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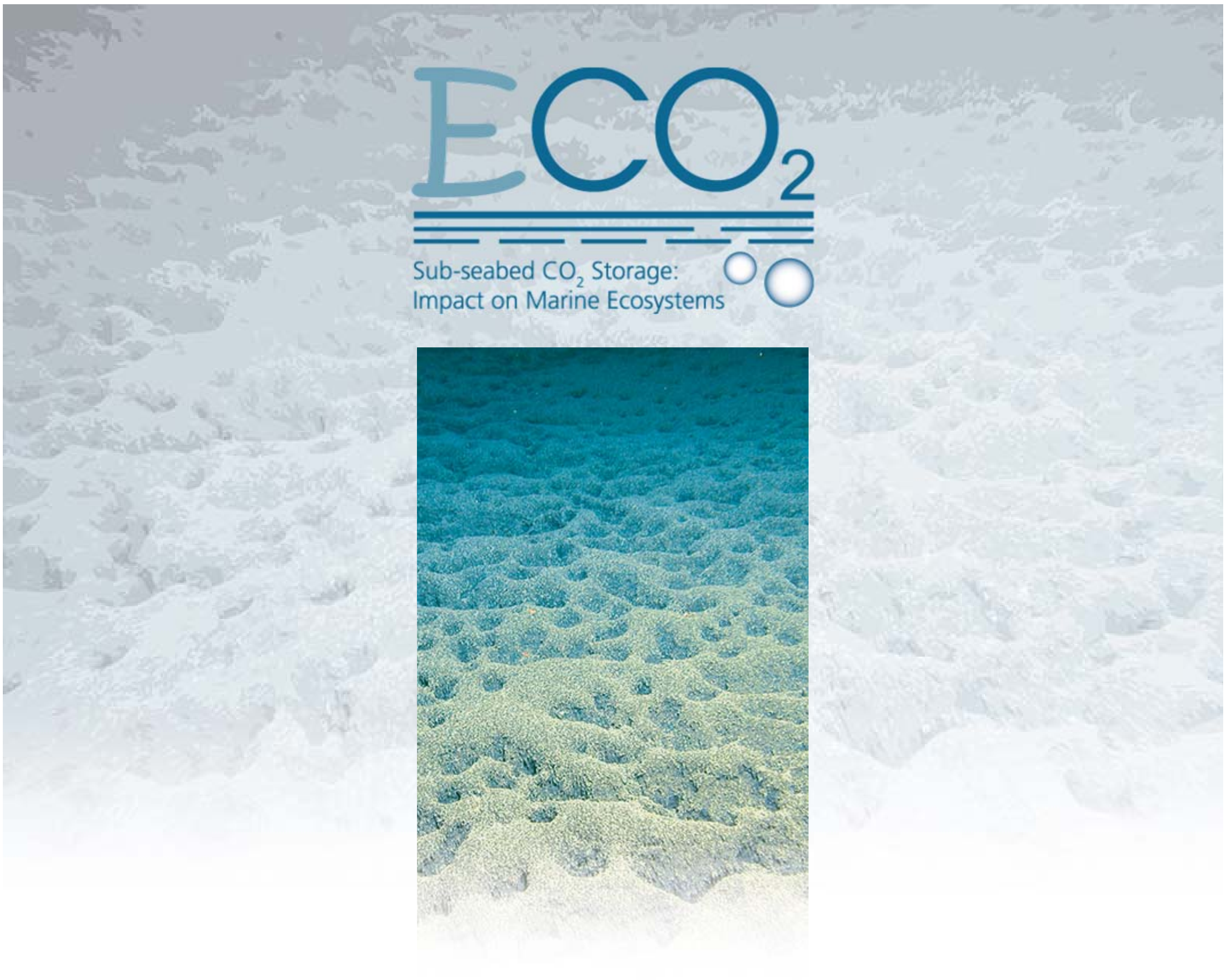

ECO_2 Briefing Paper No. 4

Offshore CO_2 storage and marine ecosystems

A scientific summary of the ECO_2 project

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Introduction

by Thomas Rentzow, German Marine Research Consortium

The EU's tackling of climate change has focused on a number of priority areas over the past decade. One area which has been held up as offering particular potential to reduce CO_2 emissions has been carbon dioxide capture and storage (CCS). The EU's efforts relating to CCS were given concrete form in 2009 with the adoption of the CCS Directive. And yet, CCS is societally controversial and requires substantial financial investment and technological development. One specific concern relates to the potential environmental implications of offshore CCS. To better understand these, the European Commission funded ECO_2 under the 7th EU Framework Programme for Research.

With the project now drawing to a close, this fourth and final ECO_2 briefing paper seeks to summarize some of ECO_2's key findings (with an emphasis on monitoring possibilities) and to provide an outlook for future research on this topic.

The first contribution is by ECO_2 Coordinator, Klaus Wallmann, who reviews the project's main foci. This is followed by a contribution from legal scholar Alexander Proelss, who comments on the legal conditions established by the CCS Directive. Proelss points out that the directive, which was originally adopted to remove legal barriers to CCS, instead inadvertently established new obstacles by applying a zero-leakage approach. One of the consequences deriving from the particularly strict implementation of the precautionary principle on which the directive is based, is the great importance allocated to the issue of monitoring.

In order to be able to establish effective monitoring systems, a deeper understanding of the various factors influencing the likelihood of leakage is necessary. In their contribution, Stefan Buenz and Douglas Connelly argue that a proper risk assessment of CO_2 storage hinges on a thorough understanding of both the geological evolution of an area and the sub-surface characteristics associated with the flow of fluids and their governing geological controls. They explain how the ECO_2 project has employed and adapted new baseline and monitoring technology to facilitate a better identification of potential leakage pathways, detection of leaking CO_2 and monitoring.

In the fourth article, Rachael James suggests that the lack of information about the potential impacts of CO_2 leakage from sub-seafloor storage reservoirs on ocean biogeochemistry poses a challenge that still needs to be addressed before CCS can be deployed as an effective CO_2 mitigation strategy. She discusses the implications of this work on the ability to detect, monitor and quantify CO_2 leakage at the seafloor, which are cornerstones of the EU CCS Directive.

Building on the review by James, Steve Widdicombe argues that the leakage of CO_2 up through the seabed and into the overlying seawater not only potentially causes considerable changes in the chemical environment within and close to the seabed, but that these chemical changes have been shown to have both direct and indirect impacts on marine organisms. Widdicombe reviews how ECO_2's work has led to a more nuanced understanding of the specific impacts on biology that CO_2 might have should it leak from offshore storage sites.

As a modeller, Guttorm Alendal was tasked in ECO_2 to model some of the experimental work being done in ECO_2. In his contribution to this paper, Alendal corroborates the results summarized in the above contributions.

His work suggests that CO_2 leakage would probably only have a limited spatial footprint and that a distinct signal of a CO_2 leak within marine waters will be highly localized around the leak. Alendal argues that this research finding emphasises the challenge of designing a monitoring programme capable of covering a large area, while simultaneously capable of detecting small and localized changes in the marine environment.

Ultimately, the scientific partners in ECO_2 are confident that the project has provided specific tools and observation techniques potentially useful to storage site operators and regulatory bodies as well as made a substantial contribution to the debate about the safety of CCS storage sites.

Building on the successes of ECO_2, Klaus Wallmann and Douglas Connelly close this briefing paper with an outlook on some future research priorities. Specifically, research in ECO_2 has raised new questions about the geodynamics of the sub-seafloor around some storage sites. For example ECO_2 cruises found geological structures cutting vertically through the sediments of the North and Norwegian Seas. Our understanding of these structures is limited, but if permeable they could act as pathways for CO_2 if they intersect a storage reservoir. Another open question relates to the effects of pressure during storage operations on pockmarks as well as newly discovered structures at the Utsira formation and the sediments surrounding storage sites. Wallmann and Connelly highlight these and other research questions requiring, in their estimation, more detailed attention in future.

The ECO_2 project: An Overview

By Klaus Wallmann, GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany

Carbon dioxide Capture and Storage (CCS) is regarded as a key technology for the abatement of carbon dioxide (CO_2) emissions from power plants and other industrial sources. Hence, the European Commission adopted the Directive 2009/31/EC on the geological storage of carbon dioxide in 2009 and supports the implementation of CCS in Europe. However, the large-scale demonstration projects envisioned by the EC were not realized since the low price for CO_2 emission certificates provides an incentive to emit CO_2 rather than to invest in costly separation, transport, and storage facilities. Moreover, onshore storage is inhibited by a lack of public acceptance. The United Kingdom is currently the only EU Member State investing significantly into the implementation of CCS. Two large-scale demonstration projects have been shortlisted by the UK; both seeking to store CO_2 below the North Sea.

