Understanding reservoir processes in injection operations from advanced microseismic analysis

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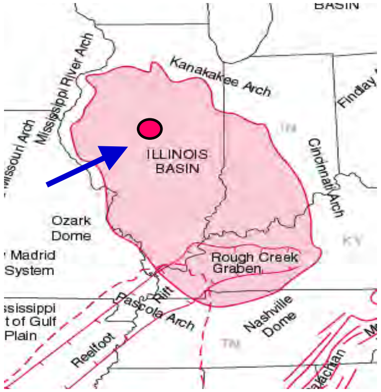
NORSAR

3rd Schatzalp workshop, Davos, March 8, 2019

Outline

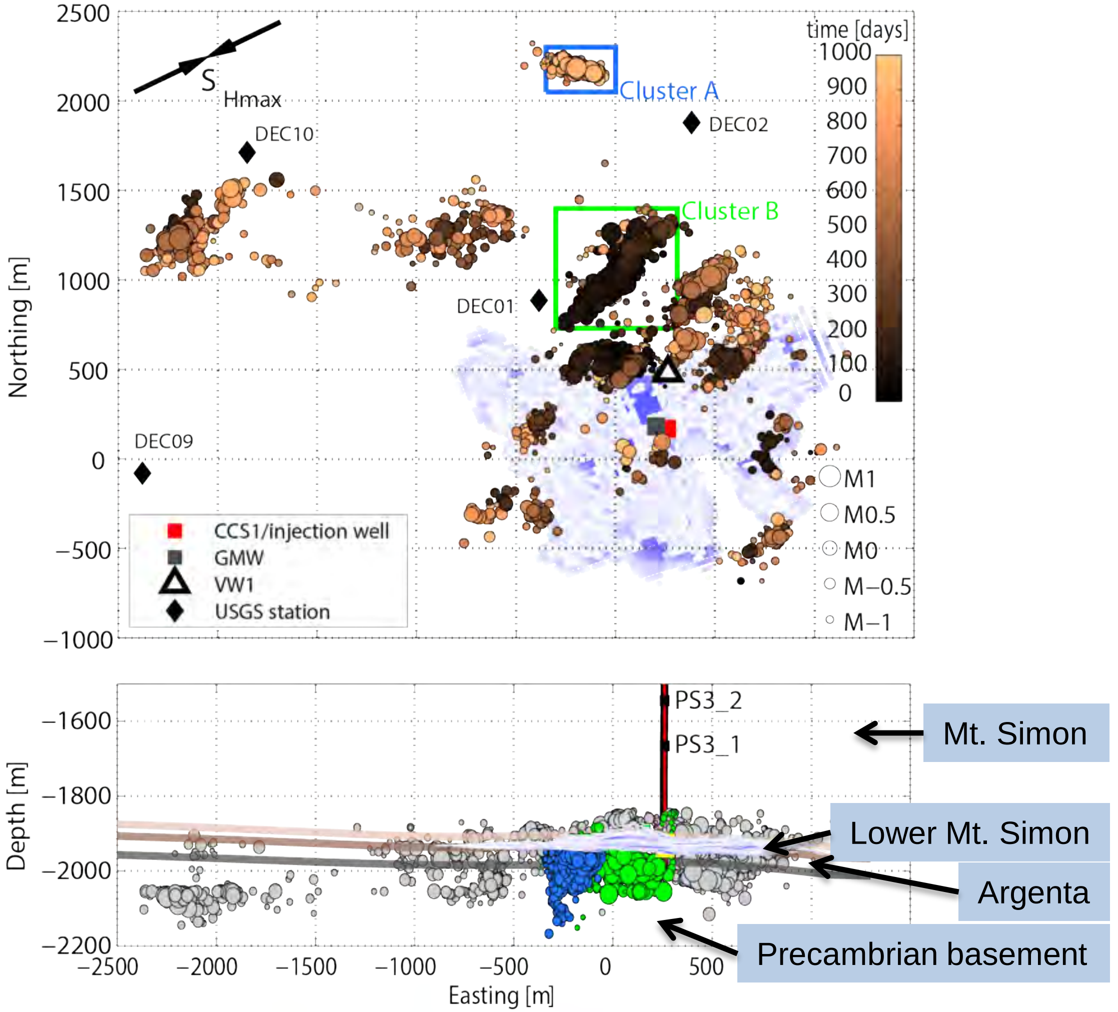
- Reservoir characterization using microseismicity at the IBDP
  - Waveform cross-correlation and source analysis
  - Full-waveform modelling for hypothesis testing & interpretation
- Constraining event depth with examples from
  - In Salah
  - Oseberg
- Conclusions

The IBDP CCS site



- Inject 1 MT of CO_2 into Mt. Simon sandstone at ~1.9 km depth over three years (end 2011-2014)
- Microseismic monitoring includes borehole & surface sensors
- Events occur in distinct clusters with heterogeneous timing

~ 4,800 microseismic events



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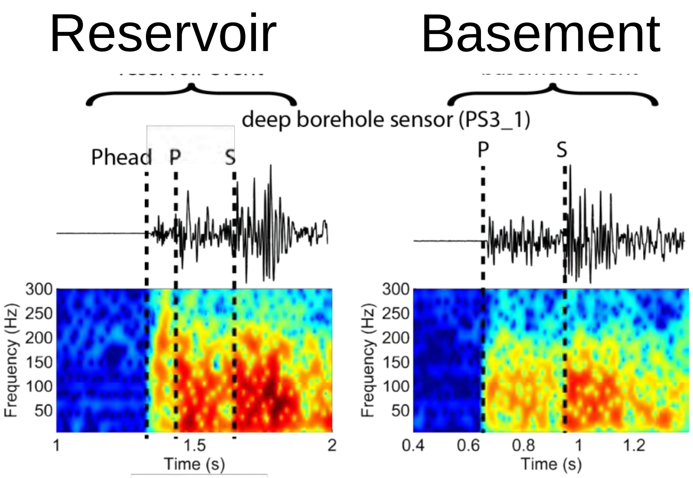
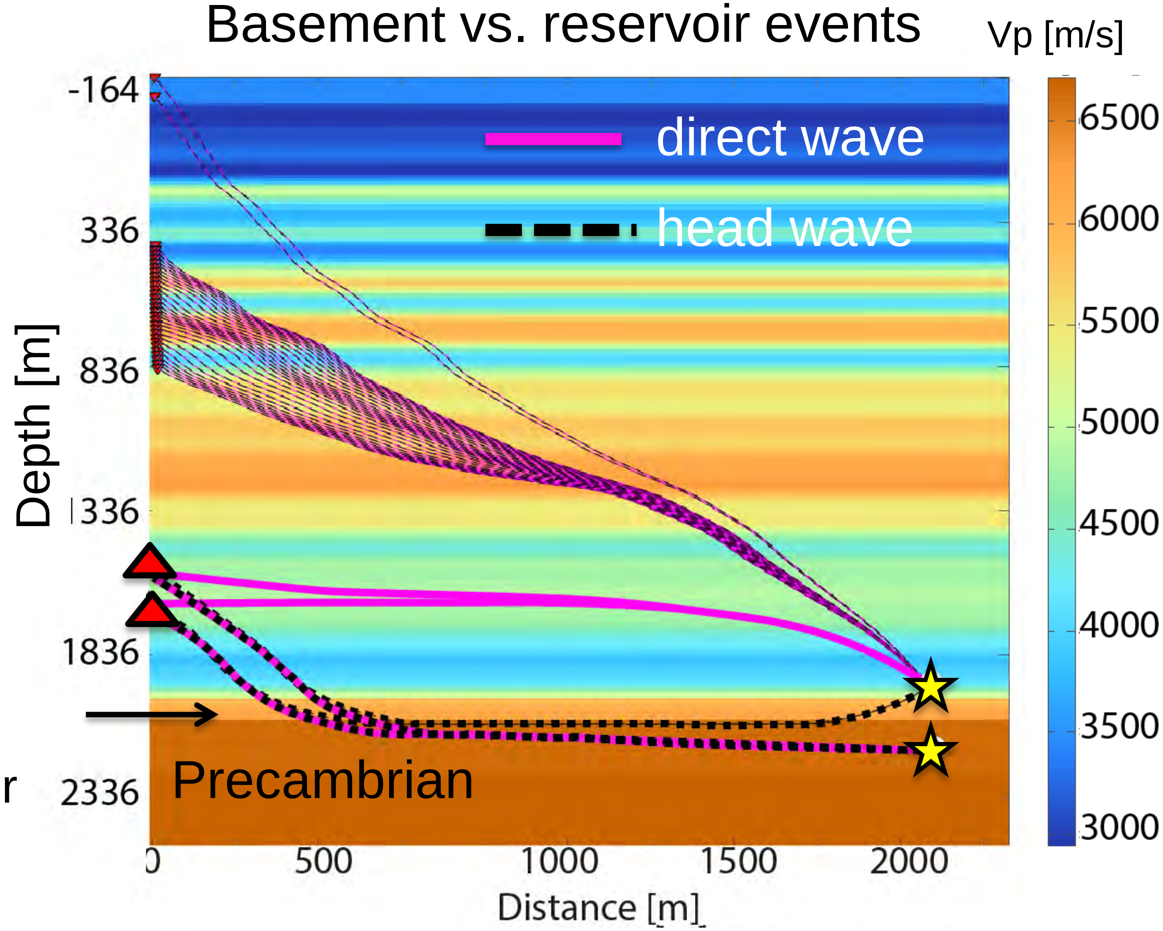
Event characterization

