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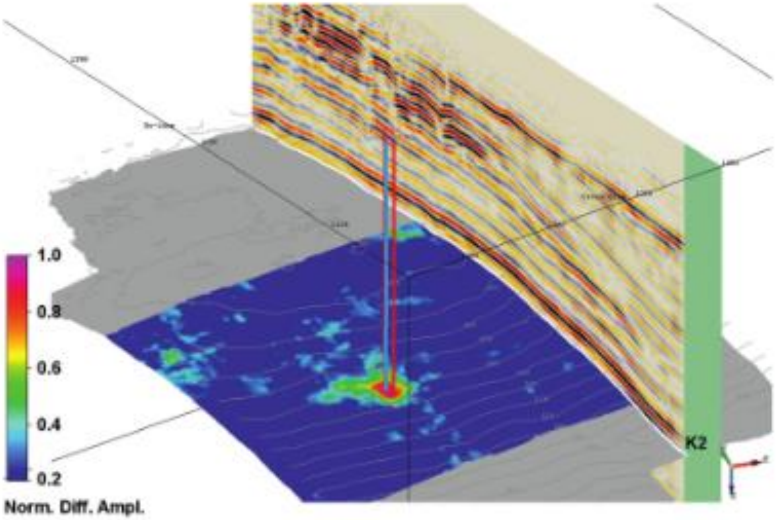
3D time-lapse seismic monitoring of the pilot CO_2 storage site at Ketzin, Germany



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Uppsala University, Sweden

Reflections on Seismic Acquisition, Utrecht, Feb 2017

Outline

- Ketzin CO_2 pilot storage site
- 4D seismic monitoring at Ketzin
- Time-lapse signature
- CO_2 plume development and migration
- Conclusions

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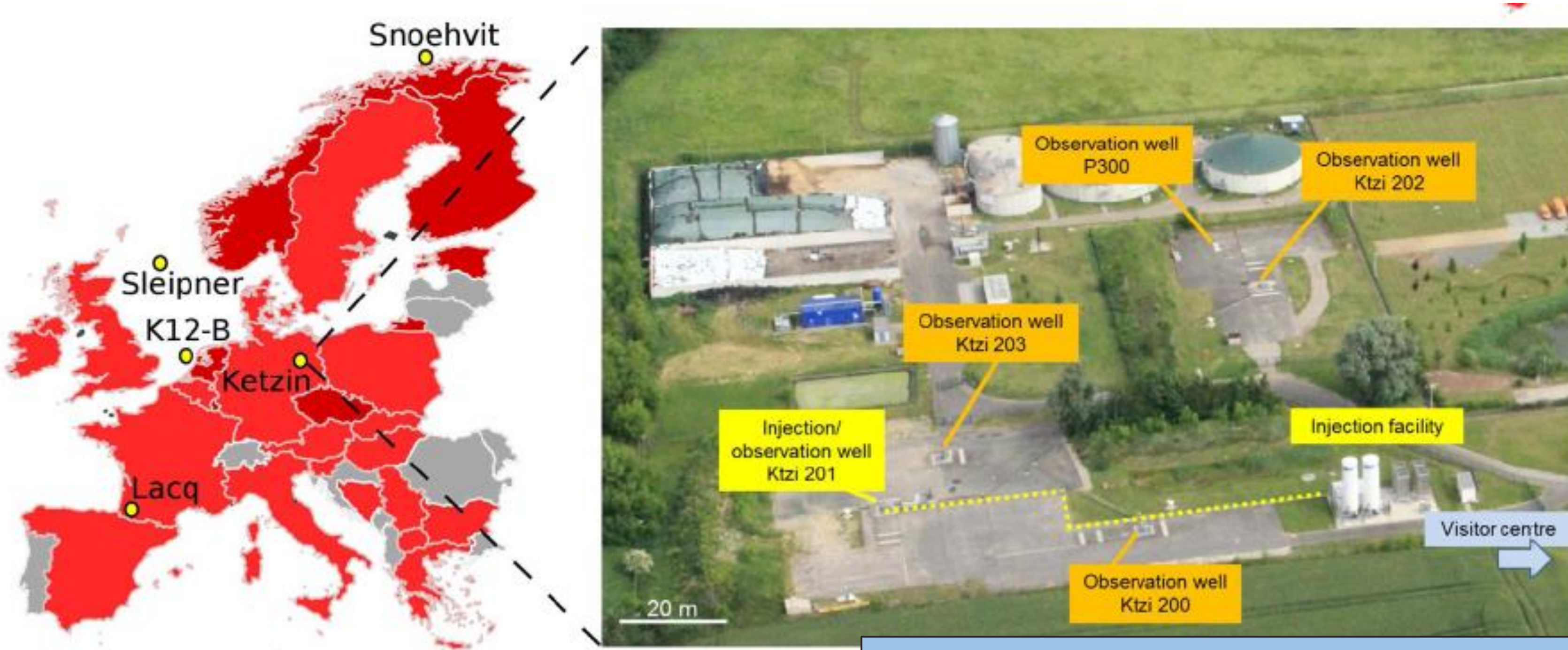
Ketzin CO_2 pilot storage site

THE MAIN OBJECTIVES:

- improve the scientific understanding of the geological storage of CO_2 in deep saline formations
- study the subsurface processes of the CO_2 injection and distribution



Areal view of the Ketzin site and its facilities.

Start/End of injection: June 2008/August 2013 (food-grade CO_2; Linde AG)

Total amount of injected CO_2: ~ 67 kt

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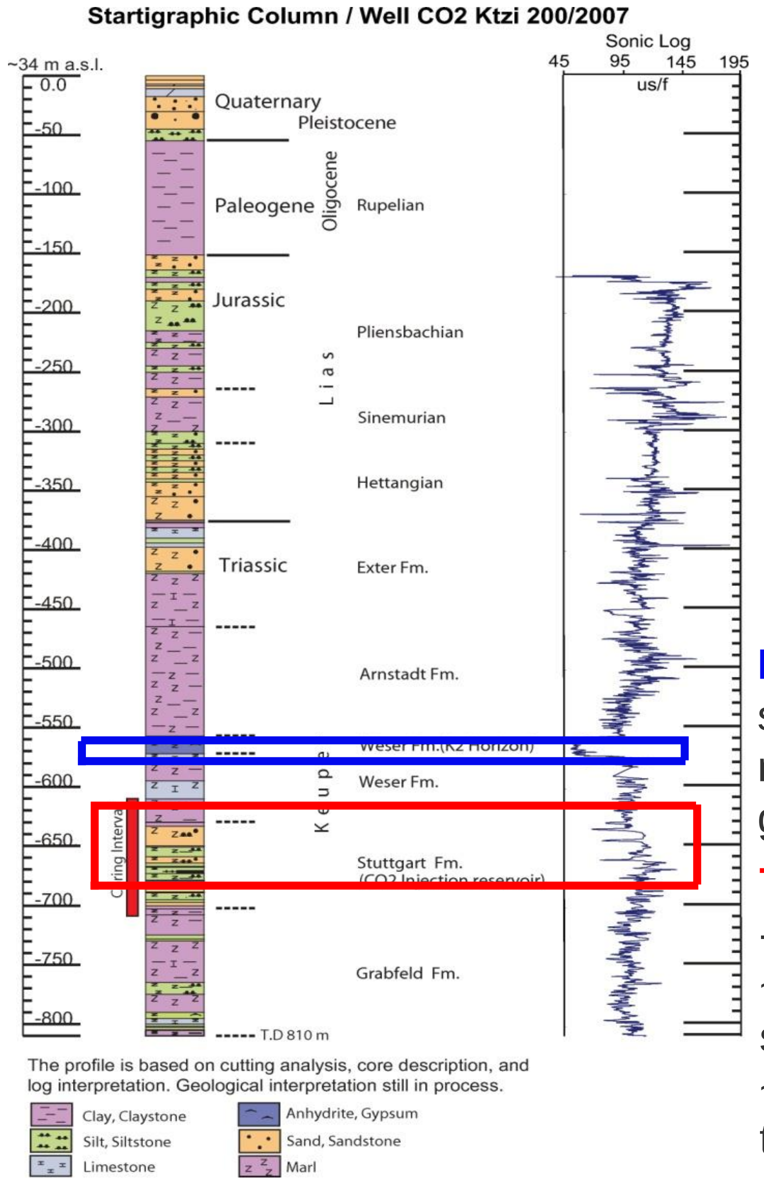
Ketzin CO_2 pilot storage site

