STEMM-CCS

Strategies for Environmental Monitoring of Marine Carbon Capture and Storage

News update

Autumn 2017

Defying the weather in the North Sea

Expeditions to the STEMM-CCS study areas battle challenging sea conditions to deploy instruments and collect essential baseline data

In this issue:

Collecting environmental baseline data at Goldeneye

By Peter Linke and Matthias Haeckel, GEOMAR

Above: landers ready for deployment on the deck of RV Poseidon. Image courtesy P. Linke.

Poseidon cruise 518 ventured out into the North Sea in September-October 2017 to collect the necessary oceanographic and biogeochemical baseline data to underpin the STEMM-CCS controlled CO_2 release experiment scheduled to take place at the Goldeneye site in 2019. The team on board aimed to collect data to help address the following project goals:

1. Define and measure sensitive but robustly measurable environmental background parameters that are indicative for potential subsea CO_2 leakage.

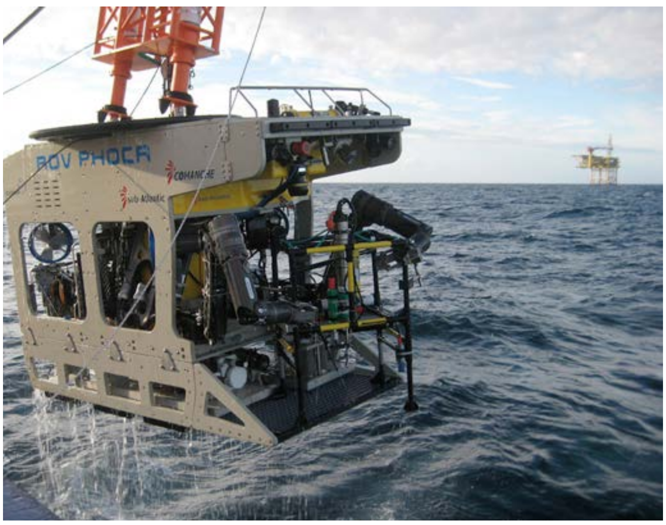
2. Provide water column measurements of trace gases, nutrients and carbonate chemistry variables to assess baseline conditions in the study area, and collect geochemical porewater data under natural (baseline) conditions to underpin a quantitative, process-based interpretation of porewater and benthic fluxes by state-of-the-art numerical modelling. This baseline data is also needed for monitoring and analysing the results of the CO_2 release experiment in 2019.

3. Test newly-designed benthic chambers, novel sensors, and hydroacoustic detection systems for measuring benthic and pelagic carbon fluxes, i.e. by using lab-on-chip technology, optodes, membrane inlet mass spectrometry, 3D-visual bubble imaging and multibeam echosounder quantification.

During Leg 1 of the cruise (26 September - 10 October 2017; PI Matthias Haeckel), the ROV PHOCA (pictured below) was used to deploy a tool for high-precision measurements of O_2, CO_2 and pH in the bottom water at Goldeneye. In addition, ROV-mounted push cores and gravity cores were collected in the area for sediment biogeochemical analyses, and video-CTD casts were conducted to study the water column chemistry. The stereo-camera system and a horizontally-looking multibeam echosounder, both used for determining gas bubble emissions at the seafloor, were deployed at the Figge Maar blowout crater in the German Bight. This crater was created 54 years ago and measures some 500m in diameter and 17m deep relative to the surrounding seafloor. Investigations were complemented by hydroacoustic surveys detecting gas bubble leakages at several abandoned wells in the North Sea and at the Figge Maar crater. Surface water alkalinity as well as methane, CO_2 and water partial pressures in the air above the sea surface were measured continuously during the cruise.

During Leg 2 of the cruise (11-27 October 2017; PI Peter Linke), three different benthic lander systems were deployed to obtain baseline data of oceanographic and biogeochemical parameters. The first lander was equipped with an acoustic Doppler current profiler (ADCP), a CTD and an O_2 optode. This was deployed for 6 days close to the Goldeneye platform to obtain high resolution data. The second lander was equipped with a suite of sensors to monitor temperature, conductivity, pressure, current speed and direction, hydro-acoustic, pH, pCO_2, O_2 and nutrients over a period of about 10 months, with pop-up telemetry units for data transmission via IRIDIUM satellite every 3 months.

Two short-term deployments of the third lander were conducted to determine the ratio between total oxygen uptake (TOU) and dissolved inorganic carbon (DIC) across the sediment water interface. The TOU to DIC ratio is a



Left: The ROV PHOCA being deployed from RV Poseidon, with the Goldeneye platform on the horizon. Image courtesy D. Koopmans.

biogeochemical means to detect possible CO_2 leakages from submarine CCS sites, indicated by strong deviations from the typical TOU to DIC ratio in a given region. The N_2/Ar ratio, total alkalinity, nitrate, nitrite, phosphate, ammonium and silica were also measured. Sediment cores obtained with a gravity corer and a multi-corer were collected for sediment biogeochemical analyses. Replicate video-CTD casts were used to study the hydrography and chemistry of the water column close to the Goldeneye platform.

Despite the difficult weather conditions resulting in a loss of 11 working days, useful datasets were successfully acquired to accomplish the project tasks of STEMM-CCS and prepare for the upcoming cruises in 2018 and 2019.

Want to know more? Read the POS518 weekly cruise blog entries at stemmccs.blog.

Above: Participants on Leg 2 of cruise POS518. Image courtesy P. Linke.

Want to know more about the STEMM-CCS controlled CO_2 release experiment at Goldeneye in 2019? Check out the new animated cartoon online at www.stemm-ccs.eu/work-package

The NOC lander and corer strapped down on the deck of RV Poseidon amid heavy swell in the North Sea. Image courtesy P. Linke.

Tracing CO_2: Pioneering work on tracers

Anita Flohr, University of Southampton

Robust strategies for leak detection and management are crucial in making carbon capture and storage (CCS) a safe and reliable strategy for the long-term mitigation of atmospheric CO_2 concentrations. STEMM-CCS builds on precursor studies such as QICS, which have contributed important knowledge on the detection and effects of CO_2 leakages in the marine environment (e.g. Blackford et al., 2014; Lichtschlag et al., 2015). In the framework of STEMM-CCS, diverse techniques and methodologies will be developed and tested during the controlled CO_2 release experiment at the Goldeneye site in 2019, mimicking the late stage of CO_2 leakage across the seabed. A key objective in this experiement is to examine the utility of natural and artificial tracers to detect, trace and quantify CO_2 leakage.

CO_2 – a special gas

CO_2 gas is special: not only does it dissolve in seawater, but it also reacts with seawater to form mainly bicarbonate (HCO_3) and carbonate (CO_3^{2-}) ions - collectively described as dissolved inorganic carbon (DIC). This process is the chemical basis for the mitigation of atmospheric CO_2 concentrations by the ocean (Volk and Hoffert, 1985). Secondly, CO_2 is both the source and the product of biogeochemical processes such as heterotrophic respiration, carbonate precipitation and dissolution. Thus, CO_2 is quite a reactive compound with diverse sources and sinks in the marine environment, which makes it challenging to differentiate between natural variability and a leak, especially when the leak is small.

Why use tracers?

