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SECURe – Subsurface Evaluation of Carbon capture and storage and Unconventional risks

REPORT ON STATE OF THE ART AND NEW DEVELOPMENTS FOR DEFINING THE SEISMIC BASELINE FOR GAS STORAGE AND EXPLOITATION

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Public introduction

Subsurface Evaluation of CCS and Unconventional Risks (SECURe) is gathering unbiased, impartial scientific evidence for risk mitigation and monitoring for environmental protection to underpin subsurface geoenergy development. The main outputs of SECURe comprise recommendations for best practice for unconventional hydrocarbon production and geological CO2 storage. The project is funded from June 2018–May 2021.

The project is developing monitoring and mitigation strategies for the full geoenergy project lifecycle; by assessing plausible hazards and monitoring associated environmental risks. This is achieved through a program of experimental research and advanced technology development that includes demonstration at commercial and research facilities to formulate best practice. We will meet stakeholder needs; from the design of monitoring and mitigation strategies relevant to operators and regulators, to developing communication strategies to provide a greater level of understanding of the potential impacts.

The SECURe partnership comprises major research and commercial organisations from countries that host shale gas and CCS industries at different stages of operation (from permitted to closed). We are forming a durable international partnership with non-European groups; providing international access to study sites, creating links between projects and increasing our collective capability through exchange of scientific staff.

Executive report summary

Since the end of the 1990's, several unconventional hydrocarbon production operations and geological CO_2 storage projects have taken place in different countries with various monitoring plans. These plans often include either active or passive seismic monitoring in order to provide feedback on the geomechanical effects of CO_2 injection.

In order to realise an effective monitoring plan a baseline must be established – and to date these have been carried out with varying degrees of success using different methods. The goal of this deliverable is therefore:

- Analyze the most pertinent case studies using published documentation to assess the effectiveness of the baseline
- Set up a list of recommendations for future active/passive seismic baselines based on the experience gained from these case studies

This report explores several case studies for different settings: CO_2 storage pilots, Enhanced Oil Recovery (EOR) operations, non-conventional hydrocarbon extraction in both onshore and offshore settings.

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1 Introduction

Carbon Capture and Storage (CCS) technology represents one of the possible answers to increased CO_2 emissions. The IPCC 15th special report (2018) states that Carbon Dioxide Removal methods, including CCS, are in most carbon reduction roadmaps for 1.5°C global temperature increase. The EU has taken regulatory steps to enable CCS with the EU directive 2009/31/EC. This directive puts emphasis on goal-driven evaluations: a CCS project has to demonstrate that CO_2 stays in place and behaves as expected towards a state of long-term stability. Activation of and leakage through a fault due to CO_2 pressure build-up is one of the risks that future operators will be required to evaluate during the life cycle of the project.

Unconventional gas exploitation faces the same risks of uncontrolled activation of the existing faults, and subsequent leaking of extraction fluids that can harm the environment. Therefore, unconventional gas exploitation operators share similar contexts and therefore will use

1.1 CONTROLLING THE BUBBLE POSITION AND MECHANICAL BEHAVIOUR

The EU directive requires the operator to demonstrate that the storage site is secure, in order to make sure that CO_2 injected will not ultimately return to the atmosphere or react with minerals or pore fluids of the host aquifer. In order achieve this goal, the operator has to show that during CO_2 injection no leaking paths are propagated, for instance through reactivated faults.

In order to demonstrate the long term safety of the CO_2 storage, models of its behaviour will be used. The validity of these models is expected to be tested with regular monitoring operations during the storage lifecycle and the first years after its closure.

Injecting CO_2 in an underground storage site induces several changes of geological, chemical and mechanical properties in the following areas: the reservoir, the overlying caprock and the surrounding geological objects including faults and aquifers The following sections of this report will detail changes that can be detected by active and seismic monitoring methods, and discuss how these methods can inform CO_2 storage operators.

1.2 BASIC PRINCIPLES OF ACTIVE AND PASSIVE SEISMIC MONITORING

1.2.1 Active seismic monitoring: detecting changes in seismic attributes

Active seismic surveys record the seismic waves that are generated by a controlled vibration source and travel through the underground. The main idea behind monitoring with active seismic monitor is to detect changes in seismic waves records caused by underground changes.

To achieve this goal, several values called “seismic attributes” are measured :

- The wave traveltime
- The amplitude of the waves, relative to the source initial energy (ie the dampening)
- The phase of the waves, ie the relative orientation of the waves from the initial energy emission

These attributes, for underground exploitations, can change for several reasons :

- There are direct effects, such as displacements caused by the exploitation that can be directly measured with traveltimes
- Pressure changes have also effects on the seismic wave speed and dampening
- Opening fracturation will slow down seismic waves and increase the attenuation through wave diffusion
- More generally, changing a fluid by another (such as replacing water by CO_2) will change how the seismic waves will interact with the reservoir, which will change several attributes

Therefore, the operator will measure changes in attributes, locate them, and try to interpret them in the context of the field history – which is critical since different causes may have the same quantitative effect on seismic waves.

1.2.2 Passive seismic monitoring: detecting where stress changes cross threshold

CO_2 injection in the underground induces a change in the stress state of the system. For CO_2 storage systems without brine extraction, overpressure builds up at the reservoir level and propagates far beyond the CO_2 plume, as shown by models developed by Zhou et al. (2008) in Figure 1:

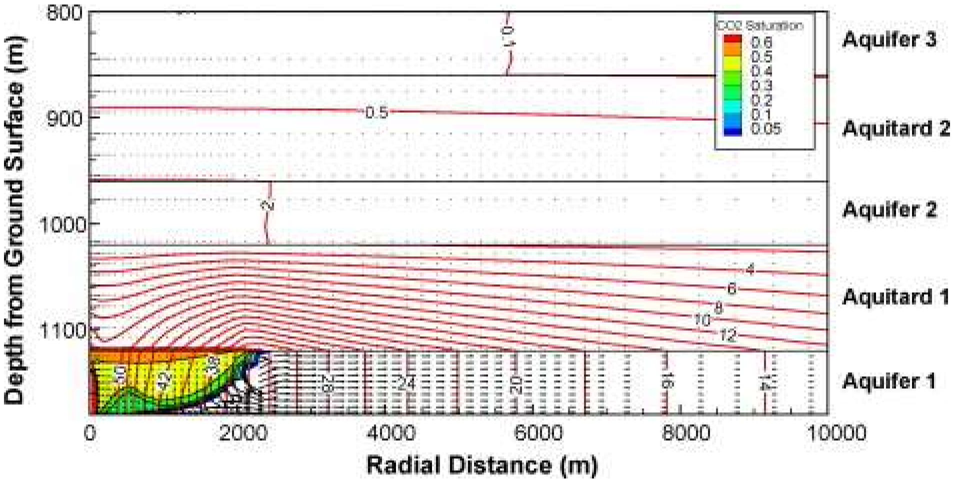


Figure 1 : Contours of CO_2 saturation (flooded contours) and pressure buildup, given in bar (lines), as well as water flux vectors in m/s at the end of the injection period (30 years), obtained for the base case with a seal permeability of 10^{-18} m^2. From Zhou et al. (2008)

This overpressure front will change stress conditions for the impacted fault systems, leading to their possible reactivation: for example, wastewater injection in Oklahoma were shown to induce earthquakes several kilometers away from the injection point because of the increase in pressure (Ellsworth 2013).

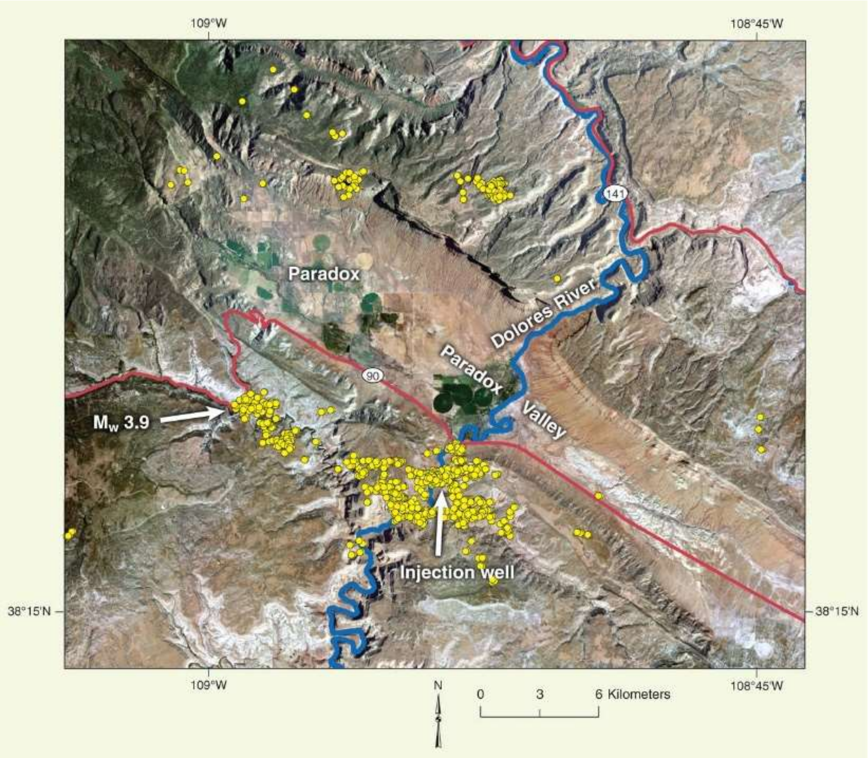


Figure 2 : Map of the induced earthquakes in Paradox Valley caused by the injection process. From Ellsworth (2013)

For unconventional oil operations, increasing pressure to stimulate fracture propagation or reactivation is the main goal; however, the operator seeks to avoid unintentional activation of fault systems leading to damaging earthquakes or fluid circulation beyond the expected zone.

Reactivated faults and their associated earthquakes generate a seismic hazard occurring in areas that may not have known significant earthquakes during the last decades and thus do not have paraseismic building norms; even in areas where seismicity is a known occurrence, the public perception of induced seismicity is very poor and can lead to an end of operations, as it occurred recently in France for a geothermal exploitation near Strasbourg (Dernières Nouvelles d'Alsace, 2020). Permeability in the reactivated fault may be increased and if the fault is located within the caprock or reservoir of a CO_2 storage site, CO_2 may escape through this path. This is also a potential problem for unconventional oil and gas extraction, where uncontrolled leakage at surface or subsurface should be avoided to reduce the possibility of environmental harm (Royal Society, 2012).

Stress changes cannot be measured directly, but reactivated faults can be detected through seismicity detection. Seismic monitoring is therefore an important tool for operators during CO2 injection or hydraulic fracturing and the initial period after site closure, in order to demonstrate the mechanical stability of the system and the absence of any leakage pathways.

1.3 OF THE IMPORTANCE OF BASELINES FOR SEISMIC MONITORING

1.3.1 Active seismic baseline: initial snapshot

4D seismic rely on the comparison of subsequent surveys to a initial state snapshot. This snapshot serves two purposes :

- Creating a 3D seismic image for characterization purposes, used by reservoir engineers to plan the future project
- Measuring the base seismic attributes of the different horizons, so that differences with subsequent surveys can be computed either by direct comparison with this initial image or by directly inverting difference measurements

In this light, an active seismic baseline for 4D seismics has to be well designed in order to cover the future areas of interest with a good precision, on top of the information brought for initial operations. Therefore it is expected that more time is invested, so that the initial survey covers more land and uses better equipment than normal 3D seismic surveys.

1.3.2 Passive seismic monitoring: what is the local stress state ?

Discriminating between natural and induced earthquakes is of critical importance to the operator to better understand how the target layers react to fluid injection. It is very difficult however to distinguish between natural and induced earthquakes using only signal analysis, as these events will mainly display a double couple behaviour.

It is therefore of utmost importance to measure the "background seismicity level", i.e. the seismicity generated by natural or unrelated anthropic causes. Measuring the background seismicity level allows the operator to identify the already active fault structures and its associated events, so that at later phases these events are not associated with induced seismicity; it may also provide data about the local and regional stress regimes that can be used in geomechanical models to greatly enhance their accuracy.

By design, background seismicity shall obviously be recorded before the injection operations to get unambiguous results. Recording time may vary with each site, but it should be at least several months long to be sure to catch meaningful events even within an active zone.

1.4 TEST CASES FOR ACTIVE AND PASSIVE SURVEYS ON CO_2 FIELDS

CO_2 storage sites can currently be divided into two categories : CO_2 onshore pilots, and oil fields using CO_2 for enhanced recovery operations.

CO_2 onshore pilots, used for R&D: these pilots are developed to test and deploy new technologies, and assess the feasibility and the environmental impacts of future onshore CO_2 storage. As such, they are operated with research goals in mind by public or private operators, which means that they are typically better equipped with monitoring systems. They are usually small in size, in order to get better monitoring conditions and to limit the costs for a research operation.

Several oil fields capture CO_2 emitted by production wells and use it for EOR operations, with several advantages:

- CO_2 has beneficial properties for extraction operations, as it reduces oil viscosity

- Capturing and re-using CO_2 instead of using another fluid allows for long-term cost reductions

CO_2 onshore pilots are built to host a wide range of geophysical and geochemical surveys far beyond what is done on operational sites, and are therefore not representative of future CO_2 commercial storage projects where cost efficiency should be higher; however, these pilots have reviewed a wide range of settings and therefore bring very useful insights into monitoring methods, especially for detecting small patches that can emulate a leak. EOR fields however, are closer in size and operational needs to future commercial sites, and thus can provide useful feedback to upscale operations.

2 CO_2 injection pilots

2.1 SLEIPNER REINJECTION SITE

2.1.1 Description of the site

Feature	**Comment**	
Location	North Sea, Norway	
Funding/Operator	Equinor	
CO_2 Source	Offshore natural gas processing platform	
Geologic Setting	North Sea	
Reservoir	Utsira Sand, 800-1000 meters deep	
Caprock	Nordland Group Shales	
Total CO_2 Storage	~17,000,000 tonnes (1996-2018)	
Major Risks	CO_2 migration seabed leakage caprock leakage	
Geophysical Monitoring Methods	**Comments**	Years
4D Seismic	11 surveys (including baseline)	1994,1999,2001,2002,2004,2006,2008,2010, 2012,2015,2019
Gravimetric surveys	4 surveys	2002,2005,2009,2013
Controlled Source EM survey	1 survey	2008
Seabed imaging surveys	4	2006,2011,2012,2013

The Sleipner CO_2 storage site is the first and longest running commercial-scale offshore storage facility in the world. The CO_2 separated from the produced natural gas in the Sleipner West field located in the North Sea is being stored at about 1000 m depth below sea level into a relatively thick reservoir unit, the Utsira formation, with an approximate injection rate of 0.85 Mtpa. To monitor the CO_2 plume development in the reservoir and the caprock integrity, a geophysical monitoring program including seismic, gravimetric, and electromagnetic measurements has been conducted. Several time-lapse (4D) seismic surveys have been acquired at regular intervals since the original pre-injection survey of 1994. The extensive monitoring program offers an opportunity to evaluate strategies for monitoring the CO_2 migration and early detection of eventual leakages through the overburden.

