Deliverable 2.2. Concept description for the use of fibre-optic measurements for seismic tomography

Digital monitoring of CO_2 storage projects

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1 Introduction

1.1 Cross-well Seismic tomography and fibre optics

High resolution mapping of CO_2 plumes in the geological storage formations can be obtained using cross well seismic experiments designed to characterise velocity changes in the subsurface, see figure 1. High resolution studies are facilitated by using dense measurement surveys with many wireline operations that adjust seismic source and detector positions. Distributed fibre optic acoustic sensing may enhance traditional wireline cross wire surveys by providing an aliasing-free method for characterising seismic waveforms, and potentially enable a reduction in the number of individual measurements (and therefore cost) required for performing cost sensitive CO_2 plume surveys. In addition, seismic tomography involving fibre optic receivers and ambient noise techniques, could enable permanent monitoring of subsea CO_2 storage with seismic tomography.

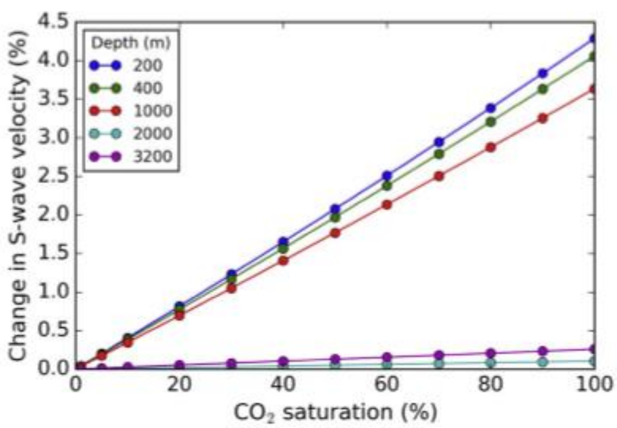

Figure 1. Expected % change in S-wave velocity if CO_2 replaces brine as the in-situ pore fluid. Stork (2018)

This document gives a basic concept description of cross-well seismic technology, both with active seismics and ambient noise, and their application with distributed fiber optics sensing. The document also describes the infrastructure for carrying out cross well/fibre optic measurements at Svelvik, and a proposal for a measurement campaign to be carried out as part of the DigiMon project.

1.2 How does cross-well tomography fit into the DigiMon concept?

The Digimon concept involves the combination of low cost, low fidelity distributed measurements covering large areas, and high-fidelity measurements covering smaller areas. Conventional cross-well seismic tomography falls into the latter category and could provide a good deal of value to DigiMon in this role. The need for wireline operations indicate that conventional cross-well tomography is most suited to land-based and survey oriented CO_2 storage applications.

There are two potential approaches for adapting cross-well seismic tomography in order to make it more suitable for subsea and continuous monitoring CO_2 storage applications:

- Using ambient noise as the source (No wireline operations for the source).
- Using fibre optics as the receiver (No wireline operations for the receiver).

2 Concepts in seismic tomography

2.1.1 Conventional cross-well seismic tomography

Multi-borehole seismic experiments involve the placement of seismic sources and receivers (typically 3C geophones) in nearby boreholes (figure 2). Typically, datasets are gathered at different intervals to detect changes in seismic wave velocities through the subsurface and to provide high-resolution 2D or 3D images of seismic velocities between these boreholes. This tomographic method is usually used to delineate geological structures, to detect fractures and fracturezones and to specify sediments and rocks and rock properties. Seismic tomography not only images the material properties of the subsurface itself, but also its exact position in the plane or in space.

For monitoring the effects of CO_2 injection on the subsurface, reference measurements (baseline measurements) should be done prior to injection. The subsurface between the boreholes can be investigated at different depths by a cross-hole test providing a depth profile of shear wave velocities (V_S) and compressional wave velocities (V_P) between boreholes at a high vertical resolution (figure 2b). Alternatively, 2D mapping (or 3D with more than two boreholes) can be carried out by tomographic measurement setup (figure 2c). The number of measurements required for conventional cross-well experiments scales linearly with the spatial resolution of the survey, and quadratically for tomography surveys. Standard tomography surveys therefore can be quite time consuming, which could be an issue for cost sensitive applications such as a CO_2 storage. Therefore, the added value should also be taken into consideration.

