CO_2 Storage

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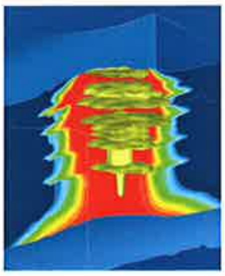
Exploration • Production • Induced Ground Movement • CO_2 Storage • Geobiology

Geo energy



CO_2 Storage

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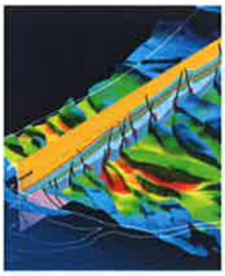

Exploration

- Low Cost Sharing of 3D Basin Maps
- ExploSim:Exploration Portfolio Simulation tool for determining future productionand throughput profiles at production locations
- TNO conceptual framework for "E&P Uncertainty quantification and Technical-to-Business Integration for Improved Asset Investment Decision-Making"
- A Bayesian Belief Network approach for assessing the impact of exploration prospect interdependency
- Renewed interest in geothermal energy
- Petroleum Geological Atlas of the Southern Permian Basin Area (SPBA)
- NCP-2:Detailed 3D subsurface mapping ofthe Netherlands Continental Shelf
- Seismic velocity model building based on sonic data of boreholes in the Netherlands
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- Basin subsidence mechanisms during the Carboniferous in the Netherlands
- Quantitative Modelling of the Hydrocarbonof Inverted Basins
- Interpreting anomalies indicating leakage
- Pressure and fluid dynamic study
- High-resolution quantitative reconstruction of Late Cretaceous-Tertiary erosion in the West Netherlands Basin using multi-formation compaction trends and seismic data

Production

- ISAPP Integrated System Approach PetroleumProduction
- Reservoir permeability estimation from production data
- Coupled modeling for reservoir application
- Toward an integrated near-wellbore model
- TNO conceptual framework for “E&P Uncertainty quantification and Technical-to-Business Integration for Improved Asset Investment Decision-Making”
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Induced Ground Movement

- LOFAR: The eyes of the Earth
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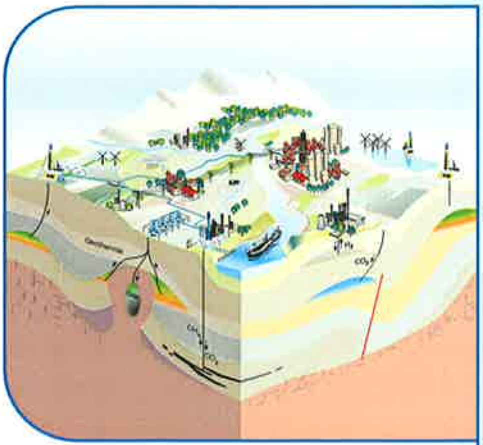
CO2 REMOVE
research monitoring verification

CO_2 ReMoVe –

a New European Project to Research Monitoring and Verification of technologies for the geological storage of CO_2



The CO_2 ReMoVe project will investigate ways of monitoring and verifying CO_2 injected into geological storage sites. This large Integrated Project is coordinated by TNO, (the Netherlands Institute for Applied Scientific Research) and is funded by the European Commission's Sixth Framework Programme for Research, Technological Development and Demonstration Activities. The project started on the 1st March 2006 and over 5 years 30 partners from 12 different countries from all over the world will invest € 15 million to bring together all relevant research, industry experience and know how in the field of underground storage of carbon dioxide.

Since 1990, Europe and the European Commission have invested large research efforts in CO_2 geological storage, first developing inventories of possible storage sites and volumes, then building models to study the subsurface behavior of CO_2 and reservoir to assess possible problems, moving on to risk analysis at different relevant time scales.

Since the start of the industrial-scale injection at Sleipner, (Norway) in 1996, the focus of research has shifted to monitoring the injected CO_2. Over the last ten years, experience has been acquired from large scale projects (Sleipner, Norway; Weyburn, Canada) and smaller, "laboratory" projects in the Netherlands and Poland. Three new geological storage projects (In Salah; Algeria, Snøhvit; Norway, and Ketzin; Germany) provide the opportunity to build on this work. Other storage projects in Poland (Tarnow, Kaniow) or Canada (Weyburn) will be considered in the course of the project.

The consortium of industrial, research and service organizations propose a range of monitoring techniques, applied over an integrated portfolio of storage sites in order to develop:

1. methods for base-line site evaluation;
2. new tools for monitoring geological CO_2 storage, including well performance;
3. new tools to predict and model long term storage behavior and risks;
4. a rigorous risk assessment methodology for a variety of sites and time scales;
5. Guidelines for best practice for the industry, policy makers and regulators.

As a result an extensive range of monitoring datasets will be collected including repeat time-lapse seismic data, microgravity surveys, down hole fluid sampling, tracers, soil gas measurements.

The project will use and adapt methods already developed independently for predicting hydrocarbon production performance and for predicting safety performance of stored CO_2.

CO_2 ReMoVe

a New European Project to Research Monitoring and Verification of technologies for the geological storage of CO_2

CO_2ReMoVe will combine these methodologies in an industrial risk assessment, for all phases of storage, i.e. base line evaluation, operation, site closure and long-term.
In parallel, monitoring tools will be compared and benchmarked to recommend programmes for generic monitoring. This will be combined with innovative tool development and tool optimization, for monitoring surface and atmospheric CO_2 fluxes, as well as for detection and measurement of CO_2 in the subsurface, allowing detection and quantification of CO_2 which may have migrated from the storage site.
All of the research will be systematically integrated into an experience platform that will provide the basis for best practice guidelines.

The recommendations from these international efforts will form an important step towards a worldwide consensus in licensing and certification of the storage sites in different geological settings, including oil and gas reservoirs, coal seams and saline aquifers.
The project will build towards a better understanding of how CO_2 can be stored and monitored safely. Results will be disseminated to the public and policy makers. It will also provide the tools for quantifying and monitoring injected CO_2 required for geologically stored CO_2 to qualify for credits under the emissions trading mechanism.

Photos courtesy of BP, Statoil, Sonatrach, GFZ

CO_2 ReMoVe

CO_2ReMoVe: A consortium of leading energy industry companies, research organizations, universities and the European Union join forces in a research program into the long term reliability of geological storage of carbon dioxide to reduce global greenhouse gas emissions. The partners will undertake the R&D necessary to establish standards for monitoring future storage operations.

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CO_2 storage

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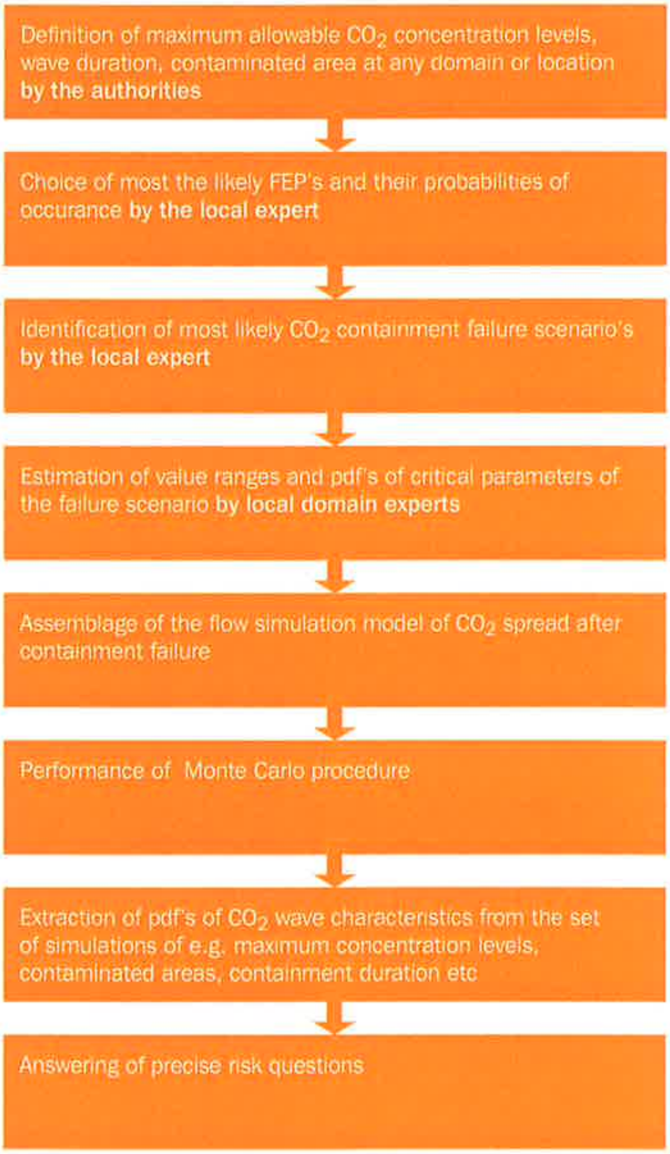
Risk Assessment for analysing the safety of geological CO_2 sequestration operations in the deep subsurface

Risk assessment is a vital part of the work plan of any company or agency wanting to pursue CO_2 sequestration. You may well be able to inject the CO_2 safely but what about the future? What hazards might there be? And is it realistic to expect those hazards to occur within a given time frame? What if…?


Definition of maximum allowable CO_2 concentration levels, wave duration, contaminated area at any domain or location **by the authorities**

Choice of most the likely FEP's and their probabilities of occurance **by the local expert**

Identification of most likely CO_2 containment failure scenario's **by the local expert**

Estimation of value ranges and pdf's of critical parameters of the failure scenario **by local domain experts**

Assemblage of the flow simulation model of CO_2 spread after containment failure

Performance of Monte Carlo procedure

Extraction of pdf's of CO_2 wave characteristics from the set of simulations of e.g. maximum concentration levels, contaminated areas, containment duration etc

Answering of precise risk questions

Policymakers at such agencies and companies want access to methods that help them answer these questions as fully as possible. At TNO we develop procedures to assist them, to show what is needed in a full study. Many researchers have tried to find their way through the complex of approaches and tools needed to assess the risks of geological CO_2 sequestration. Such a procedure – a cogent calculation of the probability of CO_2 escape from the geological injection spot in the subsurface – revolves around developing a comprehensive and quantitative risk analysis for CO_2 sequestration.

Escaping CO_2 utilises pathways in several domains: the deep subsurface, up to, say, 300 m below the earth's surface; the shallow subsurface, including soils from 300 m upwards; then, possibly, the sea, if the site is offshore; and, finally, the atmosphere. For obvious reasons (i.e., the health and safety of man and the environment), authorities should set acceptable limits for CO_2 levels in any of these domains, as regards surface, volume, time or duration of CO_2 wave passage. Indeed, based on the specified levels and given the sequestration location, researchers can calculate the probability of such levels being exceeded. TNO has already proposed a methodology for arriving at these results (see Wildenborg et al., 2003).

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In terms of the overall risk analysis, we have to begin by asking what could go wrong in the broadest sense. If CO_2 appears anywhere near the surface, it is certainly clear that something has gone wrong with the deep underground containment. But what exactly? What processes might have occurred that could lead to the unwanted appearance of CO_2? To answer those questions, we need to identify all of the possible escape processes, which will obviously require help from many experts. We simply cannot run the risk of overlooking something important...

So, the first step is to identify all possible Features, Events and Processes that could lead to the unwanted presence of gas. These FEPs are collected in an FEP database. In fact, at TNO we have done this, creating a database from the collective efforts of workshops held in 2002-2003 (see Kreft, 2003). Experts can use information from this comprehensive FEP collection 'site', combined with their specialised knowledge, to pinpoint the most relevant combination of FEPs in terms of escape risk.

The next step involves a significant task: setting the subsurface parameters and their ranges with respect to the properties of the reservoir, seal and overburden that determine the processes of flow, dissolution, mineral fixation, pore capillary entrapment and so forth of the CO_2. This task should be carried out by site experts in the relevant domains. The model evolution must reflect all these parameters and their ranges. To clarify, we look at models of what we assume can 'go wrong' in terms of CO_2 containment. We just want to know what to expect in terms of surface concentrations, contaminated areas and other factors if it does go wrong. All flow simulation work is based on 3D simulation models designed for the main processes triggered by the FEP-induced containment failure.

The parameters thus scrutinized give rise to thousands of input data sets for the CO_2-dedicated software. (We used the commercial package SIMED II, which we at TNO can taylor to our needs.) Relevant computer models are then run for thousands of combinations of these parameters. The resulting calculations, the output, can be used by other experts as basic input for such tasks as calculating water pollution scenarios in the sea or groundwater, computing CO_2 concentrations in the atmosphere and so forth. The results are condensed in such a way that they provide the critical output parameters under scrutiny by the authorities (e.g., the maximum concentrations, the duration of a CO_2 concentration above a specified level, etc.). A probability density function for these critical output parameters can be constructed from all this. And it is this function that can be used to answer specific questions about expected casualties and specified environmental risks, for instance.

The FEP methodology and calculation procedure of linked processes thus result in an estimation of the impact of risky scenarios with regard to CO_2 concentrations in the shallow subsurface, the aquatic environment or the atmosphere.

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CO_2 storage pressure in finite saline aquifers

Most European research studies and pilots on CO_2 storage, such as the K12-B site injection project in the Netherlands, have focused on containment in trap structures, preferably in depleted fields where seal integrity is well proven. The majority of depleted oil and gas fields in Europe, however, have insufficient storage capacity to effect a significant reduction of CO_2 emissions. To provide an idea of what we are talking about: A typical power station produces on the order of 10 million tonnes of CO_2/year (2x800 MW). With the life of most power plants averaging 40 years, that means having to store some 400 million tonnes of CO_2 for every single power plant, far more than can be accommodated in even the largest depleted oil or gas field in Europe.

Following the success of the Sleipner project, more attention is now being given to storage in aquifers. Since CO_2 is soluble in water, any aquifer in which it is stored will eventually become saturated with CO_2. We have explored various aspects of the dissolution process, based on numerical simulation studies for storage locations that are similar to the Sleipner field. A recent IPCC publication [1] quotes many papers that claim that CO_2 'disappears' as it is gradually absorbed by water. We investigated the justification for this claim.

Introduction

CO_2 injected into an aquifer will dissolve if there is enough water, but if a lot of material (CO_2) is added, it affects fluid volumes and pressures in the overall storage system. Earlier work on storage capacity was based either on the solubility potential, ignoring the volumetric consequences of the process, or on a fixed percentage of a volume. The latter approach, in particular, precludes any further quantification. In our storage capacity calculations, we have included a concept of total effect space (i.e., all of the space whose state or properties are changed by the storage operation over the course of the total storage time). By studying a practical, real storage location, we try to discover some of the pressure effects of CO_2 solubility on the total storage capacity of the selected storage site.

Implementation of CO_2 solubility

We extended the simulator, SIMED II, with the results of recent work by Durst [2] and Duan [3], who calculated equilibrium concentrations of CO_2 dissolved in water at relevant pressures, temperatures and salinity. This enabled us to quantify the amount of CO_2 dissolved in the water and also the downward flow of water in which CO_2 had been dissolved. This convection, triggered by the greater density of the water in which the CO_2 has dissolved, causes the water with dissolved CO_2 to sink in the aquifer and be replaced by 'fresh water' capable of dissolving more CO_2. The present solubility model is a great improvement over the modelling method used in the past. We believe that the implementation of the new solubility model in SIMED has created a more accurate prediction method.

Aquifer Simulation Model

For the present study we constructed a typical Mid-European type of aquifer. All aquifer properties (Table 1) are based on real data. Furthermore, we manipulated a real structure map to create a more or less general subsurface model. The grid dimensions of the model are 145 x 114 x 5, resulting in a total of 82,650 grid blocks. All of the inner blocks are nearly 400 x 400 x 20 m in size and all of the blocks at the edges of the model were extended outward by 125 km to ensure that the average pressure increase in the total area would not exceed 10 bars over the 40-year injection

Layer	Type	Porosity [fraction]	Permeability [mD]	N/G [fraction]	Thickness [m]
1	Shaly Sand	0.11	161.4	0.53	20.3
2	Shale	0.07	7.4	0.30	11.04
3	Shaly sand	0.11	161.4	0.49	22.1
4	Shale	0.03	0.007	0.0	20.1
5	Clean sand	0.18	379.7	0.73	23.4

Table 1. Average reservoir properties by layer for realistic sample aquifer model.

