Strategies for Environmental Monitoring of Marine Carbon Capture and Storage

News update

Summer 2019

A tale of two vessels: STEMM-CCS hails controlled release experiment success

A bird's eye view of RRS James Cook, RV Poseidon and the Goldeneye platform, taken by the NOC drone in spectacular conditions in the North Sea.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement no. 654462

Blowing bubbles in the ocean: simulating CO_2 escape under real-life conditions in the North Sea

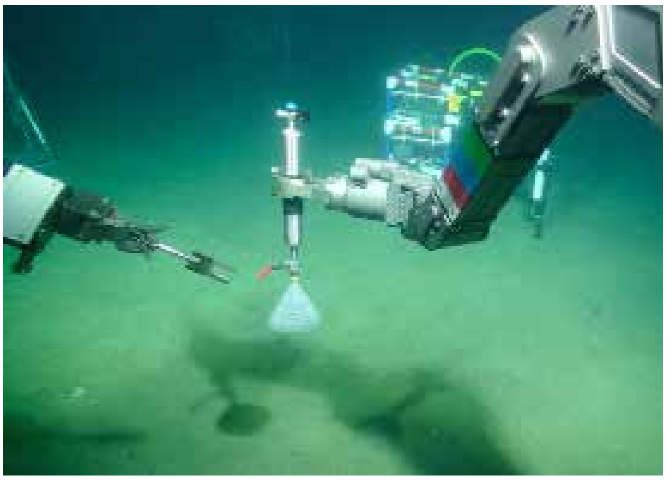
By Doug Connelly, NOC

The STEMM-CCS team has just successfully completed the main field experiment phase of the project. The work was performed by two research vessels: the UK research vessel the RRS *James Cook* and the German vessel RV *Poseidon*. The focus of the experiment was the release of CO_2 beneath the sediments of the North Sea adjacent to the Goldeneye platform, above the proposed CCS Goldeneye storage complex.

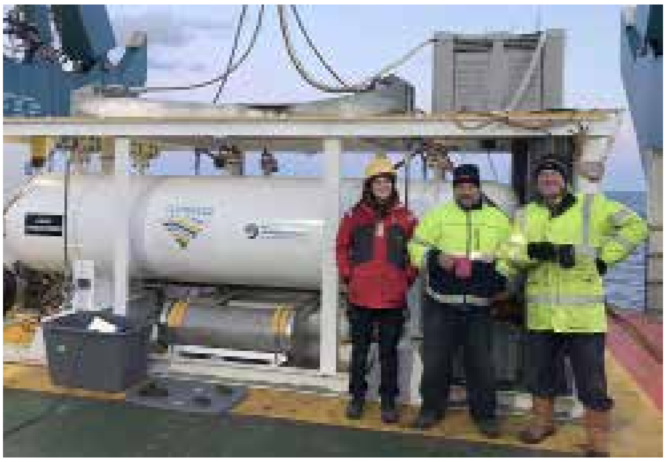
The ships left their home ports of Southampton and Kiel in late April and early May respectively, and rendezvoused close to the Goldeneye platform. The *James Cook* deployed the gas containers and placed the release pipe beneath the sediments, and the UK's ROV *Isis* performed the complex processes of connecting the gas supply to the pipe we inserted into the sediments. The *James Cook* deployed a new baseline lander at a site away from the experimental area, to determine the background conditions so that we could ensure that any changes produced by the experiment could be distinguished from the ever-changing natural conditions of the North Sea.

Then came the nervous wait to see what would happen when the gas flow was turned on: would the gas break through the sediments in a way that would be reflective of a real life release from a storage reservoir? Would we create a large pockmark on the seabed, which would limit our study of the effects of the dissolving gas on the sediments? We had placed our full array of sensors and samplers on the seabed around the area we had predicted the release would occur, and it was a great relief to everyone on board both vessels when we saw the first bubbles gently rising from a small hole in the seabed. The release spot was a matter of tens of cm from where we predicted and data collection began immediately.

From that point on, work was constant around the clock with sensors collecting data, the ROV controlling gas flow rates from the *James Cook*, and the *Poseidon* doing a series of water column sampling with their video-guided sampling system and high sensitivity gas analysis instruments. We combined this on-site work with a series of baseline surveys testing new chemical sensors and photo and seismic data collection techniques using our autonomous marine robot, the AUV *Gavia*. All this data adds to our understanding of the natural variability on the North Sea, as well shedding light on the impacts of other activities in the area such as trawling.



Top: Deployment of the CO_2 gas containers from the back of the RRS James Cook. Middle: An anxious wait - Doug awaits the first sighting of bubble at the seafloor. Bottom: Sampling the escaped gas with the ROV.



After working through a series of increasing CO_2 flow rates from our gas supply, the experiment came to a successful conclusion some 2 weeks after we turned the gas supply on. Everyone had done a phenomenal amount of work, collecting samples and data that will keep us all very busy over the coming months. To get to this point we had overcome massive technical challenges around the logistics of the getting gas to the seabed, releasing it below the sediments and developing the fantastic range of new sensing approaches to detect and quantify the release. This was only possible thanks to the amazing teamwork across the whole project, with close collaboration and effort from every project partner.

There were many great achievements during this cruise - we've highlighted a few of them here in this newsletter - but there will hopefully be many more successes to celebrate in the coming months as we analyse the data and work up the results.

To read the full story of the expedition, please visit our blog site at stemmccs.blog

Left, top: Deployment of the AUV Gavia with the Goldeneye platform in the background. Left, bottom: NOC's engineering gurus Hannah, Rob and Kevin in front of the CO_2 gas tanks prior to deployment.

And the view from RV Poseidon...

RV *Poseidon* left Kiel on 1 May, meeting the RRS *James Cook* near the Goldeneye platform in the North Sea a few days later. Once the controlled release exepirment was under way, the team on board *Poseidon* tracked the rising gas bubbles by means of echosounders, and took parallel water samples with a CTD. In addition, a mass spectrometer and various sensors were used directly above the seabed. to investigate, amongst other things, the CO_2, nitrogen, methane, O_2 and pH value of the water.

In addition to the work related to the controlled release experiment, the team on board *Poseidon* also carried out investigations to estimate the leakage of gases from old boreholes in the North Sea.

Although *Poseidon* was delayed by a storm in the Skagerrak during the first week, the team was able to make up for the loss of time thanks to intensive work. The expedition ended in Bremerhaven on 29 May. "We even gained more data than we had originally hoped. But now we still have to evaluate it", cruise leader Dr. Schmidt summed up after their return.

Right: Depoyment of a seafloor lander from Poseidon, with James Cook in the distance. Below: The view from RV Poseidon across the unusually calm North Sea towards RRS James Cook and the Goldeneye platform.

JC180: Sensing the ocean with lab-on-a-chip technology

By Allison Schaap, Sam Monk & Rudolf Hanz, NOC

We brought 33 lab-on-a-chip (LOC) autonomous sensors along with us on JC180. Our goal was to deploy the sensors in, around, and far away from the CO_2 plume during the STEMM-CCS release experiment. All three of us (Fig. 1) work in the Ocean Technology & Engineering Group at NOC. This cruise was the first time any of us had worked on a British ship and we all thoroughly enjoyed the experience, thanks to the crew's kind hospitality and the excellent camaraderie of the rest of the STEMM-CCS researchers.

Figure 1. The JC180 "sensors squad" from the NOC Ocean Technology & Engineering Group enjoying the sunshine while setting up the replacement baseline lander.

We brought along five types of LOC sensor: nitrate, phosphate, pH, alkalinity, and dissolved inorganic carbon. One of each type of sensor was deployed on each platform: the new baseline lander, on the ISIS ROV, on two MPI landers, and on the ship's underway system.