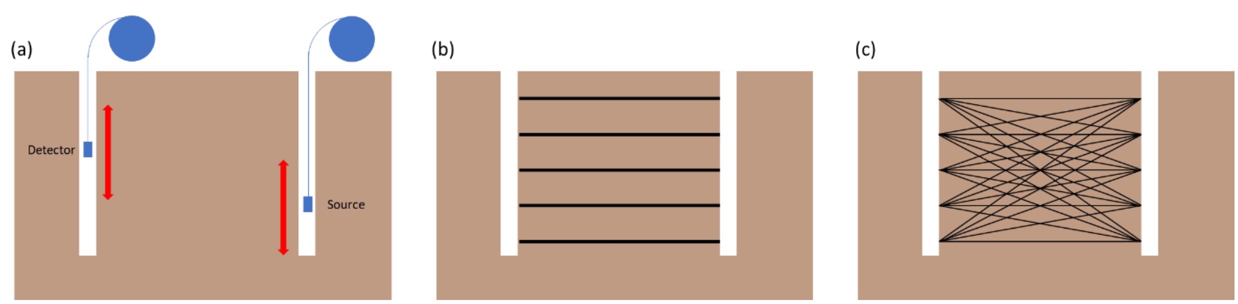

Figure 2. a) Schematic setup for conventional borehole seismic experiments. b) Seismic ray path defining source and detector positions for conventional cross-well experiments. c). Seismic ray paths defining source and detector positions for conventional borehole tomography experiments.

In most cases, P-wave tomography is used to predict high-resolution spatial continuity of lithological structures where P-waves are generated in one borehole and being transmitted to the other. However, the P-wave is strongly influenced by the groundwater table and its application for deriving geotechnical parameters is limited. It has been well-reported in the literature that in multi-phase media like saturated soils, the P-wave velocity of the media is significantly influenced by the presence of pore water, depending on the degree of saturation (Ng et al. 2019). Therefore, the P-wave velocity model within the tomographic analysis cannot provide sufficient information about the geology e.g. soil layers, especially when the ground water table is near the surface. In contrast, shear waves react sensitively to changes in dynamic soil parameters, such as shear strength or modulus of elasticity. Due to the heterogeneous structure of the soil, these parameters also have a 3D structure.

There are relationships between the petro-physical properties and the compressional and shear wave velocities based on datasets measured under laboratory condition reported in several studies. However, the empirical relationships derived by various researchers are valid only to the particular dataset for which the relationship was derived (Garia et al. 2019). A generally valid derivation is not possible.

P- and S-wave tomographic results from previous studies show a significantly higher velocity contrast for S-wave tomograms (factor 3) compared to P-wave tomograms (factor 1.5). The S-wave velocity profile within sediments is thus mapped in much more detail compared to the structure resolved with the P-wave. In addition, the S-wave tomogram is capable of covering both saturated and unsaturated sediments and rocks , since the groundwater level does not influence the S-wave.

There are various examples for the application of seismic methods in the exploration of CCS sites, whereby borehole measurements are particularly suitable for the generation of high-resolution seismic images of the subsurface. E.g. cross-well seismics was used to detect the propagation of CO_2 during the injection in Ketzin. The change in seismic velocity caused by the displacement of the saline water by CO_2 could be used to monitor the CO_2 migration behaviour (Zhang et al., 2012; Götz 2013). Götz (2013) showed that borehole seismic methods can image the distribution of CO_2 in the reservoir and contribute to the quantification of geometrical and petrophysical parameters of the plume. A time-lapse cross-well seismic tomography was conducted to detect and monitor the movement of CO_2 injected into an aquifer at the Nagaoka test field in Japan (Onishi et al. 2009). Onishi et al. (2009) reported a maximum velocity decrease as a result of CO_2 injection of about 9%.

