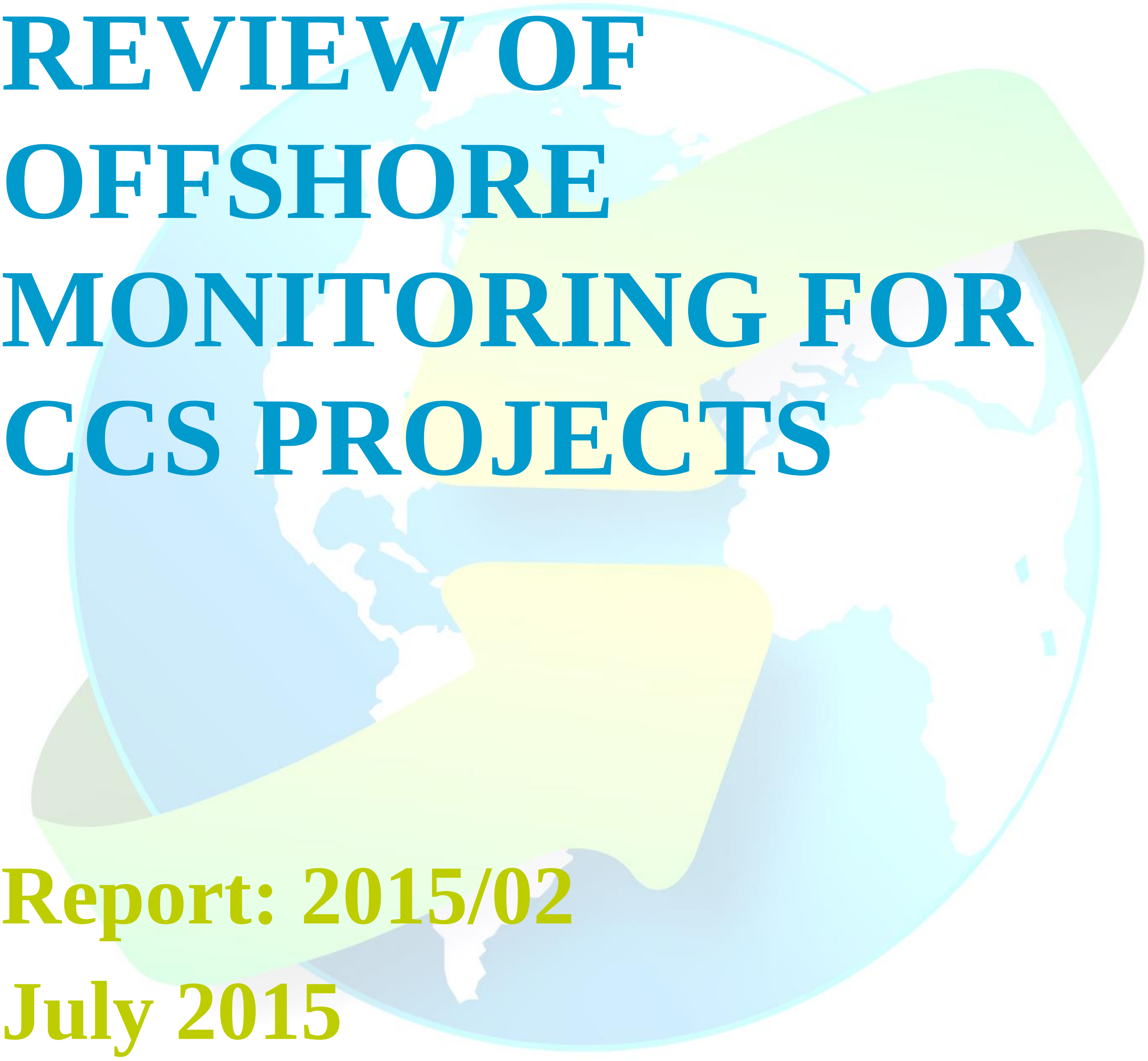
REVIEW OF OFFSHORE MONITORING FOR CCS PROJECTS



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REVIEW OF OFFSHORE MONITORING FOR CCS PROJECTS
(IEA/CON/14/223)

Key Messages

- A range of monitoring techniques are available for CO_2 geological storage offshore, both deep-focussed (providing surveillance of the reservoir and deeper overburden) and shallow-focussed (providing surveillance of the near seabed, seabed and water-column).
- Deep-focussed operational monitoring systems have been deployed for a number of years at Sleipner, Snøhvit and also at the pilot-scale K12-B project in the offshore Netherlands, and conclusions regarding the efficacy of key technologies are starting to emerge. 3D seismic surveys have been highly effective for tracking CO_2 plume development in Sleipner and Snøhvit reservoirs. Measurement of downhole pressure was crucial in establishing non-conformance at Snøhvit. A combination of 3D seismic and downhole pressure / temperature monitoring at Snøhvit has demonstrated the benefit of complementary techniques.
- Shallow-focussed monitoring systems are being developed and demonstrated. New marine sensor and existing underwater platform technology such as Automated Underwater Vehicles (AUVs) and mini-Remotely Operated Vehicles (Mini-ROVs) enable deployment and observation over large areas at potentially relatively low cost. Seafloor and ocean monitoring technologies can detect both dissolved phase CO_2 and precursor fluids (using chemical analysis) and gas phase CO_2..
- Developments in geophysical techniques, such as the P-Cable seismic system for higher resolution 3D data collection in the overburden, have been demonstrated successfully and effective integration of these shallow subsurface technologies with the seabed monitoring data can help to understand shallow migration processes.
- Controlled release sites such as QICS[1] have proved to be useful test-beds for shallow seismic techniques and acoustic detection systems. They can also reveal how CO_2 migrates through, and is partially retained by, unconsolidated sediments.
- Monitoring strategies need to be devised to cover large areas, typically tens to hundreds of km^2 and also achieve accurate measurement and characterisation possibly over lengthy periods. Limited spatial coverage could lead to the risk that anomalies remain undetected or are only detected after a lengthy period of time. Ameliorative measures might then be harder to implement.
- Search areas could be narrowed down by the integration of information from deeper-focussed monitoring such as 3D seismics, which can identify migration pathways, with shallow surface monitoring such as acoustic detection.
- Assessment of the results from both the operational (predominantly deep-focussed) and research (predominantly shallow-focussed) monitoring activities from Sleipner and Snøhvit indicates that many elements of the European storage requirements have been met at these large-scale sites which were both initiated before the CCS Directive was introduced.

Background to the study

Since the inception of CO_2 injection into the Sleipner gas field in 1996 there has been considerable progress in monitoring offshore geological storage sites. There have also been recent developments, in-situ experiments, large-scale tests, and reviews on monitoring techniques for offshore monitoring applications. Some of these developments have occurred outside of the CCS sector. This is in addition

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[1] *QICS = Quantifying and Monitoring Potential Ecosystem Impacts of Geological Carbon Storage

to the deep monitoring for Statoil's Sleipner project in the North Sea and Snøhvit project in the Barents Sea.

In addition to technology developments there has been a corresponding series of regulations and related objectives which are designed to ensure that CO_2 storage in offshore reservoirs can be retained within secure repositories without detrimental environmental effects. As with onshore CO_2 geological storage, the objectives for offshore monitoring include: CO_2 geological storage performance, baseline studies, leakage detection, and flux emission quantification. There are advantages and disadvantages of offshore monitoring compared to onshore. There is better and more consistent seismic coupling to the geology because of the water contact, there are less access issues in terms of landowners and infrastructure. In addition, emissions at the seabed can be both 'seen' and 'heard' as bubble streams. On the other hand, there are the challenges of working in a more remote and hostile marine environment.

Sub-seabed geologic storage sites will have large spatial seafloor extent and large overlying ocean volumes (with potentially dispersed and localised emission sources) which provides a monitoring challenge. One requirement of any offshore leakage monitoring strategy development is to ensure wide area monitoring combined with sensitive detection thresholds. Potential CO_2 leakage may have precursor fluid release of chemically-reducing sediment pore fluids and aquifer brines (each of which has a unique chemical signature). New marine sensor and existing underwater platform technology such as Automated Underwater Vehicles (AUVs) and mini-Remotely Operated Vehicles (Mini-ROVs) and seabed landers are under development to enable deployment and observation over large areas at potentially relatively low cost. Seafloor and ocean monitoring technologies can detect both dissolved phase CO_2 and precursor fluids (using chemical analysis) and gas phase CO_2 and seabed. Such chemical and physical monitoring systems may also provide tractable and robust methods for quantifying leakage loss beyond just detection.

Developments in geophysical techniques, such as the P-Cable seismic system for higher resolution 3D data collection in the overburden, have been demonstrated successfully in the last few years and effective integration of these shallow subsurface technologies with the seabed monitoring data can help to understand shallow migration processes.

Deep-focussed monitoring of reservoir and overburden has proved successful offshore, notably at Sleipner and Snøhvit. This study has reviewed and assessed the performance of these monitoring technologies and methodologies tools, and how new or modified tools might contribute to monitoring capability.

Scope of work

This report reviews offshore monitoring practice for CO_2 storage projects in terms of tool capabilities, logistical practicalities and costs. The focus is on large-scale 'commercial' storage monitoring and draws together published experience from existing large offshore CO_2 storage sites as well as monitoring research at experimental test sites and in areas of natural CO_2 seepages. The strengths and limitations of monitoring techniques, strategies and methodologies are discussed, and relevant experience from onshore sites are also included. Monitoring over the full life-cycle from pre-injection (baseline) through injection and post-injection phases to transfer of responsibility to the competent authority is considered. The review draws on selected examples of current or planned monitoring practice.

Current regulatory and technical requirements for large-scale offshore CO_2 storage (for Europe, Australia, Japan and the United States) are summarised. The objectives, capabilities, practicalities and costs of the monitoring techniques deployed at operational (or planned) offshore CO_2 storage sites are assessed. Monitoring experience gained from experimental and natural analogue sites and modelling studies have also been reviewed. The efficacy of current (and planned) offshore monitoring plans with respect to regulatory requirements have been investigated. The report concludes with a synthesis of a sample offshore monitoring strategy and template to improve meeting regulatory needs in a cost-effective manner.

Additional insights have been provided by comparisons with equivalent onshore monitoring practice. Technology gaps and synergies have been included. The report also gives recommendations on priorities for further research and development.

Findings of the Study

Offshore regulation and monitoring objectives

There are two key over-arching regulations that cover offshore CO_2 storage. The London Protocol and the OSPAR[2] Convention. The London Protocol, which is a global agreement to protect the marine environment by regulating waste disposal at sea. It was amended in 2006 to include CO_2 storage. Both of these conventions have similar two-stage monitoring guidelines. The first stage covers the performance of monitoring of CO_2 within storage formations and the second deals with the environmental impact in the event that leakage is suspected. The implications mean that impacts on the sea floor and marine communities need to be ascertained.

It is in Europe that the regulatory framework is most mature but offshore storage regulations also exist and are developing elsewhere, notably in Japan, Australia and the Unites States. Although drafted at various levels of detail, the regulatory documents from the different national jurisdictions all emphasise the key role of monitoring and the range of objectives it should serve. These can be broadly distilled as demonstrating that the storage site is performing effectively and safely and that it will continue to do so into the future. This approach can therefore be expressed as providing assurance of containment and conformance.

Since 2007 the international regulatory framework has been evolving notably in Europe with the introduction of the European Storage Directive for CO_2. These regulations will be particularly pertinent to the planned projects Peterhead - Goldeneye, White Rose and ROAD. Sleipner, Snøhvit and K12-B predate current EU legislation. The EC Storage Directive specifically addresses monitoring for the purposes of assessing whether injected CO_2 is behaving as expected, whether any migration or leakage occurs, and if this is damaging the environment or human health.

OSPAR is primarily focussed on detecting and avoiding leakage and emissions and therefore identifies the following objectives for a monitoring programme:

- Monitoring for performance confirmation.
- Monitoring to detect possible leakages.
- Monitoring of local environmental impacts on ecosystems.
- Monitoring of the effectiveness of CO_2 storage as a greenhouse gas mitigation technology.

The following essential elements of monitoring and control are stated as required to help achieve these objectives:

- The injection rate.
- Continuous pressure monitoring.
- Injectivity and pressure fall-off testing.
- The properties of the injected fluid (including temperature and solid content, the presence of incidental associated substances and the phase of the CO_2 stream).

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[2] OSPAR is so named because of the original Oslo and Paris Conventions ("OS" for Oslo and "PAR" for Paris)

- Mechanical integrity of seals and (abandoned) wells.
- Containment of the CO_2 stream including performance monitoring and monitoring in overlying formations to detect leakage.
- Control measures, overpressure and emergency shutdown system.

It is clear from the wide range of regulatory requirements that have been developed, but regulation has reached different stages of maturity across the world. There are two relatively consistent monitoring-related themes: the requirement firstly to demonstrate that a storage site is currently performing effectively and safely; and secondly to ensure that it continues to do via the provision of information supporting robust prediction of future performance.

These requirements for monitoring offshore storage can be distilled into a number of necessary actions (Table A1), which fall within two main monitoring objectives, containment assurance and conformance assurance. A third category, contingency monitoring may be required in the event that containment and/or conformance requirements are not met. The categories and requirements shown in this table are an interpretation by the authors of the report.

In terms of the types of monitoring tools used, it is sometimes convenient to categorise them as deep-focussed (providing surveillance of the reservoir and deeper overburden) and shallow-focussed (providing surveillance of the near seabed, seabed and water-column).

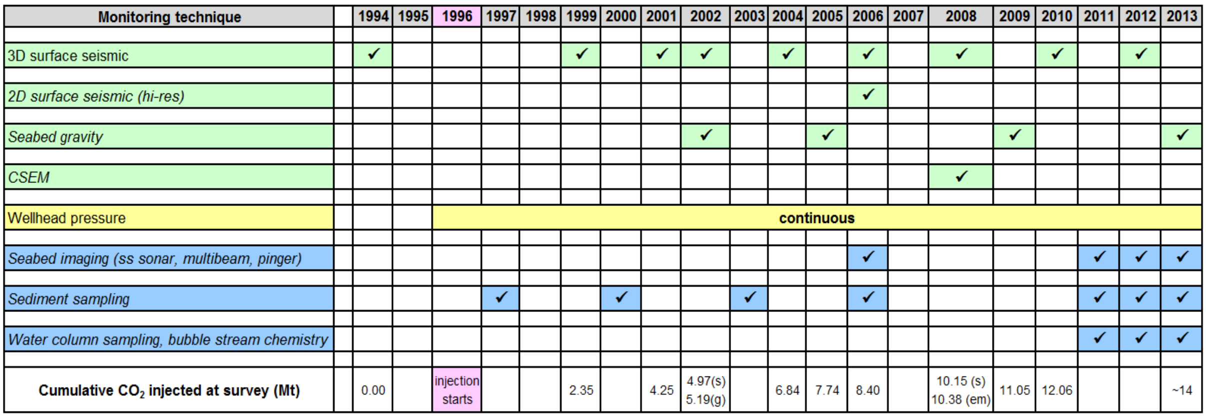
		OSPAR	EU Directive	EU ETS	
Deep-focussed monitoring actions	Migration in overburden	▨	▨		Containment
	Containment integrity	▨	▨		Containment
	Migration in reservoir		▨		Conformance
	Performance testing and calibration and identification of irregularities	▨	▨		Conformance
	Calibration for long-term prediction		▨		Conformance
	Testing remedial actions		▨		Contingency
Shallow-focussed monitoring actions	Verification of no leakage	▨	▨		Containment
	Leakage detection	▨	▨		Containment
	Emissions quantification	▨		▨	Contingency
	Environmental impacts	▨	▨		Other
	Testing remedial actions		▨		Contingency

Table A1 Objectives for Deep and Shallow-focussed monitoring.

Experience at current and operational CO_2 storage sites

The report outline results from the monitoring programmes that are being currently deployed in Europe at the world's two large-scale offshore storage sites: Sleipner and Snøhvit, as well as the smaller, pilot-scale project at K12-B. It has also reviewed the monitoring tools that are proposed for the Peterhead - Goldeneye project in the UK, the ROAD project in the Netherlands, and the Tomakomai project in Japan.

The monitoring objectives at Sleipner are linked closely to the identified storage risks: migration through the geological seals resulting in leak pathways to the seabed; lateral migration into wellbores, resulting in leak pathways to the seabed and lateral migration of CO_2 outside of the Sleipner license area. The monitoring programme is primarily based around tracking CO_2 migration in the storage reservoir in order to predict future behaviour and providing the capability to reliably detect changes in the overburden which might indicate out of reservoir movement of CO_2. These objectives were all addressed through the application of time-lapse 3D seismics. Although predating the European legislation, the monitoring programme at Sleipner does address the main high level requirements of containment and conformance in a number of ways. Table A2 summaries the monitoring surveys deployed at Sleipner between 1994 and 2013.



Monitoring technique		1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
3D surface seismic		✓					✓		✓	✓		✓		✓		✓		✓		✓	
2D surface seismic (hi-res)														✓							
Seabed gravity										✓			✓				✓				✓
CSEM																✓					
Wellhead pressure				**continuous**																	
Seabed imaging (ss sonar, multibeam, pinger)														✓					✓	✓	✓
Sediment sampling					✓			✓			✓			✓					✓	✓	✓
Water column sampling, bubble stream chemistry																			✓	✓	✓
Cumulative CO_2 injected at survey (Mt)		0.00		injection starts			2.35		4.25	4.97(s) 5.19(g)		6.84	7.74	8.40		10.15 (s) 10.38 (em)	11.05	12.06			~14

Table A2 Research monitoring tools are shown in italics. Green denotes deep-focused techniques that operate from the surface, yellow denotes well-based techniques and blue denotes shallow-focused techniques. Note that for years with more than one survey, the amount of CO_2 injected for each specific survey is stated: thus "s" denotes "seismic", "g" gravimetric, and "em" electromagnetic surveys.

Throughout its operation the Sleipner field has been used as a test bed for other monitoring technologies (summarized in Table A2).

At Snøhvit the main monitoring aims are firstly to ensure that injection pressures do not exceed the fracture threshold of the caprock and secondly to track the CO_2 plume. Two deep-focussed monitoring technologies have been deployed at Snøhvit: downhole pressure and temperature monitoring; and time-lapse 3D seismic surveys. In addition a number of shallow-focussed research surveys have also been carried out as part of the ECO2 project. These surveys include multibeam echo-sounding, conductivity and temperature depth profiles, sediment sampling and water column sampling.

Longer term measurement of downhole pressure was crucial in establishing non-conformance at Snøhvit. The long-term pressure increase was faster than expected and eventually threatened the geomechanical stability of the storage formation as fluid pressures approached the estimated fracture pressure. In addition, modelling of the pressure decay (or fall-off) curves, which followed cessations in injection, indicated that the capacity of the storage reservoir was smaller than expected, likely due to no-flow barriers a few kilometers from the injection well. The most complete understanding of reservoir performance came from a combination of the accurate, integrative pressure measurements and the positional imaging ability of the time-lapse seismics. The operators were therefore able to implement an alternative storage plan by switching to an alternative reservoir.

Peterhead - Goldeneye has a monitoring programme that is designed to meet European offshore requirements that covers both deep and shallow focussed monitoring. The deep-focussed component will include surveillance of the reservoir and overburden and utilises a number of proven technologies: time-lapse 3D seismics; down-hole pressure and temperature; geophysical logging and fluid sampling. A comprehensive shallow environmental monitoring programme is also planned, including seabed imaging, seabed sampling and seawater sampling technologies. Contingency monitoring is also addressed, for example a P-Cable seismic survey to help image and understand shallow migration in the event of leakage being detected at the top of the storage complex.

The Dutch ROAD project is the first project to be permitted under the EU Storage Directive. The permit is subject to updates and the inclusion of more detail. Further study is underway to assess specific local pressure build-ups, pressure barriers and later-stage fault leakage. Results will be used to update the risk assessment which will feed into the updated monitoring plan to provide evidence for containment and to demonstrate integrity of seals, faults and wells.

The Japanese Tomakomai CCS project is a large scale demonstration project located 3 - 4 km off the coast of Hokkaido. The monitoring programme includes 2D and 3D seismic surveys. These will be deployed via ocean bottom cables (OBC) because greater repeatability is achievable and the busy port precluded streamer deployment. The 2D survey line aligns with the two injection wells and uses a buried OBC for similar reasons. Heavy emphasis has been placed on the detection of natural earthquakes and microseismicity which also uses the OBC, in addition to 4 dedicated ocean bottom seismometers (OBS) and downhole sensors in the observation wells.

The report covers the monitoring techniques commonly used to verify containment and conformance. A summary of these techniques, and where they have been deployed or planned, has been compiled by IEAGHG and is presented in Table A3.

Table A3
Surface seismic methods

Method	Capabilities	Practicalities	Deployment	Containment Monitoring	Conformance	Cost	Limitations
Streamer – 3D seismic	High detection & resolution capabilities. Data suitable for advance analysis especially the investigation of reservoir properties & plume tracking	Routine deployment, robust & mature but requires large unobstructed areas of sea Detection threshold depends on geometry of CO_2 accumulation	Sleipner, Snøhvit. Planned for Goldeneye, ROAD, Tomakomai*	Can provide robust & uniform spatial surveillance of storage complexes. Can detect small changes in fluid content & therefore useful for leakage detection. Changes in time-lapse seismic images can detect small quantities of CO_2.	Ability to track CO_2 plumes is useful to corroborate model predictions and can be used to refine or modify them. Plume mobility & storage efficiency can be checked. Measured time-shifts can reveal indicative pressure changes in reservoirs.	£10M+ depending on survey area, specification, and locality. Processing time up to £1M in computing time	Lack of significant azimuthal variation in wave propagation which limits azimuthal analysis for evaluation of anisotropy & geomechnical integrity. Interpretation & detection of CO_2 relies on good repeatability which may not always occur.
Streamer 2D seismic	High detection & resolution capabilities similar to 3D seismic. Star survey configuration can provide image of plume spread.	More compact compared to 3D. Time-lapse is reputedly poor.	Sleipner, Tomakomai (OBC 2D seismic)			<£1m depending on survey area, specification, locality	Lack of 3D migration in processing precludes optimum imaging of some subsurface structures.
Streamer – P Cable seismic	High resolution 3D seismic system suited to shallow sections (<1,000 m) therefore useful for imaging shallow overburden. High spatial and temporal resolution possible Useful for 3D mapping of structures especially faults.	Relatively compact and short than 3D & 2D configurations gives high manoeuvrability.	Snøhvit, Gulf of Mexico	Useful for containment risk assessment & leakage monitoring by tracking CO_2 migration above storage complexes		<£1m depending on survey area, specification, locality	Sea bed multiple can obscure important features. Vulnerable to reduced performance in poor sea conditions.
Chirps, boomers & pingers	Designed for very high resolution surface seismic surveys direct detection of bubble-streams may be possible in favourable circumstances.	Can be deployed from small site-survey vessels. AUV systems can be equipped with Chirp transducers. AUV survey has detected clear images of natural gas pockets in central North Sea	Sleipner, planned for Goldeneye			<£100k	Designed for shallow surface surveys. AUV based systems have limited penetration due to lower power availability.

Surface seismic methods

Method	Capabilities	Practicalities	Deployment	Containment Monitoring	Conformance	Cost	Limitations
Ocean bottom nodes (OBN) & cables (OBC)	As static observation data recorders these devices can provide full azimuth coverage with multicomponent sensors with p and s-wave recording for geomechanical & isotropy characterisation. Long-term recording is useful for detecting natural & induce seismicity	Can provided information in close proximity to platforms	OBN planned at Goldeneye OBC planned at Tomakomai			£10M+ but unlike streamer surveys there is a high initial cost to set up the system and relatively low costs for repeat surveys.	Vulnerability to trawling operations. Limited spatial sampling density compared with streamer surveys.

Downhole seismic methods

Method	Capabilities	Practicalities	Deployment	Containment Monitoring	Conformance	Cost	Limitations
4D VSP (Vertical seismic profiling)	High resolution imaging of near-wellbore region 10s – 100s metres radius	Permanent downhole sensors allow for cost-effective time-lapse imaging. Data processing can be complex. Fibre-optic acoustic cable might improve reliability.	Goldeneye (under consideration)				Coverage is non-uniform (spatially variable offsets & azimuths) which can make interpretation difficult. Time-lapse repeatability is uncertain. Reliability of sensors is a key issue.
Passive seismic monitoring	Allows continuous monitoring for microseismic events	Deployment in one or more shallow wells (<200m). Microseismic events can be used to identify structures such as faults and fractures. Important to establish natural background seismicity to distinguish events related to CO_2 injection & migration.	Planned for ROAD and Tomakomai Considered for Goldeneye		Important to establish natural background seismicity to distinguish events related to CO_2 injection & migration.	High initial costs required for deployment. Maintenance costs could also be high	Sensor reliability can make the method vulnerable leading to potentially limited signal records.

Potential field methods

Method	Capabilities	Practicalities	Deployment	Containment Monitoring	Conformance	Cost	Limitations
Seabottom gravimetry	Directly measures mass change within reservoirs which is a conformance-related parameter	Offshore deployment is logistically complex requiring ROV and boat support to emplace concrete benchmarks	Sleipner			Low compared to 3D streamer surveys. A 50 station near-shore survey would cost ~£1M.	
Controlled source electromagnetics (CSEM)	Can provide complementary information to seismics. Method is sensitive to fluid saturation at higher CO_2 saturation levels	Offshore deployment is logistically complex	Sleipner			Costs high & comparable with offshore 3D seismics.	The technique is severely hampered in shallow water (<300m).

Downhole measurements

Method	Capabilities	Practicalities	Deployment	Containment Monitoring	Conformance	Cost	Limitations
Downhole pressure and temperature	Downhole gauges are capable of detecting very small temperature and pressure changes which are a primary method for monitoring injected CO_2 physical properties and reservoir performance. Position of gauge across permeable units can give indications of out-of-reservoir migration.	Deployment is a requirement under the EU Storage Directive, Long-term surveillance needs to take account of instrument drift and reliability.	Snøhvit, K12-B. Planned for Goldeneye, ROAD, Tomakomai	Key for controlling geomechanical integrity of the reservoir and caprock. Any unexpected pressure reduction in the reservoir could indicate potential leakage.	Essential for monitoring fluid flow performance and model calibration demonstrating reservoir permeability, storage capacity and geomechanical stability.	Relatively low <£100 plus installation and retrieval of gauges	
Geophysical logging	Standard oilfield technique used for calculating CO_2 saturation. Provided there is a good baseline survey, repeat surveys can be used to calculate CO_2 saturations	Downhole logging is dependent on access to wellbores which might be restricted. Obstructions such as scale accumulation may preclude logging.	Planned at ROAD and Goldeneye		Pulsed neutron capture logging is planned for Goldeneye to acquire a good baseline and quantify CO_2 thickness interval.	Cost varies depending on the suite of logs run	

Downhole measurements

Method	**Capabilities**	**Practicalities**	**Deployment**	**Containment Monitoring**	**Conformance**	**Cost**	**Limitations**
Wellbore integrity monitoring	Standard oilfield technique including cement bond logs used to check integrity of the cased wellbore. Quality and availability of legacy data from abandoned wells may limit effectiveness of integrity checks. Ultrasonic imaging, Multi-finger calliper and Electromagnetic imaging, downhole video and real time borehole stress and tubing/ casing deformation imaging are used to check casing and tubing integrity.	Techniques is reliant on access to wells and different operations. Build-up of scale can cause problems by obstructing logging tools.	K12-B, planned at ROAD & Goldeneye		Wellbore integrity is essential for long-term CO_2 storage security by preventing leakage. At Goldeneye logs will be run prior to injection to establish a baseline. Integrity will be checked initially in year three and then every five years until injection is completed.	Cost varies depending on the suite of logs run	
Downhole fluid sampling.	Analyses of reservoir fluids can yield pCO_2,pH HCO_3^-, dissolved gases, stable isotopes and tracers	Sampling should be carried out at ideally at reservoir pressure. Requires access to specific reservoir zones. U-tube is deployed onshore but does not have safety certification for offshore deployment.	K12-B planned at Goldeneye		At K12-B analyses of gas samples from two production wells revealed heterogeneous nature of the reservoir. Wireline downhole sampling proposed for Peterhead - Goldeneye.	Onshore cost per sample ~£5-10k per sample.	Accuracy of breakthrough timing depends on temporal sampling frequency.
Chemical tracers and gas analyses	Tracers and isotopic signatures can help to identify CO_2 origin and monitor migration or potential leakage.	Tracers can be injected in a pulse or continuously. Tracers can be detected in extremely small quantities using gas chromatography or mass spectrometry.	K12-B planned at Goldeneye	At Goldeneye use of tracers is being considered to distinguish between natural CO_2 being emitted from the sea bed and CO_2 from the storage complex.	Tracer studies at K12-B showed breakthrough occurred at two producer wells after 130 days and 463 days depending on distance from the injector. Differing CO_2 and CH_4 solubilities and insoluble tracers mean these breakthrough rates may not reflect real CO_2 migration rates.	Noble gases analyses are ~£350 compared with £125 for SF_6	

Under sea monitoring

Method	Capabilities	Practicalities	Deployment	Containment Monitoring	Conformance	Cost	Limitations
Seabed and water column imaging.	Active acoustic techniques can be effective at detecting gas fluxes. Multibeam echosounders (MBES) can be used for 3D bathymetric surveys. In time-lapse mode method could be used to detect slight changes in seafloor that might be caused by CO_2 leakage. Acoustic bubble detection can identify bubble releases	These are established techniques that can be carried out by a survey vessel with multiple imaging systems. This is a cost-effective means of surveying large areas of sea bed. AUV and ROV systems can operate closer to the seabed, the scale and operational duration of surveys is limited the size of the device.	Pervious side-scan sonar, single beam and multibeam echosounding and pinger seabottom profiles were conducted. Surveys at Sleipner and Snøhvit. Pockmarks were clearly identified but no bubble streams. Acoustic bubble detection is planned at ROAD. A MBES plus side-scan sonar is planned for Goldeneye			Surveys 10 km2 cost ~£100k - £200k but cost efficiencies are possible if multiple techniques are carried out.	There is a trade-off between the scale of the survey area and the ability to survey the sea floor from an AUV. Static seabed sensors can achieve high resolutions but over smaller fixed areas. However, they are generally more costly to install, maintain and retrieve compared to mobile equipment.
Underwater video	Detection and recording of high definition images of bubbles and other features such as bacterial mats and biota behaviours which may give an indication of CO_2	Image quality can vary depending on water quality and height above seabed.	Sleipner			~£1k-10k	A highly qualitative technique with a poor ability to resolve the size and shape of bubbles.
Seabed displacement monitoring	Vertical displacements of the seabed can be indicative of pressure changes in reservoirs. GPS system could measure rates with a accuracy range of 1-5mm.	Sensor networks on seafloor that use acoustic ranging techniques, pressure gauges or tiltmeters can give very accurate measurements of seabed movement	Planned for Goldeneye. Single GPS station mounted on a platform.	Monitoring subsidence or uplift can provide evidence of containment and conformance.		~£1k-10k for single GPS station mounted on a platform.	

Under sea monitoring

Method	Capabilities	Practicalities	Deployment	Containment Monitoring	Conformance	Cost	Limitations
Geochemical water column sampling.	Water column measurements using conductivity, temperature and depth (CTD probes) in combination with pH pCO_2, dissolved O_2, inorganic and organic carbon, nitrogen, phosphate, Eh, salinity can be sued to detect anomalous chemistry.	CTD probes can be conducted from survey ships. Continuous measurements can be made. Interpreting a leakage signal above background measurements can be extremely challenging. Baseline measurements ideally need to reflect a degree of natural variability.	Sleipner and Snøhvit, and planned at Goldeneye (permanently attached to platform) & Tomakomai. A survey over a period 2011 -2013 above Sleipner found no evidence of CO_2.			~£1k – 10k for a survey when deployed from a vessel conducting other surveys	The density, timing and the vertical spacing separation of surveys may mean small leakage plumes could remain undetected depending on plume dispersion.
Sediment sampling	Time-lapse sediment sampling can be used to detect changes in sediment, pore fluid that could indicate CO_2 leakage. Detecting CO_2 leak induced changes above background requires a good understanding of natural variability	Quality of sample depends on substrate and whether core has retained pore fluid at the original insitu pressure. Specialist vibrocorer equipment is required.	Sleipner and Snøhvit, and planned at Goldeneye) & Tomakomai. Repeat surveys will be conducted to detect possible changes induced by CO_2 leakage.		Seabed sediment samples from Goldeneye will be analysed for a suite of dissolved gases to provide a background baseline.	£5k / day for equipment deployment and excluding ship time.	
Ecosystem response monitoring	Time-lapse sediment sampling can be used to detect changes in benthic flora and fauna caused by elevated CO_2 concentrations either as a gas phase or by a reduction in pH. Avoidance behaviour needs to be distinguished by changes induced by natural variability	Species density and variety can be recorded with underwater video.	At Goldeneye ecosystem sampling using Van Veen Grab is planned.			~£100s per sample excluding processing and organism identification	Most effective biomarker species have not yet established.

Experience from experimental and natural seepage sites and modelling.

Natural CO_2 seepage sites are prevalent in several areas around the world and especially in geothermally active areas. The hydrothermally driven seeps off the island of Panarea in the Aeolian Islands are a good example. Observations near these seeps shows that the local biology has adapted to the presence of these seeps, but this adaptation is in distinct contrast to conditions in colder, deeper and more turbid sites. The Hugin Fracture is another example of natural seepage, in this case in the central North Sea. The 3 km long structure is covered by soft sediments with wide patches of methanotrophic bacteria which metabolise methane from a natural seep. There is no evidence of CO_2 at this location. The report also outlines the observations of the QICS artificial CO_2 test injection experiment in Ardmucknish Bay off the west coast of Scotland. CO_2 was released beneath 11m of sediment. Over a period of 37 days. Although bubbles occurred soon after injection CO_2 was retained within sediments and trapped in pore waters. The QICS experiment also clearly revealed the influence of cyclical hydrostatic pressure induced by tides. Acoustic tomography has been tested at Takatomi in Japan. By using dispersed transponders it is possible to detect the location of bubble streams by triangulation. Although the system allows continuous measurement it is susceptible to biofouling, suspended sediment and trawler damage. One of the main challenges encountered with passive acoustic measurements is the extent of background noise from artificial and natural sources which can mask a specific acoustic signal.

The use of high-resolution seismic reflection using chirp and boomer technology proved highly effective during the QICS experiment. The technique produced clear images of gaseous CO_2 trapped in sediments above the release point (see Figure A1).

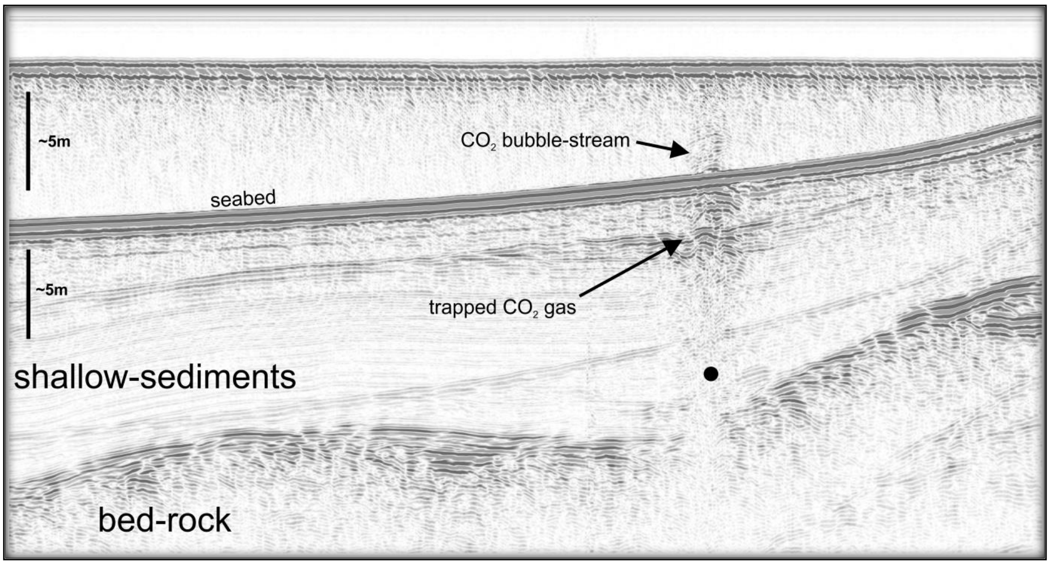


Figure A1 Seismic profile showing gaseous CO_2 trapped in shallow sediments and a bubble stream above the release point.

The impact of higher concentrations of CO_2 in seawater has been reviewed. Laboratory and mesocosm studies have shown that an increase in CO_2 in seawater reduces infaunal diversity and alters community structures. The precise nature and severity of the impact is strongly influenced by both sediment type, length of exposure and species-specific sensitivity to environmental changes. The response on benthic communities to CO_2 will be site specific as well as the duration of exposure. However, behavioural alterations might take place through natural seasonal variation and consequently comprehensive baseline studies are necessary to distinguish between natural variability and potential leakage impacts.

Hydrodynamic modelling, which can be used to predict distribution patterns and changes in marine conditions, are widely used for predictive purposes. The models can be used to predict the vertical and lateral spread of CO_2 for example and the likely mixing process but understanding water-column dynamics is essential. Tidal currents are a major agent in many shelf seas where storage is likely to be situated (see Figure A2).

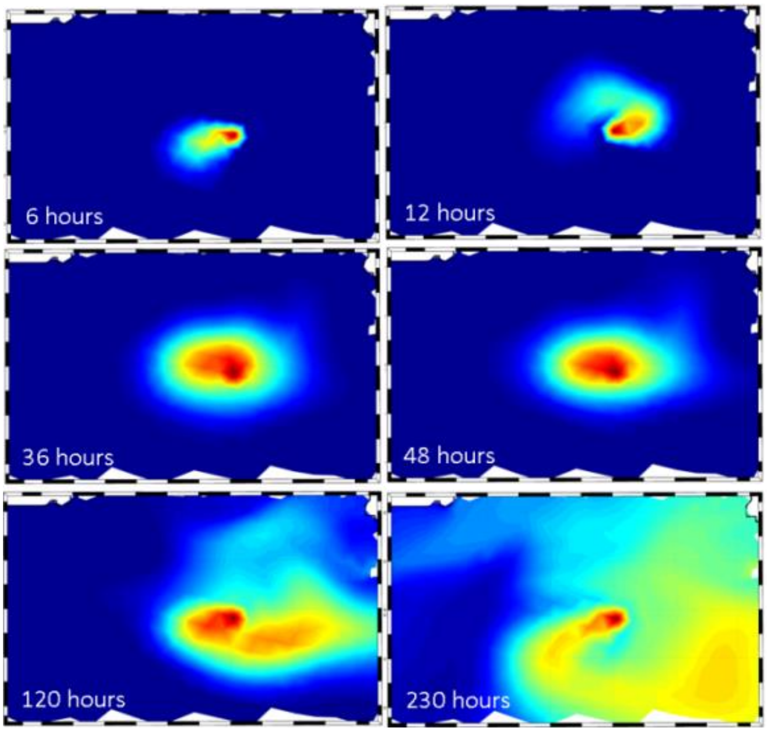


Figure A2. An example of a dispersion plume of dissolved CO_2 *from a point source influenced by tidal mixing using the FVCOM*[3] *model. Red represents the highest concentration of* CO_2 *whilst dark blue represents the background concentration.*

There are some key issues that affect offshore monitoring. Monitoring strategies need to be devised to cover large areas, typically tens to hundreds of km^2 and also achieve accurate measurement and characterisation possibly over lengthy periods. Limited spatial coverage could lead to the risk that anomalies remain undetected or are detected after a lengthy period of time. Monitoring data is used to build a robust baseline but data interpretation can be used to improve the knowledge of storage sites and where anomalies could occur. A combination of point sampling and large spatial surveys should help to improve the quality of monitoring. Search areas could be narrowed down by the integration of information from deeper-focussed monitoring such as 3D seismics, which can identify migration pathways, with shallow surface monitoring such as acoustic detection.

Seasonal variability, seawater chemistry variability and other features such as the presence of shallow gas (CH_4, CO_2, H_2S) in marine sediments need to be considered in any monitoring programme. Other factors such as seabed recycling and sediment transport and anthropogenic activities such as trawling also need to be taken into account.

Expert Review Comments

- Monitoring techniques have to be able to demonstrate conformance. This has been explained where a technique can be used to verify conformance.
- Cost information was too imprecise. Cost information has been included where possible but expressed as a ranges because cost can depend on a number of site-specific factors and whether different techniques can be carried out simultaneously.

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[3] Finite Volume Coastal Ocean Model

- The development of regulations for offshore CO_2 storage was queried. The report includes details of the extent of development by different jurisdictions including US and Japanese examples.
- The structure of the report was changed so that the subject matter is presented in a more fluent sequence and is cross-referred.
- Natural seeps, including hydrocarbons and other gases, need to be distinguished from potential CO_2 leakage from storage sites. The report includes a section on the origin and occurrence of natural seeps.
- The ability to track CO_2 plumes was raised. The report does include good examples of highly effective tracking and where it is more challenging. It also explores the use of complementary monitoring techniques and demonstrates their effectiveness.
- The potential solutions to the challenges presented by different monitoring techniques was queried. There is a synthesis section and an appendix which discusses R&D priorities that addresses the key challenges.
- Discussion about the monitoring of the Sleipner injection programme and the Hugin Fracture observations have been separated to avoid any misconstrued link between them.

Conclusions

- Dedicated storage regulation was initiated by amendments to the London Protocol and the OSPAR Convention in 2006 and 2007 which put in place for the first time the legislative means for storing CO_2 beneath the seafloor. This was followed by publication of the European Storage Directive in 2009 which set out a comprehensive framework for storage site operation including detailed requirements for monitoring and verification.
- Deep-focussed operational monitoring systems have been deployed for a number of years at Sleipner, Snøhvit and also at the pilot-scale K12-B project in the offshore Netherlands. Time-lapse 3D streamer seismics at both Norwegian sites have proved strikingly effective at both storage sites providing strong capabilities for conformance and containment assurance.
- Downhole pressure monitoring at Snøhvit proved crucial in identifying non-conformant storage behaviour and triggering a modification of injection strategy. At K12-B downhole pressure also proved to be the key tool for conformance history-matching.
- A number of deep-focussed research monitoring tools have been deployed at Sleipner and K-12B. Of these seabed gravimetry has so far perhaps shown the most promise providing indications of natural complementarity with seismics.
- Many tools for the detection of shallow leakage and CO_2 emission at the seabed have been tested at both natural and artificial emission sites. Shallow monitoring tools fall into three categories, geophysical, chemical and biological. The former principally comprise variants of sonar/echosounding and aim either to detect changes of seabed morphology and reflectivity in time-lapse mode, or to directly detect bubble-streams in the water column. An ongoing research challenge is to quantify bubble fluxes with geophysical methods and both active and passive ‘listening’ acoustic systems have demonstrated quantitative measurement potential via advanced processing of the bubble-stream measurements. Chemical sampling methods aim to detect and characterise changes in the shallow sediments or seawater column due to emitted CO_2 or precursor fluids from the subsurface. Deployment of all shallow-focussed technologies can be via ship, remotely-operated vehicle (ROV) or automatic underwater vehicle (AUV). The latter offers the potential for low-cost long-term monitoring deployments but battery life and data collection and transmission constraints are still significant. Biological methods of emission detection are still in their infancy and reliable, practical methods have yet to be developed.

- Natural variation is a key issue for shallow monitoring and properly characterised baseline datasets are essential to capture naturally-occurring spatial and temporal variation. In this regard stationary monitoring systems deployed on the seabed via landers have the potential for tracking time dependent changes over periods of several months or more.
- Assessment of the results from both the operational (predominantly deep-focussed) and research (predominantly shallow-focussed) monitoring activities from Sleipner and Snøhvit indicates that many elements of the new European storage requirements have been met at these large-scale sites.

Knowledge Gaps

Deep-focussed monitoring relies heavily on established hydrocarbon industry tools which are mature. There is scope for improving some of these technologies and related data processing and interpretation for CO_2 storage. R&D priorities for seismics include:

- Better understanding of how seismics can discriminate between changes in pressure and saturation.
- Improvements in hardware (spatial positioning, data transmission, sensitivity, sensors, real-time recording, improved seismic sources, sensor reliability in passive mode).
- Improvements in data processing and analysis (improved imaging, visualisation, integrated interpretation, and joint inversion).
- Improved shallow imaging (e.g. by further development of the P-Cable system).
- Robust communication systems for permanent systems (so the data are available in real time).
- Low-cost monitoring systems such as seismic interferometry using both passive and active sources are being tested in a variety of settings but are far from proven.
- Continued improvement in the emerging area of fibre-optics.
- The quantification of CO_2 within a reservoir still remains a challenge. The detection and quantification of leakage also remains a technical challenge.

Improvements in other methods include seabottom gravimetry, downhole logging to identify fluid saturation. The development of wellbore monitoring tools to test wellbore integrity would be beneficial. Downhole fluid sampling is not advanced for offshore deployment.

Shallow-focussed monitoring is less advanced compared with deep focused monitoring. AUV technology capable of long-range deployment needs to be developed so that the AUV can be tracked transmit data via a satellite communications system. Real-time data retrieval and navigation will enable onshore operators to modify or refine surveys without costly intervention using a survey vessel. Further development in integrated in situ sensors has been underway over the last five years. An integrated approach to the powering, communications and data management of developed sensors is being pioneered by the active sharing of knowledge by the research groups engaged in this field, which combine academic groups with sensor development companies to enable commercialisation. Trawler proofing subsea sensors to protect them from damage remains a risk.

Model development of marine systems is required to improve their predictive capabilities. Advances are needed so that systems can simulate leakage in the context of natural variability by combing both pelagic and benthic dispersion and chemistry, including carbonate and redox processes. There is also a need to develop models that can simulate large scale dispersion of multi-phase plumes whilst simultaneously simulating tidally-induced dispersion in the near- and far-field. The development of dispersion models is a potential topic for the environmental network which meets in September 2015 at the National Oceanography Centre (NOC) in Southampton, UK. The NOC, for example, has 3D general circulation models (GCMs) that can provide a realistic representation of ocean physics.

Recommendations

- A review should be commissioned by IEAGHG on the requirements for monitoring large surface areas at high sensitivity including cost-effectiveness and complementary benefits of different monitoring techniques. It should also review the effectiveness of monitoring techniques to adequately detect and monitor secondary accumulations at shallower depths. These techniques could be used to detect gas chimneys and help to distinguish the origin of natural seeps. An example of research in this field from the Gulf of Mexico was presented at a combined monitoring and modelling network meeting in August 2014, but research for similar applications in other regions like the North Sea would be beneficial.
- Future monitoring network meetings need to present and review the development or emergent technologies that are under development or have been tested in an offshore environment. The use of natural submarine seeps could provide a useful test bed for monitoring research.
- Review examples of natural CO_2 migration along or across faults and fractures that extend to the seabed in an IEAGHG study.

REVIEW OF OFFSHORE MONITORING FOR CCS PROJECTS: IEA/CON/14/223

by specialists from BGS, NOC, PML, UoS

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Executive summary

The world's first large-scale dedicated CO_2 storage operation commenced at the Sleipner gas field in the Norwegian North Sea in 1996; this was followed by the Snøhvit project, also in Norwegian waters, in 2008. There are current plans for up to three more large-scale storage projects in the North Sea Basin: Goldeneye and White Rose in the UK and ROAD in the Netherlands; and a pilot-scale project in Japan. If these come to fruition then near-term rollout of full-chain CO_2 storage will be predominantly offshore. It is timely therefore to review the issues surrounding the monitoring of large-scale offshore storage.

Dedicated storage regulation was initiated by amendments to the London Protocol and the OSPAR Convention in 2007 which put in place for the first time the legislative means for storing CO_2 beneath the seafloor. This was followed by publication of the European Storage Directive in 2009 which set out a comprehensive framework for storage site operation including detailed requirements for monitoring and verification. It is in Europe that the regulatory framework is most mature but offshore storage regulations also exist and are developing elsewhere, notably in Japan, Australia and the Unites States. Although drafted at various levels of detail, the regulatory documents from the different national jurisdictions all emphasise the key role of monitoring and the range of objectives it should serve. These can be broadly distilled as demonstrating that the storage site is performing effectively and safely and that it will continue to do so into the future. This approach can therefore be expressed as providing assurance of containment and conformance. It is important to stress however that even in Europe rigorous operational implementation of a regulatory regime has not yet occurred. The Sleipner and Snøhvit projects both pre-date establishment of the European legislative framework, and so the interaction of operational monitoring practice with regulatory requirements remains to be tested.

Monitoring can be split into two main categories: deep-focussed (providing surveillance of the reservoir and deeper overburden) and shallow-focussed (providing surveillance of the near seabed, seabed and water-column).

Deep-focussed operational monitoring systems have been deployed for a number of years at Sleipner, Snøhvit and also at the pilot-scale K12-B project in the offshore Netherlands, and conclusions regarding the efficacy of key technologies are starting to emerge. Time-lapse 3D streamer seismics have proved strikingly effective at both large scale storage sites, providing strong capabilities for conformance and containment assurance. The seismics have proved capable of imaging the CO_2 plume with high resolution both in the Sleipner reservoir (at 800 m depth) and in the much thinner Snøhvit reservoir (at ~2600 m depth). In addition they have shown the ability to detect and map pressure changes at reservoir level. The full spatial coverage of 3D seismics also offers robust and potentially quantifiable leakage detection capability (in the sense of detecting unintended CO_2 migration in the subsurface). Downhole pressure monitoring was not deployed at Sleipner but at Snøhvit this proved crucial in identifying non-conformant storage behaviour and triggering a modification of injection strategy. At K12-B downhole pressure also proved to be the key tool for conformance history-matching.

A number of deep-focussed research monitoring tools have been deployed at Sleipner and K-12B. Of these, seabed gravimetry has so far perhaps shown the most promise, providing indications of natural complementarity with the seismics in providing preliminary constraints on amounts of CO_2 dissolution at Sleipner. Variants on the 3D seismics theme are also likely to emerge, such as seabottom sensor deployment which offers the potential for improved data quality and flexibility (notably multi-azimuthal and multi-component analysis) and better coverage around offshore infrastructure.

No operational shallow-focussed monitoring has been yet been deployed offshore, but this will change with the new regulated projects coming on stream. Extensive research deployments of shallow monitoring systems have taken place at both Sleipner and Snøhvit and in both cases normal seabed conditions have been encountered throughout. Many tools for the detection of shallow leakage and CO_2 emission at the seabed have been tested at both natural and artificial emission sites. Shallow monitoring tools fall into three categories, geophysical, chemical and biological. The former principally comprise variants of sonar/echosounding and aim either to detect changes of seabed morphology and reflectivity in time-lapse mode, or to directly detect bubble-streams in the water column. An ongoing research challenge is to quantify bubble fluxes with geophysical methods and both active and passive 'listening' acoustic systems have demonstrated quantitative measurement potential via advanced processing of the bubble-stream signals. Chemical sampling methods aim to detect and characterise changes in the shallow sediments or seawater column due to emitted CO_2 or precursor fluids from the subsurface. Deployment of all shallow-focussed technologies can be via ship, remotely-operated vehicle (ROV) or automatic underwater vehicle (AUV). The latter offers the potential for low-cost long-term monitoring deployments but battery life and data collection and transmission constraints are still significant. Biological methods of emission detection are still in their infancy and reliable, practical methods have yet to be developed.

Natural variation is a key issue for shallow monitoring and properly characterised baseline datasets are essential to capture naturally-occurring spatial and temporal variation. In this regard stationary monitoring systems deployed on the seabed via landers have the potential for tracking time dependent changes over periods of several months or more. This is sufficient to capture key seasonal changes, but longer-term variability might need multi-year survey campaigns. Onshore, the value of baselines has been proven in refuting leakage allegations.

Assessment of the results from both the operational (predominantly deep-focussed) and research (predominantly shallow-focussed) monitoring activities from Sleipner and Snøhvit indicates that many elements of the new European storage requirements have been met at these large-scale sites. Based on this and also taking into account the monitoring plans for the new planned projects which are designed to meet the European regulatory requirements (specifically the monitoring plan for Goldeneye), we can outline a generic monitoring approach for offshore storage.

The monitoring plan would comprise a 'core' element designed to meet the regulatory requirements of a site that performs as expected throughout its history and a 'contingency' component held in reserve to address any unexpected behaviour that might occur. It is anticipated that a relatively small number of key tools should suffice for the 'core' monitoring element and simplicity should be the byword. The 'contingency' monitoring portfolio might include a more specialised toolset. With deep-focussed monitoring for containment and conformance the emphasis is on technologies of proven reliability, resolution and robustness, particularly in terms of spatial coverage. Shallow-monitoring, for containment and environmental impacts, is a less mature field and relies on a mixture of commercial and research technologies currently at various stage of development.

It is instructive to compare the different aspects of offshore monitoring with onshore equivalent practice. Deep-focussed monitoring systems have much in common, though with different logistical and technical issues. Some techniques, notably time-lapse seismics, can be compromised by near-surface complexity onshore. On the other hand downhole tool deployments are much more logistically complex and expensive offshore which might lead to a lower emphasis on downhole monitoring. Thus key down-hole tools used successfully onshore, mainly through CO_2-EOR and pilot-scale projects, such as wireline fluid saturation logging and passive seismics have not yet been deployed offshore for operational monitoring, although some are included at the planned offshore sites. Issues connected with shallow monitoring differ markedly from the offshore to the onshore. Logistics and difficulty of access characterise the offshore and particular issues, such as trawler damage, constrain what can be achieved in terms of permanent monitoring installations. On the other hand it is possible both to 'see' and 'hear' emissions offshore via bubble-streams whereas onshore, near surface hydrogeological complexity and surface infrastructure can render leakage and emissions monitoring very challenging.

The capabilities of monitoring tools and the understanding of how to deploy them optimally for robust containment and conformance assurance have improved markedly in the past few years, but challenges do remain. Wellbore integrity is a significant issue, particularly the ability to assess and monitor plugged and abandoned wellbores which cannot be readily accessed. The measurement of CO_2 emissions at seabed (such as might be required to satisfy an emissions trading system) still presents significant difficulties, notably in establishing methodologies which can provide robust detection and quantification over extended areas. Other more generic challenges remain as well, notably in data transmittal for real time monitoring, power supply and consumption for remotely operated monitoring platforms, and in the general reduction of monitoring costs and its environmental impacts.

Contents

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Chapter 1: Introduction

This report reviews offshore monitoring practice for CO_2 storage projects in terms of tool capabilities, logistical practicalities and costs. The focus is on large-scale 'commercial' storage monitoring and we draw together published experience from existing large offshore CO_2 storage operations as well as monitoring research at experimental test sites and in areas of natural CO_2 seepage. The strengths and weaknesses of monitoring techniques, strategies and methodologies are discussed, and relevant learnings from onshore sites are also included. Monitoring over the full life-cycle from pre-injection (baseline) through injection and post-injection phases to transfer of responsibility to the competent authority is considered. The review is not intended to be fully comprehensive, but rather draws on selected examples of current or planned monitoring practice, which we believe can stand as bellwethers for the large-scale rollout of regulated offshore storage.

The report details our findings and conclusions as outlined below:

Chapter 1 Introduction

Chapter 2 Offshore regulation and monitoring objectives

Chapter 3 Current experience at operational CO_2 storage sites

Chapter 4 Findings from natural analogues sites, experimental sites and modelling

Chapter 5 Review of efficacy of current and planned monitoring plans with respect to regulatory requirements

Chapter 6 Concluding synthesis and sample offshore monitoring template

APPENDIX 1 Offshore – onshore comparisons

APPENDIX 2 R & D priorities for offshore monitoring

Following this introduction, **Chapter 2** summarises current regulatory and technical requirements for large-scale offshore CO_2 storage with examples from Europe, Australia, Japan and the United States. **Chapter 3** reviews current monitoring experience at both operational and planned offshore CO_2 storage sites, and assesses the objectives, capabilities, practicalities and costs of the monitoring techniques deployed there. **Chapter 4** reviews monitoring experience gained from experimental and natural analogue sites and modelling studies. **Chapter 5** discusses the efficacy of current and planned offshore monitoring plans with respect to the relevant regulatory requirements. **Chapter 6** synthesises the report findings into a sample offshore monitoring strategy and template aiming to meet regulatory needs in a cost-effective manner.

Additional related issues are examined in the Appendices. **Appendix 1** provides comparisons with equivalent onshore monitoring practice. **Appendix 2** assesses technology gaps and synergies and gives recommendations on priorities for further research and development.

Chapter 2: Offshore regulation and monitoring objectives

In this chapter we set out the key regulatory and technical requirements for large-scale offshore CO_2 storage. For purposes of clarity it is useful to define a small number of key terms which will be used hereafter. Our usage is broadly as set out in the European Storage Directive (EC, 2009):

1. *'geological storage of CO_2' means injection accompanied by storage of CO_2 streams in underground geological formations;*
2. *'water column' means the vertically continuous mass of water from the surface to the bottom sediments of a water body;*
3. *'storage site' means a defined volume area within a geological formation used for the geological storage of CO_2 and associated surface and injection facilities;*
4. *'geological formation' means a lithostratigraphical subdivision within which distinct rock layers can be found and mapped;*
5. *'storage complex' means the storage site and surrounding geological domain which can have an effect on overall storage integrity and security; that is, secondary containment formations;*
6. *'leakage' relates to the unintended subsurface migration of CO_2, specifically release of CO_2 from the storage complex;*
7. *'emission' means any release of CO_2 from the subsurface into the water column (note that this definition is not from the EC Directive, but is used for the purposes of this report).*
8. *'exploration' means the assessment of potential storage complexes for the purposes of geologically storing CO_2 by means of activities intruding into the subsurface such as drilling to obtain geological information about strata in the potential storage complex and, as appropriate, carrying out injection tests in order to characterise the storage site;*
9. *'exploration permit' means a written and reasoned decision authorising exploration, and specifying the conditions under which it may take place, issued by the competent authority pursuant to the requirements of this Directive;*
10. *'operator' means any natural or legal, private or public person who operates or controls the storage site or to whom decisive economic power over the technical functioning of the storage site has been delegated according to national legislation;*
11. *'storage permit' means a written and reasoned decision or decisions authorising the geological storage of CO_2 in a storage site by the operator, and specifying the conditions under which it may take place, issued by the competent authority pursuant to the requirements of the Directive;*
12. *'CO_2 stream' means a flow of substances that results from CO_2 capture processes;*
13. *'CO_2 plume' means the dispersing volume of CO_2 in the geological formation;*
14. *'migration' means the movement of CO_2 within the storage complex and elsewhere in the subsurface;*
15. *'significant irregularity' means any irregularity in the injection or storage operations or in the condition of the storage complex itself, which implies the risk of a leakage or risk to the environment or human health;*
16. *'corrective measures' means any measures taken to correct significant irregularities or to close leakages in order to prevent or stop the release of CO_2 from the storage complex;*
17. *'closure' of a storage site means the definitive cessation of CO_2 injection into that storage site;*
18. *'post-closure' means the period after the closure of a storage site, including the period after the transfer of responsibility to the competent authority;*

2.1 Offshore storage regulation

International restrictions to the offshore geological storage of CO_2 were modified in 2007 with amendments to the London Protocol and the OSPAR Convention (which applies to the Northeast Atlantic). Both of these have similar two-stage monitoring guidelines in place. The first stage is for performance monitoring of the CO_2 in the storage formation and leakage detection at depth. The second stage is for environmental impact assessment in the event that leakage to surface is suspected, which then requires monitoring of the seafloor and marine communities (Dixon et al., 2009; London Protocol, 2007; OSPAR Guidelines, 2007).

