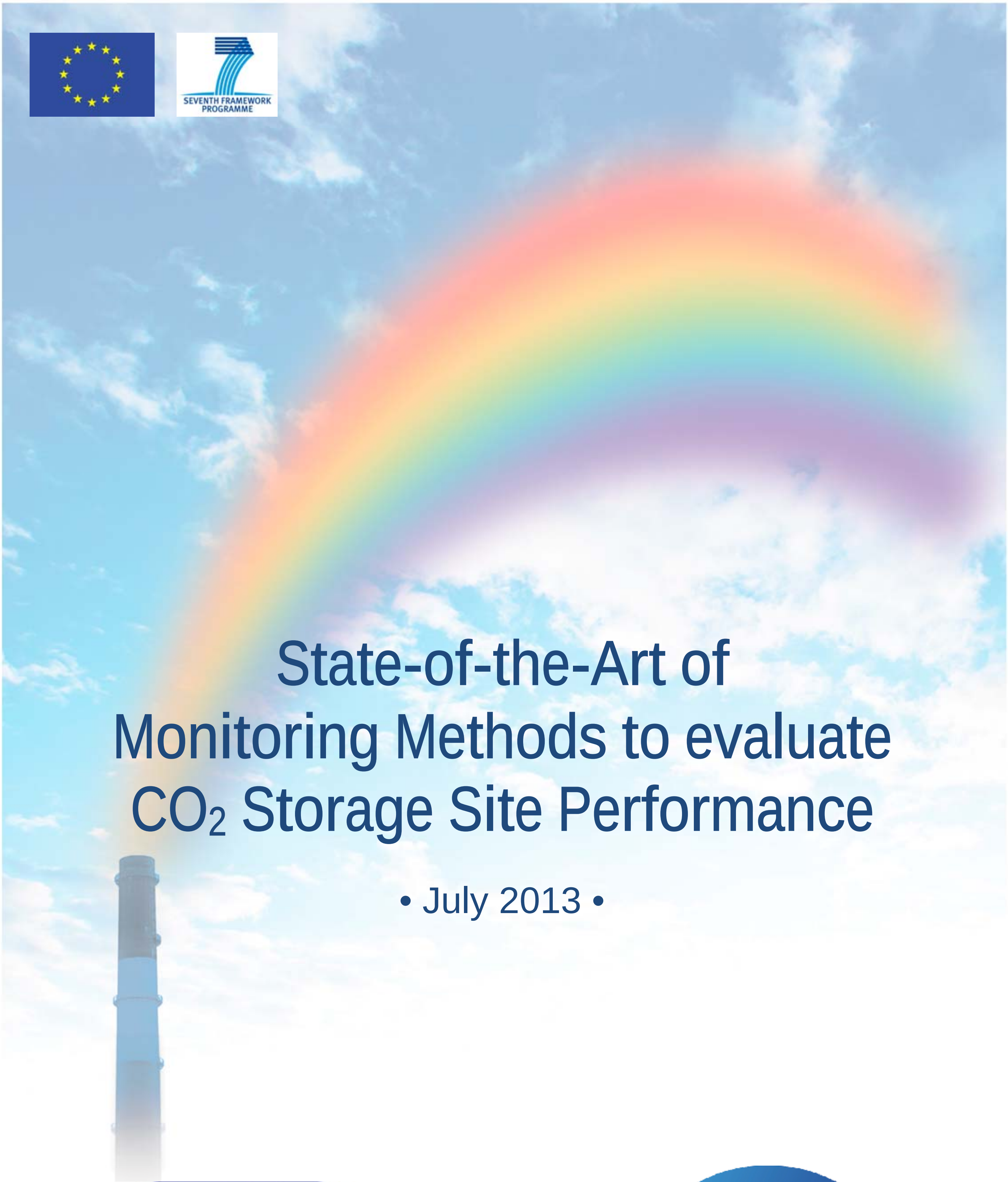

State-of-the-Art of Monitoring Methods to evaluate CO_2 Storage Site Performance

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CGS Europe
FP7 Pan-European Coordination Action on CO_2 Geological Storage

CO_2GeoNet
The European Network of Excellence on the Geological Storage of CO_2

CGS Europe Key Report

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PREFACE

This report is the result of a joint effort carried out by various members of the CGS Europe project (www.cgseurope.net) - the “Pan-European Coordination Action on CO_2 Geological Storage”, funded within the 7th framework programme of the EU. The report is based on current literature on monitoring of CO_2 geological storage sites and illustrated with exemplary monitoring plans proposed for two potential future CO_2 storage projects. It focuses on Europe and the EU CCS and Emission Trading Directives and closely follows their definitions and terminology.

The report is not a monograph, but rather an edited compendium of contributions from individual network partners. Hence, chapters and sections may vary in style and level of detail. The authors gratefully acknowledge the various CGS Europe partners who participated in reviewing the draft and the resulting fruitful discussions.

The report is public so that any interested party can readily make use of it. CGS Europe does not claim completeness, nor comprehensive consideration of all legal or regulatory requirements on monitoring in Europe. In particular, the monitoring plans that are set up in this report for two potential future storage sites should only be considered as examples for site-specific monitoring plans.

The authors hope that this report will provide concise and ultimately helpful information to various stakeholder groups including scientists, competent authorities, operators and regulators. The reader is expected to have some basic understanding of CO_2 geological storage and related monitoring technologies.

EXECUTIVE SUMMARY

The basic idea of the "Carbon dioxide Capture and Storage (CCS)" technology is to store CO_2 produced by fossil fuel combustion and industrial processes in the deep geological underground, rather than releasing it into the atmosphere. To have a beneficial effect on climate and to prevent interaction between the surplus CO_2 and the biosphere, the CO_2 needs to remain safely underground for a sufficiently long time, of the order of at least 10,000 years, although it is expected to remain contained for much longer time periods in properly selected reservoirs. To ensure and verify the safe geological containment of CO_2 underground, monitoring of CO_2 storage site performance is mandatory. This includes, among other things, monitoring the injection process, tracking the CO_2 plume migration in the reservoir and installing monitoring systems to give (early) warning in the case of CO_2 leakage, i.e. CO_2 leaving the storage complex. Not only do the impacts of the CO_2 itself need to be considered, but also potential associated impacts due to co-injected incidental substances ("impurities"), mobilised substances, displaced migrating saline formation water and pressure increase following CO_2 injection.

The main objective of this report is to identify and review monitoring methods for a performance assessment of geological CO_2 storage sites. This report discusses state-of-the-art monitoring techniques, introduces general concepts and gives recommendations for procedures to set up site-specific monitoring plans. This is complemented by an overview of monitoring applications employed at demo or pilot CO_2 storage sites or in field tests. There is a special focus on establishing site-specific monitoring plans, with two examples selected to represent the two major storage options in Europe and worldwide, namely saline aquifers (Romanian example) and depleted gas fields (Slovakian example). Finally, recommendations for future research and development activities are derived.

Monitoring - general considerations and definitions (Chapter 1)

The monitoring of CO_2 storage sites provides data on the state of and processes within the storage complex and the surrounding environment for the durable, safe, efficient and environmentally friendly management of storage operations. As such, monitoring must provide all the information needed for planning, performing and supervising actions in all stages of storage, during normal operations, incidents and after site closure. Thus, monitoring is laid out as a continuous task allowing basic target-performance comparisons (progress against plan) and it provides a basis for decision-making, e.g. on corrective measures, if the state of a process is not as foreseen.

Various monitoring purposes have to be integrated in monitoring concepts: i) health, safety and environmental (HSE) provisions, ii) injection management and site operation, iii) verification of CO_2 storage and quantification of CO_2 leakage according to the European Emission Trading Scheme (ETS, Directive 2003/87/EG) and iv) satisfying the public interest on environmental information, especially in the case of deviations from the predicted storage behaviour.

Site-specific monitoring plans include various levels of monitoring scale, intensity and precision and must be flexible to allow adaptations to the actually observed processes and migration of fluids in the subsurface. Different technologies need to be employed for surveying larger areas, for detecting unexpected leakage and for local, detailed observations of potential or actual leakage pathways in high resolution.

Risk-based monitoring, as required according to the EU CCS Directive (2009/31/EC), must pay special attention to potential pathways and subjects of protection. The main potential leakage pathways of concern are: spill points, fractures and faults, weak points or gaps in the cap rocks and (abandoned) wellbores. The prime subjects of protection are human life, health and safety; other protected subjects include climate, landscape, cultural heritage, quality of life and socio-economic stability, soils, groundwater, natural resources, surface water bodies, ambient air, flora and fauna (including farm animals, agricultural crops or forests). Apart from CO_2, associated incidental substances in the CO_2 stream, displaced formation fluids like saline brines or crude oil and substances released from rocks and soils can be a matter of concern and require appropriate monitoring.

A comprehensive monitoring concept is needed to integrate requirements by the different monitoring purposes and to address potential risks for various subjects of protection during the individual phases of a CO_2 storage project. Such a comprehensive monitoring concept is summarised in the overview table given below. This table may also be used to set up and check site-specific monitoring concepts for completeness.

Comprehensive, generic monitoring framework: Monitoring purposes with regard to different compartments and project phases (May *et al*., 2011). Symbols in brackets indicate the need of case-specific considerations.

Compartment \ Phase	Pre-Injection, Baseline	Operation		Post-Closure	
		normal	significant irregularities	before transfer of responsibility	after transfer of responsibility
Injection facilities, incl. wells		⚒ ⦸ 📄 ☺	⚒ ⦸ 📄 ☺	⦸ ☺	
Near-surface environment, incl. local communities and biosphere	⚒ ⦸ 📄 ☺	⚒ ⦸ ☺	⦸ 📄 ☺	⦸ ☺	⦸ ☺
Marine environment and/or	⚒ ⦸ ☺	⚒ ☺	⚒ ⦸ 📄 ☺	⦸	
Freshwater aquifers (potable water)	⦸ (📄) ☺	⦸ ☺	⦸ (📄) ☺	⦸	⦸
Hydraulic unit (area beyond storage complex)	⚒ ⦸	⚒ ⦸	⚒ ⦸ ☺	⦸	(⦸)
Storage complex: Overburden, incl. faults	⚒ ⦸	⚒ ⦸	⚒ ⦸ ☺	⦸	
Storage complex: Secondary containment formation	⚒	⚒	⚒ ⦸ ☺	⦸	(⦸)
Storage complex: Storage formation, incl. caprock	⚒	⚒ ☺	⚒ ⦸ ☺	⚒ ⦸	⦸

Monitoring purposes:

⚒ Storage operation
📄 Accounting for emission certification
⦸ Health, safety and environmental protection
☺ Communication with local communities

Monitoring techniques for different compartments (Chapter 2)

The report discusses various monitoring techniques and concepts in a practical context of monitoring specific compartments and/or processes, such as monitoring CO_2 plume migration in the storage reservoir or potential CO_2 leakage out of the storage complex. In addition to the storage reservoir itself, the considered compartments comprise the overburden (mechanical reaction of overburden, surface uplift, induced seismicity and faults), abandoned wells, overlying and adjacent aquifers, freshwater aquifers and the near-surface eco-compartments flora and fauna, soils, the shallow atmosphere and surface water bodies.

Monitoring concepts – status quo (Chapter 3)

General monitoring concepts provide a framework for setting up site-specific monitoring programmes and give general recommendations for potentially suitable techniques. The general monitoring concepts suggested in pertinent publications are briefly introduced. The monitoring requirements by the EU CCS Directive, the respective Guidance Documents and those of the EU ETS Monitoring and Reporting Guidelines are described in this chapter. In addition, other high-level regulations in place are presented, including the OSPAR and London protocol for a protection of the marine environment and the Clean Development Mechanisms of the United Nations Framework Convention on Climate Change. On a national level, many different directives, regulations and laws concerning CO_2 storage site monitoring are in place, implemented or being developed in different parts of the world, in particular in the USA, Canada, Australia and member states of the European Union. In Europe, there is one common EU CCS Directive that builds the frame for national CCS legislation in all 28 Member States and countries of the European economic area. In the US, Australia and Canada, the monitoring requirements are defined at state and provincial level. An overview of the current state of transposition of the EU CCS Directive to national laws is also given in Chapter 3.

Extensive monitoring programmes have been deployed in current CO_2 storage projects in order to fulfil the requirements by the regulations in place and to test the applicability of diverse geophysical, geochemical and biological monitoring methods. These are introduced for the full-scale industrial projects at Sleipner, Weyburn-Midale, In Salah and the smaller scale research and pilot projects K12-B and Ketzin. Monitoring programmes implemented at demo and industrial-scale projects are primarily oriented towards the most technically effective and cost-effective monitoring methods to comply with legal and safety requirements. In contrast, a wide variety of monitoring tools is developed, adapted, tested and validated at the pilot sites. Some of the demo and industrial-scale projects have been involved in research projects to gain additional information beyond the monitoring data required by the regulators and to advance new monitoring approaches.

Setting up a site-specific monitoring plan (Chapter 4)

To establish site-specific monitoring plans, location-specific features and risks must be identified and adequately addressed. After an introduction of the monitoring requirements in the EU CCS Directive, the procedure of transferring a general monitoring concept to a site-specific monitoring programme is exemplified for two sites.

The first example site is a deep saline aquifer in the south of Romania. The results of a site-specific risk assessment are presented and techniques to monitor the identified risks are listed. The target compartments for monitoring are ground surface, groundwater, soil, wells, possible faults and air. Suggested methods include logs, seismic surveys, cross-well techniques and microseismic surveys.

The second example is a depleted gas field in Slovakia at the border with Austria. The present irregular network of 35 old production wells and the existing geological fault system need particular attention in setting up a monitoring plan. Geochemical and geophysical baseline monitoring as well as monitoring during the injection phase and for the post injection period is suggested for this field. The methodology proposed follows those developed and applied for other storage projects in depleted natural gas reservoirs currently in operation, in particular the Otway Project in Australia.

Conclusions and Recommendations (Chapter 5)

Monitoring must form an integral part of the overall risk management of geological CO_2 storage sites. A number of established, reliable methods and tools exist for near-surface monitoring at CO_2 storage sites as well as for monitoring reservoir performance. The different suites of techniques are useful for i) tracking the extension and migration of the CO_2 plume, ii) large-scale surveys to detect eventual leakage pathways on a regional level, iii) detailed small-scale verification and characterisation procedures for selected, confined areas of CO_2 release.

All CO_2 storage sites need a comprehensive, integrative, dynamic monitoring strategy that addresses identified site-specific risks. A flexible multi-level approach must comprise the elements detection, verification, characterisation and long-term monitoring. Baseline monitoring will reveal natural (e.g. seasonal) variations for relevant parameters and unravel controlling factors of these variations. The interpretation of monitoring data needs to relate the results to local baselines and local knowledge on topography and geology, for example. For an overall assessment of site performance, the monitoring data need to be related to dynamic storage simulations. Monitoring data are further needed for updating geological models of the storage site.

The EU CCS Directive does not specify which methods or monitoring technologies should be used, but requires that the choice is based on best practice available at the time of design. Consequently, it is very important to test and evaluate the applicability of emerging monitoring tools that may provide new insights and additional information.

Based upon experience from existing CO_2 storage projects, other underground activities and research on natural analogues and at test sites, the following recommendations are derived:

- Monitoring plans must be site-specific, comprehensive, and flexible in order to satisfy various monitoring needs during normal operation and for contingency monitoring.
- Monitoring must form an integral part of the overall site management and needs to be continuously improved along with any associated activities.
- New, efficient, durable, precise and inexpensive monitoring tools and concepts should be tested at ongoing and future demo and industrial-scale storage projects under *in situ* conditions.
- Criteria and threshold values are needed for the evaluation of differences between monitoring results and model predictions.
- All stakeholders should be involved in the definition of i) acceptable conditions, ii) significant irregularities, iii) site-specific thresholds and iv) corrective measures and remediation plans.
- The systematic connection of near-surface and subsurface monitoring results is essential for the detection of irregularities.

- Thorough baseline monitoring and an understanding of natural processes is vital for the verification of anomalies and the quantification of deviations from model predictions.
- CO_2 injected into a storage formation should be regarded as contained within the storage complex, provided that no indication of a deviation has been observed by a reasonably extensive, sensitive and appropriate monitoring programme.
- Planning, operation, performance, and updating of monitoring activities, as storage operation in general, should be under independent supervision.

1 INTRODUCTION

Chapter Summary

The main objective of this report is to compile and review existing and emerging geotechnical methods for the monitoring of CO_2 geological storage. It includes examples of general concepts and site-specific applications. This introductory chapter provides a summary of the general context, conditions and requirements for monitoring of CO_2 storage. Monitoring purposes include health, safety and environmental provisions (HSE), quantification of emissions according to the Emission Trading Scheme (ETS), operational and contingency monitoring and information of local citizens. The legal acts and regulations for the various subjects of protection are listed briefly.

The EU Directive on CO_2 Geological Storage requires that monitoring plans are to be based on risk assessment. Thus, HSE monitoring must pay special attention to protected subjects and potential pathways for leakage, e.g. spill points, fractures and faults, weak points or gaps in caprocks or (abandoned) wellbores. An overview of the potential impacts of leaking CO_2 are given from different perspectives – namely the HSE, ETS and operational perspectives, considering different compartments, e.g. the reservoir, neighbouring aquifers, (abandoned) wellbores and near-surface eco-compartments. In addition to potential impacts by CO_2, risk assessment and monitoring need to take into account potential impacts related to associated incidental substances ("impurities"), mobilised substances and displaced fluids. Potential impacts may also include movement and deformation of rocks caused by changes of fluid pressure in the reservoir and surrounding rocks.

A comprehensive monitoring concept considers all monitoring purposes in all spatial compartments and all storage phases. Site-specific monitoring plans have to enable the tracking of the migration of fluids in the subsurface and adapt to the dynamic evolution of a CO_2 storage site. Monitoring techniques must provide information on the storage complex performance and on substances and processes of concern. The elements of such a comprehensive monitoring concept are outlined and summarised in an overview table that can be used to check site-specific monitoring plans for completeness.

The main objective of this report is to compile and review existing and emerging geotechnical methods and concepts for an evaluation of the performance of geological CO_2 storage sites. The report includes a summary of the general context, conditions and requirements for monitoring, and it provides an overview of proposed general monitoring concepts. General monitoring concepts are useful for the development of comprehensive site-specific monitoring plans and the selection and application of appropriate technical tools to consider all monitoring purposes and address all identified risks. The provisions of the EU CCS Directive and the relevance of other guidelines and regulations in place for procedures to set up site-specific monitoring plans are discussed.

In this report, monitoring techniques are introduced and discussed in the context of specific compartments and/or monitoring purposes, like e.g. monitoring the CO_2 plume migration in the storage reservoir, monitoring of faults and abandoned wells or monitoring of separate freshwater aquifers above a CO_2 storage reservoir. More detailed information about different monitoring methods can be found in the IEA GHG technical report 2012/2 (IEA GHG, 2012) prepared by members of CO_2GeoNet.

The technical descriptions of monitoring methods in this report include examples for specific applications or monitoring tasks and for the evaluation of the performance of geological CO_2 storage. They are supplemented with examples of site-specific monitoring applications at demo or pilot CO_2 storage projects and test sites.

Two examples for potential future storage sites illustrate the procedure of setting up site-specific monitoring plans, meeting multiple monitoring purposes. These examples were selected to represent the two major storage options in Europe and worldwide namely saline aquifers and depleted gas fields.

The report and its conclusions and recommendations shall stimulate the ongoing dialogue between regulators, operators, researchers and developers of monitoring tools for a long-term, safe CO_2 geological storage.

1.1 General considerations and monitoring framework

In general, monitoring is the systematic collection and analysis of information on the status of objects and processes. It is a continuous task to:

- compare expected and observed storage behaviour;
- decide on storage operations, if they are according to plan as well as in the case of irregularities when supervision of corrective measures is necessary;
- learn from acquired experience in order to improve future actions, e.g. update risk assessment and monitoring plans;
- document storage performance and keep account of emissions.

According to the EU CCS Directive (2009/31/EC) monitoring of CO_2 storage site performance has to be based on risk assessment. Monitoring is one important piece of an integrated risk management. According to the Intergovernmental Panel on Climate Change (IPCC) with appropriate site selection based on available subsurface information, a monitoring programme to detect problems, a regulatory system, and the appropriate use of remediation methods to stop or control CO_2 releases, if they arise, the local health, safety and environment risks of geological storage would be comparable to the risks of current activities such as natural gas storage, EOR and deep underground disposal of acid gas (IPCC, 2005).

1.1.1 Purposes of monitoring

The principal purposes for monitoring of storage complexes and their surroundings are:

- **HSE monitoring**: Health, safety and environmental (HSE) provisions, which are in the focus of Annex II of the European CCS Directive, are the main reason for storage monitoring, especially with respect to human safety. It includes standard monitoring for normal operations, according to permitted conditions as well as contingency monitoring in the case of unexpected events.
- **ETS monitoring**: Quantification of emissions from storage sites according to the European Emission Trading System (ETS; as defined in the Directive 2003/87/EC, the EU ETS Directive), is required in order to assure that CO_2 storage is compatible with the overall aim of providing a market-based mechanism for emission reduction.
- **Operational monitoring**: Providing technical data for injection management and site operation. Monitoring the migration of the CO_2 plume within the storage complex is needed for efficient storage operation. This may be of economic interest to the operator. It may be required by regulators also who care for an efficient utilisation of limited underground storage space.
- **Informational monitoring**: Satisfying the public interest on environmental information, especially in inhabited areas and in the case of deviations from the predicted storage behaviour. Though some of

these data may neither be required by the regulators, nor needed for storage operation, providing such data may be critical for the local acceptance of on-shore storage sites in particular.

1.1.2 Subjects of protection

Storage operations may affect various subjects of protection, public and private goods, single or complex objects. The protection of many of these goods is regulated in specific legislation. The EU CCS Directive does not list single subjects of protection. However, protection of the environment and human health is explicitly named in Article 1 on the purpose of the Directive. Consequently monitoring of these and other protected subjects has to be considered. Protected subjects include:

- Individual **human life and health** is generally of highest priority (Article 3 of the Universal Declaration of Human Rights; UN, 1948).
- Monitoring of the **ambient air** is a precaution for human health at injection sites and inhabited places where leakage risks may be seen. Maximum working place concentrations or exposure limits are defined for many gaseous substances including CO_2.
- As the mitigation of **climate** change is the overall aim of CO_2 geological storage, monitoring of the effectiveness of CO_2 storage and leak detection are mandatory for storage operations under the European Emissions Trading System (cf. EU ETS Directive).
- **Quality of life** may be locally affected (e.g. injection facilities in build-up areas may require noise protection and monitoring).
- **Socio-economic stability** is a rather abstract good which generally will not require specific monitoring, but can be affected by the overall storage performance, which is judged on the basis of storage monitoring data (e.g. effects on property values or local employment opportunities).
- **Flora and fauna**. Individual plant and wildlife species as well as terrestrial and aquatic life communities, especially endangered species, including their habitats, are subject to nature protection laws. Monitoring of CO_2 storage needs to pay special attention to such protected areas. Aspects of biodiversity and ecosystem value have been included in the decisions about protected areas.
- Species or ecosystems which are not specifically protected, such as **forests, farm animals or agricultural crops** are still subject to individual property rights and could require monitoring depending, e.g. on economic risks.
- **Soils** may be legally protected. Apart from being the basis for agriculture, soils fulfil multiple ecological functions. Thus, in many parts of the world, soil conservation is an important issue and soils are subject to legal protection in European Countries as well. A European Framework Directive for Soil Protection (2006/0086 (COD); European Commission, 2006a) is in preparation, as part of the implementation of the European Commission’s Soil Thematic Strategy (COM (2006) 231; European Commission, 2006b).
- **Landscape**. Apart from the installation of surface infrastructure, the operation of underground storage will generally not affect landscape appearance. However, morphological elements of landscapes could be affected in particular cases. The protection, management and planning of landscapes in Europe is promoted by the European Landscape Convention (Council of Europe, 2000) that has been signed and ratified by most member states of the Council of Europe.
- **Protected areas**. The installation of surface infrastructure or invasive monitoring (e.g. observation wells, acquisition of 3D seismic data) may be prohibited in protected areas like national parks. Nature reserves are of particular interest because of their outstanding value, e.g. as habitats of endangered species or for scientific, historical and regional reasons or simply due to their beauty, specific character or rarity.

- Monitoring **groundwater** aquifers is mandatory under the EU CCS Directive that requires compliance with the EU Groundwater Directive (2006/118/EC) and also the EU Water Framework Directive (2000/60/EC). Annex II part B and Annex III of the EU Groundwater Directive provide practical orientation for groundwater monitoring. One of the monitoring purposes explicitly mentioned in the CCS Directive is detecting significant adverse effects on the surrounding environment, in particular on drinking water. Thus, freshwater aquifers that serve for drinking water production should be monitored to detect potential pollution, before polluted groundwater flow reaches water works so that appropriate preventive or corrective measures can be taken in time.
- Onshore **open water bodies** may be used for drinking water production, leisure, aquaculture, public waterways, waste water discharge or aquatic biotopes. All of these forms of utilisation are subject to regulation. Generally, injection of substances requires permits that are bound to strict conditions. Pollution is prosecuted. Thus, monitoring of open water bodies will probably be required by permitting authorities. In addition, it is in the interest of a storage operator to gather water quality information to trace potential consequences of his activities.
- **The sea** is an open water body that is protected against pollution as well. In addition to national legislation for coastal waters, international treaties regulate CO_2 storage in international waters. CO_2 injection into the open water column or on the sea bed is prohibited by the OSPAR Convention (see 3.2.1). Monitoring shall ensure the integrity of marine ecosystems above off-shore storage sites.
- **Natural resources**. CO_2 geological storage is in competition with other utilisations of the deep underground and it may influence utilisation/exploitation of mineral or energy resources in the vicinity of a storage complex, e.g. hydrocarbon reservoirs, coal seams, natural brine, geothermal fields. Monitoring shall demonstrate the integrity of these resources in the neighbourhood of a storage complex. Active mining of resources may even give reason to exclude storage of CO_2 in their vicinity, or impose strict monitoring because of health and safety reasons.
- **Cultural heritage** or assets in general might be affected by geomechanical reactions of the storage complex and the Earth's surface to CO_2 injection. For conservation reasons, some heritage objects are left in the subsurface. Changes of soil properties and the geochemical milieu might affect the integrity of buried artefacts and structures.

1.2 Potential risks

1.2.1 Risks - general considerations

Monitoring according to the European CCS Directive has to be based on a risk assessment. "Risk" is generally defined according to ISO31000:2009 as an "effect of uncertainty on objectives". Therein effect means any deviation from the expected; the uncertainty results from a lack of knowledge or understanding about events, consequences, or likelihood. This general definition integrates various conceptions about risk from specific perspectives and focuses on different objectives, e.g. medical, financial, security or social issues. General concepts of risk basically include:

- the perception that something could happen,
- there is a possibility to influence the outcome (in contrast to fate),
- the probability of something that could happen,
- the consequences if it does happen,

whereby at least one of the possible outcomes is undesired.

A widely accepted risk definition refers to risk as the product of an events' probability times its consequences. For practical purposes of risk management, risk levels may be classified accordingly: An unlikely occurrence of an incident in combination with small consequences describes the lowest risk (lower left corner; Fig. 1-1), while high probability and hazardous consequences mark highest risks (upper right corner; Fig. 1-1).

Consequence	High	medium	high	highest
	Medium	low	medium	high
	Low	lowest	low	medium
Levels of risk		Low	Medium	High
		Probability		

Fig. 1-1: Schematic levels of risk classified according to the probability of an incident and its impact.

The risk levels are often associated with further measures for risk management and in particular for monitoring (Tab. 1-1). High or highest risks would correspond to 'significant risk', as defined in the EU CCS Directive as "a combination of a probability of occurrence of damage and a magnitude of damage that cannot be disregarded without calling into question the purpose of this Directive for the storage site concerned". Monitoring is required for low risks, but also for lowest risks, as risk levels could change during storage operation, e.g. the total mass of CO_2 injected will increase with time. Therefore, Article 13 of the EU CCS Directive requires monitoring for updating the assessment of the safety and integrity of the storage complex in the short and long-term. If the assessment of risks changes during storage operations, the monitoring plan has to be updated (Annex II, EU CCS Directive).

Tab. 1-1: Risk levels and associated measures for risk management and monitoring.

Risk level	Consequences
highest	unacceptable, not permissible or injection stop, corrective measure required
high	actions to reduce consequences or probability
medium risk	actions to reduce consequences or probability
low risk	acceptable, monitor and be prepared for further measures
lowest risk	acceptable, low level monitoring, unless the risk level changes

Only for a few risks, the probability of an incident can be derived directly from observations, e.g. frequency-magnitude relations for earthquakes recorded by regional networks. In most cases, numerical simulations are the only way to quantify the probability of different scenarios for various risks derived from storage features, events and processes (FEPs). However, the probability of basic assumptions used in the numerical models often cannot be quantified and is only taken into account as model properties or boundary conditions for site-specific or generic risk assessments. Chadwick *et al.* (2008), e.g. conclude that an "overall, quantitative assessment of the probability of any particular scenario occurring is very difficult, particularly for scenarios involving geological FEPs (e.g. fault leakage, caprock, failure, etc.)".

1.2.2 Potential leakage pathways

Monitoring of "Health, safety and environment (HSE) risks" is focussed on the Earth's surface or the shallow subsurface. The probability of negative effects on protected subjects is highest where pathways could facilitate the ascent of fluids from the storage reservoir to the surface (Fig. 1-2). Such pathways have to be detected and mapped, and their properties have to be determined during site characterisation. This information provides input to site-specific risk assessments, which, in turn, provide fundamental data for setting up site-specific monitoring plans that include monitoring of these pathways.

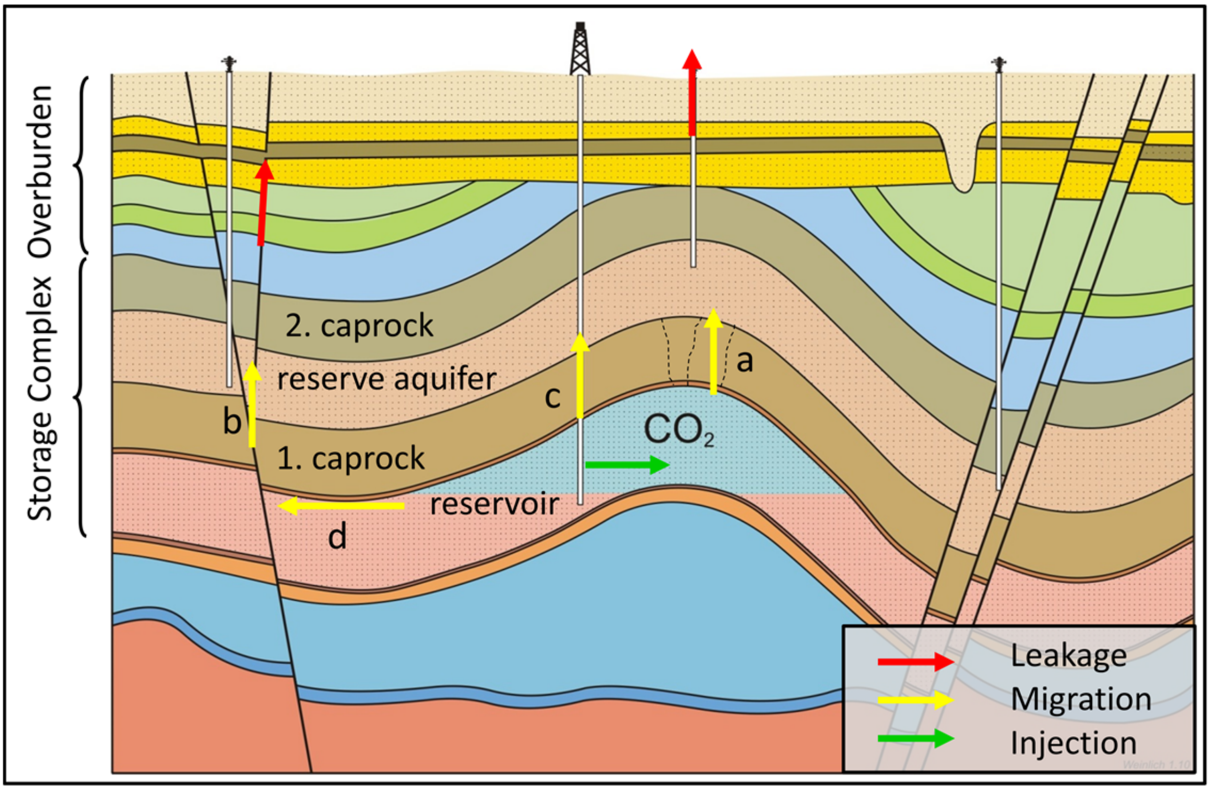

Fig. 1-2: Schematic representation of potential leakage pathways for CO_2 injected into saline formations (not to scale; slightly modified after v. Goerne *et al*., 2010).

Potential leakage pathways may comprise:

Caprocks (a; Fig. 1-2): A central task of site characterisation is to demonstrate that thickness, strength, lateral distribution and sealing properties of caprocks facilitate safe and efficient storage of CO_2. However, the presence of potentially weak spots of caprocks that could provide leakage pathways cannot be excluded. Indications for leakage through caprocks by such unknown pathways can be obtained by monitoring secondary containment formations. The selection of suitable sites and parameters is critical for the early detection of such, potentially diffuse, leakage. For example in anticlinal structures, the largest pressure differences across a caprock above a static gas column prevail at the top of a structure. Thus, this might be a strategic point for monitoring caprock integrity. The risks of undiscovered "gaps" in caprock can be further minimised by monitoring areas where general geological features indicate chances for pathways. Such indicators could be trends and variations of sedimentary facies or formation thickness.

Faults (b; Fig. 1-2): Permeable faults in caprocks and in the overburden of reservoirs may provide pathways for fluid ascent and hence imply potential HSE risks. Older faults are often impermeable, sealed by mineralisation. Faults in neo-tectonic active regions may also provide barriers to fluid flow e.g. through fault gouge or clay in unconsolidated sediments. Within the reservoir these faults may act as barriers to fluid flow and limit injectivity and reduce storage capacity and, thus, pose economical risks to storage operators.

Fault zones often comprise networks of faults and fractures that are difficult to characterise in seismic images. Fault properties vary along fault planes. Hydraulic properties of faults can change due to pressures induced by CO_2 injection. Closed faults become permeable, when pressures exceed the fault strength (e.g. Chiaramonte, 2008). Geochemical reactions between fluids and adjacent rock or precipitation of minerals from ascending fluids may lead to self-sealing of faults or dissolution of carbonate fracture fillings. Therefore, detection and prediction of possible fluid pathways along faults is rather uncertain, so that faults need to receive special attention in monitoring.

Boreholes (c; Fig. 1-2): Boreholes, especially from improperly installed and/or abandoned wells, may provide direct leakage pathways between reservoirs, groundwater, and the surface. Due to technical improvements in well cementation and logging, recently sealed boreholes are often considered safer than older, plugged ones, where less information on the well condition may be available. Thus, monitoring of older, plugged wells has to be considered in monitoring plans.

Spill points (d; Fig. 1-2) of structural traps are crucial areas for monitoring the movement of a buoyant CO_2 plume in saline aquifers. The actual expansion of a gas plume in a reservoir may be different from simplified reservoir simulations. In addition, spill points may be difficult to map in gently inclined structures. Spill points may be the starting points of leakage pathways. If a CO_2 plume expands beyond spill points, it has to be carefully monitored. The ascent of fluids may follow a combination of several of the pathways described above in case of leakage. An illustrative example for such a complex leakage path is provided by the incident at the Bad Lauchstädt gas storage (Katzung *et al*., 1996), where gas leaking from a cavern storage well at 110 m depth found its way via faults and secondary accumulations to the surface. Finally, gas burst to surface in several vents in a zone of 1.5 km length. Scenarios of such combined pathways have to be considered in risk assessments and for the positioning of monitoring instruments.

1.3 Potential impacts

CO_2 and CO_2-bearing fluids might have various effects in the deep underground, in drinking-water aquifers, in the shallow subsurface and in the aboveground environment. The impact of the CO_2 differs depending on its concentrations, the compartment affected and also the location. Thus, two major challenges in evaluating the risks posed by released CO_2 are:

- estimating the spatial and temporal distribution of CO_2 fluxes entering spaces or objects that should be protected;
- predicting ambient CO_2 concentrations resulting from given CO_2 fluxes.

Depending on the characteristics of the leakage pathways, a surface release may be concentrated and spot-like or diffuse and widespread over a broad area. High flux densities (mass flow per area and time) could occur in the vicinity of leaking wells (including blow-outs), resulting in high concentrations in the affected locations. However, the evaluation of the risk depends largely on the released quantity and, if direct damage occurred, it would be restricted to the vicinity of the leak. In contrast, a diffuse leakage of large quantities over large areas might result in low flux densities that may not be noticed for a while. In either case, a significant risk to humans or the environment may or may not be created depending on the amount of CO_2 that has leaked out, the flux density and the resulting concentrations (Benson, 2006). The latter example of a diffuse flux highlights the necessity of comprehensive monitoring plans.

The leakage of large quantities of CO_2 might be detected, e.g. by monitoring reservoir pressures, well before CO_2 will reach the surface or build-up to detectable geochemical anomalies in shallow groundwater. At such first indications of leakage, measures can be taken to prevent negative effects on protected goods at the surface. In addition, monitoring at the surface and of the shallow subsurface may be intensified in order to detect and quantify possible diffuse fluxes.