Offshore storage is the preferred option in Northern Europe since the operational lifetime of large infrastructures built by oil and gas industries in the North Sea and elsewhere can be extended when CCS projects are implemented after the oil and gas fields have been depleted. Moreover, CO_2 can be injected into offshore fields to enhance and prolong the oil and gas production. Despite CO_2 having been stored below the seabed in the North Sea (Sleipner, Utsira storage formation) since 1996 and in the Barents Sea (Snøhvit) since 2008, little is known about the potential short and long-term impacts of CO_2 storage on marine ecosystems.

As a consequence of this lack of knowledge, the 7^{th} EU Framework Research Programme project ECO_2 set out to assess the environmental risks associated with storage of CO_2 below the seabed (http://www.eco2-project.eu). Starting in May 2011 and ending in April 2015, the project encompasses 27 partners from 9 European countries. In the end, the project will deliver a framework of best environmental practices to guide the management of offshore CO_2 injection and storage as its final project result. The project is investigating two currently operating sub-seabed storage sites which are storing CO_2 in saline aquifers at the continental shelf at ~90 m water depth (Sleipner) and the upper continental slope at ~330 m water depth (Snøhvit). Additionally, a soon to be depleted oil and gas reservoir in the Polish Sector of the Baltic Sea (B3 field site) is being studied as a potential storage site. Between them they cover the major different geological settings to be used for sub-seabed CO_2 storage. Comprehensive process and monitoring studies at natural seepage sites, regarded as natural analogues for potential CO_2 leaks at storage sites, as well as laboratory experiments and numerical modelling support the fieldwork at the sites listed above.

In order to achieve its goals, ECO_2 is pursuing the following five key objectives:

- To investigate the likelihood of leakage from sub-seabed storage sites;
- To study the potential effects of leakage on benthic organisms and marine ecosystems;
- To assess the risks of sub-seabed carbon dioxide storage;

- To develop a comprehensive monitoring strategy using cutting-edge monitoring techniques; and
- To define guidelines for the best environmental practices in implementation and management of sub-seabed storage sites.

Novel technologies and strategies for environmental monitoring were successfully tested by ECO_2. These include new approaches designed to i) identify geological structures cutting vertically through the overburden that may potentially allow for CO_2 leakage from the storage complex, ii) locate structures at the seabed where formation fluids, dissolved gases and gas bubbles are released into the marine environment, iii) quantify rates of gas and water leakage across the seabed, iv) track and trace the spread of CO_2 in the water column, and v) determine CO_2 fluxes into the atmosphere. These techniques allow for a comprehensive monitoring of the shallow subsurface, seabed, seawater and atmosphere above storage sites.

The cutting-edge monitoring techniques developed and applied by ECO_2 did not detect any CO_2 anomalies in sediments and bottom waters above the storage complexes and thus confirmed that CO_2 is safely stored at Sleipner and Snøhvit. However, high-resolution seismic data revealed a large number of vertical pipes and chimney structure cutting through the sedimentary overburden in the vicinity of all storage sites. A high density of seafloor depressions (pockmarks) characterizes the seabed above Snøhvit. Most of these circular structures were probably formed by gas and fluid ascent in the geological past. Even though some are associated with deep-reaching roots, the studied pockmarks do not emit water or gas into the marine environment.

Seepage of natural gas (methane) from the overburden into the overlying water column was detected at numerous sites around the Sleipner storage site. Formation waters are released through a 3 km long fracture-like structure 25 km north of the Sleipner platform while both natural gas and formation water are seeping through three abandoned wells located in the vicinity of the Sleipner storage complex. The currently available data imply a mostly shallow origin of gases and fluids seeping at the seabed. These newly discovered geological features pose a number of important questions: Are there any high permeability pathways for gas and fluid flow cutting through the overburden and linking the storage formations to the seep sites and pockmarks discovered at the seabed? Are seepage rates amplified by the ongoing storage operation? May CO_2 stored below the seabed ultimately leak through the overburden via seismic pipe and chimney structures, fractures and abandoned wells?

CO_2 release at the seabed was studied at three natural seep sites (Salt Dome Juist, Jan Mayen vent fields, and Panarea) and via deliberate CO_2 release experiments conducted in the vicinity of the Sleipner storage complex. The field work confirmed previous modelling results predicting that CO_2 gas bubbles and droplets are rapidly and completely dissolved in ambient bottom waters. The efficient dissolution inhibits CO_2 release into the atmosphere and produces a significant pH drop in ambient bottom waters with potential adverse effects on benthic biota.

The European legal framework: lessons learnt for the revision of the CCS Directive

By Alexander Proelss, Trier University

Directive 2009/31/EC on the geological storage of carbon dioxide (CCS Directive) was adopted in order to provide a common legal framework for carbon dioxide capture and storage (CCS) in the European Union (EU). It attempts to remove legal barriers associated with the geological storage of carbon dioxide and at the same time regards CCS as a bridging technology that "should not lead to a reduction of efforts to support energy saving policies, renewable energies and other safe and sustainable low carbon technologies, both in research and financial terms" (4th recital of the directive). Its purpose and main focus is the safe geological storage of CO_2 that guarantees a permanent containment of CO_2 "in such a way as to prevent and, where this is not possible, eliminate as far as possible negative effects and any risk to the environment and human health" (Art. 1 (2) CCS Directive). The key mechanism of the directive is a permit approach that ensures compliance with its provisions (cf. 24th recital).

> "[The directive's] purpose and main focus is the safe geo-logical storage of CO_2 that guarantees a permanent contain-ment of CO_2"

The provisions of the CCS Directive were to be implemented by the Member States into their domestic legal orders by 25 June 2011. The European Commission adopted a Decision on 10 February 2011 introducing a questionnaire to be used for the first report on the implementation of the directive, which addresses the major elements of the CCS Directive such as the provisions of the permits conditions and the CO_2 stream acceptance criteria. Notwithstanding this, implementation of the CCS Directive has been quite slow until this day. The Commission received notifications of implementation measures from all Member States only by October 2013 and was thus able to close 19 of the 26 infringement cases that had been initiated in 2011. The reasons for non-implementation range from general opposition towards the use of CCS technology among the public (e.g. in Germany) and issues of technical feasibility to deploy CCS technology in the territory of the Member State concerned (e.g. in Finland) to missing incentives to develop and test CCS technology due to the extremely high precautionary standards embodied in the CCS Directive.

The CCS Directive foresees an overall review of its provisions by 31 March 2015. In this regard, the European Commission is obliged to assess, on the basis of experiences gained concerning the implementation of the directive and with a view to the technical progress and scientific knowledge, several provisions of the directive. This relates in particular to whether the permanent containment of CO_2 has been sufficiently demonstrated so as to "prevent and reduce as far as possible negative effects on the environment and any resulting risk to human health and the environmental and human safety" (Art. 38 (2) CCS Directive). Moreover, the Commission is called upon to examine whether the draft storage permits as outlined in Art. 10 CCS Directive and the draft decisions on the transfer of responsibility as stipulated under Art. 18 CCS Directive are still necessary. The Member States are obliged to share their experiences regarding the CO_2 stream acceptance criteria as well as the provisions of third-party access to the transport network and storage. Also, the necessity and relevance of the "Carbon Capture Readiness" clause pursuant to Art. 33 CCS Directive shall be assessed. The review of the directive reflects a "learning by doing approach" and thereby safeguards that new technical and scientific developments are taken into account.

In order to assist the Member States in pursuing the overall aim of the CCS Directive (long-term storage), the European Commission has issued four (non-binding) Guidance Documents addressing (1) the implementation of a CO_2-storage life cycle risk management framework, (2) the characterisation of the storage complex, CO_2 stream composition, monitoring and corrective measures, (3) criteria for transfer of responsibility to the competent authority, and (4) the implementation of a financial security framework. The "CO_2 storage life cycle risk management framework" forms the basis of assessing the risks associated with CCS. This framework includes the assessment of the storage capacity, the characterisation and assessment of the storage complex, the site development, the operation of the site, the post-closure pre-transfer monitoring phase and post-transfer phase. Once a storage permit has been granted by the competent authority of the Member State on the basis of the requirements codified in the CCS Directive and substantiated by the Guidance Documents, the operational phase of the project commences. In this respect, the CCS Directive covers the following elements: (1) the purity of the CO_2 stream, (2) the monitoring and measuring of migration or leakage of CO_2 from the storage site or within the storage complex, and (3) inspection and reporting obligations.

