Oscillation of fluid-filled cracks triggered by degassing of CO_2 due to leakage along wellbores

Marco Bohnhoff [1] & Mark D. Zoback [2]

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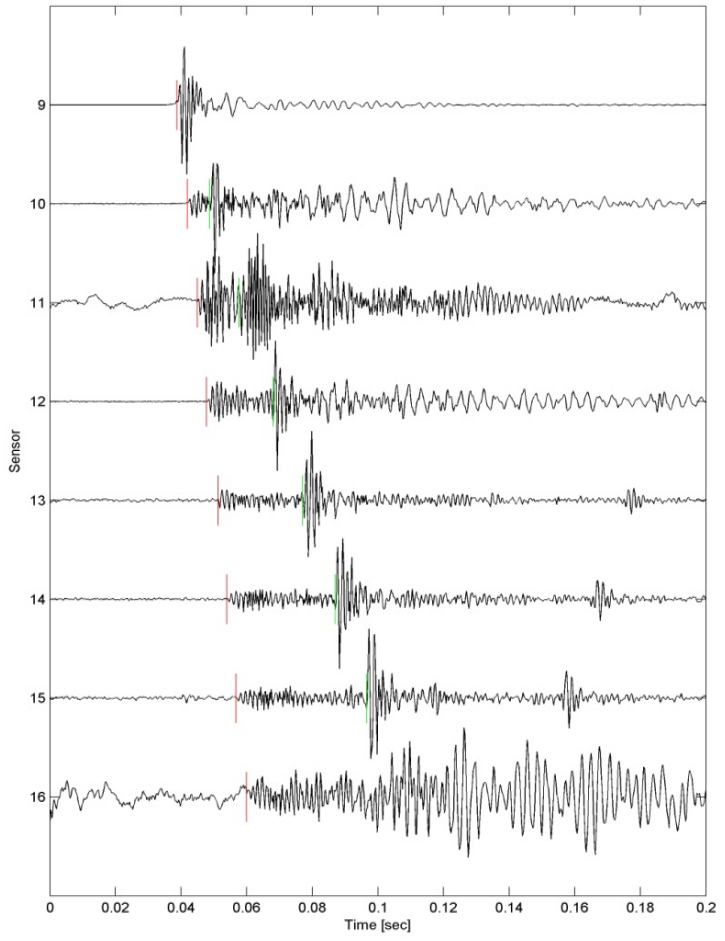

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STANFORD UNIVERSITY

Outline:

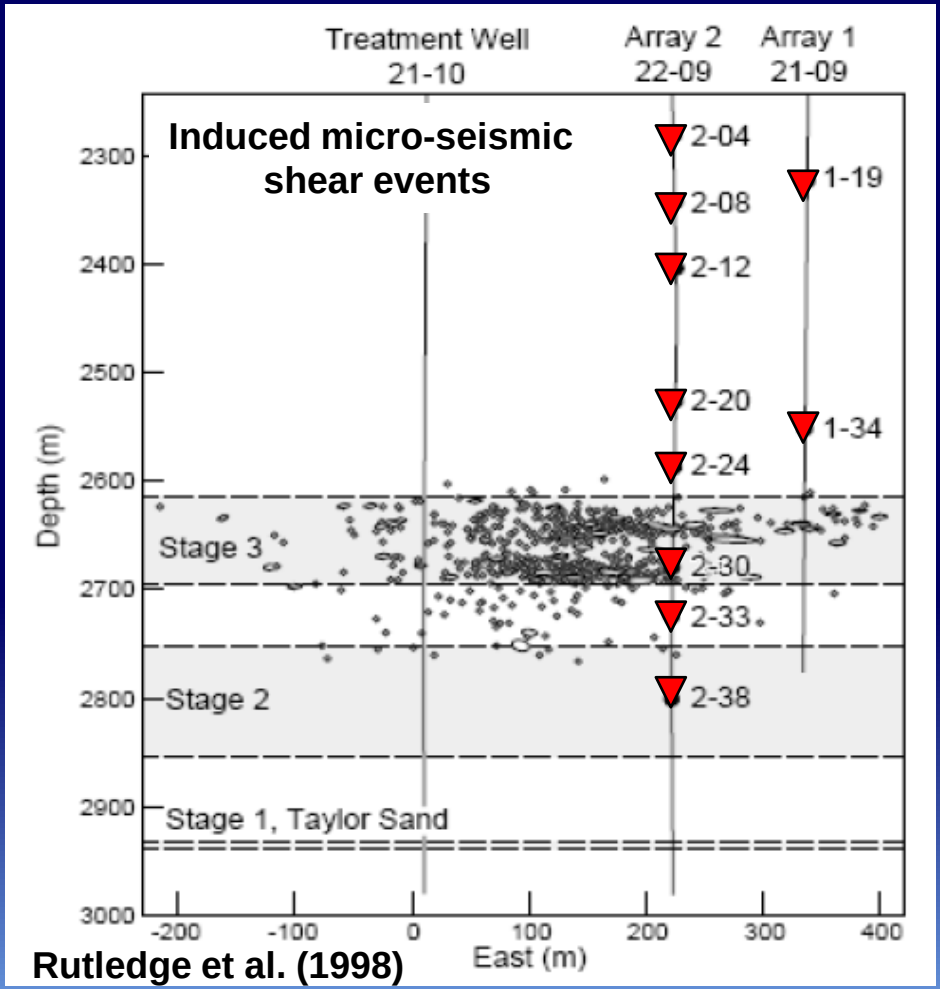
Passive Seismic Monitoring of CO_2 injection induced seismicity