Experiments with P-waves are very relevant for CO_2 storage because the velocity decreases dramatically as a function of percentage of gas inside the pore volume. The SBS42 from Geotomographie GmbH as a conventional P-wave source works through electric discharge electrodes that generate water vapour bubbles which expand and collapse generating high-frequency seismic waves.

In addition, S-waves are also relevant since their velocities are dependent on dynamic properties that vary during the CO_2 injection progress. It was reported that high-pressure CO_2 injection induces CO_2-brine-rock interactions in which geochemical reactions potentially lead to changes in hydraulic properties, i.e., porosity and permeability, and geomechanical properties, i.e., stiffness and strength of rock (Vilarrasa et al. 2018). Bemer and Lombard (2010) reported 1–2% increase in porosity for carbonate-rich wackestone from Lavoux formation altered in the presence of CO2 and a resulting decrease in strength and elastic moduli of up to 20–30%. Grombacher et al. (2012) showed that the ultrasonic velocities reduction in different carbonate rocks subjected to CO2-rich water injection by the decrease in stiffness at grain contacts caused by dissolution that was observed through microimaging. We assume that the S-wave is sensitive to changes in geomechanical properties such as stiffness which are expected during injection.

S waves are generated in distinctly different SH and SV (horizontal and vertical, respectively) polarisation components. The borehole source BIS-SH from Geotomographie GmbH generates horizontally polarized shear waves (SH) and compressional waves (P). Within the project, a novel SV Source is going to be developed. By generating S-waves of SH and SV type, paired shear wave profiles could be obtained to potentially describe the soil stress history. Many geotechnical parameters are influenced by the soil stress history, for example deformation properties and soil stiffness (Mackens et al. 2017).

If measurement data from P, SH and SV waves are available, a comprehensive characterization of the elastic rock or material parameters is achieved. In comparison to the baseline measurement, changes in the ratio of SH/SV can give an indication of an anisotropic material behaviour and be be directly assigned to a stress redistribution (anisotropy) in the rock due to pressure changes and can be reproduced in a detailed and spatially accurate image by seismic tomography.

2.2 Fibre-optics and cross-well tomography

Cross-well seismic experiments could be enhanced or made more cost effective by including a distributed acoustic sensing (DAS) fibre either instead of, or in addition to, the detector wireline, see figure 3. A fibre has the advantage that it can be permanently installed in the borehole, and the distributed nature of the sensor means no adjustment of the fibre position is required during a survey, since seismic "snapshots" are taken over the whole borehole. This is particularly significant for borehole tomography experiments, since it allows the number of measurements to scale linearly with the source depth intervals, as opposed to quadratically with conventional schemes (without using sensor strings). It may be possible to enhance the final results by combining/calibrating DAS measurement with a few point senor measurements.