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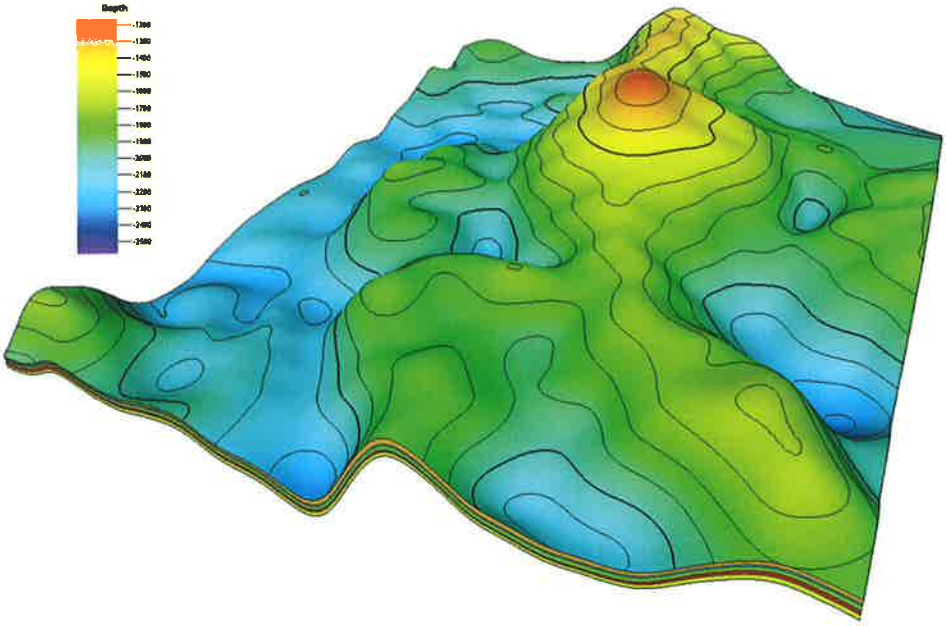

Figure 1. Top structure map of realistic example aquifer. The blue part is the main storage target dome.

period. Figure 1 depicts the grid system showing the top structure. In this picture the large grid blocks at the edges of the model have been omitted for clarity.

Simulation results

We ran a limited number of CO_2 injection realisation simulations. All runs were based on injecting 400 million tonnes of CO_2 over a period of 40 years into an aquifer formation (shown in Figure 1). With injection into a finite space, the average pressure increases. This pressure increase is reciprocal to the available space. Of course, we must distinguish the average pressure from the injection pressure, a very local pressure increase needed for injecting fluid into a well area. Another pressure, still local, is the reservoir pressure, which will show a distribution over the reservoir. With respect to CO_2 injection and the integrity of the cap rock, the injection pressures applied are of great importance. In general, these depend on several factors: the local reservoir permeability, the length and quality of perforations, the injection rate and the size and degree of heterogeneity of the storage system. In general, large aquifers with high permeability are good candidates for storage locations.

We performed five runs to test the sensitivity to aquifer size. Figure 2 shows the resulting volume-weighted average pressures. The 125 km case represents an area of some 295 x 295 km. Indeed, we can state that a large volume is needed to limit the overall average pressure increase. Figure 3 depicts the CO_2 distribution after injection over a period of 5000 years. The injected CO_2 moves up-dip and accumulates at the crest of the structure underneath the sealing shale layers. After some 80 years, the CO_2 bubbles from individual wells will join up at the top.

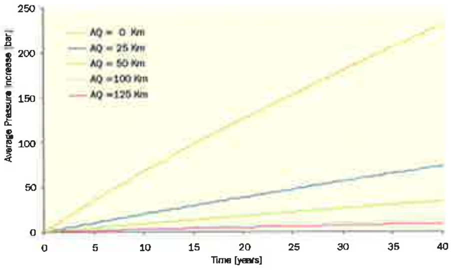

Figure 2. The volume-weighted average pressure increase as a result of CO_2 injection for several aquifer sizes.

Long-term Fate Prediction

As a consequence of CO_2 dissolution, the density of the saline formation water increases slightly, up to 2% to 3%, depending on saturation level, pressure, temperature and salinity. CO_2 dissolution processes are therefore highly relevant for the long-term fate of CO_2, since they initiate the migration of CO_2-saturated formation water into the deeper parts of the formation. CO_2 dissolution also plays a key role in safety issues. Dissolved CO_2 could have a geochemical impact on the reservoir rock and cap rock because carbonic acid is formed. However, dissolved CO_2 reduces the risk of supercritical CO_2 escaping if there were to be a leak in the storage system. Nevertheless, degassing and reformation of a supercritical gas phase might occur and pose a risk to reservoir integrity. These difficult-to-predict risks could occur if CO_2-saturated water were able to migrate across large distances into areas with different subsurface conditions.

In our simulations, about 11% of the 400 million tonnes of CO_2 injected (44 million tonnes) had dissolved in the formation water by the end of the injection period (40 years), increasing to some 28% (112 million tonnes of CO_2) after 10,000 years. Our numerical simulations also indicate that a considerable amount of dissolved CO_2 could possibly escape from the anticlinal closure after a hundred years and reach the marginal lows. First the dissolved CO_2 that was injected into the lower reservoir layer would reach the marginal lows, owing to the favourable reservoir properties of this layer. Figure 4 shows the graduated progression of the spatio-temporal, reservoir-wide spread of CO_2-saturated formation water over 10,000 years, as simulated. Note that a large portion of dissolved CO_2 will have left the structural trap by then. Accordingly, the total area affected by dissolved CO_2 is much larger than the anticlinal structure itself.

In the example used here, we have adjusted the total affected storage space to the

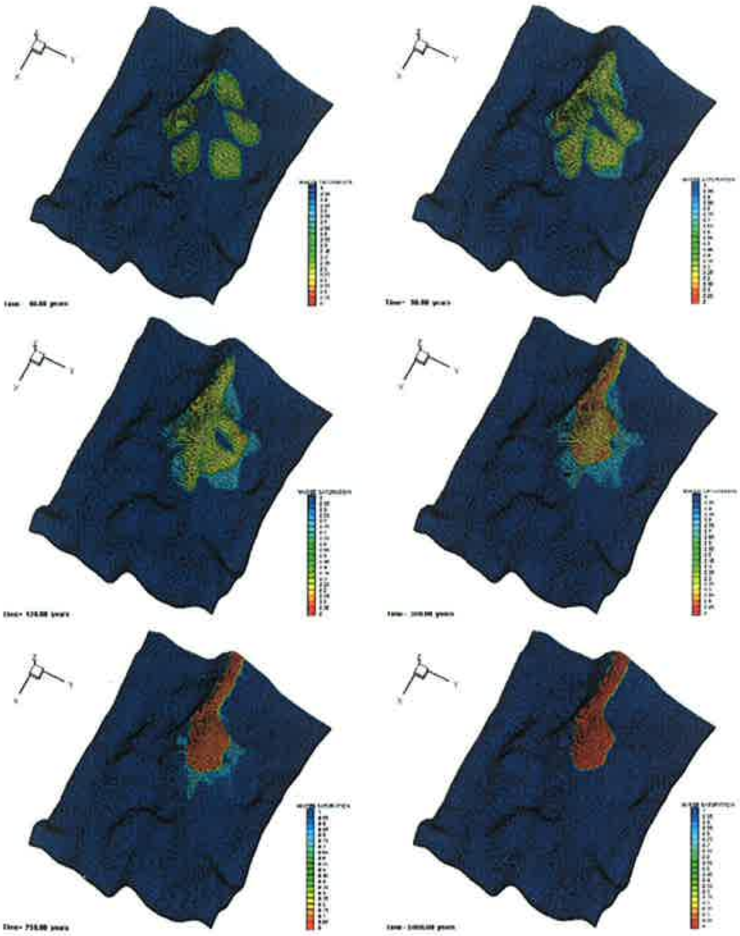

Figure 3. Spatiotemporal spread of 400 million tonnes of CO_2 injected in the example structure after the 40-year injection phase. The initial injection of CO_2 through ten injection wells positioned at the flank of the structure is followed by migration into the crest of the structure due to buoyancy. All the free CO_2 has accumulated in the top of the structure after some 1000 years.

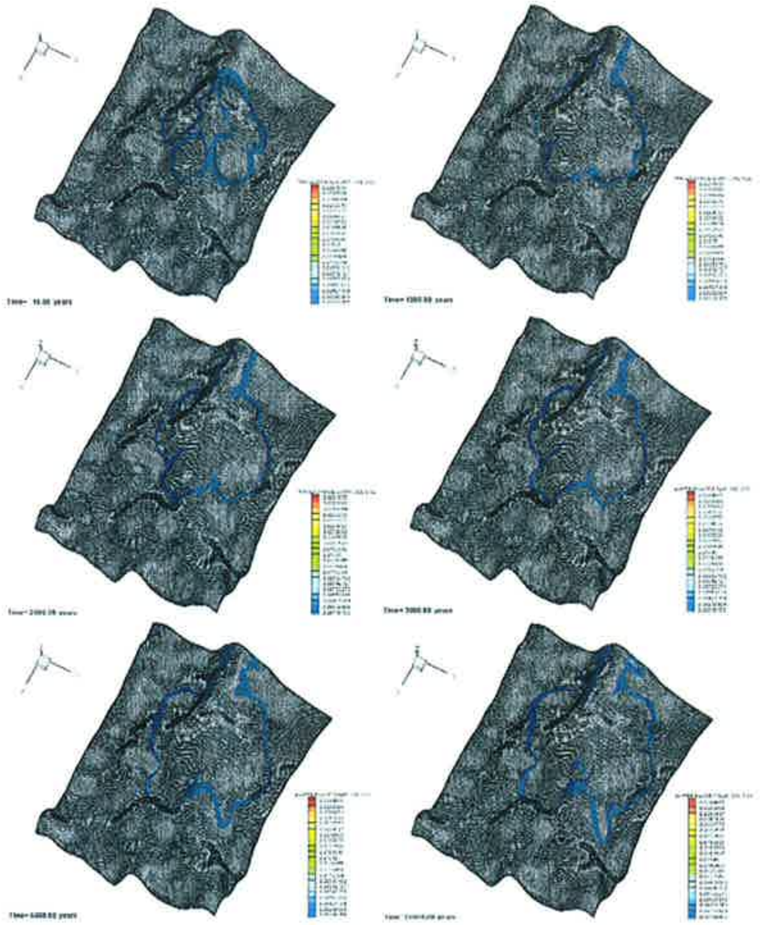

Figure 4. Isosurface of the predicted CO_2-saturated water distribution for the time intervals 40, 1000, 2000, 4000, 6000 and 10,000 years.

volume that needs to be stored (400 million tonnes) to arrive at a sensible average pressure increase of 10.5 bar over the total space. Local pressures are controlled by the permeability and porosity distributions of individual sand bodies. Figure 5 displays the development of the local pressures over time. The picture shows the cross-sectional pressure profile for several time slices. In the middle of the storage location, the maximum pressure was reached after 40 years. It took almost another 200 years following this build-up to reach pressure equilibrium throughout the affected space. Still, although the average pressure increase was limited to 10.5 bar by increasing the total affected volume, it is debatable whether or not the local pressure could be allowed to increase to a much higher level during the injection cycle (see Figure 5, up to 100 bars after 40 years). These pressure profiles are achieved with realistic permeability levels of, on average, 200 md. Not only the average pressure, but also the dynamic pressure behaviour could limit the maximum storage capacity of an aquifer.

We have also performed tentative simulations to investigate the influence of CO_2 solubility on pressure. The transition of CO_2 from the free gas phase into the dissolved phase in water will have a pressure-reducing effect. The dissolution effect on pressure can be made visual by plotting the average pressure development over time. This plot is shown in Figure 6. All material is present after 40 years; the average pressure will decrease because CO_2 is converted from one phase to another. The reduction is proportional to the amount of CO_2 dissolved but will never go down to zero. In this instance, it can be observed that a solubility rate of 28% after 10,000 years will yield a pressure reduction of only some 5%.

Discussions and conclusions

Sleipner is often referenced as a benchmark for CO_2 injection into a saline aquifer, having shown no pressure increase. However, the

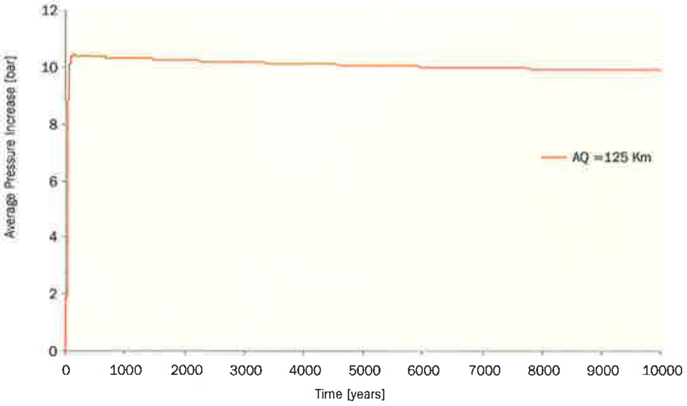

Figure 6. Predicted average total pressure development for 10,000 years.

Sleipner Utsira storage formation is an extremely large and thick aquifer extending across hundreds of kilometres in a north-south direction; it reaches from the Norwegian coast far into the UK sector. Furthermore, only about 1 million tonnes of CO_2 is injected every year into a very porous and very permeable aquifer. Any pressure build-up will be dispersed over a very large area. Most comparisons with Sleipner disregard relative proportions.

The perception that pore water will be pushed away to create space for the injected CO_2 is naive and does not take into account that the removed water will migrate somewhere else, and that this other place has to be taken into account in the total storage concept. It is essential to consider the total affected space in all CO_2 storage concepts.

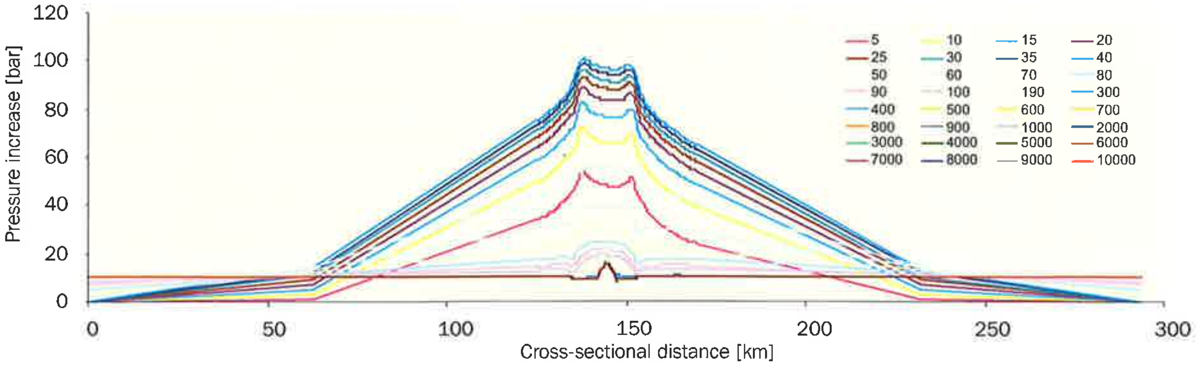

Figure 5. Cross-sectional pressure profile development over time. Colour lines in the legend show the simulated times in years for the given pressure profiles. The cross-section is taken across the middle of the formation.

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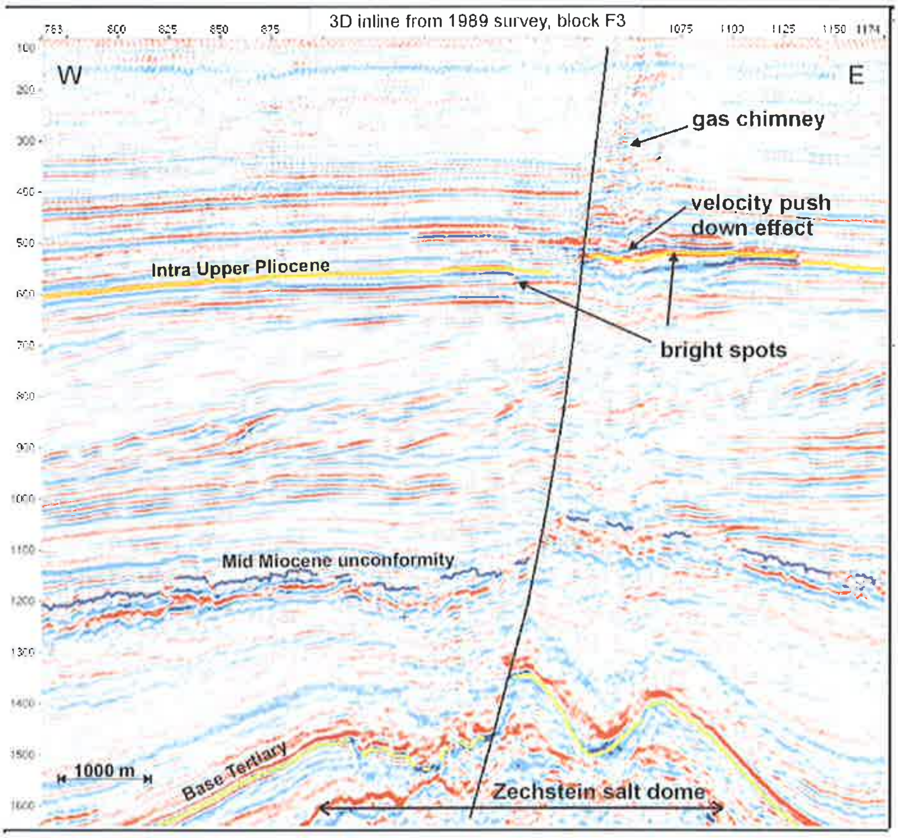
Interpreting anomalies indicating leakage

Seismic anomalies indicating leakage are common in most hydrocarbon basins. The proper interpretation of such features is important both for geohazard assessment and as an exploration tool. By interpreting the data in an integrated manner, i.e. also using the results from methods such as geochemical surveying (either gas-analysis of seabed samples or sniffer surveys), multi-beam surveys and sub-bottom profiling, a more reliable model for gas migration in the shallow section and to the seabed can be made. Such a model contributes to a better understanding of the entire hydrocarbon system of the area. TNO has demonstrated the added value of such an integrated approach in a recent North Sea study.