- CO_2 injected into the upper Triassic Stuttgart Formation.
- Reservoir depth is approximately 630-650 m below sea level,9-20 m thick and effective porosities in the range of 20-25%.
- Reservoir is heterogeneous, consisting of sandy channel facies mixed with muddy flood plain deposits



Cap-rock:
- mudstone

K2 horizon:
strong seismic marker (Anhydirtic gypsum)

Target depth
- sandstone
~630 m below sea level
~550 ms seis. travel time

Ketzin CO_2 pilot storage site

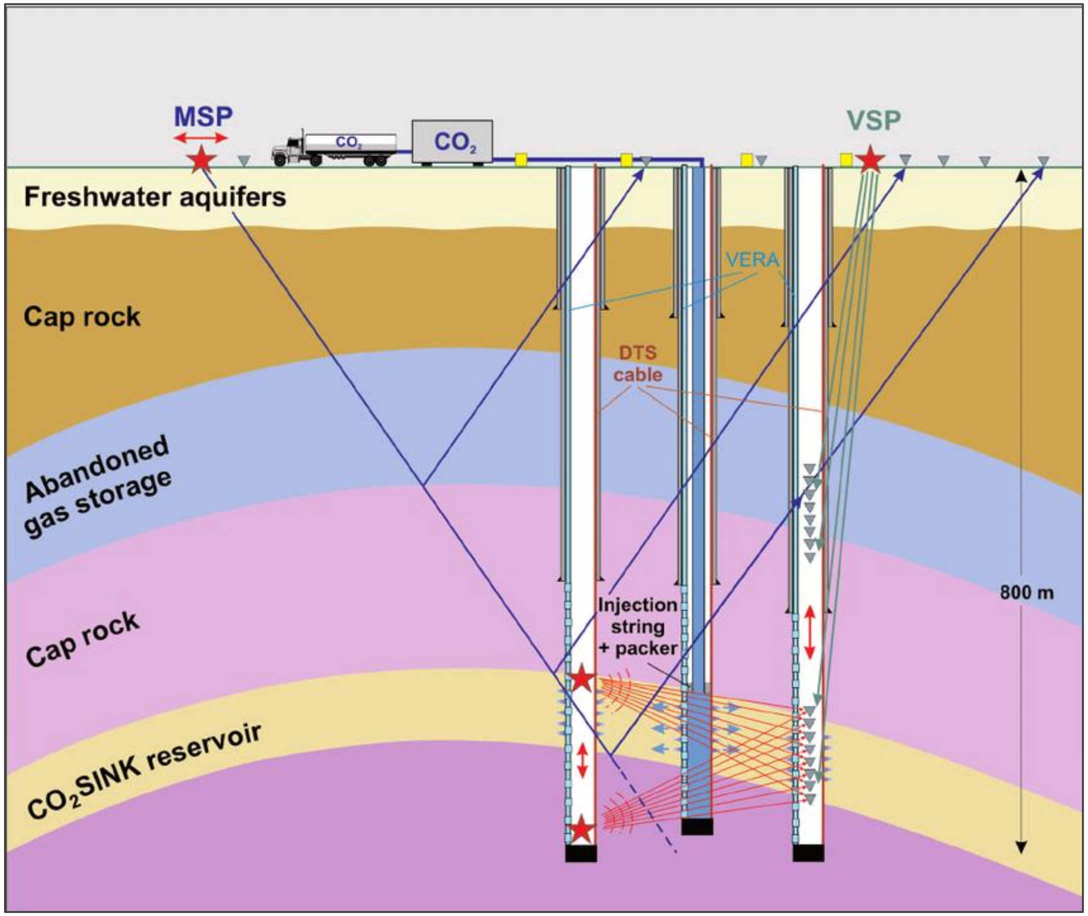
Monitoring

- Geochemical
- Biological
- Geoelectrical
- Seismic (active):

  Crosshole

  Surface-Downhole (VSP, MSP)

  Surface (2D, 3D)
- Passive seismic
- Temperature
- Fluid flow modeling



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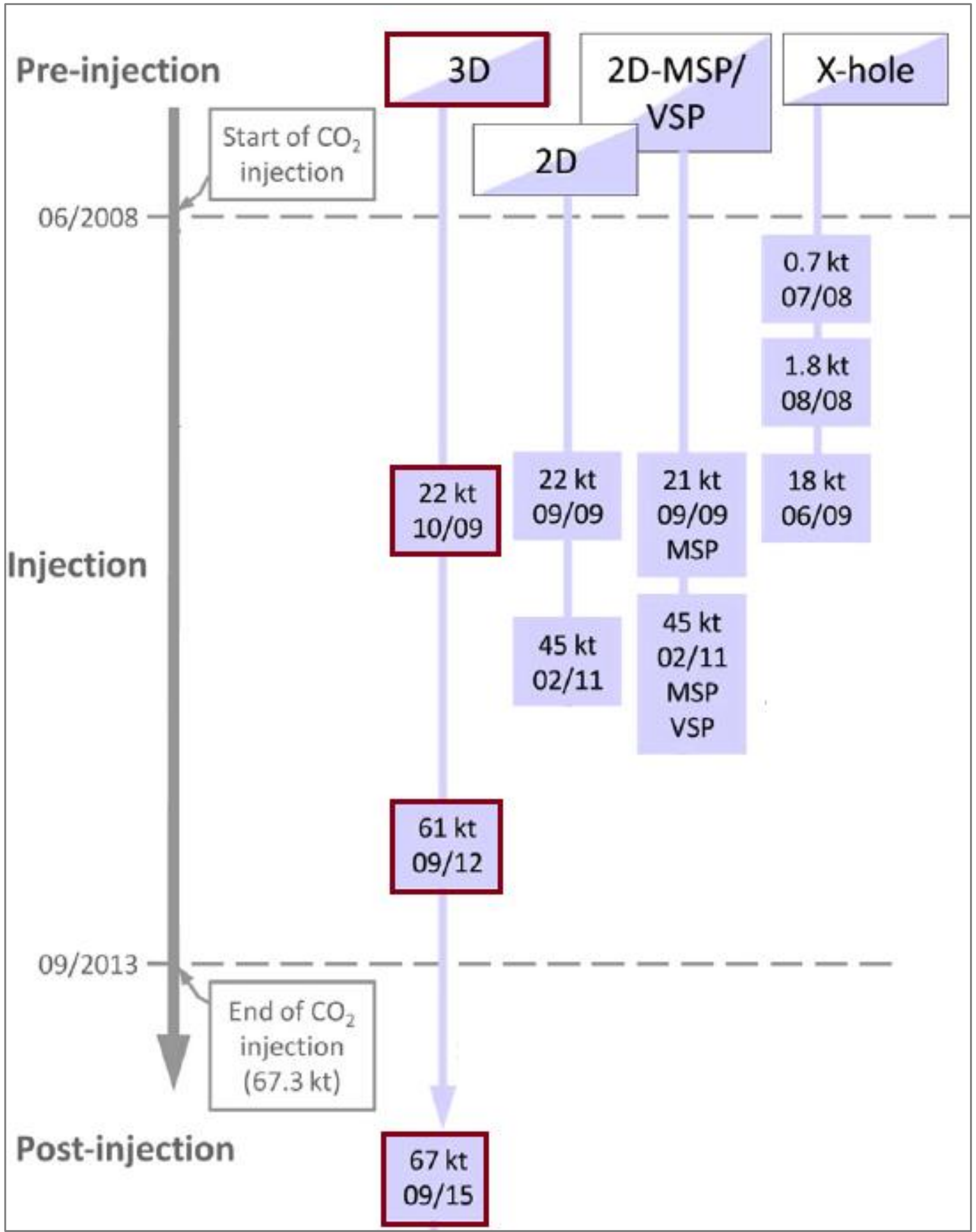
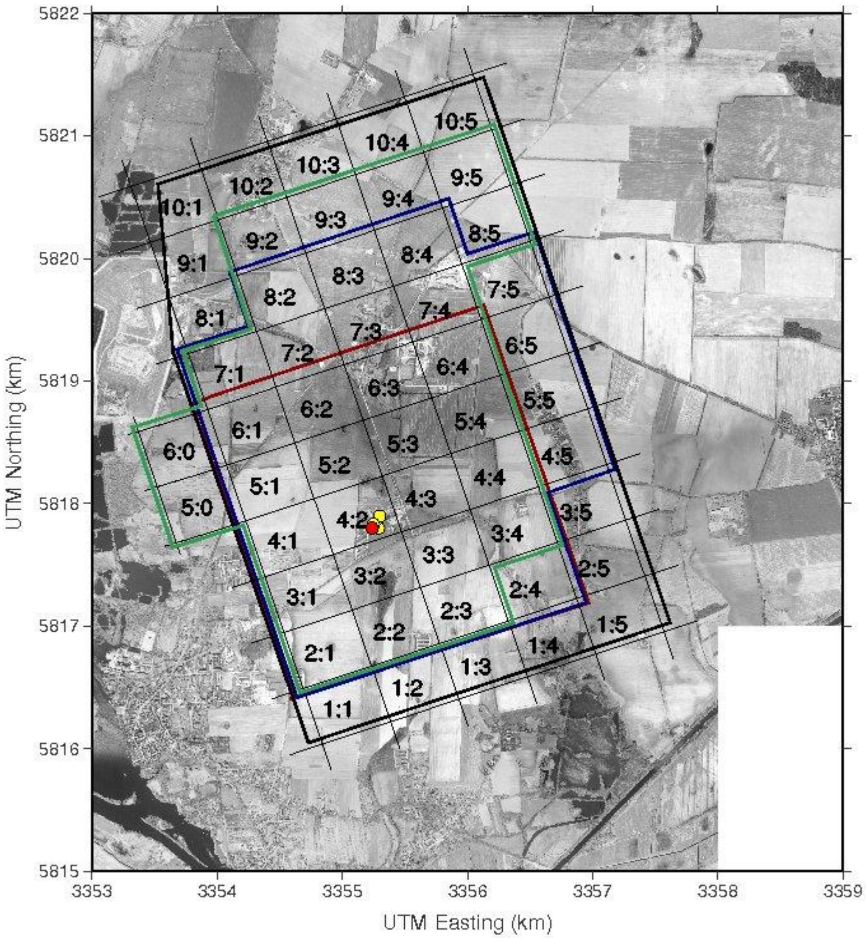
Seismic monitoring at Ketzin