All of the aforementioned factors indicate the central role of monitoring. This importance is even more evident when taking into account the fact that monitoring schemes are to be established with a view to ensure the permanent storage of CO_2 that could be jeopardized by leakage, migration or significant irregularities. "Leakage" is defined in the CCS Directive as "any release of CO_2 from the storage complex (Art.3 (5) CCS Directive) and "significant irregularities" as "any irregularity in the injection or storage operations or in the condition of the storage complex itself, which implies the risk of leakage or risk to the environment or human health." If interpreted literally, leakage of CO_2 from the storage complex would already occur if any of the stored CO_2 is released from the storage complex. Even a migration of CO_2 outside of the storage complex that does not reach the water column could be considered as leakage. The standard established by the CCS Directive thus constitutes an extreme application of the precautionary principle ('zero-leakage' approach). It assumes that the risks associated with the consequence of leakage are so high that no minimal threshold of leakage would suffice. This approach clearly differs from past statements by the European Commission concerning the application of the precautionary principle, according to which

"[…] the measures envisaged must make it possible to achieve the appropriate level of protection. Measures based on the precautionary principle must not be disproportionate to the desired level of protection and must not aim at zero risk, something which rarely exists" (European Commission, Communication on the precautionary principle, COM(2000) 1 of 2 February 2000, p. 17). From a factual point of view, applying a zero-leakage approach to the situation of a geological setting is problematic as no storage complex is self-contained. Should any irregularities or leakage be observed, so-called corrective measures are to be taken, and the operator might, depending on the circumstances, be held liable for the damage that has occurred. The approach on which the CCS Directive is based has had the effect of creating an obstacle to the implementation of sub-seabed storage of CO_2.

> "The approach on which the CCS Directive is based has had the effect of creating an obstacle to the implementation of sub-seabed storage of CO_2."

Having this in mind, it is indispensable to monitor the surrounding environment. Monitoring as laid out in the CCS Directive is risk-based and specific to a storage site and complex. This implies that the monitoring should be oriented along the initial risk assessment elements and particularly focused on the specific risks of a storage site. The monitoring obligations rest on the operator and extend to the monitoring facilities, the storage complex (including, if possible, the CO_2 plume) and, "where appropriate", the surrounding environment. With a view to streamline the monitoring efforts, the operator is obliged to establish a monitoring plan following the criteria as provided by Annex II of the CCS Directive. These criteria relate to all stages of a CCS project and cover baseline, operational and post-closure monitoring schemes. The concrete parameters include, inter alia, fugitive emission of CO_2 at the injection facility, chemical analysis of the injected material and reservoir temperature and pressure. In accordance with the review provision of Art. 13 (2) in the CCS Directive, an update of the monitoring plan is necessary if "new scientific knowledge and improvements in best available technology" have been developed. Furthermore, Annex II of the CCS Directive also prescribes possible monitoring technologies. Generally, the plan shall be updated and then submitted to the competent authority for approval every five years in order to integrate new scientific knowledge as well as considering changes to the assessed risks. All results of the monitoring must be communicated from the operator to the competent authority at least once a year.

Besides the monitoring and reporting obligations on the side of the operator, the Member States shall ensure compliance with the requirements of the directive through routine as well as non-routine inspections. Routine inspections should be carried out on an annual basis until three years after closure, and from this point on a five-year basis until the transfer of responsibility has taken place. In contrast, non-routine inspections are intended to investigate serious complaints related to the environment or human health. The competent authority enjoys a margin of discretion to inspect installations since the directive provides the mandate to do so "in other situations where the competent authority considers this appropriate" (Art. 15 (4) CCS Directive). Based on the results of the monitoring, the operator is under the obligation to notify the competent authority in case it detects leakages or significant irregularities.

Leakage assessment and monitoring of the shallow overburden of CO_2 storage sites

By Stefan Buenz, Arctic University of Norway and Douglas Connelly, National Oceanography Centre, UK

The permanent containment of CO_2 in sub-surface formations of sedimentary basins is the ultimate goal of CO_2 sequestration. In order to achieve this goal a thorough understanding of the overburden, i.e. the sedimentary strata from the cap rock to the seabed, is necessary.

A proper risk assessment of CO_2 storage hinges on a thorough understanding of the geological evolution of an area and a sound comprehension of sub-surface anomalies associated with the flow of fluids and their governing geological controls.

Leakage is the process by which CO_2 escapes the storage formation into overburden sediments, ultimately potentially ending up seeping into the water column. Leakage can occur in different forms (from slow seepage to catastrophic release) and along different pathways including pre-existing pathways including well bores or self-enhanced, hydro-fractured systems. The flow of the leaking fluids is driven by hydrological gradients and buoyancy. Most often, the latter two are governed by site characteristics and the geological setting of an area, e.g. due to compaction from tectonic stress or sedimentation.

Leakage assessment is a process by which an understanding of potential leakage scenarios is developed. It is a purely hypothetical process and does not imply that storage site integrity is compromised by the sheer presence of potential leakage structures.

This leakage assessment process includes four key components:

- the ability to detect a potential leakage pathway;
- the ability to detect small fractions of leaking gas;
- the identification of potential leakage scenarios;
- the qualitative assessment of the likelihood of leakage considering site characteristics and the geological setting.

The analysis of sub-surface data may reveal a number of fluid-flow features, such as, for example, gas chimneys, pipes, shallow gas accumulations, leaking faults, fractures along the seafloor as well as gas hydrates. Each of these structures or set of structures must be evaluated with respect to their occurrence, distribution, origin and as a means for providing a potential pathway for CO_2 leaking from the storage formation. On the basis of this evaluation and the assumptions that paleo fluid-flow structures may be reactivated by CO_2 injection and that the caprock of the storage formation may breach, a number of potential leakage scenarios may be formulated for offshore CO_2 storage sites. The leakage scenarios largely include leakage along a chimney (blow-out structure) or along a fault but are adapted to the specific geological background at each storage site and hence, depending on its exact sub-surface location and context may yield a complex migration pathway for CO_2 from the storage formation to the seafloor. Leakage scenarios can be implemented into fluid flow simulations that cover the whole overburden and thus support the leakage assessment and provide rough estimates on leakage rates and duration, though, with yet large uncertainties.

The ECO_2 project has employed and adapted new baseline and monitoring technology for the shallow overburden of a storage site to facilitate a better identification of potential leakage pathways, detection of leaking CO_2 and monitoring. The two key technologies are:

Figure 1: After a successful mapping mission, the AUV Huggin 1000 is taken back on board the research vessel G.O. Sars.

1. an Automated Underwater Vehicle (AUV) mounted high-resolution synthetic aperture sonar and multibeam systems and
2. a P-Cable high-resolution 3D seismic system.

The newly developed AUV mounted high-resolution synthetic aperture sonar (HISAS) and multibeam systems opened a new era in seafloor mapping and imaging. The HISAS is capable of synthetic aperture sonar (SAS) imaging, resulting in a range of independently

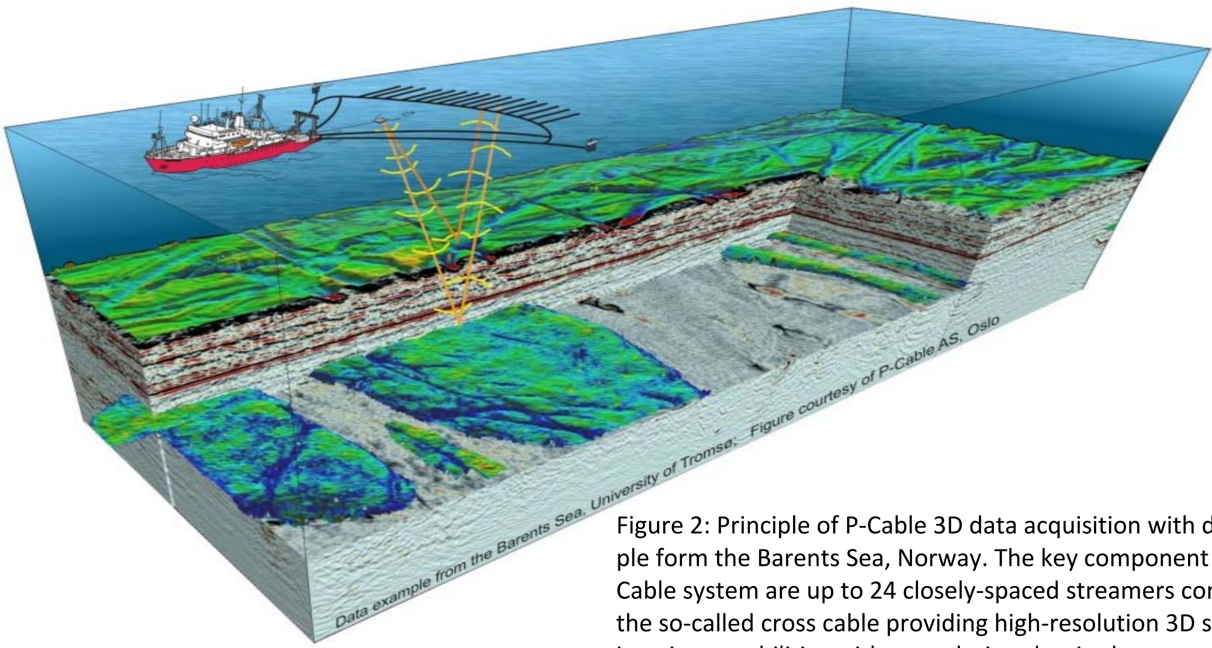


Figure 2: Principle of P-Cable 3D data acquisition with data example form the Barents Sea, Norway. The key component of the P-Cable system are up to 24 closely-spaced streamers connected to the so-called cross cable providing high-resolution 3D seismic imaging capabilities with a resolution that is about one order of magnitude better than conventional 3D seismics.