The quantification of risks includes predictions of magnitude and impact of CO_2 on the surrounding environment. Natural CO_2 release is a frequent phenomenon in various regions, world-wide. These sites can be used to establish magnitude-impact relations for various environments (Roberts *et al.*, 2011). Field measurements demonstrate a wide range of fluxes that results from CO_2 ascending through various crustal rocks. Natural sites can be used to validate monitoring methods at different surface conditions in the storage area and to test concepts for different magnitudes expected. Because of the natural variability, various methods are required for site-specific monitoring of CO_2 leakage risks.

Though the total release or flux rates are proportional to possible impacts, for human health and safety the actual concentrations in the breathing air are critical. In poorly ventilated rooms low fluxes may accumulate over time to hazardous concentrations, while in open air conditions turbulent mixing can maintain concentrations in tolerable ranges, even in the surroundings of a well blow-out (Ferrara and Stefani, 1977).

Thus, depending on the monitoring purpose, various monitoring parameter have to be recorded:

- total release for emission trading,
- flux for operators and regulators decisions about corrective measures,
- ambient concentrations for human safety.

1.3.1 Health, safety and environmental (HSE) monitoring

Negative effects on human health, plant or animal life are at risk, if concentrations of hazardous substances (see 1.3.4) exceed critical concentrations. Thus, detection and monitoring of concentrations in or surrounding protected subjects (see 1.1.2) is the main task of HSE monitoring.

The impact magnitude of an incident is primarily related to the leakage rate, but subject to further factors:

flux density ⇒ concentration and concentration, vulnerability and value of subject ⇒ impact

Concentrations resulting from a leakage flux (mass flux per time) depend on the volume of the affected subject and on the intensity of mixing within this volume. Hazardous concentrations may accumulate, if mixing, dispersion or turbulence are low, if chemical reaction rates are fast or if sufficient time for accumulation is available, e.g.

i) CO_2 pipeline failure on a calm day in a lowland valley:

large flux large affected volume little mixing	⇒	high concentrations	⇒	potential of high impact on life close to the ground

ii) CO_2 flux into a non-ventilated, rarely used cellar:

small flux rate small volume little mixing long accumulation time	⇒	high concentrations	⇒	localised potentially lethal impact

Within one protected subject, e.g. an ecosystem, the vulnerability of various species may differ significantly. For human safety, detailed relations between concentration, duration of exposure and effects caused by CO_2 have been established (Tab. 1-2). Human health can be at risk in enclosed environments (cellars, caves etc.) or topographical depressions, where CO_2 may accumulate because CO_2 is denser than air (1.98 vs. 1.2 kg m^{-3}, respectively) and tends to build up on ground levels.

For other species more general, critical concentration thresholds have been published (e.g. Blackshaw *et al*., 1988; Zaller and Arnone, 1999; Loranger *et al*., 2004; Asshoff, 2005; Leach *et al*., 2002; Niel and Weary, 2006). The impact of substances depends also on the environment. For example, saline formation water leaking into the sea may be less dramatic than a comparable saltwater leakage into a freshwater environment. In addition, the value of the protected good matters: An acre of trees dying in a large plantation (subject to individual property rights) may not be as valuable, as an acre of the same tree species, being unique in a wider region.

The examples demonstrate that the classification of impacts in a risk assessment process cannot be directly linked to flux rates calculated for leakage scenarios in subsurface numerical models. Site-specific features have to be included into the assessment.

Tab. 1-2: CO_2 thresholds and effects regarding human health. Compiled from safety data sheets "carbon dioxide" of the companies Knauber Gas (Bonn, 2007), Linde (Höllriegelskreuth, 2010), Praxair Tech. (Danbury, 2007) and Air Liquide Germany (Düsseldorf, 2010).

Air CO_2 conc. (% vol.)	Increase against ambient air value	CO_2 thresholds and effects
0.039	---	Global average concentration in ambient air in 2010 (WMO, 2011)
0.15	3.9-fold	Hygienically recommended value for indoors fresh air
0.3	7.7-fold	MIC value (= maximum indoor concentration), no health concerns to long term exposure below this value
0.5	12.8-fold	MAC value (= maximum allowable concentration at workplaces)
1.5	38.5-fold	Breathing rate increases to 40% above the normal level
4	103-fold	Normal concentration of exhaled air. Weak narcotic effects, impaired hearing, headache, increased blood pressure and pulse rate
5	128-fold	Breathing increases to approximately four times the normal rate, symptoms of intoxication become evident, vertigos, slight feeling of choking
8 – 10	205- to 256-fold	Very laboured breathing, headache, visual impairment, ringing in the ears, sick, judgment may be impaired, loss of consciousness, exposure of 30-60 minutes leads to death
>10	> 256-fold	Unconsciousness occurs more rapidly; prolonged exposure may result in death from asphyxiation

1.3.2 Monitoring for accounting of emission certificates (ETS monitoring)

In contrast to HSE monitoring, concentrations of substances do not matter for monitoring according to the Monitoring and Reporting Guidelines (MRG, COD 2010/345/EU) under the EU ETS Directive. From the ETS perspective, the economic impact is proportional to quantity of emitted CO_2, i.e. the total mass of CO_2 that has leaked into a water column or into the atmosphere has to be specified. In case of terrestrial leakage, CO_2 flux densities (mass flux per time and area) are measured, e.g. in accumulation chambers. The total mass of CO_2 emitted can be calculated by integration of repeated flux density measurements over time and area. The integration of a sufficient number of measurements is a challenge for monitoring, if the determination shall be within the limits of uncertainty stated in the guidelines for the monitoring and reporting of greenhouse gas emissions (MRG), i.e. ± 7.5%.

In principle, accumulation chambers can also be used for monitoring gas fluxes through lake beds or the sea floor. In the water column dissolved CO_2 has to be taken into account in addition to a free CO_2 phase. The reliable quantification of the total CO_2 flux in an aquatic environment with reasonable effort is challenging. In consequence, the financial impact of CO_2 leakage under water may be more severe as on land, because the uncertainties of CO_2 quantification exceeding 7.5% will be added to the liability of the permit holder to return emission certificates equivalent to the remaining uncertainty of leakage quantification.

1.3.3 Operational monitoring

For the purpose of storage operation, the focus of monitoring is on the storage reservoir and the caprock. Early detection of leakage may be in time to take actions to prevent leakage to the surface that would cause HSE risks or require monitoring according to the ETS. Therefore, operational monitoring aims at processes of fluid migration at depth. Indications of leakage may be derived from a variety of parameters that can be measured in the subsurface, without measuring actual concentrations or fluxes of substances. Mainly physical parameters are considered, such as pressure or temperature recorded in observation wells or geophysical investigation of larger rock volumes.

The operator faces a variety of risks, in addition to HSE risks that ultimately are financial risks. He may monitor the corrosion of well materials for maintenance and work-over measures or near-well reservoir properties in order to maintain sufficient injectivity for CO_2.

The impact of possible disturbances in storage operation is inversely proportional to the chances for precisely localising a problem and to the chances of successful remediation of the problems. For example, leakage through well bores likely could be fixed. Leaking cap rocks would be classified as serious impact that could endanger storage permits.

1.3.4 Substances of concern

Risks may arise directly from CO_2 (see 1.3.1 to 1.3.3) or from its associated incidental substances, saline formation water, hydrocarbons, mobilised substances from rock or soil and indirectly from the geomechanical reaction of the storage environment (see 1.3.5). For monitoring purposes, risk assessments need to specify possible locations of leakage, magnitudes and impacts of possible incidents. Though the discussion of risks initially often was restricted to CO_2, all of the risks require adequate monitoring.

Incidental associated substances

Depending on the capture technology, the CO_2 phase may contain various incidental associated substances, such as SO_2, NO_x, CO, H_2S, He, N_2, O_2, Ar, Hg, As, Se, and other trace elements. These impurities pose potential risks or may affect the level of risks due to their various potential impacts on the storage complex and on health, environmental and safety issues: Some species can be toxic, others form acids (SO_x, NO_x, H_2S) that could cause corrosion problems, alteration of reservoir and caprocks, or the mobilisation of heavy metals from soils or aquifer rocks, which is of particular concern in freshwater aquifers.

Whether these minor components will cause risks in addition to effects caused by the CO_2 itself, depends on the concentration of these impurities and the subjects exposed to them. These risks need to be assessed individually for each separated CO_2 stream and storage project. For many risks, the monitoring of one indicator or proxy may be sufficient as long as the impurities are in the CO_2-bearing phase. Detection of CO_2 may be sufficient for early warning purposes.

Formation fluids

In an incident of leakage, formation fluids, phases naturally present in the storage formation or the overburden may migrate together with the CO_2-rich phase to the surface and affect protected goods. Mobilised formation brines, natural gas or crude oil may be eco-toxic or pose risks to human health and safety. The displacement of formation water from saline aquifers is seen as a particular risk for freshwater aquifers. As water is almost incompressible, the injection of pressurised CO_2 will push formation brine away from the injection wells. Displaced brine can potentially migrate or leak through fractures or wells into shallow aquifers and may thereby contaminate resources used for drinking water extraction.

Rock and/or soil constituents

Rock and/or soil constituents can be mobilised by various geochemical reactions. At depth, supercritical CO_2 is an excellent solvent for organic material that may be extracted from reservoir or caprocks. The solubility of organics will decrease during fluid ascent according to the pressure and temperature conditions along the flow path. Precipitation of higher hydrocarbons may lead to permeability reductions in porous media. In open fractures such phases may be transported as mixtures with fluids of lower viscosity. Subsurface water and CO_2 can react with wall rocks, e.g. mobilising toxic heavy metals or just ubiquitous formation water constituents.

If impurities or mobilised substances pose additional risks to CO_2 leakage, than these risks have to be addressed by monitoring as well. For example at injection facilities for H_2S-bearing CO_2 both gaseous species should be monitored because of occupational safety, to avoid asphyxiation by CO_2 or poisoning by H_2S. Well materials may need more intensive monitoring when the concentrations of corrosion-enhancing substances (acidic gases, H_2O, O_2, Hg) exceed material-specific critical levels.

1.3.5 Geomechanical processes of concern

Geomechanical effects of CO_2 storage may also have negative consequences for HSE. CO_2 injection in the deep underground causes inevitably changes of the pre-existing underground pressure patterns. The influence of injection may reach far beyond the space occupied by the injected fluid. The geomechanical reaction of the storage complex on these induced stresses will result in the deformation of the storage complex. Deformation can either be localised or may affect large rock volumes. It can be rapid or slow.

Accordingly, different phenomena may be expected. Locally, incidents of rapid deformation may result in severe impacts and thus pose high risks. Geomechanical monitoring data are needed for keeping injection rates and resulting pressures within limits permitted for safe storage operation.

Leakage risks are given, when the pressure within a storage reservoir exceeds its fracture strength or the capillary entry pressure of caprocks. Fracturing may not only result in leakage, it could trigger micro-seismic events, that can be recorded and provide an early warning to operators so that counter-measures could be taken to reduce pressures and prevent/stop leakage. Pressures could also exceed the strength of pre-existing faults, which could trigger macro-seismic events (induced earthquakes) or open older mineralised fault zones, which could become a pathway for leakage then. Hence, pressure monitoring at critical points within the storage complex is essential for safe storage operations. While risks for fracturing of a caprock are highest at high points within the storage reservoir and close to injection wells, fault reactivation might happen in the surroundings of the storage site as well.

The gradual gentle deformation of larger rock volumes including the land surface, known from natural gas storage or natural gas production, can be monitored, e.g. by remote sensing in case of on-shore sites (e.g.

Kühn *et al*., 2009). This way, areas of localised strain can be identified and monitoring could be intensified in such areas to provide baseline data for the quantification of further movements which eventually might cause damage to buildings. Then, additionally, monitoring tools for strain measurements can be installed in places of concern for health and safety monitoring. Even gentle, aseismic deformation of larger areas might pose environmental risks, e.g. in flat low lands where subtle changes of the drainage patterns might affect sensitive ecosystems such as wetlands or tidal flats.

1.4 Comprehensive monitoring concepts

A comprehensive monitoring concept shall meet the different monitoring purposes (see 1.1.1.) in the spatial dimension, and in the temporal dimension providing information on substances and processes of concern (see 1.3.4 and 1.3.5).

For practical purposes different compartments can be distinguished in the spatial dimension. These compartments fulfil different functions in storage operation and may comprise various subjects of protection. The individual compartments are accessible for installation and application of different monitoring techniques. Relevant compartments to be considered for setting up a comprehensive monitoring concept may include:

- storage formation, including caprock,
- secondary containment formations,
- the overburden, including faults,
- injection facilities, including wells,
- the hydraulic unit, extending beyond the storage complex,
- shallow, potable water aquifers,
- the marine environment,
- surface of the storage site and surrounding biosphere.

The practical delineation of a “storage complex” as defined in Art. 3 of the European CCS Directive and the extent of it are a matter of ongoing debate. Depending on the position of the protagonists, it could be restricted to the first two compartments of the list above, or include the first five compartments. The term “surrounding environment” is not well defined by the EU CCS Directive either. However, it should include at least the area of the hydraulic unit. This list of compartments may be adapted to the local situations. For example, shallow potable groundwater resources and the marine environment may be mutually exclusive, or caprock and reservoir may be split up into separate compartments. The different compartments are partially nested, adjacent or interconnected. Though the compartments are fixed in space, the phases within these compartments migrate with time within the compartments and may change at a particular site within a compartment. In general, there will be an outward migration of different phases away from the injection well. In a saline aquifer these expanding zones are (Fig. 1-3):

- supercritical CO_2 saturated reservoir near the injection wells (g),
- partially saturated gas-water transition zone (g, f),
- CO_2 dissolved in formation water ($CO_{2(aq)}$),
- zone of brine displacement (q_f),
- outer zone of the hydraulic unit, with negligible brine displacement but measurable pressure increase (Δp_f).

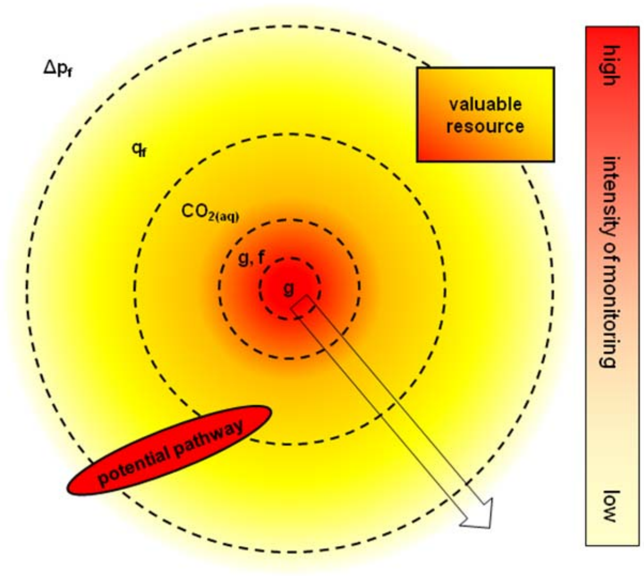

Fig. 1-3: Schematic illustration of expanding monitoring zones (dashed lines) and fixed features within different compartments (solid lines). Colours indicate monitoring intensity. An explanation of the labelling of zones is given in the text (Modified after May *et al*., 2011).

According to the various phases present in the zones, different monitoring techniques are required to record key parameters or proxy data as indicators for subsurface processes. Monitoring intensity will follow these zones and is generally more intensive in the dynamic region surrounding injection wells and less intensive, at the margins of the hydraulic unit. However, areas of particular concern, such as potential pathways or valuable resources at the surface, may need special attention throughout all monitoring phases. For monitoring of fluid migration processes and pathways the relations between compartments and zones have to be taken into account. Provisions for obtaining the required data have to be specified in the site-specific monitoring plans.

On the time scale different phases can be distinguished, which also will require different levels of monitoring intensity (Figs. 1-4 and 1-5):

- Baseline monitoring in the pre-injection period,
- Standard operational monitoring during normal injection according to permit,
- Intensified contingency monitoring during times of significant irregularities and following corrective measures,
- Closure and post closure period, before transfer of liability to the competent authority,
- Long-term monitoring after the transfer of liability (Art. 18.6, EU CCS Directive).

Monitoring intensities may be highest for baseline acquisition and during the injection phase in case of irregularities and consecutive corrective measures (Fig. 1-5; Tab. 1-3). The general, descriptive term "intensity" includes the frequency of measurements, the numbers of sampling points and methods applied. Apart from these peak times, monitoring intensity may be reduced if injection performance is according to plans. After the end of injection and transfer of liability, the monitoring efforts may be reduced to a level, which allows for detection of leakages or significant irregularities. Slow geochemical processes, e.g. may lead to risks, long after site closure. If any leakages or significant irregularities are detected, monitoring shall be intensified again.

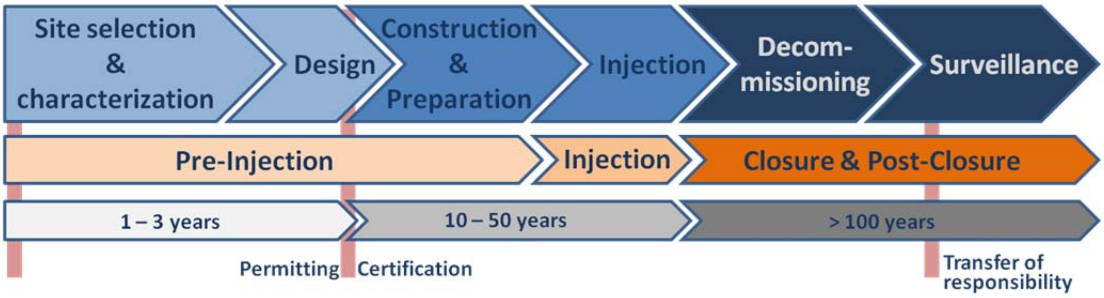

Fig. 1-4: Phases of CO_2 geological storage projects from a monitoring perspective.

Table 1-3. Level, scale and monitoring intensity considering the purpose and type of observations required.

Level	Scale	Intensity	Purpose	Observations
normal operation, after transfer of responsibility	regional	low	reconnaissance	indicative parameter, proxies
significant irregularity	restricted area	moderate	search and detection	direct measurements
leakage, negative impacts	local	high	characterisation	flux and magnitude determination

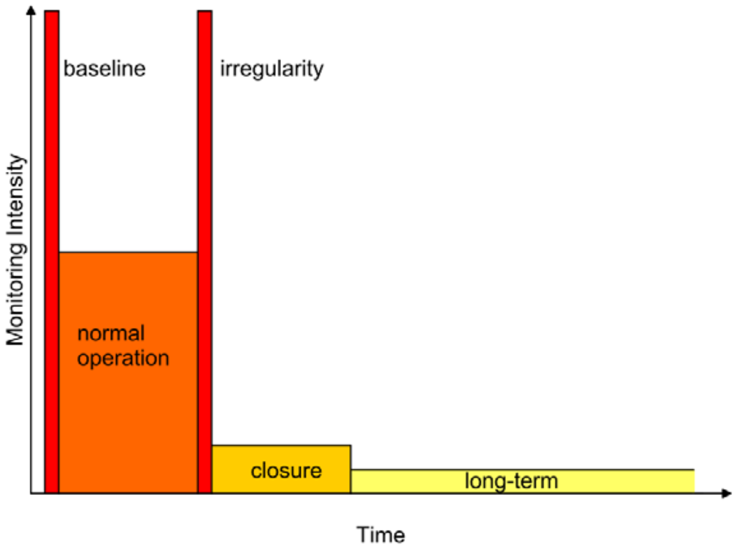

Fig. 1-5: Schematic illustration of variable monitoring intensity with time (after v. Goerne *et al*., 2010). The occurrence of an irregularity has been placed arbitrarily towards the end of the operational phase. This does not imply that a site has to be closed after such an incident.

Temporal and spatial scales can be combined to a generic table. Allocating monitoring purposes (see Section 1.1) on this table yields a matrix that can be used to generate comprehensive lists of monitoring tasks (Tab. 1-4). The arrangement of the compartments according to their occurrence with depth represents potential pathways for continuous transition from the actual storage formation up to the surface, where injection facilities are usually located.

For establishing site-specific monitoring concepts local settings and features must be well known and site-specific risks need to be addressed. Plans must be kept sufficiently flexible in order to react in cases of significant deviation from the predicted behaviour, either through more intensive monitoring efforts or by monitoring the effectiveness of corrective actions according to an associated safety concept.

May *et al*. (2011) proposed a structured procedure for preparing site-specific monitoring plans, including the following steps:

- Mapping of monitoring areas;
- Classification of monitoring intensity;
- Definition of monitoring tasks;
- Selection of monitoring methods;
- Specification of measurements and observations.

Within this procedure, the allocation of the purposes to the matrix (Tab. 1-4) can be used to verify the completeness of site-specific monitoring plans. Integrating various monitoring purposes and tasks helps reducing the number of methods required to provide all the information needed for safe, durable and environmentally friendly storage of CO_2 during the entire life-time of a project. Examples for site-specific monitoring plans are given in Chapter 4.

Tab. 1-4: Comprehensive, generic monitoring framework: Monitoring purposes with regard to different compartments and project phases (May *et al*., 2011). Symbols in brackets indicate the need of case-specific considerations.

Compartment \ Phase	Pre-Injection, Baseline	Operation: normal	Operation: significant irregularities	Post-Closure: before transfer of responsibility	Post-Closure: after transfer of responsibility
Injection facilities, incl. wells		🛠 🚫 📄 ☺	🛠 🚫 📄 ☺	🚫 ☺	
Near surface environment, incl. local communities and biosphere	🛠 🚫 📄 ☺	🛠 🚫 ☺	🚫 📄 ☺	🚫 ☺	🚫 ☺
Marine environment *and/or*	🛠 🚫 ☺	🛠 ☺	🛠 🚫 📄 ☺	🚫	
Freshwater aquifers (potable water)	🚫 (📄) ☺	🚫 ☺	🚫 (📄) ☺	🚫	🚫
Hydraulic unit (area beyond storage complex)	🛠 🚫	🛠 🚫	🛠 🚫 ☺	🚫	(🚫)
Storage complex: Overburden, incl. faults	🛠 🚫	🛠 🚫	🛠 🚫 ☺	🚫	
Storage complex: Secondary containment formation	🛠	🛠	🛠 🚫 ☺	🚫	(🚫)
Storage complex: Storage formation, incl. caprock	🛠	🛠 ☺	🛠 🚫 ☺	🛠 🚫	🚫

Monitoring purposes: 🛠 Storage operation; 📄 Accounting for emission certification; 🚫 Health, safety and environmental protection; ☺ Communication with local communities

2 MONITORING TECHNIQUES

Chapter Summary

A number of established, reliable methods and tools exists for near-surface monitoring at CO_2 storage sites regarding i) gas monitoring, ii) biomonitoring (micro- and macrocosm), iii) ecological monitoring (populations and systems). Well-established deep subsurface technologies are also available that give information about the amount and the migration of CO_2 underground. For example, seismic measurements are at present the dominating geophysical methods for monitoring CO_2 injection in saline aquifers and depleted hydrocarbon reservoirs. The method allows, in most cases, detailed mapping of the migration of the CO_2 plume, and reasonably accurate volume estimates may be achieved by using appropriate assumptions.

The various monitoring techniques have their specific advantages and shortcomings in terms of sensitivity, reliability, capability, e.g. for point vs. wide area measurements or continuous vs. discontinuous measurements. These aspects are introduced and discussed in the relevant Sections that cover the various monitoring compartments. For example, to provide an early warning of CO_2 migration to shallower depths, monitoring can be performed in wells in the subsurface. Monitoring in injection or observation wells typically involves low background variability; however, often results in small/weak signals. Shallow subsurface technologies are able to detect and quantify amounts of CO_2 that have leaked into the shallow overburden, soils or the seabed or, ultimately, the oceans or atmosphere. In contrast to measurements in the shallow subsurface where background variability is typically moderate, the high background variability noted at the surface is a major challenge for surface/water monitoring technologies.

For a comprehensive monitoring, various techniques are needed with very different characteristics combining i) continuous and discontinuous techniques, since a leak may vary with time and thus might be missed by one-off sampling, as well as ii) point and wide-area techniques, since large areas need to be covered rapidly because storage sites can cover many km^2, but targets (leaks) may be rather small.

In this chapter state-of-the-art and emerging monitoring techniques are introduced and their applicability, shortcomings and detection limits will be discussed in the context of monitoring of identified risks of geological CO_2 storage. This collation of techniques is done compartment-wise, i.e. distinguishing techniques:

i) to monitor the extension and migration of the CO_2 plume in the storage reservoir,
ii) to track potential CO_2 leakage out of reservoir considering neighbouring aquifers (saline and freshwater) and the overburden including faults;
iii) to detect potential impacts such as surface uplift, induced seismicity, fault reactivation,
iv) to assess the sealing of abandoned wells and ,
v) to detect potential leakage and monitor potential impacts in near-surface eco-compartments.

In addition to the techniques' specific characteristics, special reference will be given to various "boundary conditions" to be considered when selecting monitoring tools such as location of the site (onshore/offshore), site accessibility (depending on land-use, topography, wells), volume to be monitored (considering depth, spread, pressure footprint).

An overview of potential CO_2 monitoring techniques and their applicability for monitoring of deep or shallow processes, for locating the CO_2 plume, monitoring of fine scale processes, detection and quantification of a leakage was given by Pearce *et al*. (2005) (Fig. 2-1). These authors group the potential monitoring techniques as techniques for primary and secondary use.

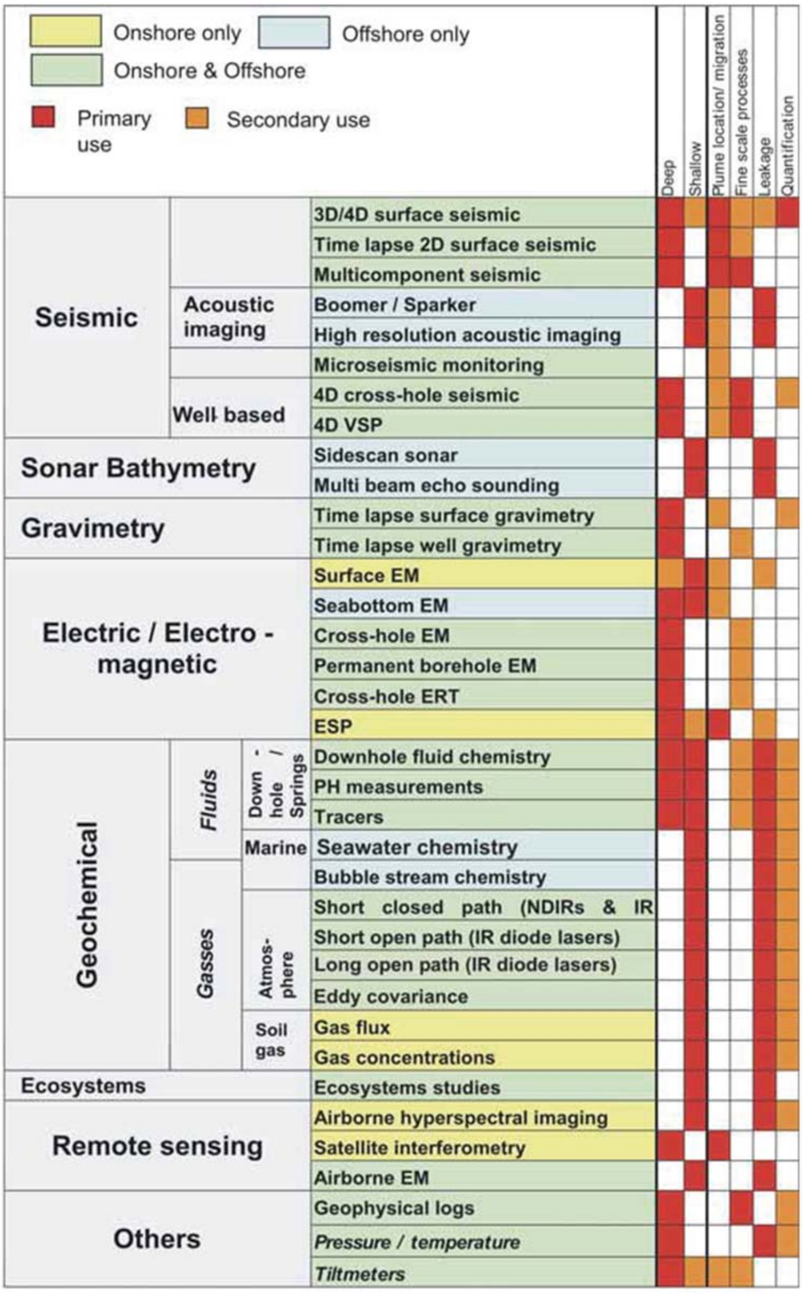

Fig. 2-1: Potential CO_2 monitoring techniques and their applications (from Pearce *et al*., 2005); ESP = Electric spontaneous potential; VSP = Vertical Seismic Profiling; EM = Electromagnetics; ERT = Electrical Resistance Tomography; IR = Infrared detector; NDIR = Non-dispersive infrared spectrometer.

For the purposes of tool selection for site-specific monitoring plans, monitoring methods can be grouped into three categories, based on application, function, and stage of development:

Primary Technology – A proven and mature monitoring technology or application.

Secondary Technology – An available technology that can provide insight into CO_2 behaviour and that will help refine the use of primary technologies.

Additional Technology – A technology which is research-related and might answer fundamental questions concerning the behaviour of CO_2 in the subsurface and which might have some benefit as a monitoring tool after testing in the field.

2.1 CO_2 plume migration in the storage reservoir

Subsurface monitoring techniques play a vital role in identifying CO_2 plume location, pressure propagation, and reservoir and seal integrity. These techniques can detect CO_2 and compare observations with the predicted fate and transport results from modelling efforts. Many techniques can be imported from oil and gas exploration and reservoir management disciplines. A variety of techniques is also available to assess the condition of the well and ensure that the well itself does not provide a leakage pathway for CO_2 migration.

However, no techniques are available to measure the CO_2 in situ with precision. Therefore, it is not possible to directly quantify CO_2 in the injection zone. Hence, it is necessary to use indirect or inferential methods to document that the storage site is performing as expected and that CO_2 and brine are not escaping the storage reservoir in unacceptable directions and at unacceptable rates.

For geological storage, CO_2 is injected at depths of $\geq$ 800 m so that it will be present as a supercritical fluid under typical temperature and pressure conditions prevailing at these depths. Since compressibility and density of supercritical CO_2 are smaller in comparison to those of saline formation water, the pore space in a saline aquifer will be filled with a less compressible and less dense fluid after substituting formation water by injected CO_2. This contrast in properties is useful for different geophysical monitoring techniques. The situation is more complicated in depleted hydrocarbon reservoirs due to the large variations in the physical properties of oil, and since CO_2 will modify the physicochemical properties of the oil in short time scales.

A recent overview of the different geophysical monitoring techniques can be found in Sayers and Wilson (2010). Estimates of CO_2 detection limits for some of the most commonly used geophysical methods are given by JafarGandomi and Curtis (2011). Tab. 2-1 gives a summary of the most common monitoring techniques to monitor CO_2 injection and follow the migration of the CO_2 plume.

Tab. 2-1. Geophysical methods commonly used for monitoring CO_2 injection and tracking CO_2 plume migration.

Measurement method	**Physical parameter(s)/**	**General characteristics in terms of tracking CO_2 plume**
Seismic	Seismic velocities, density	High spatial resolution
Geoelectrical	Electrical resistivity	Intermediate spatial resolution
Electromagnetic	Electrical resistivity	Intermediate spatial resolution
Gravity	Density	Low spatial resolution, although an advantage is that the response is linear

2.1.1 Seismic reflection

In seismic measurements surface sources (e.g. dynamite, vibrating machines or air gun arrays for onshore and offshore use, respectively) are utilised to generate downward propagating elastic waves that are reflected from subsurface features and return to the surface where they are recorded by ground motion sensors (geophones), resulting in a three-dimensional view of the subsurface. In the case of a 3D survey, a regular 2D grid of surface sources and sensors is deployed. The recorded data are combined to produce a 3D image of the subsurface. The seismic survey provides an initial baseline that can be compared to changes in subsequent seismic surveys to create a time lapse image of CO_2 plume migration and to detect significant leakage or migration of CO_2 from the storage site. Surface seismic techniques provide detailed spatial resolution of CO_2 distribution, but are less sensitive than well-based methods and, therefore, may require the presence of large volumes for detection of CO_2 (Monea *et al*., 2008).

Lumley (2010) describes various aspects of seismic monitoring for CO_2 injection: The effectiveness of the seismic monitoring depends on the properties of the pore fluid (including the CO_2) and the compressibility of the dry rock frame. If the dry-frame compressibility is low, i.e. the rock is stiff, the seismic measurements will not easily sense the properties of the pore fluid. When injecting into a depleted hydrocarbon reservoir, depleted oil with low solution gas-oil ratio (GOR) will give more favourable conditions for seismic monitoring of CO_2 injection than depleted oil with high GOR. The presence of residual hydrocarbon gas in the pores will furthermore provide less favourable conditions for seismic monitoring (cf. Picotti *et al*., 2012).

In addition, the effectiveness of seismic monitoring depends on the nature of the seismic acquisition set-up, in particular on the temporal frequency content of the data. This influences both subsurface resolution and the sensitivity for detection of gas or fluids. In order to achieve high resolution, it is necessary to record the high frequencies; however, high-frequency signals are also attenuated more quickly (which limits depth penetration) and more susceptible to effects of reverberation and scattering.

The injection of CO_2 alters the compressibility and the density of the reservoir fluid, which has several effects on the seismic response. Firstly, the injection changes the velocity of the seismic waves, which affects the time required for a seismic wave to pass through the reservoir. In seismograms, this can be observed, for example, as time shifts in waves reflected from layer boundaries below the reservoir, and this is a valuable tool for quantifying the amount of injected CO_2 (Fig. 2-2). In order to calculate the CO_2 layer thickness from the time shift, the velocity must be estimated, e.g. by using assumptions about porosity and CO_2 saturation (Chadwick *et al*., 2004).

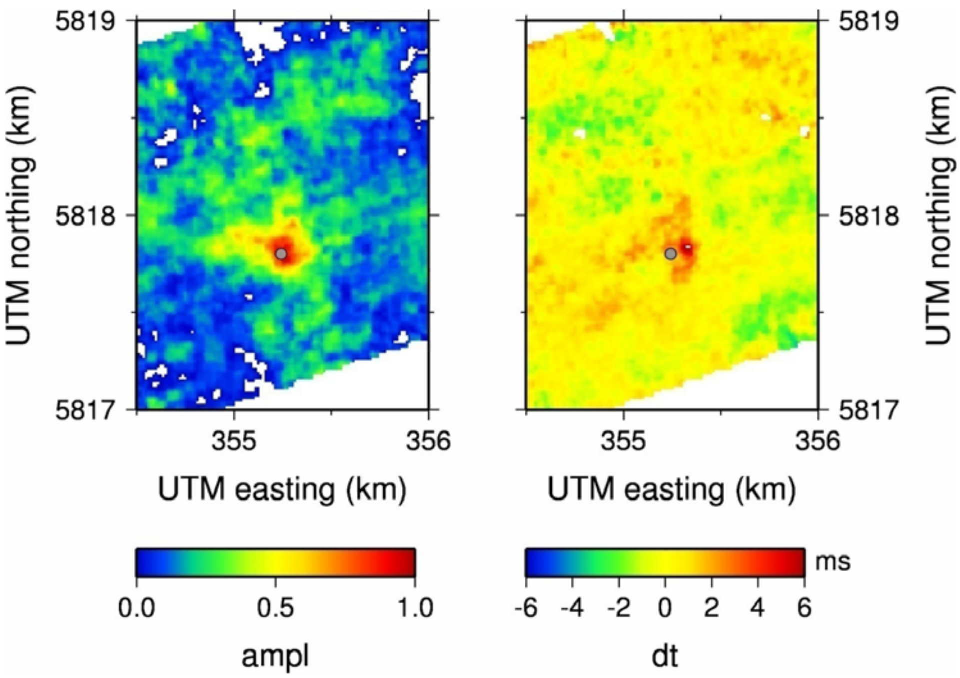

Fig. 2-2: Seismic attribute maps from time-lapse measurements during the project CO_2SINK at Ketzin, Germany (Ivanova *et al*., 2012). The grey symbol marks the injection borehole. Left panel: Normalised time-lapse amplitude at the level of the reservoir, showing an amplitude anomaly due to the injected CO_2. Right panel: Time shift of a reflection below the reservoir caused by a velocity pull-down effect due either to partial CO_2 saturation in the reservoir or to a pressure increase.

Secondly, the injection-induced changes in the reservoir have an effect on the amplitude and the frequency content of the reflected waves. By comparing seismic amplitude and frequency maps from measurements carried out before and after injection, it is possible to track the CO_2 migration with high lateral resolution (e.g. Chadwick *et al*., 2004, Ivanova *et al*., 2012). Volume estimates can also be derived by assuming relationships between reflection amplitude and CO_2 layer thickness, also requiring that additional assumptions are made about porosity and saturation (Chadwick *et al*., 2004). It is also possible to combine the time shifts and the amplitudes to derive volume estimates, e.g. by using the time shift to estimate the thickness of the CO_2 layer and the amplitude to estimate saturation (Ivanova *et al*., 2012).