An overview on the time history of the seismic measurements performed at the site

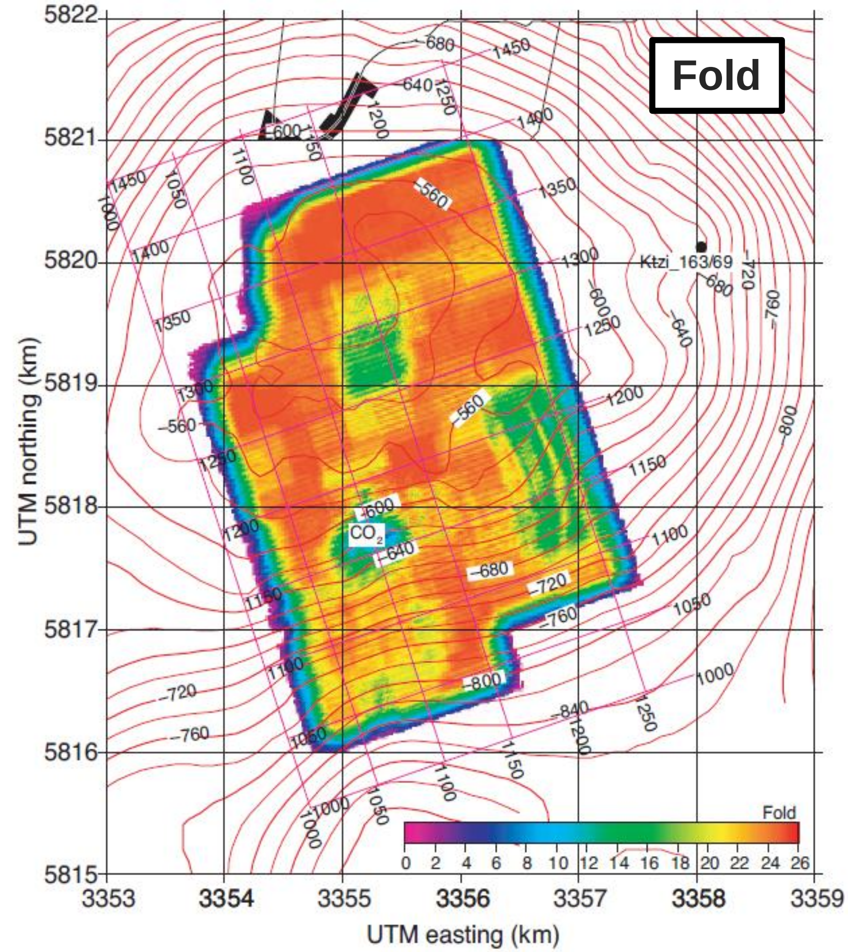


after Bergmann et al. (2016)

4D seismic monitoring at Ketzin



after Huang et al. (2016)



Juhlin et al. (2007);

3D Baseline 2005: 41 Templates, ~14km^2

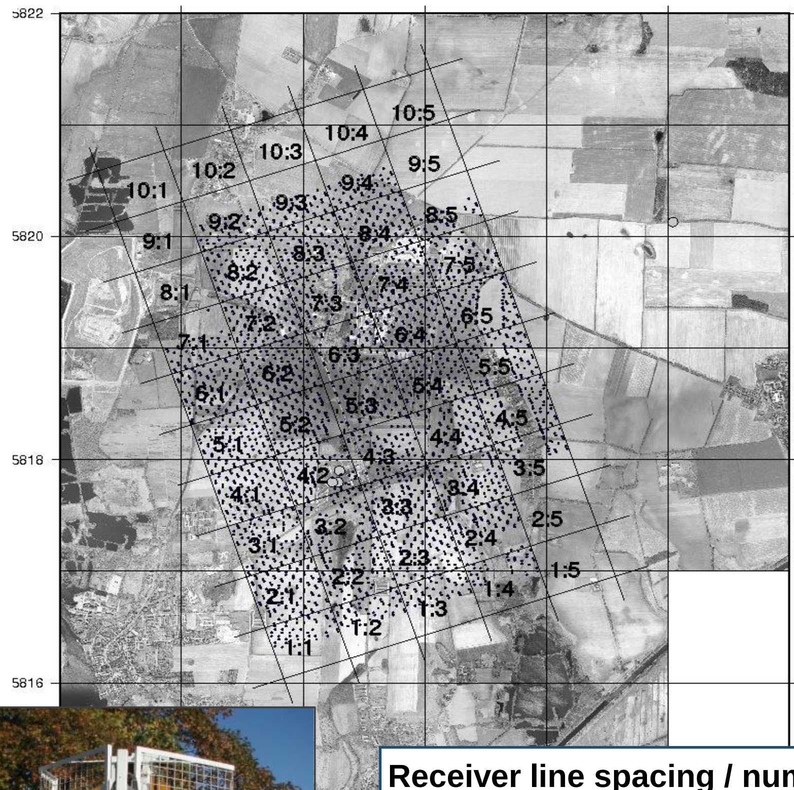
3D Repeat 2009: ~22 kt of CO_2, 20 templates, ~7 km^2

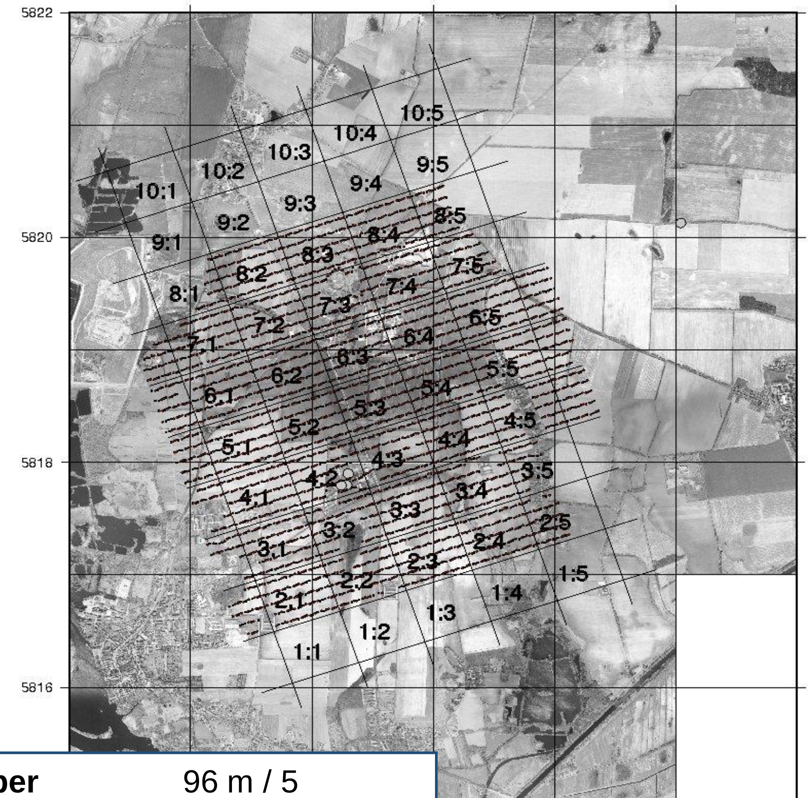
3D Repeat 2012: ~ 61 kt of CO_2, 31 templates, ~9.5 km^2

