Deliverable 1.1 Addendum 3:

Cross hole seismic experiment with DAS/DTS data

Svelvik CO2 field lab

DigiMon

Digital monitoring of CO_2 storage projects

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1 Introduction

1.1 Survey Objectives

Primary purposes of the fieldwork at Svelvik include the provision of datasets which supports task 1.2 ‘determining the DAS transfer function’ and task 1.3 ‘develop DAS data processing techniques and workflow’. The fieldwork also serves as a test of the novel SV wave seismic source developed as part of Task 1.4. ‘Active source technology development and optimising monitoring design.

Relevant functions of the fieldwork for Digimon:

1. Microseismic dataset, detection of CO_2 injection:
    - Testing processing workflow, e.g. testing detection algorithms;
    - Temporarily densify the broadband network with 3C nodes.
2. Dataset for ambient noise interferometry:
    - Classify noise sources and compare response on broadband and fibre arrays;
    - Joint cross-correlation of nodes/Broadband seismometers and fibre.
3. Transfer Function:
    - deconvolving response from co-located nodes.
4. Response of straight and helical wound fibre:
    - Sensitivity of different fibre configurations.
5. SV source characterisation
    - Measuring uplift phenomena and stress induced anisotropy
6. Comparisions between cross-hole conventional and DAS tomographic data

2 Description of Dataset

2.1 Site Description

Svelvik CO_2 Field Lab, near Drammen in Norway, consists of an injection well and four monitoring wells. The injection well is designed for injecting CO_2 and is equipped with a screen at 64-65 m depth. The four monitoring wells are 100 m deep and positioned at the corners of a rhombus with the injection well (#2) in the centre. The monitoring wells are located 9.9 m (M3 and M4) and 16.5 m (M1 and M2) from the injection well. The section between M1 and M2 is oriented in the EW direction, while the section between M3 and M4 is oriented in the NS direction. The monitoring wells are completed with PVC casing and instrumented behind the casing with:

- Sensors measuring pressure and temperature at the depth of injection
- Commercial fibre optic cables from SOLIFOS: Straight DTS (Distributed Temperature Sensing) and DAS (Distributed Acoustic Sensing)
- Helical fibre optic cables provided by Lawrence Berkley National Laboratory (LBNL).

Figure 1: Aerial image showing Verket with the site area of Svelvik CO_2 Field Lab marked as a rotated rectangle with white border close to the centre of the image.

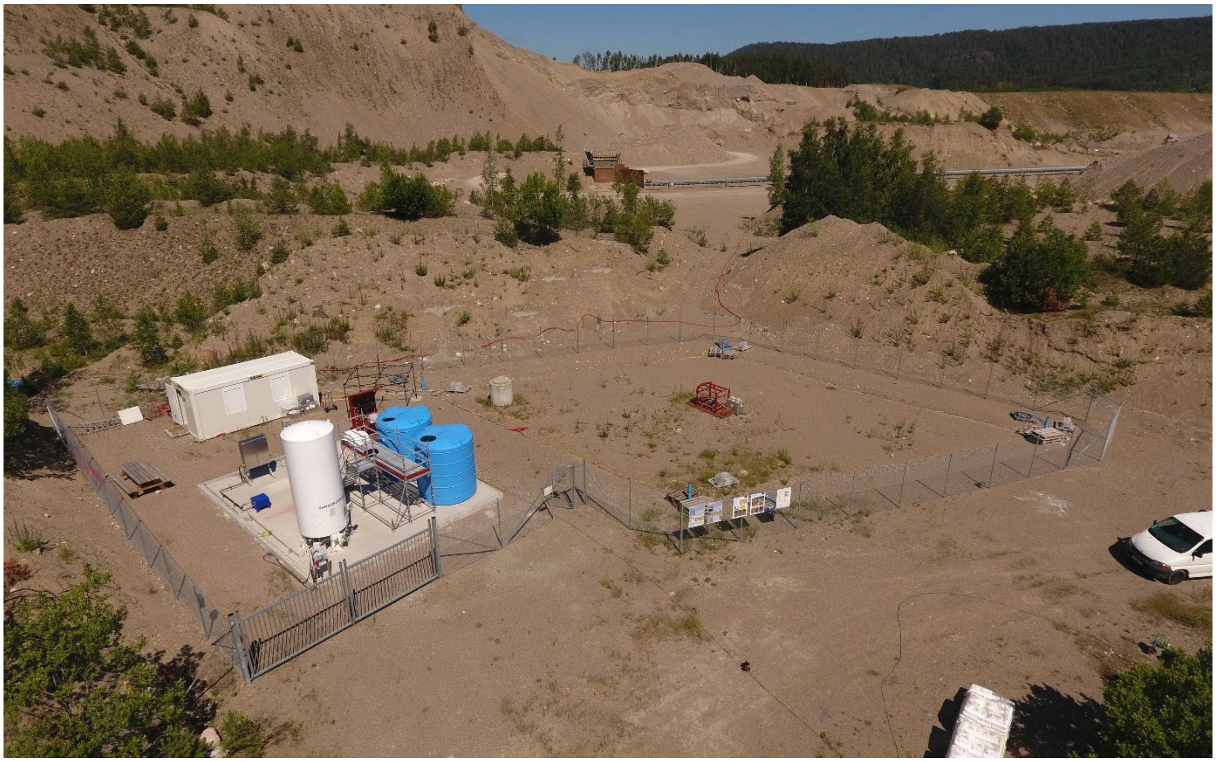

Figure 2: Drone view of Svelvik CO_2 Field lab

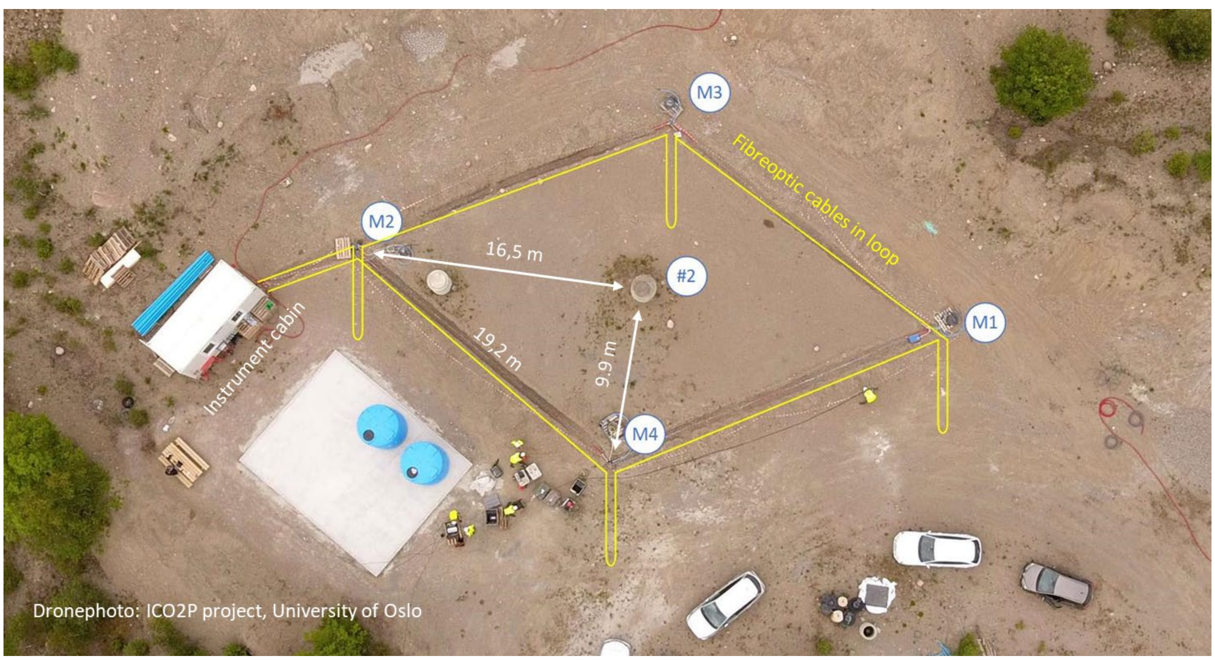

Figure 3: Aerial view of the Svelvik CO_2 Field Lab with injection (#2) and monitoring wells (M1-M4) marked. The loops with commercial fibre optic cables are shown in yellow indicating how the cable goes down and up the monitoring wells.

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2.2 Acquisition Timetable

Table 1 below shows the timeline for the survey acquisition at Svelvik.