Ideally, tracers should be detectable to very low concentration ranges and have a low background concentration or a characteristic isotopic signature. Used in combination with the compound that needs to be traced (e.g. CO_2), tracers help to significantly extend the detection range of CO_2 and DIC anomalies. This is extremely helpful for weak CO_2 escape scenarios in an environment with strongly fluctuating natural variability. Important criteria for assessing the tracer's utility in the CCS context include whether they are helpful to (i) explicitly attribute the observed CO_2 anomaly to a leak, (ii) quantify the leak, and (iii) differentiate between the physical and biogeochemical leakage pathways of CO_2 in the sediment and bottom water.

For a tracer to be suitable for commercial-scale monitoring of CO_2 storage in the marine environment, it is not only its chemical and physical properties that are important, but also the logistics and technology behind the sampling, processing and analysis protocols. Thus, a key criteria of the tracer approach will involve in-situ sampling and fast (online) analysis.

To differentiate between biogeochemical and physical processes affecting CO_2 and DIC concentration upon injection into the subsurface, a set of reactive and inert tracers will be tested. Carbon ($\partial^{13}C$) and oxygen isotopes ($\partial^{18}O$) are natural tracers, i.e. they are a chemical property of the injected CO_2 and of the seawater. They are reactive - i.e. they leave an isotopic finger print in the potential reaction pathways of CO_2, in both physical (e.g. dissolution, mixing, advection) and biogeochemical processes (e.g. respiration, carbonate dissolution and precipitation). In the context of geological CO_2 storage these tracers have been applied successfully for in-reservoir monitoring, for example to trace the migration of the plume of injected CO_2 gas, to quantify the amount of CO_2 sequestered in the formation, and to study its interaction with reservoir fluids and rocks (Khararka et al., 2006; Serno et al., 2016; Gilfillan et al., 2014; Györe et al., 2017; Györe et al., 2015).

Artificial tracers such as sulphurhexafluoride (SF_6), perfluorocarbons (PFCs) and noble gases can be added to the CO_2 upon injection and have been used successfully to detect in-reservoir CO_2 breakthrough (Boreham et al., 2011; Jenkins et al., 2015; Matter et al., 2016). These tracers are biogeochemically inert and can help track the physical processes affecting CO_2 upon injection.

Site characterisation

The majority of tracer-related studies in the CCS context have been performed in the framework of onshore demonstration projects with a focus on in-reservoir monitoring (e.g. Jenkins et al., 2015; Myers et al., 2013). Additionally, most of our current knowledge on the background concentrations of the tracers in the marine environment relies on published data from regions other than the central North Sea. To derive the tracer's natural background concentrations at the Goldeneye demonstration site we sampled the sediment, its pore waters and the water column during Leg 2 of the POSEIDON 518 cruise (see lead article in this newsletter). This work will provide essential baseline data to support the use of tracers in the controlled CO_2 release experiment at Goldeneye in 2019.

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Left: Selection of samples for tracer analysis during cruise POS518/2

Developing a bespoke lander for STEMM-CCS

By Mario Esposito, GEOMAR

Habitats and biogeochemical processes at the seafloor and within the water column of shelf seas such as the North Sea are affected by environmental cycles at various timescales (from days to decades) and by sporadic and sustained anthropogenic disturbances. In STEMM-CCS, it is crucial for us to be able to detect changes in the marine environment, and distinguish between natural variations and anthropogenic influences. Before any change can be detected, however, it is essential to establish an environmental baseline of the variable to be measured.

In order to provide the baseline data needed to define measurement strategies for the controlled CO_2 release experiment in 2019, an autonomous in-situ seafloor lander (the NOC lander) equipped with a suite of sensors has been deployed to monitor temperature, conductivity, pressure, current speed and direction, hydro-acoustic, pH, pCO_2, O_2 and nutrients in the experimental area over a period of about 10 months.

Lander specifications

The NOC lander is a bespoke submersible autonomous device manufactured by Develogic GmbH subsea systems. It is composed of four main parts:

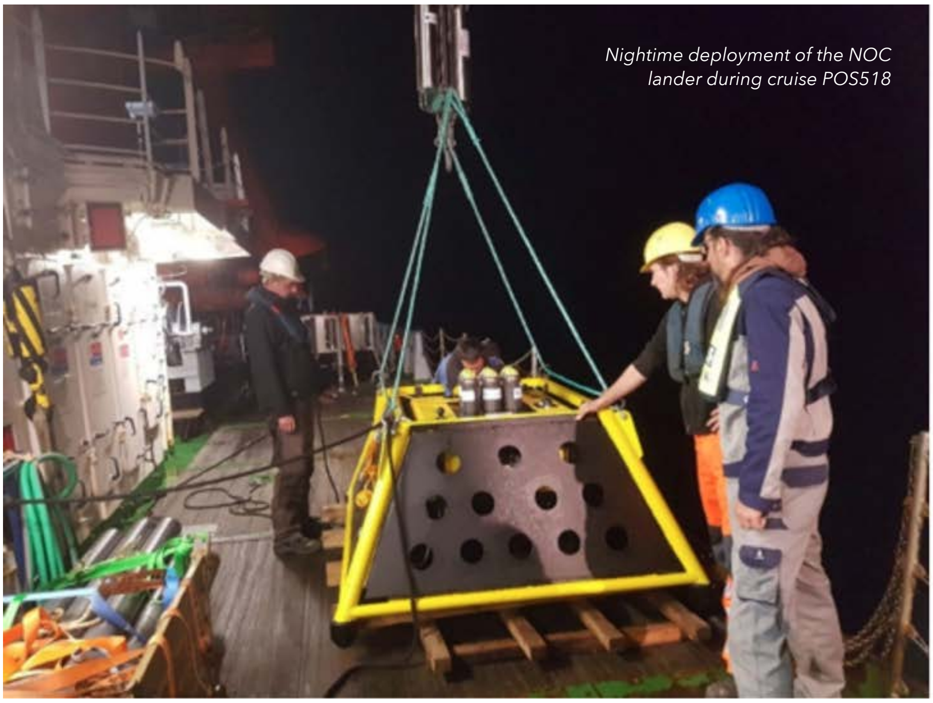
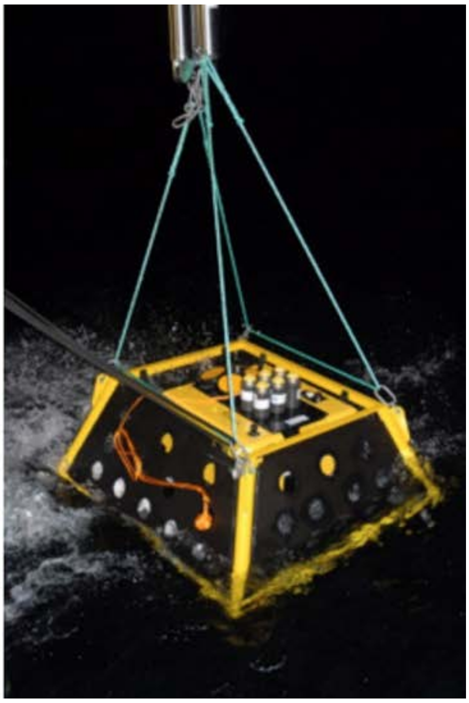
- A trapezoid trawl-resistant frame;
- A fully integrated solution with all mechanical and electrical components accessed and configured via interface connection or acoustic telemetry;
- A recovery subsystem with 250 m tether reel connected to a ballast plate through a remote-controlled titanium release;
- A surface hydro-acoustic modem with a 35 m rugged kevlar reinforced cable for real-time communication.