Example of a gas chimney adjacent to a fault situated over a salt-dome.

The approach uses a 3D (or 2D) seismic survey made available by the client. The seismic data are carefully examined for any expressions of seismic anomalies related to the presence of gas. These can include smaller or larger bright spots and flat spots indicating the trapping of gas and seismic anomalies indicative of leakage. The latter may include gas chimneys, leaking fault systems, shallow enhanced reflectors and shallow disturbed zones. Where a 3D survey Is available, dTEct – a licensed product of dGB Earth Sciences – could be used to invert seismic chimneys from the seismic volume through a neural network based multi-attribute approach. At the end of this first phase, the resulting model shows the occurrence and distribution of seismic anomalies likely to be related to gas.

The second phase of the study comprises the acquisition of additional data using a marine vessel. For example, for an average North Sea licence block about one week of boat-time Is normally needed to collect seafloor sediment samples (using the vibrocore method) and

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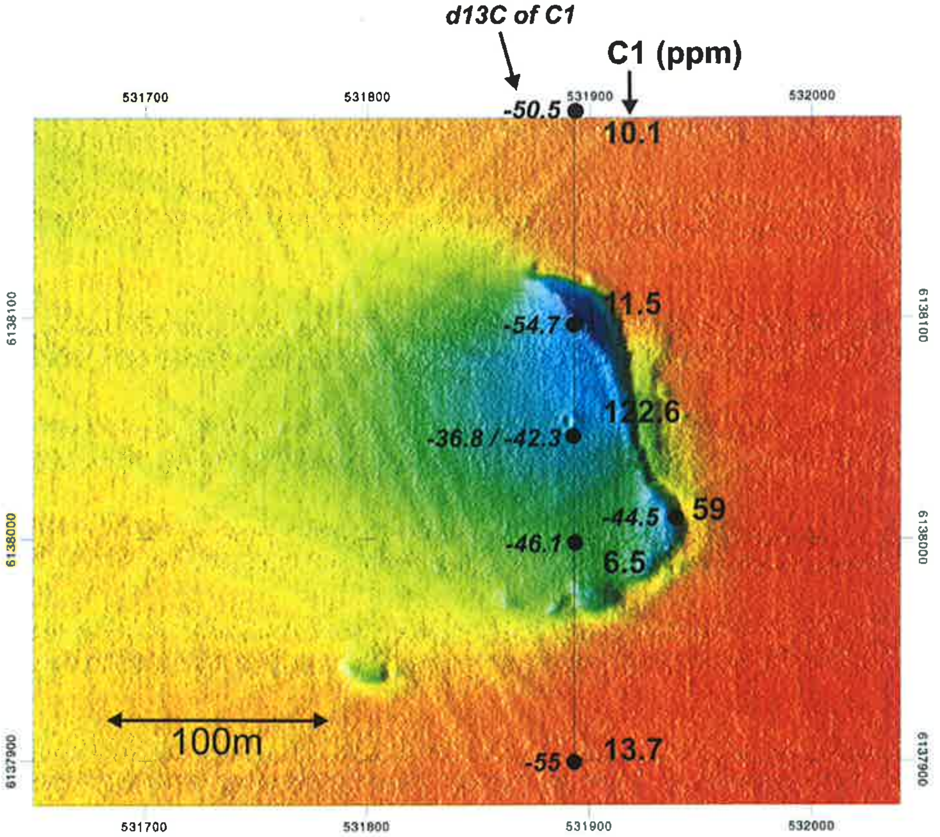

Multi-beam image of a pockmark on the seabed of the southern North Sea (Block A11) with dots indicating vibrocore locations.

acquire both multi-beam and high-frequency acoustic surveys over selected identified zones of interest. Multi-beam data reveal the presence of seafloor bathymetry anomalies associated with gas venting (such as pockmarks and carbonate mounds), whereas high-frequency, sub-bottom profiles reveal disturbances, due to the presence of gas in the uppermost 20 metres of the subsurface, as well as gas-plumes in the water column. From the vibrocores retrieved from the shallowest 4-5 metres of sediment, sub-samples are analysed in terms of their gas content. The concentrations of the lighter hydrocarbon fractions can be measured and stable isotopes determined. The interpretation of geochemical anomalies is integrated with the interpretation of the various seismic and acoustic methods, yielding a comprehensive model for the migration of gas in the shallow section and to the seafloor.
This model can then be integrated with existing models for the generation and migration of hydrocarbon in the deep subsurface.

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Time lapse Seismic Activities

Currently TNO Built Environment and Geosciences *Geological Survey of the Netherlands* is involved in several projects related to time-lapse seismic data comprising both research and applied field studies. Research encompasses the physical modelling of time-lapse seismic experiments to investigate and improve dedicated repeatability acquisition geometries and processing techniques. An applied field study is being carried out in a European project (SACS/CO2STORE) to monitor the injection of CO_2 in a saline aquifer offshore In Norway. This enables time-lapse seismic results to be linked to a reservoir simulator for history matching and, ultimately, fluid flow prediction.

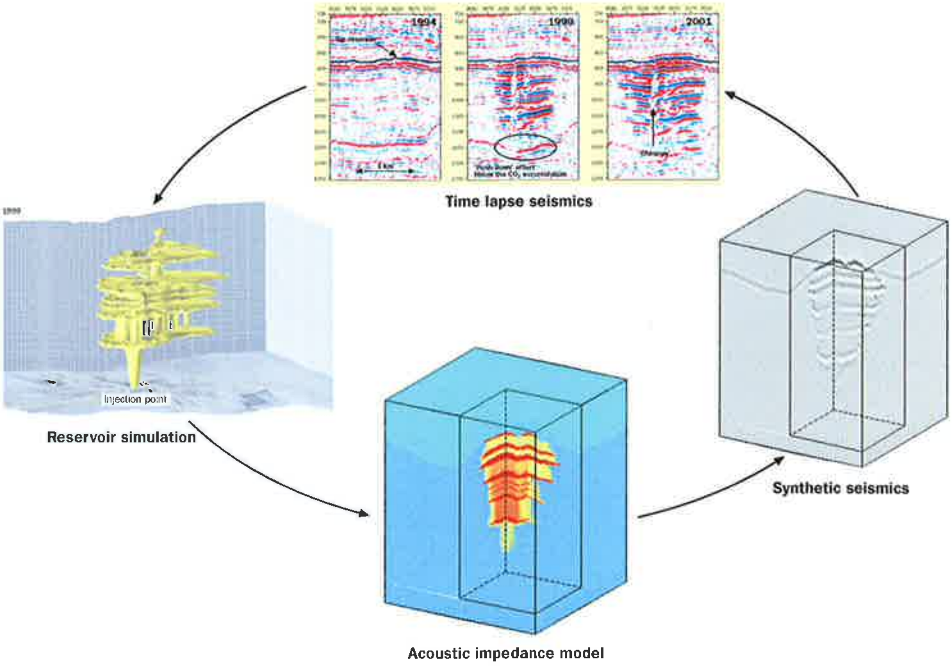

Figure 1. Integrated workflow using time-lapse seismic data to calibrate a reservoir simulation model and to verify the simulation model using synthetic seismics.

Applied field study (SACS/CO2STORE)

Since October 1996, Statoil and its Sleipner partners have injected CO_2 coming from the Sleipner Vest Field into a saline aquifer at a depth of approximately 1000 metres. The aquifer Is more than 200 metres thick near the injection site and is sealed by thick shale. A multi-institutional research project SACS/CO2STORE (Saline Aquifer CO_2 Storage) was formed to predict and monitor the migration of the injected CO_2. To this end four time-lapse seismic surveys have been performed over the injection area (in 1999, 2001, 2002 and 2004), with a further survey having been planned for 2006.

The interpreted seismic data have led to the construction of a full 3D reservoir simulation model. The saturation models derived from the reservoir simulation at the timesteps of the monitoring surveys have been converted to acoustic impedance models, using rock physics models (i.e. Gassmann). In their turn, the acoustic impedance models have been used for synthetic seismic modelling. The results of the synthetic seismics have been

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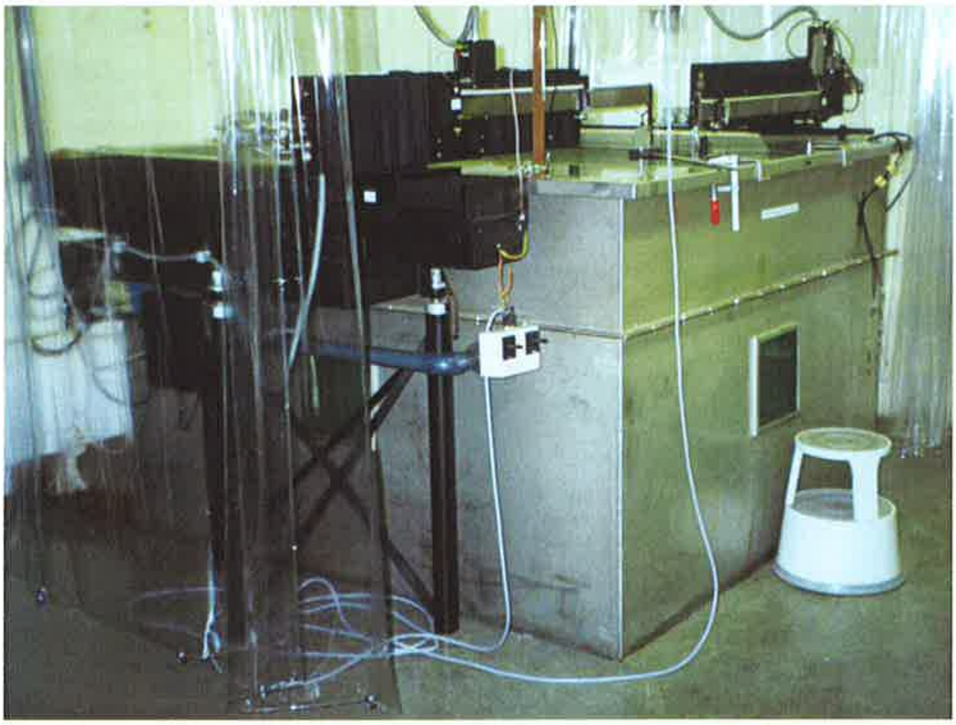

Figure 2. Water tank facility at TNO used for acquiring seismic data over a physical scale mode.

compared to the real seismic data at the different timesteps. This workflow (Figure 1) allows the reservoir simulation model to be calibrated with the seismic interpretation at different timesteps and therefore improve the prediction of future CO_2 migration.

Physical modelling of time lapse seismic data

As an alternative to synthetic 3D seismic modelling, data can be acquired using a real physical scale model. TNO has a water tank facility to acquire such data (Figure 2). The materials used in the model contain the same acoustic characteristics as in the real subsurface. This model enables data to be acquired as fast as In real marine seismic acquisition (approximately 11 traces per second). By making changes in the model and repeating the acquisition, time-lapse seismic data can be obtained. Research to optimise both the acquisition geometries for time-lapse seismics and the processing algorithms is ongoing.

Geo energy and Geo information

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Synthetic modelling of time-lapse seismic data versus real data at the Sleipner CO_2 injection site

Carbon dioxide injection at the Sleipner field in the North Sea commenced in 1996, the first industrial scale CO_2 injection project specifically for greenhouse gas mitigation. CO_2 separated from natural gas is being injected into the Utsira Sand, a major saline aquifer of late Cenozoic age. The injection point is at a depth of about 1012 m bsl, some 200 m below the reservoir top. Baseline 3D seismic data were acquired in 1994, with repeat surveys in 1999, 2001, 2002, 2004 and 2006, with, respectively, 2.35, 4.26, 4.97, 6.84 and 8.4 million tonnes of CO_2 in the reservoir.

The CO_2 plume is imaged on the seismic data as a prominent multi-tier feature, comprising a number of bright sub-horizontal reflections, growing over time. The reflections are interpreted as arising from up to nine discrete layers of high-saturation CO_2, each up to a few metres thick. The layers have mostly accumulated beneath thin intra-reservoir mudstones, with the uppermost layer being trapped beneath the reservoir caprock. However, the structural geometry of the intra-reservoir mudstones is not well known because they are too thin to be imaged on the baseline dataset.

Previous interpretations of the seismic data have estimated the thickness of the individual high-saturation CO_2 layers from a seismic amplitude-thickness tuning relationship. In this paper the 1999 seismic data is evaluated by pre-stack elastic modelling, applying realistic field acquisition geometries. Results of the modelling and acquisition effects on the seismic imaging are demonstrated.

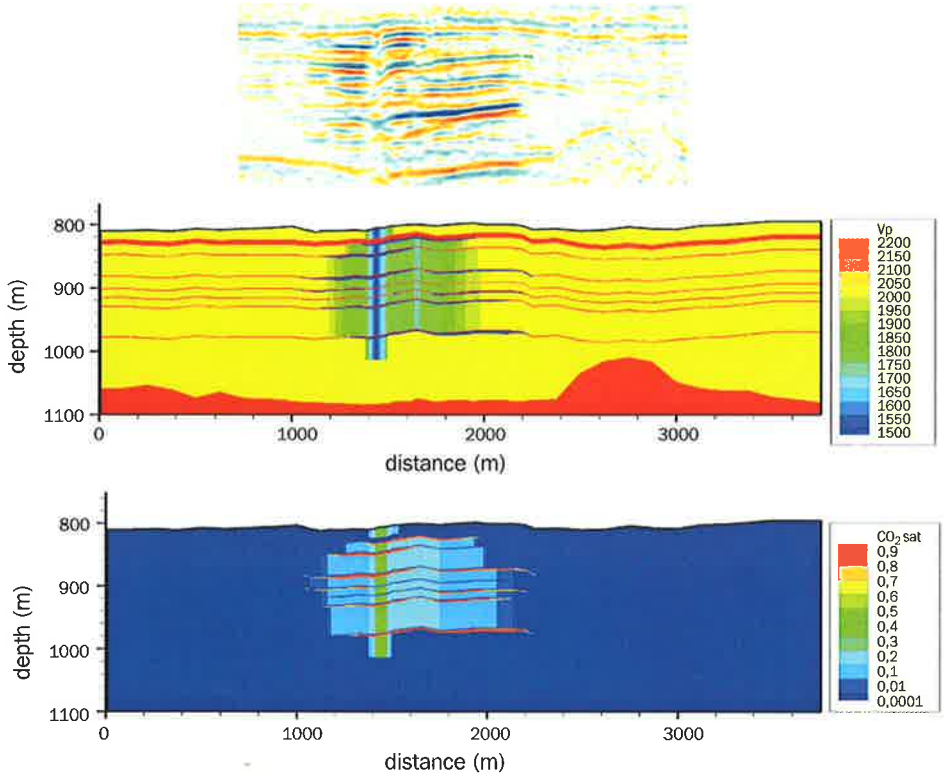

Figure 1. Detailed model of the Sleipner plume in 1999, derived from acoustic modelling. Seismic inline 3838 (top), modelled Vp (centre), modelled co_2 saturation (bottom). Note the vertical column of velocity pushdown and reduced reflectivity, interpreted as a vertical feeder chimney of higher saturation CO_2.

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Synthetic modelling of time-lapse seismic data versus real data at the Sleipner CO_2 injection site

Reservoir description

Around Sleipner, the Utsira Sand is a highly porous (35-40%), weakly consolidated sandstone at depths between about 800 m and 1100 m, with a thickness of about 250 m around the injection site. The overburden comprises a predominantly mudstone-siltstone sequence up to the seabed, with a sealing unit of more than 200 m of silty mudstone directly above the reservoir. Within the reservoir itself, thin mudstone layers in the order of 1 m thick have been identified, which act as baffles to the upward migration of the CO_2.

Seismic Modelling

A 2D, fully elastic, finite-difference wave propagation simulation was used here. Input data for the modelling comprised a 2D north-south cross-section through the central part of the 1999 plume (Figure 1). The section was extracted from the CO_2 saturation model of Chadwick et al. and modified for partially 'patchy' mixing of dispersed CO_2. Although the model has some limitations, mostly in the simplified vertical distribution of dispersed CO_2 in between the main reflective layers, it does give a reasonable picture of likely CO_2 distributions within the plume.