A case study from the Michigan Basin/US

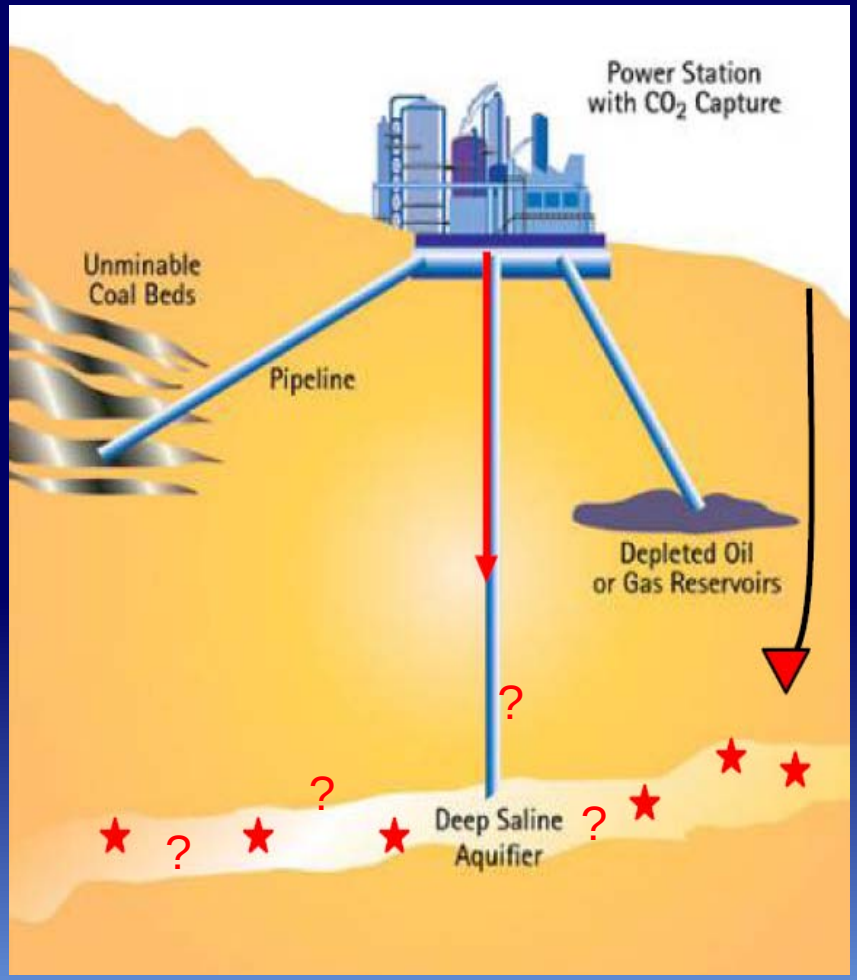
Seismic source processes during degassing of CO_2

Summary, Conclusions and Outlook

Will CO_2 Injection Induce Seismicity?



Rutledge et al. (1998)