3D Repeat 2015: ~ 67 kt of CO_2, 33 templates, ~10 km^2

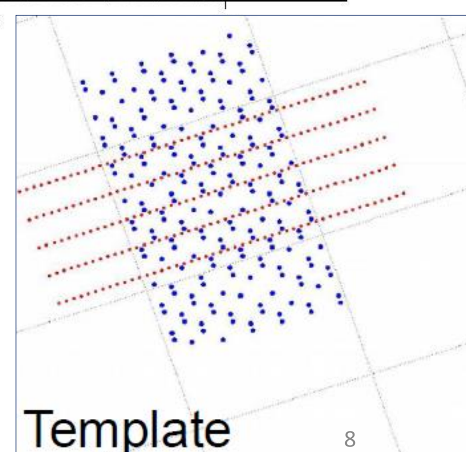
Due to logistics such as roads, villages, nature reserves, etc., it was not possible to have a regular geometry

4D seismic monitoring at Ketzin





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 accel. weight drop



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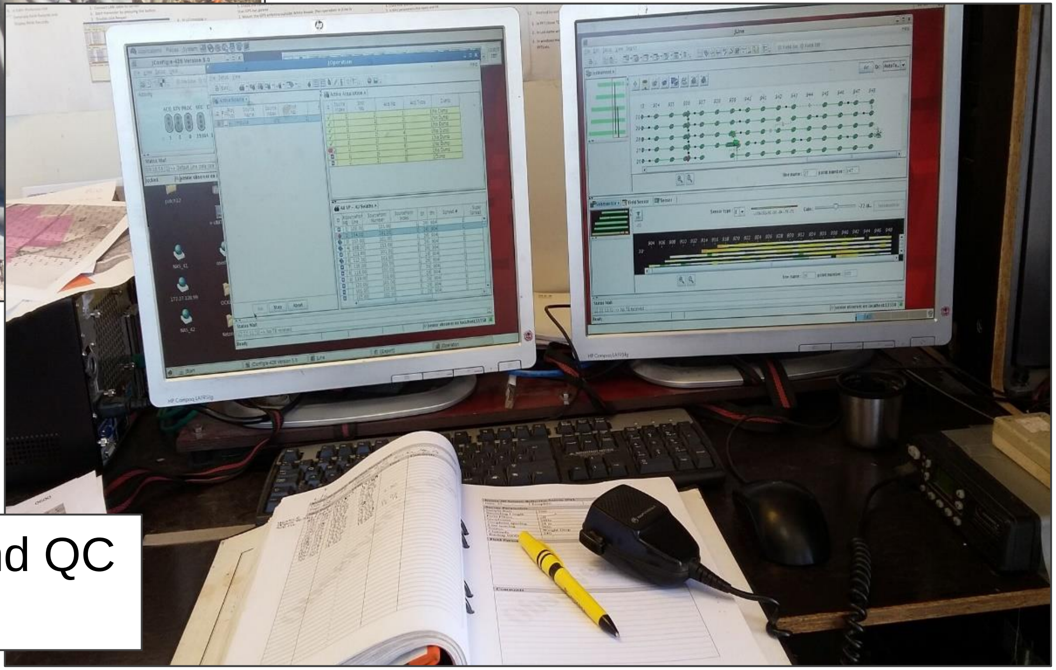
4D seismic monitoring at Ketzin

Seismic receiver deployment
28 Hz single vertical comp.
240 channels on 5 lines/template



Seismic data recording and QC
Sercel 408 UL / 428 XL

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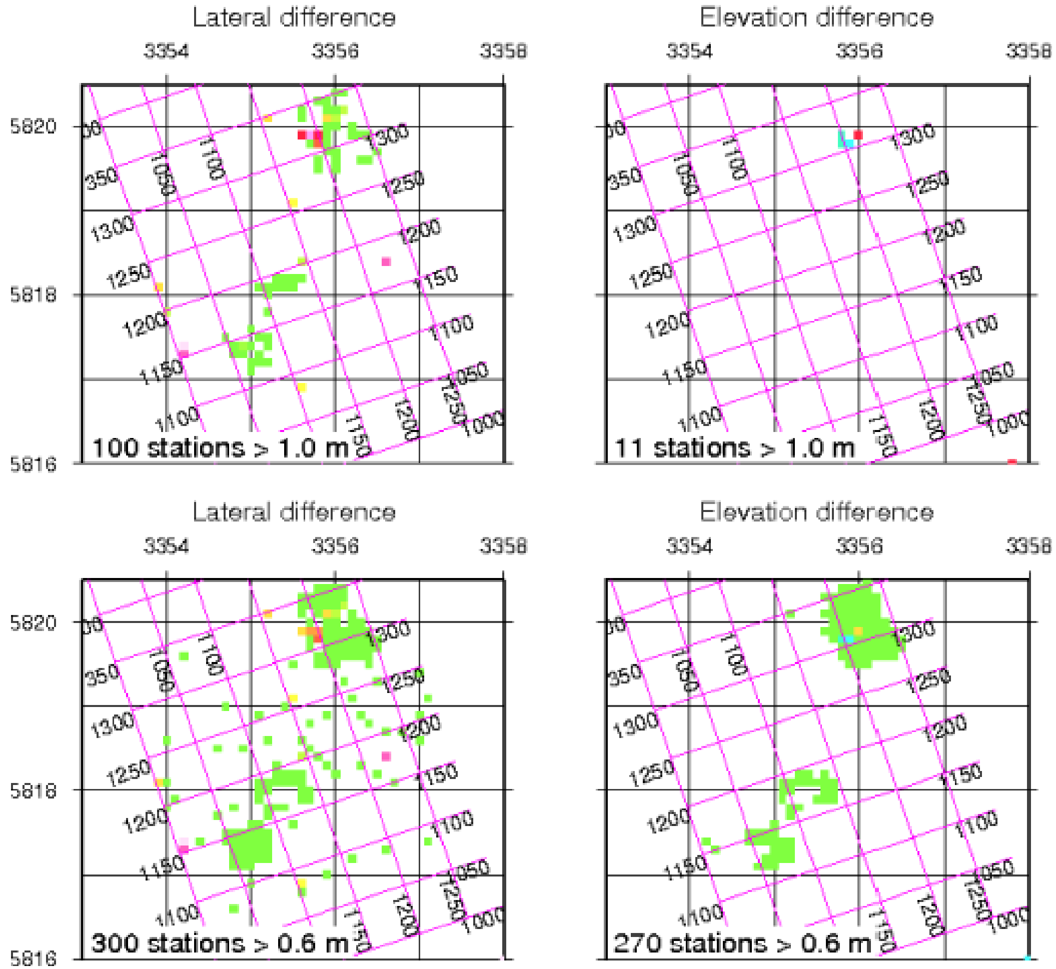
4D seismic monitoring at Ketzin

