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Exploring the Earth

Developments on Microseismic Monitoring and Risk Assessment of Large-scale CO_2 Storage

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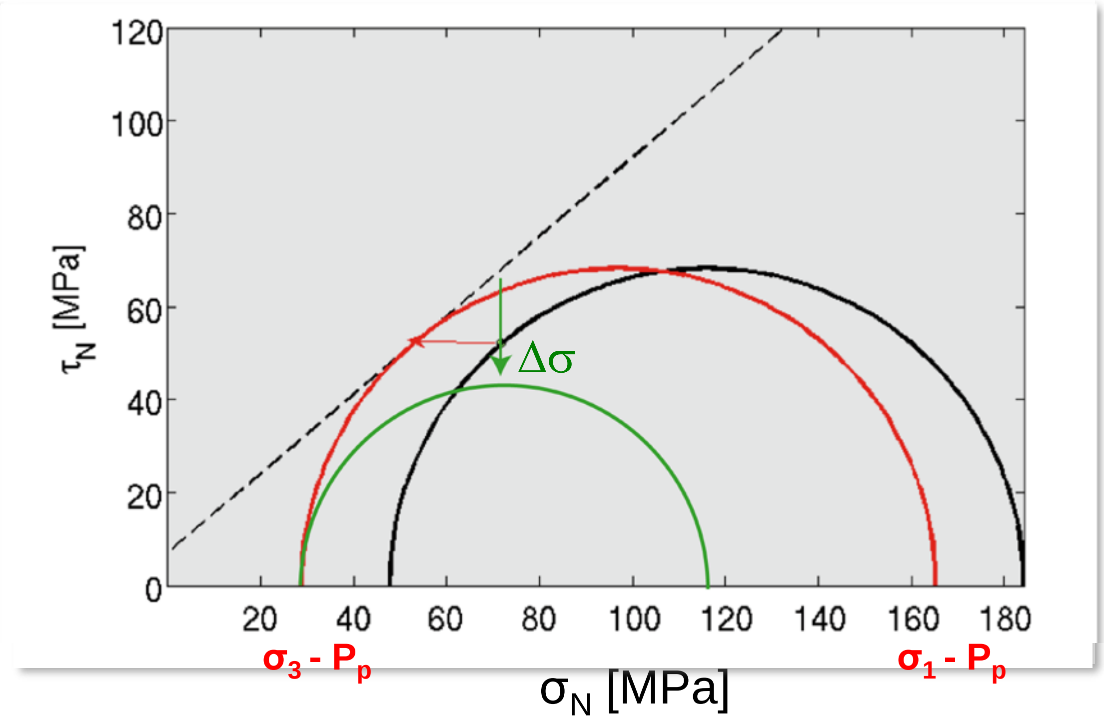
Outline

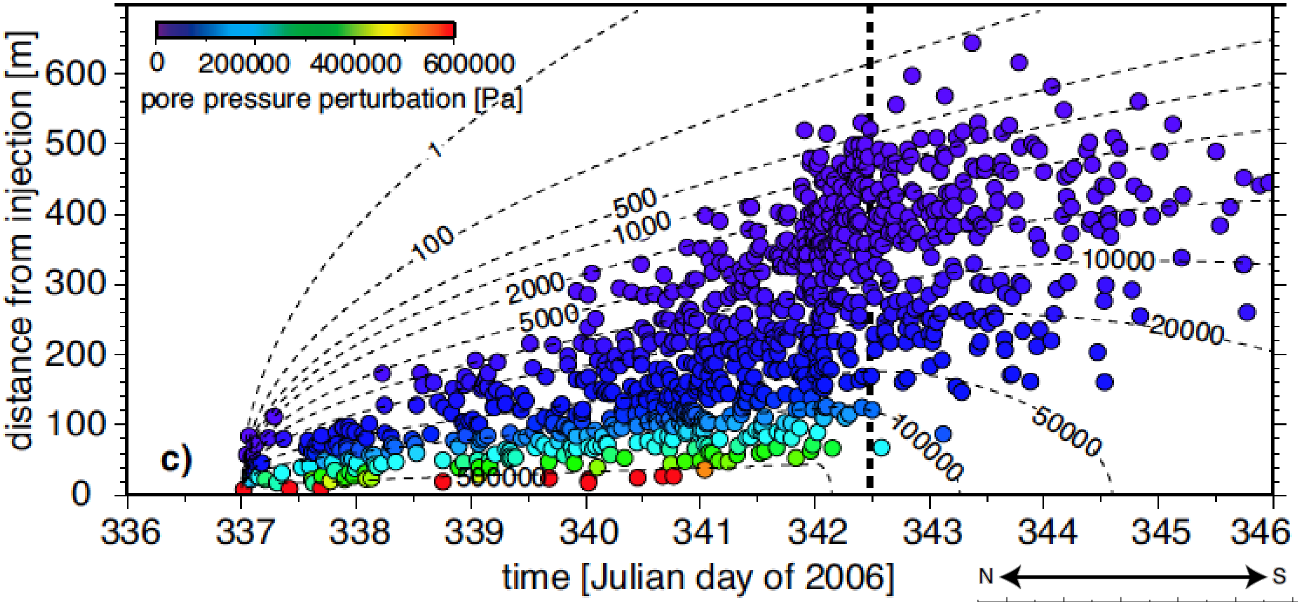
- Introduction: Induced seismicity & CCS
- Two case studies
  - In Salah, Algeria
    - Event detection & analysis
    - Confining event depth
  - Decatur CCS site
    - Microseismic event characterization
    - Full-waveform modelling
- Summary & Conclusions

Induced Seismicity



- Increasing pore pressure (fluid injection) brings rock closer to failure
- Near-critical stress state (typical) → microseismicity
- Examples: shale gas fracking, wastewater injection, geothermal stimulation, CO_2 injection

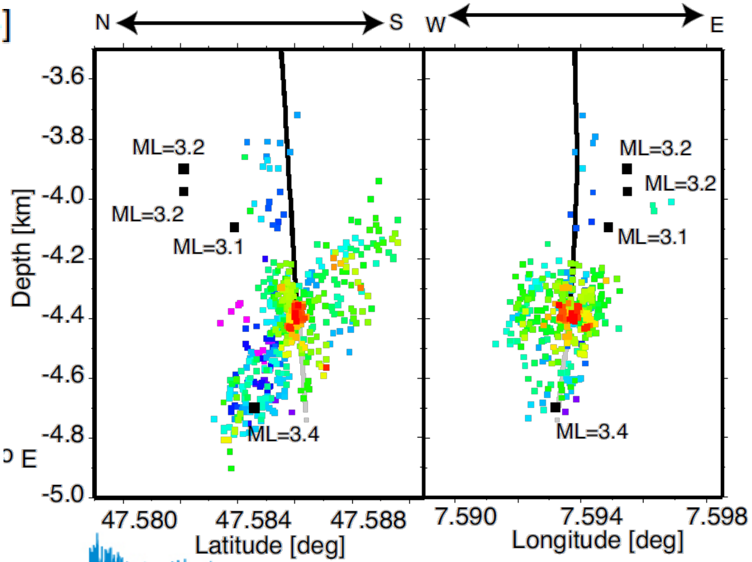
Induced Seismicity



Example from Basel geothermal stimulation

(Goertz-Allmann et al., 2011, 2012)

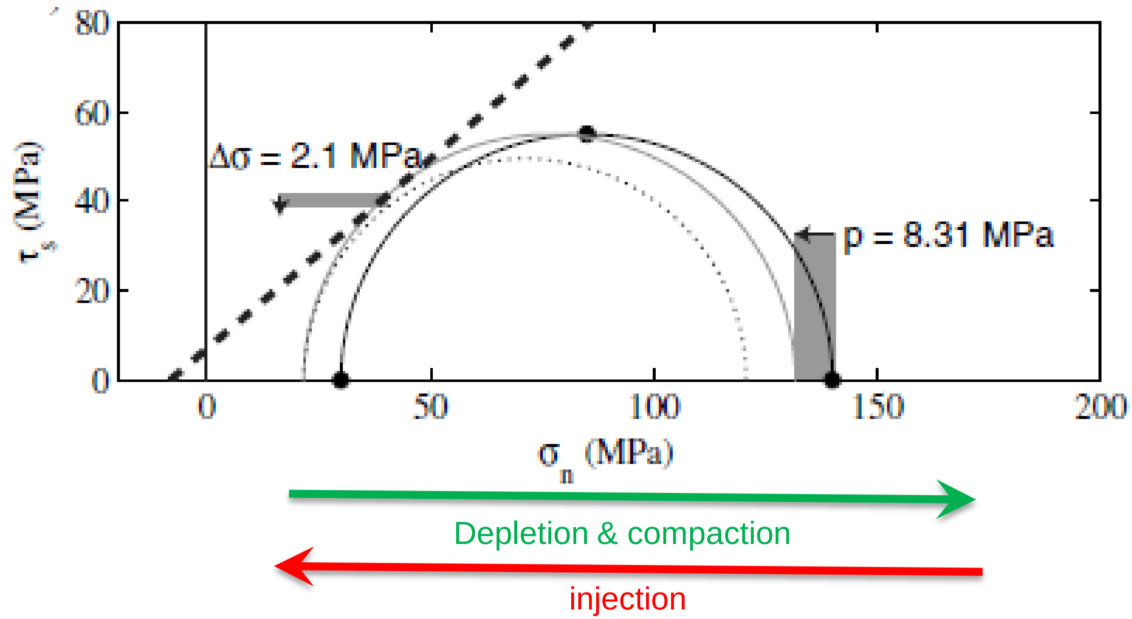
- Time-distance distribution of seismicity follows pressure diffusion
- Seismicity sometimes induced by very small pressure perturbations (tides, rain)
- At large perturbations (e.g. Basel), source parameters (stress drop and b-value) appear to correlate with pressure or differential stress.



Induced Seismicity

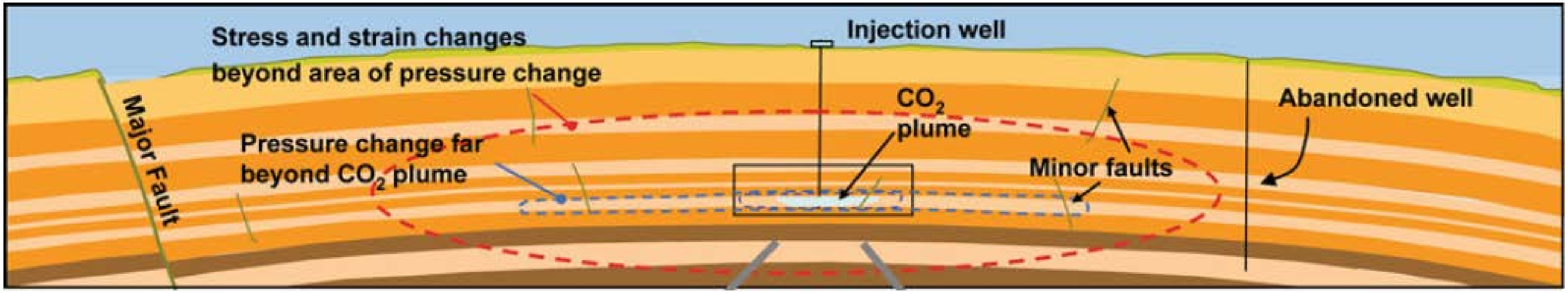
Seismicity can be induced by a variety of other mechanisms:

- Depletion & compaction (e.g. oil production)
- Stress transfer in over- and sideburden
- Fracture opening (P > fracture pressure, «fracking»)
- Fault reactivation



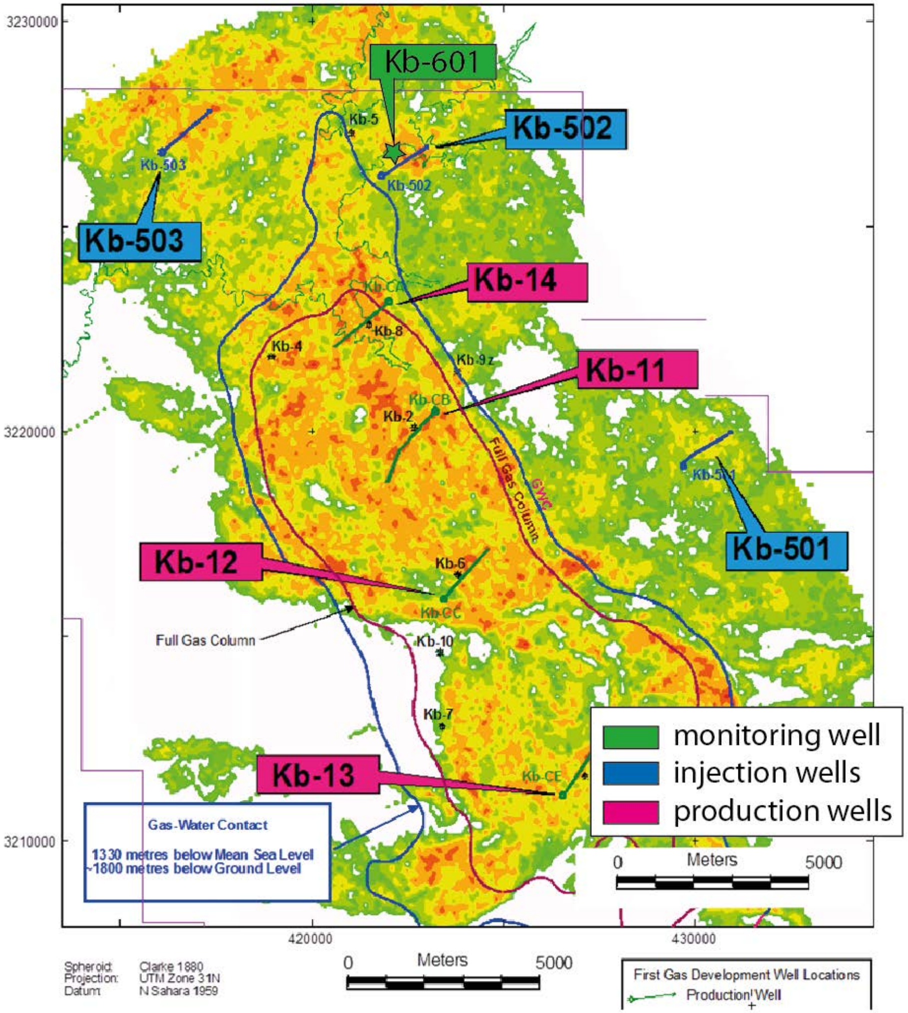
Induced Seismicity and CCS

(Rutqvist, 2013)



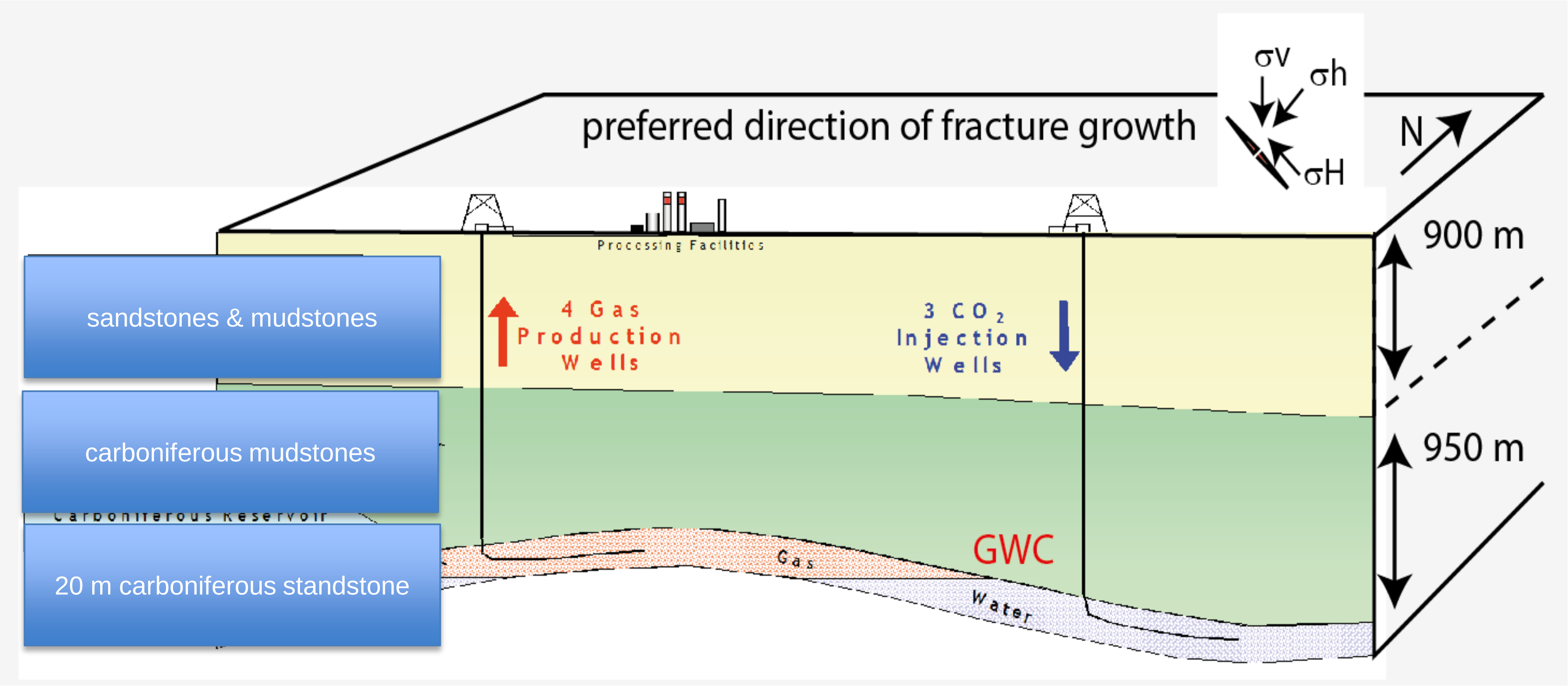
- ➢ In CCS, we expect a number of the listed mechanisms to contribute to seismicity
  - Pressure-induced seismicity mainly near injection and at plume front
  - Stress-induced seismicity and other mechanisms further away
- ➢ Goals:
  1. Verify seal integrity (risk assessment)
  2. Track plume progression (monitoring)
  3. Reservoir characterization (management / optimization)

The In Salah CO_2 storage site



- Injection commenced in 2004 via three injection wells.

