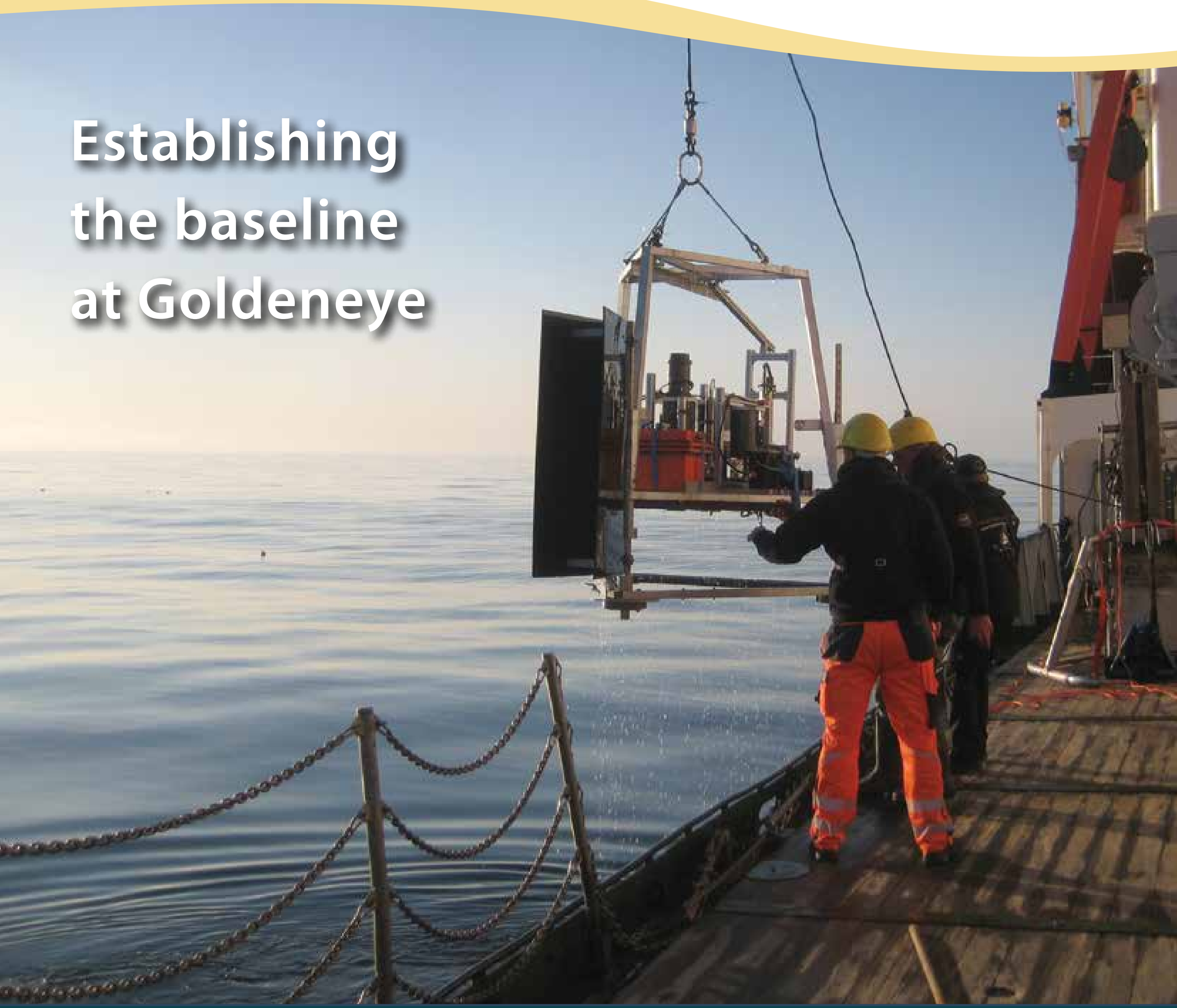
Strategies for Environmental Monitoring
of Marine Carbon Capture and Storage

News update

Autumn 2018



Establishing the baseline at Goldeneye

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Baselining the Goldeneye experimental site

New data to strengthen our knowledge of background values ahead of next year's controlled release experiment

Departing Kiel in mid-August, expedition POS527 aboard RV *Poseidon* set out to further advance our knowledge of the environmental baseline at the Goldeneye experimental site in the North Sea. Establishing a robust baseline for this area is critically important for STEMM-CCS: in shelf seas such as the North Sea environmental parameters such as seawater O_2, pH, pCO_2 and phosphate are strongly affected by natural daily/seasonal environmental variations, and also by anthropogenic disturbances. It is crucial to be able to detect and discriminate variations caused by potential leakages at CCS sites from variations in natural background signals. Our goal is to determine an effective environmental baseline in order to provide the data needed to define measurement strategies for a controlled sub-seabed CO_2 release experiment, which is planned for May 2019 (see next page).

In this context, the cruise planned to further the project's investigations of water column chemistry, and biogeochemistry and ecology of the seafloor at Goldeneye using the latest sensing technology and instrumentation.

The main objectives of this cruise were:

1. Pre-define and measure sensitive and robustly measurable environmental background variables which provide an indication for subsea CO_2 leakage;
2. Provide water column measurements of trace gases, nutrients and carbonate chemistry variables to assess baseline conditions in the study region. Collect under natural (baseline) conditions a geochemical porewater dataset to provide a quantitative, process-based interpretation of porewater and benthic fluxes using a state-of-the-art numerical model. This baseline data will be used for comparison with measurements taken during the controlled CO_2 release experiment in the same area in spring 2019;
3. Undertake benthic ecology baseline measurements, to compare against conditions with perturbations from the controlled CO_2 release experiment;
4. Test novel chemical sensors, and hydroacoustic detection systems for measuring benthic and pelagic carbon fluxes (i.e. by using lab-on-a-chip technology, optodes, eddy co-variance techniques for O_2 and pH, 3D-visual bubble imaging, and (multibeam) echosounder quantification);
5. Retrieve, service and re-deploy the project's benthic lander, including downloading of data from sensor measurements over the last 12 months, and cleaning and refurbishing sensors before redeployment of lander for near-seafloor measurements over the coming year.