obtainable image resolution better than 5x5 cm (max. 2x2 cm, depending on the conditions) and high area coverage rates (typically 2 km^2/h) depending on the resolution achieved. High-resolution bathymetric maps are obtained by compositing the interferometric product between the two vertically offset receiver arrays. While technically range invariant the system normally provides a 400 m swath. The AUV may also be configured with multiple geochemical sensor systems and HD digital camera systems, thereby being able to map geochemical anomalies and provide bottom photography that may confirm seep activity.

The P-Cable 3D high-resolution seismic system consists of a seismic cable towed perpendicularly (cross cable) to the vessel's steaming direction. An array of multi-channel streamers is used to acquire many seismic lines simultaneously, thus covering a large area with close in-line spacing in a cost efficient way. The cross-cable is spread by two paravanes that due to their deflectors attempt to move away from the ship. The P-Cable system is designed and developed as a tool for marine geological research and the petroleum industry. It may be used in both frontier and mature regions in an intelligent, versatile way to acquire successive small-size surveys (25 to 250 km^2) in areas of special interest, e.g. 4D seismic monitoring of the shallow overburden at CO_2 storage sites. This is due to the fast deployment and recovery of the P-Cable and the short turns needed between adjacent sailing lines. The P-Cable technology has proven data quality, surpassing conventional 3D and equal or better than HiRes 2D. The increase in lateral resolution compared to conventional 3D seismic data is approximately one order of magnitude. This technology images the top 500-800 m of the overburden in high detail and ideally complements conventional 3D seismic data, which is the premier monitoring tool for CO_2 storage.

Impacts of CO_2 leakage on ocean biogeochemistry

By Rachael James, University of Southampton, UK

The paucity of information about the potential impacts of leakage of CO_2 from sub-seafloor storage reservoirs on ocean biogeochemistry is a challenge that needs to be addressed before carbon dioxide capture and storage (CCS) can be deployed as an effective CO_2 mitigation strategy. Here we summarise the insight gained during the ECO_2 project, based on field studies at natural seafloor CO_2 seeps and an operational CCS site (Sleipner), laboratory based experiments, and modelling. We also discuss the implications of this work for our ability to detect, monitor and quantify CO_2 leakage at the seafloor, which are cornerstones of the EU CCS Directive.

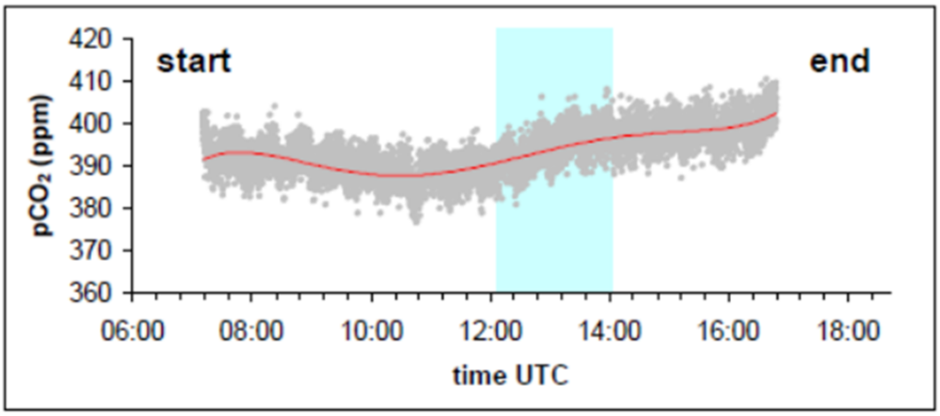


Figure 3: Variation in bottom water pCO_2 measured along a transect extending across the sub-seafloor CO_2 plume at Sleipner (shown by the blue shaded region). pCO_2 varies naturally as a function of the tidal cycle. Note that there is no indication of elevated levels in the vicinity of the sub-seafloor CO_2 plume. Deployment of a seafloor observatory system close to the Sleipner site during ECO_2 also revealed that over the course of one year, bottom water pH varies naturally by >0.5 pH units. Field studies conducted at natural seafloor CO_2 seeps (Okinawa Trough, Jan Mayen, Panarea, Salt Dome Juist) reveal that over the course of one year, bottom water pH varies naturally by >0.5 pH units.

Shallow marine sediments and pore waters

Extensive field work in the vicinity of the sub-seafloor CO_2 plume at the Sleipner CCS site found no evidence for leakage of CO_2 from the storage reservoir into the shallow sub-surface sediments or into the water column. Nevertheless, this work has revealed that fluxes of CO_2 across the seabed due to natural microbial respiration can be highly variable (up to 2-3 orders of magnitude), which may make it challenging to detect small changes due to leakage of CO_2 from sub-seafloor reservoirs (see Figure 3).

- Sediment pore waters affected by relatively high rates of CO_2 seepage (CO_2 saturated sediments), such as those at Panarea and Okinawa Trough, are characterised by low pH (as low as 4.5), low Eh (indicating more reducing conditions) and elevated concentrations of metals, including dissolved iron and manganese.
- At lower rates of CO_2 seepage, increases in pore water alkalinity and calcium ions indicate that CO_2 in solution promotes the dissolution of carbonate minerals naturally present in the seabed sediments. This initially acts to buffer changes in pore water pH, but if the pore waters become saturated with respect to $CaCO_3$, this buffer is no longer effective.
- Pore waters affected by seepage of CO_2 have enhanced concentrations of metals (including Ca, Fe and Mn) and dissolved silicon, indicating that CO_2 seepage promotes the dissolution of mineral phases. Dissolution of carbonate minerals is the principal source of released metals, and rates of dissolution of silicate minerals (which are more abundant in most sediments on the continental shelf) are therefore much lower than the rates of dissolution of carbonate minerals.

These field observations are corroborated by experimental studies investigating the effects of enhanced CO_2 on weathering of shallow marine sediments from the Sleipner and Snøhvit CCS sites. Release of Ca, Sr, Rb, Si, Al, Li and K is significantly enhanced in the presence of elevated CO_2 due to dissolution of carbonate and aluminosilicate minerals. In general, sediments from Snøhvit appear to be more reactive than those from Sleipner (under the same conditions), indicating that the impact of CO_2 leakage is not only dependent on CO_2 concentrations and pH, but also on the chemical composition and mineralogy of the sediment overburden.

Water column

In addition to studies of natural CO_2 seeps, the effects of CO_2 leakage on seawater chemistry was also assessed in ECO_2 by controlled release of CO_2 at the seafloor in an experiment conducted close to the Sleipner CCS site. This work has revealed that:

- Plumes of CO_2 bubbles rising from the seafloor can readily be detected and monitored using passive and active hydro-acoustic techniques. At deep sites (e.g. Okinawa Trough and Jan Mayen), CO_2 may be in the form of CO_2 hydrate (a solid, ice-like substance), but the CO_2 hydrate dissociates as it rises through the water column, releasing CO_2.
- CO_2 released at the seafloor in the gas phase at flow rates comparable to leakage from an abandoned well or microfractures in the sediments will rapidly dissolve, and enhanced levels of CO_2 (and low pH) may only be detected within ~2 m of the seafloor, at distances of less than a few 10's of meters from the release site. Small gas bubbles dissolve more rapidly than larger bubbles, so the acidification impact on the seafloor environment is higher if the bubbles are small.
- The footprint of CO_2 leakage at the seafloor is strongly dependent on tides (release of CO_2 at the seafloor is higher at low tide), and the current regime. Strong currents rapidly disperse CO_2, so the environmental impact of leakage rapidly diminishes with distance from the release sites. Studies at Panarea indicate that release of CO_2 at the seafloor may be greatly enhanced during periods of tectonic activity.