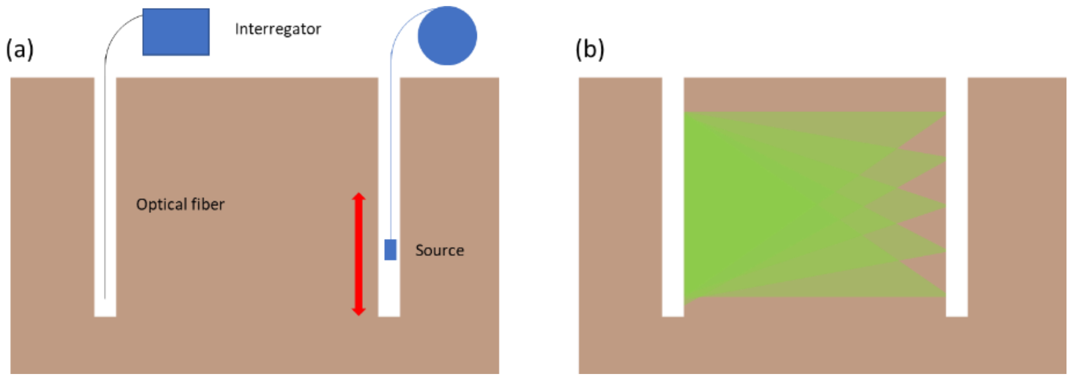

Figure 3 a) DAS cross-well seismic configuration b) Detectable seismic ray paths tomography measurement made using a distributed acoustic sensor. When using a distributed fiber, only the source position needs to be changed.

The spatial resolution of the DAS measurements is governed by the gauge length and sampling resolution of the DAS instrument, as well as the fibre cable geometry. Typical DAS gauge lengths and sampling frequencies are typically on the order of 10 m and 1 m respectively. Helical cable geometries typically contain ~ 2m optical fiber for every meter of borehole, influencing the effective spatial resolution.

The sensitivity of straight DAS cables is propagational to $cos^2\theta$ and sin2θ for P-Waves and S-Waves respectively, where θ is the seismic wave angle of incidence relative to the fiber axis. Therefore, vertical cables responds to vertically propagating P waves but are insensitive to horizontally travelling waves. This could present a challenge for cross-well measurements using DAS. On the other hand, horizontally propagating SV waves are suitable for detection with a vertical cable, but vertically propagating SV waves are not.

In order to tackle the broadside sensitivity issues associated with standard, or “straight” cables, “helical” cables with fibre wound about a central axis have been developed, the P-wave sensitivity, becomes less dependent θ, see figure 4.

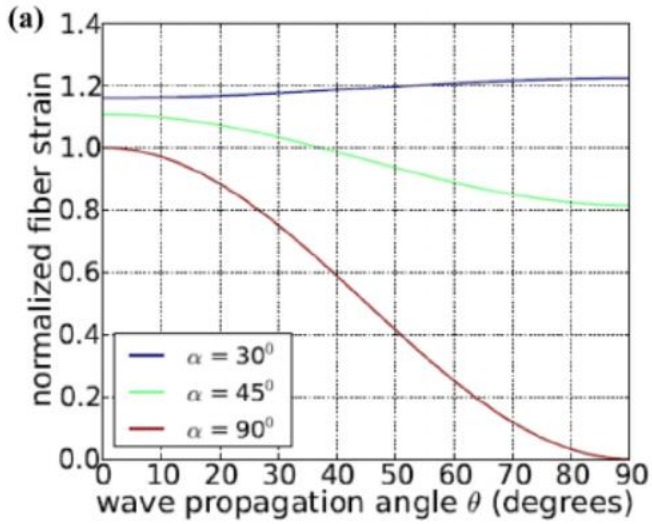

Figure 4) P-wave sensitivity function for a helical fibre for different helical fibre wrapping angles, α=90 corresponds to a straight fibre. (Kuvshinov 2016)

2.3 Ambient noise cross-well tomography

Ambient noise interferometry (ANI) has recently become a well-established technique to obtain velocity measurements from ambient seismic noise, and an extensive literature review of the subject is provided by Snieder and Larose (2013). The method extracts the Green's function by cross correlating the seismic noise wavefield between two receivers and stacking over time, which produces a response at the second receiver that would be measured if the first was an impulse source. As a result, this operation finds the travel-time difference between waves recorded on the two receivers which is often termed a virtual seismogram. Creating multiple travel-time measurements between different pairs of receivers enables tomographic inversion of the data, which produces velocity estimates within the confines of the receiver array. Where these arrays are permanent and the receiver geometry is unchanged between surveys, a high degree of repeatability can be achieved which is ideal for monitoring CO_2 storage sites.

