Microseismic monitoring of a CCS site at In Salah, Algeria

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Outline

- The In Salah CO$_2$ storage site
- Microseismic event detection and location
- Magnitude estimation and b-value analysis
- Shear-wave splitting
- Geomechanical analysis
- Confining event depth with respect to seal
- Conclusions
The In Salah CO₂ storage site

- 4 MT CO₂ injected into a naturally fractured carboniferous sandstone reservoir at 1.9 km depth
Microseismic array at KB-601

- Downhole array of 48 3C geophones between 30-500 m depth
- 6 geophones were connected to 3 digitizers
- GPS timing problems and strong electronic noise
- Only uppermost geophone provided reliable data
Event detection method

- Master event waveform cross-correlation method to detect and pick seismic events within continuous data
- More than 5000 events are detected between August 2009 and June 2011
Event analysis: distance

- Differential S-P onset time gives an estimate of event-to-receiver distance
- Several clusters with similar arrival-time differences can be identified

![Graphs showing S-P time differences over time with markers indicating specific delays and corresponding distances.](image)
Event analysis: distance & direction

- Determine event direction from particle motion of P-waves.
- Further separate clusters by combining S-P, azimuth, and inclination (clusters A-D).
- Overall events are oriented in the direction of the largest horizontal stress.
- No seismicity within a radius of about 1 km around the injection well -> Kaiser effect?

(Oye and Ellsworth, 2005 BSSA)
Together with InSAR data the clusters may give an indication on the extent of the CO2 plume in 2010.
Event analysis: example waveforms

Additional phase arrivals

S-P ~ 1s

S-P ~ 0.7s

Shear-wave splitting

stack

stack

In Salah site - Detection & location - Magnitude & b-value - Shear-wave splitting - Geomechanical analysis - Confining event depth - Conclusions
**M_w estimation**

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**$M_w$ estimation**

\[ m_0 = 4\pi \rho v^3 \Omega_0 / F \]

\[ M_w = \frac{2}{3} (\log_{10}(m_0) - 9.1) \]

- Distance and attenuation correction
- Determine the low-frequency spectral level $\Omega_0$
- Compute seismic moment $m_0$ and $M_w$
- Most $M_w$ estimates are between -1 and 0, largest $M_w$ is about 1
- $M_w P > M_w S$
- Effect of different radiation pattern

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b-value analysis of event clusters

- b-value is the slope of the Gutenberg-Richter law
- Allows extrapolation from observed small events to expected larger events
- b-value can be linked to in-situ reservoir stress state

\[ \log_{10}(N) = a - b \cdot M \]

\( b = 1.6 \)

Log-log plot showing the relationship between magnitude (M) and frequency (N) with highlighted effect of b-value and stress state.
b-value analysis of event clusters

- Similar b-values for P and S but significant variations between clusters.
- $b \sim 1$ for cluster A (average tectonic).
- Larger $b$ (1.5 to 2) for clusters B-D.
- High b-value when new fractures open and low b-value when pre-existing fractures are reactivated.
Shear-wave splitting analysis

- Significant time delay $\Delta t$ up to 0.1 s on $S$ arrival.
- Splitting is a manifestation of anisotropy $A$ within the medium.
- We analyse shear-wave splitting using the eigenvalue $\lambda_2$ method (Wüstefeld et al. 2010)

$$A = (\beta \Delta t)/R$$

$A$: percentage anisotropy
$\beta$: average $S$ velocity
$R$: source–receiver distance
$\Delta t$: time delay
Shear-wave splitting analysis

- 83 events with good splitting
- 5% of anisotropy for clusters B-D
- Less than 2% of anisotropy for cluster A
Estimating formation fracture pressure

- Formation fracture pressure is about **155 bar**
- Separate two different fracture periods: **matrix** & **fracture** injection
Comparison of detected events and CO2 injection data

- High correlation between occurrence of microseismic events and injection rate
- Periods of matrix injection and fracture injection

Kaiser effect?