Use of modelling studies

Modelling work within ECO_2 has focussed on assessing the footprint and biogeochemical impact of CO_2 leakage for different CO_2 leakage rates, and different environmental conditions (water depth, current direction and strength, sediment permeability, etc). Key results from this work are:

- At deeper water depths, formation of CO_2 hydrate within marine sediments will result in changes to leakage pathways, and in some circumstances may prevent leakage of CO_2 at the seafloor.
- Reaction-transport models for shallow sub-surface sediments can be used to help distinguish between the natural variations in CO_2 fluxes across the seabed, and CO_2 leakage from an anthropogenic source.
- Simulation of CO_2 behaviour for different CO_2 leakage rates predicts that retention of CO_2 within marine sediments is strongly dependent on the CO_2 dissolution rate, and the concentration of calcium carbonate in the sediments (which will buffer changes in pore water pH). CO_2 will be released at the seafloor as CO_2 bubbles as soon as the sediment pore waters are saturated with CO_2; this may take 10's to 100's of years, although it may be instantaneous if the CO_2 leakage rate is very high (e.g. blowout scenario).

Implications for detection, monitoring, attribution and quantification of CO_2 leakage

Work done in ECO_2 demonstrates that leakage of CO_2 can be revealed by the appearance of

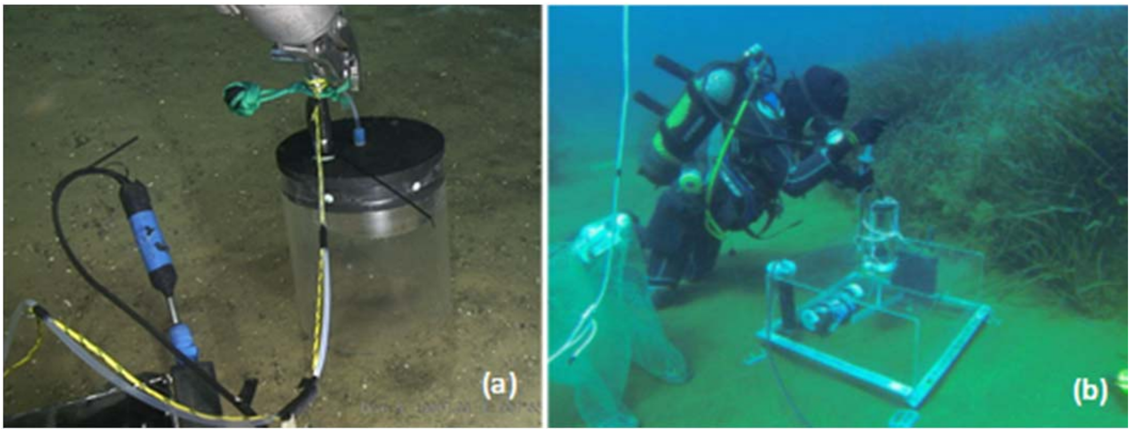


Figure 4: Techniques for estimating fluxes of fluids and gas across the seabed tested during ECO_2: (a) Accumulation chamber, deployed by an ROV, for measurement of gas fluxes. (b) Small benthic chamber, deployed by divers at a shallow site at Panarea.

CO_2 bubble plumes at the seafloor close to the leak epicentre, and/or by perturbations in the carbonate chemistry (DIC, total alkalinity, pH, pCO_2) in sediment pore waters and the water column (see Figures 4 and 5).

The presence of bubble plumes can be detected using acoustic techniques (e.g. ship-based echosounder surveys, or hydrophones deployed at the seafloor), and perturbations in carbonate system parameters can be measured via deployment of in situ sensors, or collection of water samples and sediment cores. Instrumentation for the in situ analysis of pH and pCO_2 in the water column and sediment pore waters is available, and has been extensively tested during ECO_2. These sensors have proven effective for monitoring of these variables during relatively short-term deployments (<1 week), but drift in the calibration of these instruments was problematic during longer deployments.

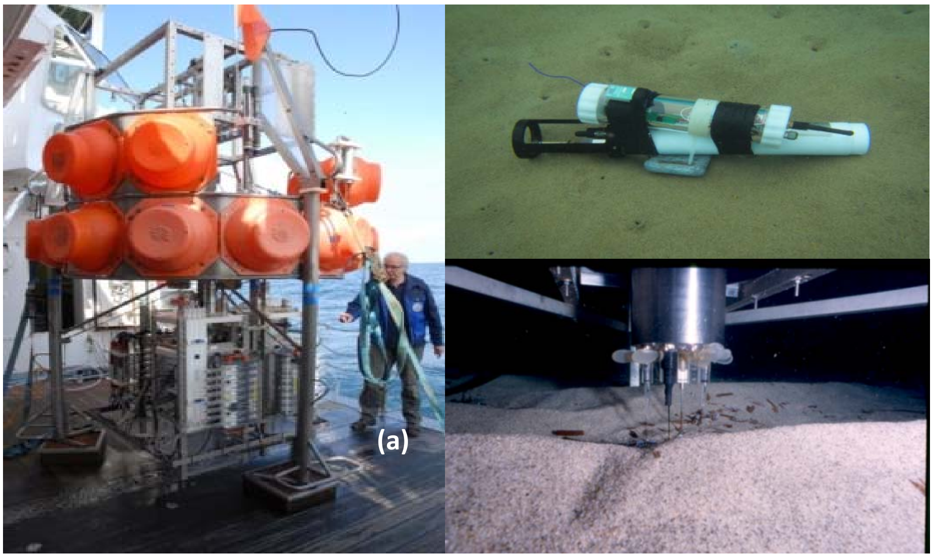


Figure 5: Techniques for estimating fluxes of fluids and gas across the seabed tested during ECO_2: (a) Large benthic chamber system, deployed using a video guided launch. (b) pCO_2 sensor, for measurement of pCO_2 concentrations at the seafloor. (c) Microprofiling system for *in situ* analysis of various pore water constituents, including pH, ORP, pCO_2 and dissolved oxygen.

Our work also reveals that marine systems are highly dynamic, and the magnitude of the perturbation in carbonate system parameters is likely to decrease exponentially with distance from the leak epicentre. This means that signals from low flux diffuse leakage even only a few 10's of metres away from the epicentre may be difficult to detect against the background heterogeneity. Monitoring of carbonate system parameters will therefore need to be supported by robust baseline surveys that characterise the spatial and temporal dynamics of the relevant biogeochemical process. Once an anomaly is detected, a full assay of carbonate chemistry in the sediment pore waters, the water column (if close to the leak epicentre) and/or direct sampling of gas bubbles can confirm if CO_2 is present. The carbon isotopic composition of the CO_2 may be used to attribute the source of the CO_2, if it is significantly different from background values. Though not addressed in ECO_2, addition of natural or artificial tracers to the CO_2 injection stream prior to storage would also allow the source to be identified.

Work done in ECO_2 demonstrates that the CO_2 flux from bubble streams may be estimated from video observations combined with bubble dissolution modelling, although some direct sampling of gas by remote vehicles (or divers, if the water depth is shallow) is necessary to verify estimates.

Critically, the gas flow at a single point was observed to vary by more than an order of magnitude on timescales of years to a few hours, which may introduce substantial uncertainty to estimates of total gas flux. Fluxes of dissolved CO_2 across the seabed were estimated from benthic chambers, and from pore water chemistry coupled with reaction transport modelling, but the difficulty with both of these techniques is that their footprint is small (<1 m^2), so small scale heterogeneities may lead to significant under- or over-estimation of CO_2 flux. Attempts to quantify seabed CO_2 fluxes based on the excess CO_2 inventory in the water column and current field have also proven to be problematic. This is partly due to large variability in current patterns, but also because the leaking CO_2 is confined to the region close to the seafloor, which is difficult to survey using AUV technology. If CO_2 leakage is confined to a relatively small area of the seafloor, quantification of the leakage flux may be possible, but it is clear from the work done in ECO_2 that accurate quantification of CO_2 fluxes across the seafloor, especially over wide areas, remains a considerable challenge.

Impacts of CO_2 leakage on ocean biology and implications for monitoring

By Steve Widdicombe, Plymouth Marine Laboratory, UK

It is clear from the previous section that the leakage of CO_2 up through the seabed and into the overlying seawater can cause considerable changes in the chemical environment within and close to the seabed. In turn, these chemical changes have been shown to have both direct and indirect impacts upon marine organisms. These biological impacts were the subject of many studies conducted within ECO_2. However, it should be noted that leakage from CCS could have two impacts: CO_2 passing up through the sediment, or from a plume of CO_2-enriched water flowing out from the centre of the leak active release zone. It is now clear that these two types of impact may have very different impacts on seabed communities both in terms of the nature and the severity of the impact. The biological studies in ECO_2 used a wide range of approaches including laboratory experiments, mesocosm studies, field observations in areas of naturally high CO_2 (primarily Panarea, Italy) and computer models.