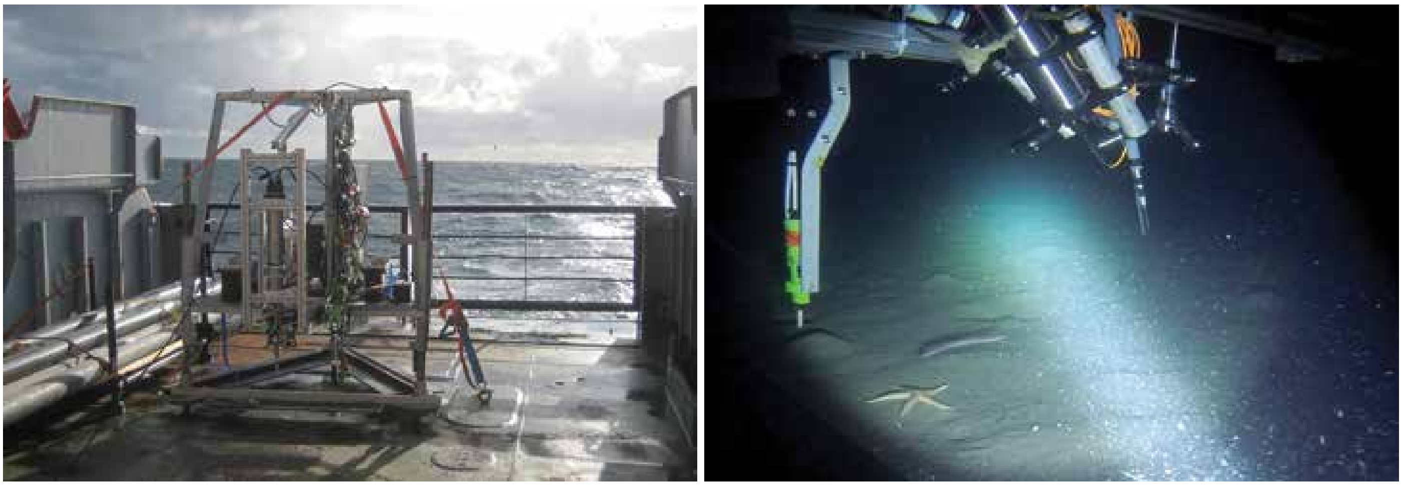
After a couple of days of inclement weather, the team on board were able to commence CTD casts, deploy the MPI lander to measure sediment-water fluxes of oxygen and inorganic carbon, and take box cores in order to sample the seafloor sediment for macrofauna and particle size analysis back at the lab.

One of the goals of this expedition was to test some new sensor technology developed at NOC. 13 autonomous chemical sensors to measure nitrate + nitrite, phosphate, pH, total alkalinity (TA) and dissolved inorganic carbon (DIC) were tested; the latter two (TA and DIC) are brand new and were being tested for the first time outside the NOC laboratories. Also under advanced testing was the new eddy covariance

Above: NOC's Allison Schaap monitors lab-on-chip chemical sensors aboard RV Poseidon *as they continuously measure seawater composition.*

methodology developed by the team at GEOMAR using ion sensitive field effect transistors specially adapted by engineers at MPI for rapidly detecting pH fluctuations in seawater (see article in the Spring 2018 issue of this newsletter, and on page 8-9 of this issue).

After 16 days of calm weather, RV *Poseidon* headed back to port in Kiel, confident that the data collected during the cruise will substantially advance our knowledge of baseline conditions at Goldeneye. With 78 box cores and 5 gravity cores taken, plus 5 deployments of the eddy covariance system resulting in hours of unique data on the biological activity of the seafloor, there is plenty of work to be done back at base ahead of the controlled CO_2 release experiment next spring.



Above, left: the MPI benthic lander on the back deck, ready for deployment. Above right: Fast-response sensors measure turbulence at the seafloor.

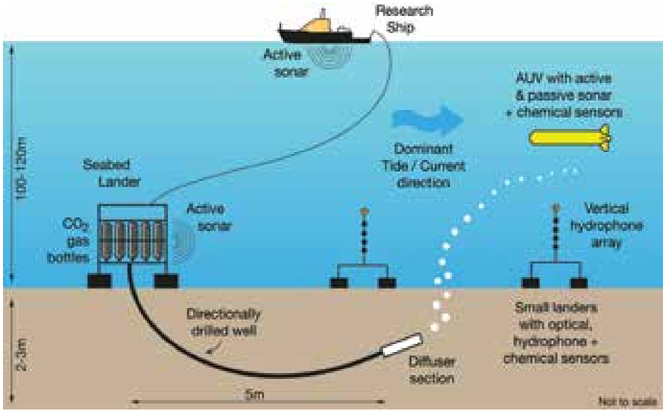
The STEMM-CCS controlled CO_2 release experiment: two vessels, one experiment ... and many, many measurements

The keystone of STEMM-CCS is a novel experiment to simulate a sub-seafloor CO_2 leak under real-life conditions in the North Sea. Over a period of two weeks in spring 2019, CO_2 gas - augmented with inert chemical tracers - will be injected into seafloor sediments at a carefully chosen experimental site near the Goldeneye complex. The consequences of this CO_2 release will be carefully monitored by a sophisticated array of chemical sensors, acoustic devices, visual observations and seismic surveys operated by scientists aboard research vessels RRS *James Cook* and RV *Poseidon*.

Whilst the main CO_2 release experiment is being run and monitored in the near-field by RRS *James Cook*, a second research vessel - RV *Poseidon* - will carry out parallel water column surveys in the far-field in order to determine the lateral spread of CO_2 away from the release site. This will involve *in situ* measurements of biogeochemical parameters throughout the water column using video-CTD, towed membrane inlet mass spectrometer (MIMS) surveys at 5-120m above the seafloor, and deployment of the Ocean Floor Observatory System (OFOS) at the seafloor.

Once the CO_2 release experiment is concluded and all seafloor installations removed, RV *Poseidon* will undertake a comprehensive survey of the release site, encompassing water column, benthic and sediment sampling. These data will complement measurements made by RRS *James Cook* during the period of CO_2 release.

One experiment, two vessels - and hopefully a new understanding of how best to detect, trace and quantify CO_2 escape in the ocean.



Above: schematic of the STEMM-CCS controlled CO_2 release experiment planned for spring 2019. Artist: K.Davis.