Goertz-Allmann et al. (2017), JGR



Basement vs. reservoir events



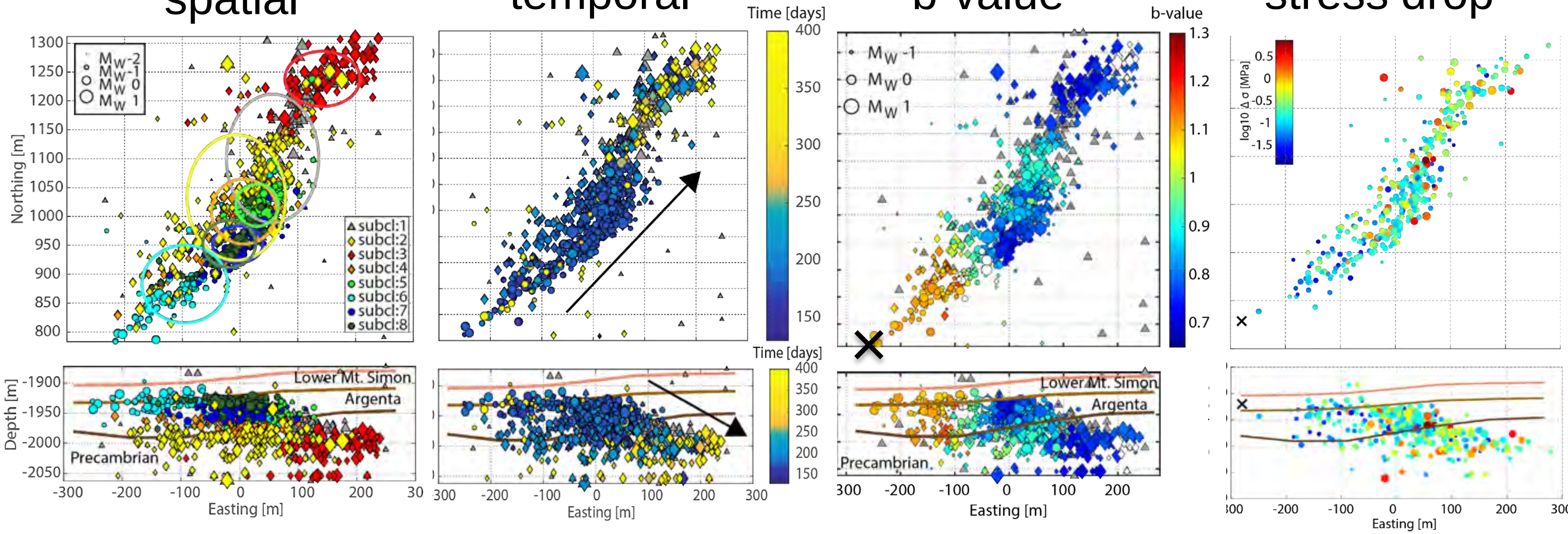
- Theoretical ray diagrams for reservoir & basement events.
- Different waveform signature: head wave and direct wave arrivals clearly visible for reservoir events.
- Events can be distinguished using waveform cross-correlation.

Event characterization

Goertz-Allmann et al. (2017), JGR

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.

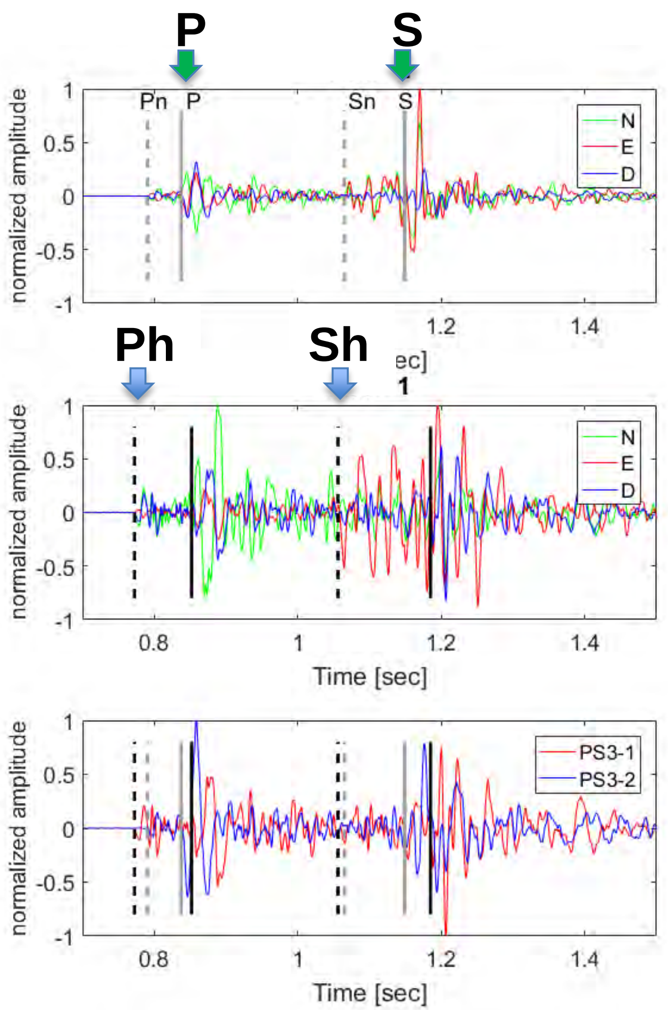
- Evidence for a fluid-driven process at the cluster level.
- Possible punctual hydraulic connection between reservoir and basement (i.e., confined to faults).