Several recent studies on CO_2 storage reservoirs (Rabben and Ursin, 2011; Rubino and Velis, 2011) utilise the amplitude variations of the reflected seismic wave as a function of incidence angle. This approach has been used for a long time in the hydrocarbon industry through amplitude versus offset (AVO) analysis, and there are different classes used to distinguish reservoirs based on the AVO characteristics. For a saline aquifer environment, the injection will cause a much smaller change in the S-wave velocity than in the P-wave velocity, and this has effects on the variation of reflection amplitude with incidence angle. Rabben and Ursin (2011) applied amplitude versus angle (AVA) analysis to seismic data from Sleipner to estimate seismic reflection coefficients, which ultimately can be used to calculate the mass of injected CO_2. Numerical studies by Rubino and Velis (2011), again with focus on Sleipner (cf. Section 3.3.1), indicate that it may be possible to obtain reasonable thickness estimates for CO_2-bearing layers having a thickness of only a few meters using AVA analysis.

The most established seismic method for detailed mapping of CO_2 migration is 3D seismic reflection measurements, or rather 4D when carried out in time-lapse mode. Numerous 3D/4D surveys have been carried out in connection with CO_2 injection, both on land and offshore (e.g. Arts *et al*., 2004; Juhlin *et al*., 2007; Urosevic *et al*., 2011). For seismic time-lapse measurements it is important to achieve high repeatability. A useful procedure for assessing the similarity of two or more time-lapse data sets is to use repeatability metrics (cf. Kragh and Christie, 2002). Poor data quality can considerably reduce the detection sensitivity (presence of noise and/or non-repeatable acquisition patterns). Therefore, the same seismic recording parameters should be used for the baseline and repeat surveys. The shot points and geophones should be placed at approximately the same locations for all measurements. Also, the source of the seismic signal should preferably be the same. In land measurements, the position of the groundwater table affects the seismic response, and therefore all measurements should ideally be carried out at the same time of the year. Even after taking precautions to ensure that the data acquisition is carried out correctly, it is necessary to apply careful data processing in order to enable a comparison of the various datasets (e.g. Bergmann *et al*., 2011).

Seismic 2D surveys (i.e., seismic measurements carried out along profiles), are much cheaper than 3D measurements. Sometimes 2D land measurements can be better in resolving structure, e.g. thin layers, than 3D measurements acquired with similar instrumentation. By using a suitable arrangement of 2D profiles it can thus be possible to monitor CO_2 injection, although it can be difficult to know exactly where to place the profiles and there is a risk to miss the CO_2 plume.

The usefulness of seismic measurements varies depending on several factors, e.g. the geometry of the layer boundaries and the physical properties of the rock matrix and the pore fluid. The applicability of seismic methods needs to be assessed when selecting techniques for site characterisation and monitoring, and in some settings seismic methods will not work well. When selecting techniques, it is also necessary to consider the environmental impact of the seismic data acquisition, e.g. the potential damage caused by using dynamite charges or Vibroseis trucks, clearing the vegetation to install geophones or building new roads to transport equipment and personnel.

Seismic borehole measurements can provide higher resolution data than surface measurements, although the lateral coverage is in general more limited. Cross-hole measurements, using a combination of borehole sensors, potentially have very high resolution in a limited volume of the subsurface. It is also common to use a combination of borehole sensors and surface signal sources, commonly referred to as vertical seismic profiling (VSP). VSP provides valuable information about the geological structure of the subsurface and is one of the best techniques to study seismic anisotropy. In VSP exploration, the seismic energy is produced via a surface source at or near a borehole. By using a receiver array in the well it is possible to record both the downgoing and upgoing seismic waves. One big advantage of the method is the ability to correlate the upgoing, or reflected waves, directly to the layer boundaries. The VSP method also produces full volumetric images of the subsurface structures around the well with improved seismic resolution in comparison to surface seismic methods.

The common use of VSP is to depth-correct a seismic survey, i.e. to bind surface seismic (2D or 3D) to well logs and stratigraphy information. VSP can be implemented in a "walk-away" fashion to monitor the footprint of the plume as it migrates away from the injection well. In the walk-away VSP configuration the sources are arranged on radial profiles around the injection well in order to create an offset at the surface as the receivers are held in a fixed location. In connection with the CO_2 injection at Ketzin, a seismic experiment has been carried out using a number of seismic sensors buried in shallow boreholes (at depths of around 50 m), below the groundwater table. Preliminary results show that it is possible to image the CO_2 reservoir with high resolution, by avoiding the degradation of the seismic signal when passing through the highly attenuating dry overburden. (Ivandic *et al*., 2012).

2.1.2 Gravity

Gravity measurements are most useful for monitoring CO_2 injection in saline aquifers. The CO_2 will push away the brine and change the mass (locally) since the density of the CO_2 is significantly lower (i.e. 600 kg/m^3 at a depth of 800 m, and 700 kg/m^3 at 1.5 km depth; IPCC, 2005) in comparison to brine. For example, Bickle *et al*. (2007) assume a brine density of 1020 kg/m^3 for the Sleipner field. Provided that CO_2 replaces the brine, the injection will cause a negative gravity anomaly. Note that the gravity response is linearly dependent on the mass of injected CO_2.

Time-lapse gravity measurements have been used at the Sleipner field to monitor the CO_2 injection in the Utsira formation and the gas production in the deeper Ty formation (Alnes *et al*., 2008; 2011). Using a remotely operated underwater vehicle, the gravimeters were placed on a number of fixed benchmarks on the seafloor. The measurements show a negative anomaly due to the CO_2 injection, as expected.

In addition, the density of the CO_2 in the reservoir can be estimated based on the gravity measurements. There have also been plans to test gravity measurements on land in connection with the CO_2 injection at In Salah, Algeria (Mathieson *et al*., 2010).

Based on the experiences at Sleipner and the noise conditions at this site it has been suggested that the detection limit for a time-lapse gravity anomaly is on the order of 5 µGal (Alnes *et al*., 2008). This would correspond to an injected mass of about 470 000 tons CO_2, assuming that the plume can be approximated as a point mass and using a density of 650 kg/m^3 for the CO_2 and 1020 kg/m^3 the brine. At other locations detection limits may be different.

2.1.3 Geoelectrics and electromagnetics

One method for investigating the resistivity of the subsurface is to use geoelectrical measurements, which are based on the injection of electrical currents into the ground. Geoelectrical measurements can detect changes in fluids (i.e. fluid substitution). The depth of penetration of a surface array depends on the rock and fluid properties. In addition, data quality drops as electrodes are placed further apart.

Saline water or brine can have a very low electrical resistivity. For example, at the Ketzin injection site the brine resistivity is approximately 0.05 Ωm (Kiessling *et al*., 2010). The injection of CO_2 into a saline aquifer will increase the bulk resistivity of the reservoir. However, dissolved CO_2 has very little effect on brine resistivity. Hence, this method is mainly suitable for detecting free CO_2.

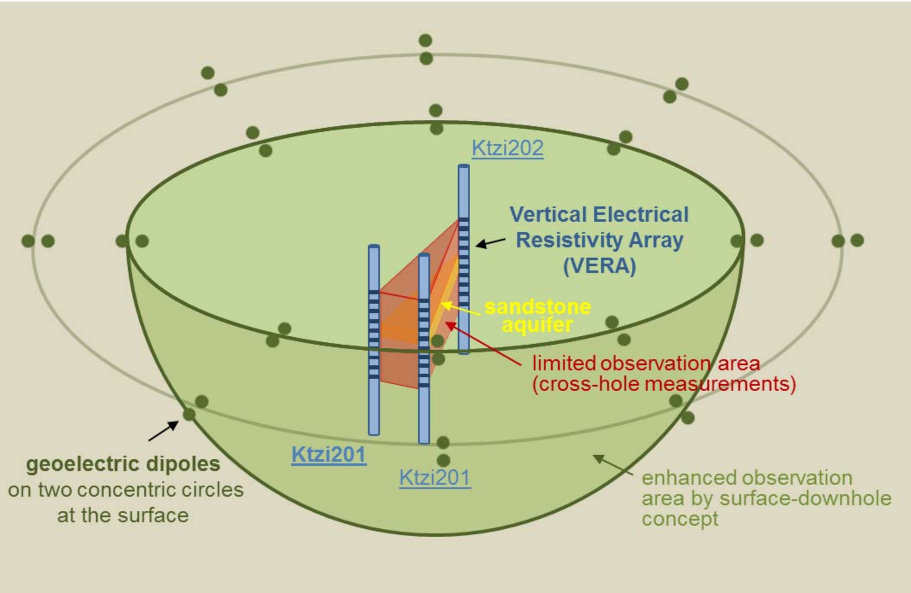

Fig. 2-3: Layout of the combined surface and downhole geoelectrical measurements at Ketzin, Germany (Kiessling *et al*., 2010). Cross-hole measurements provide high-resolution images in the area between the boreholes. The combination of downhole sensors and 16 surface dipole sensors (dipole length of 150m) is used to extend the observation area. The surface dipoles are arranged on two concentric circles with radii of 800 and 1500m. The injection is carried out in borehole Ktzi 201.

In Electrical Resistivity Tomography (ERT) electrical measurements are made at the surface or by electrodes in one or more boreholes. This method can be used to obtain “snapshot” images of relatively static subsurface conditions for site screening or characterisation. It can also be used to obtain a series of images showing relatively rapid changes. ERT works well in both the vadose (unsaturated) and saturated subsurface zones. The extensive data resulting from measurements taken between the electrode arrays are processed to produce electrical resistivity tomographs using state-of-the-art inversion algorithms. These calculated tomographs show spatial variations in electrical resistivity and these images can be used as a guide for focusing more detailed characterisation and monitoring evaluations (Newmark *et al*., 2001). In connection with the CO_2 injection and storage experiment at Ketzin geoelectrical measurements have been carried out using a combination of permanently installed surface and borehole sensors (Fig. 2-3), also including sensors in the injection borehole (Kiessling *et al*., 2010).

At Ketzin the cross-hole measurements provide the highest resolution data and give a smoothed image of the plume (Fig. 2-4). A combination of surface and downhole sensors was also used at Ketzin to extend the investigated subsurface volume. The geoelectrical measurements at Ketzin indicate a maximum increase in the reservoir resistivity of around 200 % after injection.

The resistivity can also be investigated using electromagnetic (EM) methods. The magnetotelluric method images subsurface structures by mapping spatial resistivity variations using electrical currents (or telluric currents) created by natural variations in the Earth’s magnetic field, e.g. by long-period electromagnetic waves from distant thunderstorms. The Earth’s naturally varying electric and magnetic fields are measured over a wide range of frequencies (0.0001 to 10,000 Hz). Concurrent measurements of orthogonal components of the electric and magnetic fields permit the calculation of the impedance tensor, which is complex and frequency-dependent. Using this tensor, it is possible to gain insight into the resistivity structure of the surrounding material (Cantwell, 1960). The magnetotelluric sounding method was used successfully for the mapping of geothermal reservoirs starting in the early 1980s and became a standard application. In recent years, magnetotellurics has also become increasingly popular in oil and mineral exploration. Since it can probe the earth to depths of several tens of kilometres it may also be applied for monitoring CO_2 injection. For this, further developments are required. The resolution of magnetotelluric surveys are, however, limited by the diffusive nature of electromagnetic propagation in the earth.

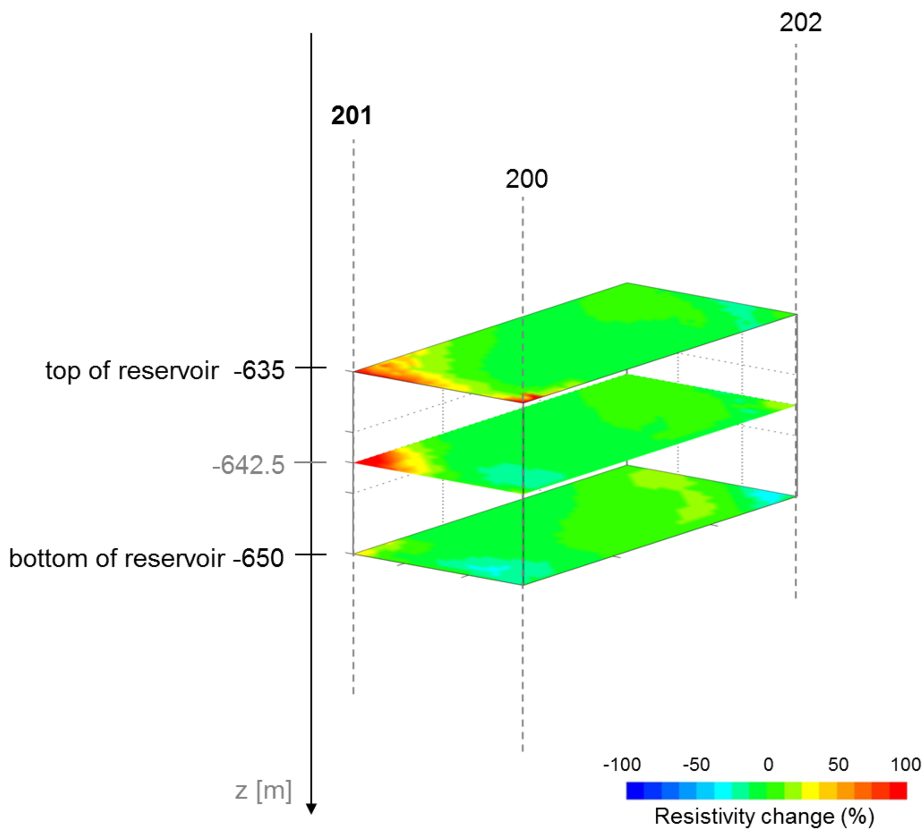

Fig. 2-4: Resistivity difference images for the portion of the reservoir between the three boreholes at Ketzin (Kiessling *et al*., 2010). The CO_2 plume spreading away from the injection borehole (Ktzi 201) is clearly visible as a high-resistivity zone.

There are also possibilities to use a modified version of magnetotellurics in which man-made signals are used, so-called controlled source electromagnetics or CSEM (Bourgeois and Girard, 2010). This method is an established tool in marine work but has so far not been used much on land. An experiment at the CO_2 injection site in Ketzin has showed promising results, although there are still issues with noise (e.g. from power lines) disturbing the measurements and with the practical fieldwork procedure (Streich *et al*., 2011). The transient electromagnetic method (TEM) is another potentially useful monitoring tool, provided that the electrical current loop used to generate the signal is large enough (e.g. Carcione *et al*., 2012; Dodds, 2005). Further tests are needed to fully establish the electromagnetic methods as monitoring tools for CO_2 injection.

2.1.4 Well Logging / Wireline Logging

One of the most common methods for evaluating geological formations is the use of well logs. Logs are conducted by lowering an instrument into the well and taking a profile of one or more physical properties along the length of the well. A variety of well logs is available that can measure several parameters from the condition of the well to the composition of pore fluids and the mineralogy of the formation. Permanent downhole measurements of pressure and temperature are standard for oil and gas production and likewise, e.g. in the Snøhvit CO_2 storage project, pressure and temperature are continuously measured every second in the CO_2 injection well.

Well logging in CO_2 storage projects will also be very useful for inspecting the condition of the well and ensuring that the well itself does not provide a leakage pathway for CO_2. Several logs are routinely used for this purpose, including temperature, noise, casing integrity, and radioactive tracer logs (Benson *et al*., 2002). However, the resolution of well logs may not be sufficient to detect very small rates of seepage through microcracks (Benson and Myer, 2002).

A sonic log is a porosity log that measures interval transit time (Δt) of a compression sound wave travelling through one foot of formation. Sonic logging is essential to calibrate surface seismic methods. The sonic log device consists of one or more sound transmitters and two or more receivers. However, in sonic logging only sound travel time is measured and additional data manipulation is required, e.g. compensation for borehole size variations as well as for errors due to tilt of the sonic tool, to arrive at porosity. No standard protocol is available for conversion from travel time to porosity; there are many variations of the travel time/porosity relationship.

Sonic logging is used usually for the determination of porosity and permeability in porous rock, the detection of fractures, and even for lithology characterisation (Paillet and White, 1982). The sonic velocity contrast between water and CO_2 is strong, so that this log type can be used to assess changes in fluid as the CO_2 plume moves past the wellbore.

2.1.5 Satellite interferometry and other techniques for surface movement detection

Monitoring of surface uplift can be used as an indirect method for mapping of the area affected by CO_2 storage, which can also be interpreted as a form of approximate extension of the CO_2 plume (McColpin, 2009). Limited, differential ground movements have been reported for recent CO_2 storage projects like In Salah, Algeria and were successfully used to track the CO_2 plume migration (e.g. Onuma and Ohkawa, 2009). A relatively wide range of very reliable, established geodetic techniques exist to monitor ground movements. Most of them rely on the periodically repeated surveillance of fixed ground control points. New methods based on remote sensing approaches are able to cover large areas in short time. Interferometric Synthetic Aperture Radar (InSAR, e.g. Ketelaar, 2009) and Persistent Scatterer Interferometry (PSI) are only two examples for a suite of remote sensing techniques which have already proven their suitability for many different other purposes. More details about these techniques are given in Section 2.2.

Monitoring results on ground surface movement represent invaluable input in coupled reservoir/geomechanical models that – through inverse modelling and the history-matching procedure – provide an improved insight into the real behaviour of the CO_2 and the accompanying processes deep in the storage reservoir, occurring during the CO_2 injection phase (e.g. Rutqvist *et al*., 2008; 2010; Shi *et al*., 2012).

2.2 Surface uplift

Surface uplift can represent an (undesirable) accompanying consequence of CO_2 storage, especially at shallower storage sites with higher pressure increase in the storage reservoir. In the worst-case scenario, excessive or uneven uplift can result in damage to installations and real estates on the surface.

The phenomenon of surface distortions is well known from the oil and gas industry, especially at producing oil and gas fields or at natural gas storage sites (e.g. Gurevich and Chilingarian, 1993; Kühn *et* *al*., 2009; Nagel, 2001). It has long been recognised that the withdrawal or injection of any kind of fluid or material from or into the subsurface will generate displacement zones and underground deformations, which can be described in terms of volumetric changes. Such subsurface deformations induce ground level movements. These induced ground surface deformations are measurable quantities that are typically measured as vertical displacements, horizontal displacements and tilts, which are the gradient of surface deformations (Monfared and Rothenburg, 2011). Injection of CO_2 for geological storage purposes does not defy these rules.

An overview of methods suitable for monitoring of surface uplift, or surface deformation in general, is provided, e.g. by McColpin (2009). According to this author, the methods in question fall under the general term Surface Deformation Monitoring (SDM) that is defined as “the process of monitoring ground dilation and/or subsidence caused by the injection or extraction of fluids and gases”. Tiltmeters, Differential Global Positioning Systems (DGPS) and Interferometric Synthetic Aperture Radar (InSAR) are the main monitoring techniques available for these purposes.

2.2.1 Tiltmeters

A tiltmeter is in principle a high-tech carpenter’s level firmly fixed to the ground and able to measure tilt movements with an accuracy up to 1 nanoradian (McColpin, 2009). The principle of a tiltmeter is shown in Fig. 2-5. The device contains a gas bubble, a conductive fluid and three pick-up electrodes that allow the sensor to measure smallest changes in resistance caused by moving of the air/liquid interface in case the surface moves.

Tiltmeters are normally deployed in surface arrays where they pick up ground deformations caused by subsurface strain changes, or they can be placed in boreholes (McColpin, 2009). Several commercial companies offer this technology. In CO_2 storage projects, tiltmeters can be strategically placed around the site to determine surface deformation caused by interaction of the CO_2, brine, and rock.

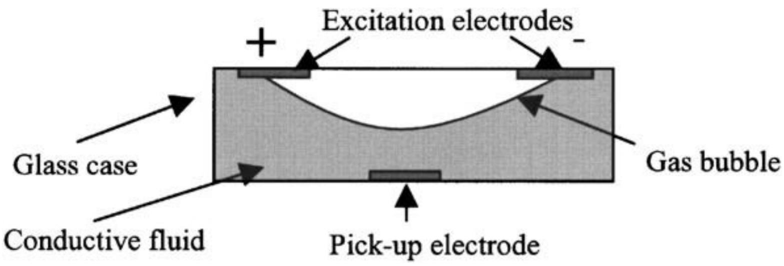

Fig. 2-5: Schematic structure of a tiltmeter (Calderón *et al*., 2004).

Readings are commonly taken every few minutes from a surface array, collated daily by a data acquisition computer and then processed. Measurements can also be collected remotely and sent for interpretation via radio or satellite telemetry. This approach may be useful in places where long-time series can be collected to remove noise. The size of the surface deformation is usually less than a few centimetres, which can be measured with existing tiltmeters (NETL, 2009).

A valuable attribute of tilt measurements is that the size of the surface deformation increases with decreasing depth of the strain change. This makes tiltmeters a favourable tool for quick identification of events like out-of-zone fluid migration or caprock integrity failure, which correspond to significant irregularities in the CO_2 storage site behaviour according to the EC CCS Directive.

A disadvantage of the tiltmeters is that they only provide a point-related information. An array of many tiltmeters might be required (often far from the injection site) to measure the area of deformation. The anomalies usually do not directly identify the CO_2 plume (NETL, 2009). Another issue is their high sensitivity to Earth tides caused by the gravity effect of the sun and the moon (McColpin, 2009). The tides represent a very large signal for these instruments and need to be suppressed by data processing. In this respect, good local knowledge of the tidal variations is essential, based on baseline surveys and simulations carried out before the storage operations commence.

Use of tiltmeters is a mature oil field technology for monitoring stream or water injection, CO_2 flooding and hydrofracturing, especially in North America. For monitoring of CO_2 storage, NETL (2009) considers tiltmeters a “promising technology”. Deployment of tiltmeters for monitoring of CO_2 storage sites has been reported in several cases. CONSOL Energy, Inc. is employing surface tiltmeters to measure reservoir deflection and track plume movement in a US-DOE funded project that demonstrates a novel drilling and production process that reduces potential methane emissions from coal mining, produces usable methane (natural gas), and creates a sink for CO_2 in unmineable coal seams in West Virginia, USA. Several U.S. Regional Carbon Sequestration Partnerships have proposed employing tiltmeter surveys in their monitoring programmes (NETL, 2009). At In Salah, tiltmeters are being used as one of the monitoring technologies with the purpose to monitor three types of risk: plume migration, caprock integrity and pressure development. The main purpose of their deployment is the necessity to calibrate satellite (InSAR) data (Mathieson *et al.*, 2011).

2.2.2 Differential Global Positioning Systems (DGPS)

DGPS is a monitoring technique which uses a minimum of two GPS receivers and sophisticated Kalman filtering to achieve millimetre level measurements of horizontal and vertical motion. One receiver is usually located in an area that is expected to be relatively stable and subsequent receivers are located in regions of interest where motion is expected. By using the two stations, atmospheric variations can be identified and backed out, resulting in the desired millimetre level accuracy (McColpin, 2009). The principle of the method is shown in Fig. 2-6.

DGPS readings, similarly to InSAR (see Section 2.2.3), can be influenced by vegetation or interference caused by buildings, fences and any other objects which might reflect or delay the GPS signal. Evaluating site conditions is critical for proper receiver placement and good-quality results. DGPS is a mature technology used for monitoring of surface deformations in a broad spectrum of applications, starting from seismology, earth crust studies and volcanology, through oil and gas industry operations to landslide stability and engineering applications.

An example of DGPS results from a project focused on crustal deformation is shown in Fig. 2-7. This project was focused on monitoring of surface movements in the seismically active area of the Central Ionian Islands. In the particular case of the Cephallonia island, a local GPS network was established in 2001, and 4 repeat surveys were carried out in 2001 - 2006. Both horizontal and vertical movements were observed. The DGPS results for the whole observational period show horizontal displacements between 10 and 35 mm and a clock-wise rotation of the whole island. Vertical displacements range from 65 mm uplift in the western part of the island to 30 mm subsidence in the East. The results are in agreement with InSAR data (see the text below for technical details of this method) gathered in the same area within several campaigns in 1995 - 2005 (Lagios *et al.*, 2007).

Due to the high hardware cost, DGPS stations are normally used to supplement tiltmeter arrays and InSAR data acquisition. They are critical for providing a long-term and stable ground truth reference (McColpin, 2009). At In Salah, DGPS has recently been used as one of the monitoring technologies with a similar main purpose of deployment to tiltmeters, i.e. to calibrate the satellite (InSAR) data (Mathieson *et al.*, 2011).

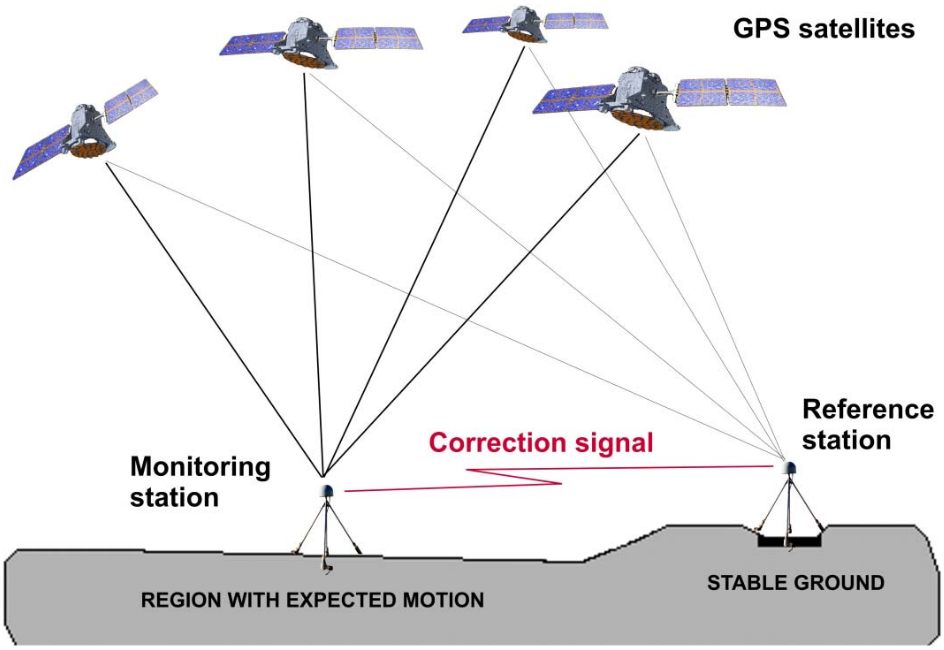

Fig. 2-6: Operational principle of DGPS.

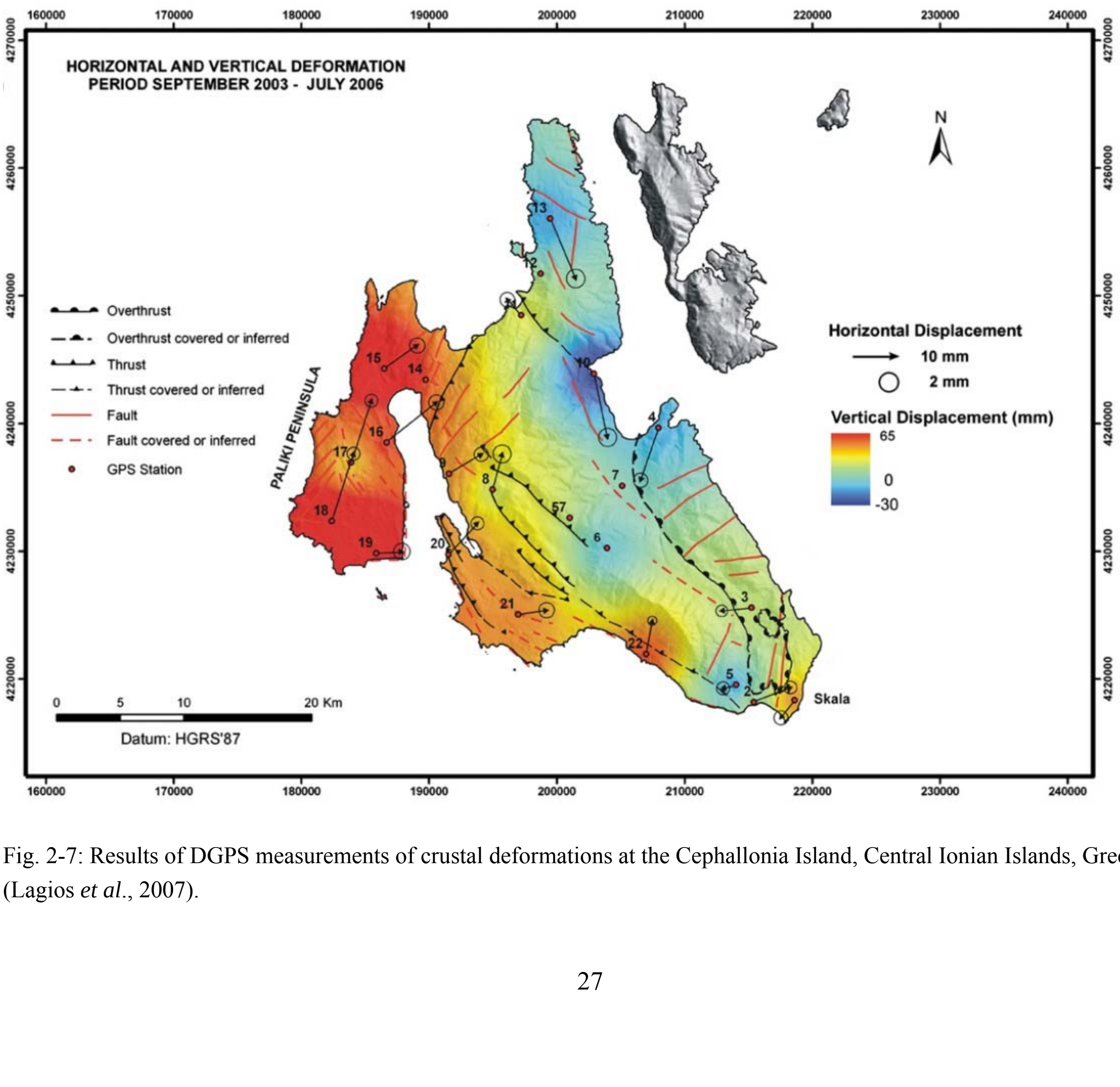

Fig. 2-7: Results of DGPS measurements of crustal deformations at the Cephallonia Island, Central Ionian Islands, Greece (Lagios *et al*., 2007).

2.2.3 Interferometric Synthetic Aperture Radar (InSAR)

InSAR is a satellite-based radar measurement technique able to survey large areas of the earth's surface and provide, at a minimum, monthly updates on ground deformation (McColpin, 2009). The user only has to ask for a satellite to be tasked to a project area and purchase a data subscription to begin acquisition. Images normally cover 2,500 to 10,000 square kilometres. Searches can be easily done for historical baseline data, which may exist in the industry's extensive archives.

InSAR works by taking readings at regular intervals and comparing changes from month to month (see Fig. 2-8). Accuracy with just two scenes is in the centimetre range but millimetre accuracy can be achieved by stacking many months of data to eliminate atmospheric errors. Accuracy can also be improved through integration of DGPS and tiltmeter data, which can provide finer resolution over smaller areas (McColpin, 2009). Differences between scenes are usually represented as coloured bands with each band representing an interval of ground movement.

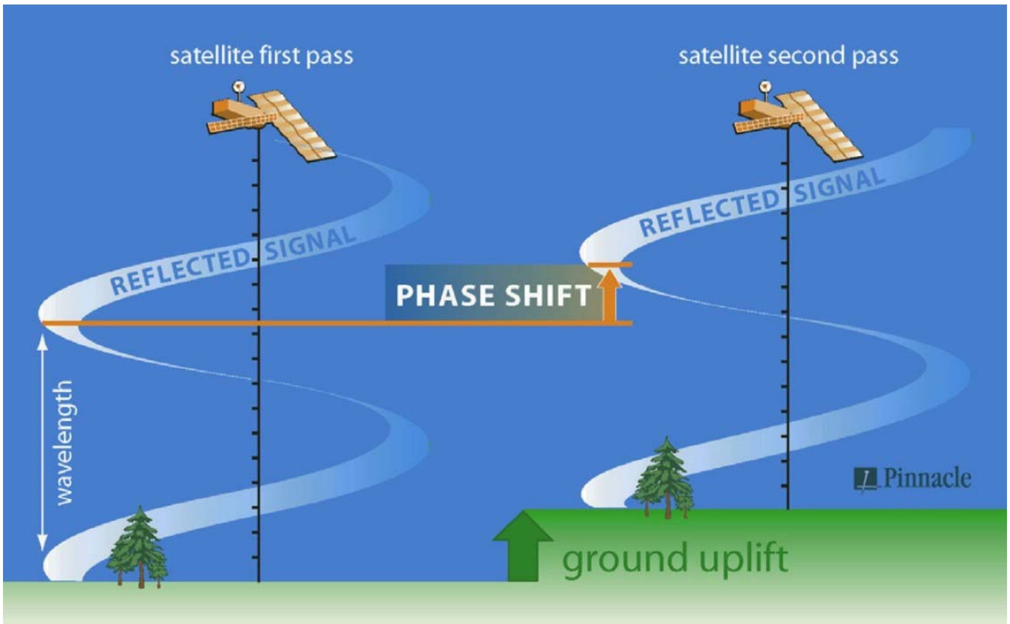

Fig. 2-8: Principle of the InSAR method (McColpin, 2009).

InSAR works best in areas with consistent radar reflections. Areas with dense vegetation can be problematic, as well as areas with natural variations in the surface caused, e.g. by frost heave or wetting-drying cycles, which mask the changes that occur due to pressure changes (IPCC, 2005). Earthworks represent another type of "masking" effects in the survey area.

Results in the above-mentioned problematic areas can be improved by installation of simple sheet metal corner reflectors, which create a high surface-to-noise ratio. By properly placing and installing these reflectors, generation of accurate reflections from month to month can be ensured (McColpin, 2009). Another deficiency of standard InSAR measurements is that the method is unable to resolve the horizontal and vertical components of the recorded motion.

The technology is now being used in various modifications, of which in particular the DInSAR (Differential Interferometric Synthetic Aperture Radar) and PSInSAR (Permanent Scatterers) techniques have provided interesting results. DInSAR is based on pixel-by-pixel computation of interferometric phase using two satellite radar acquisitions: such differential phase is a measurement of what has changed in the time interval between the two satellite acquisitions (ERS: 35 days, Envisat: 35 days, Radarsat: 24 days and TerraSAR-X: 11 days). Apparent phase variations between two satellite images can be caused by actual ground displacement or by atmospheric effects that delay electromagnetic wave propagation. An example of DInSAR results is shown in Fig. 2-9.

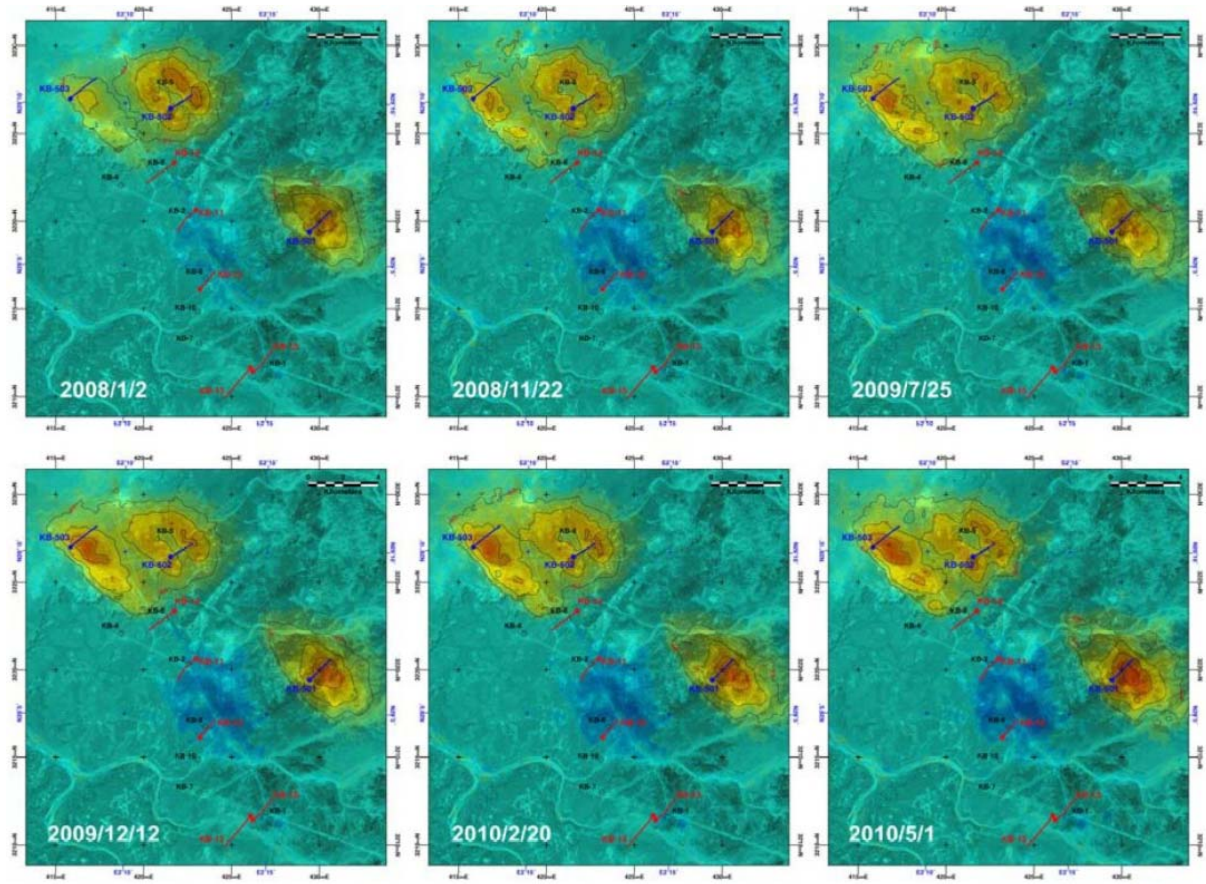

Fig. 2-9: DInSAR results from In Salah showing deformation time series with respect to July 31, 2004 for six selected dates. Areas around the KB-501 and KB503 wells are swelling up, while KB-502 is slightly subsiding. Contour interval is 5 mm (Onuma *et al*., 2011).