Since then the global regulatory framework has been evolving, particularly in Europe where the European Commission has developed a specific Directive for underground CO_2 storage. Even in Europe, which hosts all of the operational and currently planned large-scale offshore storage projects[1], it is recognised that precedents for the finer details of regulatory implementation have not yet been set. The Sleipner (Norwegian North Sea), Snøhvit (Norwegian Barents Sea) and K12-B (Netherlands North Sea) storage projects have been active for several years and predate the current legislation, whereas the planned Goldeneye (UK North Sea), White Rose (UK North Sea) and ROAD (Netherlands North Sea) projects will all be subject to European storage regulation. The main focus on regulations in this report is therefore in a European context (Section 2.1.1). Japanese, Australian and US regulations are outlined in sections 2.1.2-2.1.4, as the main other areas that have considered offshore storage regulation to date.

The London Protocol (LP)

The London Protocol (1996) is a global agreement protecting the marine environment by regulating dumping of waste in the sea. It incorporates 42 countries and is an updated version of the London Convention (1972), which incorporates 87 countries. Amendments were made in 2006 to allow environmentally sound geological storage and were ratified by sufficient countries to come into force (London Protocol, 2007, annex 3; reviewed in Dixon et al., 2009). The list of substances that could be dumped was amended to include "*CO_2 streams from CO_2 capture processes for sequestration*" but only if "*the disposal is into a sub-sea-bed geological formation and they consist overwhelmingly of carbon dioxide*".

In addition two sets of guidance documents were produced to encourage best practice.

- Risk Assessment and Management Framework for CO_2 sequestration in sub-seabed geological structure (RAMF)
- Specific guidelines for the assessment of CO_2 streams for disposal into sub-seabed geological formation (Also known as the CO_2 Specific Guidelines or the CO_2 Waste Assessment Guidelines (WAG) – as in Section 2.1.3)

These include guidance on site-by-site characterisation and risk assessment requirements and introduced the environmental impact assessment process, in addition to the two-stage monitoring previously mentioned (monitoring for measuring performance and monitoring when leakage is suspected). Other key monitoring-related guidance include revision to monitoring activities in response to monitoring results and the reduction in monitoring frequency as confidence in storage security increases.

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[1] Note the planned very large-scale project at Gorgon, offshore of NW Australia, will actually store its CO_2 beneath Barrow Island, and will deploy principally land-based monitoring.

The London Protocol was further amended in 2012 to take trans-international-boundary CO_2 storage into account, whereby consent from all parties is needed, and to allow adequate information sharing between parties. (London Protocol, 2012, Annex 8).

2.1.1 European offshore storage regulations

The two key regulatory treaties governing CO_2 storage in the European offshore area are the OSPAR Guidelines (OSPAR, 2007) and the European Storage Directive (EC, 2009). A third document, the EU Monitoring and Reporting Guidelines (EC, 2011b), deals with the accounting of leaked emissions from storage sites under the EU Emissions Trading Scheme (ETS). The OSPAR Guidelines for Risk Assessment and Management of Storage of CO_2 in Geological Formations**,** published in 2007 (in light of the London Protocol amendment), place emphasis on monitoring through all stages of a storage project from collation of baseline data to long-term post injection monitoring, for the dual purposes of detecting potential leakages and emissions and verifying that such leakage does not occur. OSPAR stipulates that no storage shall take place without a risk management plan to include monitoring and reporting requirements, mitigation and remediation options and a plan for site closure. In terms of the latter, the guidelines also stipulate that monitoring shall continue 'until there is confirmation that the probability of any future adverse environmental effects have been reduced to an insignificant level'. Ongoing review of monitoring results is central to continued permitting.

OSPAR is primarily focussed on detecting and avoiding leakage and emissions and therefore identifies the following objectives for a monitoring programme:

a. Monitoring for performance confirmation.

b. Monitoring to detect possible leakages.

c. Monitoring of local environmental impacts on ecosystems.

d. Monitoring of the effectiveness of CO_2 storage as a greenhouse gas mitigation technology.

The following essential elements of monitoring and control are stated as required to help achieve these objectives:

a. The injection rate.

b. Continuous pressure monitoring.

c. Injectivity and pressure fall-off testing.

d. The properties of the injected fluid (including temperature and solid content, the presence of incidental associated substances and the phase of the CO_2 stream).

e. Mechanical integrity of seals and (abandoned) wells.

f. Containment of the CO_2 stream including performance monitoring and monitoring in overlying formations to detect leakage.

g. Control measures, overpressure and emergency shutdown system.

The EC Directive on the Geological Storage of CO_2, published in 2009, provides a regulatory framework for the permanent storage of CO_2 in amounts exceeding 100 kilotonnes. It further develops the OSPAR principles and provides more detail of the practical implementation of a licensing regime. The

Directive applies to the geological storage of CO_2 in the territory of the Member States, their exclusive economic zones and on their continental shelves within the meaning of the United Nations Convention on the Law of the Sea (UNCLOS).

Note that a review of the EC Directive (during April – December 2014) is, at the time of writing, currently ongoing.

The EC Storage Directive specifically addresses monitoring for the purposes of assessing whether injected CO_2 is behaving as expected, whether any migration or leakage occurs, and if this is damaging the environment or human health. Specifics are set out in Article 13:

> *"Member States shall ensure that the operator carries out monitoring of the injection facilities, the storage complex (including where possible the CO_2 plume), and where appropriate the surrounding environment for the purpose of:*
>
> a. *Comparison between the actual and modelled behaviour of CO_2 and formation water, in the storage site;*
>
> b. *Detecting significant irregularities;*
>
> c. *Detecting migration of CO_2;*
>
> d. *Detecting leakage of CO_2;*
>
> e. *Detecting significant adverse effects for the surrounding environment, including in particular on drinking water, for human populations, or for users of the surrounding biosphere;*
>
> f. *Assessing the effectiveness of any corrective measures taken...[in case of leakage];*
>
> g. *Updating the assessment of the safety and integrity of the storage complex in the short- and long-term, including the assessment of whether the stored CO_2 will be completely and permanently contained.*

Annex II of the Directive sets out criteria for establishing and updating the monitoring plan and for post-closure monitoring. It states that monitoring shall be based on a monitoring plan which will be updated throughout the project lifetime as the risk profile changes and which takes into account improvements in scientific knowledge and best available technology. Member States are therefore required to ensure that during the operational phase, the operator monitors the storage complex and the injection facilities on the basis of an approved monitoring plan designed to address specific monitoring objectives. The Competent Authority is the regulatory organization designated within the Member State responsible for applying the regulations. The operator should report the results of the monitoring, including information on the monitoring technology employed, to the Competent Authority at least once a year. Routine inspections are required to be carried out at least once a year. The inspection will examine relevant monitoring facilities. If a Competent Authority withdraws a permit it will temporarily take over all legal obligations related to acceptance criteria, including monitoring, until a new permit has been issued.

To enable site closure and transfer of responsibilities, the operator should submit a post-closure plan approved by the Competent Authority. This must include demonstration that actual behaviour of the injected CO_2 conforms to the modelled behaviour, the absence of any detectable leakage and that the storage site is evolving towards a situation of long-term stability.

The monitoring plan itself should provide details of the monitoring to be deployed at the main stages of the project, including baseline, operational and post-closure monitoring. The following shall be specified for each phase:

- Parameters monitored.
- Monitoring technology employed and justification for technology choice.
- Monitoring locations and spatial sampling rationale.
- Frequency of application and temporal sampling rationale.

In terms of monitoring tools, the Directive requires a number of continuous or intermittent measurement activities that might be considered mandatory: fugitive emissions at the injection facility; CO_2 volumetric flow at injection wellheads; CO_2 injection pressure and temperature at injection wellheads; chemical analysis of the injected material; reservoir temperature and pressure. These aside, the Directive restricts itself to providing general guidance on technologies and their purpose, suggesting consideration of technologies that can:

- Detect the presence, location and migration paths of CO_2 in the subsurface and at surface.
- Provide information about pressure-volume behaviour and spatial distribution of the CO_2 plume to refine numerical simulations.
- Provide wide aerial spread in order to capture information on any previously undetected potential leakage pathways across the areal dimensions of the storage complex and beyond.

During the closure of a storage site, the operator should remain responsible for monitoring until a post-closure plan has been submitted and approved by the Competent Authority. Part of the approval process and transfer of responsibilities (Article 18) is the provision of a transfer report, which includes a demonstration that all available evidence indicates that the stored CO_2 will be completely and permanently contained and:

a. The conformity of the actual behaviour of the injected CO_2 with the modelled behaviour.

b. The absence of any detectable leakage.

c. That the storage site is evolving towards a situation of long-term stability.

These crucial closure-related criteria are critically dependent on the monitoring plan and its efficacy.

Once a project is completed and the storage site closed to the satisfaction of the Competent Authority, any liabilities associated with the site (termed responsibilities in the Directive) are transferred to the Competent Authority. At this point, monitoring may be reduced to a level which still allows identification of leakage or significant irregularities. If any leakages or significant irregularities are detected, monitoring should be intensified as required to assess the scale of the problem and the effectiveness of corrective measures. The Directive indicates that monitoring costs would be covered by a financial contribution from an operator (before site closure and revocation of the storage licence) and that these costs should cover anticipated monitoring over a period of at least 30 years.

In order to expedite practical implementation of the Directive, a set of Guidance documents have been issued. Four Guidance Documents were published in 2011 by DG Climate Action:

- Guidance Document 1: CO_2 Storage Life Cycle Risk Management Framework.
- Guidance Document 2: Characterisation of the storage complex, CO_2 Stream Composition, Monitoring and Corrective Measures.
- Guidance Document 3: Criteria for Transfer of Responsibility to the Competent Authority.
- Guidance Document 4: Financial Security (Art. 19) and Financial Mechanism (Art. 20).

Guidance Document 2 is the most relevant for this study (EC, 2011a). It emphasises that the monitoring plan will be developed from the identified risks for the specific site. Site-specific criteria for monitoring requirements may include threshold values which if exceeded would require the implementation of corrective measures. Some of these threshold values will be determined from baseline monitoring and the operational constraints provided by the monitoring systems. Monitoring will also be used to determine the efficacy of corrective measures. Plans, which will be revised throughout the project, will use the best available technologies. The effectiveness of the selected monitoring technologies must be considered and justified.

Guidance Document 2 encourages the use of performance standards:

- *Targets related to operational, plume, pathways and environmental elements of the plan; these must be aligned with objectives of detecting significant irregularities, leakage or migration under Article 13.*
- *Targets relating to the timing, frequency and accuracy of monitoring plan elements.*
- *Defining normal, alert and threshold values for key monitoring elements related to identified risk and linked to triggers for preventive or corrective measures, e.g. formation pressure not to exceed fracture pressure of the caprock (that would be expected to result in an irregularity or leakage). Threshold values should be based on site characterisation, modelling and monitoring technology detection characteristics and resolution.*
- *Establishing a baseline for background emissions. Identified potential leakage pathways and other parameters that will be monitored for environmental performance to detect significant adverse effects on the surrounding environment as required under Article 13 (e.g. water properties, background* CO_2 *flux) before injection.*

It might also prove useful to develop overall performance measures and standards for the entire monitoring scheme e.g. in terms that probability is X% of detecting a leak of Y tonnes per year or more within a time periods of Z days or less.

Performance standards should be reassessed periodically and updated to take account of new information.

The EC Monitoring and Reporting Guidelines (MRG) (EC, 2011b) cover greenhouse gas emissions from the capture, transport and geological storage of carbon dioxide. The MRG state that a monitoring plan should be established, that should include detailed documentation of the monitoring methodology for a specific installation, including the data acquisition and data handling activities, and quality control. For the subsurface storage element, emissions are taken as zero if there is no evidence for release of CO_2 to the seabed or seawater on the basis of monitoring results. However, if leakage from storage is detected, monitoring techniques should be deployed which are capable of quantifying any actual emissions to a specified level of accuracy. Under these circumstances (but not otherwise), the MRG demands additional monitoring to that already required by the Directive and OSPAR.

2.1.2 Offshore geological storage regulations, Victoria, Australia

In Australia, the federal government has jurisdiction from three nautical miles (4.8 km) from the coast. Within the three mile limit the individual states or territories have jurisdiction. Offshore geological storage is based on the London Protocol. Federally, the relevant legislation is the Offshore Petroleum and Greenhouse Gas Storage Act 2006 (available from www.comlaw.gov.au). So far as we are aware, Victoria is the only Australian state to have enacted specific offshore legislation as the Offshore Petroleum and Greenhouse Gas Storage Act 2010 (available from www.legislation.vic.gov.au). It largely mirrors the wording of the federal act, although differences include the requirement for separate state consents and the application of Victorian criminal legislation (relating to the long term liability of storage).

Exploration of an offshore area requires a Greenhouse Gas Assessment Permit which would be awarded over a block or blocks of offshore Victoria. This allows the holder to explore for storage formations, injection sites and undertake injection tests on an appraisal basis.

Approval of greenhouse gas storage operations must take into account potential impacts on existing or future petroleum exploration or production. Injection of CO_2 can only be performed by holders of a Greenhouse Gas Injection Licence.

Greenhouse gas safety zones (paragraph 670) may be imposed to prevent vessels from entering a specified area to a distance of 500 metres around a well or structure. It is not clear if this relates to survey vessels.

A licensee can apply for a Site Closing Certificate which would be accompanied by a report that sets out:

i. *the applicant's modelling of the behaviour of the greenhouse gas substance injected into the identified greenhouse gas storage formation; and*

ii. *information relevant to that modelling; and*

iii. *the applicant's analysis of that information.*

A written report is also required that sets out the applicant's assessment of:

iv. *the behaviour of the greenhouse gas substance injected into the identified greenhouse gas storage formation; and*

v. *the expected migration pathway or pathways of that greenhouse gas substance; and*

vi. *the short-term consequences of the migration of that greenhouse gas substance; and*

vii. *the long-term consequences of the migration of that greenhouse gas substance; and the applicant's suggestions for the approach to be taken by the Commonwealth, after the issue of the certificate, to the monitoring of the behaviour of a greenhouse gas substance stored in the identified greenhouse gas storage formation.*

This Act does not require that monitoring must take place, nor indeed that monitoring for leakage must take place. In fact monitoring, in the sense applied in this study, is not directly mentioned at all. Rather, it is implied that monitoring might be required in order to eliminate, mitigate, manage or remediate a ‘serious situation’ (paragraphs 405-409). Serious situations are those that have resulted in, or might lead to, leakage and emission of CO_2.

2.1.3 Offshore geological storage regulations, Japan

In 2007, The Ministry of the Environment amended the Marine Pollution Prevention Act in line with the London Protocol CO_2 Waste Assessment Guidelines to allow initial demonstration projects in Japan, such as the Tomakomai CCS Demonstration Project to proceed.

Key Provisions for Offshore CO_2 storage regulation in Japan are as follows:

1. Anyone intending to dispose of a CO_2 stream under the seabed must obtain a permit from Minister of the Environment (Article 18.8). Re-permitting is required every 5 years.
2. The Minister of the Environment shall not issue a permit for CO_2 stream storage under the seabed unless the way of storing CO_2 stream will not harm the conservation of the marine environment at the storage site (Article 18.9).
3. Those who hold a permit for CO_2 stream storage under the seabed must monitor status of the pollution at the storage site and report monitoring results to Minister of the Environment. (Article 18.12).

In 2009 the Industrial Science and Technology Policy and Environment Bureau of the Ministry of Economy, Trade and Industry (METI) issued a report which provided a standard “For Safe Operation of a CCS Demonstration Project” (METI, 2009).

METI standard for safe operation of CCS demonstrations

This standard assumes that prior to the start of monitoring a detailed model of the storage system including the reservoir and upper stratum will be created. Reservoir simulations will be undertaken to predict the behaviour of the CO_2 plume. These predictions will be validated and refined through comparison with data obtained during a water injection test, prior to the start of CO_2 injection. Furthermore, sensitivity analyses will be performed to assess those parameters which might impact the most on the behaviour of the site during and following CO_2 injection.

Background data must be collected for a sufficient time prior to the start of injection, to allow comparisons of the acquired data before and after injection starts.

The stated monitoring aims are to:

- Monitor the behaviour of the injected CO_2 (to confirm that the CO_2 is injected and stored securely and stably as it was originally planned).

- Improve the accuracy of the simulation model through comparison of the acquired data with the detail model simulations.
- Detect abnormalities, such as CO_2 leakage if any such should occur.

Constant monitoring of the following is proposed:

- Pressure and temperature at the bottom of the injection well (by estimation if it is impossible to place pressure gauges and thermometers at the bottom of the injection well).
- Injection rate, pressure, and temperature of CO_2 at the well-head of the injection well.
- Annulus pressure at the well-head of the injection well.
- Pressure and temperature in the same formation (continuously linked) where the CO_2 is injected and pressure at this well-head, if observation well(s) exist.
- Annulus pressure at the observation well(s), if observation well(s) exist.
- Microseismicity at the injection site and in its vicinity.

Periodic monitoring of the CO_2 concentration of the injected stream and any impurities within it.

The following should be monitored “as much as possible”:

- Pressure and temperature in the formation located shallower than the cap rock.
- Properties effective for detecting CO_2 such as electrical resistivity, acoustic wave velocity, and saturation.
- Chemical properties of groundwater sampled in the observation well(s).
- Volume and geochemical properties of the fluids, if there are discharge points of subsurface fluids on the ground.

In addition, it is noted that it is desirable to undertake monitoring of the CO_2 behaviour with higher accuracy (for the purpose of demonstration) and specific monitoring technologies are proposed for this.

Other key points in the standard relating to monitoring include:

- Seismic surveys are expected once every two years within the four year permit period.
- History matching to improve the reliability of the numerical simulation models used in estimating CO_2 behaviour after CO_2 injection is encouraged.
- The integrity of injection well, exploration wells should be monitored.
- Following injection, monitoring should continue until at least the CO_2 injection well is shut in. At the stage for specifying the time to abandon the injection wells, subsequent monitoring methods and contents should be studied again.

The standard also includes a list of the main monitoring methods, of which those relevant to offshore monitoring are included in Table 2.1.

Measurement technique	Measurement parameter	Example application
Artificial and natural tracers survey	Travel time, Partitioning of CO_2 into rock, brine or oil, Fluid pathway	Tracing migration of CO_2 in the storage formation Quantifying solubility trapping Tracing leakage
Water composition measurement	CO_2, HCO_3^-, CO_3^{2-}, Major ions, Salinity	Quantifying solubility and mineral trapping Quantifying CO_2-water-rock interactions Detecting leakage into shallow groundwater aquifers
Subsurface pressure measurement	Formation pressure, Annulus pressure, Groundwater aquifer pressure	Controlling formation pressure at fractures Wellbore and injection tubing conditions Leakage from the reservoir
Well loggings	Brine salinity, Sonic velocity, CO_2 saturation	Tracking CO_2 migration in and above the reservoir Tracking migration of brine into shallow aquifers Calibrating seismic velocities for 3D seismic surveys
3D seismic survey	P and S wave velocity, Reflection horizons, Seismic amplitude attenuation	Tracking CO_2 migration in and above the reservoir
Vertical seismic profiling Seismic wave cross hole tomography	P and S wave velocity, Reflection horizons, Seismic amplitude attenuation	Detecting detailed distribution of CO_2 in the reservoir Detecting leakage through faults and fractures
Electrical and electromagnetic surveys	Formation conductivity Electromagnetic induction	Tracking of CO_2 migration in reservoir and the upper portion Tracking of brine migration into shallow aquifer
Gravity measurement	Density changes caused by fluid displacement	Detecting CO_2 migration in or above the reservoir Underground CO_2 mass balance
Land Surface deformation survey	Tilt, Vertical and horizontal displacement using interferometry and GPS	Detecting geomechanical effects on the reservoir and cap rock Detecting CO_2 migration pathways

Table 2.1: Main offshore-relevant monitoring methods identified in Japan (RITE, 2006)

Technological Development Projects

Two methodologies have been produced between 2008 and 2010 on the Technological Development of an Environmental Impact Assessment Methodology and a Technological Development of a Monitoring Methodology. The latter has the following aims:

1. Provide data for “oceanographical simulation” which is a main component of “technological development of EIA”.
2. Consider methods to measure background CO_2 concentration and detect CO_2 leak.

The Technological Development of a Monitoring Methodology led to a research programme to test offshore monitoring technologies at a site of natural CO_2 seeps into the seawater column in Kagoshima Bay, Japan. Data collected included water temperature, salinity, current direction, current speed, CO_2 concentration in seawater, as well as side-scan sonar and an ROV was deployed to collect gas and water samples.

2.1.4 Offshore geological storage regulations, United States of America

Unlike Europe, Japan and Australia, in the United States of America, the regulations are not based on the London Protocol (explained below). Instead, offshore geologic storage of CO_2 is covered by at least three applicable Federal statutes: the Safe Drinking Water Act, the Clean Air Act and the Outer Continental Shelf Lands Act (outlined below). Each of these has a different geographic extent. This is because the coastal States and the Federal government have specific geographic areas of jurisdiction for offshore geologic storage of CO_2 and thus different regulatory regimes exist across this boundary. The jurisdiction of the coastal States extends to the submerged lands offshore for three geographic miles (4.8 km) from the shore baseline for all the coastal States, except Texas and the western (Gulf) coast of Florida. The State-Federal boundary is nine nautical miles (16.7 km) from the shore baseline off the Texas coast and the western (Gulf) coast of Florida. In general, state laws apply only within state submerged land, while Federal laws may apply on either side of a state’s seaward boundary. The submerged lands seaward of the State-Federal boundary that are under Federal jurisdiction are known as the Outer Continental Shelf (OCS).

Safe Drinking Water Act (SDWA) (U.S.A. CFR, 2010a)

The SDWA applies to injection wells within state boundaries, including in state submerged lands, also known as state territorial waters. Under the SDWA, the United States Environmental Protection Agency (EPA) implements the Underground Injection Control (UIC) Program which is responsible for regulating the construction, operation, permitting, and closure of injection wells that place fluids underground for storage or disposal. The UIC Program protects underground sources of drinking water (USDWs) from activities such as subsurface injection of hazardous waste for disposal, enhanced oil recovery, and most recently, CO_2 sequestration, which is also termed Geologic Sequestration (GS).

The EPA promulgated *Federal Requirements Under the Underground Injection Control (UIC) Program for Carbon Dioxide (CO2) Geologic Sequestration (GS) Wells* (75 FR 77230, December 10, 2010) to authorize and regulate (including site monitoring) CO_2 storage within state lands. The regulations include requirements for all aspects of underground storage from site selection well construction, injection operations, testing and monitoring, and financial responsibility, to post injection site care and well closure. The UIC program developed specific guidance documents for Class VI GS wells which outline the specific required elements in well permits via Project Plans, and for detailing the well testing and monitoring necessary for these GS projects. Currently under SDWA there is no mechanism to transfer liability to a third party, so the injection well operator or owner remains liable to protect underground sources of drinking water even after a site has closed.

Clean Air Act (CAA) (U.S.A. CFR, 2010b)

The CAA can apply to facilities both in state submerged lands and beyond. Within state boundaries, the CAA gives authority to both the EPA and the states to regulate emissions. Outside of state boundaries, the CAA gives the EPA authority to regulate emissions from Outer Continental Shelf Sources on the Atlantic and Pacific coasts and the Eastern Gulf of Mexico. [2] (42 USC 7627). The CAA also gives the authority to require reporting of information that applies to facilities both within States and anywhere on the OCS. Under this authority, the EPA promulgated the *Mandatory Reporting of Greenhouse Gases: Injection and Geologic Sequestration of Carbon Dioxide* (75 FR 75060, December 1, 2010).

Outer Continental Shelf Lands Act (OCSLA) (U.S.A. 43 U.S.C.; U.S.A. CFR, 2011)

Under OCSLA, the Department of the Interior (DOI), Bureau of Ocean Energy Management (BOEM) and the Bureau of Safety and Environmental Enforcement (BSEE) may authorize and regulate the development of mineral resources and certain other energy and marine related uses on the OCS. Under this authority, DOI may permit the use and sequestration of CO_2 for EOR activities on existing oil and gas leases on the OCS, and permit the sequestration of CO_2 for certain types of projects.

BOEM is conducting research to develop Best Management Practices (BMPs) for CO_2 sub-seabed sequestration on the OCS (Batum, 2014). The BMPs will address the following:

- Site Selection and Characterization (data collection, capacity/injectivity assessments, modelling, etc.)
- Risk Analysis
- Project Planning and Execution (design, construction, operation, and maintenance)
- Environmental Monitoring
- Mitigation
- Inspection and Auditing
- Reporting Requirements
- Emergency Response and Contingency Planning
- Decommissioning and Site Closure
- Legal Issues (liability, bonding, long-term stewardship)

International law considerations in the United States of America offshore

The United States is a Party to the London Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter, 1972 (London Convention). The London Convention is implemented domestically by the EPA under the Marine Protection, Research, and Sanctuaries Act (MPRSA). The MPRSA prohibits the dumping of material into the ocean (water column) that would unreasonably degrade or endanger human health or the marine environment. While the London Convention does not deal with sub-seabed sequestration, it was modified in 1996 by the London Protocol, which obligates Parties to subject CO_2 stream sequestration in sub-seabed geological structures to the regulatory regime applicable to dumping under the London Protocol. The United States has signed the London Protocol, but it has not yet ratified it (i.e. the United States is not a Party to the London Protocol); and therefore, has not yet amended the MPRSA to include sub-seabed

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[2] In the Western Gulf of Mexico and North Slope of Alaska OCS, the Department of the Interior regulates emissions from activities authorized under the Outer Continental Shelf Lands Act.

"dumping" (including sequestration of CO_2). However, as a signatory, the United States may not take any action to defeat the London Protocol's object and purpose.

2.2 Monitoring objectives

It is clear from the above that a wide range of regulatory requirements, at various levels of detail and in a range of contexts, have been devised for the regulation of offshore storage worldwide. It is also clear that regulatory development is at different stages of completion across the world. Nevertheless, taken in the round, we believe that two relatively consistent monitoring-related themes have emerged: the requirement firstly to demonstrate that a storage site is currently performing effectively and safely and secondly to ensure that it will continue to do so via the provision of information supporting and calibrating prediction of future performance.

These requirements for monitoring offshore storage can be distilled into a number of necessary actions (Table 2.2), which fall within two main monitoring objectives, containment assurance and conformance assurance. A third category, contingency monitoring may be required in the event that containment and/or conformance requirements are not met.

In terms of the types of monitoring tools used, it is convenient to categorise them as deep-focussed (providing surveillance of the reservoir and deeper overburden) and shallow-focussed (providing surveillance of the near seabed, seabed and water-column).

		OSPAR	EU Directive	EU ETS	
Deep-focussed monitoring actions	Migration in overburden	▨	▨		Containment
	Containment integrity	▨	▨		Containment
	Migration in reservoir		▨		Conformance
	Performance testing and calibration and identification of irregularities	▨	▨		Conformance
	Calibration for long-term prediction		▨		Conformance
	Testing remedial actions		▨		Contingency
Shallow-focussed monitoring actions	Verification of no leakage	▨	▨		Containment
	Leakage detection	▨	▨		Containment
	Emissions quantification	▨		▨	Contingency
	Environmental impacts	▨	▨		Other
	Testing remedial actions		▨		Contingency

Table 2.2: Key monitoring actions for offshore storage required under the European regulatory framework

2.2.1 Containment Assurance

The principal element of proving storage performance is to demonstrate that the stored CO_2 is securely retained within the storage site such that it presents no hazard to health or the environment, and further, that the overarching greenhouse gas mitigation objectives of the storage are met. For offshore storage, a distinction can be made between 'leakage' which refers to subsurface migration of CO_2 out of the storage complex and 'emission' which refers to escape of CO_2 from the subsurface into the sea-water column. We adhere to this usage throughout the report.

Containment monitoring therefore has two elements: deep and shallow focussed. Deep-focussed surveillance aims to identify unexpected migration of CO_2 out of the primary storage reservoir, subsequent migration into the overburden and possible secondary reservoirs and movement out of the storage complex triggering the onset of leakage. Thus early warning should be given of potential movement of CO_2 to the seabed.

Shallow-focussed monitoring aims to detect CO_2 migration in the shallow subsurface and emissions at surface either by changes of the seabed or by physical changes (bubbles) or chemical changes in the seawater column or sediments. Shallow-focussed monitoring has the potential to detect small leakages and emissions that could not be detected by deep-focussed surveillance. Note that reservoir emissions are not the only potential source of CO_2 at the seabed or in shallow sediments (see Chapter 4) and natural variability may render the detection of emission signals above background challenging. Containment monitoring should also address the possibility of other, displaced, fluids escaping from the storage site. These could include shallow *in situ* formation water or natural gases displaced across the sediment / seawater interface, or deeper subsurface fluids escaping from depth.

A practical minimum requirement for a deep-focussed monitoring system might be that it can reliably detect any leakage (from the storage complex) that is sufficiently large to compromise the greenhouse gas mitigation function of the storage. That is to say, with no gaps in spatial coverage and to a specified detection threshold depending on the amount of CO_2 stored. The shallow monitoring system should be capable of detecting any emission at seabed likely to pose a health and safety threat or environmental impact.

2.2.2 Conformance Assurance

The second element of proving storage performance is to show that storage processes at a site are understood with a sufficient level of certainty to preclude the possibility of significant future deviation from expected storage behaviour. The basis of this is to demonstrate conformance, which is a measure of the agreement between modelled simulations of site behaviour and monitoring observations thereof.

Conformance is where models and observations agree within acceptable limits. Monitoring enables the testing and calibrating of models of current site behaviour, and forms the basis for reliable prediction of future site behaviour, long-term secure storage and satisfactory site closure.

Non-conformance is where observed site behaviour deviates from that predicted to a significant degree, for example, falling outside stated uncertainty ranges, or with the potential to lead to unfavourable outcomes. In this eventuality the monitoring system is required to guide suitable corrective actions such as additional (contingency) monitoring or other interventions.

Conformance monitoring is primarily deep-focussed, aimed at imaging and characterising processes in and closely adjacent to the storage reservoir. Technologies should have sufficient resolution, sensitivity and / or quantitative capability to test simulation models in a robust way.

2.2.3 Contingency monitoring

Contingency monitoring is for situations where assurance monitoring has detected significant deviation from planned performance. Additional monitoring might be required to track the deviation and assess possible consequences, to design corrective measures if necessary, and, should these be deployed, to confirm that they have been effective. An example might be where CO_2 is observed to be migrating into the shallower geological section, with a threat of future emissions. Contingency monitoring would be necessary to track the migrating CO_2 in the shallow subsurface, to assure that no emissions reach the water column and, if they did, to quantify them. Emissions monitoring under the EU ETS requires that the measurement accuracy of the monitoring system is known.

Chapter 3: Review of experience at current and operational CO_2 storage sites

A number of published studies have reviewed storage monitoring technologies and possible strategies, and some forty or more individual tools have been identified as suitable, or potentially suitable for monitoring CO_2 storage sites (e.g. Benson et al., 2004; Arts et al., 2005; Pearce et al., 2005, 2007; Chadwick et al., 2009; Chadwick 2010; NETL 2012; Hovorka et al., 2014; IEAGHG 2014). Only a subset of these will be technically suitable for monitoring offshore storage and taking into account costs and logistical issues, a still smaller subset will be actually deployed.

This chapter reviews the key tools which have actually been deployed, or are planned for deployment, at the world's offshore storage sites, in terms of their performance, capabilities, practicalities and costs. We outline results from the monitoring programmes that are being currently deployed in Europe at the world's two large-scale offshore storage sites: Sleipner and Snøhvit, as well as the smaller, pilot-scale project at K12-B. We also review tools that are proposed to be deployed at three planned projects: the Goldeneye project in the UK, the ROAD project in the Netherlands (Figure 3.1, Table 3.1) and the Tomakomai project in Japan. Note that the UK White Rose project has not been included because insufficient published information is available at the time of writing.

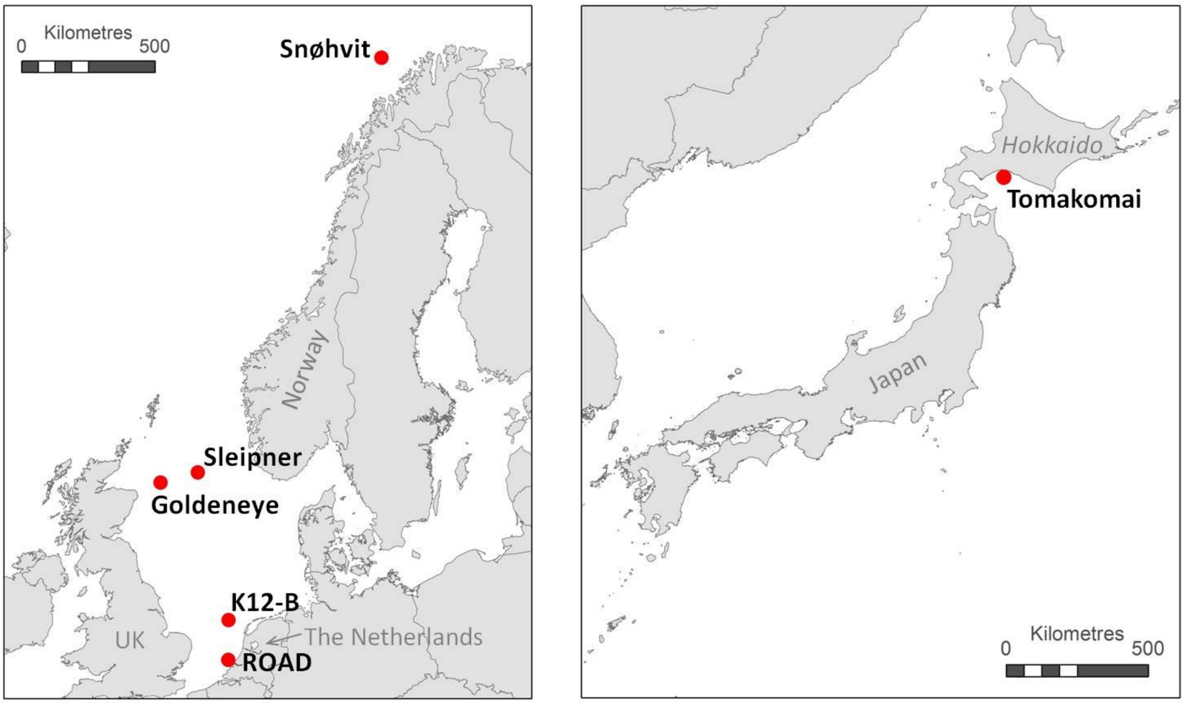


Figure 3.1 Location of offshore CO_2 storage projects discussed in this report (British Geological Survey © NERC 2014).

The Sleipner, Snøhvit and K12-B projects commenced prior to implementation of the EU Storage Directive and their monitoring plans are designed to address particular site-specific objectives. Goldeneye and ROAD are being developed within the European offshore regulatory framework (EU Directive and OSPAR) and their monitoring plans will be compliant with this. Tomakomai is compliant with the London Protocol and relevant Japanese regulations and guidelines. Issues arising from the imperfect alignment of project implementation and regulatory development are discussed in Chapter 5.

Site name:	Sleipner	Snøhvit	K12-B	Goldeneye	ROAD	Tomakomai
Location	Norwegian North Sea	Norwegian Barents Sea	Netherlands North Sea	UK North Sea	Netherlands North Sea	3-4 km offshore Hokkaido Island, Japan
Water depth	90 m	250-330 m	~27 m	120 m	24 m	20-40 m
Injection start	1996	2008	2004	Planned 2019, 10 - 20 years injection	Planned 2015, 8 years injection	Planned 2016 -2018
Injection rate	1 Mt/year	0.77 Mt/year	0.020 Mt/year	1 Mt/year	1.1 (Max 1.5) Mt/year	≥0.1 Mt/year
Injection wells	1 subhorizontal injector	1 injector	1 injector, 1 injector/producer	To be confirmed	To be confirmed	2 deviated onshore wells, 1 for each reservoir (offshore)
Amount injected (at 2014)	~15 Mt	2.3 Mt	> 0.080 Mt	0	0	0
Total intended	~20 Mt	~23 Mt		10 - 20 Mt	8.1 Mt	0.2-0.3 Mt Demo, upscale to commercial?
Type of storage detail	CO_2 extracted onsite from gas production and re-injected into shallower saline aquifer storage	CO_2 extracted onshore from gas production and re-injected into deeper saline aquifer storage	CO_2 extracted onsite from gas production and re-injected for enhanced gas recovery and storage	Onshore gas power plant CO_2 capture piped to depleted gas field storage	Onshore coal power plant post combustion CO_2 capture piped to depleted oil & gas field storage	CO_2 extracted onsite from hydrogen production unit, injected into saline aquifer storage
Type of reservoir	Mio-Pliocene regional sandstone saline aquifer	Heterogeneous Mesozoic interbedded sandstone-shales, fault-compartmentalised	Fault-compartmentalised, heterogeneous Permian sandstones	Cretaceous regional sandstone, 10 km x 130 km "fairway"	Fault-compartmentalised, Triassic sandstones	Lower Quaternary sandstone / Miocene volcanic and volcaniclastic
Porosity and permeability	27-40 % porosity, 1-8 D	10-15 % porosity, 185-883 mD	Mostly low (5-30 mD), ~11 % High (300-500 mD)	18-28 % porosity, 400-1500 mD perm	5-13% porosity, <0.1- 207 mD (mostly <1mD)	20-40 %, 9-25 mD / 3-19 %, 0.01 mD-2.6 D
Injection depth	1012 m (close to base of ~250 m thick reservoir)	~2600 m (Tubåen reservoir), ~2400 m (Stø reservoir)	~3800 m	~2500 m	~3500 m	1168 m / 2789 m
Initial reservoir conditions	36 °C, 10 MPa	98 °C, 29 MPa	127 °C, depleted to 4 MPa	Depleted to 15.2 MPa	Depleted to ~4 MPa (from 34.9 MPa)	10.7 MPa, 45 °C / 35 MPa, 91 °C
Overburden character	Laterally continuous 50-100 m thick mudstone capillary seal of very low permeability, overlain by ~700 m argillaceous rocks.	Regional caprock is formed of upper Jurassic shales and thick Cretaceous shales	The top and lateral seal are provided by the impermeable rock salts of the Zechstein Group ~ 500 m thick above reservoir.	300 m mudrock and tight marl primary seal. Regional mudstones form secondary seals	~150 m primary seal of mudstones and evaporites	Shallow reservoir capped by 200 m mudstones / Deeper reservoir capped by 1100 m mudstones

Table 3.1 Comparison of the main features of the three operational and three planned storage sites discussed in this chapter

3.1 The offshore sites

3.1.1 Sleipner

The CO_2 injection operation at Sleipner in the Norwegian sector of the North Sea is the world's longest-running industrial-scale storage project, commencing in 1996 in response to environmental legislation (Baklid et al., 1996; Korbøl and Kaddour, 1995). Natural gas produced from the Sleipner Vest field has a CO_2 content ranging from 4 % to 9.5 %. This is separated out on the platform and injected into the Utsira Sand, a regional-scale saline aquifer. Injection is via a deviated well, sub-horizontal at the injection point, which lies some 3 km from the platform at a depth of 1012 m below sea level (Figure 3.2a). The average injection rate is rather less than one million tonnes (Mt) per year, with over 15 Mt of CO_2 stored by 2014. The CO_2 shows two-phase behaviour in the wellbore, with wellhead conditions of 25 ^{o}C and 6.3 MPa and initial reservoir conditions at the injection point of around 36 ^{o}C and 10.5 MPa.

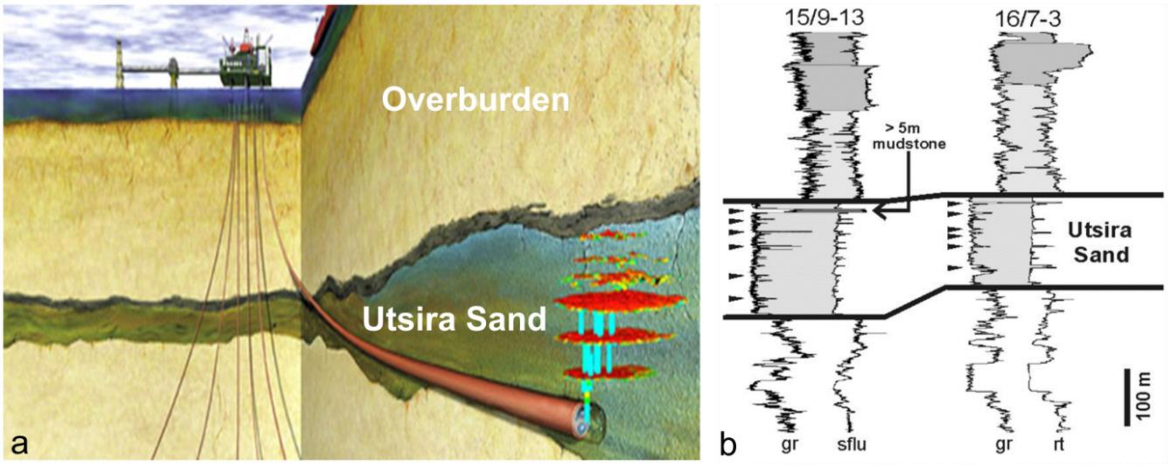


Figure 3.2 a) Schematic diagram of the Sleipner injection infrastructure and the CO_2 plume b) Sample geophysical logs through the Utsira Sand from two wells in the Sleipner area. Note the low γ-ray (GR) signature of the Utsira Sand, with peaks denoting the intra-reservoir mudstones. (a) Courtesy of Statoil ASA b) British Geological Survey © NERC 2014).

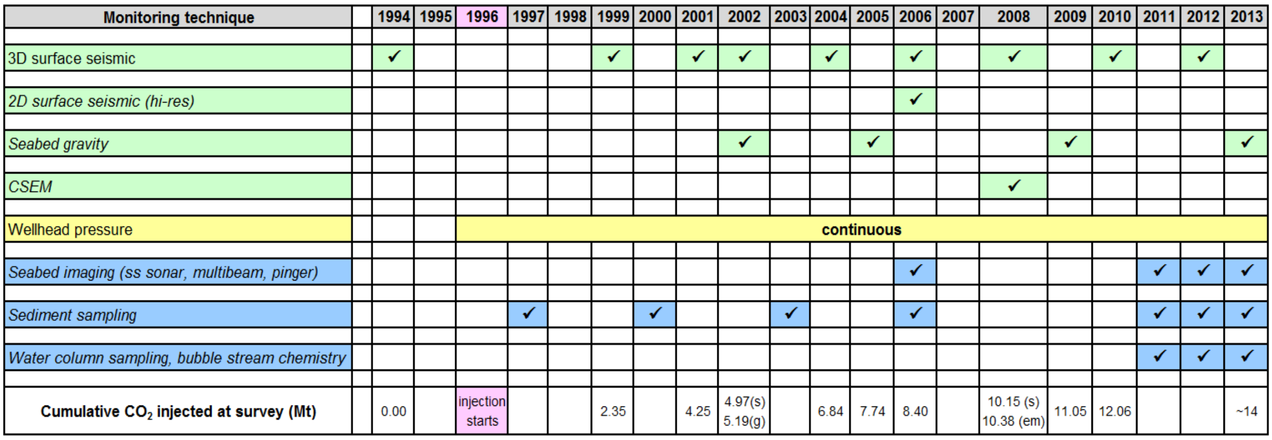
The geological setting of Sleipner is relatively simple and details are set out in a number of publications (e.g. Zweigel et al., 2004; Chadwick et al., 2004). In summary, the Utsira Sand is locally about 250 m thick and comprises predominantly uncemented and weakly consolidated sand of late Cenozoic age. Porosities are typically in the range 35 – 40 % with permeabilities (from core testing and water production testing) ranging from around 1 to 8 darcy. The non-sand fraction largely comprises thin mudstones (typically about 1 m thick), which show as peaks on the gamma-ray and resistivity logs (Figure 3.2b). In the Sleipner area, a thicker mudstone, some 5 to 7 m thick separates the uppermost sand unit from the main reservoir beneath. The mudstone layers form important permeability barriers within the sand and significantly affect CO_2 migration through the reservoir imposing a prominent multi-layered, or tiered, structure to the CO_2 plume (Figure 3.2a). The overburden of the Utsira reservoir comprises about seven hundred metres of dominantly argillaceous rocks. The immediate reservoir topseal comprises a basin-restricted mudstone some 50 to 100 m thick. Geophysical logs, cuttings from surrounding wells, and seismic stratigraphy show the topseal to be laterally continuous and to extend well beyond the predicted lateral spread of the CO_2. Core analysis (e.g. Harrington et al., 2010) shows it to be a capillary seal of very low permeability.

Sleipner monitoring objectives

The monitoring objectives at Sleipner are linked closely to the identified storage risks: migration through the geological seals resulting in leak pathways to the seabed; lateral migration into wellbores, resulting in leak pathways to the seabed and lateral migration of CO_2 outside of the Sleipner licence area. The monitoring programme is primarily based around tracking CO_2 migration in the storage reservoir in order to predict future behaviour and providing the capability to reliably detect changes in the overburden which might indicate out of reservoir movement of CO_2. A secondary, but important, objective is to reduce the likelihood that imperfect understanding of the storage performance could result in inaccurate or poorly- informed criticism of the site from external parties. Although predating the European legislation, the monitoring programme at Sleipner does address the main high level requirements of containment and conformance in a number of ways.

Sleipner monitoring programme

A significant time-lapse monitoring programme has been deployed at Sleipner (Table 3.2). The main early emphasis was on non-invasive deep-focussed surveillance of the reservoir, with no downhole monitoring.



Monitoring technique	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**
3D surface seismic	✓					✓		✓	✓		✓		✓		✓		✓		✓	
2D surface seismic (hi-res)													✓							
Seabed gravity									✓			✓				✓				✓
CSEM															✓					
Wellhead pressure			**continuous**																	
Seabed imaging (ss sonar, multibeam, pinger)													✓					✓	✓	✓
Sediment sampling				✓			✓			✓			✓					✓	✓	✓
Water column sampling, bubble stream chemistry																		✓	✓	✓
Cumulative CO_2 injected at survey (Mt)	0.00		injection starts			2.35		4.25	4.97(s) 5.19(g)		6.84	7.74	8.40		10.15 (s) 10.38 (em)	11.05	12.06			~14

Table 3.2 Monitoring surveys deployed at Sleipner from 1994 to 2013. Research monitoring tools are shown in italics. Green denotes deep-focussed techniques that operate from the surface; yellow denotes well-based techniques and blue denotes shallow-focussed techniques. Note that for years with more than one survey, the amount of CO_2 injected for each specific survey is stated: thus "s" denotes "seismic", "g" gravimetric, and "em" electromagnetic surveys.

The programme subsequently developed in a rather complex way which merits explanation. The monitoring objectives outlined above were all addressed by a single tool; the time-lapse 3D seismics. However throughout its operation Sleipner has participated in a number of scientific research projects (e.g. SACS, SACS2, CO2STORE, CO2REMoVe, CO2CARE, ECO2), and has been utilised as a test-bed for other monitoring technologies, such as potential-field methods and shallow-focussed tools. This research component is also reflected in the high (roughly biennial) repeat frequency for the time-lapse 3D surface seismics which reflects the serendipitous adoption of datasets which were primarily acquired for monitoring the deeper gas reservoir. The strict operational requirements for monitoring the CO_2 storage project, purely as a commercial operation, would require a much sparser repeat frequency of the time-lapse surveys.

3.1.2 Snøhvit

The Snøhvit storage project is located offshore of northern Norway in the south-western Barents Sea in the central part of the Hammerfest Basin, where average water depths range from 250 to 330 m (Linjordet and Olsen, 1992; Hansen et al., 2013). The Snøhvit gas complex comprises three gas reservoirs, Snøhvit, Albatross and Askeladd. The natural gas contains between 5 % and 8 % CO_2 and so needs CO_2 removal prior to sale. The produced gas is transported 160 km by pipeline onshore to the Melkøya LNG plant near Hammerfest. After separation the CO_2 is piped back offshore for injection via a single injector well. Injection of CO_2 started in 2008 at a rate of about 0.8 Mt per year, with some 23 Mt of CO_2 planned for storage over the projected thirty year project lifetime. The CO_2 is in the dense phase throughout, with wellhead conditions of 4 ^{o}C and 12 MPa and initial storage reservoir conditions of 98 ^{o}C and 29 MPa.

The Tubåen Formation formed the initial CO_2 storage reservoir with CO_2 being injected at a depth of about 2600 m beneath and down-dip of the main gas accumulations (Figure 3.3). Following pressure build-up in the Tubåen reservoir, injection was switched to the Stø Formation in 2011 (see below).

The Tubåen Formation is 45 - 75 m thick and dominated by sandstone with thin shale layers and minor coals. Porosities are in the range 10 -15 % and permeabilities vary widely from 185 – 883 mD. However the highly variable depositional and cementation patterns lead to significant lateral and vertical permeability barriers and effective reservoir permeabilities seem to be much lower than the core measurements suggest.

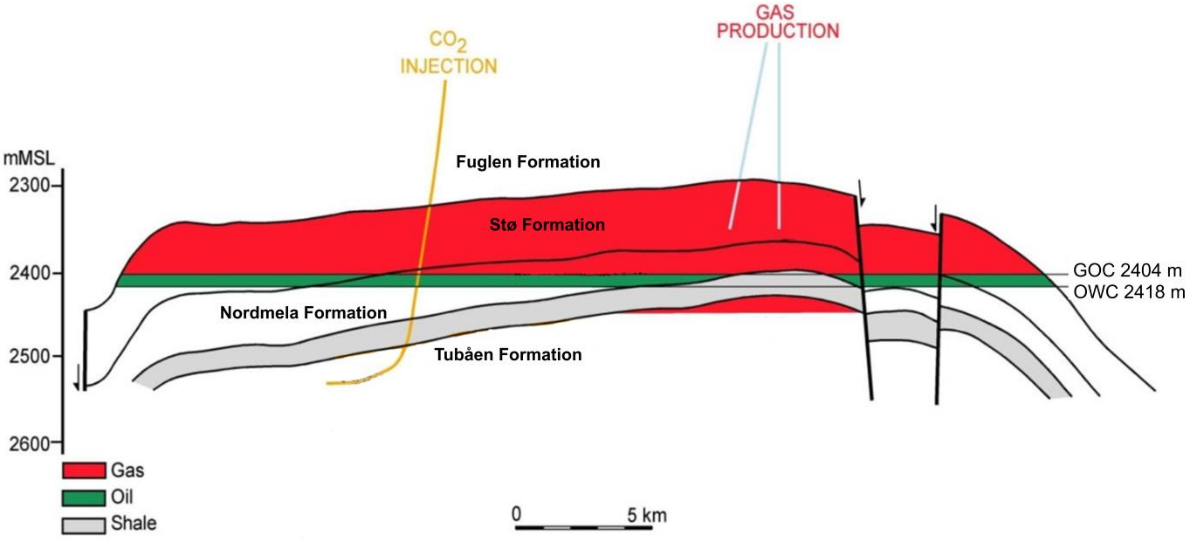


Figure 3.3 West-east simplified cross-section showing CO_2 injection into the Tubåen formation at Snøhvit (modified from information provided by Statoil). GOC = gas-oil contact, OWC = oil-water contact.

The 60 – 105 m thick Nordmela Formation is divided into a lower unit with very poor reservoir characteristics which forms the caprock of the underlying Tubåen storage reservoir, and an upper unit which has reservoir properties that vary from poor to moderate. The main natural gas reservoir is the Stø Formation which is 70 – 100 m thick and consists of thick sandstones alternating with thin shales and mudstones. The regional caprock is formed of upper Jurassic and thick Cretaceous shales. The Late Triassic to Middle Jurassic successions are made up mostly of sandstones interbedded with thin shale layers, including the Fuglen Formation which forms the immediate caprock to the Stø reservoir.

It is notable that the reservoir succession is affected by faulting (Figure 3.3), the 3D baseline seismic survey showing a series of fault-blocks and significant structural compartmentalisation (see below).

Snøhvit monitoring objectives

The main monitoring aims at Snøhvit are twofold: firstly to ensure that injection pressures do not exceed the fracture threshold, to maintain mechanical integrity of the reservoir and its caprock, and secondly to monitor where the CO_2 plume is moving and whether it is migrating to shallower depths, with the risk of impinging on the natural gas accumulations. The storage reservoirs are at considerable depth with a great thickness of sealing overburden strata, so migration into the shallow section and leakage to seabed are not considered to be realistic risks

Snøhvit monitoring programme

Two key deep-focussed monitoring technologies have been deployed at Snøhvit; downhole pressure and temperature monitoring and time-lapse 3D (4D) surface seismic surveys. In addition a number of shallow-focussed research surveys have been carried out by the ECO2 project.

Monitoring technique		**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**
3D surface seismic		✓						✓		✓	✓	
High resolution 3D seismic (p-cable)										✓		✓
Seabed gravity						✓				✓		
Downhole pressure							**continuous**					
Wellhead pressure							**continuous**					
Multibeam echosounding										✓		✓
Conductivity - temperature - depth profiles										✓		✓
Sediment sampling												✓
Water column sampling												✓
Cumulative CO_2 injected (average, Mt)		0					injection starts	0.5		1.0		

Table 3.3 Monitoring surveys deployed at Snøhvit from 2003 to 2013. (Research monitoring tools are shown in italics. Green denotes deep-focussed techniques that operate from the surface; yellow denotes well-based techniques and blue denotes shallow-focussed techniques).

3.1.3 K12-B

The K12-B gas field is located in the Dutch sector of the North Sea, around 150 km northwest of Amsterdam (Figure 3.4). It was designed as a research project, primarily to investigate the efficacy of CO_2 enhanced gas recovery (EGR), and as such the monitoring programme is largely research oriented. Gas has been produced from the field since 1987 and it is nearing depletion. The produced gas is relatively high in CO_2 (around 13 %) and this is reduced to 2 % on site in order to meet export pipeline specifications. Since 2004, over 80000 tonnes of the extracted CO_2 has been re-injected into the field to investigate both CO_2 storage and possible enhancement of natural gas production.

The K12-B reservoir is formed of heterogeneous Permian sandstones, compartmentalised into fault blocks at around 3800 m depth (Figure 3.4). Prior to gas production pressures were around 40 MPa, with an IGIP (initial gas in place) of around 14.5 billion cubic metres (bcm). As of January 2012, 13 bcm had been produced. At the start of CO_2 injection in 2004, pressures had been reduced to 4 MPa and temperature was around 128 °C. The CO_2 is stored in the Schlochteren Formation, a sand-shale sequence deposited under mainly desert and desert lake conditions. About 11 % of the formation is made up of high permeability (300-500 mD) aeolian sands. The remainder is of lower permeability (5-30 mD) fluvial and mud flat facies, with 16 % of the formation made up of shale streaks which form vertical permeability barriers, but these have a continuity of less than a few hundred metres.

The top and lateral seal of the K12-B field are provided by the impermeable rock-salts of the Zechstein Group whose thickness directly above the reservoir is about 500 m. None of the faults within the reservoir penetrate to the top of this seal.

CO_2 injection was initially into compartment 4 (red in Figure 3.4) for one year (over10 000 tonnes), followed by a two-year shut-in period and gas production during 2007-2008. CO_2 injection was switched in 2005 to compartment 3 (yellow in fig 3.4) with around 70000 tonnes injected by 2013 (Van der Meer, 2013; Vandeweijer, 2013). Injection was at a rate of up to 20 kilotonnes/year, with a number of shut-in periods for maintenance.

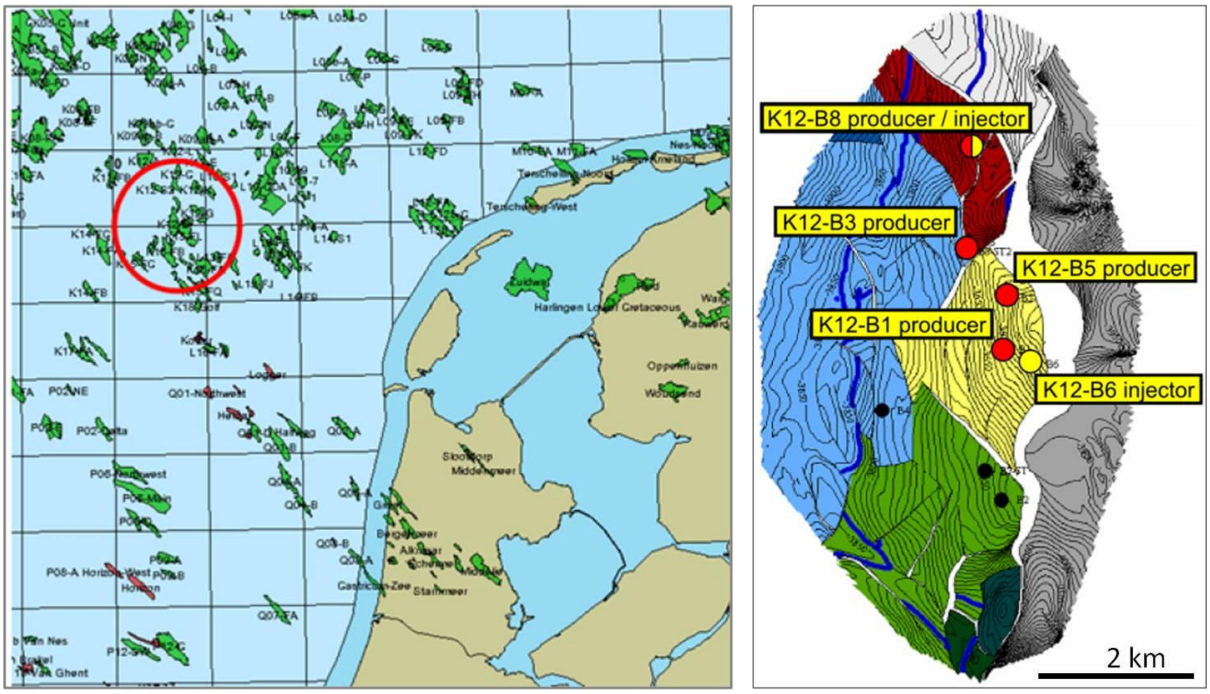


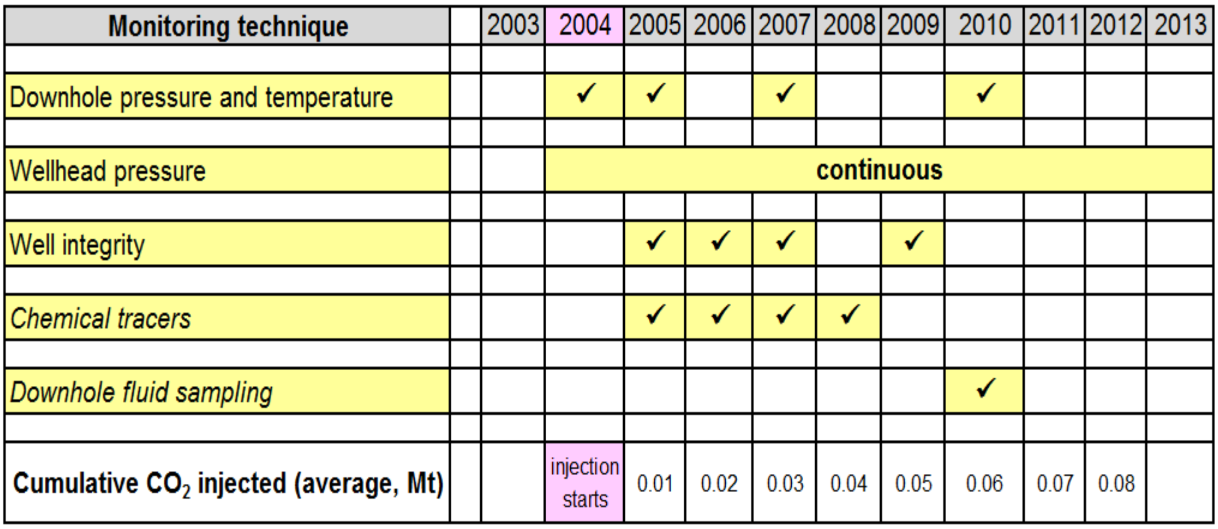
Figure 3.4 Left: Location map of the K12-B gas field in the Dutch North Sea. Right: Plan view of top reservoir in the K12-B gas field. Structural compartments 1-4 are individually coloured. (After Geel et al., 2005).

