

ECO₂ Final Publishable Summary Report

Executive summary

Carbon dioxide (CO₂) separated from natural gas has been stored successfully below the seabed off Norway for almost two decades. Based on this experience several demonstration projects supported by the EU and its member states are now setting out to store CO₂ captured at power plants in offshore geological formations. The ECO₂ project was triggered by these activities and funded by the EU to assess the environmental risks associated with the sub-seabed storage of CO₂ and to provide guidance on environmental practices. ECO₂ conducted a comprehensive offshore field programme at the Norwegian storage sites Sleipner and Snøhvit and at several natural CO₂ seepage sites in order to identify potential pathways for CO₂ leakage through the overburden, monitor seep sites at the seabed, track and trace the spread of CO₂ in the water column, and study the response of benthic biota to CO₂. ECO₂ identified a rich variety of geological structures in the broader vicinity of the storage sites that probably served as conduits for gas release in the geological past and located a seabed fracture and several seeps and abandoned wells where natural gas and formation water are released into the marine environment. Even though leakage may occur if these structures are not avoided during site selection, observations at natural seeps, release experiments, and numerical modelling revealed that the footprint at the seabed where organisms would be impacted by CO₂ is small for realistic leakage scenarios.

Based on these results, a new approach for environmental risk assessment (ERA) was developed for sub-seabed storage sites. It uses the EBSA (Ecologically or Biologically Significant Marine Areas) approach to describe marine resources in the studied area and to assess a site-specific environmental value for each highlighted resource. Subsequently, potential leak features that can connect the CO₂ stored in the target formation with the seabed are identified and the size of the affected seafloor is estimated for a range of leakage scenarios. Overlay analysis between the affected area and the identified valuable resources reveal the consequences of leakage. Bayesian methods are applied to determine a propensity-to-leak factor dealing with the geological complexity of the overburden. The environmental risk is finally assessed as the product of consequences and propensity of leakage. The novel ERA approach was tested and applied to assess the environmental risks of the storage operation conducted at Sleipner.

The monitoring strategy proposed by ECO₂ is organized around a suite of surveys covering the area above the storage formation. ECO₂ recommends that overburden, seabed, and water column should be monitored and surveyed applying the following techniques: i) 3-D seismic, ii) high-resolution bathymetry/backscatter mapping of the seabed, iii) hydro-acoustic imaging of shallow gas accumulations in the seabed and gas bubbles ascending into the water column, iv) video/photo imaging of biota at the seabed, v) chemical detection of dissolved CO₂ and related parameters in ambient bottom waters. Additional targeted studies have to be conducted if active formation water seeps, gas seeps, and pockmarks with deep roots reaching into the storage formation occur at the seabed. These sites have to be revisited on a regular basis to determine emission rates of gases and fluids and exclude that seepage is invigorated and pockmarks are re-activated by the storage operation. Baseline studies serve to determine the natural variability against which the response of the storage complex to the storage operation has to be evaluated. All measurements being part of the monitoring program, thus, need to be performed during the baseline study prior to the onset of the storage operation to assess the spatial and temporal variability of leakage-related structures, parameters, and processes.

ECO₂ conducted additional studies to assess the legal framework, analyse the economics, and evaluate the public perception of CO₂ storage below the seabed.

1. Project context and objectives

Carbon dioxide Capture and Storage (CCS) is regarded as a key technology for the abatement of carbon dioxide (CO₂) emissions from power plants and other industrial sources. Hence, the European Commission adopted the directive on the geological storage of carbon dioxide (CCS-Directive; 2009/31/EC) 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 CO₂ emission certificates provides insufficient incentive 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 member state investing most significantly into the implementation of CCS. Two large-scale demonstration projects have been shortlisted by the UK; both are planning to store CO₂ 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, CO₂ can be injected into offshore fields to potentially enhance and prolong the oil and gas production. Despite CO₂ 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 CO₂ storage on marine ecosystems.

As a consequence of this lack of knowledge, the 7th framework European collaborative project ECO₂ set out to assess the environmental risks associated with storage of CO₂ below the seabed (<http://www.eco2-project.eu>). Starting in May 2011, it included 27 partners from 9 European nations. The project ended in April 2015 and delivered a framework of best environmental practices to guide the management of offshore CO₂ injection and storage as its final project result. The project investigated two currently operating sub-seabed storage sites which are storing CO₂ in saline aquifers of the North Sea at ca. 90 m water depth (Sleipner) and the upper continental slope of the Barents Sea at ca. 330 m water depth (Snøhvit). Additionally, a soon depleted oil and gas reservoir in the Polish Sector of the Baltic Sea (B3 field site) was studied as potential storage site. Between them they cover the major geological settings to be used for sub-seabed CO₂ storage. Comprehensive process and monitoring studies at natural seepage sites, regarded as natural analogues for potential CO₂ leaks at storage sites, as well as laboratory experiments and numerical modelling support the fieldwork at the CO₂ storage sites (Fig. 1).

The ECO₂ consortium drew expertise from at least three different scientific communities, including biologists studying the effects of ocean acidification on marine biota, geoscientists investigating natural seepage of gas and formation water at the seabed, and experienced scientists with a strong track record in CCS research from multiple perspectives. The questions raised in the call could only be addressed through the convergence, within the ECO₂ consortium, of these previously separate scientific communities. ECO₂ partners were involved in major initiatives in ocean acidification, natural seepage, and CCS at the national, EU, and international level. ECO₂ integrated these latter results where relevant, but focussed its own efforts and resources on those novel aspects specifically relevant for sub-seabed CO₂ storage.

The work programme included social science and humanity studies assessing the public perception of sub-seabed carbon storage. The existing legal framework of offshore CO₂ storage was evaluated and economic analysis was applied to assess the consequences of leakage. The scientific work was complemented by an extensive stakeholder dialogue programme and underpinned by effective and rigorous data and project management.

The ECO₂ consortium partners committed significant non-EU resources to fulfil the aspirations raised in the call. The total effort committed to this project was significantly higher than the EU contribution through the contribution of ship time, storage site data, staff effort, and high-end instrumentation (ROVs, AUVs, lander systems, *in situ* sensors, mesocosm facilities, high-pressure labs, etc.). ECO₂

results had and will have a strong impact on the assessment, evaluation, and implementation of sub-seabed storage not only at the European level but also internationally.

Europe plays a leading role in this technology since large-scale CO₂ storage below the seabed has been tested and implemented in European waters, solely by the operator Statoil. Statoil is the world-market leader in this technology and contributed its outstanding expertise and extensive data-base to ECO₂. Scientists involved in ECO₂ are from the best European laboratories with access to cutting-edge marine equipment and technology, and have a proven record of scientific excellence and delivery. These partners provided the best possible assessment of environmental risks associated with sub-seabed storage using information provided by the operator Statoil and independent data acquired during research cruises, laboratory experiments, and modelling studies.

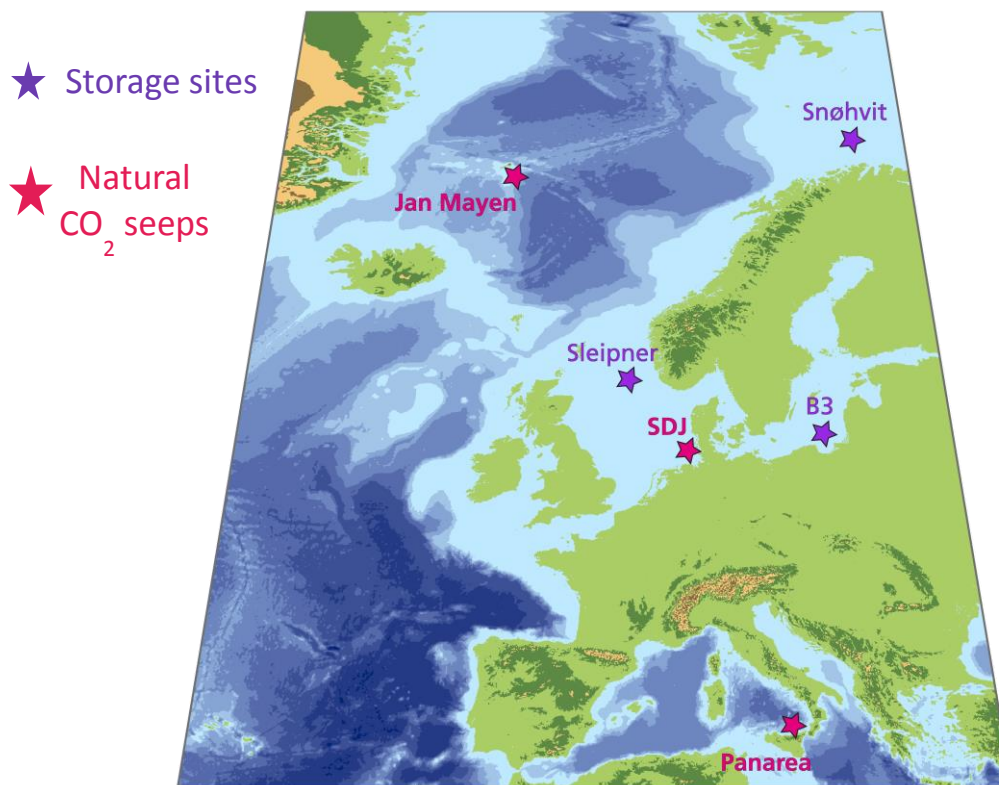


Figure 1. Study areas of the ECO₂ project including storage sites and natural CO₂ seeps

In order to achieve its goals, ECO₂ pursued the following 5 key project 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
- To define guidelines for the best environmental practices in implementation and management of sub-seabed storage sites

The likelihood of leakage (objective 1) was assessed through an extensive field work programme supported by laboratory experiments and numerical modelling. The field work at storage sites and natural CO₂ seeps started in 2011. It included ca. 20 cruises with research vessels from Germany, Norway, UK, Italy, Poland, and Ireland augmented by rubber boat and diving operations. The unique data set assembled during these cruises provided vital information on the integrity of the

sedimentary overburden at storage sites and the pathways for CO₂ leakage through the overburden. Emission rates were quantified at natural seeps applying advanced lander technologies while relevant processes such as the self-sealing of migration pathways by CO₂ hydrate formation were further evaluated in the laboratory. Numerical models simulating the ascent of CO₂ from the reservoir through the overlying sediments were developed and adopted to the specific conditions at the studied storage sites. The model results were evaluated to constrain the likelihood of leakage for the broad range of different geological settings studied by ECO₂.

The potential effects of leakage on benthic organisms and marine ecosystems (objective 2) were studied in the lab, during field experiments, and at natural CO₂ seepage sites. The footprint of a leak, that is the size of the seabed area covered with CO₂-enriched bottom waters, was determined at natural CO₂ seeps and during a deliberate CO₂ release experiment conducted at the seabed close to Sleipner. These studies also served to determine dissolved CO₂ and pH gradients within the CO₂ plume spreading around the leakage site. The field data were further evaluated by numerical models simulating the dissolution of CO₂ gas bubbles and the dispersion of dissolved CO₂ by ambient bottom currents. Exposure experiments revealed how organisms living in marine surface sediments and at the seabed respond to elevated CO₂ and low pH conditions in ascending pore fluids and ambient bottom waters.

The environmental risks of sub-seabed storage (objective 3) were assessed by all partners collectively under guidance of Det Norske Veritas (DNV, now DNV-GL). The environmental risk assessment (ERA) was based on the likelihood of leakage constrained under objective 1 and the hazard identification achieved under objective 2. The set-up of an appropriate ERA scheme started during the first year of the funding period and evolved over the following years considering the continuously growing knowledge generated within ECO₂. The optimized approach was finally applied and tested using the storage operation at Sleipner as a case study.

Monitoring approaches and techniques (objective 4) were proposed and critically reviewed in an iterative process drawing on the experiences and knowledge gained during the project. As part of this process cutting-edge technologies were repeatedly tested and further optimized during the various cruises. The comprehensive monitoring strategy that was defined by the ECO₂ consortium relies on those sea-going technologies that performed best and offer the optimal cost-benefit ratio. It guarantees that even minor leaks are detected and localized at the seabed.

Finally, guidelines for environmental practices in implementation and management of sub-seabed storage sites (objective 5) were formulated by the ECO₂ consortium during the concluding project meeting at April 2015. This high-level document (<http://oceanrep.geomar.de/28739/>) includes i) an overview on the legal framework that needs to be considered in the planning and operation of storage sites, ii) an assessment of the public perception of sub-seabed CO₂ storage, iii) a novel framework for the assessment of environmental risks, iv) criteria and recommendations for site selection in the marine environment and v) recommendations for environmental monitoring and baseline studies at sub-seabed CO₂ storage sites.

Further information on the ECO₂ project and its major outcomes can be found at:

<http://www.eco2-project.eu/>

2. Main results

2.1. Leakage pathways

ECO₂ performed a detailed analysis of the overburden and the seabed at the storage sites Sleipner and Snøhvit. Seismic data revealed a large number of shallow gas accumulations and seismic pipe and chimney structures in the sedimentary overburden in the vicinity of both storage sites. These vertical seismic anomalies are interpreted as focused fluid flow structures, which hydraulically connect deeper stratigraphic layers with the overburden. Their formation is generally believed to be controlled by overpressure-induced hydro-fracturing of an impermeable cap rock. The data from the Sleipner area indicate a complex fluid flow system, which can be divided into a shallow and a deep subsystem with the Utsira Formation representing the boundary between both subsystems (Fig. 2). Leaking fluids from deep hydrocarbon reservoirs seem to have entered the Utsira formation at some point in geological time. The overlying Nordland Shales prohibited migration further upward due to their low permeability until additional pressure increase caused seal-breaching of the Nordland Shales (KARSTENS and BERNDT, 2015). Based on the geophysical data collected in the Sleipner area, a geological model of the overburden, including the identified leakage structures and the storage complex was implemented into a 3-D multiphase flow model (DuMux, University of Stuttgart). DuMux predicts that the closest seismic chimney structures (C01 and A01 in Fig. 3) would be reached, if CO₂ injection at Sleipner proceeded for more than 110 years. However, the storage operation at Sleipner is scheduled to end within the next decade. Thus, CO₂ will not leak from the Utsira Formation through these structures.