Engineering a CO_2 leak:

Technological challenges of the Goldeneye controlled release experiment

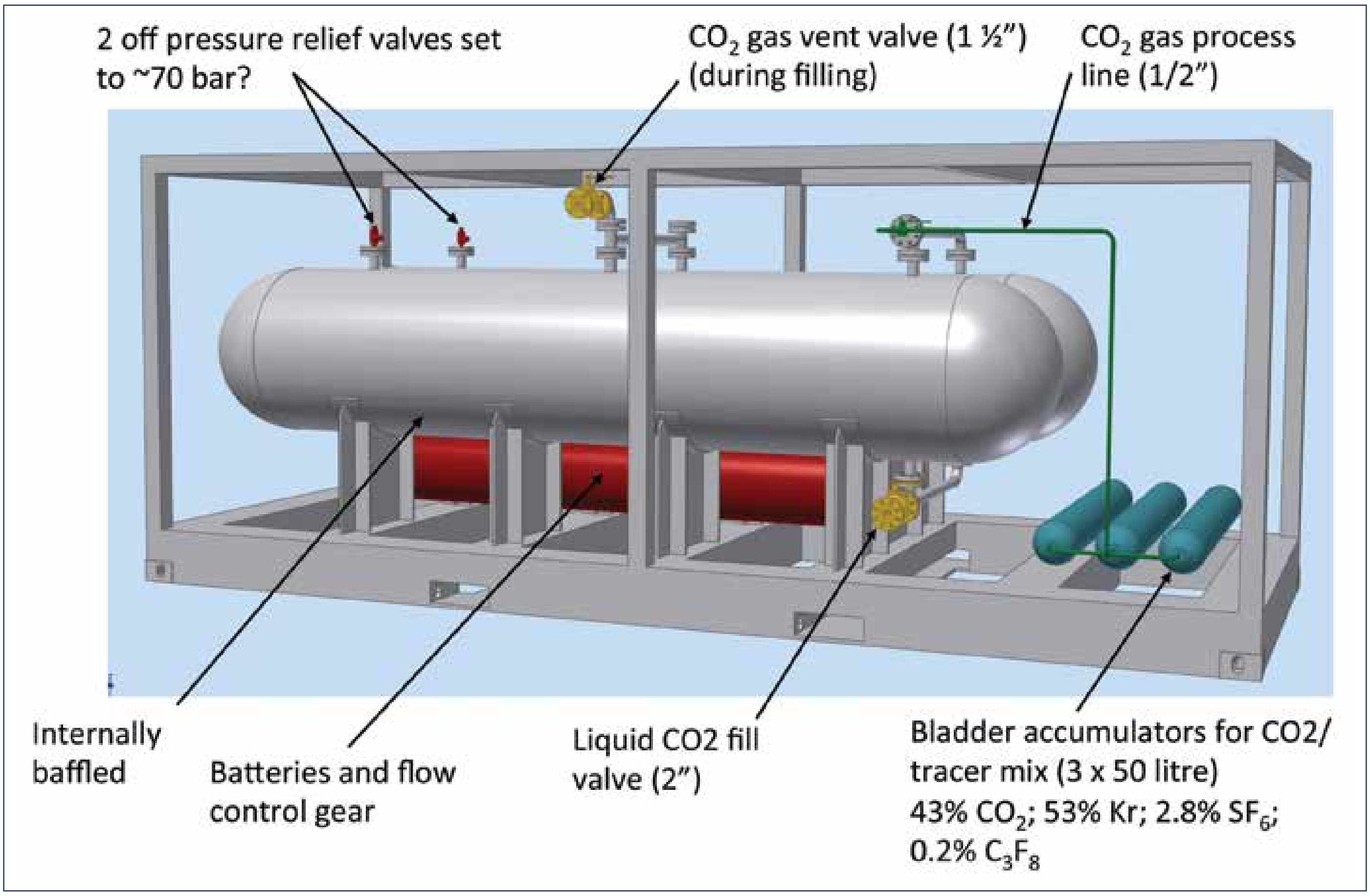
A key factor in public acceptance of CCS as a mainstream climate change mitigation strategy is confidence in the integrity and security of CCS storage sites, and reassurance that any potential leakage can be quickly and reliably detected. The aim of STEMM-CCS is to demonstrate that we have the technological capability to detect any potential leak from a sub-seafloor CCS facility.

Next spring, a team of STEMM-CCS scientists aboard the RRS *James Cook* will spend two weeks at the Goldeneye experimental site in the North Sea to carry out controlled release of CO_2 into sub-seafloor sediments and determine the fate of that CO_2 as it works through the sediments and into the water column.

But how do we engineer a realistic CO_2 leak in order to demonstrate that we can measure it?

On the face of it, this should be a straightforward task: inject CO_2 into seafloor sediments and watch for bubbles emerging at the seafloor above. Sounds simple enough, but making this happen presents a number of significant engineering challenges. Chief amongst these are getting the CO_2 supply safely to the seafloor, and how to inject the CO_2 into the sediments without disturbing them.

First, let's consider the infrastructure required: a source of CO_2 large enough to supply the experiment for two weeks, with the ability to remotely control the flow rate from the ship so that we can simulate as closely as possible a 'natural' CO_2 leak. We need to know precisely how much CO_2 we are releasing and at what rate. The gas needs to be injected within the seafloor sediments, meaning placement of the CO_2 release point below the seabed via a drilled hole and pipe.



Above: Schematic of the bespoke CO_2 container that will be built at NOC to deliver the required supply of CO_2 and tracer gases to the Goldeneye controlled release experiment in spring 2019.

The experiment demands 3 tonnes of CO_2 over the two-week period - whilst this quantity is a very small amount in comparison to the background levels of CO_2 in the region, it is still a large amount of gas to handle! The CO_2 also needs to be mixed with a fixed quantity of tracer gases prior to release. Ideally the gas would be supplied from an anchored barge or supply ship at the surface, but this is expensive and carries the risk of disruption of supply in rough weather. The presence of anchor ropes and supply hoses also presents a significant entanglement risk to ROV operations and potential for interference with the experiment itself. So, a seafloor-based CO_2 supply is required.