<u>K12-B monitoring objectives</u>

The thick Zechstein evaporite at K12-B forms an excellent upper and lateral seal. The main risk of potential migration out of the site is therefore considered to be via wellbores, so the primary objective of monitoring is to ensure wellbore integrity. As this is the first enhanced gas recovery (EGR) storage site, monitoring to improve understanding of the behaviour of CO_2 in the wellbore and gas mixing in the reservoir was also a priority.

K12-B monitoring programme

The monitoring programme at K12-B was devised prior to the European CO_2 Storage Directive. Monitoring techniques were deployed through a number of research projects (ORC, CASTOR, MONK, CO2ReMoVe, CATO, and CO2CARE) according to the various research objectives. As such the monitoring programme might not correspond to what would be expected at a full-scale storage site. The programme was revised several times throughout the project due to new insights and also financial complications. For example, the negotiated "loss or damage in hole" insurance for the wellbore deployed techniques was found to not apply for the planned continuous downhole pH monitoring. This tool was therefore not deployed and pH was measured from a downhole fluid sample instead, which provided just a single time snapshot.



Monitoring technique		2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Downhole pressure and temperature			✓	✓		✓			✓			
Wellhead pressure			**continuous**									
Well integrity				✓	✓	✓		✓				
Chemical tracers				✓	✓	✓	✓					
Downhole fluid sampling									✓			
Cumulative CO_2 injected (average, Mt)			injection starts	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	

Table 3.4 Monitoring surveys deployed at K12-B from 2003 to 2013. (Research monitoring tools are shown in italics. Yellow denotes well-based techniques).

3.1.4 Goldeneye

The Peterhead - Goldeneye full-chain CCS project proposes to capture CO_2 from an existing gas -fired power-station at Peterhead and store this at a depth of around 2600 m beneath the outer Moray Firth. The project succeeds an earlier proposal to capture CO_2 from the Longannet coal-fired power-station in eastern Scotland. The plan is to store 10 to 20 million tonnes of CO_2 over about a ten year period commencing in 2019.

Storage will utilise the depleted Goldeneye gas condensate field with the Captain Sandstone reservoir as the primary storage container. The storage site covers some 70 km^2, and comprises the Captain Sandstone and underlying strata of the Cromer Knoll Group, bounded by a polygon some 2 to 3 km outside of the original Goldeneye oil-water contact. The storage complex is larger, around 154 km^2, bounded some 2 to 7 km outside of the original oil-water contact, and extending upwards to the top of the Dornoch Mudstone at a depth of more than 800 m. The topseal of the primary container is a proven caprock for natural gas and is formed by the mudstones of the Upper Cromer Knoll Group, the overlying Rødby and Hidra formations and the Plenus Marl. A number of additional seals are present in the overburden within the storage complex, as are a number of potential secondary containers which could also serve as monitoring horizons.

Goldeneye monitoring objectives

A comprehensive risk assessment has been carried out based on the bow-tie method, linking threats to consequences via a range of preventative and corrective measures. Potential risks include short and long-term releases of CO_2 to seabed, sub-sea and platform blowouts, lateral migration to adjacent fields and wellbores, and lateral migration of dissolved CO_2.

The monitoring plan aims to demonstrate containment and conformance and is closely linked to the risk assessment.

Goldeneye monitoring programme

The monitoring programme[3] is designed to meet European offshore storage requirements and so has comprehensive plans both for deep-focussed and shallow-focussed monitoring activity (Table 3.5), covering baselines, operational and post-closure phases. The main deep-focussed element provides surveillance of the reservoir and overburden and utilises a number of proven technologies: time-lapse 3D seismics, down-hole pressure and temperature, geophysical logging and fluid sampling – the latter to be deployed both in the injection wells and in a dedicated monitoring well. A comprehensive shallow environmental monitoring programme is also planned, including seabed imaging, seabed sampling and seawater sampling technologies. Contingency monitoring is also addressed, for example a P-Cable seismic survey to help image and understand shallow migration in the event of leakage being detected at the top of the storage complex.

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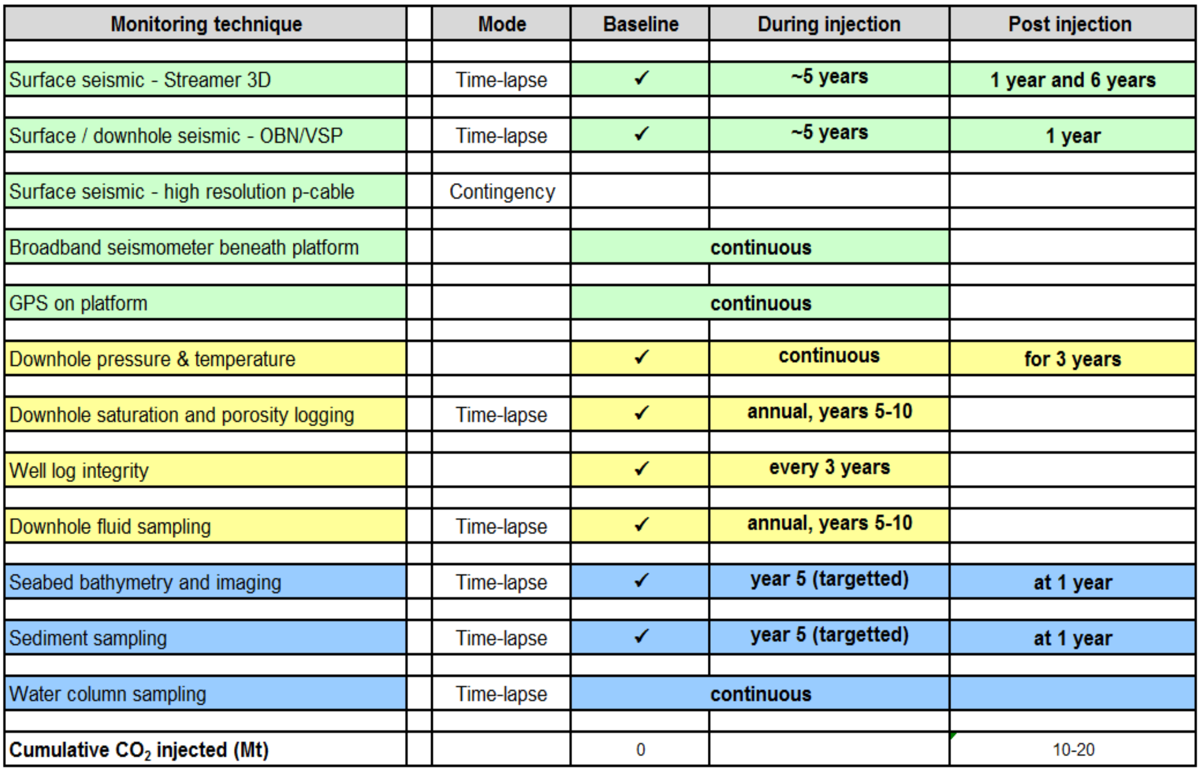
[3] The monitoring plan outlined here is based on that set out in the FEED (Front End Engineering Design) documentation (ScottishPower CCS Consortium, 2011) for the Longannet-Goldeneye project. This has subsequently evolved into the currently ongoing Peterhead-Goldeneye project. The monitoring plan for the latter is currently confidential but, with Shell's permission, we have included some additional ideas for monitoring from it.



Monitoring technique	Mode	Baseline	During injection	Post injection
Surface seismic - Streamer 3D	Time-lapse	✓	~5 years	1 year and 6 years
Surface / downhole seismic - OBN/VSP	Time-lapse	✓	~5 years	1 year
Surface seismic - high resolution p-cable	Contingency			
Broadband seismometer beneath platform		continuous		
GPS on platform		continuous		
Downhole pressure & temperature		✓	continuous	for 3 years
Downhole saturation and porosity logging	Time-lapse	✓	annual, years 5-10	
Well log integrity		✓	every 3 years	
Downhole fluid sampling	Time-lapse	✓	annual, years 5-10	
Seabed bathymetry and imaging	Time-lapse	✓	year 5 (targetted)	at 1 year
Sediment sampling	Time-lapse	✓	year 5 (targetted)	at 1 year
Water column sampling	Time-lapse	continuous		
Cumulative CO_2 injected (Mt)		0		10-20

Table 3.5 Monitoring programme proposed for Goldeneye in the Front End Engineering Design (FEED) document (ScottishPower CCS Consortium, 2011a). (Green denotes deep-focussed techniques that operate from the surface, yellow denotes well based techniques and blue denotes shallow-focussed techniques).

3.1.5 ROAD

The ROAD project (Rotterdam Opslag en Afvang Demonstratieproject) aims to store CO_2 in the P18-4 depleted gas field reservoir, 20 km NW of Rotterdam, in the Netherlands Southern North Sea. It is the first project to be permitted under the EU Directive (and also under the London Protocol and OSPAR Convention). In July 2013, the project was granted a permit to store up to 8.1 Mt of CO_2 at a maximum rate of 1.5 Mt/year starting in 2015 (latest Jan 2018), subject to conditions, which include updates to various plans and provisions[4]. The P18-4 reservoir lies within Triassic sandstones of the n Buntsandstein Subgroup (equivalent to the UK Bunter Sandstone Formation) at about 3500 m depth. The reservoir has heterogeneous porosities and comprises ~200 m thick sands and clayey siltstones deposited in lacustrine, fluvial and aeolian settings. The primary seal is provided by siltstones, claystones, evaporites and dolostones. P18-4 is one of a number of neighbouring gas reservoirs which are bounded by a system of mainly NW-SE oriented faults. The structural compartments are hydraulically sealing on production timescales (Arts et al., 2012).

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[4] Note that many of the permit-related documents are in Dutch, so this report will only refer to those documents available in English.

ROAD monitoring objectives

The monitoring programme is still the “concept plan, 1st June 2011”. In order to meet the European offshore storage requirements it is therefore subject to updates and the inclusion of more detail, as set out in the conditions of the storage permit granted on 13th July 2013. It is largely risk-based with an emphasis similar to K12-B (see Section 3.1.3), and the monitoring of potential leakage via wellbores being the primary focus. The key objectives are to ensure the safety and the integrity of the storage complex and to provide the necessary information to allow transfer of responsibility. An additional objective is to monitor the effectiveness of any corrective measures that might be required.

Following feedback from the European Commission review of the project, further study is underway to assess specific local pressure build-ups, pressure barriers and later-stage fault leakage. Results will be used to update the risk assessment which will feed into the updated monitoring plan to provide evidence for containment and to demonstrate integrity of seals, faults and wells.

ROAD monitoring programme

The monitoring plan needs to be updated at least 6 months before injection starts and this plan must be approved by the Minister. The monitoring plan will also be updated no later than 4 years and 9 months after injection starts, and every 5 years thereafter.

In addition to pre-injection and injection monitoring phases, the plan also includes a breakdown of post-injection monitoring explaining the phases leading to well abandonment and transfer to the competent authority.

Monitoring technique		**Mode**	**Baseline**	**During injection**	**Post injection**	**Post closure**
Shallow focused 2D or 3D seismic[1,2,3]		Contingency		(✓)	(✓)	(✓)
Microseismics[1,2]			Continuous			
Well head pressure and temperature[1,3]			Continuous			
Downhole pressure and temperature[1,2,3]			✓	✓	✓	
Downhole pressure in adjacent reservoir[3]		Contingency		(✓)	(✓)	(✓)
Downhole saturation logging[2]			✓	✓		
Downhole fluid sampling[2]			✓	✓		
Well integrity logs[1,2,3]			✓	✓	✓	
Seabed bathymetry, imaging and bubble detection[1,2,3]			✓			✓
Seafloor gas/sediment sampling[1,3]		Contingency		(✓)	(✓)	(✓)
Cumulative CO_2 injected (Mt)			**0**		**8.1**	

Table 3.6 Monitoring programme proposed for ROAD taken from various documents (referred to by the superscript numbers as follows: [1]: “Monitoringsplan, 1 juni 2011”, [2]: CATO2, 2011 and [3]: Steeghs et al., 2014. (Note that a final pre-injection monitoring plan update is expected 6 months prior to

injection start) (Green denotes deep-focussed techniques that operate from the surface, yellow denotes well based techniques and blue denotes shallow-focussed techniques).

3.1.6 Tomakomai

The Tomakomai large scale demonstration project is located 3 - 4 km off the island of Hokkaido , Japan, about 800 km NNE of Tokyo (Figure 3.1). It is a full-chain CCS demonstration scale project, planning to capture CO_2 from an industrial source (a hydrogen production unit) and storing it in two separate reservoirs just offshore from Tomakomai Port. The 4 year engineering, procurement and construction works were commissioned by METI in April 2012. Storage of 100000 tonnes of CO_2 per year from 2016 - 2018 is planned prior to commercial scale-up. Two saline aquifers are targeted for storage. The shallower is a Lower Quaternary sandstone 1100 deep and 100 m thick called the Moebetsu Formation. It forms a gently dipping monocline and has an estimated porosity of 20 – 40 % and permeability of 9 - 25 mD. It is overlain by 200 m of mudstone caprock. The deeper reservoir is a Miocene volcanic and volcaniclastic unit 2400 m deep and 600 m thick called the Takinoue Formation, with an estimated porosity of 3-19 % and permeability of 0.01 mD to 2.6 D. It is capped by 1100 m of mudstones (Tanase et al., 2013). Initial reservoir conditions in the Moebetsu are estimated as 10.7 MPa and 45 °C (Ito et al., 2013) and in the Takinoue as 35 MPa and ~ 91 °C (Matsuura et al., 2013). Water depth in the port area is 20-40m (Yamanouchi et al., 2011).

Injection is planned via two deviated injection wells drilled from onshore and projecting 3-4km offshore under the port area. There are 3 observation wells, 2 are vertical and purpose-drilled, one for each reservoir and the 3rd is the converted, deviated survey/injection test well (Tanase et al., 2013, 2014).

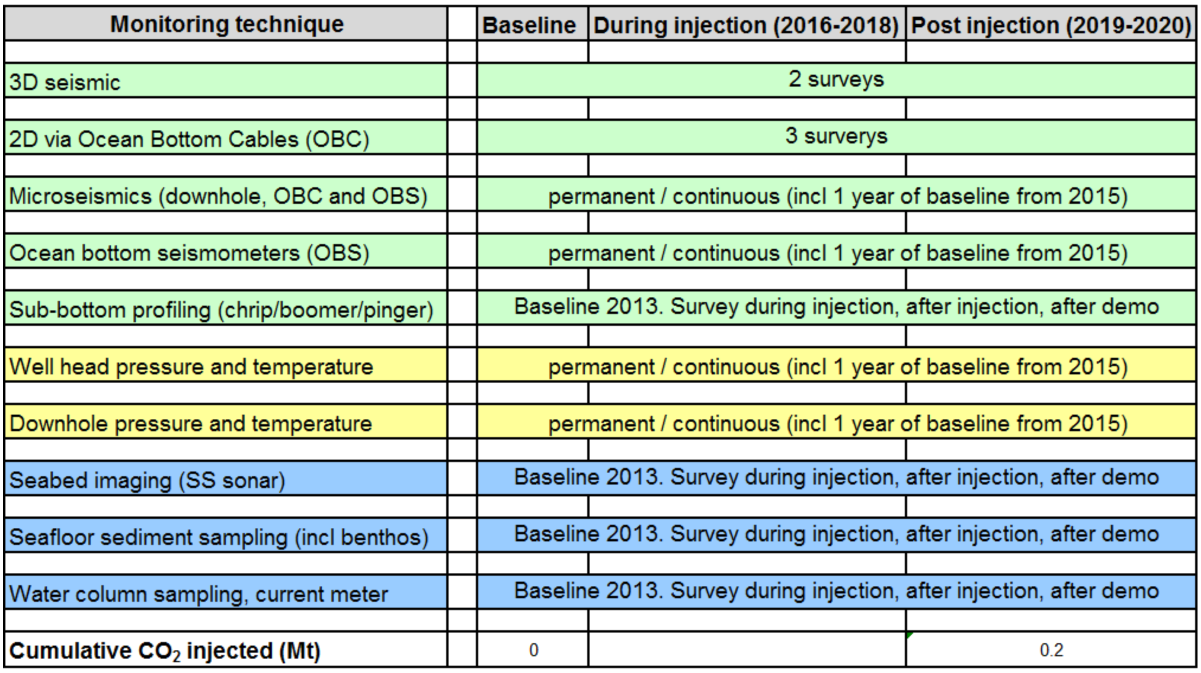
Tomakomai monitoring objectives

The main objective of monitoring at Tomakomai is to confirm that the injection and storage of CO_2 are executed safely and stably in accordance with Japanese legislation. Monitoring is therefore designed to comply with METI's technical guidance (Section 2.1.3). Other overseas standards, guidelines, manuals and technical trends are also taken into account. Marine environmental surveys (to investigate chemical, physical and biological aspects) are in accordance with the Marine Pollution Prevention Act.

The monitoring itself has been targeted towards understanding reservoir behaviour, detecting any leakage out of the reservoirs and in particular, investigating seismicity. The latter is particularly important in Japan, to demonstrate that CO_2 storage and significant natural seismicity are not mutually exclusive (Tanase et al., 2013, 2014).

Tomakomai monitoring programme

The Tomakomai monitoring programme includes 2D and 3D seismic surveys. These will be deployed via ocean bottom cables (OBC) because greater repeatability is achievable and the busy port precluded streamer deployment (Yamanouchi et al., 2011). The 2D survey line aligns with the two injection wells and uses a buried OBC for similar reasons. The heavy emphasis on detection of natural earthquakes and microseismicity also uses the OBC, in addition to 4 dedicated ocean bottom seismometers (OBS) and downhole sensors in the observation wells. Note that the wells at Tomakomai originate onshore, so wellbore access for monitoring will be more straightforward than offshore. The suite of marine environmental monitoring is still being planned (Tanase et al., 2014). The site's close proximity to the port (and the fact that the wellheads are located onshore) mean that it is relatively cheap and easy to maintain and replace seabed equipment compared to a more remote site.



Monitoring technique		Baseline	During injection (2016-2018)	Post injection (2019-2020)
3D seismic		2 surveys		
2D via Ocean Bottom Cables (OBC)		3 surverys		
Microseismics (downhole, OBC and OBS)		permanent / continuous (incl 1 year of baseline from 2015)		
Ocean bottom seismometers (OBS)		permanent / continuous (incl 1 year of baseline from 2015)		
Sub-bottom profiling (chrip/boomer/pinger)		Baseline 2013. Survey during injection, after injection, after demo		
Well head pressure and temperature		permanent / continuous (incl 1 year of baseline from 2015)		
Downhole pressure and temperature		permanent / continuous (incl 1 year of baseline from 2015)		
Seabed imaging (SS sonar)		Baseline 2013. Survey during injection, after injection, after demo		
Seafloor sediment sampling (incl benthos)		Baseline 2013. Survey during injection, after injection, after demo		
Water column sampling, current meter		Baseline 2013. Survey during injection, after injection, after demo		
Cumulative CO_2 injected (Mt)		0		0.2

Table 3.7 Monitoring programme proposed for Tomakomai based on information in Tanase et a., (2013, 2014). Note that the environmental impact monitoring is still being planned. (Green denotes deep-focussed techniques that operate from the surface, yellow denotes well based techniques and blue denotes shallow-focussed techniques).

3.2 Surface seismic methods

Surface seismic methods offer the potential for high resolution imaging and characterisation of the subsurface over wide areas, including the detection of changes in fluid distributions and pressure. Resolution and detection capability depend on subsurface conditions: shallow, thick, unconsolidated reservoirs are more suitable for seismic monitoring than thin, deep lithified ones (Lumley et al., 1997). Survey repeatability (the accuracy with which successive surveys are matched) is also a key determinant of time-lapse detection capability, and offshore settings are generally particularly well-suited to high seismic repeatability. Seismic methods are best suited to aquifer storage because of the markedly different seismic properties of dense-phase CO_2 and reservoir brine. They are less well suited to storage in depleted reservoirs where discrimination between the injected CO_2 and residual hydrocarbons can be challenging. On the other hand, robust overburden monitoring is a key requirement for all storage site scenarios, irrespective of reservoir conditions, however the common occurrence of minor hydrocarbon accumulations in thick offshore overburden sequences can make detection of CO_2 more problematical.

Offshore surface seismic monitoring methods fall into two main categories: surveys with a source boat and towed streamers providing 2D or 3D data, and surveys with a source boat and ocean bottom sensors – cables (OBC) or nodes (OBN), which may or may not be permanently deployed and generally provide 3D data and the capability of recording shear-waves.

3.2.1 Streamer - 3D seismic

3D surface seismics are unique in offering full 3D high resolution imaging of the subsurface with roughly uniform subsurface coverage, both in terms of ray-path geometry and multiplicity. Uniform coverage is important for detailed interpretive analysis of seismic attributes, particularly in time-lapse mode.

Deployed at: *Sleipner, Snøhvit, planned for Goldeneye, ROAD, Tomakomai*

Capabilities: *Analysis of the Sleipner datasets over several years (e.g. Arts et al., 2010, Chadwick et al., 2005) has shown that 3D streamer seismics have very high detection and resolution capabilities. In terms of resolution the latest dual-sensor streamer technology deployed at Sleipner is explicitly resolving CO_2 layers around 5 m thick (Furre and Eiken, 2014). In addition, wavelet tuning effects allow quantification of layer thicknesses below the explicit resolution limit, with a minimum thickness detection limit of around 1 metre. These capabilities are important, because modelling studies indicate that CO_2 tends to migrate laterally as thin, mobile layers on the metre-scale, so very high detection and resolution capabilities are essential for conformance monitoring. Leakage detection capability is very much a function of repeatability (see below).*

Seismic data is also very suitable for more advanced analysis, and at Sleipner and Snøhvit a number of analytical and processing studies have focussed on obtaining more information on reservoir and CO_2 plume properties (e.g. Chadwick et al., 2010). Current research is ongoing via techniques such as frequency dependent attenuation, frequency dependent AVA (amplitude versus angle), spectral inversion and full waveform inversion.

A particular limitation of streamer data is the lack of significant azimuthal variation in the wave propagation. This severely limits the data for azimuthal analysis aimed at evaluating anisotropy and geomechanical integrity. The streamer method is also not suitable for the collection of multicomponent (shear-wave) datasets.

Practicalities: *Streamer seismic is deployed routinely offshore and methodologies are mature and robust. The technique does however require a wide unobstructed sea area and so cannot be used around platforms or other obstructions such as wind-farms. From an environmental point of view concerns have been raised about possible adverse effects of the seismic source on marine wildlife, particularly cetaceans. In general it is desirable to keep the spatial extent and frequency of time-lapse monitoring surveys as low as possible.*

Costs: *A typical marine 3D survey will cost in the order of tens of millions of UK pounds (GBP) to acquire depending on survey area, specification, locality etc. In practice, careful cost control will be exercised in survey design to minimise acquisition footprints and the number of time-lapse repeats. Other cost-reduction measures might include for example, the selective utilisation of re-processed 'legacy' datasets for baseline purposes, rather than acquiring brand-new dedicated baseline data. Processing time-lapse data from a large 3D survey can cost up to 1milion GBP in computing time.*

The 3D time-lapse surveys at **Sleipner** and **Snøhvit** (Tables 3.2 and 3.3) give the current definitive picture of 3D time-lapse survey capability for underground CO_2 storage, in terms of plume imaging and the provision of other seismic attributes suitable for addressing conformance and containment requirements.

At Sleipner no dedicated baseline data were acquired and a legacy dataset from 1994 was used instead. Subsequent repeat surveys were acquired as part of research projects or by piggy-backing onto surveys acquired to monitor the deeper gas-field. All but one of the repeat surveys were acquired in the same direction as the baseline survey with similar overall recording geometry[5]. Acquisition parameters for the Sleipner surveys are summarised in Boait et al., (2012) and Furre and Eiken (2014); suffice to say here that progressive evolution of the acquisition system has followed normal industry development, the main change being in the number of streamers (4 to 5 in the early surveys, 8 to 12 in the later ones). A significant technical step came in 2010 when Statoil deployed a streamer with dual-sensor technology that allows the source to be towed at a shallower depth with significant gains in frequency bandwidth and improved resolution (Furre and Eiken, 2014).

At Snøhvit a dedicated baseline 3D survey in 2002 was followed by subsequent repeats with similar parameters. In general, for any given depth, the Snøhvit data has the superior time-lapse performance, generally as a result of technological developments since the Sleipner baseline was acquired.

Plume imaging

At **Sleipner** the CO_2 plume is imaged as a tiered feature comprising a number of bright sub-horizontal reflections within the reservoir, growing with time (Figure 3.5). The plume is roughly 200 m high and elliptical in plan, with a major axis exceeding 4000 m by 2010. The plume is underlain by a prominent

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[5] Note the 2004 survey at Sleipner was acquired perpendicular to all of the other time-lapse surveys.

velocity pushdown and an attenuation shadow which introduces significant time-shifts and amplitude reductions to the Base Utsira reflection and deeper events.

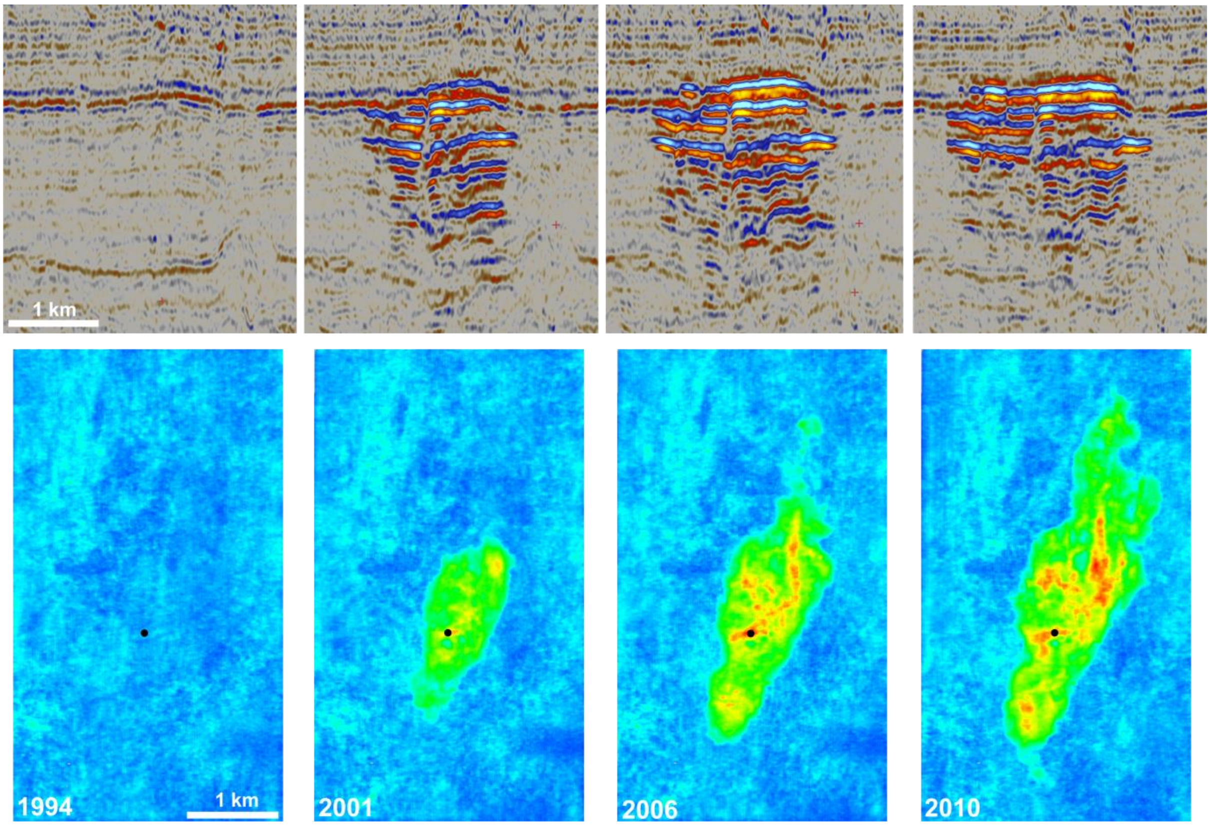


Figure 3.5 The Sleipner CO_2 plume showing its evolution from 1994 (baseline) to 2010. Top panels show the development of reflectivity on a N-S cross-section (inline), bottom panels show the development of total plume reflectivity in map view (British Geological Survey © NERC 2014).

Interpretations of the Sleipner plume reflectivity (e.g. Arts et al., 2005; Chadwick et al., 2004) identified nine separate reflective levels in the reservoir which trap CO_2. These individual and interpretatively distinct reflections have remained consistently identifiable from the first time-lapse survey in 1999 to the latest in 2010 and are interpreted as arising from thin (mostly < 8 m thick in the earlier years) layers of CO_2 trapped beneath thin intra-reservoir mudstones and the reservoir topseal. The detectability limit at the outer edge of the layers is reckoned to be around 1 m or less. The patterns of reflectivity and time-shifts within the time-lapse data have been used for a wide range of interpretive and analytical studies related to demonstrating containment and conformance.

At **Snøhvit** the Tubåen reservoir is deeper and thinner than the storage reservoir at Sleipner with significantly less CO_2 injected (Eiken et al., 2010; Hansen et al., 2013). The reservoir is also cut by faults which might serve to compartmentalise fluid flow. Nevertheless the 3D seismic clearly images reflectivity changes in the reservoir, both close to the injection point and also farther afield within the reservoir (Figure 3.6).

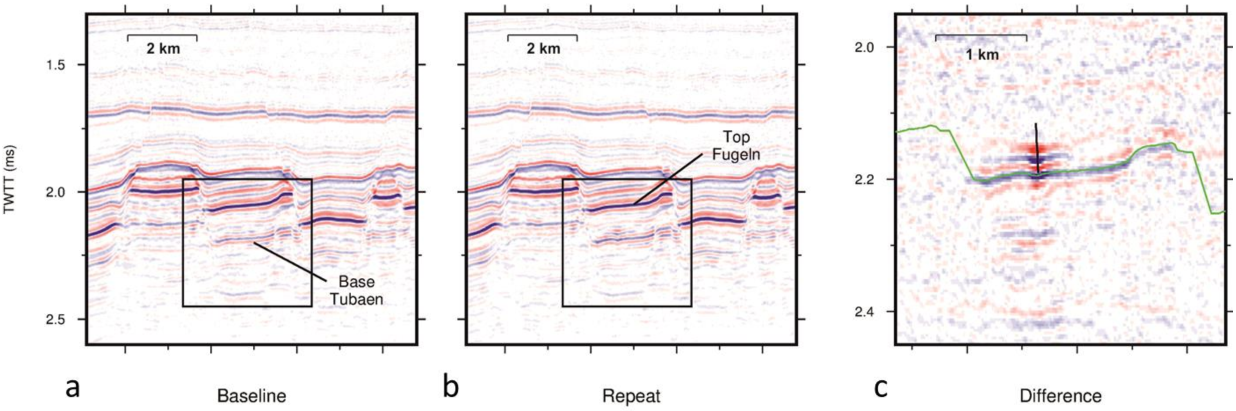


Figure 3.6 S-N seismic sections through the Snøhvit injection point. a) 2003 baseline survey showing the reservoir cut by normal faults b) 2009 repeat survey c) time-lapse difference (2009 – 2003) showing significant difference response around the injector well (black line) and also more widely within the local fault-block. Seismic data courtesy of Statoil ASA. (British Geological Survey © NERC 2014).

Mapping of the time-lapse seismic changes at Snøhvit (Figure 3.7) offers intriguing insights into storage performance. The largest changes in reflectivity and time-shifts occur close to the injection point, whereas more diffuse changes extend laterally into the reservoir, but appear to be bounded by the faults (Figure 3.6). The former are interpreted as corresponding to the CO_2 plume itself, whereas the latter have been interpreted as arising from pressure changes within the surrounding water-filled reservoir (e.g. Hansen et al., 2013). Significant pressure change is confirmed by downhole measurements (Section 3.6.1, Figure 3.20) and it is evident that by combining the seismic and downhole observations a clear picture of reservoir performance is starting to emerge.

More detailed analysis of the Snøhvit time-lapse seismics has suggested the possibility of discriminating between fluid saturation changes (the CO_2 plume) and pressure changes in the wider (water-filled) aquifer. AVO analysis by Grude et al. (2013) and work on spectral attributes (White et al., in press), both suggest that the seismic response at Snøhvit might be used to discriminate between pressure and fluid substitution effects. This is a potentially powerful finding, enabling surface seismic and downhole pressure measurements to be used in a strongly complementary fashion.

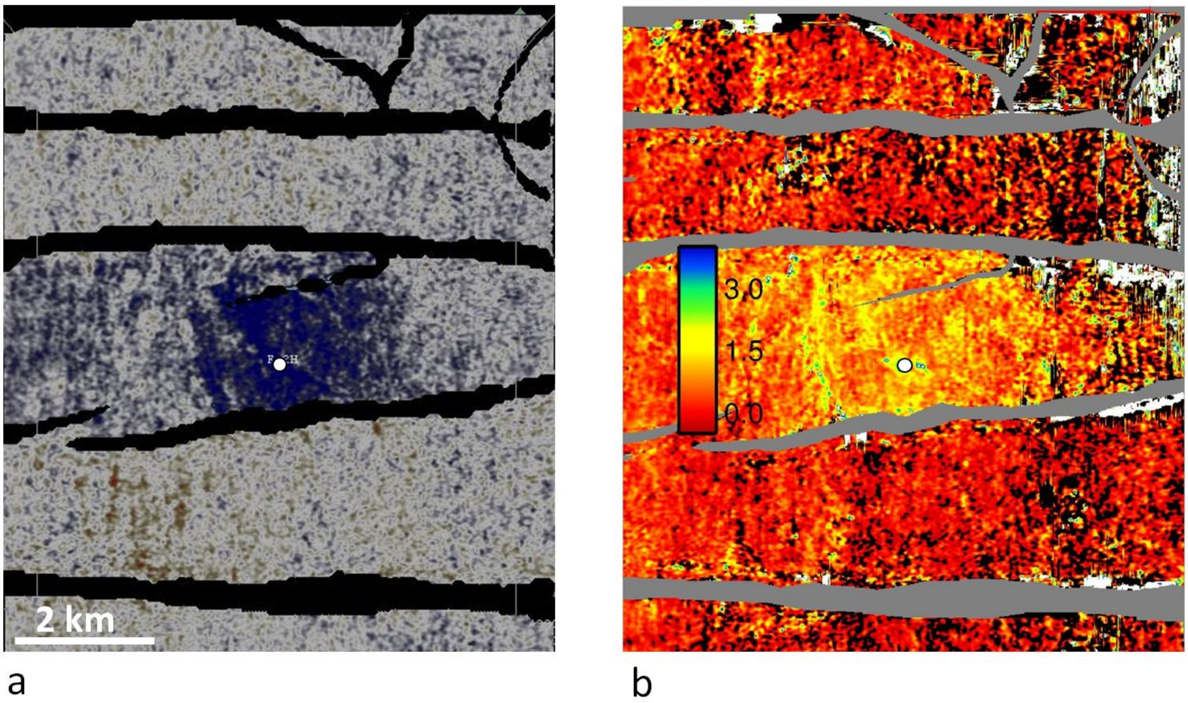


Figure 3.7 Maps of time-lapse changes in the Tubåen Formation at Snøhvit a) Reflectivity changes in the reservoir b) time-shifts at base reservoir (in milliseconds). Note how the more extensive changes terminate at the faults (black polygons). White disc denotes position of injection point. Seismic data courtesy of Statoil ASA. (British Geological Survey © NERC 2014).

Following the switching of CO_2 injection to the Stø Formation in 2011, further time-lapse seismic has been acquired at Snøhvit and preliminary results are described in Osdal at al. (2014).

Containment monitoring

Time-lapse 3D seismic surveys can give robust and uniform spatial surveillance of the storage complex and provide a very powerful leakage monitoring tool because of their ability to detect small changes in fluid content of the overburden rock volume above the storage reservoir. Accumulations of CO_2 in the overburden are likely to occur within higher permeability regions, either as sub-vertical columns ('chimneys') of vertically migrating CO_2, or as thin sub-horizontal layers of ponded CO_2 which grow laterally. In both cases, changes in the time-lapse seismic signature are manifest as either reflectivity changes, or time-shifts in reflectivity, that are extremely sensitive to even very small amounts of CO_2. A key factor in the ability of time-lapse data to detect small time-dependent changes is the accuracy to which successive datasets can be repeated. Perfect repeatability would produce a noise-free difference dataset capable of detecting tiny time-lapse changes. In practice, repeatability is far from perfect.

At **Sleipner** difference datasets show variable amounts of repeatability error or noise which acts to obscure real changes in signal (Figure 3.8). Repeatability noise is caused by changes in ambient noise on repeat surveys which lead to an overprint of essentially random noise, and changes in acquisition parameters or near-surface velocity structure which give imperfect repeat imaging of the subsurface and lead to systematic repeatability noise which adumbrates the geological reflectivity. A key element of repeatability noise is that it shows a systematic amplitude relationship to the original signal. Thus the seismic ‘bright-spots’ in the overburden (Figure 3.8) show very similar repeatability metrics (such as NRMS) to bright spots elsewhere, far from the CO_2 plume, and so are demonstrably not related to CO_2 leakage.

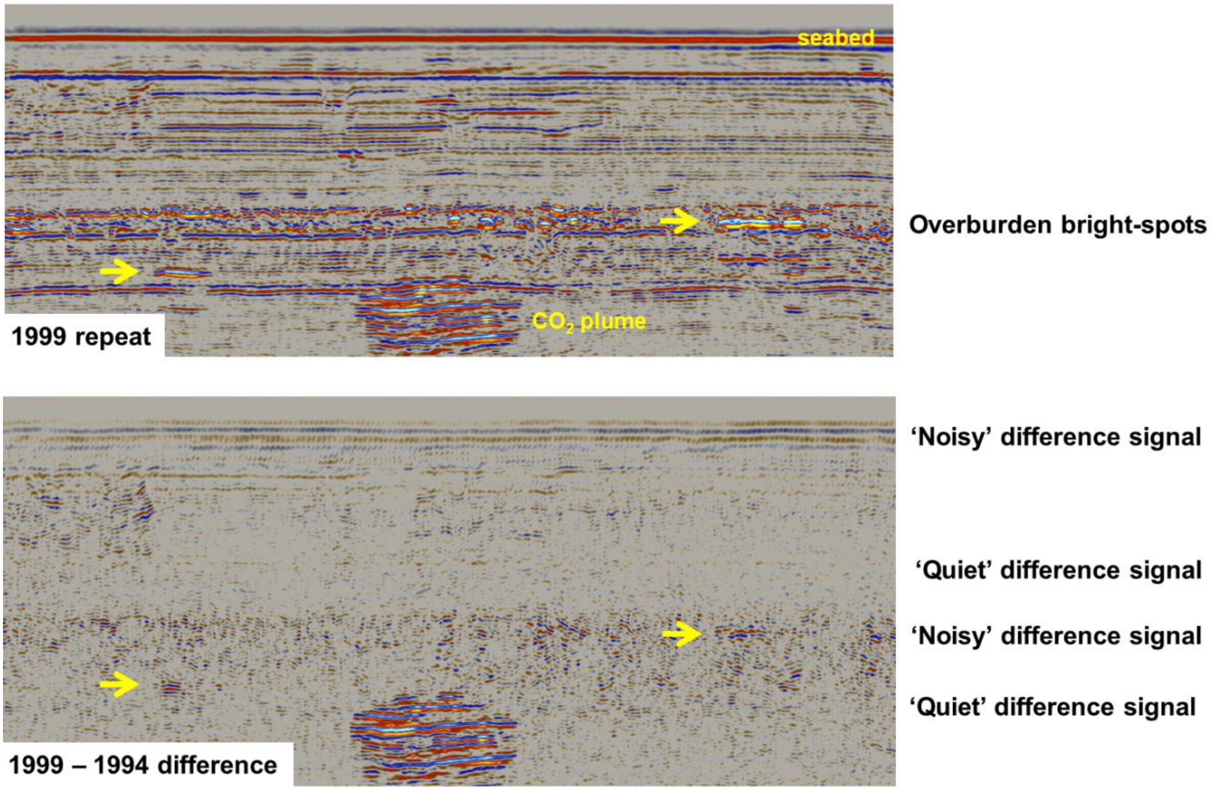


Figure 3.8 Time-lapse 3D data from Sleipner showing the 1999 repeat survey (top) and the time-lapse difference between 1999 and the 1994 baseline survey (bottom). Note the difference signal ‘bright-spots’ (arrowed) which relate to imperfect repeat imaging of natural reflectivity in the overburden. Section length is ~7 km, depth to top of CO_2 plume is ~800 m. Seismic data courtesy of Statoil ASA. (British Geological Survey © NERC 2014).

Detection threshold therefore depends on the level of repeatability noise, the geometry of the CO_2 accumulation, notably its thickness and area, and the reflectivity and properties of the CO_2 itself. A spatial-spectral methodology has been developed (Chadwick et al., in press) to determine the actual detection limits of the datasets which takes into account both the reflectivity of a thin CO_2 layer and also its lateral extent. Preliminary analysis indicates that, at the top of the Utsira reservoir, CO_2 accumulations with pore volumes greater than about 3000 m^3 should be robustly detectable for layer thicknesses greater than one metre (Figure 3.9), which will generally be the case. Taking a conservative assumption of full CO_2 saturation, this pore volume threshold corresponds to a CO_2 mass detection threshold of around 2100 tonnes (lower saturations would convert to lower mass detection thresholds). Within the overburden, at shallower depths, CO_2 becomes progressively more reflective, less dense, and correspondingly more detectable, as it passes from the dense phase into a gaseous state. The analysis indicates that the detection threshold falls to less than 1000 tonnes of CO_2 at 590 m depth, and to less than 500 tonnes at shallower levels in the overburden where repeatability noise levels are particularly low.

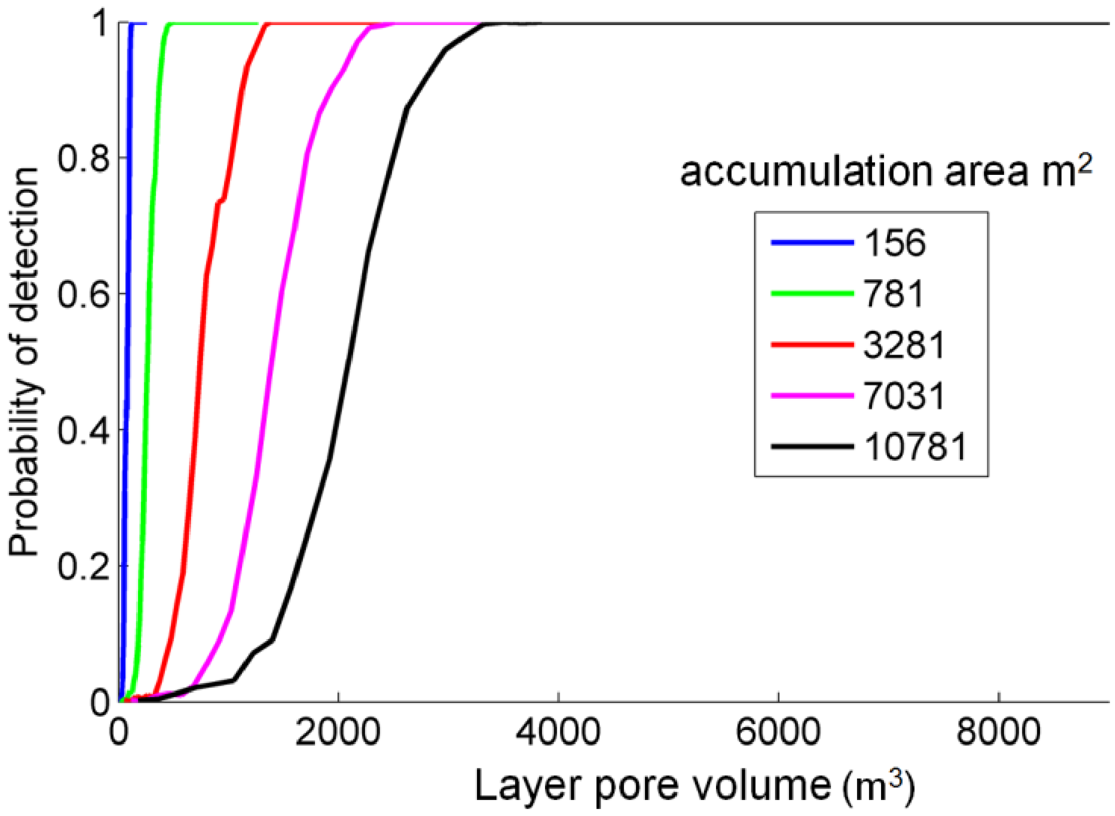


Figure 3.9 Probability of detecting CO_2 accumulations at the top of the Utsira Sand reservoir at Sleipner. (After Chadwick et al., in press. British Geological Survey © NERC 2014).

At **Snøhvit** the current datasets also show no evidence of CO_2 migration out of the Tubåen storage reservoir, but to the best of our knowledge, no quantitative analysis of leakage detection thresholds has been carried out. Preliminary analysis being carried out in the ECO2 project indicates the data do have generally superior repeatability to the Sleipner data, most likely due to the much newer baseline. If this is the case then repeatability thresholds in the shallow section at Snøhvit might well be even smaller than at Sleipner.

Conformance

Conformance is a key requirement of the European Storage Directive, both for demonstrating understanding of current storage performance and as a basis for establishing reliable predictions of future performance. It is the procedure by which monitoring data are compared with predictive simulations to demonstrate that the storage site is behaving as expected and that understanding of processes in the reservoir is to a level of accuracy such that adverse or unexpected future outcomes are exceedingly unlikely.

At **Sleipner** the risk analysis indicates that migration of the CO_2 plume is the key conformance parameter. A number of predictive flow simulations have been carried out over the years aiming to match the known CO_2 injection history with the observed evolution of the plume (e.g. Figures 3.10 and 3.11). These are summarised in the CO2STORE Best Practice Manual (Chadwick et al., 2008) and references therein. The simulations are all based around history-matching plume layer growth against the layer geometries from the 4D seismic repeats. All of the full plume simulations are however hampered by uncertainty in the geometry and flow properties of the intra-reservoir mudstones. This precludes unique simulations of the layer growth and a number of flow models with different controls on layer trapping have been proposed.

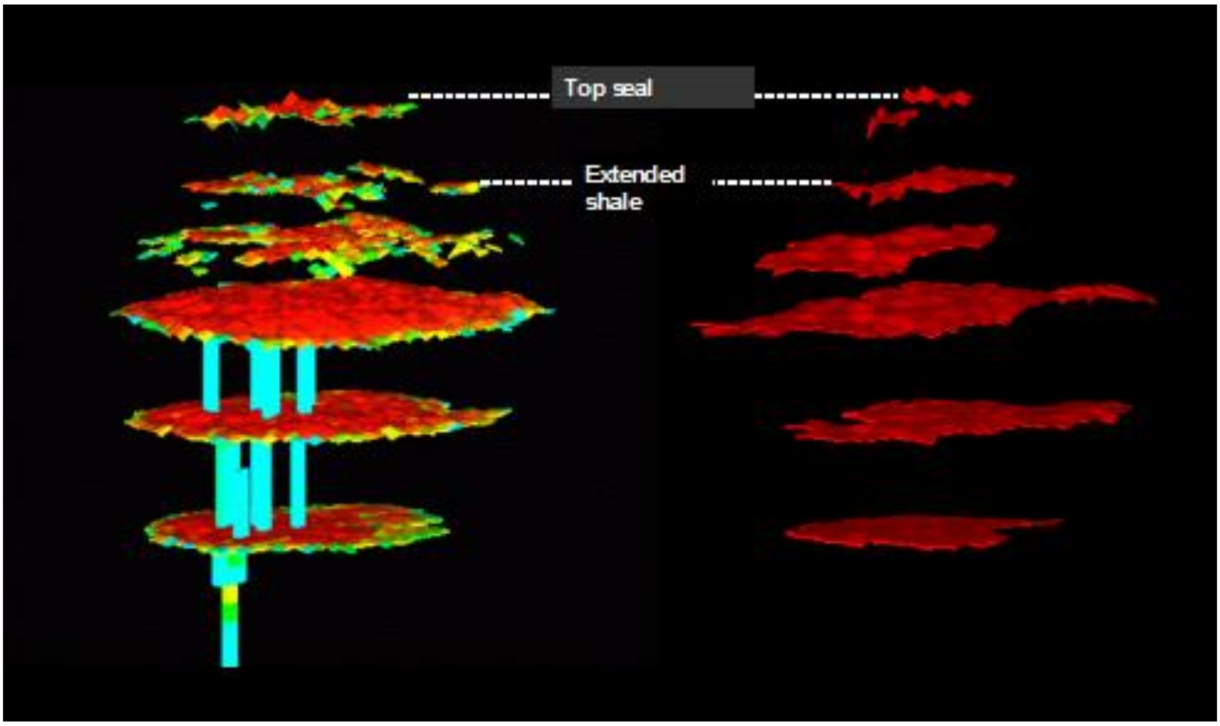


Figure 3.10 An early history-match of the CO_2 plume at Sleipner showing the simulated plume in 1999 with individual CO_2 layers (left) matched to the observed reflective horizons on the 3D seismics (right). The topmost layer is about 200 metres above the injection point and the lateral span of the largest reflection is about 2 km. (Image courtesy of SINTEF Petroleum Research).

More recently attention has switched to the topmost layer of CO_2 which is trapped directly beneath the reservoir topseal. Because of this it is very clearly imaged and its geometry can be constructed more accurately than for the deeper layers. Also it is predicted that most of the injected CO_2 will end up trapped at the reservoir top, so the topmost layer is a powerful predictor of medium to longer-term plume evolution. A number of studies (e.g. Chadwick and Noy, 2010) have obtained satisfactory matches of the observed monitoring data with numerical models and it is quite clear that the CO_2 is migrating under topographic features in the reservoir topseal via a buoyancy-driven fill and spill process. However modelling uncertainties remain regarding the very high migration mobility of the CO_2 and also the layered distribution of the deeper plume. While the geophysical monitoring sufficiently constrains the boundary conditions on these phenomena, there is ongoing discussion regarding the appropriate governing equations for flow simulation (e.g. Nilsen et al. 2011; Cavanagh 2013; Cavanagh and Haszeldine, 2014).

Taking a broader view of conformance, the CO2CARE project carried out a detailed study at Sleipner, which examined how accurately the large-scale development of the CO_2 plume could be modelled and predicted with time as more monitoring datasets became available, summarised in CO2CARE (2014), Chadwick and Noy (submitted). A number of key performance measures were assessed: plume footprint area; maximum lateral migration distance of CO_2 from the injection point; area of CO_2 accumulation trapped at top reservoir; volume of CO_2 accumulation trapped at top reservoir; area of all CO_2 layers summed and spreading co-efficient. These give diagnostic insights into plume mobility and storage efficiency in the reservoir. The study essentially reconstructed predictive modelling scenarios for 1996 (prior to the start of injection when only baseline and characterisation datasets were available), 2001 (when two repeat time-lapse surveys were available) and 2006 with five repeat datasets plus additional reservoir temperature data. Results showed a dramatic improvement in predictive accuracy as more data became available – some uncertainties do remain in terms of reservoir properties and flow processes but the study concluded that these are very unlikely to lead to unexpected or adverse outcomes in the future.

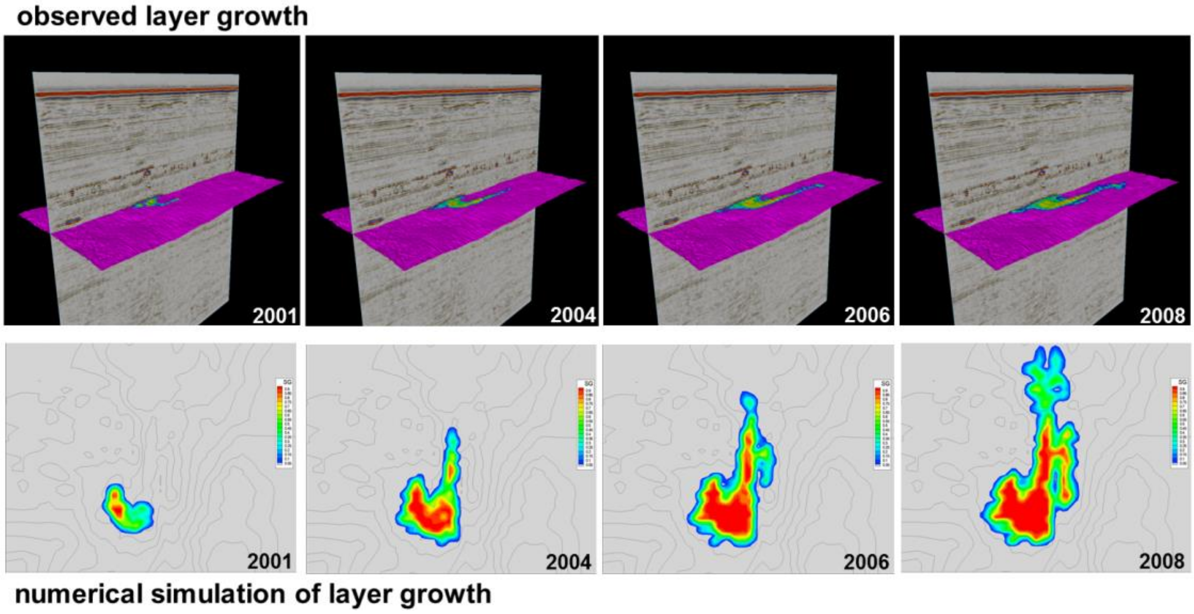


Figure 3.11 History-matching the topmost layer of CO_2 in the Sleipner plume. Upper boxes show 3D views of the top reservoir surface (purple) and the observed topmost CO_2 layer reflectivity (colours). The lower boxes show maps of the modelled topmost layer (bottom). The top reservoir surface in the 3D views covers an area of around 3 x 7 km. Seismic data courtesy of Statoil ASA. (British Geological Survey © NERC 2014).

As a consequence of the properties of the Utsira Sand (its great spatial extent, large thickness and high permeability) pressure is not thought to be an important key performance issue at Sleipner. Ehlig-Economides & Economides (2010), however, suggested that pressure increase was significantly impeding plume spreading. Chadwick et al., (2012) carried out a detailed assessment of travel-time changes (time-shifts) through the Utsira Sand, between the baseline data and 2006, to see if any pressure induced velocity decrease could be detected. The analysis focussed on measuring small time-shifts on thousands of seismic traces in the brine-filled part of the reservoir, well outside the footprint of the CO_2 plume. Measured time-shifts are of a few milliseconds, positive and negative, and show a symmetric Gaussian distribution about a small positive value of about 0.2 ms. This is indicative of only a very small velocity decrease (Figure 3.12), consistent with a pressure increase of less than 0.1 MPa (Figure 3.12). This matches the modelled pressure increase in a hydraulically connected (not compartmentalised) reservoir (more detail in Chadwick et al., 2012).