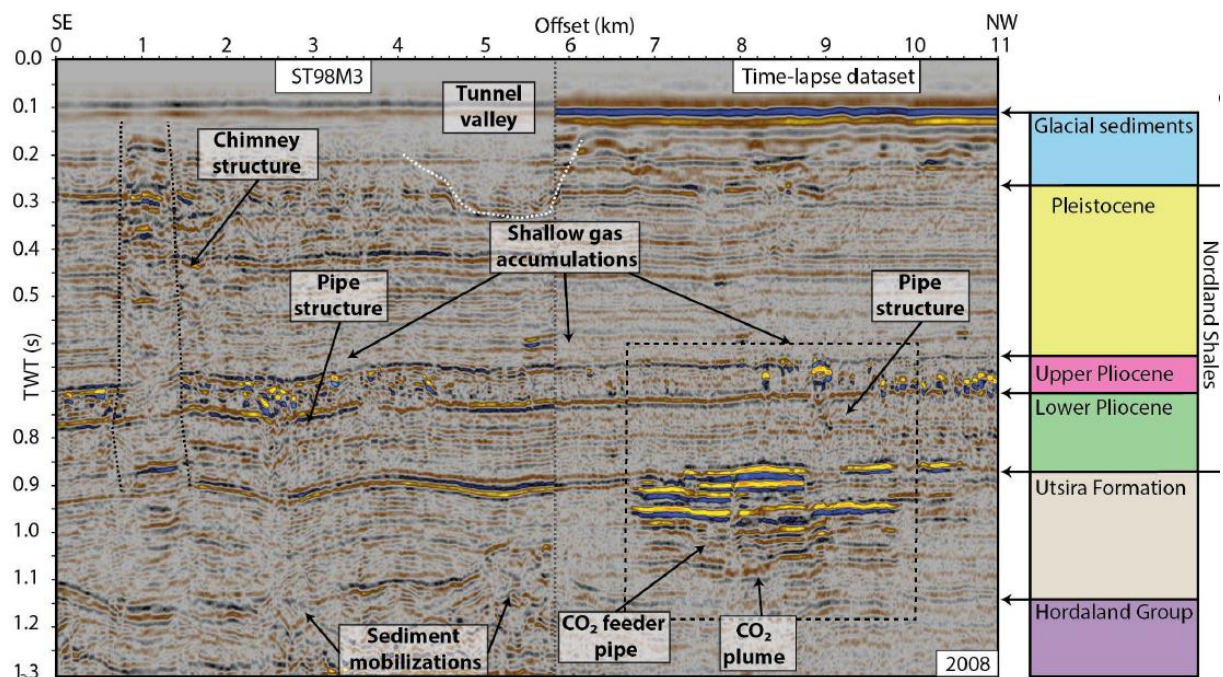


Figure 2. Seismic profile in the Sleipner area showing the 2008-extent of the CO₂ plume in the Utsira Formation (lower right part) and several features associated to fluid flow: seismic chimney, pipes, and shallow gas pockets (KARSTENS and BERNDT, 2015). The seismic profile was merged from ST98M3 data (left side; kindly provided by Statoil Petroleum AS and the Norwegian Petroleum Directorate) and the Sleipner time-lapse dataset (right side; kindly provided by Statoil Petroleum AS, ExxonMobil Exploration & Production Norway AS, and Total E&P Norge AS).

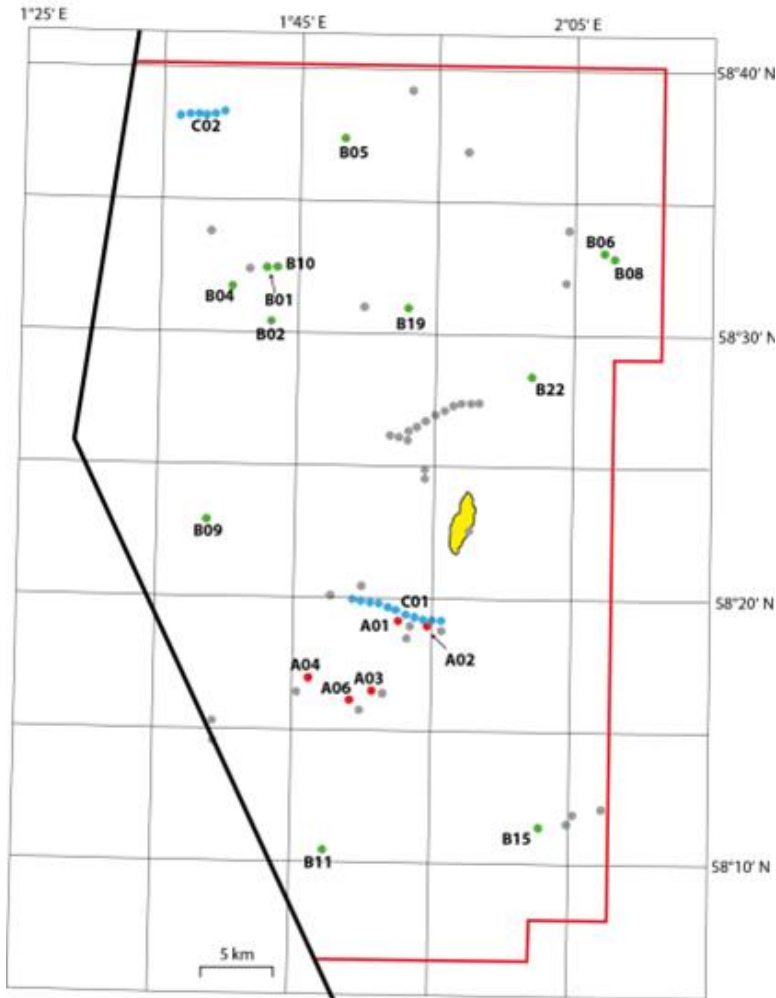


Figure 3. Map of the Sleipner area showing fluid flow manifestations in the overburden. Seismic chimney structures marked in red, green, and blue colors are directly connected to the Utsira Formation, whereas structures marked with gray dots do not reach down to the Utsira Formation. In yellow, the mapped CO₂ plume (size in 2008) in the Utsira Formation is displayed.

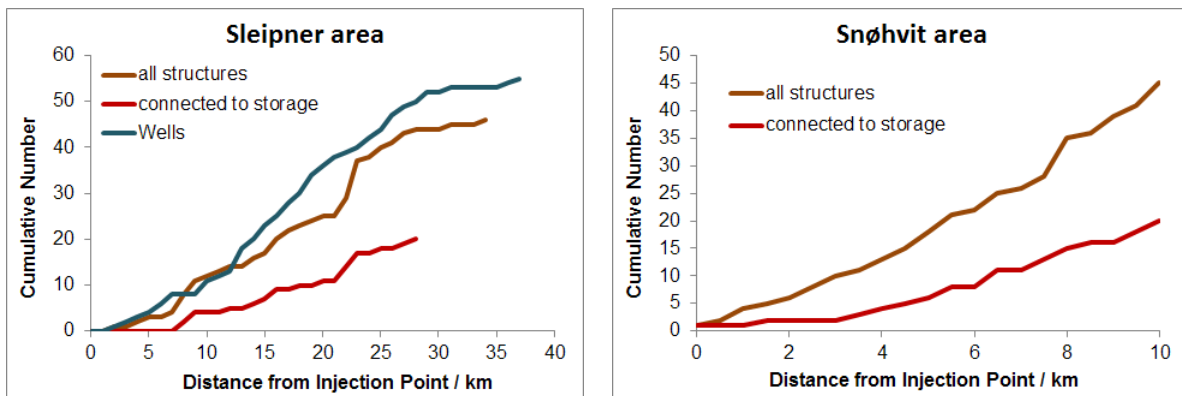


Figure 4. The number of identified seismic chimneys in the overburden of the Sleipner (left) and Snøhvit (right) areas increases with distance from the injection location. 40-50 % of those structures (and abandoned wells at Sleipner) are connected to the CO₂ storage unit and, thus, pose potential pathways for leakage. (Data provided by J. Karstens, GEOMAR, and A. Tasiannas, University of Tromsø)

However, models developed within ECO₂ indicate that leakage would occur if CO₂ would be stored beneath these up to 500 m wide columnar structures. Numerous seismic chimneys are located in the vicinity of Sleipner and Snøhvit (Fig. 4) as in many other sedimentary basins. They are as numerous as

abandoned wells in oil and gas provinces (Fig. 4). Chimneys and wells may serve as pathways for CO₂ leakage and should be avoided during the selection of storage sites to minimize the likelihood that leakage will occur.

The Hugin Fracture was probably the most surprising discovery made by the ECO₂ project (Fig. 5). This ca. 3 km long and up to 10 m wide seabed fracture is located 25 km north to the Sleipner storage site in an area that has been used and mapped extensively by oil and gas industries since many decades. The discovery was made possible by new technologies tested and applied by ECO₂. It was imaged by high-resolution interferometric synthetic aperture sonar (HISAS 1030) mounted onto AUV HUGIN measuring the backscatter intensities of the seabed in unprecedented resolution. The system detects the distribution of bacterial mats thriving in the seabed fracture since the acoustic HISAS signal is not scattered back by these soft biological structures.

Bacterial mats indicate the ascent of methane-charged fluids since they feed on reduced chemicals (hydrogen sulfide) formed by the anaerobic oxidation of methane. Sampling of pore fluids below the bacterial mats confirmed that methane-charged fluids are ascending through the fracture. The methane is of dominantly biogenic origin. However, traces of ethane were found that may indicate a minor admixture of thermogenic gases originating from the deep subsurface. The discovery of the Hugin Fracture demonstrates that the uppermost, clay-rich, impermeable seal of the overburden is broken along a several km long structure.

The Hugin Fracture seems to follow the margin of a subsurface channel structure. It is situated on top of a channel focal area where several generations of channels are observed down to 300 m sub-seabed depth. Seep fluids that are emanating from the fracture are less salty than seawater and appear to stem from a subsurface fresh water reservoir, suggesting that the channel structure has a glacialfluvial/fluvial origin. The Hugin Fracture seems to have formed as a result of brittle failure of very stiff and clay-rich Quaternary sediments that are present in this region. The brittle failure may have been caused by differential compaction along the margin of a shallow fluvial channel structure. The abundance of channel structures in the North Sea suggests that such seafloor fractures may be a common feature in this region. It is therefore possible that the top sediment seal may be broken by many similar fracture systems, and that these may provide pathways for fluid flow from the shallow permeable fluvial channels to the seafloor. Analyses of the 3D seismic data from the Sleipner area show that the lower seal of the Utsira Formation is penetrated by chimney structures (Fig. 2). Along such chimneys, fluids may migrate from the Utsira Formation into the fluvial channels, which are common above the top Pliocene. If these channels are then permeable, and if they are interconnected, then they could form channel pathways for linking lateral and vertical fluid flow. However, the analysis of pore fluids from the Hugin Fracture clearly showed that the ascending fluids do not originate from the Utsira Formation since they did not feature the very high level of dissolved boron and lithium concentrations characterizing this storage formation.

The seabed above the Snøhvit storage site in the Barents Sea is covered by hundreds of pockmarks. Some of these crater-like structures have diameters of several hundreds of meters and depths reaching 12 m. They were probably formed by the emission of large volumes of natural gas during the last deglaciation. High-resolution seismic data recorded at the Snøhvit storage site with the novel P-Cable 3-D system revealed that some of the larger pockmarks are located above deep-reaching faults and high amplitude anomalies interpreted as shallow gas accumulations (Fig. 6). Hydro-acoustic surveys showed that none of the numerous pockmarks at Snøhvit are currently emitting natural gas or CO₂ into the overlying water column. However, pressure built-up induced by the storage operation may re-activate gas and fluid flow through these structures. Pockmarks with deep roots reaching into the storage formation constitute potential pathways for CO₂ leakage. They should either be avoided during storage site selection or need to be monitored closely during the operational lifetime of the storage site.

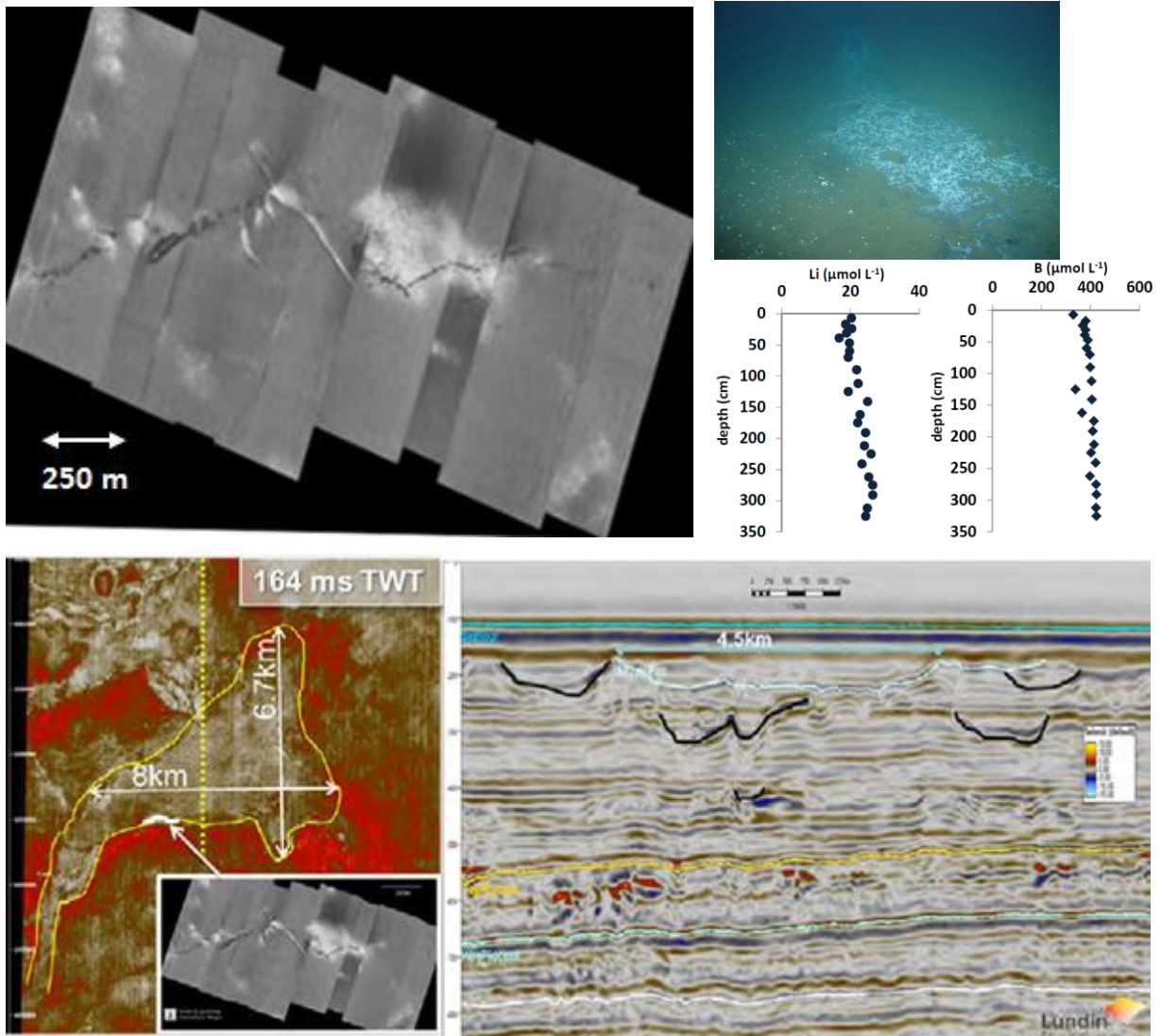


Figure 5. Hugin Fracture in the central North Sea, 25 km north of the Sleipner area, imaged by high-resolution interferometric synthetic aperture sonar (HISAS) mounted onto AUV HUGIN (top left). The seabed is predominantly composed of sandy sediments showing low-to medium backscatter intensities (gray areas), while shell hash areas correspond to high backscatter intensities (white patches). Bacterial mats (top right) do not scatter back any signal (black branched line in the HISAS image), thereby indicating the location of the Hugin Fracture at the seafloor. Biogeochemical analyses of sediment porewater and expelled fluids confirm active fluid flow along the 3-km long and up to 10-m wide fracture. (Top right) Expelled porewaters carry, for example, lithium ($\sim 25 \mu\text{mol L}^{-1}$) and boron ($\sim 410 \mu\text{mol L}^{-1}$) concentrations similar to those of ambient seawater, whereas these elements are strongly enriched in Utsira Formation water ($\text{Li} \approx 390 \mu\text{mol L}^{-1}$; $\text{B} \approx 1500 \mu\text{mol L}^{-1}$). This chemical signature clearly shows that fluids seeping through the Hugin Fracture do not originate from the Utsira Formation but from the shallow overburden. (Bottom) Interpretation of the collected 3-D seismic data volume revealed several buried channels with indications of fractures in between. By combining subbottom profiler and 3-D seismic data, a complex network of fractures and channels could be identified and tied to the Hugin Fracture near the seafloor, going all the way down to sediment layers of Pliocene age. (HISAS and seismic images provided by R. Pedersen, University of Bergen; photo of bacterial mats provided by M. Haeckel, GEOMAR; porewater data provided by R. James, NOCS).