The alkalinity and dissolved inorganic carbon sensors were developed specifically for STEMM-CCS, so this cruise represented a big technical milestone in the development of those sensors. It's hard not to be protective of your few prototype systems after spending the past few years coaxing them into existence and performance. By the end of the cruise though, watching them drop into the water had transitioned from inducing gut-wrenching anxiety to being a nearly routine experience.

While we did have to dismantle and repair a few sensors on the ship, we were relieved to return to land having left most of our "in case of sensor emergency" supplies untouched. Only three sensors broke during the cruise and we had enough spares on board that we could replace them quickly and fix them as needed.

This was a major deployment for the group, representing most of the year's manufacturing output. Before STEMM-CCS a typical deployment for us involved two to four LOC sensors; the jump to deploying 25 at once was a huge change in scale. It took the effort and support of the whole group to make this

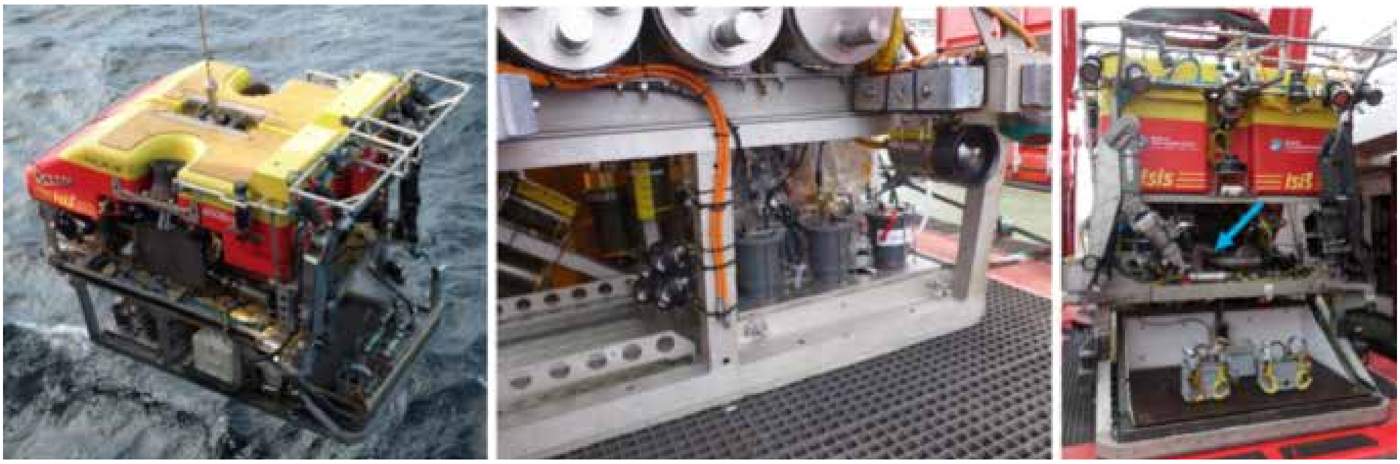


Figure 2 - Left: ISIS being deployed with the LOC sensors just visible in the bottom left of the vehicle. Middle: Rear view of ISIS, showing the LOC sensors mounted on the rear starboard bottom corner on their aluminium sled. Right: Front view of ISIS with the position of the intake pump marked with a blue arrow.

deployment happen, and we were so pleased to be able to report back to them that their efforts paid off.

Deployments

The baseline lander was deployed for 25 days, bracketing the start and end of the gas release. The lander – which Rob Brown built out of some old equipment that he found at NOC – was intended as a replacement for the 2017 lander, which was temporarily missing in action. It was deployed about 475 m southeast of the main experimental site to provide local background data. Alongside the LOC sensors, it also included a current meter, depth sensor, some acoustic sensors, and a SeapHOx for measuring pH and oxygen.

The ISIS ROV had a set of five LOC sensors on it as well, mounted onto an equipment sled at the back of the vehicle (Fig. 2). A pump brought water to the sensors from a single sample point at the front centre of the ROV. The sensor data was transmitted back to the ship's lab in real-time over the ROV's data transmission line. We used our sensors and other commercial instruments on the ROV to measure the water chemistry during the general ROV operations but also to do specific surveys during some long overnight dives. Getting real-time data back during the dives was extremely helpful during the all-night "find the plume" missions that Rudi undertook.

Another set of LOC sensors were deployed next to the CO_2 emission site on the Benthic Boundary Layer (BBL) landers provided by MPI-MM Bremen. One half of the lander contained an eddy covariance system (see article by Dirk Koopmans et al. on p6) and the other half had the LOC sensors (Fig. 3). The LOCs were sampling water at two different heights above the seafloor to quantify benthic chemical gradients. This was particularly successful with the pH LOC sensor, which saw a noticeably lower pH closer to the seafloor every time the currents caused the CO_2 plume to pass over the lander.

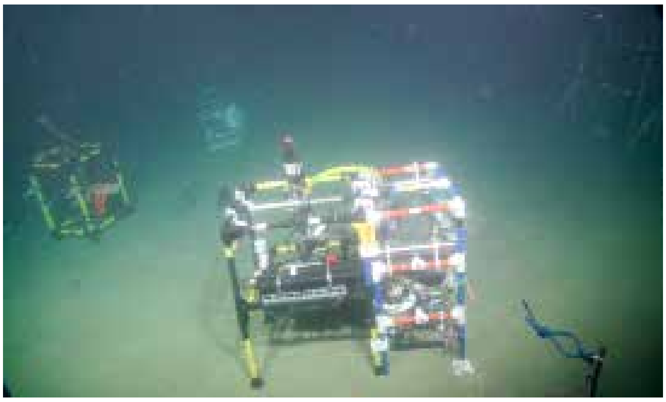


Figure 3. The MPI BBL lander on the busy seafloor around the bubble emission zone. The right half of the lander (with the blue and red frame) contains five LOC sensors with their associated reagents, standards, and batteries.

Lastly, five sensors were kept in the lab to sample the surface water pumped by the ship's underway system. While not vital for the experimental study, this was a nice opportunity for us to get a feel for the variability of the water in the area and to directly co-sample the measured water for later comparison to the sensors' results.

What's next?

The next big task for us is, of course, analysis. With over 40 ROV dives and lander deployments, and with 5 sensors on each of those deployments, we have a huge collection of data at and around the site. We'll be going through it with a fine-toothed comb to provide quality-controlled and carefully-checked results for further discussion and analysis.

JC180: Eddy covariance proves to be a robust and sensitive tool for identifying leaks of CO_2 at the seafloor

By Dirk Koopmans[1], Moritz Holtappels[2], Volker Meyer[1], Dirk de Beer[1]

[1]Max Planck Institute for Marine Microbiology, Bremen, Germany

[2]Alfred Wegener Institute for Polar and Marine Research, Bremerhaven, Germany

Generally, for sub-seafloor marine CO_2 storage to succeed, effective techniques will be needed to verify the integrity of sub-seafloor storage reservoirs. Seafloor CO_2 leaks may be detected acoustically as plumes of gas bubbles and chemically as reduced seawater pH. As CO_2 gas comes into contact with seawater it dissolves rapidly, forming dissolved inorganic carbon (DIC) and hydrogen ions (H^+), reducing pH. A low pH anomaly at the seafloor is, therefore, a potential indicator of a CO_2 leak. However, the risk of a false positive is high. The natural decomposition of organic material can also create a low pH anomaly at the seafloor. Therefore, techniques are needed to determine whether low pH anomalies have a biotic or abiotic origin. Among the successes of STEMM-CCS is evidence that the pH and O_2 eddy covariance technique is highly effective at this.

pH and O_2 eddy covariance

The pH and O_2 eddy covariance technique is well-suited to identifying an abiotic source of CO_2 (e.g., a leak) at the seafloor. Eddy covariance fluxes are calculated from rapid (5 Hz or greater) measurements of water velocity and solute concentration in turbulent flow above the sediment surface (Berg et al., 2003). The technique is primarily used to quantify oxygen fluxes over benthic aquatic ecosystems. In a recent modification, CO_2 fluxes can also be determined with the technique (Long et al., 2015). The primary cause of a pH increase or decrease in seawater is a source or sink of CO_2. Therefore, if the pH flux can be quantified, the corresponding CO_2 flux can also be quantified. If the seafloor release of CO_2 is matched by seafloor uptake of O_2, the source of CO_2 is biological. If the seafloor release of CO_2 is greater than the seafloor uptake of O_2, the source is abiotic.