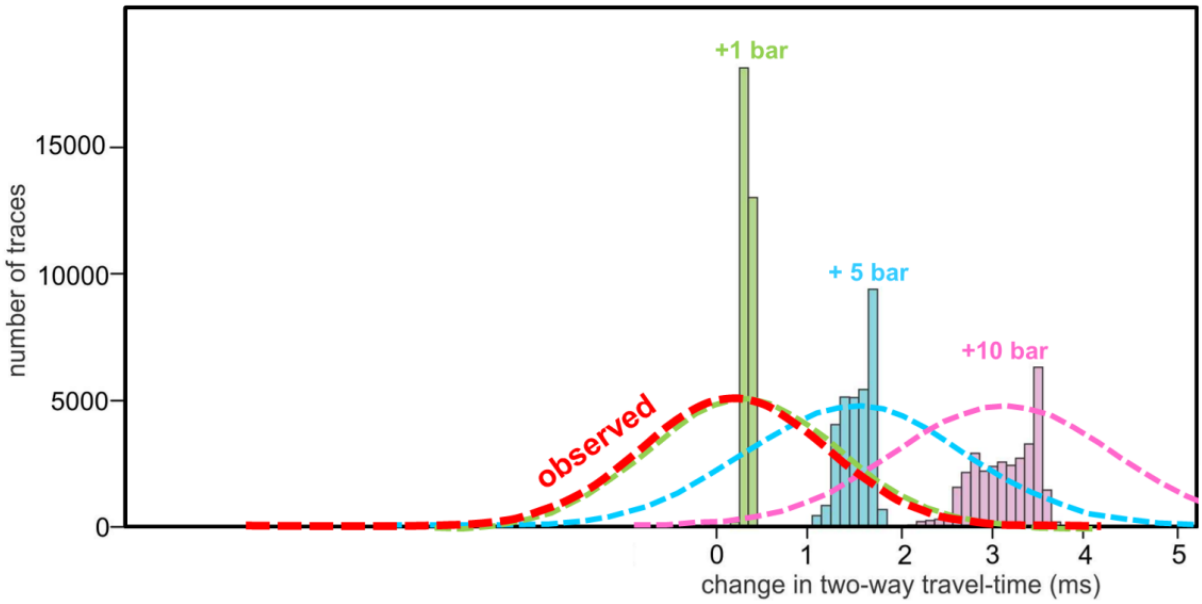
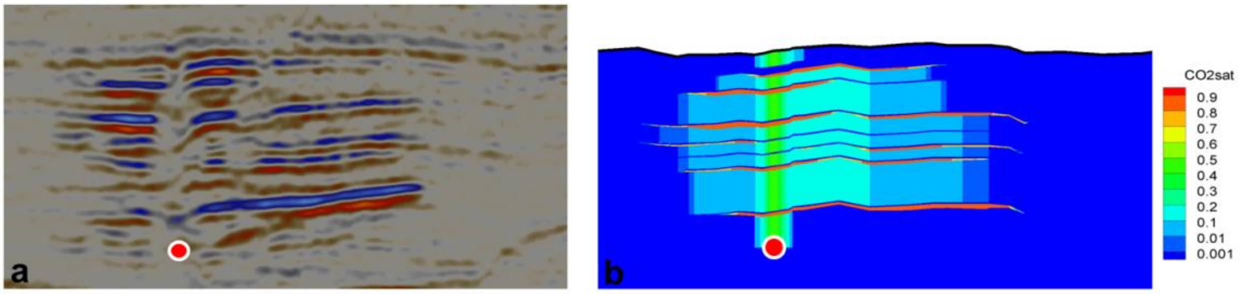


Figure 3.12 Seismic time-shifts for the Utsira Sand at Sleipner between 1994 and 2006. Bars show theoretical 'noise-free' pressure response distributions from the reservoir for 1, 5 and 10 bars (0.1, 0.5 and 1 MPa). Corresponding dashed lines show the theoretical responses convolved with time-lapse repeatability noise. Red dashed line shows observed time-shifts distribution. (Modified from results in Chadwick et al., 2012, British Geological Survey © NERC 2014).

In situ quantitative verification of the injected CO_2 is not a regulatory requirement of the European Directive, nevertheless the ability of monitoring to obtain quantitative information, either of the whole plume or of particular layers or parts of the plume is useful for model calibration and general process understanding. In principle, with regards to quantification from seismics, the Sleipner storage site with its shallow reservoir and sensitive rock physics properties is more or less optimally situated for monitoring (Lumley et al., 1997). On the other hand, the lack of any invasive (well-based) measurements does make quantitative analysis challenging. Early papers concentrated on quantification of the seismic signal with the aim of verifying the measured injected amount of CO_2 (Arts et al., 2004; Chadwick et al., 2004, 2005; Arts et al., 2010). A 3D CO_2 saturation model for the 1999 dataset was derived (Figure 3.13) which has a satisfactory match with the seismic data and contained around 85 % of the known injected CO_2. Allowing for the fact that some of the CO_2 has dissolved, becoming invisible to the seismic, the model probably matches more than 90 % of the injected free CO_2.

Significant uncertainties remain however and render a unique quantitative verification very challenging; most notably the seismic insensitivity to saturation when the CO_2 and aqueous phases are mixed uniformly in the reservoir, the possibility of 'patchy' mixing with its own different seismic response and the very significant effects of signal attenuation in the deeper parts of the plume. In general terms it appears that the more recent Sleipner datasets are becoming more difficult to model with time, as reflectivity in the deeper plume is fading and velocity pushdown is becoming more difficult to map (Figure 3.5). These may be seismic imaging effects (attenuation) arising from generally increasing CO_2 saturations within the plume envelope, or may signify real and significant changes in CO_2 distribution in the deeper part of the plume. Nevertheless a broader ‘semi-quantitative’ analysis based on a simple parameter such as total integrated velocity pushdown (Figure 3.13c), shows consistent relationships between the time-lapse seismic response and the known injected amount of CO_2 through time. This indicates that the processes which controlled early plume development, via layer migration and trapping, have continued to act in a similar way through time.



Plume image 1999

Calculated CO_2 distribution (3D)

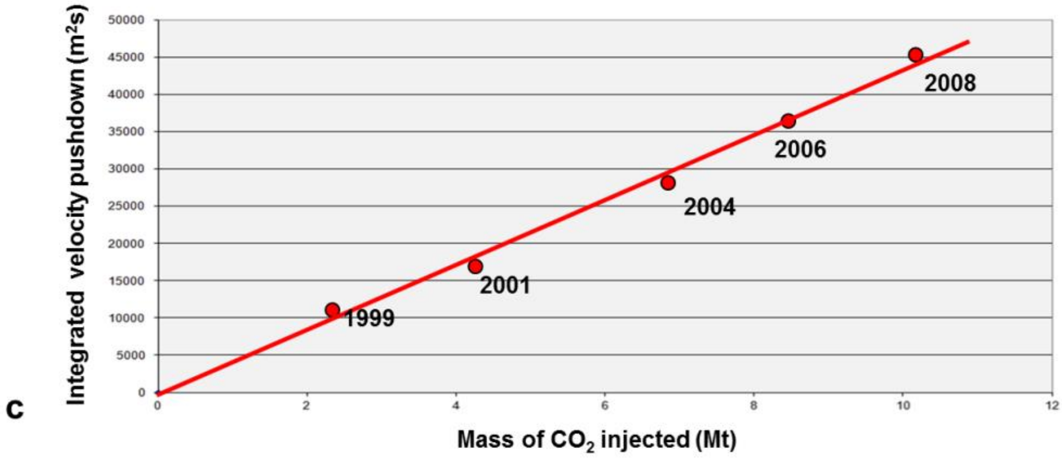


***Figure 3.13** a) Section through the 1999 3D time-lapse datasets b) equivalent section through the calculated 3D CO_2 saturation model c) Plot of plume velocity pushdown against injected amount. Section length in (a) and (b) is about 3 km, height of the CO_2 plume is about 200 m. Seismic data courtesy of Statoil ASA. (British Geological Survey © NERC 2014).*

At **Snøhvit** time-lapse seismics also forms a potentially powerful tool for assessing conformance, even though the storage environment is wholly different. It enables mapping of the CO_2 plume and possibly also the pressure footprint, crucially demonstrating fluid flow compartmentalisation by the faults cutting the reservoir. Combined with continuous downhole pressure measurements it offers fundamental insights into storage performance (see Section 3.6.1).

3.2.2 Streamer - 2D seismic

2D streamer seismics offer a low-cost option for high resolution subsurface imaging, albeit without the robust subsurface coverage of the 3D method.

Deployed at: *Sleipner (OBC 2D seismic planned at Tomakomai - see Section 3.2.5)*

Capabilities: *The resolution and detection capabilities of 2D seismics are similar to 3D, though the lack of 3D migration in processing precludes optimum imaging of some structures. The lack of 3D subsurface coverage precludes containment monitoring, but the acquisition of a profile in a star configuration over a CO_2 plume can provide effective imaging of plume spread for basic conformance studies. This would also provide a measure of local azimuthal imaging.*

Practicalities: *The 2D streamer is more compact than the 3D one, particularly with higher resolution configurations with shorter streamers, so 2D should in principle be more manoeuvrable. The time-lapse performance of 2D seismics is reputedly rather poor, due to the difficulty in accurately reproducing recording conditions along single 2D lines.*

Costs: *A typical marine 2D survey will cost in the order of hundreds of thousands of GBP depending on survey area, specification, locality etc. The use of 'site survey' type boats with high resolution acquisition can be a lower cost option where target depths are less than about 1000 metres. Processing costs are proportionally less compared to 3D data.*

In 2006 a 'site survey' vessel was used to acquire a high-resolution 2D seismic survey at **Sleipner**, in the form of a number of parallel profiles oriented NNE over the CO_2 plume with additional lines arranged in a star arrangement centred on the plume (Figure 3.14a). Data quality was excellent with superior resolution of the uppermost parts of the plume compared to the 3D datasets (Figure 3.14b, c). Imaging of the deeper plume on the 2D data is not as good as with the 3D data, due to poorer signal penetration and less effective rejection of multiples.

The 2D data has cast light on the detailed structure in the uppermost plume layers, including locally, true temporal resolution of the topmost CO_2 layer, by imaging the top and base of the layer explicitly (Williams & Chadwick 2013). Full temporal resolution was not achieved on the 3D time-lapse data until 2010 when layer thicknesses had increased and high resolution dual-sensor streamer technology was available (Furre and Eiken, 2014).

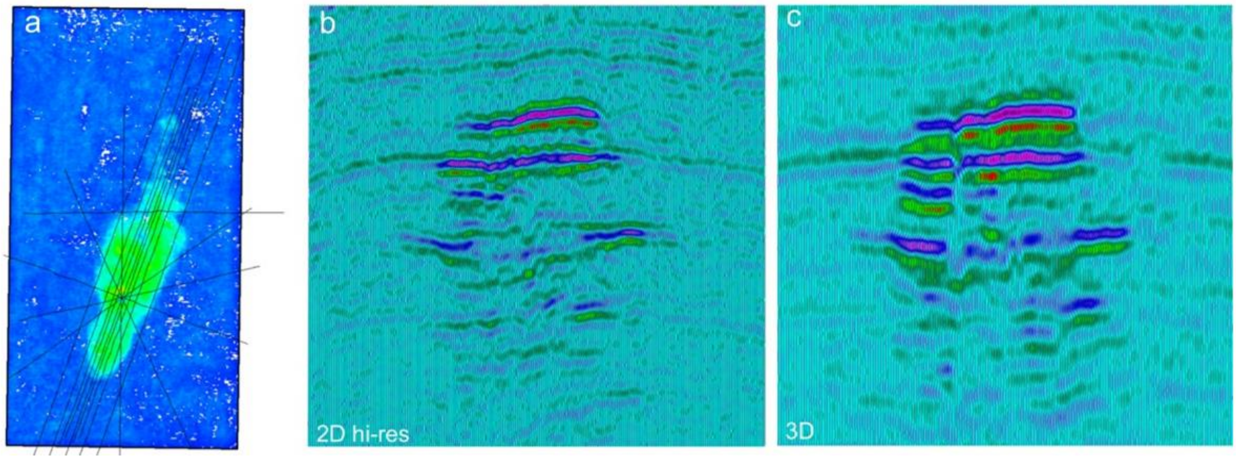


Figure 3.14 2D high resolution data acquired in 2006 a) map of 2D lines relative to the plume footprint b) example 2D profile c) corresponding profile from the 2006 3D dataset. Map dimensions in (a) is ~3 km x 7 km. Seismic data courtesy of Statoil ASA. (British Geological Survey © NERC 2014).

3.2.3 Streamer - P-Cable seismic (High resolution 3D seismic)

P-Cable is a high resolution 3D seismic system using small airguns with frequencies up to 250 Hz, in conjunction with a seismic cable towed perpendicular (cross-cable) to the streaming direction with a number of short streamers attached to it. It is designed for relatively shallow subsurface imaging focussing on the shallow subsurface beneath the seabed, where conventional seismics lose quality and coverage. Targets are typically gas chimneys, shallow gas and gas hydrate reservoirs typically within the top 500 – 1000 m of the seabed (Petersen et al., 2010).

Deployed at: *Snøhvit, Gulf of Mexico, USA*

Capabilities: *P-Cable offers full 3D imaging of the shallower geological section (down to about 1000 metres or so), the small source and compact streamer offering the capability of high spatial and temporal resolution. P-Cable does not substitute for conventional 3D seismic but rather complements it by offering improved imaging in the shallow overburden. Its primary use in* CO_2 *storage therefore would be for containment risk assessment and leakage monitoring – tracking migrating* CO_2 *above the storage complex to the seabed.*

Practicalities: *The P-Cable streamer is relatively compact; fairly wide but much shorter than conventional 3D and 2D streamers, resulting in high manoeuvrability. However, the short streamer results in poor multiple rejection, particularly of the seabed multiple. The effect of this depends on water depth, as particularly in shallow water, the seabed multiple can obscure important features.*

The technique with its small shallow towed streamer is prone to reduced performance in poor sea conditions and there is uncertainty over the time-lapse performance. This is currently being tested in the ECO2 project.

Costs: *Much lower than conventional 3D seismics (hundreds of thousands of GBP depending on survey area specification etc).*

Two P-Cable surveys have been acquired at **Snøhvit** in 2011 and 2013 by the ECO2 project (Bünz et al., 2011, 2013). As deployed the cross-cable has a total length of 233 m with 14 streamers attached. Each streamer is 25 m long with 8 channels at a spacing of 3.125 m. The source was a mini-GI gun (15/15 in^3). Data quality is reasonable (Figure 3.15) with good resolution of near-seabed stratigraphy and amplitude anomalies related to shallow gas accumulations. Because water depths at Snøhvit are more than 300 m, the seabottom multiple does not obscure shallow events (Figure 3.15).

Time-lapse processing is now underway in the ECO2 project, so the repeatability of these surveys is currently uncertain.

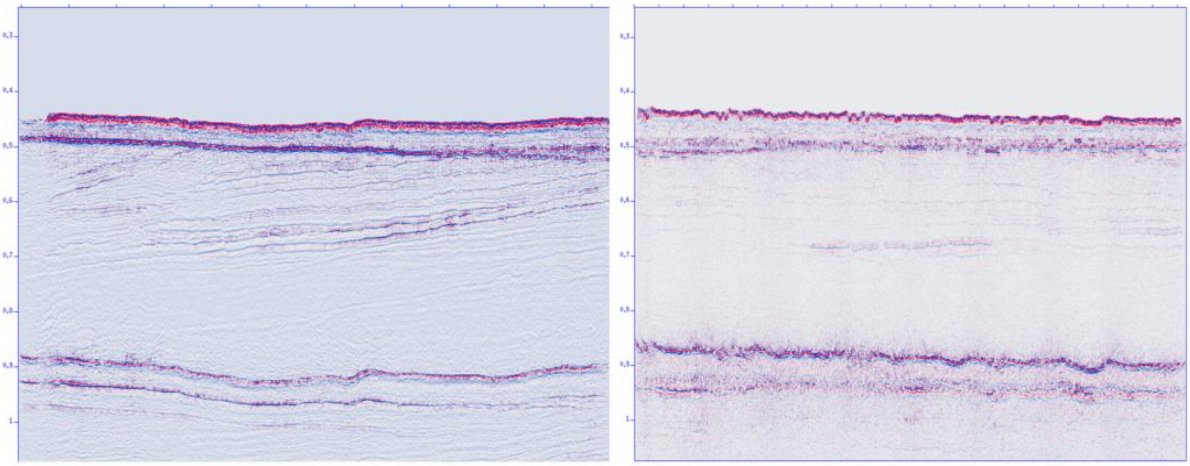


Figure 3.15 Examples of the P-Cable data acquired in the Snøhvit area showing fine details of shallow stratigraphy and shallow amplitude anomalies. The seabed is at a depth of around 330 m and the base of the sections at about 900 m. Note the strong seabottom multiple. Impaired data quality on the right hand panel is due to the presence of pervasive shallow natural gas in the sediment (Data courtesy of University of Tromsø and the ECO2 project).

P-Cable surveys have also been deployed in the **Gulf of Mexico, USA** as part of ongoing CO_2 storage site identification and characterization efforts (Meckel and Treviño, 2014). Surveys totaling about 137 km^2 were collected in 2012, 2013 and 2014. These allowed high resolution 3D mapping of faults (Figure 3.16), stratigraphical geometries and any historical fluid movement in the overburden above potential storage sites for the assessment of containment risks. The data was integrated with conventional 3D seismic to allow continuity of data from the reservoir to the seabed.

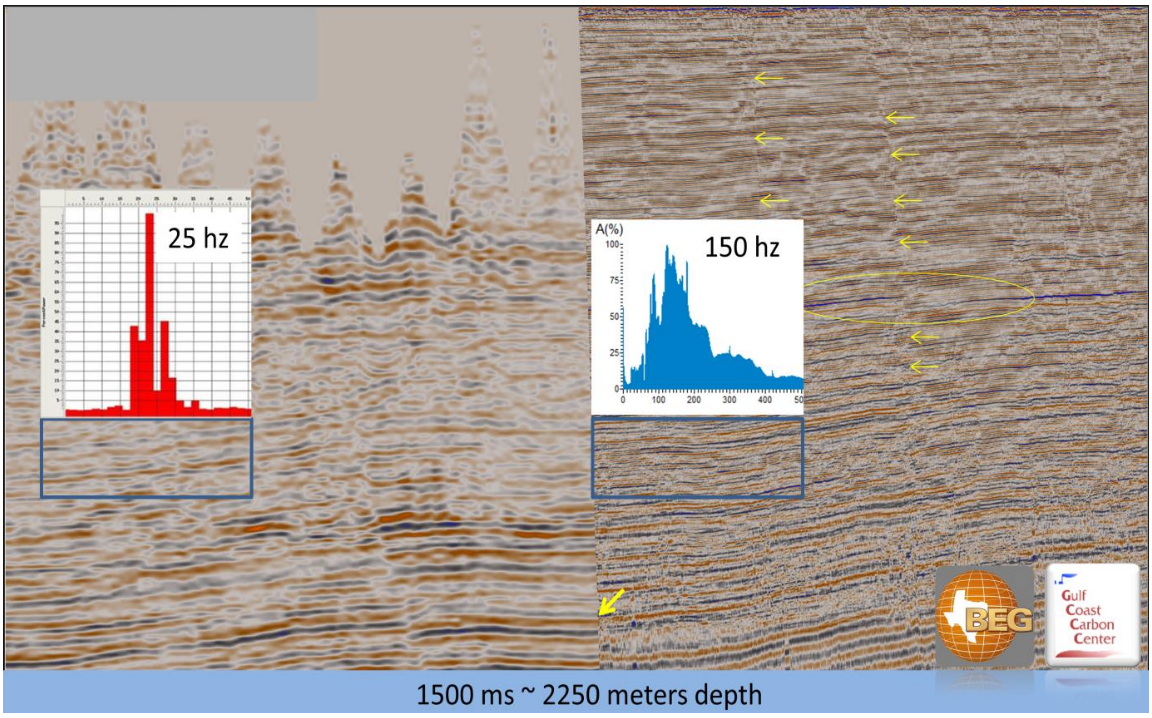


Figure 3.16 Comparison of conventional 3D seismic data (lower frequency content; left) with higher resolution P-Cable data (right). Calculated approximate vertical resolutions are left ~15m, right ~2.5m. (Courtesy of Tip Meckel, Gulf Coast Carbon Center, University of Texas at Austin).

3.2.4 Chirps, boomers and pingers

Very high resolution surface seismic techniques can be used in time-lapse mode to detect changes to the seabed that may result from CO_2 leakage. Direct detection of bubble-streams in the water column may also be possible in favourable circumstances. These systems have source frequencies in the kHz range which causes free gas bubbles to resonate and scatter energy, making them particularly suitable for imaging.

Deployed at: *Pingers at Sleipner. Shallow overburden monitoring seismic is planned at Goldeneye using chirps and pingers. Unspecified sub-bottom profiling is planned at Tomakomai.*

Capabilities: *Pingers are a relatively old and simple technology with a source frequency from around 3.5 – 7 kHz and depth penetration up to about 20 m or so, more in unconsolidated sediments. They have largely been replaced by chirp systems which use transducers to produce a wide bandwidth (2 – 13 kHz) swept frequency source which is known and repeatable and can produce decimetre high resolution imaging of the top 30 – 40 m of marine sediments (Bull et al., 1998; Bull et al., 2005; Vardy et al., 2008). Boomer systems use implosive sources where an electrical current is discharged through a coil, inducing eddy currents which cause a rigid metal plate to move sharply, generating the sound energy. They have frequencies between ~500Hz and 6 kHz, slightly lower than chirp sources and with lower resolution, but greater penetration (typically imaging down to 60 m beneath the seabed), and can produce exceptional images of the sub-surface (see for example McNeill et al., 2005). A drawback of all these systems is that they do not produce 3D coverage, but rather grids of 2D profiles.*

Practicalities: *The systems can be deployed readily from small 'site-survey' vessels. AUV systems can also be equipped with Chirp transducers to image the near seabed. Data acquired from an AUV in 2012 as part of the ECO2 project gave clear images of natural gas pockets in the central North Sea within the top 3 m of sediment beneath the seabed. The limited penetration achieved by AUV-based seismic systems is due to the lower power available for operation.*

Costs: *These tools can be deployed for minimal additional costs on seismic survey boats. Dedicated surveys would require a small site-survey vessel, costs are in the order of a few tens of thousands of GBP.*

3.2.5 Ocean bottom nodes (OBN) and cables (OBC)

Ocean bottom sensors can either be deployed temporarily or permanently. In terms of time-lapse performance it is likely that permanent deployments will offer the greatest advantages. Permanent sea bottom seismic recording systems have not yet been deployed in large-scale offshore storage projects. Up to now streamer surveys have been utilised for two main reasons: cost benefit and the risk. The initial expense of laying the sensors, their lower data coverage (compared to streamer surveys), and the risk of them being damaged by trawling has precluded their use.

Deployed at*: Not yet deployed at existing CO_2 storage sites, but OBN planned at Goldeneye, OBC planned at Tomakomai.*

Capabilities: *Seabed, and in particular, permanent seabed arrays do provide a number of additional capabilities compared with conventional streamer seismics. They can provide full azimuth datasets and multicomponent sensors with p-wave and s-wave recording, for geomechanical and isotropy characterisation, fracture detection etc. They can also be used in passive mode, for long-term recording* *of natural and induced seismicity and ambient noise, providing data suitable for applications such as seismic interferometry. High precision time-shift mapping (see below) will enhance capability to detect pressure changes in the reservoir and /or geomechanical changes in the overburden. One of the most significant benefits is in time-lapse mode via improved repeatability. A permanent OBC system (termed PRM) using fibre-optic cables trenched 1.5 m below seabed was deployed at Ekofisk in 2010 (Eriksrud 2014). The array covered an area of 60 km^2 with 4000 4-component sensors. After a number of repeat surveys remarkable levels of repeatability were attained, significantly superior to the streamer data from Ekofisk, and in principle capable of detecting reflectivity changes as low as 2-3 % and time-shifts of 0.2 ms or less.*

Practicalities: *A key practical advantage of seabottom arrays is their ability to provide data from around and beneath offshore platforms, where streamer surveys cannot easily image. Ronen et al., (2012) have carried out an in-depth cost benefit and survey design study of the use of OBC around offshore platforms. A disadvantage of some seabed systems is their vulnerability to damage from trawling and the generally rather limited spatial sampling density compared with streamer surveys. Permanent OBC systems can be trenched offering a high level of protection.*

It is also notable that with near real-time data transmission via an optic-fibre link to the onshore processing centre, 4D processing can be achieved in less than 4 weeks from completion of acquisition.

Costs: *Overall costs are comparable to streamer seismics – in the tens of millions of GPB range, but the cost profile is significantly different. For streamer data costs are roughly proportional to the number of repeat surveys. For permanent systems, initial costs are high because they involve laying out the seabottom array: OBC by ship, OBN usually via an ROV, but the incremental costs of time-lapse repeats is vastly reduced. Once the array is positioned repeat surveys can be acquired with just a source boat. So the more repeat surveys are acquired the better the value of permanent systems compared to streamer seismics.*

At **Goldeneye** a (non-permanent) seabed recording array at Goldeneye is proposed, either in conjunction with or as an alternative to repeat 3D streamer survey. The main purpose of the seabottom array will be to obtain data from directly beneath the Goldeneye platform where the streamer survey cannot gain access. This is important because it enables surveillance of the shallower parts of the injection wells. In fact a relative large array is proposed which will also cover the spatial footprint of all of the injection wells to obtain high fidelity repeat imaging of this key subsurface volume in and above the reservoir. The decision on whether the seabed array will comprise individual nodes or a cabled system is yet to be made. Compared to cables, nodes in general are more flexible regarding positioning, offer fuller azimuthal range and are generally better coupled to the seabed.

At **Tomakomai** seismic surveys by OBC are proposed mainly because of the proximity to the busy port area means that streamer seismic is impractical. Non-permanent OBC were used for the characterisation and baseline 3D seismic survey in 2009 and single cable is planned to be permanently installed 2 m below the seabed primarily for 2D seismic monitoring, but also for passive listening for natural or induced seismicity (section 3.4). The 3D survey was deployed in 4 patches using 2 or 3 OBC, each 3 km long and laid out N-S on the sea floor (10 receiver lines in total). Receiver position error is expected to be less than 5 m and acoustic positioning surveys enable the receiver positions to be determined with an accuracy of 1 m (Yamanouchi et al., 2013). The buried cable for 2D seismic and passive listening is 3.6 km long with three-component sensors spaced at 50 m intervals along the cable which is positioned along and above the toes of the 2 injection wells (Tanase et al., 2013, 2014).

3.3 Downhole seismic methods

Downhole seismic monitoring methods fall into two main categories. Vertical seismic profiling (VSP) methods use downhole sensors and surface located sources to provide imaging around the wellbore. Cross-hole methods generally involve downhole sources and receivers and aim to image 2D cross-sections between wellbores, usually by some form of travel-time or attenuation tomography.

3.3.1 4D VSP

With modern VSP, sources are commonly offset from the wellbore in a variety of radial positions to provide 3D multi-azimuth imaging. In principle repeatability can be very good with potential for high resolution characterisation around the wellbore.

***Deployed at**: No downhole seismic tools have yet been deployed in large-scale offshore storage projects. At Goldeneye, an option for multi-well 4D VSP acquisition using optic-fibre distributed acoustic sensor (DAS) cables in the injection and monitoring wells is being considered.*

***Capabilities:** 4D VSP offers high resolution imaging of the near-wellbore region (typically a conical volume, tens to hundreds of metres radius) with multi-azimuthal wave propagation. Coverage is however non-uniform (spatially variable offsets and azimuths) which can make interpretation difficult. Time-lapse repeatability is uncertain.*

***Practicalities:** Permanent downhole sensors allow for cost-effective time-lapse imaging by deployment of a source-only boat. Processing of the recorded data can be complex and time-intensive. Reliability of the downhole sensors is a key issue and recent development with fibre-optic acoustic cable might prove to be an asset in this respect.*

***Costs:** Apart from the initial cost of installing the downhole sensors, cost will be moderate as only a source boat is required for repeat surveys. However, this makes the processing costs more significant compared to the survey cost, than for streamer seismic.*

3.3.2 Cross-well methods

No cross-well seismic methods have so far been deployed or proposed for monitoring offshore storage. Current deployments onshore utilise well spacings in the order of tens of metres (Appendix 1.1.4). No current offshore projects have monitoring wells so close, so from a practical point of view the method seems unsuited to offshore deployment.

3.4 Passive (including microseismic) seismic monitoring

A number of passive or microseismic monitoring systems for CO_2 storage have been deployed onshore (Appendix 1.1.4), but so far there none deployed offshore, although several are being planned. Downhole sensor deployments are primarily designed for detecting and locating small magnitude (microseismic), reservoir-level events whereas seabed surface deployments are preferred for regional seismicity assessments.

***Deployed at**: Microseismic monitoring is planned at ROAD and Tomakomai. Seismic monitoring with seabed seismometers is being considered at Goldeneye and at Tomakomai. Microseismic monitoring has been deployed at a number of onshore sites, mainly where induced seismicity is a concern (Appendix 1.1.4).*

***Capabilities:** Passive continuous monitoring for microseismic events can be used to improve understanding of injection processes, injectivity and seal integrity. Some research based deployments have shown events located along existing or previously unrecognised fault planes. Early warning of the occurrences of such events could allow changes in injection strategy e.g. to avoid damaging seal integrity or causing seabed uplift or subsidence.*

***Practicalities:** Microseismic monitoring is usually via downhole deployment of several 3-component geophones in an array sometimes complemented by a hydrophone. Surface (seabed) seismometers are likely to have greater coverage for monitoring regional seismicity, but are less accurate at locating reservoir level events and distinguishing them from background natural seismicity. Conventional microseismic monitoring arrays are usually deployed in one or more shallow wells (<200 m depth), their ability to accurately detect and locate reservoir level events depending on the number and spacing of wells. Research-oriented deployments of arrays at reservoir-level show great promise for more accurate and precise 3D location of events. For example, fibre-optic accelerometers were able to detect extremely low magnitude events (-3) within 500 m radius at the Lacq Rousse project (Maisons and Payre, 2014). Geophones require good coupling to the formation and so are often cemented into the shallow wells. Continuous monitoring generates vast quantities of data and processing can be time consuming.*

***Costs:** Initial costs of installing the seabed seismometers and/or downhole sensors (e.g. drilling a network of shallow wells or a dedicated reservoir-level monitoring well) are substantial although microseismic monitoring could also potentially be deployed in the injection well itself (like at the onshore projects at Lacq-Rousse, France and Decatur, USA, see Appendix 1.1.4). Maintenance or data collection requirements will be more costly at remote sites and as data can be collected continuously, processing costs can be significant.*

A key benefit of passive seismics is for public assurance, and to avoid ill-informed or mischievous claims of induced seismicity. The latter was illustrated vividly in September 2009 when the magazine New Scientist published an article claiming that the **Sleipner** injection operation had triggered a Magnitude 4 earthquake in 2008. The BGS global seismicity database was checked to test the validity of this claim. In fact the data show clearly that no such earthquake occurred (Figure 3.17). If anything, due to natural variation, seismicity in the Sleipner area was somewhat higher before injection commenced than afterwards. The New Scientist article was subsequently retracted.

Japan is in a seismically active area, and given the economic and societal impact of previous natural earthquakes, it is especially important to provide assurance that there is no link between CO_2 storage and damaging earthquakes. To try and achieve this at the **Tomakomai** site, passive seismic monitoring is deployed via four ocean bottom seismometers (OBS) (and one onshore in a well 200 m deep). One of the planned OBSs is to be positioned directly above (and between) the injection points. This is wire-connected for data transfer with an annual replacement schedule for maintenance. The other three OBSs are standalone units positioned within the 3D seismic survey area. These will be replaced at 4 month intervals for data acquisition and maintenance. The OBC (section 3.2.5) is also deployed in passive listening mode. In addition, downhole seismic sensors have been deployed for microseismic monitoring, placed just above the deeper injection horizon in the two deep observation wells and just above the shallower injection horizon in a third (shallower) observation well (Tanase et al., 2014).

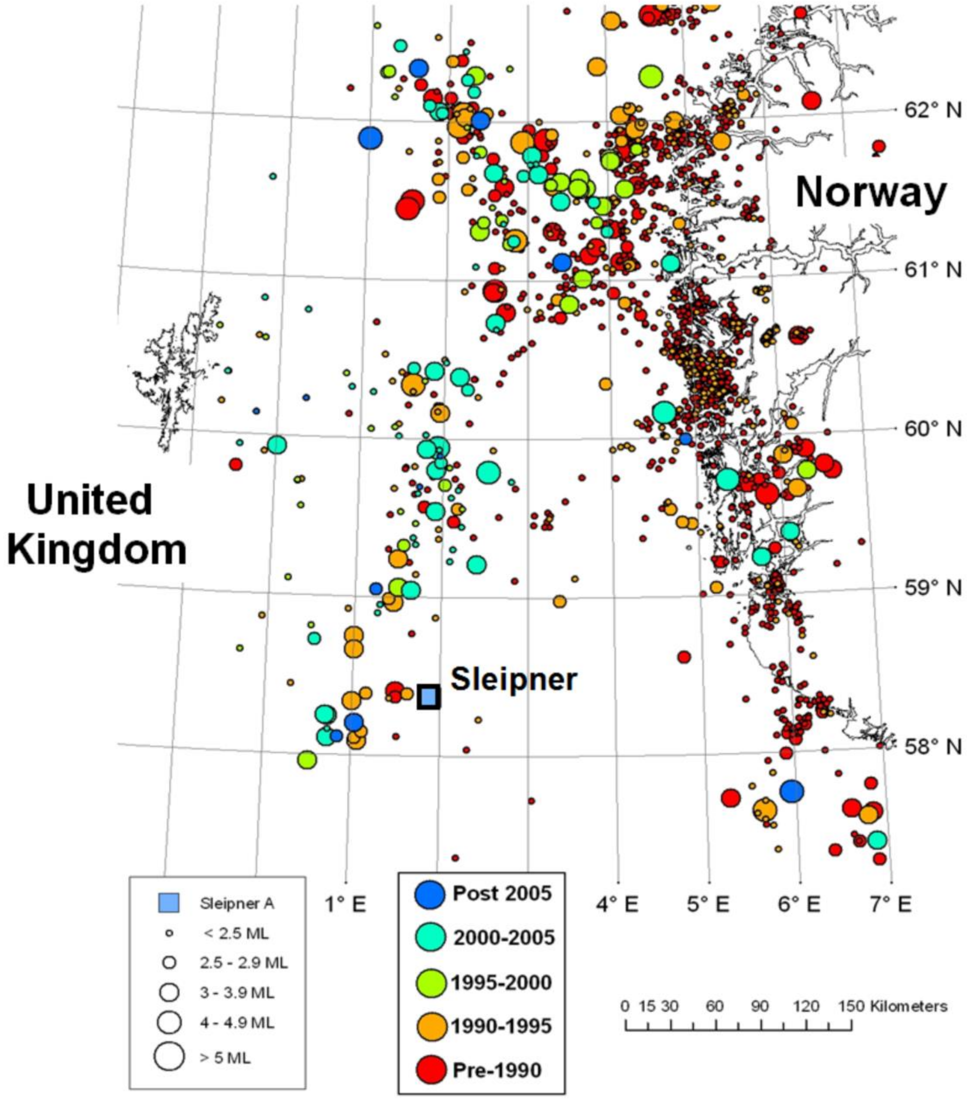


Figure 3.17 North Sea recorded seismicity around Sleipner (British Geological Survey © NERC 2014).

The feasibility of deploying a broadband seismometer permanently on the seabed beneath the **Goldeneye** platform is being considered, principally for establishing baseline levels of seismicity. A seismometer at Goldeneye will markedly reduce the seismicity detection threshold compared with the current, largely land-based, monitoring system and will provide a more robust pre-injection baseline.

3.5 Potential-field methods

Potential field techniques can offer complementary information to the seismic methods and two methods have been tested at Sleipner.

3.5.1 Seabottom gravimetry

For aquifer storage dense-phase CO_2 is significantly less dense than typical reservoir brine, so an injected CO_2 plume will produce a gravitational response proportional to the mass deficit of the plume compared to an equal volume of formation water. The response is of the order of microGals (µGal), so to achieve the necessary accuracy, the gravimeter has to be deployed on the seabed, rather than on-ship.

Deployed at: *Sleipner. Considered at Goldeneye but was screened out because a feasibility study showed that CO_2 in the reservoir was below the detection limit and it would be difficult to determine the depth or presence of a CO_2 leak in the shallower overburden using this technique.*

Capabilities: *For aquifer storage gravimetry is an attractive complementary tool to seismics because it directly measures mass change within the reservoir. Mass change is principally a conformance-related parameter and is relevant in terms of CO_2 dissolution, a key medium-term stabilisation process that cannot be easily detected by time-lapse seismics. Optimal conditions for gravimetry are a shallow reservoir with a thick (tall) CO_2 plume.*

Practicalities: *Offshore gravimetry is logistically quite complex, requiring a boat and ROV to place permanent concrete benchmarks on the seafloor and to deploy the gravity station. Shallow water depths generally improve logistical aspects.*

Costs: *Costs are relatively low compared to 3D streamer seismic, requiring deployment of a basic boat, ROV and gravimeter for a few days. For a typical 50 station survey not too far from shore, layout costs could be up to around one million GBP, vessel inclusive. Processing costs are low.*

Time-lapse seabottom gravimetry has been deployed at **Sleipner.** The initial survey was acquired in 2002 (Nooner et al., 2007), with 5.19 Mt of CO_2 in the reservoir. Repeat surveys were then acquired in 2005 with 7.74 Mt of CO_2 injected, in 2009 with 11.05 Mt of CO_2 injected and most recently in 2013. The surveys were based around pre-positioned concrete benchmarks on the seafloor that served as reference locations for the gravity measurements. Relative gravity and water pressure readings were taken at each benchmark by a customised gravimetry and pressure measurement module (Figure 3.18) mounted on a remotely operated vehicle (ROV). Thirty concrete benchmarked survey stations were deployed in two perpendicular lines, spanning an area of about 7 km east-west and 3 km north-south and overlapping the subsurface footprint of the CO_2 plume (Figure 3.18). A number of additional stations were added for the 2009 survey to allow for the increased plume footprint. Each survey station was visited at least three times to better constrain instrument drift and other errors, resulting in a single station repeatability of about 4 µGal. For time-lapse measurements an additional uncertainty of 1–2 µGal is associated with the reference null level. The final detection threshold for Sleipner therefore is estimated at about 5 µGal.

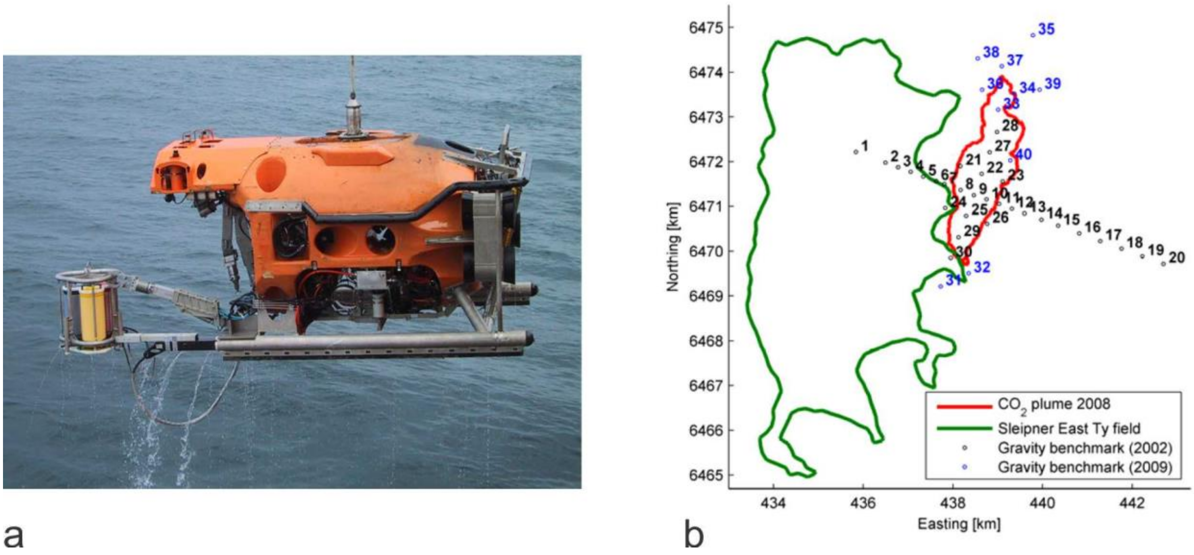


Figure 3.18 a) ROV and seabed gravimeter deployed at Sleipner b) location of the gravimetry benchmarks with respect to the 2008 CO$_2$ plume footprint (courtesy of Statoil ASA).

Prior to modelling the response, a number of corrections have to be applied to the data, for such as benchmark elevation changes and water-depth / tidal variations. In addition the gravimetric time-lapse response from the Sleipner East field (the deeper gas reservoir currently in production) has to be allowed for. Gravity modelling initially focussed on constraining the *in situ* density of CO$_2$, which constituted a significant uncertainty at a time when reservoir temperatures remained uncertain (Nooner et al., 2007; Alnes et al., 2008). More recently Alnes et al. (2011) obtained a best-fit CO$_2$ density of 720 ± 80 kgm^{-3} from the 2009 dataset. This compares with a theoretical average CO$_2$ density in the plume of 675 ± 20 kgm^{-3}, based on a thermal model using much improved reservoir temperature information (Alnes et al., 2011). The density (mass deficit) discrepancy is interpreted by Alnes et al., as significant, and perhaps indicative of CO$_2$ dissolution within the plume. Taking into account the full range of uncertainty, in terms of the gravity modelling and also in the thermal calculation of plume density, Alnes et al. concluded that the upper bound on total dissolution is 18 %, with a most likely figure significantly lower. Flow simulations of the plume development suggest that dissolution values up to around 10 % are quite likely, so the gravimetry seems to be in good accordance with this.

3.5.2 Controlled source electromagnetics (CSEM)

In a similar way to gravimetry, electromagnetic (EM) methods offer the potential for storage site monitoring. EM techniques deploy time-variant source electrical fields to induce secondary electrical and magnetic fields that carry information about subsurface electrical structure. Because dense-phase CO$_2$ has significantly lower electrical conductivity than reservoir brine, in principle, CSEM can image changes in the distribution of CO$_2$, albeit at much lower resolutions than seismic.

Deployed at: *Sleipner. Considered at Goldeneye but screened out because modelled signals were below the detection threshold.*

Capabilities: *In principle electrical and electromagnetic methods can provide complementary information to seismics, by remaining sensitive to fluid saturation changes at higher CO$_2$ saturation levels, where in many situations, seismic becomes insensitive. In practice this complementarity is difficult to realise because of the radically different spatial resolutions of the two methods.*

***Practicalities:** Offshore CSEM is logistically quite complex, requiring a source boat and a seabed sensor array. The technique is severely hampered in shallow water (< 300 metres) where the airwave obscures the signal.*

***Costs:** Costs are high, roughly comparable with offshore 3D seismics.*

A seabottom CSEM survey was acquired at **Sleipner** in 2008 with about 10.4 Mt of CO_2 in the reservoir. A 2D profile was recorded roughly along the long axis of the CO_2 plume (Figure 3.19a), comprising 20 stations 500 m apart, in places shifted slightly to avoid seafloor infrastructure (pipelines, gravity benchmarks etc.). Two tows were carried out, one at frequencies from 0.5 to 7 Hz, the second at frequencies of 0.25 to 3.5 Hz.

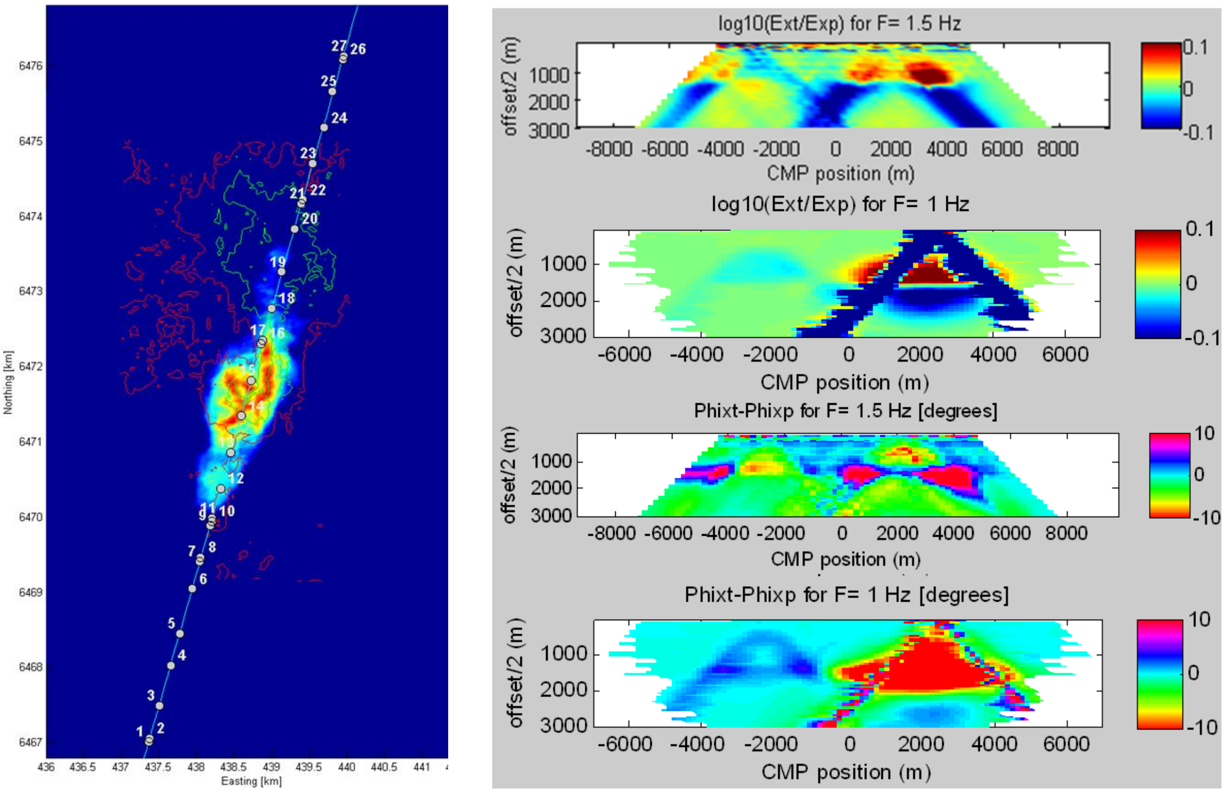


Figure 3.19 a) Location of the CSEM profile, relative to the plume footprint (Courtesy Ola Eiken) b) Comparison on amplitude (top) and phase (bottom) between field data and synthetic normalized by a synthetic baseline. Map dimensions are ~5.5 km x ~10 km. (Courtesy of the CO2ReMoVe project – Cécile Noël and Jean-François Girard, BRGM).

The recorded data quality is apparently quite good, but shallow heterogeneities (associated with geology or man-made structures at the seafloor) above the plume generate artefacts that are mixed with the CO_2 plume response. Such artefacts are of high spatial frequency whereas the CO_2 signature shows a large spatial extent (i.e. for short and large offsets).

In the CO2ReMoVe project a synthetic baseline (or reference signal) was built from data outside the zone of CO_2 injection (northern edge of the 2008 EMGS survey). The normalized data were compared with a synthetic model built based on the logging data and lateral plume extent from the seismic (Figure 3.19b). The observed and modelled variation reaches an increase of amplitude up to a factor of 3 inside the plume zone and more than 10° on the phase which are variations clearly above the threshold of detection with marine CSEM survey.

The survey was undoubtedly hampered by lack of a true baseline. Processing and analysis of the dataset is continuing.

3.6 Downhole measurements

Downhole measurements are a key element of storage monitoring providing high sensitivity point or line sampling of *in situ* reservoir and downhole properties, fluids and conditions.

3.6.1 Downhole pressure and temperature

Pressure and temperature are usually measured using downhole gauges placed at or as close to the reservoir level as practicable, because the density of CO_2 in the wellbore can vary significantly depending on pressure and temperature conditions (this issue is illustrated by the Sleipner case where wellhead pressure measurements cannot be used to determine reservoir pressure due to two-phase behaviour of CO_2 in the wellbore). Gauges may be connected to the surface to allow continuous data collection, or deployed as retrievable memory gauges. Downhole pressure is a key conformance tool and can also be used for containment monitoring (see wellbore integrity section, 3.6.3 and onshore deployment tests in Appendix 1.1.4). It is a regulatory requirement in many jurisdictions (Chapter 2).

Fibre-optics installed along the length of the wellbore can be used for distributed pressure or temperature sensing (DTS), but with a precision inferior to that of dedicated gauges (onshore deployment tests are discussed in Appendix 1.1.4). Temperature measurements can be useful for assessing localized fluid flow behind casing in the wellbore (see wellbore integrity section, 3.6.3). This is because thermal anomalies tend to be very localized (compared to the pressure response of the same event). Optic-fibre technology has not been deployed at any offshore CO_2 storage site to date. This situation might change however as deployment is being considering at Goldeneye.

Deployed at: *Snøhvit, K12-B, planned for Goldeneye, ROAD and Tomakomai.*

Capabilities: *Current gauges are able to detect very small temperature and pressure changes (typical ratings below) and are a primary method for monitoring injected CO_2 physical properties, reservoir fluid flow performance (conformance) and controlling reservoir geomechanical integrity (containment assurance). Downhole gauges are typically rated to 138 MPa and 150 °C and operate with a pressure and temperature accuracy of ±13.8 kPa to 20.7 kPa and ±0.1 to 0.5 °C at a resolution of 138 Pa to 345 Pa and 0.01 to 0.02 °C. Positioning of gauges across permeable units in the reservoir overburden can give indications of out-of-reservoir migration. This configuration has been deployed onshore. Pressure is an 'integrating' rather than an imaging tool, so it essentially measures the sum of many processes acting in and around the reservoir. As such, pressure is one of the key parameters for some types of model calibration and classic history matching. Conversely it is weak in terms of positioning the causes of anomalous events. Measurements in multiple wells can improve this via a form of triangulation.*

Practicalities: *The EU Directive states that the injection wells must be instrumented, but otherwise, suitably positioned wellbores might be in short supply offshore. Installation, maintenance and communications are limited by offshore wellhead access. There are also issues connected with long-term drift of sensors and ultimate life-span. Permanent downhole gauges planned for use at Goldeneye have a 10 year life and a drift stability better than ± 7 kPa at 82,740 kPa and 150 °C (±*

1 °C at 12,000 psi and 302 °C). Installation of 2 such gauges in each of 4 wells during recompletion is planned, along with up to 3 fibre optic lines for DTS. Long term memory gauges which last 1 year with standard wireline installation are planned as a backup. Distributed sensing using fibre-optics is based on using the optical properties to sense strain within the fibre. The source of that strain is may be thermal or barometric so the technology cannot distinguish between thermally induced or pressure induced strains. As a result DTS can only be accurately used to measure temperature when the pressure variations are negligible and, conversely, the performance of DPS will degrade if thermal conditions are not consistent. In the presence of a leak one would anticipate both thermal and pressure changes to occur locally, and those combined effects should be detectable using a fibre-optic system through the strain induced through a combination of temperature and pressure changes.

Costs: *Relatively low (thousands to tens of thousands GBP) assuming dedicated down-hole tripping is not required. In addition to the sensor costs would be costs of installation and retrieval of gauges.*

Conformance

Pressure measurement is a key conformance tool, demonstrating reservoir permeability, storage capacity and geomechanical stability.

At **Snøhvit** downhole pressure/temperature sensors are positioned at a depth of 1782 m below sea surface some 860 m above the injection perforations (2616 – 2669 m). Because the CO_2 column is in the dense phase its properties are known and reservoir pressures can be quite reliably calculated from the depth difference for steady-state conditions. However, under non-steady state conditions, such as at injection start-up and shut-down, temperature transients affect the wellbore CO_2 density and the estimated reservoir pressures are not so reliable (Hansen et al., 2013).

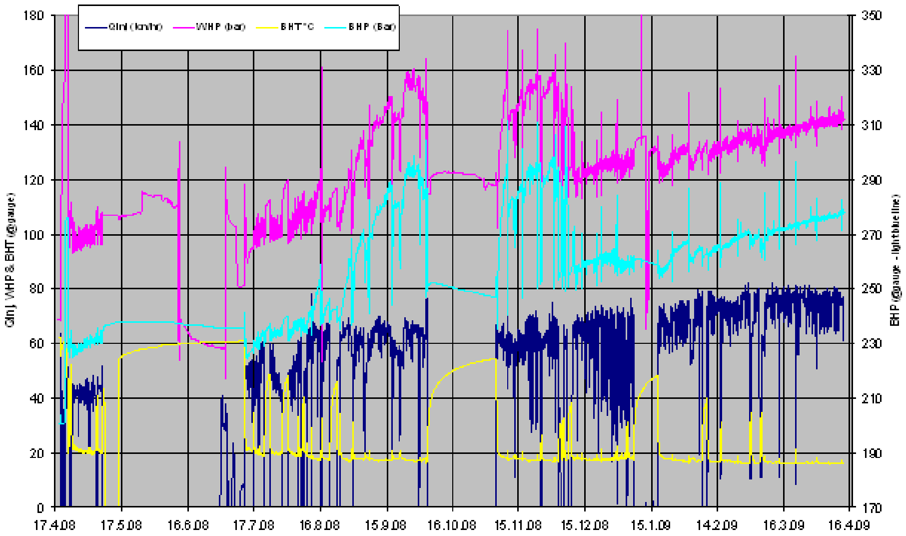


Figure 3.20 Measurements at Snøhvit from April 2008 to April 2009. Downhole pressure (pink), wellhead pressure (pale blue), temperature (yellow) and CO_2 injection rate (dark blue). (Data courtesy of Statoil ASA and CO2ReMoVe project).

Sample output from the sensors (Figure 3.20) shows detailed correlation with the CO_2 injection profile. Early pressure increase in 2008 was related to near wellbore salt precipitation and was successfully remediated. The steady decrease in downhole temperature reflects progressive near-wellbore cooling by the injected CO_2 which is colder than the formation at depth.

Longer term measurement of downhole pressure (Figure 3.21) was crucial in establishing non-conformance at Snøhvit (Hansen et al., 2013). Long-term pressure increase was faster than expected and eventually threatened the geomechanical stability of the storage formation as fluid pressures approached the estimated fracture pressure. In addition, modelling of the pressure decay (or fall-off) curves, which followed cessations in injection, indicated that the capacity of the storage reservoir was smaller than expected, likely due to no-flow barriers a few kilometres from the injection well.

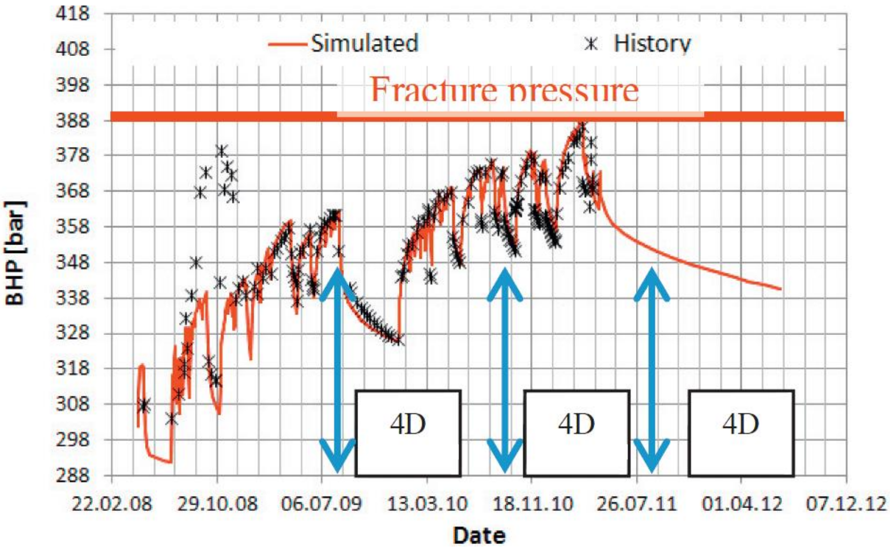


Figure 3.21 Downhole pressure measurement and history matching at Snøhvit, 2008 to 2012. The timing of time-lapse 3D seismic surveys is also shown. (Image from Hansen et al., 2013)

These measurements and interpretations were instrumental in the decision to cease injection into the Tubåen reservoir. Following a well intervention, injection was subsequently resumed in the shallower Stø Formation.

It is notable that although the pressure monitoring at Snøhvit ultimately led to the decision to cease injection into the Tubåen storage unit it was not by itself sufficient to understand the detailed situation. The seismic data were able show the disposition of the faults within the reservoir and the fact that they were acting as flow barriers and also the stratigraphical barriers to flow that were preventing the CO_2 from moving upwards in the reservoir. The most complete understanding of reservoir performance therefore came from a combination of the accurate, integrative pressure measurements and the positional imaging ability of the time-lapse seismics.

At **K12-B** continuous pressure and temperature measurements were deployed in a number of wells (Figure 3.4, left, all wells except K12-B8), important at K12-B because conditions vary near the CO_2 critical point. The CO_2 is dense-phase in the wellbore, but becomes gaseous in the reservoir because of the pressure-depleted conditions. The measurements enabled detailed history-matching against flow simulations (Van der Meer et al., 2006) focussing on pressure rises and decays as CO_2 injection was switched on and off. Satisfactory, but not perfect matches were achieved, indicating that a robust solution for reservoir permeability and capacity was not identified (Figure 3.22). Nevertheless the history-matching does confirm that injection has not caused any problems such as changing reservoir permeability or unexpected storage capacity issues.

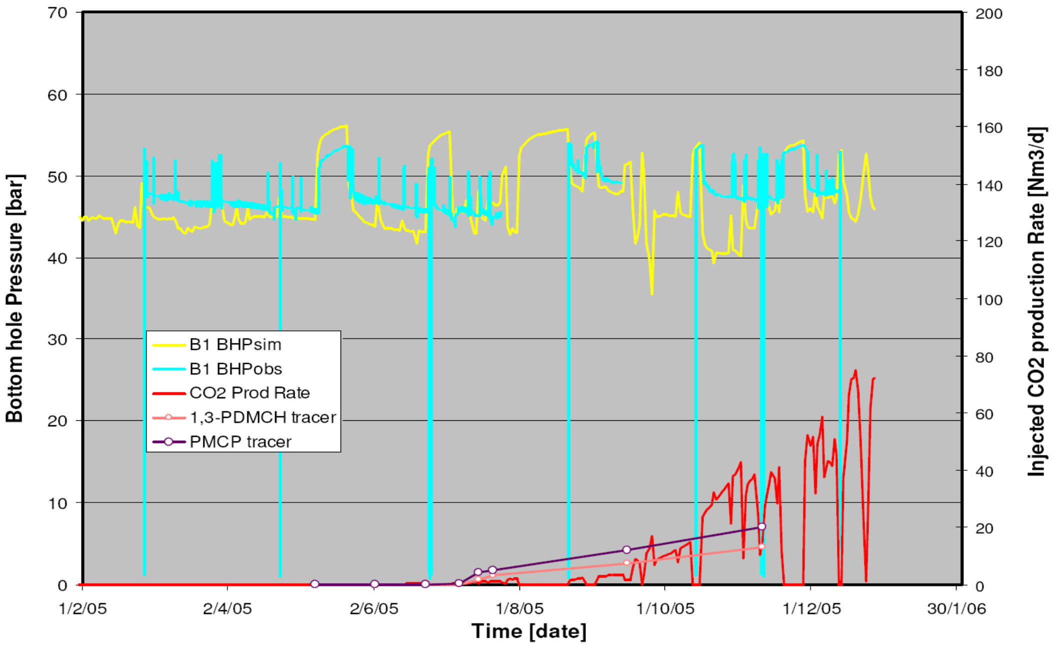


Figure 3.22 Bottom-hole pressure measurements (Observed and simulated) and tracer measurements at K12-B (Van der Meer et al., 2006, Data from CO2ReMove project)

In addition memory gauges were installed in the injection well K12-B6 at 3676 m, 12 m above the top of the perforations. Data were recorded continuously for 2 weeks (April 15th to May 2nd 2010: Figure 3.23). These were used to verify and constrain reservoir models and to monitor for any changes in injectivity.