The In Salah CO_2 storage site



sandstones & mudstones

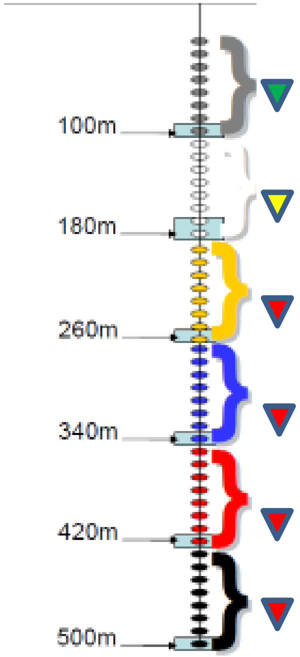
carboniferous mudstones

20 m carboniferous standstone

- ➢ 4 MT CO_2 injected into a naturally fractured Carboniferous sandstone reservoir at 1.9 km depth.

Microseismic array at KB-601

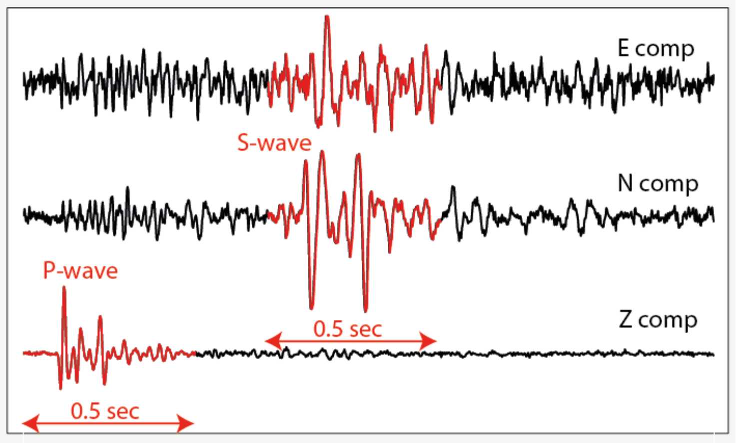
2009-2011



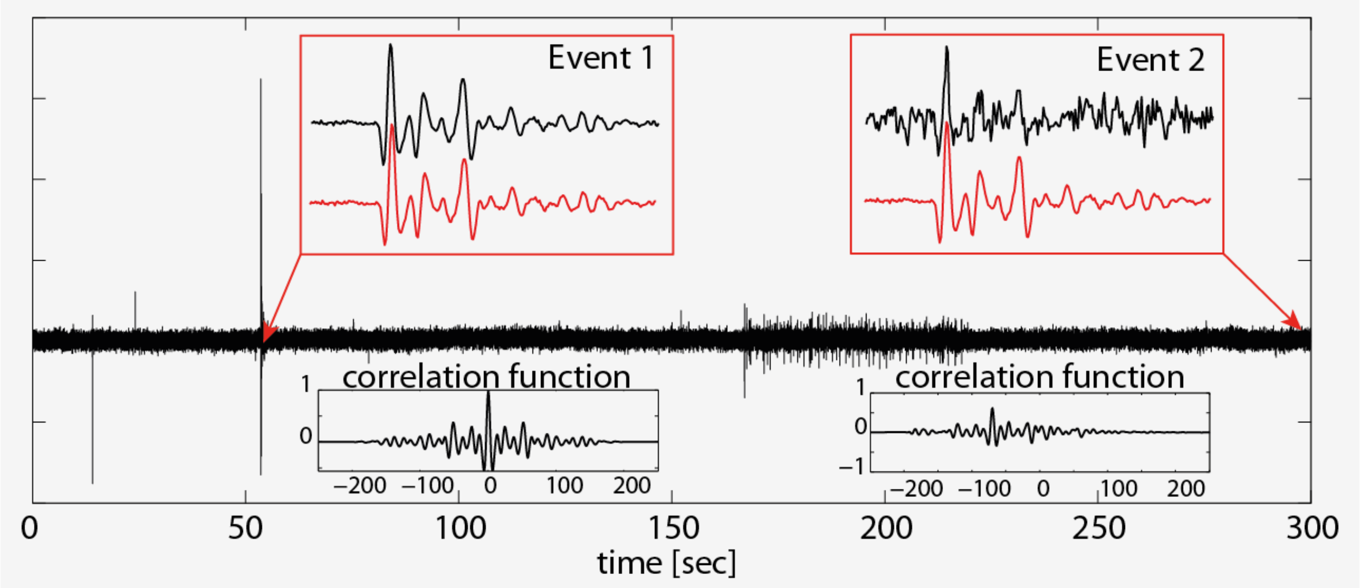
- Downhole array of 48 3C geophones between 30-500 m depth
- 6 geophones were connected to 3 digitizers
- GPS timing problems and strong electronic noise
- **Only uppermost geophone provided reliable data**

Event detection method

Goertz-Allmann et al. (2014)

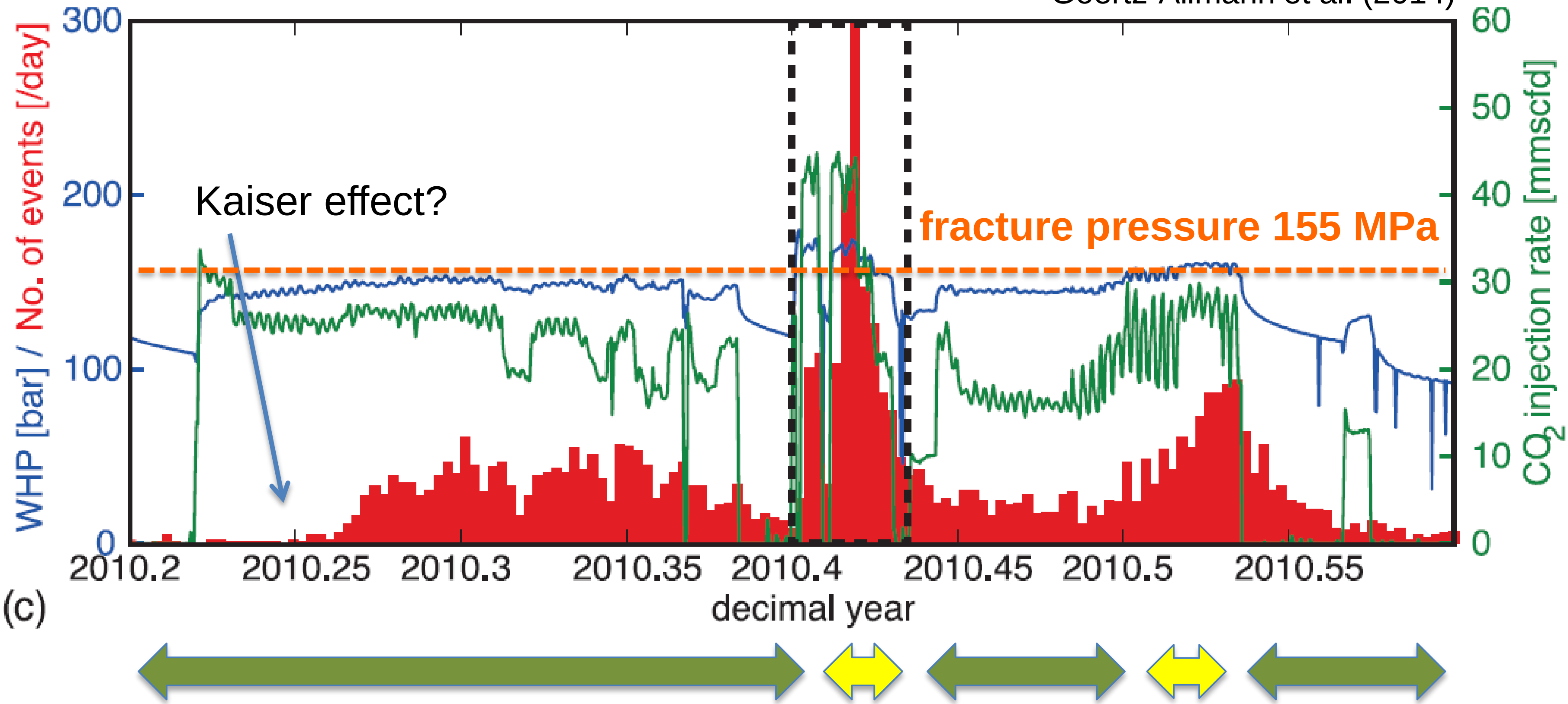


- Master event waveform cross-correlation method to detect and pick seismic events within continuous data
- More than 5000 events are detected between August 2009 and June 2011



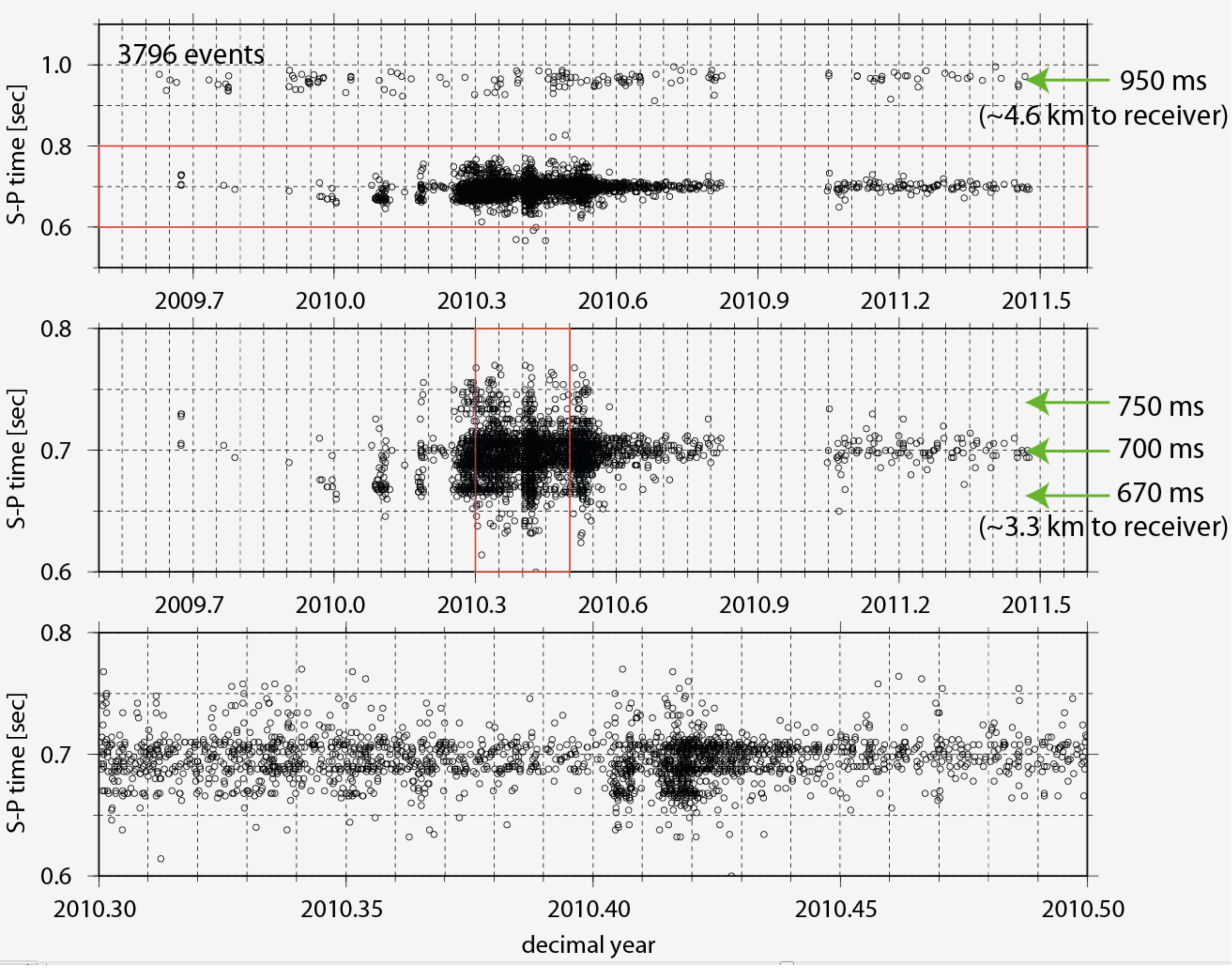
Comparison of events and injection data

Goertz-Allmann et al. (2014)

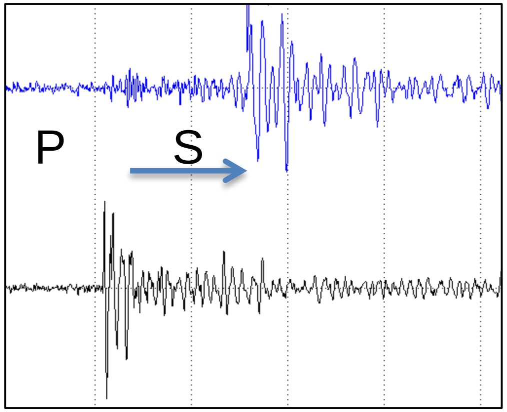


- ➢ High correlation between occurrence of microseismic events and injection rate
- ➢ Periods of matrix injection and fracture injection

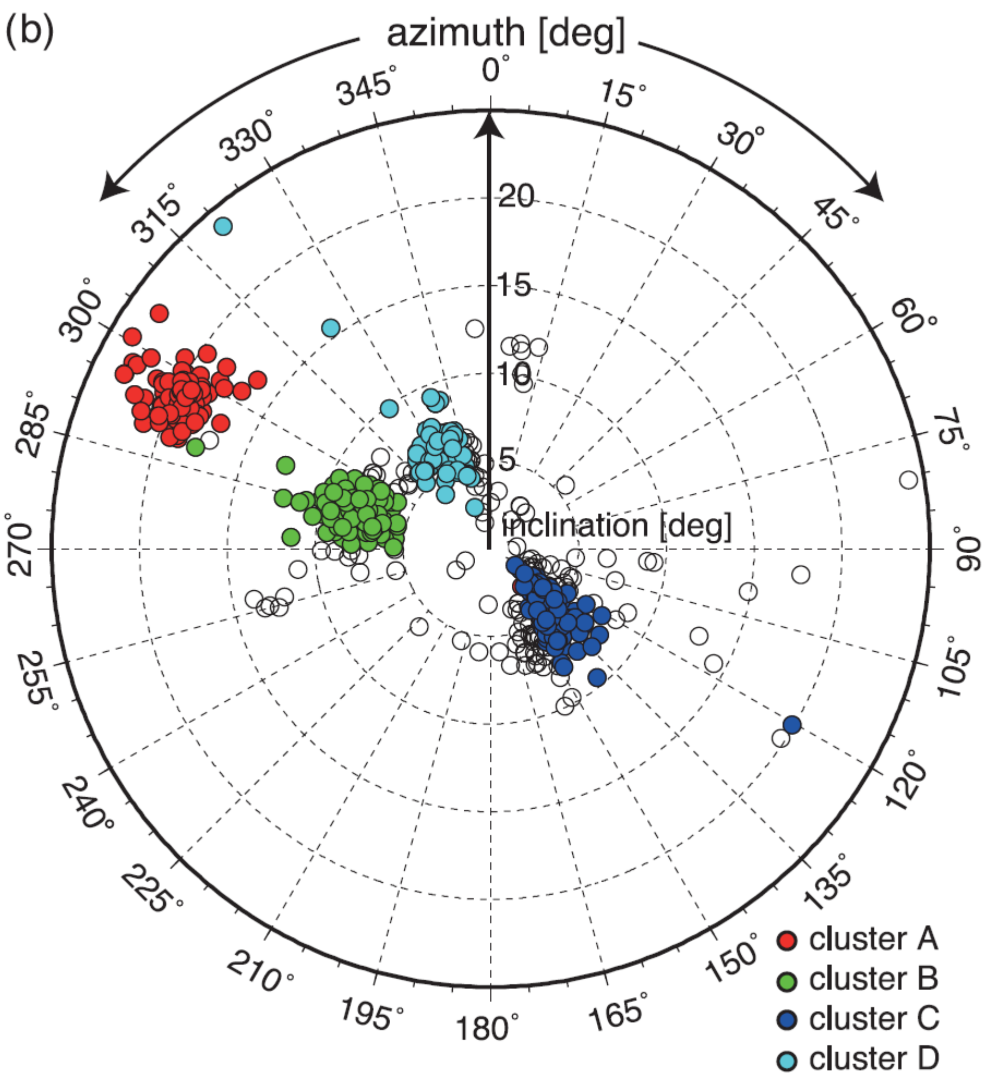
Event analysis using one geophone



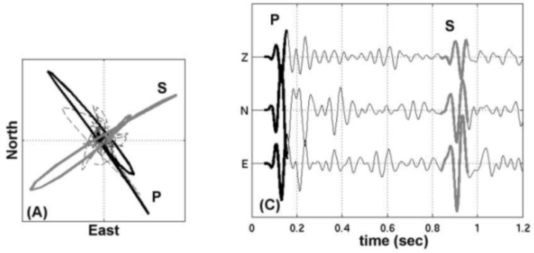
- Differential S-P wave onset time gives an estimate of event-to-receiver distance
- Several clusters with similar arrival-time differences can be identified