Full-waveform modelling

Observed waveform example

Shallower
PS3_2

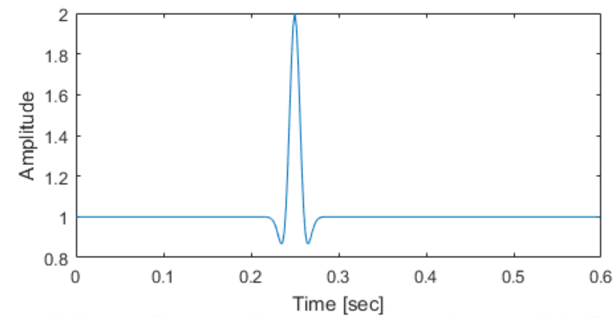
Deeper
PS3_1

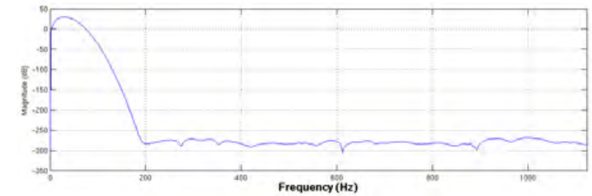


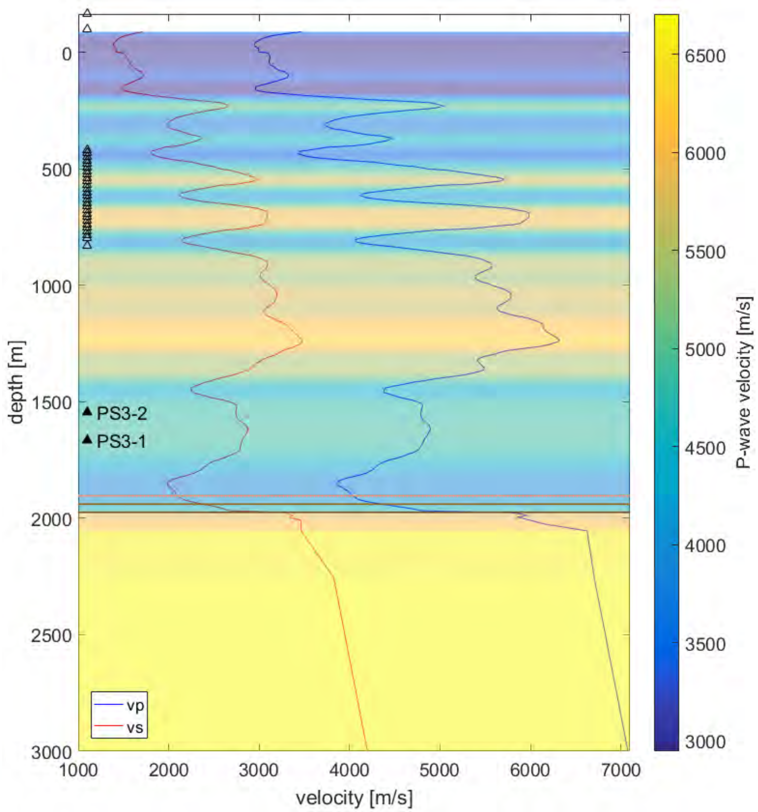
- Different phase arrivals with head wave and direct wave arrivals.
- Ph/Sh phase arrives first at deeper sensor (PS3_1).
- P/S phase arrives first at shallower sensor (PS3_2).
- Waveform modelling can help us to better understand the observed waveform characteristics.
- Gain a complete picture of the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

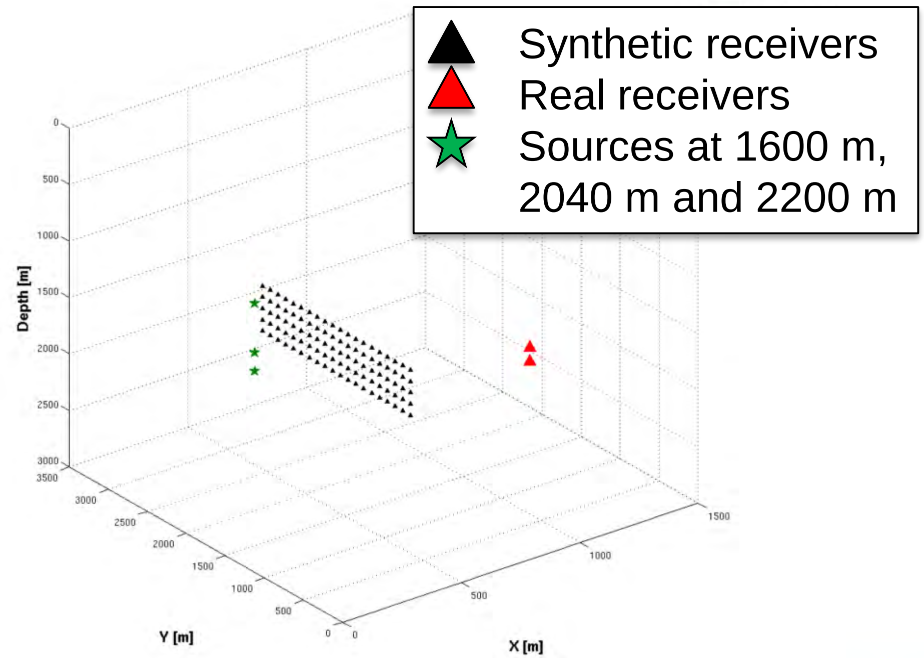
Full-waveform modelling

- 3D FD modelling using 1D velocity model
- 30 Hz Ricker wavelet.
- Compare sources placed at 1600 m, 2040 m, and 2200 m depth.









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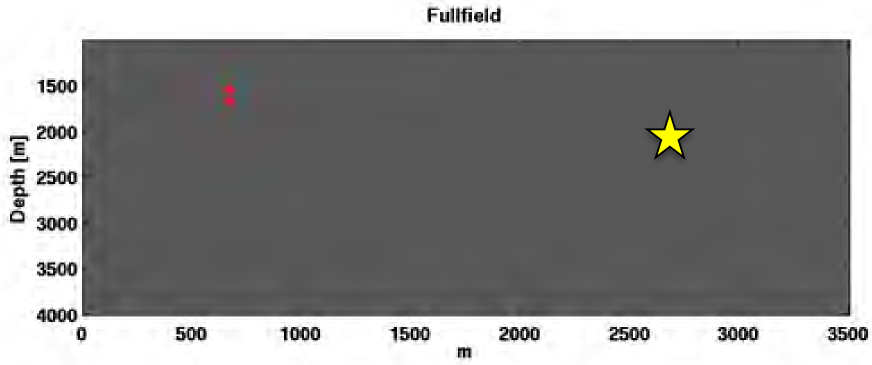
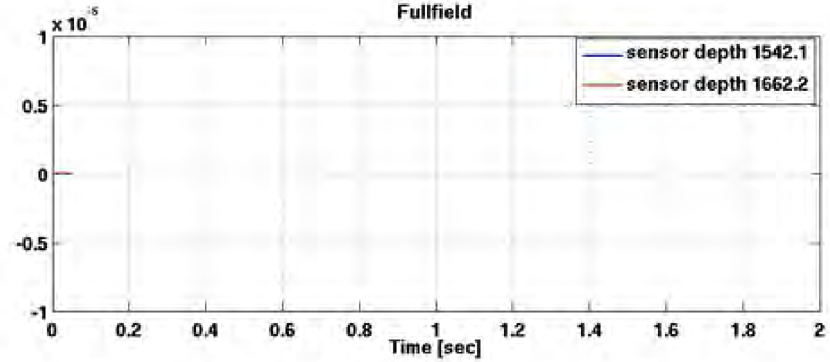
Full-waveform modelling