Direct impacts on organism health and survival

When marine organisms are exposed to low pH seawater the primary physiological effect is a decrease in the pH or an "acidosis" of the extracellular body fluids such as blood, haemolymph, or coelomic fluid. In some species this extracellular acidosis is fully compensated for as levels of extracellular bicarbonate are increased by either active ion transport processes in the gills or through passive dissolution of a calcium carbonate shell or carapace. However, in other species from a variety of different taxa, such as mussels, crabs and sea urchins, studies have reported only partial, or no, compensation in the extracellular acid-base balance. Clearly, if some species are physiologically better equipped to cope with elevated levels of CO_2 than others, the potential for species extinctions and biodiversity loss exists. At the phylum level, experiments have suggested that echinoderms will be more vulnerable than molluscs, then crustaceans, with annelids showing the greatest tolerance to hypercapnia and acidification. This will certainly reduce both taxonomic richness and species diversity and could lead to a reduction in some of the key ecosystem functions performed by seabed ecosystems (e.g. nutrient cycling, production, remediation of waste).

However, even within the same taxonomic groups, variability in tolerance can exist between even closely related species with this variability seemingly linked to key elements of an organism's lifestyle. Organisms that already exist in habitats regularly exposed to highly variable levels of CO_2 may be more likely to possess the physiological mechanisms necessary to cope with rapid changes in environmental conditions than organisms from areas with more stable conditions. It seems clear that the likelihood that a species will be lost from an area as a result of CO_2

Figure 6: Sampling equipment for meiofauna, nutrient pools, organics and microbial data used during cruises and mesocosm
Figure 7: Water samples used to monitor O_2 content of mesocosm systems during the formation water experiment (Dr Ana Queiros and Dr Karl Norling, NIVA's marine research station, Solbergstrand)

leakage will be determined by both its phylogeny and its ecology.

Organisms can use their physiology to gain some short-term resistance to CO_2 leakage

In extreme cases of CO_2 leakage, severe acidification will result in most organisms being killed. However, this will not be the case for every leak scenario as many marine species, even some heavily calcified taxa, can deal with shorter periods of more moderate acidification. This is because that, unlike other potentially toxic substances, CO_2 is a naturally occurring and fluctuating substance in the marine environment. So whilst this means that large changes in seawater carbonate chemistry can potentially affect many aspects of an organism's physiology, there is also the potential for organisms to temporarily alter or adjust their physiology to cope with these chemical changes. So in addition to the process of extracellular buffering described previously, many species have been seen to change their respiration rates, their activity levels and their reproductive outputs when exposed to high CO_2. This response, known as physiological plasticity, has the ability to protect organisms from rapid changes in their environment and can provide temporary protection against moderate acidification.

Short-term CO_2 resistance can come at an energetic and ecological cost

Plasticity, however, does not offer permanent protection for any organism against CO_2 leakage. This is because an organism's ability to express plastic responses is, to a large extent, governed by the energy it has available to fuel the physiological responses needed to, in this case, maintain acid-base balance and physiological function. To maintain calcification rates under low pH, low carbonate saturation state conditions, some organisms can temporarily reallocate more energy to this process and use less energy on other processes such as growth or locomotion. In the short term this can be an effective strategy to deal with an acidification shock. However, if leakage were to persist the increased energetic demand associated with living in a high CO_2 environment would inevitably lead to reduced growth, lower reproductive output and eventually death. So, the environmental consequences of CO_2 leakage therefore depend on both the severity and longevity of the leak. This means that even if a leak is fairly small, if it were to continue for many years the ongoing energetic costs could ultimately cause some species to go extinct and change the structure and the function of the community living around the leak. Over extremely long time periods it is possible that the communities around a leak could start to adapt to this new habitat and the evidence from natural CO_2 seeps would suggest that these new communities are low in abundance and diversity but do contain a number of specialised fauna.

Figure 8: Dr Ana Queiros (PML), benthic ecologist, layering the fluorescent tracer used for the bioturbation assessments carried out during the high CO_2 and formation water mesocosm experiments (NIVA's marine research station, Solbergstrand). The sediment mesocosms can be seen on the floor, with tubing providing input for the experimental water treatments. The experiment lasted 20 and 3 weeks, respectively.

Using biological responses in a programme of Environmental Monitoring

The vast spatial extent over which any CO_2 leak could appear presents a serious challenge to using biological indicators to locate and identify CO_2 leakage from the seafloor. The best candidate indicators are therefore those that can be integrated into broad-scale visual mapping activities in which towed or autonomous vehicles fly close to the seabed and use high-definition cameras to video large areas of seafloor.

A potential indicator that could be observed in this way is the unusual appearance of large numbers of animals on the sediment surface. Recent experiments have shown that exposure to high levels of CO_2 can elicit a surfacing response in several species whereby animals which normally burrow deep within the sediment (known as infauna) come up onto the sediment surface. This is an extremely risky thing for infaunal species to do as it increases the dangers from predation and also increases the chances of being relocated to less suitable habitats by strong tides, currents or storms. Whilst this surfacing behaviour is widely considered as a classic stress-response and not necessarily limited to high CO_2 levels, it may still be a useful early indicator that something is having a negative impact on the benthic fauna. At this point more targeted sampling can be used to determine the identity and source of the environmental impact. Care should be taken with this indicator as it will be a transient signal. It will not take long for the dead or dying organisms at the sediment surface to be consumed by mobile predators and scavengers or to be decomposed by benthic microbes. Another visual indication of CO_2 seepage could be the presence of microbial mats on the sediment surface. In the photic zone (typically water depths less than 50m) mats of benthic algae and photosynthetic bacteria form on sediment surfaces. Also known as microphytobenthos, these mats are coloured green, brown or even pink depending on the species present and there is evidence that elevated levels of CO_2 likely enhance the growth of these photosynthetic microbes. Therefore, in areas receiving sufficient light input, monitoring for blooms of microphytobenthos may prove useful as an indicator of a CO_2 leak. In deeper waters, where light levels are too low to support photosynthetic organisms, the presence of microbial mats can indicate the seabed leakage of substances other than CO_2. Most commonly these deeper mats are made up of microbes feeding on either methane or sulphur. It is conceivable that should CO_2 leak from a reservoir it could liberate methane or sulphur from the shallow sediment layers and that the presence of the associated microbial mats could indicate areas where future CO_2 leakage could be expected.

Apart from the visible biological indicators, most other biological responses would be either too time consuming to measure or too spatially restricted to act as rapid indicators of leakage. To this end, biological responses are not best suited to locate potential leaks but are more ideally suited to monitor the progress of leakage impact once a leak is detected, to assess or quantify the scale of the impact or to monitor ecosystem recovery once a leak has stopped. For these purposes, biological responses offer an integrated measure of CO_2 exposure that actually relates CO_2 leakage to a biological consequence.

"… biological responses are … more ideally suited to monitoring the progress of leakage once a leak is detected, to assessing or quantifying the scale of the impact or to monitoring ecosystem recovery."

With that said it would be unwise to abandon biological monitoring altogether from any environmental monitoring plan for two main reasons. Firstly, it could be argued that under certain scenarios, CO_2 could leak slowly up into the sediment, significantly impacting the sediment chemistry, whilst the nature of the leak combined with the geology of the sediment could mean that no visible or chemical indications of the leak would be detected in the overlying water. By regularly checking both the biogeochemical nature of the seabed and health and structure of benthic communities these specific leaks could be identified. Secondly, the majority of public concern over offshore CCS activities is likely to focus on the potential for impacts on marine organisms and habitats. A robust and effective biological monitoring programme is a powerful tool in reassuring public concerns that any environmental impacts will be detected.

Obviously it would be impractical to implement a full biological survey across the entire storage area, especially at the fine-scale spatial resolution needed to be sure of detecting all leaks. The most resource effective solution would be to concentrate seabed intensive survey activities around areas of perceived high leakage risk, such as existing or derelict wells or geological features such as chimneys. To this end, operators could employ a spatially nested approach to environmental monitoring whereby different monitoring activities were deployed across different spatial scales and with different spatial resolution. At the broadest scale, visual surveys would be conducted across the whole storage area looking for the presence of unusual biological features such as microbial mats or the appearance of infauna at the sediment surface. These surveys could be conducted at the same time as any broad-scale chemical surveys using the same AUVs or ROVs. Around areas with potentially higher risk of leakage, comprehensive biological monitoring should be conducted. This monitoring would involve determining the identity, abundance, biomass and distribution of seabed fauna. In particular, observers should be looking for changes in the community structure and diversity of infaunal organisms that have been shown to be indicative of CO_2 impact. For CCS leakage, these changes could be a reduction in the presence of calcified taxa or a reduction in the biomass of calcium carbonate structures (e.g. shells and exoskeletons).