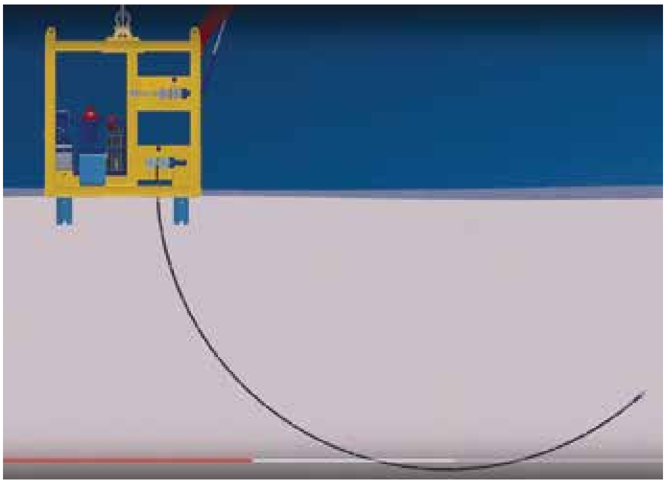
Standard gas cylinders stacked on a pallet would seem an obvious solution, but the reality is that they would be too heavy to deploy as one unit - 3 tonnes of CO_2 and associated infrastructure would equate to something in the region of 12 tonnes. Several deployments would be required to provide the required volume of gas to the experiment and ensuring accurate placement of multiple gas pallets on the seafloor would not be an insignificant task.

There would then be the challenge of how to connect the individual cylinders to each other and to the experiment, and how to switch over from depleted cylinders to fresh ones whilst maintaining supply to the experiment. Additional risks to this approach are the leakage of CO_2 from the cylinders during connection/disconnection operations, disturbance of the site during cylinder delivery, and potential lack of control over fluctuations in the CO_2 flow rate.

The solution is the design and manufacture of a bespoke frame to hold large-capacity gas tanks, fitted with a gas flow control system and acoustic communication system that allows full control from the ship. An optical communications system is installed as a backup. The frame is built to standard ISO 20′ container size for ease of transport and handling, and will be lowered into position on the seafloor using the ship's crane. Once the experiment is finished, the entire apparatus will be removed.

So, we have the CO_2 source in place. Now how to inject the CO_2 into the seafloor sediments in order to accurately simulate a realistic leak scenario? The CO_2 container is placed 100m distant from the injection site so that the equipment doesn't interfere with the natural dynamics of the experimental site itself - the aim is to mimic a real life scenario as far as possible.

The CO_2 needs to be released approximately 1m below the seafloor, but it is critical to the success of the experiment to minimise disturbance to the sediments in the vicinity of the gas release. As we are working with semi-consolidated sediments, it is not possible to drill a hole and then insert a hose or pipe as the sediment would collapse around the hole as the drill string is withdrawn. Additionally, to avoid sediment disturbance over the point of gas release, the hole needs to be drilled horizontally so that the pathway of CO_2 through the overlying sediment is as close as possible to a natural scenario.



Above: The bespoke drill rig by Cellula Robotic designed to insert the CO_2 delivery pipe into seafloor sediments.

To address these requirements a bespoke, innovative sub-sea drill rig, designed and built by Cellula Robotics, will be lowered into place from the ship onto the seafloor with the aid of downward-facing cameras. Once in place, the rig will use hydraulic rollers to push a 10m-long, rigid, pre-curved carbon steel pipe into the seafloor sediments. This is the first time this approach with a pre-curved pipe has been used. The end of the pipe will be capped by a spear-like head to ease the pipe through the sediments, and a gas diffuser unit with backward-facing apertures to avoid sediment clogging during the pipe insertion process. A magnet on the end of the pipe will enable its location (and hence the exact CO_2 emission point) to allow detection by ROV once the pipe is in place. Cameras on the rig will feed a control panel operated on the ship. Once the pipe is in position, the rig will be brought back up to the ship, loaded with another pipe and the operation repeated to provide a backup system. If any pipe fails to insert properly or connect, further backups will be carried on the ship.

When everything is in place, the drill rig will be recovered back to the ship, an ROV will connect the pipe to the CO_2 supply and the experiment will begin. A range of instruments and sensors (chemical, acoustic, visual) will be deployed in and around the experimental area to monitor and detect CO_2 as and when it emerges into the water column.

An animation of the drill rig and the pipe emplacement process can be viewed online at www.youtube.com/watch?v=DmpWsp1vJ-E

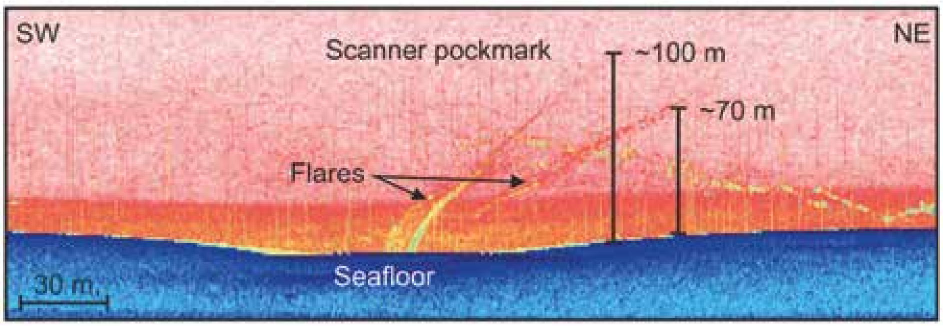
Dissecting the anatomy of a fluid flow chimney: Scanner Pockmark revisited

By Jens Karstens, GEOMAR

Focused fluid conduits are common geological structures in sedimentary basins and hydraulically connect deep reservoirs with the shallow subsurface or the seafloor. These structures are interpreted as the result of an overpressure release by hydrofracturing or the fluidisation and injection of sediments, but their nature and in particular their permeability are poorly understood. The parameterisation of the hydraulic properties of focused fluid conduits is crucial for the industrial scale implementation of CCS as these could directly influence the leakage propensity of affected storage formations.

During the cruise MSM78 aboard RV *Maria S. Merian* in October 2018, we aim to conduct a seafloor drilling experiment, which was originally scheduled for the second leg of last year's cruise MSM63 and could not be completed due to technical problems (see Issue 2 of the STEMM-CCS newsletter, Nov 2017). The main objective of this expedition is to collect sediment cores from the Scanner Pockmark in the British sector of the North Sea using the British Geological Survey's Rock Drill 2 system. The experiment aims to recover sediment cores and to collect downhole logging data from the central fluid conduit of the Scanner Pockmark and from an additional background site unaffected by fluid flow. The sediment cores will be analysed with various geochemical and geophysical logging techniques, which will allow us to constrain the hydraulic properties of a focused fluid conduit and its fluid flow history. The Scanner Pockmark is a key target of the STEMM-CCS project and has already been surveyed by various seismic, hydroacoustic and electromagnetic experiments during the project.