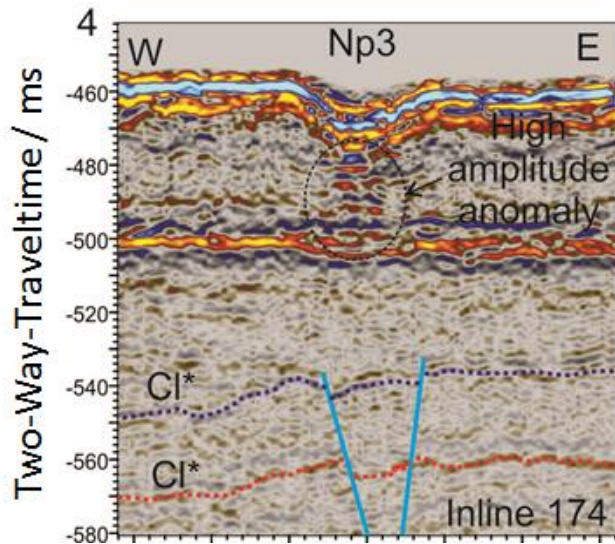


Figure 6. High-resolution P-Cable 3-D seismic images of a pockmark structure at Snøhvit, which is underlain by high-amplitude anomalies and deep-reaching vertical faults. Conventional 3-D seismic data cannot visualize these structures (Seismic images provided by S. Bünz, University of Tromsø.)

At storage sites in water depths greater than ca. 250 m, such as is the case at Snøhvit, leaking CO₂ will enter a zone in the shallow overburden, where temperatures become low enough (i.e. <10 °C) to form CO₂ hydrate. These ice-like solids can clog the sediment pore space, and seal the leakage structure. ECO₂ has quantified the effect of CO₂ hydrate formation on reducing sediment permeability in laboratory experiments, and has shown that hydrate formation can significantly reduce CO₂ leakage across the seabed. The likelihood that leakage may occur at Snøhvit is reduced by this self-sealing effect.

In summary, the studies of ECO₂ revealed a large number and rich variety of possible leakage pathways through the overburden including seismic chimneys and pipes, abandoned wells, a seabed fracture associated with subsurface channel structures, and pockmarks with deep roots. Release of natural gas was observed at the seabed fracture, at abandoned wells in the Sleipner area and at a number of natural seep sites in the B3 field in the Polish sector of the Baltic Sea. Leakage of CO₂ was not observed by ECO₂, neither at Sleipner or at Snøhvit.

2.2 Leakage rates and footprints

Leakage rates of gaseous methane measured by ECO₂ at abandoned wells in the central North Sea vary over a range of 1-19 t CH₄ yr⁻¹. The highest emissions (19 t CH₄ yr⁻¹) were measured at a site where the well was drilled through a seismic chimney (VIELSTÄDTE et al., accepted). Previous work showed that active methane seeps located above a seismic chimney in the Central North Sea (Tommeliten seep area) emit methane at a similar rate with a total gas flux of ca. 26 t per year (SCHNEIDER VON DEIMLING et al., 2011). Lander deployments at the Hugin Fracture suggest an annual leakage rate of only ca. 1 t of dissolved methane from this more than 3 km long seabed structure. It is likely that potential leakage rates from CO₂ storage sites in the North Sea fall in the same order of magnitude since CO₂ and CH₄ gas fluxes through the sedimentary overburden are controlled by the same set of physical sediment properties (grain size, porosity, absolute permeability, relative gas permeability, pore entry pressure, etc.). However, numerical models developed in ECO₂ suggest that leakage rates are also affected by the chemical properties of the ascending gases. They show that the high solubility of CO₂ retards gas ascent until the pore fluids residing in the high-permeability conduits are saturated with dissolved CO₂. Subsequently, CO₂ dissolution is limited by the very slow lateral diffusion of dissolved CO₂ from the small-scale vertical conduits into the surrounding sediments. Therefore, CO₂ and CH₄ leakage rates converge as soon as fluids in the high-permeability pathways for gas ascent are saturated even though the water solubility of these gases differs by several orders of magnitude. Considering the data on methane fluxes and the higher molecular

weight of CO₂ compared to CH₄, it can be tentatively concluded that CO₂ leakage rates at abandoned wells and seabed fractures could amount to ca. 1 – 50 t yr⁻¹ while seismic chimney and pipe structures may allow for leakage rates of ca. 50 – 500 t yr⁻¹. Leakage rates may be higher when the storage formation is strongly over-pressured by CO₂ injection.

In ECO₂ a sequential system of inter-connected models was employed simulating the migration of the injected CO₂ in the storage formation, its leakage through potential pathways in the overburden including induced geochemical reactions, and the resulting CO₂ emissions and dispersion in the overlying oceanic waters, including predictions of the expected impact on marine ecosystems and estimates of the exchange fluxes with the atmosphere. A worst case scenario was constructed for Sleipner assuming that the subsurface CO₂ plume reaches the large chimney structures and that these structures are permeable (>10 mD) over their entire cross section. Under these unrealistic assumptions, the DuMux model predicts leakage rates of up to 55 000 t yr⁻¹. These leakage rates approach methane emission rates during natural gas blowouts, such as at Well 22/4b in the UK sector of the North Sea (SOMMER et al., accepted). They exceed the data-based estimates of CO₂ leakage through seismic chimney structures by 2-3 orders of magnitude. Even under these extreme assumptions, the footprint of the resulting CO₂ leak is modest (Fig. 7).

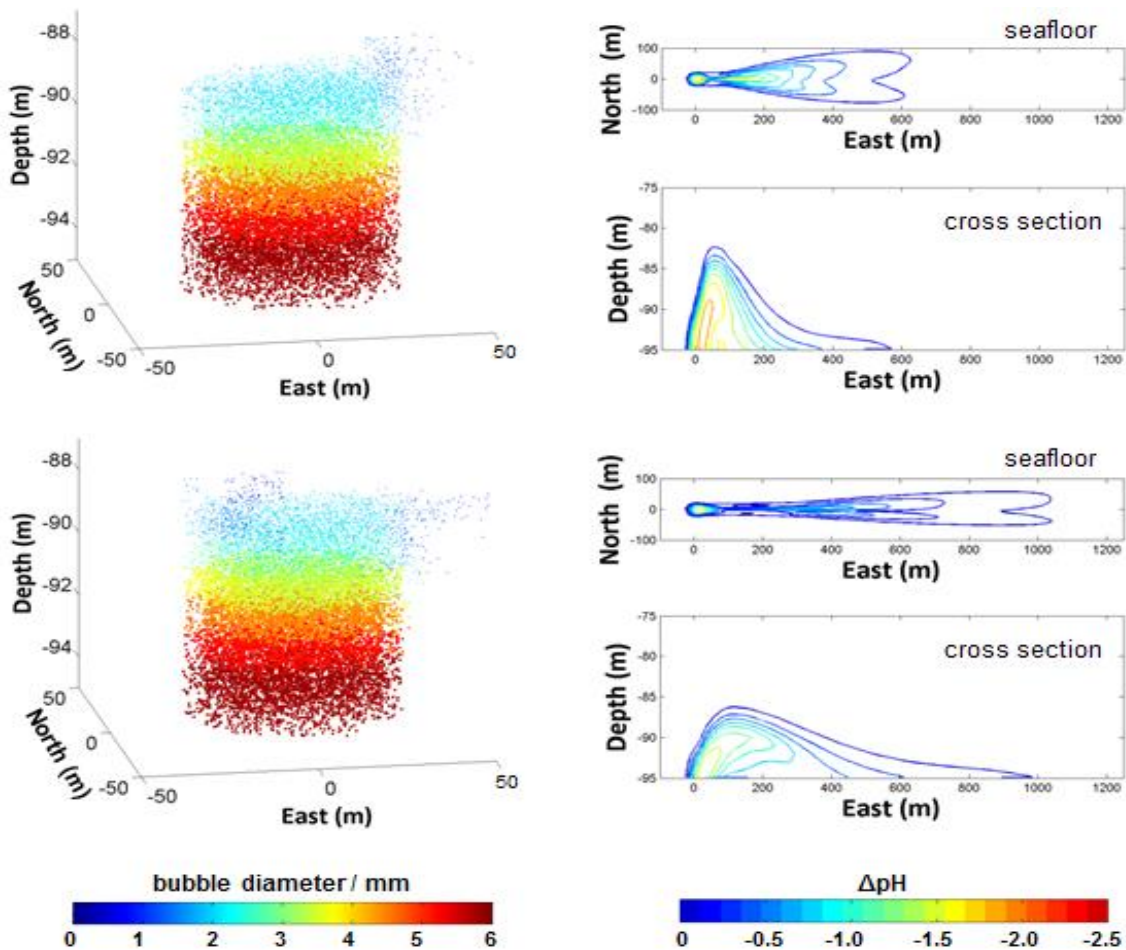


Figure 7. Simulated CO₂ gas bubble release and dissolution in the water column for the worst case scenario (left column; 55 000 t yr⁻¹ emitted over a circular area of 50 m in diameter in a water depth of 95 m) as well as resulting lateral and vertical footprints of pH changes (right column) for typical bottom current velocities in the North Sea (top rows: 10 cm/s; bottom rows: 20 cm/s). While the varying current directions, e.g. due to tides, keep the affected footprint small and the pH anomaly low, patches of higher CO₂ concentrations may occur further from the leak. (Simulation results provided by B. Chen and M. Dewar, Heriot-Watt University)

The ascending gas bubbles dissolve rapidly within a few meters above the seabed and acidify ambient bottom waters. However, the dissolved CO₂ is rapidly dispersed by fast bottom currents such that the acidification (pH drop) decays almost completely within a distance of less than 1 km from the leakage site. The emitted CO₂ does not reach the atmosphere locally at the leakage site. However, large-scale modelling of the entire North Sea system conducted by ECO₂ predicts that a significant CO₂ fraction will be mixed upward (especially during the winter and autumn seasons) and released into the atmosphere during its passage through the North Sea before it reaches the open North Atlantic.

The strong dilution and quick dispersion of the CO₂ and pH anomalies in the water column become even more evident in more realistic leakage scenarios, where 20 tons of CO₂ per year are released (Fig. 8). The detectable pH anomaly is limited to a narrow bottom water plume with a length of less than 50 m.

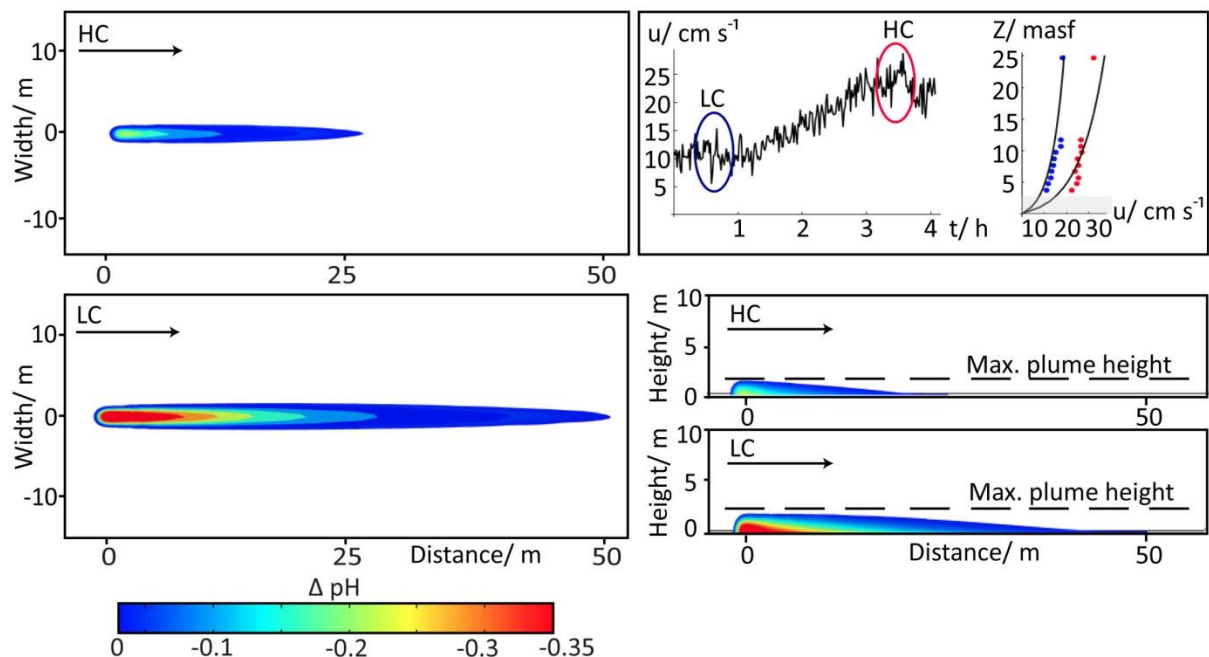


Figure 8. Simulation of CO₂ release (20 t yr⁻¹, equivalent to a leaky well) at typical low (LC, 10 cm/s) and high (HC, 25 cm/s) bottom current velocities, measured in the Sleipner area during a research cruise with RV Celtic Explorer in 2012 (top right panel: bottom current velocities over half a tidal cycle and vertical velocity profile for HC and LC conditions). Under high current velocities (HC, top left panel), mixing is much more efficient and the resulting pH anomaly and footprint impacted by reduced pH values (>0.1 pH units) is about 3 times smaller than at low velocities (LC, bottom left panel). The height of the affected water plume is also slightly smaller at high velocities compared to low velocities (HC versus LC, bottom right panel). (Simulation results provided by L. Vielstädte, GEOMAR)

To validate the small footprint predicted by numerical models, ECO₂ conducted a gas release experiment at 83 m water depth in the Sleipner area. CO₂ and Kr (used as inert tracer gas) were released on top of a benthic lander at varying gas flows (10 - 50 t yr⁻¹) and bubble sizes (d_b : 1-6 mm) (Fig. 9), both equivalent to those observed at CH₄ leaking abandoned wells in the Central North Sea. *In-situ* measurements of pCO₂ and pH in different vertical heights and distances downstream of the artificial leak confirmed the rapid dissolution of CO₂ bubbles within the first 2 m of bubble rise and the quick dispersion of the CO₂ anomaly in the water column, i.e. within ca. 30 m distance around the release spot (Fig. 9).