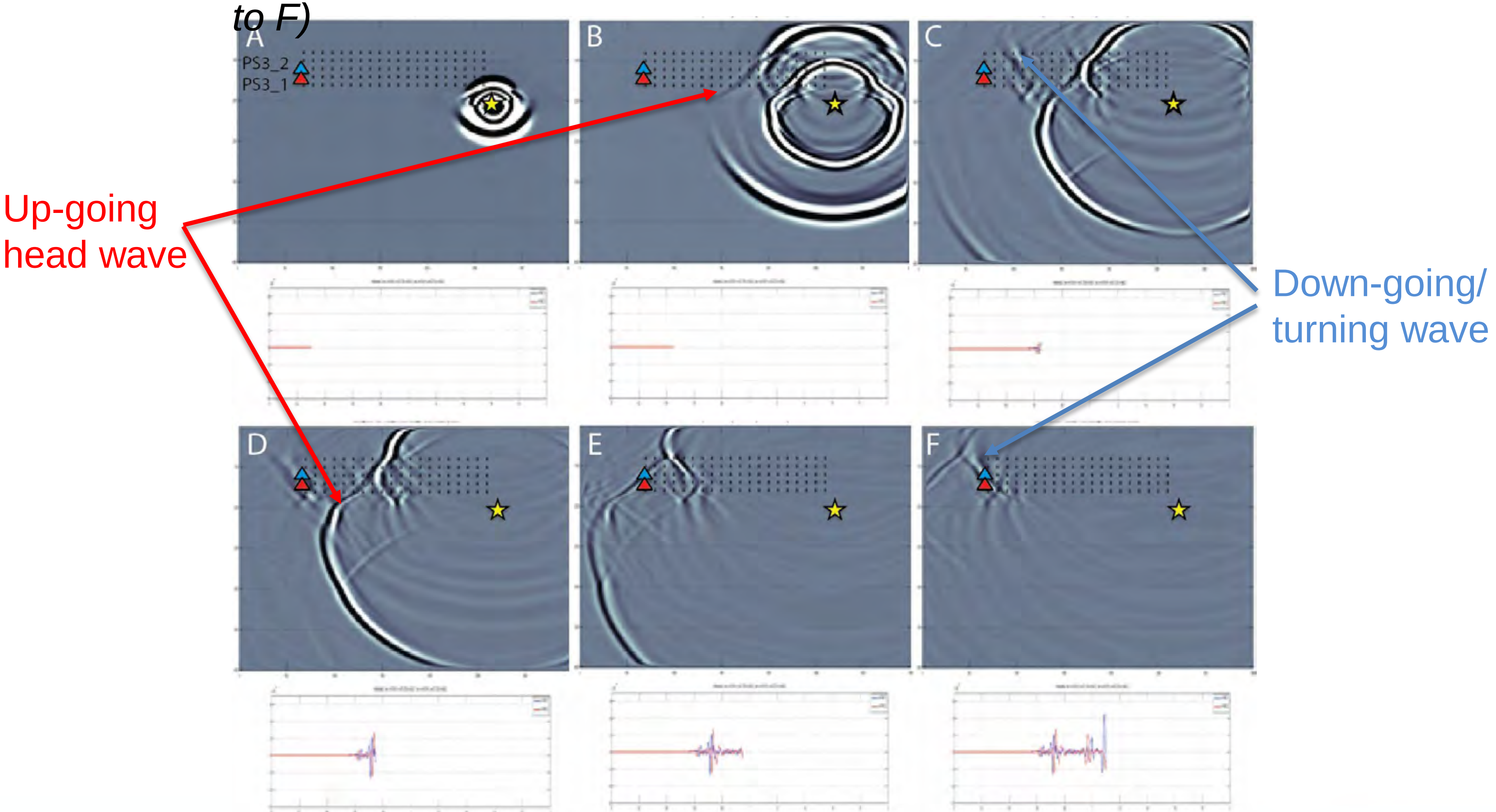
Source at 2040 m depth





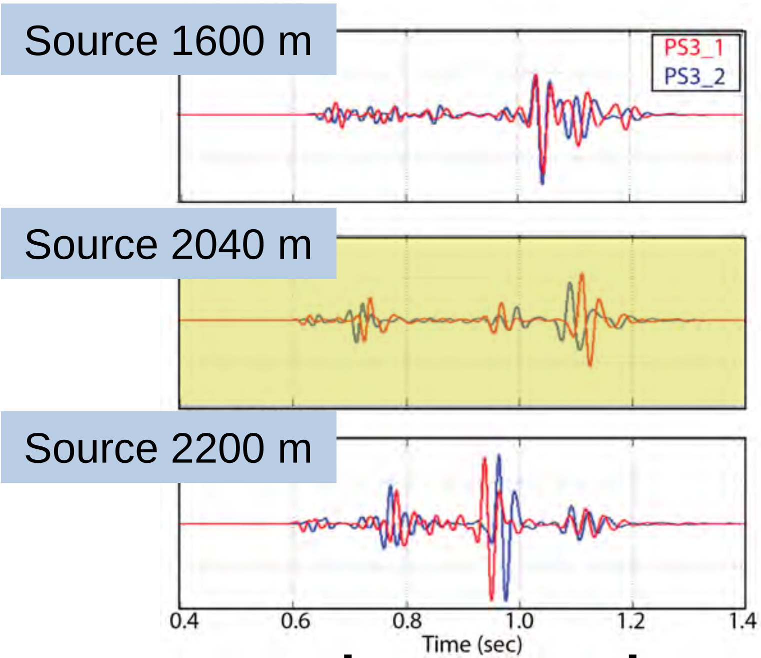
Full-waveform modelling

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

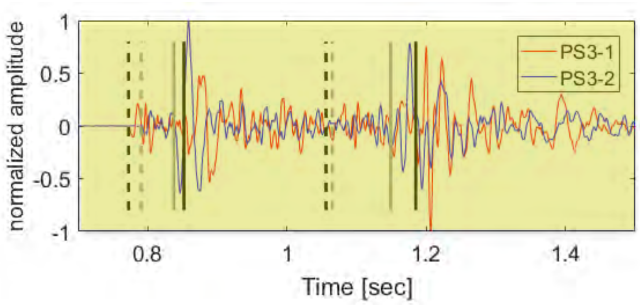


Full-waveform modelling

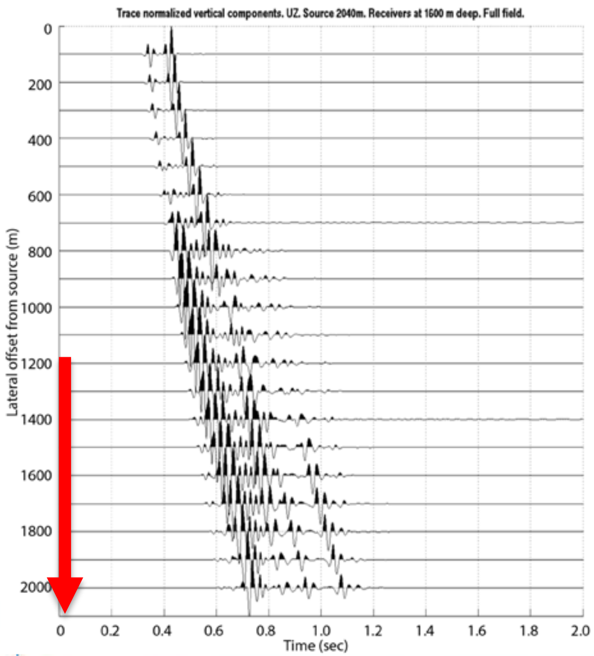
modelled



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).