The combination of multi-resolution geophysical data and direct measurements from the Rock Drill 2 experiment will enable improved understanding of the hydraulic properties of focused fluid conduits and their impact on the long-term integrity of marine CCS sites. Furthermore, we will be able to improve the inversion of the geophysical measurements and to test the robustness of our interpretations. In addition to the drilling experiment, we aim to collect further bathymetric and echosounder data linking the study sites at Goldeneye and Scanner with existing boreholes and coring sites in the study area.

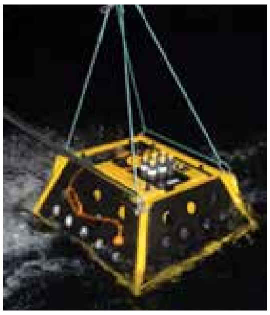


Water column imaging showing gas flares above the Scanner Pockmark during cruise MSM63 in 2017. The flares are defected by the bottom current, but ascend up to 100 m into the water column from the seafloor. A fish shoal is visible as clear disturbance of the water column in form of small blue/yellow specks in the bottom right of the image. Blue colours represent high backscatter and red colours low backscatter.

STEMM-CCS at GHGT14

Melbourne, Australia is the venue for the 14th event in the Greenhouse Gas Technologies (GHGT) conference series. Taking place on 21-16 October 2018, this event is the the premier international technical conference addressing carbon capture and storage (CCS), charting the significant progress and growth in the science behind CCS. The conference is a major dissemination channel for the research and results generated by STEMM-CCS. The project will field 11 oral and poster presentations, and will also have a presence in the main exhibiton hall. The STEMM-CCS exhibiton stand will highlight the project's aims and objectives, early results and showcase the controlled release experiment that will take place at the Goldeneye site in the North Sea in spring 2019. A large screen will feature a series of short films about the project and the forthcoming 2019 cruise, including interviews with project scientists, footage from fieldwork and animations of the controlled release experiment.

Missing STEMM-CCS data pod turns up in Norway



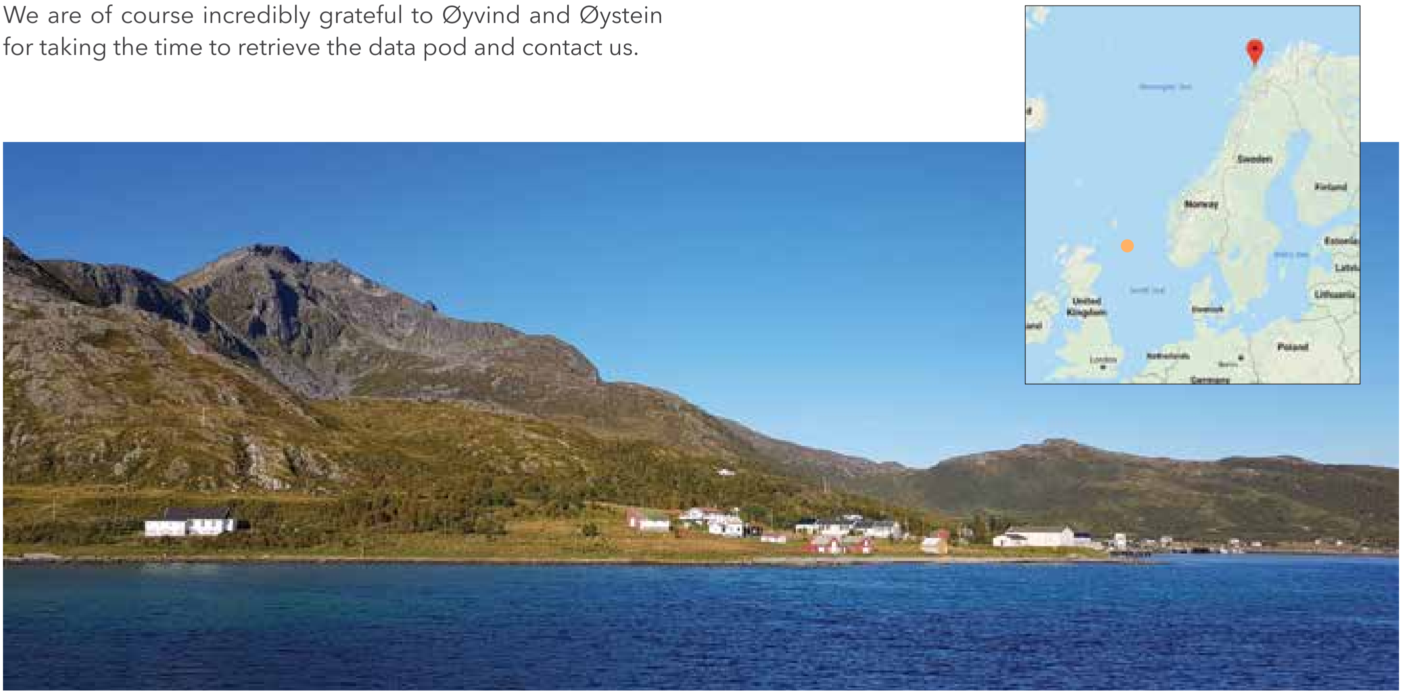
In October 2017, the STEMM-CCS team aboard RV *Poseidon* deployed a bespoke autonomous lander (pictured above) on the seafloor at the Goldeneye experimental site in the North Sea. Manufactured by Develogic GmbH Subsea Systems, it is equipped with a suite of sensors to monitor temperature, conductivity, pressure, current speed and direction, hydroacoustic, pH, pCO_2, O_2 and nutrients over a period of about 10 months, contributing to our knowledge of the environmental baseline in the area (see Issue 2 of the STEMM-CCS Newsletter, Nov 2017).

An integral part of the lander's design is a series of data pods - expendable communication buoys used to periodically transmit data back to base. Data are stored on the pop-up units, released fom the lander and, once at the surface, selective data can be downloaded via Iridium satellite communication. However, when one of the data pods surfaced during the winter months, we were unable to locate it due to rough weather and thought it had been lost.

However, recently we were contacted by Øyvind, the son of Norwegian fisherman Øystein. Øystein had found and recovered a 'small torpedo device' marked with the NOC name and logo, drifting in the fjords near a small island called Vengsøy in northern Norway. Photographs confirmed that it was our data pod! It has now been collected by one of our partners, Stefan Bünz, who is based in Tromsø and will be sent to our scientists in GEOMAR to retrieve and analyse the data.