fracture pressure 155 MPa
- No correlation between injection parameters and cluster A.
- High correlation with clusters B-D.
- High activity of cluster C only during main injection phase.
Confining microseismic event depth

- Additional phase on Z between direct P & S
- S-to-P converted phase at strongest velocity contrast (850 m).
Use 3D ray tracing to identify converted SP.
Test potential source locations employing the wavefront construction method (Vinje et al. 1993 and 1996).
Waveforms at A and A’ have similar S-P traveltimes but converted phase only matches real data at shallower position A.
Confining microseismic event depth

- Cluster A at about 1.7 km (well above the reservoir but still within lower cap rock).
- No shear-wave splitting is observed and anisotropy may occur mainly in deeper layers.
- Inclination angles for cluster A are distinctly higher than for cluster B-D also pointing to a shallower source.
Conclusions

- Over 5000 microseismic events were detected during the In Salah CO2 injection using a master event waveform cross-correlation method.
- Earthquake location can not be determined with only one geophone but various event clusters can be identified.
- $M_w$ between -1 and 0 but values up to 1 are observed.
- The formation fracture pressure is 155 bar and periods of matrix versus fracture injection are distinguished.
Conclusions

Class I events:
- largest S-P differential traveltimes
- ~150 m above reservoir formation top in lower cap rock
- not correlated to injection history
- b-value ~ 1 indicates seismicity on pre-existing faults
- 3D seismic has identified the end of a fault zone
- only weak or no anisotropy

Class II events:
- smaller differential traveltimes
- high b-value of 1.5 to 2 indicates new fractures
- strong anisotropy is observed
- highly correlated to the injection history
- no major faults identified
Thank you for your attention!

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Acknowledgements
“How can we devise a monitoring strategy for safe operation?

- CCS: most important is depth resolution to verify seal integrity
- Accurate moment magnitudes important for risk assessment (event discrimination and forecast with b value)
  - network needs to be planned accordingly (need vertical aperture with several borehole sensors in same well, and azimuthal coverage for accurate magnitudes)
- need knowledge of fracture pressure from comparison with pumping data.
- Real-time data stream and automatic processing can provide “traffic light” feedback to keep injection below fracture pressure
- In cases microseismicity can not be used to track CO2 plume because of lack of brittle deformation (which is what we want at the end of the day) we need to use a complimentary method (4D seismic, InSAR (deserts!), microgravity (offshore), geochemical sampling, …. )
Define intrinsic differences among fluid injection (Austin), geothermal development (Ivan) and CCS (offshore by Daiji and onshore by Bettina)

Seismic Moment differences:
Wastewater injection < geothermal < CCS (so far – pilot projects!)

CCS: often shallower, and different rheology (shales). Event size bounded by formation thickness. Higher compressibility of CO2 vs. water. Large volumes over decades would be a concern (Zoback & Gorelick 2012).

Offshore CCS: lower detection threshold due to larger noise, prohibitive cost for permanent installations.

Geothermal: in or near basement, so size unbounded by dimension (like formation thickness). Pre-existing faults “by design”. Large pressures initially. Near population. Sometimes events after years of circulation (Landau, Unterhaching)

Wastewater injection: seems to be worst near basement or with basement connection where size can be unbounded by formation thickness. Large volumes (McGarr: $M \propto V$)
Basel induced microseismicity b-values
Basel induced microseismicity stress-drop
Comparison of detected events and CO2 injection data

- Number of events per hour compared to injection data during main injection phase in 2010

![Graph showing comparison between detected events and CO2 injection data during the main injection phase in 2010.](image-url)
Velocity model
For most events, $M_w$ of the P-wave estimate is larger compared to the S-wave estimate.

Effect of the different radiation pattern.
Fracture pressure & injectivity

Injectivity = injection rate / wellhead pressure

- Periods of matrix injection and fracture injection
- Injectivity decreases with time
Shear-wave splitting analysis

- 83 events with good splitting
- 5% of anisotropy for clusters B-D
- Less than 2% of anisotropy for cluster A

Processing with Split-lab software (Wuestefeld et al. 2008)