The borehole depths and deviations were determined in all four monitoring wells. The seismic sources were always placed in monitoring well M4 and the seismic receivers were placed in M3. To understand the spatial distribution two extra measurements were made with the seismic P-wave source in M2 and receivers in M3. Three different sources were used and surveying was focused on those depths where most changes are expected due to CO2 injection.

Survey 1: P wave receivers and source range from 30 – 77 m @ 1m spacing
Survey 2: SH wave receivers and source range from 32-46 m @ 2m spacing and different polarization (+ and -)
Survey 3: SH wave receivers and source range from 58-72 m @ 2 m spacing and different polarization (+ and -)
Survey 4: SV wave receivers and source range from 32-46 m @ 2m spacing and different polarization (up and down)
Survey 5: SV wave receivers and source range from 58-72 m @ 2 m spacing and different polarization (up and down)

Day	Date	Activity
1	Monday 13.09	Depth Measurement of all monitoring wells Borehole deviation of all monitoring wells. Cable mapping of DAS and DTS cables
2	Tuesday 14.09	Survey 1 Survey 2 Survey 3
3	Wednesday 15.09	Survey 4 Survey 5
4	Thursday 16.09	Injection started 8kg /h Survey 1 (AM) Survey 3 Survey 5 Survey 1 (PM)
5	Friday 17.09	Survey 1 (AM) Survey 2 Survey 3 Survey 5 Survey 1 (PM)
6	Saturday 18.09	Survey 1 Survey 2 Survey 3

		Extra Survey with source in M2 and receiver in M3: P wave 30–77 meter, 1 m spacing
7	Sunday 19.09	Survey 1 Survey 2
8	Monday 20.09	Survey 1 Survey 2
8	Tuesday 21.09	Survey 1 Survey 2 Extra Survey with source in M2 and receiver in M3: P wave 30–77 meter, 1 m spacing
10	Wednesday 22.09	No measurements

Table 1: Survey timeline

2.3 Survey Personnel

- Peter Thomas and Inge Klepsvik (part of survey), NORCE
- Anna Stork and Rumen Karaulanov (part of survey), Silixa
- Thomas Fechner, Uta Koedel and Moritz Woltemate (Geotomographie GmbH)

The responsible person of the test site was Martin Raphaug from Sintef.

***Figure 4: Core DigiMon Survey team supported by Martin Raphaug*.**

2.4 Instrumentation for cross-hole seismic experiments

At the Svelvik site tomographic measurements were used to image structures in the subsurface in 2D. The change of the source position within the borehole enables the measurement of many rays with different angles to reach a complete/high ray coverage so that small scaled structures in between can be resolved and located. While, P-wave tomography is a standard method for high-resolution geological structure exploration between boreholes, S-waves provides a much higher resolution. However, the processing of S-wave data requires more sophisticated and skilled personnel. Figure 5 and 6 illustrate the applied devices for P- and S-wave tomographic measurements.

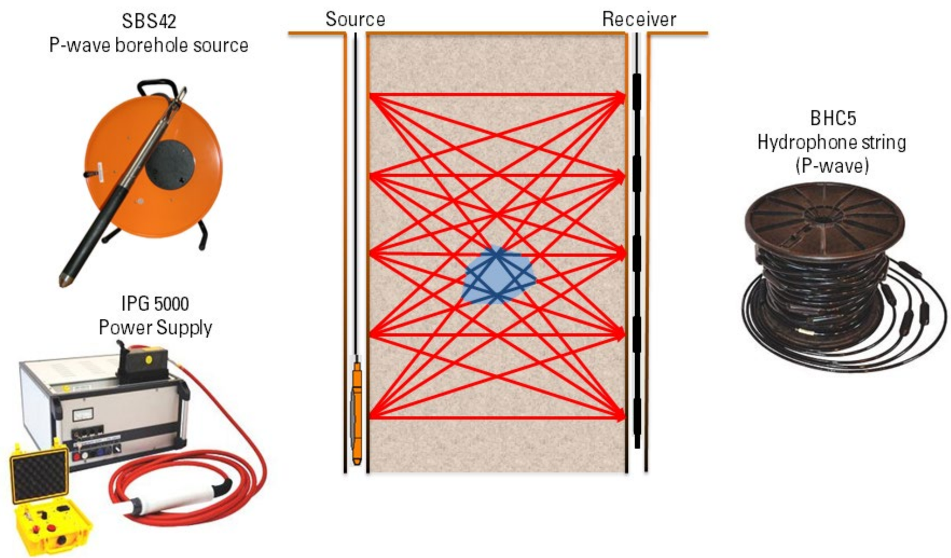


Figure 5: Devices for P-wave tomography (Geotomographie GmbH)

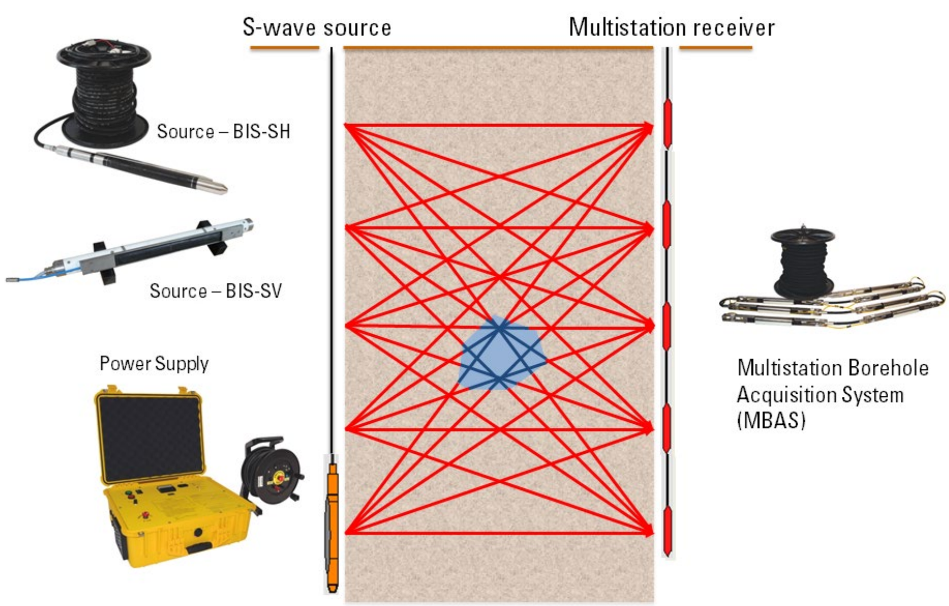


Figure 6: Devices for S-wave tomography (Geotomographie GmbH)

At the test site in Svelvik we applied P-wave sources, SH-wave (horizontally polarized, where particle motion is horizontal) and the novel SV-wave (vertically polarized shear wave, where particle motion is vertical) sources.

Figure 7: Three applied seismic sources (SBS42 right, BIS-SV middle and BIS-SH left)

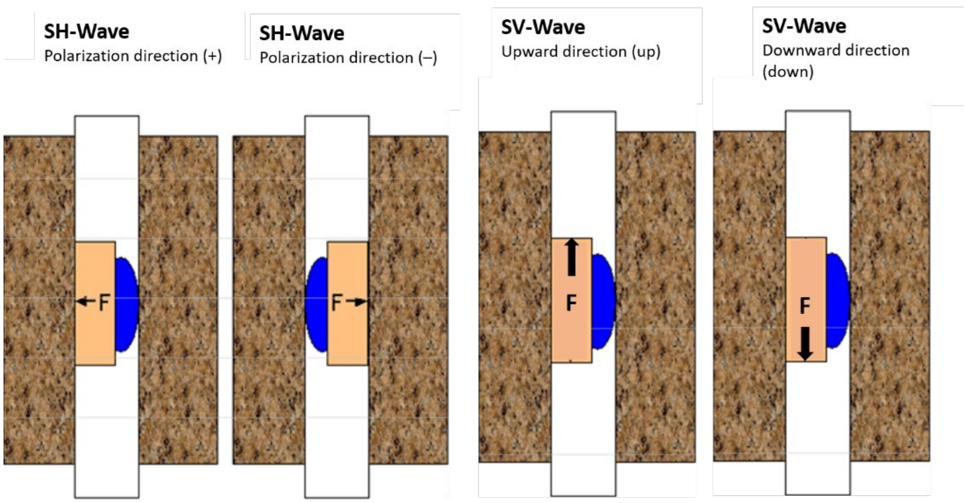


Figure 8: Characteristics of SH and SV source.