Lander deployment

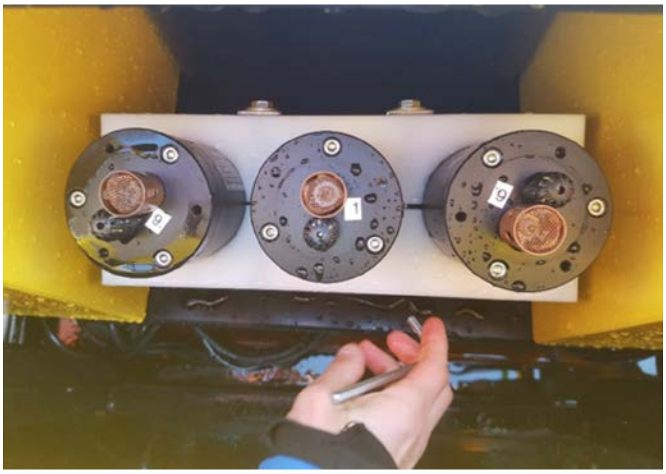
The first deployment of the NOC lander took place during the POS518 cruise, in the early hours of 16 October 2017. After deployment the lander was interrogated via hydrophone to confirm all the sensors were operating correctly. Two days later the lander was interrogated a second time but strong currents prevented successful communication. Despite heavy weather coniditons, a third attempt on 20 October was successful and remote access to the lander's data logger confirmed the lander and its devices were operating correctly. On the same cruise, CTD casts were performed in the area surrounding the NOC lander and these measurements will be crucial for a first inter-comparison and potential re-calibration of the lander's integrated sensors.

Lander configuration and sensors specification

In order to monitor the environmental conditions of the area, and focusing on the lower part of the water column, the suite of lander-integrated sensors was configured in the following way:

Nighttime deployment of the NOC lander during cruise POS518



Above: The TUG self-loggers

Acoustic Doppler current profiler (ADCP): An ADCP measures current speed and direction by transmitting high-frequency sound waves into the water column from above or below the area of interest. The measuring principle is based on the Doppler effect, a change in frequency of a wave when a wave source moves in respect to an observer. The device transmits a wave/sound pulse and listens for the return pulse. In order to get higher resolution data from the lower part of the water column, the ADCP was configured to sample the 40 m of the water column above the seafloor with a 4 metre cell size resolution every 20 minutes averaging over a sampling interval of 3 minutes.

The SeaBird Scientific Deep SeapHOx system combines the SeaFET pH sensor with a SeaBird Electronics CTD and O_2 sensor. The primary sensor element is an ion-sensitive field effect transistor (ISFET). The device has two potentiometric cells, both immersed in the sensed medium. Each cell contains a working electrode and an internal reference electrode. The potential of the external reference electrode varies according to the concentration of H^+ ions, hence pH. Measuring salinity, oxygen and pH at 20-minute intervals with high precision will provide reliable data to assess variations from baseline. In particular, pH measurements are crucial as there can be up to a 10 mpH change over 1 m of water in CO_2 leak scenarios.

The Sono Vault hydrophone is an acoustic recorder and signal analyser able to continuously record underwater acoustic emission. The device is ideal for "listening" for bubbles coming from the seafloor, as would occur during a CO_2 leak. The device was configured to sample every hour for a period of 10 minutes at 125 kHz.

Lab-on-Chip NOC sensors are portable and deployable devices able to accurately measure the concentration of chemical elements in the marine environment. Currently there are three devices that allow measurement of nitrate, phosphate and pH in the marine environment. The measuring principle is based on spectrophotometric methods: a specific chemical compound reacts with the reactive species of interest in the sample to generate a change in colour which is proportional to the concentration of the element to be measured. The systems are composed of a series of valves and pumps that sequentially operate to mix sample and reagents into microfluidic channels. Colour change is read by LED lights and sensors at specific wavelengths. Extensive tests were performed in order to optimise the chemistry and reduce power consumption for maximum deployment length. The nitrate, phosphate and pH chemical sensors were set to sample every 6 hours.

The TUG self-loggers (provided by University of Graz) are optical chemical sensors based on a fluorescent indicator dye immobilised on a polymer layer that changes its fluorescence properties based on pH or pCO_2 values. An LED light excites the dye molecule and the emitted light is guided by an optical fiber, captured and internally analysed by the device. These optodes measure and record data autonomously and they are ideal for long term deployment as power consumption is very low. As both pH and pCO_2 are strongly dependent on temperature, the devices were calibrated at varying temperatures from 5 to 25°C. During the STEMM-CCS long-term baseline characterisation deployment, one pCO_2 and two pH optodes were configured to sample every hour.

Lander pop-ups: The expendable communication buoys (ECB) are an innovative solution for periodically sending data remotely. Data are stored on the pop-up units and once at the surface, selective data can be downloaded via Iridium satellite communication.

For more information on this instrumentation please contact Mario Esposito, mesposito@gemoar.de

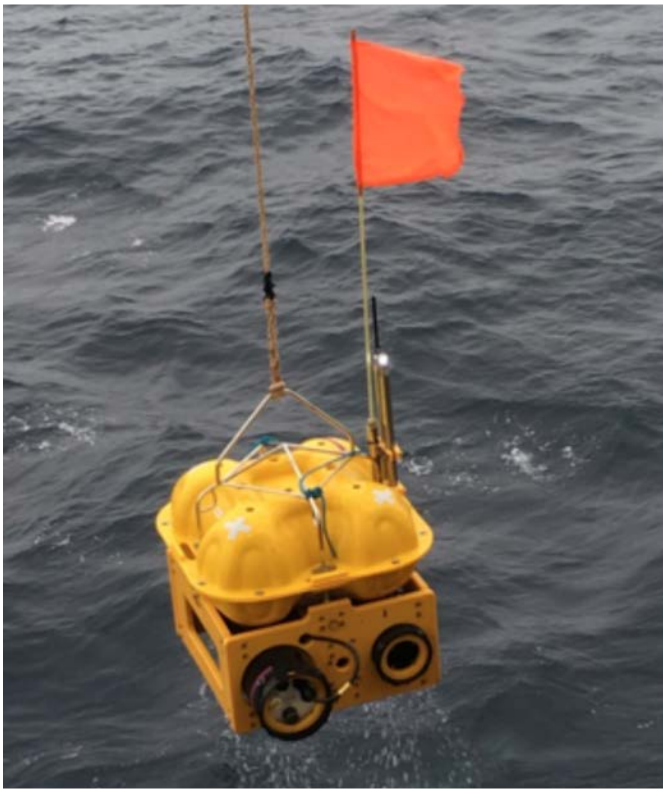
Below: Pop-up communication buoys ready for action

Characterising leakage pathways at the Scanner and Challenger pockmarks: the JC152 CHIMNEY cruise

By Jon Bull, University of Southampton

The Scanner and Challenger pockmarks in the North Sea were the target of investigations for expedition JC152 aboard RRS James Cook in August-September this year. The cruise was conducted as part of the CHIMNEY project, a UK-funded (NERC) CCS project to investigate likely leakage pathways through seafloor sediments in the North Sea. The CHIMNEY project is designed to be complementary to STEMM-CCS and to the recently completed EU-funded ECO2 project. As well as its geophysical field programme, the CHIMNEY project will conduct rock physics experiments, geochemistry and mathematical modelling to enable a better understanding of how to constrain sub-surface permeability in areas associated with fluid flow. The JC152 expedition aimed to build on work conducted aboard the RV Maria S Merian in April-May 2017 in the same area (see page 10), during which seismic and electromagnetic data were collected.