The PSInSAR^{TM} technique uses a temporally complete set of SAR scenes obtained over an identical target area. The approach is based on a few basic observations: atmospheric artefacts show strong spatial correlation within individual SAR acquisitions but are uncorrelated in time and, conversely, target motion is usually strongly correlated in time, exhibiting varying degrees of spatial correlation depending on the type of deformation (e.g. subsidence due to water pumping, fault displacements, localised sliding areas, collapsing buildings, etc.). In order to separate these phenomena, atmospheric effects are estimated and then removed by combining data from long time series of SAR images (such as those available in the ESA-ERS archive), which were acquired from late 1991.

In order to improve the accuracy of ground displacement estimations, only scatterers minimally affected by temporal and geometrical decorrelations are selected for processing (Ferretti *et al*., 2001; Tamburini *et al*., 2010). The PSInSAR^{TM} technique was introduced by the Politecnico di Milano (POLIMI) in the late nineties, and later improved by Tele-Rilevamento Europa (TRE). Its main advantages are the extension of area that can be monitored (up to thousands of square kilometres) and the accuracy of the obtained measurements (deformation rates accurate to millimetres/year).

Due to the geographical characteristics of the area, the In Salah CO_2 storage site in the Algerian part of the Sahara desert has become a field laboratory for testing of the InSAR technology for the purposes of CO_2

storage monitoring. Results of several independently working groups have been published (e.g. Onuma *et al*., 2011; Vasco *et al*., 2010). Moreover, the InSAR data were used for geomechanical, reservoir and fluid-flow analyses of processes occurring within the reservoir during CO_2 injection (e.g. Rutqvist *et al*., 2010; Morris *et al*., 2011; Shi *et al*., 2012) or CO_2 distribution simulations (Cavanagh and Ringrose, 2011).

Surface deformation monitoring techniques are generally applicable only onshore. The only exception is tiltmeters: underwater tiltmeters are commonly deployed to monitor sea bottom-based structures. They have not been, however, deployed in larger arrays yet. The issues connected with the use of underwater tiltmeters embrace on-site deployment, power supply and transfer of measured data. Nevertheless, this method could prove to be cost-effective in future compared to other offshore monitoring techniques (McColpin, 2009).

2.3 Induced seismicity and mechanical reaction of overburden

2.3.1 Induced seismicity

Induced seismicity may be related to the injection of CO_2 into deep aquifers (Sminchak *et al*., 2002) and (depleted) hydrocarbon fields. Generally, induced seismicity has long been recognised as a part of human activities such as oil and gas production, dam building, geothermal energy production, mining, quarrying and underground gas storage. The study of induced seismicity has been going on for more than 50 years with two main drivers: (a) the risk, damage and public concern caused by ground motion and (b) the potential to monitor subsurface processes via the induced seismicity. Therefore, induced seismicity is recognised as a potential issue affecting geological storage of CO_2, both as a hazard and as a reservoir monitoring tool. Regarding the potential hazard, there is a significant technical knowledge base referring to seismicity induced from human activities. One important distinction can be made between 'triggered' seismicity and true 'induced' seismicity. 'Triggered' seismicity includes those events that would have occurred naturally at some point in the future but were triggered by human activity, while 'induced' seismicity comprises those events entirely caused by human activity. It is important for CO_2 storage projects to develop a uniform general approach to the induced seismicity hazard. Additional investigations will be needed to improve the understanding and estimation of the potential induced seismicity hazard at any individual site (Myer and Daley, 2011). These investigations may include a structural study of the area, historical seismicity, evaluation of the critical fluid pressure for failure and pre-injection seismic monitoring of the area to define "zero-state" seismicity (Holloway, 2001; Chang, 2007).

Injection of CO_2 into porous rocks at pressures higher than formation pressures can induce fracturing and fault activation. This may pose two kinds of risks (Benson *et al*., 2005):

- brittle failure and associated microseismicity induced by overpressurisation can create or enhance fracture permeability (secondary permeability), thus providing pathways for unwanted CO_2 migration.
- fault activation may induce earthquakes.

An understanding of the structural geology, lithology and hydrology of the CO_2 storage site is critical to determining if injection will induce seismic events (Sminchak *et al*., 2002).

Mechanisms and processes

A conceptual model of possible processes potentially involved in triggering seismic activity by underground injection wells is given in Fig. 2-10.

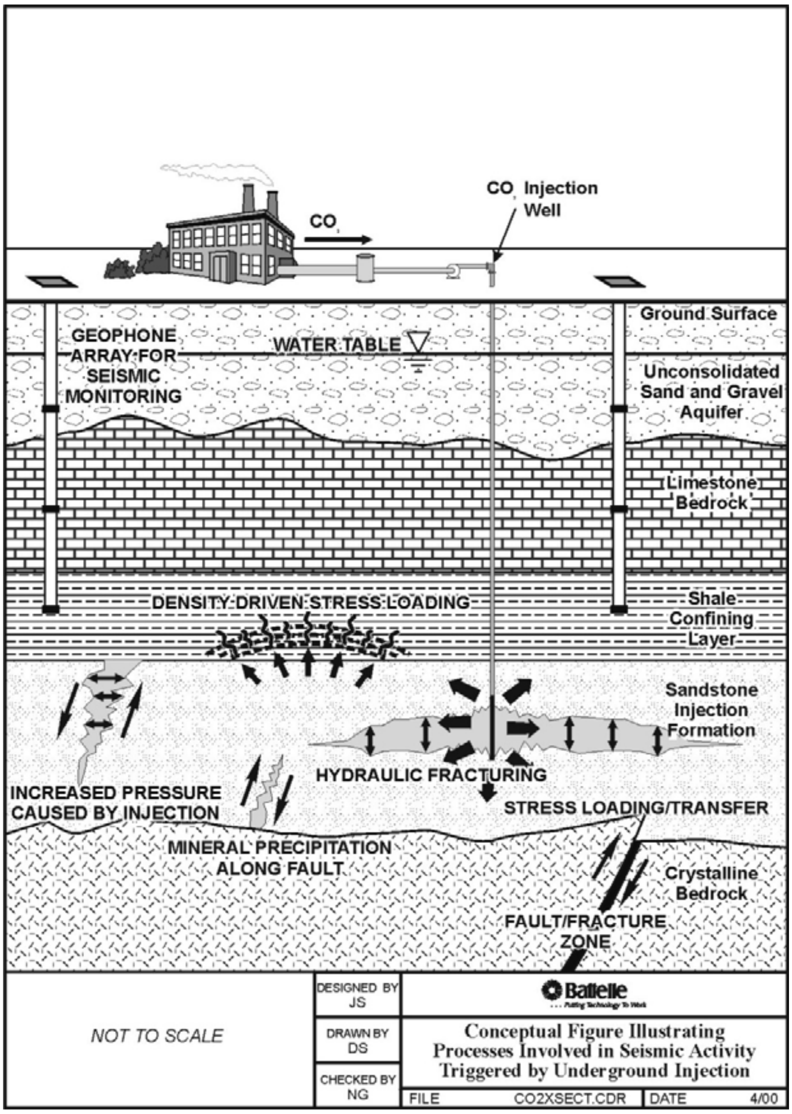

Fig. 2-10: Conceptual figure illustrating potential processes involved in seismic activity possibly induced by underground injection wells (Sminchak *et al*., 2002).

During the process of CO_2 injection at a storage site, in-situ stresses will be modified by pore pressure increases, creating a potential for seismic events due to slippage upon pre-existing discontinuities or due to creation of new fractures (Myer and Daley, 2011). The greatest risk for induced seismicity will probably arise from slip on pre-existing faults and fractures. Other processes involved in the triggering of seismic activity may include transfer of stress to a weaker fault, hydraulic fracture, mineral precipitation along a fault, density-driven stress loading etc. Processes involving faults are described and discussed in more detail in Section 2.4.

In terms of stress equation, deep well injection reduces both the principal and confining pressure in the injection formation while keeping the differential pressure constant, moving the system toward failure (cf. Fig. 2-11). Hence, injection pressures need to be monitored to determine if the changes in pressure may trigger fracture. Geological formations with low permeability and low porosity require higher injection pressures and are thus more susceptible to induced seismicity.

In addition, mineral precipitation by geochemical interactions between CO_2, formation water and reservoir rocks has the potential to significantly decrease formation porosity and permeability. These changes may result in unexpected (local) pressure build-up and formation faulting or fracturing.

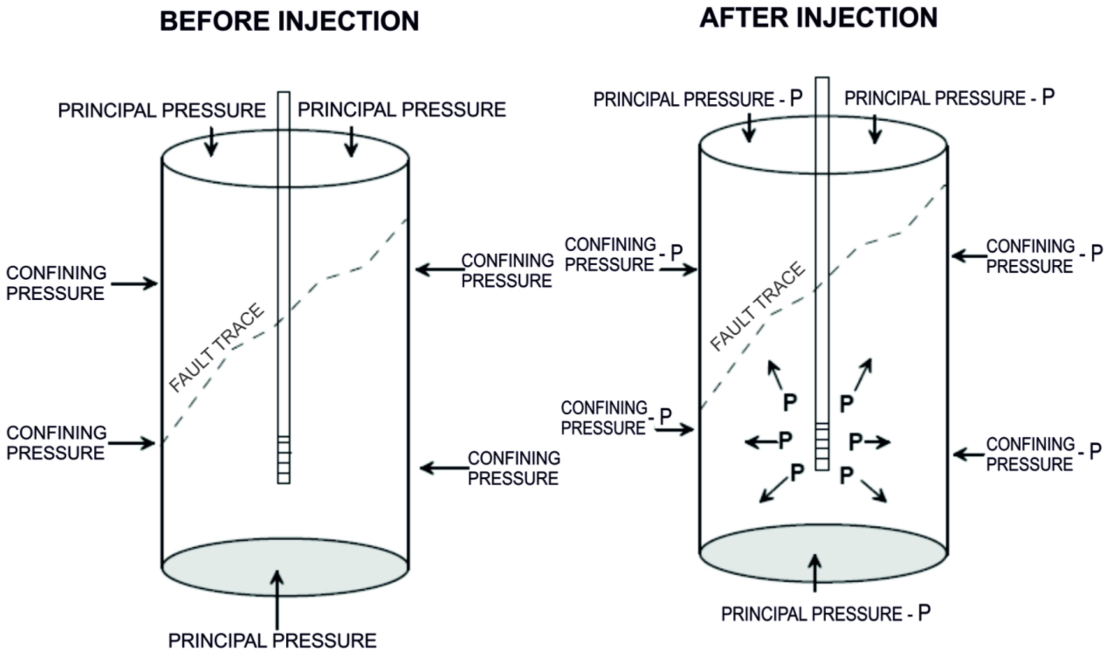

Fig. 2-11: Diagram illustrating how injection pressures (P) reduce the effective confining and axial strength of a rock formation. Injection pressure counteracts confining and axial pressures, reducing the strength of the rock and causing fracture or faulting (Sminchak *et al*., 2002).

Formation pressure may also influence the stress-strain system. At very high injection pressures, rocks may fracture in a process termed 'hydraulic fracturing'. Hydraulic fracturing occurs when the injection pressure exceeds the intergranular strength of the rock, creating or expanding fractures which may trigger seismic activity.

In addition, the density contrast between formation water and injected CO_2 may produce a density-driven flow as the lighter, injected fluids migrate upward. Given the large volumes of fluid involved in CO_2 storage operations, the impact of the density contrasts could be capable of influencing stress conditions at depth, thereby causing seismic events (Sminchak *et al*., 2002).

Risks and potential impacts

Injection activities may affect a formation far beyond the location of the deep injection well(s). Sometimes, seismic events may occur after injection activities are stopped. In addition, earthquakes may be induced in formations well below the injection formation. In conclusion, induced microseismicity must be viewed as a manifestation of wider geomechanical deformation (Verdon, 2010) which must be taken into account for risk assessment.

Generally, the intensity of induced seismicity related to CO_2 injection is low (Environmental Protection Agency, 2008; Pagnier *et al*., 2009). The vast majority of induced seismic events does not release enough energy to be felt by people on the surface and the energy from these events can be used for monitoring of process in the reservoir (Myer and Daley, 2011). However, they may be precursors to larger events (Myer and Daley, 2011). Moderate earthquakes (e.g. of magnitude of 5.1 and 5.2) have already been reported in relation to fluid injection activity (Sminchak *et al*., 2002). None of these, however, were connected with injection of CO_2. The risk of inducing seismicity might be increased when CO_2 is injected into a reservoir in tectonically active regions with high density of active faults (Damen *et al*., 2006).

The risks of induced seismicity can be addressed from a technical perspective through a combination of site characterisation, engineering design, operational procedures and monitoring (Myer and Daley, 2011). In particular, the risk of induced seismicity caused by CO_2 storage operation can be minimised by controlling the injection pressure (Damen *et al*., 2006; Price and Smith, 2008). Regulatory limits are imposed on injection pressures to avoid significant injection-induced seismicity.

In the early stage of site characterisation, data on the general fault and fracture network geometry in the area will be derived from existing data sources such as wells and seismic surveys. The ideal data set is one from a microseismic network established specifically for each CO_2 storage project (Myer and Daley, 2011; Chalaturnyk and Gunter, 2005; Benson *et al*., 2005).

2.3.2 Passive seismic monitoring

Passive seismic monitoring provides a different kind of information to controlled-source seismic techniques. In passive seismic monitoring recording is continuous and information can be analysed in near real time. This technique can only image areas between locations where microseismic events occur and receivers are located. Passive seismic monitoring is an excellent technique for identifying geomechanical deformation induced by injection (Verdon *et al*., 2010). In addition, passive seismics can be used to monitor the formations above the reservoir for evidence of CO_2 migration through the caprock and to assess fracture propagation.

Microseismic monitoring has been employed for about 40 years to measure down-hole processes. Microseismic events can be monitored with geophysical instrumentation such as accelerometer, hydrophone or geophone arrays. For example, microseismic surveys are regularly used to monitor hydrofracturing in commercial oil fields, as well as to track flow fronts and pressure waves during water injection. These technologies are rooted in earthquake seismology and thus, the basic theoretical underpinnings are clearly known. Microseismic monitoring provides an image of fractures by detecting microseismicity (micro-earthquakes) triggered by shear slippage.

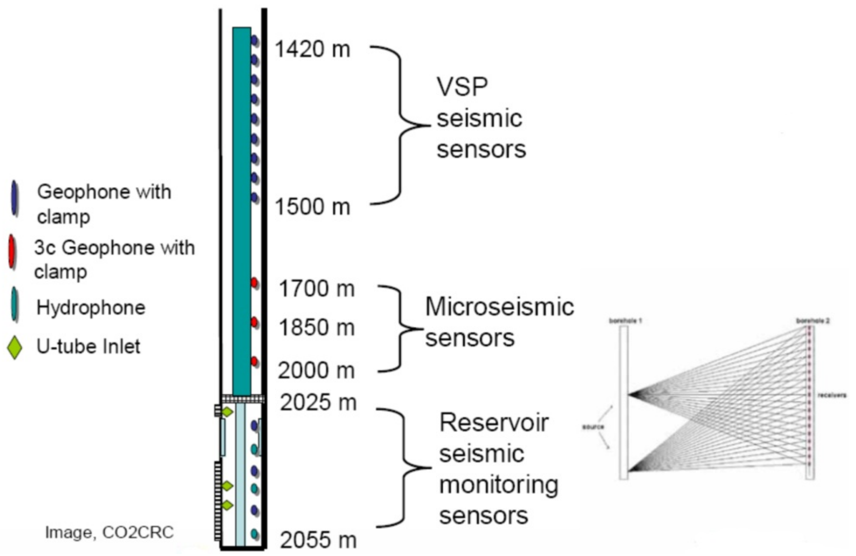

Fig. 2-12: The permanent array in the CO_2CRC Otway project well (sensors installed in Naylor-1 monitoring wellbore) for downhole passive seismic monitoring (Causebrook, 2010; Daley *et al*., 2009).

The location of the microseismic events is obtained, e.g. using a down-hole receiver array that is positioned at depth in a second (monitoring) well near the injection well (Streit and Siggins, 2004;

Fig. 2-12). This way, very small seismic events, commonly between M -4 and 0, can be measured. In cases where suitable offset monitoring wellbores are not available, microseismic mapping can be performed in the injection well. However, the seismic waves attenuate in the rock environment, and it is therefore often difficult to detect events that are more than 800 m away. Furthermore, some fluid-rock systems may not produce any acoustic signal.

Passive seismic monitoring should be performed before injection activities start to obtain baseline conditions. The frequency of seismic activity compared to previous seismic trends may be examined to reveal changes introduced by the injection practices. The magnitude of the seismic events is another line of evidence to link earthquakes to injection.

Detection of induced seismic activity and operational control

Passive seismic monitoring is an important part of assessing induced seismic activity from an injection well (Sminchak *et al*., 2002) and to mitigate the risks of induced seismic activity (Sminchak and Gupta, 2003). Various methods exist to locate microseismic event hypocentres based on the energy recorded at the geophones in order to delineate fracture geometries and to reveal fracture activation and fluid-flow paths (Rutledge *et al*., 2004; Streit and Siggins, 2004). Depending on the frequency of seismic activity at the injection site, months to years of monitoring may be required to achieve an adequate depiction of baseline seismic conditions prior to injection. This may involve the installation of several subsurface seismic sensors around the proposed injection site.

Recording of microseismic events in monitoring wells of CO_2 storage sites can be used to provide real-time control to keep injection pressures below the levels that induce seismicity. Once microseismic recording arrays (geophones) have been installed, the costs of maintenance, operation and data processing are small in comparison with controlled-source seismic techniques (Verdon, 2010; Verdon *et al*., 2010). This is an important consideration for CCS where a site may need to be monitored long after injection has ceased and the field shut in (Verdon *et al*., 2010).

Microseismic monitoring for reservoir characterisation

The microseismic monitoring has a potential for reservoir characterisation. The magnitudes of seismic events are such that they cannot usually be detected at the surface. The Richter magnitude of induced events is typically between +2 and -2 in crystalline rocks and it ranges from -2 to -4 in sedimentary rocks (Streit and Siggins, 2004). During injection, the seismic event locations image the growth of fractures from the injection site, both laterally and above the injection point. By tracking the event locations, one may track potential areas of failure, and thereby stress changes. Since seismic velocities vary according to the density of material, the density contrast between formation waters and injected CO_2 may also provide evidence of the extent of the injected fluid (Benson *et al*., 2005; Sminchak *et al*., 2002). Geophones should be installed in (abandoned) boreholes to provide an early warning of leakage.

The waves from microseismic events recorded on downhole geophones have travelled through only reservoir and caprock materials and wave propagation effects, such as anisotropy, can be used to make inferences about the properties of these rocks and materials. Analysis of shear wave splitting can be performed on recorded microseismic events (Verdon, 2010). S-wave splitting is particularly useful, as it allows the direct measurement of anisotropy, which may indicate the presence of sedimentary layering or aligned fractures.

Microseismic arrays have been installed at the Aneth oil field CCS-EOR pilot site, Utah (Zhou *et al*., 2010), and recently at the In Salah CCS site, Algeria (Mathieson *et al*., 2010; Verdon *et al*., 2011). In 2003 in the Weyburn CO_2-enhanced oil recovery (CO_2-EOR) project (see 3.3.2), a downhole recording array of 8 triaxial 20-Hz geophones was installed in a disused borehole above the reservoir within 50 m of a planned new vertical CO_2 injection well to monitor microseismicity (Verdon, 2010; Verdon *et al*., 2011; Verdon *et al*., 2010). The array has detected microseismicity and events have been located using automated location algorithms. 86 microseismic events have been located over five years of monitoring, representing a low rate of microseismicity and indicating that the reservoir is undergoing little deformation and that the CO_2 is generally moving through the reservoir aseismically (Fig. 2-13). Microseismicity rates correlate with periods of elevated CO_2 injection rates.

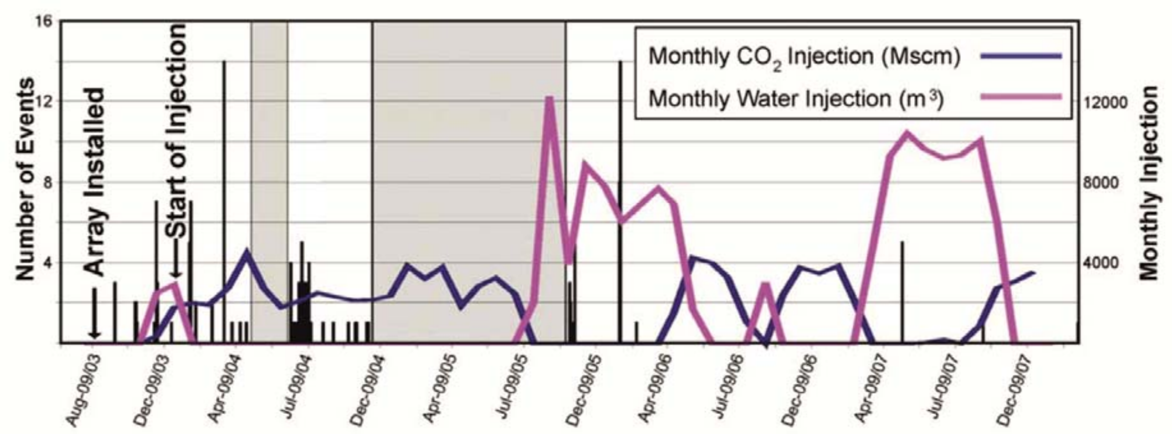

Fig. 2-13: Histogramme of located microseismic events from August 2003 to January 2008 at Weyburn CO_2 injection project. Also shown are the monthly injection volumes for the WAG (water-alternating-gas) injection program in nearby vertical well. The grey shaded areas indicate periods when the passive array (geophones) was not recording (Verdon *et al*., 2010).

2.3.3 Mechanical reaction of overburden

The caprock and overburden are an integral part of a CO_2 storage project. The caprock must be able to bear the change in stress fields during and after injection (Shukla *et al*., 2010). When stress is applied to a porous material, part of stress is supported by the matrix material and other part is supported by the fluid in the pores. The part of the stress supported by the matrix material is termed 'the effective stress' and it determines the deformation of the rock frame. Injection of CO_2 will increase the pore pressure in the target reservoir. This will decrease the effective stress at the injection well due to changes both in pore pressure and the external stress, leading to expansion of the reservoir rocks. This expansion will also lead to deformation of the rocks (a small amount of compaction) in the overburden (Verdon, 2010; Verdon *et al*., 2011). Small reservoirs that are softer than the overburden are more prone to stress arching, where much of the load induced by injection is accommodated by the overburden. These smaller reservoirs are more likely to generate fracturing, both inside and above the reservoir. This may be an important criterion when selecting potential CO_2 storage sites and for monitoring (Verdon, 2010).

Deformation of the overburden can cause a problem for storage complex integrity if fractures and faults are created or re-activated, providing a leakage pathway for CO_2. Most important impacts of a mechanical deformation of the overburden include:

- **Hydraulic fracturing**: Rutqvist and Tsang (2002) mention that the greatest risk of rock failure is at the lower part of the cap rock because of the strongly coupled hydromechanical changes which are generated as a result of reduction in the effective mean stress induced in the lower part of the cap rock. The lower layers of the caprock possess a very high propensity to hydraulic fracturing.

- **Fault reactivation**: Any slight change in the stress conditions or in permeability of the caprock, could lead to the reactivation of existing faults or slips. The propensity for shear reactivation of faults increases due to any increase in the aquifer pressure during the injection period and the development of poro-elastic stresses in the rocks towards the bottom of the reservoir.
- **Fluid-flow driven pressure**: Upward pressure is exerted on the caprock layer when the CO_2 changes its phase from supercritical to liquid or to gaseous form, after injection or when a density-driven flow takes place. This could trigger the initiation of microcracks which can eventually lead to macro-level fracturing of the caprock (Shukla *et al*., 2010).

Indications for these processes can be derived, e.g. from passive seismic monitoring. For applicable monitoring techniques to follow surface deformation see Section 2.2.

Geomechanical modelling of the subsurface is necessary in any storage site assessment and should focus on the maximum formation pressures that can be sustained in a storage site. As an example, at Weyburn, where the initial reservoir pressure is 14.2 MPa, the maximum injection pressure (90% of fracture pressure) is in the range of 25-27 MPa and fracture pressure is in the range of 29-31 MPa (Semere, 2007). For geomechanical modelling it may be important to consider reservoir heterogeneity. Differences in porosity through a reservoir imply differences in rock fabrics. Differences in grain-size can exert significant influence on elastic stiffness. Differing degrees of carbonate cementation will produce different elastic stiffness as well. Small heterogeneities will probably not lead to changes in the shape of stress loops around the reservoir. Larger scale heterogeneous zones may act to change the nature of the geomechanical response of a reservoir. To assess these impacts, a geostatistical model could be used, which varies the difference in mechanical properties between the heterogeneous zones and the ‘background' reservoir material, the proportion of the reservoir made up of the ‘heterogeneous' material, and, importantly, the characteristic length scale of the heterogeneous zones (Verdon, 2010).

To guarantee security, site operators must be able to demonstrate that geomechanical deformation will not be of sufficient magnitude to damage the cap rock. Operators must also ensure that CO_2 injection will not induce earthquakes on any nearby faults (Verdon, 2010). This can best be achieved by combining appropriate monitoring tools and geomechanical modelling.

2.4 Faults

Faults represent an important geological feature significantly influencing the CO_2 storage complex. Their role with respect to the storage reservoir can be twofold:

- Permeable faults serve as preferred migration routes for both the injected CO_2 and the original reservoir fluids. In case they intersect the impermeable caprock, they may become migration pathways leading to leakage of CO_2 out of the reservoir.
- Impermeable faults act as barriers for migration of CO_2 and reservoir fluids, often causing reservoir compartmentalisation. Consequences of this situation might be, e.g. reduced storage capacity and/or injectivity of the reservoir, rapid pressure increase around the injection well.

Determination of exact location and geometry of faults in the storage complex and investigation of their character belong to the most important goals of site characterisation. Usually, the first information on fault presence and geometry as well as their first-order characterisation are obtained from a 3D seismic survey. To assess the large-scale heterogeneity of the storage container, including its vertical and lateral compartmentalisation and the sealing nature of fractures and faults, pressure measurements may be employed, e.g. during well-tests or by Repeat Formation Tester (RFT) or Modular Formation Dynamics Tester (MDT) logging (Arts *et al*., 2009).

Mapping of faults from seismic data and building a fault model is an important activity when creating the three-dimensional static geological earth model of the storage complex. This commonly involves simplification or generalisation of fault planes. This initial fault model is usually refined by well correlation when sub-seismic faults may become apparent, especially in cases when stratigraphic sections are missing (normal faults) or doubled (reverse faults).

It is important to assess the sealing capacity of faults as this may lead to compartmentalisation of the storage reservoir and/or leakage through the caprock. Compartmentalisation is a key input in the earth model, as it will lead to rapid pressure increase and demands for a relatively high number of injection wells (Arts *et al*., 2009). At the same time, knowledge of fault properties is also critical for geomechanical modelling of the reservoir.

Fault properties are also important for geochemical characterisation of the site and related geochemical modelling. The nature of fault-filling minerals must be assessed, since the sealing potential of faults cutting the reservoir or overburden may be reduced as a result of CO_2 induced dissolution. To avoid the risk of decreasing sealing potential in response to dissolution of carbonates, the carbonate content of sealing formations should be accurately studied and incorporated in the earth model, in particular if these formations are fractured or faulted (Arts *et al*., 2009).

Monitoring of faults

Monitoring of faults can be divided into two main issues:

- monitoring of changes in the fault system in and around the reservoir, which especially comprises changes in the integrity and sealing properties of the faults;
- monitoring of potential leakages of CO_2 from the storage reservoir via faults as preferential migration pathways.

The integrity of faults is part of the storage reservoir integrity as a whole, and the monitoring methods for these purposes are well established. Usually, the first indicator of a change in the reservoir behaviour is a sudden change in reservoir pressure.

Such a change needs to be detected as soon as possible since it normally indicates an unpredicted, and often undesired, event in the reservoir, which may (in the worst case) correspond to a significant irregularity according to the EU CCS Directive or even to a CO_2 leakage from the reservoir. Such a pressure change can have various causes, a change in fault integrity being one of them. Alternatively, the change in fault properties can be a slow process with slower changes in reservoir pressure. In both cases, however, reliable continuous reservoir pressure measurement is the main condition for timely detection of the change.

Permanent measurements of reservoir pressure are part of commonly used, permanent downhole monitoring technologies that have been used in the oil and gas industry for several decades. Measurement devices and downhole installation services are commercially available. The gauges are usually installed in the well casing to be able to read the formation pressure directly (see Fig. 2-14). The gauges are normally installed in monitoring wells penetrating the storage formation but they can also be placed in adjacent overburden layers, preferably on places where presence of faults has been detected or assumed. An example of a pressure monitoring record is shown in Fig. 2-15.

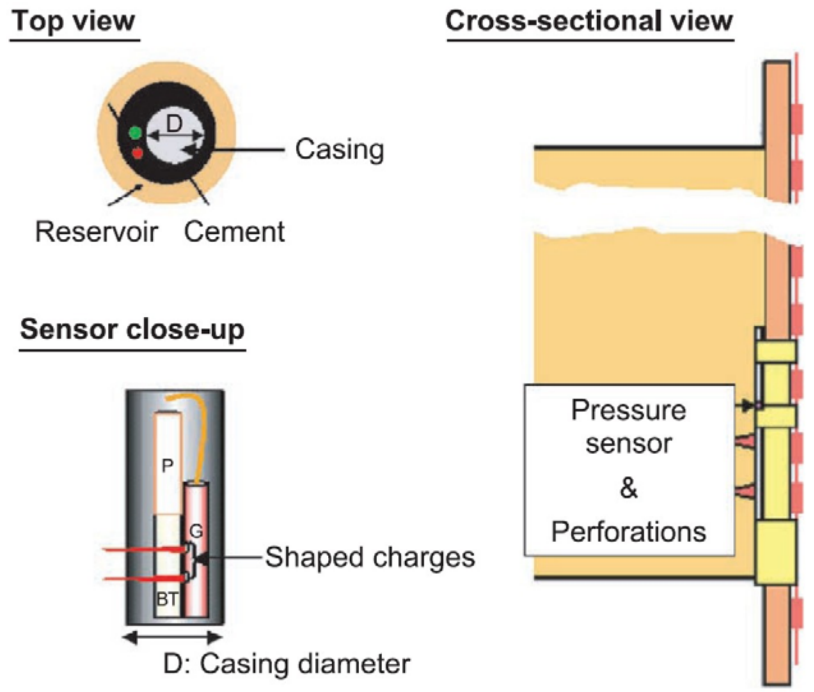

Fig. 2-14: Graphical illustration of a permanent downhole pressure gauge installation. The gauge is cemented behind casing and operates in direct hydraulic communication with the formation (Alpak *et al*., 2004).

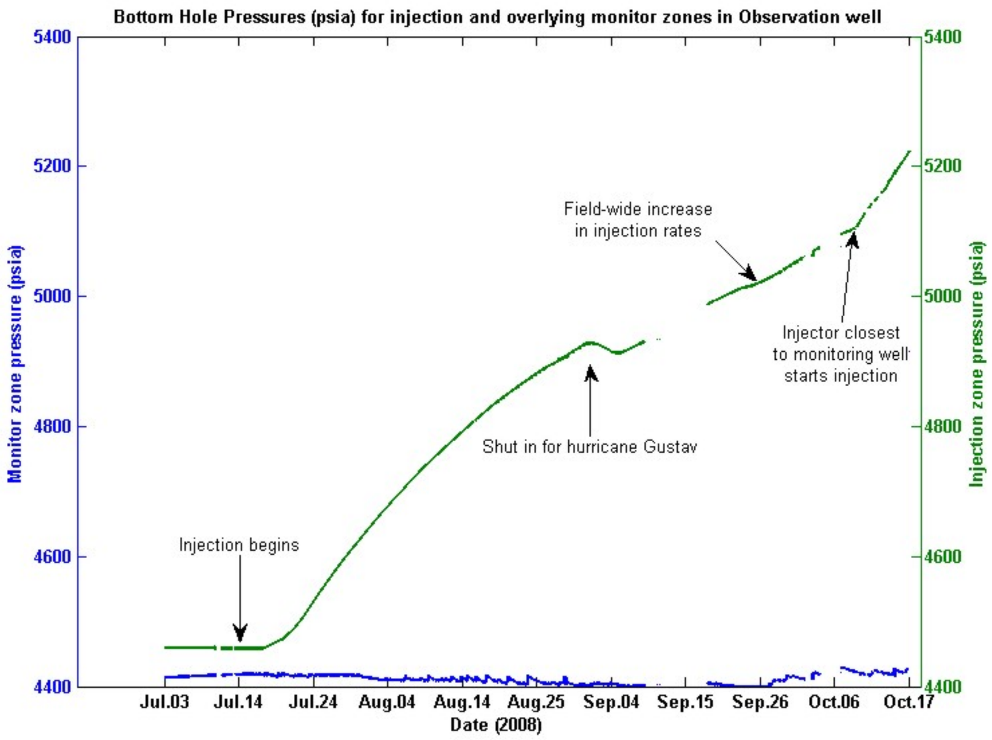

Fig. 2-15: Example of reservoir pressure monitoring at the Cranfield CO_2-EOR site in Mississippi, USA. The plot shows evolution of pressure within injection zone (green) and overlying monitoring zone (blue). Pressure in the injection zone has significantly increased since injection start, while monitoring zone pressure has stayed constant, indicating no communication between the two zones. Annotations are for various events during field injection. Data gaps are a result of data communication issues between downhole gauges and surface recording devices (Meckel *et al*., 2008).

Another technique able to detect changes in fault integrity is passive seismic monitoring. Re-activation of existing faults or formation of new faults and fractures caused by increased reservoir pressure produce seismic activity that may be monitored in the form of microseismic or even seismic events by passive seismic monitoring (see example in Fig. 2-16). For more details regarding this technique see Section 2.3.

Changes in fault extent, shape and properties can also be derived from time-lapse measurements of various kinds that are part of the site monitoring plan. This is especially valid for 3D seismics, well-logging in monitoring wells or surface deformation monitoring. The results of time-lapse measurements may lead to updates in both reservoir and geomechanical models and simulations, including the characteristics and role of the fault system (see also Sections 2.1 and 2.2).

Methods for monitoring of potential leakages of CO_2 from the reservoir via permeable faults are more or less identical with the methods suitable for monitoring of overlying and adjacent aquifers (Section 2.6), freshwater aquifers (Section 2.7) and near surface eco-compartments (Section 2.8). The known presence of faults leads to a special areal or spatial focus of monitoring layouts that can be concentrated to places/areas above or close to existing faults to allow early detection of a potential leakage.

These monitoring targets correspond to the segments of the subsurface where the CO_2 migrating from the storage reservoir can accumulate. The NETL Best Practices manual (2009) mentions two techniques particularly suitable for monitoring for leakage into overlying formations through faults or fractures:

- pressure monitoring in the overlying formation (see Fig. 2-14 for example), and
- monitoring for tracers (e.g. PFCs).

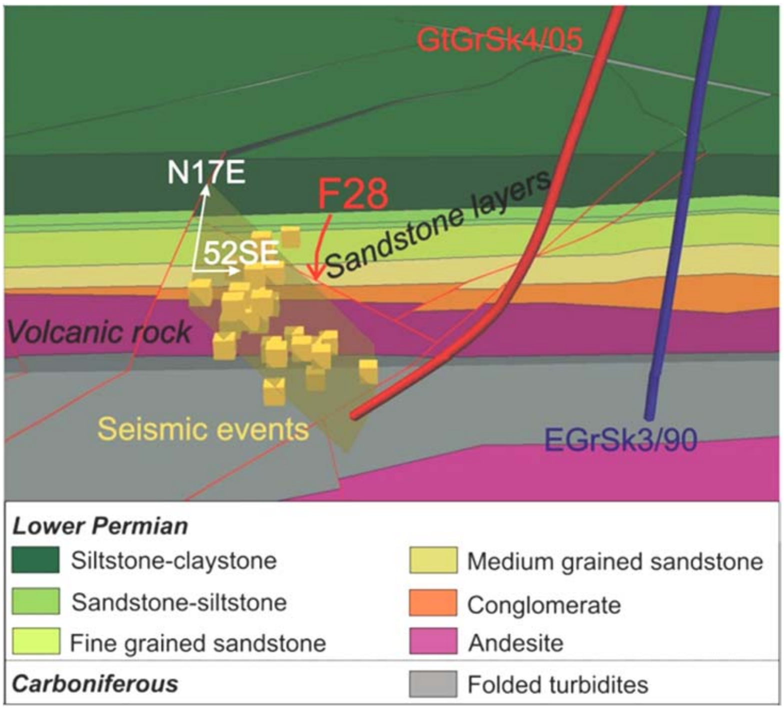

Fig. 2-16: Interpretation of microseismic events recorded during water injection operations at the Groß Schönebeck geothermal research field, Germany. Yellow boxes show interpreted locations of low-magnitude microseismic events, probably occurring along an existing fault plane and indicating thus reactivation of an existing fault. The additional fluid pressure was between 20 and 24.5 MPa (Moeck *et al.*, 2009). Similar events may potentially happen at CO_2 storage sites, if the reservoir pressure exceeds safety pressure limits.