In the following all relevant devices are described.

2.4.1 Borehole depth

To measure the borehole depth a water level meter was used. With help of this device the water level and the depth of the boreholes were measured.

2.4.2 Deviation probe

Borehole deviation is required to determine the precise XYZ location of a seismic source or geophone inside a borehole. For the experiment the Deviation Probe DevProbe1 (Geotomographie GmbH) is used to measure the borehole deviation. A three-axis magnetometer measures the azimuthal direction of the borehole and a dual tilt sensor provides information about the inclination.

Figure 9: Borehole deviation tool (Geotomographie GmbH)

Bohrloch M4 **Geotomographie / Germany 16.9.2021**

Depth*	Values		Deviation		True	Absolute Coordinates UTM32		
	υ	δ	East	North	Depth*	East	North	Elevati
[m]	[°]	[°]	[m]	[m]	[m]	[m]	[m]	[m]
						0.000		
0	-	-	0.000	0.000	0.00	580445.790	6609368.200	1.984
2	0.17	30.3	0.003	0.005	-2.00	580445.793	6609368.205	-0.016
3	0.73	159.9	0.007	-0.007	-3.00	580445.797	6609368.193	-1.016
4	0.34	233.5	0.003	-0.010	-4.00	580445.793	6609368.190	-2.016
5	0.23	143.3	0.005	-0.014	-5.00	580445.795	6609368.186	-3.016
6	0.18	33.2	0.007	-0.011	-6.00	580445.797	6609368.189	-4.016
7	0.17	273.6	0.004	-0.011	-7.00	580445.794	6609368.189	-5.016
8	0.32	217.1	0.000	-0.015	-8.00	580445.790	6609368.185	-6.016
9	0.26	326.8	-0.002	-0.011	-9.00	580445.788	6609368.189	-7.016
10	0.23	278.3	-0.006	-0.011	-10.00	580445.784	6609368.189	-8.016
11	0.14	351.2	-0.006	-0.008	-11.00	580445.784	6609368.192	-9.016

Figure 10: Example of borehole deviation data

2.4.3 Trigger

The data collection by the iDAS was triggered using a novel wireless trigger unit and a normal trigger box with a TTL pulse.

The novel wireless trigger unit works with nearly all impulse sources and has an antenna range of 18 metres. It consists of two boxes which include the sender and the receiver unit connected to the source (sender) and to the seismograph (receiver).

Figure 11: Wireless trigger Unit

2.4.4 Seismic sources

Three different waves were generated at the Svelvik test site by three different seismic sources; the compressional waves (P), the horizontally polarized shear waves (SH) and the vertically polarized shear waves (SV).

The Impulse Generator IPG5000 supplied high voltage (up to 5kV) to all seismic borehole sources. The Summit X One (manufacturer DMT) was used as the seismograph.
The seismic signals of all three sources (P, SH and SV) are highly repeatable. The sparker pulses are released through manual or automatic triggering of the impulse generator (IPG5000) controlled by the remote-control unit (RCU) (Figure 12). The RCU converts the reference signal of the impulse generator to an accurate time break with an accuracy of a few microseconds.

Figure 12: Impulse generator IPG and remote-control unit RCU

Figure 13: Impressions from measurements in Svelvik

For all experiments a stacking of the seismic signals was performed to increase the signal-noise ratio (P-wave: 4 stacking, SH-wave: 6 stacking, SV-wave: 6 stacking).

2.4.4.1 P-Wave Source

The SBS42 (Geotomographie GmbH) was used as the P-wave source (Figure 14). This borehole source SBS42 generates compressional waves (P) in water filled boreholes (Figure 15).

Figure 14: SBS42 (Geotomographie GmbH)

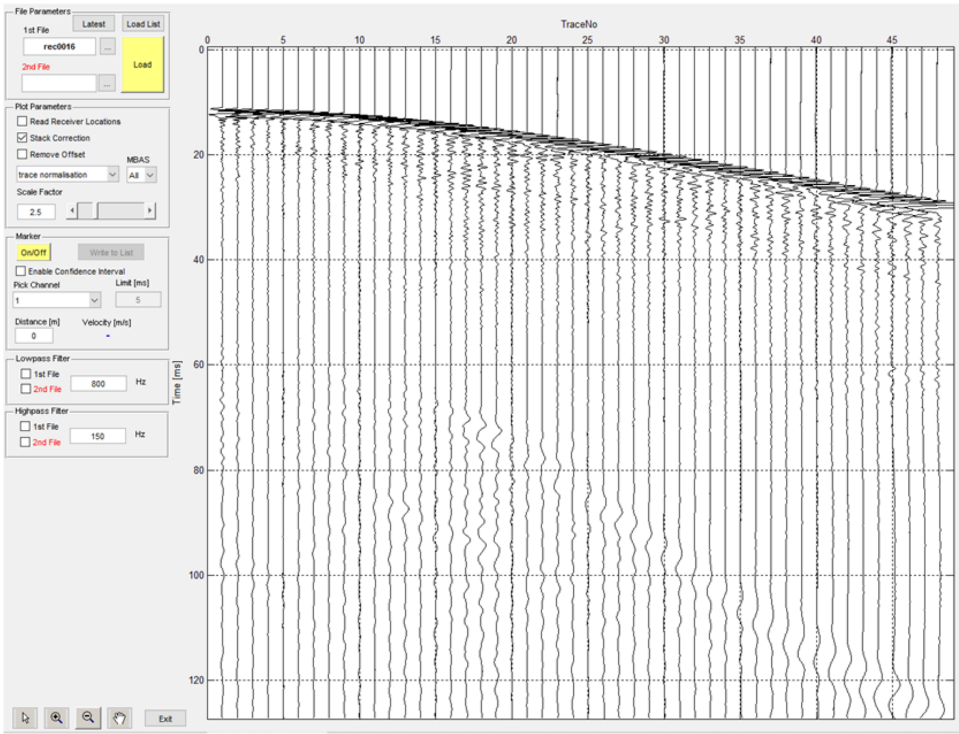


Figure 15: Data example of P-Wave source SBS42

2.4.4.2 SH-Wave

The shear wave source BIS-SH (Geotomographie GmbH) was used (Figure 16). This borehole source BIS-SH generates horizontally polarized shear waves (SH) and compressional waves (P) (Figure 17). In Figure 18 the polarization direction related to the installed boreholes is illustrated.

Figure 16: BIS-SH (Geotomographie GmbH)