As with all biological indicators, understanding the natural temporal variability in these data by the acquisition of a comprehensive biological baseline will be needed so unnatural changes in benthic communities can be discriminated from those natural changes that occur between seasons and years. Not only is this important for identifying impact but also in guarding against the false attribution of natural changes to CCS activities. By adopting effective biological monitoring operators and regulators could address both of the issues of leak detection and public confidence.

The fate of CO_2 entering the water column

By Guttorm Alendal, University of Bergen, Norway

This is a brief report on activities and findings of work in ECO_2 on the fate of CO_2 released at the seafloor.

Background

- The EU Directive 2009/31/EC establishes a legal framework for geological storage, eliminating as far as possible negative effects and environmental risks associated with geological storage operations, aligned with the amendments to the 1996 London Protocol and to the OSPAR Convention.
- Annex I of the directive specifies criteria for characterisation and assessment of storage sites, which includes exposure assessment, based on characteristics of the environment and the "potential behaviour and fate of the leaking CO_2". This assessment will lay the foundation for later required effects assessments ("at a range of temporal and spatial scales") and risk characterisations (worst case environmental impact and identify sources and reduction of uncertain-ties).
- Annex II of the directive specifies criteria for establishing and updating a monitoring plan using best available technologies and use of "technologies that can detect presence, location and migration paths of CO_2 in the subsurface and at surface" should be consid-ered. Further, technologies that can provide a wide areal spread to capture information on any previously undetected leakage pathways and detect significant irregularities or migra-tion of CO_2 will be necessary.
- The monitoring plan shall be updated at least every five years "to take account of changes to the assessed risk of leakage,

changes to the assessed risks to the environment and human health, new scientific knowledge, and improvements in best available technology".

- The cornerstone for exposure assessments and the possibility of detecting a CO_2 leak to the marine environment is the spatial extent of the CO_2 signal in a varying marine environment, the footprint of a leak, governed by a number of biogeochemical and physical processes. In addition, instruments, their capabilities and uncertainties, will determine our ability to assure detection of a leak to marine waters.

Achievements

- ECO_2 has had an extensive cruise programme, during which characteristics of bubble dynamics, near-field plume, and the evolution of dissolved constituents under the influence of local hydrodynamics have been studied at natural leakage sites and during a CO_2 release experiment performed in the North Sea. The studies indicate that the impact of CO_2 seepage is primarily limited to bottom water and will be very localised.
- The marine environment is hostile to instruments. ECO_2 has reviewed available chemical sensors (Fig. 9), emphasising the challenges of long-term deployment including drift related to for example biofouling. Some newly developed tools taking into consideration the full biogeochemical changes in the water column do show potential for autonomous continuous monitoring, and approaches to account for the natural variability have been suggested.
- Acoustic methods have been assessed. It was demonstrated that multibeam echo sounders (*MBES*) have the potential to provide fast and affordable surveys, with high resolution, to detect gas seeps. The concurrent acquisition of bathymetric data offers a detailed look at seafloor features that may be related to the gas seeps. Single-beam echo sounders (*SBES*) are appropriate for gathering time-series at a single location.

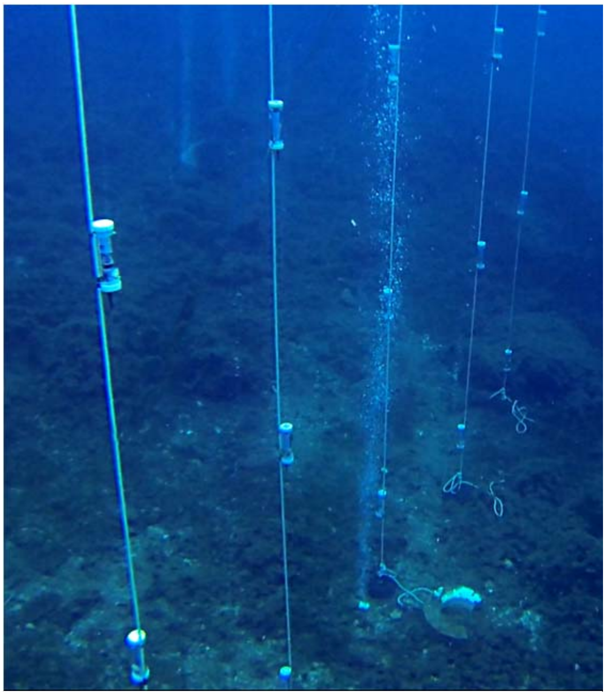


Figure 9: Deployment of 20 pCO_2 sensors in the water column near Panarea Island, Italy, centered on a CO_2 leak and bubble flare

- The four numerical models used; a marine chemistry model (scale: 10^{-2} m), two different near-field two-phase plume models (scales: m to km), and a regional scale general circulation model (scale: km) have used data from the ECO_2 cruise program (and other sources), to tune and to better estimate sub-model parameters. This has produced more reliable model formulations as a result.
- A number of leak scenarios have been simulated as part of the overall scenarios as defined under the umbrella of ECO_2 as related to the interfacing of numerical models. An objective in ECO_2 has been to estimate the spatial footprint of a leak, including level of acidification.
- Even though the models used in this study are very different; they all support the field

campaign observation that the distinct footprint of a leak will be very localised. The flux, topology of the leak (dispersed small leaks vs. single point large flux), and bubble size distribution at the seafloor influences the maximum concentration and spatial extent of the footprint. This emphasises the need for proper and reliable predictions on how the CO_2 reaches the seafloor.

- Transport and dilution of dissolved CO_2 is highly dependent on local stratification, current and mixing conditions. The varying current direction (e.g. tide) also determines the movement of the dissolved CO_2 plume. Even though the average signal may be very low at a location, spots of higher concentration may pass sporadically making detection possible given appropriate continuous monitoring systems.

Key Considerations

The limited spatial footprint of a leak suggests that a distinct signal of a CO_2 leak within marine waters will be highly localised close to the leak. This emphasises the challenge of designing a monitoring programme capable of covering a large area, while simultaneously capable of detecting small and localised changes in the marine environment.

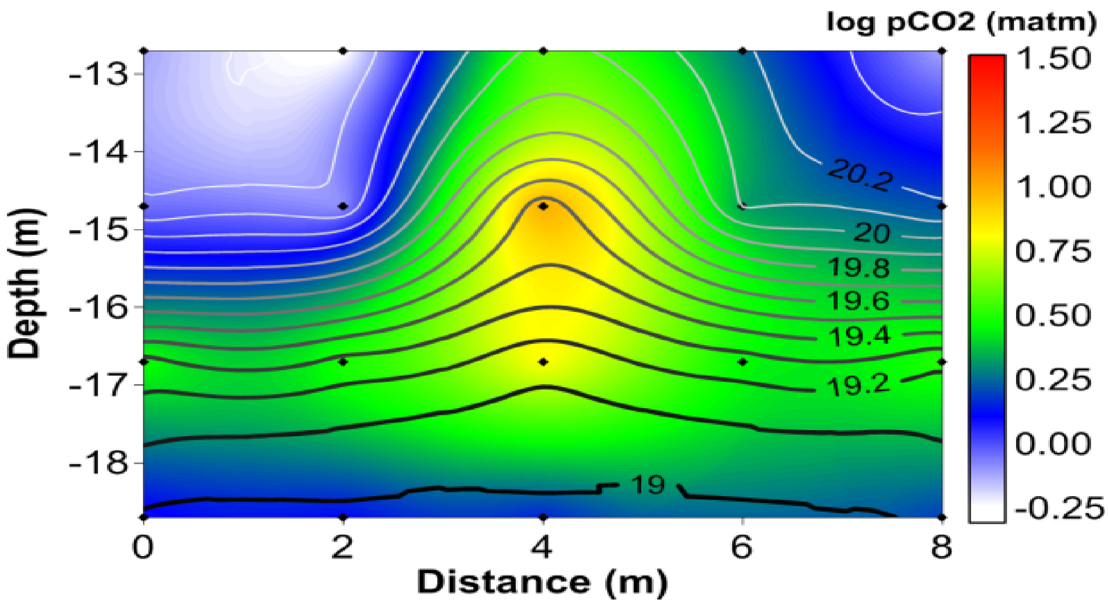


Figure 10: Data showing water temperature upwelling (contour lines) and the spatial distribution of dissolved CO_2 (coloured contours) around the flare pictured in Figure 9 (Beaubien et al., 2014).