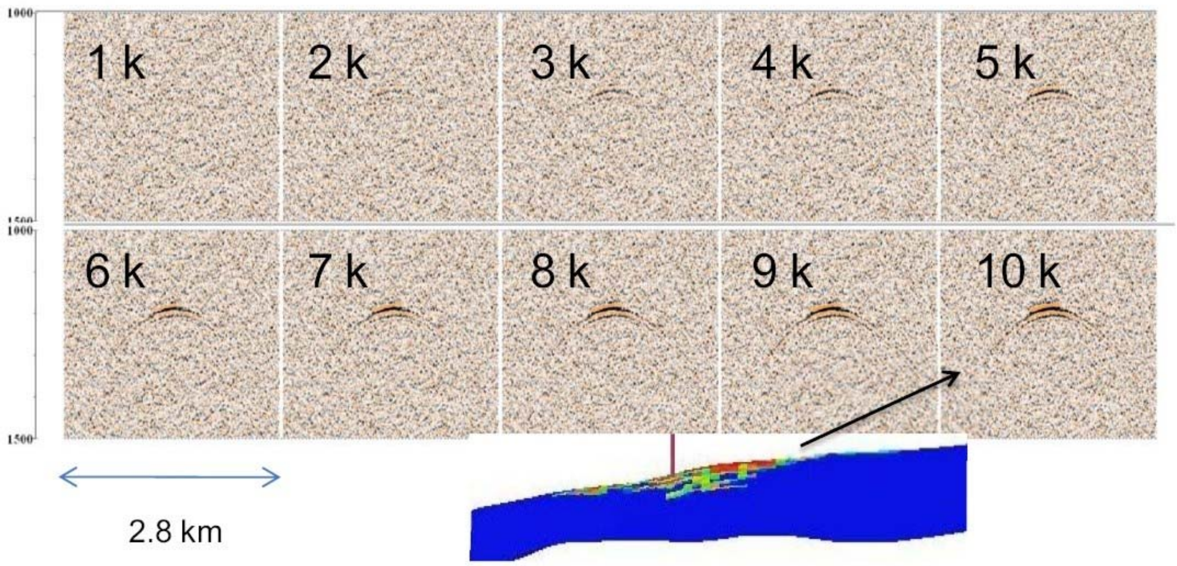

Fig. 2-17: Results of seismic 4D modelling of the “leak” scenario at the Otway Basin Pilot Project in Australia. In the modelled case, CO_2 migrates from the Naylor reservoir along the Naylor fault into the overlying Paaratte formation. Distribution of CO_2 for the model was extracted from reservoir simulation for various leakage quantities. The leaked CO_2 shows up as diffraction, in this case submerged into the background noise proportional in magnitude and frequency content to the actual one observed during field experiments (Urosevic *et al*., 2011).

Time-lapse measurements represent another group of techniques potentially capable of detecting leaking faults. Urosevic *et al*. (2011) modelled 4D seismic response of CO_2 leaking along a fault from the Naylor reservoir within the Otway Basin Pilot Project in Australia. The authors demonstrated that small quantities of CO_2 are likely to produce very strong changes in the elastic properties of the host rock that would be readily detected by time lapse seismic monitoring (see Fig. 2-17).

2.5 Abandoned wells

Exploration and production wells are drilled for the discovery and exploitation of hydrocarbon reserves. The wells which are not feasible to produce from are abandoned following the drilling and testing operations. Production and injection wells (used for injecting fluids into reservoirs for improved oil recovery applications or to dispose produced water) continue operating until the economic limit is reached, where the utilisation of the wells is no longer feasible, and then they are abandoned. The abandonment can either be temporary, if the operator is to make use of the well in the future, or permanent, if the well is no longer required.

Temporary abandonment of the well requires the removal of the production equipment and setting retrievable/drillable barriers in the wellbore to prevent any flow from the well. When the well is permanently abandoned, the production equipment is removed from the well, mechanical barriers are set in the wellbore, the wellhead is removed, the casings are cut off below the ground level, caps are welded on top of the casings, and the well is usually buried. An abandoned well may sometimes be re-entered and restored to production or injection, but usually the re-utilisation of an abandoned well is economically and technically not feasible.

There have been different approaches for the rules and regulations for well abandonment. Different countries, different environments and different time periods show variance in applied rules and regulations for abandoning exploration, production or injection wells. An overview of relevant regulations in various countries is given in Korre (2011).

The proper abandonment of the wells is aimed to achieve mainly three goals:

- prevention of cross flow between reservoirs,
- protection of freshwater aquifers from contamination and
- prevention of leakage of reservoir fluids to the surrounding formations or to the surface.

In order to achieve these goals, physical barriers are placed in the wellbore. These barriers can be mechanical plugs or cement plugs set into the wellbore and caps welded on top of the casings.

2.5.1 Significance of abandoned wells in CO_2 leakage

Abandoned wells which penetrate the CO_2 storage sites or which are in the close vicinity to those can provide pathways for CO_2 to leave the storage environment and reach overlying aquifers or to the surface.

Especially if the CO_2 storage is implemented in depleted natural gas and oil fields, there may be many abandoned wells within the radius influenced by the injected fluid. All of the temporarily and permanently abandoned wells located in the influence area have to be evaluated before the CO_2 injection is commenced and their integrity has to be monitored over long time frames during the injection and storage operations and post-closure periods, to ensure that these wells will not be providing a pathway for the injected CO_2 to leave the storage complex and migrate to upper formations or to the atmosphere (Syed, 2011).

The well abandonment procedures applied in the oil and gas industry are based on oil field practices and requirements, without any consideration of the integrity of the abandoned wells under CO_2 storage applications. Although the reactivity of pure CO_2 is generally considered to be low, once contacted with brine, it forms H_2CO_3, a weak acid. This causes the pH of the brine to decrease and makes the brine more corrosive. Therefore, the presence of CO_2, particularly the presence of water acidified by CO_2, may deteriorate the well cement and cause corrosion. Unless measures are taken for ensuring the long term integrity of the abandoned wells in the presence of CO_2, the existing abandoned wells may be potential conduits for the leakage of CO_2.

2.5.2 Possible pathways and common causes for CO_2 leakage in an abandoned wellbore

In an abandoned well, there are various pathways for the leakage of CO_2 to overlying permeable intervals or to the surface (Nygaard and Lavoie, 2010; Duguid and Tombari, 2007; Syed and Cutler, 2010). These include:

- CO_2 migration through the pathways and/or pores of the well cement (both for cement plugs in the wellbore and for the cement behind the casing, in the production casing/outer casing annuli),
- CO_2 leakage through the annular space between the production casing and the cement behind the casing,
- CO_2 leakage through the annular space between the cement behind the casing and the formation,
- CO_2 leakage through damaged casing and
- CO_2 leakage through damaged bridge plugs or other mechanical plugging equipment set in the wellbore.

The most common cause of leakage from abandoned wells is failure of the cement to prevent CO_2 flow. This can be either due to failures in the proper application of primary casing cement jobs, cement squeeze jobs and cement plugs or due to cement deterioration when the cement is exposed to both CO_2 and the water acidified by the presence of CO_2. Although a study on the analysis of the cement in an oil well with 30 years of CO_2 exposure showed that the cement retained its capacity to prevent any significant flow of CO_2 (Carey *et al*., 2007), various laboratory studies (Carey *et al*., 2010; Brandvoll *et al*., 2009) demonstrate the deteriorative effect of CO_2 and CO_2-brine mixtures on cements. Research has demonstrated that there may be CO_2 leakage even from wells which are properly cemented and abandoned, mainly because of the weak acid formed by the interaction of CO_2 with formation water which deteriorates the cement quality.

A study performed to investigate the factors affecting wellbore leakage in Alberta, Canada (Watson and Bachu, 2009), indicates that the factors which have the greatest impact are:

- **Geographical location**: The study showed that wells at certain regions demonstrated a higher probability of leakage. This may be due to the geological setting, site-specific problems with drilling, completion and cementing, and varying operating practices applied by different companies operating in different regions.
- **Wellbore deviation**: Compared to vertical wells, the occurrence of leakage was higher in deviated wells. The reason may be improper casing cementation in deviated wells due to casing centralisation problems and cement slumping, increasing the probability CO_2 migration behind the casing.
- **Well type**: Cased wells have higher potential for CO_2 leakage compared to drilled and abandoned wells without casings. The reason can be more stringent abandonment procedures required for drilled and abandoned wells and also, additional pathways for CO_2 migration existing in cased and perforated wells.
- **Abandonment method**: For cased and completed wells, the most commonly used abandonment technique in Alberta is setting bridge plugs capped with cement. The study showed that 10% of these types of abandonment applications will fail in long term (hundreds of years). In comparison, other methods such as setting a cement retainer and squeezing cement through perforations or placing a cement plug across perforations is expected to have a lower failure rate. The damaging effect of CO_2 on the elastomers and metal elements of bridge plugs may also add to the failures of such mechanical plugging equipment.
- **Oil price and regulatory changes**: As the oil price increases, the drive to achieve more with lower cost may have led to lower quality of performed primary cement jobs. Regulatory changes, imposing stricter procedures for well abandonment, are expected to improve the abandoned well integrity.
- **Uncemented casing/hole annulus**: Low cement tops behind casings were found to be the most important factor for CO_2 leakage in the Alberta study. The absence of cement behind the casing increased the external corrosion of the casing significantly and also allowed the CO_2 to move up the uncemented pathway.

2.5.3 Current well abandonment practices

Different regulations exist in different countries for the abandonment of wells (Korre, 2011). The regulations may show variances, but they all serve the purpose of preventing the flow of formation fluids between permeable zones and to the surface. Most of the abandonment practices require at least two barriers to prevent the flow of reservoir fluids up the wellbore. The applications show some variations based on well type, reservoir and fluid properties and environmental and safety concerns specific to the location and application. An overview can be found in Wollenweber *et al*. (2012).

The regulations of Alberta Energy Resources Conservation Board (ERCB, 2010) may serve as an example for the required abandonment procedures for three different well types (Watson and Bachu, 2009):

i) Wells drilled and abandoned before setting casing to the total depth: Any porous interval must be isolated to prevent cross flow between different zones. Also aquifers with salinities less than 4000 mg/L must be covered with cement to prevent contamination. After setting the cement plugs, the well has to remain open for five days to detect if there is any leakage. If no leakage is observed, the casing is cut one meter below the ground level and a cap is welded on top of the casing.

ii) Wells drilled, cased, completed and abandoned: If the well is cased and perforated for production/injection, the applied abandonment procedures can be one or more of the following:

- setting bridge plug above perforations and capping with cement,
- performing squeeze cementing operations for the perforations with a cement retainer,
- setting cement plug across perforations.

Squeeze cementing is performed if communication behind the casing is expected due to poor primary cement.

Sections of wells not filled with cement must be abandoned with fluids inhibiting corrosion before abandonment. Pressure testing is required with a minimum of 7000 kPa. The well must be checked for any leaks. If any leak is detected, remedial operations must be performed to stop the flow before cutting the casing and abandoning the well. If no leakage is observed, the casing is cut one meter below the ground level and a cap is welded on top of the casing.

iii) Wells drilled, cased and abandoned: If the well is cased but not perforated, the abandonment procedures are the same as the previous case, without the necessity for isolating any perforations. Abandoning non-completed wells with cemented liners can be done by setting a bridge plug within 15 m above the liner top and capping it with either a minimum of 8 vertical metres of class "G" cement or with a minimum of three vertical metres of resin-based, low-permeability gypsum cement. Instead of using a bridge plug, a cement plug can also be set across the liner top, extending from a minimum of 15 vertical metres below the liner top to a minimum of 15 vertical metres above the liner top (ERCB, 2010).

2.5.4 Applicable monitoring techniques

Many different techniques are available for the CO_2 leakage monitoring both within the wellbore and at the surface, around the wellhead (Clyne *et al*., 2011, Plasynski *et al*., 2011). The monitoring methods applicable to abandoned wells are basically limited to surface measurements because the abandoned wells commonly have their casings cut below the ground level and a cap welded on top of the cut casings. Therefore, monitoring technologies involving wireline equipment and downhole tools are not applicable to abandoned wells unless these wells are re-entered and the mechanical plugs and cement plugs are drilled to provide access to the wellbore. Since the leakage of CO_2 from the abandoned wells can be confined to the wellbore or the gas can migrate outside the casing, surfacing around the well, the known presence of wells leads to a special areal or spatial focus of layouts of surface monitoring focussing on the vicinity of wells. Applicable monitoring techniques for abandoned wells use direct and indirect methods for monitoring CO_2 leakage. Direct methods measure CO_2 or tracer concentrations or flow rates to detect leakage, such as analysis of CO_2 concentrations in air or in soil/sediment gas. Indirect methods use measurements which indicate CO_2 leakage like ecosystem stress monitoring, groundwater monitoring etc. These techniques are described in more detail in Section 2.8.

Wells are commonly abandoned by cutting the casings below the ground level and welding a cap on top of the casings. Leakage through the cap may occur if the welding is not done properly or if the cap corrodes with time. If there are other indications of CO_2 leakage from the abandoned well, the cap and the welding can be checked and wellhead pressure can be monitored to identify any leaks (Watson and Bachu, 2009).

2.6 Overlying and adjacent aquifers

Generally, the degree of mineralisation of formation waters increases with increasing depth, although locally other settings may occur, e.g. in deep karst or in arid and coastal environments. Hence, overlying and adjacent aquifers may comprise saline and/or freshwaters. Measuring the geochemical evolution of subsurface formation waters is one tool to directly detect the potential impact of leaking CO_2, brine or other fluids into overlying or adjacent aquifers. These measurements require fluid sampling on a regular basis. Monitoring could be undertaken in boreholes that penetrate the reservoir or in monitoring wells that penetrate overlying formations. Measurements could include parameters, such as: pH, alkalinity, HCO_3^-, dissolved gases, hydrocarbons, major and minor elements, TIC, TOC, stable isotopes, redox potential, specific conductance, TDS, density, natural and introduced tracers. It is important to design the sample retrieval system that will conserve the properties that are required for analysis. Fluid mixtures (CO_2, brine plus any other relevant fluid or hydrocarbons) will density-separate in the wellbore, and this fractionation will increase as fluids move upward through tubing and gases expand and become less dense. Temperature and solubility relationships will also change, for example gas in solution will evolve. If needed, several techniques can be used to reduce these complications.

Extraction of fluids is labour-intensive, requiring a gas lift or pumping system except where pressure or gas saturation are high enough to lift fluids to the surface. Commercial downhole sampler systems can be deployed on wireline or slickline to collect samples at reservoir pressure and temperature and then conserve this volume during transport to the surface. Well drilling and completion may cause contamination of the near wellbore environment with allochthonous fluids that must be reduced and corrected for.

A U-tube sampler was designed for the Frio Project that allows samples to be returned to surface at near reservoir pressures (Freifeld and Trautz, 2006). The U-tube is composed of a double length of high pressure stainless steel tubing with a check valve open to the reservoir. Formation fluid is collected in the U-Tube, driven at reservoir pressure into evacuated sample cylinders at the surface by high pressure, ultra-pure nitrogen. Free gas in the sample and gases coming out of solution are pumped from the top of the gas separator through a quadrupole mass spectrometer analyser and a landfill gas analyser to measure changes in gas composition in the field (Fig. 2-18). Geochemical analysis must also be matched to the analysis requirements, which may require measurement of gas and liquid fractions at known pressure and temperature, collection of field parameters, filtration, stabilisation, labelling, storing, and shipping of samples.

Investigating aqueous geochemistry provides detailed information needed to confirm model predictions on CO_2 migration and potential leakage pathways. In particular, it is the only technique available that has promise to document dissolution and mineral trapping or, conversely, any geochemical interactions that may lead to increased risk (e.g. damage to formation, confining zone, or engineered system).

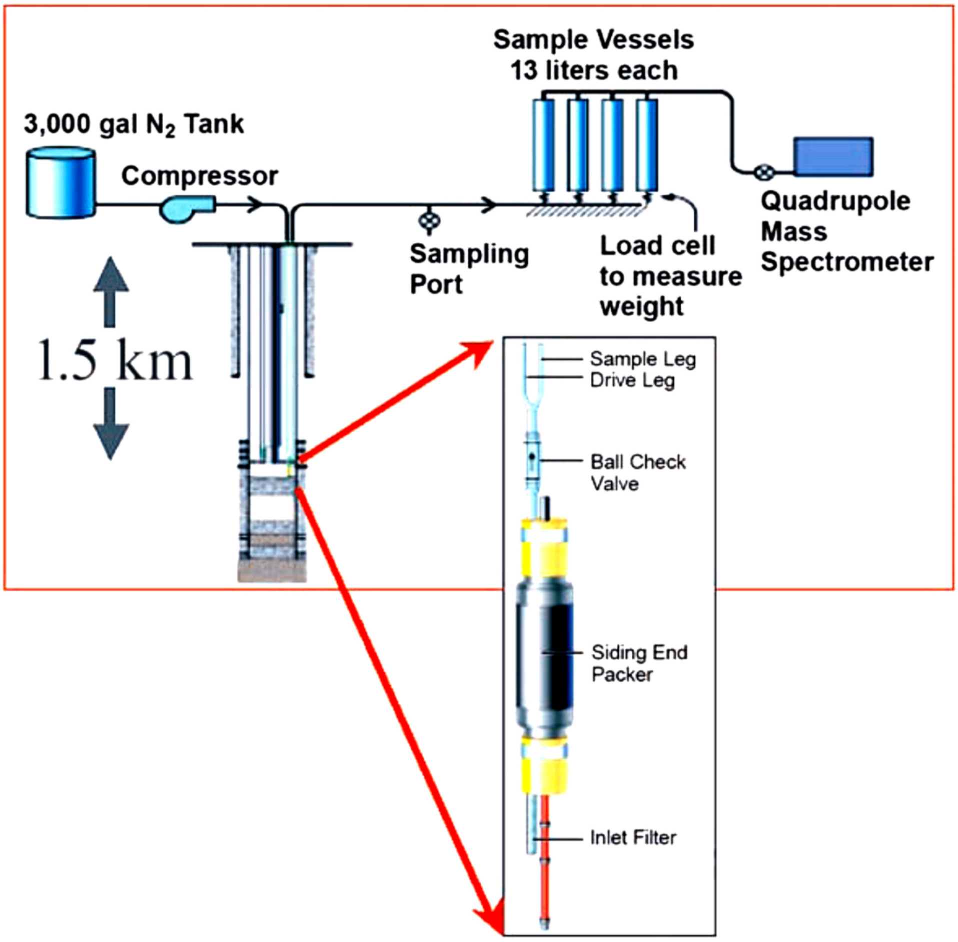

Fig. 2-18: Schematic drawing of the U-tube sampling technology (Freifeld and Trautz, 2006).

2.7 Freshwater aquifers

Since freshwater is a valuable commodity and protected good, the European Parliament and the Council adopted the Directive 2000/60/EC establishing the framework for Community action in the field of water policy (EU Water Framework Directive; WFD). The purpose of this Directive is to establish a framework for the protection of inland surface waters, transitional waters, coastal waters and groundwater. In Article 11 it is stated that "member states may authorise, specifying condition for (inter alia) injection of natural gas or liquefied petroleum gas for storage purposes into other geological formations where there is an overriding need for security of gas supply, and where the injection is such as to prevent any present or future danger of deterioration in the quality of any receiving groundwater". Accordingly, one of the monitoring purposes explicitly mentioned in the EU CCS Directive is detecting significant adverse effects on the surrounding environment, in particular on drinking water. Additionally, compliance with the EU Groundwater Directive (2006/118/EC) and the EU Water Framework Directive is required. Thus, freshwater aquifers that are used for drinking water production must be monitored, if there is a risk of pollution. Annex II part B and Annex III of the EU Groundwater Directive provide practical information for groundwater monitoring.

Groundwater protection requires monitoring at three principal levels, at which appropriate methods can be applied in a sequential manner with increasing effort and intensity (May, 2012):

1) Observation of the storage reservoir and overlying deep aquifers should provide early indications of irregularities and the possible migration of fluids out of the storage formation. In case such indications occur, monitoring can be focussed on potential connections to shallow aquifers.

2) If there are indications for leakage of fluids out of the storage complex, along pathways towards shallow freshwater aquifers, monitoring plans can be intensified in order to detect signs of leakage into shallow aquifers.

3) If groundwater contamination is detected, monitoring is needed to quantify the extent of the contamination (mass, fluxes, area, concentration etc.) in order to take appropriate actions to minimise the effects of the spill and eventually remediate the affected aquifer.

Impacts on groundwater may result from migration of CO_2, mobilised fluids/substances or saline formation water into freshwater resources (IEA GHG, 2011; Lemieux *et al*., 2011). Freshwater monitoring can be used to assess changes through time and across an area using indicators such as pH, specific conductance, alkalinity, major and trace chemical constituents, dissolved gases including noble gases, stable isotopes, radio-isotopes (^{14}C), and redox potential. Changes in the chemical composition of freshwater could be used to detect leakage or indications for the risk of water quality changes by saline formation water, mobilised fluids/substances or CO_2 migration.

A monitoring programme should include both pre- and post-injection sampling and assessment of baseline water chemistry and mineralogy. Evaluating the extent of spreading CO_2 may not be trivial as the lateral extension of aquifers can reach up to tens of km. Spacing of monitoring wells needs to consider site-specific controls on sensitivity and attenuation, risk factors, groundwater flow direction and rate, and account for non-geological storage changes (cf. Fahrner *et al*., 2012). For large area surveys, airborne electromagnetic methods can provide valuable information on a potential salt water intrusion into freshwater aquifers at shallow depth (e.g. Siemon *et al*., 2009).

Apart from possible effects of CO_2 on water composition and quality, the availability of groundwater resources may also be affected by displacement of deep saline or shallower groundwater. This may be the case in shallow parts of formations, if saline water is used for down-dip CO_2 storage. Any modification of the groundwater pressure regime may lead to changes in water table levels and, thereby, may affect flow rates and geometry of water bodies (IEA GHG, 2011).

2.8 Near surface eco-compartments

Near-surface techniques play a vital role in the preservation of shallow groundwater sources and supply critical information on any major vertical migration of injected CO_2. Characterisation of the near-surface environment begins during site selection with assessing any sensitive environmental and cultural features, e.g. wetlands, floodplains, significant habitats, groundwater, soil and other resources, land use, archaeological sites, human populations, and infrastructure. The exact elements will be specific to the local requirements.

The surface and shallow subsurface are more accessible than the deep subsurface at lower cost. The residence time of CO_2 is longer in the shallow subsurface than in the atmosphere above the leak, increasing the probability of detecting the leak.

Comparable to the atmosphere, there are numerous sources of near surface CO_2 emissions, such as soil microbes and vegetation; in-situ remediation of oil spills produces large amounts of CO_2. The soil gas system is complex and affected by factors, such as moisture content, temperature, nutrients, and barometric pressure that vary daily, seasonally and in complex patterns. Leaking CO_2 may be found in the soil gas as very localised occurrence around the leakage point, although it is possible that a build-up in the vadose zone results in leakage at a topographic low point that is distant from the actual leakage point. Groundwater systems may be dynamic, responding to recharge and discharge.

CO_2 leakage from a storage reservoir may create CO_2 fluxes from the surface that may be difficult to distinguish from background CO_2 fluxes. The magnitude of CO_2 seepage fluxes depends on a variety of factors, such as the mechanism of emission (e.g. focused CO_2 flow along a near-surface fault or more diffuse emission through sediments), wind and density-driven atmospheric dispersion. Hence, it is extremely important to record baseline measurements for a sufficiently long period of time before the CO_2 injection begins. Anomalous surface CO_2 fluxes may be detected using several proven and readily available techniques.

2.8.1 Soil and Seabed Gas Monitoring

Gas composition and isotopic signatures: Chemical composition of gases collected at soil and subsoil depth (or sea bed samples in offshore wells) can be used to quantify CO_2 concentrations at a certain depth (usually 1–2 m) or concentration profiles (by depth) and assess whether CO_2 originates from natural or non-biologic sources (e.g. fossil fuel combustion). Numerical simulation studies of leakage and seepage demonstrate that CO_2 concentrations can attain high levels in the shallow subsurface even for relatively moderate CO_2 leakage fluxes (Oldenburg and Unger, 2003).

Soil pore gas concentrations and isotopic composition can be measured using a variety of techniques, including drive points (geoprobes), infra-red gas analysis (see 2.8.2), gas chromatography, and mass spectrometry.

The soil gas technique provides accurate measurements of CO_2 concentration at a particular location, but data interpretation depends on the sampling grid. The spatial resolution must be considered. From studies on natural analogues, it is known that leak points could be small and localised. A higher sampling density is achievable increasing the costs and decreasing the speed of ground coverage. In general, the application of soil gas monitoring is a more time consuming and expensive method than surface gas monitoring for CO_2 leakage detection (e.g. Klusman, 2011).

Distinct isotopic signatures can be used to detect CO_2 leakage (e.g. Klusman, 2011). Reaction of CO_2 with the formation water results in more acidic water with increased dissolved inorganic carbon (lowering the $\delta^{13}C$ value of bicarbonate). The more acidic brine drives calcite and dolomite dissolution, resulting in higher pH values, increasing $\delta^{13}C$ ratios of bicarbonate, and increased Mg^{2+}, Ca^{2+}, dissolved inorganic carbon concentrations and total alkalinity in the water. The net result is an average field-wide $\delta^{13}C$ (HCO_3^-) decrease with time (Shevalier *et al.*, 2005). Monitoring of these isotopic signatures at or around the abandoned wellbore can indicate leakage of CO_2.

Flux Accumulation Chambers: An accumulation chamber with an open bottom (cm^2 scale) is placed either directly on the soil surface or on a collar installed on the ground surface. Air contained in the chamber is circulated through, e.g. an Infrared Gas Analyser, and the rate of change in CO_2 concentration in the chamber is used to derive the flux of CO_2 across the ground surface at the point of measurement (Norman *et al.*, 1992). Advanced techniques include using other trace gases, such as radon, as proxies for determining and differentiating gas fluxes from depth (Baubron, 2005). These chambers quantify the CO_2 flux from the soil at a small, predetermined area. This technology can quickly and effectively determine CO_2 fluxes from the soil. It allows collection of high quality gas sample, from which naturally occurring tracers, such as isotopes or noble gasses, or introduced tracers can be detected.

Alternatively, the CO_2 flux at a given locality can be evaluated using monitoring probes that are set in the ground at different levels and/or at the surface.

Flux is assumed to be more closely related to leakage rate than is concentration. However, monitoring a large area requires many installations. Also, soil gas flux has a strong seasonal and other temporal variability that has to be understood in order to provide leakage estimates. For this, baseline measurements are essential. Soil flux measurements are not effective if the water table is close to surface or if the soil is wet or frozen.

(Sea)Water chemistry and hydroacoustic techniques*:* For offshore CO_2 storage sites and in onshore surface water bodies, the chemical analysis of the sea/lake bed sediment samples, water samples (Annunziatellis *et al*., 2009; Schuster *et al*., 2009), combined with indirect monitoring techniques such as ecosystems stress monitoring of the sea bed and hydroacoustic techniques, can be jointly used for detecting CO_2 leakage on the sea (or lake) floor.

Hydroacoustic techniques comprise a variety of possible sources (e.g. single beam and multibeam echosounders, sidescan sonar systems) all with broad frequency contents of thousands to tens of thousands of Hz. These hydroacoustic techniques allow detection of gas bubble streams resulting from a potential CO_2 leakage. In more detail, these techniques are capable of detecting individual bubble streams in the water column, tracing them to the seabed and estimating gas fluxes. For example, observation of bubble streams above the abandoned wells or in their close vicinity may indicate CO_2 leakage directly through the abandoned wellbore or from the wellbore to the surrounding formations due to casing and cement failure (von Deimling *et al*., 2010). In particular, multibeam methods can be used to rapidly and efficiently survey lakes and larger offshore areas.

2.8.2 Atmospheric Monitoring

CO_2 Detectors: Leakage of CO_2 can be detected by analysing the air at the ground level. The measurements can be performed continuously by permanently installed detectors or intermittently with mobile CO_2 detectors. Chemical CO_2 sensors and infrared CO_2 sensors are the most commonly used devices in the detection and measurement of CO_2 concentrations. Chemical CO_2 gas sensors have the advantage of consuming less energy compared to infrared detectors and are smaller in size. Short and long term drift effects and relatively low life times are the drawbacks of chemical sensors.

Infrared sensors are used to detect CO_2 in a gaseous environment based on the characteristic absorption of CO_2. The key components of an infrared sensor are an infrared source, a light tube, an interference (wavelength) filter, and an infrared detector. This type of monitoring is mostly used for initial assessment and to assure worker safety on site triggering automated alarm systems to warn at high CO_2 levels. Higher sensitivities may be reached using the more sophisticated FTIR instruments.

Laser Systems: The laser systems use a laser beam with a wavelength of infrared light matched to CO_2 absorption wavelength. The emitted light is absorbed by the CO_2 in the air. If there is CO_2 leakage to the surface, e.g. in the vicinity of an abandoned well, it can be detected by the attenuation of the emitted light. Concentration of CO_2 in the air can be calculated by using the difference in the power of emitted light at the source and the detected light at the detector. Laser detection techniques offer more advantages than other gas detection methods: Laser technology does not suffer from interferences, except from other CO_2 sources. It provides fast response and can measure a wide range of concentration values. Laser systems are more expensive compared to chemical and infrared sensors, but their ease of calibration and maintenance-free operation decreases the long-term cost of the equipment. In the field, open path laser detection can be used for measurements over short or greater distances (i.e. metre scale or tens of meters). Thus, traditional gas analysers and detectors are being replaced by laser systems based on the advantages they offer in measuring CO_2 concentrations (Jones *et al*., 2009; Humphries *et al*., 2008).

An advanced leak detection system generates georeferenced CO_2 concentration data along a path or route. The system incorporates a high sensitivity three-gas detector (CH_4, total hydrocarbons, and CO_2) with a Global Positioning System (GPS) with real-time mapping. This system is commonly applied to pipeline monitoring, transmission and liquid line monitoring, and landfill liner integrity monitoring via a ground or airborne vehicle. Detection of total gas composition can be used to separate leakage signal from processes that produce CO_2. CO_2 leakage by itself would displace all other gasses equally, whereas in-situ generation of CO_2 by biologic action or combustion decreases oxygen. Similarly, open path lasers may be used for mapping of CO_2 concentrations in the shallow atmosphere (e.g. Jones *et al*., 2009). However, this kind of mapping is sensitive to local meteorological conditions (especially wind blow) that may alter the atmospheric distribution of released gas. In consequence, precise location of gas vents on the ground may require the supplementary use of the chamber method.

Light Detection and Ranging (LIDAR): Light detection and ranging (LIDAR) is an optical remote sensing technology that measures properties of scattered light to find the range (or other information) of a distant target. Laser pulses are used to determine the distance to an object or surface. Similar to radar technology, which uses radio waves instead of light, the distance to an object is determined by measuring the time delay between transmission of a pulse and detection of the reflected signal. An open-path device uses a laser to shine a beam (with a wavelength that CO_2 absorbs) over many meters. The attenuated beam reflects from a mirror and returns to the instrument for determination of the CO_2 concentration. One instrument can sample a large area, if the beam can reflect from more than one mirror. The LIDAR technology is highly sensitive to aerosols and cloud particles and has many applications in atmospheric research and meteorology (Cracknell, 2007). Differential Absorption LIDAR is typically applied to detect atmospheric concentrations of CO_2 above storage sites and in the vicinity of pipelines in R&D CO_2 storage projects. It is a non-intrusive method to collect data in areas of limited access or containing potential physical or chemical hazards and it can penetrate vegetative canopy With this technique large areas can be covered in short time. In addition, LIDAR data collection is not limited to daylight hours, but appropriate weather conditions needed for operation since water absorbs or scatters laser pulses. The produced large data sets are difficult to store, manipulate, interpret and utilise.

Eddy Covariance: The Eddy covariance technique measures atmospheric CO_2 fluxes at a height above the ground surface. These systems can detect CO_2 fluxes over large areas in real time, along with micro-meteorological variables, such as wind velocity, relative humidity, and temperature (Anderson and Farrar, 2001; Baldocchi *et al*., 1996). Integration of these measurements allows derivation of the net CO_2 flux over the upward footprint (either m^2 or km^2 scale, depending on tower height). Open-path systems tend to underestimate covariance due to sensor placement. Precipitation, winds from unfavourable directions, or extremely calm conditions can cause erratic, non-interpretable results (Baker, 2008). CO_2 from many sources (vegetation, soil gas, industry, compressors, pipelines, etc.) may mask leakage signal because of the magnitude and temporal variability of these sources.

2.8.3 Tracers – natural and introduced

Tracers are unique or highly indicative chemical species that can be used to “fingerprint” the CO_2 of interest and distinguish it from other sources. Chemical tracers, both natural and introduced, can be used for potential leakage detection. Utilisation of tracers requires the availability of a number of boreholes in and around the injection plume.

Naturally occurring chemical constituents, such as stable isotopes of C, H, O, or S, can be used to assess fluid origin, detect CO_2 migration or leakage into the atmosphere and assess interaction with host rocks along flow paths (Cole *et al*., 2004). A variety of sampling and analytical approaches are available, including direct extraction from flux chambers, simple or complex soil gas wells, and sorbent approaches. Analysis can be done in the laboratory or via various types of field instruments. The isotopic composition of carbon and oxygen in the injected CO_2 (if different from the ambient CO_2), as well as minor entrained impurities, can be used to distinguish injected CO_2 from ambient CO_2. These constituents, however, are not conservative and, hence, as CO_2 moves though rock/fluid/soil/ecosystem, the ratios of isotopes and entrained constituents will be modified, giving a record of the reaction pathway.

Phase-partitioning tracers could be used to determine the amount of immobile phases (such as the residual oil in a petroleum reservoir) and to estimate the amount of residual gas trapping that has taken place. Residual gas trapping is an important parameter for estimating long-term storage integrity.

Tracers employed in CO_2 storage projects have included noble gases and perfluorocarbon tracers (PFTs) (Nimz and Hudson, 2005; Fahrner *et al*., 2012). The occurrence of these chemicals in natural systems is so low that detection and attribution may be done at parts-per-billion detection (e.g. Jeandel *et al*., 2010). Many introduced tracers (PFTs, SF_6) are benign in water and ecosystems, but are powerful greenhouse gasses. They, therefore, need to be used conservatively. Due to low detection limits, contamination is a serious risk. Thus, it is important to use best practices to inject tracers (separate handling for injection and detection). Natural tracers are known to have complex reactions with rock, water, and soil, requiring a fairly sophisticated approach to reach a correct interpretation. For this reason, more knowledge is required with regards to the interaction of introduced tracers with water, different rock types, soil, and organic material.

2.8.4 CO_2 detection in shallow subsurface

Shallow 2D Seismic methods implement the principles of subsurface imaging from reflected seismic waves. Seismic reflection technology has been applied to characterising the shallow geology at locations that are environmentally contaminated and in detecting shallow subsurface voids that might be related to sinkholes, tunnels, or construction, in mapping faults or bedrock surfaces and in other situations. Shallow seismic might be deployed in time-lapse mode to look for changes from the baseline, or post-injection when a leak is suspected to try to image a concentration of trapped gas phase CO_2 by mapping a bright spot. This technology can provide high-resolution images of the subsurface for monitoring. Should CO_2 leak and accumulate at shallow depth, the low density of the gas phase would be expected to produce an area of significantly lower velocity, readily mapped as change from baseline, or even in a single survey, as a bright spot.

Seismic techniques respond to a significant change in velocity of sound through the rock/fluid system, so that CO_2 dissolved in groundwater would not likely produce a measurable signal. Thin or low-saturation gas phase CO_2 (near wells or faults) may also produce signal below the resolution sensitivity and, therefore, undetectable. Resolution of sound waves and depth of penetration are inversely related; cost of surveys and processing and the source and receiver spacing are also related, requiring careful design. Static errors caused by changes in shot points or in near surface conditions can reduce detection; they may also add noise. It is not possible to quantify the amount of CO_2 using seismic methods, as occupied formation thickness and saturation are both difficult to quantify. Mass-balance and dissolution/mineral trapping are difficult to monitor. It is noted that only migration in the acquisition direction can be followed, whereas migration in any other direction cannot be quantified directly.

2.8.5 Vegetation stress and changes

CO_2 or brine leaks from underground storage sites may have significant impacts on local ecosystems in the shallow subsurface, the sea floor, and within the water column that could provide useful indicators. Detection techniques require initial surveys to establish baseline conditions above storage sites. Confidence in leakage detection will require improved understanding of how plant populations change in composition, quantity and health, as conditions change. One of the reasons for plant stress can be an increased CO_2 concentration in the soil. Typically, the baseline CO_2 concentration in the soil is expected to be only a few percent. Higher concentrations can kill plants through asphyxiation and soil acidification. The deterioration of the vegetation may indicate CO_2 leakage. Locating such anomalies in the vegetation will help to identify pathways for CO_2 leakage to the surface (Male *et al*., 2010).