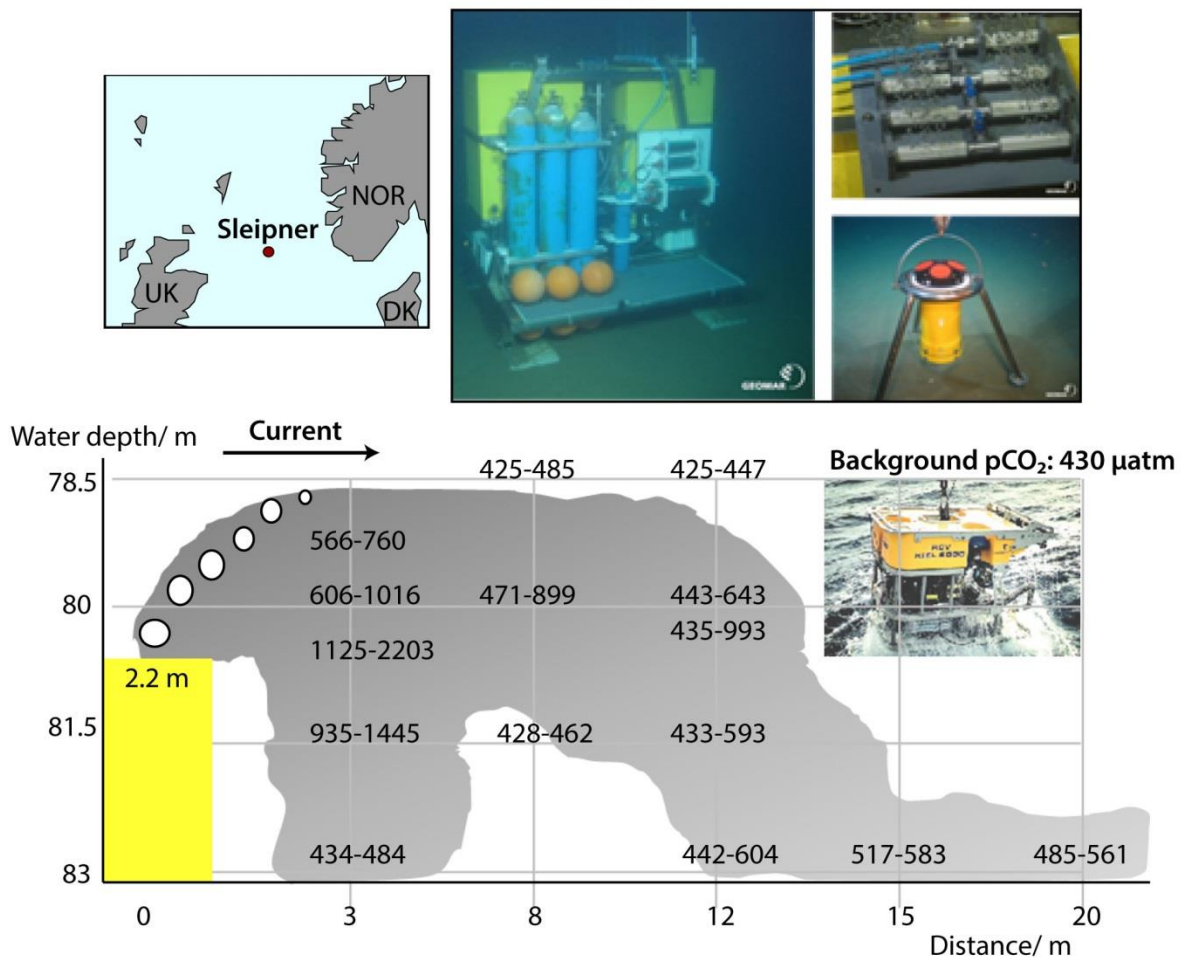


Figure 9. Images showing the experimental set-up of a small-scale CO₂ release experiment conducted at 83 m water depth in the Sleipner area. Illustrations in the top row show the lander performing the gas release at the seabed, the gas release unit with rising gas bubbles, and a current meter placed in the vicinity of the lander. The lower panel illustrates the resulting dispersion of elevated CO₂ water masses close to the seafloor and the lander marked as yellow rectangle. Values represent pCO₂ measurements at different heights and distances downstream of the artificial leak and are expressed in μatm. (Data provided by P. Linke, M. Schmidt, and L. Vielstädte, GEOMAR).

Additional studies were performed in the Panarea Island area of Sicily where large amounts of volcanic CO₂ are released at the seabed. More than 20 low-cost CO₂ sensors (GasPro probe system Uni Roma1) were installed close to the seabed to resolve the spatial and temporal dynamics of dissolved CO₂ dispersion in ambient bottom waters (GRAZIANI et al., 2014). These natural laboratory studies revealed extremely sharp gradients in dissolved CO₂ around seep sites. A few meters upstream from the seep, CO₂ concentration approach normal values while concentrations exceed the background by one order of magnitude a few meters downstream from the seep. Small scale eddies and tidal currents induce a strong temporal variability in CO₂ concentrations, while storm events showed efficient mixing and dilution of the entire water column. Sessile organisms living close to a CO₂ leak thus experience strong changes in ambient bottom water properties fluctuating from background to acidic within hours or even minutes. Thus, these organisms have to cope with an extreme pH and CO₂ variability rather than a constant exposure to low pH/high CO₂ conditions.

Early precursor signs of potential CO₂ leakage at the seabed are the release of formation waters filling the sub-surface plumbing system which are pushed towards the surface by rising, buoyant CO₂. Formation water leakage can indicate that CO₂ may soon leak from the storage formation but

formation water itself may pose a risk for marine biota if the fluids contain toxic substances. Work done in ECO₂ has shown that concentrations of major elements (Na, Mg, K, Ca and Cl) in Sleipner formation fluids are close to normal seawater, although they have much lower levels of dissolved oxygen and higher levels of some metals (including iron). By contrast, formation fluids from Snøhvit are 5 times more salty than normal seawater; like the Sleipner formation fluids, they also have low levels of dissolved oxygen and relatively high concentrations of some metals. As salinity can be easily and precisely measured, and it is not affected by reactions between fluids and sediments, salinity would be an effective tracer of leakage of formation fluids from the Snøhvit CO₂ storage reservoir. The best tracer of formation fluids from the Sleipner CO₂ storage reservoir is lithium (Fig. 5). Concentrations of most elements in the formation fluids at Sleipner and Snøhvit are lower than current environmental quality guidelines designed to protect sensitive marine areas, with the exception of boron (in Sleipner fluids) and iron (in Snøhvit fluids). Thus, the toxicity of these fluids is relatively low, but we recommend that geological formations that contain high levels of toxic chemicals are not used for CO₂ storage.

The high salinity of formation fluids residing in the Snøhvit storage formation may be problematic since work done by ECO₂ shows that benthic organisms would be adversely affected by exposure to these brines (section 2.3). However, formation fluids expelled at the seabed may be rapidly dispersed by bottom waters. This was observed at the Hugin Fracture where formation waters seeping from this structure at an overall rate of ca. 10³ m³ per year are rapidly dispersed and diluted since North Sea bottom waters flow over this structure at a rate of ca. 10¹² m³ yr⁻¹ exceeding the rate of formation water flow by nine orders of magnitude. Observations at natural brine seeps in the Gulf of Mexico, Red Sea and Mediterranean confirm this conclusion and show that ascending brines are only conserved if they discharge into seabed depressions or accumulate within surface sediments where they are protected against dispersion and dilution (WALLMANN et al., 1997). Collectively these observations suggest that sessile organisms settling in pockmarks that are ubiquitous at Snøhvit (Fig. 6) would be killed if these seabed depressions are filled by high-density brine ascending from the storage formation. However, detailed studies at Snøhvit clearly showed that these fluids are not emitted into pockmarks but retained in the storage formation. Nevertheless, we recommend that these structures should be monitored at a regular basis to detect a possible inception of brine release.

2.3 Response of marine biota to leakage

If leakage were to occur from sub-seabed storage sites, then flora and fauna living within, on or near to the seafloor would be exposed to unnaturally high levels of CO₂ and low levels of pH and carbonate ions. 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 (PÖRTNER, 2008). In some species this extracellular acidosis is fully compensated by active bicarbonate 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 (WIDDICOMBE and SPICER, 2008). In these instances the uncompensated acidosis can lead to more or less severe metabolic depression in the affected organism in turn having a negative impact on that individual’s contribution to the ecosystem.

Species with calcified external structures are at risk of dissolution in response to seawater acidification. Seawater acidification increases the concentration of H⁺ ions in solution, a process which reduces the pH of the external environment. Through a process of bicarbonate buffering these H⁺ ions combine with carbonate ions in solution to form bicarbonate (HCO₃⁻ ions). This reaction limits the concentration of H⁺ ions in solution and so buffers the reduction in system pH. Sediment pore water buffering may limit the magnitude of impacts to benthic infauna. However, in non-carbonate

sediments and for continuous CO₂ releases the buffering capacity of sediments is rapidly exceeded. In these situations biogenic carbonate structures (bivalve shells and urchin tests) will undergo dissolution to liberate aqueous carbonate ions as confirmed by experimental work conducted within ECO₂ (Fig. 10). The dissolution of biogenic calcified structures has been widely reported with effects generally more pronounced in juvenile and larval stages. However, these impacts are not universal, and notable exceptions (normal calcification, hypercalcification) have been reported, especially in situations in which the exposed shellfish are not resource limited (THOMSEN et al., 2013). Ultimately, the variability in response of closely related species and individuals precludes the formation of general predictions of likely *in situ* impact. As such, it is currently necessary to adopt a precautionary approach to predicting the direction and magnitude of calcification responses to limited CO₂ release.

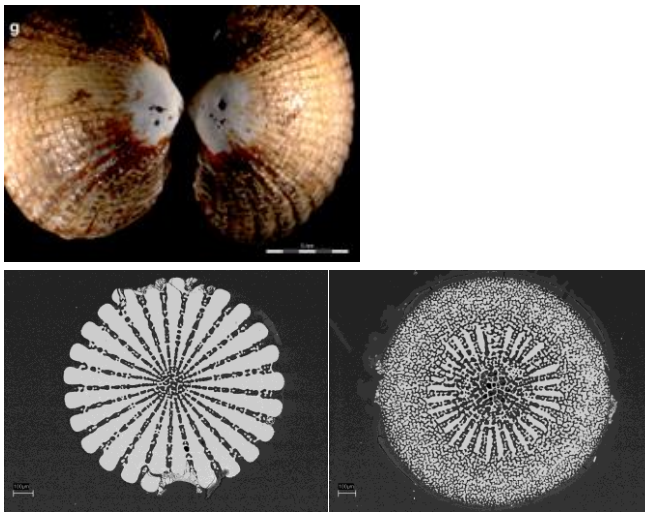


Figure 10. Examples of calcite dissolution in response to chronic exposure to elevated pCO₂ in the cockle *Cerastoderma edule* (top panel: pCO₂ of 24,400 μatm) and in spines of the sea urchin *Paracentrotus lividus* (bottom panel: comparing cross sections of spines from urchins held for 66 days at pH 8.1 (left) with those held at pH 7.3 (right)). (Cockle image provided by F. Melzner, GEOMAR; urchin images provided by E. Morgan, University of Southampton)

In extreme cases of CO₂ leakage, severe acidification will result in most non-mobile benthic organisms being killed. However, this will not be the case for every leak scenario as many marine species, even some heavily calcified taxa, can tolerate shorter periods of more moderate acidification. This is because that, unlike other potentially toxic substances, CO₂ is a naturally occurring and fluctuating compound in the marine environment. As a result of millions of years of exposure, marine creatures have incorporated this CO₂, along with other elements of carbonate chemistry, into many of their routine physiological processes. 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 CO₂. This response, known as physiological plasticity, affords some protection to organisms from rapid changes in their environment and can provide temporary protection against moderate acidification. It may help organisms to survive around CO₂ leaks in the North Sea and other regions where velocity and direction of bottom currents defining the CO₂ exposure change periodically due to tidal forcing (section 2.2).

Plasticity, however, does not offer permanent protection for any organism against CCS leakage. This is because an organism's ability to express plastic responses is to a large extent governed by the energy it has available (THOMSEN et al., 2013). 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, locomotion or development of reproductive tissues. 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 CO₂ environment would inevitably lead to reduced growth, lower reproductive output and,

eventually, death. The environmental consequences of CO₂ 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 it could ultimately cause some species to locally die out and change the structure and the function of the community living directly on the leak where biota are continuously exposed to high CO₂ levels.

As the previous findings have illustrated, in any marine community there will be some species which are physiologically better equipped to cope with elevated levels of CO₂ than others, so the potential for leakage to cause species extinctions and biodiversity loss exists. So after exposure to extreme seawater acidification, we could predict that the resulting communities would be made up of species from a limited number of tolerant taxonomic groups. These more tolerant species may even increase in abundance due to a reduction in ecological pressures such as competition for food and predation. These alterations in community structure will certainly reduce both taxonomic richness and species diversity and could also lead to a reduction in some of the key ecosystem processes (e.g. bioturbation, mineralization) and functions performed by seabed ecosystems (e.g. nutrient cycling, production, remediation of waste). Laboratory-based experiments including one conducted within the ECO₂ project, have shown that exposure to low-pH / high-CO₂ seawater does cause significant changes to community structure, loss of biodiversity and reduced ecosystem function (e.g. bioturbation and community biomass) in benthic macrofauna and meiofauna (Fig. 11).

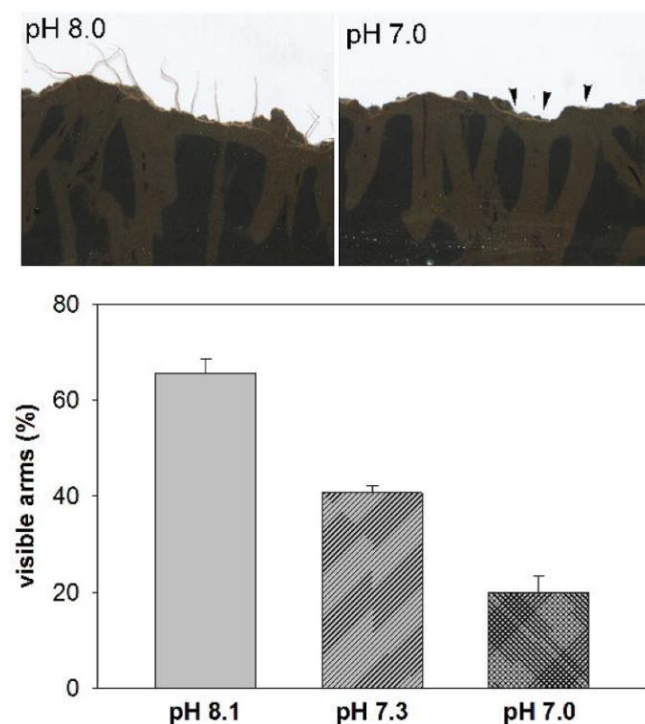


Figure 11. Decrease in the activity of the burrowing brittle star in response to decreased pH (from an increase in pCO₂). As the pH is lowered from 8.1 to 7.0 there is a significant decrease in the percentage of visible arms above the sediment. Such changes will influence sediment bioturbation, an important ecosystem function that can affect the production and nutrient cycling of seabed communities (Hu et al., 2014).

These experimental results are supported by observations made by ECO₂ in the Panarea Island area where large volumes of natural volcanic CO₂ have been released at the seabed over hundreds of years. Both macrofaunal and meiofaunal abundance was lower and community structure different in areas where CO₂ was actively seeping out of the seabed, when compared with control areas where no CO₂ seepage was observed. Interestingly, there were no differences in the number of macrofauna species found at the seep sites and the number found at the control sites. However, the macrofauna community composition at CO₂ seep sites differed markedly from the control sites based on the occurrence of more oligochaetes and amphipods, and less polychaetes and gastropods at the seep sites. This illustrates again the potential for more CO₂-tolerant taxa to capitalise on the loss of more CO₂-sensitive competitors or predators and persist in areas of active CO₂ leakage (Fig. 12).