The Scanner Pockmark is a composite feature on the seabed characterised by two overlapping pockmarks, each a few hundred metres in diameter at approximately 155 m water depth. The pockmarks, themselves up to 20 m deeper than the surrounding flat seafloor, are sites of active and persistent methane gas venting. Although these sites are producing methane rather than CO_2, understanding the geometry and physical properties of fluid pathways from the deeper sub-surface to the seabed and into the water column provides insight into potential leakage pathways from CO_2 storage reservoirs.



Above: Deployment of an Ocean Bottom Seismometer from RRS James Cook.

Above: Gaye Bayrakci and Dan Ellis opening up the acoustic recorder to recover the data. The acoustic recorder was used to record the seismic sources within the water column, as well as the methane bubbles.

The location and intensity of CO_2 leaks are both dependent on the distribution of fluid pathways within the sediment overburden, and on the permeability of those pathways. Evaluation of seismic reflection data as part of the STEMM-CCS project has revealed ubiquitous structures cross-cutting vertically through the overburden within the North Sea and Norwegian Sea. These seismically-imaged pipes and chimneys are considered to be pathways for fluid flow. Natural gas (methane) from deeper strata is likely to have migrated through these structures into the water column at some point in geological time. If a subsurface plume of captured CO_2 should reach the base of these structures, and if their permeability is high enough, they will act as pathways for CO_2 leakage. To provide a reliable prediction of seep sites and a quantitative assessment of CO_2 escape, the nature and the permeability of these pathways needs to be constrained. It has been suggested that many chimney and pipe structures imaged on seismic reflection profiles in the North Sea represent (1) a fracture network that has been reactivated by pore fluid pressure, which facilitates the migration of fluids upwards; and (2) nearer-surface lateral migration of fluids along stratigraphic interfaces.

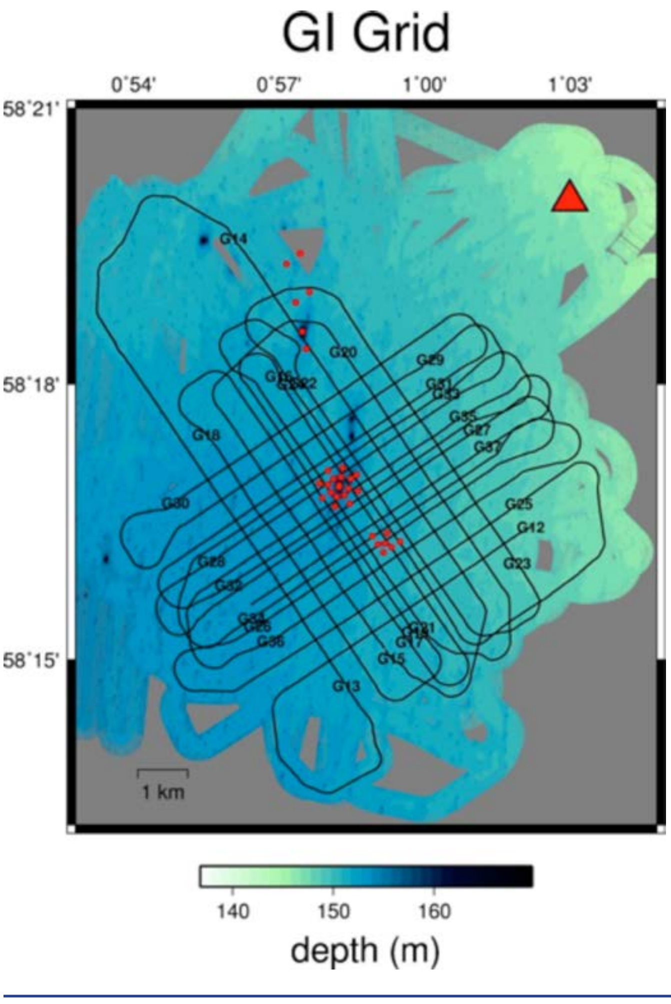
The JC152 cruise comprised scientists from the University of Southampton, National Oceanography Centre Southampton, the University of Edinburgh, the Ocean Bottom Instrument Facility, and Applied Acoustics Ltd. The scientific party included two research fellows, five PhD students and three undergraduate students, and presented a great opportunity for the training of early career researchers.

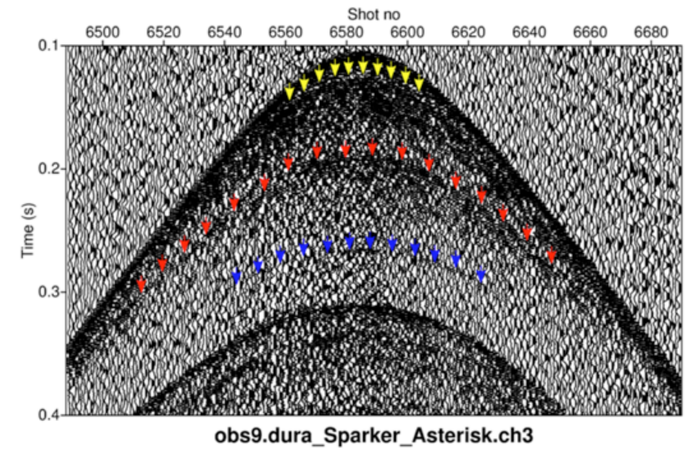
Unlike conditions on the Poseidon 518 cruise a month later, the weather in the North Sea was unexpectedly good during JC152, allowing all the planned work to be carried out as intended. With the help of the crew, scientists successfully completed two seismic anisotropy experiments over the Scanner and Challenger pockmarks. This involved shooting various seismic sources into a grid of ocean bottom seismometers: 25 at the Scanner site and 7 at Challenger site. Five different seismic sources (Bolt airguns, GI guns, Squid surface sparker, Duraspark surface sparker, and Deep Tow Sparker) were recorded by the ocean bottom seismometers, and an acoustic recorder was deployed at about 25 m above the seabed. Anisotropy experiments were completed to detect the orientation of fractures within the seabed sub-surface and to determine whether they are currently open or closed.

Multichannel seismic reflection profiles were collected with GI guns and two surface sparker sources, and single channel seismic reflection profiles were collected with the Deep Tow Sparker source. The acquired reflection profiles will be used to constrain the geometry of the fluid flow pathways and to determine the physical properties of near-surface sediments. Single and multichannel echo sounder data were collected along all seismic profile routes, which clearly showed the methane plumes within the water column.