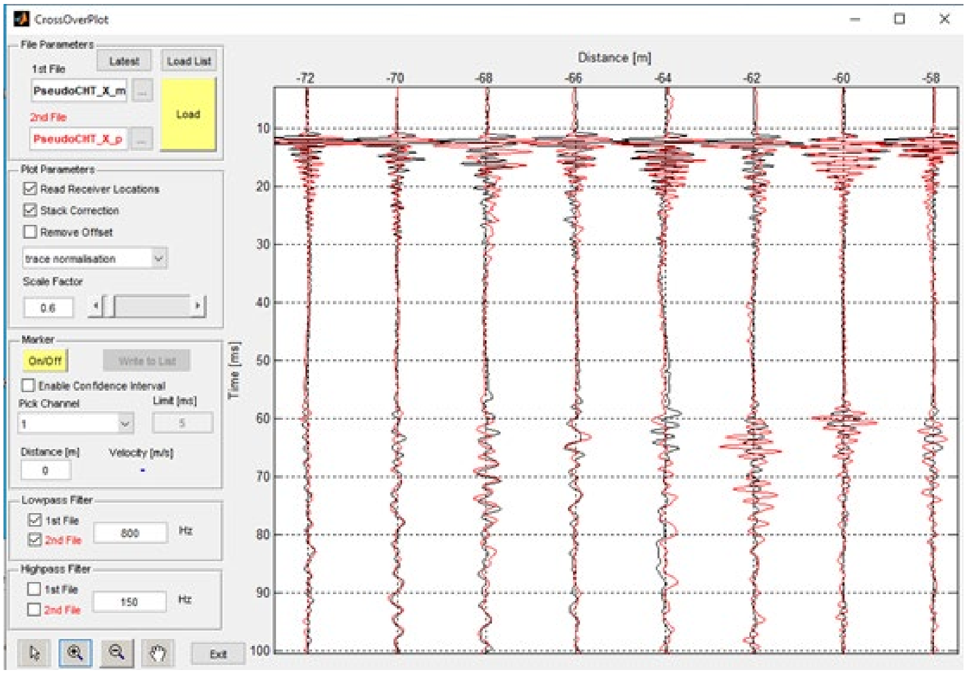


Figure 17: Data example of SH-Wave source BIS-SH

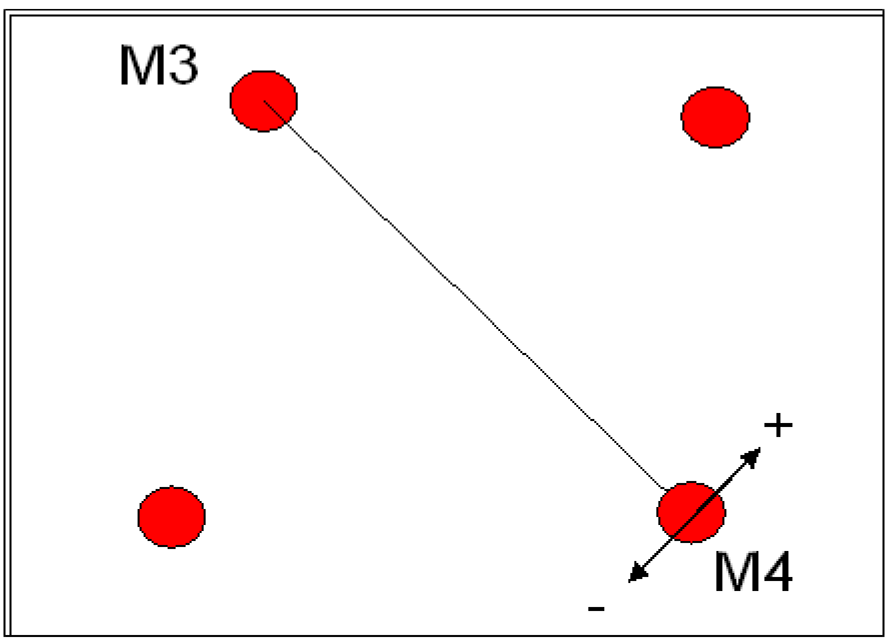


Figure 18: Shot direction of SH source

2.4.4.3 SV-Wave

Within this project a novel BIS-SV (Geotomographie GmbH) was developed (Figure 19). This borehole source BIS-SV generates vertically polarized shear waves (SV) and compressional waves (P).

Figure 19: Prototyp of novel SV source BIS-SV

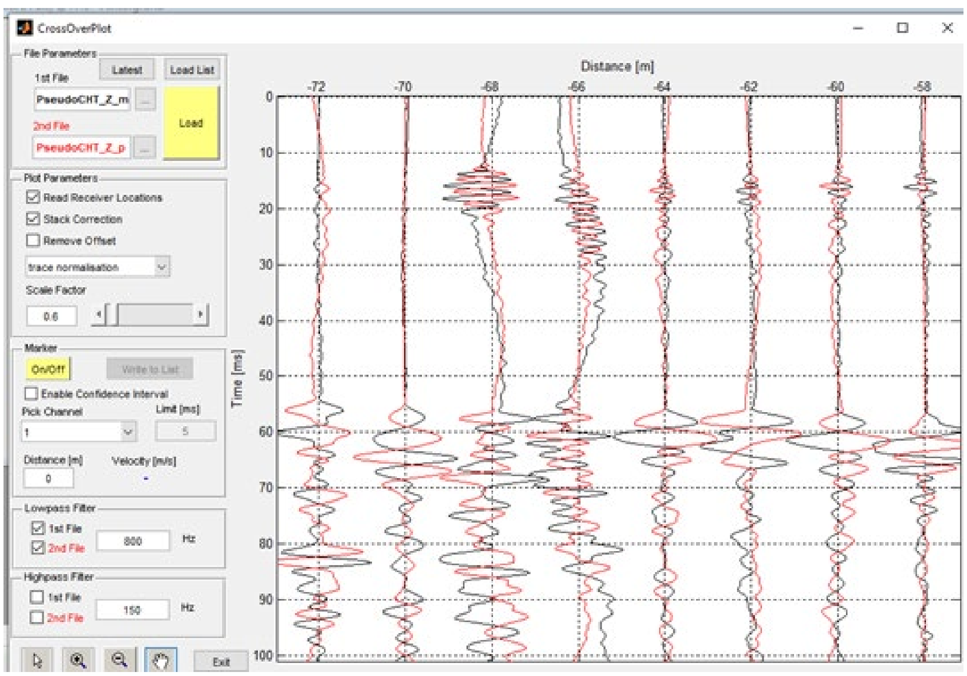


Figure 20: Data example of novel SV Wave source

2.4.5 Seismic Receivers

2.4.5.1 Hydrophone string for P-Wave

Two hydrophone strings BHC5 (Geotomographie GmbH) were used to receive P-waves in the water filled boreholes. The BHC5 consists of a downhole cable containing a Kevlar tension string and a number of moulded hydrophones at pre-defined interval. At Svelvik, a BHC5 with an interval of 1 meter was used. To cover a greater depth range, two hydrophone strings were connected allow the data acquisition in a depth range of 30 – 77 meter.

***Figure** 21: BHC5 (Geotomographie GmbH)*

2.4.5.2 Multistation Borehole Acquisition System for SH/SV wave:

An Multistation Borehole Acquisition System (MBAS) was used to receive P- and SH/SV-waves in the boreholes. The MBAS is a digital three-component geophone string and was redesigned to meet the environmental requirements at Svelvik (Figure 22, 23). The MBAS used had eight individual stations with tri-axial sensors. The stations were aligned to ensure that all horizontal sensors are oriented in same direction. Each station was clamped to the borehole wall by two pneumatic cylinders.

***Figure** 22: Components of re-designed Multistation Borehole Acquisition System (MBAS)*

Figure 23: Redesigned MBAS system at Svelvik test site

	P-wave	SH-wave	SV-wave
Sampling Rate	32kHz	32kHz	32kHz
Samples	4096	8192	8192
Pre-Trigger	20ms	20ms	20ms

Table 2: Applied acquisition parameters

2.5 DAS cables

The fibre-optic cables were installed previously, and data was collected on fibre optic cable loop consisting of linear and HWC cables. Figure 24 shows schematics of the cables used in the survey. A standard telecommunication cable connects the borehole cables. Data were collected on linear fibre in all four monitoring wells, M1, M2, M3 and M4, and on HWC in boreholes M1, M2 and M3. The boreholes are all approximately 100m deep. The exact depths, as measured by Geotomographie GmbH, are given in Table 3. Easting, Northing and elevation data for the boreholes were provided by SINTEF and were measured before boreholes were drilled. To determine the fibre receiver channel positions, Silixa conducted tap tests at the points where the cable entered and exited the boreholes. A schematic of the fibre loop is shown in Figure 25 and the tap test locations are given in Table 4.

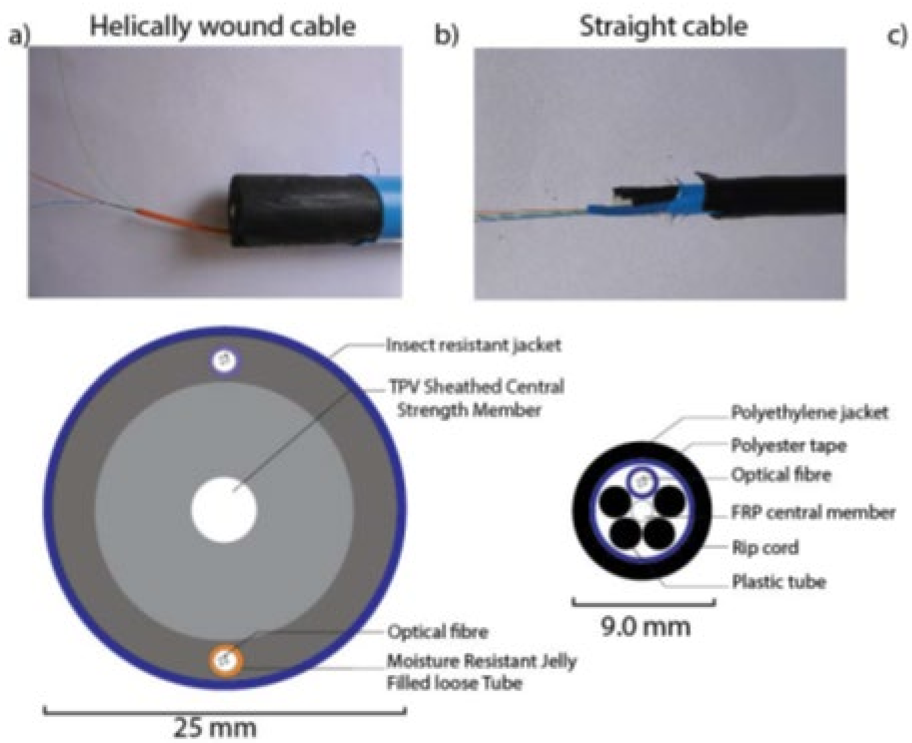


Figure 24. a) HWC and b) linear cables installed at the Svelvik site.