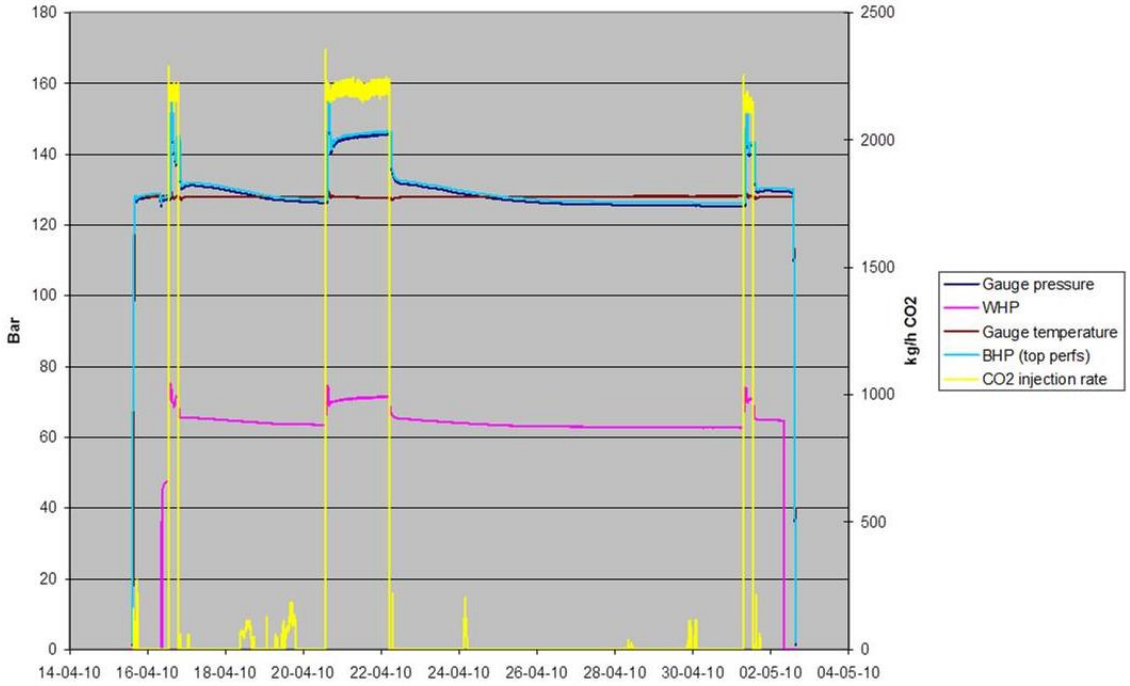


Figure 3.23 Plot of pressures, temperatures and flow at well K12-B6. (Courtesy of Vandeweijer et al., 2011 and TNO contribution to the CO2ReMoVe project).

Containment

Downhole pressure monitoring for containment has been implicitly deployed offshore, in that any unexpected pressure reduction in the reservoir could indicate potential leakage, but explicit containment monitoring such as 'above reservoir' pressure surveillance has so far only been tested onshore (Appendix 1.1.4).

At **Snøhvit** pressure measurements also contributed indirectly to containment assurance in that they were used to prevent reservoir pressures exceeding the fracture pressure, thereby maintaining topseal integrity.

3.6.2 Downhole geophysical logging – for CO_2 saturation or CO_2 induced changes

Geophysical logs are routinely collected in open (uncased) wellbores to determine a wide range of *in situ* formation and fluid properties. To monitor for CO_2 related changes in a borehole, repeat logging will be required once the hole is cased ("cased-hole"), whereby formation measurements are made through the casing and cement. At some onshore sites, various types of repeat cased-hole logging have been used to monitor CO_2 breakthrough at monitoring wells and to monitor CO_2 saturation changes around the well bore (see also Appendix 1.1.4). However, offshore access to wells for repeat logging is often limited (dedicated monitoring wells are costly and may not balance with the value of monitoring information gained from them). Access to injection or production wells for logging may be possible during routine maintenance.

Deployed at: *Planned at ROAD and Goldeneye (for onshore examples see Appendix 1.1.4).*

Capabilities: *Most are standard oilfield practice but interpretation has been modified for calculating CO_2 saturation (rather than hydrocarbon saturation). For example,* ***Pulsed neutron capture (PNC)*** *tools are commonly used in the oilfield to measure water saturation in cased boreholes. These measure 'sigma' (Σ), the 'thermal neutron capture cross section' of the formation, which is related to the water saturation. Monitoring CO_2 saturation requires a sufficient Σ contrast between CO_2 (low Σ) and the in situ fluids (saline formation water has high Σ, natural gas has low Σ). With a good baseline survey and knowledge of borehole completions and fluid phases, repeat surveys can be processed to calculate CO_2 saturations. This has been tested at onshore storage sites such as Ketzin, Cranfield and Frio. Other tools that can be sensitive to CO_2 saturation through casing include* ***neutron porosity****,* ***resistivity and acoustic tools*** *(tested through fibreglass casing at Nagaoka, but tool variants could potentially also work through steel casing) and* ***carbon – oxygen*** *logging tools. In general, saturation logging is used over the reservoir interval (e.g. to monitor CO_2 breakthrough at monitoring wells), rather than for containment monitoring in the overburden (e.g to monitor for CO_2 in shallower formations), because of difficulties with imaging through multiple casings.*

Practicalities: *Access to the well is the main hindrance for repeat logging, for example if the well doubles as an injector/producer, operations may need to be halted or completion tubing may be too narrow for standard logging tools, so logging may only be possible for limited time periods (e.g. when tubing is pulled for maintenance). The depth of investigation is small and processing may be challenging where casing or tubing sizes change, or casing-cement-formation bond quality change. At Ketzin, the CO_2 saturation logging processing was complicated by halite precipitation. Build-up of scale in a K12-B well caused an obstruction which precluded logging below that point.*

Costs: *Downhole logging costs are typically a small percentage of the cost of drilling a "standard" oil field well. The cost varies depending the type of tools, the type of well (e.g. logging highly deviated* *wells may require more costly specialist deployments) and mainly the depth and length of the interval of interest (and repeat logging frequency). Lost/damaged-in-hole tool insurance is usually available.*

Conformance

At **Goldeneye**, pulsed neutron capture logging is planned over the reservoir in the injection and monitoring wells to measure CO_2 saturation around the wellbores. Baseline logging of both is planned when recompletion of the wells is performed. A good baseline is necessary to be able to quantify the CO_2 thickness interval from the existing CH_4. A watered out former production well was chosen as the monitoring well because the large sigma contrast between saline formation waters (high Σ) and CO_2 (low Σ) relative to CO_2 and CH_4 (also low Σ) means that CO_2 saturation changes should be possible to determine. Models were used to test the feasibility of CO_2 detection at different anticipated pressures when CO_2 replaced either CH_4 or CH_4 and 50kppm brine. Logging is only planned across the reservoir interval, because processing will be more challenging in the overburden interval as a result of the changing borehole and tubing sizes. Other possible methods for deriving CO_2 saturation were discounted for various reasons (e.g. because they were too large for borehole size restrictions, unsuitable for the completions, or insufficiently sensitive in the presence of residual CH_4 gas) (ScottishPower CCS consortium, 2011b).

3.6.3 Downhole wellbore integrity monitoring

Geophysical logs are routinely collected once a well is cased and cemented ("cased-hole") to assess the effectiveness of the cement job and, particularly later in a well's life, to determine the state of the casing. The same methods can be used to assess wellbore integrity at CO_2 storage sites for wells where wellbore access is available (with baseline and post-injection repeat surveys a likely minimum requirement). In fact a thorough investigation into the likely integrity of any wells that are predicted to come into contact with the CO_2 plume is likely to be necessary prior to storing CO_2 to provide containment assurance. Often wells may be plugged and abandoned with no current access, so integrity assessment is reliant on the study of legacy data such as cement bond logs and abandonment schematics (diagrams which show the depths and thicknesses of cements plugs etc). Wells for which the wellbore integrity cannot be sufficiently confidently determined might require works or other mitigating actions such as additional monitoring of the overburden (see Section 3.2) or sea bed (see Sections 3.7-3.10) above and around the well. A similar wellbore integrity investigation incorporating any monitoring evidence and any time-lapse wellbore integrity logs for the accessible wells is likely to be needed prior to closure of the site, to provide assurance of continuing containment. Good wellbore design with e.g. hydraulic isolation tests can improve confidence wellbore integrity in addition to the downhole methods described.

Deployed at: *K12-B, also planned at ROAD and Goldeneye.*
Capabilities: *Many of the downhole geophysical tools to determine wellbore integrity fall within standard oilfield practice and work in the same way for CO_2 storage. Capabilities of individual tools are discussed in the subsections below (in bold italics) but broadly, these fall into 4 main containment objectives:*

- *Tools to evaluate the cement bond between the casing and the formation particularly to determine if there are any potential fluid pathways behind the casing or cement (e.g.* ***Cement bond logging (CBL)****,* ***ultrasonic imaging****)*
- *To investigate the state of the casing or tubing itself i.e. its inner diameter and thickness to check for holes or pitting (that might be signs of corrosion and could affect its integrity). (e.g.* ***Multi-finger calipers, electromagnetic imaging, downhole video****)*
- *To detect any leakage either directly out of the wellbore or from the reservoir behind the casing e.g. through the noise it makes (noise logging e.g.* ***Well annular flow (WAF)****), changes to the fluid movement inside the borehole (e.g. flow logging)or outside the casing (e.g. radioactive tracer logging and any downhole logs that can detect changes in gas saturation (see section 3.6.2)), or physical changes caused by a leak (e.g. wellbore annular pressure monitoring, downhole temperature logging) Note that permanently installed downhole methods could contribute to monitoring wellbore integrity for example along-borehole fibre optics for pressure and temperature sensing (section 3.6.1) or passive listening using microseismic sensors.*
- *To investigate borehole stress and deformation (that might compromise borehole integrity). (Note this is relatively specialist, but it was considered at Goldeneye). (e.g.* ***Real time borehole stress and tubing/casing deformation imaging.*** *Tiltmeters have been used onshore (Appendix 1.1.3), but current re-calibration requirements make them unsuitable offshore)****.***

Practicalities: *As for Section 3.6.2*

Costs: *As for Section 3.6.2*

Containment

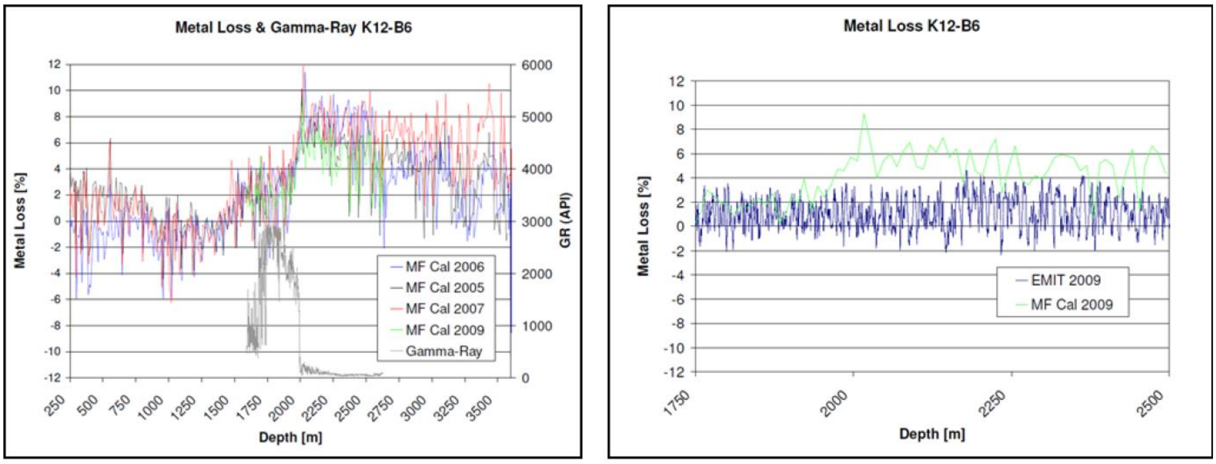
At the **K12-B** storage site (and also at **ROAD**), because of the nature of thick Zechstein evaporitic topseal, the sites are extremely unlikely to leak, but potential leakage via wellbore pathways has been identified as a possible risk and so monitoring efforts are focussed on this. Multiple tools were used to assess any changes in integrity in the injection wells. Problems were encountered due to the build-up of mineral scale from previous natural gas production, which led to changes in the logging programme.

At **ROAD** the well integrity monitoring tools planned are similar to those deployed at K12-B: ***Cement bond logging (CBL),*** and imaging via downhole video, multi-fingered caliper and electromagnetic tool (described below). In addition ***ultrasonic imaging*** (which transmits an ultrasonic signal and uses the received reflected waveform to return 360° images of casing and cement thickness and quality) and ***well annular flow (WAF)*** (which detects low levels of ultrasound created by flowing fluid outside casing to detect and locate flow between the casing and formation or between two casings), are also used.

At **Goldeneye**, similar types of well integrity tool are planned for deployment. These can only be run in hole on recompletion of the wells, so this will be done prior to injection as a baseline, to assess well integrity. Tubing integrity will be run to assess impact of pressure. In those wells that have been injecting, this is planned for deployment in year 3 to be repeated every 5 years until the end injection.

Multi-finger caliper tools provide high resolution, multiple internal tubing radii measurements using mechanical calipers. This provides internal casing dimensions to help identify and quantify any corrosion, scaling or mechanical damage. Depth of pitting and percentage metal loss can be calculated. At **K12-B** a downhole interval (2600 m – 1600 m) was monitored and although internal radii were within the tolerances for this tubing there were significant changes between time-lapse results. This is because the calipers cannot distinguish between casing damage and the build-up of scale that had occurred. Misleading pit depth and metal thicknesses were therefore reported over the affected intervals. Downhole video was therefore deployed in 2007 and in 2009 an electromagnetic imaging tool was run, to further investigate the apparent changes.

Electromagnetic imaging tools measure and map the inner tubing diameter and the total (metal) thickness of all concentric pipes. Different frequency measurements allow for differentiation of internal tubing features and those external to it. The measurements are not affected by non-magnetic scale. At **K12-B**, this method (which at the time was experimental) allowed reliable measurements of the tubing and casing thickness. The measurements showed that the tubing and casing integrity was consistently well within acceptable range over the measured interval.



a. b.

Figure 3.24 Time-lapse well integrity studies in the K12-B injection well. Left: Multi-finger caliper (MF Cal) calculated metal loss results and gamma ray. Right: Detail of electromagnetic imaging (EMIT) and multi-finger (MF) caliper calculated metal loss (Vandeweijer V.P. and Arts R personal communication).

Cement bond logs (CBL) are used to assess the bonding quality of cement between the casing and the surrounding formation. The tools transmit an acoustic signal through the casing, cement and formation, the strength and transit time of the refracted signals providing information about the cement bond at each interface. The planned logging of the injection well at **K12-B** failed, due to scale build up obstructing about half of the tubing inner diameter at the top of the perforations.

At **K12-B** a ***downhole video*** tool was used to view the nature of the obstruction met by the CBL tool. It was interpreted as accreted scaling, which subsequent sampling confirmed as mineral precipitation from previous gas production in the well. The differences in multi-fingered caliper time-lapse results (Figure 3.24) are thought to be caused by the scrape marks (visible in Figure 3.25, right), probably due to the passage of tool rollers, centralisers or cables.

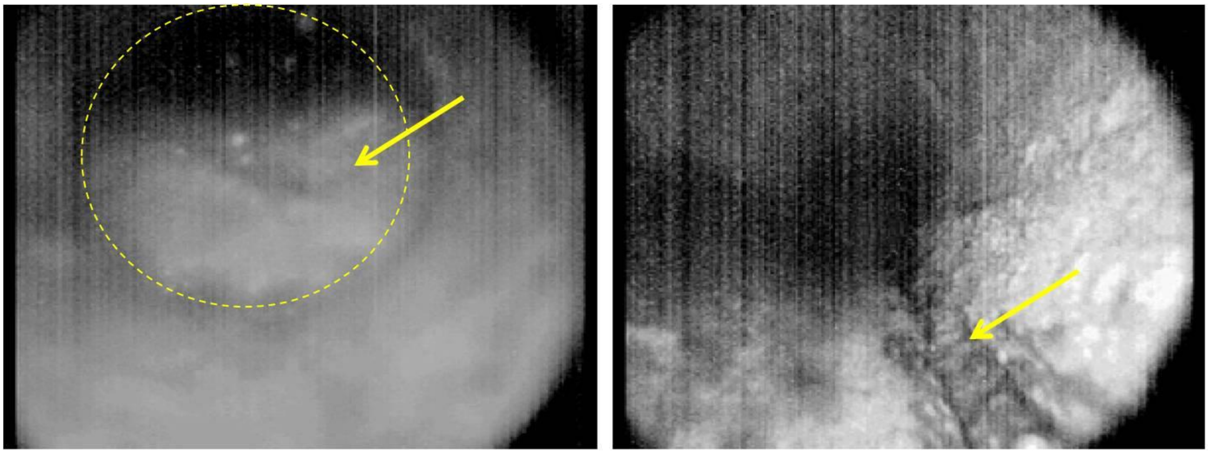


Figure 3.25 Downhole video images from the injection well (looking downhole). Left: The obstruction that hampered the CBL log (paler region indicated by yellow arrow). Right: Bright, cloudy structured mineral scale on the liner walls is clearly visible. The straight features in the scale (indicated by yellow arrow) are probably scrape marks of centralizer arms of logging tools (after Vandeweijer et al., 2011).

Real time borehole stress and tubing/casing deformation imaging was considered at Goldeneye, but was discounted. It uses a fibre optic based system wrapped around the outside of casing or tubing. The cable contains strain gauge sensors every centimetre, capable of measuring less than micro millimetres of deformation. This high resolution strain data can be processed to provide a real time image of borehole stress.

3.6.4 Downhole fluid sampling

Downhole fluid sampling can be useful for constraining and calibrating reservoir models, particularly those incorporating geochemical reactions. It is also helpful for confirming breakthrough of CO_2 at wellbores.

Deployed at: *K12-B, planned at Goldeneye.*

Capabilities: *Laboratory analyses of reservoir fluids can yield* pCO_2*, pH,* HCO_3^-*, alkalinity, dissolved gases, hydrocarbons, cations, stable isotopes and tracers (Section 3.6.5). Wireline downhole samplers used for hydrocarbon exploration are also suitable for fluid sampling in* CO_2 *storage situations. Some have inbuilt analysers to make in situ measurements (during sampling) to determine fluid type, gas composition and concentrations (including* CO_2*) and gas-oil ratios.*

Practicalities: *Ideally downhole fluid samples need to be preserved at reservoir pressures when they are brought to surface to avoid excessive degassing. Such samples can be taken and retrieved in a number of ways; either through wireline deployed tools or permanently installed equipment such as u-tubes. Sampling access to the zones to be monitored is required without hindering operations and as such these are more easily deployed in a monitoring well or during recompletions. Baseline sampling and analyses is useful to predict likely geochemical reactions (through laboratory experiments and modelling). So far the u-tube is a scientific tool deployed onshore. It does not currently have safety certification for offshore use and might well be unsuitable for unmanned platforms. Accuracy of wellbore breakthrough timing depends on the temporal sampling frequency.*

Costs: *Depends on type of deployment (periodic or permanent and frequency and complexity of analysis) but typically a small percentage of the cost of drilling a "standard" oil field well. Onshore cost per sample at a pilot site was of the order of £5-10 k GBP per sample, and the same for specialist PVT analysis, with some reduction in cost for multiples*

Conformance

At **K12-B**, chemical analyses of downhole fluid samples were taken from the injection well in 2010 for pH and chemical composition (downhole pH logging had been cancelled from the monitoring programme). The water was found to be only slightly acidic with a pH of 6.1 @ 20°C. Water ionic composition was recorded and dissolved solids, gas composition, gas-water ratio and related data were also gathered.

Chemical analyses of produced gas samples from two production wells have been collected since 2005 on a more regular basis to assess CO_2 and tracer concentration levels. Results highlight the heterogeneous nature of the reservoir as both wells are within the same compartment as the injector (K12-B6), which started injecting CO_2 in 2005, but show differing results. Well K12-B1 shows a CO_2 concentration increase by mid-2006 whereas K12-B5 does not show significant CO_2 concentration change, despite tracer chemicals having been detected in the stream, suggesting it must be connected to the injector, but maybe by a more tortuous or less favourable pathway. Production water samples from prior to injection and from 2005 and 2007 were also analysed but without any conclusive results - water composition varied widely, perhaps due to water rising irregularly with the gas stream.

At **Goldeneye**, wireline downhole sampling of the reservoir fluids at periodic intervals throughout injection has been proposed for conformance monitoring. This was selected over permanent installation options (e.g. u-tube) which were considered too expensive to install and had well integrity and safety concerns. One example, which could be run in conjunction with the saturation logging tools, has a sample volume of 100 cm^3. Simulations suggest annual repeat logging between years 5 and 10 would be most appropriate, with two samples taken from the interpreted hydrocarbon column and one from the water leg.

3.6.5 Chemical tracers and gas analyses

Tracers can be added to the injected CO_2 to give it a unique 'fingerprint'. They consist of soluble gas or liquid samples of exotic compounds which are injected, either as a pulse, or continuously into the CO_2 stream. Alternatively, the injected CO_2 may already have a different signature from "natural background" either in its isotopic signature, or, for example, its noble gas content (e.g. helium, neon, argon, and their isotopic ratios) which could help give indications of CO_2 origin. The tracer 'finger print' can help monitoring CO_2 migration, for example to estimate volume and flow rate using downhole sampling, or to identify the CO_2 source, if potential evidence of seabed leakage were discovered. Information on reservoir fluid interactions such as dissolution can be gained via tracer partitioning.

Deployed at: *K12-B, planned at Goldeneye.*

Capabilities: *Tracers can provide evidence of CO_2 migration in the reservoir (for plume tracking or to understand fluid flow pathways) and also indicate leakage (and "ownership") of CO_2 if detected at the seabed. Note that CO_2 leakage rates can only be determined from tracer flux rate if the tracer and CO_2*

are evenly mixed and the tracer leaks at the same rate as the CO_2 which may not necessarily be the case. In the reservoir, depending on the tracer's partitioning into the water and gas phases, its breakthrough into observation wells may not exactly coincide with that of the CO_2. However, adding more than one type of tracer allows study of the relative breakthrough times to provide information on fluid flow through the reservoir and potentially on dissolution and residual saturation trapping (LaForce et al., 2014). Sulphur hexafluoride (SF_6) and the noble gas Krypton (Kr) have been used as tracers at the pilot injection sites at Frio (in 2004) and Otway (in 2008). The Otway site is also investigating the use of perdeuterated methane (CD4) as a tracer in the depleted gas field. At the Pembina Cardium CO_2 EOR project, the injected CO_2 naturally has a different isotopic signature than that in the reservoir so $\delta^{13}C$ analysis was used to monitor plume migration (Johnson et al., 2011). Myers at al., (2013) provide a useful summary of tracer use for CO_2 storage site monitoring.

***Practicalities:** Injected as a pulse or continuous injection into the CO_2 stream (if not already naturally present). 1kg pulses were injected at K12-B, but greater quantities would likely be required for larger scale projects to avoid too much dilution and dispersion in the CO_2. Continuous tracer addition could be done prior to transporting the CO_2 offshore or just prior to injecting it (this is being considered at Goldeneye). Detection limits are different for each tracer, but generally they can be detected in extremely small quantities (using gas chromatography or mass spectrometry). Many artificial tracers are greenhouse gases themselves so they should be used as sparingly as practicable. Noble gases are an exception, but are generally considered to be more difficult (expensive) to obtain and analyse for (fewer laboratory facilities offer analysis).*

***Costs:** Depends on the quantity required (pulse or continuous). Noble gases are generally more expensive and difficult to obtain (in large quantities) than perfluorocarbon based tracers. At a noble gas lab prices are more than double per sample for noble gas analysis compared to SF_6 (350 GPB compared to 125 GBP) (www.noblegaslab.utah.edu/services_pricing.html)*

Conformance

At **K12-B**, in March 2005, two tracers pulses (1 kg each) were injected in 10 minutes into the injection well (K12-B6) together with the CO_2. Produced gas from the production wells (K12-B1 and B5) has been analysed for tracer content at intervals since that time. The CO_2 being injected is isotopically the same as the reservoir gas it was extracted from so artificial tracers were introduced to help investigate the efficiency of the EGR operation and monitor CO_2 migration. These were 1,3-Perfluorodimethylcyclo-hexane (1,3-PDMCH) and Perfluoromethylcyclo-pentane (PMCP). Samples were taken weekly from the two producing wells (K12-B1 and K12-B5). K12-B1 is 420 m from the injector and tracer breakthrough occurred after 130 days (Figure 3.26). K12-B5 is about 1000 m from the injector well and tracer breakthrough was detected after 463 days. It is possible that, because of the differing solubilities of CO_2 and CH_4 in water (CO_2 being much more soluble), the CO_2 flow is retarded by its interaction with the water, whereas the (insoluble) tracer flows with the CH_4 and arrives at the wells before the CO_2. As a result of operational complications and the complexity of the matter, no conclusions have been drawn. An additional produced gas sample from a well in a neighbouring compartment (K12-B3 in Compartment 3a) tested negative for tracer chemicals. This does not rule out a connection between the compartments, but suggests there is a very limited chance of reservoir communication through the fault.

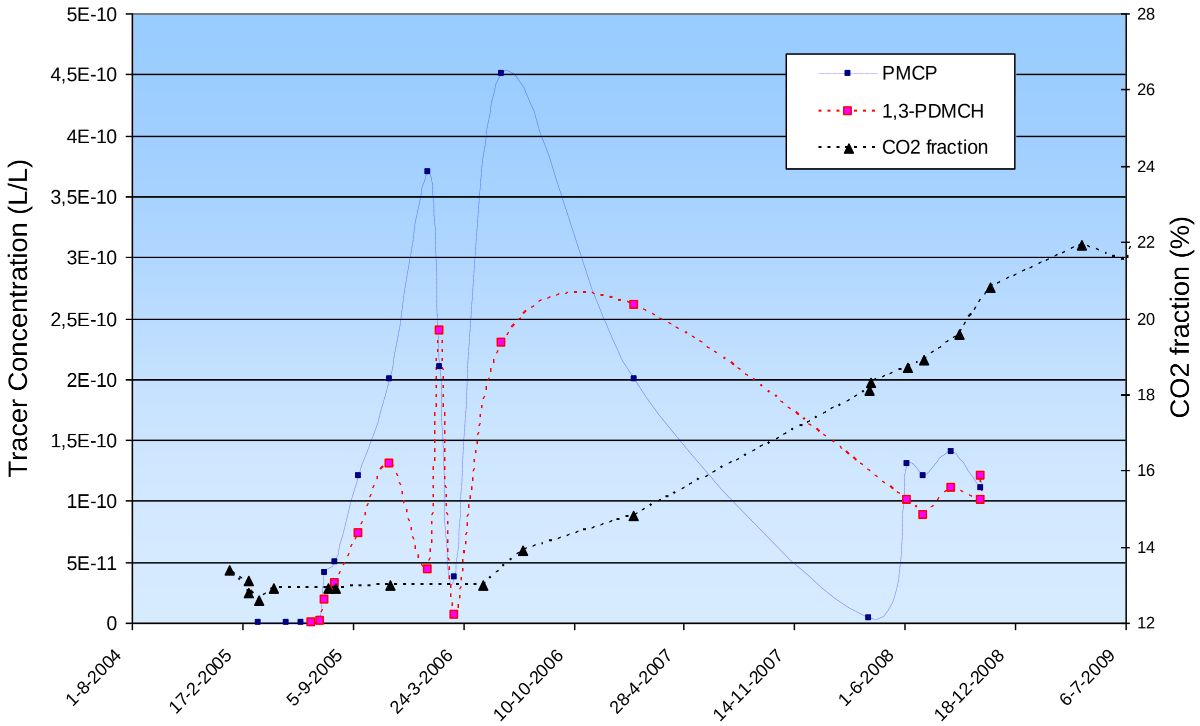


Figure 3.26 Tracer concentrations and CO_2 concentration at the K12-B1 production well. (420 m from the injector well) (after Vandeweijer et al., 2011b).

Conformance & containment

At **Goldeneye**, the use of tracers is being considered to distinguish between natural CO_2 being emitted at the sea bed and CO_2 leakage from hypothetical storage sites. Their selection and use will depend on feasibility studies, including study of the different $\delta^{13}C$ and $\delta^{18}O$ isotopic fingerprints of the fluids and gases that already exist in the Goldeneye system, to see if they could act as a natural (non-added) tracer. Noble gases were favoured in the 2011 published monitoring feasibility study as they are non-reactive, experience minimal partitioning, have low detection limits, low cost and low environmental impact. PFCs are more easily and cheaply obtainable, but are themselves a GHG. A continuous tracer stream is proposed, rather than the pulse method deployed to help monitor gas flow for EOR or EGR (K12-B) and at onshore pilot sites. This could be added either onshore at the St Fergus terminal or offshore at the platform.

3.7 Seabed and water-column imaging

A number of shallow-focussed geophysical monitoring tools have been deployed at, or are planned for, the offshore storage sites. These all contribute to the Containment element of monitoring assurance.

3.7.1 Active acoustic techniques

Active acoustic techniques propagate an acoustic wave into the water column and diagnostic parameters can be inferred from the detected acoustic returns, usually from the acoustic scattering that occurs, although future systems might use acoustic attenuation and velocity perturbations. These techniques have generally been effective at detecting gas fluxes, although further research is required to allow accurate quantification of fluxes. (Note that Chapter 4 includes discussion of ***passive*** acoustic techniques, where oceanographic parameters are inferred from the sounds made in the sea, so that an external acoustic source is not required. These have shown promise in both detecting and quantifying gas emissions at experimental test sites).

A number of acoustic seafloor imaging tools are available (see also Chapter 4), including multibeam echo sounding (MBES) and side-scan sonar which produce high resolution images of the seabed. Some can be specifically set up and processed to detect bubble-streams (using "fish-finder" technology). These may be either ship-mounted, mounted on remotely operated underwater vehicles (ROV), tethered to and operated from a ship, or on autonomous underwater vehicles (AUV), which are pre-programmed and operate independently. The latter are capable of travelling a few metres above the seabed and can also be equipped with underwater still/video cameras.

Deployed at: *Sleipner, Snøhvit, planned at ROAD, Goldeneye and Tomakomai*

Capabilities: Multibeam echosounders (MBES) *are commonly used for 3D seafloor bathymetric surveys. They integrate acoustic bathymetry and backscatter information, permitting detailed mapping of seabed morphology and allowing inferences to be made regarding the nature of the sediment. In time-lapse mode the method could be used to detect slight changes in seafloor elevation or hardness that might occur as a consequence of* CO_2 *leakage to the seabed.* ***Side-scan sonar*** *is a towed echo-sounding system and is one of the most accurate tools for imaging large areas of seabed. In general side-scan sonar is able to provide higher resolution than the MBES tools, but only in 2D. Side-scan sonar transmits a specially shaped acoustic beam perpendicular to the path of the support craft, producing a swath profile. Images produced by high quality sonar systems can be highly accurate, often photograph-like in quality, and can be used to delineate even very small (< 1 cm) objects, particularly using the synthetic aperture sonar (SAS) variant. Interferometric side-scan sonar deployed by AUV can also measure bathymetry by analysis of the phase of the returning signal. The key application is in time-lapse mode to detect slight changes in seafloor topography that might be associated with* CO_2 *leakage to the seabed.* ***Acoustic bubble detection*** *via onboard instrumentation such as "fish-finder" technology, MBES or side-scan sonar, is able to identify bubble releases into the water column and can be used for emissions detection. These systems are available on most scientific research vessels, and are widely used in the fishing industry. Research into quantification of bubble-streams using acoustic techniques is currently underway (Chapter 4). The presence of bubbles at the seafloor indicated by these shipboard systems gives no indication of the type of gas that is leaking - direct sampling is required for this.*

Practicalities: *With a survey vessel equipped with multiple imaging systems, the collection of data is a relatively straightforward process. Systems such as MBES-beam need an experienced operator to process the images and produce a useful product. The 'fish-finder' systems are easier to interpret as the system basically detects bubbles in the water column, so simple inspection of the data can indicate if the bubbles form a plume in the water column and if this originates at the seabed. Shipboard imaging systems are generally a cost-effective means of surveying large areas of seabed, but AUV and ROV mounted equipment operate closer to the seabed than ship-based surveys and may be able to achieve higher resolution. AUVs are subject to limitations based on the physical size of the sensor packages they can carry, and the effect running sensors will have on survey duration. For instance a newly* *developed long-range AUV has a maximum range of 4000 km (91 days) without the sensor payload, but with an active acoustic system the range is reduced to 1261 km (18.3 days). This means there will always be a trade-off between the technologies deployed on AUVs and the area they can survey.*

Seabed placed sensors can also achieve high resolutions with the ability to collect continuous or frequent repeat monitoring surveys albeit over smaller, fixed areas (e.g. around abandoned wellheads). However, these are generally more costly to install, maintain and retrieve compared to the mobile survey equipment.

One key practical issue, depending on sea bed environment, is that it may be difficult to distinguish any CO_2 *injection induced seabed changes (e.g. topographic or flora/faunal changes) from unrelated seabed changes due to tides, currents or trawling. Time-lapse application therefore might be very challenging.*

A further issue is that of data storage and transfer, particularly with the AUV survey option.

***Cost:** Ship time is the main cost. Close to shore, smaller, cheaper vessels can be deployed, but surveys beyond about 80 kilometres offshore will require larger vessels. Surveys of 10* km^2 *are likely to be of the order of 100 - 200 k GBP but potentially multiple techniques can be deployed simultaneously (e.g. water column sampling, sea bed sampling etc). Ship deployment in summer may be more expensive due to higher demand, but in winter weather may cause delays or affect data quality. AUV deployments are becoming more common in industry. Additional costs are associated with manpower to process the data into a usable format (especially from 'fish-finder systems).*

Shipboard imaging techniques are well known for their ability to image features on the order of 2-3 m on the seafloor, and to detect, for instance, bubble plumes from leaking wellheads, natural methane seeps and hydrothermal vents. In the case of CO_2 storage sites, this could include baseline identification of features that might indicate potential leakage pathways in the shallow subsurface, such as existing active seeps, pockmarks or fault lineaments. These techniques can pinpoint areas of interest on the seafloor and allow the survey team to focus survey effort quickly. They are unable to show if such features are actively leaking fluids, but may pick up bubble-streams if gas is escaping. At **Sleipner** and **Snøhvit**, no bubble-streams were found, but natural seabed features including pockmarks were clearly identified (Bünz 2011, 2013). This ship-based survey work would normally precede more time-consuming, costly and spatially limited survey techniques such as AUV, ROV and water column sampling. At a CO_2 storage site the more detailed surveys would only be deployed if the ship-based surveys indicated any features of concern that required further investigation. Seabed imaging using underwater still photographs or videos can also be used to identify seabed features or bubble-streams but are more of a supplementary technique for close-up observation of interesting features found using the other methods.

Acoustic bubble detection is planned at the **ROAD** project. This will be deployed as a baseline survey, and then is planned for contingency deployment (i.e. if a significant irregularity occurs and sea bed leakage is a possibility).

At **Sleipner**, a range of ship-borne seabed imaging profiles was acquired in 2006. Side-scan sonar, single beam and multibeam echosounding (Figure 3.27) and pinger seabottom profiles were acquired along the lines of the high resolution 2D profiles (Figure 3.14a). The highest resolution imaging was obtained from the side-scan sonar, which was able to detect the benchmarks positioned for the seabed gravimetry survey (about 1.5 m in diameter and 0.3 m high). A basic interpretation carried out by the contractor found no evidence of gas leakage or emission.

In 2011 various additional seafloor surveys were deployed at Sleipner as part of the ECO2 project which also found no evidence of CO_2 leakage. These included an AUV equipped with synthetic aperture sonar (SAS) to measure the acoustic back-scatter intensity of the seafloor, further multibeam echosounding and sub-bottom profiling surveys (ship-based) and a hydrophone (to listen for bubbles) mounted on a small satellite lander. No bubbles were heard and the lander revealed normal oceanographic conditions.

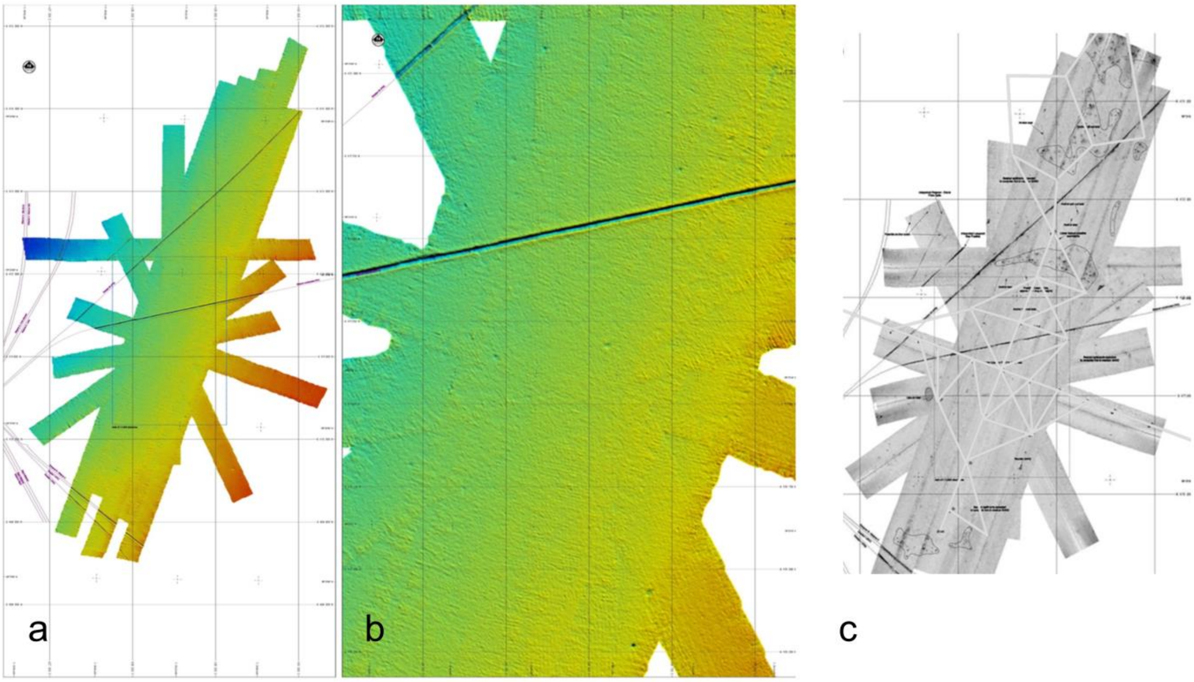


Figure 3.27 Seabed imaging data from Sleipner. a) MBES image of the seafloor above Sleipner (whole survey) b) zooming in on the area above the injection point, showing small seabed features (and prominent linear pipelines) c) side scan sonar data with ROV (video) tracks in 2009 superimposed. Map are in (a) is ~4 km x ~8 km. (Images courtesy of the CO2STORE project and Statoil ASA).

At **Snøhvit** repeat multibeam seabed mapping was acquired over an area of 3 x 10 km as part of the ECO2 research project in 2011 and 2013 (Figure 3.28). P-Cable high-resolution seismic was acquired at the same time and water column sampling was concurrently deployed to calibrate the MBES. Water depths ranged from 310 to 355 m. The MBES data were processed to give swath bathymetry at a resolution of 5 m by 5 m in 2011 improving to 4 m by 4 m in 2013. The main features observed were iceberg ploughmarks and two populations of pockmarks. The interpreted ploughmarks form roughly linear or sinuous features 3 – 5 m deep almost covering the seafloor surveyed. They form u-shaped furrows typically 2 km long and up to 100 m wide, oriented predominantly ENE - WSW with a headwall at the “end” of the furrow. Iceberg ploughmarks form when the keel of an iceberg grazes the seafloor and erodes soft sediments. The surveys also showed hundreds of small pockmarks 1 m deep and up to 20 m diameter and a few large pockmarks up to 10 m deep with diameters of up 700 m. The surveys did not detect any indications of current gas emission from the seafloor.

At **Goldeneye**, a high resolution (1 x 1 m) MBES baseline survey is planned over the whole storage complex (ship or ROV deployed) to image the seabed in 3D and identify any active pockmarks (bubbles) or other possible fluid expulsion conduits. Side-scan sonar is included to aid MBES interpretation, although originally it was discounted along with echoscopes (acoustic cameras) as they were considered to have poorer imaging range versus image resolution and lack the depth information provided by MBES. MBES will also be acquired around the abandoned wellbores within the storage site area about five years after injection start-up to provide leakage assurance. Modelling suggests that any seabed uplift as a result of injection would be beneath the resolution of this technique. Contingency MBES monitoring will also be deployed if unexpected lateral migration of CO_2 out of the site or migration in shallower formations were to be detected (e.g. by time-lapse 3D seismics). Subsequent seabed surveys will be acquired one year after cessation of injection over the entire storage complex (as for the pre-injection baseline), to serve as a post-injection/closure baseline.

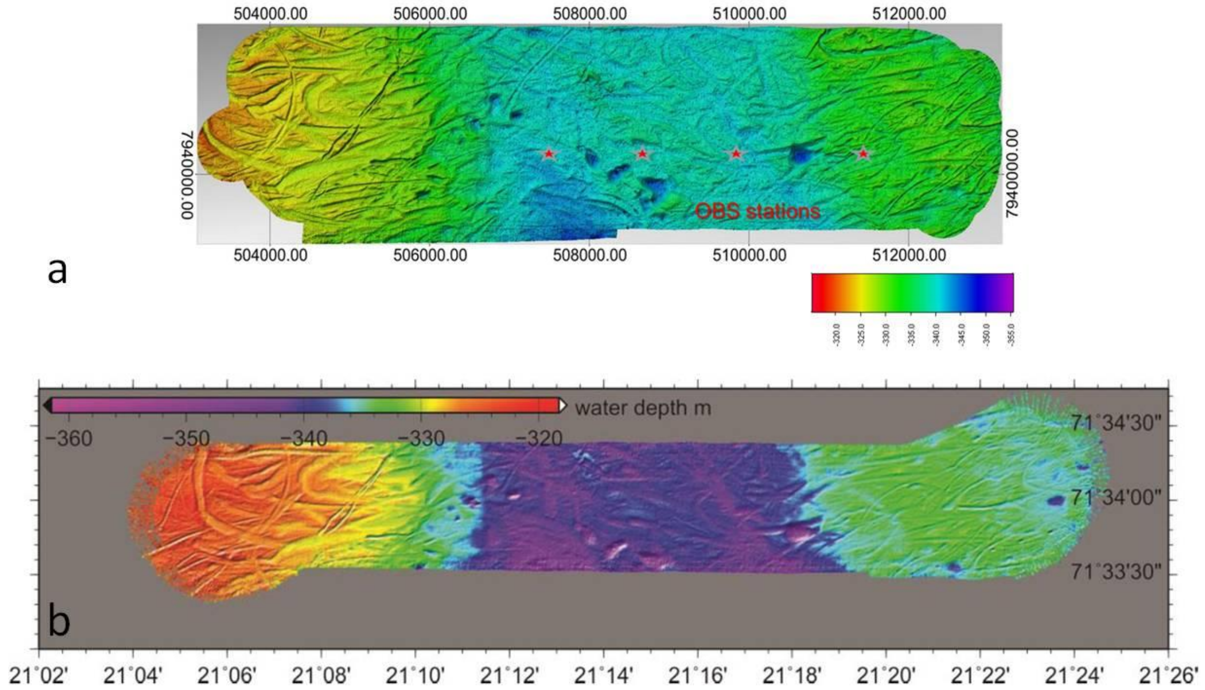


Figure 3.28 Bathymetric seafloor map from the multibeam data acquired at Snøhvit a) in 2011 with 5 x 5 m resolution b) in 2013 over a slightly narrower repeat area with 4 x 4 m resolution). (Courtesy of University of Tromsø and ECO2 project).

3.7.2 Underwater video

Seabed imaging in the form of still photographs or video images are widely available from AUVs, ROVs or towed camera vehicles.

Deployed at: *Sleipner*

Capabilities: *The quality of systems is increasing and it is possible to obtain images and video that can be used to provide mosaics of the seafloor. High definition images can allow even the detection of bubbles, bacterial mats and biota behaviour (Section 3.10 and Chapter 4), although the "field of view" is very limited compared to that of acoustic imaging techniques. Whilst current camera systems can photograph or video bubbles rising from the seabed (the movement captured in video being particularly good for detecting rising bubbles), they often have very poor ability to resolve the size and shape of bubbles (and hence estimate gas fluxes). However, in experiments, stroboscopic methods to determine the bubble size from the rise time have been tested (Leighton et al., 2012a,b).*

Practicalities: *Except when mounted on ROVs, where there is a degree of operator control, image quality can vary greatly, this is often a function of the variable heights at which the ROV or towed vehicle operates, as well as seawater clarity (depends on amount of suspended material). Towed camera sledges or AUV deployments are also possible.*

Costs: *Low (~1-10k GBP) when deployed from a vessel that is performing other surveys.*

At **Sleipner**, video footage was taken from the ROV used to deploy the gravity meter in 2002, 2005 and 2009. In each survey the ROV transmitted from the seafloor continuously for a period of 3-4 days, during which time, the ROV pilot maintained careful observation. Normal seabed conditions were encountered (Figure 3.29). During the 2011-2013 ECO2 research cruises, digital video in "bottom view" mode was used to help control the distance of water sampler from the sea floor and to site the benthic chambers (section 3.8).

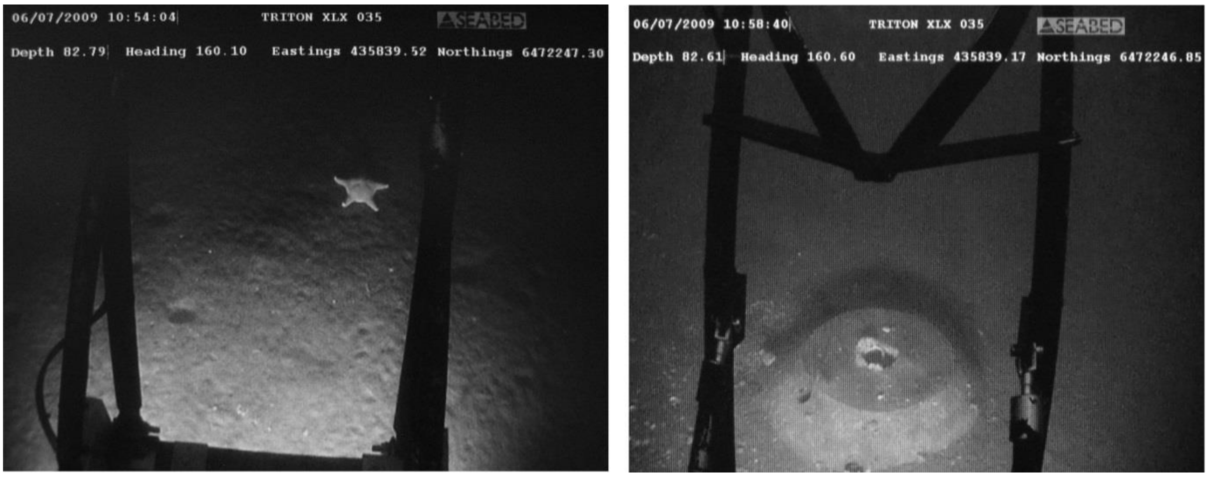


Figure 3.29 Still from the ROV video survey at Sleipner in 2006 showing local fauna (left) and one of the concrete benchmarks from the gravity survey (right). (Images courtesy of CO2ReMoVe project and Statoil ASA).

3.7.3 Seabed displacement monitoring

Vertical displacements of the seabed can be indicative of pressure changes in the reservoir and also overburden integrity. Monitoring subsidence or uplift therefore has potential application for both conformance and containment.

Deployed at: *Planned for Goldeneye*

Capabilities: *The differential GPS system planned for Goldeneye could measure displacement rates with a 1-5 mm accuracy depending on the distance to the reference station and a sufficiently long monitoring period (>2-2.5 years).*

Practicalities: *Whilst satellite interferometry (InSAR) can be effective at favourable onshore locations for measuring and mapping ground movement related to CO_2 injection (Appendix 1.1.3) this level of accuracy and wide aerial coverage is not possible offshore where a suitable density of InSAR sensors (reflectors) is unlikely to be available. Sensor networks on the seafloor that use acoustic ranging techniques, pressure gauges or tilt-meters can give very accurate measurements of seabed movement, but may require many sensors to give sufficient coverage. Tilt-meters also require frequent sensor calibration that may be impractical offshore.*

Costs: *Low (~1-10k GBP) for single GPS station mounted on platform.*

At Goldeneye a limited seafloor displacement monitoring programme is planned using high resolution GPS mounted on the platform. Pressure changes associated with the CO_2 injection are likely to cause seabed uplift with maximum predicted displacement of 36 mm. The GPS would monitor platform safety and act as an early warning system of unexpected events. Acoustic ranging, seafloor pressure gauges and tilt-meters were also considered for deployment but were not selected because sensor spacing and calibration requirements were either not practical or cost-effective. It was considered that monitoring targets such as pockmarks could be more cost-effectively monitored with repeat MBES surveys.

3.8 Geochemical water column sampling

Water column measurements using a CTD (Conductivity, Temperature, Depth) probe are commonly used in combination with water sampling, to enable shipboard measurements of parameters such as pH, partial pressure of CO_2 (pCO), dissolved oxygen, inorganic and organic carbon, nitrogen, phosphate etc, redox potential, salinity and potentially, isotopic carbon and tracers. Again, Containment assurance is the primary monitoring function.

Deployed at: *Sleipner, Snøhvit, planned at Goldeneye and Tomakomai*

Capabilities: *CTD (Conductivity, Temperature and Depth) probes with 10 litre sampling bottles allows collection of seawater for analysis or sample preservation. The combination of the CTD with sensors such as Eh (redox potential – a measure of whether the conditions are oxidising or reducing) and turbidity allows the user to identify parts of the water column that have anomalous chemistry. These systems have been widely used in the location of hydrothermal plumes above mid ocean ridges, but with the development of sensors for the carbon system (see Chapter 4) their utility for CO_2 storage site monitoring will improve. Shipboard analysis of the collected samples for such measurements as* *methane and CO_2 allows real-time identification of areas for wider study. More accurate measurements can often be made onshore on preserved samples, but with a subsequent time delay and there is no ability to re-examine anomalous areas during the cruise.*

Practicalities: *CTD probes can be deployed (cast) over the side of a ship during other surveys (e.g. at Snøhvit the velocity of sound in water was calculated using probe measurements to calibrate the MBES). Measurements are taken continuously and can be averaged over depth intervals to create depth profiles. However, as with other discrete sampling methods, the vertical spacing separation of individual casts may mean that small leakage plumes could remain undetected between them, depending on plume dispersion. Interpreting a leakage signal above background measurements can be extremely challenging. Baseline measurements that include some indication of the background ranges and variability would be necessary.*

Costs: *Relatively low (~ 1- 10 k GBP) when deployed from a vessel that is performing other surveys, or via an umbilical attached to the platform as is being considering at Goldeneye. The equipment itself may cost of the order of 30-50 k GBP, but most research vessels will already be equipped as standard. As with other marine surveys the ship time is likely to be the most expensive component, although cost of onboard personnel to perform sample analysis should also be considered.*

CTD sampling is proposed at **Goldeneye** to monitor conductivity, temperature, pressure, pH, redox, salinity and potentially, partial pressure of CO_2 (*p*CO). The probe would be permanently connected to the platform for power and real-time data transfer and optimally positioned on the seabed as early as practicable to gain a suitable baseline. During injection it will monitor for CO_2 flux beneath the platform.

Geochemical water-column sampling at **Sleipner** was carried out in the period 2011-2013, in water depths of around 80 m, through the ECO2 project to perform hydrological and geochemical characterization of the water column. No evidence of CO_2 emissions were found or any other anomalous conditions. The cruises were equipped with a water sampling rosette (12 x 10 litre Niskin bottles to sample for dissolved gas concentrations and dissolved inorganic carbon (DIC) at selected depths and locations). The rosette also included a CTD probe with sensors for pressure, temperature, oxygen and conductivity and an additional sensor package to measure pH, CO_2, CH_4 and polyaromatic hydrocarbons (PAH). These sensors were used to help chose appropriate locations to take the water samples. In addition, water from an inlet tube at the depths of the sensors was pumped to an onboard mass spectrometer which allowed continuous measurement of dissolved gases (pCO_2, CH_4, N_2, Ar, O_2). Onboard gas chromatography was used to analyse the headspace gas from the sample bottles. Concentrations and stable isotope ratios of higher hydrocarbons, permanent atmospheric gases, DIC and alkalinity were measured in an onshore laboratory.

Measurements were taken both on transects across the plume footprint and at vertical measurements stations. The survey took in measurements around the injection well toe, abandoned wells nearby (none exist within the plume footprint) and reference transects. Results from 2011 showed that the water was stratified with a thermocline at water depths of 50 and 60 m. Temperature varied from 11.5 °C at sea surface to 6.75 °C at 80 m. Bottom water salinities were in the region of 35.06 PSU and oxygen contents of about 8.6 mg/l. CO_2 (from the sensor) varied from 410 ppm below thermocline to 310 ppm near surface, thought to indicate CO_2 consumption by photosynthesis above the thermocline and CO_2 production by respiration below (Linke, 2011). Results from later cruises showed no significant variation in the measured parameters (Linke 2012, 2013).

A benthic chamber was also deployed to measure fluxes of pCO_2 and O_2 across the sediment water interface (via 2 flux chambers driven into the sea floor). These represent background emissions and during the measurement pCO_2 increased and O_2 decreased due to benthic respiration (Linke, 2011).

At **Snøhvit**, water column sampling was deployed from a survey vessel, in water depths from 310 to 355 m, to calibrate the MBES surveys and to perform hydrological and geochemical characterization of the water column as part of the ECO2 project. A CTD probe measured the speed of sound in water, fluorescence, turbidity, salinity and oxygen, in addition to the standard temperature, conductivity and pressure (converted to depth). A rosette of 12 x 10 litre Niskin bottles was used to collect samples, which were analysed on the ship for dissolved oxygen concentration and pH, and in the laboratory for pH, CO_2, CH_4, dissolved inorganic carbon (DIC), dissolved organic carbon (DOC), nutrients, dissolved organic nitrogen and phosphate. Salinity samples were also collected in order to check the stability of the conductivity sensor during the whole cruise.

During the ECO2 2013 cruise, a 12 x 8 km grid of 37 depth-profile measurements were collected across the Snøhvit site, and one each from 5 km either end of the grid (E-W) and one from a reference site 40-50 km to the north. Five sampling stations were selected for full water column profiles and sediment sampling (at the CO_2 injection point, over two large pockmarks, at the far end of the grid and at the reference site). Six depths were chosen, based on likely vertical variability: seabed, ~280 m, ~200 m, ~110 m, ~70 m, ~30 m and a salinity and temperature transect constructed (Figure 3.30). A thermocline and halocline (and hence a pycnocline) are situated at approximately 30-50 m depth. The average depth of the oxygen maximum was 43 m, with values greater than 6 ml/l. Most of the stations revealed a decrease of the oxygen concentration in the bottom layer (below ~300 m depth). There was no evidence of CO_2 emission (Bünz et al., 2013).

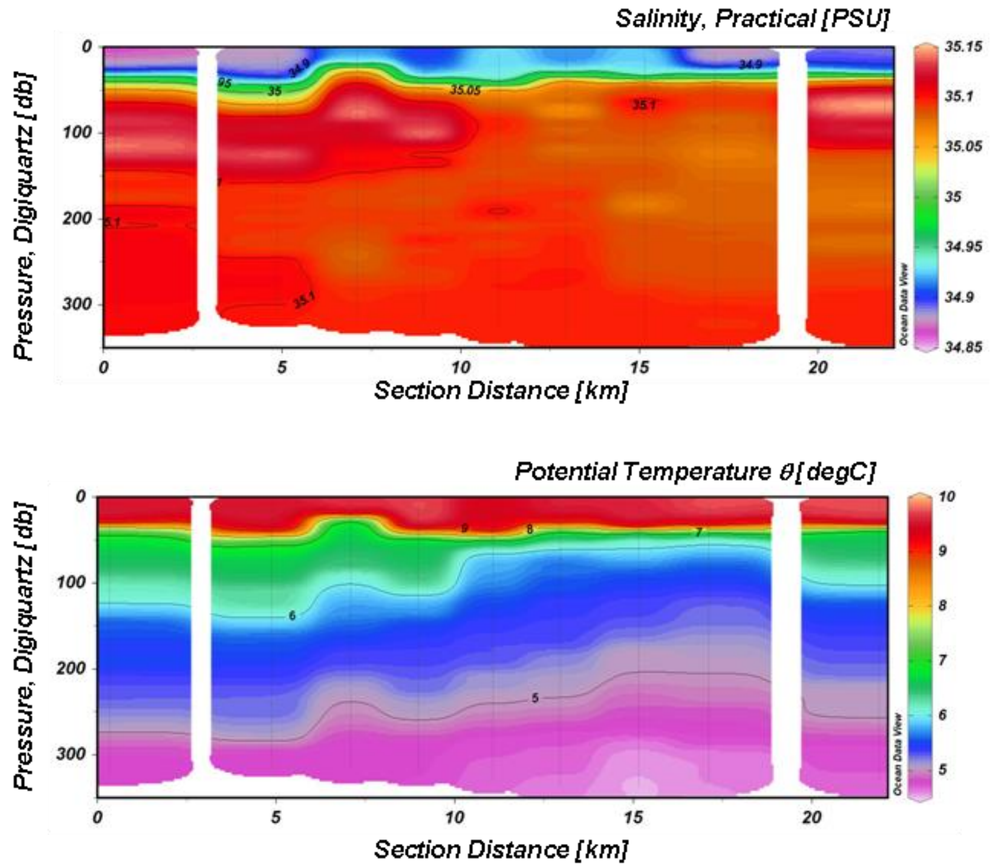


Figure 3.30 Snapshot salinity and potential temperature along the west-east transect in the central part of the study area at the time of the ECO2 cruise (July 2013). (Data are courtesy of the ECO2 project, and were processed and quality checked by Manuel Bensi, OGS).

3.9 Sediment sampling

The collection of sediment material, either in the form of a simple grab, or more usefully, intact cores which retain pore water integrity, is generally combined with chemical analysis to inform on Containment assurance and also a wide range of shallow characterisation issues.