We are of course incredibly grateful to Øyvind and Øystein for taking the time to retrieve the data pod and contact us.

Above: Øyvind pictured with the STEMM-CCS data pod recoverd by his father Øystein. Below: the island of Vengsøy (main picture) and map showing its location (red marker) relative to the Goldeneye site (orange dot). Photos courtesy Stefan Bünz.



Optodes for seawater pH measurements

By Birgit Ungerböck and Sergey M Borisov

Institute of Analytical Chemistry and Food Chemistry, Graz University of Technology

pH optodes as useful tools for oceanography

One of the key outputs of STEMM-CCS is the development and deployment of new oceanographic sensors. pH is one of the most important parameters for marine measurements, because it is related to all biological processes. Specifically for marine carbon capture and storage as it can serve as an indicator to detect CO_2 leaks by measuring the decrease of seawater pH caused by dissolution of CO_2.

pH sensors are therefore highly desirable for a variety of applications, including sediment profiling, flux measurements with eddy covariance technique, and autonomous long-term pH monitoring. Each of these applications poses specific challenges for pH sensor performance, affecting the desired pH range, sensor resolution, response time and stability. Optical pH sensors (optodes) are promising tools to be used in all these applications, because they can not only be read using compact and cost-effective equipment with low energy consumption, but also provide flexibility in design to meet the requirements of different applications. Therefore, they can make a significant contribution to widespread pH monitoring in marine science and specifically in marine carbon capture and storage, identifying CO_2 leakage at the seafloor.

The research group led by Ingo Klimant and Sergey Borisov from the Institute of Analytical Chemistry and Food Chemistry (ACFC) at TU Graz has been developing O_2, pH and CO_2 sensors for several decades. For STEMM-CCS several sensor systems have been developed, tailor-made for specific applications in pH monitoring or CO_2 leak detection. To accomplish this, several sensors previously designed and applied in related projects (SenseOCEAN) were further optimised and new sensors were developed for various applications within STEMM-CCS.

How pH optodes work

Our pH optodes are based on dyes that change their fluorescence properties upon protonation or deprotonation, leading to high fluorescence at low pH and a low fluorescence at high pH (figure 1a). The pH-sensitive dyes are embedded in a so-called sensor matrix, which is then applied to the end of an optical waveguide. To yield a complete sensor setup, the waveguide is connected to an instrument that converts the optical information into an electrical signal. Such instruments contain a light source, from which light is guided through a waveguide to the sensor material on the tip of the waveguide, inducing an analyte-dependent fluorescence of the sensor material. The emitted light is then guided back through the waveguide to a detector and converted into an electrical signal, which is then further processed. To enable reliable measurement independent of the intensity of the excitation light, sensitivity of the photodetector and variation in the scattering properties of the probe, reference phosphorescent particles are added to the sensing material. In the phase fluorimetric read-out, luminescence phase shift (dPhi) is measured. The calibration curve exhibits a characteristic sigmoidal shape, as can be seen in figure 1b.

By exchanging sensor material and/or waveguide, several types of pH sensors can be manufactured, allowing easy optimisation of the respective sensor in respect to pH range, sensor resolution, response time and stability.

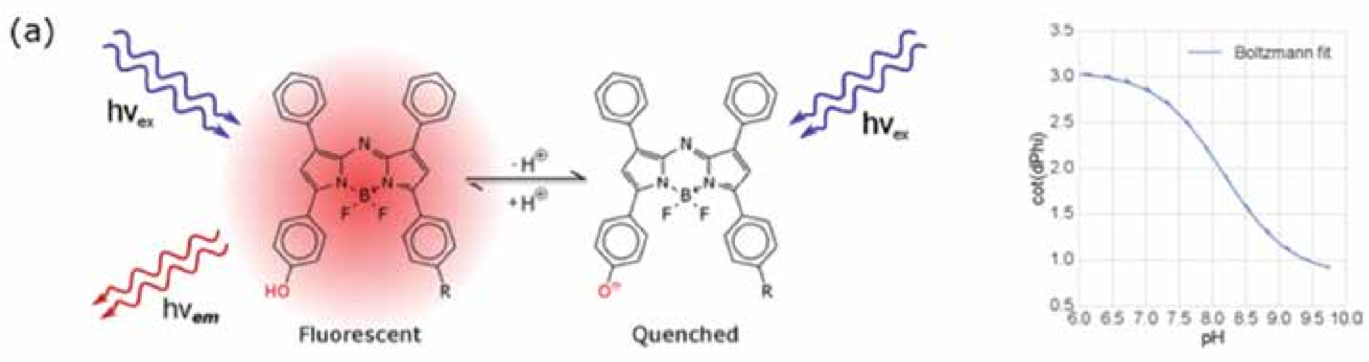


Figure 1: (a) Chemical structure of the employed fluorescent indicators showing the acid-base equilibrium; (b) Example of the calibration curve showing experimental data (points) and the Boltzmann sigmoid fit.

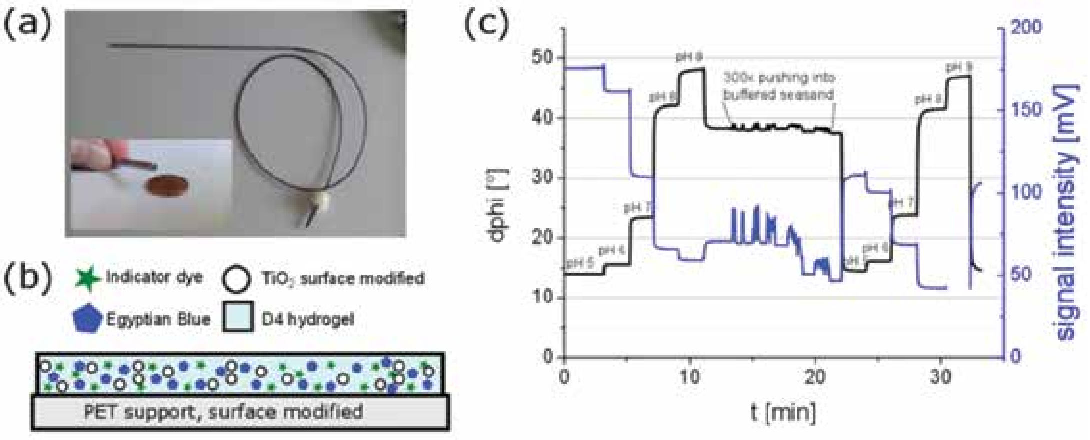


Figure 2: *(a) Photographic image of the fiber-optic pH sensor for sediment profiling with robust metal sleeve (insert); (b) cross-section of the pH sensing material; (c) response of the sensor in buffers and in sediment.*