The change in vegetation can be monitored by periodic visual inspections, or by imaging systems installed on platforms (Rouse *et al*., 2010). Satellite technology and planes can also be used to monitor the vegetation stress locations employing techniques such as colour infrared ortho-imagery and aerial photography. These approaches allow rapid large-area surveys. In offshore locations ecosystem stress monitoring is more difficult, but similar to onshore locations, changes in the flora and fauna around abandoned subsea wells can indicate CO_2 leakage at the sea bottom.

Direct monitoring of ecosystem health provides confidence that the storage system is not causing damage, reduces the risk in case of leakage, and allow to decide if observed changes are the result of CO_2 injection or not. However, ecosystem sensitivity towards CO_2 leakage varies with species and setting, which may lead to methods to be insensitive (false negatives). Furthermore, many other factors may lead to ecosystem stress and to abundance changes that must be followed up using other techniques (false positives). In addition, there may be a time-shift between the occurrence of the leakage and the occurrence (and measurement) of changes in ecosystem health induced by a leakage. Data interpretation is complicated by a lack of quantitative data on the effects on marine and terrestrial ecosystems of excess CO_2 from leaking storage sites (West *et al*., 2005).

Colour Infrared Transparency Film: This technology utilises three sensitised film layers that reproduce infrared as red, red as green, and green as blue, due to the way the dyes are coupled to these layers. All three layers are sensitive to blue so the film must be used with a minus blue (i.e., yellow) filter. Vegetative health can be determined from the relative strengths of green and infrared light reflected; this shows in colour infrared (CIR) as a shift from red (healthy) towards magenta (unhealthy). CIR aerial photos of specific project sites can be taken from an aircraft or by satellite to determine vegetative health in the vicinity of the project site as an indicator of a possible CO_2 leakage pathway. Using a combination of wavelengths provides a better understanding of events occuring on the earth’s surface. However, the presence of water interferes with the quality of the image due to absorption of near infrared wavelengths (appears black on the image).

Thermal Hyperspectral Imaging: Hyperspectral imaging collects and processes information from across the electromagnetic spectrum as a set of images. Each image represents a range of the electromagnetic spectrum, also known as a spectral band. These images are then combined and form a three dimensional hyperspectral cube for processing and analysis. Sensors may be airborne, satellite mounted, or hand held. Like CIR, hyperspectral imaging is an excellent tool in assessing vegetative integrity around an injection site. In Aerial hyperspectral imagery an entire spectrum is recorded at each point, the operator needs no prior knowledge of the sample, and post-processing allows all available information from the dataset to be mined. Data can be acquired over a relatively large area quickly and efficiently. Airborne or satellite deployment can image the whole area, even the poorly accessible on the ground. For data processing, fast computers, sensitive detectors, and large data storage capacities are needed.

2.8.6 Biological monitoring

The impact of increasing CO_2 concentrations in the soil column on plants, microorganisms or invertebrates due to upwardly migrating gas has been examined by several studies at sites of natural CO_2 emanations (e.g. Beaubien *et al*., 2008; Macek *et al*., 2005; Pfanz *et al*., 2007; Oppermann *et al*., 2010). According to all studies, increased CO_2 concentrations in the soil lead to changes in the vitality, abundance and diversity of plants, invertebrates and microorganisms. It is also recognised that diverse factors, besides CO_2 concentration in the soil column, affect biological systems. The impacts of leaking CO_2 are usually restricted to spots of a few square metres only, which often represent the cores of venting areas where the highest soil CO_2 concentrations exist (cf. Fig. 2-19).

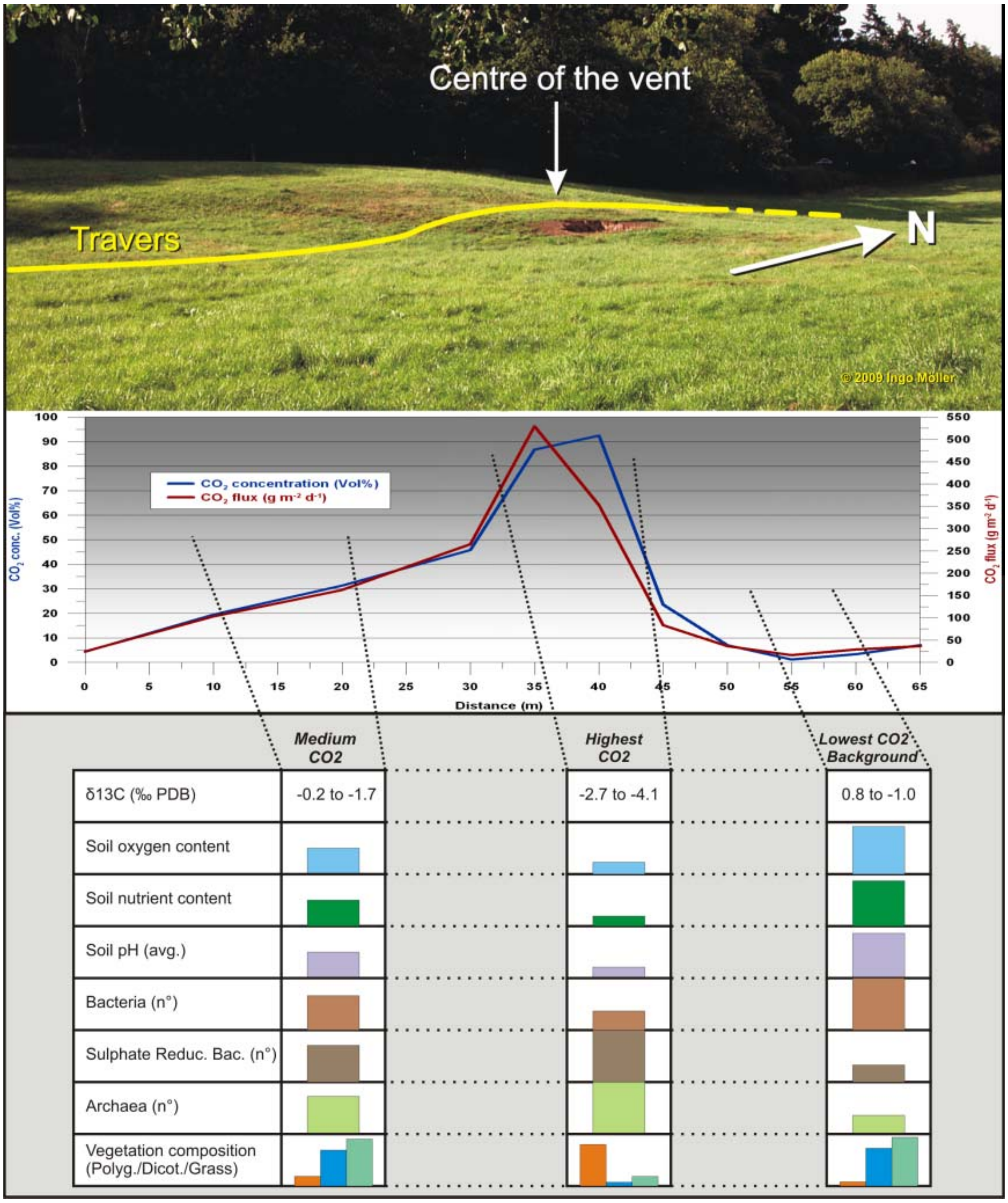

Fig. 2-19: Idealised geoecological conditions around a natural CO_2 vent at the western shore of Lake Laach, Germany (from Möller, 2008). Abundances of bacteria, sulfate-reducing bacteria and archaea are given in relative numbers; vegetation composition with Polyg. = *Polygonum arenastrum*, Dicot. = other dicotyledons, Grass = grasses in total.

Numerous other experimental field and lab studies, which were often ecologically and/or physiologically oriented, have contributed to a broad and diversified knowledge of direct and indirect impacts of elevated CO_2 concentrations on different scales, from single organisms to entire life communities, for example, for invertebrates (e.g. Zaller and Arnone, 1999; Loranger *et al*., 2004; Asshoff, 2005), and even for small animals (e.g. Blackshaw *et al*., 1988; Leach *et al*., 2002; Niel and Weary, 2006).

Several studies have been published regarding the effect of increased atmospheric CO_2 concentrations on ecosystem levels (e.g. Jossi *et al*., 2006; Calfapietra *et al*., 2009; NIPCC, 2011), where, once again, specific elevated concentrations and the exposure time to these concentrations are very important for particular impacts.

Knowing the potential impacts, investigating the condition/status of different species, communities or of ecosystems can provide indications for areas of high CO_2 concentrations in the soil (e.g. Pfanz *et al*., 2007; Krüger *et al*., 2011). Similar approaches can be applied to the monitoring of the marine environment (e.g. Beaubien *et al*., 2008; Widdicombe *et al*., 2009; Karuza *et al*., 2012).

3 MONITORING CONCEPTS – STATUS QUO

Chapter Summary

This chapter briefly introduces the general monitoring concepts suggested in pertinent publications. General monitoring concepts provide a framework for setting up site-specific monitoring programmes and give general recommendations for potentially suitable techniques. The monitoring requirements are then described in more detail, as specified by the EU CCS Directive and the respective Guidance Documents and by the EU ETS Monitoring and Reporting Guidelines.

High-level regulations in place are summarised including the OSPAR and London protocol for protection of the marine environment and the Clean Development Mechanism. Examples of international and national regulations in place focus on the EU CCS Directive and its transposition into national CO_2 Storage Acts.

Examples of monitoring activities are summarised for five current CO_2 injection projects involving the full-scale industrial projects at Sleipner, Weyburn-Midale, In Salah and the smaller scale (research) pilot projects K12-B and Ketzin. Complex monitoring programmes have been implemented at the different sites. These monitoring programmes comprise methods that are needed in order to perform the required operational and HSE monitoring as well as technique/tools to be tested for research purposes.

General monitoring concepts give a comprehensive guideline on parameters to be potentially monitored and features to be considered when selecting appropriate monitoring techniques. However, there is still a need for guidance on how to transfer general recommendations in monitoring concepts to comprehensive, adequate, site-specific monitoring plans. In particular, the criteria to be used to define adequate and comprehensive monitoring plans are still a matter of debate. This chapter introduces published general monitoring concepts, summarises international and national regulations defining requirements for monitoring and illustrates monitoring activities in five current CO_2 storage projects to support this debate. For more specific guidance on establishing a site-specific monitoring plan the reader is referred to Chapter 4.

3.1 General concepts and proposed monitoring guidelines

General monitoring concepts provide a high-level framework for setting up site-specific monitoring plans and give general recommendations for potentially suitable techniques (v. Goerne *et al*., 2010). General concepts often comprise a selection of methods that have been classified according to different criteria such as:

- parameters to be measured,
- physico-chemical processes,
- monitoring purposes,
- leakage pathways,
- subjects of protection,
- monitoring intensity and duration,
- compartments: reservoir, caprock, surface - (migration, leakage, seepage),
- project phases,

- applicability of methods,
- marine / terrestrial setting,
- resolution of methods,
- normal operation (basic monitoring) and irregularities (supplementary monitoring).

According to v. Goerne *et al*. (2010) most published monitoring concepts focus on addressing and meeting the risk of increased CO_2 concentrations in case of CO_2 leakage to the surface and its impacts on near-surface ecosystems (e.g. Benson and Myer 2002; Pearce *et al*. 2005), i.e. focussing on HSE monitoring. Benson (2006) discusses the possibilities and limitations of monitoring methods for ETS monitoring. In the following, examples of published general concepts will be briefly summarised following v. Goerne *et al*. (2010).

- Benson and Myer (2002) and Benson (2006) propose methods for the monitoring of different "parameters" including physico-chemical parameters and processes considering various monitoring purposes, leakage pathways and subjects of protection.
- Similarly to Benson and Myer (2002), Chalaturnyk and Gunter (2005) assign monitoring methods to different subjects of protection, leakage pathways, parameters and monitoring purposes. In addition, they suggest following the movement of the CO_2 plume with time and distinguish migration (migration of CO_2 within the storage reservoir), leakage (migration of CO_2 out of storage reservoir) and seepage (CO_2 emanation at surface).
- Pearce *et al*. (2005) differentiate various monitoring purposes in the different project phases. They point out that the area to be monitored is usually larger than the areal extent of the CO_2 plume, because the area of the pressure footprint and potential brine displacement also needs to be monitored. Based on a discussion of characteristics and the suitability of individual techniques for monitoring of the underground, criteria are derived for site-specific selection of appropriate monitoring methods. The BGS concept provides the basis for the monitoring-selection-tool, a web application available on the IEA GHG R&D programme's website (http://www.ieaghg.org).
- The concept of Benson (2006) considers different system components (compartments) from the storage reservoir to the atmosphere and differentiates terrestrial and marine environments. In the concept the most advanced technology and alternative methods for the different system compartments are selected based on the resolution potential of each technology.
- Benson (2007) distinguishes different project phases and suggests basic sets of methods for the preparation, operation and closure of a storage site: These basic sets contain suitable monitoring methods for normal operation that are supplemented by additional methods in case of irregularities.
- Srivastava *et al*. 2009 assigned different monitoring techniques to the compartments atmosphere, near-surface environment and subsurface. For definition of monitoring tasks they consider operation and closure of the storage site as well as time spans before and after these, respectively.

A comprehensive overview of various monitoring techniques, their applicability and limitations can be found in IEA GHG (2012). High-level guidance on monitoring can be found in the following international legal and regulatory frameworks:

- IPCC (2006) Guidelines for National Greenhouse Gas Inventories; these consist of a number of steps leading to the inventory and quantification of emission terms during injection and storage of CO_2 for national greenhouse gas inventories;
- OSPAR (2007) Guidelines for Risk Assessment and Management of Storage of CO_2 Streams in Geological Formations, which are only applicable for offshore areas, and

- Guidance Document 2 (2011) “Implementation of Directive 2009/31/EC on the Geological Storage of Carbon Dioxide. Characterisation of the Storage Complex, CO_2 Stream Composition, Monitoring and Corrective Measures.”

3.1.1 Monitoring guidelines according to EU CCS Directive and related Guidance Documents

According to the EU CCS Directive monitoring is essential to assess:

- whether injected CO_2 is behaving as expected,
- whether any migration or leakage occurs, and
- whether any identified leakage is damaging the environment or human health.

For this, the operator is required to monitor the storage complex and the injection facilities on the basis of a monitoring plan. The operator needs to report the results of the monitoring to the competent authority at least once a year. In addition, Member States are required to establish a system of inspections to ensure that the storage site is operated in compliance with the requirements of the EU CCS Directive. Detailed monitoring guidelines based on EU CCS Directive requirements are available in the Guidance Document 2 (2011) “Implementation of Directive 2009/31/EC on the Geological Storage of Carbon Dioxide. Guidance Document 2. Characterisation of the Storage Complex, CO_2 Stream Composition, Monitoring and Corrective Measures”.

According to the EU CCS Directive (Article 13, Annex II and other articles) monitoring of injection tests may be included in the exploration permit. Applications to the competent authority for storage permits shall include a proposed monitoring plan including details on the monitoring in accordance with the guidelines established by Article 14 and Article 23(2) of the EU ETS Directive 2003/87/EC. The plan shall be updated in any case every five years to take account of changes to the assessed risk of leakage, changes to the assessed risks to the environment and human health, new scientific knowledge, and improvements in best available technology.

The monitoring plan shall be established according to the risk assessment analysis and updated with the purpose of meeting the monitoring requirements at the different CO_2 storage project phases. The established monitoring plan shall provide details of the monitoring to be deployed at the main stages of the project, including baseline, operational and post-closure monitoring. The following features 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.

The parameters to be monitored will be identified as to fulfil the monitoring purposes. The monitoring plan shall in any case include continuous or intermittent monitoring of the following items:

- fugitive emissions of CO_2 at the injection facility;
- CO_2 volumetric flow at injection wellheads;
- CO_2 pressure and temperature at injection wellheads (to determine mass flow);
- chemical analysis of the injected material;
- reservoir temperature and pressure (to determine CO_2 phase behaviour and state).

The choice of monitoring technology shall be based on best practice available at the time of design. The following options shall be considered and used as appropriate:

- technologies that can detect the presence, location and migration paths of CO_2 in the subsurface and at surface;
- technologies that provide information about pressure-volume behaviour and areal/vertical distribution of CO_2 plume to refine numerical 3D simulation to the 3D-geological models of the storage formation;
- technologies that can provide a wide areal coverage in order to capture information on any previously undetected potential leakage pathways across the areal dimensions of the complete storage complex and beyond, in the event of significant irregularities or migration of CO_2 out of the storage complex.

The monitoring data shall be collated and interpreted. The observed results shall be compared with the behaviour predicted in dynamic simulation of the 3D-pressure-volume and saturation behaviour undertaken in the context of the safety characterisation. Where there is a significant deviation between the observed and the predicted behaviour, the 3D model needs to be recalibrated to reflect the observed behaviour. Where new CO_2 sources, pathways and flux rates or observed significant deviations from previous assessments are identified as a result of history matching and model recalibration, the monitoring plan shall be updated accordingly.

After a storage site has been closed, the operator remains responsible, amongst other things, for monitoring (post-closure period). After the transfer of responsibility, monitoring should be reduced to a level which still allows for identification of leakages or significant irregularities, and it should again be intensified if leakages or significant irregularities are identified.

3.1.2 Integration of EU ETS monitoring and reporting guidelines

The Monitoring and Reporting Guidelines (MRG) under the EU ETS Directive (Commission Decision 2007/589/EC and its amendment Commission Decision 2010/345/EU) provide monitoring and reporting guidelines (MRG) for greenhouse gas emissions from the capture, transport and geological storage of CO_2 (Implementation of Directive 2009/31/EC, 2011). The MRG specify how emissions of the CO_2 storage activity have to be accounted for and reported for purposes of the EU ETS (MRG Annexes I and XVIII). The following emission sources at a storage site have to be monitored under the EU ETS:

- Combustion emissions at the injection site;
- Fugitive emissions and emissions from venting at the injection site;
- Emissions from vents and flaring at enhanced hydrocarbon recovery;
- Leakage from the storage reservoir into the water column or atmosphere.

The MRG places emphasis on the verification, accounting and reporting of any emissions, including quantification of greenhouse gas emissions. Some monitoring methods used for monitoring under the EU CCS Directive may be suitable for quantification of any emissions resulting from leakage. Furthermore, quantification of any leakage will be useful in assessing the significance of the leakage risk as required under the CCS Directive. Monitoring activities and plans need to meet the requirements of the EU CCS Directive, but should be extended to meet the requirements of the MRG under the EU ETS. It will be more efficient for both the operator and the competent authority of a storage site to set up and manage monitoring on an integrated basis, covering both CCS and EU ETS issues.

Emissions sources at the injection site and from enhanced hydrocarbon recovery can be monitored using existing approaches from the MRG. Combustion emissions at injection can be monitored with approaches from Annex II (stationary combustion), vented emissions at injection and at enhanced hydrocarbon recovery with approaches from Annex XII (continuous emission measurement) and fugitive emissions at injection by industry best practice. For the MRG formats for monitoring plans already exist at Member State level. This includes industry best practice approaches.

3.2 Regulations in place

3.2.1 International agreements

At the international level, major regulations that affect CCS are international conventions dealing with or possibly applying to transnational transport of CO_2. Two such agreements are the Protocol to the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (London Protocol), and the Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR Convention; http://www.ospar.org). The London Protocol establishes a scheme to prevent and control the pollution of the international marine environment, whereas the OSPAR Convention identifies threats to the marine environment of the North-East Atlantic and has programmes and measures to ensure effective national action to combat them. Ratification of the amendments by a required seven parties will now enable the 2007 revisions to enter into force. These revisions will specifically allow for CCS under the Convention, including allowing the storage of CO_2 in geological formations under the seabed. Amendments to the OSPAR Convention, agreed in 2007, have been ratified and entered into force for those Contracting Parties to the OSPAR Convention that have ratified (Norway, Germany, United Kingdom, Spain, European Union, Luxembourg and Denmark) on 23 July 2011. On 28 October 2011 the amendments also entered into force for The Netherlands and additional Contracting Parties to the OSPAR Convention will continue the process of ratification, acceptance or approval through their official national channel. In 2012, the process of ratification of these amendments by Sweden was still on-going.

The OSPAR Commission is giving further consideration how to progress with the development of monitoring and assessment capacities for climate change and ocean acidification at the regional scale, including tools to assess the rate of change.

Steps towards the full ratification of an amendment to Article 6 of the London Protocol, which would allow for the export of CO_2 streams in certain circumstances, remain more tentative. Twenty-seven of the current 40 contracting parties to the Protocol are required to ratify the amendment for it to enter into force. To date, only Norway has completed the ratification process. The failure to ratify these amendments means that trans-boundary transportation of CO_2 for the purpose of geological storage still remains prohibited under the Protocol. For a small number of countries and project proponents, whose anticipated projects include transnational elements, this will continue to be viewed as a major uncertainty and barrier to further development (GCCSI, 2011a).

3.2.2 Clean Development Mechanism (CDM)

On December 9th 2011, it was decided to include carbon capture and storage technology in the Clean Development Mechanism (CDM). This decision came after five years of campaigning by several international organisations. There has been extensive debate during UN negotiations in recent years and 2011 was a year of tough negotiations, following the preliminary decision at COP16/CMP6 in Cancun in 2010. Inclusion of CCS in the CDM reflects final international acceptance that CCS is a legitimate low carbon technology. It supports use of the technology in developing countries, bringing clean, reliable, base-load electricity to the developing world with 1.3 billion people lacking access to electricity. The decision also provides a set of internationally accepted rules for CCS projects, dealing with key issues such as site selection, liability and environmental assurance. It also sets an important precedent for the inclusion of CCS into other financing and technology support mechanisms (http://www.worldcoal.org/blog/ccs-in-cdm-gets-green-light-in-durban/). The draft decision on “Modalities and procedures for carbon dioxide capture and storage in geological formations as clean development mechanism project activities", including requirements for monitoring is under development in UNFCCC (for further information see http://unfccc.int/files/meetings/durban_nov_2011/decisions/application/pdf/cmp7_carbon_storage_.pdf).

3.2.3 International and national regulations

There are many different directives, regulations and laws concerning CO_2 storage site monitoring in place, implemented or developing in different parts of the world in particular in the USA, Canada, Australia and European Union. Only in the EU there is one common CCS Directive applicable to all 27 Member States countries of the European economic area. In the US, Australia and Canada the monitoring requirements are defined at state and provincial level. As a consequence, for example, requirements for post-closure monitoring range between 15 and 50 years.

In Europe, "Directive 2009/31/EC of the European Parliament and of the Council of 23 April 2009 on the geological storage of carbon dioxide" was published on 5 June 2009, and entered into force on 25 June 2009. This Directive established a legal framework for the environmentally safe geological storage of CO_2. In article 39 "Transposition and transitional measures" it is stated that "Member States shall bring into force the laws, regulations and administrative provisions necessary to comply with this Directive by June 25th 2011", that they "shall communicate to the Commission the text of the main provisions of national law which they adopt in the field covered by this Directive" and that they "shall ensure" that the storage sites "are operated in accordance with the requirements of this Directive by 25 June 2012".

By the end of 2011, the transposition of the Directive into national law was approved by the European Commission for Spain only, although it was ready at national/ jurisdictional level in 13 countries (Austria, Denmark, Estonia, France, Greece, Ireland, Italy, Latvia, Lithuania, Malta, Slovakia, Sweden and the Netherlands) and two regions of Belgium. The process of transposing the EU CCS Directive into national law and the assessment by the EC whether the relevant national laws properly transpose the Directive is still on-going in 2013.

As a result, CO_2 storage is now, as of July 2012, permitted in several European countries (France, Lithuania, Portugal, Romania, Slovakia, Spain, The Netherlands and U.K.) and it is expected that it will be permitted in Hungary. Only offshore storage, mainly use of CO_2 for EOR purposes, is permitted in Denmark until 2020. CO_2 storage is permitted in Italy, excluding seismic areas; permitted in Belgium except in selected areas (without storage capacity); and permitted in Greece, excluding areas where the storage complex extends beyond the Hellenic territory. CO_2 storage is permitted with limitations in Bulgaria. CO_2 storage is temporarily forbidden in Austria, Latvia, Sweden, and the Czech Republic. CO_2 storage is forbidden except for research and development in Estonia and Ireland. CO_2 storage is expected to be forbidden in Finland, and in Poland, except for demonstration projects (until 2024).

According to EC requirements, countries have to transpose the EU CCS Directive in full extent, including CO_2 storage site monitoring. Even the countries that decided to forbid storage within their territories are required to have CCS regulations including regulation that refer to monitoring of storage sites. Exceptions from this requirement could be countries which do not have physical possibilities (capacity) for CO_2 storage (e.g. Estonia, Finland, parts of Belgium and Slovenia). In most of the national regulations the requirements for CO_2 storage site monitoring are included in the law in line with the Directive, often prepared using "copy-paste" approach (Romania, U.K., etc.). According to the Directive, the results of the monitoring must be included in the annual report submitted by the storage site operator to the competent authority. Specific and additional requirements for monitoring could be also included in regulations. For example Spain prolonged requirement for post-closure monitoring specified in the Directive as minimum 20 years up to 30 years (Krämer, 2011).

3.3 Monitoring in selected current CO_2 storage projects

Complex monitoring programmes have been deployed in current pilot and demo projects in order to respond to the requirements of the regulations in place, to respond to the issue of CO_2 geological storage safety and to test the feasibility of using diverse geophysical, geochemical and biological methods for monitoring purposes.

Monitoring programmes implemented at demo and industrial-scale projects are restricted to most technical and cost effective monitoring methods to comply with the legal and safety requirements. Many techniques applied have been adopted from well-established systems of the oil and gas industry. In the case of pilot projects, a wide variety of monitoring tools have been developed, adapted, tested and validated at a high level. Although not all tested techniques will be used widely at industrial scale, it is very important to obtain detailed information on the application of different monitoring tools that can replace - if needed - a monitoring tool that did not give the expected/reliable results or that provides additional information. Furthermore, some of the demo and industrial-scale projects have been involved in research projects to gain additional information beyond the monitoring data required by the regulators.

There are still open questions regarding the use of some techniques in CO_2 injection and storage monitoring and these techniques should be further investigated in order to decide on their use in this field and to specify the terms of applicability. Therefore, the future pilot and demo projects should contribute to this aspect. In addition, the list of monitoring techniques should be extended, more techniques should be tested and their feasibility investigated. Furthermore, some practical guidelines for monitoring of natural gas storages may be adapted to CO_2 storage.

Several monitoring programmes from current pilot and demos are presented below, listing the techniques deployed and the results of monitoring at Sleipner, Weyburn-Midale, K12-B, In Salah and Ketzin. As shown from these monitoring programmes, the common technique used for deep monitoring, tracking the plume and leakage detection is the time-lapse seismic survey, deployed at a intervals of several years. Additional methods to time-lapse seismic were deployed in several sites, e.g. time-lapse gravimetry, seabed bathimetry and controlled source electromagnetic at Sleipner; passive seismic, electrical resistivity imaging, geochemical and soil gas surveys at Weyburn; microseimic, InSAR, groundwater monitoring, soil gas and microbiological surveys, complex wireline logging at In Salah; extensive logging at K12-B; VSP, MSP, passive seismic, geoelectrical monitoring, microbiological and geochemical monitoring at Ketzin.

3.3.1 Sleipner

The Sleipner CCS project, the first commercial scale CCS project, began in 1996 with the injection of the CO_2 separated from the extracted natural gas into a deep saline aquifer contained in the Utsira Sand formation at approximately 1000 m below sea bottom. From 1996 until present 1 Mt CO_2 per year were injected. Since 1998 several research projects were linked to the commercial CCS project intending to monitor and model the injected CO_2 plume (Chadwick *et al.*, 2006). The monitoring programme implemented, includes 4D (time-lapse) seismics (7 surveys), high-resolution 2D seismic (in 2006), seabed gravity (in 2002, 2005 and 2009), seabed controlled source electromagnetic (CSEM) (in 2008), and seabed imaging and bathymetry (in 2006) and continuous monitoring of the wellhead pressure and flow rate. Neither downhole sensors, nor gas/liquid-ratio measurements were included in this monitoring programme (Alnes *et al.*, 2011).

The monitoring programme started in 1994 with the acquisition of baseline 3D seismic data, prior to injection (Chadwick *et al.*, 2006). After the injection, several 3D seismic surveys were implemented in 1999, 2001, 2002, 2004 and 2008 in order to track the CO_2 plume (see Fig. 3-1) and to show that the CO_2 is safely contained within the storage complex. The seismic data indicated that no detectable leakage into the caprock has occurred and that the plume was roughly 200 m high and elliptical in horizontal cross section (Chadwick *et al*., 2006), the CO_2 has been rising buoyantly to the level of the top seal at a depth of 800 m (Boait *et al*., 2011).

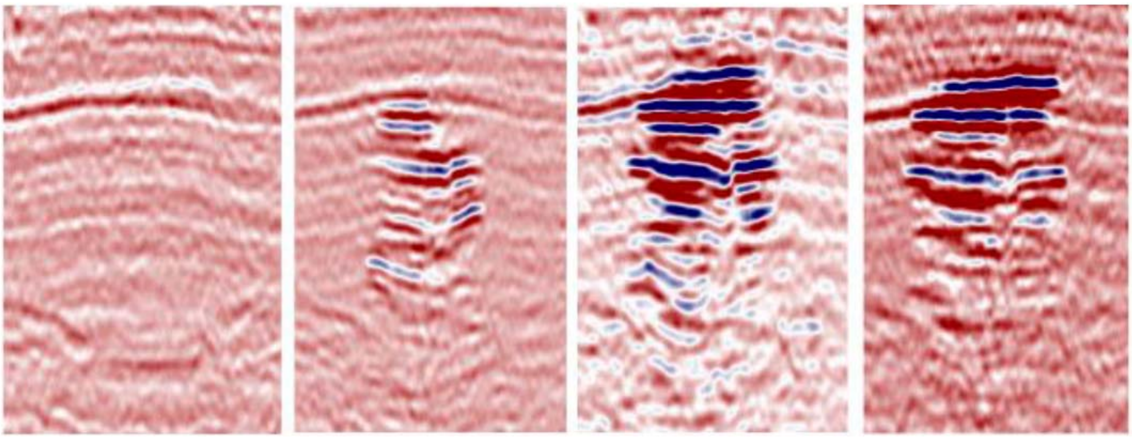

Fig. 3-1: Vertical sections through the time-lapse seismic volumes. Uninterpreted slices clearly show growth of the CO_2 plume (Boait *et al*., 2011).

Time-lapse gravimetry was implemented at Sleipner in order to complement the seismic information in the idea that the periodically deployment of this method could lead to an estimation of the CO_2 going into dissolution and the eventual accumulation of the CO_2 in the shallow overburden traps contributing to an "early warning system" (Chadwick *et al.*, 2006). The high precision gravimetric surveys were conducted in 2002 and 2005 at 30 seafloor stations (concrete benchmarks) and at 40 seafloor stations in 2009 (Alnes *et al*., 2011). The stations were aligned on two perpendicular lines, one oriented east-west and one north-south, initially 7 km east-west and 3 km north-south, extended towards north in 2009 in the direction of observed plume growth (Fig. 3-2). The measurements were made using a customised gravity and pressure measurement module mounted on a remotely-operated vehicle (Chadwick *et al.*, 2006).

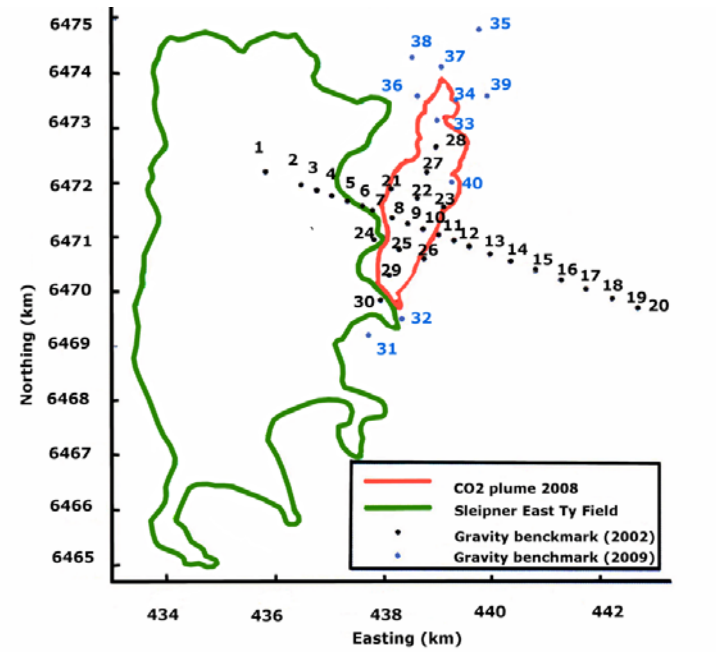

Fig. 3-2: Location of the benchmarks used for the gravity survey and contours of the CO_2 plume (from Alnes *et al*., 2011).

The observations were interpreted taking into account the vertical movements of the benchmarks caused by sediment scouring, the water influx to a deep hydrocarbon reservoir and the injection of the CO_2. The results were that the CO_2 injection caused a reduction on seafloor gravity of 12 μGal in the surveyed period with an estimated average CO_2 density derived from the observed gravity of 720 ±80 kg/m^3 (Alnes *et al.*, 2011).

Recent findings lead to a more accurate description of the temperature distribution in the Utsira Formation and to a more precise estimation of the average CO_2 density (675±80 kg/m^3) (Alnes *et al.*, 2011). All this information leads to the conclusion that the rate of dissolution of CO_2 into brine is less than 1.8 % per year (Alnes *et al.*, 2011).

3.3.2 Weyburn-Midale

The Weyburn CO_2-enhanced oil recovery (CO_2-EOR) project is located in the Williston Basin, a geological structure extending from south-central Canada into north-central United States. The source of the CO_2 is the Dakota Gasification Company facility, located approximately 325 km south of Weyburn, in North Dakota, USA. A relatively pure stream of CO_2 is dehydrated, compressed and piped to Weyburn in Canada, for use in the field. The Weyburn field covers an area of 180 km^2 and the oil reservoir is a fractured carbonate, 20 - 27 m thick. The primary upper seal for the reservoir is an anhydrite zone; a thick, flat-lying shale forms a good regional barrier against leakage from the reservoir. The basal seal is also anhydrite. CO_2 injection began in May 2000, the approximate average daily injection rate is 3,000 - 5,000 t/day and it is expected that some 20 MtCO_2 will be stored in the field. The research programme attached to the Weyburn-Midale project intended to study the site as natural laboratories for understanding the processes associated with the long-term storage of greenhouse gases (Wilson and Monea, 2004; Rostron and Whittaker, 2011). A very important part within the complex research program is prediction, monitoring and verification of CO_2 migration (Rostron and Whittaker, 2011). A complex monitoring programme was therefore put in place including geophysical and geochemical monitoring.

The preferred geophysical method used was time-lapse 3D seismic. The seismic data were acquired within a baseline survey prior injection in 2000 and within three subsequent seismic surveys conducted between the years 2001 and 2007.The seismic data were proved effective first in mapping the distribution of CO_2 in the reservoir (Rostron and Whittaker, 2011). This type of data was also used to examine caprock integrity (Rostron and Whittaker, 2011), mapping the presence of anisotropy within the caprock that could be related to the existence of fractures (White, 2011).

Another monitoring method used at Weyburn is passive seismics. The deployment of this method started with the settlement of a geophone array in 2003 (Rostron and Whittaker, 2011) and the actual monitoring began in 2004 when a new CO_2 injection well started to function. 97 of the 100 seismic events recorded were related to the early stages of injection (Rostron and Whittaker, 2011).

Microseismicity rates correlate with periods of elevated CO_2 injected rates and with changes in production activities in nearby production wells (White, 2011). The rate of seismicity related to the geomechanical processes within the reservoir is very low (Rostron and Whittaker, 2011). The location of microseismicity is controlled by pressure-induced stress changes in the reservoir, in general not related to the CO_2 distribution (Fig. 3-3; Verdon *et al.*, 2010; White, 2011).

Electrical resistivity imaging was also deployed at Weyburn, but the signal-to-noise ratio and sensitivity proved to be too low to allow useful inversion of the electrical resistivity data (Rostron and Whittaker, 2011; White, 2011) due to large inter-electrode distances, long casings, large depth to reservoir, presence of other casings etc.