Well	Easting [m]	Northing [m]	Depth from TOC [m]	Elevation TOC [m]	Elevation bottom [m]	Elevation cable in/out [m]
M1	580464.79	6609373.20	100	1.70	-98.29	0.58
M2	580433.0	6609382.0	99	1.89	-97.10	0.67
M3	580451.99	6609387.00	100	1.71	-98.28	0.61
M4	580445.79	6609368.20	98	1.98	-96.00	0.83

Table 3. Coordinates of observation boreholes. In UTM Zone 32V. Borehole depths from top of casing (TOC) and elevations of TOC, cable entry/exit to the borehole and the bottom of the borehole are given.

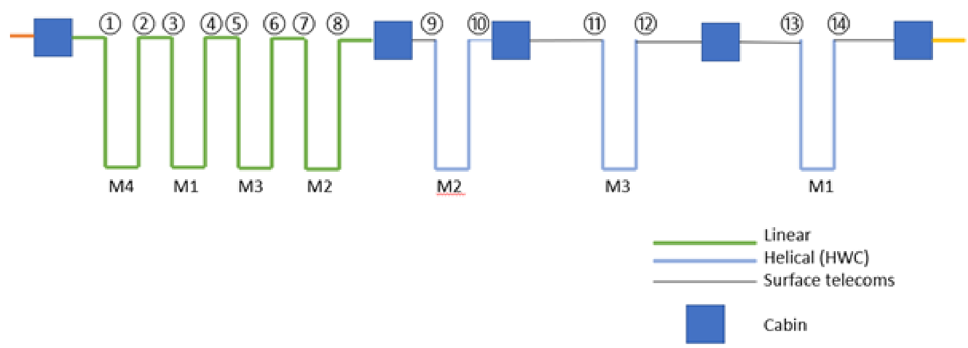


Figure 25. Fibre loop used for recording data. Numbers indicate tap test locations.

Tap Test Location	Well / Fibre / Direction	Fibre distance from start [m]
1	M4 Lin In	84.5
2	M4 Lin Out	282.5
3	M1 Lin In	322.5
4	M1 Lin Out	523.0
5	M3 Lin In	555.5
6	M3 Lin Out	755.5
7	M2 Lin In	778.5
8	M2 Lin Out	979.0
9	M2 HWC In	1032.5
10	M2 HWC Out	1267.0
11	M3 HWC In	1386.0
12	M3 HWC Out	1613.5
13	M1 HWC In	1791.0
14	M1 HWC Out	2020.0

Table 4. Fibre distances for tap test locations labelled in Figure 24.

2.6 DTS cables

BRUsens DTS 6.0 mm non-metallic cable was installed in all four observation wells as indicted by the figure. NORCE carried out a mapping of the cable position using freezing spray to cool the cable, see table 5.

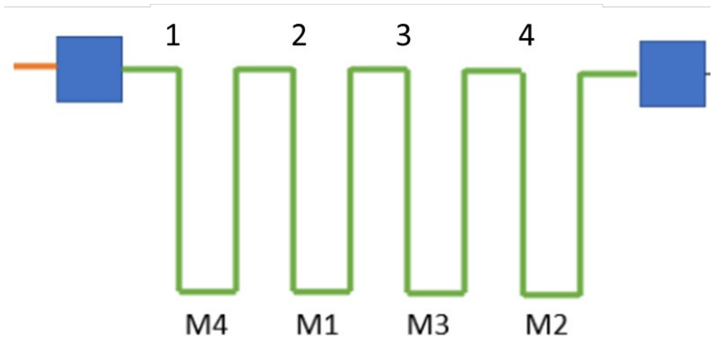


Figure 24. Fibre loop used for recording data. Numbers indicate tap test locations.

Freeze test location	*Well/fibre direction*	*Fibre distance from start /m*
1	*M4 Lin in*	*90.0*
2	*M1 Lin in*	*329.0*
3	*M3 Lin in*	*562.0*
4	*M2 Lin in*	*786.0*

Table 5. Fibre distances for freeze test locations labelled in Figure 24.

2.7 DAS and DTS instrumentation and data collection

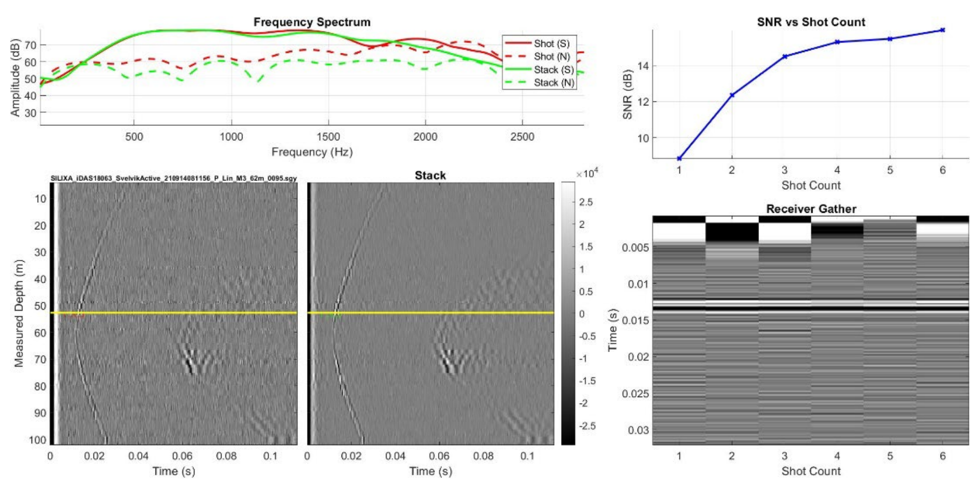
The equipment was set up in the field within the cabin provided by SINTEF situated within a few metres of the wells.

2.7.1 Silixa iDAS

A photo of the Silixa iDAS and associated equipment set up is shown in Figure 26. A GPS antenna was used (which was located outside the cabin). All files were timestamped. This timestamp is recorded in UTC time.

Figure** 26. **Silixa equipment set-up in cabin.

Data were successfully recorded throughout the survey with no data gaps. For the active seismic survey data collection by the iDAS was triggered by trigger devices of Geotomographie GmbH with a TTL pulse. Example stacked shot data for the linear and HWC are given in Figure 27. Passive seismic data were recorded outside of working hours and over the weekend 18-19 September.



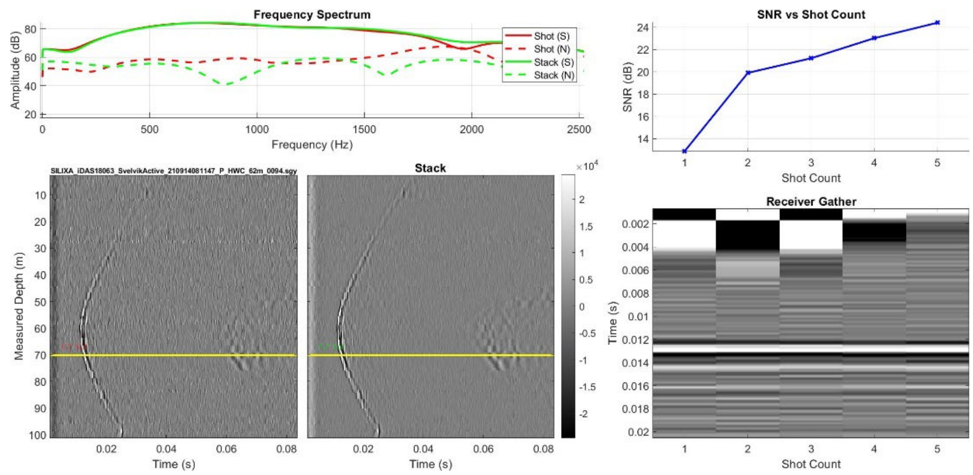


Figure 27. Example single shot and stacked P-wave survey data recorded on the Silixa iDAS on the a) linear and b) HWC. The P-wave source is at 62m depth in M4. Data are recorded in M3 borehole. S-waves are also observed with the P-wave source.