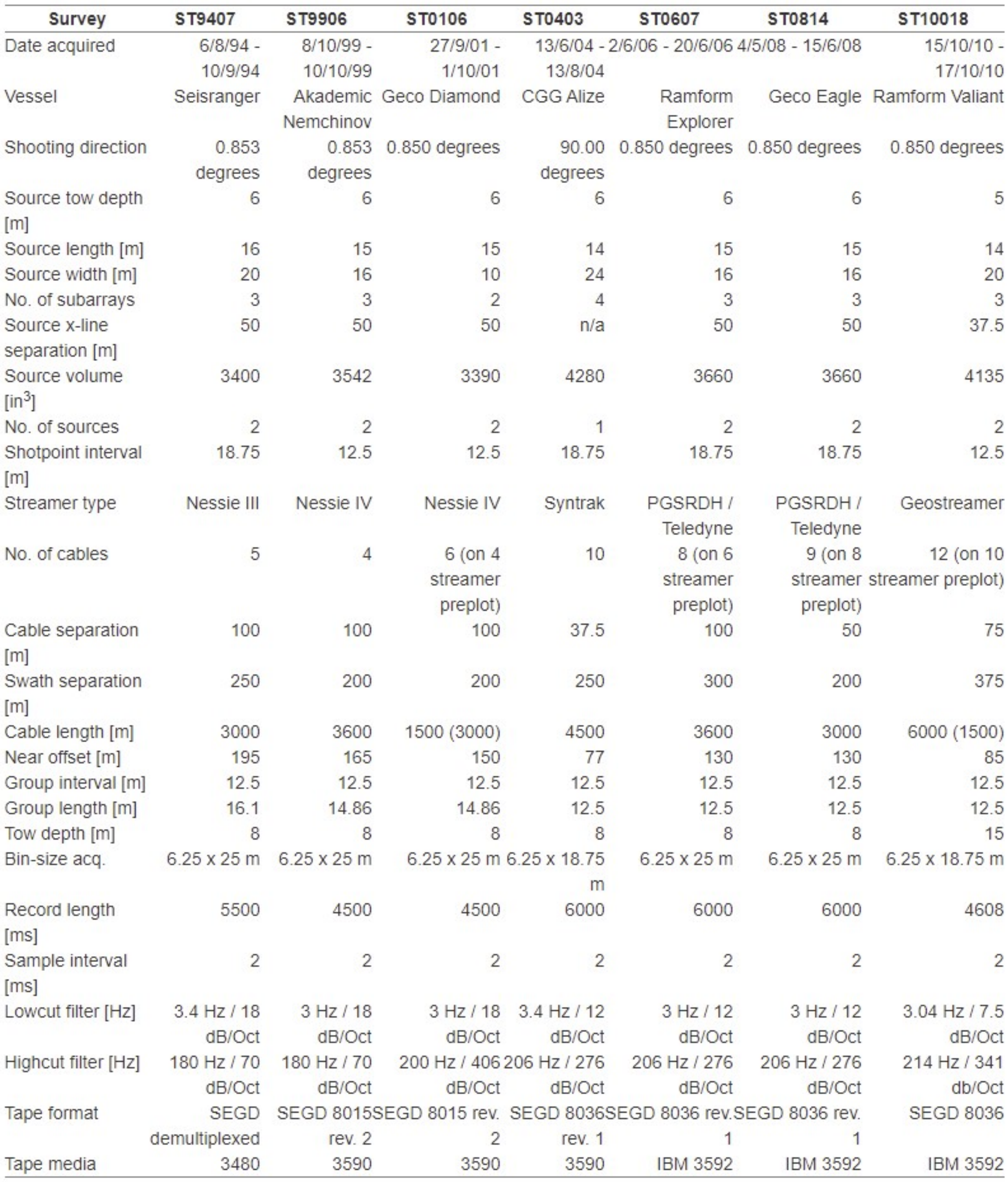
A more complete description can be found in Arts et al (2004)

2.1.2 Marine seismic surveys

2.1.2.1 DESCRIPTION OF THE SURVEYS

As soon as 1994, a baseline was established, followed by several surveys. These campaigns are summarized in the following table (Table 1):

Table 1 : survey acquisition parameters for the released seismic data (up to 2010)



Survey	ST9407	ST9906	ST0106	ST0403	ST0607	ST0814	ST10018
Date acquired	6/8/94 - 10/9/94	8/10/99 - 10/10/99	27/9/01 - 1/10/01	13/6/04 - 13/8/04	2/6/06 - 20/6/06	4/5/08 - 15/6/08	15/10/10 - 17/10/10
Vessel	Seisranger	Akademic Nemchinov	Geco Diamond	CGG Alize	Ramform Explorer	Geco Eagle	Ramform Valiant
Shooting direction	0.853 degrees	0.853 degrees	0.850 degrees	90.00 degrees	0.850 degrees	0.850 degrees	0.850 degrees
Source tow depth [m]	6	6	6	6	6	6	5
Source length [m]	16	15	15	14	15	15	14
Source width [m]	20	16	10	24	16	16	20
No. of subarrays	3	3	2	4	3	3	3
Source x-line separation [m]	50	50	50	n/a	50	50	37.5
Source volume [in^3]	3400	3542	3390	4280	3660	3660	4135
No. of sources	2	2	2	1	2	2	2
Shotpoint interval [m]	18.75	12.5	12.5	18.75	18.75	18.75	12.5
Streamer type	Nessie III	Nessie IV	Nessie IV	Syntrak	PGSRDH / Teledyne	PGSRDH / Teledyne	Geostreamer
No. of cables	5	4	6 (on 4 streamer preplot)	10	8 (on 6 streamer preplot)	9 (on 8 streamer preplot)	12 (on 10 streamer preplot)
Cable separation [m]	100	100	100	37.5	100	50	75
Swath separation [m]	250	200	200	250	300	200	375
Cable length [m]	3000	3600	1500 (3000)	4500	3600	3000	6000 (1500)
Near offset [m]	195	165	150	77	130	130	85
Group interval [m]	12.5	12.5	12.5	12.5	12.5	12.5	12.5
Group length [m]	16.1	14.86	14.86	12.5	12.5	12.5	12.5
Tow depth [m]	8	8	8	8	8	8	15
Bin-size acq.	6.25 x 25 m	6.25 x 25 m	6.25 x 25 m	6.25 x 18.75 m	6.25 x 25 m	6.25 x 25 m	6.25 x 18.75 m
Record length [ms]	5500	4500	4500	6000	6000	6000	4608
Sample interval [ms]	2	2	2	2	2	2	2
Lowcut filter [Hz]	3.4 Hz / 18 dB/Oct	3 Hz / 18 dB/Oct	3 Hz / 18 dB/Oct	3.4 Hz / 12 dB/Oct	3 Hz / 12 dB/Oct	3 Hz / 12 dB/Oct	3.04 Hz / 7.5 dB/Oct
Highcut filter [Hz]	180 Hz / 70 dB/Oct	180 Hz / 70 dB/Oct	200 Hz / 406 dB/Oct	206 Hz / 276 dB/Oct	206 Hz / 276 dB/Oct	206 Hz / 276 dB/Oct	214 Hz / 341 db/Oct
Tape format	SEGD demultiplexed	SEGD 8015 rev. 2	SEGD 8015 rev. 2	SEGD 8036 rev. 1	SEGD 8036 rev. 1	SEGD 8036 rev. 1	SEGD 8036
Tape media	3480	3590	3590	3590	IBM 3592	IBM 3592	IBM 3592

The figure below (Figure 3) shows the area covered by the 4D seismic survey together with the location of the nearby available wells.

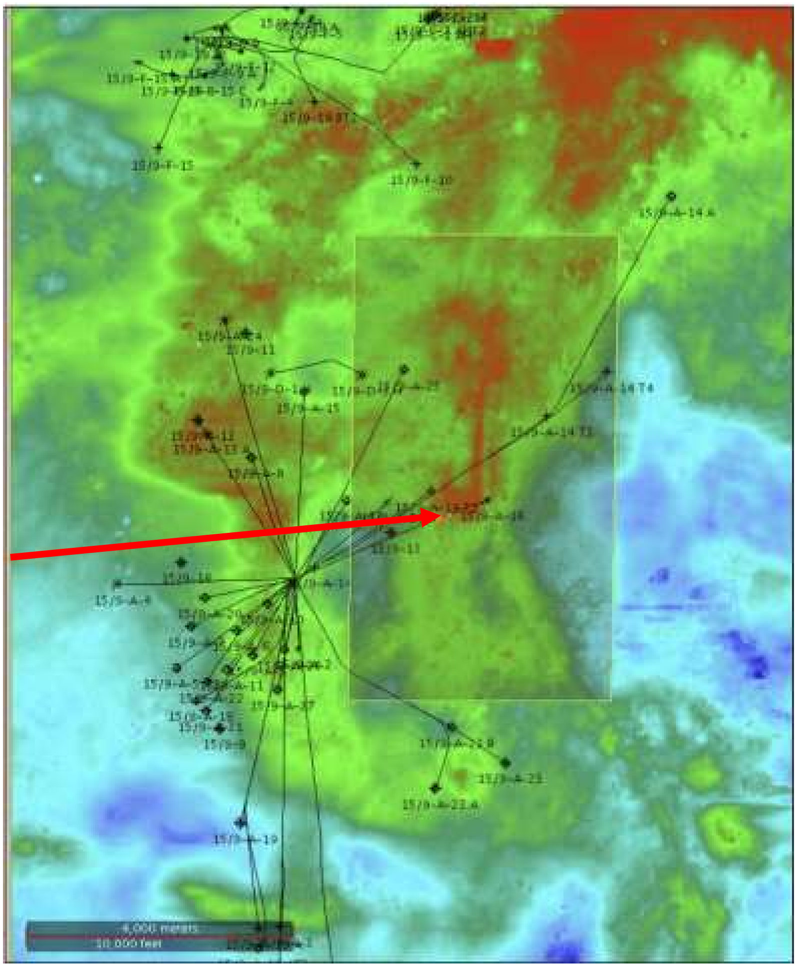


Figure 3: Area covered by 4D seismic data (yellow rectangle) and available wells. The background corresponds to the top Utsira TWT. The location of the injection well is depicted with the red arrow. (source: https://co2datashare.org)

2.1.2.2 MAIN RESULTS

In multi-channel seismic data from Sleipner, the variation in seismic reflection characteristics due to CO_2 accumulations are strong and easily identified on seismic images (Arts et al., 2004). However, it has been shown that the interpretation is not straightforward due to tuning effects related to thin-layer interferences (Brown et al., 2007, Ravazzoli and Gomez, 2014). Ghaderi and Landrø (2009) developed an analytical technique for simultaneous inversion of thickness and velocity of a brine-CO_2 partially saturated thin layer based on measured travel-time shifts and 4D amplitude changes. Buddensiek et al., (2010) applied an advanced AVO methodology to analyze the top-most reflection from the series of thin-layer reflections at Sleipner. Ghosh et al., (2015) estimated CO_2 saturation from post-stack seismic impedance considering dual porosity and a pressure-dependent differential effective medium model.

One of the most important challenges at Sleipner is the proper understanding of the saturation development during CO_2 injection. The effective seismic velocity of the brine-CO_2 mixture is uncertain and depends on the saturation distribution. The reservoir unit is located at 800-1100 m depth below sea level (the water depth is around 82 m), with pressure and temperature conditions very close to the supercritical point for the supercritical CO_2 phase. Small changes in temperature and pressure conditions can therefore result in significant CO_2 property changes, which lead to large velocity and density changes. In addition, geological characterization of the sandy Utsira formation shows the presence of thin mudstone beds, with thicknesses ranging from less than 1 m up to 3 m (Zweigel et al., 2004). These thin layers are partially preventing the CO_2 from rising (due to buoyancy effects) towards the thick mudstone caprock above the reservoir. Analysis of velocity contrasts between these thin mudstone layers and CO_2-bearing sand layers suggests the presence of complex effects including thin bed tuning, apparent seismic attenuation, and inter-bed multiples. Such detailed sub-seismic geological features can strongly affect the in-situ CO_2 distribution. Several attempts at seismic inversion have also been made with the aim of providing a more quantitative interpretation from seismic velocities or induced time shifts. Stratigraphic inversion (Clochard et al., 2010; Delépine et al., 2011) showed layers of low acoustic impedance. It is not clear how this compares to layer thicknesses found from amplitude inversion by the thin-layer tuning assumption. The inverted layers are possibly thicker and with less velocity reduction. Jullum and Kolbjørnsen (2016) developed a framework for Bayesian inversion, inverted a 2D line for saturation, and found the same five CO_2 layers as could be seen in qualitative interpretation of the seismic data. Queisser and Singh (2013a, 2013b) tested full waveform inversion (FWI) on a 2D line and related the velocity changes to CO_2 saturation using a rock physics model. They found that applying FWI to real seismic data was challenging. Possibly they could identify places where the CO_2 saturation had reached maximum. Raknes et al. (2015) carried through a 3D elastic FWI study. Ghosh et al. (2015) inverted poststack data for saturation, and found large uncertainties attached to the rock physics modelling. Romdhane and Querendez (2014) inverted, and then prestack depth migrated, a 2D test line using FWI and Dupuy et al. (2017) used the result of FWI and rock physics models to estimate saturation of the CO_2 bearing layers and Eliasson and Romdhane (2017) investigated of the value of combining CSEM inversion and FWI.

More generally, the containment monitoring of CO_2 at Sleipner has been demonstrated by the seismic surveys. Both seismic and gravimetric monitoring have been important for the verification of conformance. An important spin-off from the project has been the wealth of knowledge that has evolved through monitoring, and which has been shared with the scientific community over more than twenty years of operation. Statoil and the Sleipner Licence partners have released all the seismic, gravity, and CSEM data acquired up to and including 2010. The seismic time lapse imaging has been successful. It provided crucial insights to both researchers and storage operators about the physics of the storage process. An extensive summary of the results and lessons from the CO_2 monitoring at Sleipner is available in Furre et al., 2017 and in Eiken, 2019

Monitoring and modelling data from the Sleipner CO_2 project have been widely shared for a wide range of applications including improving reservoir characterization, constraining flow modelling, and developing new techniques for seismic inversion, seismic spectral decomposition, and joint inversion. The seismic data is a part of a Sleipner benchmark model openly available at the CO_2 Datashare portal (https://co2datashare.org).