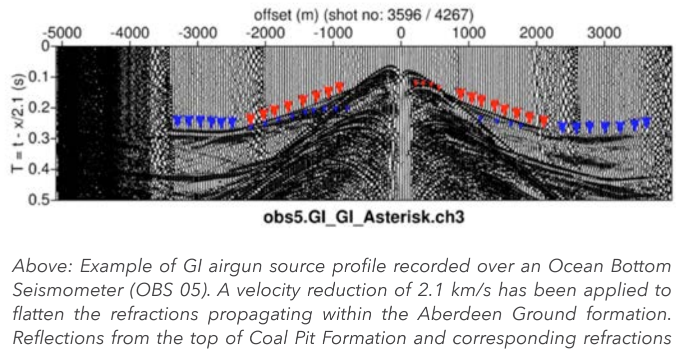
Further work at the Scanner Pockmark site will take place in autumn 2018 aboard RV Maria S Merian, with the collection of cores using British Geological Survey's RD2 rock drill. This will enable the ground-truthing of the sediment type detected on the seismic profiles and determination of the physical properties (including permeability) of the uppermost 50m of sediment beneath the seabed.

Below: Example of one of the seismic reflection grids that was collected on JC152 superimposed on the bathymetry. The map shows the ships profiles along which GI airgun sources were used. The airgun acoustic energy was recorded by a multichannel streamer towed behind the vessel as well as on ocean bottom seismometers sitting on the seabed (shown by red dots). The red star shows one of the locations of the water column acoustic recorder. The pock marks are shown by the dark blue colours.





Above: Example of data recorded by an Ocean Bottom Seismometer (OBS 09). In this case the acoustic source was an Applied Acoustics Duraspark Sparker. No velocity reduction has been applied. Yellow, red and blue arrows show the reflections from the top of geological units (Witch Ground, Coal Pit and Aberdeen Ground formations respectively).

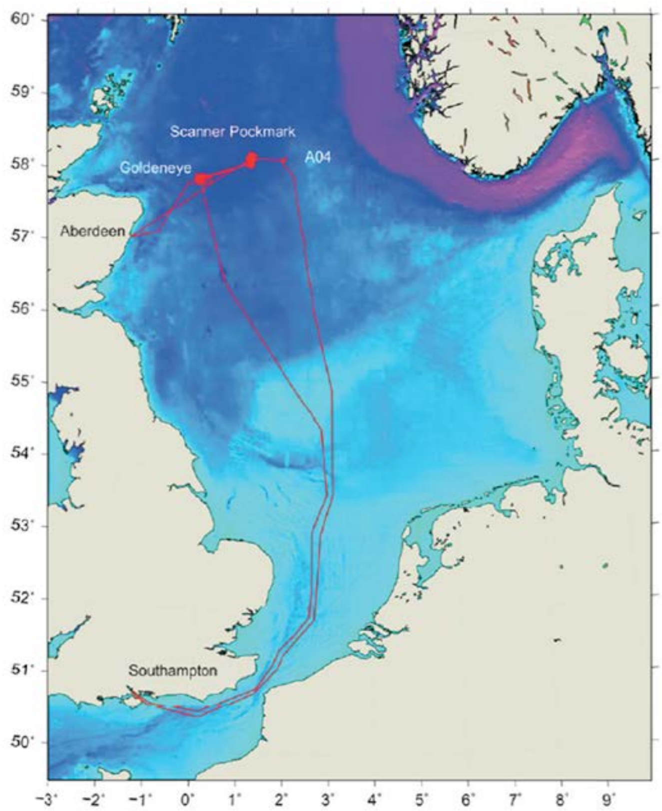


Above: Example of GI airgun source profile recorded over an Ocean Bottom Seismometer (OBS 05). A velocity reduction of 2.1 km/s has been applied to flatten the refractions propagating within the Aberdeen Ground formation. Reflections from the top of Coal Pit Formation and corresponding refractions have been shown with small and large red arrows respectively. Small and large blue arrows show reflections and refractions from the Aberdeen Ground Formation.

MSM63 PERMO cruise: Investigating seismic pipe structures in the North Sea

By Christian Berndt, GEOMAR

At the end of April 2017, 21 scientists set sail from Southampton on the research vessel RV Maria S. Merian for the first research cruise within the STEMM-CCS field programme. The expedition aimed to collect data to contribute to WP3, in which we are trying to constrain the geological relevance of seismic anomalies known as pipe structures. In seismic profiles, these structures do look exactly like pipes, and they are believed to form conduits for fluids such as CO_2 in the subsurface of sedimentary basins. Because pipe structures can be as wide as 500 m and 1100 m high they may transport large amounts of fluids and potentially change the entire fluid migration pattern in sedimentary basins, thus affecting the suitability of formations identified for CO_2 storage.



Map showing the track of the MSM63 PERMO cruise and location of study areas at Goldeye and Scanner Pockmark.

The objective of the MSM63 PERMO cruise was to provide necessary geophysical data, sediment cores and downhole logging data that help testing the following hypotheses:

- Seismic pipe structures have significantly higher hydraulic permeability compared to the surrounding country rock leading to focused fluid migration;
- Seismic pipe structures remain open pathways for a long geological time after their formation; and
- Seismic pipe structures are characterised by continuous fluid migration.

Because of the complex logistical requirements - not all the geophysical and drilling equipment could fit on Maria S.

Merian at the same time - the cruise was split into two legs. The first leg commenced in Southampton on 29 April and ended in Aberdeen on 13 May, followed by the second leg starting on 18 April and finishing in Southampton on 25 May.

At the beginning of the first leg we investigated two potential targets to decide which one was more suitable as a study area. After discounting a site in the Norwegian sector of the North Sea close to the Sleipner oil and gas field, we focused on the Scanner pockmark in the UK sector further west. There we collected a comprehensive geophysical data set consisting of multi-beam bathymetry data, Parasound sub-bottom profiler data, 2D seismic data, ocean bottom seismometer data, and controlled source electromagnetic (CSEM) data. Unfortunately, the planned high-resolution 3D seismic data could not be collected after we had lost a couple of working days due to a big storm. This should not present a big problem for the project however, because we received fantastic 3D seismic data from an industry sponsor before the cruise.

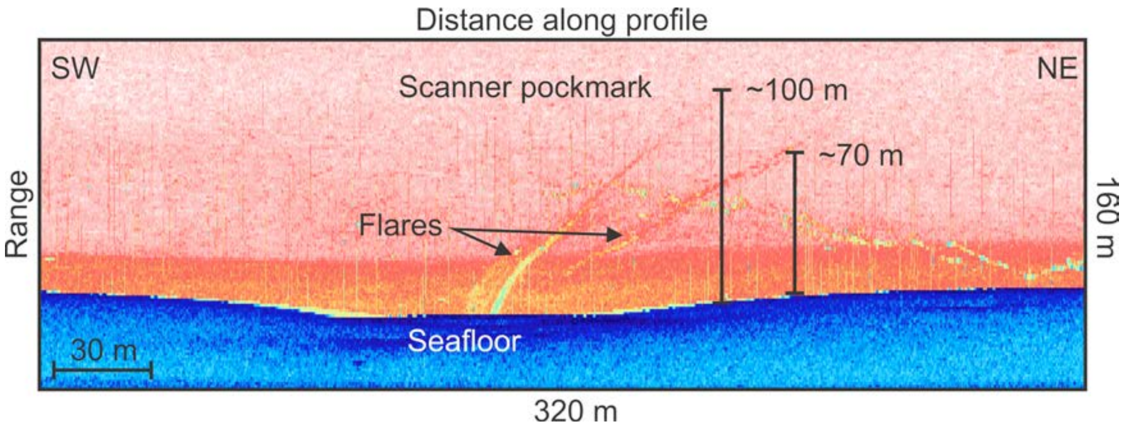
Above: deployment of an Ocean Bottom Electo-Magnetic (OBEM) receiver

The second leg was dedicated to surveying the second study site of the STEMM-CSS project in the Goldeneye area. In preparation for an Alkor cruise later this year, we collected a bathymetric grid and numerous Parasound sub-bottom profiler lines in order to determine a suitable target

Above: Cheerful despite many challenges - the MSM63 team

for the planned CO_2 release experiment. We also collected numerous water samples while running CTD casts to determine the origin of gas seeping from the seafloor. The idea behind these samples is to determine the depth to which the pipe structures reach. If they are penetrating most of the 800 m thick cap rock formation we would expect to detect thermogenic gas as well as biogenic methane. Unfortunately, the drilling operation planned for the second leg had to be cancelled because of technical problems with the vessel. There are plans, however, to drill the two boreholes in autumn 2018.