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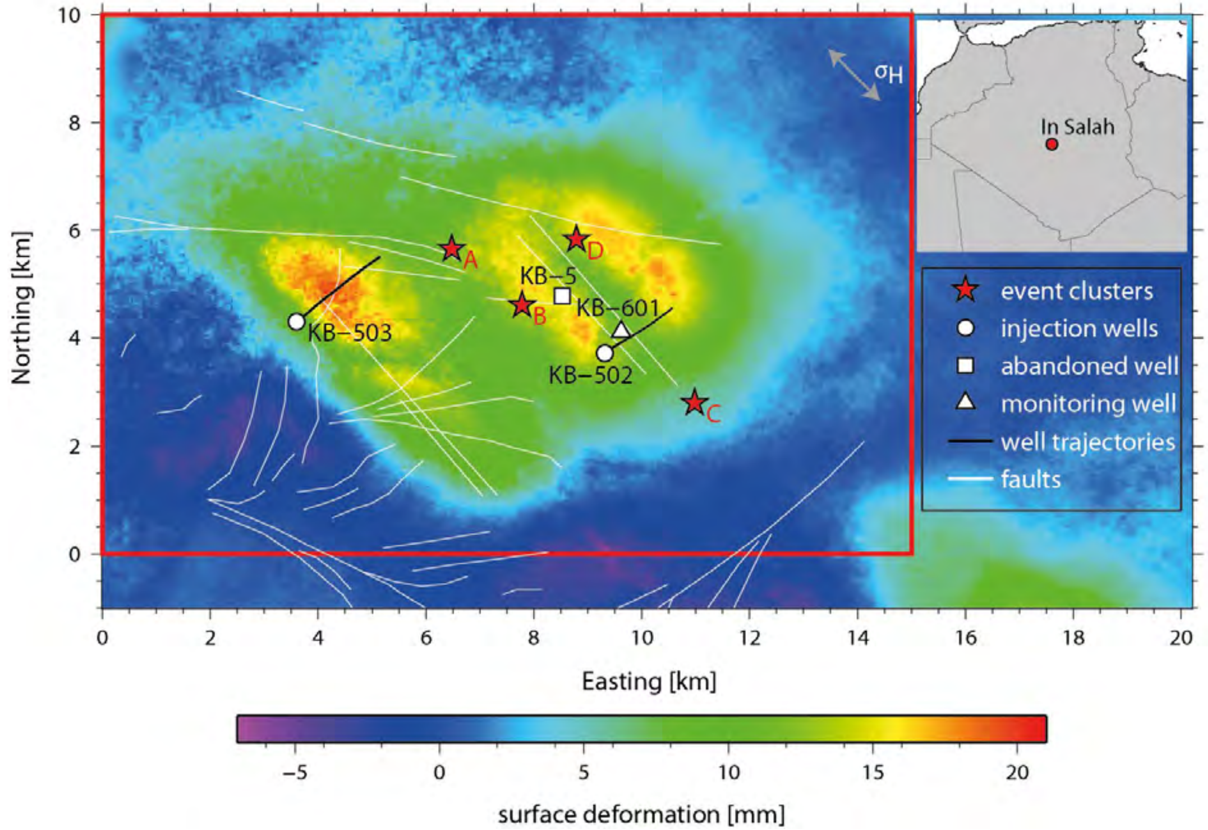
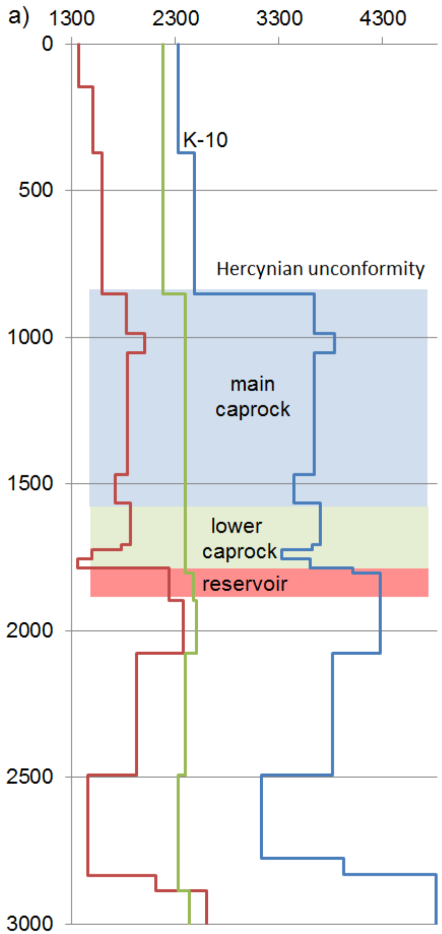
Confining microseismic event depth at In Salah

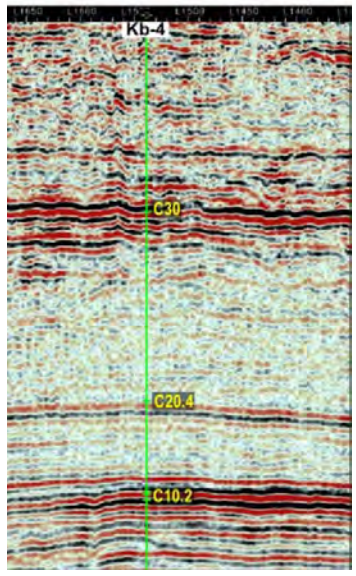


- ➢ 4 MT CO_2 injected into sandstone reservoir at 1.9 km depth.
- ➢ > 5000 microseismic events detected during injection.
- ➢ Events grouped in four clusters but no accurate locations and no depth resolution (only one geophone analysis)

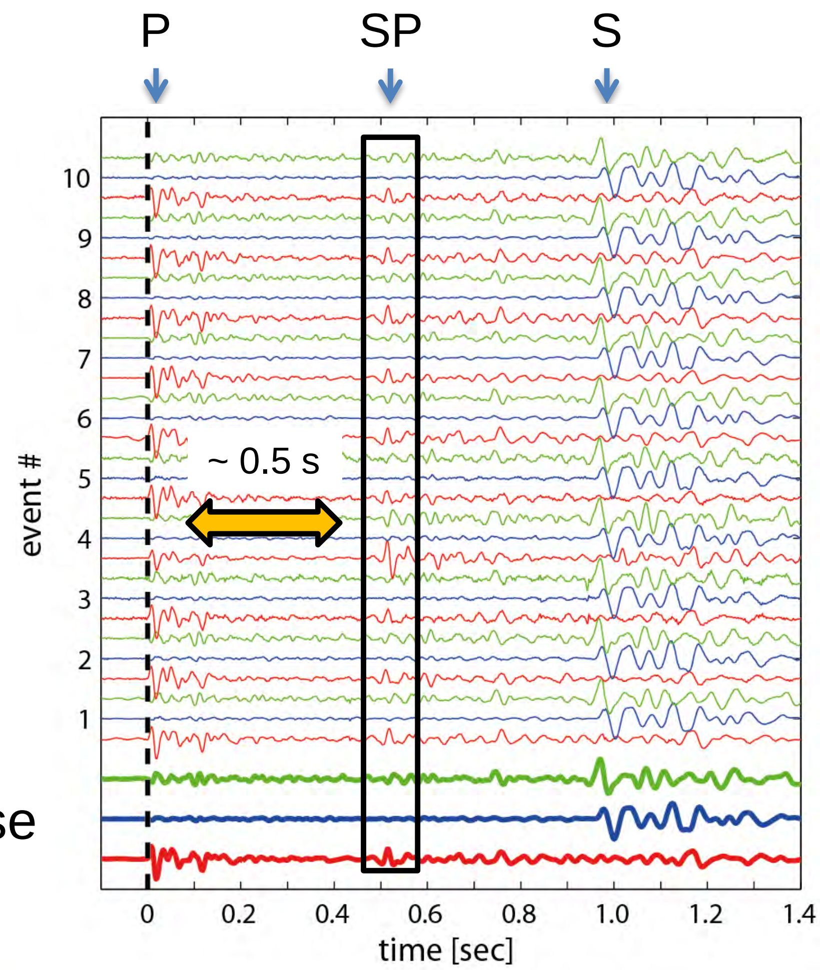
Goertz-Allmann et al. (2014)