A lot of technical development was needed to adapt the pH sensor, an ion sensitive field effect transistor (ISFET), into a robust eddy covariance system. Signal amplifiers linearized the output voltage. A housing was constructed to seal against seawater and shield from ambient light. A bi-directional gear pump was developed that periodically reversed direction, expelling clogs. A reference electrode was constructed with minimal velocity-sensitivity and integrated into the housing. The final pH and O_2 eddy covariance system works even in environments with abundant suspended particulate material.

Lander deployments

We mounted the eddy covariance instruments and lab-on-chip sensors (in collaboration with NOC) to a lightweight fiberglass frame that the remotely operated vehicle (ROV) could carry to the seafloor (Figure 1). The combined instrument frame was called the benthic boundary layer (BBL) lander. Lab-on-chip sensors determined seawater pH, alkalinity, DIC, nitrate and phosphate. These were used to investigate the temporal and vertical dynamics of the carbonate chemistry of the plume. These measurements will be further used to independently quantify plume-derived DIC.

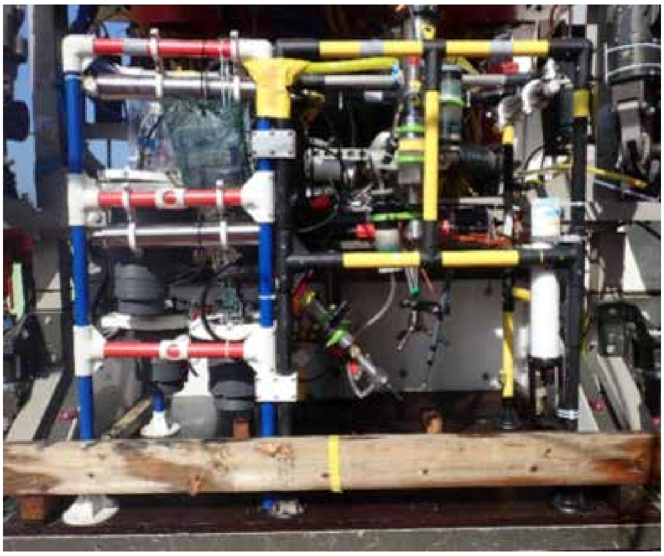


Figure 1. A benthic boundary layer lander on the tool sled of the ROV immediately before deployment. Eddy covariance instruments are mounted on the right. Lab on chip sensors are mounted on the left.

Two identical BBL landers were constructed so that one could be placed at the seafloor when the other was retrieved. This allowed for continuous measurement. The BBL lander was positioned 4 m south of the expected point of release (Figure 2).

The experiment

Ten minutes after the flow of CO_2 was turned on by the ROV, a single stream of bubbles erupted from the sediment surface 3 m north of the BBL lander. Flow direction follows a tidal

Figure 2. The experimental site just prior to CO_2 release. Clockwise from lower left are the sediment profiler (on the ROV), a hydrophone wall, a BBL lander, and a sediment pH optode.

ellipse at the seafloor, tracking through most of the points of the compass with every tidal cycle. As current flowed from the north, the calculated DIC fluxes from the plume exceeded DIC fluxes from other directions by two orders of magnitude (Figure 3). Lab-on-chip sensors confirmed the temporal pH dynamics.

Over the following ten days of the experiment, we increased the CO_2 release rate from 2 liters per minute to 50 litres per minute (at standard temperature and pressure). At a depth of 120 m, this volume is compressed down to 0.15 to 4 litres per minute. The magnitude and duration of calculated DIC fluxes increased with the increases in flow (Figure 4). Calculated plume-derived DIC fluxes exceeded simultaneous oxygen uptake by 200-fold. Thus, the elevated DIC fluxes were abiotic.

Conclusion

The O_2 and pH eddy covariance technique was a sensitive tool for the detection and quantification of benthic DIC flux during the release experiment. Natural and abiotic sources of DIC were easily discriminated, even at the lowest rate of CO_2 release. This technique is a robust and sensitive way to detect CO_2 leaks at the seafloor.

References

Berg, P., H. Røy, F. Janssen, V. Meyer, B. B. Jørgensen, M. Huettel, and D. de Beer. 2003. Oxygen uptake by aquatic sediments measured with a novel non-invasive eddy-correlation technique. Marine Ecology Progress Series 261: 75–83.

Long, M. H., M. A. Charette, W. R. Martin, and D. C. McCorkle. 2015. Oxygen metabolism and pH in coastal ecosystems: Eddy Covariance Hydrogen ion and Oxygen Exchange System (ECHOES). Limnology and Oceanography: Methods 13: 438–450.