Preliminary results of the cruise show a deep-seated fluid migration pathway below the Scanner Pockmark that rises from at least 300 m below the seafloor. During the cruise we observed a continuous gas flare in the water column, suggesting that the pathway remains open and that seepage is not episodic. The multibeam bathymetry and Parasound data show that there are at least five episodes of pockmark formation. Four of these are associated with the glaciomarine or glaciolacustrine Witchground Formation, whereas only the biggest pockmarks such as Scanner Pockmark can be linked to the deep subsurface. Evaluation of ocean bottom seismometer data and controlled source electromagnetic data is ongoing.



Range stack of water column imaging showing gas flares above the Scanner pockmark. The flares are defected by the bottom current, but ascend up to 100 m into the water column from the seafloor. A fish shoal is visible as clear disturbance of the water column in form of small blue/yellow specks in the bottom right of the image. Blue colors represent high backscatter and red colors low backscatter.

Natural variability in marine chemistry and its implications for CCS monitoring

By Jerry Blackford, Plymouth Marine Laboratory

Scientists at Plymouth Marine Laboratory (PML) have published work that demonstrates optimal criteria for the effective monitoring of CO_2 storage, based on an in-depth understanding of marine chemistry.

For successful CCS implementation, it is critical to demonstrate that CO_2 is safely and robustly stored in geological reservoirs. Primary monitoring uses seismic techniques to image CO_2 stored deep underground, however this is expensive and is only able to "see" relatively large accumulations of CO_2. Consequently, secondary monitoring at the surface, or at the seafloor for offshore storage, is required to ensure that storage is secure or to alert us to the unlikely event of leakage. Such monitoring must be inexpensive, able to cover a significant area – perhaps up to 100 km^2 - and be highly sensitive without giving large numbers of false positives. Sensitivity is crucial as the chemical signature of a release could be very small, especially if the sensor is at some distance from the leak location. Therefore we must understand how this potential signature of leakage compares with the natural variability of the same chemistry in the environment.

Herein lies the challenge. The most appropriate marine sensors measure changes in pH (or pCO_2) caused by carbon dioxide dissolving in seawater. However many biological and physical processes cause significant variability in pH (and pCO_2) over a range of time and spatial scales. This is compounded by a paucity of available observations that allow us to characterise this variability in a statistically robust way. Hence the group at PML have turned to complex simulation models that contain all the processes known to affect pH in the marine environment. By running this simulation model for several decades, at time steps as low as 20 minutes, and over the whole of the NW European shelf seas we have produced a huge data set describing the natural variability of marine pH.

Using this data we can then ask the question – what are the best criteria by which we can unambiguously distinguish a leak event from natural variability? In this study we chose to analyse three regions in the North Sea that have been considered for storage, but have very different characteristics: Goldeneye, around 120m deep, which becomes thermally stratified during the summer; a shallow (28m) unstratified region coinciding with the Bunter Closure and Hewett fields, and the 38m deep Endurance site that demonstrates weak stratification. An immediate outcome from our work is that the natural dynamics of pH at each of these sites are very different (Fig. 1), so consequently a monitoring strategy optimised for one site would be unlikely to work at another.

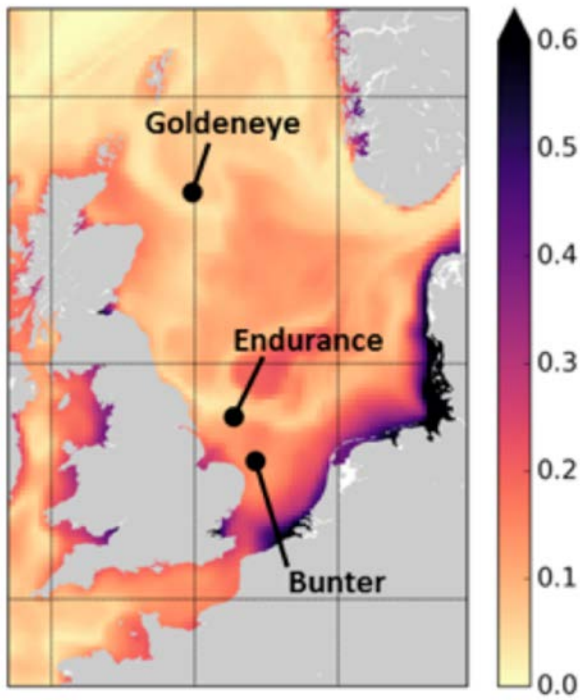


Figure 1: The annual range of pH in the NW European shelf seas.

Because the natural range of pH seen at each site is relatively large compared with some potential signals from a leakage event, it is apparent that using the seasonal pH minima as a demarcation between natural variability and a suspicious event would not deliver a sensitive detection criteria, so we needed something a little smarter. The key was to consider the rate at which pH changes due to natural processes. We show that over short time periods natural changes in pH are generally very small, therefore looking for relatively small but rapid changes in pH could be effective. Previous modelling work has shown that plumes of high CO_2 from a leak event are very mobile due to tidal forces. Couple this to the idea that sensors would be mounted on mobile autonomous vehicles, then the likelihood of deployed sensors encountering discontinuities between normal seawater and leakage plumes would be high, further suggesting that using rapid changes as a detection criteria would be valid.

The published work shows that at Goldeneye, which has less natural variability than the other sites, a tiny change of 0.01 pH units over 20-40 minutes could be considered a robust indicator of an anomaly. At more variable shallower sites observations would need to be more frequent, or a larger but still sensitive pH change should be used as a criterion.

Models are never perfect, but confidence in them increases when they are calibrated with monitoring data. The recent deployment of sensors by the STEMM-CCS project will gather high frequency pH data that will enable us to refine this theory and then test it during the planned CO_2 release later in the project.