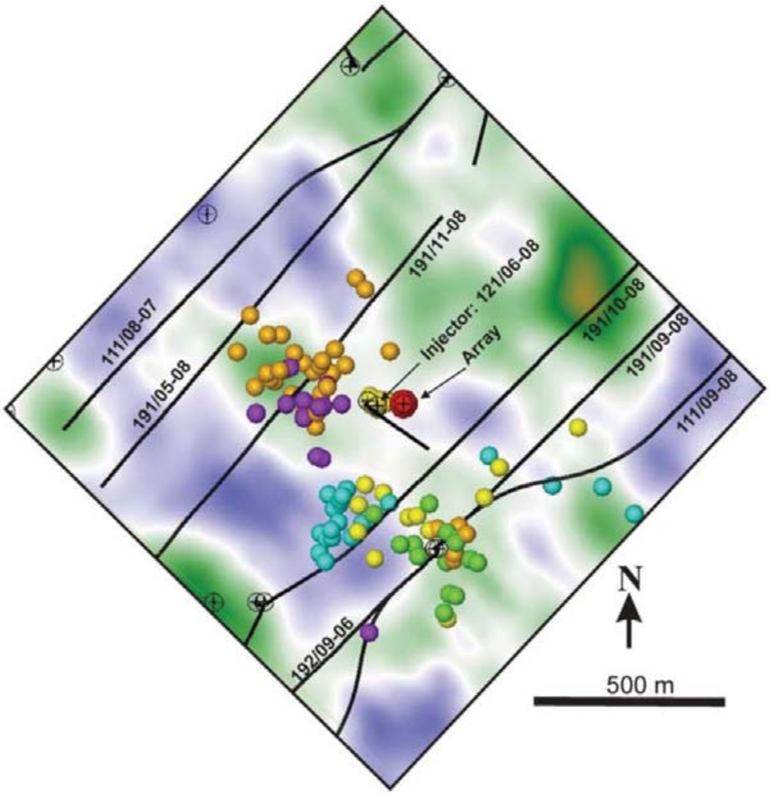

Fig. 3-3: Microseismic event locations at Weyburn from August 2003 to January 2006, superposed on the 2004 time-lapse amplitude difference map (from 4D surface seismic). Green-to-orange and blue background colours represent negative and positive differences, respectively. The amplitude differences represent the 2004 minus the 2000 amplitudes. Negative time-lapse amplitude differences represent zones where the impedance has been further reduced by the presence of CO_2. Event clusters are colour-coded according to time intervals: pre-injection period (yellow); initial injection (purple); production well shut-in 18-19 March 2004 (green); high-injectivity period (orange); low-frequency events during January 2006 (light blue). The locations of the injection, production and monitoring wells are also marked (yellow, transparent, red crosses) (Verdon *et al*., 2010).

Besides geophysical monitoring, geochemical methods were also used to monitor the site. Ten shallow groundwater sampling surveys at Weyburn (2000 - 2009), one groundwater sampling survey at Midale (2006) and soil gas surveys were conducted to monitor Weyburn-Midale storage sites. The water sampling programmes were conducted on approximately 60 different wells, mostly domestic water wells (Rostron and Whittaker, 2011). Over 70% of the water samples exhibited no significant changes in water chemistry, the rest being to associated with shallow farm wells and thus correlated with near surface operations (Rostron and Whittaker, 2011). The conclusion of the groundwater and soil surveys was that there were no discernible changes in the quality of the groundwater and the soil composition related to CO_2 storage (Whittaker *et al*., 2011).

Additionally sixteen monitoring surveys of produced reservoir fluids documented the compositional evolution of formation brines and hydrocarbons (Whittaker *et al*., 2011). The geochemical dataset that contains more than 30,000 entries was used for reactive-transport modelling.

3.3.3 In Salah

The In Salah Gas project in Algeria is an industrial-scale CO_2 storage project that has been in operation since 2004. The CO_2 stripped from the natural gas is re-injected at a rate of 0.5 - 1 Mt per year into a sandstone reservoir at 1800 m depth, sealed by a thick succession of Carboniferous mudstones (Ringrose *et al*., 2012). The injection is made at the Krechba site through three injection wells, KB501, KB502 and KB503 (Fig. 3-4). At In Salah the implemented monitoring programme included time-lapse 3D seismic surveys, microseismics, InSAR measurements, collection of GPS/tiltmeter data, groundwater sampling , surface flux/soil gas measurements, microbiology surveys, complex wireline logging and sampling, wellhead/annulus sampling and tracers injection (in each injection well in 2006) (Mathieson *et al*., 2011).

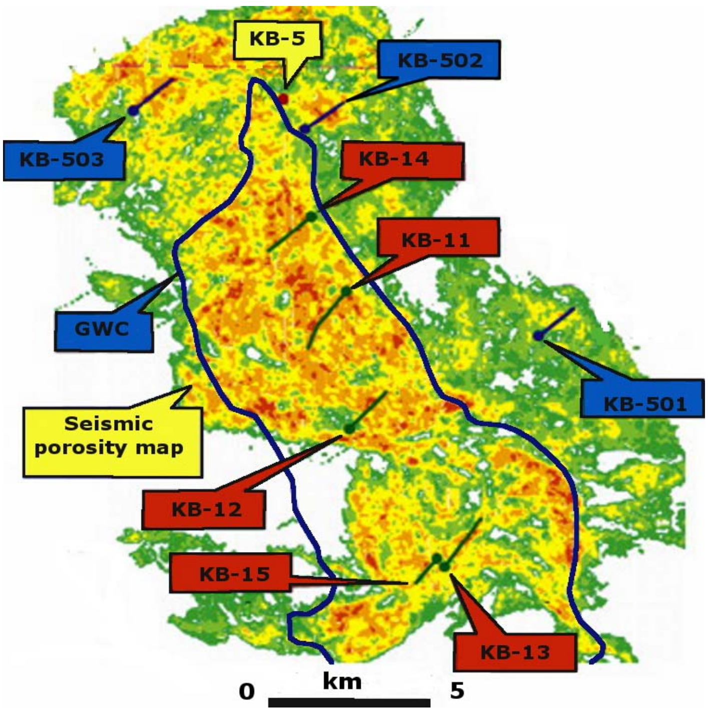

Fig. 3-4: Krechba Field layout (from Mathieson *et al*., 2011).

A baseline 3D seismic survey was conducted in 1997, focused on imaging the reservoir section. This data was reprocessed in 2006 trying to improve the overburden imaging. The recent interpretations revealed that there are minor faults at the Carboniferous level and the immediately overlying caprock (Mathieson *et al*., 2011). The 3D seismic survey was repeated in 2009 and has provided high quality data. Microseismics was used in order to monitor caprock integrity. For this reason, a 500 m test well was drilled and recorded information above KB502 (Mathieson *et al*., 2011).

For groundwater monitoring, five shallow aquifer wells have been drilled at 350 m depth, one beside each injector, one in a remote control location and one between KB-5 and KB-502 wells (Fig. 3-4) and two sampling programmes have been conducted (Mathieson *et al*., 2011).

Another monitoring technology used at In Salah was InSAR. Satellite images were collected on two systems (Mathieson *et al*., 2011). The result of the InSAR monitoring was that ground deformation (surface uplift) has taken place around the injection wells as a result of pressure-induced poro-elastic expansion of the storage reservoir in the area surrounding the injection points (Onuma and Ohkawa, 2009; Onuma *et al*., 2011). Tiltmeters/DGPS data were additionally collected in order to calibrate and confirm the satellite deformation information till 2011 (Mathieson *et al*., 2011).

Soil gas surveys started prior to injection when this type of survey was implemented around each new injection well (Mathieson *et al*., 2011). After the injection, surface gas measurements at Krechba were made in March 2009 and November - December 2009 in the area between KB-502 and KB-5 (to see the movement of CO_2 from the injection well to the later well), in an area around KB-4 and at a background site to the west of the gas reservoir (provide contrasting data in an area far from injection and exploitation site). One of the methods used for gas measurements involved continuous measurements using mobile laser equipment. Traverses with the mobile laser were made on the plateau around KB-502, near KB-5 and then in the accessible parts of the wadi floor between KB-5 and KB-502, around KB-4 well and in a background area to the west of the gas field. Apart from these mobile measurements, in situ stationary measurements, sampling and CO_2 flux measurements were made. Additionally, two Barasol probes were buried in excavated pits, one to the east of KB-502, other far away from the CO_2 injection area to the south near KB-7 (Jones *et al*., 2011). So far most of the data did not reveal anomalous concentrations of CO_2 in the atmosphere or in soil. Thus, data from the November 2009 survey show the anomalous nature of the CO_2 concentrations measured at the KB-5 wellhead (Jones *et al*., 2011).

Biological baseline measurements were made at Krechba in November/December 2009, including a botanical survey and assessment of microbial numbers and activity (Jones *et al*., 2011). The biological work was centred on the three injection wells. A traverse was made from KB-5 south-eastwards towards KB-502, observations were made around KB-503, and on a traverse westwards from that well, and a traverse was undertaken north-eastwards from KB-501 (Jones *et al*., 2011). Widely spaced (100 - 200 m) sample points were used on each biological transect in order to cover the entire planned area. The botanical study revealed a wide range of plants at Krechba, all of which exhibited xerophytic characteristics necessary to survive in the arid conditions. The study did not establish the types of microbes present, only the numbers, which are typical of desert aerobic microbial populations.

The wellhead and annulus fluid and tracer sampling and measurement programme was initiated in 2005 and 2006 respectively and samples are collected every two months except in locations deemed to be at potentially higher risk of wellbore leakage where the sampling is increased to monthly (Mathieson *et al*., 2011). In 2007, high concentrations of CO_2 were recorded in KB-5 well (an old appraisal well located at NW of KB-502), proven to come (through tracer analysis) from KB-502 and caused by a wellbore integrity problem (Mathieson *et al*., 2011). The KB-5 well was decommissioned successfully and the injection in KB-502 restarted in November 2009 (Mathieson *et al*., 2011).

3.3.4 K12-B

Various monitoring tools are used for monitoring the K12-B storage complex, located in the Dutch sector of the North Sea. The storage demonstration project started in 2004 when a part of the CO_2 separated from the natural gas extracted from the K12-B was re-injected into the same reservoir containing the gas deposit via injection well K12-B8. In 2005 the injection started in another well, K12-B6. The reservoir top is at 3,800 m depth below sea level and its cap rock is represented by rock salts alternating with clay intervals. Since 2004 a total of 60,000 tonnes of CO_2 has been injected.

A very important part of the monitoring programme has been related to a continuous well integrity assessment in relation to the specific down-hole conditions induced by the CO_2 injection and storage. For this purpose, several monitoring tools were deployed, as multi-finger imaging tools (surveys in 2005 and 2006), cement bond logging, downhole video logging (2007), electromagnetic imaging tool, gamma ray logging (Fig. 3-5; Vandeweijer *et al*., 2011).

Gaining a better understanding of the behaviour of the CO_2 in the injection wells and the migration of the CO_2 in the reservoir were also important goals of the monitoring programme. In order to achieve this goal, multiple reservoir models were built over the years using 3D seismic data, well logs, production logs, etc. Additional measurements and analysis were used in order to refine these models, such as well head production and injection measurements, production and injection analysis, down-hole pressure and temperature measurements, chemical tracer analysis and dynamic flow modelling (Vandeweijer *et al*., 2011).

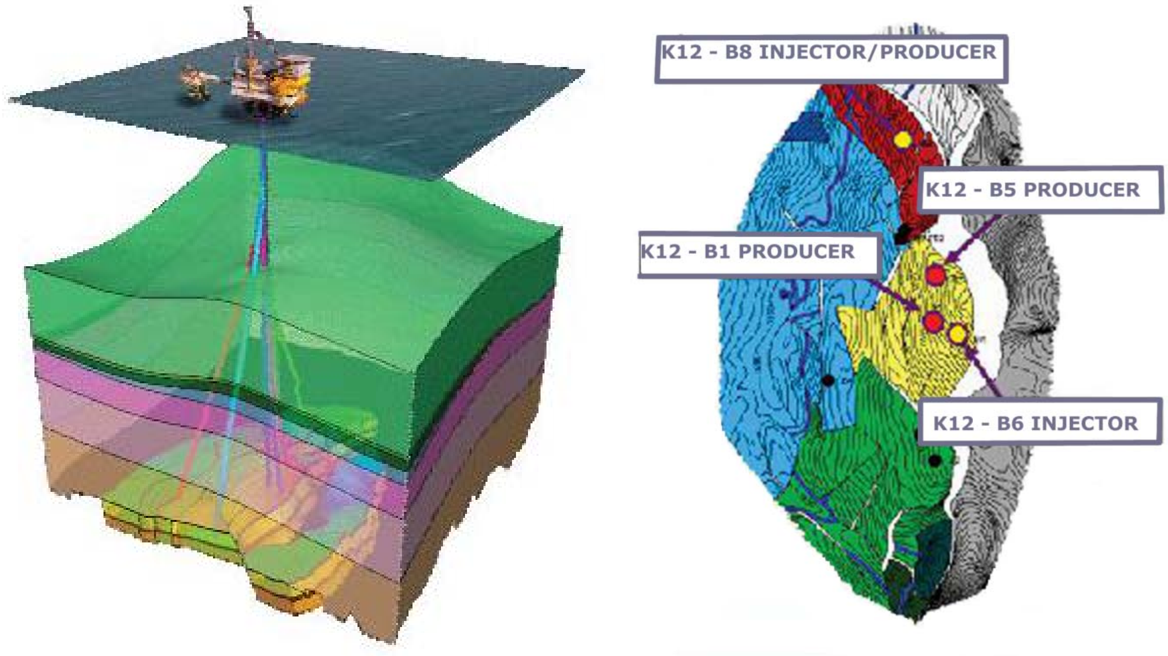

Fig. 3-5: Location, 3D visualisation and overview of relevant wells and compartments of the K12-B gas field (from Vandeweijer *et al*., 2011).

3.3.5 Ketzin

The Ketzin research pilot CCS project is the first European onshore CO_2 storage site. Since June 2008 food grade CO_2 has been injected into a saline sandstone aquifer at approximately 650 m depth formed as an anticlinal structure by salt tectonics (Lüth *et al*., 2011). An interdisciplinary monitoring programme comprising geophysical, geochemical and microbial investigations was implemented at Ketzin (Martens *et al*., 2011).

One of the geophysical monitoring techniques used to monitor CO_2 migration in the reservoir is time-lapse 3D seismics. In autumn 2005, prior to CO_2 injection, a baseline 3D seismic survey was conducted to provide a reference for later surveys aiming to image the distribution of CO_2 in the subsurface and to contribute to a more suitable reservoir characterisation. This updated model revealed the existence of a fault-and-graben system that could not be detected using old 2D vintage data (Lüth *et al*., 2011). A repeat 3D seismic survey was carried out from end of September to November 2009, focusing on an area covering about 50% of the baseline survey, where the flow simulations indicated that CO_2 will propagate. In addition, 2D seismic reflection data were acquired along seven radial profiles around the injection site (Fig. 3-6). The analysis and modelling of the time-lapse 3D seismic data indicated an anisotropic propagation of the CO_2 in the laterally heterogeneous reservoir (Lüth *et al*., 2011).

As an extension of the surface seismic acquisition programme, combined surface-downhole and downhole measurements, as VSP (Vertical Seismic Profiling) and MSP (Moving Source Profiling, or walk-away VSP) were implemented. MSP data allowed for a more detailed characterisation of the reservoir close to the observation well (Lüth *et al*., 2011). The location of both surface and downhole monitoring surveys is shown in Fig. 3-6. Cross-hole tomography surveys were also performed between two observation wells CO_2 Ktzi 200/2007 and CO_2 Ktzi 202/2007, a baseline survey and two repeats in 2008 m and a third repeat in 2009 (Lüth *et al*., 2011).

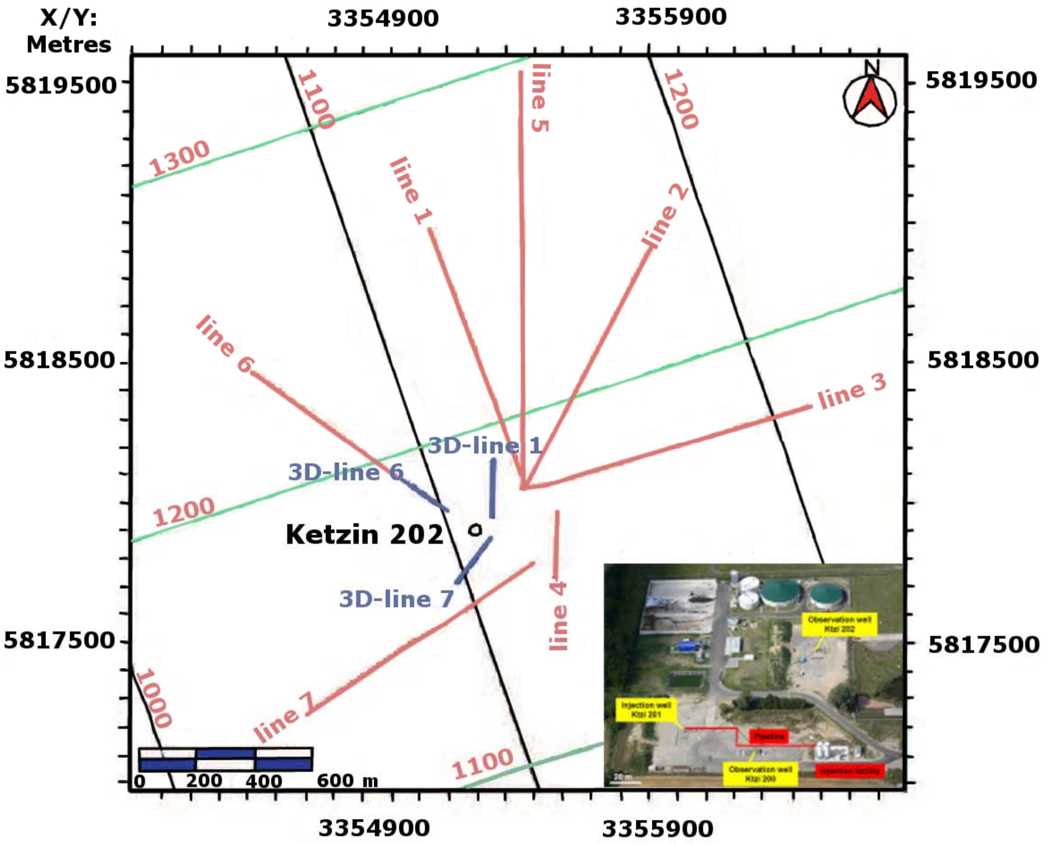

Fig. 3-6: Location map of the combined surface-downhole monitoring programme. Red lines indicate 2D reflection profiles and source lines for walk-away VSP (or MSP - Moving Source Profiling) surveys. Blue lines show the locations of the CDP lines that were extracted from the 3D volume to be compared with the MSP images (from Lüth *et al*., 2011).

A permanent seismic monitoring system was designed and installed at 13 locations to be used for both passive and active seismic observations (Arts *et al*., 2011). At each location, a 3-component geophone and a hydrophone were placed at 50 m depth, at seven locations a geophone was placed at surface and at one location additionally geophones and hydrophones were placed at 10 m depth intervals (Arts *et al*., 2011). The distance between the boreholes is 10 m. In October 2009 an active seismic survey was conducted using an accelerated weight drop source and consisting of two shotlines (Arts *et al*., 2011).

Geoelectrical monitoring at Ketzin includes cross-hole measurements using the permanently installed vertical electrical resistivity array (VERA), consisting of 15 electrodes in each well, and additional surface and surface-downhole electrical resistivity tomography (ERT) (Martens *et al*., 2011). The cross-hole measurements were conducted daily prior to injection and weekly since March 2009. As for the surface-downhole measurements, three sets of repeat measurements were carried out in July 2008, November 2008 and April 2009, the baseline surveys being conducted in October 2007 and April 2008 (Martens *et al*., 2011).

Apart from geophysical monitoring, a complex well monitoring programme was deployed at Ketzin. One of the well monitoring techniques was permanent *in situ*-gas monitoring. CO_2 arrival and gas composition was permanently monitored at the observation wells with a gas membrane sensor (GMS) since 2008 and from March 2010 with a 6 mm stainless steel riser tubing installed down to a depth of 640 m into observation well Ktzi 200 (Martens *et al*., 2011). All geoelectrical surveys have imaged a significant resistivity increase near the injection well Ktzi 201, which extends towards the observation well Ktzi 200 with diminishing amplitude (Martens *et al*., 2011).

The temperature conditions in all three wells at Ketzin are monitored by distributed temperature sensing (DTS) and, in addition, three distributed thermal perturbation sensing (DTPS) measurements were carried out in 2009 (Martens *et al*., 2011).

The microbiological and geochemical processes in the injection and observation wells are monitored through the sampling and analyses of downhole fluid samples from all three wells. Microbiological investigation of the downhole samples were made using Polymerase Chain Reaction – Single Strand Conformation Polymorphism (PCR-SSCP) and Fluorescence *in situ*-hybridisation (FISH) (Martens *et al*., 2011).

4 SETTING UP A SITE-SPECIFIC MONITORING PLAN

Chapter Summary

The EU Guidance Documents distinguish three different monitoring categories: i) mandatory monitoring that is required for all sites, ii) required site-specific monitoring, and iii) optional contingency monitoring. The EU CCS Directive does not specify which methods or monitoring technologies should be used, but requires that the choice is based on the best practice available at the time of design. A good monitoring strategy should include plans for intensified monitoring in the event of irregularities. Plans are required to be reviewed and updated on a regular basis.

Two examples of site-specific monitoring plans for future potential storage sites are given here:
Example A is a deep saline aquifer which is a prospective storage site in the south of Romania. Modelling work has indicated that the reservoir can store up to 1.5 Mt CO_2 per year for at least 20 years. Site-specific risk assessment has been performed. Monitoring techniques to mitigate the identified risks are proposed. The target compartments for monitoring are ground surface, groundwater, soil, wells, possible faults and air. The suggested methods include logs, seismic surveys, cross-well techniques and microseismic surveys.

Example B is a depleted gas field in Slovakia at the border with Austria. Since this is a depleted field, the present irregular network of 35 old boreholes from hydrocarbon exploration and exploitation and the Láb fault systems need particular attention in the monitoring plan. Geochemical and geophysical monitoring to establish a baseline before injection starts, monitoring during the injection phase and for the post-injection period are recommended for this site. The methodology proposed follows the monitoring plans implemented for depleted natural gas reservoir projects currently in operation, in particular the Otway Project in Australia.

According to Article 13 in the EU CCS Directive, all Member States shall ensure that the operator of a CO_2 storage site monitors the injection facilities, storage complex and surrounding environment, based on a monitoring plan. Minimum criteria for establishing and updating the monitoring plan are given in Annex II of the Directive. The monitoring plan should be based on the site-specific risk assessment analysis as required in Annex I of the Directive and provide details for the monitoring during all major stages of the project, including baseline, operational and post-closure monitoring (cf. Annex II of EU CCS Directive, 2009). The plan must, inter alia, include details of parameters monitored, technology employed, and sampling frequency in time and space for each project phase.

The monitoring concept for a given CO_2 storage site must be chosen according to the environmental and geographical conditions and extent of the underground geological formation, the effects each method may have on infrastructure, environment and human health in short and long term, the effects on existing business and industry in the area and the cost and effectiveness of the methods. Surroundings, surface and subsurface conditions, and local infrastructure vary and site-specific monitoring plans are required. The monitoring plan must be updated regularly to take into account changes related to the assessed risk of leakage, impacts on the environment and human health; new scientific knowledge; and improvements in best available technology. Updated plans shall be re-submitted for approval to the competent authority.

Acquiring baseline data regarding CO_2 that may be present in the system before CO_2 injection starts is very important. Any natural or industrial CO_2 sources and fluctuations in observed CO_2 levels at surface must be quantified to establish a baseline. In addition, a good monitoring concept should be flexible and designed to respond to unforeseen events and changes in the project development.

Fig. 4-1 shows a generic workflow for assessment, monitoring and verification in a CO_2 storage project that is taken from the EU-funded CO_2ReMoVe project (Wildenborg *et al*., 2009).

Site assessment:
- geological characterisation
- short & long-term characterisation (fluid flow, geomechanics, geochemistry)
- risk assessment

Design monitoring programme
Design leakage mitigation programme

Application/site certification

Acquire monitoring baseline data

*Start CO_2 injection

Monitor site
- Acquire monitoring data,
- Interpret monitoring data

Update risk assessment (incl. update simulations)
Update future monitoring programmes
Update leakage mitigation programme & site exit strategy

(Repeat monitoring and updates)

Eventually: site abandonment

Fig. 4-1: Generalised workflow for assessment, monitoring and verification purposes (after Wildenborg *et al*., 2009).

4.1 Mapping of relevant areas

The EU CCS Directive requires that the storage site operator monitors the injection facilities, the storage complex and, where appropriate, the surrounding environment and carries out comparisons between modelled and actual behaviour of CO_2 and formation water. All hydraulic units in sequences above or around the storage site that might be connected directly, through connected fractures or caprock failure to the CO_2 reservoir must be mapped and relevant areas for monitoring and observation must be defined. If CO_2 migrates via faults into porous and permeable reservoir rocks outside the storage site, it may be transported to the surface several kilometres away from the storage site and result in CO_2 emissions.

Monitoring should cover the storage complex and, when appropriate, the surrounding environment to ensure that leakage through other aquifer systems or fracture networks is observed and related to the storage site. It is important to identify and map structural trends, possible leakage pathways (e.g. faults, fracture networks) and shallower aquifer systems to identify the critical areas for monitoring and to reduce the acreage and cost of monitoring.

In addition to naturally occurring pathways for CO_2, all possible existing and planned manmade pathways including wells and boreholes, which could provide leakage routes, must be identified and considered for monitoring. Abandoned and existing boreholes and wells - both deep hydrocarbon wells and shallower water wells, mines, tunnels and constructions that may have damaged or intersected the caprock of the CO_2 reservoir or shallower hydraulic systems can be potential leakage pathways for CO_2.

Furthermore, the ownership and borders of commercial and residential areas, recreational and nature reserve areas at the surface must be established and legal rights, obligations and restrictions to perform monitoring must be made clear.

The type of monitoring equipment and its use must be selected to avoid conflicts. Nevertheless, it should still be sufficient and adequate to observe the behaviour of CO_2 in the subsurface and to detect signs of potential leakage at an early stage, so as to enable mitigation and limit possible damage to the environment and human health. In addition to HSE and operational monitoring, the ETS monitoring requirements need to be considered. This may result in employment of additional monitoring tools, enabling the quantification of a potential leakage.

4.2 Definition of monitoring objectives and intensity

According to the EU CCS Directive, the main objectives/purposes of monitoring are to: i) assess whether the injected CO_2, including CO_2 plume, is behaving as expected, ii) identify if any migration, leakage or significant irregularities occur and iii) assess whether any identified leakage is damaging the environment or human health.

Three categories of monitoring can be identified according to the Guidance Document 2 (2011):

- Mandatory monitoring (for all sites). This includes the parameters (injection rate, pressure, temperature, gas composition) described in Section 3.2.2 that are important for the operational monitoring. These parameters are typically measured by downhole instrumentation or at the well head and are required to be monitored continuously or intermittent during the injection phase. Downhole pressure and temperature measurements as well as measurements at the well head are also recommended during the post injection period.
- Required (site-specific) monitoring. The objective of this monitoring is to demonstrate the integrity of the seal, fault and wells at the specific site. This monitoring will be closely linked with the site-specific risk assessment. To assess fault integrity repeated 3D seismic surveys and pressure interference can be employed. The operator is required to perform monitoring with a frequency that gives sufficient input to dynamic modelling. The optimal schedule for seismic surveys is site-specific and depends on the model parameters, dominant trapping mechanism, target depth, caprock and overburden etc. The well integrity (annular pressure, wireline logging, optical well logging, cement bond logging, soil gas measurements) needs to be measured in the order of months during the injection phase.
- Optional contingency monitoring (site-specific). The third category refers to a contingency monitoring system which will be used in the event of irregularities. Contingency monitoring needs to be considered and planned for at an early stage in the project and should be based on the site-specific risk analysis. For example, microseismic monitoring (geophones behind casing of a well) can be a useful method for contingency monitoring during the injection phase.

Different phases of the project require different frequency of monitoring (cf. Chapter 1). The monitoring frequency during baseline survey and baseline data collection in the pre-injection phase will typically be same as or higher than during the operational phase. In the event of an irregularity, higher frequencies of monitoring and possibly additional monitoring tools will be required.

4.3 Selection of methods and specification of measurements

The EU CCS Directive does not specify the method or monitoring technology that should be used, but requires that the choice is based on best practice available at the time of design. As stated in Section 3.2.1, Annex II of the CCS Directive does give some guidelines for the selection of monitoring technology. Technologies that can detect migration pathways of CO_2 in the subsurface and at the surface, areal/vertical distribution of CO_2 plume and technologies that can provide wide areal spread of the complete storage complex and beyond are recommended.

The resolution of a specific monitoring method depends on the instrument specifications, but also on site-specific conditions. The monitoring instrument's ability to measure the distribution, phase and mass of CO_2 in a subsurface reservoir varies with geology of the site and surrounding area, target depth, ambient conditions of temperature, pressure and water saturation underground as well as by the theoretical sensitivity of the techniques or measurement instruments themselves. For example when acquiring seismic data onshore it makes a large difference if the geophone is placed in soil with good coupling and little background noise (e.g. no noise from surrounding traffic or industry).

At the general level for any site the main questions that need to be considered are according to the Guidance Document 2 (2011):

- Which methods are relevant for the specific site?
- What is the resolution of monitoring in detecting leakage?
- How accurately can leakage be quantified?
- What quantity of CO_2 can be resolved in the plume or deep subsurface?
- If continuous monitoring is considered in order to increase time sampling, what shall be the lifespan of the system?

Detecting and quantifying leakage

For offshore sites, the North Sea Basin Task Force (NSBTF, 2009) suggests to use a model driven approach where simulations are combined with data collection. For the North Sea, a good strategy would be to use "geophysical methods like seismic data (detection of gas chimneys) or sea bottom echo-sounding (detection of pockmarks) and then sample these leakage areas for direct CO_2 detection repeatedly. Based on the sampling profiles an estimate can be made of leakage rates in time for the area. In case of wellbore leakages an additional monitoring programme in and around the well is suggested" (NSBTF, 2009). Similar to sea bottom echo-sounding, other techniques that are able of detecting gas bubble streams in the water column, such as hydroacoustic techniques, may be employed for large area surveys, as outlined in Section 2.8.1.

For onshore sites there are several technologies to choose from as described in Section 2.3.4. Both direct methods for leakage detection and indirect methods where, e.g. ecosystems, groundwater or isotopic signatures are monitored can give reliable indications of irregularities. The main challenge for measuring absence of leakage with both direct and indirect detection methods consists of temporal and spatial coverage. At present there is no technology that can detect CO_2 releases at the surface - diffuse or localised, strong or weak - in an area corresponding to the size of the underground pressure plume. Therefore, a range of technologies are likely to be required to increase the probability of leakage detection. Given a storage complex size of more than a few hundreds of km^2 in comparison to potential surface leakage diameter of less than 1 m^2, the chances of missing a leak are high. To ensure leakage detection a comprehensive monitoring strategy should be implemented comprising techniques with different spatial and temporal coverage and resolution.

Definition of an adequate spatial and temporal coverage based on identified risks is the best strategy to employ. A plan for intensified monitoring in the event of irregularities is an important part of a good monitoring strategy. For this, the sensitivity and reliability of different techniques to quantify a potential leakage needs to be considered. An overview of the capabilities of currently employed monitoring techniques for quantifying leaking CO_2 is given in IEA GHG (2012).

Fig. 4-2 gives an overview of surface, near-surface and subsurface monitoring methods used in the large-scale CO_2 injection demo projects In Salah (onshore), Sleipner (offshore) and Snøhvit (offshore) (after Wildenborg *et al*., 2009).

	Subsurface monitoring								Surface and near-surface monitoring				
	Seismic methods				Non-seismic and borehole methods								
	4D surface seismic	hi-res 2D seismic	well seismics / VSP	microseismicity	EM / electrical	gravity	tiltmeters	well flow / well pressure	seabottom imaging	soil gas	surface flux/ atmospheric	ecosystems	satellite remote sensing (InSAR)
In Salah	■		■	■		■	■	■		■	■	■	■
Sleipner	■	■			■	■		■	■			■	
Snøhvit	■							■					

Fig. 4-2: Monitoring techniques deployed at large injection sites (adapted from Wildenborg *et al*., 2009). Selected techniques are indicated by yellow boxes.

Quantifying CO_2 in the plume

Strategies for monitoring and quantifying CO_2 in the subsurface have been successfully applied in several projects. Repeated 3D seismic surveys with an interval of several years in the onshore Weyburn oil field and the offshore Sleipner CO_2 storage site have shown that deep seismic methods can be used to quantify CO_2 with sufficient accuracy. However, the success rate depends on the target depth, reservoir quality, caprock and overburden. The optimal target depth with current technologies is 500 - 3000 m according to the Guidance Document 2 (2011).

4.4 Examples

Whereas general monitoring concepts provide a high-level framework for setting up site-specific monitoring programmes and give general recommendations on potentially suitable techniques, the site-specific monitoring plans need to take into account the identified location-specific risks. The procedure of transferring a general monitoring concept to a site-specific monitoring programme is exemplified for two sites representing the major storage options in Europe. One of the examples is on CO_2 storage in a saline aquifer (Example A), while the other involves a depleted gas field (Example B). The two storage projects are at different stages of project development. The aquifer site is Romania's NER300 candidate, whereas for the depleted gas field only preliminary capacity estimates are available. The authors of this section claim neither completeness of these monitoring plans, nor full compliance with and comprehensive consideration of all (national) regulatory requirements.

4.4.1 Saline aquifer/Romania

Example A involves a deep saline aquifer located in the south of Romania within the Getic Depression as a possible storage site. More information about the project is available at the dedicated website: www.getica-ccs.ro.

4.4.1.1 Site characterisation

The Getic Depression represents a sedimentary basin developed at the contact between the South Carpathians nappe pile and the Moesian Platform. The 50 - 100 km wide basin comprises more than 6 km of Uppermost Cretaceous to Tertiary sediments deposited in a poly phase tectonic regime. Following a general tectonic scheme, the evolution of the Getic Depression was characterised by Paleogene to Lower Early Miocene extension/transtension followed by large scale Middle to late Miocene contractional to transpressional deformations, with the entire system being buried by 1 - 2 km of flat-lying Pliocene sediments, slightly deformed during the last, late Pliocene tectonic event.

The Tertiary evolution of the Getic Depression is mainly characterised by major variations in sedimentary and structural patterns. A roughly S-ward thinning clastic wedge is observed, three main sedimentary cycles being are defined in connection with the tectonic activity: A first *Uppermost Cretaceous - Paleogene cycle* characterised by molasses type sediments, *the Miocene sedimentary cycle* mainly composed by clastic deposits and *the third sedimentary cycle (Upper Sarmatian - Pliocene)* mainly characterised by up to 2 km thick clastic deposits.

Several deformations control the development of different lithological and seismic sequences:

- *Pre-Middle Burdigalian deformations* which created two major normal fault systems with NE-SW trending and WNE-ESE trending, which defined several tilted blocks;
- *Late Burdigalian – Badenian deformations* represented by the reverse faults, which structurally define various uplifted areas along the fore deep;
- *Sarmatian – Early Pliocene deformations* are the most important tectonic event in the foredeep, characterised by the formations of transpressional strike–slip duplexes and flower structures associated with the frontal thrusting of the foredeep upon the Moesian platform.

The proposed storage area is located in the south of Getic Depression. Two Sarmatian sequences have been found suitable for CO_2 storage at 1800 - 2100 m depth, while the overlying Sarmatian sequences constitute the caprock within the storage complex. The reservoir sequences are composed of porous permeable strata (sandstones) alternating with impermeable strata (marls) with an average thickness of about 15 m. The Sarmatian sequences (including reservoir and caprock sequences) pinch-out on a Pre-Tertiary relief (a large canyon), creating a structural-stratigraphic trap. The lateral boundaries of the storage complex are constrained by bounding faults and pinch-outs of the reservoir formations.

Modelling work revealed that the reservoir has sufficient storage capacity to accommodate 1.5 Mt CO_2 per year for an operation period of at least 20 years, but that the injectivity is relatively low, requiring several injectors to accomplish the proposed injection target. Therefore, several small scale plumes will be formed at the beginning of injection which will keep their individuality for at least 300 years after the beginning of injection according to the modelling work performed so far.

4.4.1.2 Setting up a site-specific monitoring plan

The risk analysis did not reveal a major/critical risk; however, several elements and potential hazards should be considered when drawing the monitoring plan. One of the aspects to be carefully monitored is conformity with modelled behaviour and control of injection operations. The risk of leakage and potential environmental consequences should be taken into consideration and appropriate monitoring techniques should be deployed to control these risks. Special attention should be paid on monitoring the abandoned wells in the area. A detailed overview of the risks identified by the risk analysis carried out and the monitoring techniques chosen to address these risks is provided in Tab. 4-1.

Tab. 4-1: Overview of the identified risks and the monitoring techniques proposed to mitigate the risks. The number in column 2 is assigned to monitoring methods for internal reference purposes and is also applied in Tab. 4-2.

Risk	Monitoring method used		Rationale for the Choice of Monitoring Method
	No.	Name	
Aseismic movements at the surface	3	InSAR	InSAR monitoring technique can detect movements of the ground surface. In order to overcome the difficulties caused by vegetation or rough terrain specific to the selected site, control points will be carefully chosen.
Groundwater contamination	5	Groundwater sampling	Potable water sampling can be a very efficient method for detecting groundwater contamination. It is very important to apply this method especially since many people from the storage area use the water from fountains and water wells for drinking.
Soil contamination	4	Soil gas surveys	Soil gas surveys can indicate an increase of the CO_2 concentration in the soil compared to the reference level assessed through baseline surveys acquired previous to injection.
	19	Microbiological monitoring	Modifications in the microbiological activity within the soil can be a good indication of soil contamination.
Well leakage	10	Sonic logging	Sonic logs are very effective to determine unconformities at well, as non-sealing cementing and tubing.
Leakage through faults	1	Time-lapse 3D seismics	Time-lapse 3D seismics can be used as primary method for plume tracking and can provide also an image of the entire storage complex, including structural elements present (including faults).
	8	Cross-well seismics	The main advantage of the technology is the very high spatial resolution. The technique can provide a higher resolution than surface seismic. It can detect leakage only the two wells are placed on the leakage pathway.
	7	Cross-well EM	The cross-well EM Resistivity service is designed to map resistivity distribution between wells and can indicate changes in resistivity. Can be an additional method to seismic and has a great potential to detect leakage, but the two wells used for the application of this technique should be placed on the leakage path.
	2	Time-lapse gravity	Time-lapse gravity can be used as an additional method to time-lapse seismic for long-term tracking of the plume (lateral movement only) and to detect fractures and faults in the reservoir.