Dispersive surface waves are typically used for ANI as these signals are easily extracted from the noise record. When using surface waves, the depth of the measurement is directly related to the period of the signal, with higher frequencies confined to the shallow subsurface and lower frequencies extending to greater depths. Stork et al. (2018) used surface waves to assess to the potential of ANI to monitor the Aquistore CO_2 storage project, Canada, and showed the method was sensitive to depth of 100-400 m for surface wave periods between 0.5-1.4 s when using surface deployed geophones. Borehole arrays provide the opportunity to extend the sensitivity depth and have been shown to be capable of retrieving body waves from noise data which can be used to image both P- and S-wave velocity structure. Using cross correlations from geophones located at ~3km depth, Zhou & Paulssen (2017) retrieved direct P-wave arrivals in the 3-80 Hz band from vertical components and 3-50 Hz S-waves on the horizontal component from noise signal generated on the surface.

2.4 Fibre-optics with Ambient noise interferometry for CO_2 storage monitoring-

For the purposes of monitoring CO_2 storage sites using DAS, ANI has the potential to provide a cost-effective, repeatable measurements for early warning of leakage. Potentially fibre-optics combined with ANI could offer wireline operation free permanent CO_2 storage monitoring capability.

For CO_2 storage applications, the depth of interest necessitates the use of borehole deployed receivers, as surface deployed arrays are relatively insensitive to velocity changes relating to CO_2 movement below ~400m depth. As borehole arrays are also capable retrieving body waves, this has the further potential to increase resolution due to the high frequency content of these signals. However, receiver pairs will need to straddle the monitoring region in order to capture body waves which have passed directly through the rock volume to detect these velocity changes. When these receivers are contained within a single well, Zhou & Paulssen (2017) observed S-wave particle motion in the horizontal direction. This is sub-optimal for DAS measurements from straight fibre, however this may be overcome through using receivers located within different wells or helically wound fibre, see section 2.2.

3 Svelvik CO_2 Field Lab

3.1 General

A photo of the test site is shown in figure 5. The site is located in a old sand and gravel quarry in a glaciofluvial /glaciomarine environment. The site consists of a well in which CO_2 can be injected at rates of up to 21 kg/h. The CO_2 injection occurs at 65m (figure 6) , which is a sand rich level. The injection well is surround by four observation wells, with depths of around approximately 100 m. Wells 1 and 2 lie along the WE axis with a separation of 35 m, wells 3 and 4 lie along the NS axis and are separated by 20 m. DTS and straight DAS cables are installed in all 4 wells in a continuous loop of approximately 1.1 km in length. No Helical cables are currently connected up, although they are present at the site. The structure of the straight and helical cables are shown in figure 6. Normal single mode fibres are used in both. A straight cable containing multimode fibres is also installed in a continuous loop in all four wells for the purposes of temperature measurements.

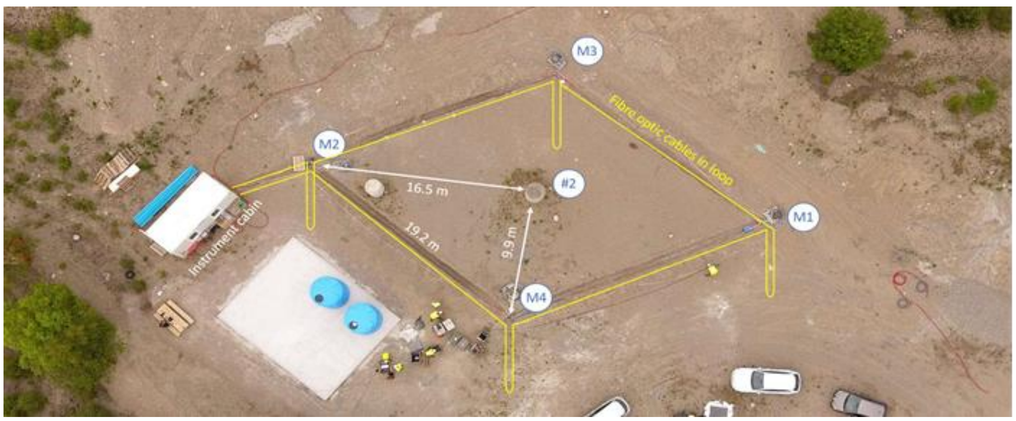

Figure 5) Aerial view of the Svelvik CO_2 injection site.