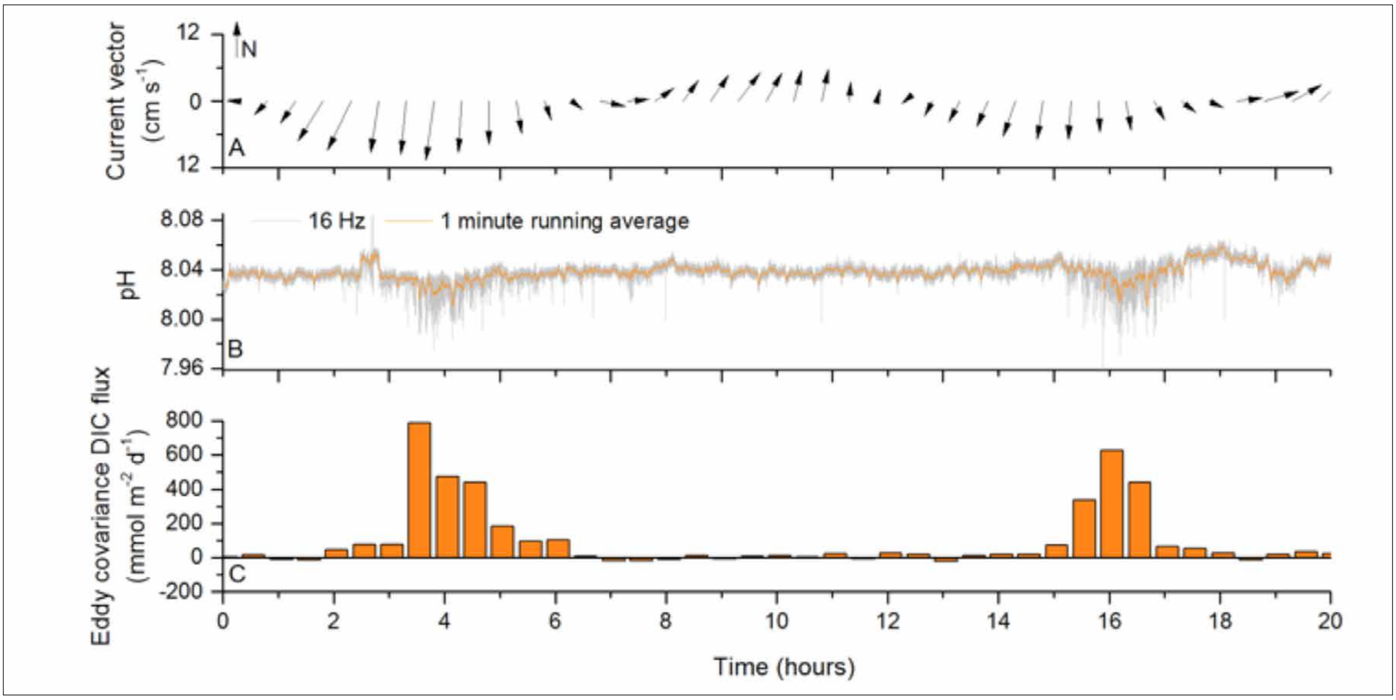


Figure 3. An example of the effect of the bubble plume – positioned to the north of the instruments – on calculated eddy covariance DIC fluxes. A) The current vector, B) eddy covariance pH measurements, C) the DIC flux calculated from the flux of hydrogen ions.

[Continued over...]

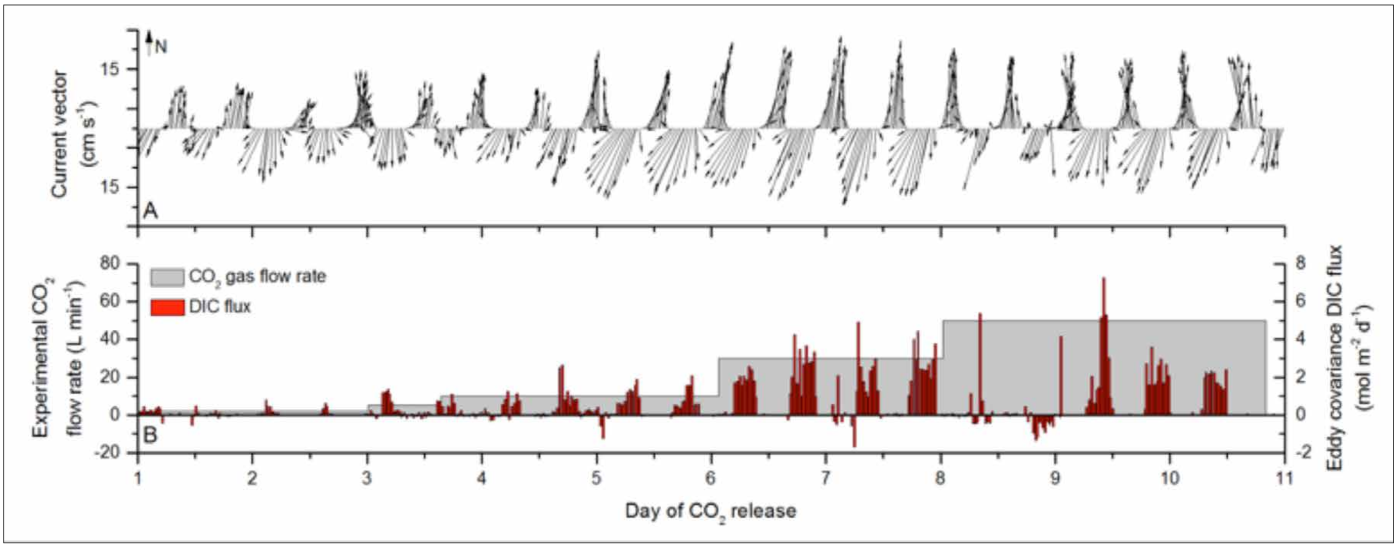


Figure 4. Time series of A) the current vector and B) eddy covariance DIC fluxes calculated throughout the experiment. On day 8 fluxes were corrupted by biofouling. Fluxes presented in Figure 3 occurred on day 2 of CO_2 release.

ROV Isis at sunset, with the Goldeneye platform on the horizon. Image courtesy Chris Pearce.

JC180: Benthic fluxes during the Goldeneye CO_2 release experiment

By Jonas Gros, Isabelle Mekelnburg, Mark Schmidt, Andrew W. Dale, Peter Linke, Sergiy Cherednichenko, Elke Kossel, Christian Deusner, and Stefan Sommer

GEOMAR Helmholtz Centre for Ocean Research, Kiel

Above, left: Benthic chamber on the front porch of the ROV ISIS, ready for deployment. Middle: benthic chamber about to be placed by ROV ISIS in the seafloor in the vicinity of a CO_2 bubble stream. Right: Recovery of a benthic chamber by the mechanic arm of the ROV ISIS after a 2-day deployment.

There were many activities carried out during the STEMM-CCS controlled release experiment. Here we focus on the efforts to monitor benthic fluxes - the exchange of dissolved chemical species across the sediment-water interface.

Benthic fluxes play a key role for CO_2 release, as a sizable fraction of this extremely soluble gas dissolves before escaping into the water column. It is therefore key to be able to monitor the fluxes of dissolved chemical species and to evaluate potential impacts of the released CO_2 on natural processes within the sediments.

Activities aboard RRS James Cook

In order to monitor the upwards and downwards movement of dissolved chemical species across the sediment-water interface, benthic chambers isolate a known surface of sediments (284 cm^2) together with a known volume of overlying bottom seawater (6-8 litres, depending on deployment). Monitoring the evolution of concentrations within this water volume enables determination of the fluxes of dissolved chemical species, including oxygen, dissolved CO_2, nutrients, etc. Two benthic chambers were deployed alternately throughout the experiment to monitor the changes happening as the CO_2 flow rate was incrementally increased. To enable precise placement of the chambers in the immediate vicinity (≤ 1 m) of visible bubble streams, the remotely operated vehicle (ROV) ISIS was used to deploy the benthic chambers and position them carefully on the seafloor.

Oxygen was monitored in real time with sensors (oxygen optodes) and showed an expected decrease, in agreement with other observations by scientists from the Max Planck Institute for Marine Microbiology (Bremen) on board the RRS *James Cook*. Other parameters will be determined in the coming weeks and months through multiple laboratory analyses of the water samples collected by the benthic chambers. These analyses will hopefully provide a more detailed understanding of this complex system. The data generated will then be investigated to identify potential impacts of the CO_2 release and seek to quantify the input

Above: Recovery of benthic chamber 2 and deployment of benthic chamber 1 on May 19 as viewed on the giant multiple screens in the control room of the ROV ISIS on board RRS James Cook.

of CO_2 and disentangle it from the natural fluxes due to biological respiration within the upper sediment layer.

Related activities on board RV Poseidon

Goldeneye is a familiar neighborhood for RV *Poseidon:* the ship visited the site back in October 2017 to monitor the benthic conditions prior to the release experiment. The benthic fluxes measured during that cruise represent one of the key comparison data sets for the new data acquired on-board the RRS *James Cook* with the benthic chambers.

Poseidon was back in its old playground for this new cruise, tasked with monitoring several parameters both near and further away from the CO_2 release point. In particular, sediment coring activities provided data that complement the benthic chamber data to deepen the understanding of processes occurring within the sediments and at their interface with the bottom seawater. Analysis of the samples collected during the final coring activities after the CO_2 release event will provide a greater understanding of how the upper few meters of the sediments were affected by the released gas. The video CTD, including a pump to collect bottom seawater for on-board analysis as well as the in-situ mass spectrometer both deployed from the ship will provide another piece of the puzzle: the field of concentrations within the water column.