- The challenge increases when recognising that the natural variability of the marine environment may cover any signal from a leak. As long as the signal stays below natural variability it will be extremely hard to detect, localise and quantify a leak.
- Other, natural or man-made, events might trigger changes in the environment that can be misinterpreted as indicators of a leak. Unless these are explained they might cause unfounded allegations of a leak.
- Each site will be different, and there might be different environments within the domain of individual projects. Hence, the approach might differ from project to project.
- The costs of marine operations are considerable and instrument capabilities will constrain the design of a monitoring program.
- Quantification of uncertainties will be a challenge.

Conclusions/recommendations

A proper statistical description of the environmental baseline is essential for estimating spatial and temporal distribution of a leak footprint. Such estimates allow for subsequent exposure assessments and provide the basis for designing a monitoring programme. To account for natural trends and rare events, i.e. tails of the distributions, a long period of data is required. As a result it is recommended that the baseline statistics gathering begins during the characterisation and assessment of a storage site, and that one of the objectives of the monitoring programme is to improve the environmental statistics.

References

Beaubien S.E., Graziani S., Annunziatellis A., Bigi S., Ruggiero L., Tartarello M.C., Lombardi S., 2014. Spatial-temporal water column monitoring using multiple, low-cost GasPro-pCO2 sensors: implications for monitoring, modelling, and potential impact. *Energy Procedia* 63, 3840-3847, doi: 10.1016/j.egypro.2014.11.413

Outlook

by Klaus Wallmann, GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany, Douglas Connelly, National Oceanography Centre, UK and Frank Melzner, GEOMAR

The ECO$_2$ project has achieved most of its aims and advanced the field significantly. However, the data and knowledge generated in the project have led to new questions related to the likelihood and mechanisms of leakage that need to be addressed in future research projects and considered by storage site operators:

The evaluation of seismic data in ECO$_2$ revealed numerous structures cutting vertically through the overburden at all existing storage sites. These seismic pipes and chimneys may be considered to be pathways for gas and fluid flow and it is commonly assumed that natural gas from deeper strata migrated through these structures into the overlying water column at some point in geological time. It seems that some of these structures could act as pathways for CO_2 leakage if the subsurface CO_2 plume reaches their base and if their permeability is high enough to allow for vertical gas ascent. New approaches need to be developed and additional data gathered to better constrain the permeability of these frequently observed structures.

The seabed above one of the studied storage sites is covered with circular depressions. These so called pockmarks were formed in the geological past by the ascent of natural gas and fluids from the shallow subsurface. However, some of the larger pockmarks have roots reaching several kilometers deep into the subsurface. More work needs to be done to evaluate whether pressure built up during the storage operation might reactivate gas seepage and initiate CO_2 leakage through these structures.

Detailed seafloor mapping with new high-resolution backscatter imaging techniques revealed a narrow and elongated fracture-like structure at the seabed above the Utsira formation. Even though the area has been extensively used by the oil and gas industry over several decades, this larger than 3km long structure has not been reported in previous surveys. It is covered with bacterial mats feeding on reduced chemical species which are transported to the surface with formation fluids originating from the shallow subsurface. So far, this unexpected structure is unique. However, it is possible that similar seabed fractures will be discovered in other parts of the North Sea applying the advanced high-resolution technologies used in ECO_2. If seabed fractures turn out to be a common feature their significance as a possible conduit for CO_2 leakage needs to be evaluated.

Seepage of methane gas bubbles was observed at all abandoned wells surveyed by ECO_2. Surprisingly, the gases emanating at the seabed did not originate from the deep target formations but from gas pockets in the shallow overburden. The bubbles did not rise through the well but through the sediments surrounding the well that were mechanically disturbed and weakened during the drilling operation. Future studies on possible CO_2 leakage through wells should thus not only address the issue of well integrity but should study the mechanical properties and gas permeability of the surrounding sediments affected during the drilling operation.

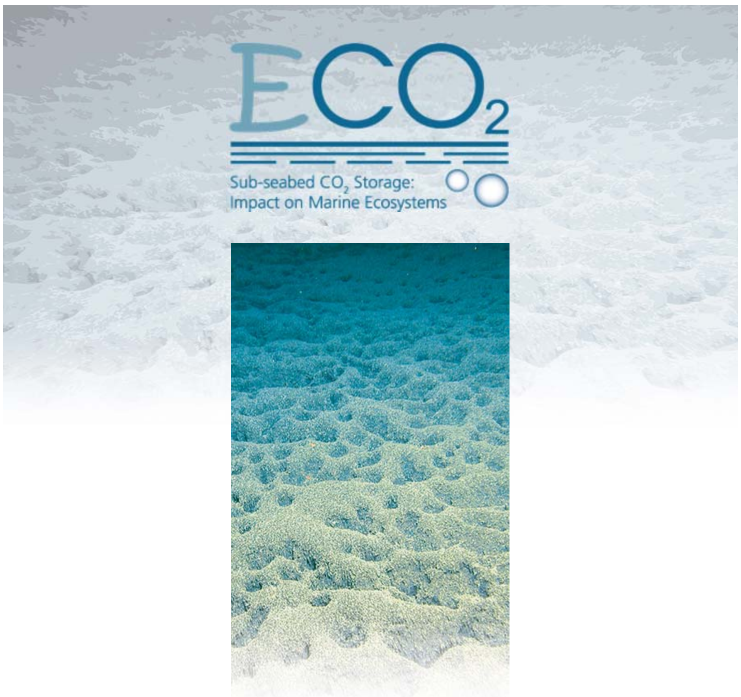
Even though the sedimentary overburden in the vicinity of storage sites may be punctuated by various seepage-related structures, the data collected in ECO_2 show that most of these structures are too shallow to reach and compromise the underlying deep storage formations. Moreover, the rates of leakage through these structures would be small, so that the overwhelming proportion of the stored CO_2 remains in place over prolonged periods of time. From a scientific perspective, brief episodes (hours to days) of small-scale leakage that could arise from storage sites do not pose a serious threat for the marine ecosystem. However, it is currently unclear how regulators and operators should respond to this kind of low-level leakage if it were to occur. Laboratory research conducted in the framework of ECO_2 has shown that long-term (weeks to months) low-level leakage scenarious potentially can impact fitness of calcifying benthic species, either through external dissolution of shells or via alterations of energy budgets that result in reduced growth and reproductive output. Future projects should address the issue of how to evaluate sub-lethal impacts of small-scale yet persistent leakage and propose new legislation to define how operators have to respond if low concentrations of CO_2 are released from their storage site into the marine environment.

Within the EU, the UK is currently most actively pursuing the implementation of sub-seabed CO_2 storage at an industrial scale. A number of the researchers involved in ECO_2 were also part of UK funded projects. The most prominent of these was the QICS project (Quantifying and monitoring potential Impacts of geological Carbon Storage) which performed a limited release of CO_2 (<1 tonne CO_2 day-1) into the seabed of a Scottish sea loch. The leakage was monitored using a suite of tools to enable the impacts of the leak to be assessed. Initial results suggest that the biological footprint of this CO_2 release is restricted to an area tens of meters around the injection site. There are plans to follow this project with a longer-term, larger-scale experiment. Another project, entitled Measurement, Modelling and Verification of CO_2 storage (MMV), has been funded by the Energy Technologies Institute with the aim of developing cost effective systems for the detection and monitoring of potential leakage from CCS sites. The main thrust of the project is to identify AUV and sensor-based technologies that can effectively do this detection and monitoring in a cost effective way. The European Commission has established a roadmap for moving to a low-carbon economy in 2050 and has aligned a number of calls under the Horizon 2020 to aid in this challenge. One such call LCE-15-2014 and 2015 has been directed towards the topic of 'Enabling decarbonisation of the fossil fuel-based power sector and energy intensive industry through CCS'. A number of researchers researchers associated with ECO_2 are addressing this call through a number of separate proposals. The expertise gained within ECO_2 will be used in follow-up projects to address the open questions listed above, to further improve strategies for biological impact monitoring. Little research attention has so far been devoted to experimental approaches that test leakage scenario impacts on benthic ecosystems while simultaneously incorporating climate change induced alterations in carbonate chemistry, temperature and oxygen levels.

New Publications online at www.eco2-project.eu

- ☞ ECO_2 Glossary *The language of CCS*
- ☞ *ECO_2 Brochure* update December 2014
- ☞ *IEAGHG Report* (in cooperation with ECO_2) - *Key Messages for Communication Needs for Key Stakeholders*
- ☞ *Nature* report about ECO_2's research on offshore CO_2 storage
- ☞ *Sub-seabed CO_2 Storage: Monitoring Techniques*

In addition, see our new sub-website http://monitoring.eco2-project.eu/ for such details as *Key Questions*, *Technology in Use* and an *Overview Map*.



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