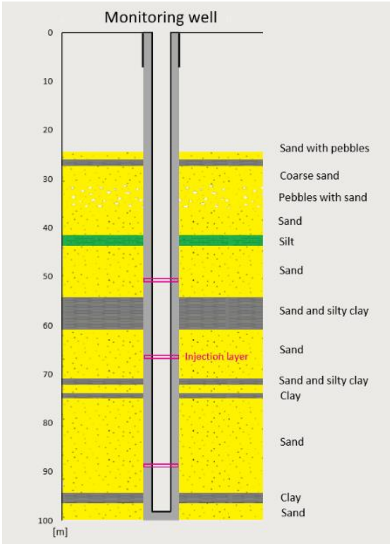

Figure 6) *The geological profile of the monitoring well at Svelvik CO_2 Field Lab*

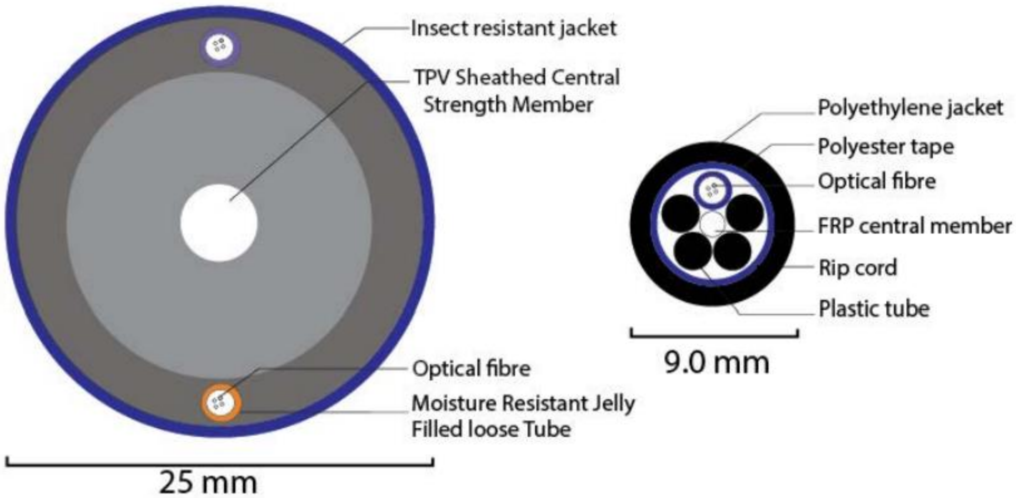

Figure 7) Structure of the helical (left) and straight (right) cables installed at Svelvik.

3.2 Previous cross-well seismic investigation at Svelvik CO_2 Field Lab – PREACTS project

The PREACTS project hosted by SINTEF is currently the only project to have used the Svelvik test site for cross-well seismic measurements in relation to CO_2 injection. Modelling carried out during the PREACTS project, predicted the accumulation of CO_2 in a pancake layer around the injection point at 65m. The modelling also anticipated that most pressure changes would be expected to occur within the first few days following injection. This knowledge was used to help establish the PREACTS measurement plan that used the BIS-SH Source from Geotomographie GmbH generating horizontally polarized shear waves (SH) and compressional waves (P). For S-wave measurements, a single S-wave seismometer was used. For cross well tomography, the S-wave source and detectors were moved at intervals of 1 m. The S-wave source and detectors were coupled to the borehole wall by a pneumatic clamping system. For P-wave measurements, a string of 24 hydrophones with one meter spacing (BHC4 from Geotomographie GmbH) was used and the seismic source was moved at one depth intervals. Neither the P- wave source nor the hydrophone strings were clamped in place.