To read more:

Blackford, JC, Artioli, Y, Clark, J, de Mora, L. (2017) Monitoring of offshore geological carbon storage integrity: implications of natural variability in the marine system and the assessment of anomaly detection criteria International Journal of Greenhouse Gas Control 64, 99-112 DOI:10.1016/j.ijggc.2017.06.020

This paper can be freely accessed at: https://authors.elsevier.com/sd/article/S1750583616309471

More information on PML modelling at http://www.pml.ac.uk/Modelling/Home

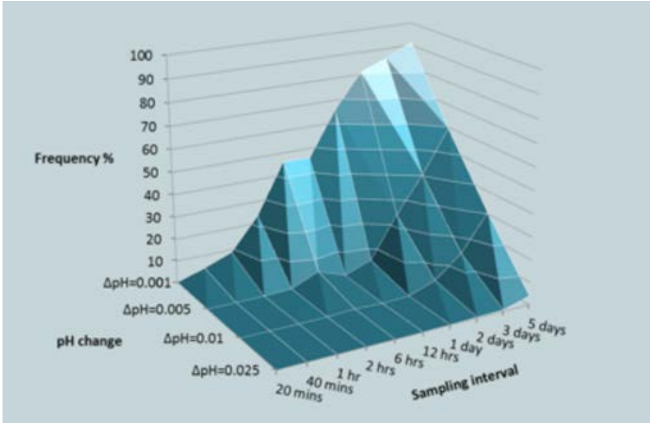


Figure 2: Illustration of how small changes in pH become increasingly rare as the sampling interval decreases

What do the search for submarines, your runaway dog and missing keys have in common with CCS assurance monitoring?

By Guttorm Alendal, University of Bergen



The search for missing objects is a challenge we all experience from time to time. Where did I put my car key, where is my favourite shirt, or where did my dog disappear to? We begin a search and, after some initial thinking, start by looking where we think the missing item is most likely be: the car keys are probably in the pocket of the jacket I wore the last time I drove my car; my shirt is still in the laundry basket, and my dog is most likely visiting the neighbour's Labrador, her favourite playmate.

These are all examples of how we use knowledge about our own habits and history to decide where to start a search. If our first guess is wrong and we don't find what we are looking for in the expected place, we update our belief with this new knowledge and decide where to look next.

This procedure is also used in search and rescue operations and is based on Bayes' theorem. This theorem has enjoyed a renaissance in the recent years but it has been used in many contexts over many decades without being named as Bayesian (Mcgrayne, 2011). For instance, it was used to crack the Enigma code during WWII, hunt for Soviet submarines during the Cold War and to search for the missing Malaysia Airlines flight MH370 in 2014. The theorem offers an approach to update our beliefs in a systematic manner after receiving new information.

In a recent article I used the theorem to develop algorithms to plan survey paths for an Autonomous Underwater Vehicle (AUV) with the purpose of detecting potential escape of CO_2 from the seafloor. Such surveys will be an important component of routine monitoring for subsea geological storage projects, and are required by regulations and international conventions. The ability to quantify our belief that there is no leak from a CCS site provides assurance against unjustified accusations of CCS causing adverse environmental effects.

Given adequate baseline data, CO_2 releases can be detected some distance away from their source. Hence, a sample measurement that shows no evidence of a release will also signal that the probability of a gas release in the area surrounding the sample site is low, in much the same manner as a completely silent neighborhood indicates that there are no dogs playing on the other side of the hedge.

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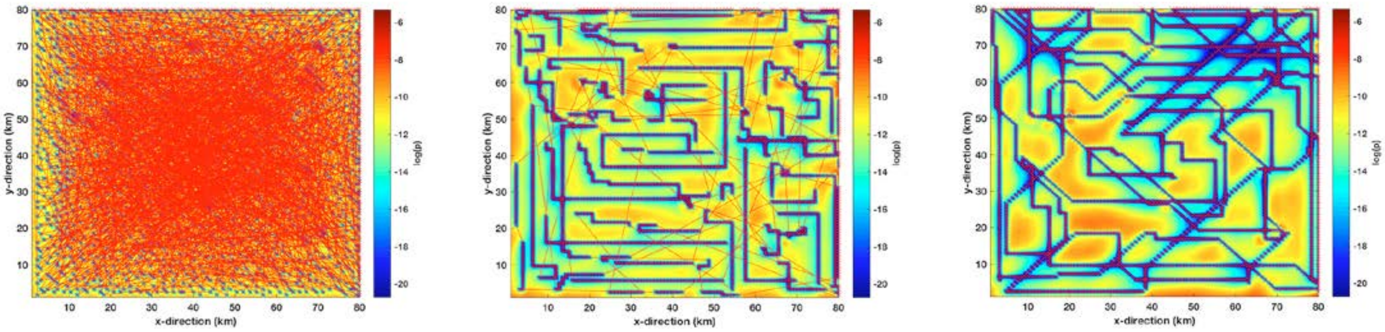

Measurement locations (blue crosses) and paths taken (red lines) when the probability of a leak being present in the area is reduced using the following three survey strategies: Left: move to the next location with the highest probability of being the location of a seep. Middle: Move to the next location taking the cost and time of movement into account. Right: as for the middle strategy, but taking measurements during propulsion. The background colors show the probability of a leak being present in that location.

We start a survey with a map of most likely gas escape locations, based on existing knowledge. This probability map is updated after each survey measurement is taken, and the AUV will use this information to decide where to go next. Since battery capacity is an issue, the AUV should prioritise available energy for propulsion and for taking measurements, therefore survey design must optimise this.

In the study I suggested three different approaches to survey design (see figure above):

1. After measurement, move directly to the next most likely location, which might result in moving long distances in an irregular fashion;
2. Take the cost and efficiency of moving to a new location into account - rather like checking the jacket next to the one you are searching now for your keys before moving upstairs to check the trousers you wore yesterday;
3. Combine approaches 1 and 2 by taking measurements while moving to a new location - just like keeping your eyes open for your keys whilst climbing the stairs.

This study was solely based on model simulations from Plymouth Marine Laboratory, Heriot-Watt University and the University of Bergen. Once we have real data from the Goldeneye area the natural variability of the environment will be better described, and the large-scale controlled CO_2 release experiment in 2019 will enable better predictions on the footprint of a CO_2 escape.

In the meantime, the procedures will be refined and extended as part of our efforts within STEMM-CCS. Unfortunately, Bayes theorem doesn't offer a way to avoid mislaying car keys or favourite clothes, or to train dogs. It only offers a way to find them again once they are lost.

Read more at:

G. Alendal. Cost efficient environmental survey paths for detecting continuous tracer discharges, Journal of Geophysical Research: Oceans (2017). DOI: 10.1002/2016JC012655

Mcgrayne, S. B. (2011), The Theory That Would Not Die; How Bayes Rule Cracked the Enigma Code, Hunted Down Russian Submarines and Emerges Triumphant From Two Centuries of Controversy, Yale Univ. Press, New Haven, Conn.

New resources online at www.stemm-ccs.eu

New resources are now available on the STEMM-CCS project website, including the first of the Science Briefs - introductory documents that explain some of the basic CCS concepts that underpin the project's research. Topics covered include:

- What is carbon dioxide capture and storage?
- Establishing baselines for CO_2 monitoring
- Detecting, tracing and quantifying CO_2 leakage
- CCS reservoirs and CO_2 pathways
- Potential impacts of CO_2 leakage in the ocean

Also new on the website is an animation showing the concept behind the controlled CO_2 release experiment that will take place at the Goldeneye site in 2019. The animation is available with or without explanatory subtitles and is suitable for use in presentations. See www.stemm-ccs.eu/work-packages

Dates for your diary: STEMM-CCS Annual Meeting 2018

14-16 March, Hotel Playafels, Castelldefels, Spain

The next STEMM-CCS annual gathering of partners will take place over 3 days on 14-16 March 2018. The meeting will take place at the Hotel Playafels in the small town of Castelldefels, just outside Barcelona and a short ride from Barcelona airport.