2.2 SNOHVIT REINJECTION SITE

2.2.1 Description of the site

Feature	**Comment**
Location	Barents Sea, Norway
Funding/Operator	Equinor (operator), Petoro, Total, Neptune Energy, Wintershall Dea
CO_2 Source	LNG plant Melkøya
Geologic Setting	Hammerfest basin
Reservoir	Tubåen Fm (2600m) until 2011, then Stø Fm (2400m)
Caprock	Upper Jurassic and thick Cretaceous shales
Total CO_2 Storage	0.77 Mt/yr, 2.3 Mt at 2014 (planned 23 Mt)
Major Risks	Injectivity, pressure conformance
Geophysical Monitoring Methods	**Comments**/Years
3D surface seismic	1 baseline (2003), 3 monitors (2009, 2011, 2012)
P-cable 3D seismic	2011, 2013
Seabed gravity	2007, 2011

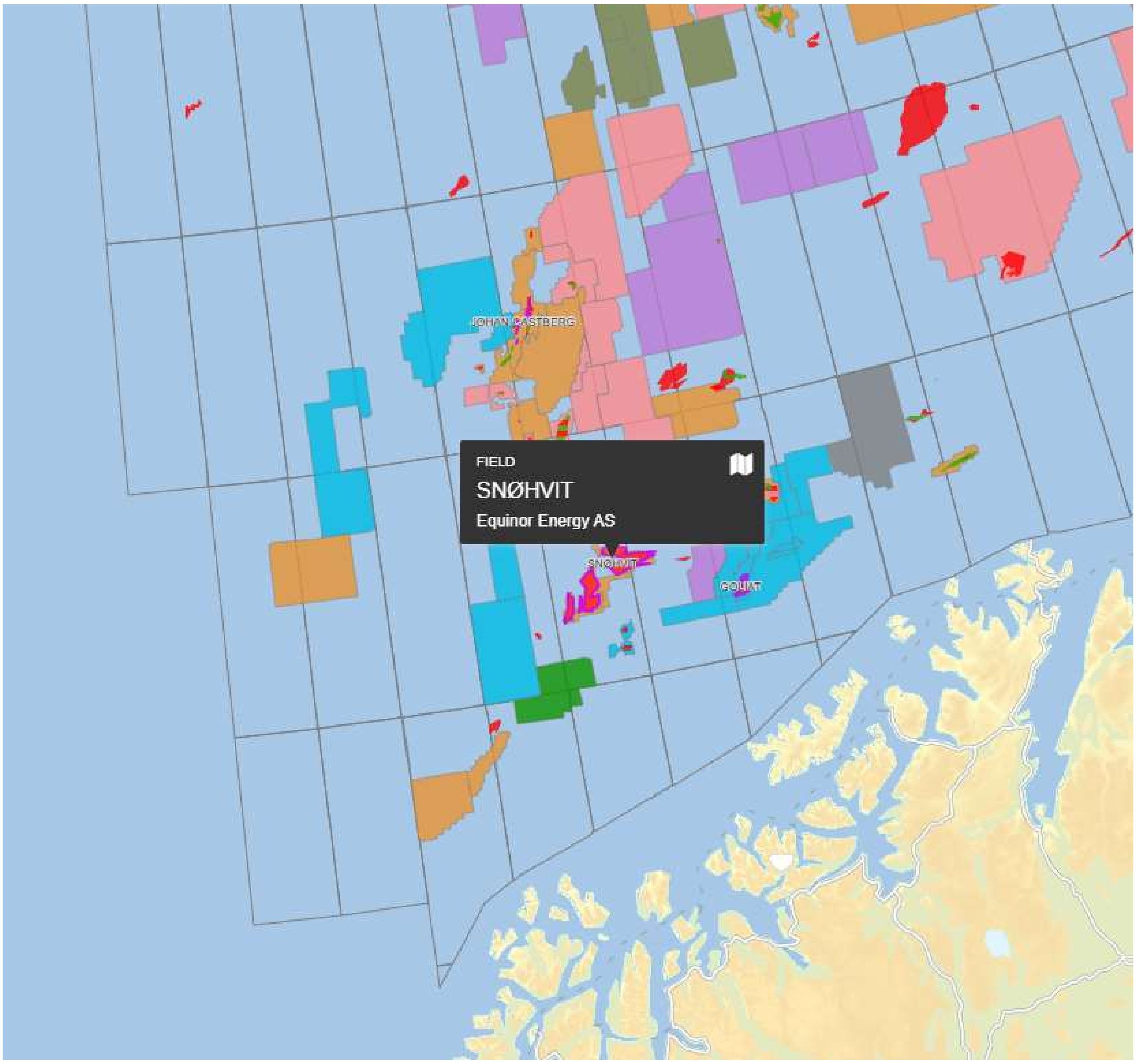


Figure 4 : Location of Snøhvit field in Barent Sea (from NPD)

Snøhvit is a CO_2 storage site in the Barents Sea, offshore Norway. CO_2 is captured in an LNG plant on the island of Melkoya near Hammerfest, northern Norway. The CO_2 comes from extracted natural gas which contains ~6% carbon dioxide. A processing facility onshore separates the CO_2 before it is returned to infrastructure on the seabed for injection (Hansen et al., 2013). Gas production has started in 2007 and CO_2 capture, using amine technology, started in 2008.

Around 0.77 million tonnes per year of CO_2 have been injected and stored in the Tubåen sandstone (2600 metres beneath the seabed and about 45-75 metres thick) between 2008 and 2011. The Tubåen Formation is a heterogeneous fluvial-deltaic to tidal sandstone unit of around 100 m thickness. 1.1 to 1.6Mt were injected before injection was stopped. The injection was stopped due to an unforeseen pressure build-up in the reservoir observed by injection well pressure gauges and anomalous seismic signature. Hansen et al., (2011) shows that measurable seismic time-shifts due to pore pressure change are observed on the 4D seismic data. The pressure changes are estimated to be equal to 6 MPa. Overlying Tubåen formation, the Stø reservoir (2450m deep) is a shallow-water marine sandstone typically 85 m thick. The phase 2 of the CO_2 injection is targeting Stø reservoir, using the same injection well.

A more complete description of the site can be found in Hansen et al. (2013)

2.2.2 Active seismic acquisition

Seismic data was initially acquired over the injection site in 2003, prior to any injection of CO_2. Additional repeat surveys were undertaken in 2009, 2011 and 2012 (see Table 1). The data are of high quality and enable the structure of the storage complex to be imaged where acoustic impedance contrasts allow. Alongside the downhole pressure and temperature data this forms the monitoring data suite for the Snøhvit CO_2 storage site. In addition, two P-cable surveys were acquired in 2011 and 2013 (Bunz et al., 2011, 2013). The cross cable had a total length of 233m with 14 streamers. Each streamer was 25m long with 8 channels and spacing of 3.125m.

Regarding the injection in the Tubåen formation, Grude et al. (2014) suggested relative P-wave velocity changes (decrease) of 2.8 % due to saturation, 2.2 % due to pore pressure (decrease), and 3.3 % due to porosity change (increase). This porosity change is due to salt precipitation and is most likely localised near the well bore. Consequently, the time-shifts derived from seismic time-lapse data analysis are not straightforward to interpret. Hansen et al. (2011) suggest also to consider the effect of cooling of the rock formation on the seismic signature.

In addition to 3D seismic and P-cable surveys, the monitoring system at Snøhvit consists of downhole pressure and temperature measurements, seabed and water column imaging, geochemical water column sampling and sediment sampling.

Year of survey	Extent of survey	Mass injected into Tubåen Fm. (mT)	Mass injected into Stø Fm. (mT)	Comments
2003	8.25 x 9.63 km	0	0	Baseline survey for Tubåen injection phase.
2009	7.71 x 9.63 km	0.5	0	First repeat survey for Tubåen injection phase. Baseline survey for Stø injection phase.
2011	3.15 x 8.75 km	1.05	0.13	Significantly smaller spatial extent than other surveys.
2012	8.25 x 10.2 km	1.05	0.55	Final survey available to this study.

Table 1: seismic surveys details at Snøhvit (from IEAGHG (2015) report)

2.3 QUEST REINJECTION SITE

2.3.1 Description of the site

Quest is a commercial CCS project associated with tar sands in Canada. An extended description of the project can be found in Rock et al (2017), presenting the first year post the start of injection.

Feature	**Comment**
Location	Alberta, Canada
Funding/Operator	Shell
CO_2 Source	Oil sand refining upgrader
Geologic Setting	Williston Sedimentary Basin
Reservoir	Utsira Sand, 800-1000 meters deep

Caprock	Basal Cambrian Sands, 2000 m deep
Total CO_2 Storage	~4,000,000 tonnes (2015-2019)
Major Risks	Well integrity, injectivity, public acceptance
Geophysical Monitoring Methods	**Comments**/Years
Time-lapse walkaway VSP	8 baseline walkaway surveys (2015), 3 monitor 2D borehole VSP acquisitions by 2019
2D surface seismic	2 monitor (2017,2019)
3D surface seismic	1 baseline (2010), monitors as needed
INSAR	1 baseline, monitor as needed
Downhole-microseismic	1 baseline, monitor during injection

2.3.2 Main results

The Measuring, Monitoring and Verification (MMV) plan includes a tiered system to review and assess the MMV data. Tier 1 technologies form the basis for assessing whether there is an indication of loss of containment. Depending on the outcome of that assessment, further analysis or investigation of the Tier 2 technologies will be undertaken and then, if needed, Tier 3 technologies will be assessed. No trigger events were identified during 2019 that would indicate a loss of containment according to the latest Quest report (Shell, 2020). As a result, the monitoring strategy is limited to Tier 1 technologies, corresponding to downhole pressure, temperature, and micro-seismic monitoring. With the data collected up to 2019, the operator reported that CO_2 injection is conforming to model predictions. Based on the analysis of the existing time-lapse seismic monitoring, the size of the CO_2 plume, as measured by the monitor VSPs is much smaller than the maximum plume lengths predicted by modelling. This is another indication that the reservoir is behaving better than expected, and that the displacement of brine by the CO_2 may be more effective compared to the expected one from pre-injection modelling.

2.4 DECATUR CO_2 STORAGE DEMONSTRATOR

2.4.1 Description of the site

Feature	**Comment**
Location	Illinois, USA
Funding/Operator	MGSC (DOE), ISGS, ADM and Schlumberger carbon services
CO_2 Source	Ethanol (corn processing) plant ADM
Geologic Setting	Illinois basin
Reservoir	Mt Simon sandstone (2.1km deep, 550m thick)
Caprock	Eau Claire shale (1.5km deep, 100-150m thick)
Total CO_2 Storage	1Mt (2011-2014) + 2000t/day from 2015
Major Risks	Microseismic activity in basement
Geophysical Monitoring Methods	**Comments**/Years
3D seismic VSP	2 baseline, 4 monitors
Microseismic monitoring	Continuous

2D seismic reflection lines	2 in 2007, 4 in 2009
3D surface seismic	2010, 2011, 2015

The Illinois Basin – Decatur Project (IBDP) CCS demonstration site is the first (and to date only) CCS project in the USA employing high volume CO_2 injection into a regionally extensive, undisturbed saline formation. The formation targeted for injection is the Mt. Simon Sandstone, a regionally extensive formation with high porosity and permeability.

At Decatur, super-critical CO_2 is injected at 2.1 km depth into the 550-m-thick Mt. Simon Sandstone, which directly overlies Precambrian granitic basement. The primary sealing cap rock is the Eau Claire Shale, a 100- to 150-m-thick unit at a depth of roughly 1.5 km. The Illinois State Geological Survey (ISGS) started with a three-year project in November 2011, during which carbon dioxide was injected at a rate of 1000 metric tons/day. A second phase for Decatur injection is on-going.

Decatur project description is available in Gollakota et McDonald (2014)

2.4.2 Active seismic acquisition

Two baseline and four monitor 3D VSP surveys have been acquired for the project. The three monitor surveys were acquired after approximately 74,000, 433,000, and 730,000 tonnes of CO_2 had been injected. In addition, the seismic data includes 6 baseline 2D seismic reflection lines across the site and three different 3D seismic data volumes acquired in 2010, 2011 and 2015.

The VSP array also served a secondary purpose of supporting microseismic monitoring. A 2-level array of 4-component geophones in tetrahedral configuration was installed in the injection well, CCS1. The adjacent GM1 well hosts a 31-level array of 3 component geophones in orthogonal configuration. In addition, data collected from a 5-level array of 3-component geophones that were temporarily installed in VW2 was included in the final data compilation (all details published in Bauer et al., 2016).

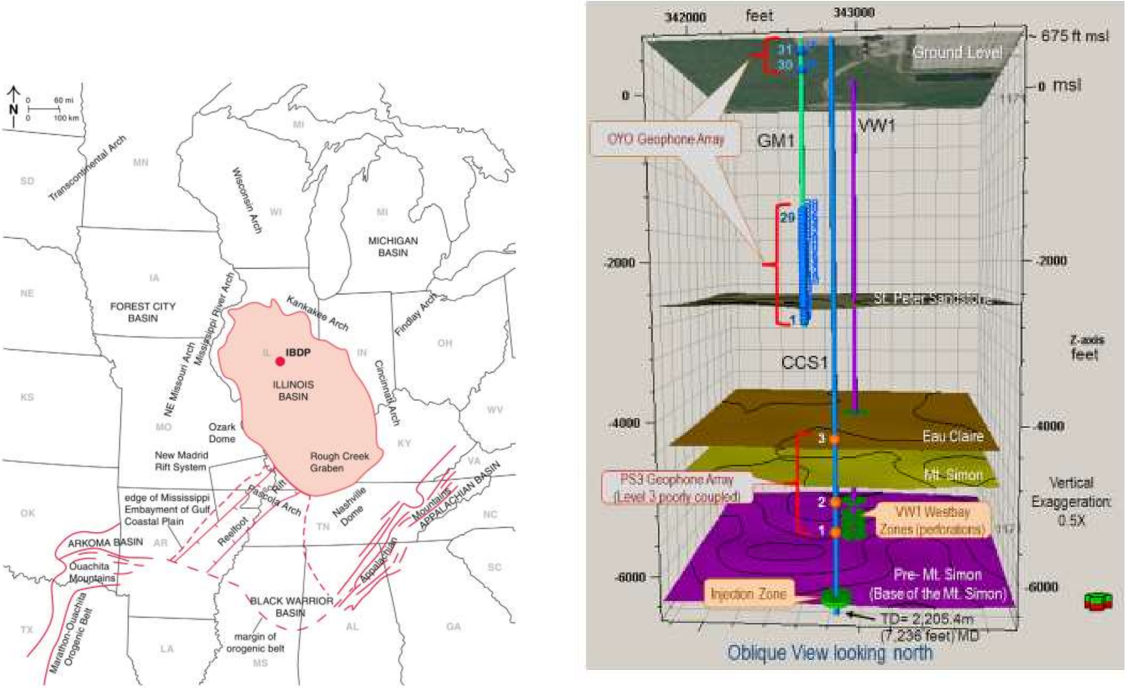


Figure 5: Location of Decatur site and diagram of injection and monitoring wells (from Bauer et al., 2016)