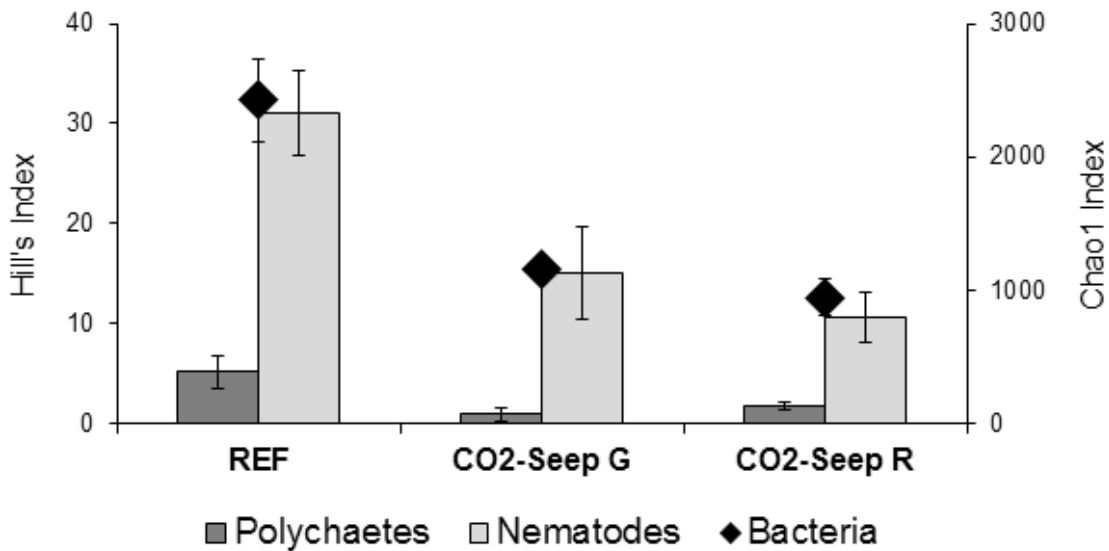


Figure 12. Change in the diversity of species with proximity to a natural CO₂ seep offshore Panarea Island, Italy. At seep sites (CO₂-Seep G and R) measures of species richness decrease for all faunal groups: Hill's index for macro-fauna (i.e. Polychaetes) and meiofauna (i.e. Nematodes) and the Chao1 index for bacteria. (Graph provided by M. Molari, Max-Planck-Institute for Marine Microbiology)

Injection of CO₂ into sub-seabed aquifers may lead to the displacement of brines low in oxygen and highly enriched in ions, which, upon reaching the seabed, could come to represent a strong change in environmental conditions. For instance, based on seismic data, the North Sea Petroleum Millennium Atlas (REFMA 2003) indicates that the majority of aquifers in the North Sea may be filled by high-salinity fluids, in some cases in excess of 300 psu, a value similar to that of the Dead Sea (~340 psu). Allowed to percolate to the surface of the seabed, such brines could cause a ten-fold increase in local salinity in surface sediments and seabed depressions, thus representing a potentially severe source of osmotic shock to benthic organisms. Results from the ECO₂ formation water experiment confirmed the expectation that this salt-rich and oxygen-depleted fluids would severely impair benthic marine fauna even though the level of hypoxia (50 μM O₂) and the increase in total salinity simulated in these experiments (48 psu) is milder than the conditions often observed in formation fluids. Marked changes were observed in most of the measured responses, for which data have been processed (Fig. 13).

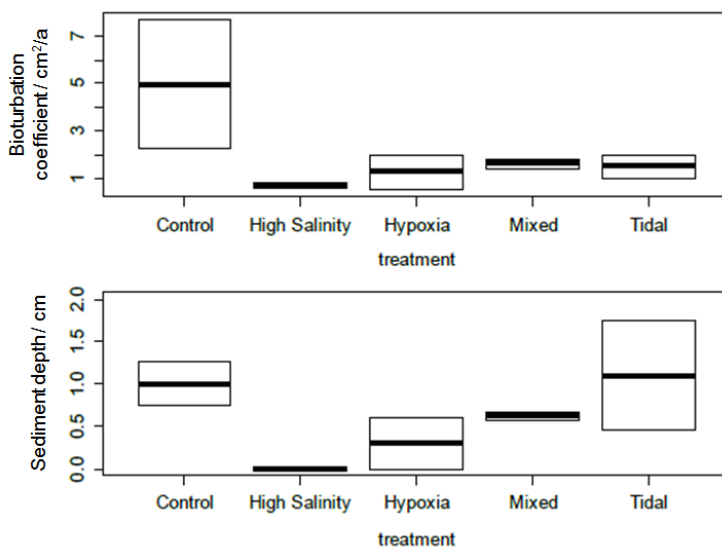


Figure 13. Impact on sediment bioturbation by benthic fauna, measured in terms of bioturbation activity (top panel) and bioturbated sediment depth (bottom panel), when exposed to high salinity, hypoxia, and a combination of both stressors (mixed). Also shown is the moderating effect from strong tidal currents (Image provided by A.M. Queirós, Plymouth Marine Laboratory).

Faunal abundances and community structure, behaviour and processes had changed markedly after two weeks of exposure, as had nutrient fluxes near the seabed, and within sediments. In some cases, sediment geochemistry was entirely altered. This was particularly apparent in nitrogen cycling, a function which in marine ecosystems supports primary productivity, and hence the base of non-chemosynthetic marine food-webs. Comparatively, for many of these responses, these results far exceeded the impact of the two week and twenty week exposure to even the most severe CO₂ treatments observed in the project. These findings suggest that the release of formation water should not be overlooked in environmental risk assessments.

A potential indicator that could be observed during the monitoring of storage sites is the unusual appearance of large numbers of animals on the sediment surface. Recent experiments have shown that exposure to high levels of CO₂ can elicit a surfacing response in echinoderms and in molluscs whereby animals which normally burrow deep within the sediment (known as infauna) come up onto the sediment surface. This was also observed during the ECO₂ high CO₂ experiments on natural communities at 20 but not 2 weeks of exposure (Fig. 14).

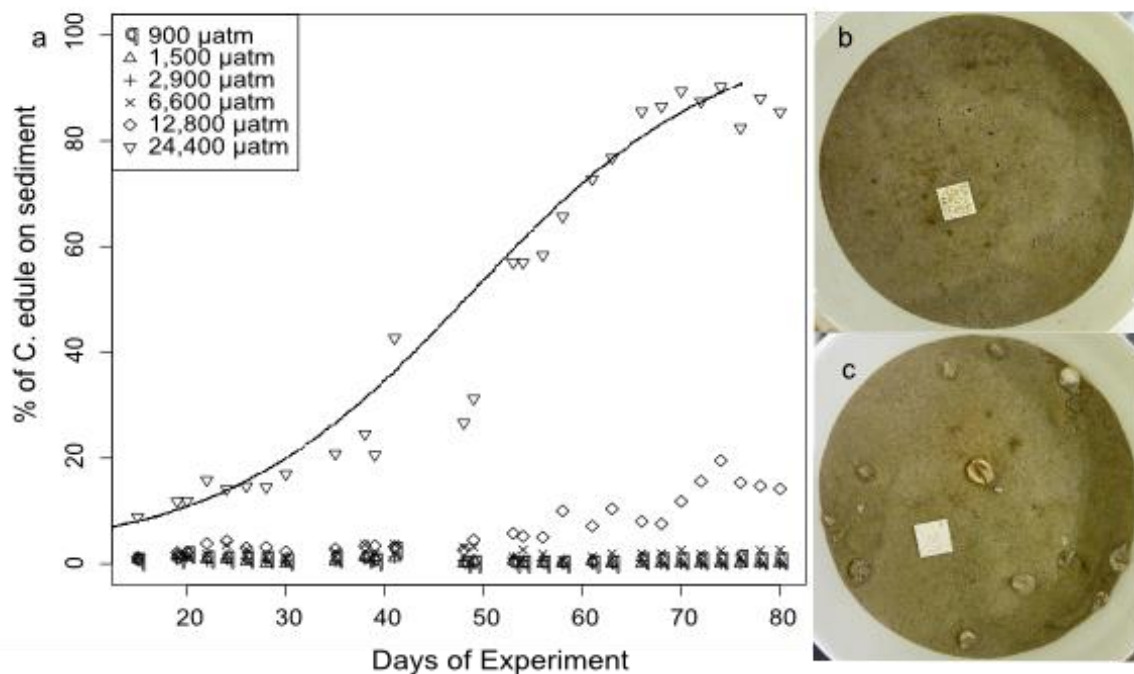


Figure 14. Behavior of the common cockle *Cerastoderma edule* in response to elevated pCO₂. (a) Average abundance (as a percentage of the total) of non-buried cockles in six different treatments over the 80-days experiment. At a concentration of 24,400 µatm over 80% of the cockles were found on the surface of the sediment after 80 days of exposure. (b) Image of the control experimental unit: sediment surface with cockle siphons opened and visible, but no cockles on the sediment surface. (c) At 24,400 µatm cockles have accumulated on the sediment surface at the end of the experiment (data and images provided by F. Melzner, GEOMAR).

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 classic stress-response and not necessary limited to high CO₂ levels, it may still be a useful early indicator that something is having a negative impact on the benthic fauna. 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. However, if the surfacing organisms have shells or calcified skeletons these may

remain on the sediment surface and help to locate sites where dissolved CO₂ is leaking from the formation.

The presence of microbial mats can indicate the seabed leakage of formation fluids (section 2.1). These mats were observed by ECO₂ only where methane-charged formation fluids and methane gas bubbles were emitted into the North Sea. They proved to be reliable indicators for formation water and natural gas seepage in the North Sea (Fig. 15).

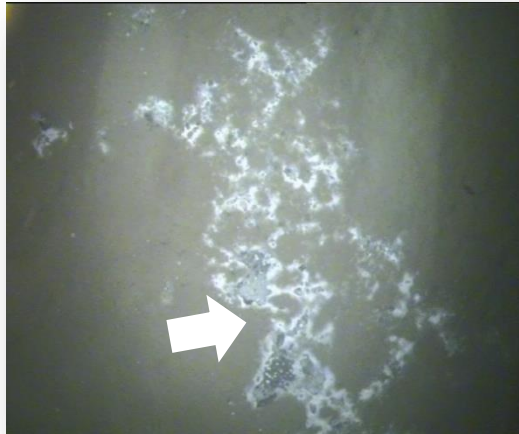


Figure 15. White bacterial mats (arrow) at the seabed in the vicinity of an abandoned well in the North Sea. Images recorded using UK HYBIS ROV deployed from UK NERC RRS James Cook in 2012 (image provided by C. Hutton, University of Southampton).

CO₂ leakage may have a significant impact on benthic biodiversity, community structure and ecosystem functioning. However, whilst generic understanding is rapidly improving, experimental and observational evidence from specific habitats and situations is still largely lacking making it extremely difficult to predict the precise nature or scale of impact that would be seen for any given leakage scenario at a specific storage site. This evidence will need to be collected to underpin effective risk assessment activities and to guide appropriate monitoring strategies. Nevertheless, ECO₂ tried to define as good as possible how North Sea fauna might respond to CO₂ leakage (Fig. 16) employing a marine ecosystem model (GOTM-ERSEM, Plymouth Marine Laboratory).

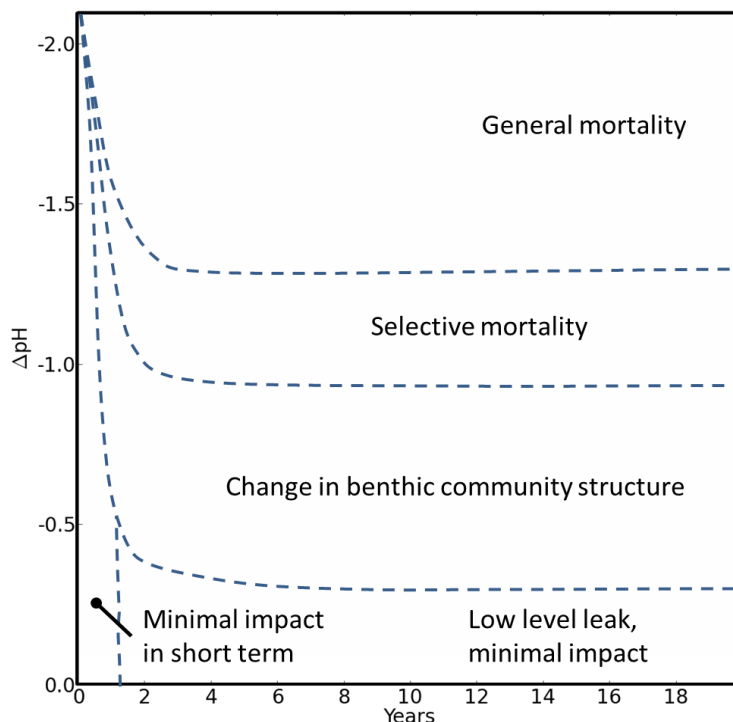


Figure 16. Summary of impact categories across simulated pH changes for the first 20 years of a leakage event. Whilst the form of the diagram is likely to be robust, the precise positioning of each category with respect to pH is not definitive and in any case would vary for different ecosystems with different resource bases and faunal components. (Simulation results provided by J. Blackford, Plymouth Marine Laboratory)

In simulations where the change of pH was less than ca. 0.5 units only minimal impact was seen. For moderate decreases of pH, where an impact was apparent the tolerant groups showed an increase in biomass, whilst the sensitive groups showed a decrease in biomass. At thresholds of change exceeding 1.0 pH units the long term impact was a decrease in biomass for all functional groups such that after 1 to 3 growing seasons the biomass loss for the macrofauna was near complete. In these circumstances meiobenthos benefited from the absence of competition and predation and become the dominant faunal class, until mortality kicked in at very large decreases of pH (Fig. 16).

The seafloor areas in the central North Sea where bottom water pH values are lowered by >0.5 units are <10 m² for realistic leakage rates (Fig. 8) and <1 km² for a worst case scenario (Fig. 7). These estimates consider that the direction of bottom currents in the North Sea is controlled by tidal forces and changes by up to 360° over one tidal cycle. Hence, organisms settling in the affected areas are not permanently exposed to low pH bottom waters but periodically when bottom currents turn such that they are located downstream from the leakage site. Their physiological plasticity may allow many benthic organisms to cope with this type of exposure even when the episodic pH decline exceeds 0.5 units. In conclusion, environmental consequences associated with sub-seabed CO₂ storage are probably small while the multiplicity of potential leakage pathways identified by ECO₂ (section 2.1) suggests that leakage is possible. The environmental risks of sub-seabed CO₂ storage, defined as product of consequences and likelihood (propensity) of leakage, may thus be expected to be small even when a large number of storage sites is installed and operated in the European Offshore.

2.4 Environmental risk assessment

Under guidance of DNV GL, the ECO₂ consortium developed a best practice approach to environmental risk assessment for offshore CO₂ storage sites (<http://oceanrep.geomar.de/28739/>). The methodology was subsequently applied to the Sleipner CO₂ storage site, in order to assess the environmental consequences of a potential leakage scenario and the propensity that leakage will occur. This case study also illustrates the stages involved in the approach and the type of input data required to assess the environmental risk as product of consequences and propensity to leak. The complete study can be found as deliverable D5.1 at <http://oceanrep.geomar.de/29081/>.

As first key step in the overall approach, an already established approach is applied, first initiated at a high end level, by the Convention on Biological Diversity (CBD). This is known as the EBSA (Ecologically or Biologically Significant Marine Areas) approach. It aims to describe marine resources within a defined area and to assess a site-specific environmental value for each highlighted resource in the area. A set of six criteria to identify ecologically or biologically important areas in the sea (see CBD COP 9 Decision IX/20) is used as the basis for the environmental value assessments. These criteria are: i) uniqueness or rarity, ii) special importance for life-history stages of species, iii) importance for threatened, endangered or declining species and/or habitats, iv) biological productivity, v) biological diversity, vi) vulnerability, fragility, sensitivity, or slow recovery. The different criteria for generating the environmental values can be up-weighted if they are considered more important than other criteria. If weighting is carried out, a description of the rationale behind it should be described.

The data sources used to assess these criteria for Sleipner include OSPAR, Norwegian Red list for Species, Havmiljø.no, Mareano program (Mareano.no) and MOD database (Environmental Monitoring database). The wealth of data on the benthos in the Sleipner area, gathered as part of the Norwegian compulsory monitoring program which has been carried out since 1997, enabled a comprehensive analysis of the benthic community in the area.