Tab. 4-1 (cont.): Overview of the identified risks and the monitoring techniques proposed to mitigate the risks.

Risk	Monitoring method used		Rationale for the Choice of Monitoring Method
	No.	Name	
Leakage through faults	6	Microseismic monitoring	The detection and interpretation of injection-induced microseismicity has seldom been deployed and tested in CO_2 storage pilot projects. Such a technique has great potential for both monitoring storage integrity and the mapping of fluid fronts. Seismic activity can be recorded and processed so as to provide unique insights into the structural features and into the in-situ hydro-mechanical behaviour of the reservoir and surrounding rock masses.
	17	Gas analysis at compressor	Gas analysis at the compressor can indicate the contamination of the CO_2 stream before the CO_2 is sent to the injection facility. It is the first point where the contamination can be observed and the necessary measures can be taken.
Composi-tion of the CO_2 stream	18	Gas analysis at injection facility	Gas analysis at the injection facility can indicate modifications/ contamination of the CO_2 stream before injecting the CO_2.
	20	Atmospheric gas measurement at monitoring well locations	Gas measurements in the air (here 1.5 m above ground level) can indicate an increase of the CO_2 concentration in the air that can be caused by leakage.
Leakage in the air	16	Wireline logging	Wireline logging at the injection wells and monitoring wells can indicate unconformities at the those wells that can compromise well integrity.
Well integrity	10	Sonic logging	Considering that CO_2 is to remain downhole for an extensive period of time, the conditions of the well bores in contact with the CO_2 plume (cement and casings) are likely to degrade in that time frame. There-fore, a specific monitoring programme should be put in place to assess the well integrity status of those wells at regular intervals in order to update the related risks of leakage and take appropriate measures such as workover if needed. The two components of the well architecture that we want to monitor are the cement sheaths and the tubular (casing and tubing). The primary way to achieve cement and tubular evaluation is through sonic tools.
	14	Wellhead pressure measurement	Pressure and temperature sensors are crucial to the operational, reservoir and assurance monitoring. As pressure and temperature relate to the geomechanics, thermodynamics, fluid displacement and geochemistry, they are major parameters to the calibration of the reservoir simulations. In the injection well, the bottomhole and the wellhead pressure and temperature are input to the control and optimisation of the injection rate. Anomalies in their evolution will be early signs of a loss of integrity in the wellbore or in the vicinity of the well. Unexpected changes in temperature or pressure may be the sign of a fracturing caprock, of CO_2 leaking through a shortcut, changing phase, reacting with cement. Similarly, in reservoir monitoring wells, pressure and temperature are input to the calibration of the reservoir models. Pressure interference tests or simple correlation of pressures during injection will give information on the sealing properties of primary barriers. Again, unexpected changes in temperature or pressure of the monitoring wells should be considered as potential sign of the leakage.
	15	Wellhead temperature measurement	
	13	Downhole pressure and temperature measurements	

The selection of the monitoring tools to be included in the monitoring plan should be oriented to the best techniques available at the given point, in order to ensure control of the injection operation (mandatory monitoring), CO_2 plume tracking, CO_2 leakage detection and monitoring of the potential leakage pathways and assessing the environmental impact.

For the control of injection operations, several types of point measurements should be made at the wellhead and downhole: wellhead pressure and temperature, wellhead flow metering and composition of the CO_2 stream, downhole pressure and temperature, along with an extensive logging programme, including wireline, acoustic, cement bond, pulsed neutron and resistivity logging. For the operational monitoring, the point measurements (e.g. gas analysis at the compressor, injection facility, wellhead and downhole temperature and pressure measurements) should be continuously recorded in order to be able to detect any irregularities related to CO_2 stream compositions and modifications of the pressure and temperature regime.

For CO_2 plume tracking, the primary method to be used is time-lapse 3D seismics. Cost considerations indicate the need for using complementary low cost methods in addition to active surface seismics, such as time lapse gravity and InSAR. The frequency of deploying such techniques should be determined based on modelling, physical properties forecast, when the contrast of physical properties is sufficient to obtain a significant anomaly. As the plumes will be rather small and will extend slowly laterally, the gravity signal is expected to be very low during the operational phase. Therefore, this method should be intended for long term monitoring. On the other hand, InSAR could be used successfully to fill the gap between two consecutive seismic surveys.

Cross-well seismic and cross-well EM could also be used for plume tracking, but their successful use implies drilling several deep monitoring wells in each injection area. This could increase very much the overall cost of monitoring. Since VSP requires just one monitoring well in each injection area, this technique could be chosen for the aforementioned purpose and also as a calibration tool for surface seismics. In addition, well logging methods can be used for CO_2 plume tracking, to be run in the monitoring wells, such as sonic log. Cased hole neutron porosity, cased hole resistivity logging and pulsed neutron logging.

CO_2 leakage detection should rely mostly on time-lapse 3D seismics applied in each injection area, above each plume. InSAR technology, sensitive to pressure changes, could prove useful only in the case of a massive CO_2 leakage that could induce a measurable ground deformation. In addition to seismics, soil gas survey, groundwater sampling and atmospheric monitoring could give evidence of an eventual leakage. The use of cross-well methods for leakage detection would require that the monitoring wells are located on the leakage path. Downhole pressure and temperature monitoring would be sensitive to CO_2 leakage, but could require some additional logging acquisitions.

Most of the techniques presented above are time-lapse techniques (except the techniques for control of injection operations); therefore, baseline surveys and baseline data should be acquired prior to the start of injection. Besides the data acquired for global (seismic, InSAR, gravity) and well logging techniques, detailed data on the air, soil, water and groundwater quality should be collected in order to monitor the evolution of the environment around the storage area.

For most of these techniques, the specific thresholds that would require taking corrective measures are not yet defined. For defining these specific thresholds, the addressed risks have to be assessed for significance. Guidelines are needed for an evaluation and interpretation of monitoring data and an appraisal of potential impacts at the site. Tab. 4-2 presents an overview of the methods to be included in the monitoring plan.

Tab. 4-2: Overview of the monitoring methods to be included in the monitoring plan.

No.	Monitoring method	Data collected	Location	Tasks of monitoring	Monitoring methods in the life-cycle phase, frequency			
					Pre-injection phase	Operational phase	Closure phase	Post-closure
1	Time-lapse 3D seismics	3D seismic surveys	Entire storage complex	CO_2 plume tracking / Assess storage system performance and conformity with modelled behaviour	Baseline survey	Order of years, based on comparison of monitoring and modelling results	Order of years, based on comparison of monitoring and modelling results	Survey after several years
2	Time-lapse gravimetry	Gravity data	Entire storage complex	CO_2 plume tracking / Assess storage system performance and conformity with modelled behaviour	Baseline survey	Order of years, based on comparison of monitoring and modelling results	Order of years, based on comparison of monitoring and modelling results	Survey after several years
3	InSAR	Satellite images on surface deformation	Entire storage area surface	Assess storage system performance and conformity with modelled behaviour	Baseline survey	At a number of years		
4	Soil gas survey	Gas measurements	Fix locations around the injection wells	Risk assessment	Baseline surveys in different seasons	Yearly		
5	Ground-water sampling	Water samples; chemical analysis	Shallow aquifers; potable water	Risk assessment	Baseline data acquired	2 per year		
6	Microseismic monitoring	Passive seismic	Network of receivers		Baseline data acquisition	Continuous		
7	Cross-well EM		Between monitoring wells	Assess storage system performance and conformity with modelled behaviour	Baseline survey	Order of years, based on comparison of monitoring and modelling results		
8	Cross-well seismics		Between monitoring wells	Assess storage system performance and conformity with modelled behaviour	Baseline survey	Order of years, based on comparison of monitoring and modelling results		

Tab. 4-2 (cont.): Overview of the monitoring methods to be included in the monitoring plan.

No.	Monitoring method	Data collected	Location	Task of monitoring	Monitoring methods in the life-cycle phase, frequency			
					Pre-injection phase	Operational phase	Closure phase	Post-closure
9	VSP		Monitoring well	Assess storage system performance and conformity with modelled behaviour	Baseline survey	Order of years, based on com-parison of monitoring and modelling results		
10	Sonic log	Well leakage related to tubing		Risk assessment		Yearly		
11	Cased-hole neutron porosity							
12	Cased-hole resistivity logging							
13	Downhole *p* and *T* measurements			Risk assessment / Assess storage system perfor-mance and conformity with modelled behaviour		Continuous		
14	Wellhead *p* measurements		At the injectors	Risk assessment		Continuous		
15	Wellhead *T* measurement		At the injectors	Risk assessment		Continuous		
16	Wireline logging at injection wells and monitoring wells		Through injection and monitoring wells		Yearly			
17	Gas analysis at compressor	Quality of the CO_2 stream	Compressor station	Risk assessment / Composition of the CO_2 stream		Continuous		
18	Gas analysis at injection facility	Quality of the CO_2 stream	Injection facility	Risk assessment / CO_2 at injection facilities		Continuous		
19	Microbiological monitoring	Qualitative and quantitative assessment of soil microbiological populations	Pre-defined sample locations around injectors	Risk assessment	Baseline survey	Yearly		
20	Atmospheric gas measurement at monitoring well locations			Risk assessment		Continuous		

4.4.2 Depleted Gas Field/Slovakia

Depleted hydrocarbons deposits are potentially suitable sites for geological storage of CO_2 because, besides proven containment of hydrocarbons, it is possible to gain valuable knowledge from the production history and the quantity of crude oil or gas, which remains in the deposit after the earlier exploitation activity seized. CO_2 storage creates a possibility to enhance recovery at least for parts of these unexploited reserves. A national research project has been carried out by the State Geological Institute of Dionýz Stúr , Bratislava, to investigate suitable CO_2 storage sites in Slovakia (Kucharič *et al*., 2012). This section is partly based on outcomes from this project.

4.4.2.1 Site characterisation

The Slovakian territory is predominantly made up by geological units belonging to the Western Carpathians. There are several small deposits of natural gas within the Neogen basin sediments. The largest accumulation of hydrocarbons in the former Czechoslovakian Republic is the deposit Vysoká-Zwendorf located in the Vienna basin, lying on the border between Slovakia and Austria. The peculiarity of this deposit is the joint ownership by both neighbouring countries, i.e. approximately 1/3 belongs to Slovakia and 2/3 to Austria. The exploitation was managed on the basis of a bilateral agreement between the former Republic of Czechoslovakia and the Republic of Austria established on 1st April, 1960. The deposit is currently completely abandoned from the Slovakian part. The last recalculation of reserves assessed a volume of 3 billion cubic metres (BCM) of methane, which remained in the deposit in the Slovakian part. The deposit is now filled with water. Equal amount of methane is known to have been exploited in the Slovakian part, bringing the total volume of original gas in place to 6 BCM. The reserves in the Austrian part were about 12 - 16 BCM according to uncertified data. The loction of the deposit is depicted in the Fig. 4-3.

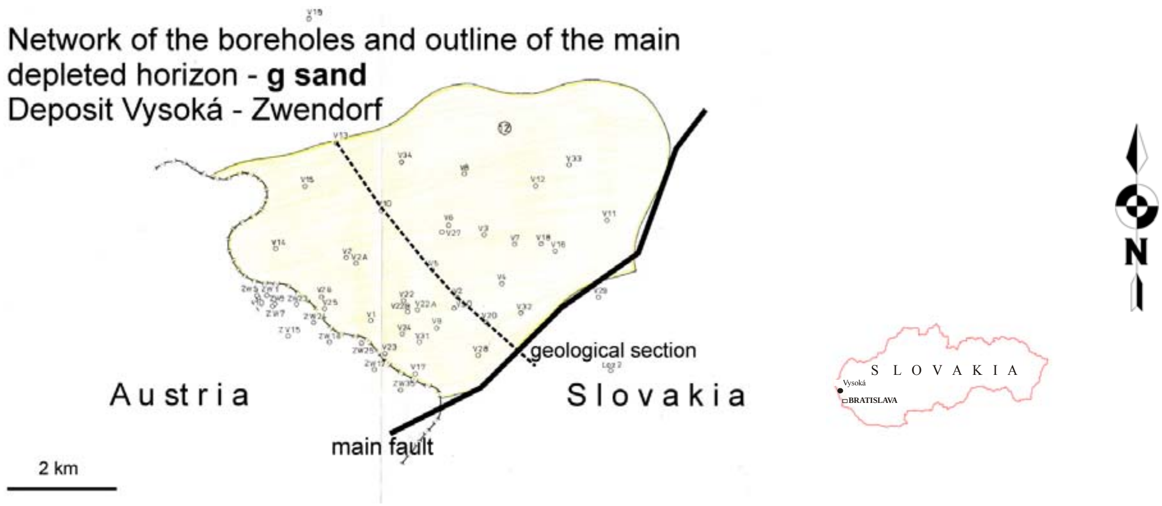

Fig. 4-3: Location map of the Vysoká deposit (Slovakian part) showing the network of boreholes and outline of the main depleted horizon - g sand (Hlavatý, 1994).

The deposit was formed during the Miocene sedimentation (Badenian-Pannonian) and consists of twelve individual horizons. The main gas-bearing horizon (cf. Fig. 4-3) is at the base of the Middle Badenian and consists of delta sedimentation products with a thickness of around 500 m. The gas-saturated part of this deposit is around 60 m thick. The reservoir rock is consolidated fine grained calcareous - loamy sand with calcareous clay bands (g-sand). The methane concentration in the gas is > 97%. The main horizon comprised 95% of all gas reserves of the whole deposit (Slovakian part). The average permeability was

108 mD, the average porosity 26%. Non-displaced water saturation was around 25%, which indicates that the coefficient of gas saturation may be around 75% for maintained deposit pressure. The average pressure was estimated at 12.3 MPa and the temperature at 64 C. The storage capacity of CO_2 was assessed as 12 Mt for the Slovakian part of deposit.

Waters contained in the aquifer are typically “marine” with total salinity in the interval 25 - 33 g/l and basically correspond to the paleosalinity of the Badenian. Regarding their chemical composition they are monotonous waters of the sodium chloride-type. The concentration of $NaHCO_3$ is in the range 3.2 - 4.6 mval%, which suggests minimal infiltration during the lifetime of the deposit. This is a very important issue regarding the security of the potential storage site, since the chemical character of the waters provides evidence that the deposit is well sealed.

The main part of deposit, the base of the Middle Badenian (95% of reserves), creates an extended brachyanticlinal structure in the SW – NE direction, which is practically tectonically undisturbed. The top of the anticline is at a depth of 1,275 m below the surface. The dip of the anticline to the North and to the East is 2°. The roof of this horizon is depicted in the Fig. 4-4. The only tectonic feature of interest is the so-called Láb fault system, which bounds the deposit from the SE side. There are dip-slip faults with aggregate amplitude 150 – 200 m and a dip of 45° to the SE.

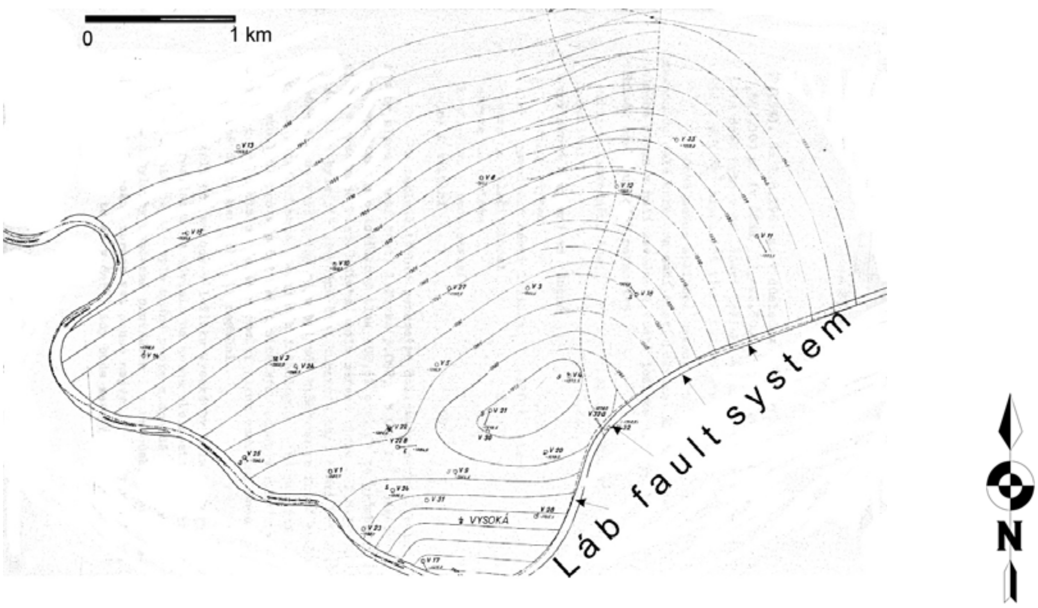

Fig. 4-4: Vysoká deposit main horizon depth isolines (Hlavatý, 1994).

The presence of small gas deposits in the Sarmatian test horizon is important for the potential storage site (Fig. 4-5) as they may serve as a suitable test horizon before filling the main deposit horizon. They represent a pilot project size reservoir with a maximum storage capacity of 30 kt CO_2. This reservoir is found at 830 - 870 m depth and even the tectonic sealing is the same as for the main horizon - Láb fault. After successfully testing the test horizon in a pilot project, CO_2 storage could be extended to industrial scale in the deeper and bigger horizon of g-sand. This site provides a unique opportunity to link pilot and industrial scale CO_2 storage.

The deposit was verified in its Slovakian part by means of an irregular network of 35 boreholes with an average distance of 500 m and depths ranging from 1,050 m to 3,085 m. All boreholes have been drilled during 1950s and 1960s. This means, that integrity of these boreholes needs to be confirmed as these may represent potential leakage pathways from the planned storage complex. Therefore, the state of the old boreholes needs to special attention in the monitoring plan layout.

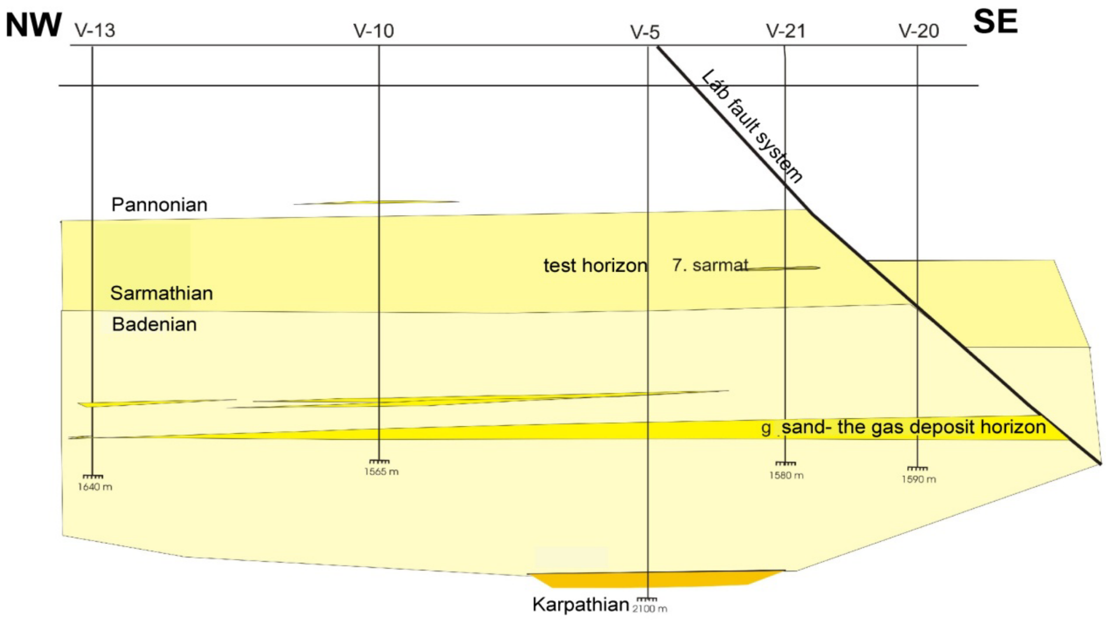

Fig. 4-5: Geological cross-section of the Vysoká deposit, marked in Fig. 4-3 (Hlavatý, 1994).

4.4.2.2 Proposed site-specific monitoring plan

From the above mentioned information it is obvious that the focus of the monitoring activities will be on the state of the old boreholes and the Láb fault system. In setting up a monitoring plan the presence of the above mentioned irregular borehole network needs to be considered.

Geophysical Monitoring

The utilisation of geophysical methods is necessary to establish the present day status of the storage site. The proven long-term containment of natural gas indicates that seal integrity of the deposit can be inferred. However, as leakage through operating or abandoned wells has been highlighted as a major risk for geological storage projects, the numerous old boreholes present are considered as the most important potential problem at this site. Monitoring must target the wells to be used for CO_2 injection, as well as all wells related to other exploration and production activities for oil and gas, water extraction, coal and minerals exploration, etc. It is necessary to evaluate the current condition of these wells/boreholes.

Baseline monitoring

We propose to monitor every borehole in the overburden above the storage reservoir. The monitoring network should cover areas where the Láb fault system and its extensions are known to outcrop. Moreover, it is recommended that satellite interferometry (InSAR) and tiltmeter measurements should be carried out.

It is expected that many of the well structures may be defective and that it will be necessary to take decisions as to which boreholes may serve as operational wells for the storage site (injection and monitoring wells), and which may be sealed. Additionally, an assessment of the number of wells that may be suitable for enhanced gas recovery (probably at the top of the brachyanticline) is required. Accordingly, the wells at the margins of structure are recommended as CO_2 injection wells, so as to benefit from the buoyancy of CO_2 (boreholes V 10, 11, 13, 14, 33, etc., see Fig. 4-3). The condition of the wells will be inspected by well logging (cement bond log – ultrasonic well logging, density logging, resistivity and gamma ray logging as well as self potential and calliper logging).

Operational stage monitoring

The operational phase of the project is expected to last 20 - 30 years. The monitoring methods utilised to establish the baseline will be used to provide time dependent comparisons with the reference levels. During the operational stage it will be necessary to track the pressure levels in the reservoir, limiting it to a maximum value of 15 % above original pressure in the reservoir. The natural trapping in the gas reservoir was excellent, and therefore creation of new cracks and fractures needs to be avoided. The tightness of the reservoir may be controlled by temporary exploitation of gas with water.

It is recommended that the spread of the CO_2 plume is monitored using time-lapse seismic measurements. Due to very high expenses for the time lapse seismics, it may be desirable to utilise the network of monitoring wells for cross-well monitoring, if the well density is sufficient.

Post-injection monitoring

It is recommended that the type and frequency of monitoring used post injection should be maintained. In the first five years after the closure of storage site, the frequency of monitoring should be the same as during the operational stage. If no adverse effects are observed and compliance with predicted behaviour is maintained, it is recommended that this time interval may be extended in the course of future years. With present day knowledge, it is not feasible to estimate the frequency of required monitoring reliably. Besides the technical constraints, such as the final pressure in the reservoir, other considerations such as financial constraints and public perception issues regarding the storage project may influence such decisions.

Geochemical Monitoring

Geochemical monitoring of potentially affected compartments (groundwater, soil gas, shallow atmosphere) should be carried out before injection starts, during the operation and post-injection stages to allow for comparisons between the relevant datasets and enable the detection of potential CO_2 leakage during the operational and/or post-injection periods. The methodology proposed in the following sections (sampling strategy, sampling frequency) is adapted from those utilised in current CO_2 storage projects, particularly the Otway Project carried out in a depleted natural gas reservoir (Etheridge *et al*, 2007, 2011; Watson *et al*., 2006; Boreham *et al*., 2011; Underschultz *et al*., 2011).

Pre-injection (baseline) monitoring:

Pre-injection monitoring is required for the establishment of baseline conditions in the selected site and the detection of possible leakage from abandoned wells. It involves soil gas, groundwater and atmospheric monitoring, and is recommended to cover a period of two years to detect the seasonal variations and to distinguish those from the variations likely to arise from possible CO_2 leakage during and/or after the end of the injection operations.

Soil gas monitoring is aimed towards characterisation of the concentration and isotopic composition of background soil gas and detection of possible leakages from abandoned wells. This is an important step in the construction of baseline conditions and definition of potential zones of possible leakage (e.g. faults, fractures, abandoned wells), recognition of the sources of soil gases, and differentiation of natural CO_2 from injected CO_2 in the future injection/monitoring programme. Both continuous monitoring and periodic monitoring are recommended:

- Continuous monitoring comprises measurement of CO_2 and CH_4 concentrations using permanently installed probes, and is aimed particularly towards detection of possible leakage from abandoned wells.
- Periodic monitoring is strongly recommended for the characterisation of the concentration and isotopic composition of background soil gas to enable the distinction of injected CO_2 from naturally occurring CO_2 in future injection/monitoring programmes. This stage of monitoring involves sampling for further analyses at laboratories, including
    i) Molecular composition analyses (CO_2, methane, ethylene, ethane, nitrogen, etc.);
    ii) C-isotope analyses ($^{13}C/^{12}C$), isotope analyses are recommended to provide background values for a strategy on the use of CO_2 tracers.

Installation of probes and sampling should follow a grid network across the study area targeting the abandoned wells. A maximum distance of 100 m spacing is recommended for the grid network to get statistical coherence in between points; even a higher number of monitoring points should be considered in the vicinity of potential leakage pathways such as defective well structures and places where branches of the Láb fault system are exposed, i.e. using grid of variable size. For periodic monitoring, biannual sampling (in winter and summer times) is recommended to identify the variations in the (molecular and isotopic) composition of gases caused by natural processes; sampling should be performed from 1 m depth in soil – vadose zone - to avoid influence of biological activity that is strongest in the uppermost decimetres of the soil and to reduce contamination from atmosphere.

Groundwater monitoring is recommended on samples collected from shallow bores/well heads in the selected site. Biannual sampling (in winter and summer periods) is accepted as suitable for the evaluation of seasonal variations. The geochemical parameters to be analysed include:

- pH, temperature, electrical conductivity;
- major and minor anions/cations (e.g. Na, K, Ca, Mg, Fe, Al, SiO_2, CO_3^{2-}, HCO_3^-, Cl^-, SO_4^{2-});
- dissolved gas composition;
- optional: isotopic composition of i) water ($\delta^{18}O$, δD); ii) dissolved constituents ($\delta^{13}CDIC$); iii) dissolved gases ($\delta^{13}C$ (CO_2), $\delta^{13}C$ (CH_4), $\delta^{18}O$ (CO_2)).

The rationale behind the analyses of all these parameters is to enable the assessment of geochemical interactions (such as CO_2 dissolution, mineral solubility, mineral precipitation) and hence an understanding of the fate of injected CO_2 during and/or following the injection period. Although the isotope analyses are relatively costly, integrated use of isotope and chemical compositions are recommended for the modelling of geochemical interactions at subsurface.

A network of atmospheric monitoring equipment is to be set up to characterise the background against which anomalous sources of CO_2 or other gases (methane or tracers) could be detected. Atmospheric monitoring comprises two main tasks:

- Near-continuous measurement of CO_2 in a station downwind of the storage site (via the use of chemical CO_2 sensors and/or infrared CO_2 sensors);
- Flask air sampling (into 0.5 L flasks, for detection of gas concentrations (molecular composition) and – optionally – analyses of isotopic compositions ($\delta^{13}C$ and δ ^{18}O of CO_2) to provide the background values for a strategy on the use of tracers - CO_2 isotopes and tracer compounds such as SF6 – during

injection. Biannual sampling is considered to be suitable for the provision of background values during pre-injection monitoring stage.

All the measurements obtained from the above stated monitoring methods are to be evaluated in terms of sources and the causes of variations in the background concentrations of the gases and CO_2 fluxes in the selected site.

Operational stage monitoring:

This stage of monitoring is supposed to start with the commencement of CO_2 injection into the subsurface and continue for the whole period of operation (20 to 30 years). The studies included are essentially the same as those involved in pre-injection monitoring, but the sampling strategy and frequency may change.

Regarding soil gas monitoring, continuous CO_2 measurement from the vadose zone is recommended using the same grid system used in pre-injection monitoring. Periodic sampling should continue (for analyses of molecular and isotopic composition of gases) with the same frequency as for baseline monitoring to provide data of similar temporal resolution.

Reservoir fluid monitoring can be accomplished via either well-head sampling or downhole sampling (i.e. at reservoir level). In the latter case, it is required to set up a bottom hole assembly in the observation well to accomplish the necessary sampling and measurement activities. Sampling is to be done through a multilevel U-tube sampling system which allows sampling directly from the reservoir levels and precludes the effect of any molecular/isotopic fractionation between well-head and reservoir due to changing *p-T* conditions from depth to surface.

Following the start of CO_2 injection into storage site, geochemical sampling from wells should continue biannually (in summer and winter periods) as in baseline monitoring. For a better assessment of the fate of the injected CO_2, it can be considered to perform a weekly sampling from the observation well for a short time period (e.g. few months) depending on the overall site performance. In addition, CO_2 injection and migration may be followed by tracer injection (e.g. SF6, and/or C-isotope tracer with an isotope composition different from that of background carbon) approximately one month later than the start of CO_2 injection. At this stage, a daily sampling from the observation well is recommended for a couple of weeks, returning to larger sampling intervals afterwards. The analyses to be conducted are the same as those applied in the pre-injection monitoring phase.

Operational-stage atmospheric monitoring incorporates the same tasks reported for pre-injection monitoring, i.e., near-continuous measurement of CO_2 and flask air sampling and analyses. For flask air sampling and analyses, tracers that have low and steady concentrations in the background atmosphere (e.g. SF6) are proposed to be added to the injected fluid to quantify leakage from CO_2 storage site. At the operational stage, the flask air sampling interval is proposed to be the same as in baseline monitoring.

Post-injection monitoring:

The monitoring carried out during the operational stage should also be performed during the post-injection period. The frequency of sampling/measurements may be reduced in years depending on the results to be obtained in the first few years of closure.

5 CONCLUSIONS AND RECOMMENDATIONS

Monitoring is an essential element within the selection, planning, installation, operation and abandonment of CO_2 geological storage sites. Monitoring provides fundamental data about a storage site's state and performance and thereby helps to meet the common public concern on potential impacts of CO_2 geological storage on the environment, human health and assets. The main substances of concern are CO_2 and, because of the large volumes, displaced formation water. Monitoring also includes the observation of impurities within the CO_2 phase, substances mobilised in the subsurface, and geomechanical effects of CO_2 injection.

Monitoring programmes implemented at current demo and industrial-scale projects are mostly restricted to the most effective monitoring methods (in terms of availability and cost) to comply with the legal and safety requirements. In contrast, a wide variety of monitoring tools are developed, adapted, tested and validated at natural release, research and pilot test sites.

Overall, well-advanced "deep" monitoring techniques are available for monitoring the performance of the storage reservoir and tracking the expansion and migration of the CO_2 plume. At present, seismic monitoring is the dominant geophysical method for the observation of CO_2 in saline aquifers and depleted oil reservoirs. Seismic methods allow, in most cases, mapping of the migration of the CO_2 plume and, in combination with other measurements, can also provide reasonably accurate volume estimates.

Also, a number of established, reliable methods and tools exist for near-surface monitoring at CO_2 storage sites. The available monitoring methods comprise different suites of techniques enabling i) large-scale surveys that contribute to baseline measurements and that can be used to detect eventual leakage pathways on a regional level, ii) rapid surveying of relatively large areas and derivation of essential results in a short time, iii) detailed small-scale verification and characterisation procedures for selected, confined areas using local knowledge to target possible spots of CO_2 and fluid leakage. Reliable techniques exist that can distinguish CO_2 from deep origins (geogenic or anthropogenic) from shallow, biogenic CO_2. In case of leakage, rates can be quantified by detailed flux measurements. The resolution of the monitoring methods and, consequently, the capacity to detect fluid migration and irregularities, depends very much on local site conditions and the intensity of monitoring. High-resolution measurements obviously increase the detection capacity but require intensive and costly monitoring efforts.

The verification activities at five active CO_2 storage sites showed that monitored site performance deviated from modelled predictions at all sites (Wildenborg *et al*., 2012). Hence, a key element of site-specific monitoring plans will be to establish relevant criteria that will allow discrimination between acceptable deviations from the permitted behaviour (which will only necessitate a model update without consequences on the performance prediction of the site) from deviations that represent significant irregularities (and require updates of the risk assessment and the monitoring plan, and potentially give indications to take remedial actions, change the injection plan and eventually require major revisions of the numerical models) (Wildenborg *et al*., 2012). In addition, criteria are needed to evaluate convergence of predicted and observed site performance with time. Such a convergence reflects a sufficient understanding of the storage system, which is a prerequisite for long-term predictions and the transfer of responsibility of a storage site.

The following recommendations for monitoring CO_2 storage site performance are based on extensive experience from groundwater observation, environmental monitoring, natural gas storage and hydrocarbon production, industrial CO_2 storage and research pilot projects, the investigation of natural analogues and controlled CO_2 release experiments:

- Comprehensive, integrated, and flexible monitoring plans are needed in order to satisfy various monitoring needs during normal operation and for contingency monitoring. Monitoring shall form an

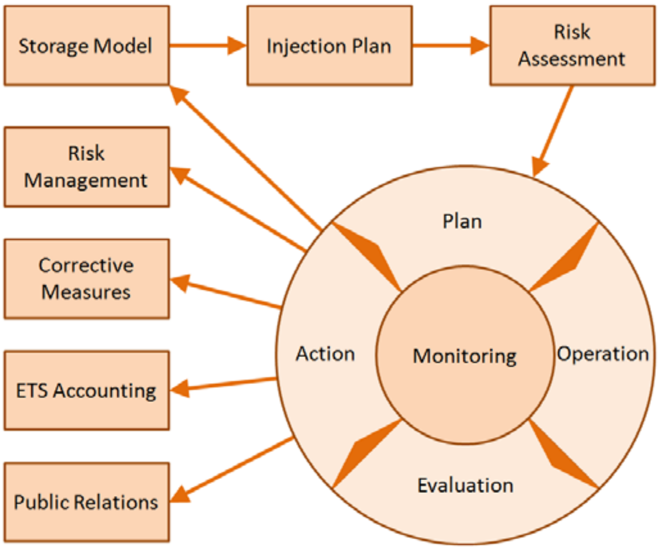

Fig. 5-1: Schematic evolution of site-specific monitoring plans in relation to other elements of CO_2 storage management.

integral part of the overall site management and must be continuously improved as well as any associated activities, as illustrated in Fig. 5-1.

- The development of tools and testing their application at ongoing storage projects under *in situ* conditions are needed in order to evaluate and provide monitoring technologies and concepts considering "new scientific knowledge, and improvements in best available technology", as required by the European CCS Directive (2009/31/EC).
- Cost effectiveness measures, such as campaign optimisation or combination of various methodologies, should be considered. Additionally, it may be beneficial to increase the lifetime of sensors in order to save costs on the maintenance activities.
- The thresholds for acceptable deviations from predictions and the demonstration of convergence must be specified prior to CO_2 injection. They should include safety margins, taking into account uncertainties from site characterisation, performance predictions and monitoring accuracy. Monitoring plans should be designed in a way that provides appropriate information to verify the specified conditions.
- All stakeholders, including the local population, should be involved in the definition of i) acceptable conditions, ii) significant irregularities and iii) site-specific threshold values. Furthermore, they should participate in the planning of the measures to be taken in the case where such values are exceeded.
- The planning, operation, performance, and updating of monitoring activities, such as storage operation in general, should be conducted under independent supervision, e.g. a competent authority, that is not the permitting agency at the same time.
- With respect to detection limits and uncertainties in quantification, the CO_2 injected into a storage formation should be regarded as contained within the storage complex, providing that no indication of deviation has been observed by a reasonably extensive, sensitive and appropriate monitoring programme.
- Concerning the detection of anomalies and the distinction of storage-related impacts from natural variations and phenomena, it is essential to integrate the results of near-surface and subsurface monitoring efforts in a thorough, systematic and plausible manner. Extensive site-specific knowledge is required because the resolution and sensitivity of many monitoring methods (and, hence, the

capacity to detect irregularities or fluid migration) depend very much on local site conditions and the intensity of monitoring.

- The comparison of monitoring results with baseline data and model predictions will be crucial for a quantification of effects. Extensive baseline monitoring is required for recording natural (e.g. seasonal) variations for relevant parameters that are needed for understanding processes and unravelling the controlling factors for these processes and the resulting variations. Baseline monitoring should start well before the first CO_2 injection, as part of site characterisation, in order to record secular natural variations and have sufficient time for the interpretation of the recorded data, so that natural processes can be considered in the risk assessment and monitoring plans.

Some of these issues are currently addressed in ongoing international research projects (e.g. RISCS, ECO2, CO_2CARE, SiteChar) and national projects around the world. Once the full range of results is available, it will be possible to further refine monitoring strategies for future CO_2 storage sites.

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