Continuous passive-seismic monitoring of CO2 geologic sequestration projects

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with

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CCS monitoring

www.e-education.psu.edu/meteo469/node/223
“Volumetric” monitoring by 3D seismic

Active sources

Surface receivers

www.e-education.psu.edu/meteo469/node/223
Volumetric monitoring by **passive 3D seismic**

Surface receivers  Active sources
History of interferometric seismic imaging

Invented on Earth

Jon Claerbout (1968)
Geophysics
History of interferometric seismic imaging

Invented on Earth

Jon Claerbout (1968)
Geophysics

Apllied on the Sun

Stanford/NASA
soi.stanford.edu/results

Sunspot data from MDI High Resolution, 16 June 1998

Sound speed beneath sunspot
History of interferometric seismic imaging

Invented on Earth

Jon Claerbout (1968)
Geophysics

Applied on the Sun

Sound speed beneath sunspot

Sunspot data from MDI High Resolution, 18 June 1998

Stanford/NASA
soi.stanford.edu/results

Back to Earth

Shapiro et al. (2005)
Geophysics
Seismic interferometry - Step 1
Record data at two receivers

Ambient seismic noise ➔ Correlations ➔ Virtual seismic source
Seismic interferometry - Step 1
Record data at two receivers at the surface

Ambient seismic noise → Correlations → Virtual seismic source
Seismic interferometry – Step 2
Cross-correlate recorded traces

- Ambient seismic noise
- Correlations
- Virtual seismic source
Seismic interferometry – Step 3
Synthesize ”virtual events” – Interface waves

1. Ambient seismic noise
2. Correlations
3. Virtual seismic source

Surface waves (transmission)
Seismic interferometry – Step 2
Cross-correlate recorded traces
Seismic interferometry – Step 3
Synthesize "virtual events" – Body waves

Ambient seismic noise \rightarrow Correlations \rightarrow Virtual seismic source

Body waves (reflections)
Ambient seismic noise

Ambient noise (time slice)

Ambient noise (time vs. distance)

2x real-time
Ambient seismic noise

Ambient noise (time slices)

Virtual source (time slices)

2x real-time
Monitor CO2 reservoir by reflections?
Sleipner - Active seismic monitoring of CCS

- CO₂ injection commenced 1996
- ~1 Mt CO₂ injected per annum
- ~11 Mt currently in situ

4D surface seismic
2D hi-res seismic
Seabed gravity
CSEM
Seabed imaging

Andy Chadwick (2009) - www.bgs.ac.uk/staff/profiles/0130.html
Sleipner - Monitoring by reflection images

vertical section

plan view

1 km

Andy Chadwick (2009) - www.bgs.ac.uk/staff/profiles/0130.html
Direct detection of CO2 plumes before they reach the surface?
Indirect detection of CO2 plumes deep in the subsurface?

Upward migrating CO2 acts as a pressure conduit and changes stress field close to the surface.
Salha (Algeria) CCS project

Allan Mathieson et al. (2010) – Energy Procedia
Allan Mathieson et al. (2010) – Energy Procedia
``Moore’s law” for seismic acquisition
Number of channels for one active source

Channel Count Doubles Every 3½ Years

credit: David Monke (Apache) & Tim Keho (Aramco)
Valhall - Life Of Field Seismic array (LOFS)

- 120 km seismic cables
- 2500 groups of 4C sensors
- 50 m receiver spacing
- 300 m cable spacing
- 15 Hz geophones, but they record down to ≈.5 Hz signals

credit: Olav Barkved (BP)
Other datasets from (semi)permanent arrays

Long Beach
3,000 autonomous MEM sensors

credit: Dan Hollis
(Nodal Geophysical)

Ekofisk
4,000 4C Fiber optic sensors

credit: Ali Tura (CP)
Other datasets from (semi)permanent arrays

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Other datasets from (semi)permanent arrays

Long Beach
3,000 autonomous MEM sensors

credit: Dan Hollis
(Nodal Geophysical)

.5 TB/day

Ekofisk
4,000 4C Fiber optic sensors

2.7 TB/day

credit: Ali Tura (CP)
Spectrum of ambient seismic field at Valhall
Valhall - Virtual seismic source
Monitor CO2 reservoir by reflections?
Monitor CO2 reservoir by reflections? Not yet
Direct detection of CO2 plumes before they reach the surface?
## Identifying velocity anomalies
Validation with active-data images at $\approx 80$ m

<table>
<thead>
<tr>
<th>Ambient seismic noise tomography</th>
<th>Full Waveform Inversion on active data</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.50-1.75 Hz</td>
<td>60-105 m</td>
</tr>
</tbody>
</table>

- Landes et al, 2007
- De Ridder, 2011
- De Ridder, 2011
- QuickTime™ and a decompressor are needed to see this picture.
Identifying velocity anomalies
Validation with active-data images at ≈ 170 m

Ambient seismic noise tomography
0.50-0.75Hz

Full Waveform Inversion on active data
150-195m

De Ridder, 2011
Landes et al, 2007
Direct detection of CO2 plumes before they reach the surface? Most likely!
Indirect detection of CO2 plumes deep in the subsurface?

Upward migrating CO2 acts as a pressure conduit and changes stress field close to the surface.
Subsidence-related stress changes in subsurface

-6.5

extension

contraction

extension

Gas Pocket

Dynamic Overburden

Porous, Thin, Fractured, Heterogeneous Reservoir

Barkved, 2012
Detecting changes in stress field

- Shear wave splitting maps
- Polarization of fast split shear wave and lag size
- Production related subsidence
- Input for geomechanical inversion
- Can be monitored over time
Indirect detection of CO2 plumes deep in the subsurface? Will test on Valhall and Ekofisk

- CO2 reservoir
- CO2 plume

Upward migrating CO2 acts as a pressure conduit and changes stress field close to the surface.
What about land data?
Preliminary results from Long Beach data

Long Beach
3,000 autonomous MEM sensors

Ambient noise (time slices)
What about land data?
Preliminary results from Long Beach data

Virtual source (time slices)

Ambient noise (time slices)
Ongoing and future investigations

- Analyze Long Beach for time-lapse effects
- Analyze Ekofisk and Valhall data for anisotropy
- Look for reflections in all three datasets by performing longer correlations to improve SNR at high frequencies
Ongoing and future investigations

- Analyze Long Beach for time-lapse effects
- Analyze Ekofisk and Valhall data for anisotropy
- Look for reflections in all three datasets by performing longer correlations to improve SNR at high frequencies
- Record data on an actual CCS project
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