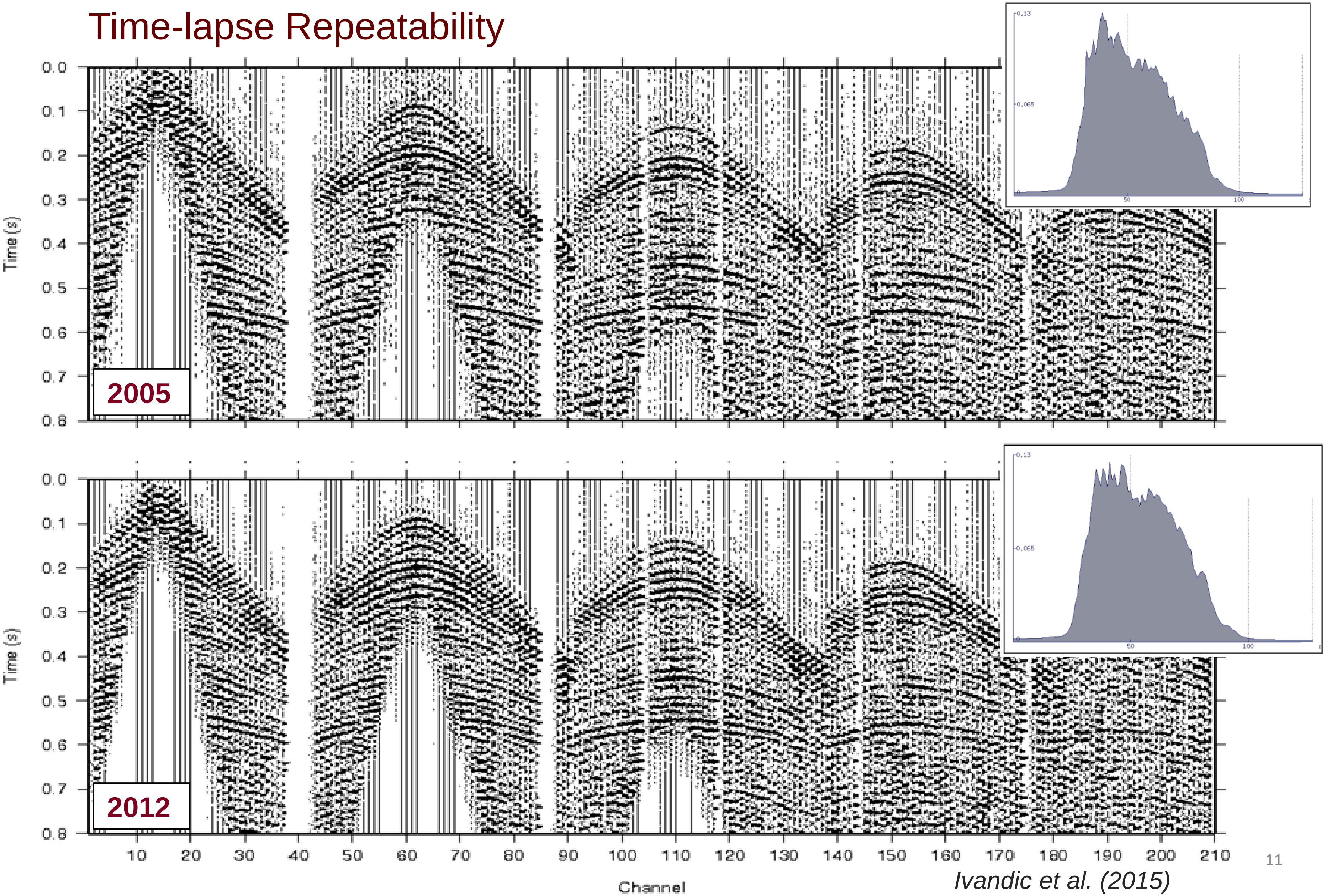
Repeatability of the 4D seismic data



Dislocated receiver stations of totally 4104 in the 2012 survey

4D seismic monitoring at Ketzin

Time-lapse Repeatability

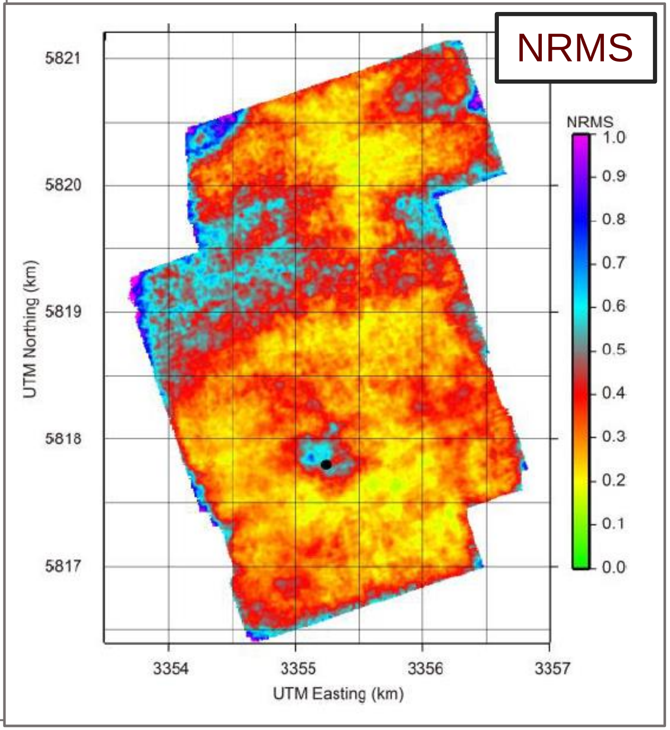


Ivandic et al. (2015)

4D seismic monitoring at Ketzin

Step	Processing workflow and parameters (Globe Caritas)
1	Read raw SEGD data
2	Vertical diversity stack
3	Bulk static shift (correction for instrument delay)
4	Extract and apply geometry
5	Trace editing
6	Notch filter: 50 Hz
7	Spherical divergence correction
8	Band-pass filter: 7–14–120–200 Hz
9	Surface consistent deconvolution: 120 ms, gap 16 ms, white noise 0.1%
10	Ground roll mute
11	Spectral equalization: 20–35–80–110 Hz
12	Band-pass filter: 0–300 ms: 15–30–75–115 Hz; 350–570 ms: 14–28–70–110 Hz; 620–1000 ms: 12–25–60–95 Hz
13	Zero-phase filter: converts an average near minimum-phase wavelet of the weight drop source to a wavelet being closer to zero phase
14	Time-lapse difference static correction (with reference to baseline survey)
15	Trace balance using data window
16	NMO
17	Stack
18	Trace balance
19	FX-Decon: inline and crossline directions
20	Trace balance
21	Migration: 3D FD using smoothed stacking velocities

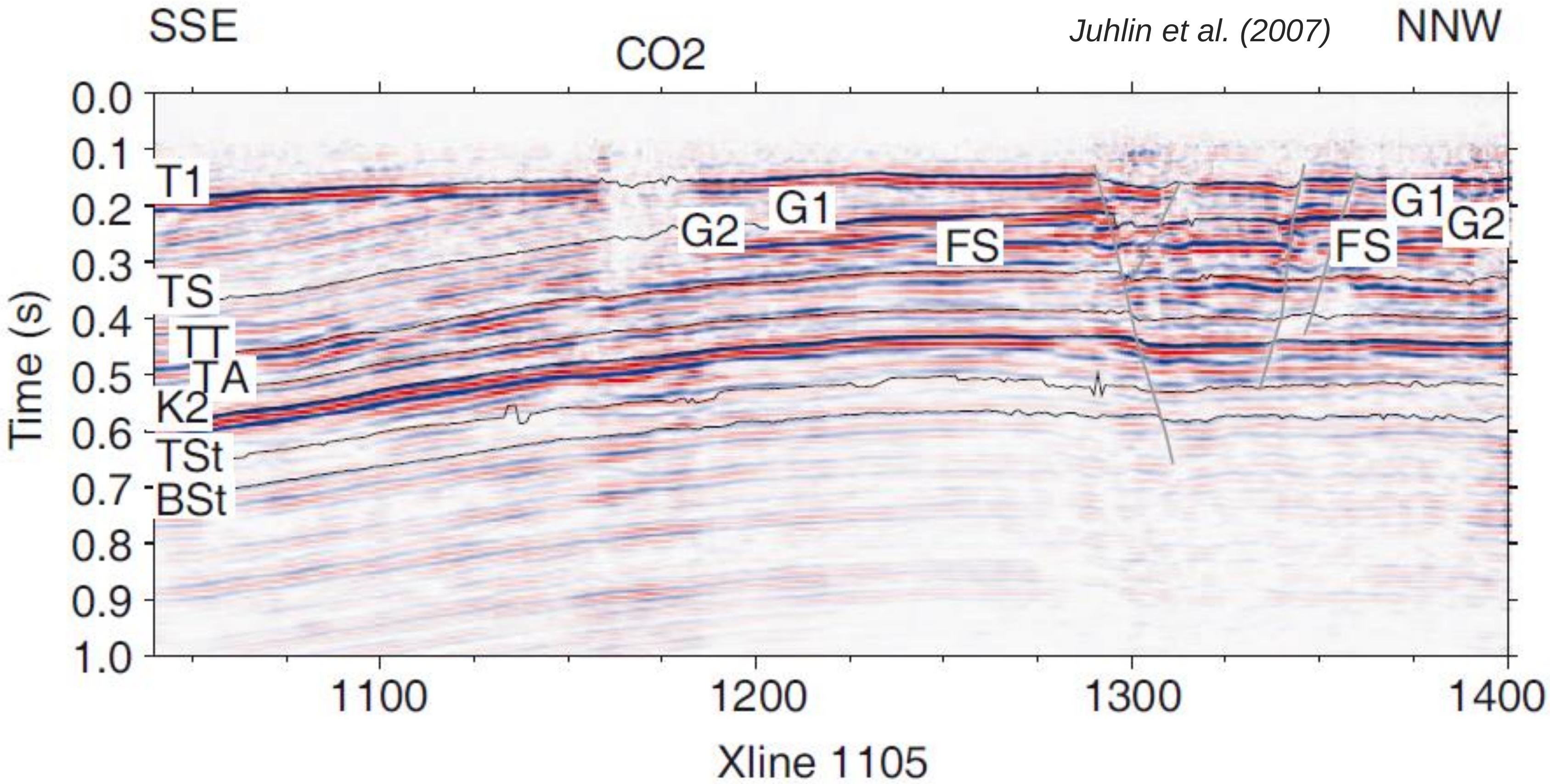
22. Cross-equalization (HRS software)