Above: Syringes filled with samples of the water within the benthic chambers that were collected at regular intervals throughout the incubation. These samples were carefully stored in gas-tight vials (inset) that will be analysed at on-shore laboratories in UK and Germany.

Harnessing people power: school children help process JC180 experiment bubble data

One of the main ways the CO_2 gas escaped during the controlled release experiment was in the form of bubbles, popping out of the seabed and slowly rising up into the water column. A big part of our research revolves around understanding these bubbles: What shape are they? How big are they? How quickly do they move? How quickly do they dissolve?

Using a specially-built optical lander we've been able to capture video footage of the bubbles right as they escape from the seabed. The system worked extremely well and definitely didn't have any leaks destroying any cameras (…well, maybe just once). As a result, we now have hours of footage of bubbles escaping the sediment, giving us thousands of bubbles ready for analysis. Unfortunately, it's very hard to train a computer to spot and measure a bubble, as they change shape far too often for any traditional detection algorithm.

That's why we've enlisted the help of school children from around the UK. Following a classroom visit by University of Southampton PhD student Ben Roche earlier in the year, the students - ranging in age from 9 to 18 years - are expertly trained in what it takes to be a bubble scientist.

During the cruise, pupils video-conferenced with the team on board the *James Cook* to chat about CCS, the experiment, life on a ship and what it's like to be a scientist at sea. Now fully up to speed on things in the field and equipped with exciting bubble videos, they are ready to get to work on quantifying bubble sizes and working out gas volumes. Meanwhile, Ben can sit back and relax, safe in the knowledge his research is in good hands!

Live on the big screen: Ben chats with school children in the UK over live weblink

From field- to fine-scale fluid flow: Unearthing the science behind the art of X-ray micro-CT image-based modelling

By Ben Callow, University of Southampton

In order to ensure that CO_2 is stored in underground reservoirs safely and permanently, careful site characterisation and selection is required. However, fluid-escape pathways in the overburden are poorly understood as the physical properties of these structures cannot be determined solely by seismic reflection imaging. Onshore geological analogues are therefore studied to provide a more detailed understanding of the geometry, permeability and composition of fluid-escape structures, to better assess the risk they present to subsurface CO_2 storage containment. This article provides a brief insight into the X-ray micro-CT imaging technique used to analyse the onshore data collected.

Above: Onshore analogues of a fluid-escape system were collected from Panoche Hills, California and analysed using X-ray micro-CT imaging at Diamond Synchrotron, Oxford.

In October 2017, onshore sample data and field observations were collected from the Panoche Hills field site in central California. This field site is assessed as a suitable geological analogue of a complete fluid-escape system. The sediments at this site were originally deposited underwater, then subsequently uplifted, tilted, and are now preserved as onshore geological analogues.

X-ray micro-CT image acquisition of the onshore sample data was undertaken successfully at Diamond Synchrotron, Oxford in May 2018. A carefully-devised methodology has been formulated for the acquisition of porosity and permeability measurements from the X-ray micro-CT data (XCT).

The aim of the XCT method validation study is to ensure that accurate, reliable and repeatable results can be generated by assessing how the porosity and permeability measurements are affected by: Image segmentation, fluid simulation type, representative volume size and image resolution. To assess these four main themes, the following questions were addressed:

1. Can rock and air phases be accurately distinguished?

The binarised images were generated from automated segmentation using a machine-learning 3D weka segmentation using open-source Fiji software. An accurate segmentation result was obtained, distinguishing between rock and air.

2. Are two different fluid simulation methods comparable: Finite element voxelised grid vs Tetrahedral mesh?

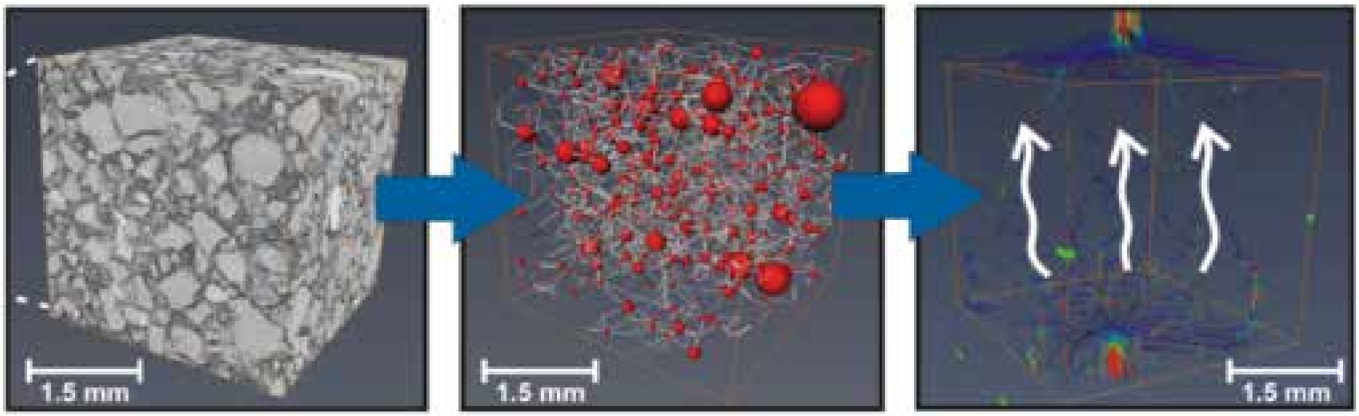
It appears that the two different fluid simulations are reasonably comparable, particularly in the 10-1000 mD range.

3. Can a representative volume size (REV) be achieved?

Pore properties are acquired from a number of different volume sizes, to demonstrate the optimum representative volume size (REV). It appears that representative porosity and permeability values are obtained from a volume size corresponding to 1.4 mm sample width (1400 voxels).

4. How does voxel size / image resolution effect porosity and permeability?

It is the high resolution and phase-contrast of the synchrotron scans (0.81 μm), not possible with lab XCT, that has allowed us to accurately visualise and quantify the multi-scale nature of pore networks in fluid escape structures.



Above: X-ray micro-CT image based modelling of the onshore analogue data, including pore network analysis and permeability simulations using Avizo.

The study has highlighted that porosity and permeability are both highly sensitive to segmentation method, image resolution and volume size. The workflow devised should ensure a robust, reliable and repeatable methodology for X-ray micro-CT image processing and image-based modelling of heterogeneous sandstone rock.

Now that a tested methodology for image analysis is in place, the porosity and permeability data, in addition to the onshore observations, will provide valuable insight into understanding the mechanisms and processes governing the formation of fluid-escape systems, as well as the spatial heterogeneity of the fluid flow properties of the complete fluid-escape system. The results of this study will be synthesised in an upcoming paper.

The same image analysis techniques will also be applied to X-ray micro-CT scans of gravity cores, sampled from beneath an active fluid-escape system in the Central North Sea, collected during cruise MSM78.