Confining microseismic event depth at In Salah





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



Cluster A

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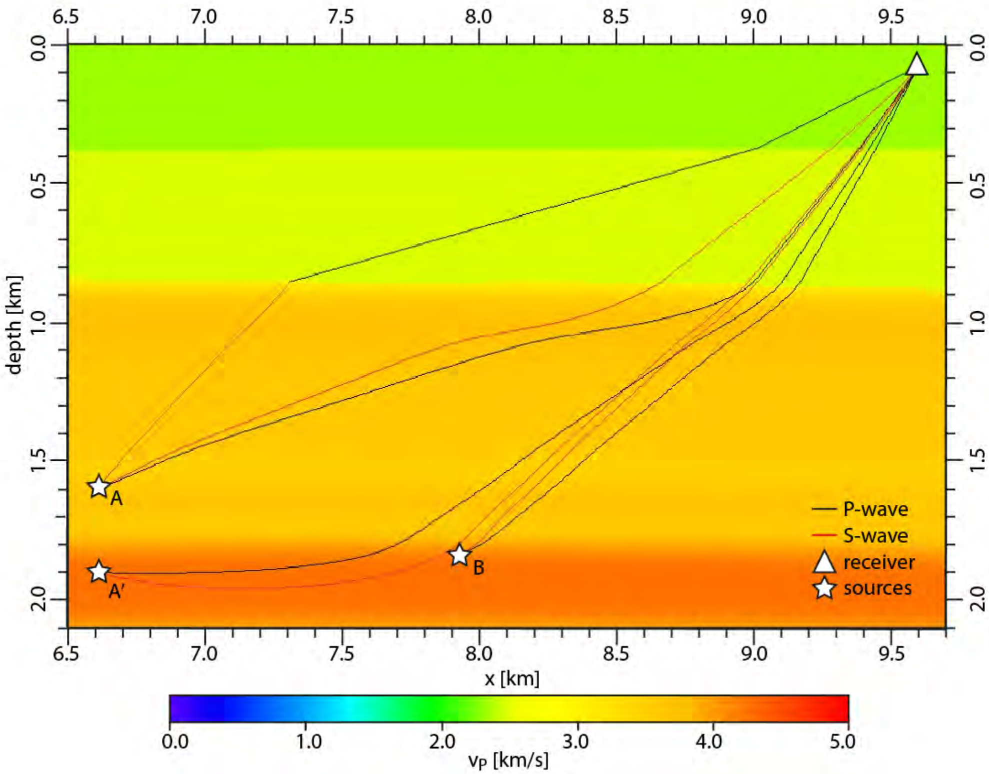
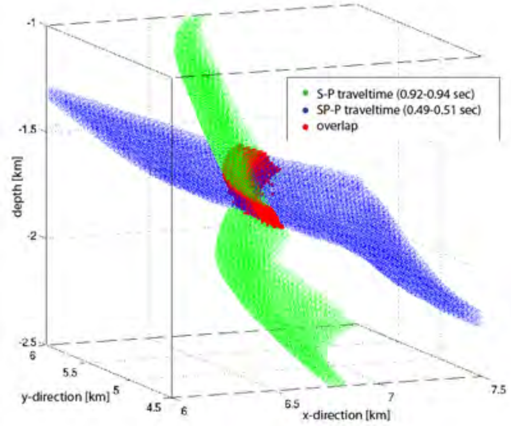
Confining microseismic event depth at In Salah

- Use 3D ray tracing to identify converted SP.



- Waveforms at A and A' have similar S-P traveltimes but converted phase only matches real data at shallower position A.



- Cluster A at about 1.7 km (well above the reservoir but still within lower cap rock).

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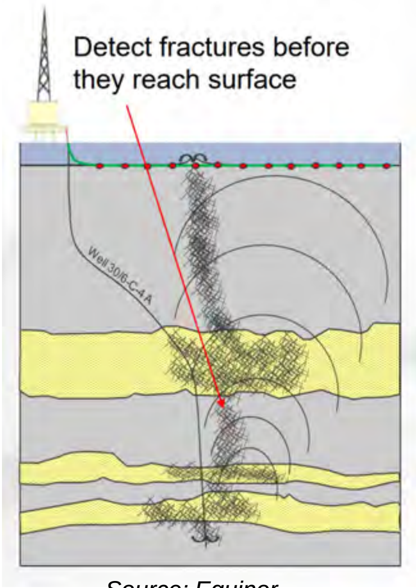
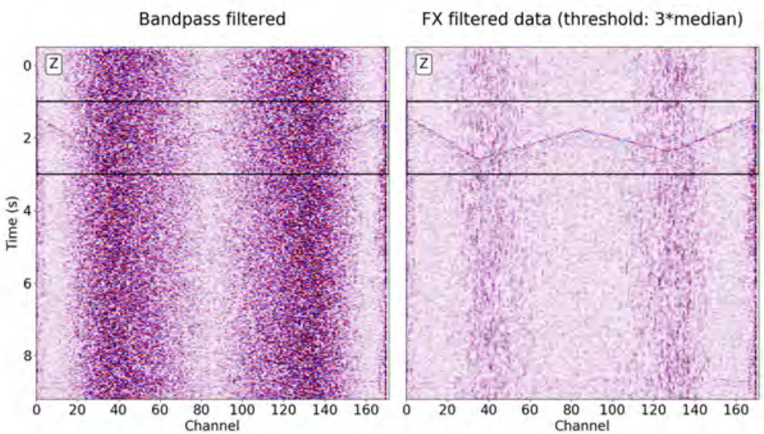
Improving microseismic event depth at Oseberg

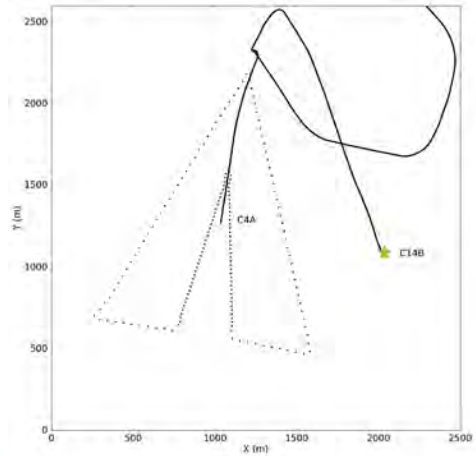


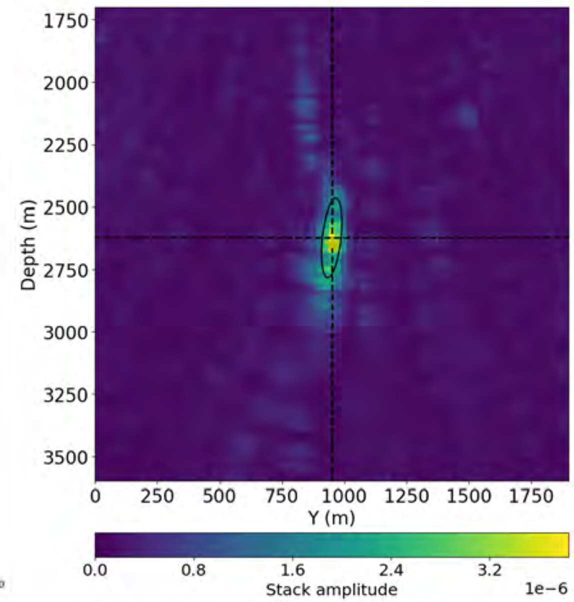
Source: Equinor

- Offshore recordings are often contaminated by a variety of noise sources
- This effects detectability and location precision
- Noise can mask part of a network:
  - Decreases effective aperture, reducing location precision (depth)
- We need smart ways of removing this noise to improve our depth constraints



172 sensors





Bussat et al. 2016

Dando et al. 2016

Conclusions

- During CCS operations: most important is event depth resolution to verify seal integrity and to map reactivated fractures outside of the reservoir.
- Reservoirs are generally thinner than depth uncertainty from standard seismological methods → additional constraints need to be exploited!
- Exploiting information contained in later arrivals / multipathing.
- Requires waveform modelling and ray-tracing for hypothesis testing and confirmation.
- Advanced noise removal techniques may be necessary in offshore operations.
- Decatur:
  - Connection between reservoir and basement
  - Confirm a source at the reservoir/basement interface
- In Salah:
  - Information on caprock integrity
  - Despite very inadequate network coverage
- Oseberg:
  - Distinguish in zone and out-off zone events

Thank you for your attention!