The model comprises a set of layers: seawater, overburden, caprock mudstone, intra-reservoir sand layers (variably saturated with CO_2), intra-reservoir mudstones and sub-reservoir mudstone. Layer parameters comprise x, y, z coordinates with linked properties (CO_2 saturation, Vp, Vs and density). A key simplifying assumption, in terms of model building and interpretation, is that the intra-reservoir mudstones are all parallel to the reservoir top. This is undoubtedly incorrect, but in the absence of specific information on mudstone geometry, the model is considered suitable for realistic modelling of both the plume and the reflections beneath it. Synthetic shots were generated along the north-south cross-section, extended at both ends by an additional 2 km, resulting in an 8-km-long model. Modelling was based on acquisition parameters similar to the real time-lapse data. Synthetic shot gathers differ markedly, depending on the relative positions of the recording spread and the subsurface plume. Away from the plume, events on the gather arise only from the model's geological interfaces and are regular and hyperbolic. Over the plume itself, reflectivity within the reservoir is increased due to the presence of CO_2, but moveout is much more irregular, with time shifts

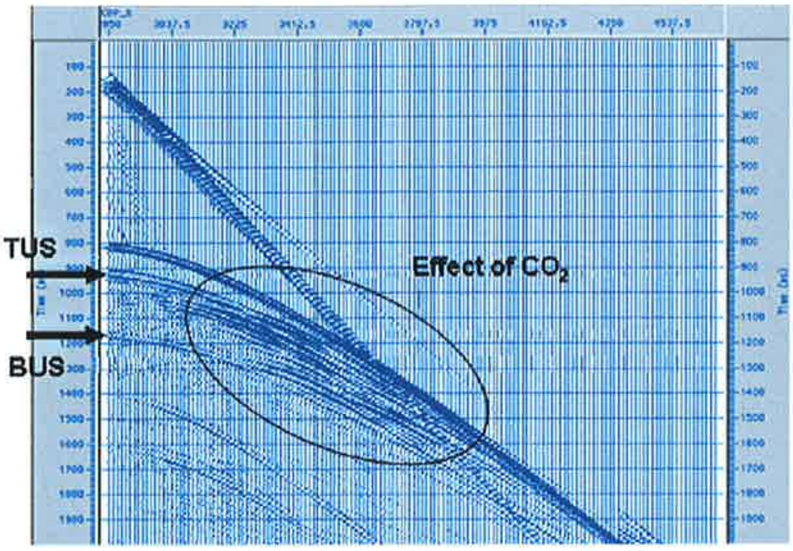

Figure 2. Synthetic shot gathers generated by elastic pre-stack modelling. Source and streamer are above the CO_2 plume, which is imaged on mid-offset traces. Note the enhanced reflectivity in the reservoir but reduction of coherency in deeper reflections due to lateral velocity changes. TUS = Top Utsira Sand; BUS = Base Utsira Sand.

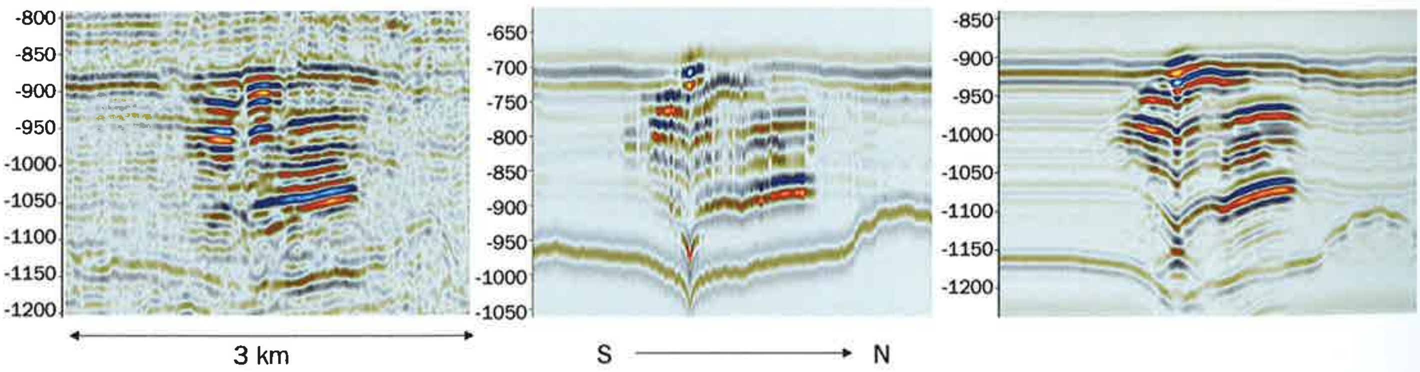

Figure 3. A comparison of a) the observed inline from the 1999 seismic survey; b) the corresponding synthetic line obtained by convolutional modelling; and c) the corresponding synthetic line after 2D elastic modelling and processing.

introduced by the lateral changes in velocity (Figure 2).

The CO_2 plume can be followed through the different shots and it is clear that the width of the plume 'reflection zone' is much less than the spread length. This results in non-hyperbolic moveout that will significantly degrade stack response, producing a false attenuation of reflections beneath the CO_2 plume on stacked datasets. The data were stacked and migrated using the NMO-velocity model, with application of a phase shift similar to the real data, to produce a migrated 2D seismic section. Results are very comparable to the observed data (Figure 3).

Interpretation results

The effect of the CO_2 on the seismic data at Sleipner is evident, with two main effects determining the seismic response:

- The negative seismic impedance contrast between mudstone and underlying sand becomes more negative (larger in absolute value) when CO_2 is present in the sand.
- The seismic response is a composite tuning wavelet caused by interference from sequences of water-saturated sand, mudstone, CO_2-saturated sand and water-saturated sand again.

The first effect leads to stronger negative seismic amplitudes similar as for a classical 'bright spot'. The second effect (tuning) can lead to destructive or constructive interference, depending on the thickness of the CO_2 layer. Simple convolutional seismic modelling has shown that as the thickness of the CO_2 column increases from 0 m to 8 m, a gradual increase in the negative amplitude is observed. Maximum reflection amplitude corresponds to a CO_2 thickness of about 8 m, the so-called 'tuning thickness'.

An interpretation of the individual seismic reflectors was carried out from the migrated synthetic data, similar to the interpretation of the observed datasets. Reflection amplitudes were mapped and compared to the thickness of the individual CO_2 layers from the input model; the comparison focused on three different levels in the plume. Overall the synthetic amplitudes show a good correlation with model layer thickness and corroborate the use of a seismic amplitude-CO_2 thickness relationship for quantitative analysis.

Conclusions

Interpretation of the Sleipner time-lapse seismic data has not been straightforward, complicated as it was by the large velocity contrast between CO_2-saturated and water-saturated reservoir rock, which assists, but also complicates, seismic imaging. Furthermore, since the thin intra-reservoir mudstones cannot be identified on the baseline seismic data, the precise details of the internal reservoir geometry remain unknown, making construction of an accurate reservoir flow model very challenging. To help overcome these problems, synthetic seismic modelling was used to

The Sleipner platform (Courtesy Statoil) elucidate CO_2 distributions in the reservoir, though so far only for the 1999 dataset.

Simple convolution-based acoustic modelling indicated that there should be a direct relationship between seismic amplitudes and CO_2 layer thickness. This assumption was further investigated by full wave equation elastic modelling, followed by a basic processing sequence, including migration similar to that applied to the real data. Comparing the processed synthetic seismic data with the convolutional synthetic seismic data, significant differences can be observed in terms of lateral coherency and horizontal resolution, but not so much in terms of amplitude information. This observation has strengthened our confidence in the seismic amplitude versus high-concentration CO_2 accumulation thickness.

Acknowledgments

We thank the SACS and CO2STORE consortia for permission to publish this work and also the operators of the Sleipner licence - Statoil, ExxonMobil, Norsk Hydro and Total - for their cooperation. SACS and CO2STORE are funded by the EU Thermie Programme, by industry partners Statoil, BP, ExxonMobil, Norsk Hydro, Total and Vattenfall, and by national governments, including the UK Department of Trade and Industry. R&D partners are BGR (Bundesanstalt fur Geowissenschaften und Rohstoffe), BGS (British Geological Survey), BRGM (Bureau de Recherches Geologiques et Minieres), GEUS (Geological Survey of Denmark), IFP (Institut Francais du Petrole), TNO (Built Environment and Geosciences *Geological Survey of the Netherlands*), Schlumberger and SINTEF Petroleum Research. We also acknowledge the EU-funded Network of Excellence CO_2GEONET for their financial support, which made the additional synthetic seismic modelling possible.

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CO_2 Storage

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K12-B, CO_2 storage and enhanced gas recovery

The mature gas field K12-B is selected as a demonstration site for offshore injection of CO_2. The project is aimed at investigating the feasibility of CO_2 injection and storage in depleted natural gas fields on the Dutch continental shelf, with the objective to realize a permanent CO_2 injection facility in the near future. It is being subsidized by the Dutch Ministry of Economic Affairs and carried out by Gaz de France Production Nederland B.V., the operator of the K12-B platform. The data collected during the test phases of CO_2 injection are currently being assessed by European research institutes cooperating in several CO_2 storage research programs.

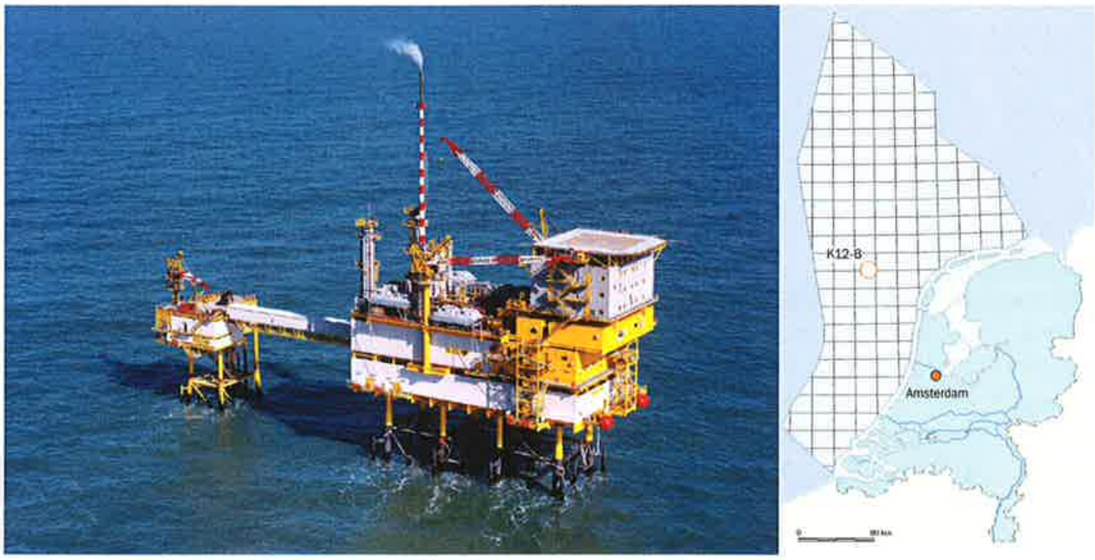

Figure 1.
K12-B platform and location.

Introduction

The K12-B gas field is located in the Dutch sector of the North Sea, some 150 km northwest of Amsterdam (Figure 1). It has been producing from the Upper Slochteren Member (Rotliegend) since 1987. The natural gas produced has a relatively high CO_2 content (13%) and the CO_2 is separated from the production stream prior to gas transport to shore. The CO_2 used to be vented into the atmosphere but is now injected into the field above the gas_water contact; at a depth of approximately 4000 m. K12-B is the first site in the world where CO_2 is injected into the same reservoir from which it originated. The CO_2 injection started May 2004. At the same time extensive measurement programs have started to take place. These programs are dedicated to determining the potential for both CO_2 storage and enhanced gas recovery (EGR). Furthermore measurements have been taken to assess the corrosion of the injection tubing caused by the CO_2. The average CO_2 injection rate can reach 30,000 Nm^3 CO_2 per day, which is approximately 20 kt per year. This paper presents the preliminary results of the measurements from K12-B. The data is currently being interpreted in several research programs, such as MONK, CATO, CASTOR and CO_2GEONET.

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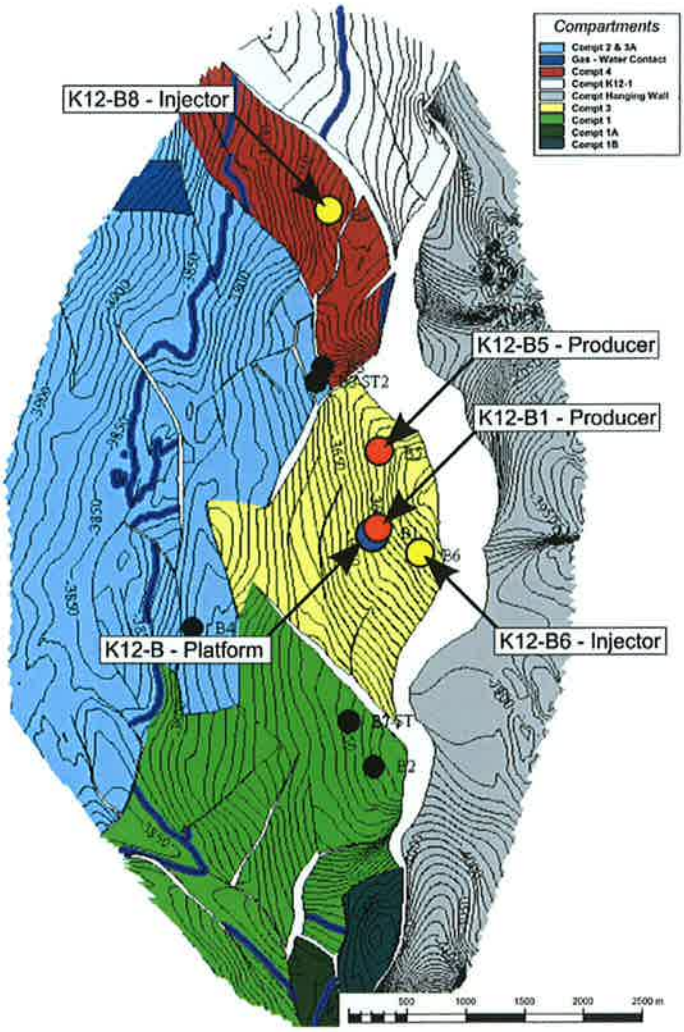

Figure 2. K12-B reservoir compartments and well locations.

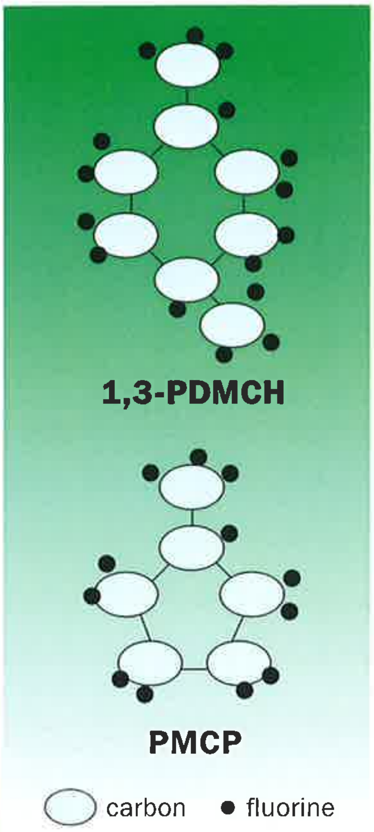

Figure 3. Injected tracers for K12-B.

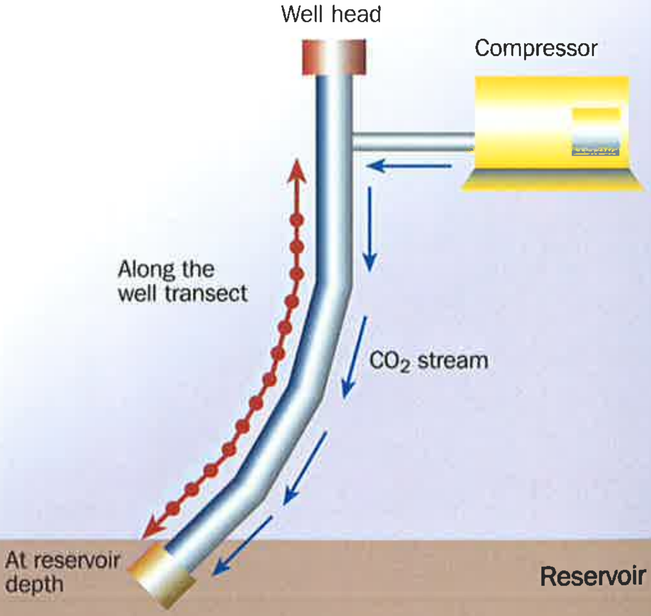

Figure 4. Schematic representation of measurement locations of pressure and temperature. Figure is not to scale.