Applying the EBSA approach, nine components/ species deserving special attention were identified. These include the benthic species i) *Apherusa bispinosa*, ii) *Eteone suecica*, iii) *Tellimya tenella*, iv) *Thyasira dunbari*, all listed in the Norwegian Red List for Species under Data Deficiency (DD), v)

Arctica islandica defined by OSPAR as a species under threat and/or in decline within the Greater North Sea (OSPAR 2009), vi) sand eel areas (spawning and foraging area), vii) spawning ground for North Sea cod, viii) mackerel spawning area, ix) North Sea herring larvae and juvenile area.

The next step in the overall approach is to identify the presence of potential leak features that can connect the CO₂ stored in the target formation with the seabed as well as understanding the behaviour of the carbon dioxide plume at the seabed (in leakage scenarios) in terms of pH change. This work was conducted considering the field work and modelling results for Sleipner obtained by ECO₂ (sections 2.1 and 2.2). A total of 16 leak features/chimneys of interest were identified at Sleipner. Each leak feature/chimney was overlaid with a generic modelled 'worst case scenario' plume of carbon dioxide, expressed as a plume of pH change. The leak features are assumed to leak perpetually. A worst case scenario is also assessed, in that the consequence of all leak features leaking at the same time is presented. This allows an understanding of the scale of the consequence, in the context of the wider geographic area.

Overlay analysis between the plumes and the identified valuable resources at Sleipner revealed that 2 of the valuable species are found within the potential leak area, and could be affected by the pH change; the bivalves *Tellimya tenella* and *Arctica islandica*. Based on value criteria, *T. tenella* is considered as 'medium' environmental value, and *A. islandica* as 'low' environmental value. Based on the seabed area impacted in relation to the extent and density of the population in the wider area, the two species could be affected at the individual level, but not at the population level, therefore the extent of influence of the CO₂ plume is small or incidental for both species.

Consequences are defined as product of environmental value of the considered resource and the degree of impact. The consequence matrix shown below summarizes the results and serves as input for the risk assessment.

Degree \ Value		Environmental value		
		Low	Medium	High
Degree of impact	Small	<i>Arctica islandica</i>	<i>Tellimya tenella</i>	
	Moderate			
	Large			

For the other identified valuable resources there is no overlap; indicating that these resources and areas will not be directly affected by a potential leak, when considering pH change.

Estimating leakage frequencies for geological storage sites is not currently feasible given the very small data set of actual storage site performance. However, even when the accumulated body of storage site operations becomes significant, it is not clear that it will be directly transformable to leakage statistics in the way that has been done with leakage from valves, pipes, process vessels, etc., which are represented by millions of data points for highly repeatable components and systems. This will never be the case for geological storage sites. Every geological storage site will likely have its own unique set of characteristics that are important for storage performance. Instead of referring to leakage probability, the ECO₂ project has chosen to frame the risk component as propensity to leak (PTL). The distinction is subtle but important and is intended to remind users that the data and methods behind leakage assessment are much more heuristic in nature than other risk analysis processes which leverage large databases of factual system performance, e.g. offshore drilling rigs. The formalism applied to apply the heuristic framing of Propensity to Leak is the mathematics of

Bayesian inference as implemented by modern, graphical-user-interface Bayesian Belief Net (or simply Bayesian Net, BN) software originally developed to more effectively process evidence of various degrees of ambiguity collected for health and disease diagnostics. A prototype BN PTL model was produced for this case study. The uncertainties associated with the estimates of propensity to leak (PTL) are dominated by geological uncertainties in the overburden and to a lesser extent the uncertainties in the target storage reservoir itself. To make a material decrease in these uncertainties implies significant and disproportionately increasing costs in data collection at the storage site. Therefore, the PTL scale is simplified in our case study to three discrete outcomes. In situations where data is more complete and uncertainties smaller, more probability and consequence discrete levels may be applied than the matrix shown here. However, a simple two-dimensional matrix model is considered as best practice to assess environmental risks related to leakage to the seabed from offshore CO₂ geological storage sites.

One specific subsurface feature was included in the case study PTL analysis. This feature is sourced from seismic survey data and commonly referred to as chimney 77. The BN PTL model main output for PTL from this feature are summarized in the table below.

Chimney 77	Bayesian Net estimate of propensity to leak to seabed
Very Unlikely	60.1%
Possible	38.5%
Very Likely	1.5%

Aggregating these values to a single propensity number gives 22%, which is in the ‘Possible’ category. The final output risk matrix for the chimney 77 feature is shown below. The horizontal axis is output from the consequence assessment, while the vertical axis is output from PTL assessment. This is done in general for each discrete leakage pathway and leakage scenario identified for the storage site and based on the associated features, events and processes characterized for the site. The aggregate results will be a collection of risks labelled by a number or letter placed in the matrix below. This will enable effective prioritization of monitoring of specific storage site locations and potentially adjusting the injection programme to avoid the stored CO₂ from contacting high-risk features in the subsurface which may lead to leakage to the seabed. The overall risk is assessed to the lowest category; Negligible/small negative for both *Arctica islandica* and *Tellimya tenella*, and summarized in the risk matrix below.

Severity measured in Environmental Value Propensity to Leak	Severity of environmental impact			
	Incidental	Moderate	Major	Critical
Unlikely				
Possible	<i>Arctica_islandica</i> _{Chim77} <i>Tellimya_tenella</i> _{Chim77}			
Very Likely				

The Sleipner case study is this first of its kind and indicates that the overall strategy and the key steps of the environmental risk assessment developed in ECO₂ are useful and applicable to other sub-seabed storage sites (Fig. 17).

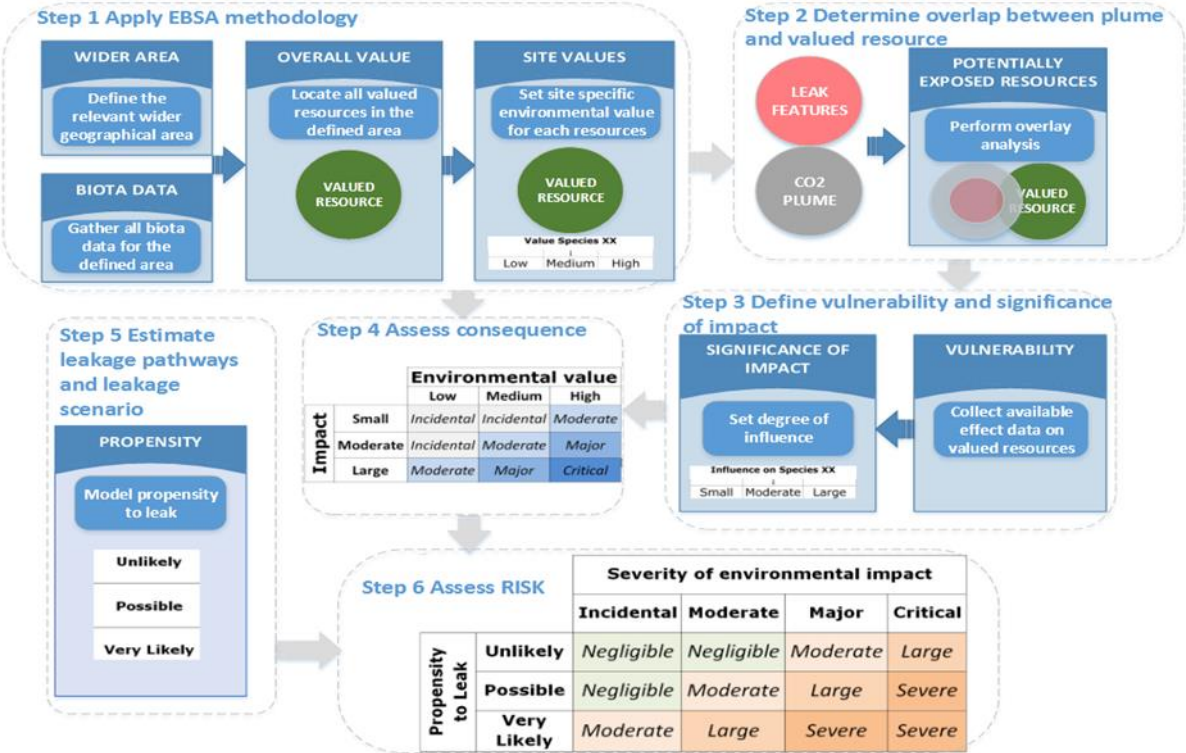


Figure 17. Key steps of the environmental risk assessment for sub-seabed CO₂ storage sites developed in ECO₂.

2.5 Monitoring and baseline studies

CO₂ leakage can occur only if fractures, seismic pipes and chimneys, or abandoned wells cutting through seals and overburden have higher permeability than the background sealing formations. While upward migration of CO₂ via large-scale vertical structures can be imaged by seismic data, leakage through wells and other narrow structures is not detectable by geophysical surveys. Additional measurements need to be conducted at the seabed to detect CO₂ release through these small-scale features. Early precursor signs of potential CO₂ leakage at the seabed are the release of formation waters and natural gas filling the sub-surface plumbing system which are pushed towards the surface by rising, buoyant CO₂. Depending on water depth and bottom water temperature, CO₂ will be subsequently emitted either as gas bubble or as liquid droplet. CO₂ also dissolves during its passage through water-filled high-permeability conduits and may be emitted in dissolved form together with expelled formation fluids. Monitoring at the seabed should thus be able to detect seeping formation water, natural gas, dissolved CO₂, CO₂ gas bubbles and, at water depth larger than ca. 300 m, liquid CO₂ droplets. Special care has to be taken to monitor active and dormant natural seepage sites identified during site selection and baseline surveys since fluids and gases migrating through the overburden will tend to use their roots as conduits and leave the seabed through these already existing outlets.

Monitoring activities can be separated in surveys covering the entire storage complex and targeted studies focused on seeps, abandoned wells, and other specific sites at the seabed. The following **surveys** should be conducted repeatedly over the life time of a storage site:

- **3-D seismic** surveys to detect/exclude CO₂ ascent via large-scale features cutting through seals and overburden (fractures, seismic chimneys). Operators will conduct and repeat 3-D seismic surveys to image the spread of CO₂ in the storage formation. It is, however, important to record and evaluate data not only from the storage reservoir but also from the overlying sequences (Fig. 2, Fig. 6) to detect/exclude changes in seismic signatures indicating upward migration of CO₂, natural gas, and formation fluids through seals and overburden.
- **Bathymetry/backscatter** surveys to identify and locate formation water seeps at the seabed. Formation water seepage creates seabed structures with distinct morphologies and specific acoustic backscatter properties. A good example is the Hugin Fracture which was discovered in the Central North Sea applying high-resolution backscatter imaging (Fig. 5).
- **Hydro-acoustic** surveys of shallow subsurface and water column to detect and locate subsurface shallow gas accumulations and gas bubble seeps at the seabed. These surveys serve to detect any signs of invigorated gas seepage activity. Sub-bottom profiler and multi-beam echo-sounder systems providing suitable spatial coverage and resolution are commercially available. They can visualize shallow gas accumulations and gas bubbles ascending through the water column (Fig. 18).
- **Video/photo** surveys to observe biological indicators for formation water and gas seepage. Mats of sulphide-oxidizing bacteria are often found at seep sites where methane-bearing formation waters and gas bubbles emanate from the seabed. These bacterial mats are easily identified on videos and still photos and are useful indicators for seepage (Fig. 15). CO₂ leaking from the storage formation affects animals living in the sediment (benthic infauna). They try to escape from the sediment and accumulate at the seabed. Conspicuous clusters of infauna and their remains at the seabed may thus indicate CO₂ leakage (Fig. 14).
- **Chemical** surveys to measure CO₂ concentrations and related parameters in bottom waters above the storage complex. Dissolved CO₂ can be detected in-situ with suitable chemical sensors and in water samples retrieved from the seabed. CO₂ leakage affects the chemical composition of seawater and creates strong chemical anomalies in bottom waters located just a few meters above the seabed (Fig. 7, Fig. 8, Fig. 19). Additional chemical substances such as dissolved oxygen and nutrients should be included in the monitoring program to better discriminate between natural background CO₂ and CO₂ leaking from the storage formation. The release of reducing formation fluids can be detected by sensors measuring the redox potential (Eh) of ambient bottom waters (Fig. 20).

Surveys can be conducted using autonomous underwater vehicles (AUVs) and/or monitoring vessels. Commercially available AUVs can be equipped with suitable instruments (echo sounders, hydrophones, chemical sensors, still camera, etc.) to conduct multiple surveys with full areal coverage at affordable costs. Each of the surveys should, however, be conducted at a specific height above the seabed to achieve optimal results.

Additional targeted studies have to be conducted if active formation water seeps, gas seeps, and pockmarks with deep roots reaching into the storage formation occur at the seabed. These sites have to be revisited on a regular basis to determine emission rates of gases and fluids and exclude that seepage is invigorated and pockmarks are re-activated by the storage operation. If new seeps develop during the operational phase, they have to be investigated and sampled in detail to determine the origin and chemical composition of the seeping fluids and gases and their emission rates. These studies have to be conducted with remotely operated vehicles (ROVs) deployed from suitable monitoring vessels. Samples have to be taken for chemical analysis and instruments have to be deployed at the seabed to measure fluxes and emission rates (Fig. 21).

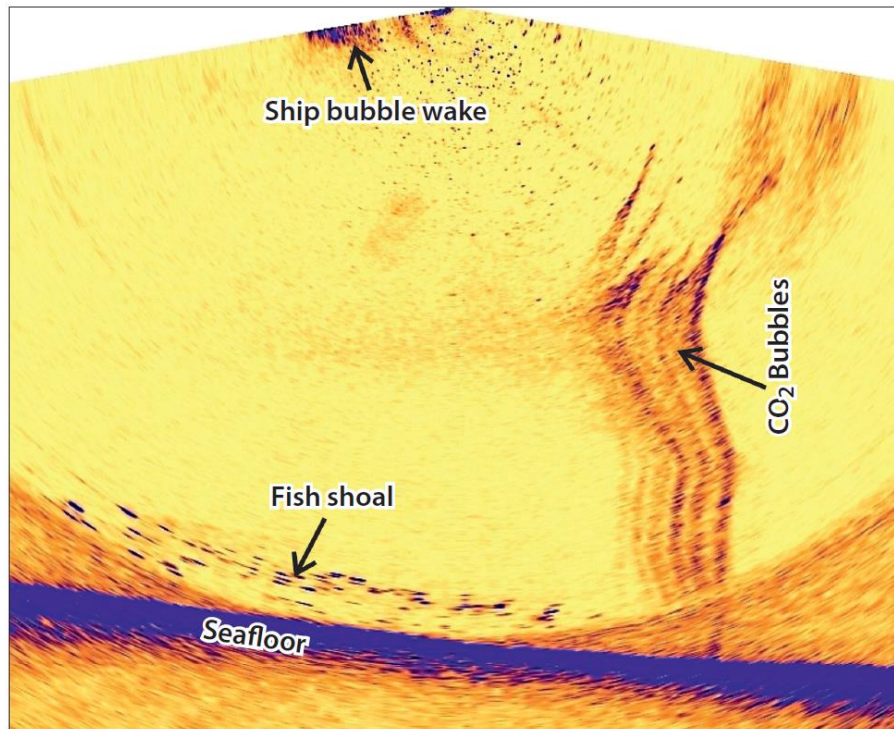


Figure 18. Hydro-acoustic image of CO₂ bubble streams emanating from the seabed at the natural seep site Panarea located in the Mediterranean Sea near Sicily. Data was recorded at 200 kHz using an R2Sonic 2024 installed on RV Urania in 2011 (SCHNEIDER VON DEIMLING and WEINREBE, 2014)