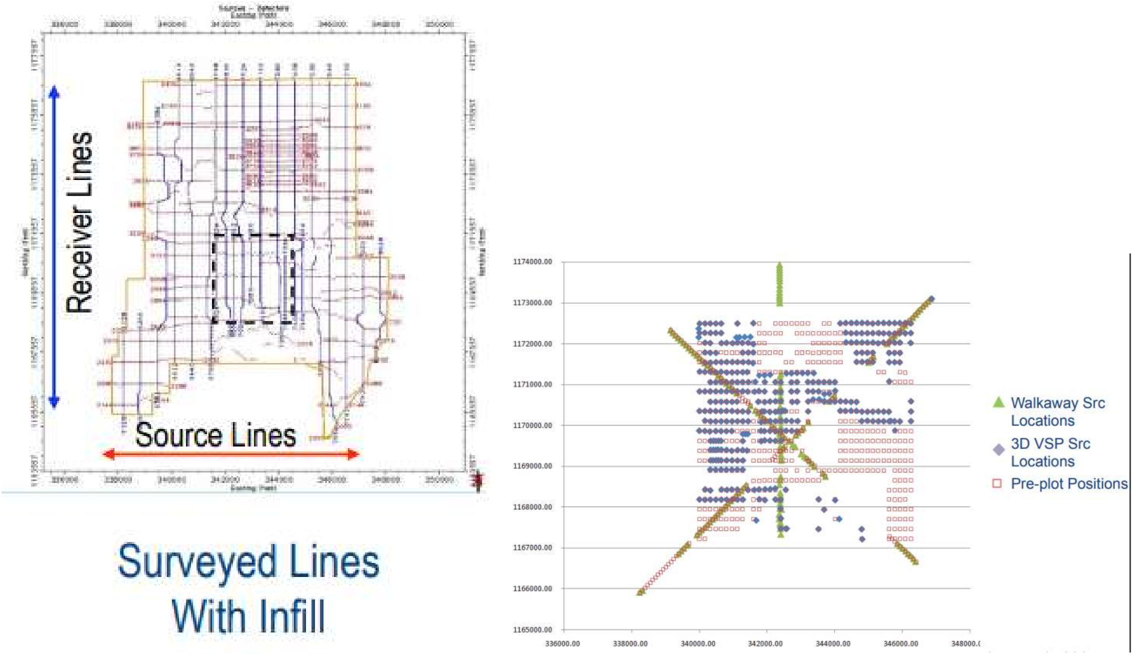


Figure 6 : surface seismic layout and VSP acquisition footprint (from Coueslan et al, 2014)

2.4.3 Passive seismic acquisition

The U.S. Geological Survey (USGS) installed a 12-station seismic network at Decatur starting in July 2013, including three borehole sensors. Of the 12 stations in the network, nine are equipped with both a three-component broadband seismometer (Trillium Compact) and a three-component force-balance accelerometer (Episensors). Three of the surface stations retain the accelerometers at the surface but have three-component, high-sensitivity geophones installed in ~150-m-deep wells (Oyo Geospace). The stations consisting of borehole and surface sensors record at 500 samples/sec, whereas the remaining sensors record at 200 samples/sec. The network has an aperture of roughly 8km centred on the CO_2 injection well CCS#1, with the three stations that include borehole sensors nearest to the injection well.

The Decatur Project partners employ two downhole seismometer strings, one with 24 currently operating three-component sensors and another with sensors in the Mt. Simon and the Eau Clair Shale, which have been running since May 2011.

IBDP began recording baseline microseismic data using the geophone arrays in CCS1 and GM1 in May 2010; eighteen months of baseline microseismic data were recorded prior to the start of CO_2 injection. During this time, 7,894 microseismic events were detected most of which were associated with VW1 drilling activity. Currently, the microseismicity at IBDP is monitored with a combination of the three geophone arrays located in CCS1, VW1, and VW2.

2.5 KETZIN STORAGE PILOT, GERMANY

2.5.1 Description of the site

This site is operated by GFZ as a pilot storage laboratory for scientific studies, undertaken with European funding from CO_2SINK, CO_2CARE and other projects. The site is in the vicinity of Potsdam, under a former gas storage site. The reservoir level is 700 m deep in a saline aquifer lying in the upper Triassic Stuttgart formation. More than 60,000 tons of CO_2 were successfully injected in this formation, and the site is currently in the post-closure period with several studies undertaken on the CO_2 bubble behaviour and long-term stability.

As a research site, several surveys were done using a wide array of seismic methods.

2.5.2 GFZ active seismic survey

2.5.2.1 PARAMETERS OF THE ACQUISITION

An active survey was done under GFZ supervision (Juhlin et al. 2007). The baseline covered a 4x6 km area, divided into a 5x9 swath grid. In each swath grid the same base pattern of sources and receivers were used. The template acquisition parameters were given by Juhlin et al. summarised in

Table 2 :

Table 2 : parameters for the active seismic acquisitions done at Ketzin. From Juhlin et al. (2009)

Parameter	Value
Receiver line spacing/number	96 m/5
Receiver station spacing/channels	24 m/48
Source line spacing/number	48 m/12
Source point spacing	24 m or 72 m
CDP bin size	12 m X 12 m
Nominal fold	25
Geophones	28 Hz single
Sampling rate	1 ms
Record length	3 s
Source	240 kg accelerated weight drop, 8–9 hits per source point
Instrument	SERCEL 408UL

The whole acquisition took 3 months, with a small field crew and few number of active channels compared to large-scale operations.

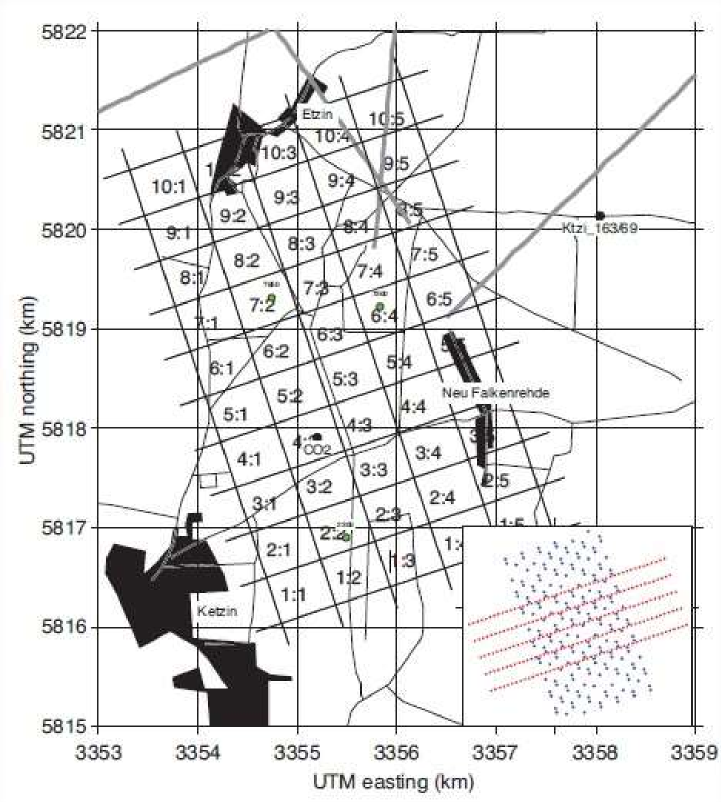


Figure 7 : map of the setup of the baseline active seismic survey in Ketzin, Germany. Inset shows a typical template, with receivers in blue and shot locations in red. From Juhlin et al (2007)

2.5.2.2 RESULTS OF THE SURVEY

Data processing is detailed by Juhlin et al. (2007). This setup was able to image the formations up to 1000 m below the surface, where fault systems with throws up to 30 m are clearly identified. The effectiveness of the baseline is illustrated (Figure 8) by the results of the two repeats shown in Lüth et al (2015).

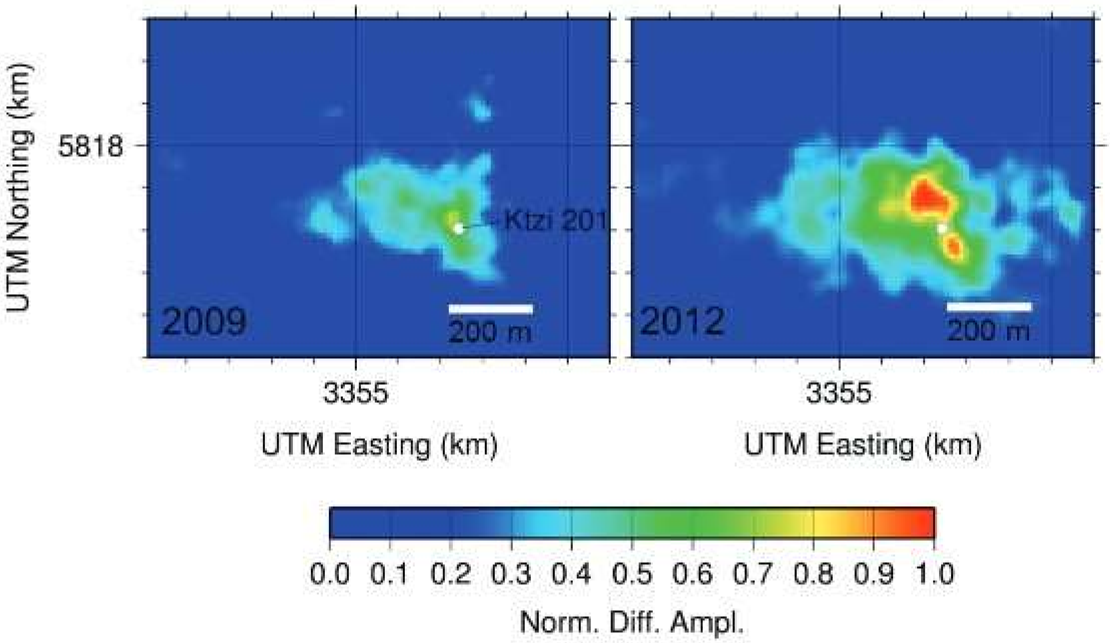


Figure 8 : maps of normalized seismic difference amplitudes at the top of the reservoir from the first repeat of 2009 (left) and the second repeat of 2012 (right). The injection well is indicated by a white dot. From Lüth et al (2015)

It is possible to get significant changes in amplitude and therefore map the location of the CO_2. However, the quantity of CO_2 cannot be determined by these images alone.

This task was reported by Ivanova et al. (2012). In a further repeat during 2012 after 50,000 tons were injected, they used the normalized RMS error from the baseline to map CO_2 coupled with petrophysical investigations This survey was able to estimate the injected CO_2 mass using only geophysical and petrophysical datas, and therefore results from this survey and injection history were compared : seismic estimates fall within 10% of the injection history data, although with several uncertainties. Spatial mass distribution of CO_2 was estimated using different CO_2 saturation scenarios, and gave the following result:

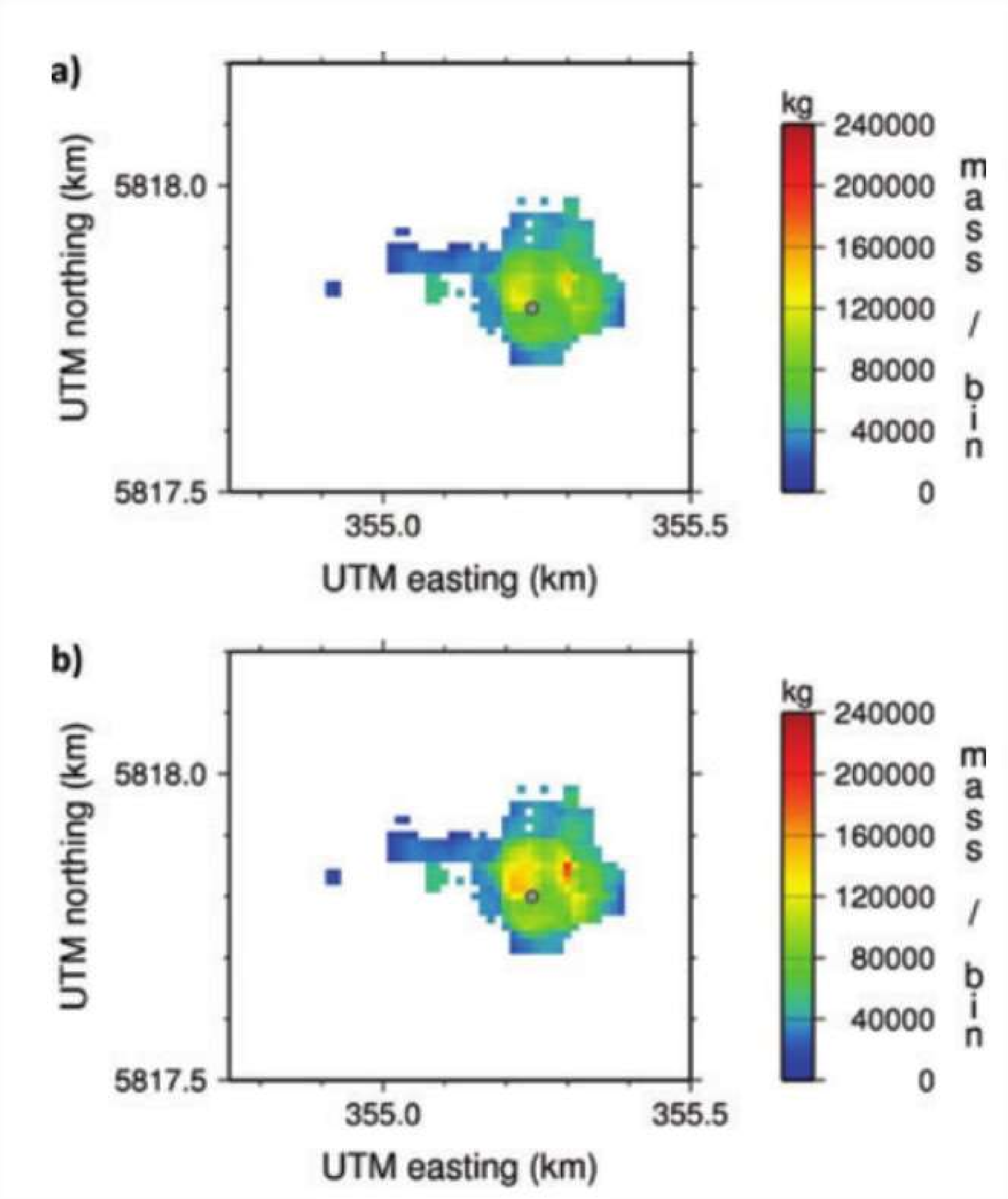


Figure 9 : CO_2 maps for minimum (a) and maximum (b) CO_2 saturation scenarios calculated for every CDP bin where the amplitude difference value is greater than 0.5. From Ivanova et al. (2012)

Different saturation scenarios yield the same result, as the spatial distribution is constrained by the 4D seismic results. Ketzin test case shows that 4D onshore seismic data with a good baseline are able to show the spatial relative distribution of gaseous CO_2.

Due to the shallow depth of the reservoir, CO_2 is not in supercritical state but in gaseous state; Ketzin test case should not be used to assess the effectiveness of 4D seismics for future supercritical CO_2 storage. However, the Ketzin test case can illustrate the 4D seismic detection capacities for gaseous CO_2 leaks. As shown by the figure above, depending on the saturation scenarios 4D onshore seismic is able to detect a perturbation generated by 40 to 100 tons of gaseous CO_2 at approximatively 700 m depth. This estimate gives a first idea for future operations aiming at detecting and mitigating leaks.

