is a need for techniques for wide area monitoring in the overburden and at the surface which are also able to find small leaks. There was a call for work on a common terminology or glossary, and it was noted that the ISO work includes this. First projects set important precedents, and there is a lack of examples of completed regulatory compliance to set such precedents. There is also a need for definition of consequences that matter, and their context (research, regulatory, accounting).

Learning from medium sized public-funded projects that will run under regulatory regimes would be good for researchers to be linked in to see where there are issues, and feedback to regulators, and IEAGHG could have a role in that feedback. This forum is good for researchers to share and consolidate ideas and experiences.

The overall conclusions were that offshore monitoring is looking promising, that near-surface monitoring has advanced significantly, recognition of the value of controlled release projects, that there is better understanding of environmental impacts and their use for monitoring, acknowledgement of the complexity of natural variability and the implications for monitoring, and that regulatory support is very important in fostering early learning with research pilot and demonstration projects. In the U.S., some demonstration scale projects are being permitted as if they were full-scale industrial injections and an additional, more-flexible, way of permitting the demonstration scale projects would be beneficial (as is done in the EU). This is important because the learning from the demonstration projects can significantly inform larger scale and longer term permitting needs.

In terms of recommendations for work and actions, the following summary list was agreed:

- More work on overburden topics, such as migration mechanisms, faults, natural analogues
- Need for meaningful engagement with regulatory community
- Value of conceptualisation and testing of failure scenarios
- Monitoring for geomechanics, including entire system geomechanics
- More controlled releases
- Need for more data for baselines and 'baseline functions', especially marine
- More consideration of diffuse leakage and mechanisms
- Understanding detection limits

It was also recognised throughout the meeting that an important next stage is the progression from research projects with more intensive monitoring, to industrial-scale projects with less intensive but appropriate monitoring, and so work in this context will be required.

Site Visits

Geoscience Australia organised very interesting sites visits to the Ginninderra controlled release site, to Geoscience Australia where the group saw the cores from the CO2CRC Otway project, and to local geological features in the Canberra region including outcrops of limestone, sandstone beds, examples of faults at different scales, an unconformity, and a new dam being filled.

Steering Committee

A steering committee was formed to develop the technical programme of this meeting, formed from members of the steering committees for the two respective networks. The steering committee members were:

- Tim Dixon, IEAGHG (Chair)
- Charles Jenkins, CSIRO/CO2CRC (Co-Chair, Host)
- Andy Chadwick, BGS
- Sue Hovorka, University of Texas
- Lee Spangler, Montana State University
- Jerry Blackford, PML
- Julie West / Dave Jones, BGS
- Hubert Fabriol, BRGM
- Katherine Romanak, University of Texas
- Don White, NRCan
- Steve Whittaker, Global CCS Institute
- Jun Kita, RITE
- Ziqiu Xue, RITE
- Millie Basava-Reddi, IEAGHG

Evaluating technology options to mitigate greenhouse gas emissions

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