***Deployed at:** Sleipner, Snøhvit, planned at Goldeneye and Tomakomai*

***Capabilities:** Depending on the type of sampling device, time-lapse sediment sampling can be used to detect changes in sediment, pore fluid/gas, or benthic flora/fauna that could indicate CO_2 leakage. At present a combination of CO_2, stable isotopes, alkalinity, pH and carbonate can be used to determine if a system is receiving CO_2. Currently the number of in situ instruments available to detect chemical species consistent with leakage is limited, but a number are in development (Chapter 4). Detecting CO_2-leak induced changes above background requires a good understanding of natural variability and so any monitoring programme should be based on an appropriate baseline study. Overpressure in the overburden is likely to cause the vertical migration of pore fluids. These are often enriched with reduced species, such as iron, manganese, methane and hydrogen sulphide and detection of such 'precursor' fluids can give early warning of potential CO_2 leakage. It is important to obtain samples of the formation fluids in the reservoir prior to injection, as this allows the analysis of conservative elements that can be used for tracing the leakage of these fluids. The passage of CO_2 rich fluids through the* *sediment overburden has the potential to leach trace metals associated with the sediments, and the detection of these can be a useful indicator of leakage. Targeted sampling of any potential leakage features detected using other monitoring methods can be used to improve understanding of processes and potential impacts.*

Practicalities: *The seafloor substrate has a bearing on the type of collection techniques that can be used - in rocky substrates it is impossible to collect sediment samples. Sandy lithologies are also difficult to sample as they do not remain in the core sampler, but this can be overcome with specialist coring instruments such as a vibrocorer. Appropriate lengths of core to collect are discussed further in Chapter 4. Additional problems relate to the difficulty in obtaining cores that truly reflect the in situ concentrations of dissolved gasses - unless cores are collected in a way that keeps them under pressure they will degas on recovery. Analysis of methane and* CO_2 *is essential to determine if any gases within sediments are derived from natural sources or from the storage reservoir. Issues may be that the gases remain in solution at such low levels that they are undetectable, or it may be difficult to fully ascribe the source to the reservoir.*

Costs: *Sediment sampling can be deployed in conjunction with other ship-based surveys to save costs (as with other marine surveys, the ship time is generally the most expensive component, although onboard personnel requirements should also be taken into account). Costs could be of the order of 5 k GBP per day for equipment deployment (not including ship time) e.g. for vibrocoring using a small vessel. Box coring, suitable for environmental surveys, could be of the order of a few hundred GBP per sample. Multicorer carousels (as deployed at Snøhvit) are commonly available on research vessels.*

There has been an ongoing programme at **Sleipner** to monitor total hydrocarbons and certain trace metals (Pb, Ba, Cu, Cr, Zn, Cd) in the sediments and pore-waters. Over the period of sampling (2001-2009) there has been no increase in any of the analytes measured. In 2011-2013 sediment sampling was deployed by the ECO2 project to monitor the pore water, distribution of solutes and microbial composition. Corers deployed included a mini multiple corer (core length up to 20 cm) and a Van Veen Grab (collects the upper 10 cm of sediment). The samples were taken in parallel with macrofauna samples (see section 3.10). Similar to the water column samples (section 3.8), samples were taken at stations along the transects across the storage site, close to abandoned wells (none exist within the plume extent) and at a reference site. Pore-water was sampled directly from the retrieved core sediment every 1 to 2 cm and analysed for hydrogen sulphide, sulphate, chloride, nutrient analysis and DIC. Microbial diversity was measured using acridine orange direct cell counts (AODC), fluorescence i*n situ* hybridisation (FISH) and DNA extraction (Linke, 2011).

At **Snøhvit**, as part of the ECO2 project, sediment sampling was carried out at five sites (the sites of the CTD profiles), using a multicorer system with six liners deployed off the side of the survey vessel in water depths of 310 to 355 m. At least 4 cores, up to about 40 cm length, were retrieved at each site. Pore-water was sampled for pH, DIC, and nutrients, and the sediment was analysed for grain size, total organic carbon, and labile organic matter (Bünz et al., 2013).

Sediment sampling (gas samples using vibrocore and laboratory analysis) is also planned at **ROAD**, although the deployment phase and timescale is not stated.

At **Goldeneye**, sediment sampling is planned to collect benthic macrofaunal, physiochemical and pore gas/water samples to address risks of leakage to seabed. Planned baseline surveys include a revisit of a 2009 (oil and gas impact) survey (19 sampling locations in a cruciform centred on the platform along with 2 reference stations 10 km upstream), 500 m radius surveys (most likely cruciform sampling at 250 and 500 m) around the five development wells and seven plugged and abandoned appraisal wells within the area of the storage complex, with an existing sampling station 1 km to the south (downstream of prevailing currents). In addition 21.1 km^2 of sampling stations will be established across the spatial footprint of the storage complex, with sampling of any active pockmarks revealed by baseline seabed imaging. Reference conditions will be provided by three sampling stations outside of the storage complex, perpendicular to predicted plume migration direction.

During injection, sediment sampling (and seabed imaging) will be undertaken around the abandoned wellbores within the storage site area, around five years after injection start-up, to monitor for leakage. If other monitoring techniques detect lateral or vertical migration of CO_2 out of the reservoir contingency sediment sampling will also be triggered. Subsequent samples will be acquired one year after cessation of injection over the entire storage complex (as for the pre-injection baseline), to serve as post-injection/closure baseline.

Sampling methods proposed include the Van Veen Grab, an industry standard benthic sampling device typically sampling an area of around 0.1 m^2, and one or two other methods. Vibrocores can collect 1 – 5 m long cores even in sandy sediments and are potentially suitable for sediment gas sampling depending on their sealing mechanism. A dedicated sediment gas sampling method known as a CPT rig with BAT probe is also proposed. The sample is drawn in using differential pressure and sealed when full to allow for lab testing. Usually deployed downhole, its use on the seabed would require testing. A hydrostatically-sealed corer, able to take twelve 100 x 600 mm cores, would potentially allow sampling of benthic flora and fauna and sediment gas simultaneously, but it is not currently industry-proven and so would require testing prior to deployment. [N.B. Box, gravity and piston coring were all discounted as sampling methods. The first two were designed for softer sediments than are found around Goldeneye, the latter two collect samples that are too narrow for benthic fauna sampling and none of the methods are sealed and so are unsuitable for gas sediment sampling].

Each 0.1 m^2 sediment sample will be measured according to OSPAR guidelines. Analyses include particle size (PSA), total organic carbon (TOC), total hydrocarbons (THC). Where THC is above background, PAHs and NODs will also be sampled for. Trace and heavy metals (Al, or Li, As, Cd, Cr, Cu, Fe, Ni, Pb, Zn, Ba and Hg) will also be analysed.

In order to cover possible eventualities under the EU Emissions Trading Scheme (ETS), background seabed gas compositions will be analysed by gas chromatography for free and dissolved gases including C_1-C_5 HCs, isotopes $\delta^{13}C$, $\delta^{18}O$ and δD, gas compositions (i.e. CO_2, O_2 etc). Seawater chemistry will be analysed for pH, conductivity, HCO_3^- , trace/heavy metals (Pb, As), total dissolved solids (TDS) including major ions (Na^+, K^+ etc), organic acids, isotopic compositions ($\delta^{13}C$ of total dissolved inorganic carbon (TDIC)).

Selected sampling stations will be sampled three times to measure in-station variability.

3.10 Ecosystem response monitoring ('biomarkers')

The ecological effects of elevated CO_2 concentrations, either as a free gas phase or as reduced pH where CO_2 is dissolved in water, form a potential tool (also termed 'biomarkers') for detecting CO_2 emissions at seabed. CO_2 can freely penetrate biological surfaces such as cell membranes and skin and

CO_2 concentrations in intra- and extracellular compartments will equilibrate with concentrations in the surrounding water. The reaction between CO_2 and water will lead to a lowering of the pH of body fluids, with, for many organisms, an adverse effect on a number of physiological processes. It is therefore of interest to investigate how different organisms react to elevated concentrations of CO_2 to assess the possible use of specific organisms as indicators of CO_2 emissions.

Deployed at: *Sleipner, planned at Goldeneye and Tomakomai*

Capabilities: *Time-lapse sediment sampling or underwater video/stills can be used to detect changes in benthic flora/fauna that could indicate CO_2 leakage. These include observations of avoidance behaviours or altered community structure. However, distinguishing CO_2 leakage-related behaviour from that induced by natural variability, e.g. seasonal scavenging or reproduction remains challenging. Currently the most effective biomarker species are not established.*

Practicalities: *Underwater video could be used at selected locations to monitor for biomarker species behaviour (e.g. numbers at seabed of a normally burrowing species). Time-lapse sediment sampling methods (Section 3.9) could be used to count numbers of species. Sampling methods that avoid disturbing the sample as much as possible to preserve the sediment-water interface and sediment structure would likely be preferred. For example Craib-type corers (although these may be small-diameter, around 6 cm) and Box-type corers (up to around 50 cm across).*

Costs: *As for other methods, if sample collection or underwater video could be deployed in conjunction with other surveys, this could reduce costs (Section 3.9). Samples could cost a few hundred GBP per sample, but there are significant manpower costs associated with processing and identifying organisms in the collected sample.*

As part of the CO2ReMoVe project, and with particular reference to **Sleipner**, the bivalve *Acesta excavata* (a species common in the deeper part of the North Atlantic) was selected for testing for suitability as a biomarker. Such deep-sea fauna are generally less tolerant to changes in CO_2 concentrations than animals living in the intertidal zone, where large variations in environmental conditions are the norm.

Groups of *A. excavata* were placed in the exposure tanks for varying lengths of time (0.5, 1, 4, 12, 24, 48 or 96 hours). The group exposed for 96 hours was further examined in a tank with normal CO_2 concentration for 1, 4, 12, 24, or 96 hours to study recuperation after the exposure to high CO_2 concentrations (hypercapnic conditions). The parameters measured during the tests and in control groups of animals were: oxygen consumption and ammonia-N excretion, and acid-base parameters (pH, PCO_2 and non-bicarbonate buffering capacity) of hemolymph and tissues.

Although the animals were highly affected by exposure to hypercapnia the acid-base parameters returned towards control values and no mortality was observed in exposed animals. On the other hand, other studies have shown that long-term effects may develop if the exposure to hypercapnic conditions is permanent. This may also develop in *A. excavata* if the exposure to high CO_2 concentrations is prolonged for (much) longer periods than the 96 hours used in these tests.

It was concluded that the studied species does show measurable biochemical changes in the presence of elevated CO_2 levels and could potentially be used as a monitoring biomarker.

Macrobenthos samples were also taken during ECO2 research cruises in 2011 to study benthic community structure and diversity and to identify abundant species that could be used a sensitive indicator species. Four replicate samples were taken using a 17 litre Van Veen Grab at 8 stations in a transect across the CO_2 plume footprint and 1 at a reference site. The samples were washed and sieved (1 mm), with 3 samples preserved for later taxanomic analysis and 1 analysed immediately. A high abundance of calcifying echinoderms were found and as these are typically very sensitive to increases in seawater pCO_2, they could potentially be used as an indicator species.

At **Goldeneye,** ecosystem sampling is planned using Van Veen Grab, an industry standard benthic sampling device typically sampling an area of around 0.1 m^2. These will be sieved on 1 mm and 0.5 mm meshes, to count the total number of species and individuals to provide data on numbers per m^2, dominant species, diversity and evenness of distribution etc. Prior to sampling, the sampling station will be photographed using a video/still camera.

Chapter 4 Experience from experimental and natural seepage sites and modelling

This chapter presents a suite of monitoring results and issues that have arisen from research work carried out over a number of years at small-scale CO_2 leakage experiments and naturally occurring CO_2 seepage sites and also from leakage and emissions modelling research. The monitoring tools deployed in this context are exclusively shallow-focussed and overlap to a degree with tools deployed for Containment assurance at the offshore storage sites (Chapter 3). The overall theme for the chapter is Containment assurance and environmental impacts, but because of the very wide variety of site settings and research objectives covered we adopt a more informal, discursive style than in the previous chapter.

Providing assurance that leakage and emission into the sea can be detected and to some extent quantified requires testing and development of shallow-focussed monitoring methodologies. In the absence of leakage from the operational offshore CO_2 storage sites (Chapter 3), monitoring tools can be tested at both naturally-occurring and experimental emission sites. Over the past decade a number of such studies have been performed to address this. **Natural seepage sites** where CO_2 and/or other gases are naturally emerging from the subsurface (Section 4.1) can be useful to test the efficacy of monitoring equipment (for example to detect and characterise). Where such sites have been active for long periods, the local environment will have become adapted and so they may also be useful for studying potential long term impacts. However, to understand and recognise potential environmental responses to *new* leakage or emission **test injection sites** are vital (Section 4.2). In addition, because a known quantity of CO_2 can be introduced, the fate of it can be more readily explored (in terms of styles of emission and leakage pathways exploited as well as testing quantification of residual trapping and dissolution in the sediment). Naturally the observations at such tests sites are dependent on the duration and amount of injection, as well as the seabed setting and water depth.

This chapter will review the findings in relation to the tools that can be deployed, and review the ways in which models, informed by new data, can aid in the development of best practice for the monitoring of leaks and emissions from offshore storage reservoirs.

4.1. Natural seepage sites

4.1.1 Panarea CO_2 seeps (shallow water depth hydrothermal vent)

There are natural hydrothermally-driven CO_2 seeps off the island of Panarea in the Aeolian Islands, Italy and has been used as a natural analogue for CO_2 leakage into the marine environment (e.g. via the CO2ReMoVe, RISCS and ECO2 projects). The seep area has a number of active bubbling sites of CO_2 release associated with faulting at the seabed. The CO2ReMoVe and ECO2 studies used these areas for testing and developing sensors and other detection and monitoring technology. As true analogues of CO_2 leakage from storage reservoirs Panarea is somewhat limited – the long-term nature of the seeps has allowed the local biology to adapt and the well-lit shallow nature of the sites ensures that adaptation is fundamentally different to that which might occur in colder, deeper and more turbid sites.

4.1.2 Hydrothermal vent systems in deep water

The Jan Mayen vents were discovered in 2005 and lie along the Mohns Ridge in the Norwegian Sea. They occur in water depths of 500-700 m and are venting water hotter than 300°C and enriched in CO_2. As with Panarea these vent sites are most useful for testing emission detection and monitoring techniques that can be used in deep water environments, rather than for example, looking at environmental impacts of high CO_2 on organisms.

4.1.3 Salt Dome Juist

Previous studies over the Salt Dome Juist area in the German sector of the North Sea had detected strong acoustic flares of gases enriched in CO_2 from the seabed, with associated pH changes in 2008 (McGinnis, 2011). However subsequent visits in 2009 and 2011 by the ECO2 project did not detect any signs of leakage in the area, illustrating, if nothing else, the significance of temporal variation.

4.1.4 The Hugin Fracture

The Hugin Fracture is a 3 km long seafloor structure that was discovered by the ECO2 project in the Central North Sea in 2011 using the Hugin AUV. Seismic and sonar data indicate that the fracture is some 1 – 10 m wide and penetrates up to 150 - 200 m into the seabed. Where the fracture meets the seabed it is covered with soft sediments and up to 3 m wide patches of bacterial mats. These consist of methanotrophic bacteria using methane gas that is coming from a source not yet fully defined. The methane dissolves in the pore waters in the sediments and the bacteria are able to use it as a chemical energy source. The Hugin Fracture is interpreted to be a natural feature that formed in the geological past, perhaps during the ice-ages, and similar natural seeps have been documented elsewhere in the North Sea. There is no evidence of leakage of CO_2 but the Hugin Fracture has been investigated in detail by the ECO2 project, and has been used to demonstrate a number of monitoring techniques and approaches. Such structural features could have the potential to localise more dispersed overburden fluid fluxes, and therefore might be considered priority monitoring targets if found in the vicinity of CO_2 storage sites where there was evidence for or risk of CO_2 migrating into the shallow overburden.

4.1.5 Onshore Lakes

A number of investigations of natural seepage sites in onshore lakes (Goepel et al., 2011; Möller et al., 2011), are relevant here because many of the techniques deployed are similar to those that can be used offshore. These include multi-parameter water-column measurements (e.g. of pH, T, conductivity) either on vertical profiles or horizontal traverses (Gal et al., 2011) and measurements of gas flux either by timing the displacement of water from a fixed volume by a bubble stream (Möller et al., 2011) or by measurement of CO_2 flux from the water surface into the atmosphere (Mazot et al., 2014). The latter approach is less appropriate to CO_2 storage because with dissolution of CO_2 in a relatively substantial water column very little direct emission of the gas to atmosphere is likely. The measurement of flux by displacement has been used offshore, for example in volcanic areas (Inguaggiato et al., 2012; Italiano and Nuccio, 1991) and offers a relatively simple way of measuring individual bubble streams. However, natural CO_2 sites tend to produce a multitude of individual streams, so overall flux rates were estimated from their total number and strength using measurements of a relatively small number in each category. Developing passive acoustic methods might offer more accurate, continuous flux rate determination with lower field-personnel requirements (Section 4.3.2). In order to determine CO_2 fluxes the gas composition (i.e. the proportion of CO_2) also needs to be established. Multibeam echosounding was also deployed to map bubble-streams and delineate lake-bed features and bathymetry (Section 4.3.1).

4.1.6 Taketomi Hot-springs, Japan

Taketomi Hot-springs in Japan were used to test and develop acoustic tomography techniques (Section 4.3.1) using a network of semi-permanent transponders on the seafloor to determine the bubble emission point. The bubbles contained only 2 % CO_2, but the 5 transponders deployed were able to successfully locate the bubble leakage area (Shitashima, et al., 2013).

4.2 Test injection sites: the QICS experiment

The QICS (Quantifying and monitoring potential ecosystem Impacts of geological Carbon Storage) experiment tested the impacts and detectability of a small artificial CO_2 injection into natural marine sediments (Figure 4.1). The site chosen was in Ardmucknish Bay in the outer part of Loch Etive in western Scotland. Baseline chirp and boomer surveys had demonstrated that the sediments were appropriate for the test release and that there was no existing gas in the sediments. A borehole was drilled from onshore and CO_2 introduced beneath ~11 m of sediments and 10 to 12 m of tidally influenced sea-water. Over a period of 37 days, 4.2 tonnes of CO_2 gas was released at rates ranging from 4 - 80 litres min^{-1}.

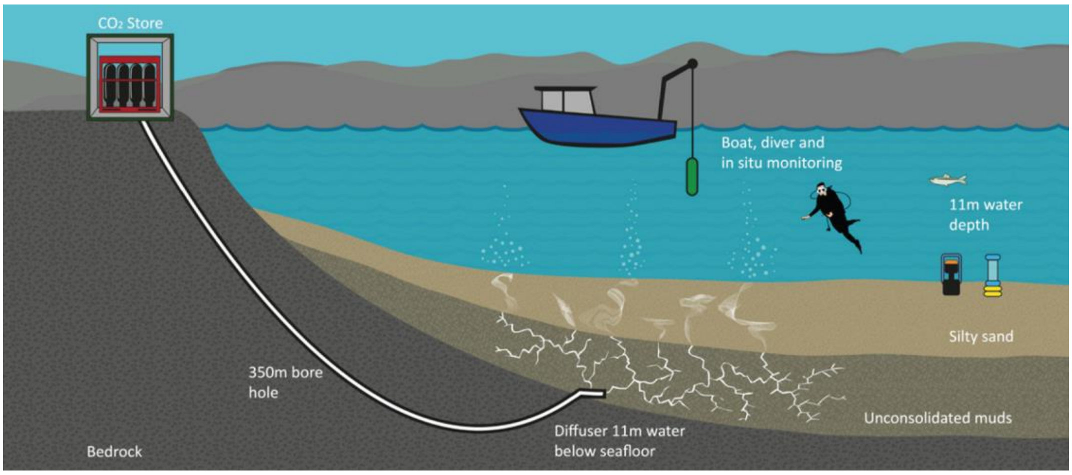


Figure 4.1 Schematic of the QICS experiment (copyright Plymouth Marine Laboratory)

Within a few hours of injection start-up bubbles of CO_2 were detected in the water column. Throughout the experiment the bubbles were sampled and estimates of flow rate were made. It was noted that the release of bubbles was in part tidally controlled; at high tide the flow rate reduced or ceased due to increased hydrostatic pressure. The water column was sampled with CTD and also a series of sensors were deployed over the release area. Sediment cores were collected and a full suite of chemical analyses was performed looking at those species directly related to inputs of CO_2, such as DIC, alkalinity and carbonate, along with those compounds and elements expected to act as precursors to release driven by possible pore-water over-pressure from below, such as Fe, Mn and H_2S. Benthic chambers were placed in the release area and surroundings, *in situ* sensors for pH and pCO_2 were deployed, and hydrophones were used to listen to the released bubble-streams (Blackford & Kita 2013; Blackford et al., 2014a).

4.3 Acoustic systems

Acoustic methods can be effective in detecting free gas in the surface sediments and for imaging the migration of CO_2 through those sediments to the seafloor and into the water column (Blackford et al., 2014a). Active systems are generally deployed as repeat surveys to detect changes, although continuous lander based systems have also been tested (Section 4.3.2). Continuous lander-based passive acoustic 'listening' techniques also show promise for leakage detection and quantification.

4.3.1 Acoustic seabed imaging and bubble stream detection

Acoustic methods with active sources to image the seabed and water column are effective in detecting seabed features and streams of bubbles that might be indicative of possible leakage pathways, or of CO_2 emissions (also discussed in Section 3.7). Many features that might be used to diagnose leakage also occur naturally. For example seabed fractures (see above) or pockmarks resulting from natural biogenic or thermogenic gas production could readily be mistaken for evidence of storage leakage. Baseline surveys to identify such features that could potentially act to focus any near-seabed fluid leakage would also be useful to help plan and locate subsequent monitoring deployments. Repeat seabed imaging could help to identify any changes in the seabed (for example, changes in topography, seabed hardness or microbial mats etc.) that might be induced by CO_2 leakage.

The use of multibeam echo sounders (MBES) for the detection and attempted quantification of gas in the water column was done at the QICS site, at Panarea (Figure 4.2), at the Jan Mayen hydrothermal vent sites and onshore in the Laacher See in Germany (Figure 4.3).

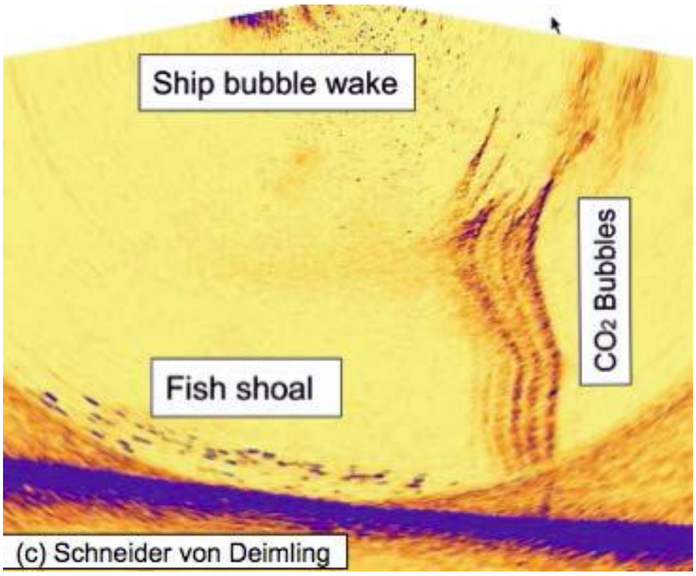


Figure 4.2 Bubble streams at Panarea imaged using active acoustics (copyright Schneider von Deimling, from Bellerby and Golmen, 2013).

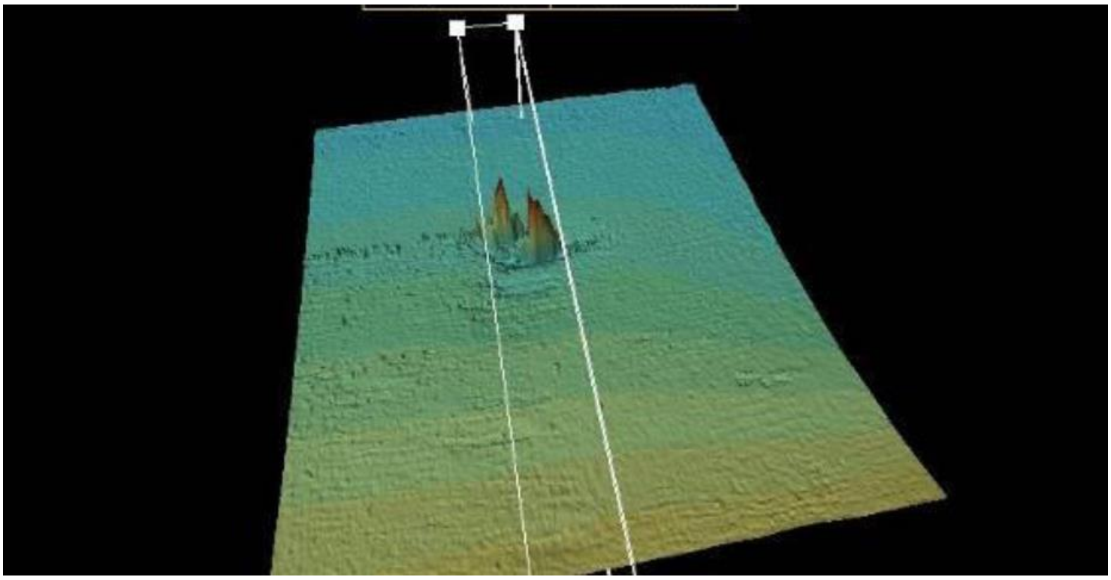


Figure 4.3 MBES image of CO_2 bubble-streams in an onshore lake (Laacher See, Germany). Bubble streams are about 50 m high. (Image courtesy of CO2ReMoVe project and BGR).

Acoustic tomography, also known as Ocean Acoustic Tomography (OAT), was tested at the Taketomi Hot-springs, Japan (Section 4.1.6). This involves a network of transponders on the seafloor which accurately measure the travel-time of sound between them. The speed of sound in seawater depends on seawater density and this is controlled by temperature, pressure, salinity and currents. CO_2 bubbles leaking from the sea floor could cause upgoing currents, dispersion of the acoustic signal by bubbles, or temperature fluctuations and would therefore change the travel-time between transponders. Repeat measurements of the travel-time allow any changes between transponders to be detected. Triangulation or tomography between the transponders can allow the changes to be mapped and can potentially pin-point the source of the CO_2 leakage. Invented in the 1970s (Munk and Wunsch, 1978), acoustic tomography has been used specifically to investigate bubbles (Kargl & Rouseff, 2002), and Shitashima et al. (2013) propose it as part of monitoring strategy for CO_2 emissions detection. Most other existing acoustic bubble detection techniques are periodic (requiring ship or AUV deployments), but acoustic tomography allows for continuous measurement. However, as with all semi-permanent seabed sensors, biofouling, suspended sediment or trawler damage may be an issue. Passive acoustic systems involving hydrophones listening for bubble noise also work continuously, but weak or slow bubble-streams may not be detected by hydrophones.

At the Hot-springs test site, bubbles containing 2 % CO_2 emerged from a ~50 m diameter depression in 20 m of water. The transponders were arranged in a pentagon roughly 200 m in diameter centred over the site. Their frequency was set to 30 kHz, appropriate for detecting multi-directional signals with a 2 km range. Lower frequencies (e.g. 100 Hz) that propagate farther could work over a range of 1000 km. The experiment required synchronised atomic clocks in each transponder, but developing the transponders into a network with centralised control and remote data access would allow effective real-time storage site sea bed monitoring (Shitashima, et al., 2013). .

4.3.2 Bubble-stream quantification

The ability to quantify gas flux remotely is a major aspiration for emissions measurement, with active ongoing research. It would be very cost effective if ship-board MBES systems could be used, not just to locate sources of gas, but also to quantify them.

In the sea-water column, bubble-streams can be detected by the strong acoustic scattering of high frequency active sonar (von Deimling et al., 2011). However, providing a quantitative estimate of the free gas content in each pixel of the bubble plume image (a so-called 'acoustic inversion') is not straightforward. This is because the wavelength of commercially available sonar systems is often larger than the bubble sizes (Ainslie & Leighton, 2009; 2011) and the inversion method assumes an infinite body of water (Leighton et al., 2012), so although estimates of gas fluxes from the seabed can be produced, their accuracy is questionable. Further research is needed to make such inversions accurate.

At the Panarea site, a newly developed lander-based active acoustic system was deployed over a bubble-stream to test the ability of high resolution systems to quantify the gas being vented. The bubble-stream was imaged (Figure 4.2) and the researchers were able to obtain estimates of the fluxes during low flow conditions of less than 10 ml/minute using post-sampling signal processing (Bellerby and Golmen 2013). However, the data processing of high flow streams remains challenging.

Another possibility with active techniques is to use the lower frequencies of a commercial chirp sub-bottom profiler to quantify the amount of gas bubbles present in the shallow sub-seabed sediment (Leighton and Robb, 2008).

An alternative approach to quantification is to use passive acoustics based on the sound bubbles produce, whose pitch relates to bubble size. Following successful experiments in test tanks with a range of gases (air, propane, helium), Leighton & Walton (1987) were able to estimate bubble size distributions in the natural world by passive detection of the acoustic signals made by bubbles as they entered the water column. In recent years the test tank studies were repeated (Walton et al., 2005; Greene and Wilson, 2012) to test the viability of passive acoustic systems for detecting methane. However the usefulness of such tank tests is limited for three main reasons: reverberations in test tanks can severely affect the results (Leighton et al., 1998, 2002); leakage in deeper marine environments might involve complexities associated with the formation of methane hydrate (Paull et al., 1995; Sauter et al., 2006; Maksimov and Sosedko, 2009) and in order for the signature acoustic emissions of single bubbles to be identified, the rate at which they are released must often be unrealistically low in tank tests. To identify these signatures at higher release rates, Leighton et al., (1998) introduced spectral and related signal processing techniques. These proved to be successful when Leifer and Tang (2006) successfully identified individual bubble emissions from a 62-metre deep seabed region at the Coal Oil Point seep field (a natural gas seep offshore California). More recently Leighton & White (2012) have developed a spectral approach to enable quantification of gas flux from seeps of a significant size.

Passive acoustic measurements in the marine environment are often complicated by background noise. Shelf seas are acoustically busy with both man-made noise (e.g. from marine traffic, oil/gas platforms, or even active sound-based seal deterrents) and natural noise from storms/waves and natural seeps (principally of methane), which all contribute to masking a specific acoustic signal.

To test the passive acoustics method of Leighton & Walton (2012) in a marine environment, three acoustic recorders were set up as part of the QICS test injection, placed near the leak site to collect the sounds emitted as the bubbles formed in the water column. The recorders were moved around within the site to collect data from various locations through the duration of the release.

By analysing the acoustic energy accompanying the bubble formation it is possible to estimate the initial size of the bubbles as they leave the sediment, and from that the flux rate. This measurement technique is subject to some uncertainty, a major cause of which relates to the amount of energy that is imparted to each bubble as it is released, a proportion of which is then radiated as acoustic energy. This quantity has been measured experimentally and found to vary considerably (as discussed above). However, the experimental data can be used to constrain the measured flux rates and the flux rates determined during the QICS experiment were constrained in this way. Calculated fluxes were compared with values obtained by divers collecting gas from individual bubble streams and it was shown that the collected values fell within the range predicted by the acoustic techniques.

An advantage of the passive acoustic technique is that it is able to monitor continuously for extended periods allowing flux rates to be estimated over time. In QICS a typical recorder deployment was 4 or 5 days during which recording was continuous. Higher flux rates associated with periods when the CO_2 flow was increased at the source could also be identified and tidal effects were observed (flux rates increasing at low tide and reducing at high tide when pressure at the seabed increases).

In summary, the passive acoustic technique was able to monitor the gas release continually over an extended period (allowing a tidal - flux rate correlation relationship to be calculated involving a decrease of 15.1 kg d^{-1} gas flow for every 1 metre increase in tidal height, Figure 4.4). Moreover, at the time of the single gas collection made by divers, the diver-measured flux fell within the bounds of the passive acoustic flux measurement (Blackford et al., 2014a).

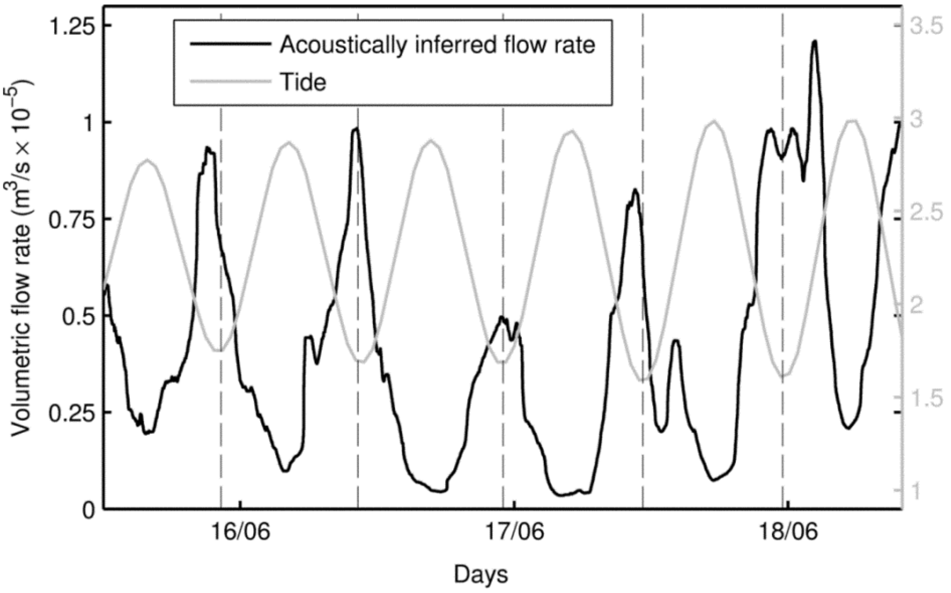


Figure 4.4 Acoustic detection of bubbles used to infer flow rate as part of the QICS experiment (modified from Blackford et al., 2014a. Copyright Institute of Sound and Vibration Research (ISVR), University of Southampton).

4.3.3 Shallow sediment imaging

Acoustic systems can use a variety of source frequencies with different resolution and penetration characteristics to detect free gas in the near-seafloor sediments and to image the migration of CO_2 through those sediments to the seafloor (Cevatoglu et al., in press), and into the water column. Seismic reflection methods are particularly sensitive to gas accumulation in the sub-surface because small increases in gas content lead to enhanced seismic reflectivity (Best et al., 2004; Hovland and Judd 1988; Petersen et al., 2010; Rajan et al., 2012; Zhang et al., 2012; Cevatoglu et al., in press), as a result of the large acoustic impedance contrast between gas-charged and water-saturated sediments. The presence of gas can also lead to characteristic acoustic attenuation 'shadows' on high frequency seismic reflection profiles (Fleischer et al., 2001; Cevatoglu et al., in press). Baseline surveys are needed to broadly identify bubble-streams, gassy sediments and any pre-existing seabed features, such as pockmarks, that might already be present above a proposed storage site. Gas (methane or hydrogen sulphide) is often naturally present in shallow sediments, and its geophysical manifestation may vary seasonally (Wever et al., 1988).

In the QICS experiment, two different types of high-resolution seismic reflection systems (chirp and boomer, see also Section 3.2.4) were used to investigate propagation of the CO_2 through the ~11 m of sediment above the release point (Cevatoglu et al., in press). Striking images were obtained of gaseous CO_2 trapped in the sediments at shallow depths and also of the CO_2 bubble-stream in the water column (Figure 4.5). Repeat surveys roughly 2 years after injection have been acquired and analysis of these is ongoing.

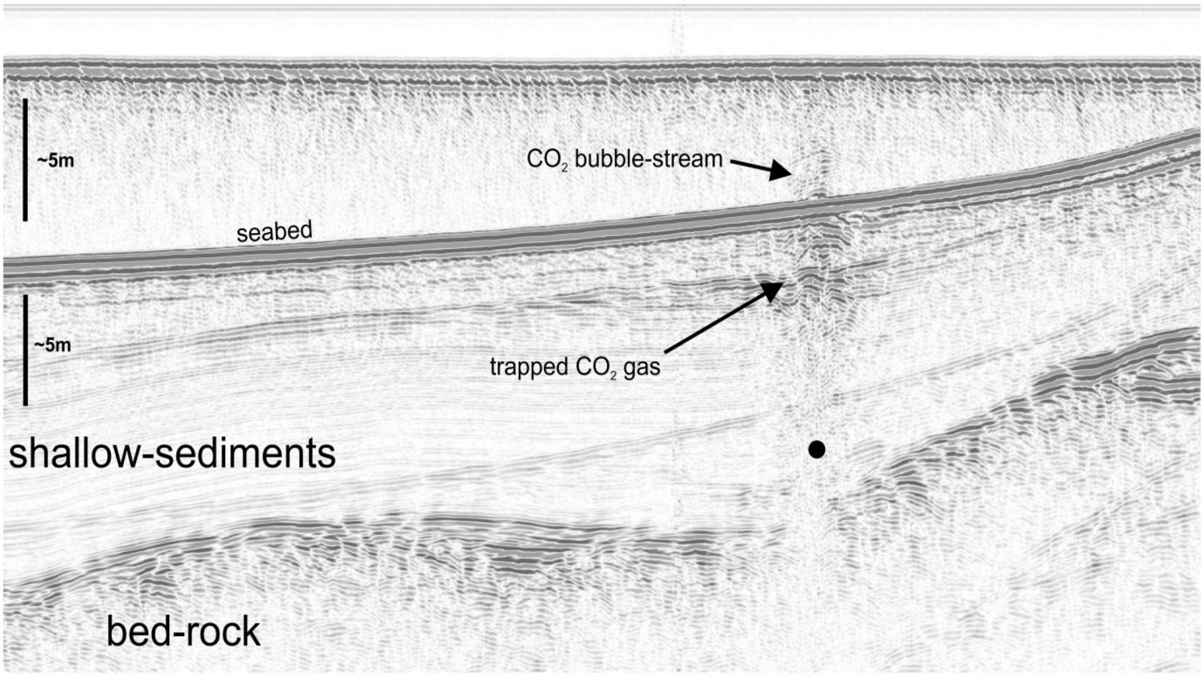


Figure 4.5 Boomer profile through the QICS injection point, showing gaseous CO_2 trapped in the very shallow sediments and the bubble-stream in the water-column (adapted from Gafeira et al., 2014).The injection point (11 m below seabed via a 5 m long diffuser) is marked with a black dot (adapted from Gafeira et al., 2014. British Geological Survey © NERC 2014).

4.4 Video imaging of the water column and seafloor

The development of small, high-resolution video and stills camera systems has enabled their wider use on AUVs, landers and ROVs (see also Section 3.7.2). These systems have been used to identify biological communities on wide area surveys over the hydrothermal vents at Jan Mayen and at Panarea. When deployed on AUVs they allow a rapid assessment of the seabed morphology that can be used as a tool to identify changes over time using repeated surveys.

In situ video has been used to capture bubbles streaming from active gas venting sites. This type of data was collected during the QICS experiment and at Panarea, and with post processing can be used to estimate gas fluxes. During the QICS experiment bubble plumes analysed in this way were combined with bubble-stream samples collected by divers to get a quantitative estimate of flow. At Panarea the work was taken further using a video sampling rig deployed at depth and a test release of CO_2, composed of the same gas that is naturally released at the site. The experiment was able to determine the dissolution rate of the bubbles, and by collection of discrete water samples, was able to monitor the internal chemistry of the released bubbles (Alendal et al., 2013).

4.5 Chemical sampling methods

Emissions in the form of bubbles may be readily detected by the various acoustic or video techniques discussed above, but if there are no bubbles, chemical indicators might be the only effective approach.

Leakage indicators may be the CO_2 itself, pre-cursor fluids such as pore-waters pushed ahead of a front of CO_2 rich fluid, compounds leached from the sediments or drilling fluids in the case of a leaking well. Common approaches to this are the collection of water samples from ships, collection of sediment samples and sediment cores and *in situ* analysis where possible. Measurement of acidity changes (pH) and the partial pressure of CO_2 in seawater (pCO_2) caused by CO_2 dissolution is operationally practicable and can potentially deliver accurate and precise data, although there are challenges with calibration and drift (see also Sections 3.8 and 3.9). However both quantities have considerable spatial and temporal heterogeneity caused by biological processes and the physical exchange of water masses and sediment. Whilst the sea surface is relatively well sampled for pCO_2 there is a dearth of direct observations at or near the seabed and much of our understanding is derived from modelling (Blackford and Gilbert 2007; Artioli et al., 2013). The major drivers of heterogeneity are the seasonal cycle of primary production and the spatial distinction between vertically mixed and intermittently stratified waters. Anomaly detection may depend on recognising abnormal changes in pH/pCO_2 over short time scales and distances.

Sediment samples, particularly long cores, can be invaluable in detecting and characterising shallow fluxes. At the Hugin Fracture in the North Sea, shorter gravity cores (<1 m) indicated the up-flow of methane rich fluids, but the analysis of the longer (3 m) cores from a vibrocorer showed that the fluids were transported laterally and not vertically (Figure 4.6).

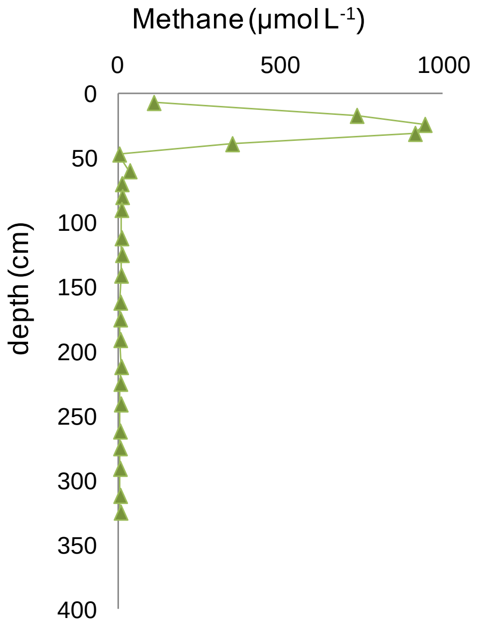


Figure 4.6. An example of a long core taken as part of the ECO2 study at the Hugin fracture indicating the methane is laterally advected (Data courtesy ECO2 project and copyright National Oceanography Centre).

As part of the QICS experiment, cores were collected to determine the effect of released CO_2 on the sediment and pore-water geochemistry. It can clearly be seen (Figure 4.7) that the highest pore water concentrations of dissolved inorganic carbon (DIC, the sum of dissolved CO_2 and its dissociation products), was found at Day 44, immediately after the injection of CO_2 had ceased. What was surprising was the slow rate of rise of the DIC in the pore-water through the cores, but it is clear that measuring DIC provides a direct indication of additional CO_2 in the sediments. By the end of the experiment only about 15% of the introduced CO_2 was accounted for as gas emissions from the sea floor (Blackford 2014a). The remainder was presumably trapped in the sediment as free gas, and also dissolved in the aqueous phase where it initiated carbonate dissolution. Alternately significant dissolved fluxes within the bubble streams may account for some of the injected CO2 (Mori et al. in press). The carbonate dissolution provoked a large rise in alkalinity and as a result changes in pH within the sediment pore water were strongly buffered.

One key feature of the QICS experiment was the control of the bubble emission rate by the tidal cycle (see figure 4.4). At high tide the extra water pressure exerted by an additional ~3 m of water above low tide was capable of shutting down the bubble streams. Whilst the tidal pressure differential in deeper settings would be less, it is important to note that detectability could be affected by the tidal cycle. In any case higher pressure in deeper water columns would restrict the formation of bubble plumes until higher concentrations of CO_2 developed in pore waters. QICS was also a short term experiment so it is quite possible that by the end of injection the sediment pore-waters were not fully saturated by CO_2. If the experiment had continued until this was the case then a significant increase in sea floor emission rate might have taken place.

During the QICS experiment the isotopic composition of the carbon in the injected CO_2 was determined and was markedly different to the ratio found naturally in the marine system. This allowed the researchers to ascribe the source of the excess CO_2. This method may be used in the future to ascribe the source of leaking CO_2 in any leakage scenario, assuming the injected CO_2 is different from the background CO_2 carbon ratio.

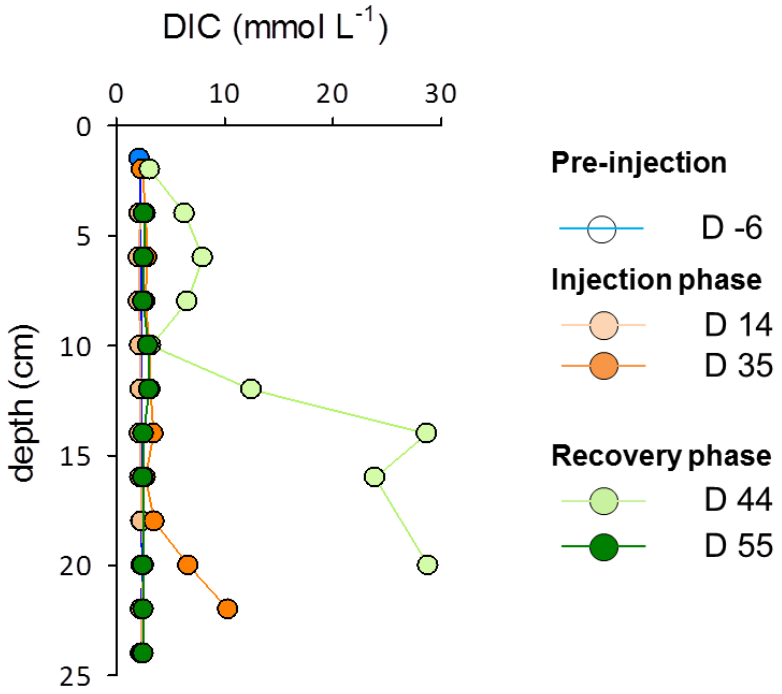


Figure 4.7 Sediment core showing concentrations of DIC rising through the sediments during the QICS CO_2 release experiment (D is day after initial release of CO_2) (Data courtesy ECO2 project and copyright National Oceanography Centre).

4.6 Stationary (non-acoustic) sensors

Marine systems are dynamic and this creates a number of problems in the monitoring and detection of any potential CO_2 leakage or emission. Modelled changes to the sediments and water column from emission scenarios show a range of changes in the environment. Natural variations in CO_2 and pH in an area such as the North Sea are often of similar magnitude to what might result from a leakage. One way of accounting for this is to have a thorough understanding of temporal variation in 'normal' environmental conditions, preferably over a number of seasonal cycles. A useful means of achieving this is through lander-based stationary systems with suites of instrumentation. Current off-the-shelf systems, such as a current recording meter plus sensors for temperature and conductivity, can go a long way towards constraining natural environmental variability. With improvements in sensor technologies these lander-based, long-term deployments have the potential to provide essential information, both for baseline studies and for monitoring, once operation at a site commences. Use of a lander in the central North Sea recorded natural variability over a twelve month period in a number of physical factors essential for environmental modelling (Figure 4.8).

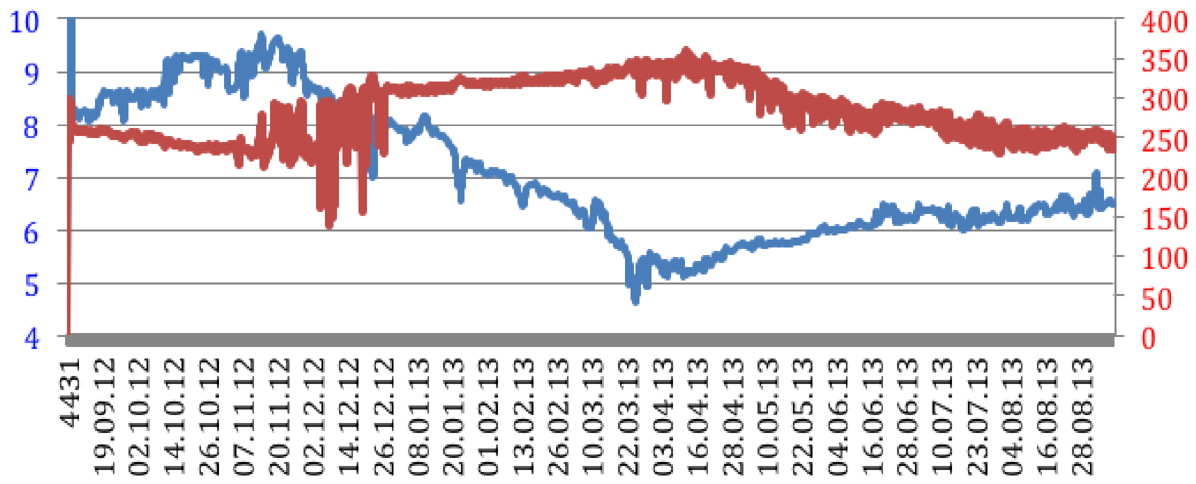


Figure 4.8 Raw data from an Aanderaa Recording Current Meter (RCM) deployed on a seabed lander September 2012- October 2013. Blue temperature (°C) and red oxygen concentration (µM). (Data courtesy ECO2 project and copyright National Oceanography Centre, NERC).

A number of sensors, both off-the-shelf and bespoke prototypes were tested as part of the QICS experiment and at natural analogues as part of the ECO2 project. Acoustic sensors in the water column were able to clearly detect the bubble streams of CO_2 once the gas had broken through the overburden. Using analytical techniques it was possible to estimate gas flow rates from bubbles, which correlated within an order of magnitude with diver measurements collected at the bubble streams (Section 4.3.2).

A number of commercial sensors for the determination of CO_2 were tested during the QICS experiment either via an AUV or deployed on the seafloor. In concert with the commercial systems a number of newly developed sensors were also tested based on optode technology for pCO_2 (Atamanchuk et al., 2014) or ISFET technology for pH (Shitashima et al., 2013). The sensors were all able to detect changes in the concentrations of pCO_2 and pH close to the release site where concentrations were high. There are issues however related to the poisoning (chemical corrosion) of the optode-based technologies, and fouling is an ever-present problem for all sensor-based methods. The research group at the University of Rome “La Sapienza” has been developing a CO_2 sensor as part of the EC funded projects RISCS and ECO2. This sensor has been extensively tested at Panarea and has shown to be very sensitive, but as with many of these systems, it has limitations including the speed of response to changing concentrations of CO_2 (Appendix 2).

A full review of the benefits and problems with all of the sensors deployed at QICS and ECO2 is beyond the scope of this report but a summary discussion is provided in Appendix 2.

4.7 Biological monitoring

Biological monitoring will primarily be focussed on impact assessment, but it might provide an element of detection monitoring capability via the appearance of anomalous features (for example usually buried fauna on the sediment surface). The challenge for biological monitoring lies in the accurate discrimination of human impacts from natural, sometimes stochastic, and potentially long-term, environmental change. Benthic systems are inherently patchy at sub-metre scales (Kendall &

Widdicombe, 1999) and vary systematically with depth and sediment type. There is also a strong seasonality driven by seasonal primary production in the overlying waters and by developmental and reproductive life cycles.

Work in both the QICS and ECO2 projects has sought to determine the physiological response to CO_2 exposure in benthic macro- and megafauna – responses that might underpin avoidance behaviours or altered community structure. The small-scale release of CO_2 gas through shallow sediment in the QICS project identified shifts in micro- and macrofaunal community structure (Blackford et al., 2014a; Widdicombe et al., in review; Tait et al., in review) as well as the emergence of some mega-infauna from the sediment (Pratt et al., in press) (also discussed in Section 3.10).

The observed impacts were limited to the area where CO_2 gas was actively leaking from the sediment or, in the case of the microbial communities, a few tens of metres away. It is likely therefore that any impact of leakage on benthic communities will be spatially limited to an area close to an active seep. In addition, it was only possible to identify impacts when comparing the community structure within the release zone directly with that seen in reference, non-impacted sites. Benthic communities naturally change with time in response to environmental drivers such as temperature, food supply and storm events. Consequently, to identify changes in benthic communities between sampling points as unusual or potentially indicative of an impact, it is essential to understand the natural patterns of change expected in any given area. This would require a robust biological baseline that included aspects of seasonal and natural variability. An alternative approach would be to identify CO_2 specific responses in benthic communities. For example, a sudden loss of calcifying species, a reduction in calcium carbonate biomass or an increase in CO_2 consuming microbes might be indicative of CO_2 leakage. However, the reliable application of such indices is yet to be fully proven. At a molecular level, Pratt et al., (in press) found no significant change in expression of genetic coding for proteins involved in acid-base regulation in the gut tissues of burrowing urchins, in spite of the fact that individuals of this species were seen to emerge from the sediment and are known to be CO_2 sensitive. It is noted though that the data were recorded in response to a small scale CO_2 injection of limited duration.

In previous studies, including those in the RISCS (RISCS, 2014) and ECO2 projects, the effects of much higher concentrations of CO_2 in seawater were established in both laboratory and mesocosm studies. Widdicombe et al. (2009) showed that exposure to CO_2 enriched sea water reduced infaunal diversity and altered community structure. In this large mesocosm study it was clear that most of the negative effects occurred when the sea water pH was reduced to around 7 or lower. However, the precise nature and severity of the impact was strongly influenced by both sediment type and the length of exposure. Impacts were worst after long (twenty weeks) exposures in sandy sediments, whilst muddy sediments were slower to respond and less severely impacted. This illustrates that the response on benthic communities to leakage will be site specific as well as dependant on the scale and longevity of any leak.

Medium-term (three month) exposures of an assembled marine infauna community from the Western Baltic Sea were investigated to six different pCO_2 levels in a mesocosm experiment. The response of different bivalve species, as well as bacterial community composition and meiofauna community abundance and composition were analysed. Increasing pCO_2 resulted in higher mortality and shell corrosion in bivalves, with smaller individuals showing greater vulnerability (>1500 µatm (152 Pa)). While the cockle *Cerastoderma edule* showed high sensitivity towards acidification – again emerging from the sediment at high pCO_2 levels, no mortality occurred in *Mya arenaria* and *Macoma balthica*, indicating responses to CO_2 leakage will be species-specific. Microbial communities and meiofauna composition also changed significantly, yet subtly, at the highest exposure level. Meiofauna community changes were also studied in Widdicombe et al. (2009) and Dashfield et al. (2008), confirming that meiofauna were less sensitive to CO_2 leakage than macrofauna.

Echinoderms are key ecosystem engineers of the soft-sediment shelf sea benthos and have been identified as potentially vulnerable to acidified conditions because of their calcareous skeletons and typically poor acid-base buffering capacity. The blood gas and acid-base status of the urchin *Paracentrotus lividus* were determined during two hypercapnic exposure investigations, including a short term (seven days) and medium term (65 days) exposure. Though lacking a significant buffer, the urchin tolerated chronic hypercapnia (20,000 ppm) for up to two months - although substantial spine dissolution was identified during exposure to $pH < 6.52$ for 65 days compared to controls. This highlights the ability of *P. lividus* to demonstrate a short term buffering capacity, which was not detected over a medium term exposure. Nevertheless long duration exposure to acidification would lead to high rates of mortality. This is also the case for infaunal echinoderm species (Spicer & Widdicombe, 2012).

In general, it is clear that there is potential for impacts to both individual organisms and community structure, in response to CO_2 leakage, but that these impacts will be species specific. Some benthic species exhibit extreme tolerance to elevated pCO_2 in the short and medium term whereas other species – including burrowing infauna – might be more susceptible to elevated pCO_2 in sediments. Susceptibility of burrowing infauna can be seen in terms of an increased incidence of avoidance behaviours in the field. However, in spite of progress made in both QICS and ECO2, there do remain significant challenges in the correlation of particular organism behaviours with an altered or impacted physiology. Behavioural alterations might take place through natural seasonal events such as reproduction or scavenging and need to be fully constrained for each release site during comprehensive baseline studies prior to the start of injection. At this stage it is considered that, in the absence of further species and site-specific studies, the use of organism behaviour for biomonitoring is not yet demonstrated.

4.8 Complementary modelling

Hydrodynamic models, and models of bubble plume dynamics and CO_2 chemistry can provide a platform by which a range of leakage fluxes, distributions and environmental settings may be examined in terms of monitorability and impact potential. Models that include sufficient biological processes, have well constrained boundaries (i.e. river or coastal inputs or exchange across open ocean model boundaries) and forcing data (such as e.g. wind speed, irradiance, heat flux, usually applied to the surface of the model) can also be used to construct baselines and examine impacts.

4.8.1 Hydrodynamic models

Marine hydrodynamic models have a long developmental history and are used for many operational and predictive purposes (e.g. Blackford et al., 2007; Siddorn et al., 2007; Holt et al., 2014). Successful application to CO_2 emissions is dependent on the ability to resolve the vertical and lateral spread of released CO_2 and describe mixing processes pertinent to the region in question. Generally inclusion of water-column dynamics is essential. For example tides are a major agent of mixing in many shelf seas where storage is likely to be situated, although enclosed seas such as the Mediterranean and Baltic are not as strongly tidal. In essence hydrodynamic models need to be developed for specific storage locations and generic model solutions are unlikely to have much value.

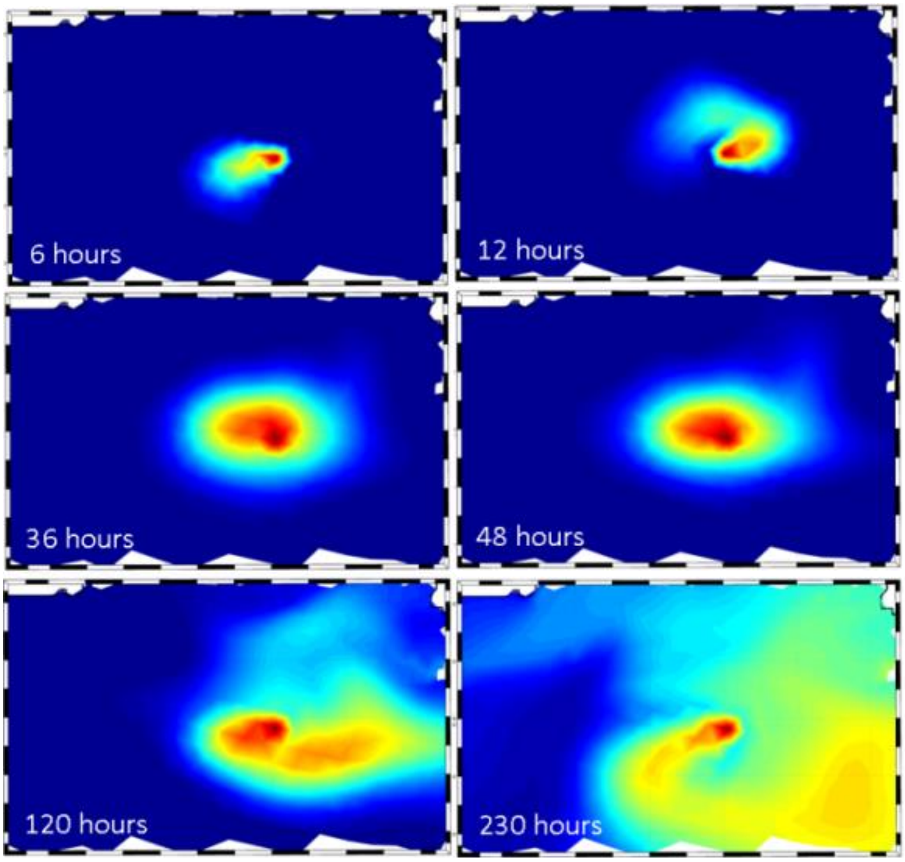


Figure 4.9 An example of a dispersion plume of dissolved CO_2 from a point source impacted by tidal mixing, using the FVCOM model. This illustrates the potential complexity of the shape of possible leakage plumes. Dark red represents the highest concentration of CO2, whilst dark blue represents the background concentration, the scale is arbitrary, hours from the start of leakage at the sea floor (copyright J Blackford, Plymouth Marine Laboratory).