2.5.3 Surface passive seismic monitoring network

2.5.3.1 NETWORK SETUP

Leipzig University and GFZ deployed a network composed of 5 broadband stations in 2008. In 2011, BRGM installed 5 more stations. The network operated until 2012 and the results associated with this network can be found in Gassenmeier et al. (2014). Stations were set up either in building basements or in field shelters, with solar panel power supply. The main purpose of this network was to assess the sensitivity of coda wave interferometry towards CO_2 injection.

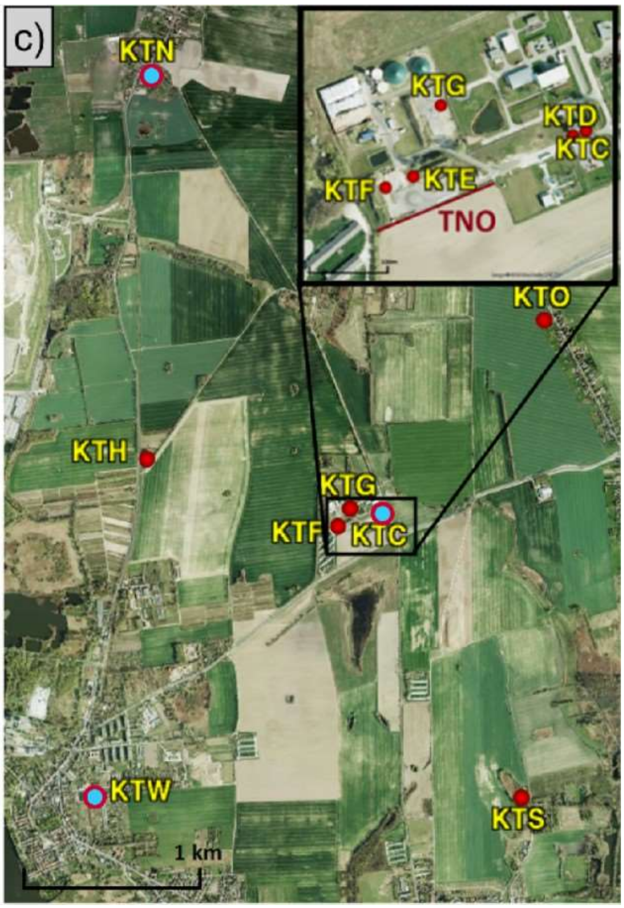


Figure 10 : setup of the surface seismic network at Ketzin. In blue: stations deployed by Uni. Leipzig, in red: stations deployed by BRGM from GFZ instrument pool. Red line represents the deployment of the TNO geophone/hydrophone line. From Gassenmeier et al. (2014)

2.5.3.2 MAINS RESULTS

The network was installed after injection commenced, it is therefore not possible to assess the initial stress regime, although regional networks don't show fault activity in the area. No local event was detected during injection.

Periodograms of the raw data show a seasonal periodicity, with more activity recorded during winter. Using beamforming methods, the noise origin was located to windfarms NE of the injection site. Weekly noise amplitude periodicity was also observed, linked to road traffic activity in this rural suburbs area.

Noise correlations were analysed, and temporal variations of noise correlation coda were studied. The following relative temporal variation was observed:

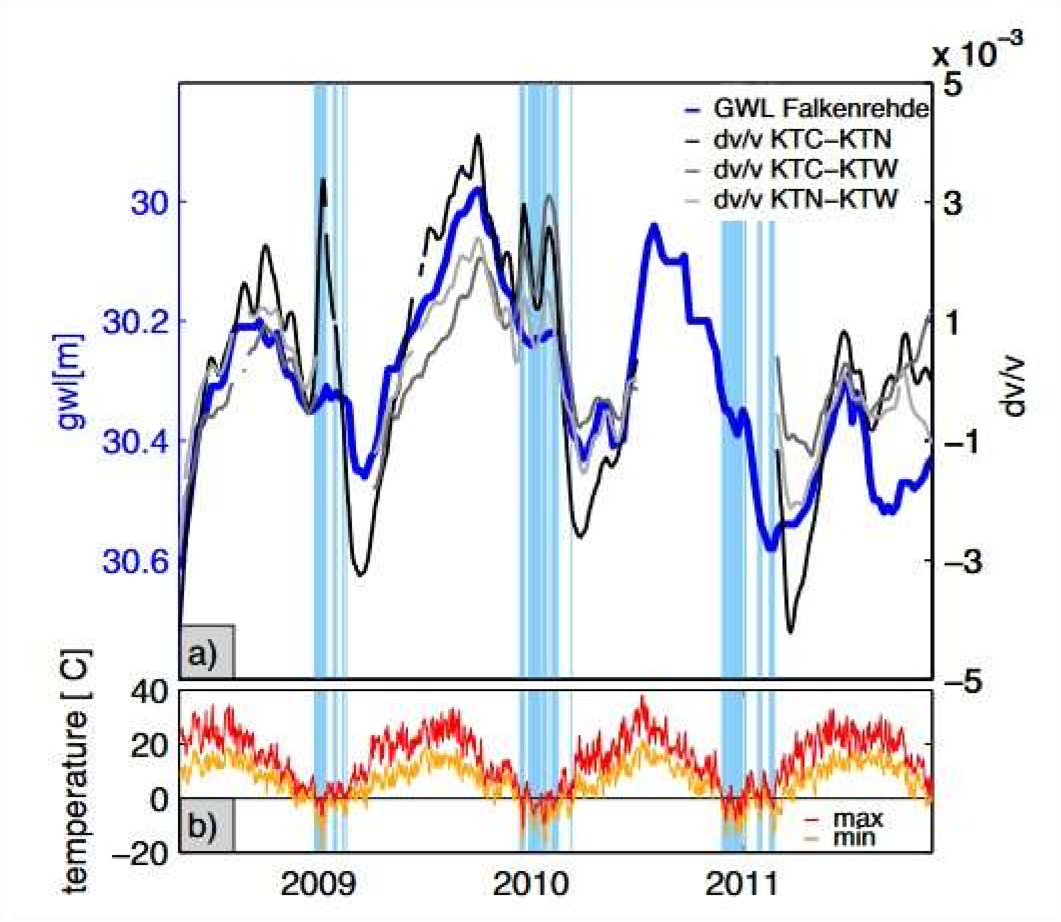


Figure 11 : Comparison of velocity change to groundwater level (GWL).(a) Mean velocity variations (grey) compared with GWL in Falkenrehde(blue), (GWL is in m above sea level, note the reversed axis orientation), (b)minimum and maximum (orange/red) temperature per day, times where the maximum temperature is below 0◦C are highlighted in light blue.

This study shows that subsurface variations such as water table changes and freezing soils generate relative coda wave changes up to 5e^{-3}, larger than the expected variations due to CO_2 injection in Ketzin. Using noise correlation as a monitoring tool does not therefore yield the expected results without more advances in research in this field.

2.5.4 Example of dual purpose survey: buried permanent seismic array

2.5.4.1 NETWORK SETUP

TNO designed and implemented a permanently installed seismic monitoring system for both passive and active seismic acquisition (Arts et al. 2011). It consists of 4C-receivers (instruments containing 1 3 component geophone and a hydrophone) placed at 13 locations at a depth of 50 m ; on 7 of these locations an additional 3C geophone was installed at a shallow depth (a few meters). This network recorded continuously for several years with a 2 ms sampling rate, generating huge amounts of data ranging in Terabytes that were processed in real time on site.

2.5.4.2 MAIN RESULTS

This network was used for three main purposes:

- Over 20,000 seismic events were detected and located; the 200 strongest events were analysed in more detail. Ninety-nine percent of the events were linked to surface activity, no event was linked to the CO_2 injection.
- A permanent vibrating source operating one hour a day was installed from May 4th to May 29th 2012 in order to do repeatable 4D seismic acquisitions. Unfortunately spurious arrivals due to the position

of the source relative to the receivers (this position was constrained by the ongoing operations on site) masked the reservoir level.

- A standard reflection seismic acquisition was done and compared to the 2006 baseline. More high frequency content was present and therefore provided more information on the shallow strata, however the deepest strata were not visible due to a high S conversion not visible by hydrophones. The comparison can be seen below :

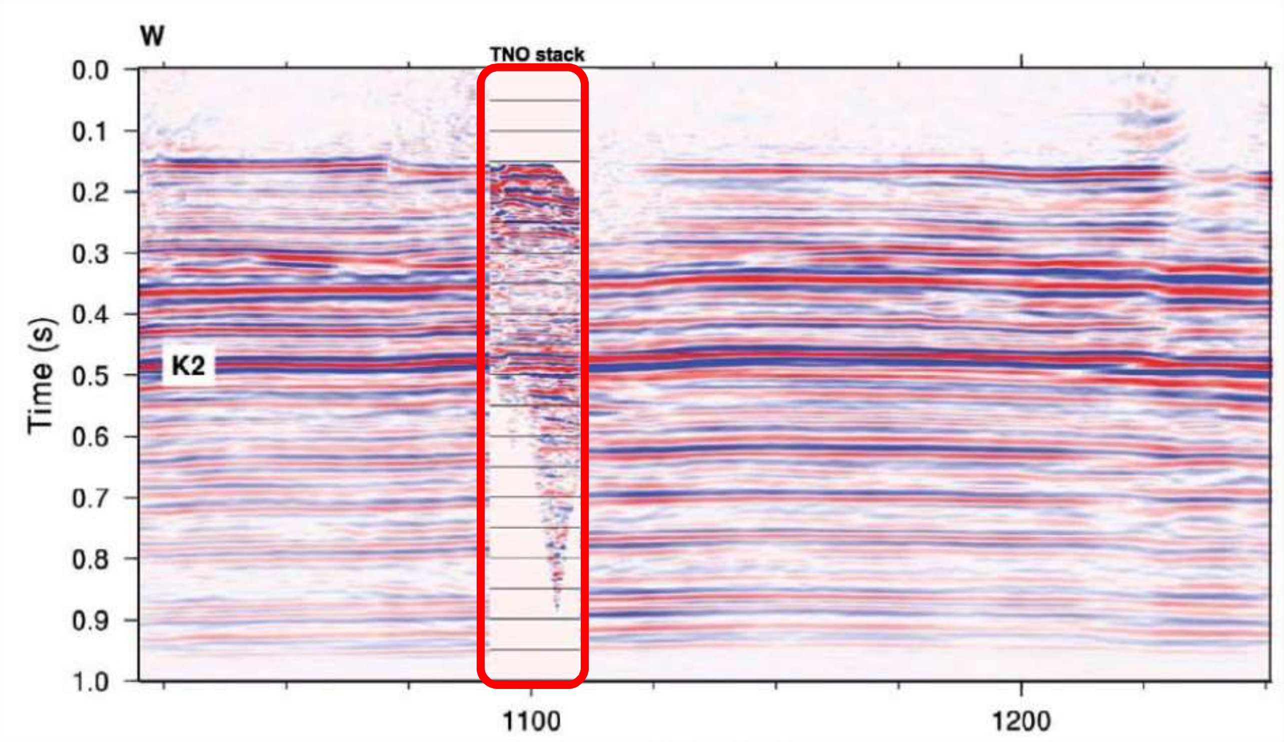


Figure 12 : TNO stack (center, outlined with red) on top of 3D seismic inline done by Juhlin et al. (2006). From Arts et al. (2011)

- The feasibility of ambient seismic noise interferometry was studied; the vast amount of data made the authors optimistic, although we are not aware of any practical application for using these data.

2.6 HONTOMIN CO_2 PILOT

2.6.1 Description of the site

This pilot is located in the Burgos province (Spain), and aims to inject CO_2 into fractured carbonates and dolomites of lower Jurassic age at a depth of approximately 1.5 km. Injection tests took place in 2014 and 2015 with brine and CO_2. CIUDEN operator planned to inject 10,000 tons in the reservoir, after tests to assess how to overcome the injectivity.

ENOS H2020 project website has a description of the Hontomin pilot at the following link : http://www.enos-project.eu/sites/operational-storage-field-site/hontomin/

2.6.2 VSP survey with DAS

2.6.2.1 PARAMETERS OF THE ACQUISITION

Taking advantage of fiber optics cemented in the injection well, walkaway 3D VSPs was undertaken in 2017 and a repeat was done in 2019 (Poletto et al., personal communication). Virtual receivers were created from iDAS using the vertical fibre optic in the well, using vibrator sources around the well up to 2.1 km in distance. Acquisition parameters were as follows:

- Receivers: virtual receivers created from iDAS, 0.5 m spacing – 2893 virtual receivers defined
- Record duration: 20s

- Source: two vibrators at the shot point, sweep duration 16s, sweep frequency 8-128 Hz, 12 vibrations per shot point

Although the record sampling rate was not given, one can assume iDAS capacities allow for high sampling frequencies (more than 1 kHz).

As shown in Figure 13, azimuthal coverage was good despite the rugged terrain:

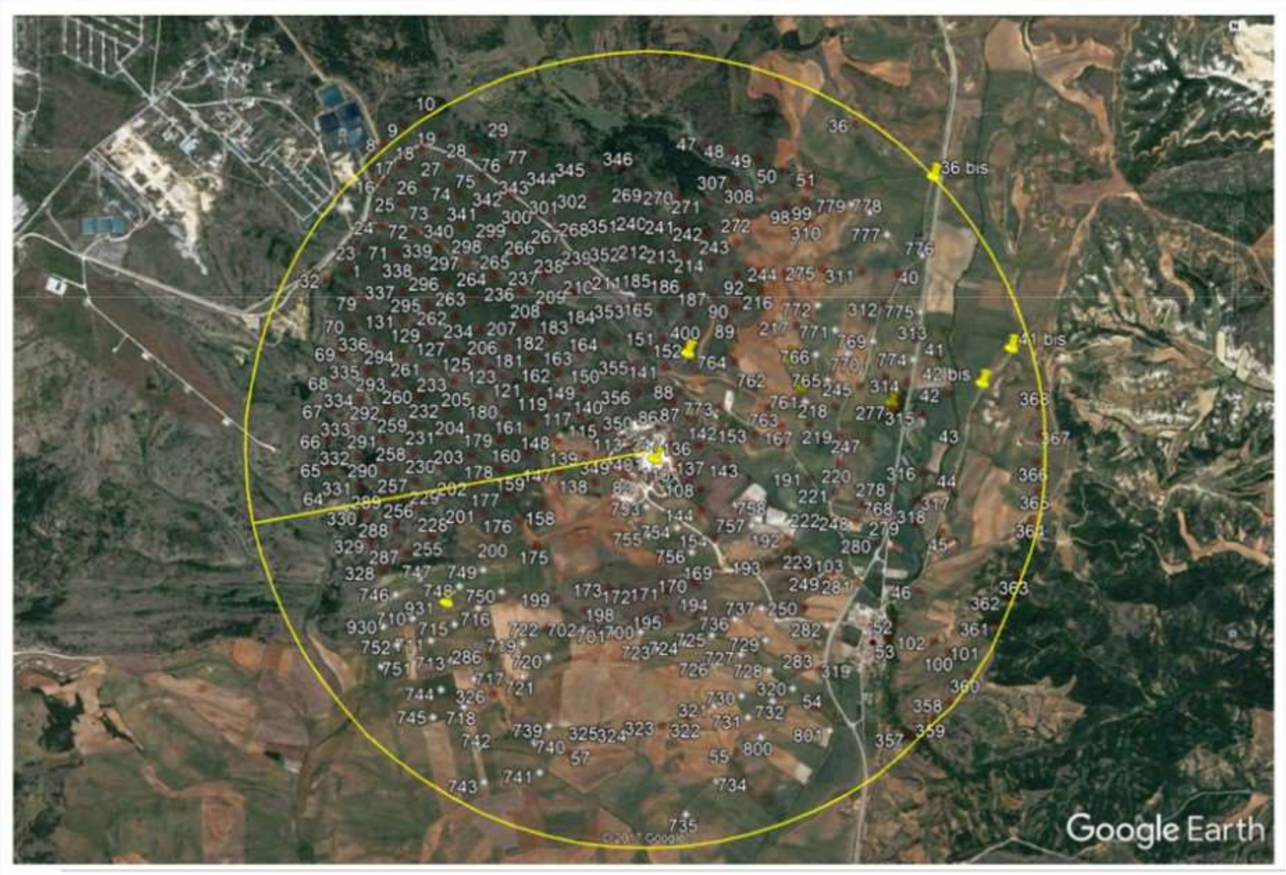


Figure 13 : map of shots realised around the DAS-equipped well. Injection well is at the centre of the circle. Circle size was limited by the explosive factory located NW of the injection site. From Poletto presentation