Huang et al. (2016)

4D seismic monitoring at Ketzin

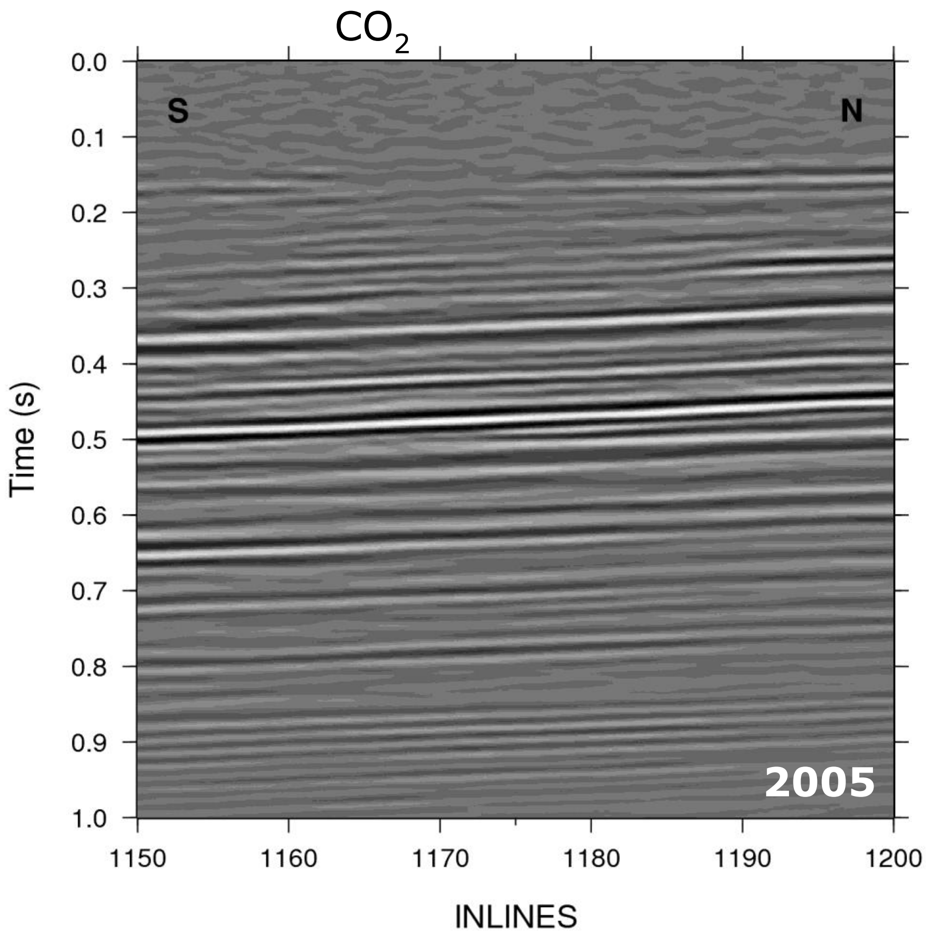
Crossline 1105 crossing nearly over the top of Ketzin anticline

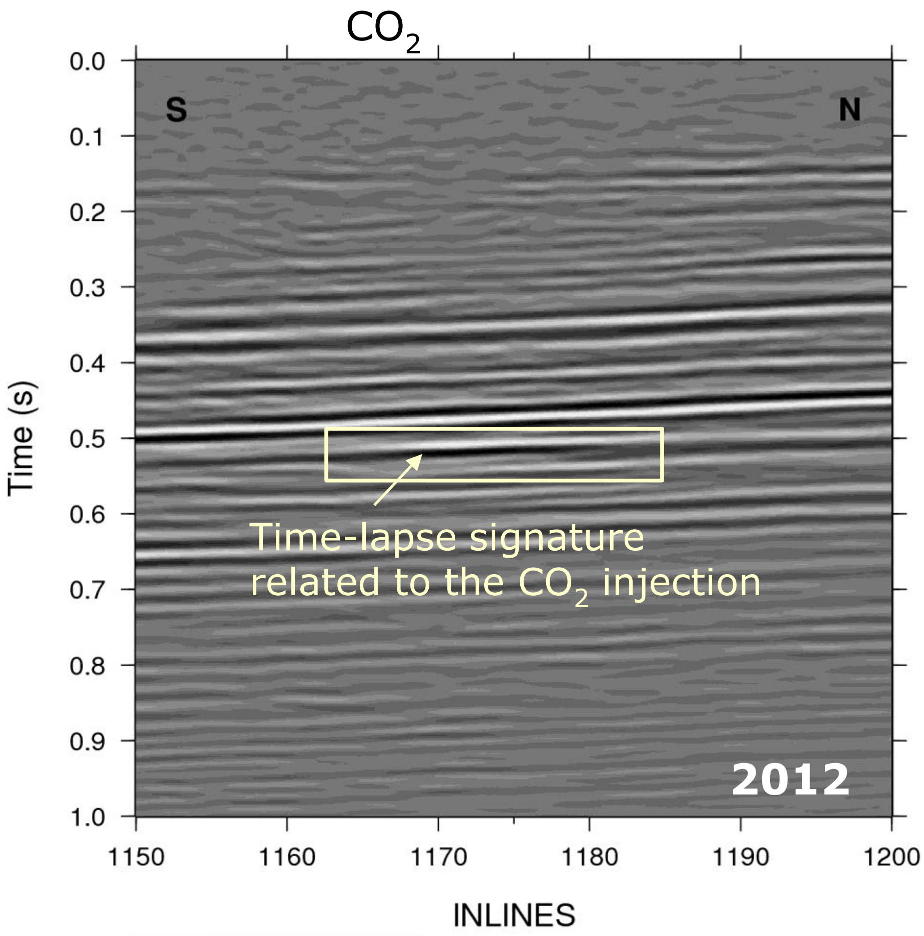


The 3D survey imaged a sequence of clear reflections from approximately 150 ms down to 900 ms two-way-time. The near-Base Tertiary (T1) and Top Weser (K2) horizons are well defined throughout the entire survey area. Reduced image quality of near-surface structures was observed where residential areas, access restrictions at the injection site, and nature reserves constituted obstacles in the acquisition geometry.