The test plan was approximately as follows:

Date	Cross well seismic measurements	Injection
Thursday 24th October	1D-4D s-wave NS 2D-4D p-wave EW (not full depth range)	11 kg/h
Friday 25th October		
Saturday 26th October	No measurements	No injection
Sunday 27th October		
Monday 28th October	1D-4D s-wave NS 2D-4D p-wave EW (not full depth range)	8 kg/h
Tuesday 29th October		
Wednesday 30th October	Cross well s-wave scan	8 kg/h
Thursday 31st October	P-wave tomography	8 kg/h
Friday 1st November	Cross well s-wave scan	8 kg/h
Saturday 2nd November	No measurements	8 kg/h
Sunday 3rd November		
Monday 4th November	Cross well s-wave scan	8 kg/h
Tuesday 5th November	1D-4D s-wave NS 2D-4D p-wave EW (not full depth range)	No injection
Wednesday 6th November	P-wave tomography	No injection

Table 1: Approximate cross well seismic test plan for tests carried out at Svelvik during the PREACTS project.

The investigations did not confirm the modelled prediction that CO_2 would accumulate in a so called "pancake" layer of around 65 m depth. Instead CO_2 migrated along the borehole and was observed to accumulate at around 38 m depth below the mud zone close to well3, see figure 8.

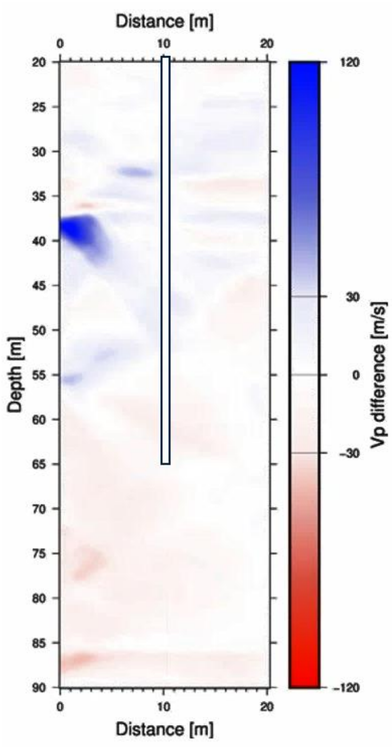

Figure 8). P-wave velocity change tomography at the Svelvik CO_2 field lab following a few days of CO_2 injection (Jordan 2020)

The PREACTS project also notice a fairly significant pressure modulation in the wells due to the tidal effects. This influence the shape of the waveforms slightly.

4 Svelvik test plan for Digimon project

4.1 Motivations

The Svelvik test is related to the following Digimon activities:

- Testing Geotomographie's SV-wave source.
- Provide input into knowledge of the DAS transfer function (variables: type of seismic source, angle of incidence, straight vs helical cable).
- Seismic tomography for measuring uplift phenomena and stress induced anisotropy.

Note that ANI cross well tomography is not covered in the Svelvik test.

4.2 Input from the PREACT investigations

NORCE and Geotomographie have had some discussions with Michael Jordan from SINTEF who was in charge of planning the Svelvik investigations in the PREACTS project, and we received the following advice concerning the planning of the DIGIMON testing:

- If you are using the S-wave source and want to observe extremely clean 4D effects (e.g., during changing pressure or CO2 saturation) and exclude any effects that are not related to changes in the subsurface between source and receiver, I would recommend to leave the source place (clamped to the casing) during the duration of the measurement since we observed that different positions of the source may cause slight changes in the waveform (potentially due to deformations of the casing caused by the clamping). This is not an issue for the P-wave source, hydrophone chains, or the DAS cables.
- I would inject over a longer time at a low injection rate of 8 kg/h). Due to time constraints, the injection was stopped after 192 h (~8 days).