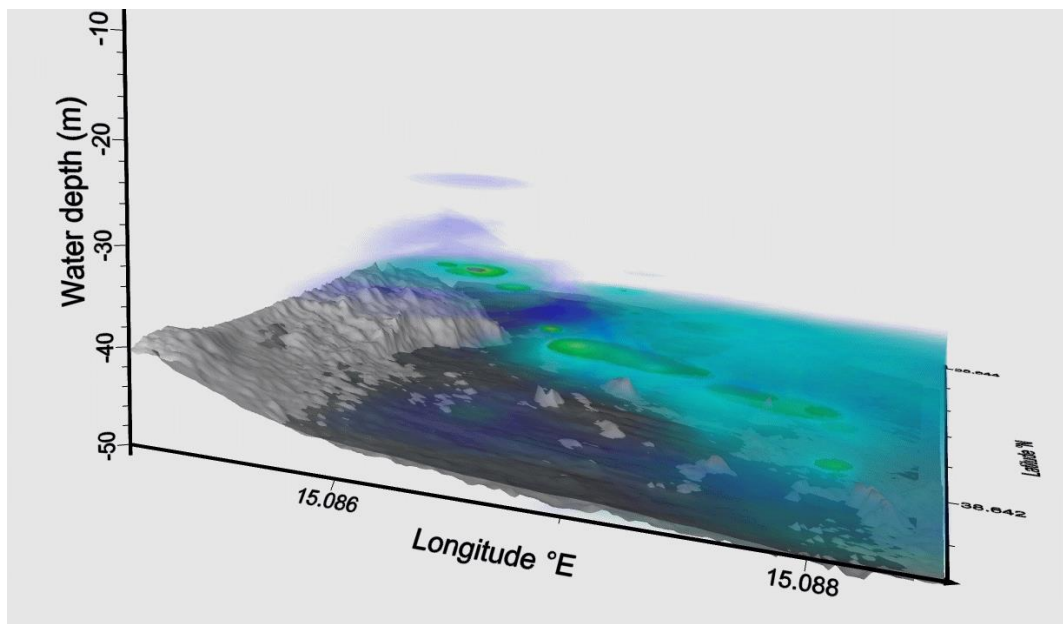


Figure 19. CO₂ plume above the seabed at Panarea (size: 300 x 400 m). Greenish colours indicate dissolved pCO₂ values in the range of 500 – 650 μ atm clearly exceeding the local background value of ca. 390 μ atm (blue colour), resulting in pH values of 0.1-0.35 units below the ambient pH of 8.15. The data were recorded with a chemical sensor (HydroC, CONTROS) which was towed above the seabed with RV Poseidon in May 2014 (SCHMIDT et al., 2015).

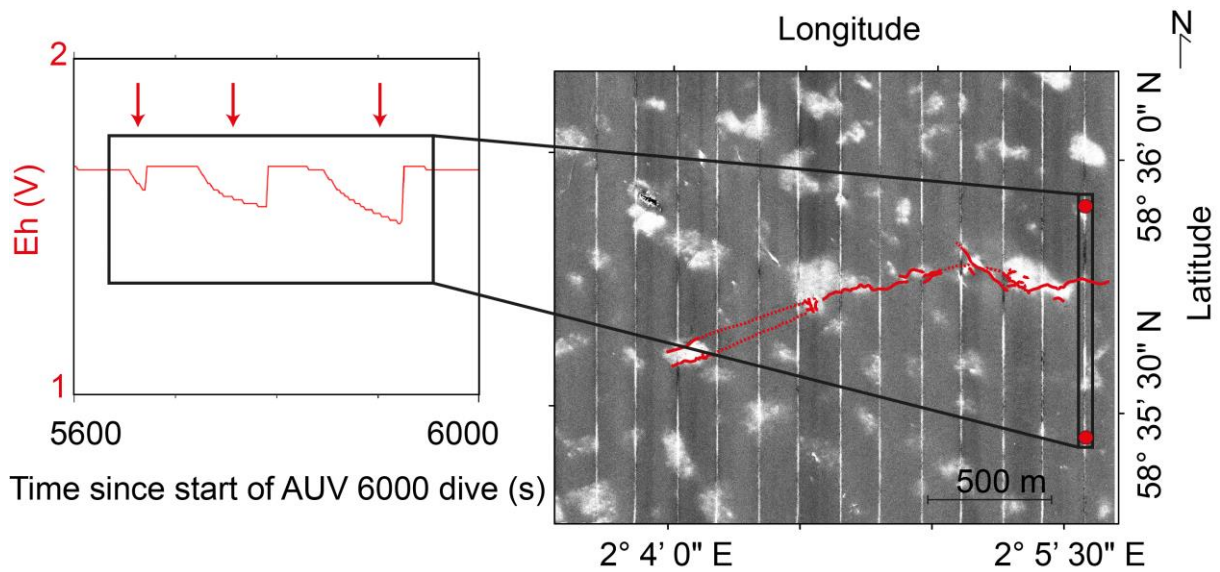


Figure 20. Chemical sensors deployed on NERC AUV Autosub 6000 successfully detected seepage of reduced (low Eh) fluids from the region of the Hugin Fracture. The figure on the right shows a backscatter image of the seafloor, with the position of the Hugin Fracture shown in red. The AUV was flown at a height of 12 m above the seafloor, from the upper red circle to the lower red circle, and data recorded by the Eh sensor are shown on the left. Arrows indicate negative excursions in Eh, as the AUV encountered reduced (low oxygen) fluids. The location of the fracture is shown by the middle arrow (data and images provided by R. James, NOCS).



Figure 21: ROV Kiel 6000 is deployed at the seabed to take sediment samples from a bacterial mat patch located within the Hugin Fracture (left). Pore fluids are extracted from the retrieved sediments to determine the chemical composition and origin of formations fluids and dissolved gases seeping through the seabed. Subsequently, a benthic chamber lander is placed at the seabed (right) to measure formation water fluxes and determine emission rates (images provided by P. Linke, GEOMAR).

Baseline studies serve to determine the natural variability against which the response of the storage complex to the storage operation has to be evaluated. All surveys being part of the monitoring program, thus, need to be performed more than once during the baseline study prior to the onset of the storage operation. Hence, an appropriate baseline study includes 1) 3-D seismic, 2) bathymetry/backscatter, 3) hydro-acoustic, 4) video/photo, and 5) chemical surveys covering the entire storage complex. Developers of CO₂ storage sites will typically aim to avoid active seep sites, deeply rooted pockmarks and other critical seabed features during site selection. However, this may not always be possible since degassing and dewatering structures are characteristic features of all sedimentary basins. If these sites occur above the storage complex, they need to be investigated in detail during the baseline study. Sediment cores and pore fluids have to be sampled at these sites and at reference stations not affected by fluid and gas flow. The chemical composition of recovered pore fluids has to be analysed to determine the source depths of ascending formation fluids and gases and the chemical signature of near-surface pore fluids at the reference locations and dormant pockmarks prior to the onset of the storage operation. Any changes in chemical composition detected during the monitoring phase would indicate that these near-surface systems are affected by the storage operation with potentially adverse effects on marine ecosystems.

Since the release of gases and fluids at active seeps may be amplified by the storage operation, emission rates and their temporal variability have to be assessed prior to the onset of the storage operation. This is a considerable challenge since gas and water fluxes at cold seeps and abandoned wells feature strong temporal variability over a wide range of time scales (hours to years). Continuous time series data recorded over a period of at least one year are thus needed to capture the variability of these systems. Stationary lander systems have been applied successfully by academia to record time series data at cold seep sites (e.g. gas flux quantification based on hydro-acoustic bubble detection, fluid flow meters based on osmosis sampling). These systems are now commercially available and should thus be employed during the baseline study at active seeps located above the storage complex.

CO₂ contents of bottom waters are highly dynamic also at storage sites where no seepage occurs. In the North Sea, pCO₂ values are close to atmospheric values during the cold season when the water column is well mixed whereas CO₂ values increase towards the seabed during the warm season when the water column is stratified. This natural CO₂ enrichment is driven by the degradation of marine organic matter producing metabolic CO₂ in the water column and at the seabed. The extent of the enrichment depends on biological activity, current velocities, and local rates of horizontal and vertical mixing. It varies not only between seasons but also from year to year. It is, thus, challenging to fully explore and quantify the natural variability of the near-seabed CO₂ system. To address and minimize this problem, ECO₂ developed and successfully tested a new sensitive tracer (C_{seep}) which highlights the impact of leakage-related CO₂ on bottom water chemistry and largely excludes the effects of metabolic CO₂ (Botnen et al., 2015). It employs the fact that biological production of CO₂ is always associated with a certain amount of oxygen consumption and nutrient release while CO₂ leakage has no specific effect on oxygen and nutrient levels in ambient bottom waters (Fig. 22). Baseline and monitoring surveys should thus aim to measure concentrations of dissolved inorganic carbon, alkalinity, salinity, phosphate and oxygen and apply these data to determine the concentration of the C_{seep} tracer in ambient bottom waters above the storage complex which should cluster at values close to zero prior to the onset of the storage operation. The chemical baseline is also shifted by the uptake of anthropogenic CO₂ via the seawater-atmosphere interface inducing a continuous increase in background CO₂. Additional measurements at reference stations upstream from the storage site can be applied to assess this effect during the operational phase since it affects the ocean at large and not just the storage area.

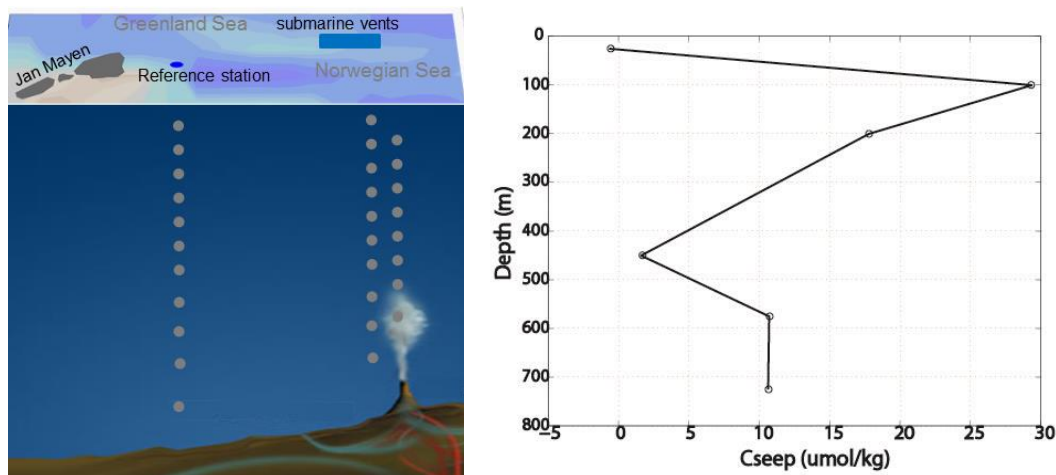


Figure 22: C_{seep} concentrations in bottom waters at a hydrothermal vent field in the Norwegian Sea near the Jan Mayen Island (BOTNEN et al., 2015). Left panel: 3-dimensional sketch of the location of the hydrothermal vents, the reference station, and sampling depths during the measurement campaign, July-Aug 2012. Right panel: Excess DIC input from subsea hydrothermal vents (in micro-moles of carbon per kg of seawater) determined for various depths in the water column. In contrast to cold seeps, hot vents produce buoyant CO_2 plumes rising towards the surface.

Efforts and costs for the recommended baseline and monitoring studies increase in proportion to the number of seep sites situated above the storage complex. The monitoring guidelines developed by ECO₂, thus, provide strong financial incentives to avoid these features during site selection as far as possible and may thereby help to minimize the likelihood that CO_2 will leak from sub-seabed storage sites.

2.6 Legal framework, public perception, and economic analysis

ECO₂ produced a comprehensive review on the legal regime concerning offshore CCS that can be downloaded at <http://oceanrep.geomar.de/25899/>. Among other outcomes this study revealed that a wide range of different environmental risk assessment (ERA) frameworks are used in instruments of public international law and European law. In this regard, the London Convention (LC) and London Protocol (LP) Risk Assessment and Management Framework for CO_2 Sequestration in Sub-seabed Geological Structures (FRAM) from 2006 and the Specific Guidelines for Assessment of Carbon Dioxide Streams for Disposal into sub-seabed geological formations (CO_2 Specific Guidelines) were analysed. This risk assessment regime was mirrored with the ERAs as provided for in the framework of the OSPAR Convention as well as the CCS Directive. From a substantive and procedural point of view, the risk assessment and management framework of CCS activities in the EU is hardly comparable to the FRAMs adopted under the auspices of the LP and the OSPAR Convention. Even though the CCS Directive is equally based on the elements of monitoring, CO_2 -stream requirements and site selection and characterisation, it regulates the planning, operation and closing phases in significantly greater detail. The associated liability structure and the envisaged surrender of allowances demonstrate the far-reaching legal consequences of violations of the substantive obligations. The regime of the CCS Directive is equipped with an “integrated” risk assessment framework in which the different steps of the permitting procedure automatically entail aspects of risk assessment and management.

Overview of environmental risk assessment and management instruments and approaches for CCS activities under public international and European Law

International level	IPCC Special Report on CCS	IPCC Special Report on Carbon Dioxide Capture and Storage (2005).
Global international law	UNFCCC	Decision 10/CMP.7 Modalities and procedures for carbon dioxide capture and storage in geological formations as clean development mechanism project activities from 2011.
	LP	Risk Assessment and Management Framework for CO ₂ Sequestration in Sub-seabed Geological Structures (FRAM) from 2006. Specific Guidelines for Assessment of Carbon Dioxide Streams for Disposal into sub-seabed geological formations (CO ₂ Specific Guidelines) from 2012.
Regional international law	OSPAR Convention	OSPAR Decision 2007/2 on the Storage of Carbon Dioxide Streams in Geological Formations and the OSPAR Guidelines for Risk Assessment and Management of Storage of CO ₂ Streams in Geological Formations (OSPAR FRAM) from 2007.
European Union law	CCS Directive	Permit approach with integrated risk assessment (storage permit: information on site selection, monitoring plans, corrective measures plan, closure and post-closure measures and transfer of responsibility) adopted in 2009. (Non-binding) CO ₂ -Storage Life Cycle Risk Management Framework (Guidance Document 1) from 2011.

The regulatory approaches are based on CCS-specific concepts and terms, the most critical of which being “leakage” and the threshold of “adverse consequences”. There is a differing understanding and approach to these two concepts in the different regulatory frameworks. The wording of the OSPAR Convention, outlining that the storage of CO₂ should not lead to “significant adverse consequences”, implies that a threshold of impact exists. Consequently, impacts could exist that are non-adverse and acceptable under the OSPAR Convention regime. This approach primarily focuses on the role of scientific knowledge that is used to determine when harm or environmental degradation has taken place. It is a challenging task to integrate precise thresholds in legal instruments, since emission standards are constantly evolving with increasing knowledge on the impacts and consequences of a substance. Establishing a benchmark of “harm” is particularly difficult, as it could refer to significant adverse consequences for an individual organism, for a population or for the surrounding marine environment in general. This is where the CO₂ Specific Guidelines come into play. The elements suggested therein such as spawning and nursery areas or seasonal or critical habitats could be used as an indicator in such an assessment. That said, the undefined boundaries of the concept assign to the Contracting Parties a wide scope of discretion when individually establishing baselines against which risks and adverse consequences are to be measured.

ECO₂'s assessment of leakage pathways (section 2.1), footprints (section 2.2) and biological responses (section 2.3) will help to better constrain the legal terminology while the ERA approach (section 2.4) and monitoring strategy (section 2.5) developed by ECO₂ define the state-of-the-art for sub-seabed CO₂ storage and provide a valuable scientific basis for the future development of ERA and CO₂ storage regulations at the European and international level.