4D seismic monitoring at Ketzin

2nd repeat - Final stacked and migrated seismic sections – Crossline 1098

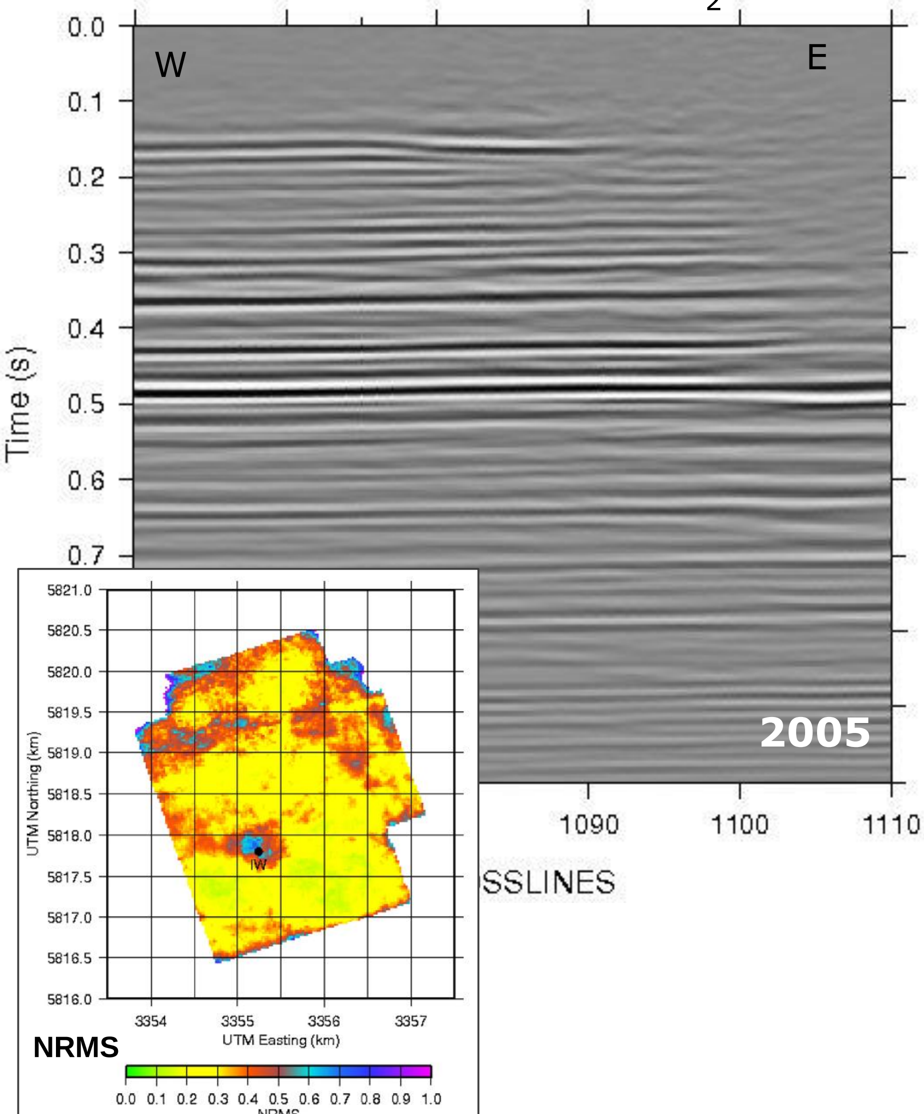


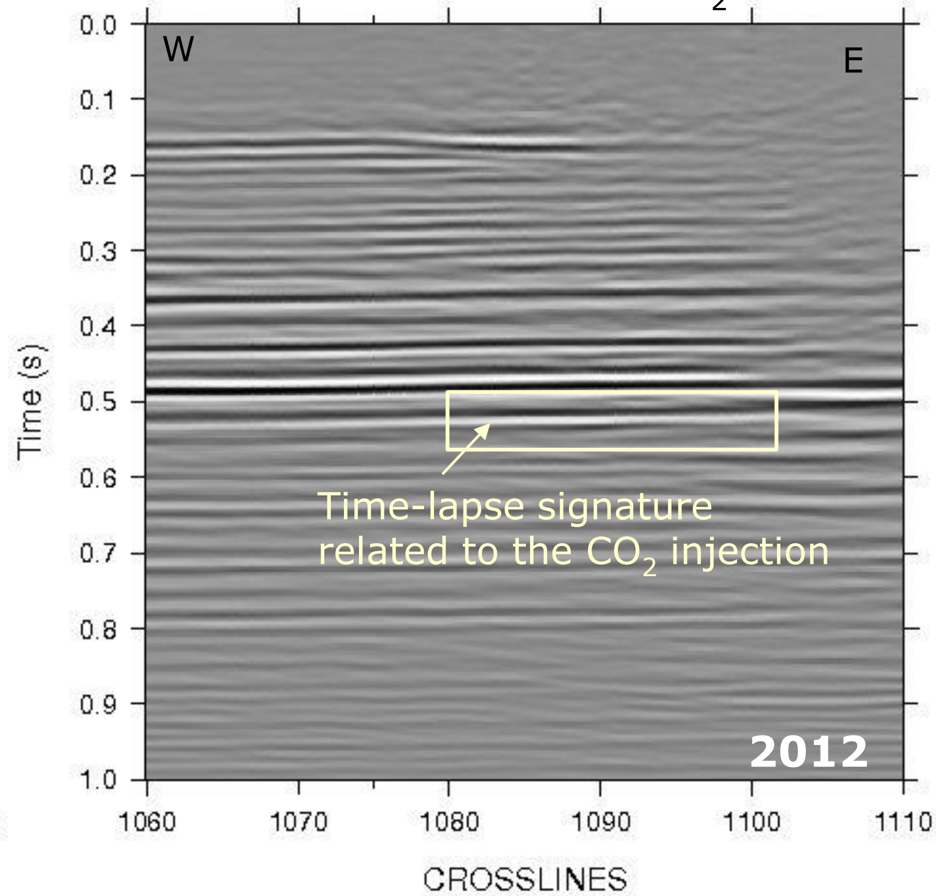


Ivandic et al. (2015)

4D seismic monitoring at Ketzin

2nd repeat - Final stacked and migrated seismic sections – Inline 1167





Ivandic et al. (2015)