Event analysis using one geophone

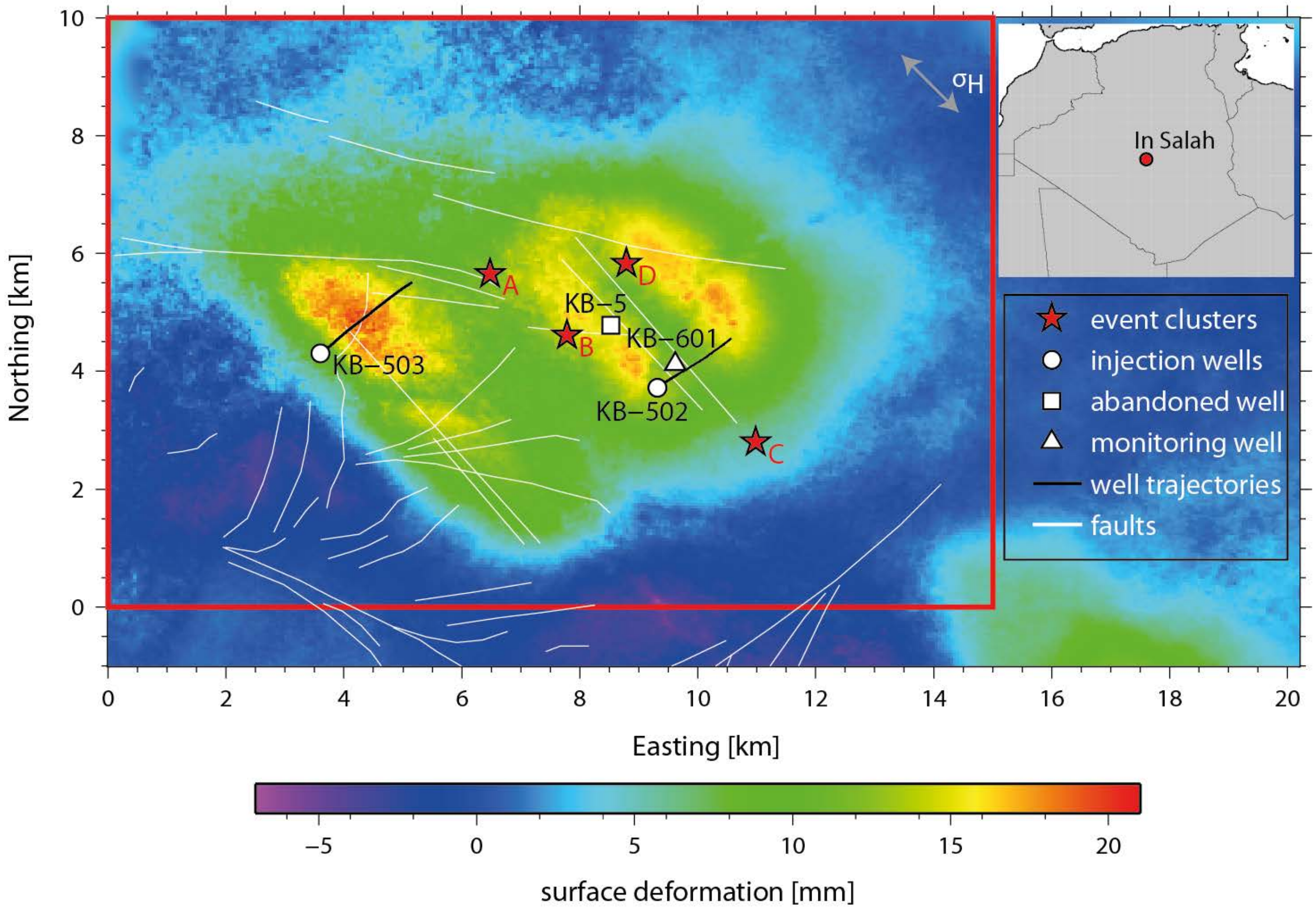


- ➢ Determine event direction from particle motion of P-waves.
- ➢ Futher separate clusters by combining S-P, azimuth, and inclination (clusters A-D).
- ➢ Overall events are oriented in the direction of the largest horizontal stress.
- ➢ No seismicity within a radius of about 1 km around the injection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



(Oye and Ellsworth, 2005 BSSA)

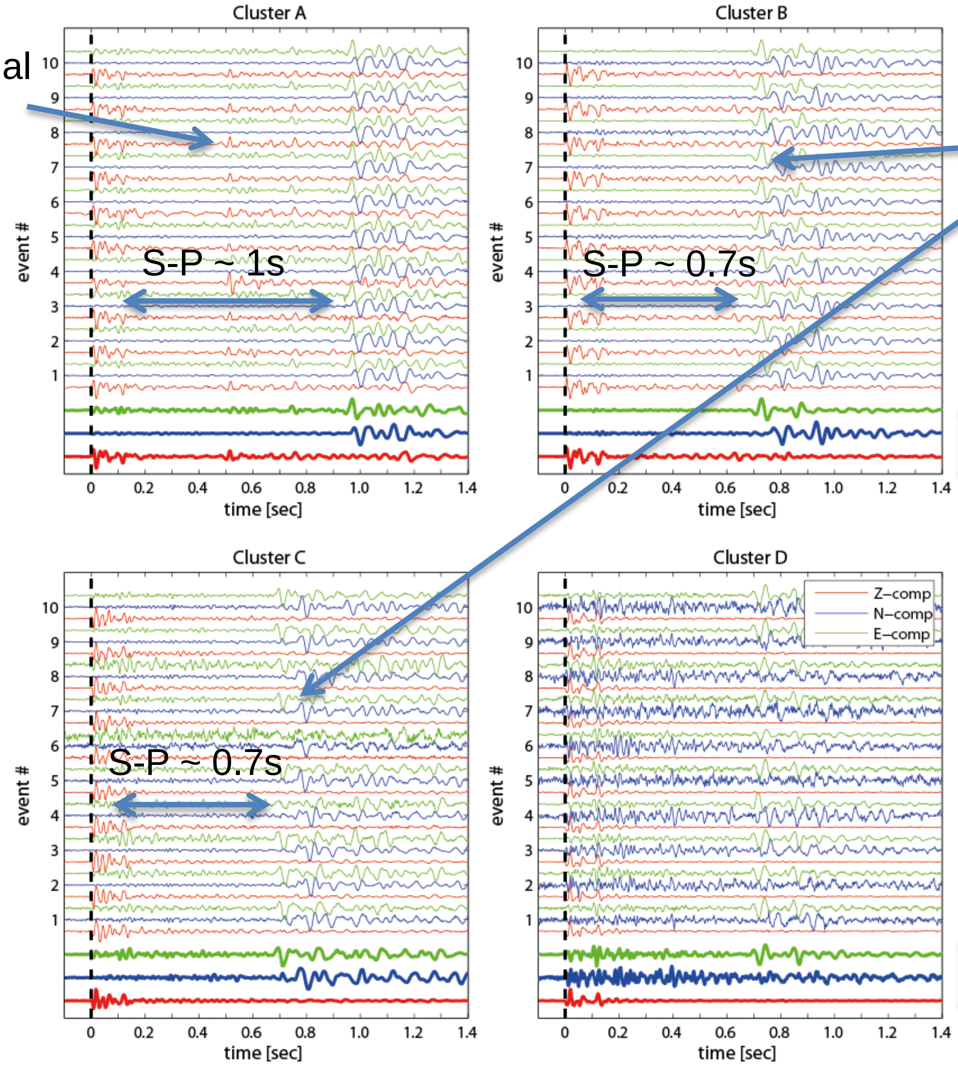
Possible location of 4 event clusters



- Together with InSAR data the clusters may give an indication on the extent of the CO_2 plume in 2010.

Goertz-Allmann et al. (2014)

Event analysis: example waveforms



Additonal phase arrivals

S-P ~ 1s

S-P ~ 0.7s

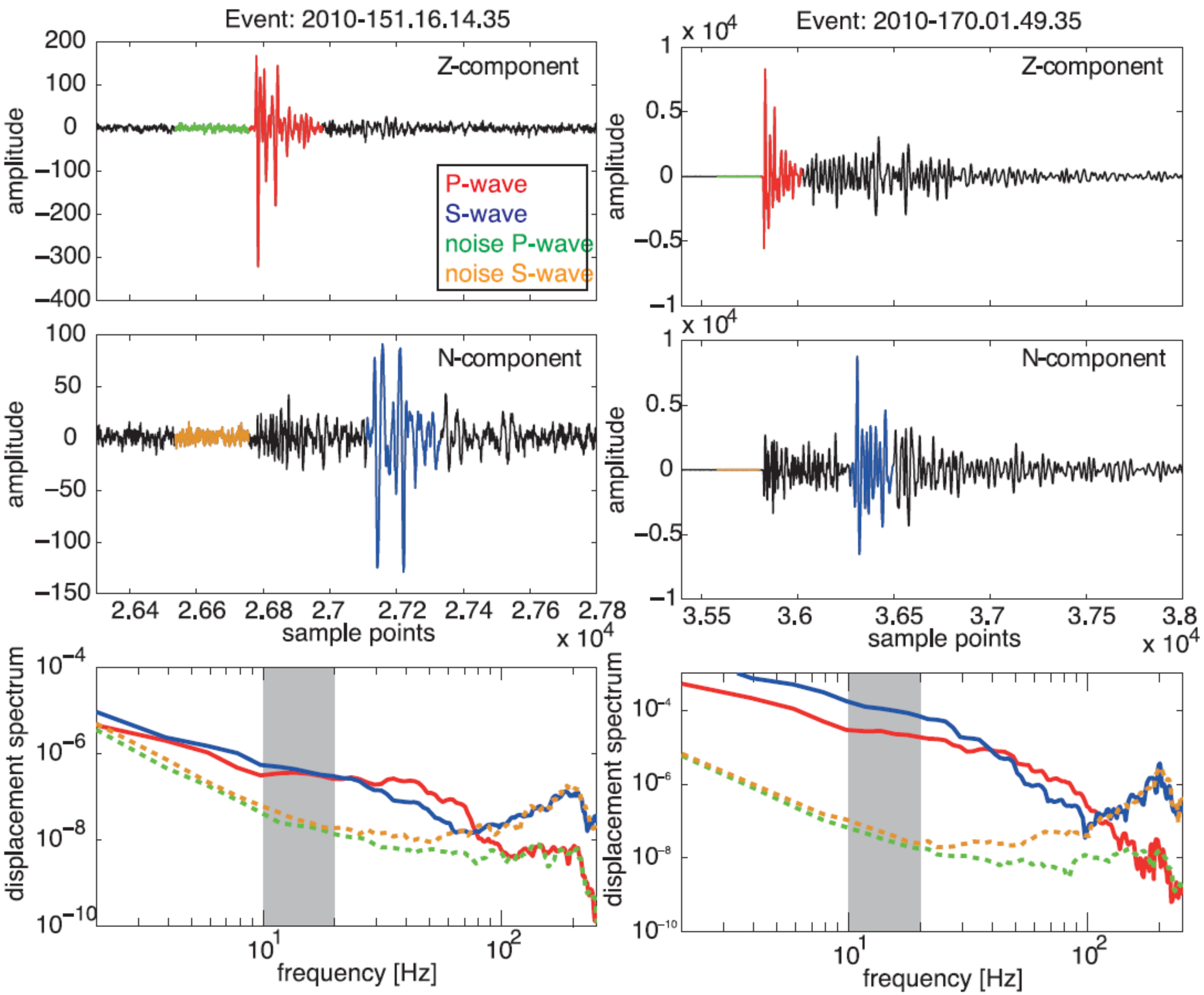
Shear-wave splitting

stack

S-P ~ 0.7s

stack

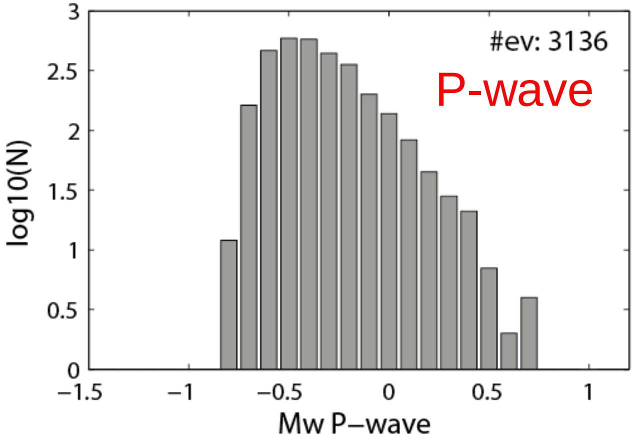
M_w estimation

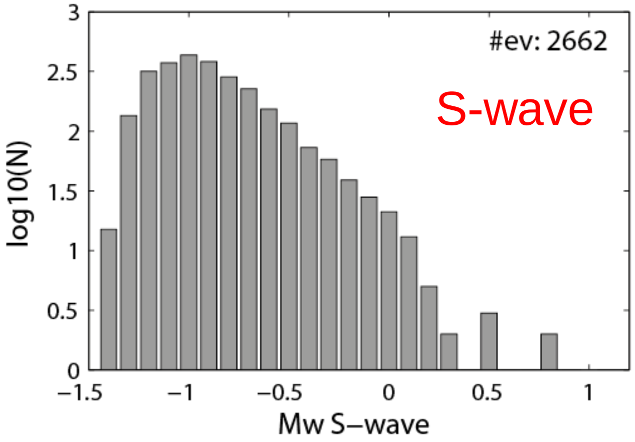


M_W estimation

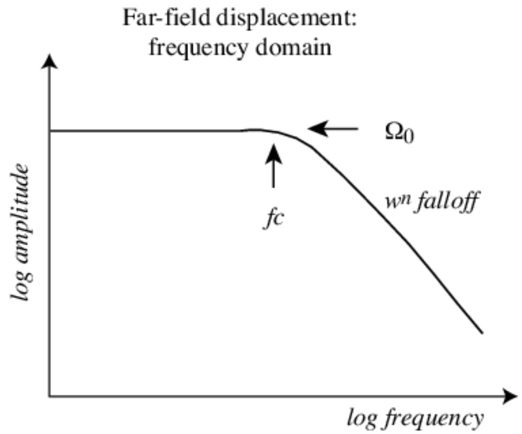
$$m0 = 4\pi\rho v^3\Omega_0/F$$

$$Mw = \frac{2}{3}(log10(m0) - 9.1)$$



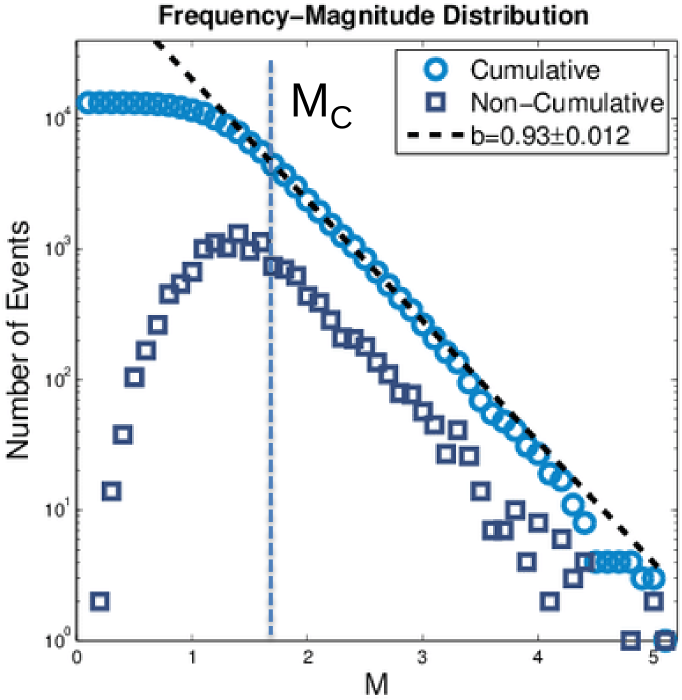


- Distance and attenuation correction
- Determine the low-frequency spectral level Ω_0 (mean of 10 or 15 Hz to 20 Hz depending on SNR)
- Compute seismic moment m_0 and M_W
- Most M_W estimates are between -1 and 0, largest M_W is about 1
- M_W P-wave > Mw S-wave
- Effect of the different radiation pattern