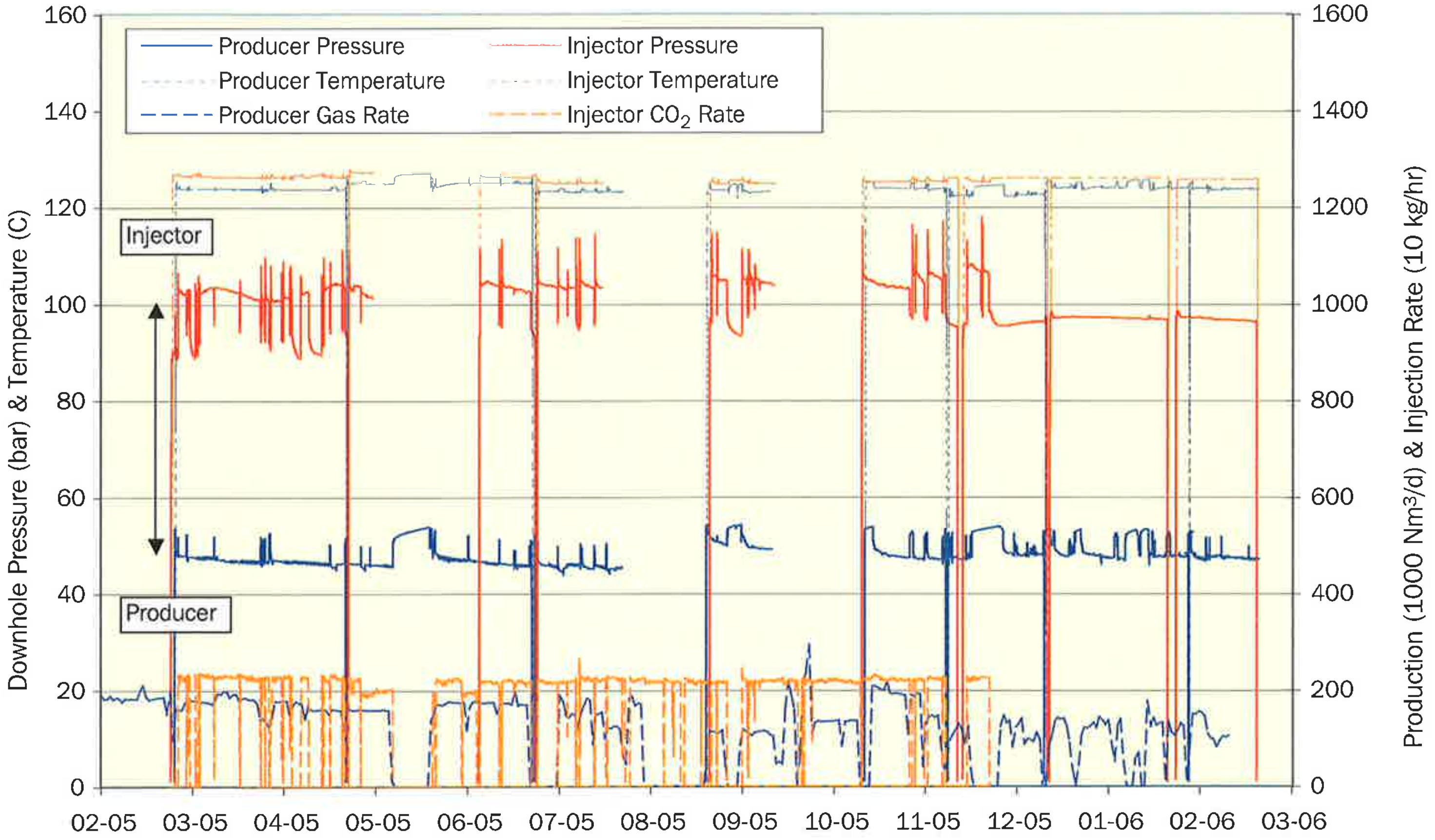

Figure 5. Down-hole pressure, temperature, injection and production data.

Measurement Program

The CO_2 injection program comprises multiple phases in different locations at the K12-B reservoir (Figure 2):

- Phase 1, CO_2 injection into a fully depleted, single well reservoir compartment (compartment 4). This phase was carried out from May 2004 until January 2005.
- Phase 2, CO_2 injection into a nearly depleted reservoir compartment (compartment 3) still under production. The wells under investigation are two gas production wells (K12-B1 and K12-B5) and one CO_2 injection well (K12-B6). This test commenced in February 2005 and is still continuing up to the time of writing.

At the start of phase 2, 2 tracers were injected (Figure 3). The total volume of each tracer injected in well K12-B6 was 1 dm^3. The tracers allow for an accurate assessment of the flow behavior in the reservoir and the associated sweep efficiency of the injected CO_2. Without the tracers it would be difficult to accurately determine the physical communication between injector and producers because the injected CO_2 originates from the reservoir gas and therefore cannot be distinguished from the naturally occurring CO_2 in the reservoir gas. Additionally the following is also measured during phase 2:

- Injection rate of the CO_2
- Composition (purity) of the injected CO_2
- Pressure and temperature at various locations (Figure 4):
  - In the compressor
  - At the wellhead
  - Along the well trajectory
  - At reservoir depth
- Composition of the produced gas and water, incl. tracer concentrations
- CO_2 injection tubing integrity
- Cement bond quality of the injection well
- Base line conditions for CO_2 and CH_4 compositions and concentrations in the biosphere

Results

The measurements from phase 1 could easily be interpreted and were used to assess the infectivity in reservoir compartment 4. It was concluded that the observed phase behavior of CO_2 and the reservoir response during injection were within the expected range, validating existing correlations and reservoir simulation predictions.

The interpretations of the measurements from phase 2 are more complicated for several reasons. An unexpected large down-hole pressure difference was observed between the injection and production wells, for a reservoir compartment that is believed to be in full communication (Figure 5). No obvious pressure interference between injector and producers could be detected. Pressure disturbances are measured in the injector and nearest producer. At this time, the cause of these disturbances is unknown. Additionally, the down-hole memory gauges failed several times during surveys, which caused gaps in the data set. The above factors complicate the assessment of the CO_2 storage capacity and the potential for enhanced gas recovery in compartment 3. These aspects are currently under investigation in the MONK, CATO and CASTOR research programs, measurements continue.

In July 2005 physical communication between K12-B6 (the CO_2 injection well) and K12-B1 the (nearest producer well) was demonstrated with the detection of both tracers in the gas stream of K12-B1 (Figure 6). The arrival of the tracers was about 4 months after the start of CO_2 injection. The lateral distance at reservoir depth between K12-B1 and K12-B6 is 420 m. So far no apparent increase in the CO_2 concentration has been observed in the production wells, but detailed sample analysis has to confirm this.
Tracer detection has taken place in the K12-B5, the second production well in compartment 3, during April 2006 (Figure 7). This well is positioned at a distance of about 1000 m from the CO_2 injection point.
In the case of K12-B the use of tracers has significally contributed to an improved understanding of the reservoir and how the pressure data could best be interpreted. The tracer observations are currently being investigated in order to assess the potential for enhanced gas recovery (EGR) and the tracer performance is being evaluated in CO2GEONET. Tracer analysis continues.

Conclusions

K12-B is the first site in the world where CO_2 is being injected into the same reservoir from which it originated. Observations of the unique measurement program are difficult to interpret because of some unexpected features in the down-hole pressure data, but additional data is being gathered which might clarify these anomalies. The use of tracers has contributed to an improved understanding of how these data should be interpreted. The storage potential and potential for enhanced gas recovery are currently still under investigation.

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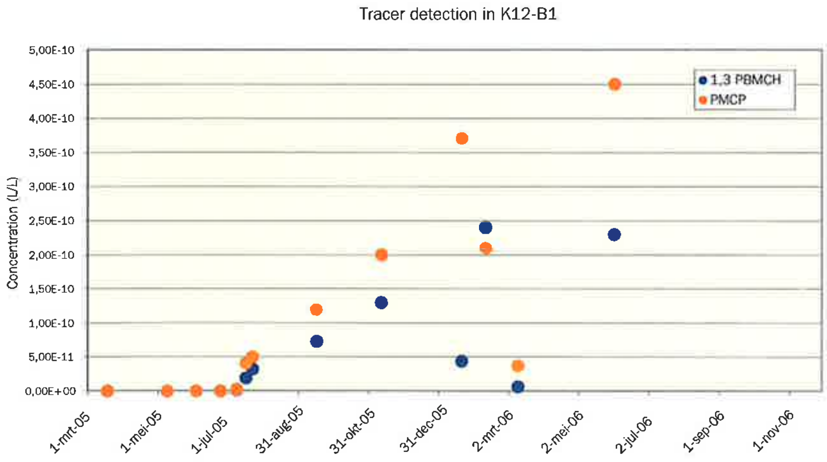

Figure 6. Tracer concentration measured in the gas stream of well K12-B1.

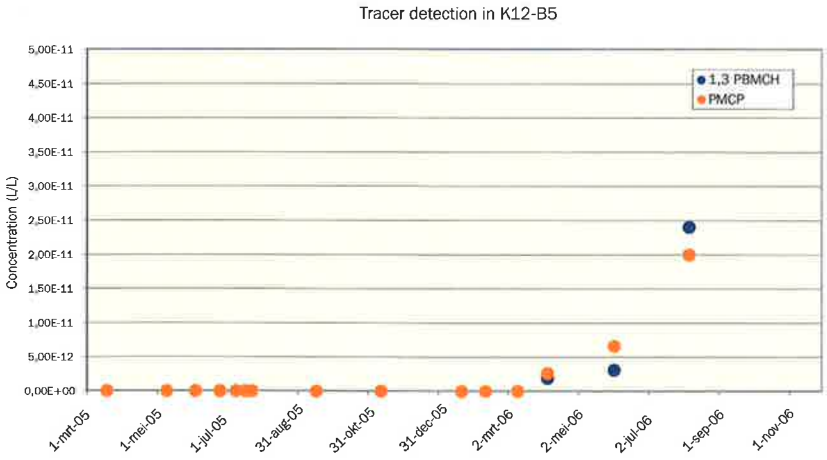

Figure 7. Tracer concentration measured in the gas stream of well K12-B5.

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From desk studies to field demonstration to commercial scale projects

CO_2 storage in underground coal seams while simultaneously enhancing CBM production

TNO led the international consortium that executed the first pilot project of CO_2 storage in underground coal seams while coal bed gas was simultaneously being produced. This demonstration in the Upper Silesian Basin of Poland, named RECOPOL, showed that CO_2 can be injected into low permeability coal seams at substantial rates. At the same time, it established that the production rates for coalbed gas could be increased. In 2006 a follow-up study, named MOVECBM, was initiated by TNO.

Introduction

The world is in need of technology options that will allow it to continue using fossil fuels without substantial CO_2 emissions. Subsurface storage of CO_2 in geological systems is considered a promising option and it is currently being investigated worldwide. The research window for projects on subsurface CO_2 storage has slowly but surely shifted from desk studies to demonstrations, for the most part. One of the options considered in this context is the storage of CO_2 in underground coal seams. The injection of CO_2 into coal while simultaneously producing coalbed methane (CBM) combines the production of a 'clean', hydrogen-rich fossil fuel (methane) with CO_2 sequestration. In 2001 the RECOPOL project was set-up to perform the first European field demonstration of this technique. The main goal of the project, co-funded by the European Commission, was to demonstrate that CO_2 injection in coal is feasible under European conditions. The MOVECBM project aims at the monitoring and verification of the CO_2 storage site in Poland and other locations.

CO_2 injection in RECOPOL

The principal targets for injection were coal seams between 1.3 and 3.3 m thick, of Carboniferous age, in the depth interval between 900-1100 m. The coal is high-volatile bituminous with a rank of about 0.8-0.85 %Rr. A new injection well (Figure 1) was drilled to a depth of 1120 m in the summer of 2003, 150 m from the existing production well). After the pilot site was completed in 2003, the initial injection tests were performed with water in early July 2004. Liquid CO_2 from an industrial source has been injected since August 2004.

In the first phase of the operations it was impossible to maintain continuous injection under the pressures and injection rates

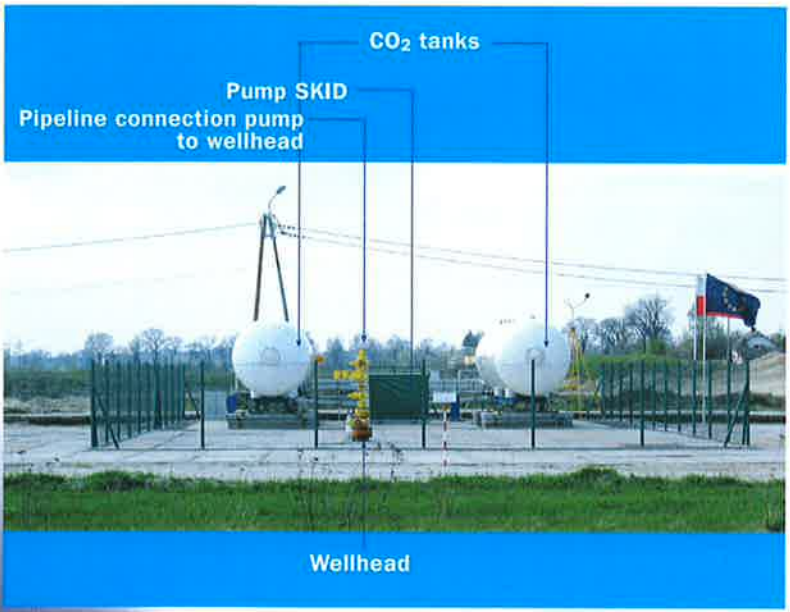

Figure 1. Picture of the RECOPOL pilot site.

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applied. The injection pressures required were higher than initially anticipated. The pressure was increased over the course of the project but continuous injection was not achieved. Meanwhile, well-head and downhole pressure and temperature data were recorded and evaluated so that researchers could learn about the reservoir behaviour. More actions were taken to establish continuous injection and this was eventually achieved in April 2005, following a frac job of the coal seams. This stimulation was also required because the permeability of the coal seams had been reduced over time, presumably due to swelling as the result of contact with the CO_2. Similar observations were made in Canada and the United States, where they were also attributed to coal seam swelling. After fraccing, approximately 12-15 tonnes per day were injected in continuous operation from late April to early June.

Gas production in RECOPOL

The coal seams have a fairly good gas content, although diffusion rates are low. The existing coalbed methane production well was cleaned, repaired and put back into production at the end of May 2004, to establish a baseline production. Gas was produced from the production well to evaluate possibilities for enhancing the gas rates. There was a clear response in the production well to the injection activities. In April 2005, after stimulation of the injection well, gas production increased rapidly within a few days. The CO_2 concentration in the production gas also increased rapidly, clearly indicating the breakthrough of the gas. However, the amount of CO_2 produced daily was much lower than the amount of CO_2 injected daily, indicating a clear sink of CO_2 in the reservoir. The absolute amounts of CH_4 that were produced are significantly higher than the estimated baseline production with conventional production (Figure 2). It can therefore be concluded that the injection activities had a positive effect on the gas recovery within the project's lifetime, probably due to exchange reactions. However, it appears that sufficient time is required to allow for diffusion of the gas into and out of the coal matrix.

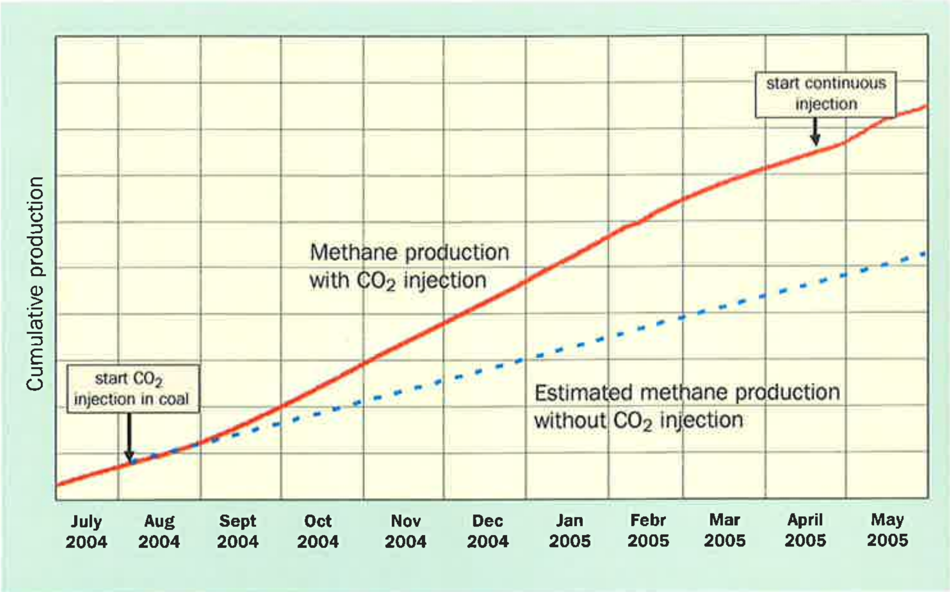

Figure 2. Cumulative amount of methane produced over time in the RECOPOL project. The positive effect on gas production of the injection activities is clearly evident when compared to the projected baseline production.

CO_2 storage in RECOPOL

In total approximately 760 tonnes of CO_2 were injected between August 2004 and the end of June 2005 (Figure 3). The amount of the injected CO_2 that was produced back by the MS-4 production well, mainly after the frac job, was estimated at 68 tonnes. The amount of CO_2 produced was much lower (approx. 9 %) than the amount of injected CO_2, indicating a clear sink of approximately 692 metric tonnes of CO_2 in the reservoir. This sink was confirmed by the rapid decrease in production rates after continuous injection stopped in June 2005. Shut-in tests of the production well and measurements of the water level, done in June 2005, showed that the reservoir pressure around the production well had increased slightly compared to the initial pressure but was returning to its equilibrium level. This also seems to confirm that CO_2 is being adsorbed around the production well.

Conclusions of RECOPOL

This project, finished in 2005, showed the potential of this application.
Several months of injection showed that injection without stimulation is difficult under the local field conditions. It had been expected that a small additional pressure above the reservoir pressure would be sufficient to establish continuous injection, but this was clearly not the case. The injection pressure required was nearly twice the reservoir pressure. Apparently, this was the result of a decrease in permeability of the reservoir during injection, most likely due to swelling of the coal.