2.7.2 NORCE DAS prototype

NORCE's DAS prototype was connected to a separate fibre to Silixa's unit. The output from a GPS antenna was used to time stamp the data. A trigger signal from Geotomographie's equipment was used to trigger the acquisition along with activation of the seismic sources. Data was acquired throughout the survey timeline. An example of the datasets collected when using the P-wave source is shown in Figure 28. Note that the S-wave signals are also generated by the source.

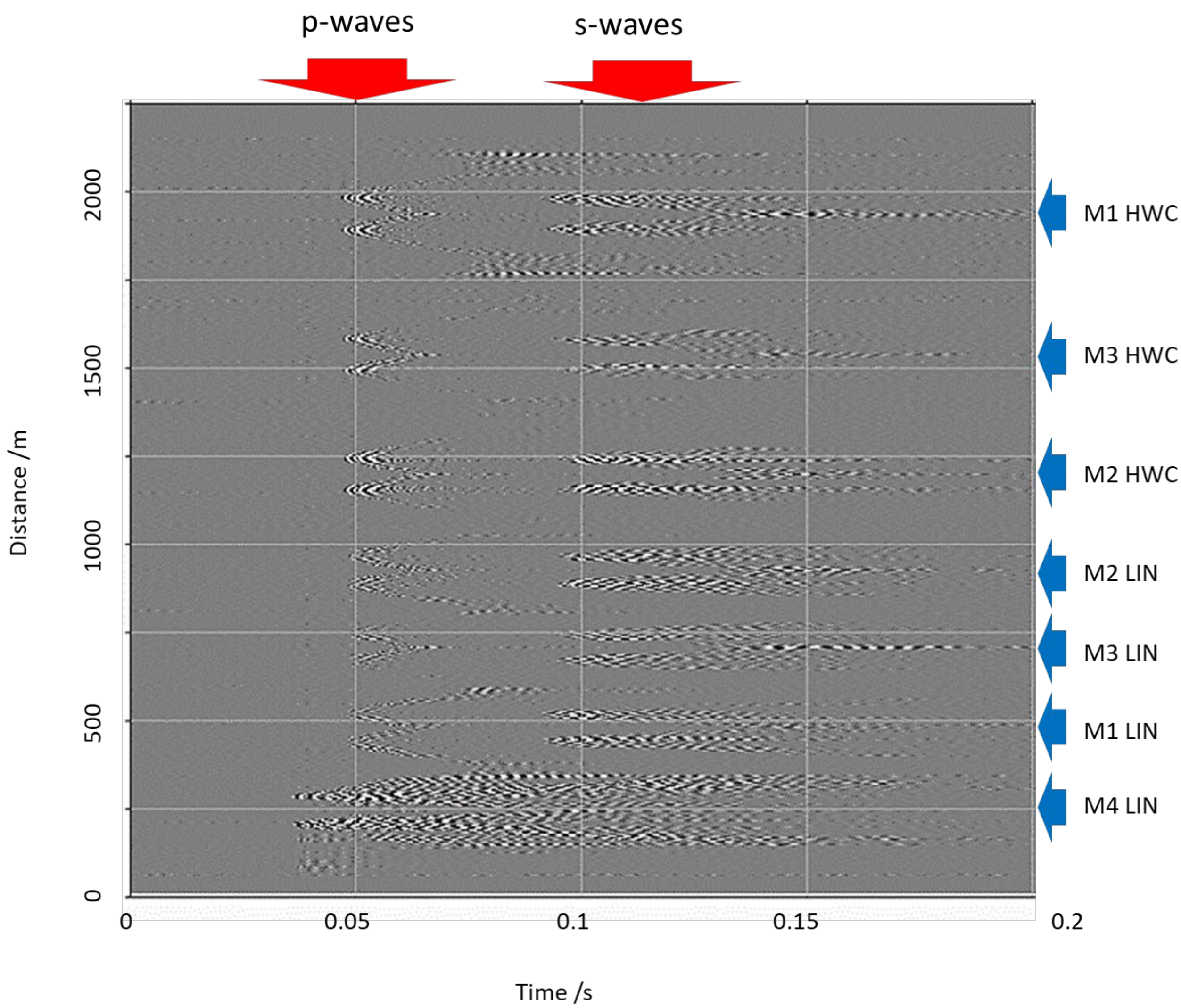


Figure 28. Example stacked P-wave survey data recorded on NORCE's prototype interrogator. The approximate positions of the Linear/helical fibres in the wells are indicated. The approximate time of the p and s wave arrivals are also shown.

2.7.3 DTS measurement (NORCE)

NORCE carried out DTS measurements in 10 minute intervals throughout the survey time line. The measurements were done with a Sensornet Oryx unit. Example data is shown in figure 29.

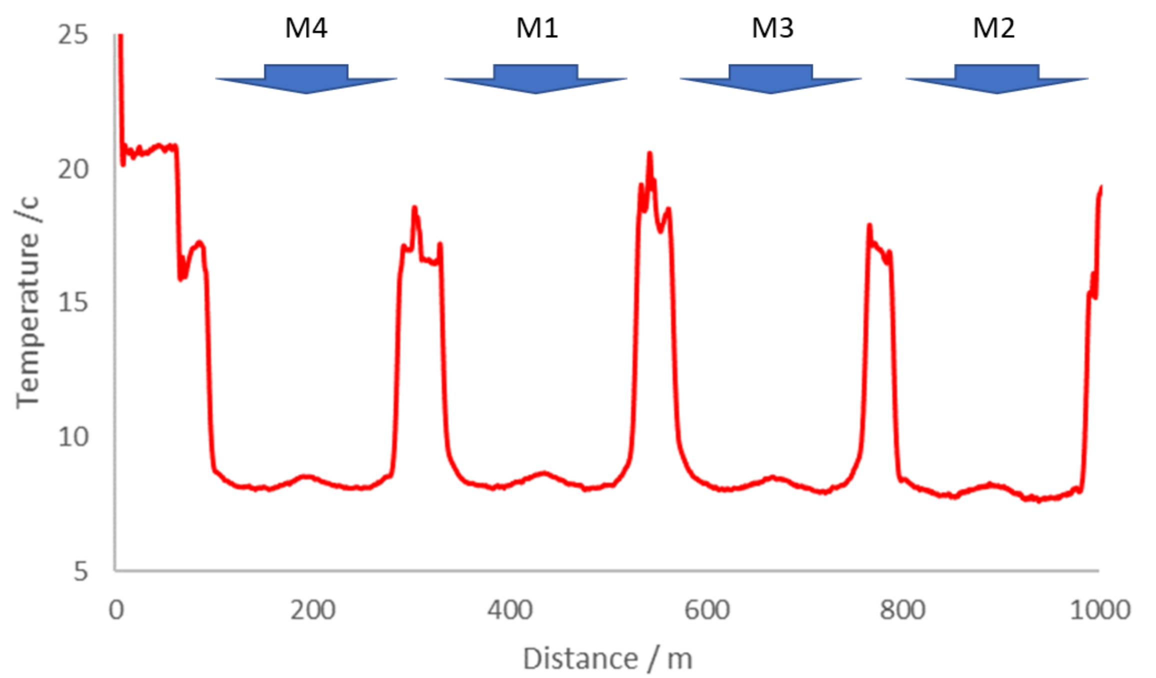


Figure 29. Example DTS data, the approximate positions of each well in the data are indicated by the blue arrows.

2.8 Additional on site measurements from SINTEF

SINTEF logged temperature and pressure in the observation wells and the injection well. The measurements covered the entire survey timeline with a measurement interval of 1 minute.