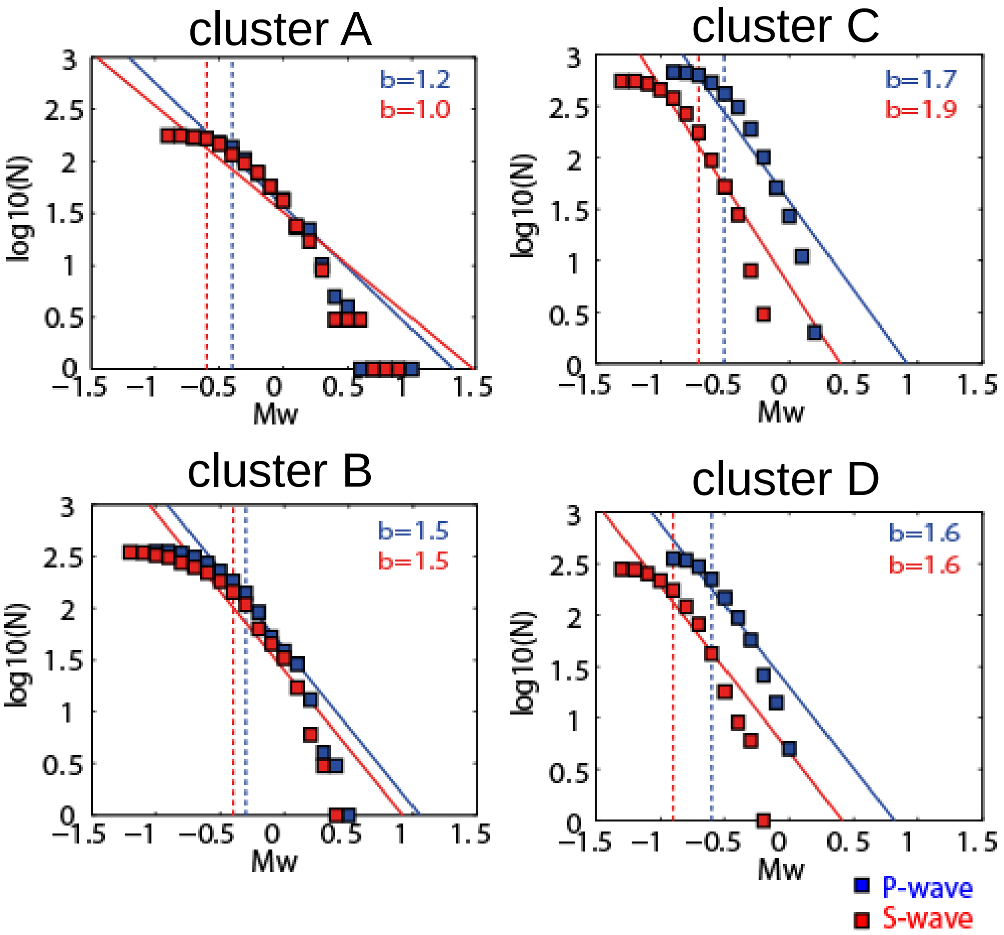
b-value analysis of event clusters

- b-value is the slope of the Gutenberg-Richter law
- b-value can be linked to in-situ reservoir stress state: e.g. high b-value when new fractures open and low b-value when pre-existing fractures are reactivated



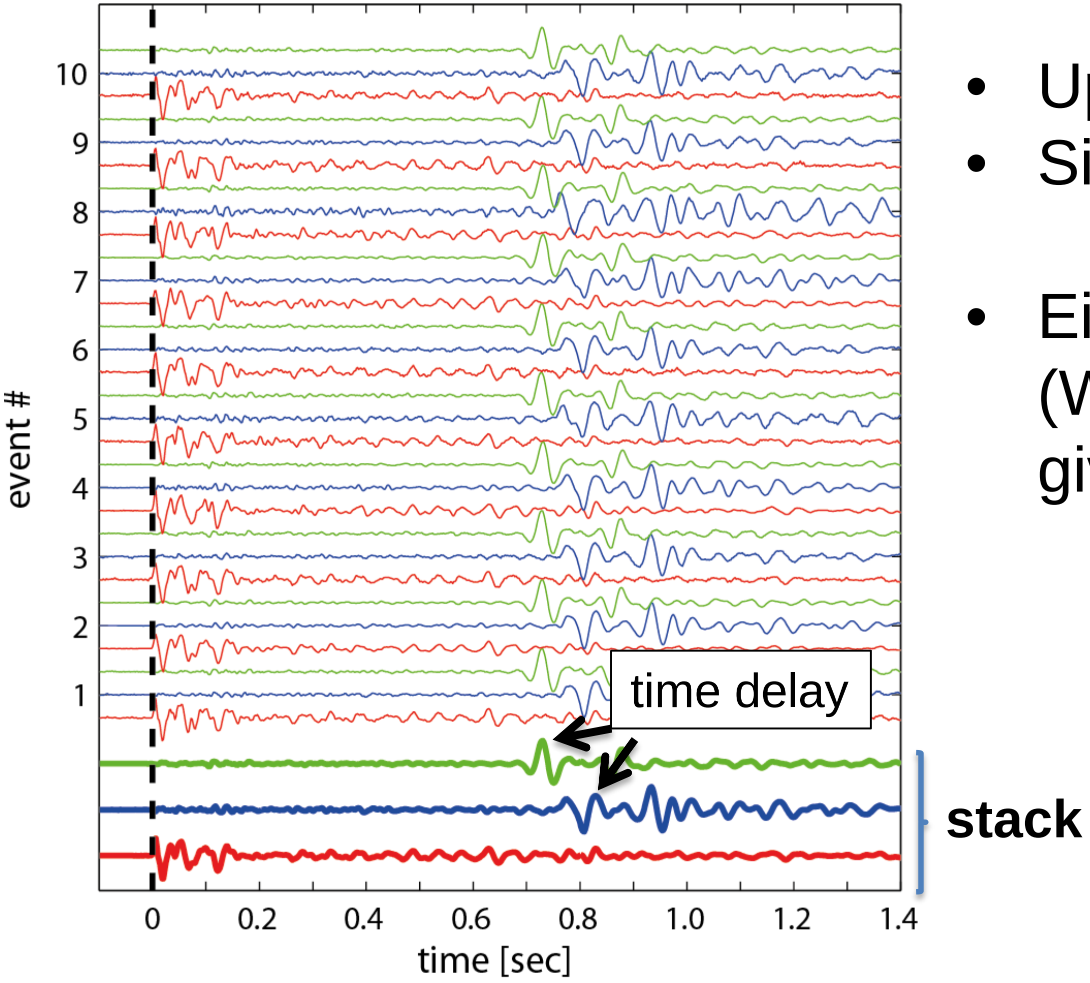
$$\log10 (N) = a – b\,M$$

b-value analysis of event clusters



- Similar b-values for P and S but significant variations between clusters.
- b ~ 1 for cluster A (average tectonic)
- Larger b (1.5 to 2) for clusters B-D

Shear-wave splitting analysis



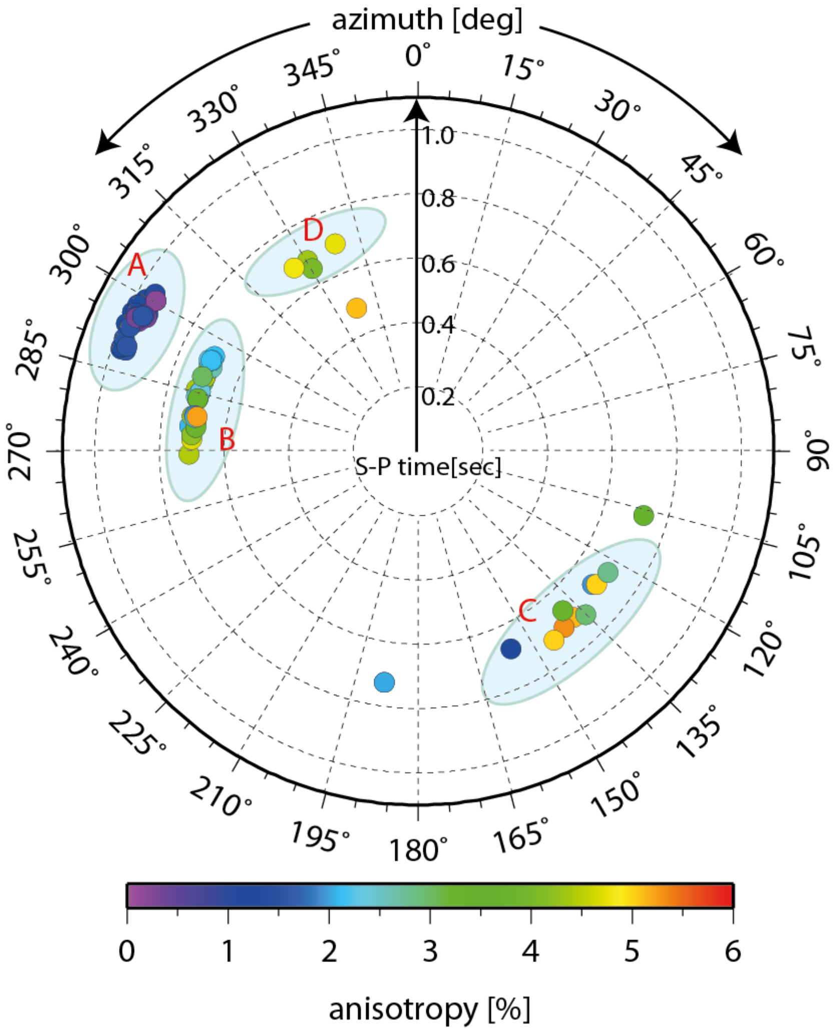
- Up to 0.1 s Δt on S arrival.
- Sign of anisotropy

- Eigenvalue method (Wüstefeld et al. 2010) gives anisotropy from Δt:

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

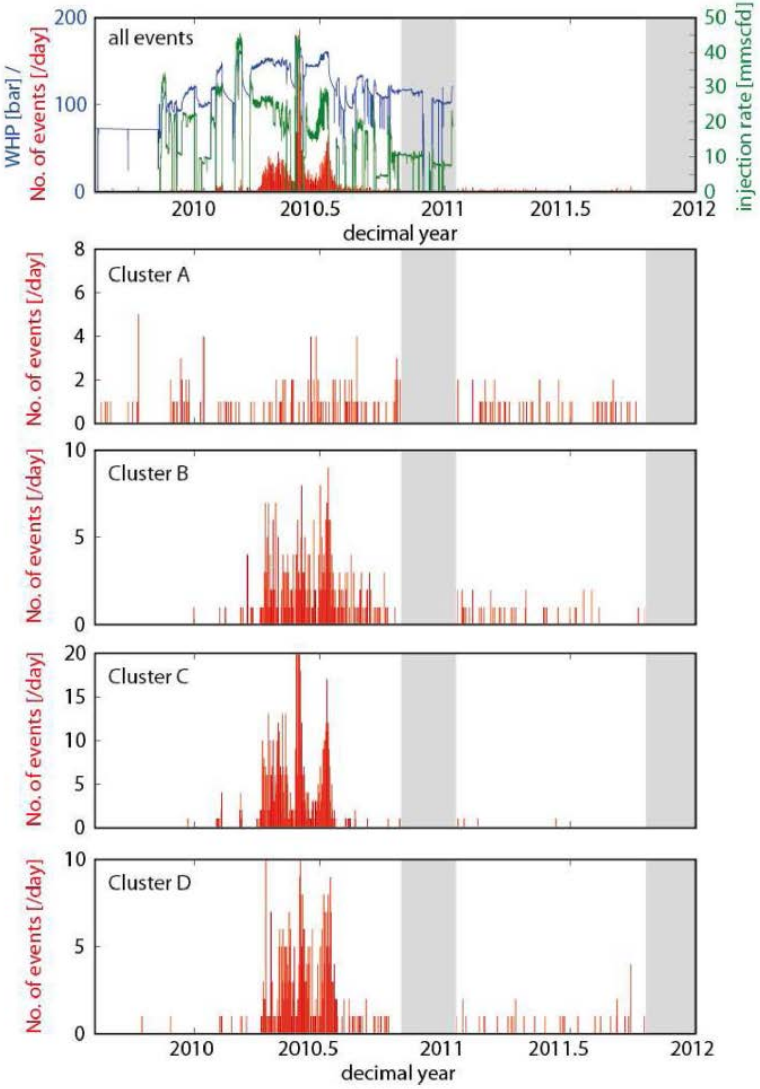
A: percentage anisotropy
β : average S velocity
R : source–receiver distance
Δt: time delay

Shear-wave splitting analysis

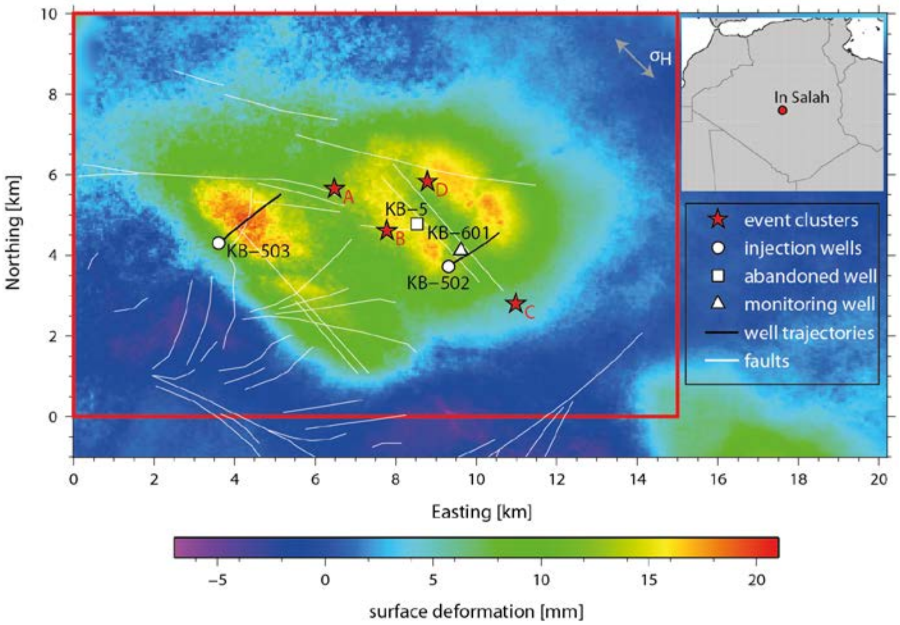


- 83 events with good splitting
- 5% of anisotropy for clusters B-D
- Less than 2% of anisotropy for cluster A