The meeting programme will start after lunch on Wednesday 14 March and conclude at lunchtime on Friday 16 March.

All project partners are encouraged to attend. Participants are responsible for organising their own travel and accommodation - rooms are available at the conference hotel for those who wish to stay there, but there are plenty of alternative options within walking distance.

Further details will be circulated by email in due course, but please ensure these dates are in your diary!

and...the first STEMM-CCS Training Course

13-14 March, Hotel Playafels, Castelldefels, Spain

The first STEMM-CCS training course will take place over two days immediately prior to the 2018 Annual Meeting. This course - open to all project partners but specifically aimed at our young researchers (PhD students and postdocs) will comprise a mix of seminars and practical exercises, delivered by external experts from the CCS community, including representatives from industry and research sectors.

Day 1 (Tuesday 13 March) will comprise a series of engaging talks from external experts, covering the full CCS cycle in order to enable our researchers to see and appreciate how their work fits within the wider CCS context.

On Day 2 (Wednesday 14 March), participants will engage in a team-based CO_2 leak detection and mitigation exercise, coordinated by Katherine Romanak (University of Texas at Austin). Groups will be set a series of challenges linked to a simulated CO_2 leak scenario, and work together to commission surveys, analyse data and make decisions on how best to locate the source of the leak and and mitigate its effects. The exercise has a competitive edge, with teams being assessed on their ability to work together as a team, as well on the effectiveness and cost of their approach to the challenge.

The course will be rounded off with an evening poster session where PhD students and postdocs can present their research topics to the broader STEMM-CCS community.

The full training course programme will be available online in due course; participation is free of charge but participants will need to cover their travel and subsistence costs.

Going full cycle: IEAGHG Summer School 2017

By Ben Callow, University of Southampton

Ben Callow is a postgraduate research student at the University of Southampton, involved in STEMM-CCS research on leakage pathways through the overburden. He was recently selected to attend the week-long IEAGHG CCS Summer School in Canada for Early Career Researchers in July 2017. Ben gives an account of his week...

I was very fortunate to be selected for the 2017 IEAGHG Carbon Capture and Storage (CCS) Summer School, hosted by University of Regina, Saskatchewan, Canada. The 11th Summer School was a week-long intensive course covering all aspects of CCS, ranging from the technical challenges of capture, transport and storage methods to discussions of policy, economic feasibility and public perspective. The CCS Summer School community comprised 35 students of varied nationalities, experiences and technical backgrounds, along with experts from industry and academia which provided a unique networking opportunity.

Whilst my research focuses on onshore geological analogues of chimney structures for improved CO_2 storage site characterisation, the week provided an excellent opportunity to step away from my focused area of research and appreciate the role it plays in the broader context of CCS. It was inspiring to work alongside and learn from like-minded Early Career Researchers (ECRs), who shared the same passion for CCS and mitigation of anthropogenic CO_2 emissions.

During the week we were also required to undertake a group research project. My team researched the role CO_2 Enhanced Oil Recovery (CO_2-EOR) plays in the CCS chain. It was intriguing to get multiple perspectives on CCS from experts in industry (Simon O'Brien - Shell, Mike Monea - SaskPower), academia (Katherine Romanak - The University of Texas at Austin), public communication (Norm Sacuta - PTRC) and from a policy perspective (Tim Dixon - IEAGHG).

A visit to SaskPower CCS plant and Boundary Dam gave me an appreciation of the technical complexity and scale of operation required to convert a coal fire power plant into a plant capable of CO_2 capture and storage. The key message I took away from the summer school was that the CCS technology, whilst improving in efficiency and understanding, is in place. What is preventing further full-scale projects is the economic feasibility and effective policy. Clear public communication is also an important factor that cannot be overlooked.

I now look forward to sharing the knowledge I have gained from the summer school. It was an invaluable and unique learning experience. I thank the IEAGHG, SaskPower, University of Regina and UKCCSRC for the fantastic opportunity, I am sincerely grateful.

Main image: A day visit to the SaskPower Boundary Dam CCS facility. Left: Ben presenting during the group project on the role of CO_2-EOR in CCS to a room of experts and fellow Early Career Researchers (ECRs). Below: Ben's team at award night by Wascana Lake,

New faces in STEMM-CCS

The STEMM-CCS project community includes a number of PhD students and early career postdoctoral researchers who are working on a range of topics within the project. In many respects these researchers are the driving force in the project, contributing more than 20 person-years between them towards the achievement of the project's objectives. Here's a quick introduction to our latest recruits...

Brett Hosking, National Oceanography Centre

Brett is a Computer Vision Researcher within the Ocean Biochemistry and Ecosystems group at the National Oceanography Centre, Southampton, UK. He completed his PhD in Electronic and Electrical Engineering at the University of Bristol where he specialised in image and signal processing, as well as video communications and compression. His main research interests now include using machine learning to automatically extract statistical and semantic information from underwater images by applying supervised and unsupervised learning methods. The aim of his work is to reduce the need of manual annotation of data which is becoming increasingly more infeasible given the growing volumes of data collected from autonomous underwater vehicles and other observation platforms.

Jianghui Li, University of Southampton

Jianghui earned his PhD in Underwater Acoustics in 2017 at the University of York, UK. He has experience in modelling of underwater acoustic channels, signal processing for underwater communications, and ocean dynamics. In STEMM-CCS, Jianghui's postdoctoral work will focus on development of novel underwater acoustic techniques for detection, location and quantification of CO_2 leakage.

Anna Oleynik, University of Bergen

Anna Oleynik is a postdoc at Department of Mathematics at the University of Bergen. She earned her PhD in Applied Mathematics at the Norwegian University of Life Sciences and Technology (NMBU) in 2011. Before joining STEMM-CCS project, she worked with mathematical and numerical analysis of continuum neural networks, the models that describe nonlinear interactions between neural populations on macro-level. These models are aimed to reduce the dimensionality and complexity of the microscopic network dynamics and are important in advancing our understanding of the brain. In the STEMM-CCS project, Anna has joined the team working with CO_2 seep predictions and designing the monitoring programs.

Ben Roche, University of Southampton

Ben's work is on developing and refining techniques for quantitatively imaging gas fluxes in the water column and across the seabed. This currently involves the use of both active and passive seismic data, with plans to incorporate optical methods. So far he has worked with data from the 2017 CHIMNEY cruise, characterising pockmark gas seeps in the North Sea. Future work will be geared towards preparing for the controlled release experiment in 2019. This preparatory work will include measurements in the laboratory\test tanks as well as at natural seep sites.

Naima Yilo, University of Southampton

Naima Yilo joined the STEMM-CCS project as a PhD student at the University of Southampton focusing on controlled source electromagnetic (CSEM) data inversion in order to understand the properties of gas chimney structures and fluid migration. She is a Geophysicist with an MSc. degree from Delft Technical University and an Experimental Geology Master Degree from Universitat de Barcelona, and has more than 12 years of industry experience in geophysics applied to environmental, geoengineering and hydrogeological applications as well as the oil and gas sector. Her primary interests are related to active seismic and EM joint inversion/interpretation, as well as shallow geohazards, hydrogeophysics and Carbon Capture and Storage (CCS) applications.