2.6.2.2 MAIN RESULTS

Data quality was deemed good, with upgoing waves visible even at maximum depth, as shown below:

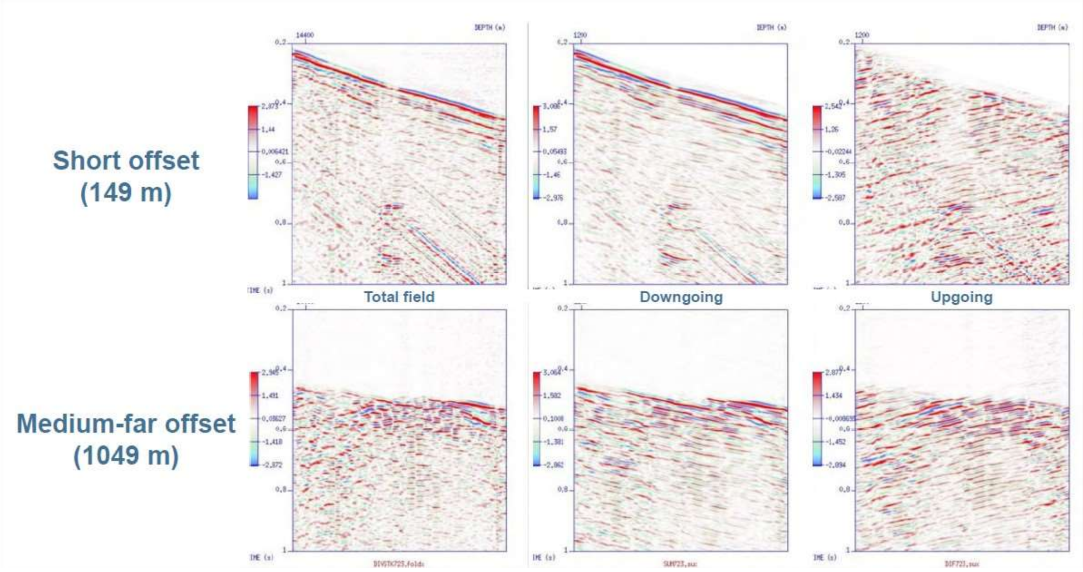


Figure 14 : example of two shots (one with a short offset, one with a far offset). Left: total field, middle: downgoing, right: upgoing.

The repeat in 2019 was easier to do compared to traditional 3D surface seismic, as only the source had to be repositioned precisely: the fibre optic is cemented in the well casing, and it is possible with iDAS to fine tune the position of the virtual receivers to match the baseline.

3 EOR sites using CO_2

3.1 WEYBURN EOR SITE

3.1.1 Description of the site

The Weyburn field is located near Midale, Saskatchewan, Canada. The CO_2 sequestration project launched in 2000 and ended in 2012, with a first phase from 2000 to 2004 seeking to predict and verify that the Weyburn oil reservoir could securely and economically contain CO_2, and a second phase expanding on the first. The initial injection rate was 5000 tons/day in the first phase, increasing to 6500 tons/day. As of May 30, 2003, cumulative CO_2 injected was 3.5 million tons.

Several papers were written on Weyburn monitoring. IEAGHG realised a quite complete report in 2004

3.1.2 Active seismic survey

3.1.2.1 PARAMETERS OF THE ACQUISITION

During the first phase, 3-D P wave seismic surveys were completed in October 2001 and October 2002. Acquisition parameters were as follows (Herawati 2002):

Parameter	Value
Receiver line spacing/numbers	140 m / 20
Receiver station spacing/channels	80 m / 60
Source line spacing/number	80 m / 28
Source point spacing	40 m or 80 m
CDP bin size	40 m X 60 m
Nominal fold	25
Geophones	Oyo
Sampling rate	2 ms
Record length	14 s
Source	Vibrator, sweep freq. 9-180 Hz, 10s sweep, 3 sweeps per shot

In order to cover the first two phases, templates were defined and implemented as per the map below (Figure 15):

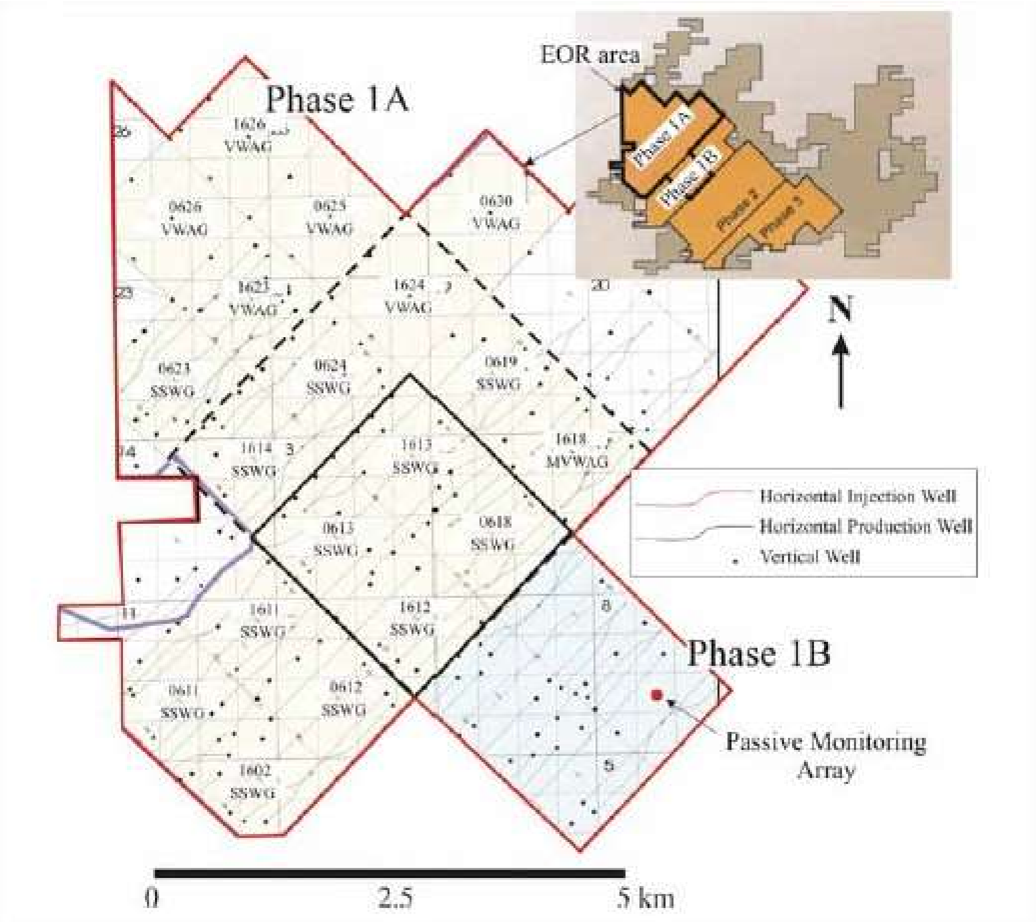


Figure 15 : map of the seismic operations on the EOR field. The larger area represents the 19 patterns implemented for time-lapse 3D seismic operations; the 4-pattern sub area (solid black box) was used for more measurements. The passive monitoring array, used in phase 1B, is shown on this map.

3.1.2.2 MAIN RESULTS

The IEAGHG Weyburn summary report 2006-2007 p.96 states that “both unit of the reservoir can be detected in the seismic section, at least locally”, although it does not state unequivocally that these reservoir levels were positively identified and thereafter tracked during the monitoring process. The frequency content of the source used may have been below what was needed to fully image these levels.

Time-lapse tests show that perturbations caused by the injection were detected, as shown in Figure 16:

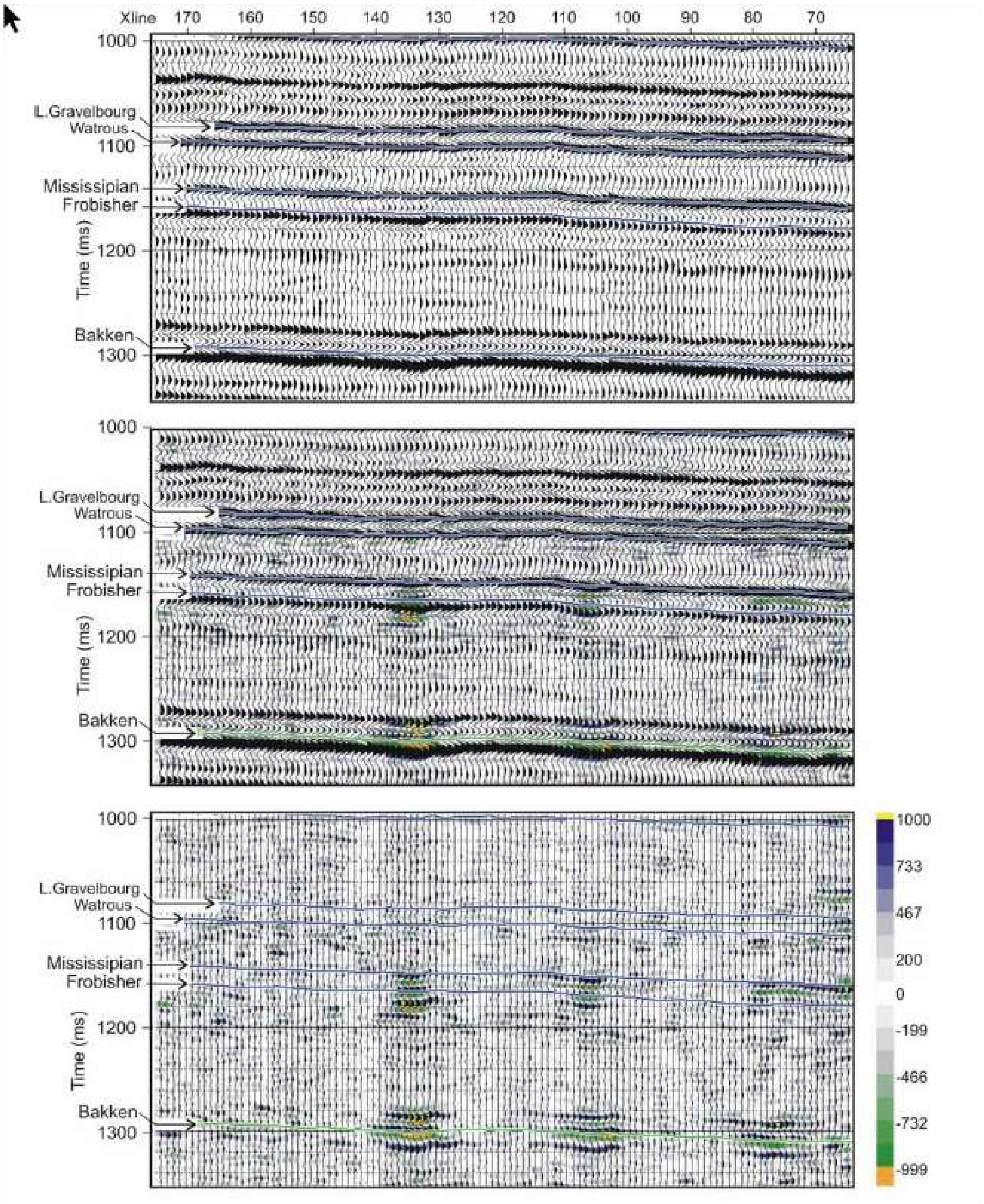


Figure 16 : Baseline (top), monitor 2 (middle) and difference (bottom) for a vertical section through the 19-pattern 3D P-wave data volume. Amplitude differences are put in colour. From Weyburn report (p. 135)

Based on these results, the report tries to estimate the minimal amount of CO_2 detectable with these operations. By using time-shift methods, the authors conclude that a reasonable detectable quantity is around 7500 tons; amplitude change methods however show a far better sensitivity to CO_2 presence, and therefore are better suited to map the CO_2 presence in the underground.

3.1.3 Passive seismic monitoring

In 2003 a microseismic array was installed to monitor a portion of the CO_2 flood. The monitoring array consisted of 8 triaxial geophones cemented into a disused vertical well, at depths of 1181–1356 m, with a spacing of 25 m. These depths place the geophones approximately 75–250 m above the reservoir. Apart from occasional pauses due to technical issues, these geophones recorded continuously from August 2003, 5 months before the start of CO_2 injection in the nearest well to the microseismic monitoring well. The array was active until November 2010 (Verdon 2016).

Over the full monitoring period (2003–2010), a total of 207 microseismic events were identified. The largest event had a magnitude of −0.5, while the smallest event had a magnitude of −3.5. Weyburn summary report shows the location of first events recorded prior to and at the beginning of the injection: events recorded take place in the vicinity of the production well, 300 m away from the array with a vertical precision of 50 m and a horizontal precision around 100 m. Magnitude-distance plot using first data show that the array was able to detect events up to 600 m. This is therefore a small scale monitoring of small energy events, intended to better understand the mechanical aspects at the injection point.

3.2 IN SALAH EOR SITE

3.2.1 Description of the site

The In Salah EOR project takes place in the Krechba gas field (central Algeria), with a reservoir level at 1.9 km depth exploited. As the gas extracted contains a significant amount of CO_2, it was decided to capture and use it for EOR purposes. Injection commenced in 2004 and in 2011, it was paused due to concerns with seal integrity, and resumed thereafter. By 2013 over 3.8Mt of CO_2 had been stored in the subsurface, with a 1 Mt/year injection goal.

Field operators presented their site in The Leading Edge, in Mathieson et al. (2010).