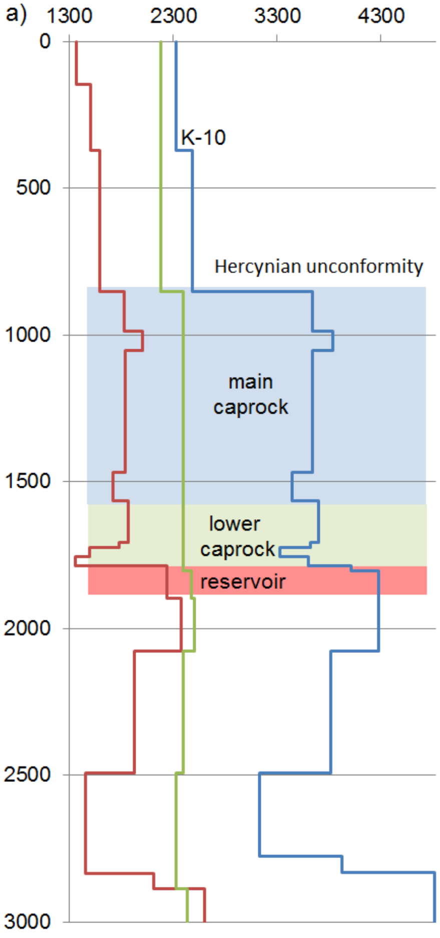
Comparison to injection parameters

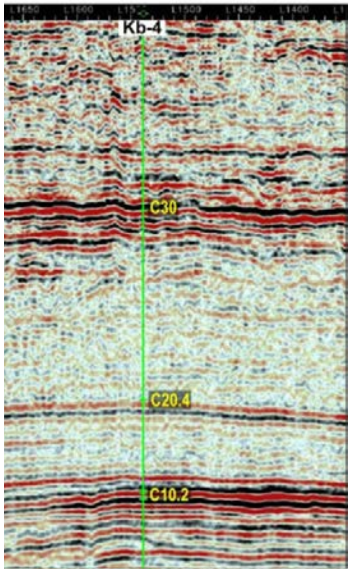


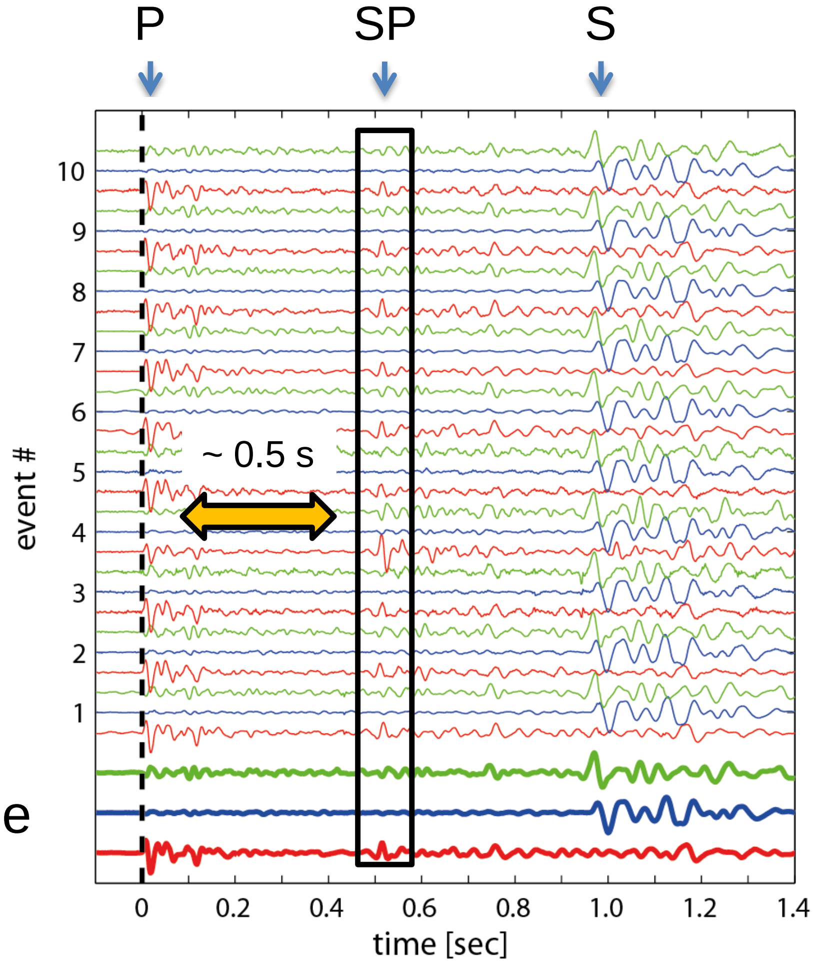
- No correlation between injection parameters and cluster A
- High correlation with clusters B-D
- High activity of cluster C only during main injection phase



Confining microseismic event depth



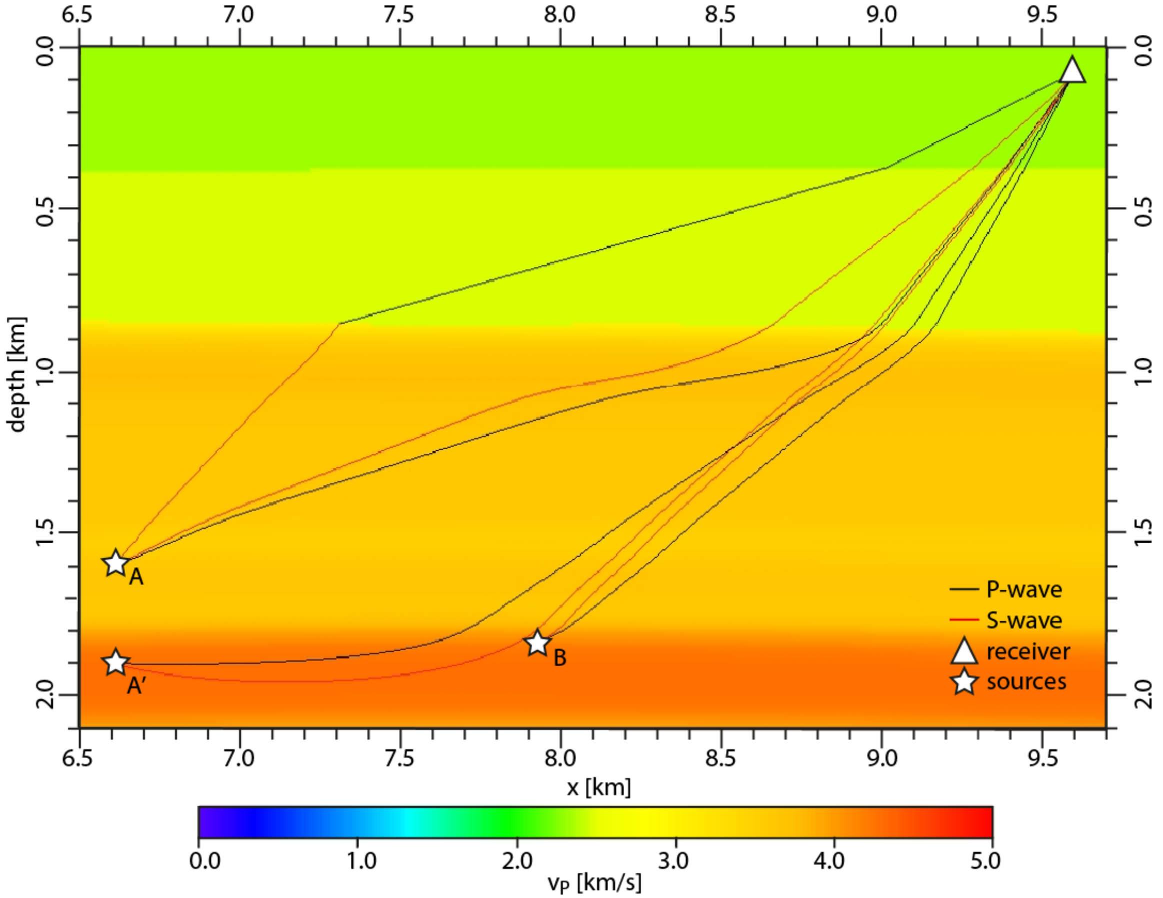




Cluster A

- Additional phase on Z between direct P & S
- S-to-P converted phase at strongest velocity contrast (850 m).

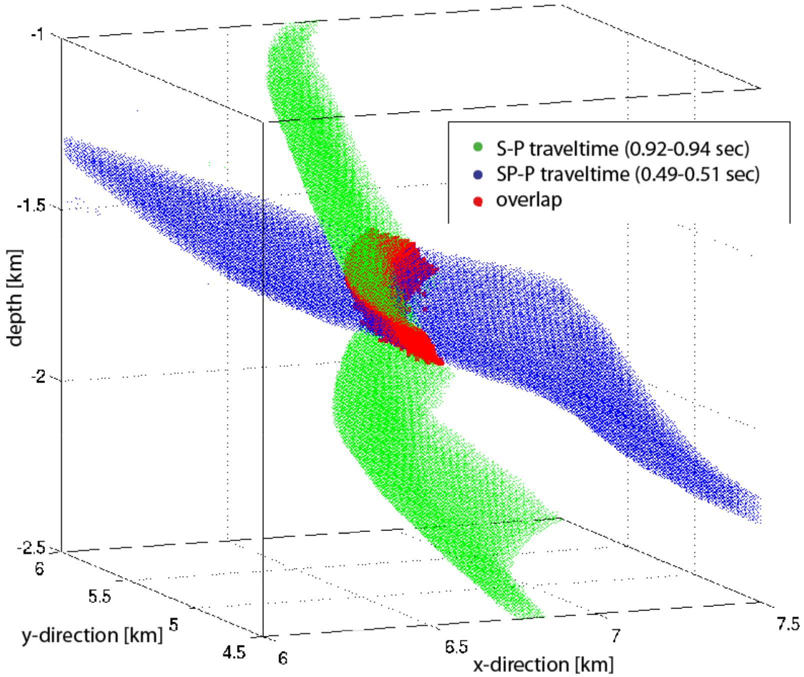
Confining microseismic event depth



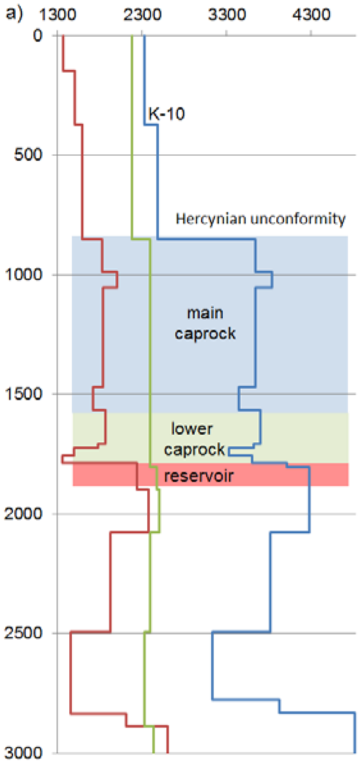
- Use 3D ray tracing to identify converted SP.

- Test potential source locations:
- 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.

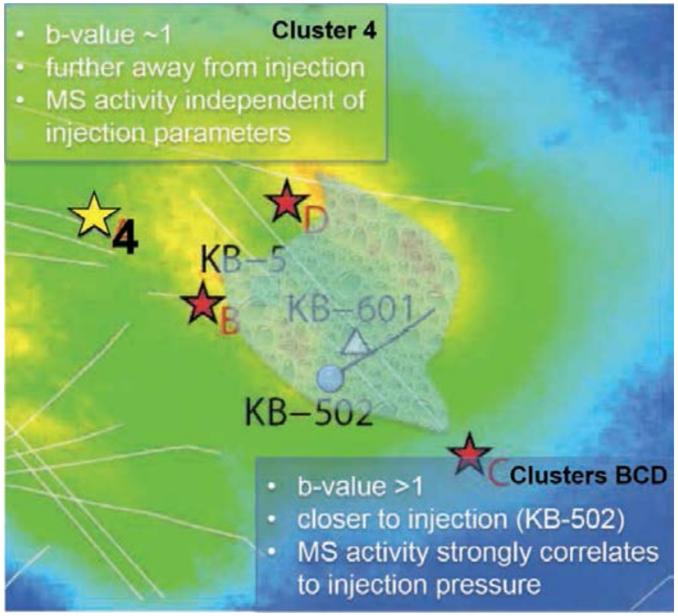


→ Cluster A: within cap rock!

Goertz-Allmann et al. (2014)

Summary of microseismicity at In Salah

- Over 5000 events detected despite only one sensor
- Clear dependence on CO_2 injection.
- Constrain event depth with later phase arrivals: we find that one cluster is in the cap rock.
- Two main groups of events are identified:
  - **Type 1**: stress-triggered seismicity (A)
  - **Type 2**: fracture opening (B-D)



Cluster 4
- b-value ~1
- further away from injection
- MS activity independent of injection parameters

Clusters BCD
- b-value >1
- closer to injection (KB-502)
- MS activity strongly correlates to injection pressure

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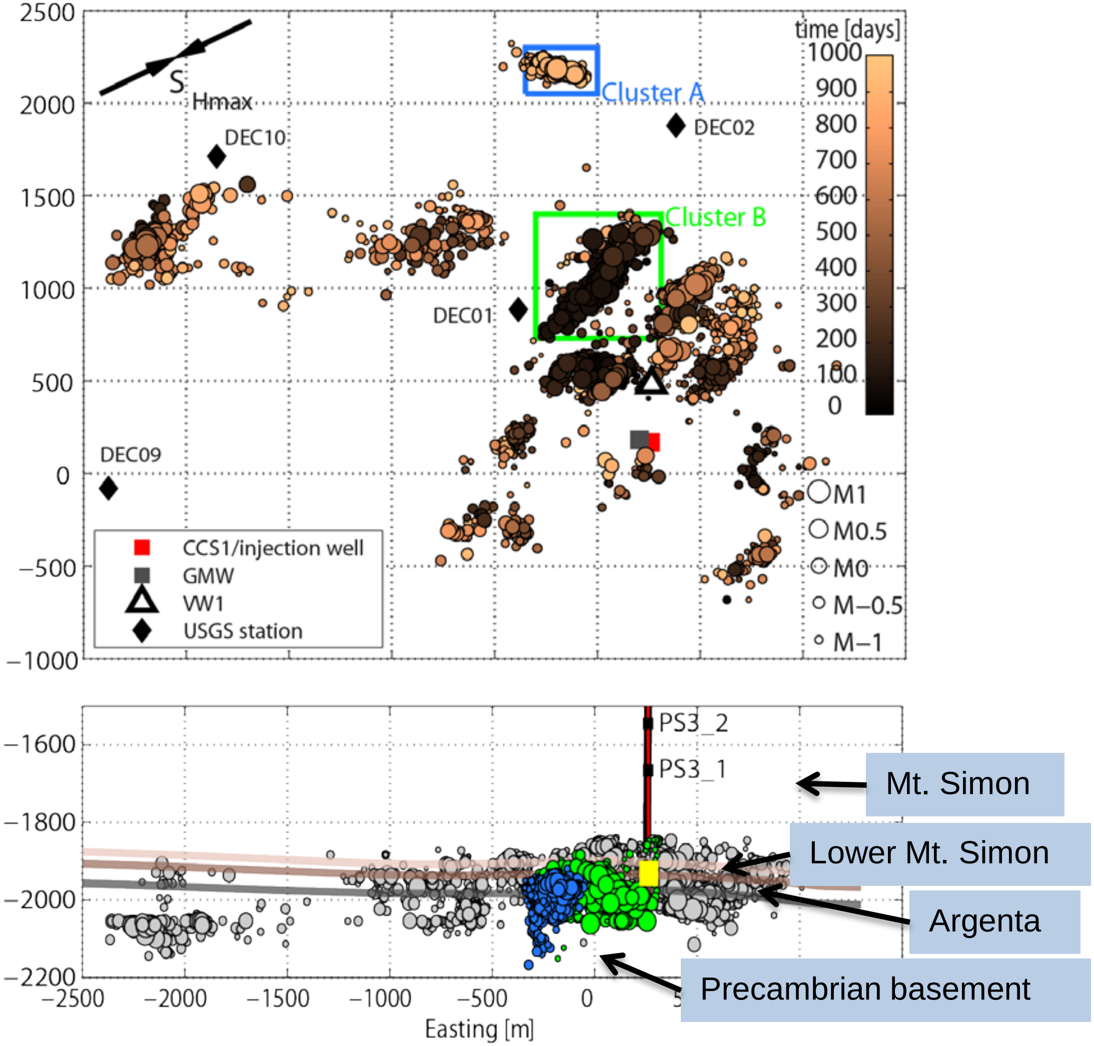
The Decatur CCS site

- Inject 1 M tons of CO_2 into Mt. Simon sandstone (460 m thick) at about 1.9 km depth (end 2011-2014).
- Borehole & surface sensors.
- About 4,800 microseismic events were located using borehole strings.
- Events occur in distinct clusters with heterogeneous activity.