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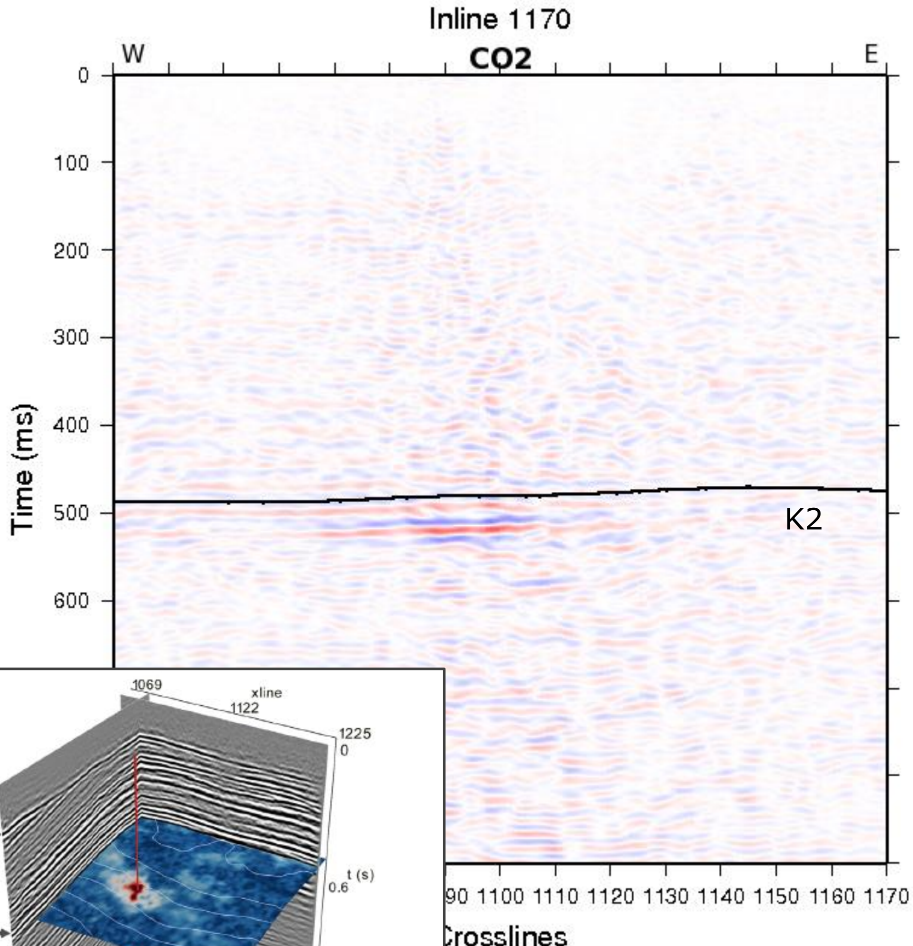
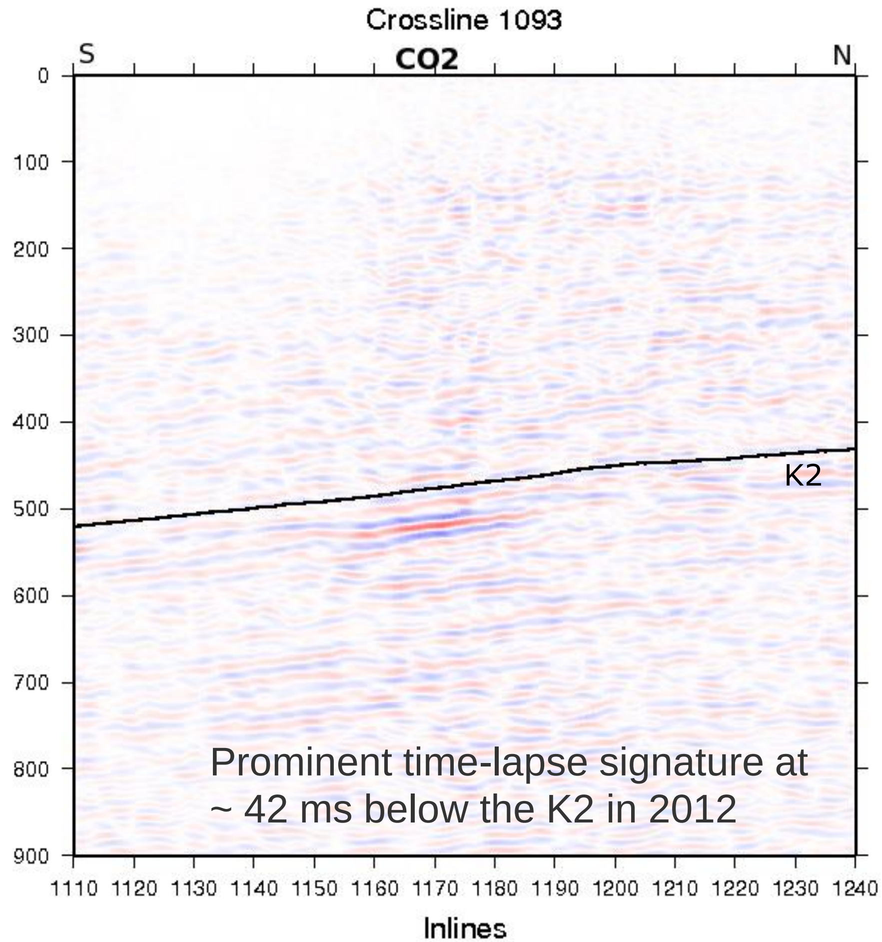
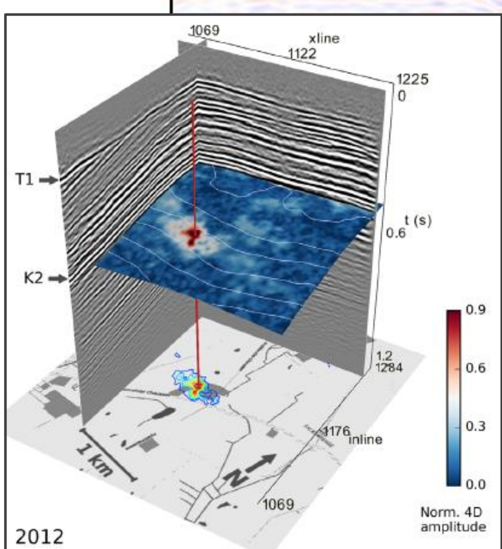
Time-lapse signature



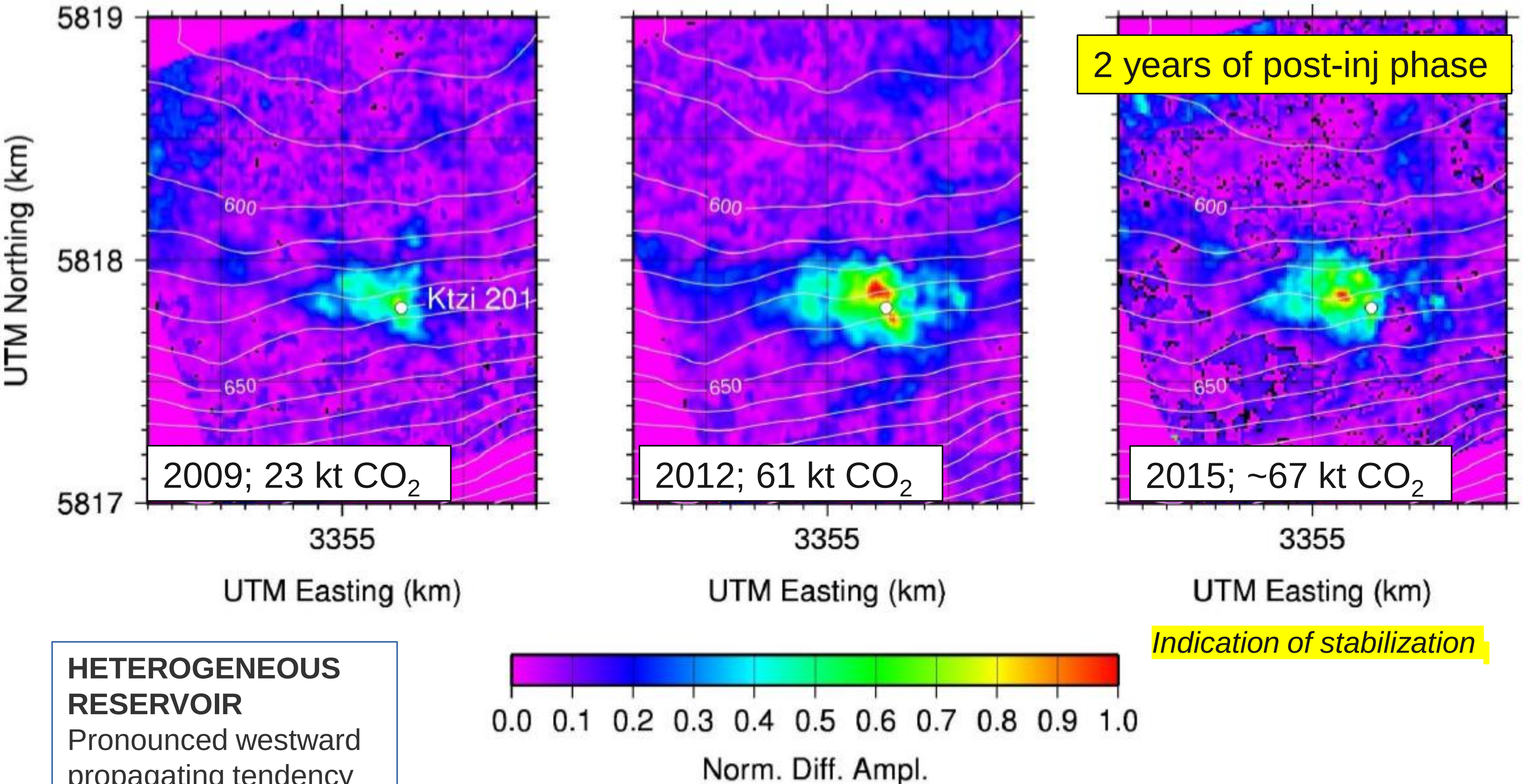


Prominent time-lapse signature at ~ 42 ms below the K2 in 2012



Ivandic et al. (2015)

CO_2 plume development and migration



Indication of stabilization

HETEROGENEOUS RESERVOIR
Pronounced westward propagating tendency

after Ivanova et al. (2012), Ivandic et al. (2015), and Huang et al. (2016)

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Conclusions

- The 3D data quality is fairly good and significant seismic events can be seen down to 1 sec.
- Seismic time-lapse observations performed after one and four years in the CO_2 injection phase and one in the post-injection phase imaged a migration and development of the CO_2 plume.
- Refined seismic processing provided geophysical images for detailed volumetric analysis and CO_2 detection limits
- This study shows that high-quality 3D seismic data required for CO_2 injection monitoring can be acquired using a small crew, single geophones and a simple weight drop source.
- This observation further implies that smaller seismic contractors could be used for monitoring of the future sequestration sites, opening up new opportunities for geophysicists.