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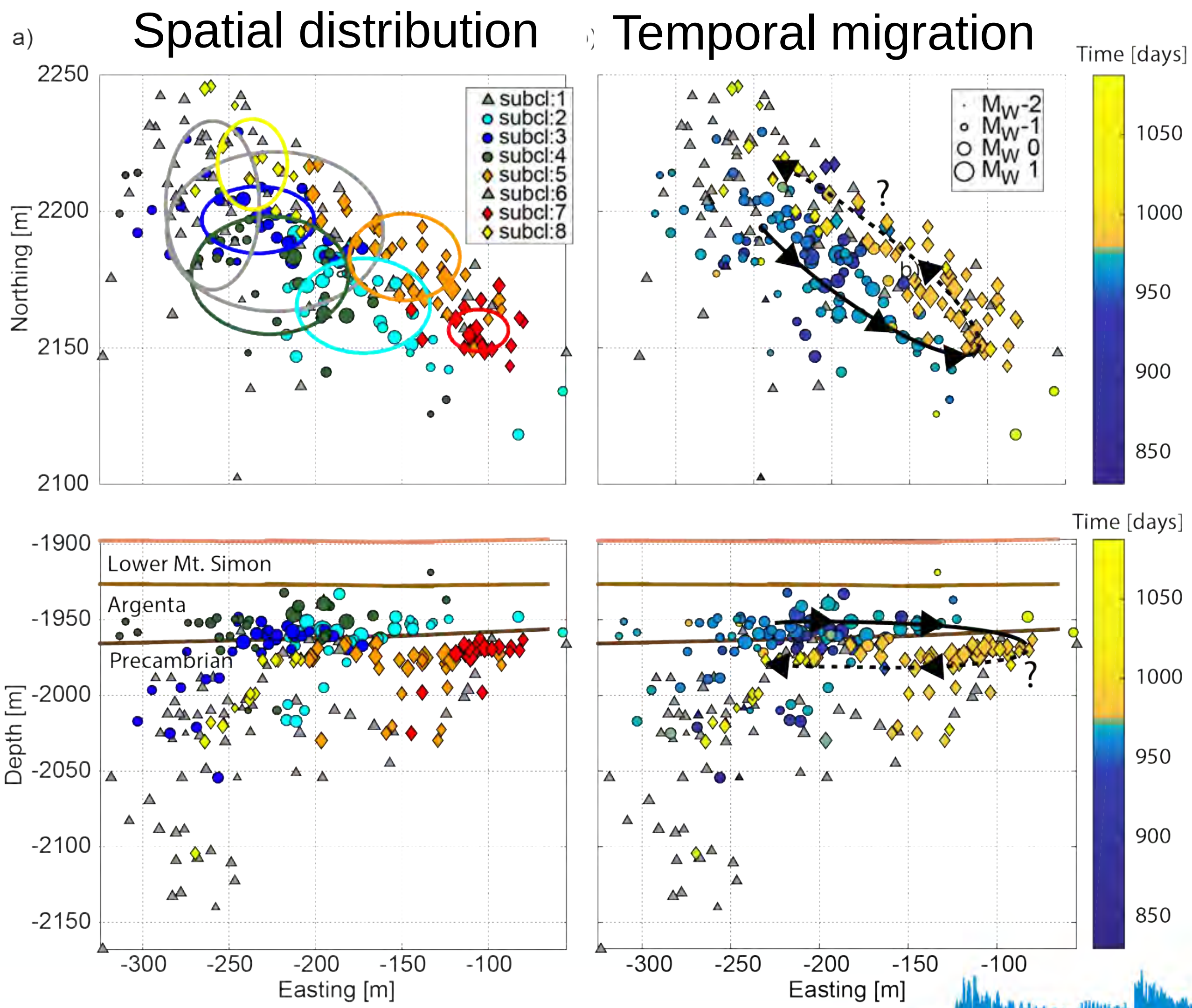
Microseismic event characterization

Cluster A



- 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

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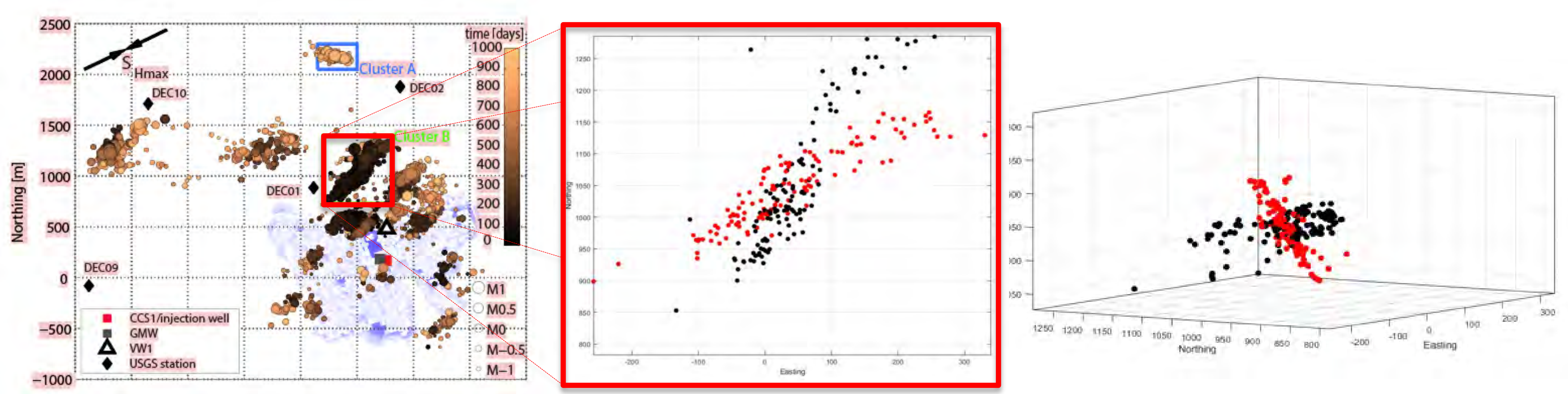
Relative event locations