InSAR datas, with an example exposed in Figure 17, show a significant deformation on the site linked to the fluid injection ; these data raised concerns about caprock integrity. A 3D seismic survey was acquired in 2009 following the first InSAR results in 2008 (Ringrose et al. 2013).

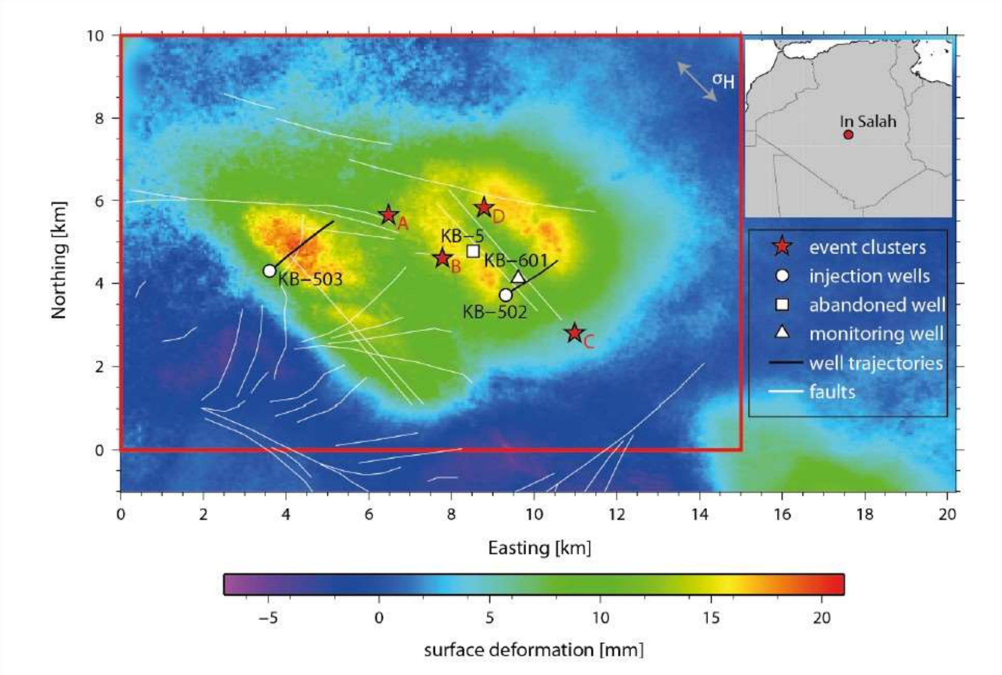


Figure 17 : vertical deformation map of the In-Salah area obtained from InSAR measurements in 2008. Injection wells are KB502 and KB503, microseismic monitoring well is KB601. Clusters A, B, C and D are indicated on the map and will be discussed later. From Goertz-Allmann et al. (2014)

3.2.2 Microseismicity monitoring

3.2.2.1 NETWORK SETUP AND EVOLUTION

A complete description of the network can be found in Oye et al (2013). A single subsurface array was deployed in a vertical well, ranging from about 30 to 500 m depth with 10 m spacing. This first array ran into several problems:

- Geophones were connected to 3 different digitizers, each one with its own time base fixed by GPS. Some of the GPS units failed, leading to some portions of the array not synchronizing with others and were therefore unusable.

- Only one geophone could be oriented correctly, due to problems in wiring
- Data were contaminated by electronic noise because of the length of the wires connecting the geophones to the digitizers.

In June 2011, the aforementioned problems were corrected by rewiring the geophones to a single digitizer. This digitizer was placed closer to the well, reducing the 50 Hz electronic noise.

3.2.2.2 MAIN RESULTS

Despite these problems, more than 1500 induced seismic events have been identified throughout 2010. Oye et al (2013) were able to determine a main cluster of 1200 events and linked this cluster to a SE-NW fault.

Goertz-Allman et al. (2014) pushed further the analysis and identified 4 clusters using direction-distance charts, with 3 clusters B,C,D close to the injection well Kb502 and 1 cluster A further away. Incidence measurements show that the clusters B,C and D are almost below the downhole array.

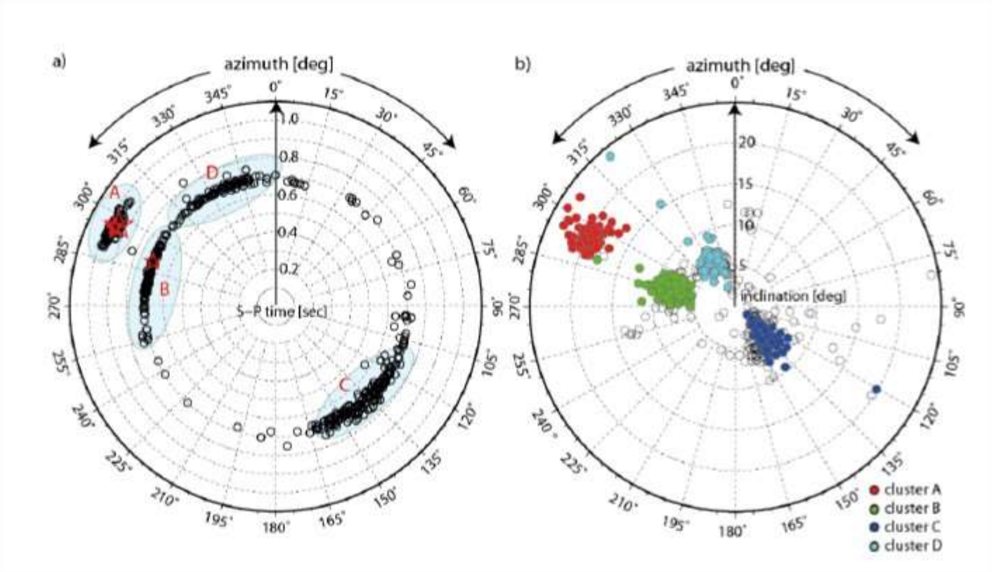


Figure 18 : polar chart plotting azimuth vs S-P traveltime (left) and incidence angle (right) for detected events. From Goertz-Allman et al (2014)

Authors studied cluster by cluster the relationship between injection rate and seismicity occurrence. Results are shown below:

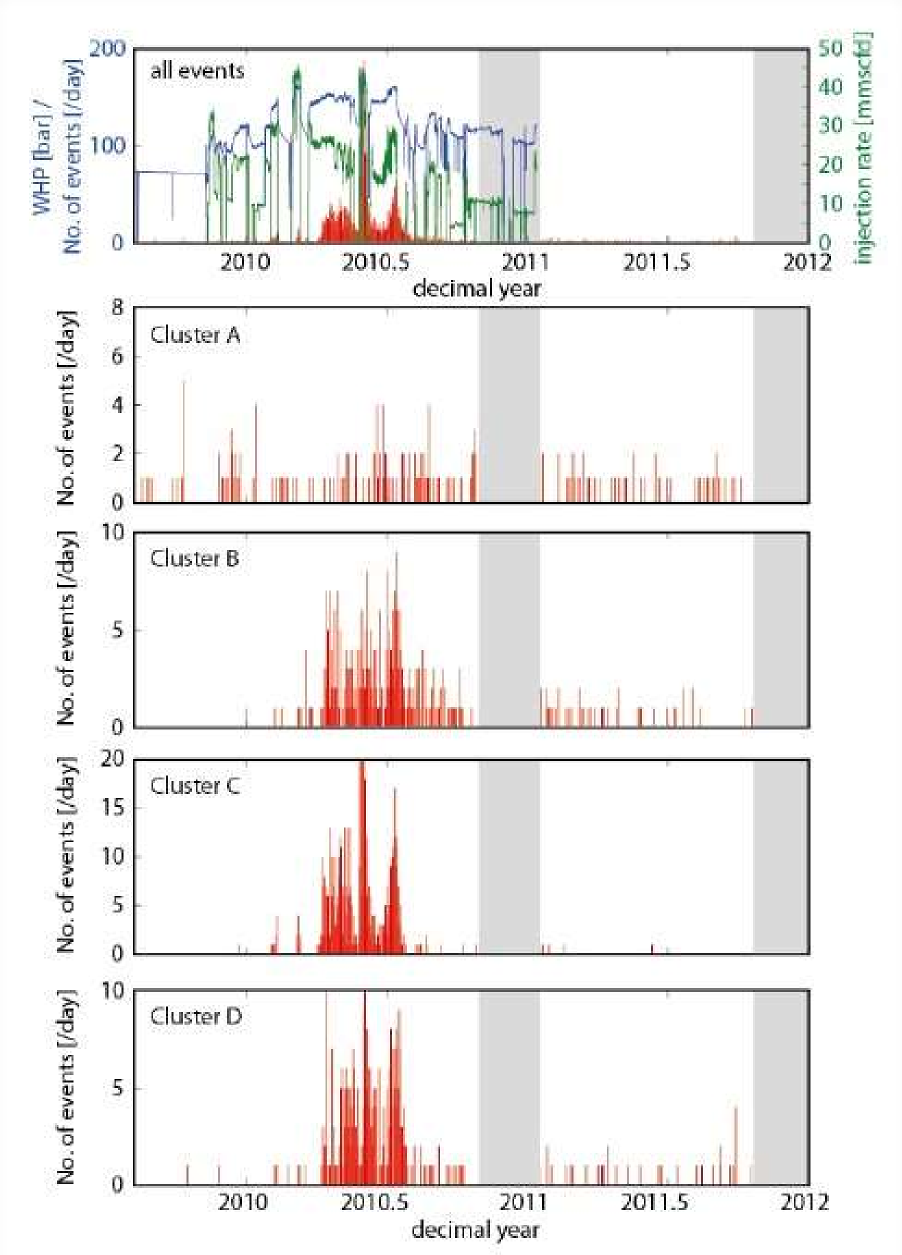


Figure 19 : **Histogram distribution of microseismic events (red) compared to wellhead pressure (blue) and injection rate (green) at well KB-502. At the top all events with available azimuthal information are shown, followed by the event distribution of individual event clusters A, B, C, and D. Grey shaded area indicated periods of missing seismic data. From Goertz-Allman et al. (2014)**

The close clusters show a strong correlation with injection rate at Kb502 well, which is an expected behaviour if we admit the hypothesis that injection at Kb502 will create seismicity nearby. Cluster A does not show such a correlation.

It should be noted that microseismicity monitoring began 5 years after the beginning of injection. The stop-start injection history at this site complicates geomechanical analysis with the absence of any kind of seismic monitoring over the whole period (Goertz-Allmann et al. 2014). On top of that, because there was no baseline, it cannot be ruled out that several fault structures were already active, because of previous oil extraction or even because of the natural tectonic activity in the area.

4 Seismological baselines examples for non CO_2 underground exploitations

4.1 STENLILLE GAS STORAGE MONITORING

4.1.1 Description of the site

The Stenlille natural gas underground storage facility is located 70 km SW of Copenhagen and has been in operation since 1989 (Figure 20). The storage facility has been re-developed over time in order to increase storage capacity. Within the SECURE framework, GEUS undertook a study on this field, whose results were exposed in deliverable 4.2 “Report on best practice methods for monitoring induced and triggered seismicity”.

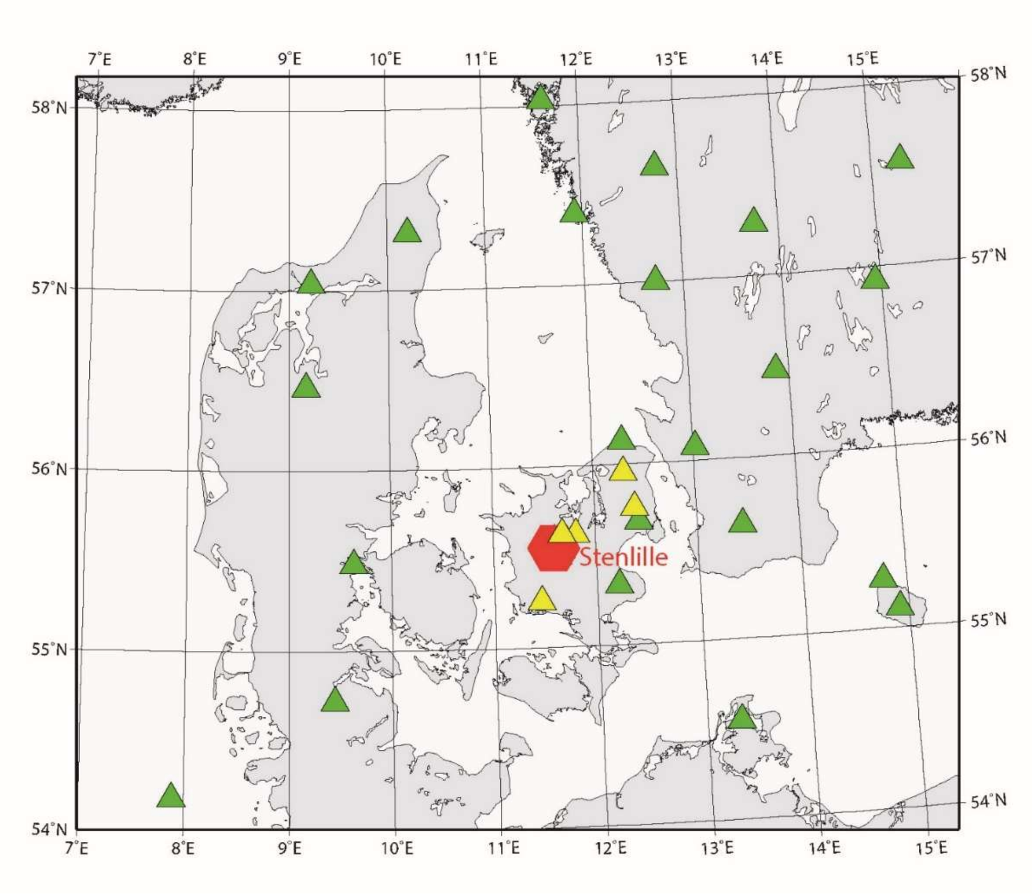


Figure 20 : The Stenlille gas storage is located on Sjælland (red hexagon). The triangles are seismological stations (green – permanent network stations; yellow – additional Raspberry Shake stations deployed and used in this study). From GEUS deliverable

The reservoir covers an area of 14 km² with a vertical closure of 35 m. It consists of Upper Triassic – Lower Jurassic sandstone at 1500-1600 m below ground, with an overlying 300 m thick claystone layer formed during the Lower Jurassic acting as caprock.

4.1.2 Setup of the seismological network

During the period between August to September 2018, GEUS established a microseismic monitoring network around the Stenlille gas storage facility (Figure 3). The network consists of 6 seismographs placed within 5 km of the main pumping facility. For the Stenlille network, Nanometrics Trillium seismometers from the DanSeis instrument pool were deployed. Continuous data sampled at 100 Hz are transmitted to GEUS 24/7. In addition, several smaller Raspberry Shake sensors where operated for shorter periods at distances up to 100 km. Permanent stations from the Danish, Swedish and Norwegian seismic monitoring networks were also included, although at larger distances. Network was operating from September 2018 to March 2020.