Advances were made in terms of understanding the process, which will lead to improvements in the dedicated numerical simulators. Enhancement of methane production was proven, although the underlying process is not fully understood. Further field experiments and laboratory studies should be undertaken to improve our knowledge of the processes involved. The permeability of the coal remains a critical factor, even though the project demonstrated that the injectivity in low permeability coal

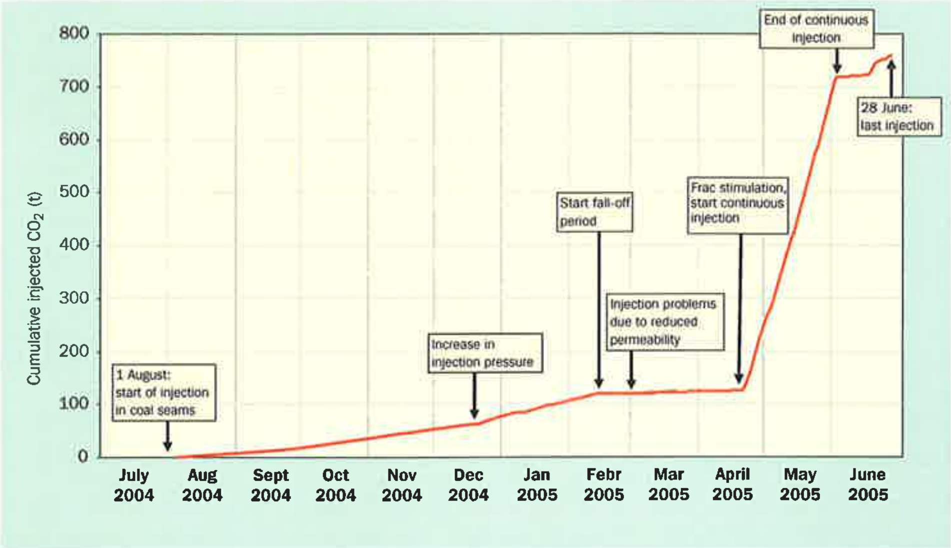

Figure 3. Cumulative amount of CO_2 injected over time in the RECOPOL project.

could be increased by substantial rates. The injected amounts provide a good basis for a future upscaling of operations.

Project leaders are convinced that they can find other locations in the Upper Silesian Basin that have higher permeability, thicker seams and higher gas content, thus providing better prospects for gas production. Based on the experiences of this project, they are in a position to optimize fields and enhance production at future sites. Since the process appears to be diffusion-controlled, planners need to find an optimum distance between the wells that will guarantee sufficient contact time between the injected CO_2 and the in situ coal. Other well completions, such as horizontal or 'fishbone' drilling, need to be researched to assess their impact on injectivity and productivity. The recovery factor could be enhanced even further through dedicated operational schemes with varying injection and production intervals. We strongly recommended instituting operational flexibility, in terms of the applied pressure and flow rates, to manage the swelling effects.
The consortium showed conclusively that it was possible to set up an onshore CO_2 storage pilot in Europe and handle all the 'soft' issues (permits, contracts, opposition, etc.) related to these kinds of innovative projects. The lessons learned in this operation can possibly help others overcome the start-up barriers to future CO_2 storage initiatives in Europe.

Although RECOPOL showed the potential of the technique, it also showed that the fundamental processes are still not fully understood. Especially, for optimal storage and enhanced CBM, the adsorption kinetics (and rate) and the diffusity of gasses into fractures / coal matrix and related monitoring were identified as main research targets. In general, monitoring CO_2 storage is situation specific. Here migration of free CO_2 and CBM through relative thin, deep coal seams and its overburden need to be monitored. For these reasons, the follow-up project MOVECBM was initiated by TNO, which started in November 2006, has a duration of 2 years, and is executed by a consortium of 17 research partners (Figure 5). The objective of the MOVECBM project is to improve the current understanding of CO_2 injected in coal and, hence, the migration of methane in order to ensure a long-term reliable and safe storage. The laboratory work and modelling will be based on parameters of the previously investigated test site in Kaniów, Poland. The injection well, realised in the EC RECOPOL project, is used in 2007 to produce gas from the coal seams (Figure 4). The composition of this gas is continuously monitored to define the actual adsorption of CO_2 that was injected in the coals seams during the RECOPOL project.

Besides the field production test in Kaniów, a small scale combined injection and production experiment will be carried out in

Figure 4. The well in Kaniów that was used as CO_2 injection well and that is used as production well in the MOVECBM project.

Figure 5. In red are indicated the major coal basins, in green is indicated the countries of the participating members of the MOVECBM research consortium. These are the Netherlands Organisation for Applied Scientific Research (TNO), The Netherlands, as coordinator; Central Mining Institute Poland (CMI), Poland; Shell International Exploration and Production (Shell), The Netherlands; Etudes et Productions Schlumberger (EPS), France; Universita di Roma "La Sapienza" (URLS), Italy; Faculté Polytechnique de Mons, Wallonia-Brussels Academy (FPM), Belgium; Universiteit Utrecht (UU), The Netherlands; State Key Laboratory of Coal Conversion (SKLCC), P.R. China; Rheinisch-Westfälischen Technischen Hochschule (RWTH), Germany; Istituto Nazionale di Oceanografia e di Geofisica Sperimentale (OGS), Italy; International Energy Agency-Green House Gas (IEA), United Kingdom; Environmental Research & Industrial Co-operation Institute (ERICO), Slovenia; Advance Resources International (ARI), U.S.A.; Commonwealth Scientific and Industrial Research Organisation (CSIRO), Australia; OXAND, France; Research Institute of Petroleum Exploration and Development, PetroChina (RIPED), P.R. China; China United Coalbed Methane Company (CUCBM), P.R. China.

the Velenje coal mine in Slovenia. Horizontal injection and production wells are drilled in the coal. The results from the mine will fill the gap between the larger scale field experiment in Kaniow and the laboratory work.

These laboratory and field results of the MOVECBM project will allow to test optimal storage and production regimes and corresponding optimal monitoring methodology. Besides the coal reservoir and the cap rock also the wells and the (near) surface are monitored. Research will be performed on the resolution, geometry and time-intervals of the applied monitoring techniques. The combination of monitoring and modelling is essential for predicting long-term CO_2 and CH_4 behaviour and, subsequently, the long-term reliability and safety. A methodology is developed where, based on field test and laboratory results, models are updated and used to predict future behaviour and can be used to optimise the storage process.

Monitoring and verification guidelines for site certification are derived from modelling results and compared to broadly accepted standards. It is emphasised that the storage technology developed in this project can also be applied to other countries (e.g. China, Australia, USA), where major CO_2 emitters are located near large coal resources. These are optimal conditions for ECBM.

Acknowledgements

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17 research partners of the MOVECBM project (Figure 5) are also acknowledged for their contributions and financial support.

Geo energy and Geo information

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Detection and mechanisms

Natural gas migration to the near-surface environment as an analogue to potential leakage of CO_2

In most of the world's hydrocarbon basins some migration of natural gas to the surface can be observed. This naturally occurring migration and seepage of gas through the subsurface to the near-surface environment can be considered as a natural analogue to the potential leakage of CO_2 from future subsurface storage sites. Although the chemical composition of natural gas (mainly consisting of CH_4) differs from CO_2 the physical behaviour is similar. Gas accumulated in or moving through the shallow subsurface can be detected with geophysical monitoring techniques. In seismic and acoustic datasets the presence of gas may result in a variety of expressions. The interpretation of such expressions, or geophysical anomalies, as features related to gas can be confirmed by the examination of geochemical anomalies. In order to study the applicability of offshore geochemical monitoring techniques a number of obvious seismic and acoustic anomalies were selected for seabed sediment sampling and subsequent chemical analysis of the gas contained by the sediments. TNO and Statoil collaborated in this research project in the scope of the EC supported NASCENT project. These results were presented at the GHGT-7 Conference in Vancouver.

Nigerian continental slope

3D seismic data from the Nigerian continental slope show indications of fluid flow to the seabed through faults. Amplitude anomalies, indicating shallow gas accumulations, are concentrated around faults. Figure 1 shows a seabed azimuth map from 3D seismic data. Pockmarks (seafloor craters resulting from venting of gas or fluids) and mud volcanoes can be seen along faults. Seabed samples taken at the location of some faults and mud volcanoes proved to contain hydrocarbons, thus confirming seepage all the way to the seabed.

Norwegian North Sea

Through the use of 3D seismic data, various seismic attributes have been applied to map features associated with gas escape, like pockmarks, amplitude anomalies, mud volcanoes and carbonate build-ups. Observations of such features at different (but not all) subsurface horizons, indicate that gas escape through the seabed takes place during limited periods in geologic time. A method developed recently (using neural network-based software) to detect gas chimneys has been applied to different 3D data volumes from the Norwegian North Sea (Figure 4). The results show that many chimneys are located at faults and fractures and, as such, indicate faults that are, or have been, working as fluid migration pathways. Faults can let through large amounts of fluids in short periods. Some chimneys do not seem to be related to faults. Such chimneys are believed to represent a much slower fluid migration process.

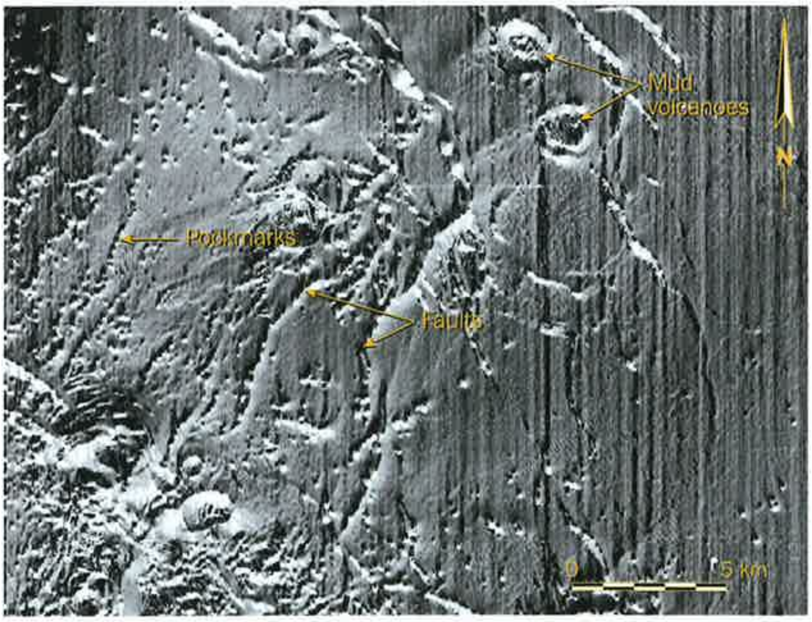

Figure 1. Azimuth map of the seafloor reflector from 3D seismic data showing the presence of pockmarks on the seabed, often aligned along fault lines (Nigerian continental slope). The pockmarks are probably caused by gas escape through the faults. Courtesy Statoil

Southern North Sea

In the Netherlands part of the Southern North Sea a variety of seismic and acoustic anomalies assumed to be related to the occurrence of shallow gas were observed. Some of these features were selected for a marine sampling campaign in the summer of 2002.

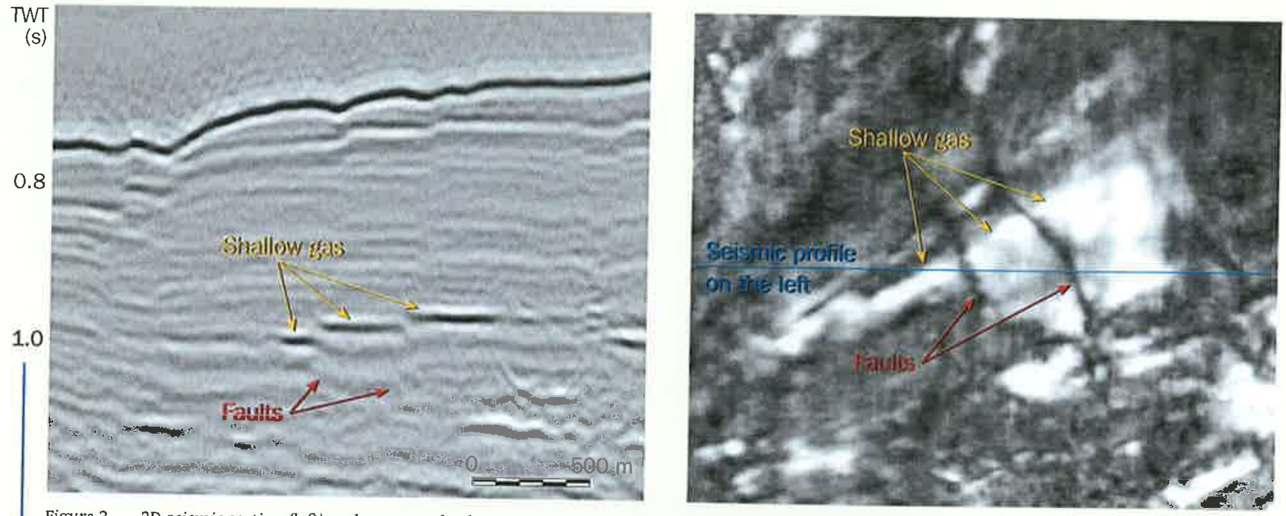

Figure 2. 3D seismic section (left) and average absolute amplitude map (right) showing a possible sand body segmented by faults, Nigerian continental slope. The sand is believed to be charged by gas migrating up the faults. Courtesy Statoil

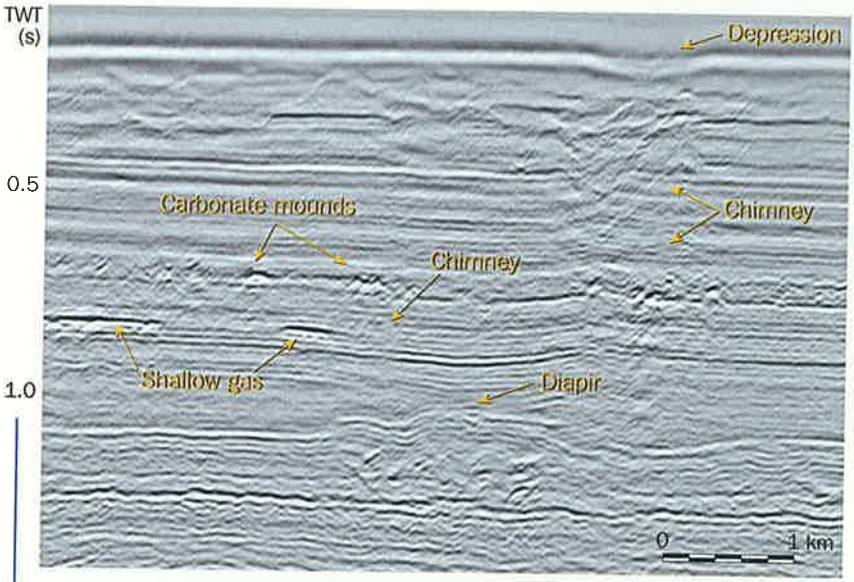

Figure 3. Seismic section showing features that are associated with gas escape through the present-day seabed and ancient seabeds. Courtesy Statoil

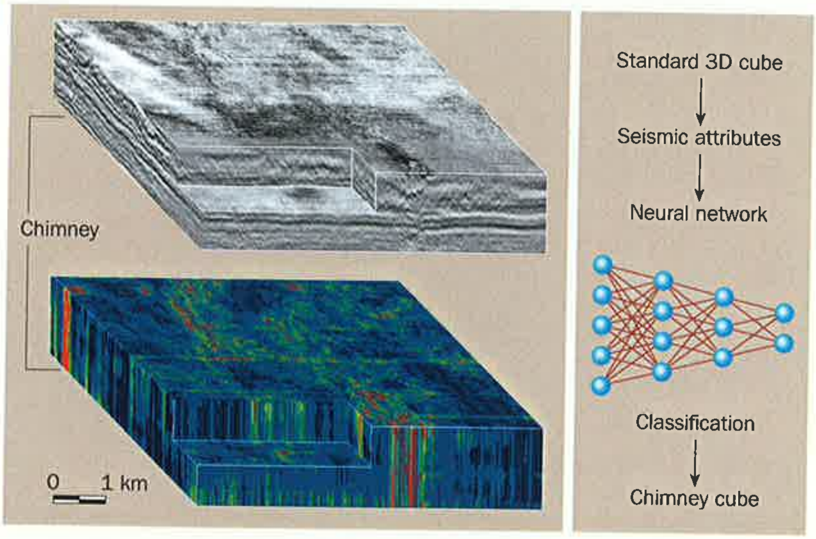

Figure 4. 3D seismic volume before and after chimney detection. Single chimneys and clusters of chimneys associated with a fault have been made visible by the chimney detection process. Courtesy Statoil

Pockmarks

A good example of a seafloor pockmark was found in the Dutch licence block A11.

Figure 5 shows a multi-beam echo image of the seafloor that clearly indicates the crater-like depression. Maximum depth of the crater is about 2 m. Six shallow sediment cores were collected in 2002 (core lengths are up to 3.4 m). The methane concentrations measured in the headspace gas of the sediment samples are plotted. The highest CH_4 concentration (122.6 ppm) is found in the core from the very centre of the feature. This value is significantly higher than background values. It is remarkable that the location of the anomaly almost coincides with that of a smaller 'unit pockmark'. Unit pockmarks are smaller features just a few metres in diameter that occur within the larger feature. They probably represent the most recent sites of venting. At distances of only a few dozen metres from anomalies concentrations can be as low as background values.