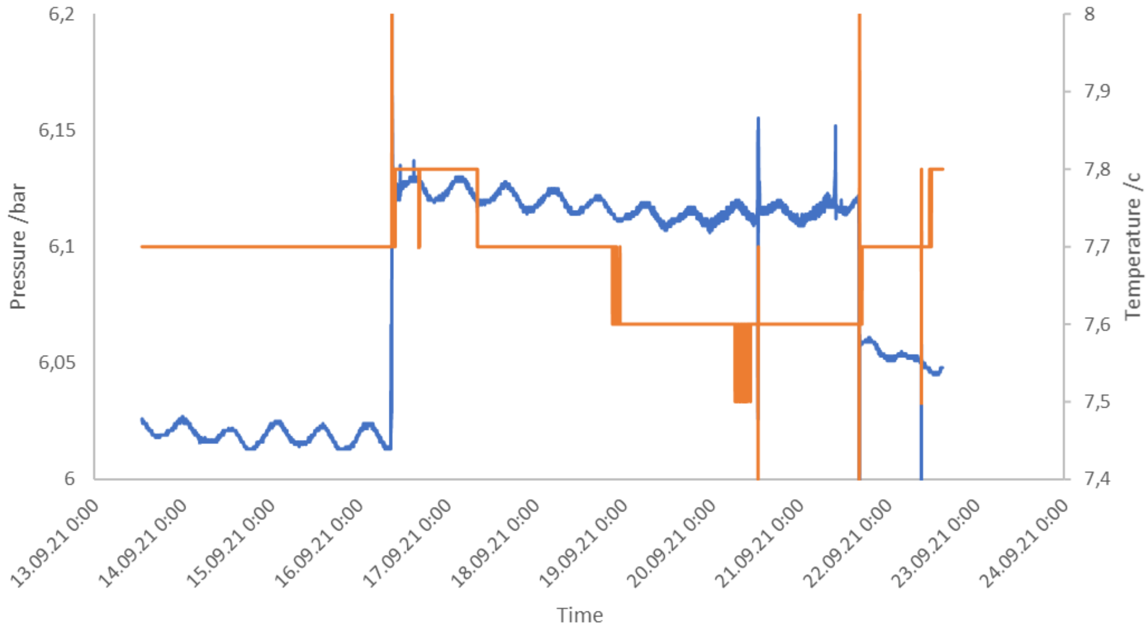


Figure 30. Pressure (blue) and temperature measurements (orange) from the injection well

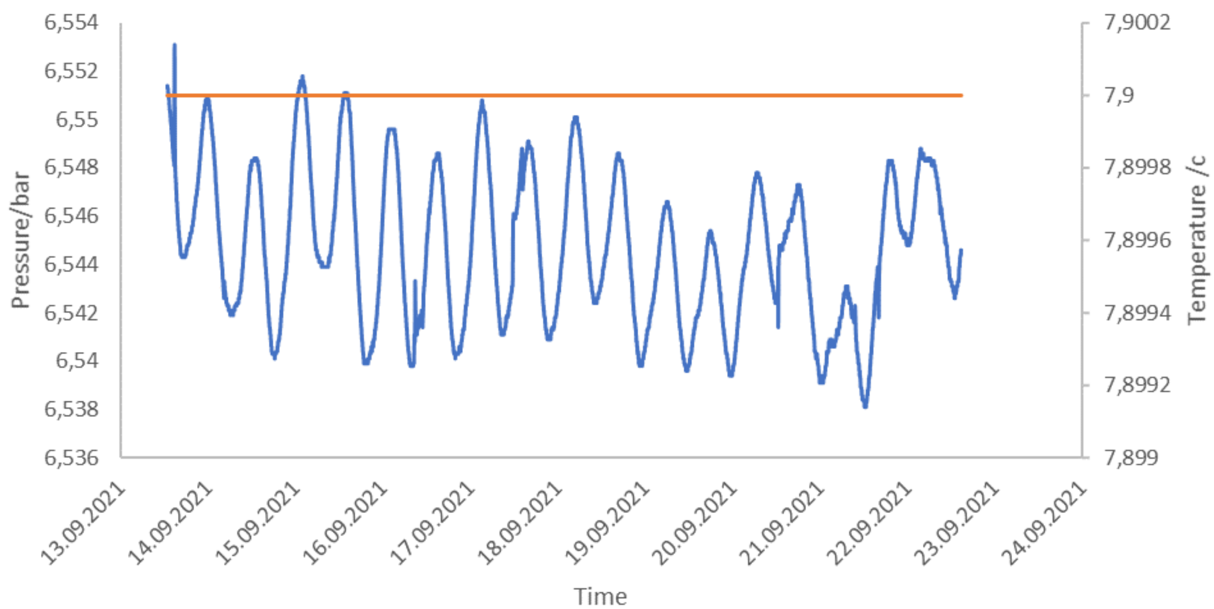


Figure 31. Pressure (blue) and temperature measurements (orange) from well M1. Similar data from the other observation wells are available.

3 Data Access

3.1 Silixa data

All data recorded by the iDAS interrogator are backed up on tape in the Silixa archives. Any requests for data should be made to Silixa. Cable mapping data were made available to Sintef.

3.2 Geotomographie data

All data recorded by the Geotomographie GmbH are available on request. The deviation data (Figure 32) and borehole depths were made available to Sintef.

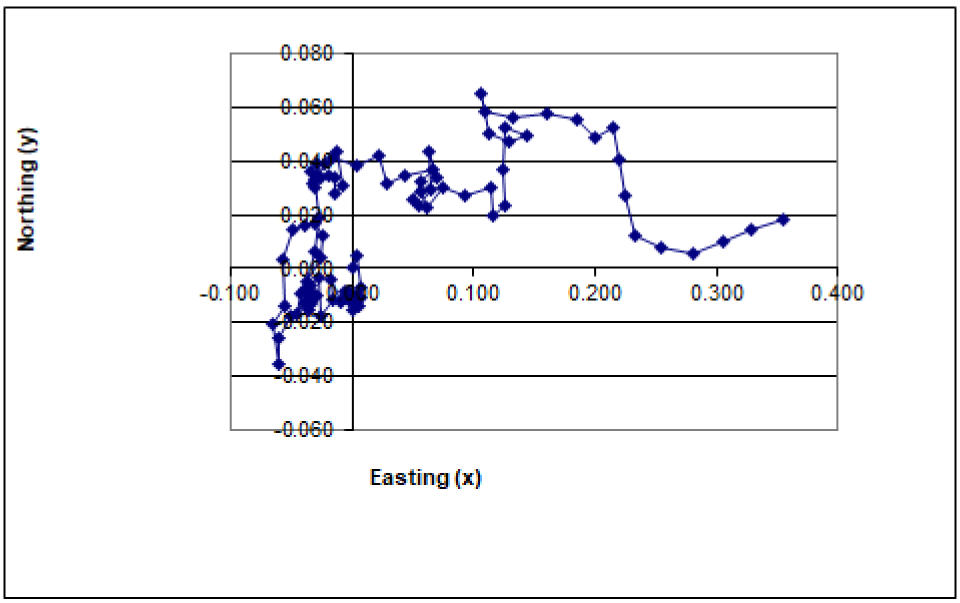


Figure 32: Example of borehole deviation in M4

From the recorded seismic data cross-hole datasets (1D) were extracted for the first data analysis. Cross hole datasets include seismic signals at selected depth intervals where the source and receiver(s) are maintained at equal elevations for each measurement. Such cross-hole datasets provide a depth profile of shear wave velocities (V_S) and compressional wave velocities (V_P) between boreholes at a high vertical resolution (Figure 33- Figure 36).