During this period, 32 locatable events were detected. Of the 32 events, 20 are previously known events (both natural earthquakes and explosions). None of the events found are within the Stenlille Gas Storage area. The found events are between ML -0.2 and ML 2.5 (and a distant event Mb6.7 and two regional events of ML 3.5 and ML 2.8); the new events are all under ML 1.0.

4.2 IRELAND SEISMOLOGICAL BASELINE

4.2.1 Project presentation

In 2012, the Ireland Environment Protection Agency (EPA) released a preliminary report after Unconventional Gas Exploration and Extraction (UGEE) preliminary permits were granted. This preliminary study was followed by a UGEE Joint Research Program to study the environmental impacts for future unconventional gas extraction operations.

One of the aspects studied within this program was the Ireland background seismicity survey, undertaken by the British Geological Survey, University of Ulster and University College Dublin. The aim of this survey was to compile all the knowledge accumulated for Ireland island current seismicity, mainly driven by the Atlantic ridge opening and the post-glacial rebound stress adjustments.

For that, both instrumental and historical catalogs were considered and compared to get the most comprehensive map of seismicity available for Ireland, shown below:

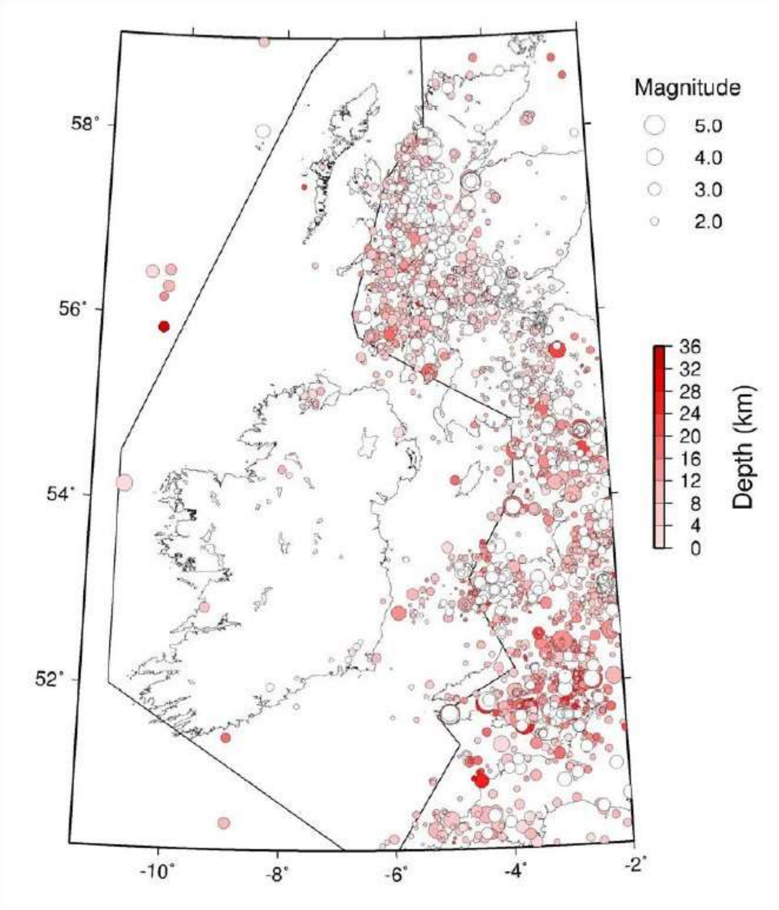


Figure 21 : map of historic and instrumental earthquakes recorded by the BGS catalogue. From Baptie et al. (2014)

4.2.2 Main results

Once the catalog was produced, the magnitude completeness was estimated using Gutenberg-Richter law and the point of inflexion indicating at which magnitude earthquakes have begun to miss – meaning that some earthquakes went unnoticed by the current network because their magnitude was too low. This value is therefore very important to assess what kind of earthquakes we can hope to detect with a given network.

Magnitude completeness is around Mw=3, meaning that the current network is able to detect significant tectonic earthquakes but not all the small earthquakes that can only be detected near a station.

The seismicity rate was also assessed using the Gutenberg Richter law: seismicity rate is deemed low in Ireland, with a Mw=4 or greater earthquake occurring every 500 years. This occurrence rate is far from several areas in mainland Europe.

The detection threshold can change depending on the network spatial coverage: for Ireland, calculations were done using the permanent network in Northern Ireland and Republic of Ireland. The authors obtain the following coverage:

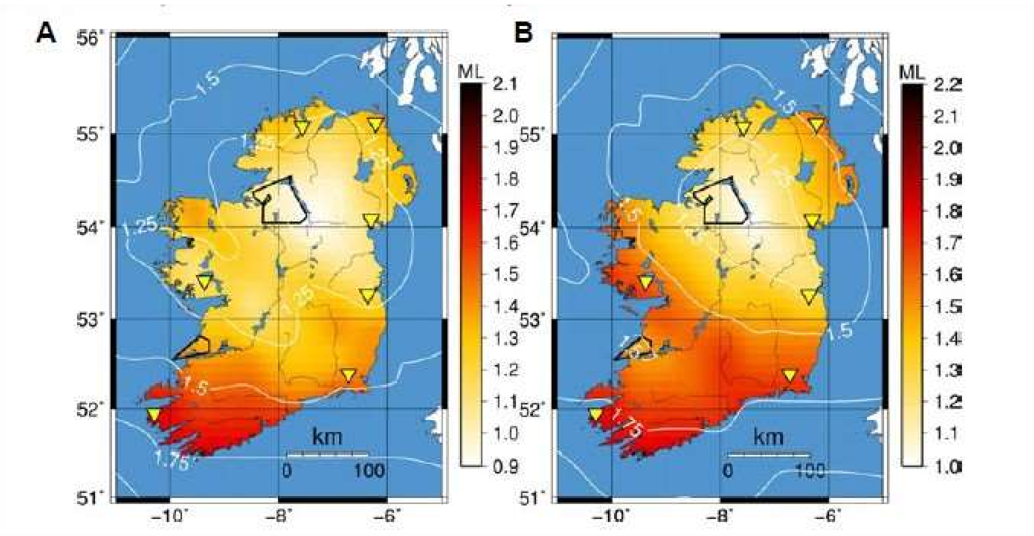


Figure 22 : minimum Ml magnitude that can be detected by the Ireland permanent network in the case of medium (left) or high (right) level noise conditions.

The map above is very useful for operation planning

5 Lessons learned from case studies

As shown in the previous chapter, the previous decades have seen the implementation of several well documented case studies. We propose to discuss in this chapter the lessons that can be drawn from them, and voice our opinions and recommendations for future projects.

5.1 FOLLOWING CO_2 POSITION WITH ACTIVE SURVEYS

5.1.1 A successful method

4D seismic surveys were in general able to provide an image of the reservoir state and evolution. These surveys have shown that it is possible to detect around 1 kT of CO_2 in a supercritical state at 1500m depth – this result will help future projects to build their monitoring system. Sleipner project represents

Ketzin pilot project also showed the potential of 4D seismic to detect gaseous CO_2 in the underground : their studies showed that it can be detected with quantities as small as 100 tons at 700 m depth, leading to interesting openings for the detection of leaks for future operational projects.

5.1.2 Acquisition sampling rate to get enough vertical resolution

One important point raised by the study of different test cases is the vertical resolution, constrained by mainly the sampling rate and the geometry. For Weyburn case study, the sampling rate was lower, leading to some lack of precision to track reservoir level in some areas as the authors of the 4D survey hinted. By contrast, a good vertical resolution showed for instance in Ketzin how the reservoir was structured, which in turn helped to understand the CO_2 flow.

From all these studies, a sampling rate of 1000 Hz appears to allow the operators to have a correct view of the processes at the reservoir level. This rate, and the receiver density needed to have good horizontal coverage, are now available due to the advances in seismic technology these last decades ; in particular, autonomous receivers made the field logistics far simpler.

5.1.3 Survey strategy to cover operational sites, and the need of a good baseline

Although the examples we showed in this report had very good results, we shall point out a drawback : 4D seismic have huge costs. These costs are not a huge concern for pilots, as their primary goal is to get a better understanding of the processes ; for EOR projects, the value extracted with oil production offsets the costs induced by reinjection and monitoring.

However, future CO_2 storage projects will not offer the same return on investment, and they will have operational objectives. There is therefore a need to think ahead and use 4D seismic survey in a smart way to reduce costs. The following ideas may be used in the future to limit the costs while retaining the resolution capacities of 4D seismics :

- One can concentrate the efforts on a few areas selected for their importance by a risk analysis, and do 4D seismics on a smaller scale
- There is also the possibility to go further and select only a few critical points to be monitored : in this scenario, operators will abandon 3D repeats for 2D surveys, or even carefully selected source-receiver couples. This approach will drop the possibility to have a complete picture in favour of a warning system, triggering more complete investigations when needed

These approaches can work only if the seismic baseline is precise and complete enough. **We shall therefore stress out the importance of implementing the best 3D seismic baseline possible, so that future studies have the needed flexibility to limit operational costs.**

5.1.4 New technologies for more significant results

One of the main concerns for 4D seismics is how to ensure that the differences between the baseline and the subsequent surveys are due to the changes in the reservoir level, and not due to bad positioning ordifferences in hardware. For long term monitoring of reservoir, this concern gains even more amplitude as the operators have therefore to ensure some stability to the monitoring processes.

One of the way to ensure more stability is to make sure receiver positions stay the same for the baseline and subsequent repeats with a permanent network. This idea, while difficult to implement with geophones, is now facilitated by the recent advances in optic fiber technology and Distributed Acoustic Systems : it is extremely simple and cheap to install a fiber optic cable in the well casing when it is drilled, and Hontomin VSP results show that they provide a good resolution similar to geophone arrays. One can imagine for future projects fiber optic cables buried at the beginning of the project to provide stable lines for seismic surveys.

5.2 PASSIVE MONITORING: HURDLES TO OVERCOME

5.2.1 On the importance of baseline

For the EOR sites reviewed, seismic networks were installed after the injection start. There is no way to know the seismicity state prior to the injection. Therefore the recorded seismicity during the injection *may* be caused by factors unrelated to field operations. For instance, In Salah shows an active fault during the injection, but it is difficult to assert with certainty if the fault was active before or not, or to which degree the activity increased with the injection.

Although geomechanical studies coupled with surface deformation observations and well pressure observations may help alleviate this lack of knowledge, these same studies benefit greatly from knowledge of the initial stress state – brought by regional studies and local seismicity monitoring before injection. A passive seismic baseline is the best tool to get enough data beforehand and make informed decisions.

5.2.2 How to design a passive seismic baseline

5.2.2.1 TYPICAL SIZE OF A BASELINE NETWORK

Baseline networks shall detect seismic events small enough on an area large enough. This leads to a contradiction: since the amplitude of the seismic waves diminish with the travelled distance, These contradicting constraints shall lead to a compromise.

A multistage approach can be proposed, following the processing done in Baptie et al. report (2012):

- First stage uses already existing networks with a magnitude completeness around Mw=3 to assess the occurrence rate of events in the area.
- Second stage shall concentrate on the exploration area with surface networks. The report did simulations showing that 30x30 km networks can detect events with Mw=0.75. Knowing that surface networks have a limited sensitivity with Mw>0 due to surface noise, one can assume quite safely assume a 10x10 km array will be more than enough to get Mw>0 or 0.5 depending on noise conditions. This area covers an operational-scale reservoir.

5.2.3 Surface arrays and downhole arrays

It is common to consider the following cost-benefit chart to compare surface networks and downhole networks:

Table 3 : cost/benefit chart for surface and downhole networks

	Costs/drawbacks	benefits
Surface network	Sensitivity to events Mw>0 only	Cheaper to deploy and operate
Downhole network	Sensitivity to smaller events and microseismicity	More expensive to deploy and operate

Several site studies in this report show however that using downhole networks without care may offset greatly the benefits of better sensitivity. As downhole networks cost more to deploy, operate and repair, it may be tempting to deploy only a small number of downhole stations. However, Weyburn case study for instance shows two shortfalls:

- Using only one antenna does not allow for precision of the horizontal position of detected events. For Weyburn events, horizontal uncertainty can be as high as several hundred metres – which is worse than the horizontal precision that can be obtained using scattered stations on the surface. It is therefore difficult to assign the detected events with geological structures, while a good horizontal uncertainty allows more in-depth analysis

- Using too few stations (less than 6) does not allow the operator to compute the focal mechanism of the best detected events; these focal mechanisms provide very useful information on the rupture processes, which adds data to the geomechanical models for a better predictive value
- As shown in the Weyburn case, downhole stations have good sensitivity to nearby events, but they have a limited range of detection. This means that, while downhole sensors will be able to bring precise information on a specific target, they cannot cover vast areas unless having many wells equipped – which is expensive.

As such, downhole sensors shall be used for pinpoint monitoring of critical targets, while surface or subsurface networks will be used for large scale monitoring. Subsurface networks, with stations 50 m or 100 m below the surface offer a good compromise between the installation price and the sensitivity: geothermal operation monitoring show that events with Mw>-1 can be observed and located by subsurface sensors several kilometres away. The choice between a surface and a subsurface array depends on the size of the operations and the expected seismicity.

5.2.4 Coupling active and passive surveys with new active wireless receivers

Receivers used for wireless active acquisitions are now advanced enough to double as passive networks for a few weeks. Several manufacturers now offer hardware and software solutions to do both at the same time.

As these kind of receivers are not expensive, it is now possible to cover large areas with a high density of stations, bringing both good horizontal precision with a wide coverage. Using receiver clusters as small seismic antennas can also bring better azimuth pickings and therefore can improve the precision of event locations.

In the baseline survey framework, it is now possible to leave active lines for some weeks in passive mode in order to acquire seismic events. These can be also used for tomographies using seismic noise (Campillo and Shapiro 2004), on the same geometry an active survey uses – it allows to build 3D images over the same area and timeframe and thus allows for easier interpretation.

5.3 RECOMMENDATIONS FOR FUTURE ONSHORE CO_2 DEMONSTRATORS IN EUROPE

Based on the review of several case studies, we propose the following recommendations for future baselines for onshore CO_2 demonstrators:

5.3.1 Passive baselines

As shown by the various case studies:

- A baseline is mandatory and shall be undertaken before the injection. Without a baseline, no definite conclusion can be drawn, and geomechanical data will lack crucial information for a better control of the injection operations.
- It is advised not to use downhole arrays at this stage and to use surface arrays or subsurface arrays instead, depending on the area to cover and the deployment costs.
- Number of stations and deployment geometry shall be determined beforehand in order to follow events with magnitude Mw>0.5 for surface arrays or Mw>-0.5 for subsurface arrays
- Observation time should be determined by the occurrence rate of events. This occurrence rate may be estimated using national catalogues. Operators shall be advised that this duration may be higher than one year (in the Ireland case), the planning must take that duration into account
- National databases can give clues about the regional activity and should be used first to determine an estimate of the occurrence rate, giving a first estimate of the needed deployment time for the seismic network. National network data can also be integrated to the deployment plan. This public data shall be examined and used to justify the monitoring plan proposed to regulatory powers.

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