Active gas vents seen as plumes in the water column

In the northernmost part of the Netherlands sector of the Southern North Sea a number of shallow Plio-Pleistocene gas fields were discovered in the 1980s by drilling clear bright spots (seismic anomalies). The gas field in licence blocks B10 & B13 is

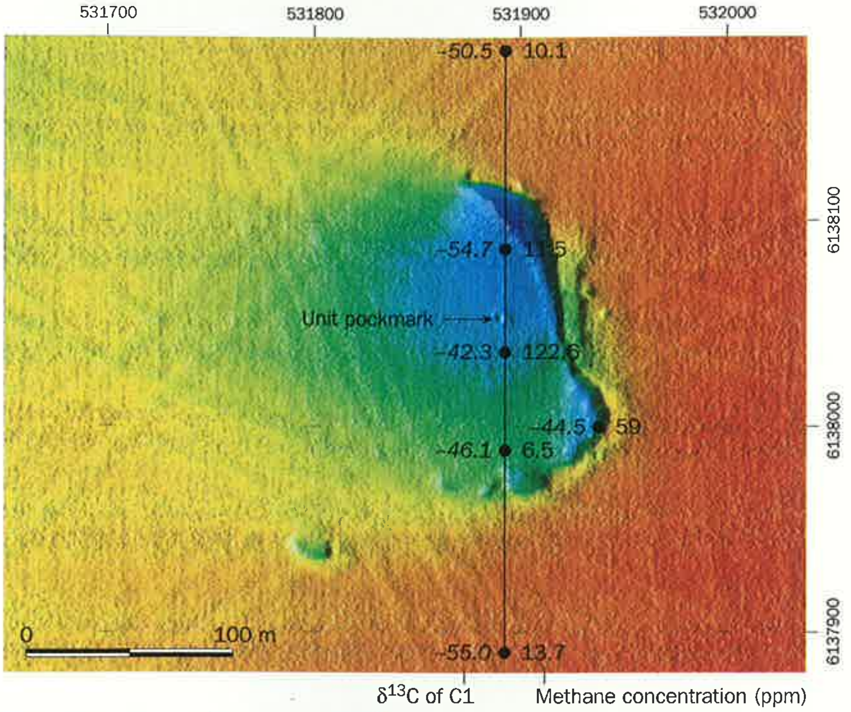

Figure 5. Multi-beam echo image of the seafloor showing a seafloor pockmark associated with gas venting. Methane concentrations in seabed sediment samples are highest in the centre of the pockmark

one example (Figure 6a). The field is obviously leaking hydrocarbons (almost pure methane) into the shallow subsurface and into the water column. This can be observed on high frequency acoustic profiles such as the XStar profiles acquired by TNO in 2002 (Figure 6b). Gas plumes are visible in the water column. Methane concentrations as high as 10,395 ppm were found close to one of the gas vents and confirm the acoustic anomalies. The fact that close to the strongest acoustic anomaly the methane concentrations are as low as 39 ppm suggests that the lateral variation in concentrations and fluxes is high. A standard 2D seismic profile (from 1987) running across the field (Figure 6c) shows the leaking gas reservoir as a bright spots and also shows shallow enhanced reflectors in the shallowest sediments over the field. The gas saturation in this shallow realm is not laterally continuous. The central patch of shallow enhanced reflectors coincides with the location of the strongest plume of Figure 6b.

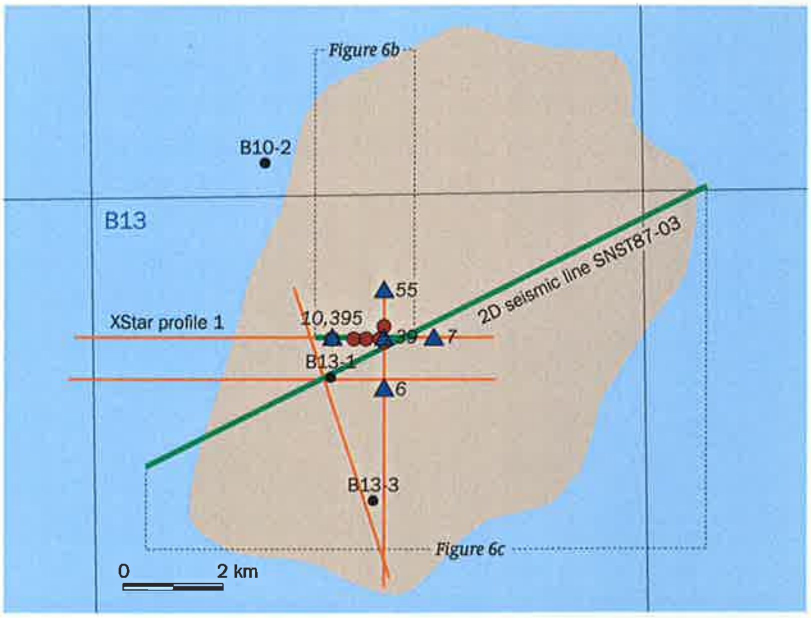

Figure 6a. Plio-Pleistocene gas field in licence blocks B10 and B13. The locations are shown of three exploration wells, four Xstar high frequency acoustic profiles (orange lines), gas plumes observed on those profiles (red circles), five vibrocores (blue triangles) with the CH_4 concentrations in the headspace gas annotated and a 13 km portion of a seismic profile across the field (green line)

Seismic chimneys

Figures 7 and 8 represent two seismic profiles from Dutch licence block F3, again both show gas accumulations at Plio-Pleistocene levels as bright

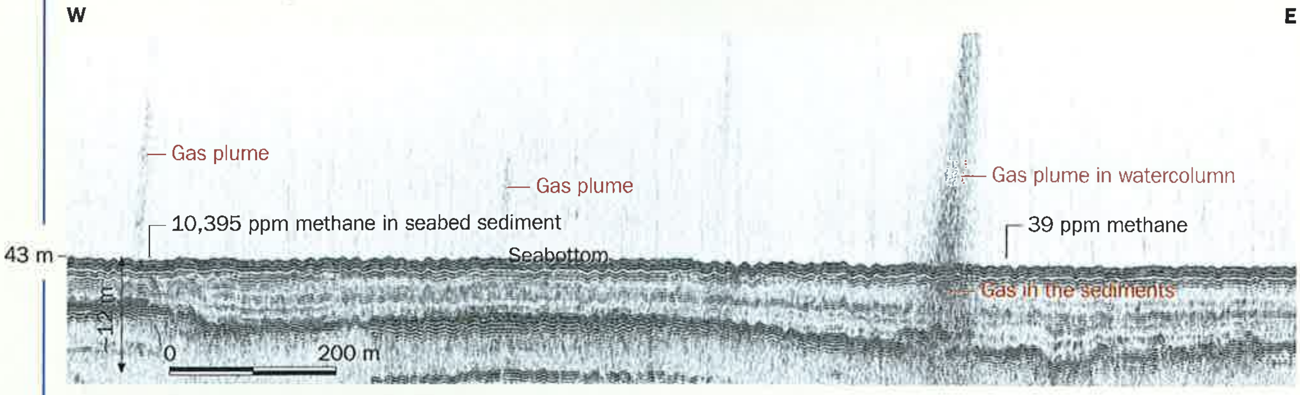

Figure 6b. About 2 km long portion of the E-W running high resolution XStar profile across two of the core sites. Penetration depth of this high frequency data is about 12 m. Gas plumes in the water column are clearly visible

spots. Like B13, block F3 is also leaking from its Plio-Pleistocene gas sands. But this time the expression on 3D seismic data is that of a gas chimney (Figure 7). The chimney is immediately adjacent to a fault, which may have provided a migration pathway for the gas. Methane concentrations in the sediment samples were only slightly elevated. Figure 8 shows a leaking fault system. At various levels where the faults intersect with highly porous layers gas is (temporarily?) trapped as small gas pockets, visible on the seismic data as small bright spots. Also visible on this profile is another bright spot that is not associated with any expressions of leakage.

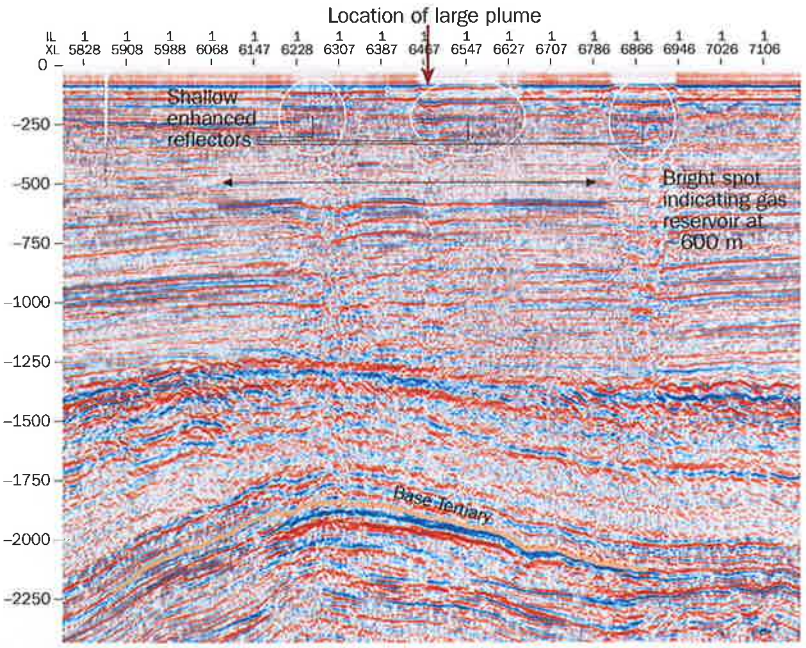

Figure 6c. About 13 km long portion of 2D seismic profile SNST87-03 from 1987 showing the bright spot corresponding to the gas reservoir and patches of shallow enhanced reflectors in the shallowest sediments visible, indicating gas saturation. The red arrow indicates the location of the strongest gas plume anomaly observed on the XStar profile

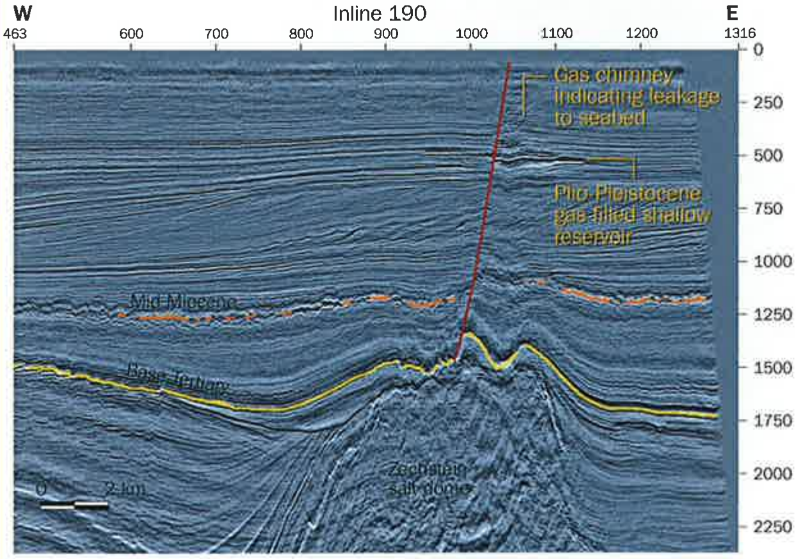

Figure 7. A shallow gas chimney visible on 3D seismic data as a seismic anomaly with higher amplitudes and lower reflector continuity in comparison to the surrounding sediments. The chimney is an expression of methane leakage from underlying Plio-Pleistocene gas sands

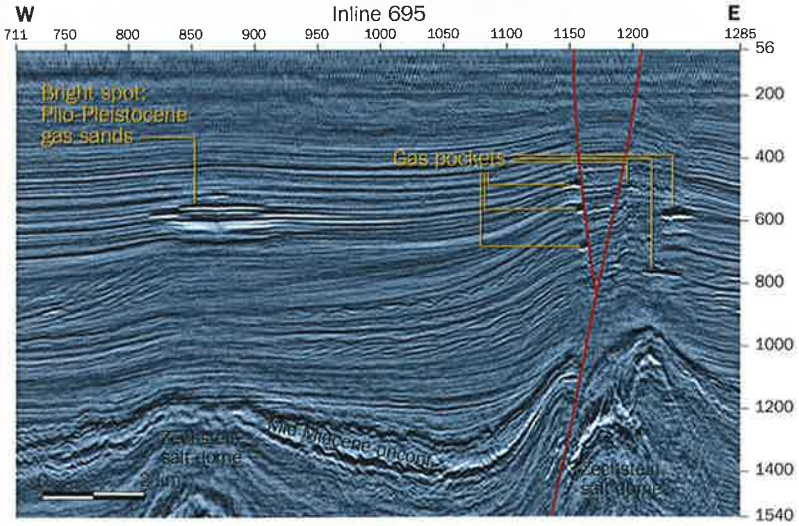

Figure 8. A fault system that appears to be leaking. Bright spots indicate small gas pockets along the faults wherever the faults intersect with highly porous layers

Conclusions

Migration of natural gas to the near-surface environment can have different expressions on seismic and acoustic data, depending on both local circumstances and types of surveys and data. Migration and leakage can be detected or monitored using the right geophysical and geochemical techniques. It is always advisable to verify the interpretations of geophysical anomalies using geochemical monitoring. Preferential migration and leakage through faults and fractures is found to be a wide-spread mechanism.

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The mechanical impact of CO_2 injection

The mechanical impact of CO_2 injection into a depleted hydrocarbon field or aquifer is caused by changes in the stress field, resulting from changes in the pore pressure and volume of the rock. Mechanical processes can lead to the loss of reservoir and caprock integrity, and the re-activation of existing faults. A geomechanical numerical modelling approach to determining the mechanical impact of CO_2 injection is presented and demonstrated on three sites studied as part of the European Community funded project 'Natural Analogues for the storage of CO_2 in the Geological Environment' (NASCENT).

CO_2 injection into a depleted hydrocarbon field or aquifer causes several interlinked physical and chemical processes. One of the most prominent processes is the mechanical impact of CO_2 injection. This is caused by changes in the stress field that result from changes to the pore pressure, buoyant pressure and volume of the rock. Stress changes may cause deterioration of the mechanical and hydraulic integrity of the caprock, causing leakage. Existing faults and discontinuities may be re-activated, or slip may occur along weakness planes in reservoir rock and overburden. This may cause the formation of preferential pathways for CO_2 escape and local seismic events.
For public acceptance of geological storage of CO_2 it must be demonstrated that the mechanical effects of CO_2 injection and storage will neither cause the deterioration of the mechanical stability and the isolation capacity of the storage site nor have negative effects on the environment.

Modelling approach

To predict the mechanical effects of CO_2 injection we use an integrated geomechanical numerical modelling approach. This approach requires the integration of the tools for geologic modelling, fluid flow modelling and finite element stress modelling. The approach has been used successfully in several hydrocarbon production studies and safety studies. Here we extend and test its applicability to predict the mechanical impact of CO_2 injection on the mechanical integrity of reservoir rock and caprock, the stability of existing faults and ground deformation.

Three sites were selected for geomechanical modelling: the Montmiral site in France and the Florina site in Greece, which represent natural accumulations of CO_2, and the Sleipner hydrocarbon field in Norway. These sites were studied as part of the EC research project NASCENT (Natural Analogues for the storage of CO_2 in the Geological Environment). Geomechanical finite element models of these three sites were constructed using DIANA, a TNO finite element software package, and the mechanical effects of a number of injection scenarios were simulated. Each scenario consists of pressure histories for a depletion phase, in which the hydrocarbon or CO_2 has been extracted from the reservoir, followed by an injection phase, in which CO_2 is injected. Sensitivity studies considered the effects of various reservoir pressures at the end of the injection phase.

Case 1 – The Montmiral natural CO_2 accumulation

The Montmiral field is a natural CO_2 accumulation that has been commercially exploited. It is located in the carbogaseous peri-Alpine province in south-eastern France. The available data about this site comprise regional geological data, well-completion data and, in contrast to the other CO_2 natural accumulations in the area, some reservoir engineering data.

The geomechanical numerical modelling of the Montmiral site was carried out in order to predict changes in the in situ stress field and the associated deformation induced by three stages of use: past CO_2 extraction; future CO_2 extraction; and possible future CO_2 injection. The stress and deformation in the subsurface are computed using a two-dimensional plane strain finite element model of the Montmiral field (Figure 1). The withdrawal of gas from the reservoir was modelled by decreasing the fluid pressure in the reservoir and in the parts of the fault intersecting the reservoir. Subsequent CO_2 injection into the depleted reservoir was modelled by increasing the pressure back up to or beyond the initial reservoir pressure.