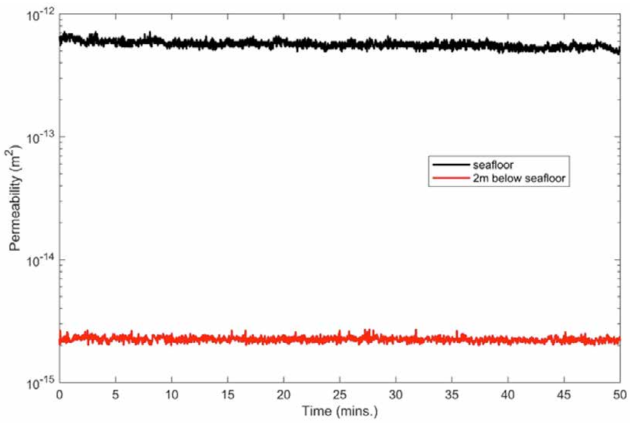
We thank our team of investigators who took part in the experiment, including: Dr Sharif Ahmed, Dr Hans Deyhle, Dr Hector Marin-Moreno, Dr Laurence North and Dr Christina Reinhard. We also give our thanks to Dr Shashi Marathe, Dr Andrew Bodey, Dr Kaz Wanelik and the Diamond Support Scientists at I13-2 for their support during the experiment. Thanks also go to Professor Andrew Hurst, Dr Antonio Grippa and the Sand Injectite Research Group from the University of Aberdeen for their help and guidance during fieldwork in the Panoche Hills.

Investigating sediment permeability changes with depth

Sourav Sahoo, NOC

We have measured 2 sub-cores (approximately 60mm diameter by 370 mm) of the same core, at 0m (seafloor surface) and at 2m below seafloor. Both were measured with a confining pressure of 1.2 MPa, representative of seafloor pressures in the North Sea. The inlet pressure for permeability measurement was 1.18 MPa and outlet pressure was 0.8 MPa. The fluid used for the permeability measurements was an artificial seawater brine.

The permeability difference between the two samples was very marked: the seafloor sample had a permeability of $5x10^{-13}$ whereas the sample from 2m below the seafloor displayed a permeability of $2x10^{-15}$ - some 250 times lower (see figure, right). This may reflect both dewatering and compaction as well as changes in composition, presumably a higher clay fraction. It was also noted that the 2m depth sample was more stable and displayed less compaction during permeability measurement, indicating its higher initial compaction. Pore fluid samples were also collected during permeability measurement for subsequent geochemical analysis. We measured P-wave velocity and attenuation for both cores in the range 1-10 KHz using the NOC Rock Physics Laboratory pulse tube system. Initial results show the seafloor sample has a P-wave velocity of approximately 1.5 kms^{-1} and the 2 m depth sample a velocity of approximately 1.6 kms^{-1} with minimal velocity or attenuation dispersion. Further analyses are ongoing.



Evaluating P-Cable's detection limits for subsurface CO_2

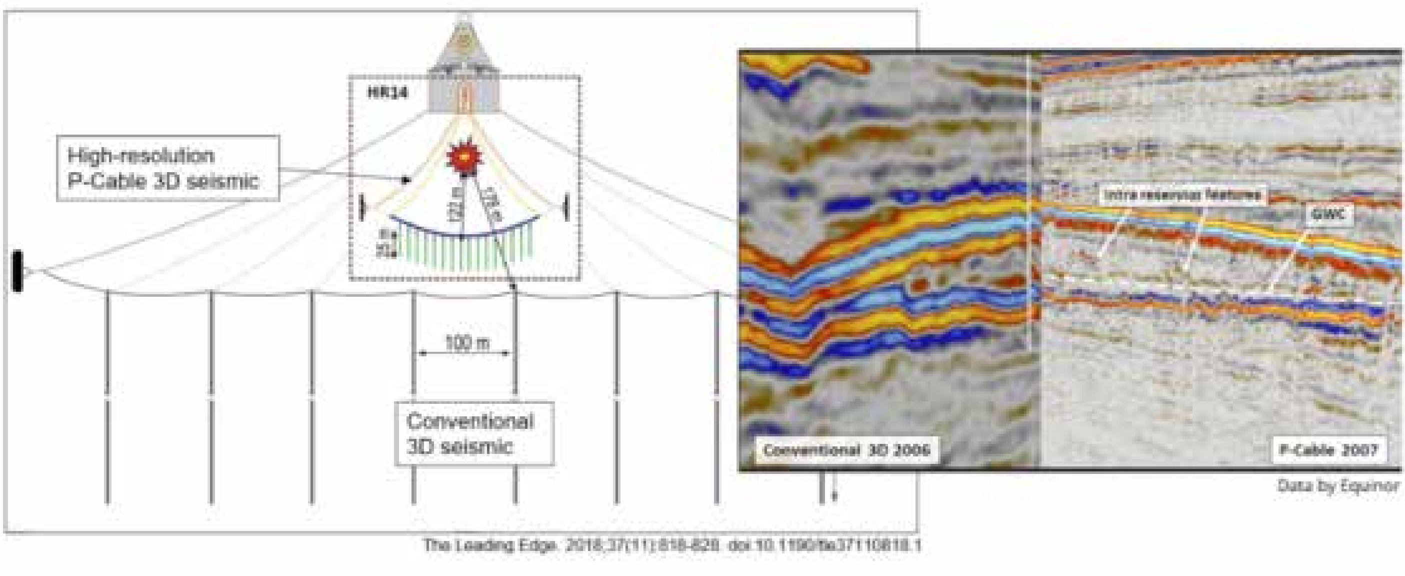
By Malin Waage, GEOMAR

In December of 2018, an article that I prepared alongside my team (Waage et al., 2018) was published in *Geophysics* highlighting the first comprehensive study with a focus on developing processing workflows for testing and assessing the repeatability of high-resolution P-Cable 3D seismic data. We showed industry standard repeatability (NRMS < 40%) in several areas over a range of geological settings, demonstrating that high-resolution P-Cable seismic data has potential as a time-lapse tool for purposes such as monitoring shallow hydrocarbon reservoirs and analysing the overburden of a CO_2 storage site.

In April of this year, I was awarded funding from the STEMM-CCS Researcher Placement Scheme to travel to the British Geological Survey in Keyworth, UK to collaborate with Dr Jim White, a research geophysicist on the BGS CCS team. The aim was to estimate the detection limits of CO_2 volume fluctuations, i.e., how much variation in subsurface fluid accumulation is required to exceed the background noise levels of high-resolution P-Cable time-lapse data. This technique and workflow were initially developed by the BGS CCS team under the lead authorship of Chadwick et al. (2014) for the analysis of conventional 3D seismic data. It is an important study for the evaluation of sensitivity in high-resolution P-Cable 3D seismics when detecting potential small leakages of CO_2 in the overburden strata

In order to determine the seismic detectability of small accumulations of fluid in the shallow subsurface, we adapted a spatial-spectral methodology originally developed to determine the actual leakage detection limits in the analysis of conventional time-lapse data (Chadwick et al. 2014). In this study, we use P-Cable time-lapse seismic data from two areas: (1) the Snøhvit field CO_2 injection site in the southern Barents Sea and (2) a glacimarine fjord located in northern-Norway. Details covering both sites and the accompanying data are presented in Waage et al. (2018).

The seismic data images the uppermost 300 – 400 m of the overburden in great detail. For both sites we assume that the difference signal detected is simply noise, i.e. no leakage is occurring. We applied a 2D discrete wavelet-transform on time-slices at a variety of depths, with horizons chosen to determine the noise components over different spatial scales for each of the amplitude grids. Subsequently, we modelled several scenarios by adding a series of anomalies that simulated a leakage of CO_2 accumulations. The results allowed us to determine the statistical likelihood of leak detection of a specific size at a certain depth, where the signal generated exceeds the noise component of the time-lapse seismic data. In order to create realistic properties and seismic expressions of a leaking CO_2 layer while associating amplitude anomalies to real CO_2 volumes, we plan to use both a two-layered 1D synthetic model as well as Gassmann's



Above: Comparison of high-resolution P-Cable and conventional 3D seismic system layout and data resolution.

fluid substitution equation to illustrate fluid anomalies detected in the high-frequency reflection seismic data at the two study areas.