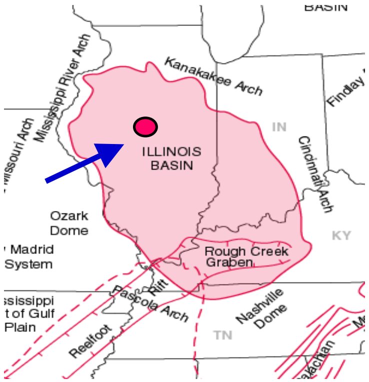


Mt. Simon

Lower Mt. Simon

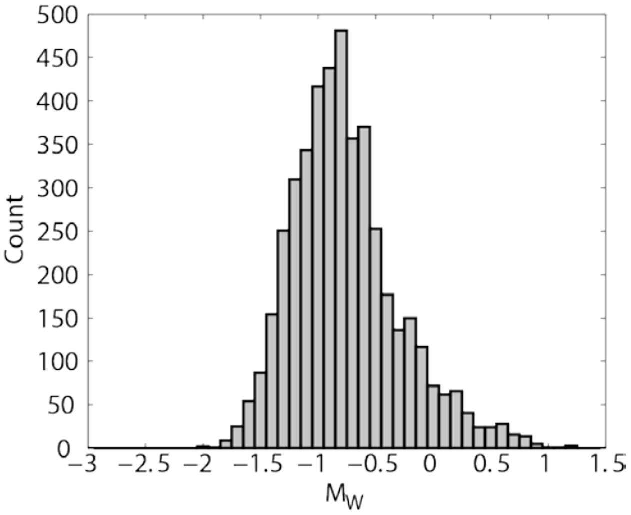
Argenta

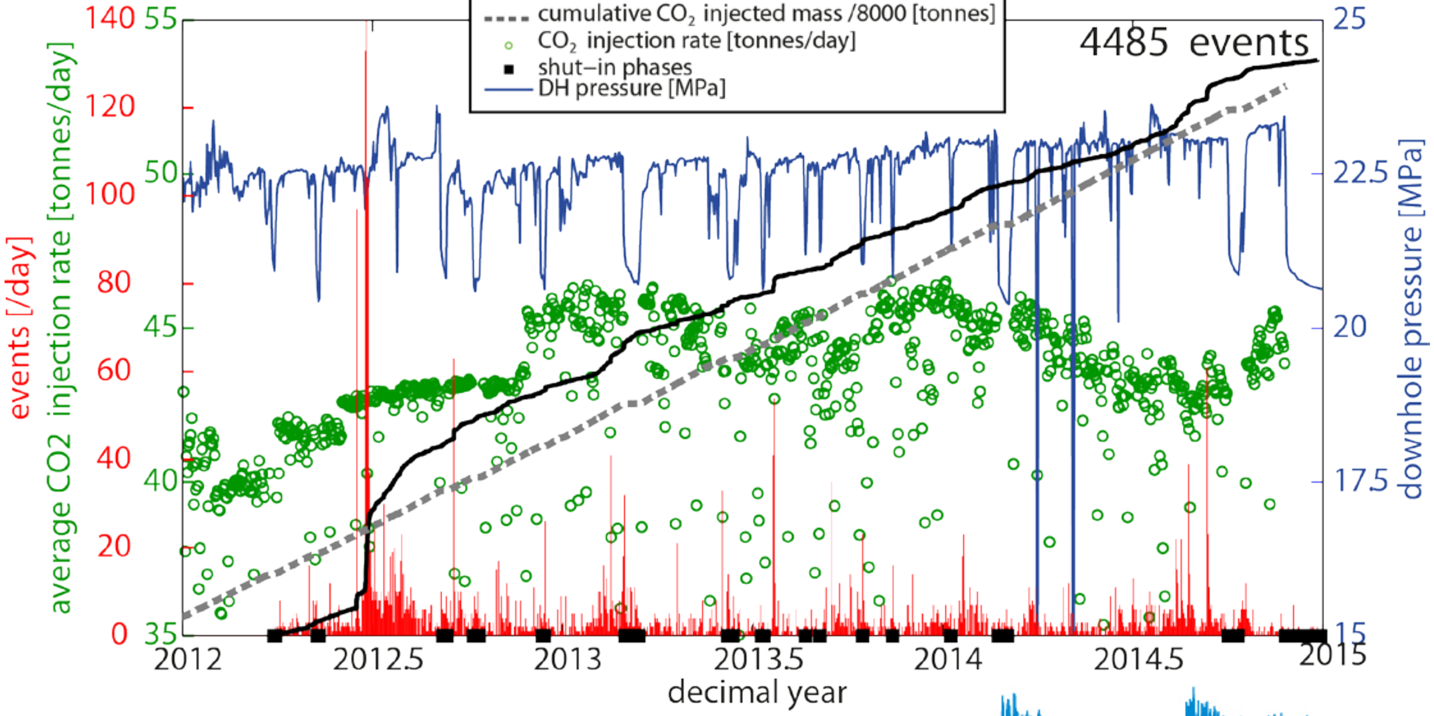
Precambrian basement



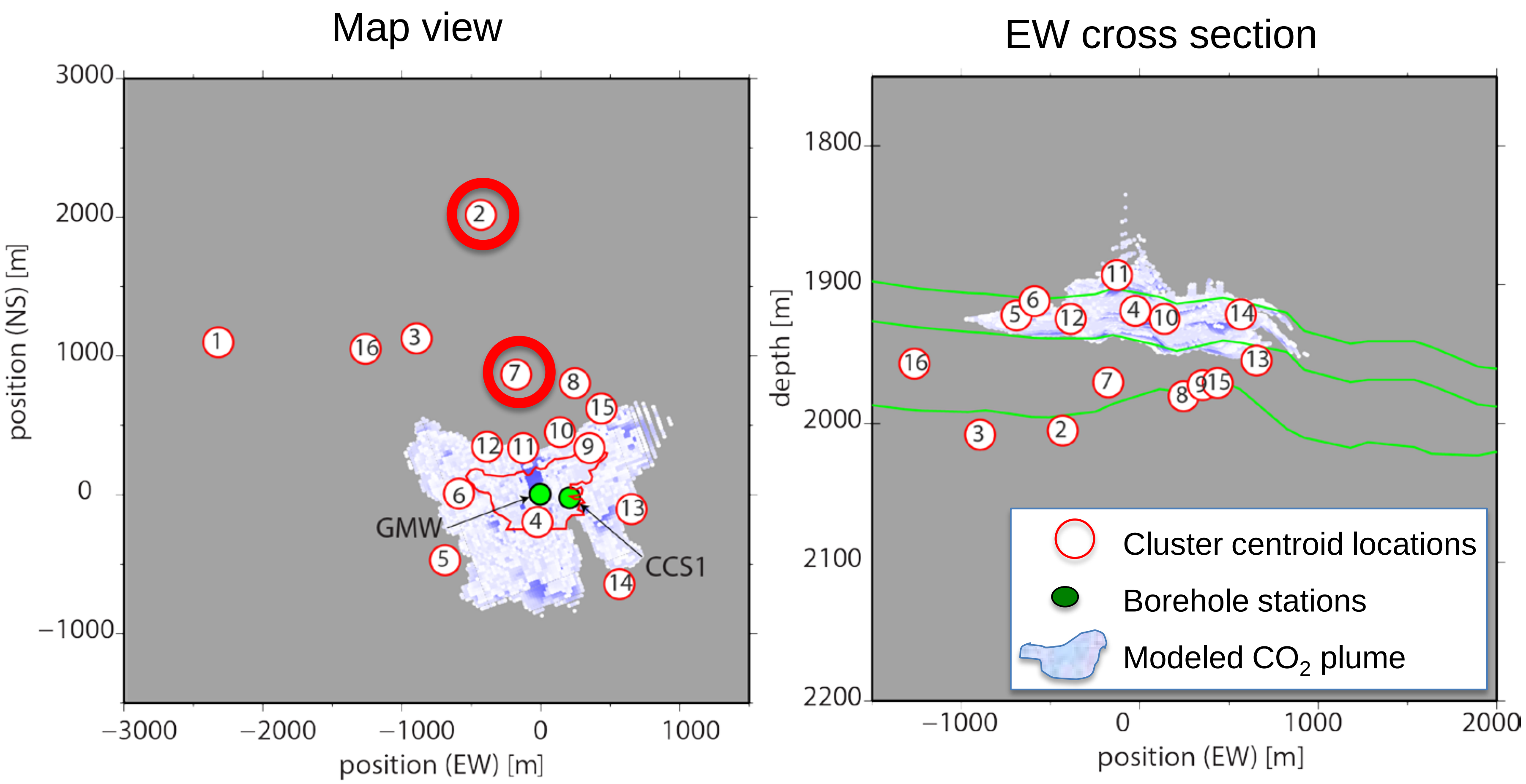
The Decatur CCS site

- Most events with $M_w < 0$.
- Injection at very low pressure (< 1 MPa)
- No obvious correlation with plume migration – events far from the injection





Spatial distribution of event clusters and comparison to modelled CO_2 plume

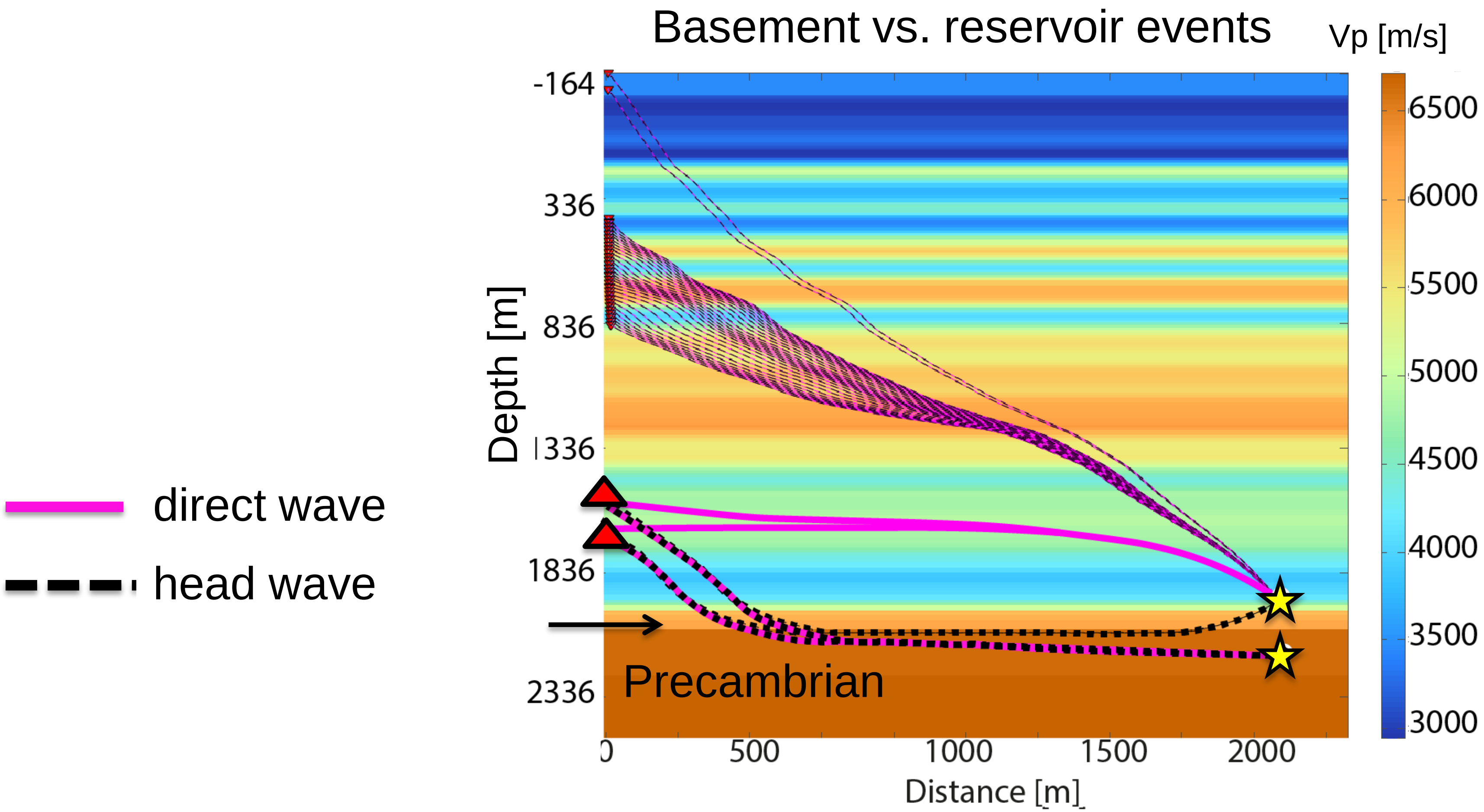


Map view

EW cross section

→16 microseismic clusters

Event characterization

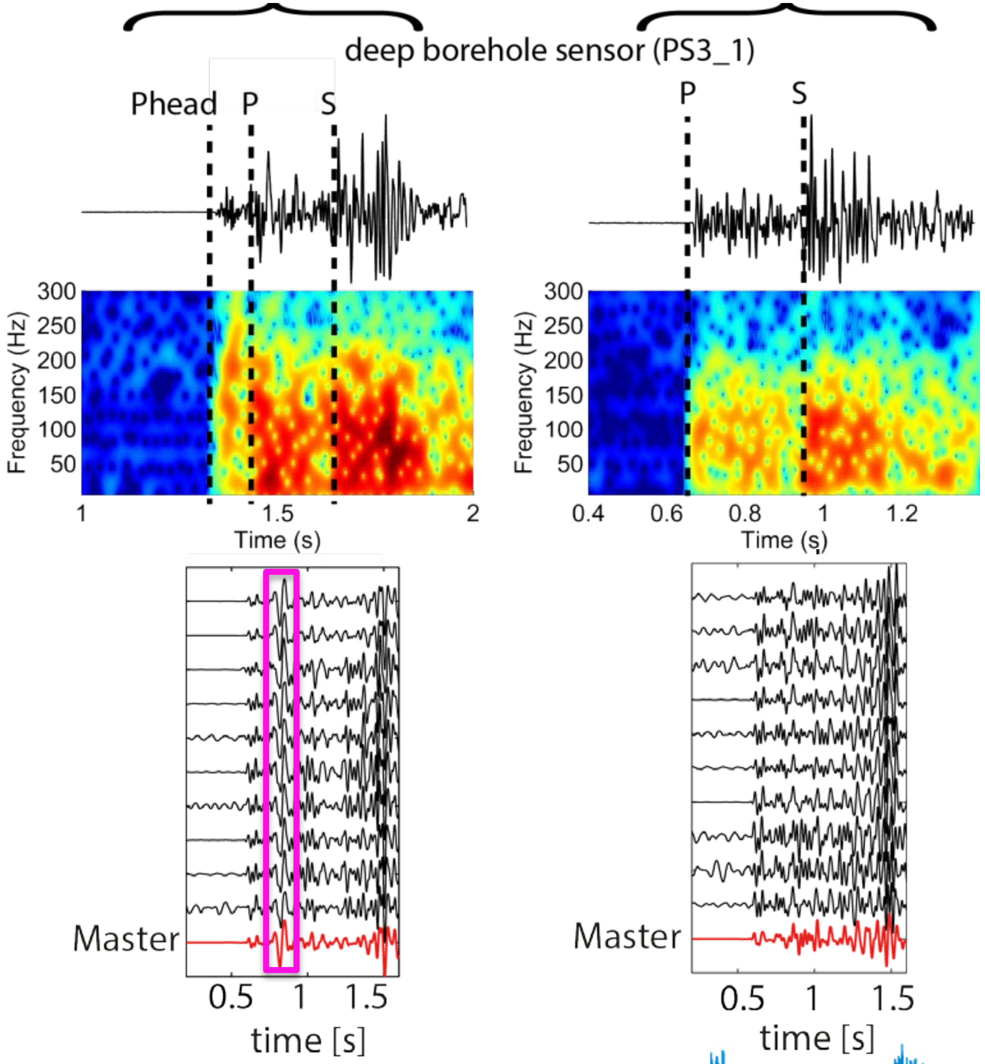

Basement vs. reservoir events

- Theoretical ray diagrams for reservoir & basement events.
- Different waveform signature: head wave and direct wave arrivals clearly visible for reservoir events