The use and application of legal terminology and their implication for CCS activities

International level	IPCC Special Report on CCS	Leakage: "The escape of injected fluid from storage." Storage: "A process for retaining captured CO ₂ so that it does not reach the atmosphere."	<ul style="list-style-type: none"> • Non-binding • Vague definition
Global international law	London Protocol (FRAM)	Leakage "in respect of carbon storage, the escape of CO ₂ from the storage formation in the water column and the atmosphere." Storage: "a process for retaining captured CO ₂ in deep geological formations so that it does not reach the atmosphere." Formation: "a body of rock of considerable extent with distinctive characteristics that allow geologists to map, describe, and name it."	<ul style="list-style-type: none"> • non-binding • contains elements that can be used as a parameter to determine threshold of harm
Regional international law	OSPAR Convention	No definition of leakage in the OSPAR Convention, but: "adverse consequences" and "permanence" requirements. OSPAR FRAM: "leakage is the escape of that CO ₂ stream from the storage formation into overlying formations, the water column and the atmosphere."	<ul style="list-style-type: none"> • role of threshold setting
European Union law	CCS Directive	Significant irregularity: "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" (Art.3 (17) CCS Directive). Leakage: "any release of CO ₂ from the storage complex"(Art.3 (5) CCS Directive).	<ul style="list-style-type: none"> • Strict application of the precautionary principle

Public involvement in the planning and development of CCS projects is required by legislation to meet the principles of the Aarhus Convention and as part of the Environmental Impact Assessment. The European Directive on the geological storage of CO₂, however, only requires that Member States make available to the public environmental information relating to the geological storage of CO₂, while more detailed provision of information about real projects and guidance on how to approach this is lacking. Members of the public have the opportunity to scrutinise and/or object to CCS development plans as part of the Environmental Impact Assessment, which is required for any new project, and it will be important to provide stakeholders with useful elements for setting the grounds of a constructive exchange with the public, to avoid public opposition which can lead to the delaying and cancellation of projects as has happened in the past, for instance in the Netherlands and in Germany. However guidance in the area of public engagement needs to take into account that each project's situation is unique and there is no proven recipe that can be applied. The benefits of an open and humble exploration of how to approach public engagement cannot be overestimated. Such an exploration, underpinned by an understanding of public perceptions, how they change, and what affects the formation of perceptions, will allow stakeholders to effectively involve the public in the process.

Through work carried out as part of the project, ECO₂ has characterised public perception and identified current gaps in public and stakeholders' relationships about this technology. The perception of CO₂ geological storage is limited by scarce information and the lack of societal debate on how the current energy mix can influence the development of the energy system in the long term.

Within this framework, we have identified that the success of single storage projects, in terms of public perception, hangs on wider and more general issues as much as on the good and safe management of each individual project's procedures. Awareness, understanding and approval of CCS are limited, but necessary, if CCS is to be deployed extensively in Europe to reduce emissions from power and heavy industry sectors. Early geological storage projects carry the burden of demonstrating efficacy, cost effectiveness, safety and environmental integrity to the public. People who learn for the first time about this technology frequently express interest in existing cases in order to form a judgement on the technology.

The level of public understanding of the overall role of CCS is key and messages to be communicated should include: the specific contribution of CCS, its role within the context of other low carbon options, understanding of costs, safety and implementation issues at the local level. Policy makers and other stakeholders should find a way to learn together on these issues and in this process they could greatly benefit from the involvement of members of the public in the discussion. What is still unclear to the public is: i) the compatibility of CCS with the development of renewables, ii) the real costs and who is going to pay for them, iii) the implementation timeline (including transport and pipeline networks), iv) means of verification of correct operation, site management and closure, and v) liability and management issues. Finding answers to these questions requires not only technical expertise but also consideration of complex socio-economic factors. The inclusion of members of the public in the discussion could be key to increase the sense of involvement and ownership of technology evaluation processes and their outcomes, and in making them understandable to the general public and non-technical stakeholders, for a global CCS communication and also with regard to single projects.

Key findings from ECO₂ public perception studies

- **There is an urgent need for policy makers and technical stakeholders to better define the role of CCS with respect to other technologies in a low carbon energy mix.**
- **Scarce communication about CCS hinders the possibility for the public to develop awareness and understanding of the technology and its possible contribution to reducing CO₂ emissions.**
- **When communication on CCS takes place it often lacks a sufficient level of tangibility or ownership for the public to get engaged.**
- **Real projects can help make CCS more tangible. There is curiosity and interest for existing projects all over the world, thus the importance for pilot or demo projects to share their experience with the public.**
- **Perceptions of CCS should not be seen in isolation, they are related to the perception of other energy and climate discussions and are influenced by values, context and experience.**
- **Because of how we learn and form perceptions, careful attention must be paid to the way in which we engage the public – this affects the way in which they come to an opinion on CCS.**
- **The main question among the public we engaged with was around whether the CCS process is worthwhile, rather than around concerns about a specific project.**
- **Policy and implementation developments around CCS would benefit from a more active role, and therefore a greater feeling of agency, of all stakeholders including the public.**

The work conducted on public perception in ECO₂ has also produced specific tools that address some of the challenges of CCS communication and which can be used by stakeholders to raise interest and to support reflection and understanding on this technological option. First of all the issue of language and jargon was considered, trying to identify the relevant terminology and to provide, as much as

possible, simple definitions. A widely used and first of its kind CCS glossary has been developed and is available on the project homepage (<http://www.eco2-project.eu>). Secondly, the lack of visual material that could raise interest for the technology was considered, especially with the young generation. This led to the production of a short film, designed according to the indications coming from the research on how to make it interesting for the lay public: “CCS a bridging technology for the energy of the future”, now available in four languages (Italian: <https://youtu.be/0sWpLlBj3Rk>; English: https://youtu.be/RDU_PTKll_g; German: <https://youtu.be/krAa3w3FxFk8>; French: <https://youtu.be/Li-vMd9iaKw>). The film introduces the concept of CCS and invites the viewer to reflect on the issue and get involved. Finally, given the importance of the understanding of public perception issues for communication between technical stakeholders and the general public, a main objective was to make the results of the work conducted in ECO₂ accessible to all. A specific report has been created where the outcomes of the public perception work are presented in a quick and easy-to-read lay report (“The Geological Storage of CO₂: and what do you think?”) that can be downloaded at <http://oceanrep.geomar.de/29076/>. This report can be useful as an entry point to the understanding of public perception issues for many non-specialist stakeholders, policy makers, authorities, or operators. At the same time, its main contributor, the public, will find some reflection and recognition of its perspectives, which could provide a base for further exchange and for reciprocal understanding of all stakeholders.

ECO₂ economists constructed a top-down energy-environment-economy model to perform a probabilistic cost-benefit analysis of climate change mitigation with on- and offshore CCS as specific CO₂ abatement options. One of the main conclusions from this modelling exercise is that, even under conditions with non-zero leakage for CCS activity globally, both onshore and offshore CCS should probably – on economic grounds at least – still account for anywhere between 20% and 80% of all future CO₂ abatement efforts under a broad range of CCS cost assumptions. This is considered by many to be a surprising and somewhat controversial conclusion which will inspire significant debate.

Another stylized economic model was applied to evaluate economic impacts of CCS leakage risks on the financial decisions of potential CO₂ storage operators. Even with a relatively high leakage risk, the effects of leakage risk on financial decisions of storage operators are small relative to other factors (e.g., uncertainty of future carbon prices). By focusing on several other uncertainties that are involved in investment decisions for a storage site, the real option model was extended to integrate uncertainty about future carbon prices which are needed to finance the storage activities and about the investment costs. The likely delay before investment could take place was also computed. A comparison of the different uncertainties shows that the uncertainty about the development of carbon prices over the lifetime of a storage project is the dominant factor inhibiting a quick launch of CO₂ storage. The next important factor is the uncertainty about the extent to which investment costs will go down as learning through deployment advances. Reducing such uncertainties requires a number of measures. First of all, a carbon price much higher than current prices could be achieved through a reform of the existing emission trading schemes by tightening the emission constraints. However, the volatility of carbon prices would not be influenced by this measure. A guaranteed price for a certain period of time or a change from emission trading to a carbon tax are two of several policy options that could be chosen to improve the profitability of CO₂ storage and create a business case for CCS.

3. The potential impact and the main dissemination activities and exploitation of results

EU funding through “The Ocean of Tomorrow” facilitated bringing together leading European experts from three key disciplines: ocean acidification, natural seepage, and CCS, from research and industry (e.g. Statoil) to jointly investigate, in a multidisciplinary way, the impact of sub-seabed CO₂ storage on marine ecosystems. Moreover, the consortium attracted key non-European countries (Japan and

Australia) involved in sub-seabed CO₂ storage. The project provided the first comprehensive assessment of environmental risks associated with sub-seabed CO₂ storage and a novel and comprehensive monitoring strategy for sub-seabed storage sites able to detect episodic events and prolonged low-flux leakage. All ECO₂ results were evaluated and combined in a best environmental practice guide for the implementation and sustainable management of sub-seabed CO₂ storage sites, as the final product of the project. The investigations of the project provide the EC, national policy makers as well as stakeholders on CCS and scientist with all relevant information on environmental risks, monitoring strategies, permanency, safety, and perception of sub-seabed CO₂ storage. Accordingly, ECO₂ assures the pooling of capacities, short-term scientific exchange, and the validation and dissemination of results throughout Europe and beyond.

The consortium assured, in line with special clause 29 on “Access Rights to Foreground for Policy Purposes and transfer of ownership of foreground (specific to environmental research)” that i) all protocols and plans for data collection and storage are in line with the Data Policy of the European Union, ii) that the European Union Institutions and Bodies enjoy access rights to foreground for the purpose of developing, implementing and monitoring environmental policies (such access rights are granted by the *beneficiary* concerned on a royalty-free basis), iii) in case foreground will no longer be used by the beneficiary nor transferred, the beneficiary concerned will inform the Commission. In such case, the Commission may request the transfer of ownership of such foreground to the European Union. Such transfer shall be made free of charge and without restrictions on use and dissemination. As agreed by the projects data policy all ECO₂ project data (foreground) are stored on PANGAEA as the central archive to all ECO₂ field, experimental and modelling data. The system supports free and Open Access to data in a partnership approach within the ECO₂ consortium. The scientists or team generating the data have the opportunity to first publish the data, and analysis based on them. For any data, provided to the ECO₂ data base, the format and description of a data set ensure its most widespread and easiest use by the scientific community following the principles of PANGAEA. ECO₂ scientists using data from the ECO₂ data base are urged to properly use the data set citation or quote the related reference of supplements. Any type of data is always accompanied by a description (metadata) allowing future users to understand and process the data. Documentation of submitted data is stored together with each dataset. Metadata was from the beginning always freely accessible. Unpublished data is password protected, however, all data collected during the lifetime of the project are finally made public two years after the termination of the project but can be published any time before this deadline (e.g. supplement to a publication or as Earth System Science Data (ESSD) publication). Beneficiaries and data providers agree, that data archived in PANGAEA are made public available through appropriate technical setups on the Internet (e.g. portals, search engines, library catalogues, GIS) without further notification. Data sets can be made citable on its own. The citation, accompanied by an extended abstract, is added to a public library catalogue and receives a DOI. Those data publications may also be added to personal or project publication lists. Data are made available under a Creative Commons Attribution (CC-by) license if not otherwise requested and outlined in the metadata. Long-term availability of data and operation of the system is ensured by the institutions AWI and MARUM, also responsible for the consistency of the content.

Dissemination of project information and results took place on many levels, but chiefly in three areas: i) to the general public; ii) to the wider scientific community; iii) to policy-makers, regulators, and storage site operators. Dissemination to the general public was mainly addressed within work packages 6 and 7 by providing the ECO₂ website, the ECO₂ brochure, the click and learn tool on monitoring (<http://monitoring.eco2-project.eu/>), and 4 videos (<https://youtu.be/d1L7ZO-NpHc>, <https://youtu.be/hv1yyZCZ-oE>, <https://youtu.be/Syks4BGbu0k>, <https://youtu.be/0sWpLIBj3Rk>). The last one, “CCS as a bridging technology for the energy of the future”, has been specifically designed for a wide and easy introduction to CO₂ geological storage, based on the work conducted on public perception, taking into account the need of people to relate the topic to their everyday life issues

and the need to support reflection on the wider implications and themes to which CCS is related. It is now available in Italian, English, German, and French (section 2.6). All the studies performed on public perception have been made available to the wider public with a lay terms report, which presents the information in a way that is easily accessible to all, with short texts in plain English, structured to facilitate comprehension of key concepts and their practical implications and cartoons to stimulate interest. Another important tool was produced for facilitating comprehension of CCS related terms, a CCS Glossary, both downloadable and with easy searchable terms on the website. Since lay knowledge of sub-seabed CO₂ storage is at a very low level, particular attention was given to the elaboration of a clear lay description of sub-seabed storage science and technology. This is vital in promoting mutual understanding of key concepts and terms and a good basis for future sharing of scientific information with stakeholders and the public. This was achieved through consultation with all ECO₂ partners via discussion groups. The content was reformulated in lay terms then going back to the researchers to check appropriateness of the reformulation. A dedicated area of the ECO₂ project website was established for public access with a simple presentation of the project, FAQ section and the possibility for people to ask questions and send comments.

The scientific publications generated by the project combined with the dissemination of project results via conference presentations, invited talks, international seminars and workshops formed the key route by which results were broadcast to the wider science community. Additionally, project publications and key results were made available via the project website and aimed at a wider audience with a broad scientific knowledge.

Stakeholders in CCS technology were addressed through work package 5 and the project coordination. ECO₂ set out to advance the state-of-the-art in sustainable offshore storage and was therefore obliged to transfer knowledge gained by ECO₂ to various stakeholders involved in offshore storage. Stakeholders addressed by ECO₂ included current and new storage site operators, SMEs offering monitoring techniques and other relevant equipment and expertise, regulators and policy makers at the EU and the national level, and NGOs. The policy stakeholder dialogue process was implemented by work package 5 as a vehicle to provide key stakeholders with the scientific knowledge necessary to facilitate implementation and management of environmentally sound offshore storage. This dissemination occurred via 4 scientific briefing papers which were presented to CCS stakeholders at the EU parliament and other relevant levels during dedicated workshops or lunch briefings. Moreover, the project coordination implemented a permanent Stakeholder Dialogue Board (SDB). This board served as a high-level policy consultative group. Meetings of the SDB took place annually in conjunction with the annual science meeting. Through these measures, ECO₂ supported the dissemination of project results and the implementation of best environmental practices in sub-seabed CO₂ storage.

More than 30 PhD students and young researchers were employed within ECO₂. The consortium included partners from multiple disciplines, sectors, and nations and provided an excellent environment for the training and education of these young scientists that were supported by dedicated young scientist workshops. Hence, ECO₂ contributed significantly to the human capacity building for sustainable offshore storage. Operators, regulators, and further public and private organisations involved in the implementation of sub-seabed storage will likely draw on this newly developing human capital generated by ECO₂. The recruitment of young ECO₂ scientists by CCS stakeholder organisations will contribute directly and considerably to the dissemination of ECO₂ knowledge.

The Scientific Advisory Board (SAB) and Stakeholder Dialogue Board (SDB) of ECO₂ both had a strategic and an active role in the use and dissemination of Intellectual Property generated by the project. As external contributors to the project they informed project partners about the most effective means of disseminating their results, including providing information to the project about new committees, government or commercial initiatives. They contributed significantly to the success

of the project and the dissemination of project results to the scientific community (SAB) and the various stakeholders involved in CCS (SDB).

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