Note that due to budget constraints, it is unlikely that the Digimon investigations will involve more than 4-5 days of injection.

4.3 Proposed measurement plan

This test plan has not yet been finalized. As of 16.12.2020, negotiations are taking place between NORCE and SINTEF to establish whether the proposed plan can be carried out within the available budget. To get a helical cable connected up in a continuous loop is too expensive. However, connecting up a helical fibre in one well is feasible. We have asked SINTEF to investigate connecting a helical fiber in M4? to the end of the straight fibre loop. This single continuous fibre configuration would mean that we would not need to make separate measurements for the straight and helical fibre, therefore saving time. DTS measurements will be carried out in parallel with the DAS measurements. In addition to Geotomgraphie's new SV source, the same equipment will be used as for the Pre-ACTs investigation (see section 3.2).

<table>
<tr><th>Day</th><th>Date</th><th>Activity</th><th>DAS</th><th>Injection</th></tr>
<tr><td>1</td><td>Monday 3rd May</td><td>Arrive on site.

Set up and test equipment:

P-wave excitations at 60 m depth in M1.</td><td>Straight cables + Helical cable in M3.

Repeat for 3 different gauge lengths</td><td>No Injection</td></tr>
<tr><td>2</td><td>Tuesday 4th May</td><td rowspan="2">Baseline measurements
P wave : Source in M4, Hydrophone string in M3.
Series 1: Hydrophone covering 28-52m, 24 source positions (24 measurements, repeat 5 times for stacking)
Series 2: Hydrophone covering 53-76m, 24 source positions (24 measurements, repeat 5 times for stacking)

SH wave : Source in M4, seismometer in M3.
Cross well measurements from 27-76m, in 1 m intervals. (48 measurements, repeat 5 times for stacking)

SV wave : Source in M4, seismometer in M3
Cross well measurements from 27-76m, in 1 m intervals. (48 measurements, repeat 5 times for stacking)</td><td rowspan="2">Straight cables + Helical cables</td><td rowspan="2">No Injection</td></tr>
<tr><td>3</td><td>Wednesday 5th May</td></tr>
<tr><td>4</td><td>Thursday 6th May</td><td>AM:
SV or SH wave: M3-M4 cross well measurements at 38m depth and 30 min intervals (6 measurements)
PM
SV or SH wave: M3-M4 cross well measurements at 65m depth and 30 min intervals (6 measurements)</td><td>Straight cables + Helical cables</td><td>TBD (constant value between 8-21 kg/h)</td></tr>
</table>

5	Friday 7th May	AM: **SV or SH wave**: M3-M4 cross well measurements at 38m depth and 30 min intervals (6 measurements) PM **SV or SH wave**: M3-M4 cross well measurements at 65m depth and 30 min intervals (6 measurements)	Straight cables + Helical cables	TBD (constant value between 8-21 kg/h)
6	Saturday 8th May	No measurements		TBD (constant value between 8-21 kg/h)
7	Sunday 9th May	No measurements		TBD (constant value between 8-21 kg/h)
8	Monday 10th May	Repeat of days 2-3		TBD (constant value between 8-21 kg/h)
9	Tuesday 11th May			TBD (constant value between 8-21 kg/h)
10	Wednesday 12th May	Pack down and leave		

4.4 Data processing plan

4.4.1 Conventional seismics

Geotomographie will carry out analysis of the conventional seismic data for the purposes of qualifying SV source, and analysis of s-wave cross-well and p-wave tomography as a function of CO_2 injection.

4.4.2 Distributed measurements

NORCE will carry out basic signal processing of the raw DAS data and make this available in a format agreed with Geotomographie. Geotomographie will pick the arrival times of the DAS data to evaluate the combination of conventional and DAS data within a tomographic data analysis. NORCE carry out additional analysis to give added information with regards to the transfer function of the straight and helical cables as a function of seismic source (P,SV, SH), and angle of incidence.

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