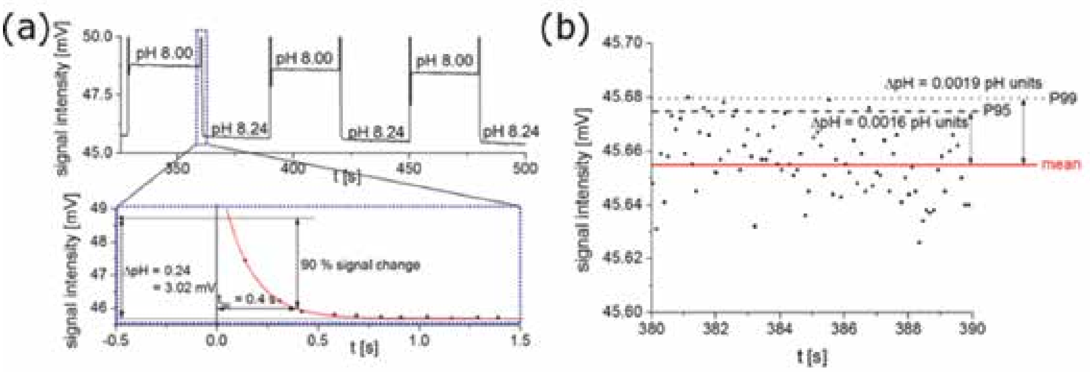


Figure 3: *Performance of the fast-responding pH optode prototype. (a) Dynamic response of the optode to pH variations showing the response time t_{90} of 0.4 s, and (b) estimation of the sensor precision (0.0016 pH units).*

Optodes for pH measurements in sediments

Within STEMM-CCS, pH optodes for sediment profiling were developed. These optodes should be mechanically stable, cover a pH range of 5 to 9, exhibit a response time below one minute and be applicable in strongly scattering media. Figure 2a shows a robust sediment pH sensor with a 25 cm sleeve for stabilisation against bending. A sensor foil is fixed to the end of an optical fiber with a second sleeve, which partially covers the sensor foil to shield it against bigger stones. The sensor layer in figure 2b consists of a pH indicator dye, Egyptian Blue microparticles as a reference material and hydrophilic TiO_2 nanoparticles. The latter is used to increase sensor brightness via light scattering and also serves as optical insulation, providing constant scattering background. These optodes showed stable pH sensing ability during repetitive pushing into sediment (figure 2c) and therefore qualify for measuring pH profiles in marine sediments. Notably, although luminescence intensity deteriorates after multiple insertions into the sediment, the luminescence phase shift dPhi remains constant, thus confirming the efficiency of the selected referencing strategy.

Fast pH optodes for use in pH eddy covariance

pH eddy covariance is considered a precise method to indirectly measure natural and artificially-induced pH and CO_2 fluxes. This technique poses challenging requirements for pH sensor performance, such as a high sensor resolution (< 0.003 pH units), fast response time (t_{90} < 3 s and preferably < 1 s) and high sensitivity around the typical pH of seawater (≈ pH 8). The fast pH sensors have been developed within STEMM-CCS, allowing extraordinarily fast and precise pH monitoring (response times below 1 s and a precision of 0.002 pH units, see figure 3).

pH optodes for long-term autonomous pH monitoring

Stable pH sensors for long-term autonomous pH monitoring have been developed and tested in the SenseOCEAN project and further improved within STEMM-CCS. The sensor material can be mounted with a screw cap system on readout devices from PyroScience and TU Graz, enabling measurements in shallow water (figure 4a, left) or water below 500 m (figure 4a, right). Low power consumption enables continuous measurements for prolonged periods of time (several months to a year). The read-out devices can then be mounted on different platforms such as a CTD (figure 4b), an AUV or a lander and allow continuous and autonomous long-term pH monitoring. Such sensors are currently deployed on a baseline lander within STEMM-CCS.

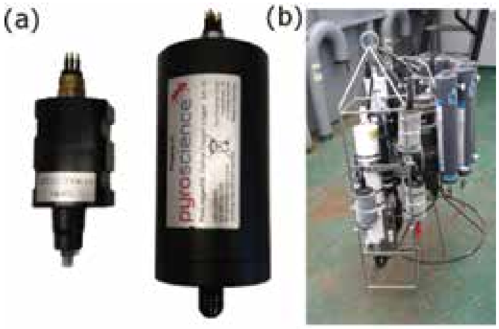


Figure 4: *pH optodes for continuous autonomous monitoring. (a) Optodes for measurements in shallow water (left) and deeper water up to 500 m (right); (b) Optodes mounted onto a CTD rosette.*

Subsea natural CO_2 seeps offshore Panarea: A testing site for analytical methods and models for the detection of potential leaks from CCS facilities

By Jonas Gros, Mark Schmidt, Andrew W. Dale, Peter Linke, Lisa Vielstädte, Nikolaus Bigalke, Matthias Haeckel, Klaus Wallmann, and Stefan Sommer, GEOMAR Helmholtz Centre for Ocean Research, Kiel

Anthropogenic emissions of greenhouse gases have already led to about 0.8°C global air temperature increase since pre-industrial times. Underground carbon dioxide (CO_2) storage (CCS) is considered as a possible mitigation option against climate change. In Europe most storage capacities are located offshore. Consequently, there is increasing scientific interest in reliable geochemical methods for the detection of potential undesired leaks from such sub-seabed CO_2 storage facilities. Hence, the natural volcanic CO_2 vent site offshore Panarea Island (Aeolian Archipelago, Italy) was visited in May 2014 during RV *Poseidon* cruise POS469 conducted by GEOMAR scientists. This site represents an ideal testing site to investigate the fate of released CO_2. The obtained field data are now used in modeling activities in order to design best-practice procedures for the monitoring of sub-sea CCS sites.