Event characterization

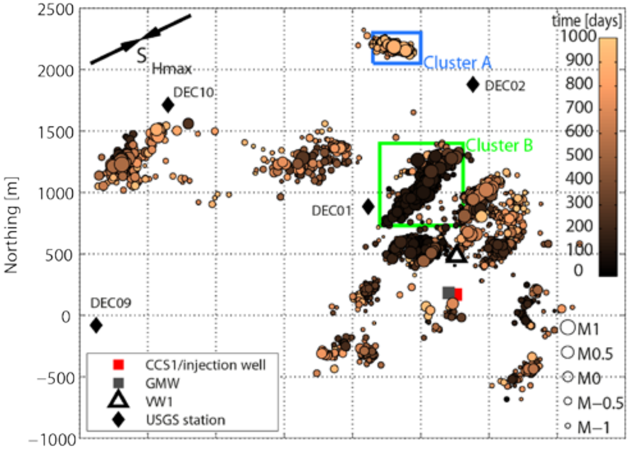
Reservoir

Basement

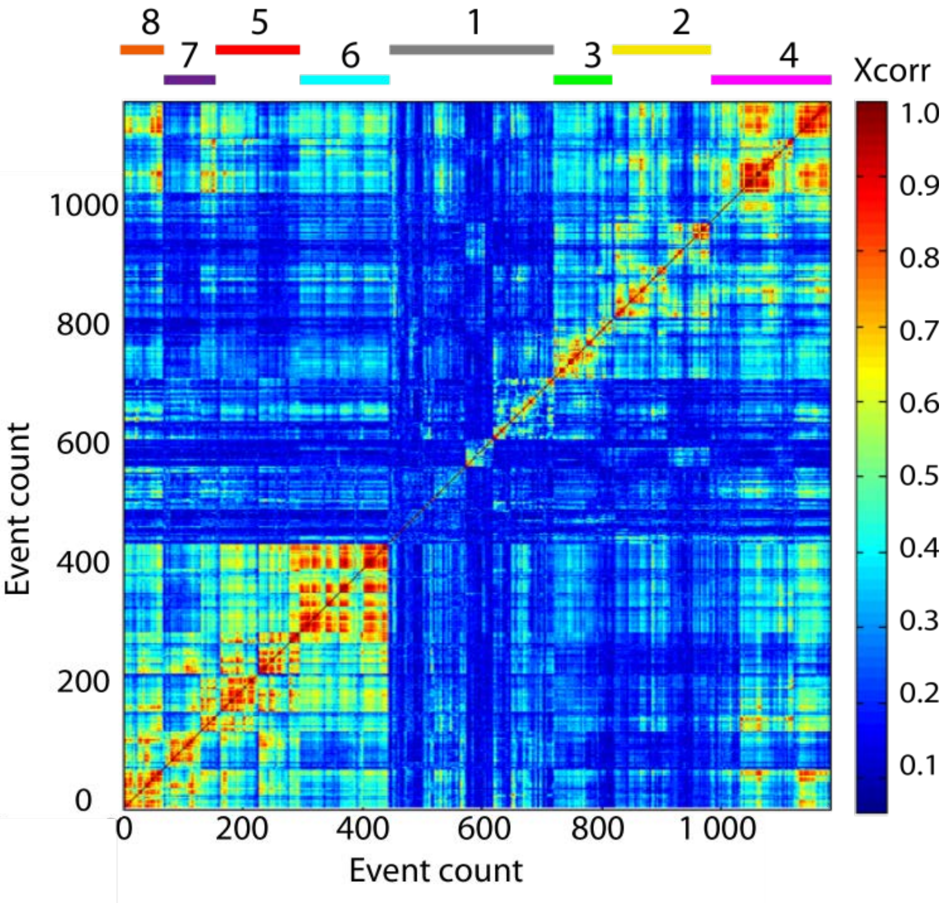


Event characterization

Sub-cluster analysis of one cluster



Cross-correlation matrix

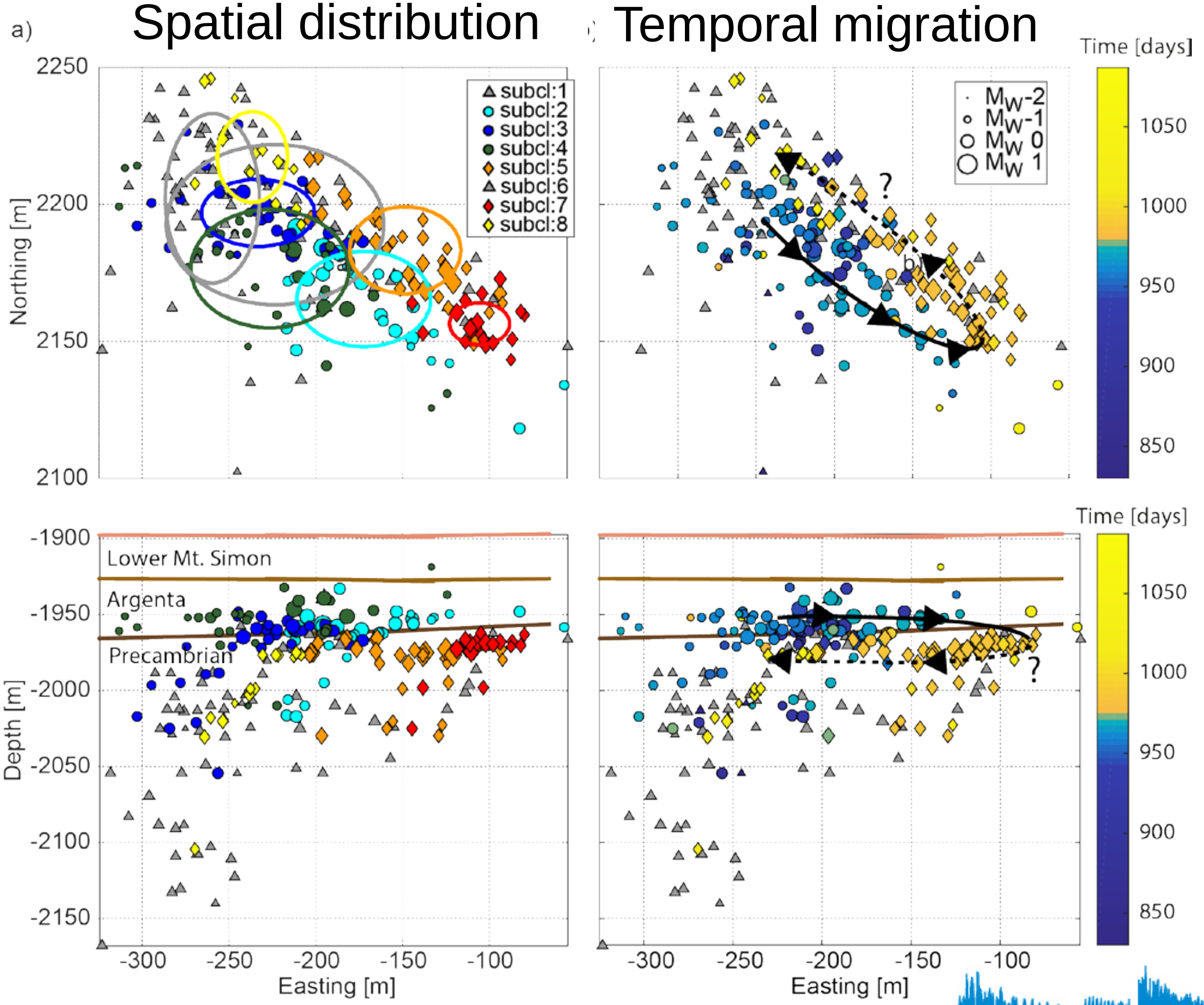


Goertz-Allmann et al. (2017)

Microseismic event characterization

Cluster A

Spatial distribution / Temporal migration



- Separate events occurring within different layers:

Cold = reservoir

Warm = basement

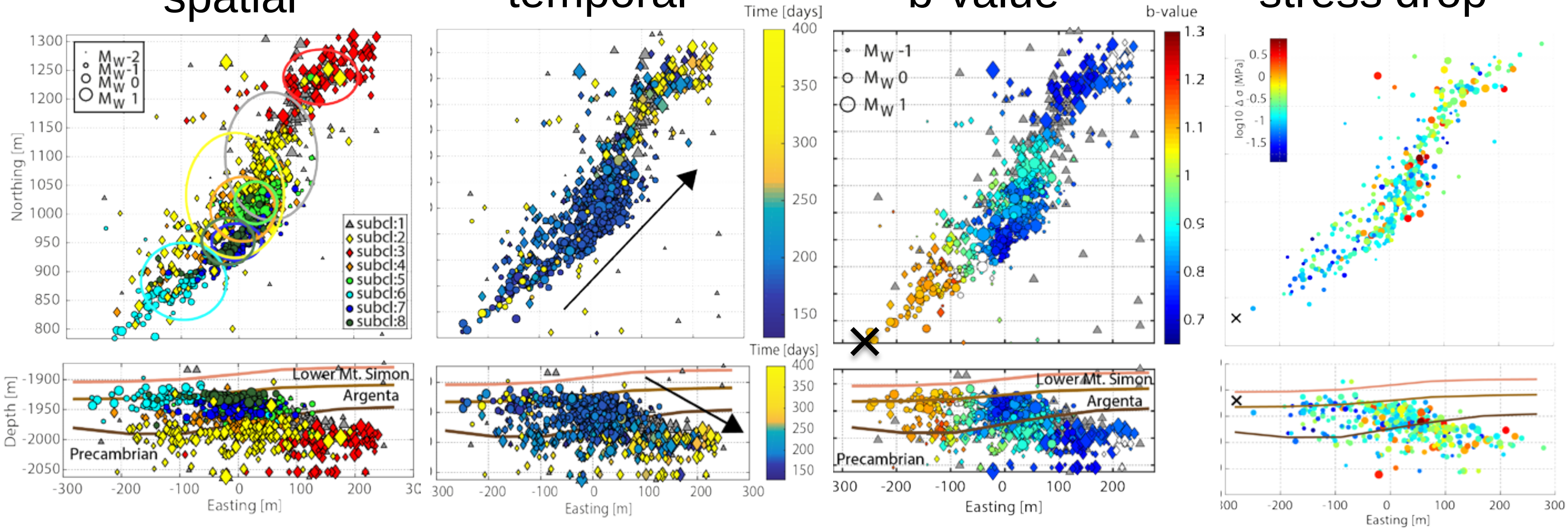
- Migration of events from the reservoir into the basement over the course of 100-200 days.

Goertz-Allmann et al. (2017), JGR

Event characterization

Cluster B

spatial temporal b-value stress drop

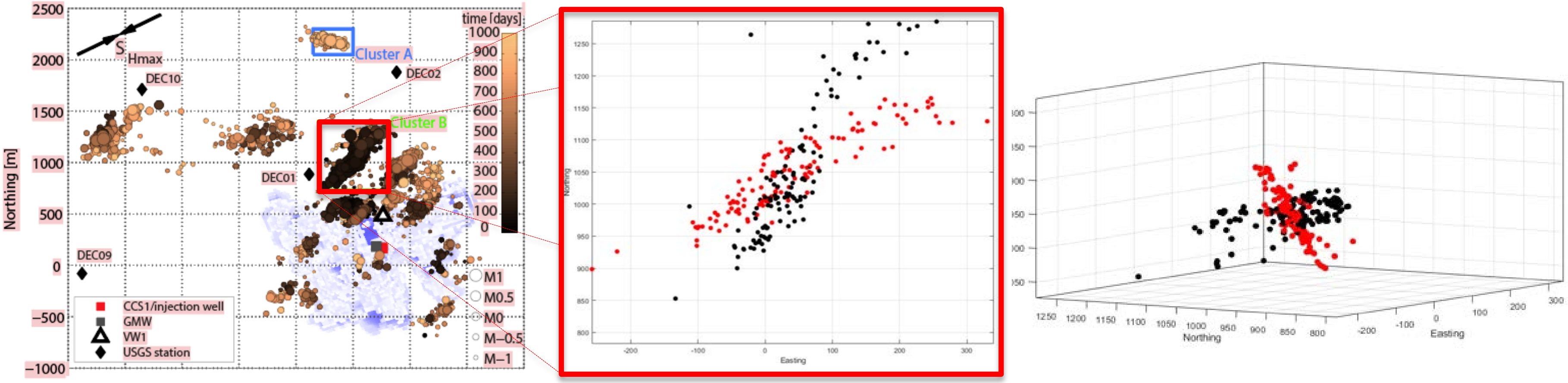


- ➢ Separation between reservoir and basement events.
- ➢ Migration from the reservoir into the basement.
- ➢ Decrease of b-value with distance.
- ➢ Increase of stress drop with distance.

- Evidence for a fluid-driven process at the cluster level.
- Signs of pressure diffusion.
- Possible punctual hydraulic connection between reservoir and basement (i.e., confined to faults).

Relative event locations

Preliminary results of improved relative event locations by developing a modified relocation method.



- Accurate event locations are necessary for any kind of interpretation
- Change of cluster orientation
- Planar feature

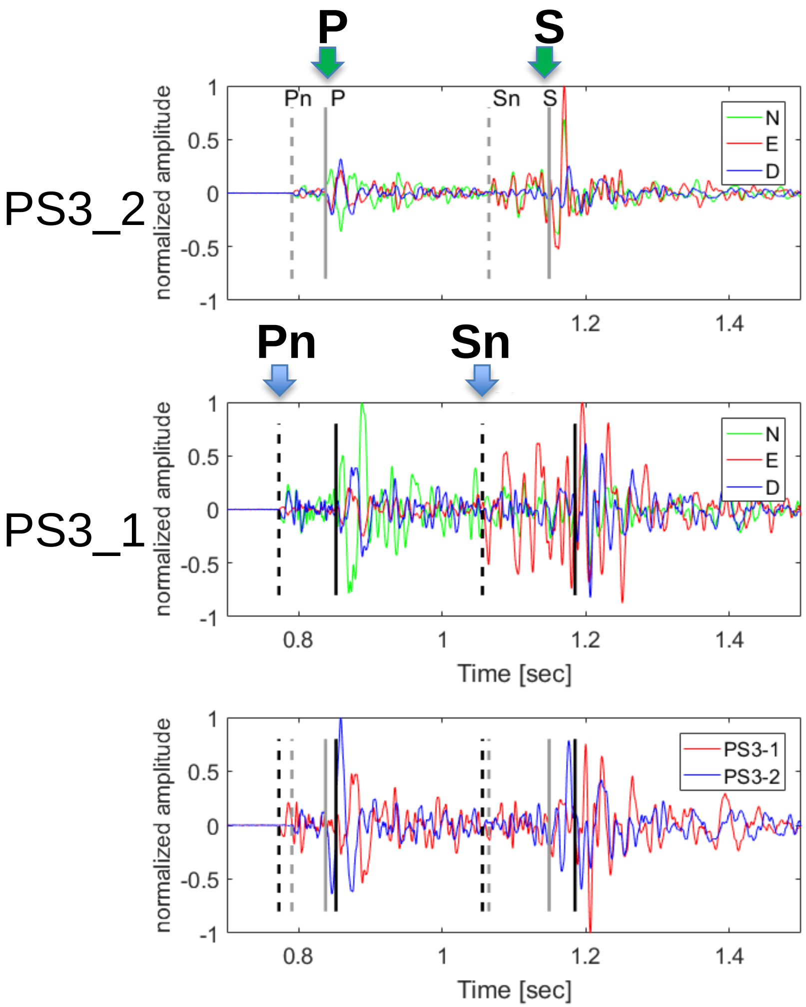
→ **Fracture?**

● Old event locations

● Relocated events

Full-waveform modelling

Observed waveform example

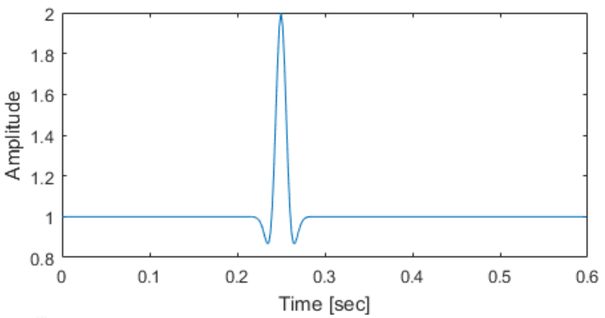


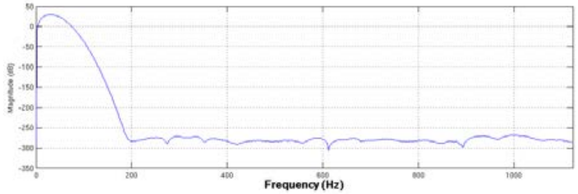
- Different phase arrivals with head wave and direct wave arrivals.
- Pn/Sn phase arrives first at deeper sensor (PS3_1).
- P/S phase arrives first at shallower sensor (PS3_2).
- Waveform modelling can help us to better understand the observed waveform characteristics.
- Gain a complete picture of the travel path of an event and helps us to select events and phases, which best sample the target area.

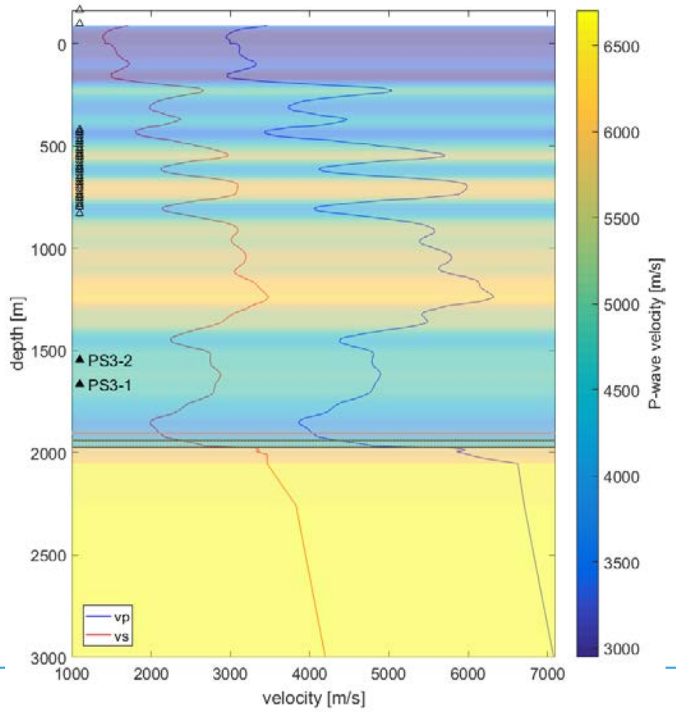
Full-waveform modelling

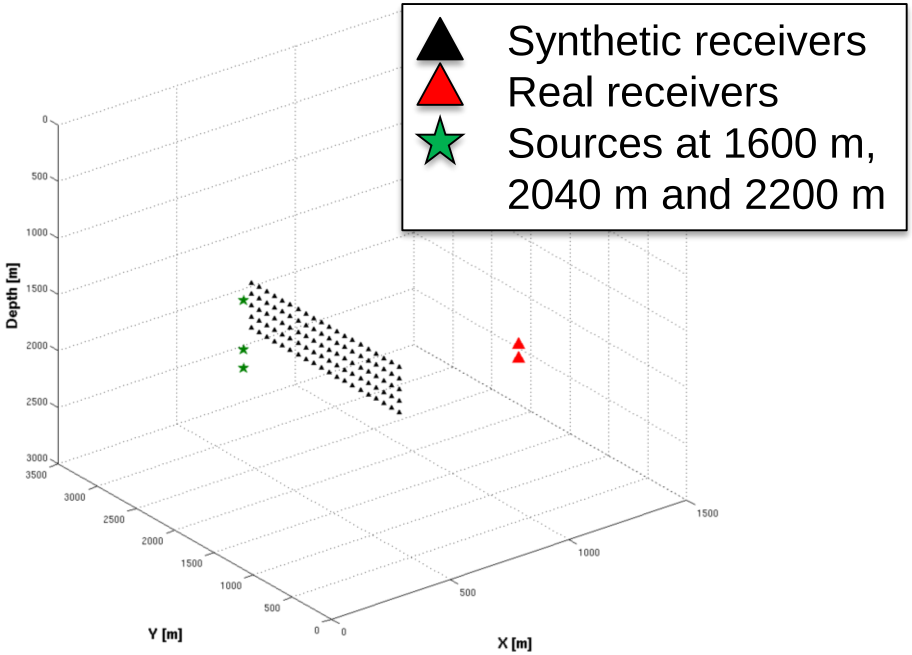
- 3D FD modelling using 1D velocity model

- 30 Hz Ricker wavelet.
- Compare sources placed at 1600 m, 2040 m, and 2200 m depth.