Model resolution is a key limitation and relates to the dimensionality of the spatial signals specific to a given emission scenario. Examination of very large emission rates can be satisfactorily achieved with medium resolution models with a grid size of, for example 7 km (Blackford et al., 2008); or 1 km (Phelps et al., in press) which address emissions in excess of 1000 t/d. At the other end of the spectrum, small emission rates (<10 t/d) and the modelling of individual bubble plumes require model resolutions at the metre scale (Dewar et al., 2013). Different emission scenarios at the same site could well require a range of model resolutions to produce an adequate simulation. There is some potential to use variable grid models such as FVCOM (Blackford et al., 2013) where the mesh size is reduced around the emission epicentre. However such an approach would still need some scaling towards particular leakage scenarios.

4.8.2 Bubble and droplet plume models

It is likely that CO_2 emission into the marine environment will occur principally via bubble plumes in shelf seas or hydrate coated droplets in deeper, cold water environments. Very fine-scale examination of the immediate vicinity of a small-scale emission will require characterisation of the bubble/droplet plume. The processes of buoyant ascent and dissolution are moderated by bubble size, bubble shape, drag, temperature and current speed, but both modelling and observational evidence indicates that complete dissolution of CO_2 will occur within a few metres of the seafloor. However, observations at Panarea suggest that the bubble itself may persist, as the CO_2 may be replaced by other gases, such as nitrogen. Dewar et al. (2013) present a bubble plume model that can be configured for a range of environments and depths. For large fluxes, detailed bubble plume dynamics can be reasonably ignored, because the length scale of the bubble plume is insignificant compared with the length scale of the dissolved plume (Blackford et al., 2008; Phelps et al., 2014). In this case the shape of the bubble plume has virtually no impact on the shape of the dissolved plume which is controlled by hydrodynamics. However for small fluxes the characteristics of the bubble plume is the critical factor in determining the height and subsequent spread of the dissolved phase (Dewar et al., 2013).

4.8.3 CO_2 chemistry models

CO_2 chemistry in seawater is complex and sensitive to a range of environmental conditions such as temperature, pressure, salinity and alkalinity. However, largely as a product of research into ocean acidification, so-called carbonate-system models have been developed and can be considered as fit-for-purpose, so long as internationally accepted protocols are followed (Dickson et al., 2007). Carbonate-system models are routinely coupled to hydrodynamic, bubble/droplet and ecosystem models (Blackford et al., 2013; Dewar et al., 2013; Blackford & Gilbert 2007) and can be used to derive the expected changes in pH and pCO_2 for a given concentration of dissolved inorganic carbon (DIC, dissolved CO_2 and its ionic products), pressure, temperature and alkalinity.

4.8.4 Ecosystem models

Ecosystem models such as ERSEM (Blackford et al., 2004), which resolved the marine carbon cycle, have a dual purpose when coupled with hydrodynamic and carbonate system models. By including processes such as photosynthesis and respiration which affect natural DIC concentrations, these models provide an ability to estimate natural variability (Artioli et al., 2013) or the baseline against which leakage must be detected (Figure 4.10). This is particularly important because there are very few direct observations of the seafloor carbonate system.

Ecosystem models have also been used to examine biological impacts from high CO_2 (e.g. Artioli et al., 2014), however as the organism response, as demonstrated by a wealth of experiments (Widdicombe et al., 2013) is complex and species specific, this is not yet well resolved by model systems. At this stage it is probably sufficient to predict changes in pH as an indicator of impact although a species-specific approach would be tractable.

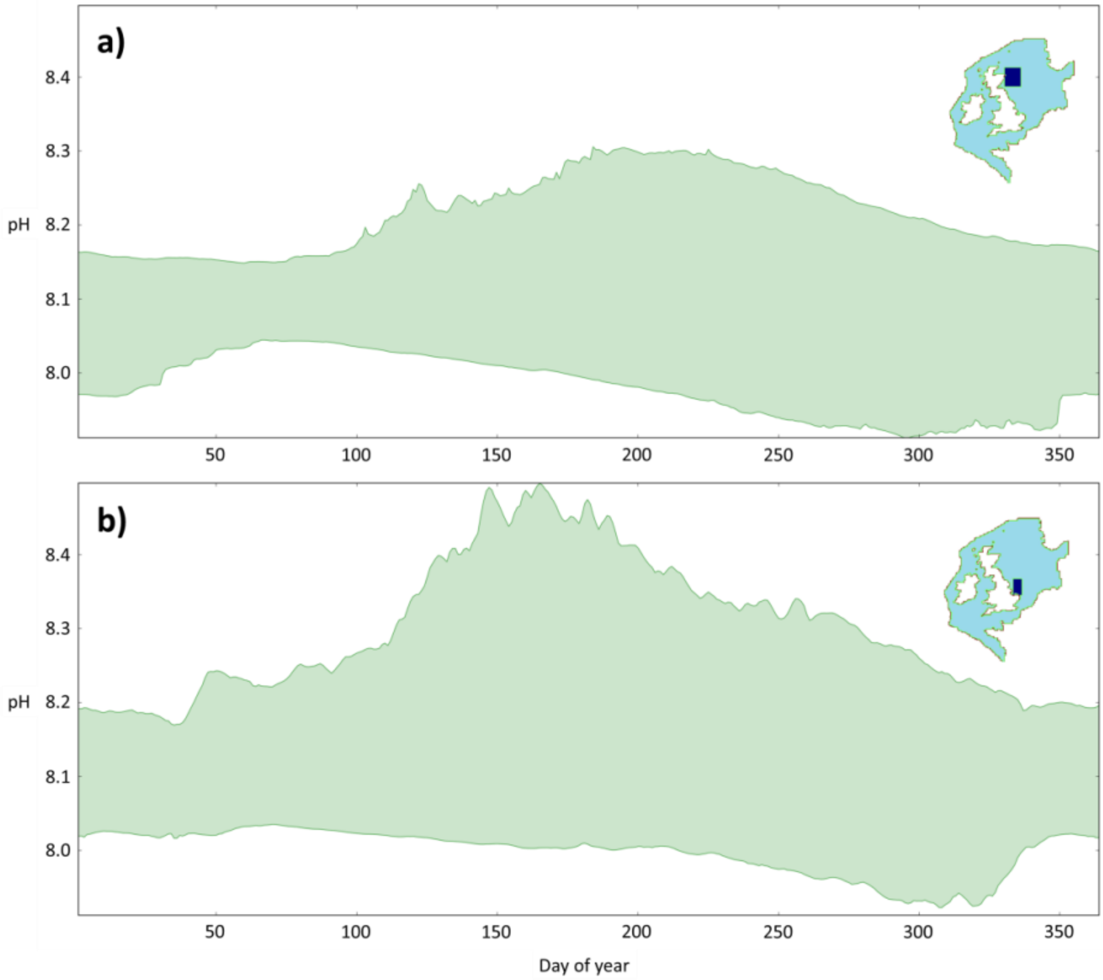


Figure 4.10 A model derived climatology of the pH range for two regions in the North Sea a) central north Sea b) southern North Sea (reproduced from Blackford et al., 2014b, copyright Plymouth Marine Laboratory).

Chapter 5 Review of efficacy of current and planned offshore monitoring practice with respect to European offshore regulatory requirements

5.1 Key monitoring requirements

A detailed review of the regulatory requirements for offshore monitoring in relevant jurisdictions is presented in Chapter 2. All current and planned large-scale offshore storage projects lie in European waters, so this chapter aims to review how well these storage projects meet the requirements of the European offshore regulatory framework which essentially comprises the European Storage Directive and the OSPAR Guidelines.

Within this framework, monitoring programmes should address site-specific risks and uncertainties and can be summarised as follows:

a. Monitoring for performance verification (conformance). To confirm the extent to which the injected CO_2 is currently behaving as expected and that the storage site will evolve towards a stable condition over the long-term. This will include:
   i. Monitoring pressure within the storage reservoir.
   ii. Tracking or constraining CO_2 migration within the storage reservoir.
   iii. Supporting predictions of the long-term containment of CO_2.
   iv. Demonstrating that the site is evolving towards stability.
b. Monitoring to detect possible leakages (containment). This will include:
   i. Early detection of indicators of potential leakage.
   ii. Detection of leakage and its source.
   iii. Identification of potential pathways that CO_2 might follow out of the storage reservoir.
c. Monitoring to measure emissions (contingency). This will include:
   i. Quantification of the amounts emitted to the seabed in projects operating within the EU ETS.
d. Monitoring of local environmental impacts on receptors, including impacts resulting from leakage. This will include monitoring the:
   i. Impacts on ecosystems and other resources.
   ii. Efficacy of any mitigation and corrective measures.

These monitoring aims require that monitoring of various parameters should be undertaken with a portfolio of techniques at a range of locations:

a. The formation(s) intended to retain the CO_2.
b. The surrounding formations for evidence of unintended migration or leakage.
c. The injection infrastructure.
d. The seabed.

The regulatory requirements also imply monitoring will be required at a number of spatial scales:

a. The total footprint of the storage complex, including the area that might be influenced by the migrating plume, at the seabed, including those locations that could be at higher risk of leakage.
b. At the reservoir scale (up to tens or hundreds of metres).
c. Isolated seabed locations at the scale of metres.
d. At the centimetre scale when assessing wellbore integrity.

Monitoring will be required at a number of temporal scales:

a. Continuous monitoring of pressures.
b. Scheduled repeat monitoring at relevant frequencies.
c. If leakage is suspected, monitoring frequencies would be expected to increase significantly.
d. Monitoring will continue from pre-injection baseline surveys, through the injection period and during the closure and decommissioning periods, if necessary.

Over these long periods, technologies available for monitoring can be expected to improve but should be selected on the basis of best practice available at the time. The ability to compare datasets acquired at different times, with different tools should be retained.

Establishing baseline conditions, which might require multiple measurements in dynamic systems, and measurements of those parameters expected to evolve over the lifetime of the project, is seen as fundamental. Such baseline conditions will be important inputs in defining normal, alert and threshold conditions.

5.2 Ability of monitoring plans to meet regulatory requirements

5.2.1 Sleipner

The Sleipner project commenced prior to the European Storage Directive coming into force and the monitoring programme was not designed to meet its regulatory requirements. Sleipner in fact operates under Norwegian offshore petroleum regulations and its initial monitoring programme was designed to address a number of identified storage risks (Chapter 3). These principally relate to migration of CO_2 out of the Utsira Sand reservoir, either laterally into adjacent licence areas or vertically through the overburden, via geological pathways or wellbores.

A number of research projects have augmented the operational monitoring programme at Sleipner and these have been primarily aimed at demonstrating and developing a range of monitoring tools, and carrying out detailed assessments of conformance and containment (Chapter 3).

Containment Monitoring

The detailed repeat 3D seismic surveys have been effective at demonstrating that the migration of the CO_2 plume can be tracked. Results have clearly shown that CO_2 has been contained within the storage reservoir and is not currently threatening any identified containment risk. There is no evidence that CO_2 has migrated into the topseal or the shallower overburden, subject to preliminary quantitative detection thresholds. In addition to the deep-focussed monitoring a number of shallow research surveys have been undertaken (by the CO2STORE, CO2ReMoVe and ECO2 projects) to test monitoring tool efficacy and develop integrated shallow monitoring strategies. So far as we are aware, no systematic shallow / environmental baselines were established at Sleipner prior to injection, but it is clear that the research surveys have not found any evidence of anomalous seabed or seawater conditions (Chapter 3).

Conformance Monitoring

This has been a prime objective of the research at Sleipner, with monitoring data being repeatedly matched against simulations both of current CO_2 plume migration and of predictions of future plume migration and dissolution (Chapter 3). Although discrepancies have been identified between observed and predicted behaviour, it is argued that these are due to minor uncertainties in the geological model and fluid flow properties. Crucially the uncertainties currently seem to be small enough to preclude, at least with current injected amounts, the possibility of unpredicted future behaviour leading to significant adverse future outcomes. Thus, lateral migration of the CO_2 is constrained by the known topseal topography, such that the plume of free CO_2 will not reach any old wellbores or seismically-detectable faults. In addition the maximum thickness of buoyantly-trapped CO_2 will not be sufficient to exceed the expected topseal capillary entry pressure.

Summary

The monitoring programme at Sleipner was risk-based and designed prior to the implementation of the EC Storage Directive. Monitoring data have been used mainly for history-matching and leakage detection and meet many of the high-level principles of the current regulatory requirements, notably for containment and conformance.

The main area where the plan might be deemed to have been lacking, at least initially, is in the shallow-focussed, environmental monitoring component with the absence of a robust baseline. In fact a series of research surveys have plugged many of the gaps here, and have shown that the site is performing as designed at all levels.

5.2.2 Snøhvit

As was the case at Sleipner, Snøhvit preceded the European Storage Directive and was licensed under Norwegian offshore petroleum regulation. Two monitoring aims have been defined: firstly to ensure reservoir pressures do not exceed the fracture threshold in order to reduce the risk of subsequent unwanted CO_2 migration that might lead to leakage; and secondly to monitor the CO_2 plume migration in order to avoid impinging on the overlying natural gas reserves.

Containment Monitoring

3D time-lapse seismic surveys of the deep reservoir and the overburden have confirmed that the storage site provides secure containment of the CO_2. A baseline survey was undertaken six years prior to the start of injection and subsequent surveys have confirmed an absence of migration out of the storage reservoir. Continuous pressure downhole measurements have demonstrated that reservoir pressures did not exceed the fracture pressure, so no induced leakage pathways have been formed.

Leakage to the seabed is considered to be a very low probability risk, due to the depth of the storage reservoir and the nature of the overlying seals. To the best of our knowledge no systematic shallow / environmental baseline surveying was carried out. Recent environmental seabed and water sampling for the ECO2 research project has found no evidence of anomalous features or conditions.

Conformance Monitoring

Downhole pressure and time-lapse 3D seismics have proven to be key diagnostic tools for conformance monitoring at Snøhvit. The downhole pressure measurement was able to show non-conformance as reservoir pressure increased more rapidly than expected. The time-lapse seismic contributed additional insights by showing that the faults which cut the reservoir were acting as barriers to fluid flow, and were, in all likelihood a significant factor in the pressure build-up (Chapter 3).

In response to the non-conformance, Statoil set in train the established remediation plan which involved re-perforating the tubing at a shallower reservoir unit and continuing CO_2 injection in the Stø Formation. Pressure and seismic monitoring of the new reservoir since the corrective actions have shown that the operation is now in conformance.

Summary

The monitoring programme at Snøhvit was risk-based and designed prior to the implementation of the EC Storage Directive. Nevertheless it meets many of the high-level principles of the current regulatory requirements, notably for containment and conformance.

Two key deep-focussed tools, downhole pressure and 3D seismics have proved notably successful in rapidly identifying and characterising a significant deviation from predicted behaviour. The deviation was identified before adverse any impacts occurred and the situation was successfully corrected.

The main area where the monitoring plan might be deemed to have been lacking in terms of formally meeting European CO_2 storage regulation, at least initially, is in the shallow-focussed, environmental monitoring component with the lack of a robust baseline. In fact a series of research surveys have plugged many of the gaps here, and have shown no evidence of any shallow migration or emissions.

5.2.3 K12-B

As a pilot–scale project storing less than 100 ktonnes of CO_2, K12-B is not required to meet the conditions of the European Storage Directive, and its monitoring programme was designed principally for research purposes (Chapter 3). Nevertheless the monitoring programme can be reviewed in the light of relevant regulatory requirements.

Containment Monitoring

The excellent sealing quality of the thick Zechstein evaporite reservoir topseal effectively eliminates the possibility of leakage along geological pathways. In addition, faults which cut the reservoir act as lateral seals, producing hydraulically isolated storage compartments. These behave effectively as ‘tanks’ with minimal fluid flow across their boundaries.

The principle risk of leakage is therefore considered to be via the wellbores, so well integrity was a key focus of the monitoring programme.

In these circumstances continuous downhole pressures can perform a containment monitoring role. Measured values were consistent with a lack of fluid loss from the storage compartment, though not uniquely diagnostic of this.

No shallow / environmental surveys have been described at K12-B.

Conformance Monitoring

K12-B is interesting in that plume migration tracking by 3D seismic is seemingly not an option. This is because the storage reservoir lies beneath a thick salt seal and also because of the presence of residual gas in the reservoir, both of which markedly reduce the efficacy of surface seismics. The main conformance tools therefore were downhole pressure monitoring and fluid analysis, together with tracers (Chapter 3). These were used via history-matching to progressively refine the reservoir flow model.

Summary

Due to its excellent geological seal and sub-hydrostatic pressures the rather simple containment monitoring programme at K12-B is probably fit for purpose. If required it could be further improved by 3D seismics to provide surveillance of the overburden and shallow-focussed monitoring deployed principally around the wellbores. The conformance modelling is also fit-for-purpose given the rather small amount of CO_2 injected.

5.2.4 Goldeneye

The monitoring programme at Goldeneye has been designed to meet the requirements of the storage permit under the European Storage Directive. The programme was developed from a comprehensive risk assessment and as such is designed to address those ‘residual risks’ which must be monitored during and after injection. The Goldeneye monitoring programme includes the establishment of baseline conditions followed by a detailed plan of operational and post-closure monitoring, as well as plans for contingency monitoring that would be deployed in the event of a significant irregularity. It is designed to meet all relevant regulatory monitoring requirements and is the most comprehensive offshore monitoring programme published to date.

Containment Monitoring

The storage is within a depleted gas field with sub-hydrostatic reservoir pressures throughout the injection operation, so leakage is considered to be very unlikely. Nevertheless containment monitoring is addressed by time-lapse 3D seismics, possibly augmented by 3D VSPs, to repeatedly image the reservoir and overburden, as well as high-resolution P-Cable surface seismic for monitoring of the shallow overburden. It is expected that imaging the plume within the original gas-water contact might prove problematical due to residual gas, but the seismic will cover possible lateral egression of CO_2 outside of the gas-water contact and also any migration of CO_2 into the overburden.

Detection of possible shallow leakage and emissions at seabed is addressed by a comprehensive surface monitoring programme. The shallow-focussed monitoring is designed to detect emissions, but it is stated that contingency monitoring for emissions quantification might require additional technologies not currently available.

Conformance Monitoring

The main conformance monitoring tool will be downhole pressure measured in a number of injection wells and a possible monitoring well, plus fluid sampling and saturation logging. 3D time-lapse seismics will provide additional constraints on lateral plume migration.

Summary

The Goldeneye monitoring plan is extremely comprehensive and provides a programme of risk-based monitoring actions, focussed on containment and conformance assurance, from baseline through to post-closure.

5.2.5 ROAD

Although ROAD has been granted the first storage permit in Europe, the monitoring programme has yet to be finalised. An initial concept has been developed by assessing key risks at the site. As the geological situation is similar to K12-B the main risks are considered to be very similar i.e. leakage via poorly abandoned well-bores. Additional risks associated with unacceptable pressure build-up and fault leakage will be addressed by the fully developed monitoring plan. This will have to meet the regulatory requirements in order for injection to start, and will be reviewed repeatedly during injection.

Containment Monitoring

This monitoring requirement will be met by downhole pressure and temperature measurements to assess geomechanical responses to injection and to monitor the injection progress. As with K12-B, imaging of the CO_2 plume within the reservoir is thought to be challenging.

Leakage detection could be achieved through 3D seismic surveying of the overburden above the evaporite seals, combined with well integrity measurements to assess the potential for the boreholes to act as leakage pathways. Environmental surveys will include imaging of the seabed and acoustic bubble detection if leakage is suspected. No contingency monitoring for emissions quantification is currently included in published plans, although this would be required.

Conformance Monitoring

Conformance assurance is provided principally by history-matching numerical simulations of reservoir pressure and temperature with downhole measurements.

Summary

The provisional monitoring plan for ROAD incorporates many of the elements required to meet the regulations, but additional detail will be required.

5.3 Comparison with the IEAGHG Monitoring Selection Tool

In addition to assessing the efficacy of the above monitoring programmes with respect to the European regulatory requirements, it is also of interest to see how they compare with the recommendations of the IEAGHG Monitoring Selection Tool. This is a web-based decision support tool on the IEAGHG website, available from www.ieaghg.org/ccs-resources/monitoring-selection-tool1. It is designed to help site operators and regulators with their selection of suitable tools to monitor sites according to a specified set of monitoring aims.

For the five storage sites described above, we compare the webtool recommendations with the tool portfolios that were actually deployed (or planned) at each site. Input data comprising reservoir and injection parameters were determined for each site (Table 5.1), together with a restricted set of monitoring aims based on the site-specific monitoring objectives (Chapter 3).

Results from the webtool are compared with tools deployed or planned (Table 5.2), together with suggested reasons for differences. The webtool outputs a list of tools that could form part of a monitoring programme, with each given a score (percentage applicability rating) to help prioritise, based on the monitoring aims selected. The background cell colour indicates whether the techniques are strongly recommended (red), probably or definitely applicable (orange), or possibly applicable (blue) to one or more of the selected aims.

For simplicity, only core monitoring tool options from the injection phase are shown In Table 5.2. In fact the webtool has the capability to return results for all storage phases (pre-injection, injection, post-injection and post-closure) and for core and contingency monitoring. Reasons why the tools deployed at the sites do not exactly correspond to the webtool recommendations are discussed below.

			Monitoring aims												
	Reservoir depth	Reservoir type	Plume	Top-Seal	Migration	Quantify	Efficiency	Calibrate	Leakage	Seismicity	Integrity	Confidence	Injection rate (Mt/year)	Duration (years)	Total CO_2 quantity (Mt)
Sleipner	0.5-1.5	Aquifer	✓	✓	✓			✓				✓	1	20	20
Snøhvit	2.5-4	Aquifer	✓	✓	✓			✓					0.77	30	23.1
K12-B	2.5-4	Gas	✓				✓	✓			✓		0.2	10	2
Goldeneye	2.5-4	Gas	✓	✓	✓			✓	✓		✓	✓	1	20	20
ROAD	2.5-4	Gas		✓	✓			✓	✓		✓		1.1	8	8.8

Table 5.1 Monitoring Selection Tool inputs for each of the five offshore sites. Injection rate and durations are approximate based on 2014 knowledge. Note that the Monitoring Aims are documented in more detail in Appendix 3.

5.3.1 Audit results

The comparison between the monitoring portfolio recommended by the webtool and the portfolio actually deployed or planned for the sites is shown in Table 5.2. Matches and discrepancies between the tool recommendations and the site deployments are identified by numerical Audit indices for each tool at each site. They arise for a number of reasons, including monitoring aims, logistics, geological setting and intent (research/commercial) and are explained below.

Sleipner

1. Deployment matches webtool recommendation. 3D surface seismic identified as key monitoring tool.
2. No suitable wellbores available for downhole logging, downhole pressure / temperature or downhole fluid sampling.
3. Tool was deployed and tested as part of research project (CO2STORE, CO2ReMoVe, ECO2).

Snøhvit

1. Deployment matches webtool recommendation. 3D surface seismic and downhole pressure / temperature identified as key monitoring tools.
2. No suitable wellbores available for downhole geophysical logging, downhole fluid sampling.
3. Tool was deployed and tested as part of research project (ECO2).
4. Function covered by alternative tool (3D surface seismic).

	Sleipner			Snøhvit			K12-B			Goldeneye			ROAD		
	Webtool	Deployed	Audit	Webtool	Deployed	Audit	Webtool	Deployed	Audit	Webtool	Deployed	Audit	Webtool	Deployed	Audit
3D surface seismic	**95**	**Yes**	**1**	**75**	**Yes**	**1**	**49**	**No**	**5**	**52**	**Planned**	**1**	**58**	**Maybe**	**5**
Geophysical logs	**45**	**No**	**2**	**50**	**No**	**2**	**75**	**Yes**	**1**	**46**	**Planned**	**1**	**55**	**Planned**	**1**
Downhole P/T	**50**	**No**	**2**	**56**	**Yes**	**1**	**56**	**Yes**	**1**	**46**	**Planned**	**1**	**55**	**Planned**	**1**
Downhole fluid chemistry	**55**	**No**	**2**	**38**	**No**	**2**	**38**	**Yes**	**1**	**46**	**Planned**	**1**	**52**	**No**	**4**
2D surface seismic	**50**	**Yes**	**3**	**37**	**No**	**4**	**29**	**No**	**5**	**31**	**No**	**4**	**34**	**Maybe**	**5**
Bubble stream detection	**13**	**Yes**	**3**	**6**	**Yes**	**3**	**17**	**No**	**5**	**26**	**Planned**	**1**	**30**	**Planned**	**1**
Multibeam echo sounding	**10**	**Yes**	**3**	**0**	**Yes**	**3**	**8**	**No**	**5**	**17**	**Planned**	**1**	**17**	**Planned**	**1**
Seabed gravity		**Yes**	**3**												
CSEM		**Yes**	**3**												
Tracers								**Yes**	**5**						
Passive / microseismic											**Planned**	**6**		**Planned**	**6**
Sea bottom gas		**Yes**	**3**		**Yes**	**3**					**Planned**	**6**		**Planned**	**6**
Sea water chemistry		**Yes**	**3**		**Yes**	**3**					**Planned**	**6**			
Seismometer & GPS											**Planned**	**6**			
High resolution acoustic imaging		**Yes**	**3**		**Yes**	**3**					**Planned**	**6**			

Table 5.2 Summary of Monitoring Selection Tool results, plus the tools that were actually deployed at each site and reasons for differences. N.B. Webtool results are for the injection phase, core monitoring package only. Each technique score represents a percentage applicability rating. Background cell colour indicates whether the techniques are strongly recommended (red) probably or definitely applicable (orange) or possibly applicable (blue) to one or more of the aims selected. Numbers in the audit column are described in the text below.

K12-B

1. Deployment matches webtool recommendation. Downhole geophysical logging, downhole pressure / temperature and downhole fluid sampling identified as key monitoring tools.
5. Site specific issue: pilot-scale research project with limited set of focussed research aims not governed by regulatory issues.

Goldeneye

1. Deployment matches webtool recommendation. 3D seismics, geophysical logs, downhole pressure / temperature, downhole fluid chemistry, bubble-stream detection and MBES all identified as key monitoring tools.
4. Function covered by alternative tool (3D surface seismic).
6. Treated as a contingency monitoring option in webtool.

ROAD

1. Deployment matches webtool recommendation. Geophysical logs, downhole pressure / temperature, bubble-stream detection and MBES all identified as key monitoring tools.
4. Function covered by alternative tool (geophysical logging).
5. Site-specific issue: Surface seismics likely not effective for reservoir monitoring. 3D overburden surveillance reduced priority owing to extremely secure geological seal.
6. Treated as a contingency monitoring option in webtool.

Chapter 6: Synthesis and sample offshore monitoring template

6.1 Monitoring Aims

In most likely regulatory scenarios, monitoring systems for large-scale offshore storage will be focussed directly on a limited number of performance measures that are necessary and sufficient to demonstrate containment and conformance. They will also have to provide additional contingency monitoring to help identify and characterise any performance deviations, to guide and monitor corrective actions, and to satisfy a carbon emissions trading or reporting system.

The main requirements for these monitoring elements have been set out in Chapter 2 so are just briefly reprised here.

6.1.1 Containment monitoring

Containment monitoring has two elements. Deep-focussed surveillance aims to identify unexpected migration of CO_2 out of the primary storage reservoir or planned storage footprint and subsequent migration within the overburden, including possible secondary reservoirs, and to provide early warning of potential movement of CO_2 to the seabed. Shallow-focussed monitoring aims to detect CO_2 emissions into the biosphere either by changes of the seabed or by physical or chemical changes in the seawater column. There is also the possibility of other, displaced, fluids escaping from the storage site which might signify precursors of impending CO_2 leakage. These could include shallow *in situ* pore-water or natural gases displaced across the sediment / seawater interface, or deeper subsurface fluids escaping from depth.

A practical minimum requirement for a deep-focussed monitoring system would be that it can reliably detect any leakage (from the storage reservoir and environs) that compromises the greenhouse gas mitigation function of the storage. The shallow monitoring system should be capable of detecting any emission at seabed likely to pose a health and safety threat or environmental impact.

6.1.2 Conformance monitoring

The second element of proving storage performance is to show that storage processes at the site are understood with a sufficient level of certainty to preclude the possibility that future deviation from expected storage behaviour would have significant adverse impacts. The basis of this is to demonstrate conformance, which is a measure of the agreement between modelled simulations of site behaviour and observed site behaviour.

Conformance monitoring enables the testing and calibrating of models of current site behaviour, and forms the basis for reliable prediction of future site behaviour, long-term secure storage and satisfactory site closure. It is primarily deep-focussed, aimed at imaging and characterising processes in and closely adjacent to the storage reservoir, such as temporal and spatial plume development or pressure evolution. Technologies should have sufficient resolution, sensitivity and / or quantitative capability to test simulation models in a robust way.

6.1.3 Contingency monitoring

Contingency monitoring is for situations where assurance monitoring has detected significant deviation from planned performance. Additional monitoring might be required to track the deviation and assess possible consequences, to design corrective measures if necessary, and, should these be deployed, to confirm that they have been effective. An example might be where CO_2 is observed to be migrating into the shallower geological section, with a threat of future emissions. Contingency monitoring would be necessary to track the migrating CO_2 in the shallow subsurface, to assure that no emissions reach the water column and, if they did, to quantify them. It is likely that emissions measurement would require that the measurement accuracy of the monitoring system is known (Chapter 2).

6.2 Offshore issues

Before setting out specific monitoring solutions in detail it is useful to summarise some key issues which affect offshore monitoring in general.

6.2.1 Spatial coverage for large monitoring areas

The first challenge for monitoring is to cover large areas corresponding to the footprint of a storage site (typically tens to hundreds of km^2 for likely North Sea options) and also allow accurate measurement and characterisation, possibly for lengthy periods, at specific leakage risk points such as the injection well, abandoned wellbores etc.

Spatial 'deep-focussed' surveillance of the reservoir and overburden will likely rely on 3D seismics which provide, in an ideal case, continuous coverage of the subsurface. In fact it would not be necessary to run repeat 3D surveys over the entire storage footprint, but just where the predictive models indicate that changes will occur (with a suitable margin for modelling uncertainty). In fact it would not be strictly necessary to acquire even an initial baseline survey over the entire storage complex; the baseline could be acquired incrementally as the monitoring data reveal how the site is behaving. This has the advantage that the newer baseline datasets can exploit improvements in technology.

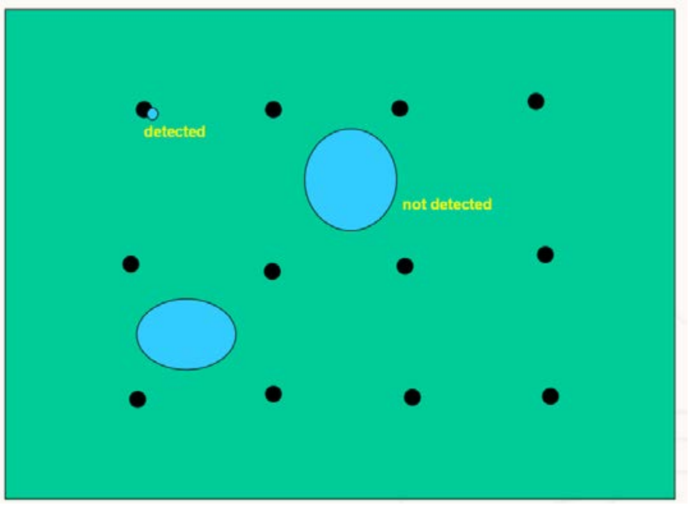


Figure 6.1 The spatial sampling problem with point-wise sampled data (applicable at any scale) (British Geological Survey © NERC 2014).

The spatial problem is perhaps more acute for shallow-focussed monitoring because individual surface emissions are likely to occupy very small areas (m^2 to tens of m^2). Thus instruments deployed on a point-wise grid might be very sensitive and/or accurate but they depend on proximity to the emission source, so there is a high risk that even quite large emissions could go undetected due to poor spatial coverage (Figure 6.1). Monitoring systems therefore need to be able to cover large areas in a reasonable length of time but also detect small discrete features (Jones et al., 2009; Schütze et al., 2013). They are likely to combine spatial 'detection' monitoring for wide area coverage with pointwise sampling for 'measurement and characterisation'. The former is likely to use either active or passive acoustics which respectively 'image' or 'listen' for bubbles (Section 3.7.1 and 4.3.1), or chemical detection (pH, pCO_2 etc) (Sections 3.8, 4.4 and 4.5). The point-wise sampling will employ principally chemical techniques (Sections 3.8, 3.9, 4.4 and 4.5).

The detection range for active acoustic bubble detection depends on frequency – lower frequency systems have increased range but lower resolution and vice versa. For example the estimated detection range for a 300 kHz system might be around 200 m, but this increases to around 1000 m for a 40 kHz system. For any type of chemical sensor the primary determinant will be the current speed and direction, and hence the dilution of the signal. If located down-current of an emission point an Eh sensor could detect a release of a reduced species over hundreds of metres, and a pH sensor on the order of tens of metres.

Initial spatial monitoring would not be able to support a full suite of active, power-hungry sensors, but need only concentrate on detecting anomalies with minimal false positives and false negatives.

Search areas may be narrowed down by integrating information from the deeper-focussed monitoring (such as the 3D seismics or P-Cable) which could indicate potential or active leakage pathways of CO_2 in the shallow subsurface and give pointers to where seabed egress could occur. This can also be problematical: at the QICS experimental site some of the CO_2 bubble-streams were displaced several metres laterally from the injection point positioned only 12 m below the seabed. Dissolution of the bubble-stream will occur rapidly and dispersion of dissolved CO_2 from an emission point will take place via physical mixing by tidal action, waves and currents). This initially means that the dissolved CO_2 plume is enlarged, facilitating possible detection, but subsequent dilution and dispersion makes detection above ambient background levels increasingly difficult.

Once any anomalies have been detected, further, more focussed or point sampling techniques can be used to confirm and establish the source of the CO_2 (for example is it of near surface biogenic origin or deeper leakage from the storage formation?), to quantify the amount of gas emission, and possibly to assess environmental impact (Blackford et al., 2014b). The current spatial extent of sensor detection capability is typically tens to hundreds of metres, which is small compared with the spatial extent of the storage complex, or a potential leakage footprint, so spatial monitoring will have to be conducted either with high spatial sampling frequency or with sensors capable of detecting very weak signals some distance from the source.

Generally signals at the epicentre of leakage will be distinct, but the natural heterogeneity of the marine environment, along with other anthropogenic signals might overwhelm signals as the distance from leakage increases. For example there are high levels of natural variability in dissolved CO_2 in marine systems due to photosynthesis and biological breakdown of organic matter, compounded by variable mixing of different water masses, especially in shallower coastal systems.

Biology varies both spatially and seasonally, so the challenge is to distinguish potentially anomalous signals from normal seasonal dynamics and other anthropogenic impacts. Acoustically the marine system is noisy, with contributions from ships, platforms, hydrodynamics and possibly marine mammals. Sediments contain many natural gas deposits, both biogenic and geological in origin, so natural phenomena can potentially be mistaken for leakage. Hence in order to maximise detection efficiency and to avoid both false positives and false negatives a thorough understanding of the marine baseline is required (see Section 6.2.2)(Blackford et al., 2014b).

It might well be the case that a number of monitoring approaches is required for robust spatial detection, including chemical, acoustic/seismic and biological. Because the form of leakage or emission is not known *a priori*, and has been observed to vary in terms of sediment type, water depth, flux rates and so on, no single monitoring approach is likely to deliver a full set of requirements (Blackford 2014a).

Another aspect of shallow-focussed monitoring that has been recognised is the need for fixed continuous monitoring at specific sites (Schlömer et al., 2013; Schlömer et al., 2014). This would include any perceived potential pathways for CO_2 leakage, such as wells (in particular any abandoned wells) and faults/fracture zones. It could also cover sensitive areas, such as Special Areas of Conservation (Natura 2000 sites), fish spawning grounds or other marine natural resources. However, Section 6.2.2 notes some potential logistical difficulties with continuous sea bed-fixed monitoring deployments.

6.2.2 Logistics and processes

Offshore monitoring is beset by a number of issues which to a large extent determine the types of monitoring technologies that can be utilised and impact upon the design, implementation and overall efficacy of storage monitoring systems. In practice these have to be robust and built around a limited number of technologies of proven sensitivity, accuracy, and reliability.

Compared to onshore, the offshore is logistically remote and difficult to access which means that offshore operations can be very expensive, particularly if ship time is involved. Health and safety is paramount and only proven (and approved) operational procedures can be undertaken (for example HSE protocols for offshore platforms).

A number of natural and man-made factors can affect the efficacy and practicality of offshore monitoring, particularly shallow-focussed methods.

Water depths: Water depth and temperature will impact both on the logistics of deploying survey equipment and also on the nature of CO_2 emissions in the water column. For example bubble sizes and rate of bubble dissolution will be a function of water pressure, temperature, salinity etc.

Water movement: Disturbance of the water column will determine the rate at which localised emissions of CO_2 or other fluids into the water column are dissipated into the wider marine environment. This will dictate the required sensitivity of instrumentation and/or its spatial coverage.

Seabed type: The nature of the sediment cover at, and immediately beneath, the seabed will affect how upwardly migrating fluids escape to the water column. In general terms, fine-grained sediments would be expected to reduce the upward migration of fluids, particularly gases, with episodic capillary sealing / breakthrough processes, manifest at the seabed as pockmarks (see below). Sandy sediments would be expected to allow more continuous upward migration of fluids, with less physical manifestation of emissions in terms of changes to seabed topography. Other seabed features may affect monitoring strategies. For example, possible shallow plumbing features such as the recently discovered Hugin Fracture in the North Sea (Chapter 4) might have the effect of ‘harvesting’ or ‘focussing’ dispersed leakage fluxes.

Seabed renewal rate: Seabed permanence is a factor in determining time-lapse seabed survey efficacy. The seabed is recycled at various rates and by different processes. In shallow waters down to storm wave-base wave action is the primary process, with variations in mobility dependant on lithology. Tidal mobilization is restricted to areas of high tidal flow; these tend to constrain the lithology of the seabed sediments. Disturbance of the seabed sediments will determine the reliability of repeat time-lapse sea-bottom surveys as an indicator of leakage-induced change (for example pockmarks or algal growths may be short-lived). This might influence aspects of monitoring survey design such as spatial sampling strategy or repeat survey frequency for example.

Anthropogenic effects: Trawling activity can have severe effects on the seabed, sufficient to modify or destroy subtle changes of the seabed that might be indicative of emissions. It will also destroy all but heavily protected *in situ* monitoring equipment. Wind-farms are an increasing component of offshore seabed infrastructure. The extent to which wind-farm development and CO_2 storage will ever be co-incident is uncertain, but the turbine installation and foundations might well compromise the logistics, coverage and quality of seabed monitoring surveys.

On the other hand, an offshore location can provide some significant advantages for monitoring, both deep and shallow-focussed. In general the quality of 3D seismics, particularly in time-lapse mode, is significantly higher than onshore due to the spatially and temporally more stable shallow velocity structure. Shallow-focussed monitoring can also benefit from the offshore environment where it is possible to ‘see’ and ‘hear’ CO_2 bubble-streams using acoustic methods. Seasonal variations are generally not so severe and establishing robust baselines might prove easier than at many onshore locations. The shallow subsurface offshore is much simpler than onshore environments in terms of fluid displacements and shallow leakage pathways are likely to be simpler and more predictable.

6.2.3 Baselines

Deep-focussed

Baselines are a necessary pre-requisite for all types of deep-focussed monitoring, both surface based and downhole. For surface seismics a purpose-designed dedicated pre-injection baseline survey covering the entire storage site is the optimal solution from a technical point of view. In practice there are a number of options which can improve cost-effectiveness and reduce environmental impacts. One possibility is to utilise a pre-existing legacy survey or surveys as the baseline. This approach was taken at Sleipner where a subset of a regional 3D seismic survey formed the baseline. The legacy data approach can reduce costs and environmental impacts significantly, but there are drawbacks. The configuration of the legacy data may well not be optimised with respect to imaging the storage reservoir, particularly if it lies at a different depth to the original exploration target and this will result in impaired time-lapse performance of future surveys. Other cost-effective possibilities include acquiring a new baseline dataset over the central part of the storage area and merging with legacy datasets in the more peripheral areas where the CO_2 plume is not expected to impact, at least in the shorter term. It is also the case that not all of the baseline dataset need be collected prior to injection. A limited area can be acquired to cover the predicted early stages of storage, with incremental portions acquired as monitoring proceeds as it becomes clearer where and when the plume will migrate. This approach also allows the newer baseline area to utilise technology improvements as they become available.

For storage in depleted hydrocarbon fields it is important to acquire and assess the field fluid production data. The reservoir response to production history provides a very strong pre-CO_2-injection characterization and calibrated model. It is also possible to use pre-production legacy seismic data, processed in time-lapse mode with the pre-injection baseline data, to assess the time-lapse effects of the production phase. This can be a relative inexpensive way of gaining *a priori* understanding of the reservoir and overburden response to large fluid saturation and pressure changes. Clearly the concept that a true 'baseline' can be established in these areas where pressure and fluid distributions have been strongly perturbed for decades is an unachievable and unnecessary expectation.

A different kind of baseline monitoring is applicable to passive seismics, where the need to establish pre-injection seismicity is more akin to acquiring baseline data for shallow-focussed systems. For natural seismicity, acquiring baseline data is most unlikely to sample the full range of natural variation, even if carried out for several years. Passive-active seismic systems also ideally require a lengthy baseline in order to establish pre-injection velocity structure.

Although Sleipner has shown that a pre-injection baseline is not strictly necessary for gravimetry, it is strongly recommended in order to sample the full mass change.

In general baseline measurements will also be made for downhole monitoring. As discussed above, from a technical point of view these need not necessarily be made prior to injection, but do need to precede the anticipated impact (e.g. for sampling in a relatively distant monitoring well). On the other hand, true, pre-injection baselines are generally to be preferred, not least from a public acceptance point of view.

Shallow-focussed

The baseline issue for shallow-focussed monitoring is potentially complex. It is crucial for baseline measurements to be carried out so that anomalous emissions can be identified, but since any deviation from baseline might be deemed to be an 'emission' it is equally important that the baseline datasets capture the full range of natural variation to avoid false positives. Because of the wide range of spatial and temporal variability in a number of different processes, repeat baseline monitoring is likely to be required to establish these natural cycles. These baselines might be acquired during the injection period as well, in the absence of indications of significant irregularities where the system might be evolving due to exogenous factors (such as increasing seawater acidification or temperature rise).

Seawater chemistry varies temporally and spatially, the major drivers of heterogeneity being the seasonal cycle of primary production and the spatial distinction between vertically mixed and intermittently stratified waters.

Shallow gas (methane or hydrogen sulphide) is often naturally present in shallow sediments, and its geophysical manifestation can vary seasonally (Chapter 4). Baseline surveys are needed to broadly identify the seismic attributes of gassy sediments, any pre-existing seabed features, such as pockmarks, and also any bubble-streams that might already be present above a proposed storage site. Offshore areas, particularly those liable to be suitable for CO_2 storage, are commonly acoustically complex. Man-made noise (e.g. from marine traffic, oil/gas platforms, wind farms or even active sound-based seal deterrents) added to natural noise from storms/waves and gas seeps (principally of methane), will contribute to masking a specific acoustic signal. Generating a baseline imparts some challenges as these sound generators may be fixed, mobile and/or intermittent and unpredictable. Thus, an effective baseline might well require a spatially and temporally detailed survey of marine noise, across the range of frequencies associated with bubble streams.

The situation is further complicated by various natural seabed reworking processes that might change or eradicate previous baseline conditions.

Robust offshore baselines might therefore have to cover a wide range of environmental variables depending on the storage situation. Here we list the issues pertinent to a range of potential monitoring methodologies and recommend some baseline sampling strategies for consideration depending on the situation (Table 6.1).

Method	Variables	Temporal sampling interval	Spatial sampling scale	Notes
Active acoustics	Sea floor bathymetry, including pockmarks.	In shallow waters where the seafloor sediments are exposed to storm driven re-suspension and biological sedimentation a seasonal discrimination, in the first instance. In deeper waters where sediments are disconnected from weather driven events an initial survey, followed by a repeat survey 1-2 years later.	The spatial extent of the storage reservoir in addition to allowing for lateral movement of migrating CO_2.	Assists identification of existent natural seeps.
	Free gas in surface sediments.	An initial survey, followed by a repeat survey 1-2 years later.		Useful for attribution.
Passive acoustics	All noise at relevant frequencies.	Seasonal in addition to targeted short term deployments to assess event driven noise.	Targeted to known fixed installations or shipping routes.	Necessary for quantification, not essential for detection.
	Acoustics of existent natural gas seeps.	Seasonal and targeted short term deployments to account for intermittent gas flow.	Spatial extent of the storage reservoir as well as allowing for lateral movement of migrating CO_2	Required for detection.
Geochemistry	pH, pCO_2, temperature, salinity, pressure. TA or DIC and O_2 if possible.	Hourly measurements for at least part of the seasonal cycle, corresponding with periods of biological or physical activity. Weekly for entire annual cycle. Repeated for at least one subsequent year to assess inter-annual variability and then on an approximately decadal repeat to assess longer term trends.	For high frequency data, if the storage site is large or includes significant changes in water depth or other hydrodynamic properties, at least a pair of landers deployed across the site. Spatial extent of the storage site via AUV deployment.	Required for detection.
Biology	Community structure, indicator species and related indices.	Weekly during periods of intense biological activity, otherwise monthly. Repeated for at least one subsequent year to assess inter-annual variability and then on an approximately decadal repeat to assess longer term trends.	Significant differences in water depth and-or different sediment types within the complex would need separate characterisation. Multiple replicates are required for statistical certainty.	Principally for impact assessment.

Table 6.1 An overview of the spatial and temporal criteria for baseline data acquisition, reproduced from Blackford et al., 2014b).

6.3 Objectives and monitoring tools

In line with the high-level requirements of Containment and Conformance, for each storage site the risk assessment will identify site specific storage risks around which the monitoring plan will be designed. Based on assessment of geological and engineered safeguards, monitoring technologies can be considered and evaluated with respect to a set of lower level specific monitoring objectives. The IEAGHG Monitoring Selection web-tool (IEAGHG 2014) identifies ten such objectives. A number of these are set out below, together with outline findings from the previous chapters.

6.3.1 Plume imaging / tracking

The ability to explicitly image the plume of free CO_2 in the subsurface is a first-order determinant of storage performance and is likely to be a pre-requisite for many, though not all, storage situations. In the early stages of CO_2 injection, plume imaging is likely to involve tracking free CO_2 in the primary storage reservoir. In the longer term, plume imaging may involve tracking CO_2 migration or leakage into strata adjacent to the storage reservoir, such as the overburden. The key tool for plume imaging and tracking is 4D seismic, either by streamer or ocean bottom sensors. If seismic is not cost-effective or operationally effective at a site for whatever reason and monitoring wells are available, then VSPs, downhole fluid sampling, geophysical logging and pressure/temperature measurement can all provide key information on plume migration and geometry.

6.3.2 Calibration and verification of predictive models

Predicting how the CO_2 will be stored over the long-term requires the integration of many geological processes in a predictive performance model. By acquiring monitoring data on these processes and their interactions during and after injection, outputs from the predictive models can be tested and calibrated, enabling the models to be suitably modified or rejected and reducing uncertainty in long term model predictions. A wide range of tools is available including 4D seismic, downhole pressure / temperature sensors, geophysical (fluid saturation) logging, downhole sampling and, surface displacement measurement such as GPS. The tools have radically different measurement characteristics. Seismics generally provide strong spatial 2D and 3D information. Downhole pressure is a strong spatial integrator, effectively 'seeing' processes across the reservoir, but with limited spatial diagnostics. Downhole tools provide high sensitivity, high resolution measurements of a range of parameters but with a highly restricted spatial footprint.

6.3.3 In-reservoir quantification

It is a regulatory requirement that the mass of CO_2 injected for storage is measured at the wellhead via some form of flowmeter, but independent confirmation of the injected mass in the subsurface is not a requirement. Nevertheless, in some circumstances it might be desirable to obtain quantitative information about aspects of the CO_2 plume in order to demonstrate understanding of flow processes in the reservoir, for example saturation distribution, amount of dissolution, and residual trapping. For in-reservoir quantification surface seismic, downhole geophysical logs and fluid sampling are all potentially important tools. Time-lapse gravimetry is proving useful as a complementary tool to the seismics.

6.3.4 Storage efficiency and fine-scale processes

Reservoir capacity and, on a much longer timescale, long-term storage security are influenced by a number of factors that include plume migration, CO_2 dissolution in reservoir pore-waters, structural and stratigraphical trapping and residual gas trapping in pore spaces. These processes are often influenced by fine-scale variations in reservoir geometry, lithology, pore architecture, permeability and pore-water chemistry. In addition, key reservoir monitoring parameters such as seismic velocity are influenced by fine-scale processes such as fluid mixing scales. Specialised monitoring tools can be targeted on particular parts of the storage reservoir to help gain insights into these processes. Typical tools might include downhole geophysical logs (to monitor saturation and dissolution) and downhole fluid sampling.

6.3.5 Topseal Integrity

Close monitoring of the reservoir topseal for evidence of failure or leakage will be important during the injection stage of a project. Depending on the type of storage, there are likely to be periods, both during and after injection, when reservoir pressures are significantly elevated immediately beneath the caprock. A maximum permissible reservoir pressure is likely to have been determined during site characterisation, prior to injection. Evidence of reducing seal integrity or fracture failure could be obtained from a number of monitoring techniques including direct detection or imaging of free CO_2 in the overburden, pressure changes in the reservoir or overburden, induced microseismicity or changes in aquifer chemistry. Key tools for monitoring topseal integrity include downhole pressure (in and above reservoir), surface seismics and passive seismics.

6.3.6 Seismicity and earth movements

In some cases CO_2 injection can lead to increased (induced) seismic activity and, in some circumstances, to detectable ground movements. For offshore storage this might not pose such a significant issue as onshore, but in some circumstances where loss of geomechanical integrity is thought to pose a risk to infrastructure or containment, microseismic monitoring and surface displacement monitoring such as by GPS (platform mounted) would be recommended.

6.3.7 Well integrity

The ability of wells to retain CO_2 during the injection, post-injection and post-closure phases, is an important issue in many storage situations. A number of wellbore integrity geophysical logging tools, both standard and innovative, are applicable.

6.3.8 Migration out of the storage reservoir to shallower depths

Monitoring to detect migration of CO_2 out of the storage reservoir to shallower depths is a critical activity, particularly in the European context where migration out of the storage complex is defined as leakage. In giving early warning of possible future emissions it also triggers the necessity for quantitative measurement under the ETS. Quantification of leakage at the storage complex boundary (likely to be situated well above the reservoir, but well beneath the seabed) is also potentially very useful, in providing constraints for the prediction of future emissions. 4D seismic is likely to give effective 3D leakage monitoring, including quantification potential, in most offshore situations. At shallower depths a high resolution technique such as P-Cable can provide 3D shallow subsurface surveillance capable of imaging leakage pathways and providing early warning of CO_2 arrival at the seabed.

6.3.9 Near surface migration and emissions to the water column: detection and measurement

Leakage to the seabed results in emission of CO_2 to the water column. As well as defining the ultimate atmospheric mitigation performance of the site, emissions might also result in significant safety and environmental impacts, so a robust monitoring system is required. An important point is that emission of subsurface pore-waters and natural gases might form precursors to CO_2 leakage and their detection will likely form part of the monitoring system.

As discussed above, a key issue with leakage / emissions detection and measurement is spatial sampling. For robust emissions detection and measurement multiple tools will need to be deployed in a variety of configurations with pointwise, spatial and temporal coverages carefully integrated to ensure surveillance continuity. A point-wise grid of monitoring stations could include seabed sediment and gas/fluid sampling via some form of grab or shallow coring device. Mobile systems will provide wide spatial coverage to identify emissions sources and tools with high accuracy will be used to measure and characterise them. General imaging tools such as multibeam echosounding and high resolution sonar can be deployed over wide areas, for time-lapse seabed imaging or bubble-stream detection. Multi-property probes such as the CTD (Conductivity, Temperature and Depth) can be used to characterise water column chemistry and a number of other properties. Wide area tools can be deployed from a ship, from an ROV or theoretically at least, via a remotely-based AUV with minimal manual control. More detailed analysis could take the form of anomalous areas bubble-stream flux measurement, chemical sampling or quantification via acoustic techniques.

Longer term temporal variations will likely be captured at selected localities by semi-permanent seabed landers equipped with chemical and geophysical sensors.

6.4 Monitoring Strategies

At a high level it is likely that a storage site monitoring programme will have two main elements:

- A ‘core’ monitoring plan to meet the regulatory requirements of a site that performs as expected throughout its history.
- A ‘contingency’ plan held in reserve to address any significant irregularities that might occur, particularly regarding mitigation actions.

Thus the Core Monitoring Plan is designed to meet the regulatory requirements of a conforming site (i.e. one that behaves as expected during its lifetime). It is aimed at performance verification, the monitoring and management of any site-specific containment risks identified in the risk assessment and the detection of performance irregularities, including early warning of potential leakage. Specific issues addressed by the Core Monitoring Plan include:

- Effective monitoring of identified containment risks e.g. wellbores (Containment).
- Demonstration of no detectable leakage (Containment).
- Comparison of actual site behaviour with modelled behaviour (model verification) and calibration of predictive modelling (Conformance).

- Indication of any performance irregularities, in particular those that may become significant, leading to a risk of leakage or a risk to the environment or human health (Conformance).

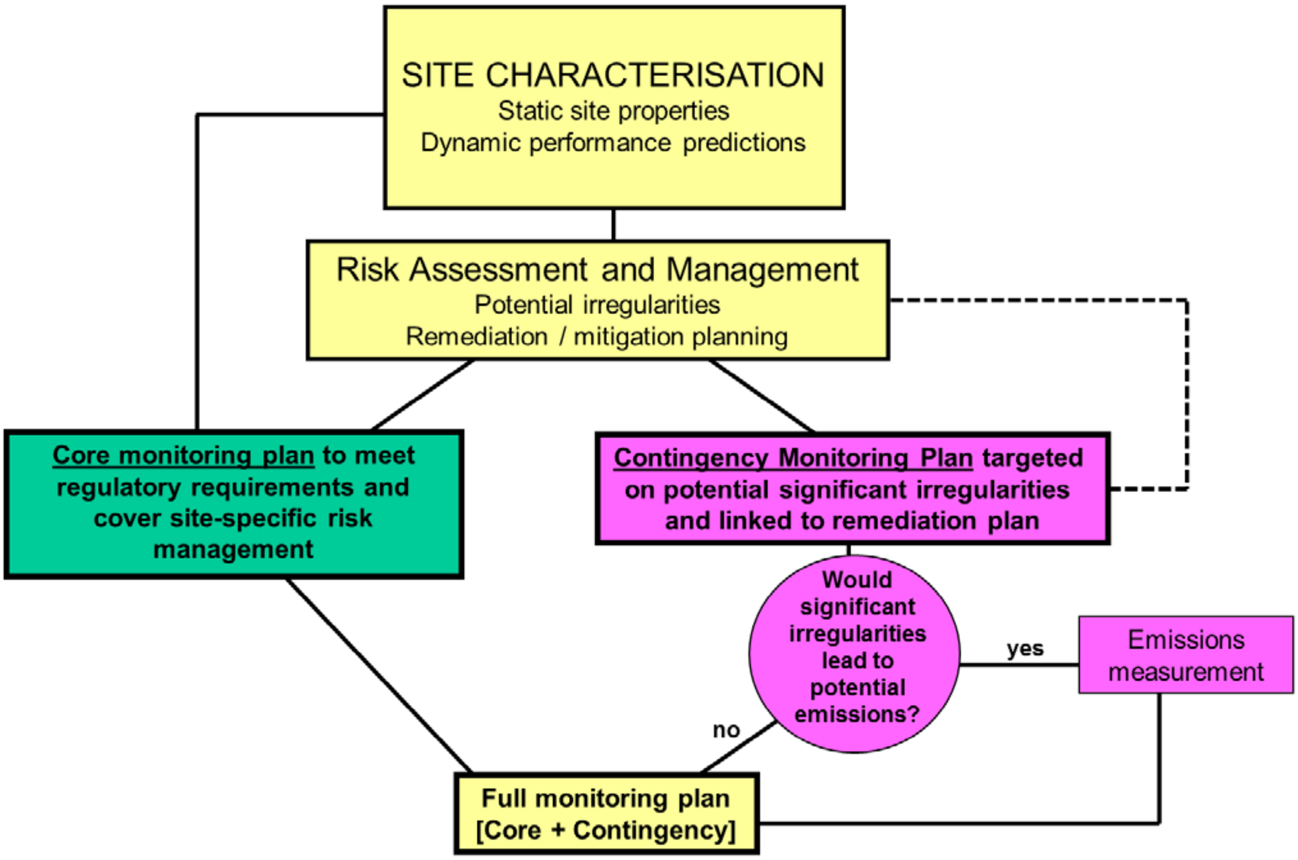


Figure 6.2 Flowchart showing the major elements of the monitoring programme (modified from Jones et al., 2014).

The Contingency Monitoring Plan contains a portfolio of tools held in reserve for use in the event of a significant irregularity. It is designed to meet the requirements of a storage site that does not perform as expected and should address the possible range of significant irregularities and the needs of any associated remediation actions. Specific issues addressed by the Contingency Monitoring Plan include:

- Provision of additional data to re-design or re-calibrate predictive performance models.
- Provision of information for remediation actions and assessment of their efficacy.
- Measurement of leakage and emissions under an emissions trading system.

Both the core and the contingency monitoring elements would be designated at the site licensing stage and be based upon detailed site characterisation and risk management plan. Both could be modified as the project progresses, understanding increases and/or monitoring technologies improve. A particular component of the contingency plan would be emissions measurement under the ETS.

6.5 Suggested monitoring template

In terms of which tools to deploy, monitoring systems should be technically effective, cost-efficient and logistically viable. Tool deployments and interfacing will be determined by the high-level aims and the more specific monitoring objectives discussed above, but will also be constrained by local site characteristics and infrastructure. For example reservoir depth and type, pressure depletion and overburden stratigraphy can all radically affect the efficacy of seismic techniques. The availability of accessible wellbores will likely dictate the type of downhole monitoring deployed. The industrial-scale storage footprint is likely to be large, abandoned wellbores are not accessible offshore and well spacings are likely to be high. The nature and longevity of the seabed will dictate baseline strategies and tools for leakage and emissions monitoring. Water depth can strongly impact on the practicality and efficacy of shallow monitoring and sampling systems, such as the seismic P-Cable.