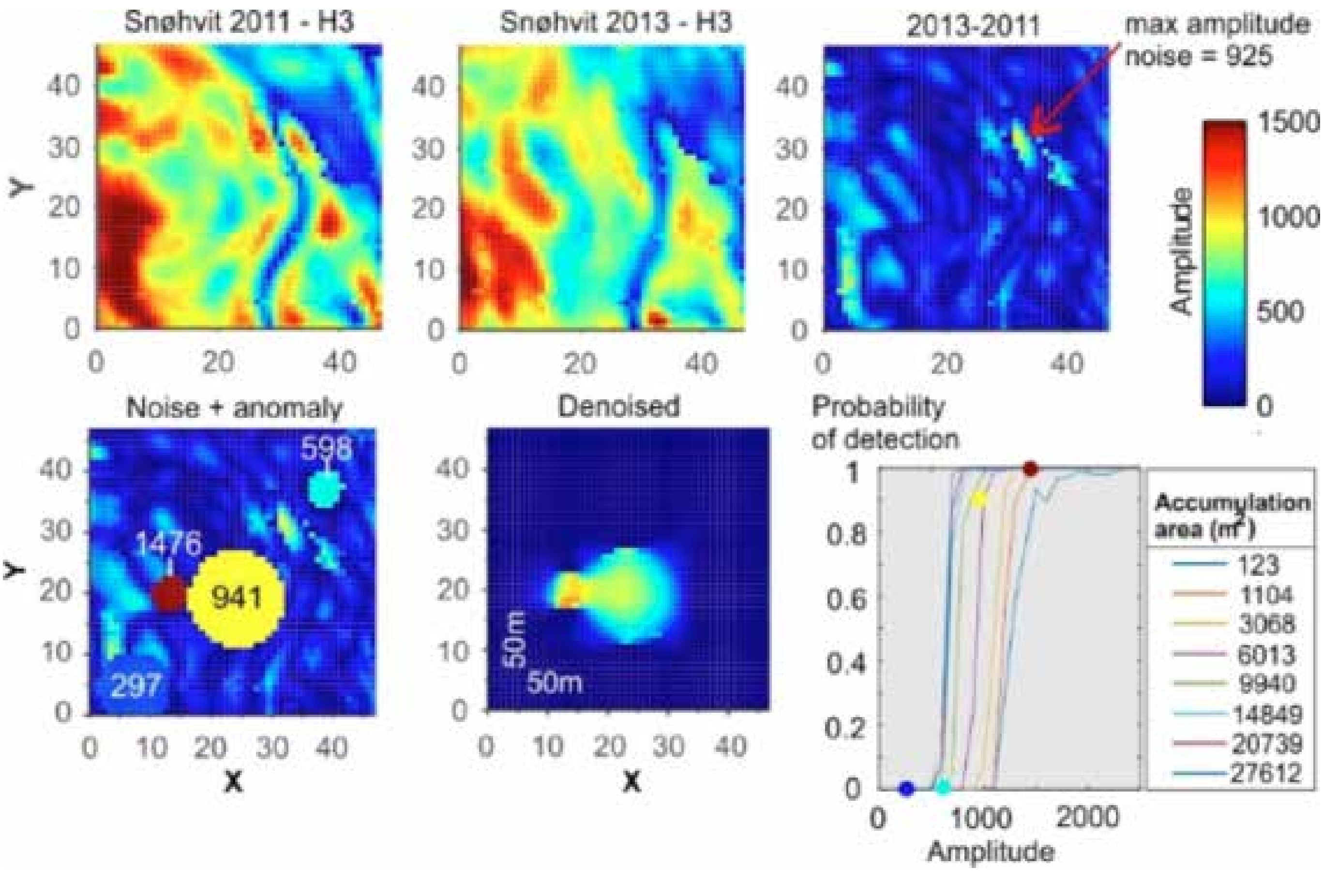
The final output of the study (yet to come) will be to estimate the limits of detection in CO_2 fluctuation necessary to surpass the background/4D noise, allowing for detection by the high-resolution P-Cable data, at various depths, in the opposing geological settings.

This collaboration with BGS provided an important opportunity for me and my colleagues to continue evaluating the P-Cable system for potential as a time-lapse tool. It was the natural next step in our research on P-Cable 4D seismic data as a monitoring technology for CCS operations. The workflow and technique described will also be an important precursor to all future time-lapse studies using high-resolution P-Cable 3D seismic data, as detectability varies with repeatability differences, geological settings and depths. We aim to compile a short scientific article summarising this study, the first article that I will lead in my new postdoc position at the Centre for Arctic Gas Hydrate, Environment and Climate (CAGE) in Norway. The position involves the analysis of P-Cable time-lapse seismic data acquired between 2012 and 2017 at the active fluid flow site of the Vestnesa Ridge, west of Svalbard, with aims to better understand subsurface fluid flow through focused fluid pathways such as chimneys. This study will therefore be important for my future work on 4D anomaly interpretations at this natural seepage site.

References

Chadwick, R. A., Marchant, B. P., & Williams, G. A. (2014). CO_2 storage monitoring: leakage detection and measurement in subsurface volumes from 3D seismic data at Sleipner. Energy Procedia, 63, 4224-4239.

Waage, M., Bünz, S., Landrø, M., Plaza-Faverola, A., & Waghorn, K. A. (2018). Repeatability of high-resolution 3D seismic data. Geophysics, 84(1), B75-B94.



Example of this study showing data and results of P-Cable 3D seismic from the overburden of the Snøhvit (southern Barents Sea) CO_2 injection site. This area reveals an amplitude distribution of 300x300m (90000m^2) along a horizon set at ~200m depth below the seafloor. (Upper left) the time-slice of the baseline survey; (Upper mid) the time-slice of the repeat survey; (Upper right) the difference time-slice; (Lower left) four anomalies are simulating a CO_2 plume of varying saturation/pressure and size (~1100-5000m^2) and their seismic response on the 4D seismic data. (Lower mid) the denoised time-slice; (lower right) The "probability of detection" plot is derived from the entire surface (~12 times larger than area presented), however, the four leakage anomalies are plotted in the graph (color and numbers refers to the amplitude strength), showing that the 297 (blue) and 598 (turquoise) anomalies will likely not be detected, whereas the 941 (yellow) and 1476 (dark red) anomalies have a 90% and 100 % probability of detection, respectively. As seen from the figure, detection probability increases with amplitude anomaly strength and size.

Perceptions, communication and risk: The second STEMM-CCS training course

The second STEMM-CCS training event took place over three days (25-27 February 2019) immediately prior to the third annual project meeting in Amsterdam. Comprising a series of seminar-style presentations, group exercises and discussions, this year's training event focused on public perceptions of CCS, communication and working with the media.

The first session was led by Dr Leslie Mabon from Robert Gordon University - a leading researcher in the field of social understanding of CCS. Dr Mabon has extensive experience in working with communities affected by CCS projects, particularly the Tomakomai CCS demonstration project in Japan where public acceptance of CCS has been carefully managed by local authorities but still presents some significant challenges. Dr Mabon presented a highly relevant and topical case study of two earthquakes that occurred in the Tomakomai region - the first in 2018 and the second just a few days before the training course took place - and the subsequent response from the project's operators, local authorities, and associated commentary on social media.

Above: Leslie Mabon shares his recent and very relevant experiences of social media exchanges relating to CCS issues in Japan.