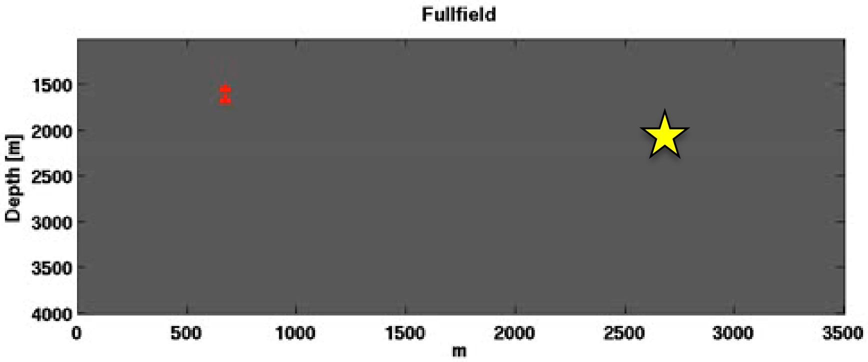


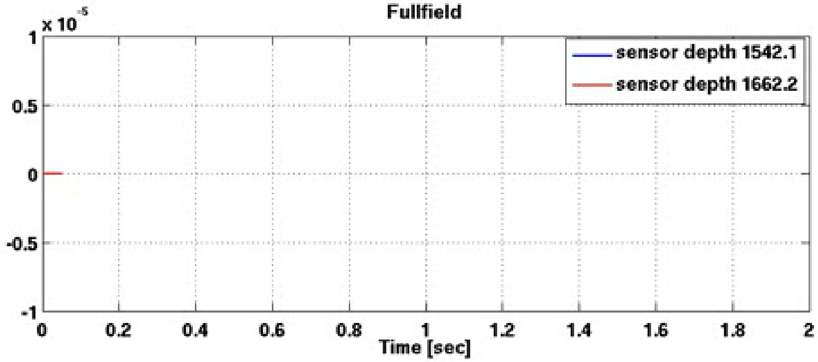




Full-waveform modelling

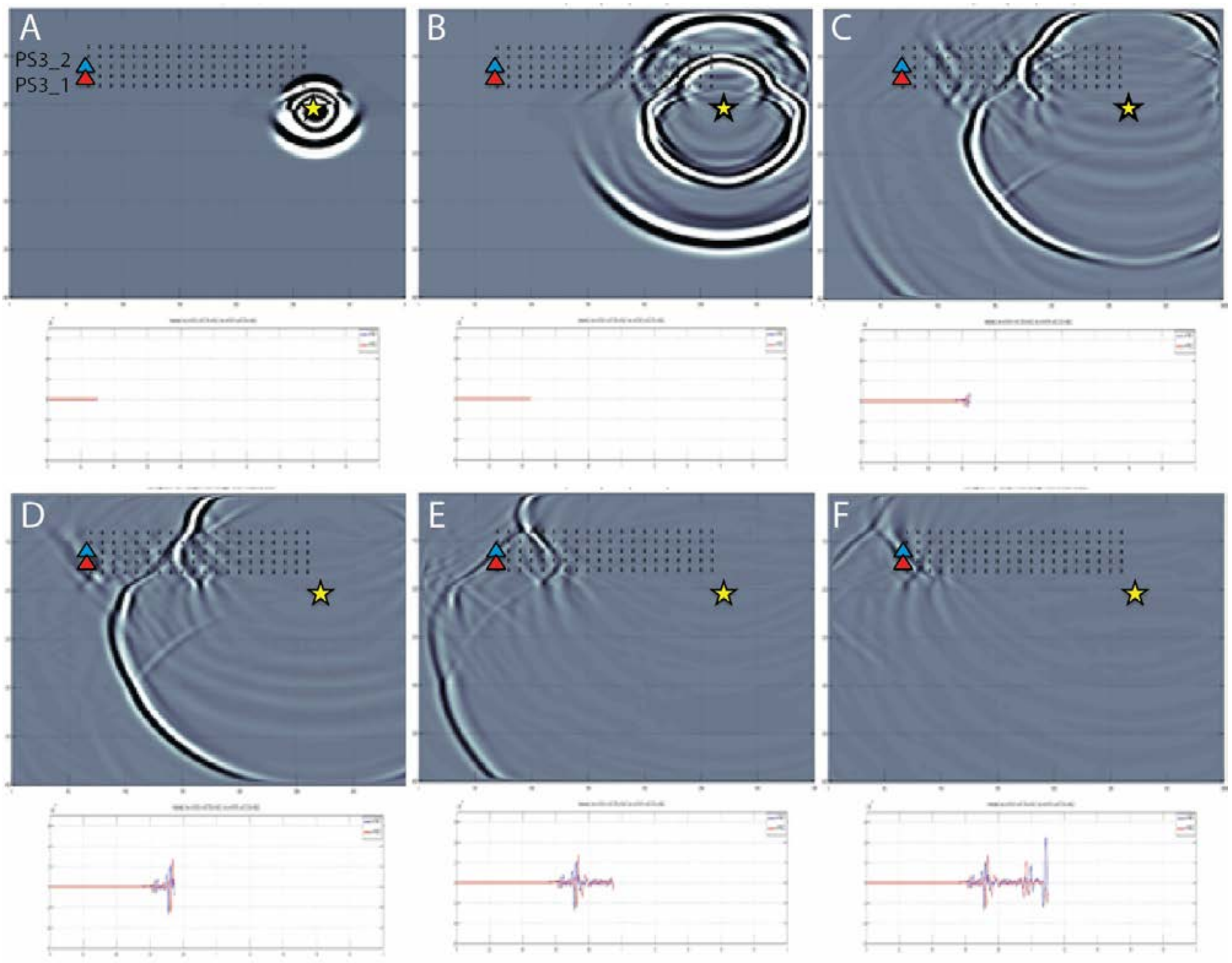
Source at 2040 m depth





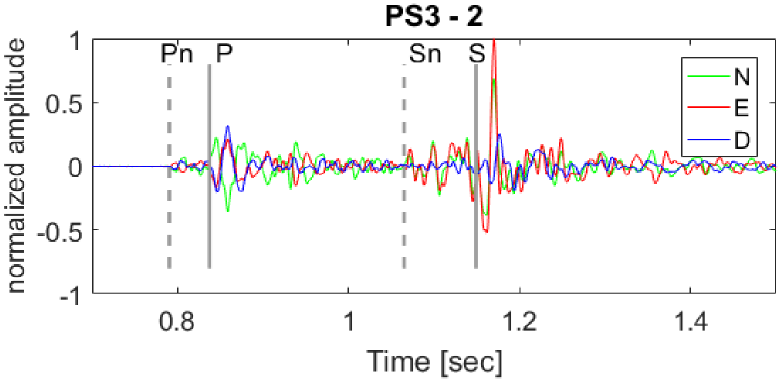
Full-waveform modelling

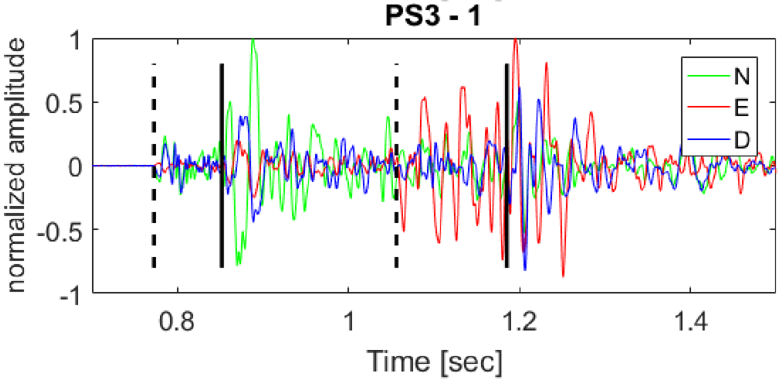
Sequential snap-shots of full waveform modelling (from A to F)



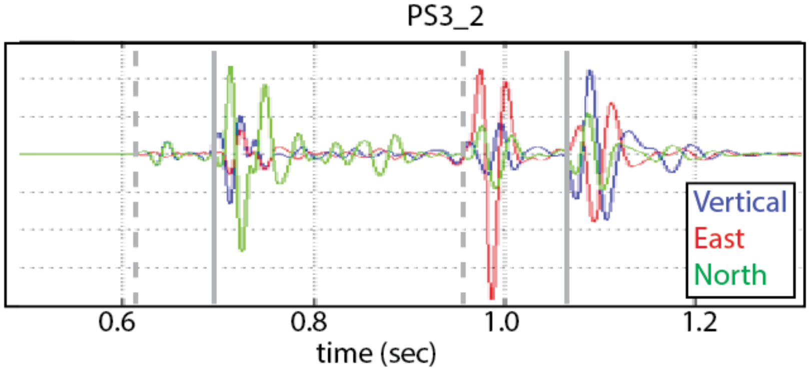
Full-waveform modelling

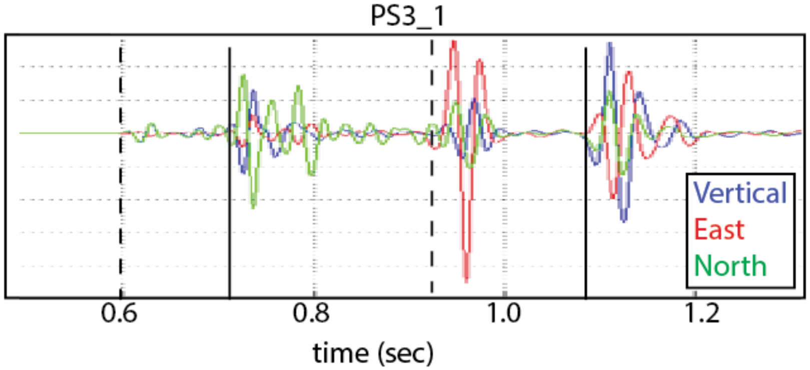
observed





modelled





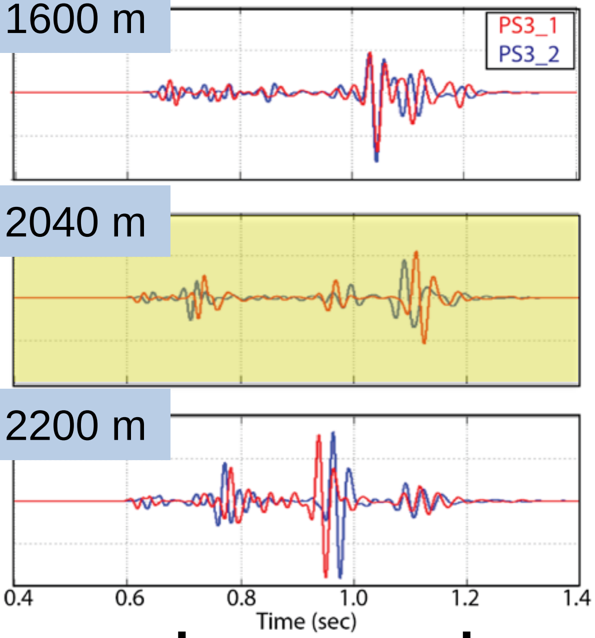
Full-waveform modelling

modelled

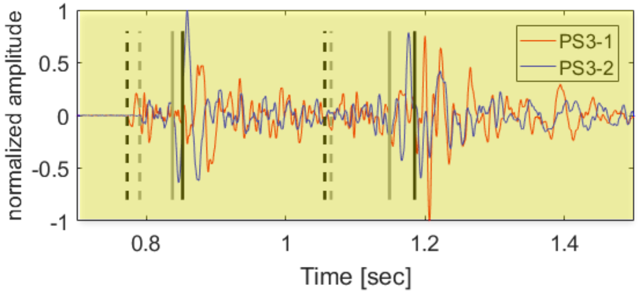
Source 1600 m

Source 2040 m

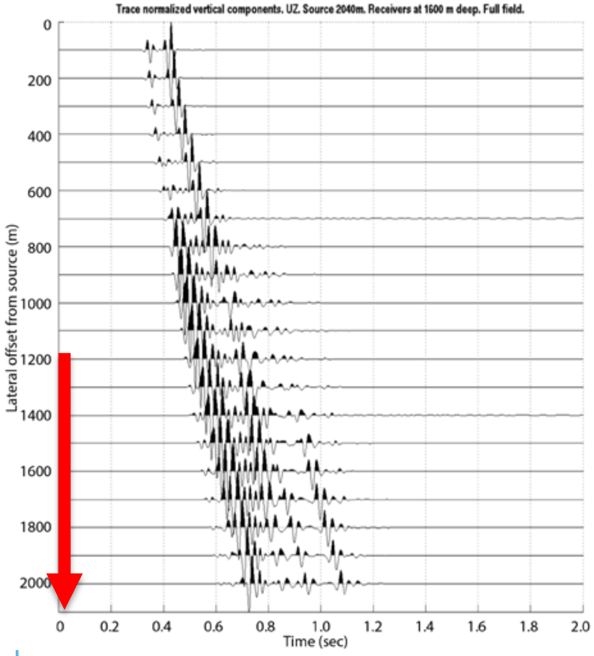
Source 2200 m



observed



- Different source depths show different signatures.
- Best match between observed and modelled data at 2040 m (reservoir/basement interface).
- Different phases can only be distinguished at larger source-receiver distances (> 1200 m).



Summary of microseismicity at Decatur

- Type 1: mainly stress-triggered seismicity
- A seismicity migration pattern from the sediment into basement is observed.
- Seismicity within a cluster exhibits signs of pressure diffusion, both through the spatio-temporal evolution of seismicity but also through source parameters such as b-value and stress drop.
- Eventually, a punctual hydraulic connection (such as, e.g., a basement-connected fault) causes migration into the basement. → may explain clustering of seismicity (i.e., weak crust around those areas).
- Finite-difference modelling helps to correctly identify seismic phases sampling the CO_2 plume and can confirm a source at the reservoir/basement interface.

Comparison In Salah and Decatur

- Depth resolution of microseismicity was critical to support reservoir characterization
- Obtained by exploiting information contained in later arrivals / multipathing
- Requires waveform modelling for hypothesis testing and confirmation

- In Salah:
  - Information on caprock integrity
  - Variations in b-value between (pressure-driven?) reservoir events and (stress-driven?) caprock events
  - Despite very inadequate network coverage
- Decatur:
  - Connection between reservoir and basement
  - Overall stress-driven seismicity/ fracture reactivation
  - But fluid-driven characteristics within cluster

More general insight

- During CCS operations: most important is event depth resolution to verify seal integrity.
  - Reservoirs are generally thinner than depth uncertainty from standard seismological methods. Therefore, additional constraints need to be exploited to improve depth resolution.
- Integration of reservoir engineering data is important for meaningful microseismic interpretation:
  - Need pressure, pumping & fluid flow data densely sampled in time with accurate time stamp.
  - Source parameters (b, $\Delta\sigma$) can provide hints of reservoir hydraulics, but require good calibration
- Accurate moment magnitudes are important for risk assessment (event discrimination and forecast with b value):
  - Ensure sufficient bandwidth of recording
  - Good prior knowledge of noise environment (particularly problematic offshore)

More general insight

- Good network planning:
  - Vertical aperture with borehole array(s) for depth resolution
  - Azimuthal coverage for location accuracy and source parameter inversion including moment tensor

- Real-time data stream and automatic processing can provide “traffic light” feedback to operations.

- In most cases I have seen, microseismicity can NOT be used to track CO_2 plume because of often lack of brittle deformation.

  Therefore a complementary method needs to be used for that (4D seismic, InSAR (deserts!), microgravity (offshore), geochemical sampling, ….).

Thank you for your attention!

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