Simulation results show the evolution of the stress and deformation during a full cycle of CO_2 extraction and injection. We present here some

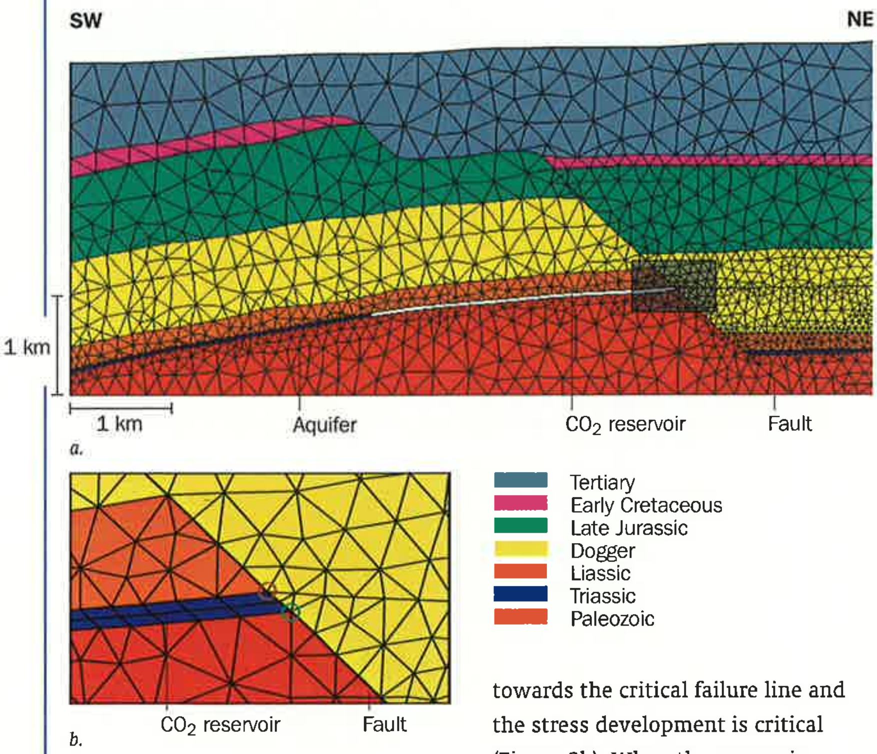

Figure 1. a. Finite element model of the Montmiral site, and b. an enlarged part of the model, showing the location of the fault elements for which the results of analyses are shown

results of fault stability analysis. The stress path presented in Figure 2a shows that the fault is initially stable, but that over 90% of its shear resistance to slip has been mobilised. The stress path diverges from the failure line, meaning that the stress development is not critical and the stability of the fault improves.

In contrast to depletion, the stress path during CO_2 injection converges towards the critical failure line and the stress development is critical (Figure 2b). When the reservoir pressure reaches the virgin pressure, the state of stress on the fault is the same as it was in the initial state of stress, before CO_2 extraction. CO_2 injection above the virgin reservoir pressure shows a critical stress development until the Mohr-Coulomb failure criterion is reached (Figure 2b). At failure, a slip on the fault occurs, which may cause a seismic event in the area.

Case 2 – The Florina natural CO_2 accumulation

The Florina natural CO_2 field is located in northern Greece, near the city of Florina. It is the only field in Greece producing CO_2 commercially. The gas has accumulated in a shallow reservoir in Tertiary sands, 300 - 600 m below the ground surface. In the wider area of the Florina sedimentary basin CO_2 leakage creates mineral springs and gas bubbles in shallow wells, where the fractures and permeable caprock allow slow gas migration. In other places, where the reservoirs do not leak, commercial CO_2 fields have formed. Before exploratory drilling, there was no indication of leakage at the ground surface although the CO_2, discharging from the reservoir into the groundwater, was over-pressured by 50 bars.

The evaluation of the geohazards associated with CO_2 extraction from and subsequent injection into this shallow reservoir was carried out assuming slow leakage of the gas from the reservoir through fractures towards the shallow subsurface. There CO_2 accumulates and dissolves in the groundwater of an existing aquifer, which is also very likely to happen in the case of a leak from geological storage in similar structural/geological settings. Numerical modelling predicted changes in the stress field and associated deformation; it was assumed that the natural CO_2 accumulation will be fully depleted before the subsequent injection of the reservoir with CO_2. A plane strain finite

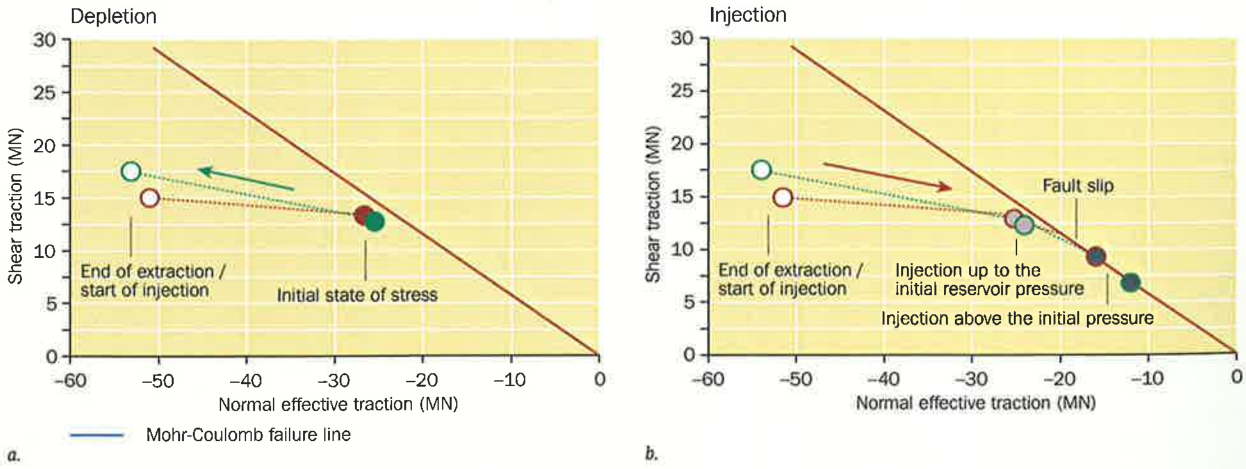

Figure 2. Stress paths for a part of the fault intersecting the reservoir for a. CO_2 extraction, and b. CO_2 injection

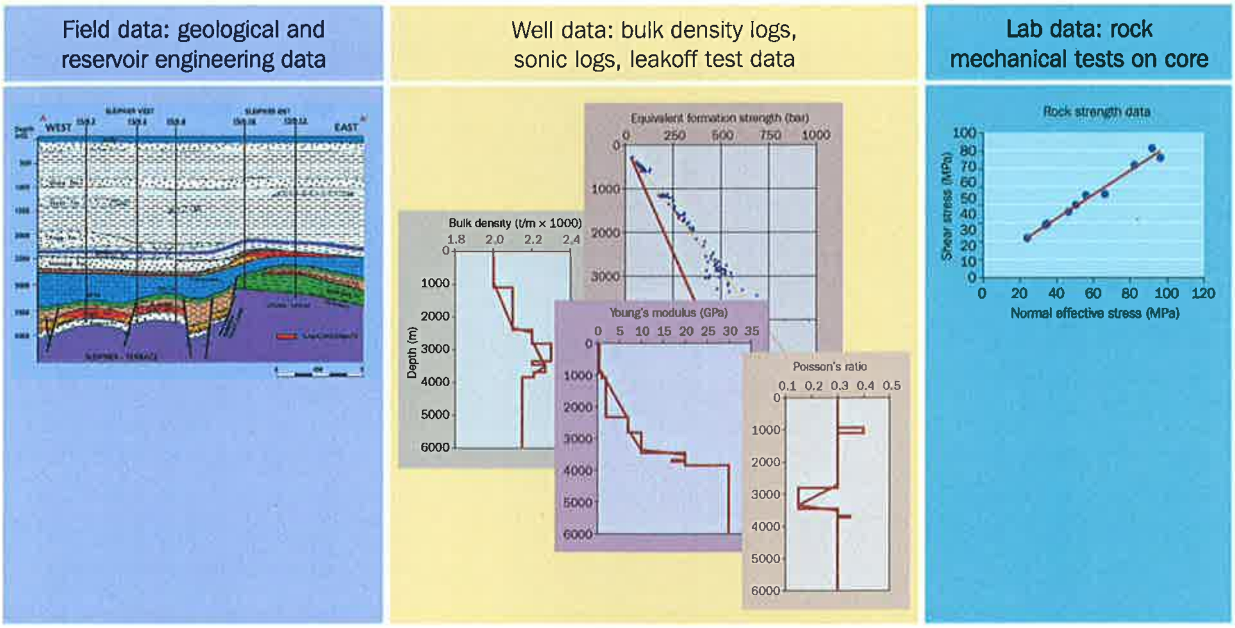

Figure 3. *Data integration for geomechanical modelling of CO_2 injection in the Sleipner fields (courtesy Statoil)*

element model was constructed, based on a geological cross section and the available field and laboratory data. The model verified the observations made during the production history. Until now, neither the seismicity of the area has changed, nor has any noticeable subsidence been observed.

Case 3 – Sleipner gas-condensate fields

The Sleipner gas and condensate fields comprise two offshore fields:

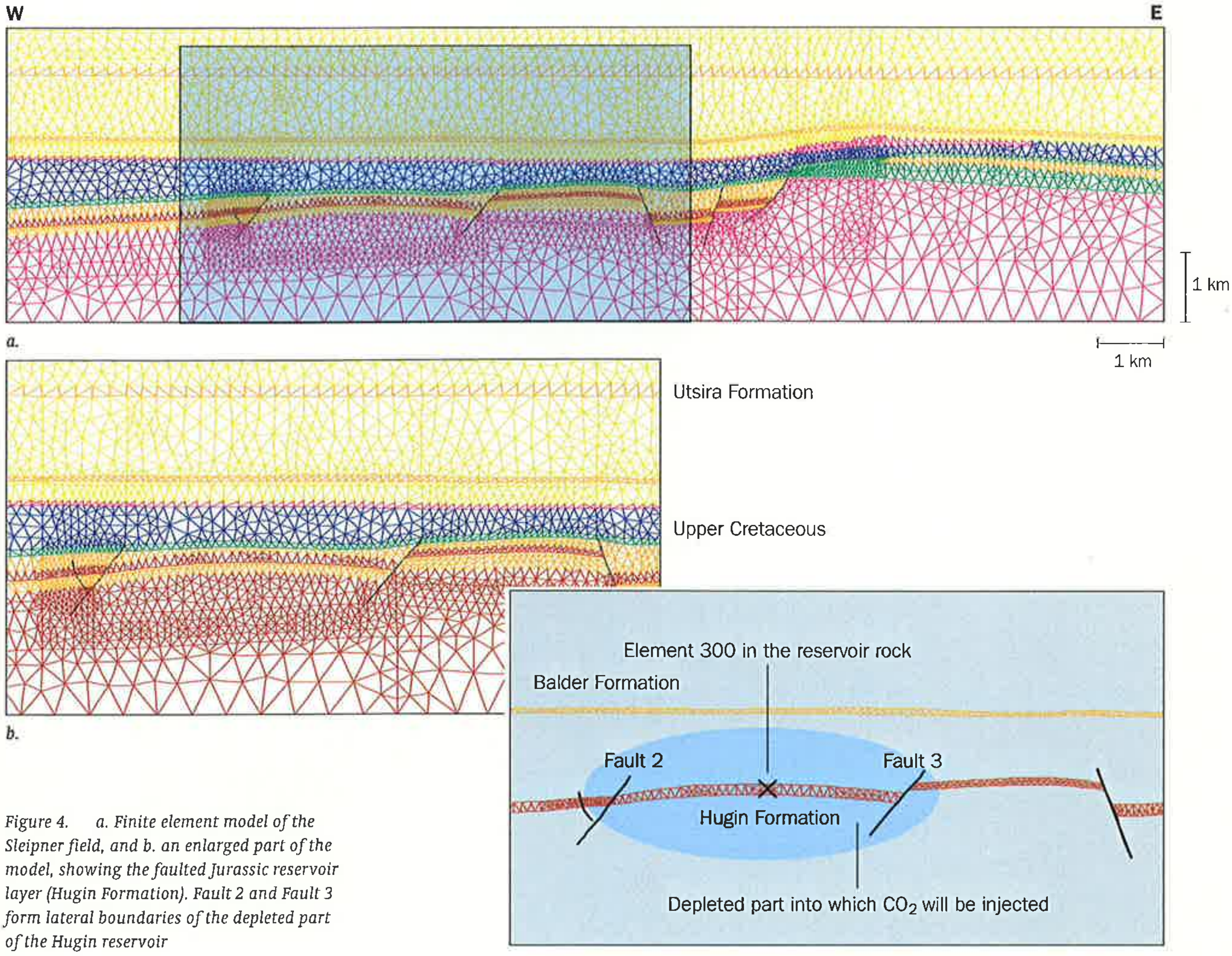

Figure 4. *a. Finite element model of the Sleipner field, and b. an enlarged part of the model, showing the faulted Jurassic reservoir layer (Hugin Formation). Fault 2 and Fault 3 form lateral boundaries of the depleted part of the Hugin reservoir*

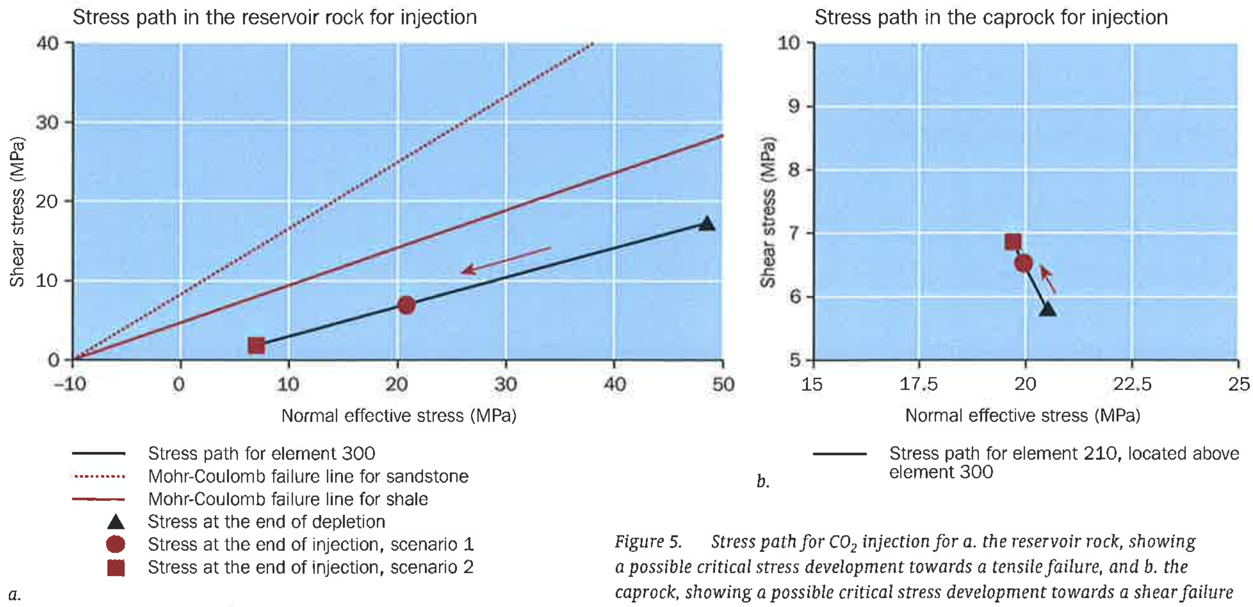

Figure 5. Stress path for CO_2 injection for a. the reservoir rock, showing a possible critical stress development towards a tensile failure, and b. the caprock, showing a possible critical stress development towards a shear failure

the Sleipner West Field, located at the southern edge of the Viking Graben, and the Sleipner East Field, located on the eastern margin of the South Viking Graben. CO_2 extracted from gas production from Hugin Formation on Statoil's Sleipner West field has been injected into a deep saline reservoir, the Utsira Formation, about 800 metres below the seabed. This is the world's first commercial-scale storage of CO_2 and it has been extensively monitored and researched by the SACS project (*www.ieagreen.org.uk/sacshome.htm*).

In contrast to the ongoing Statoil injection project, here we assume that CO_2 is injected into the same Hugin Formation from which the gas and condensate had been previously extracted. Based on a lithostratigraphic/structural cross-section and extensive field and lab data supplied by Statoil (Figure 3), a plane strain finite element model of the Sleipner Fields was developed (Figure 4).

Some results related to the analysis of the mechanical impact of CO_2 injection on the reservoir rock and caprock are presented in Figure 5. During injection, the stress path development in the reservoir rock may become critical (Figure 5a). When injection pressures approach the minimum horizontal principal effective stress in the subsurface, a tensile failure will be initiated.

The impact on the caprock is relatively limited (Figure 5b). The rate of change in the stress is at least one order of magnitude lower than in the reservoir rock. During CO_2 injection, the sense of stress development becomes critical. However, since the rate of change is low, the mechanical integrity of the caprock is not expected to deteriorate.

Acknowledgments

The study was supported by the EC NASCENT Project 'Natural Analogues for the Storage of CO_2 in the Geological Environment' (*http://www.bgs.ac.uk/nascent/*). The NASCENT partners are the Netherlands Institute of Applied Geoscience TNO – *National Geological Survey*, the British Geological Survey (project coordinator), the Geological Institute of Hungary, the Bureau de Recherches Géologiques et Minières, the Institute of Geology and Mineral Exploration, Greece, the German Geological Survey, the University of Aachen, the University 'La Sapienza' of Rome, BP and Statoil. Site data were kindly provided by Air-Liquide, BRGM, IGME and Statoil.

Conclusions

These days we have advanced geomechanical numerical modelling tools for predicting the mechanical impact of CO_2 injection on reservoir rock, caprock and faults. The keys for realistic prediction are the availability of geomechanical data about the sequestration site and the integrated modelling of geomechanical and other physical and chemical processes that can change the mechanical properties of geomaterials as a consequence of CO_2 injection.

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