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

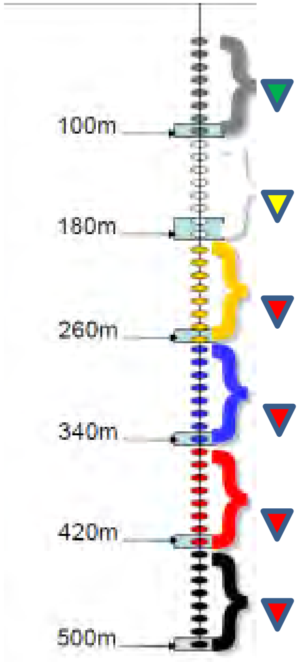
→ **Fracture?**

● Old event locations

● Relocated events

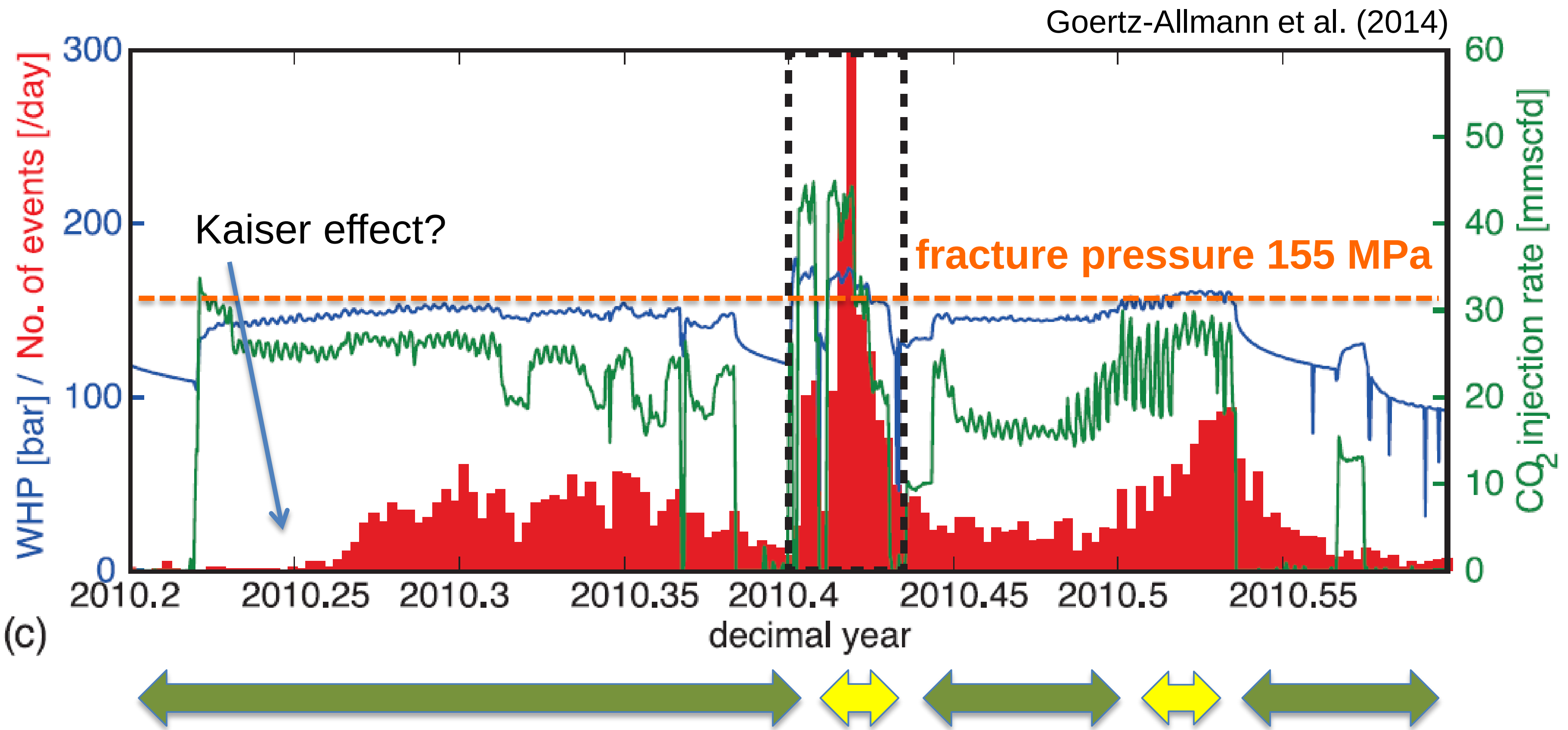
Microseismic array at KB-601

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**

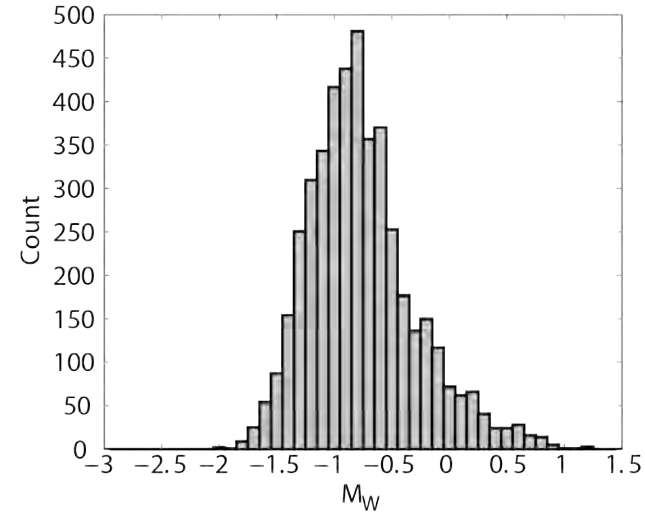
Comparison of events and injection data

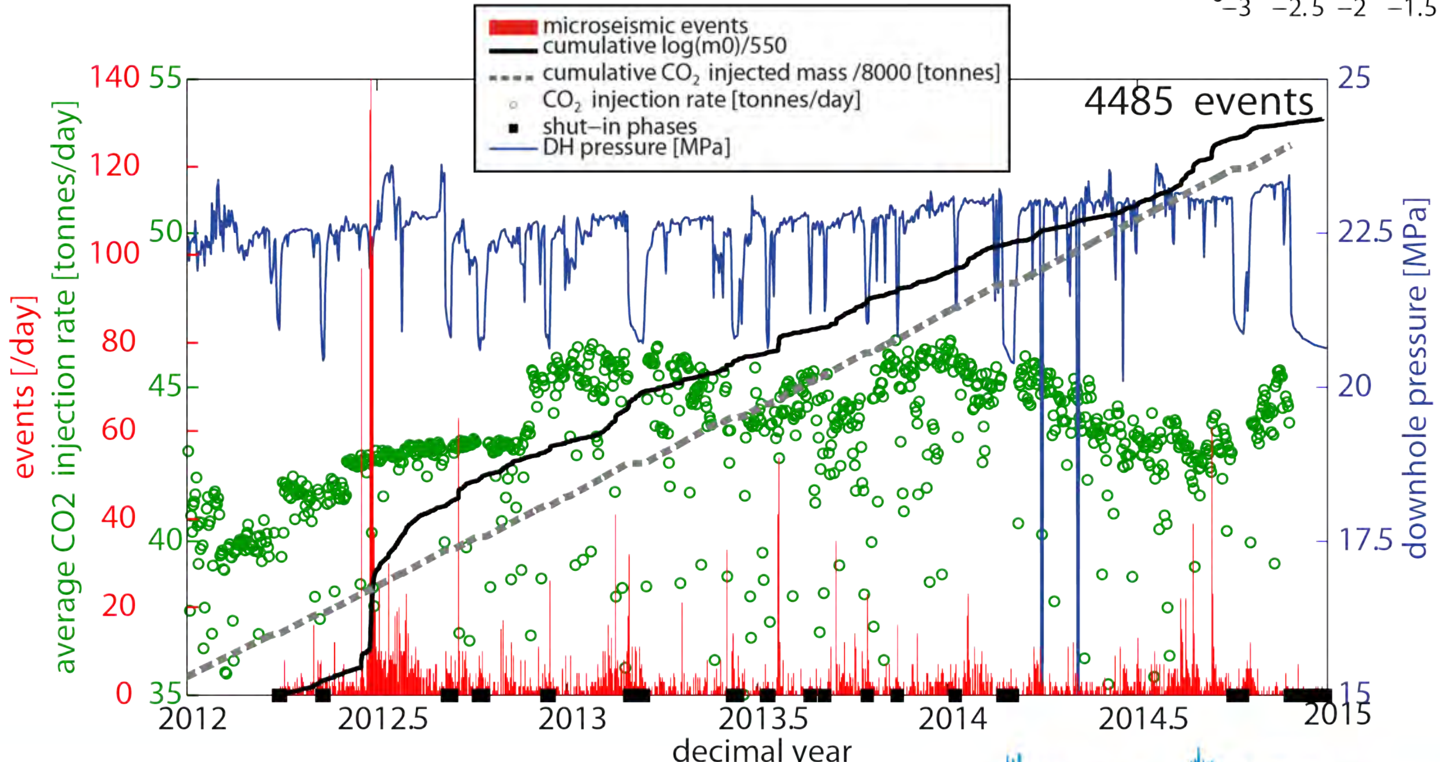


- High correlation between occurrence of microseismic events and injection rate
- Periods of matrix injection and fracture injection

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





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Ray-tracing using QSEIS