Natural sub-sea gas vents offshore Panarea Island have been known since historical times. The gas, which is more than 95% pure CO_2, is released into the sea at water depths extending down to about 100 m. The numerous venting sites range from individual bubble streams to more vigorous releases, which generate bubble plumes. Several sites covering different CO_2 release scenarios ranging from single bubble streams to vigorous gas venting and associated plume formation were investigated.

Measurements included sampling of gas bubbles for analysis by gas chromatography, and monitoring of water currents and physical water column properties. Sampling was performed by divers at the shallow, 12 m deep Bottaro Crater site, whereas deeper sites were investigated with instrumentation deployed from the RV *Poseidon*. Mapping of dissolved CO_2 using in situ CO_2 sensors and onboard membrane inlet mass spectrometry (MIMS) was conducted in combination with visual sea floor inspection and bathymetric investigations. Variation of water currents over short timescales provides scientists with a challenge when attempting to map dissolved CO_2 using towed instruments over the course of several hours.

Figure 1. A scientist collecting gas bubbles that were later analysed for their chemical composition. Evolution of the average gas bubble composition as it rises through the water column represents a fingerprint of the underlying mass transfer processes, and in particular of the rapid dissolution of CO_2.

Models of the underlying physical and chemical processes of CO_2 dynamics play a crucial role in understanding acquired field data. They represent important tools for predicting potential future leaks from CCS facilities. We developed a simulation tool that includes (1) the dynamics of bubbles (including ascent velocity, aqueous dissolution, and evolution of bubble size), (2) advection and dispersion of dissolved CO_2, and (3) the chemical equilibrium chemistry of dissolved CO_2 and its impact on seawater acidity.

For CO_2 bubbles emitted at less than 100 m depth, simulations predict fast aqueous dissolution within meters above the emission site at the seafloor. These predictions were validated using field data of evolving bubble composition with height above the release point. The comparison of model-predicted concentrations in the water column with field observations allows to estimate the total CO_2 release in the investigated area. The modeling work is in progress, but we have discovered that the offshore seeps at Panarea emit ~5,000 tons of CO_2 per year. This is as much as the average CO_2 footprint of several hundred Australians or more than one hundred thousand inhabitants of Burundi!

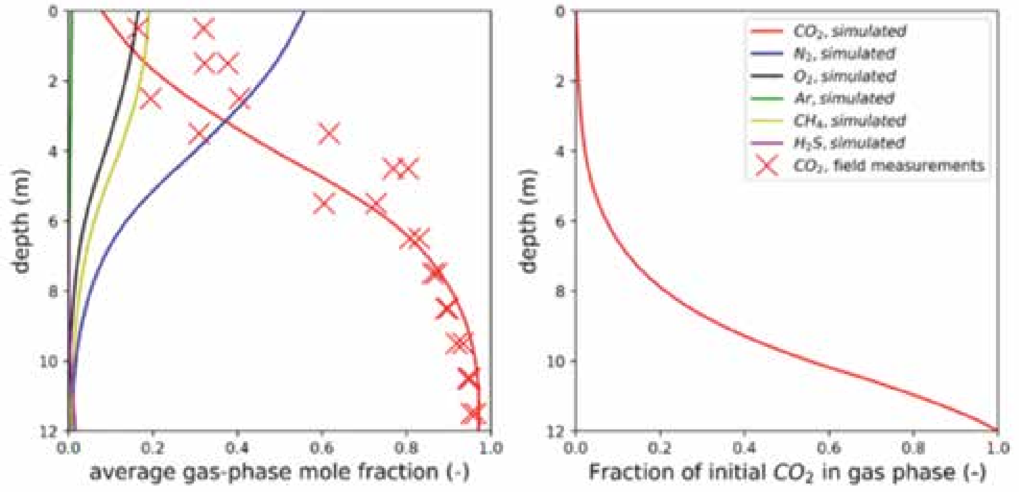


Figure 2. Comparison of the gas composition observed in the field and simulated for ascent of bubbles over a 12 m depth water column (left panel). The model predicts that >80% of the initial CO_2 exits these rather large bubbles (volume median diameter of ~18 mm) and enters the seawater within 4 m from the emission source at the seafloor.

Publications

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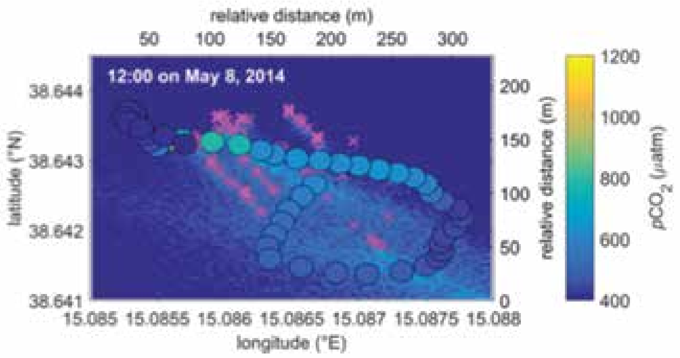

Figure 3. Simulated map of dissolved CO_2 (background image) overlaid with field measurements (circles). Pink crosses indicate bubble streams identified based on video imaging acquired during the cruise.

Bicycle pumps and fishtanks: A beginner's guide to measuring bubbles

By Ben Roche, University of Southampton

The STEMM-CCS schools outreach project kicked off in September 2018. Ben Roche (University of Southampton) visited a series of both secondary and primary schools in South Wales to talk to pupils about our work. The students learnt about the basic concepts of CCS and the forthcoming controlled CO_2 release expedition aboard RRS *James Cook* in spring 2019. The idea behind this project is to get school children excited for the coming cruise so that they can participate in live Q&A sessions with the STEMM-CCS team at sea.

The students learnt about different methods of measuring the size of bubbles before attempting it themselves. They used fish tanks and bike pumps to produce bubbles and filmed them using mobile phones. Analysing the footage, they were able to determine the size and velocity of each bubble.

This activity is actually a small-scale version of what Ben will be attempting during the cruise. He hopes to be able to supply his freshly obtained footage to the schools to analyse for him (giving him a small break at sea!).

To date over 300 students, aged 9 to 18 years old, have been involved in the project but we plan to increase this number significantly over the coming months. We are aiming to make the STEMM-CCS controlled CO_2 release cruise a uniquely educational experience and keen to engage with any ideas team members may have. If you have an idea of something you'd like to do please contact Ben Roche at Br4g13@soton.ac.uk.

Pictures below are from a session held with pupils at Llanishen High School.