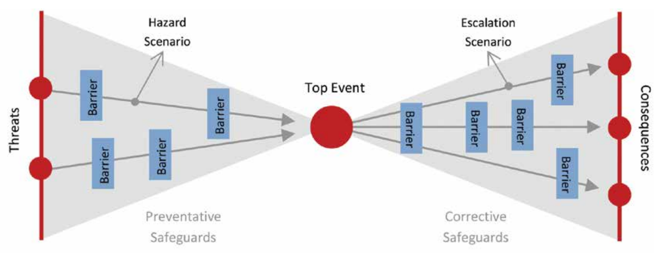
This particular example brought sharply into focus the influence of social media and the potential role of scientists in mediating between fact and fiction. Following discussion of the issues at hand, the workshop participants worked in groups to examine various media articles relating to CCS events, analyse the different approaches taken to sharing information with the public and consider the pros and cons of each approach. The subsequent group discussion touched on the transparency of information released to the public, the roles and perceived responsibilities of operators and local authorities in building relationships with local communities, and where scientists can help (or hinder!) the perception of CCS amongst communities affected by CCS activities.

Day 2 of the training course focused on the interaction between scientists and the media, how best to build a productive relationship with journalists, and the benefits of promoting research to a broader audience. Kelvin Boot (PML) led the morning session, which covered various aspects of media interaction and included a series of practical exercises that required participants to develop their own key messages and 'elevator pitches' in relation to their own research and to the STEMM-CCS project in general. Interview best practice was a particular focus of the late morning session, with participants pairing up to practice their interview technique in front of a camera, and being subjected to constructive feedback from the rest of the group.

Following lunch, attention turned to the role and use of social media by the science community. An expert in social media for scientists, Marie Saville from Minerva Communications, shared her knowledge and experience of using various social media platforms and explored the potential benefits to researchers of using these tools to promote their research and expand their professional networks. A pre-workshop questionnaire of social media use amongst the training group was used as a starting point for a discussion on which platforms users preferred and why, and to explore the reasons why some researchers choose not to engage with social media. At the end of the session, most participants in the room who were not regular users of social media said that they were more inclined to try out platforms such as Twitter as a result of the training session.

Above: Breakout groups enjoy early spring sunshine at Amsterdam's Hortus Botanicus whilst discussing their elevator pitches

The final session of the training event, on the morning of Wednesday 27 February, took place in Shell's main office in Amsterdam. Led by Shell's Marcella Dean and involving a number of her colleagues from the Shell CCS team, the focus switched to operational risk in CCS projects. Using the Bowtie Risk Analysis methodology, participants split into teams to carry out their own risk assessment of the Quest CCS project using real data. To demonstrate that a CO_2 storage site is performing as expected Shell uses a comprehensive risk-based Measurement, Monitoring and Verification (MMV) programme[1,2] based on a systematic site-specific storage containment risk assessment using the bowtie method and leakage scenario thinking. The bowtie (below) represents the relationship between the five key elements that describe how a risk might arise and how safeguards can provide effective protection against the risk and its associated consequences.



The session started with an introduction to the concepts involved using the Peterhead and Quest CCS projects as examples. Four enthusiastic groups of STEMM-CCS researchers and members of the Scientific Advisory Board had the chance to create their own bowtie using basic information from the Quest project. They identified threats or mechanisms that could potentially lead to a top event (the event we want to avoid, like CO_2 leaving the storage complex) and selected barriers or safeguards which reduce the chance that a threat escalates and eventually leads to consequences such as environmental damage or reduction of climate mitigation goals. Barriers or safeguards can be passive (those that are always in place, such as seals and well engineering elements) or active (those that trigger a corrective action, such as pressure monitoring).

Lively discussions around how to handle containment issues in a complex environment with many unknowns resulted in several insights. For example, the choice of top event and the implication this has on the number of corrective safeguards available to the storage operator: it is difficult to identify corrective safeguards if the top event is emission to the atmosphere. However, if the top event is deeper in the subsurface, several options exist such as selecting sites with geologic layers that can serve as secondary or tertiary storage. Creativity was also on display: proposals for corrective safeguards included planting trees, selling CO_2 for fizzy drinks or bribing stakeholders. Overall, the participants felt the exercise was useful to place their research in a broader context and agreed that they gained a basic understanding of how an operator might handle CO_2 storage containment risks.

References

[1] *Bourne, S. et al. (2014) A risk-based framework for measurement, monitoring and verification of the Quest CCS Project, Alberta, Canada DOI 10.1016/j.ijggc.2014.04.026*

[2] *Dean, M. & Tucker, O. (2017) A risk-based framework for Measurement, Monitoring and Verification (MMV) of the Goldeneye storage complex for the Peterhead CCS project, UK. DOI 10.1016/j.ijggc.2017.03.014*

Left: The Bowtie method. Preventative safeguards are on the left side and reduce the likelihood of a threat escalating to a top event (red circle). Corrective safeguards are on the right and reduce the severity of the consequences after the top event occurs.

Associated climatology, phenology and time series trends in primary production in the NE Atlantic

By Gavin Tilstone, Plymouth Marine Lab

Phytoplankton production reflects several environmental pressures (e. g. hydrological changes, contaminants, nutrient inputs, climate changes or elevated CO_2), which cannot necessarily be detected through changes in chlorophyll-a (Chl-a). Primary production (PP) is highly sensitive to changes in the ecosystem and can be used as an early warning indicator for direct pressure on food webs as it is an indicator of potential matter flow needed by higher trophic levels to produce biomass. From previous studies, as an indicator of good ecological status of the North Atlantic, North and Celtic Seas, daily PP should not exceed 2-3 gC m^{-2} d^{-1} and annual PP should be < 300 gC m^{-2} yr^{-1}. In the STEMM-CCS project a ~19 year time series of Copernicus Marine Environment Monitoring Service Ocean Colour data (1998-2017) is used to assess areas in the North East Atlantic and North Sea with similar peak values in PP and phenology. These areas are then used to re-define daily and annual thresholds of PP to detect CO_2 leakage from Carbon Capture and Storage sites. Changes in mean monthly and annual PP and the percentile 90 (P90) of PP over the time series and area are analysed to assess whether these thresholds are exceeded as a result of CO_2 leakage.

Reference: Tilstone, G.H., Land P.E., Pardo, S., Van der Zande, D. (submitted). Associated climatology, phenology and time series trends in primary production in the North East Atlantic from 20 years of ocean colour satellite data. Science of the Total Environment.

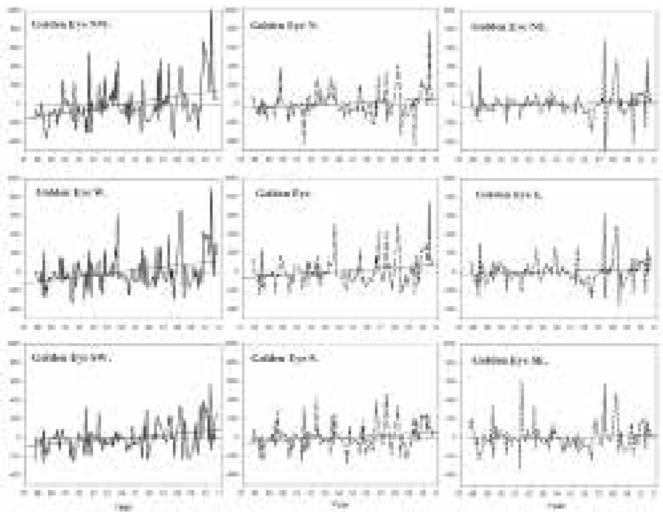


Figure 1 (above): Mean monthly satellite ocean colour time series of primary production (mg C m^{-2} d^{-1}) in 2005 for UK waters.

Figure 2 (right): Anomaly in satellite Ocean Colour Primary Production (mg C m^{-2} d^{-1}) from 1997 to 2010 at Golden Eye and in 1° x 1° boxes around the site.