Experience from Sleipner and Snøhvit suggests that effective monitoring strategies comprise a relatively limited suite of robust tools and our suggested monitoring template follows this philosophy. It is important to realise that ‘more’ is not necessarily ‘better’. Monitoring tools have to have a specified sensitivity, but they also have to be accurate in the sense of having good repeatability which ultimately determines the time-lapse performance. A number of different tools providing complementary information is generally perceived as beneficial, but it is important not to deploy tools with markedly different repeatability. A tool with poor time-lapse performance can reduce the credibility of a more accurate tool used in parallel, whilst providing little additional useful information. Nevertheless, some tools do provide genuinely complementarity, a good example being the combination of 3D seismics and seabed gravimetry at Sleipner (Chapter 3), where each technology addresses a specific limitation of the other.

The Core Monitoring Plan for offshore storage incorporates a relatively limited number of tools based around a site-specific risk assessment (Figure 6.3). Deep-focussed tools aim to track reservoir pressure, CO_2 plume migration (both within and out of the reservoir) and fluid properties and distribution. Shallow-focussed tools aim to provide spatial imaging and sampling of the seabed and water-column and to characterise any anomalous features such as pockmarks and bubble-streams.

The Contingency Monitoring portfolio aims to address specific issues of non-conformance – migration out of the reservoir, suspected topseal fracturing and leakage (including emissions measurement). Note that contingency monitoring will commonly involve specific application of tools from the Core Monitoring portfolio.

With the proviso that monitoring tool selection will be based around a site-specific risk assessment, then a likely portfolio of key tools, together with their objectives, particular issues, and position within a Core or Contingency monitoring scenario, is outlined after figure 6.3:

		monitoring tools	Containment	Conformance	comments
Core Monitoring Plan					
		Downhole P and T (including optic-fibre)	🟦	🟩	On injection wells and monitoring wells if utilised
		3D time-lapse (4D) seismic	🟦	🟩	Not applicable to all reservoirs but applicable to all overburdens
		2D time-lapse seismic		🟩	Low cost alternative to 3D for some repeats
		VSP	🟦	🟩	Option if surface seismic not effective
		Passive seismics	🟦	🟩	If geomechaical issues identified in risk assessment
		Downhole fluid sampling		🟩	Post-injection stabilisation (dissolution)
		Geophysical logging	🟦	🟩	Fluid saturation
		Multibeam echosounding	🟦		Spatial coverage to identify potential issues; bubblestream detection
		High resolution sonar	🟦		Spatial coverage - Seabed imaging
		Vehicle-mounted sonar	🟦		Hydro-acoustic bubble-stream characterisation
		Seabed fluid and gas analysis	🟦		
		Seabed CO2 flux	🟦		Semi-permanent seabed stations for temporal variation
		Water column measurements	🟦		
Contingency Monitoring Plan		3D time-lapse (4D) seismic	🟦	🟩	Test and re-calibrate models; identify migration pathways.
		Hi-resolution seismic (p-cable)	🟦		Leakage out of Storage Complex.
	ETS measurement	Multibeam echosounding	🟦		Hydro-acoustic bubble-stream characterisation
		High resolution sonar	🟦		Emissions source imaging.
		Vehicle-mounted sonar	🟦		Hydro-acoustic bubble-stream characterisation
		Seabed fluid and gas analysis	🟦		Emission characterisation including non-CO2 precursors
		Seabed CO2 flux	🟦		Semi-permanent seabed stations
		Seawater chemistry	🟦		Emission characterisation including non-CO2 precursors

Figure 6.3 Suggested monitoring tool portfolio for an offshore CO_2 storage site

Downhole Pressure and Temperature [Core]
Objectives: Pressure control; CO_2 properties monitoring; predictive model calibration / verification; wellbore integrity.
Issues: Key reservoir performance monitoring tool. Non-directional; long-term sensor reliability; relies on additional monitoring wells for good reservoir coverage. Optic-fibres can give continuous downhole temperature profiling.

3D time-lapse seismic [Core]
Objectives: Plume imaging; in-reservoir quantification; storage efficiency; model calibration / verification; topseal integrity; leakage detection.
Issues: Key all-purpose deep imaging tool giving uniform 3D coverage of storage complex; reservoir imaging not effective in all situations (e.g. sub-salt, depleted hydrocarbon reservoirs); expensive; multiple repeats have adverse environmental impacts.

2D time-lapse seismic [Core]
Objectives: Plume imaging, model calibration / verification, topseal integrity.
Issues: Does not provide full subsurface coverage; can provide azimuthal information for geomechanical anisotropy; reservoir imaging not effective in all situations (e.g. sub-salt, depleted hydrocarbon reservoirs).

VSP [Core]
Objectives: Plume imaging; model calibration / verification; topseal integrity.
Issues: Coverage limited to vicinity of wellbore; non-uniform coverage; can provide azimuthal information for geomechanical anisotropy.

Passive seismics [Core]
Objective: Topseal integrity; detection / mapping of induced seismicity
Issues: Use in specific geomechanical scenarios; requires downhole deployment; long-term tool reliability in question.

Geophysical logging [Core]
Objectives: Plume tracking; model calibration/verification; in-reservoir quantification; long-term stabilisation.
Issues: Requires additional monitoring wells; localised (point) measurement.

Multi-beam echosounding [Core]
Objectives: Seabed imaging, emission detection, bubble-stream detection and characterisation.
Issues: Key seabed spatial imaging tool, deployment via ship, ROV or AUV.

High resolution sonar [Core]
Objectives: Baseline seabed imaging and characterisation, bubble-stream detection
Issues: Deployment via ship, ROV or AUV.

Vehicle-mounted sonar [Core]
Objectives: Baseline seabed imaging, bubble-stream characterisation
Issues: Seabed deployment via ROV or AUV; low-power passive sonar option for 'listening' only.

Seabed fluid and gas analysis [Core]
Objectives: Characterising baseline seabed fluid and gas occurrences
Issues: Seabed deployment by ROV; point-wise sampling.

Seabed CO_2 flux [Core]
Objectives: Quantifying baseline CO_2 fluxes
Issues: Not required if gas not CO_2.

Water column measurements [Core]
Objectives: Characterising water column above seabed (CTD) for CO_2 or precursors.
Issues: AUV/ROV mounted; sensitivity issues with small emission sources.

3D time-lapse seismic [Contingency]
Objectives: Plume imaging; model calibration / verification; topseal integrity; leakage detection and tracking.
Issues: As above

High resolution 3D time-lapse shallow seismic (P-Cable) [Contingency]
Objectives: Leakage detection and tracking.
Issues: 3D time-lapse coverage of shallower overburden above the storage complex.

Multi-beam echosounding [Contingency]
Objectives: Bubble-stream detection and characterisation.
Issues: As above.

High resolution sonar [Contingency]
Objectives: Emissions source imaging and characterisation.
Issues: As above.

Vehicle-mounted sonar [Contingency]
Objectives: Emissions source imaging and characterisation.
Issues: As above.

Seabed fluid and gas analysis *[Contingency]*
Objectives: Testing identified new emissions, focussed on leakage pathways
Issues: As above.

Seabed CO_2 flux [Contingency]
Objectives: Measuring new emissions focussed on leakage pathways
Issues: Not required if new emissions not CO_2.

Water column measurements [Contingency]
Objectives: Characterising water column above emissions sources.
Issues: As above.

6.6 Monitoring Frequency

As discussed above, acquiring baseline data is a key step for all of the tools, deep and shallow-focussed. Shallow acquiring baseline data depends on gathering data over as long a time period as possible and, pragmatically, is likely to *continue into the injection phase* so long as there is no evidence of leakage from the deeper storage reservoir.

The frequency of time-lapse repeat measurements in the various monitoring surveys is highly site-specific and will depend upon the predictive models of storage development and the site risk assessment. Thus, the repeat frequency should be sufficient to enable robust calibration and verification of the predictive models and be sufficient to ensure that deviations from the predicted behaviour cannot lead to significant irregularities. Uncertainty is of course a key parameter, and downside model predictions should be emphasised to ensure that repeat monitoring is sufficient to give early warning of deviations.

Sleipner has had roughly biennial 3D time-lapse seismic repeats, but this should not be taken as a guide for future operations. These surveys were gathered either for research purposes or serendipitously as add-ons to surveys of the deeper gas field. At Goldeneye a much sparser time-lapse seismic strategy is proposed. In some cases such as the secure sub-salt storage scenarios beneath the southern North Sea few if any repeats may be required for a conforming site.

For scenarios where regular repeat surveys are deemed necessary, early initial repeats are recommended, because uncertainties are highest prior to the first repeat surveys. A good example of this principle is at Ketzin, where the first repeat seismic survey was carried out after only 23 kt of CO_2 had been injected. It showed that reservoir behaviour was significantly different to what had been expected, which necessitated early modifications to the predictive model.

It is envisaged that, for a conforming site, monitoring frequency should progressively decrease with time as uncertainties are reduced and model predictions converge with monitoring observations. The rate of plume spread also decreases with time; to a first approximation plume radius will generally increase as the square root of time.

For shallow-focussed leakage or emissions monitoring there is an additional driver for increased repeat frequency. The EU ETS states that if an emission is detected then, for emissions accounting, that level of emission is extrapolated back to the previous monitoring survey.

Post-injection monitoring aims to provide the information necessary to close the site and, if appropriate under the regulations, to transfer responsibility back to the state. The key objectives will be to demonstrate conformance of observed and predictive models, no detectable leakage and finally, to provide evidence that the storage site is starting to stabilise. This latter point is of crucial importance and includes the condition that the storage situation is sufficiently well-understood that unforeseen future events could not lead to significant adverse outcomes. It is likely therefore that post-closure monitoring will follow the established deployment template with the final deep-focussed time-lapse monitoring survey(s) taking place sufficiently long after cessation of injection to meet the above requirement. A minor element of shallow-focussed monitoring (such as seabed imaging) may continue for a period post-closure.

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Project webpages

QICS: Quantifying and Monitoring Potential Ecosystem Impacts of Geological Carbon Storage, http://www.qics.co.uk

RISCS: Research into Impacts and Safety in CO_2 Storage, http://www.riscs-co2.eu/

CO2CARE: CO_2 site Closure Assessment REsearch, http://www.co2care.org/

CO2ReMoVe: Monitoring and Verification CO_2 Storage Research, http://www.co2remove.eu/

ECO2: Sub-seabed CO_2 storage: Impact on Marine Ecosystems, http://www.eco2-project.eu/

APPENDIX 1: Summary comparison of offshore and onshore monitoring issues

This Appendix presents an outline comparison of how effectively various technologies and methodologies perform offshore and onshore in the light of the different environmental, logistical and cost constraints.

Table A1.1 shows the monitoring tools that have been deployed at the offshore sites outlined in Chapter 3 and also at a selection of onshore sites for comparison. As discussed previously, each storage site has different monitoring objectives depending on site-specific risks and jurisdictional requirements. Onshore sites will have different monitoring priorities compared to offshore sites, for example, demonstrating and providing assurance of safe storage for drinking water quality. Public acceptance and confidence issues will also be more highly prioritised onshore. In terms purely of CO_2 storage, most of the monitoring deployments onshore to date have had a strong research focus, and only one site, In Salah in Algeria, could be considered large-scale or commercial (the upcoming Gorgon project will change this). However if we consider onshore CO2-EOR, then the situation is quite different. A number of large-scale CO_2-EOR projects in the United States are being monitored to some extent. The longest running is at SACROC, which commenced in 1972, has some 80 million tonnes of CO_2 stored, and has a long-term shallow monitoring programme. More recent CO2-EOR projects in the United States include the Hastings Field, Bell Creek and Cranfield, the latter having an associated research monitoring programme with both deep-focussed and shallow-focussed elements (Table A1.1).

The Weyburn CO2-EOR project in Canada is of particular interest. With over 20 million tonnes of CO_2 stored over 14 years it has comprehensive deep-focussed and shallow-focussed research monitoring programmes (Table A1.1) with publication of detailed results (see Hitchon 2012 and references therein). Deep-focussed monitoring includes downhole pressure, 4D time-lapse seismics and microseismics, at a storage scale which enables direct comparison with use of similar technologies at the large-scale sites offshore.

It is clear that for deep-focussed monitoring, the offshore has much in common with the onshore in that storage reservoirs and deeper overburden successions are geologically rather similar in both situations, with the possible exception of natural subsurface water flow which can be much more significant onshore. The main differences relate to operational logistics such as ease of access, available infrastructure such as wellbores, costs and health and safety issues.

For shallow-focussed monitoring onshore-offshore comparisons are more complex, because shallow geological and hydrogeological systems differ significantly. Offshore there is essentially a gradational continuum between the shallow sedimentary pore-waters and the seawater column, whereas onshore there are major physical and chemical discontinuities at the top of the weathering zone, the water-table and also at the land-surface itself. An advantage of monitoring in the offshore environment is the ability, at least in principle, to ‘see’ and ‘hear’ emissions via bubble-streams using active or passive acoustics, whereas this is not the case onshore.

Deep	Shallow	Tool Name	Sleipner	Snøhvit	K12-B	Goldeneye	ROAD	In Salah	Weyburn	Ketzin	Nagaoka	Otway	Frio	Cranfield	Decatur	Citronelle	Lacq Rousse	Others*
			Offshore					Onshore										
		Site scale: large(L)>1 Mt,small (S)<1 Mt	L	L	S	L	L	L	L	S	S	S	S	S	S	S	S	S
x		2D surface seismic	x				x			x					x			x
x		3D surface seismic	x	x		x	x	x	x	x	x	x		x	x			x
x		Downhole pressure/temperature		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
x		Surface gravimetry	x	x														
x		Geophysical logs			x	x	x		x	x	x	x	x	x	x	x		
x		Downhole fluid sampling			x	x		x	x	x	x	x	x	x	x	x		x
x		Surface gravimetry	x	x														
x		Seabottom EM	x															x
x		Microseismic monitoring				x	x	x	x	x		x		x	x		x	x
x		Vertical seismic profiling (VSP)							x	x		x	x	x	x	x		x
x		Well gravimetry												x				
x		Single well EM											x					x
x		Tiltmeters						x										x
x		Cross-hole seismic							x	x	x		x	x		x		
x		Cross-hole EM								x			x					x
x		Cross-hole ERT								x				x				
x		Satellite interferometry						x							x			
x		Multicomponent surface seismic							x									x
x		Land ERT								x					x			x
x		Land EM								x								x
x		Airborne EM												x				
x	x	Tracers			x			x	x	x		x	x	x		x		x
	x	Shallow acoustic imaging	x	x		x												x
	x	Bubble stream detection	x	x														x
	x	Ecosystems studies	x					x		x							x	x
	x	Seabed acoustic imaging	x	x		x	x											
	x	Seabed sampling	x	x		x	x											x
	x	Seawater chemistry	x	x		x	x											
	x	Bubble stream chemistry																x
	x	Fluid geochemistry						x	x	x		x	x	x	x	x	x	
	x	Soil gas concentrations						x	x	x		x		x	x		x	
	x	Surface gas flux						x	x	x		x		x	x	x	x	
	x	IR diode lasers						x	x			x			x			x
	x	Eddy covariance							x			x			x			x
	x	Airborne spectral imaging													x			x
	x	Electric Spontaneous Potential																x
	x	Ground penetrating radar																x

*Table A1.1 Monitoring techniques deployed by storage site (at mid-2014) (after IEAGHG 2014). Whether the technique is deep or shallow focussed is indicated in the far left columns. Offshore sites are in the central columns (grey shading), onshore sites are in the columns to the right (brown shading). Techniques listed in green are exclusively onshore-based. Those in blue are only deployable in water (sea or lakes).*Others include deployments either onshore or offshore at non-listed CCS sites (e.g. Pembina Cardium, Aquistore), CCS analogue sites (e.g. hydrocarbon fields) experimental test sites (e.g. ZERT, USA) or natural analogue site (e.g. Latera, Italy).*

For onshore monitoring, the top of the water-table is a key surface. CO_2 emitted into the vadose-zone at the top of the water-table, is denser than air and so will no longer rise buoyantly but rather spread laterally. Depending on the depth of the water-table, this could mean that a leakage pathway even in the shallow subsurface might be displaced laterally from any consequent emissions at the surface. In addition, variable hydrostatic heads onshore commonly lead to major lateral and artesian water flow. Offshore, particularly away from the coast, lateral hydrological gradients are small due to the lack of hydrostatic head and lateral water flow in the shallow subsurface will generally be small. An exception to this is where hydrocarbon production has produced large subsurface pressure transients.

Seasonal and diurnal variations are much more extreme onshore, with significant displacements of the physical interfaces (e.g. water-table) and radical variations of the chemical and biological regimes due to both natural processes and also human activity.

Finally, in terms of public utility, the protection of onshore freshwater aquifers is of paramount importance but this is not the case offshore where aquifers are generally saline.

A1.1 Deep-focussed monitoring

Onshore deep-focussed monitoring for CO_2 storage has been deployed at a number of sites worldwide (Table A1.1) mostly at a pilot-scale (Cook et al., 2013). Onshore pilot research sites injecting upwards of several thousand tonnes of CO_2 from which results are publicly accessible (at mid-2014), include Frio, Cranfield, Decatur and Citronelle (USA), Otway (Australia), Ketzin (Germany), Nagaoka (Japan) and the commercial pilot at Lacq-Rousse (France). A number of larger onshore research storage projects have also been carried out, piggy-backing on to full-scale commercial projects, and principally associated with enhanced oil recovery (EOR). These include Weyburn and the more recent Aquistore project, also in Canada. Weyburn was linked to an extensive long-term CCS-oriented monitoring research programme and the same is likely to be the case with Aquistore. In Salah in Algeria is a large-scale onshore pure storage project, which has injected almost 4 Mt of CO_2. Monitoring activities at all of the above (including the storage monitoring elements of the EOR projects) are principally research-oriented, aiming to test a wide range of potential and novel monitoring technologies, rather than more pragmatically oriented commercial operations.

Two commercial onshore full-scale CO_2 storage projects are expected to commence in the near future: Shell's QUEST project in Canada and Chevron's Gorgon project in Australia. Both of these projects have comprehensive, purpose-designed monitoring programmes.

The key differences between offshore and onshore deep focussed monitoring are outlined in this chapter where we briefly touch on some of the issues that impact on monitoring practice and efficacy.

A1.1.1 Surface seismic methods

Surface seismic methods are mature and proven technologies in both onshore and offshore settings with commercially-driven technical improvements and developments continuously ongoing.

Time-lapse performance

In terms of monitoring for CO_2 storage, where time-lapse performance is paramount, offshore seismic is generally superior. The main issues for onshore acquisition are seasonal and weather-related variations in water-table and other shallow processes which adversely affect repeatability. More generically, localised variations in source / receiver coupling that compromise repeat accuracy are much more significant onshore than offshore. It is clear that a number of pilot-scale tests such as at Otway (Urosevic et al., 2010), Nagaoka and more recently Cranfield have had difficulty in imaging even quite substantial amounts (tens of kt) of stored CO_2 and this is, at least in part, a consequence of indifferent repeatability. Other onshore sites such as Ketzin have successfully imaged quite small amounts of CO_2 (~ 24 kt at Ketzin), with repeat surveys showing sufficient fidelity to enable some quantitative analysis (Ivanova et al., 2012). Seismic monitoring at the larger Weyburn CO_2-EOR site has been notably successful, with satisfactory repeatability and imaging / quantification of CO_2 in the reservoir (Hitchon, 2012). In addition, as with the offshore, onshore surface seismics do have potential utility in terms of containment monitoring, by providing early warning of migration into the overburden. A good example of this is the robust quantitative analysis at Weyburn (White et al. 2014), where maximum amounts of migrated CO_2 in the overburden were constrained.

Subsurface coverage

In general terms, offshore seismics tend to have the more uniform subsurface coverage which benefits the interpretation and analysis of geological attributes and subtle fluid saturation changes. This is because commonly occurring onshore surface features, particularly man-made infrastructure, prevents uniform deployment of source and receiver arrays. There are issues offshore as well, notably around platforms which have a wide exclusion area. Seismic streamers are particularly affected by platforms, and undershooting is expensive, requiring two ships. Seabed arrays can reduce these problems significantly.

A positive aspect of onshore acquisition is the fact that the typical 3D survey configuration with spatial arrays of sources and receivers is intrinsically well-suited to multi-azimuth acquisition which is useful for the analysis of mechanical or structural anisotropy and changes indicative of fluid flow or (incipient) fracturing. Offshore, streamer seismics are not good for azimuthal analysis due to the limited azimuthal range in source-receiver ray-paths. This limitation can be solved by deployment of sea-bottom arrays but even with these it is costly to develop very high density, wide areas of subsurface coverage.

Relative environmental impacts are difficult to gauge. Onshore there is the issue of (generally) temporary damage to agricultural infrastructure (fields, crops etc), whereas offshore it is believed that surveys can cause harm to wildlife such as whales and dolphins.

In terms of cost, surface seismic methods are expensive in all settings, onshore and offshore. As with offshore, 2D onshore lines offer low cost alternatives but with technical shortcomings, particular in terms of robust spatial coverage and repeatability.

Multi-component systems

Multi-component seismic systems which record the full signature of both compressive and shear components of the wave-field can provide important additional information for characterising changes in the subsurface, both in terms of fluid and pressure distributions and of the rock mass itself. For example shear-wave splitting (Angerer et al., 2003) can provide insights into geomechanical anisotropy and how this might change with time (such as by fracture opening) as reservoir or overburden pressures change.

Onshore settings are well-suited to multicomponent studies, and sophisticated shear-wave sources can be deployed to provide the potential for full 9-component data analysis. At the Delhi CO_2-EOR field in Louisiana, multicomponent surveys have proved to be effective in measuring fluid, pressure and geomechanical changes in both reservoir and overburden (Bishop and Davis, 2014).

The offshore is not so suited, the prime drawback being the impossibility of transmitting shear-waves through the water column. The technique therefore relies on p and s-wave conversions at the seabed to produce the necessary source.

The extent to which multi-component data will be utilised offshore in future is uncertain. Data processing is complex and it might well be the case that more conventional configurations, (particularly if multi-azimuth data is available via ocean-bottom arrays) will prove to be sufficient.

A1.1.2 Surface potential-field methods

Compared to offshore, the cost of surface potential-field methods will generally be much lower in terms of mobilisation, but onshore deployment will require significant personnel-time (to lay out the equipment at each site compared to the towed set-up offshore). Access directly to the land surface also allows easier equipment placement, for example, of concrete gravity benchmarks. In suitable locations, sources and receivers can be left in place for long time periods and operated at lower power which should improve the signal-to-noise ratio and data quality potential, despite the higher background noise levels expected onshore. However, land-access for the equipment can be problematic and so source receiver layout configuration might be limited e.g. by access to public roads, whereas offshore there is likely to be less infrastructure or background noise-generating activity to hinder survey deployment – these were the findings from land-based controlled-source electromagnetic (CSEM) and electrical resistance tomography (ERT) deployments at Ketzin (Streich et al., 2011; Schmidt-Hattenberger et al., 2013). For the ERT, a mixture of surface, downhole and surface-downhole deployments were integrated with seismic results.

Although at Sleipner seabed gravimetry has been deployed with an acceptable degree of repeatability, surface gravimetry has not yet been tested onshore. In principle onshore gravity should be less logistically complex and much cheaper than offshore, but it may not have been deployed to date because the relatively low sensitivity of the technique only lends itself to larger scale storage sites, where CO_2 is displacing a fluid of differing density (i.e. time-lapse gravity at Weyburn would be difficult given its complex field history and EOR remit). A research-based deployment of a high precision continuous passive gravity monitoring is being tested at an onshore site in Utah, USA, although the technique is very much still in development and it is not known whether its offshore deployment would be possible or practicable (Sugihara et al., 2013).

A1.1.3 Surface displacement methods

At In Salah, the surface of the site is rocky desert, which has a high coherence suitable for satellite interferometry (InSAR) monitoring. Analysis of the data through time shows clear growth of spatially delineated uplift of an area overlying the injection reservoir (at rates of around 5 mm/year), even though the reservoir is relatively deep at ~1900 m (e.g. Onuma and Ohkawa, 2009; Tamburini et al., 2010). Considerable research effort has gone into combining the InSAR results with data from other monitoring technologies to produce coherent geomechanical models and inversions to explain the observed uplift patterns and the injected CO_2 plume development. The breadth of these are summarised in Ringrose et al. (2013). Obviously this method is not applicable across a wide subsea area, but similar methods involving sea bed displacement measurements were considered at Goldeneye and deployment of a single platform-mounted differential GPS is planned (Section 3.7.3). Networks of tilt-meters have been deployed at In Salah and at some onshore enhanced coal-bed methane recovery - CO_2 storage pilot sites in the USA (e.g. Litynski et al., 2013; Wilson et al., 2012). However their frequent requirement for recalibration does not lend them to offshore deployment at present.

A1.1.4 Downhole and cross-hole methods

The additional costs of drilling combined with the entailed storage integrity risks of additional caprock penetrations, means that dedicated offshore monitoring wells are likely to be limited, so in general downhole methods have been less commonly used offshore to date. Onshore, downhole tools have been frequently deployed via dedicated monitoring wells or using access to production wells (e.g. at Cranfield). Most downhole techniques would work in an identical way offshore and onshore (geophysical saturation logging, for example), but offshore survey repeat frequency might be reduced as a result of the higher mobilisation costs. This increased-costs-but-same-benefit trade-off offshore may affect the choice of many systems and those that allow remote operation or little personnel intervention will no doubt be preferred. For example, permanently mounted downhole sampling techniques, such as u-tubes are often deployed onshore. These permit high frequency temporal sampling, but require significant personnel input. This is generally not a problem onshore, but can be a significant drawback offshore, particular if injection is via an unmanned platform (such as proposed for the Goldeneye project), or via a subsea completion such as at Snøhvit. Offshore therefore much less frequent downhole fluid sampling by wireline might be preferred. Many downhole sensors are also deployed onshore in a research capacity. These often have limited lifespan, require frequent recalibration (e.g. tiltmeters) and may have patchy reliability (e.g. failure of downhole microseismic sensors occurred at Otway) and so many may not yet be suitable for offshore deployment, given the high costs of equipment retrieval and replacement.

Downhole pressure and temperature monitoring has been deployed at most sites to date with the notable exception of Sleipner. Offshore these are mainly deployed as commercially available gauges, but onshore much research has gone into instrumenting wellbores using other methods for example along-casing fibre-optic based systems, capable of multi-depth, distributed temperature sensing (DTS), deployed at Ketzin and some USA-based sites. The DTS system has also been tested in conjunction with a heating cable, to infer CO_2 saturations from the thermal decay signal after heating, known as distributed thermal perturbation sensing (DTPS) (Freifeld et al., 2009). At Cranfield, monitoring pressure transients (changes in pressure with time) in the reservoir and zones above it has been used to determine sensitivities (distances and flux rates) to detecting potential wellbore leakage (Meckel et al., 2013).

Other offshore downhole deployments planned include microseismic monitoring (Section 3.4). These have been used successfully at a few onshore sites, notably at Lacq-Rouse, where it comprised the principal containment monitoring tool (Maisons and Payre, 2014), at In Salah where, although it was only deployed late in the injection phase, it was able to provide useful insights into the location of microseismic events with respect to the reservoir downhole (Öye et al., 2013; Verdun et al., 2013) and at Weyburn (Verdun et al., 2013). The cost of drilling and instrumenting dedicated microseismic boreholes and the logistics of storing and transmitting large amounts of digital data maybe what has precluded microseismics offshore to date.

So far, vertical seismic profiles (VSP) (Section 3.3.1) have not been deployed offshore, although they are now fairly routinely deployed onshore. The technique has shown potential utility in terms of both conformance and containment monitoring by detecting changes around the wellbore, in both reservoir and overburden at suitable sites. 3D VSP such as deployed at Ketzin is particularly useful in this respect. At Citronelle, VSPs using conventional downhole geophones were compared to those using a shorter semi-permanent array of geophones and fibre-optic distributed acoustic sensors (DAS), both in development and deployed as part of a modular borehole monitoring system that included DTS, DTPS, DAS and u-tubes (Daley et al., 2013). The shorter semi-permanent array, although giving a narrower aperture survey, was still considered sufficient to be able to see changes in response due to CO_2 injection (Koperna et al., 2014). The DAS did not have sufficient signal-to-noise ratio to allow observations as deep as the reservoir level at Citronelle (Daley et al., 2013a), but subsequent surveys (e.g. at Ketzin and Otway) have shown significant promise and improvement over the semi-permanent short geophone array (Daley et al., 2013b). It is however notable that at Weyburn, the VSP surveys were not considered to be sufficiently useful to merit further repeats (Hitchon, 2012), and the general difficulty in interpreting them in a robust geological way is a definite limitation.

Cross-well tools (seismic, resistivity and electromagnetic methods) have been deployed at several onshore sites. However, these methods require proximity of wells (much less than 1 km spacing onshore) and as discussed above, well spacings offshore will generally be more than this, monitoring wells will be at a premium, and so the infrastructure requirements for cross-hole techniques will rarely be met. Cross-well seismic has been deployed at numerous onshore sites including its novel variants such as continuous source travel-time tomography (Daley et al., 2007). They have shown utility as a conformance tool by providing high resolution velocity imaging on 2D sections between wellbores (Daley, et al., 2011 and Onishi et al., 2009). However, the sensitivity and resolution limitations of the cross-well resistivity (ERT) and electromagnetic (EM) onshore deployments suggest that they are not sufficient for containment monitoring and it is not clear to what extent they add additional useful information in terms of conformance monitoring.

A1.2 Shallow-focussed monitoring

Shallow-focussed monitoring has been deployed at many of the existing CO_2 storage sites mentioned above. However, because CO_2 is contained at depth, opportunities to test the ability of surface or shallow focussed monitoring to detect and quantify leakage are rare. Onshore shallow monitoring methods have therefore been tested, as offshore, at both natural analogue sites, where CO_2 is naturally emitted at the surface, and at specifically designed onshore experimental test injection sites. Notably, only one offshore test injection site exists to date (the QICS site described in the main text) compared to at least eight onshore test sites.

Monitoring (and environmental impacts) tools have been tested at numerous onshore sites of natural CO_2 seepage, including Latera in Italy (Bateson et al., 2008; Beaubien et al., 2008; Lombardi et al., 2008), Laacher See in Germany (Gal et al., 2011; Govindan et al., 2013; Krüger et al., 2011), Sainte Marguerite in France (Battani et al., 2010; Gal et al., 2012) and near Florina in Greece (D'Alessandro et al., 2011; Ziogou et al., 2013). Although sometimes termed 'natural analogues' the majority of such sites are better regarded as natural laboratories in which to study CO_2 leakage, rather than true storage site analogues, as most of them occur in volcanic areas or settings not suitable for storage.

Onshore experimental injection facilities have been established in a small number of countries and include the ZERT site in Montana and aquifer injection tests in Mississippi and Texas, USA (Spangler et al., 2010; Trautz et al., 2012; Yang et al., 2013), the Ginninderra site in Australia (Kuske et al., 2013), a shallow aquifer test in Denmark (Cahill and Jakobsen), the CO_2 Field Lab and Grimsrud Farm sites in Norway (Dillen et al., 2009; Moni and Rasse, 2014) and the ASGARD site in the UK (Smith et al., 2005). The latter two were established primarily to assess the environmental impacts of CO_2 whilst the other sites were designed mainly to assess monitoring techniques, although there is some overlap between these objectives. The Mississippi site injected at about 50 m depth, the CO_2 Field Lab at 20 m, the Danish site at 10 m, whilst the other sites all released CO_2 at a depth of 2 m or less. These sites have also been developed to improve our understanding of CO_2 behaviour in the near surface and to test appropriate monitoring technologies for leakage detection and quantification.

Shallow monitoring techniques used onshore, such as those sampling the vadose zone or the atmosphere, have little relevance for offshore monitoring. A few studies of CO_2 seepage in onshore lakes exist and the methods used in these cases (Section 4.1.5), since they are subaqueous, are more directly transferrable offshore. Some of the findings from onshore experiments and natural analogues are relevant to monitoring strategies both onshore and offshore.

A1.2.1 Styles of shallow or surface leakage, fluxes and areal extents

The physical size and flux rates associated with onshore seepage seem to be similar to the much smaller number of observations made offshore. The physical scale of onshore and offshore storage, and hence the surface or seabed areas needing to be monitored, are also broadly the same.

At all the onshore experimental sites the dispersion of the CO_2 at the surface appears to have occurred primarily from discrete localised seepage sites, with relatively high flux rates (e.g. Jones et al., 2014; Lewicki et al., 2010), rather than from more widespread diffuse emissions at relatively low rates. Heterogeneities in unconsolidated sediments appear to restrict fluid flow to the most permeable pathways giving rise to irregular and unpredictable patterns of seepage. These seeps are typically a few metres to tens of metres wide and very similar to natural non-volcanic CO_2 seepage sites (e.g. Annunziatellis et al., 2008). The natural occurrences can range up to a few hundred metres in size but this probably reflects the larger amounts of the gas escaping, especially in volcanic areas. This pattern of leakage from a number of small separate seeps is also true of natural sites offshore (Caliro et al., 2004; Italiano and Nuccio, 1991) and the one offshore injection experiment undertaken for the QICS project off the west coast of Scotland (Blackford and Kita, 2013).

Gas flow in shallow sediments during the QICS experiment was complex, with lateral spreading followed by the establishment of vertical chimneys observed in sub-surface layers due to a combination of fracture propagation and capillary invasion/fluidisation. Gas plumes, sometimes transient, at the sea floor were spread over an area of approximately 150 m^2 and generally separated by a metre or so.

There is limited evidence for some seepage of injected CO_2 from onshore experimental sites at flux rates within the range of natural background CO_2 emissions (Jones et al., in press; Moni and Rasse, 2014). This comes from monitoring of the isotopic signatures of the escaping CO_2. Some studies of natural CO_2 sites also implicitly assume that low-level seepage occurs over wide areas (e.g. Chiodini et al., 2007). However, others consider the bulk of the gas is released from small discrete seepage areas with higher CO_2 flux (e.g. Annunziatellis et al., 2008). If low-level seepage did prove to be widespread then the total emissions could be significant. This would also have serious implications for monitoring as much more sensitive detection techniques would be required.

There are differences in the way the seepage manifests itself onshore and offshore. The most obvious feature onshore is a change in the vegetation at high CO_2 concentrations, with commonly an area of bare earth in the centre of the seep surrounded by zones where the relative proportions of plants are affected by the CO_2 and indicator species, tolerant of high CO_2 can be the only species present, whilst grasses appear to be able to cope better than many broad-leaved species at intermediate concentrations (Beaubien et al., 2008; Krüger et al., 2011; Vodnik et al., 2006; Ziogou et al., 2013). While there can be changes in plant growth near offshore seeps, for example in sea grass, the response may not be simple (Apostolaki et al., 2014).

A1.2.2 Utility of sensors and combinations

Whilst the general strategies and principles of near surface monitoring may be similar onshore and offshore the specific techniques used are rather different except in the case of onshore monitoring in fresh water bodies such as lakes. Thus rapid wide area monitoring onshore has so far involved atmospheric gas measurements using land vehicle mounted instruments (Jones et al., 2009); airborne methods (de Vries and Bernardo, 2011; Neumann et al., 2013); fixed sensor networks such as atmospheric tomography (Kuske et al., 2013) or eddy covariance methods if winds and site layout are favourable (Lewicki et al., 2012); or remote sensing methods to investigate the effects of CO_2 on plant stress (Bateson et al., 2008; Govindan et al., 2011). Onshore large area detection methods still very much have room for development, but where they are successful at detecting anomalies, these can be targeted by ground truthing (such as by soil gas measurements). Such remote sensing options are not possible offshore, but equivalents might comprise ship-mounted multibeam surveys to detect bubbles or changes in seabed topography for example pockmarks or fractures, or other acoustic techniques such as continuous acoustic tomography. Hierarchical approaches are also appropriate offshore, whereby any features of interest or anomalies can be returned to and examined in more detail e.g. using ROV-mounted video or acoustic surveys, pCO_2 and water chemistry surveys followed by sediment cores. With all of these remote assessments, in order to arrive at CO_2 fluxes, the gas composition (i.e. the proportion of CO_2) needs to also be established.

Shallow subsurface sampling methods have also been applied at onshore experimental injection sites and areas of natural CO_2 seepage. Whilst gas sampling for analysis onshore most commonly entails soil gas methods in the vadose zone, it remains possible offshore albeit more difficult and maybe involving divers, sealed samples or the use of ROVs. Once collected, similar laboratory techniques can be applied to the analysis of different gas species including any tracers injected with the CO_2. Field measurement of gases is also possible but again more logistically challenging offshore.

Aquifer studies (Auken et al., 2014; Barrio et al., 2014; Cahill and Jakobsen, 2013; Dafflon et al., 2012; Trautz et al., 2012) have used a mix of geochemical and geophysical measurements onshore, where emphasis has been on potential impacts of CO_2 on drinking waters. This is not such a significant issue offshore.

A1.2.3 Baselines onshore versus offshore

There have been a number of onshore baseline studies for projects ranging from small injection experiments through to full industrial scale storage sites. These include time series measurements of soil gas and flux repeated over intervals ranging up to several years (e.g. Beaubien et al., 2013) and continuous measurements over a similar range of time periods (e.g. Schlömer et al., 2013; Schlömer et al., 2014). The former provide spatial variability whilst the latter show temporal changes.

Whilst onshore and offshore systems are quite different in respect of CO_2 baselines there are aspects that are common to both, such that it is worth considering the lessons learnt onshore at least briefly. Onshore experience shows the importance of processes affecting baseline values over a wide range of timescales, from diurnal, through a few days or weeks to seasonal and year-on-year (e.g. Beaubien et al., 2013; Jones et al., 2014; Klusman, 2011; Schlömer et al., 2014). These come about because of the normal day/night cycle, specific short-lived weather events, such as the passage of a frontal system, longer term seasonal variations and climatic fluctuations from year to year, such as protracted dry or wet periods.

Baseline monitoring offshore is also subject to changes over similar timescales due to similar influences and additional specific factors such as tidal effects. Monitoring of CO_2 leakage or emissions, whether directly or indirectly (e.g. through pH measurements) needs to take account of the natural variability both spatially and temporally. This has been achieved onshore by repeated surveys in different seasons/years and by the deployment of continuous monitoring. The surveys can be used to identify appropriate sites for continuous monitoring such that they cover a representative range of CO_2 concentrations and fluxes. Such an approach would be equally applicable offshore.

Onshore studies have suggested that baseline measurements might need to be collected for at least three years prior to injection (Schlömer et al., 2013). The value of background (or reference) sites, with similar characteristics to the storage site, but sufficiently removed from it to be unaffected by any leakage, has also been shown - a background site was useful in refuting leakage allegations at Weyburn (Beaubien et al., 2013). The RISCS project (RISCS, 2014) concluded that: 'Carefully selected reference sites, both onshore and offshore, could be a powerful tool for providing ongoing baseline data against which storage sites can be compared. They would allow changes related to factors other than CO_2 leakage to be assessed. Sites managed via joint industry initiatives may be a suitable approach to enable a smaller number of reference sites to be developed for use by several storage projects.

Long term continuous monitoring has shown that careful site selection and measurement depth can minimise the variability (through reduced atmospheric and biological influences) and increase the potential to detect seepage (Klusman, 2011; Schlömer et al., 2014). Similar principles could be applied offshore although clearly the influences would be different.

Onshore studies have also demonstrated the importance of measuring additional parameters, such as soil moisture, temperature and atmospheric data, to help interpret the CO_2 data (Schlömer et al., 2014) or the use of gas ratios (e.g. CO_2 to O_2 and N_2) to assess the origin of the gas (Beaubien et al., 2013; Romanak et al., 2012). Such approaches have also been recognised to be relevant offshore (RISCS, 2014) with appropriate modification.

The natural variability of CO_2 seasonally has been used, with other considerations, to select the optimum time to carry out soil gas and flux surveys. Klusman has argued for winter measurements when biological activity is lowest (e.g. Klusman, 2003, 2006) whereas late autumn was found to be more practical at Weyburn (Beaubien et al., 2013) because of severe winter conditions and the trapping of CO_2 under frozen surface layers. Seasonal variability and other weather or climate related constraints on operations also apply offshore and should be taken into account during survey design.

APPENDIX 2: R&D priorities for offshore monitoring

A2.1 Introduction

CO_2 storage monitoring is a hugely interdisciplinary topic, still in its infancy, but the techniques and methodologies which it uses range from mature tools developed over decades by the hydrocarbons industry to innovative prototype technologies developed for environmental surveying. R&D priorities therefore cover a wide range of technical and scientific areas where further technical or methodological improvements might pay rich dividends. Priorities can be broken-down into deep-focussed, shallow-focussed and more generic areas.

A2.1.1 Deep-focussed R&D needs (no priority order)

1. Technologies for detecting / measuring dissolved CO_2 in the subsurface.
2. Robust methods for quantifying rates of migration (leakage) out of the storage complex
3. Establishing detection thresholds for all quantitative monitoring methodologies.
4. Monitoring of well integrity of inaccessible abandoned wells.
5. Monitoring pressure at significant distance from the injection and monitoring wells.
6. Reliable downhole fluid measurements systems (pH and dissolved CO_2) providing capability for long-term continuous monitoring, or full pressurised recovery systems.
7. Longevity of downhole sensors.
8. Incremental improvement of tool sensitivity and resolution.

A2.1.2 Shallow-focussed R&D needs (no priority order)

1. Robust quantification of seabed emissions, particularly by remote (acoustic) methods.
2. Data on variations in natural background flux and concentration measurements of CO_2 and other gases at the seabed and in the water column – the baseline issue.
3. Integrated point-wise and spatial sampling strategies for shallow monitoring systems (where, when, how much, and linked to the deep monitoring strategy).
4. Detection of emissions precursor fluids (e.g. subsurface brines).

A2.1.3 Generic R&D needs (no priority order)

1. Improved real-time data transfer from remote localities.
2. Lack of integration of different complementary methods (joint interpretation, joint inversion).
3. Model-based interpretation and analysis of monitoring data.
4. Need to optimise monitoring methodologies on full-scale storage projects.

A2.2 Deep-focussed

Deep-focussed monitoring overwhelmingly relies on established hydrocarbon industry tools (seismics, downhole logging etc) which are very mature. Improvements are ongoing, but are rather *ad hoc* and incremental and driven by the industry rather than CCS.

A2.2.1 Seismic methods

Time-lapse repeatability

A key issue for the seismic methods is time-lapse repeatability. Streamer improvements in terms of spatial positioning are very important in this respect. Conversely it also seems likely that the development of improved permanent or semi-permanent seabed recording systems will become increasingly significant. It has been argued that improved repeatability brings the possibility of acquiring sparser datasets with fewer shots and / or receivers - the higher repeatability making up for the loss of coverage. If this is the case then it would lower both costs and environmental impacts.

Overburden imaging and characterisation

Improving seismic methods to better image and characterise the overburden for leakage detection and quantification is also required. Recent work in the CO2CARE project has developed a spectral spatial reflectivity tool to statistically discriminate between noise and real signal due to CO_2. Mechanical characterisation of 3D rock volumes is also a focus for research using multi-azimuth, multi-component and passive seismic techniques. Low-cost monitoring systems such as seismic interferometry using both passive and active sources are being tested in a variety of settings but are far from proven.

Other R&D priorities for seismics include:

- Better understanding of how seismics can discriminate between changes in pressure and saturation.
- Improvements in hardware (spatial positioning, data transmission, sensitivity, sensors, real-time recording, improved seismic sources, sensor reliability in passive mode).
- Improvements in data processing and analysis (improved imaging, visualisation, integrated interpretation, and joint inversion).
- Improved shallow imaging (e.g. by further development of the P-Cable system).
- Robust communication systems for permanent systems (so the data are available in real time).
- Continued improvement in the emerging area of fibre-optics

A2.2.2 Other methods

Seabottom gravimetry is perhaps the most promising of the alternative geophysical methods and again seems to be in a process of incremental improvements through small gains, both technical and methodological. Multiple deployments at Sleipner for example, have seen significant improvements in repeatability. Downhole gravimetry tools have also been tested in recent times, but it is not yet clear what benefits they offer over more conventional downhole tools.

Downhole logging technologies are very mature in the hydrocarbons environment, but more specific experience with CO_2 storage monitoring is required – for example in the use of fluid saturation logging. Well integrity is a key issue for CCS and improved wellbore monitoring tools would be desirable. Downhole fluid sampling technology is relatively poorly-developed. Wireline sampling is well established but time-lapse sampling is expensive. More sophisticated 'in situ' high frequency sampling systems such as the u-tube are not proven for offshore applications, moreover it is not clear to what extent these would be required.

A2.3 Shallow-focussed

Shallow-focussed monitoring for leakage detection is much less mature than deep-focussed and development has much weaker industry drivers. Because of this there is more opportunity for significant R&D. Aspects of shallow focussed monitoring are being developed as part of a current UK project funded by the Energy Technologies Institute (ETI) as outlined in more detail below.

A2.3.1 Operational requirements - vehicles and communications

The use of AUV technology is expanding rapidly, driven by commercial, military and research requirements. Current technology is limited to either larger AUVs (capable of carrying a large range of sensor packages, but requiring a relatively large vessel and onboard infrastructure for deployment and recovery, or smaller vehicles (with limited capability but easier to deploy). Most of the cost of deploying the larger systems is associated with the vessels to launch and recover the vehicles. Longer range vehicles are being developed that could be launched from a coastal location and which are capable of spending long periods of time without vessel support, recent developments providing a range of more than 6000 km and an endurance of 6 months.

Deploying AUVs for long periods necessitates a system to communicate with the 'base', for two reasons; the need to know where the vessel is and the desire to be able to collect and interpret the data the vehicle is collecting. A research project in the UK is directly addressing these issues in relation to AUV application for CCS reservoir monitoring. The goal is to develop a surface vehicle that can communicate with an AUV working at depth and relay the data back to the land via satellite communications systems. This will allow the course of the AUV to be corrected if the vehicle has deviated from its planned route, or the planned survey can be changed if data from sensors onboard the AUV indicate leakage.

New developments in AUV and sensing technologies offer potential for improved monitoring flexibility. For example a seabed docking and recharging station for an AUV has recently been tested. Further development of these systems will increase the operational survey times for AUVs and also allow the use of more power-hungry monitoring systems.

Trawler proofing and biofouling

The long range AUV technology in development is useful for wide-area surveys of the seabed at a height of some 3 m or more above the bed surface and provides a snapshot of the conditions at the time of data collection. Leakage of CO_2 from a reservoir may be episodic, and dissolved CO_2 may hug the seabed due to a lack of buoyancy, and hence could be missed by an AUV survey. The deployment of landers equipped with suites of sensors (Appendix A2.2.2), can help address this data gap. Problems around such long-term deployments include the damage that trawling and other marine anthropogenic activities can cause; the effects of biofouling on the sensors and the accessibility to data. Low-profile turtle shell type landers have been deployed in the North Sea and other areas and have collected data over periods of up to a year. These low profile landers can resist trawling to a certain level but a direct hit by the trawl door will almost certainly result in damage. Biofouling is a constant problem in the marine environment; existing approaches to biofouling are generally around the use of toxic compounds such as copper and the Tributyltin (TBT) compounds, or the *in situ* generation of chemicals from seawater.

A2.3.2 Sensors

Low cost fixed continuous monitoring systems.

Leakage detection cannot be done without a clear understanding of natural long-term temporal variability. The development of *in situ* sensors is ongoing, with the goal of delivering cheap, low powered sensors for long-term deployment. Existing infrastructure could be used as platforms for this new family of sensors, negating the need for trawl resistant landers. In areas where there is no existing infrastructures stand-alone landers as discussed earlier can be used. Sensors must be robust and capable of producing accurate and precise data, so advances are needed in remotely-deployable micro-fluidic based systems to carry on-board standards, blanks and reference materials. Solid-state optode-based systems can be calibrated in test tanks before deployment and checked again post-deployment, and corrected for any drift over time. Whilst the formers' use of reagents limits the time it can be deployed, the micro-fluidic aspect of the sensors means such reagent use is minimal. Although solid-state systems are less stable, they can be used for shorter periods with more rapid replacement/recalibration.

The development of *in situ* sensors (for all applications) is extremely costly, with an investment of many man-years to bring a sensor from the bench top to a truly effective instrument. Research councils such as NERC and the EC have funded a number of sensor development projects over the last 5 years and these are starting to deliver important advances. An integrated approach to the powering, communications and data management of the developed sensors is being pioneered by the active sharing of knowledge by the research groups engaged in this field, which combine academic groups with sensor development companies to enable commercialisation.

A2.3.3 Wide area monitoring

Research in wide area monitoring is directed towards developing low cost, large area coverage remote sensing systems to avoid spatial undersampling issues of point-wise surveys, and to reduce expensive sample collection and ship time.

The first challenge for monitoring is to cover large areas corresponding to the footprint of a storage site (typically tens to hundreds of km^2 for likely North Sea options) and also allow accurate measurement and characterisation, possibly for lengthy periods, at specific leakage risk points such as the injection well, abandoned wellbores etc. Initial monitoring will not be able to support a full suite of active, energy-hungry sensors, but need only concentrate on detecting anomalies with minimal false positives and false negatives. Once anomalies have been detected, further, more focussed techniques can be used to firstly confirm leakage, secondly attribute leakage, thirdly quantify leakage and finally assess impact. Current research is necessarily focussing on anomaly detection, mainly via passive acoustics (listening for bubbles) or chemical detection (pH). Techniques to address subsequent stages exist, but require development, testing and formalising into a hierarchical strategy. Confirmation and attribution will be facilitated by direct sampling, development of tracer techniques and active seismics can identify leakage pathways through the over burden. Quantification is likely to be challenging. Passive acoustics, tracers, reverse engineering of model simulations and direct capture of gas will all aid quantification, but research addressing the consistency of various methods is necessary and will likely require controlled release experiments. Impact assessment will require integration of detailed biological and biochemical surveys, although methodologies are largely established for these individually.

An area of promising research is the development of deep sea hyperspectral imaging systems. These can be configured to do wide aerial surveys of biological communities, geological features and man-made structures (including coral reefs, pipelines and seafloor substrates) for both baseline surveys and periodic monitoring.

A2.3.4 Emissions quantification

Quantification of bubble-streams

The determination of the CO_2 concentration in bubble-streams using acoustic bubble imaging and subsequent mathematical analysis is rapidly developing. More *in situ* ground-truthing experiments are required and there are a number of funded studies preparing to do this, such as the UK ETI-MMV project. The detection and quantification also needs to include a determination step, to analysis the gas in the bubbles to ensure it is CO_2.

Quantification of dissolved fluxes

It is not yet clear how large dissolved CO_2 fluxes might be relative to normal seabed emissions - there is a strong argument that any significant long-term offshore leak will saturate the pore-water in its pathway and soon be emitted at seabed as a gas. Nevertheless the quantification of any leaking CO_2 that is in the dissolved phase is challenging. The use of landers and benthic chambers has shown some promise but one of the main challenges is the suitability of sensors. Current off-the-shelf sensors for CO_2 and pH are only suitable for short-term deployment due to fouling and interference issues. Benthic chambers are generally deployed for short periods by ROV, which is expensive. Also there are issues around how representative they are of the virgin environment. The chambers effectively seal off a section of seabed from the normal environment and care must be taken with the interpretation of data for such a system. Leakage of dissolved CO_2 might be widely distributed and any use of chamber or lander based technology must be assessed with regard to this spatial inhomogeneity. Investment is needed to develop more sensitive, cheaper, fouling-resistant sensors for use in the benthic chambers to allow longer and more widespread chamber deployments.

A2.3.5 Baseline surveys & seabed emissions detection

Establishing a comprehensive baseline to enable leakage detection and quantification is essential, due to high natural variability in many of the observable properties. Baseline data will be used to determine 'normal, alert and react' thresholds for key parameters upon which corrective measures plans will be based. Unfortunately, even in well studied waters such as the North Sea there is a dearth of information with respect to near sea floor biochemistry, although model systems can provide some insights. As natural change has both spatial and temporal components which may be multi-scale (for example diurnal, seasonal and decadal scale cycles, metre scale patchiness and ~km scale sediment and depth variation), baseline studies need to reflect this heterogeneity. Models are able to extrapolate across wide areas, but require significant amounts of quality data to establish acceptable accuracy. Because biochemical baseline acquisition requires high frequency and fine scale data, operational techniques to achieve such comprehensive data sets require development (see above), however shorter term observations are currently tractable and useful data acquisition could be achieved in the short term, at limited cost, by piggy-backing on other sea-floor surveys. A regional (multi-national) programme to encourage, fund and collate such measurements would be highly beneficial. Acoustic (both passive and active) baselines are less susceptible to model augmentation and need to be targeted to specific storage areas. Impact baselines, primarily biological, must again have a site specific dimension, but could be supported by appropriate collation and analysis of the wealth of historical benthic focussed data available in well sampled regions such as the North Sea. The definition of 'reference environments' as proposed by the RISCS Guide to potential impacts of leakage from CO_2 storage (available from www.riscs-CO2.eu) would also help industry to compare evolution of a storage site with a reference environment.

A2.4 Supporting modelling tools

Models can be used to extrapolate baselines, investigate leakage scenarios and inform monitoring strategies and impact studies. Models may also provide strong supporting evidence towards quantification of leakage, in that the model replication of observed chemical changes in space and time can be linked to a particular leakage scenario. However whilst most components of the system are adequately modelled, there are challenges in coupling processes and dealing with the multitude of scales that need to be considered with respect to leakage. The challenge is twofold. First there is a need to develop coupled, or nested, model systems that can simulate leakage in the context of natural variability by combing both pelagic and benthic dispersion and chemistry, including carbonate and redox processes. Second there is a need to develop models that can simulate with dispersion scales appropriate to multi-phase plumes at the epicentre of leakage at the same time as simulating tidally-induced dispersion in the near- and far-field.

Whilst model systems tracking the dispersion and impact of CO_2 have been developed, comparatively little capability exists with respect to precursor fluids that may be associated with leakage. Model systems currently available are likely to be capable of adaptation to this purpose but quantification of the likely range of potential precursor fluid flux is required.

Appendix 3 (refer to Table 5.1, monitoring aims from the IEAGHG Monitoring Selection Tool)

Plume imaging

The ability to explicitly image the plume of free CO_2 in the subsurface is likely to be a pre-requisite for many monitoring programmes. In the early stages of CO_2 injection, plume imaging is likely to involve tracking/mapping free CO_2 in the primary storage reservoir using time-lapse seismic surveying. In the longer term, plume imaging may involve tracking CO_2 migration into strata adjacent to the storage reservoir, such as the overburden.

Reservoir topseal integrity

Close monitoring of the reservoir topseal for evidence of failure or leakage will be important, especially during the injection stage of a project. During this period, and for some time afterwards, reservoir pressures are likely to be significantly elevated immediately beneath the caprock. A maximum permissible (threshold) value is likely to have been determined during site characterisation, prior to injection. Evidence of reducing seal integrity or failure could be obtained from a number of monitoring techniques including direct detection or imaging of CO_2, pressure changes in the reservoir or overburden, or changes in aquifer chemistry.

Migration in the overburden (> 25 m depth)

The overburden comprises those rock units lying between the storage reservoir and the land surface (or seabed). The basal overburden unit comprises the reservoir caprock or topseal (for the purpose of the decision tool, monitoring the topmost 25 m or so of the overburden will be considered under surface leakage). Monitoring in the overburden is likely to be required if CO_2 has migrated from the storage reservoir. Many, though not all, of the techniques deployed for monitoring plume migration in the reservoir, would be equally suitable for monitoring migration in the overburden.

Quantification for regulatory and fiscal purposes

The mass of CO_2 that has been injected for storage can be readily monitored at the wellhead. However in some circumstances it may be necessary to provide supporting evidence, through geological monitoring, that the mass of CO_2 within the reservoir is equivalent or comparable to that injected and, within the bounds of uncertainty, that no losses have occurred.

Currently, accurate quantification of CO_2 in the subsurface poses a serious technical challenge. Current state-of-the-art analysis can show that quantitative estimates of CO_2 derived from monitoring datasets are consistent with known injected amounts, but unique verification has not yet been achieved. Deployment of multiple monitoring techniques providing complementary datasets, either in terms of measured property, or in terms of measurement scale, can significantly reduce uncertainty. In the event that leakage to the atmosphere or ocean has been positively identified, quantification may be required to account for these secondary emissions in national inventories, to adjust operator allowances and/or to initiate further financial transactions. Additional monitoring activities, remediation plans, regulator notification and licence conditions may also be affected by the quantified amount of CO_2 leakage.

Storage efficiency and fine-scale processes

Long-term storage potential is influenced by a number of factors that include plume migration, CO_2 solution in reservoir porewaters, structural and stratigraphical trapping and residual gas trapping in pore spaces. These processes are often influenced by fine-scale variations in reservoir geometry, lithology, pore architecture and porewater chemistry. In addition, key reservoir parameters such as seismic velocity are influenced by fine-scale processes such as fluid mixing scales. Specialised monitoring tools can be targeted on particular parts of the storage reservoir to help gain insights into these processes.

Calibration of predictive models

Predicting how the CO_2 will be stored over the long-term requires the integration of many geological processes in a predictive model. Such models require detailed site-specific geological knowledge of the reservoir, caprock and overburden. By acquiring monitoring data on key processes and their interactions during and after injection, outputs from the predictive models can tested and calibrated, enabling the models to be suitably modified or rejected. This will decrease uncertainty in long term model predictions.

Surface leakage (<25 m depth) & atmospheric detection and measurement

As well as defining storage performance, leakage to surface may also pose significant safety issues. Monitoring technologies to detect and/or measure surface leakage may well be routinely deployed prior to injection as part of the site baseline characterisation process. Repeat monitoring may be required to establish natural cycles in background variations. This will be especially relevant for onshore situations where diurnal, seasonal and annual variations in biogenic CO_2 may need to be characterised, so that any future leaks can be identified and compared to background variations. Additional atmospheric monitoring may be required around facilities and infrastructure during injection, if leaks are identified or suspected.

Seismicity and earth movements

In some cases CO_2 injection can lead to increased (micro) seismic activity and may in some circumstances, lead to ground movements, especially for shallower storage reservoirs. As well as covering safety aspects, microseismic monitoring can also enable advancing CO_2 fronts to be mapped in the subsurface. In favourable situations traveltime and attenuation tomography may allow fluid movements to be mapped.

Well integrity

The ability of wells to retain CO_2 during the injection, post-injection and post-closure phases, is an important issue in many storage situations. Geomechanical and, in the longer term, geochemical processes, can severely degrade well integrity. Mature hydrocarbon fields, especially onshore, are likely to contain significant numbers of wells of varying ages and styles of completion and abandonment. While new completion materials, such as Portland-free cements, will greatly enhance the stability of new wells, older wells may need closer monitoring.

Public confidence

Some monitoring regimes may be specifically designed to address site safety issues with regard to public opinion. Certain monitoring techniques have been identified that could be particularly helpful in raising public confidence, especially where storage is in a populated area. A suitable (site-specific) combination of these techniques can serve to provide clear evidence that the CO_2 storage site is safe. Many of the techniques will also provide data that will address other aims as well. Current demonstration and flagship projects contain a significant amount of monitoring for public confidence.