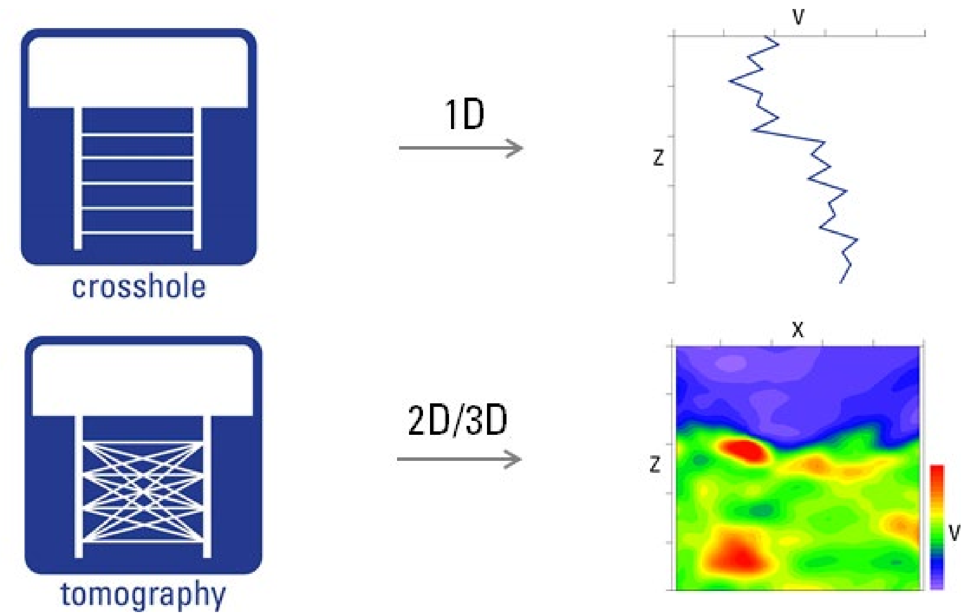


Figure 33: Schematic illustration of cross-hole and tomographic measurement

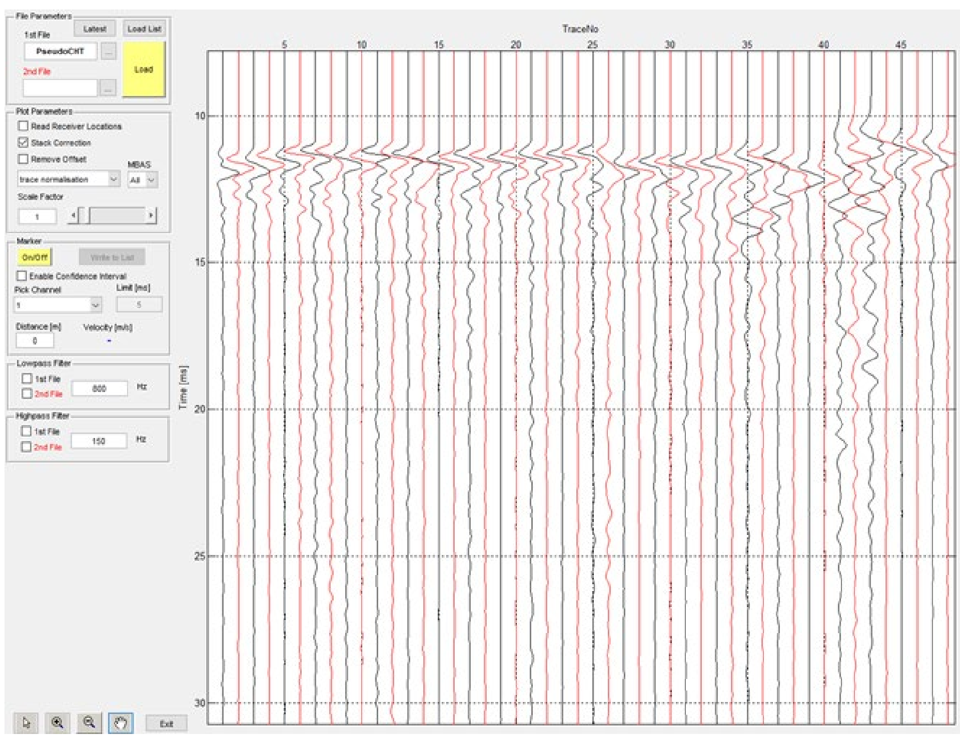


Figure 34: Cross-hole dataset for P-wave (depth 30-77 metre, distance 1 meter)

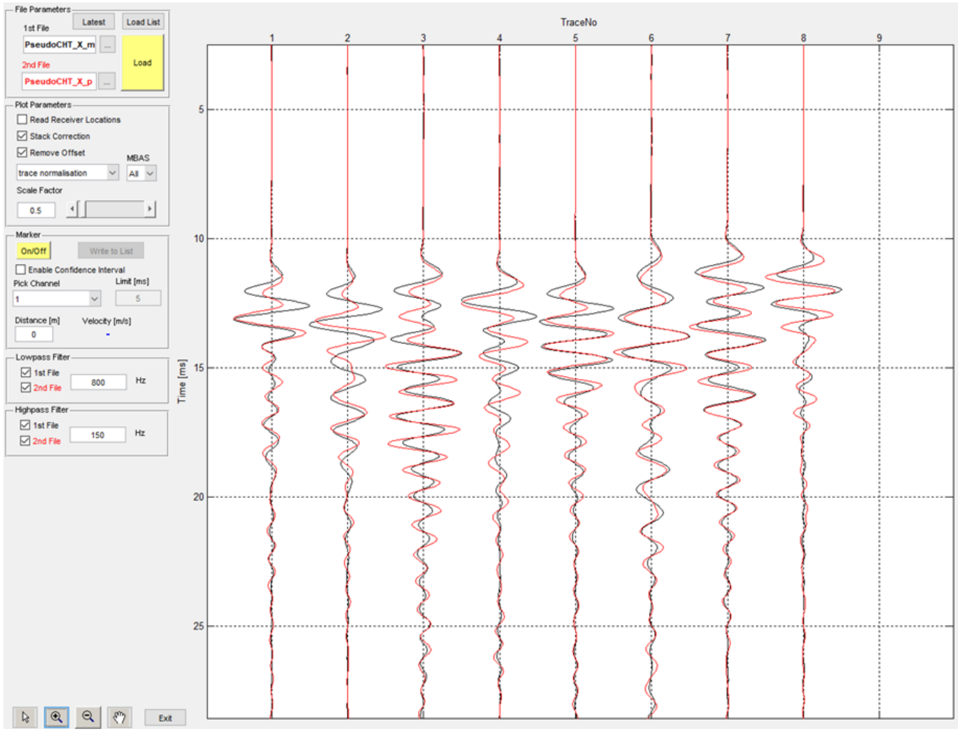


Figure 35: Cross-hole dataset for SH-wave (depth 32-46 metre, distance 2 meter, two different polarization direction (minus: black and plus: red))

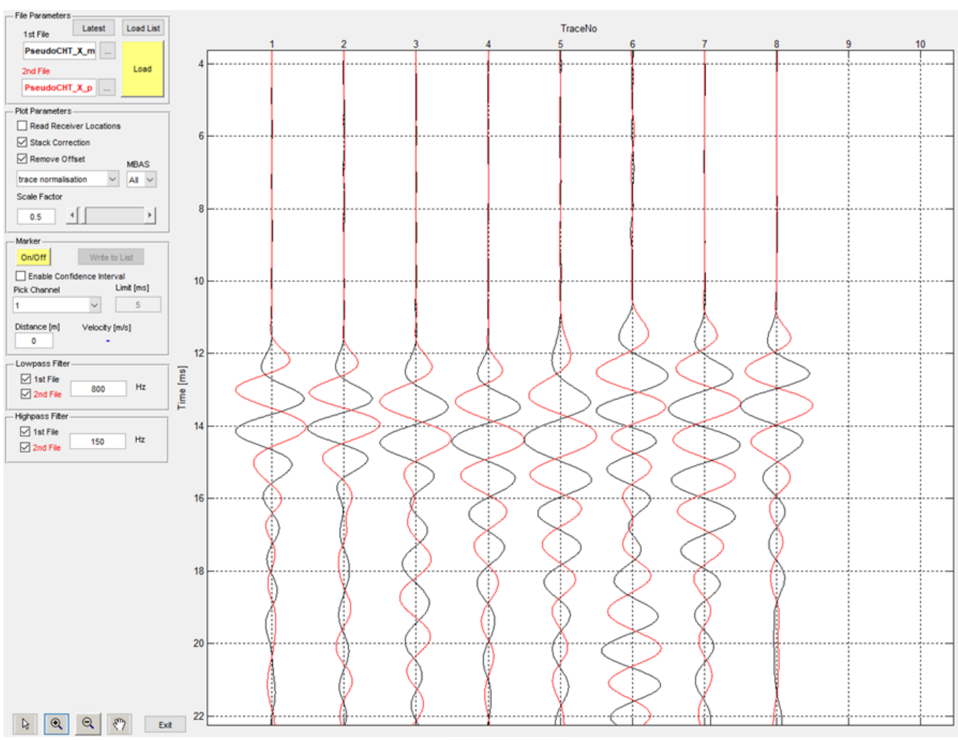


Figure 36: Cross-hole dataset for SV-wave (depth 32-46 metre, distance 2 meter, two directions Up and down)

3.3 NORCE data

Data recorded by the NORCE are available on request. Mapping of the DTS cable positions were made available to SINTEF.

4 Recommended Applications

The Svelvik dataset comprise of continuous data recorded over 8 days. The major component of the data relate to crosshole seismic experiments with p and s wave sources. Data was recorded on two DAS instruments, as well as hydrophone arrays and seismometers. DTS data was also recorded throughout the investigation. Some examples of applications for this dataset include:

- assessment of using DAS for active surveys, e.g. seismic refractions, MASW
- sensitivity of straight/helical fibreoptic cables to seismic signals
- development of a microseismic workflow, e.g. event detection
- research on the transfer function and response of DAS
- development of ambient noise DAS processing workflow