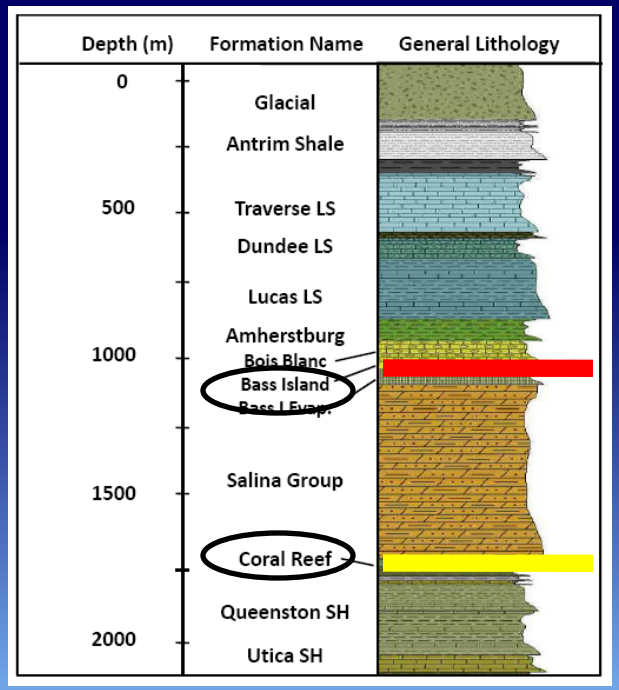


Passive Seismic Monitoring of CO_2 Sequestration

- Passive Seismic Monitoring has a long and extensive record of experience from both fundamental research and industry-scale applications and is ready to be deployed in the frame of CCS.
- As of today only a handful of studies from a total of three sites were reported despite of the relevance of CO_2 sequestration on a global scale and the need to provide sustainable techniques to monitor potential leakage and to image the CO_2 in the reservoir.
- In this study, I report unusual induced seismic events detected by Passive Seismic Monitoring which are interpreted to be associated with CO_2 leakage through or near wellbore annulus.

Case Study Michigan Basin

- The State Charlton Field (Michigan Basin) was selected as test site for a combined CO_2 sequestration and downhole Passive Seismic Monitoring experiment.
- Primary Objective: CO_2 injection into a Saline Aquifer (Bass Island Dolomite – BILD) at 1050 m depth and track its migration using induced seismicity.

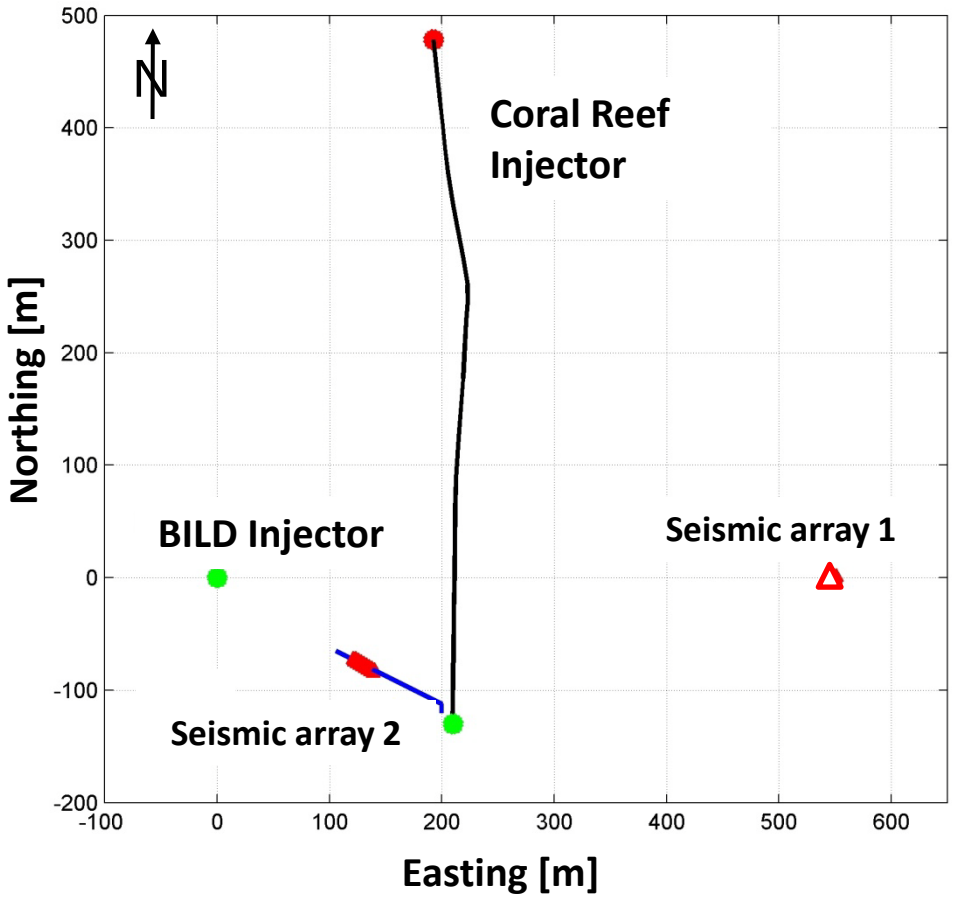


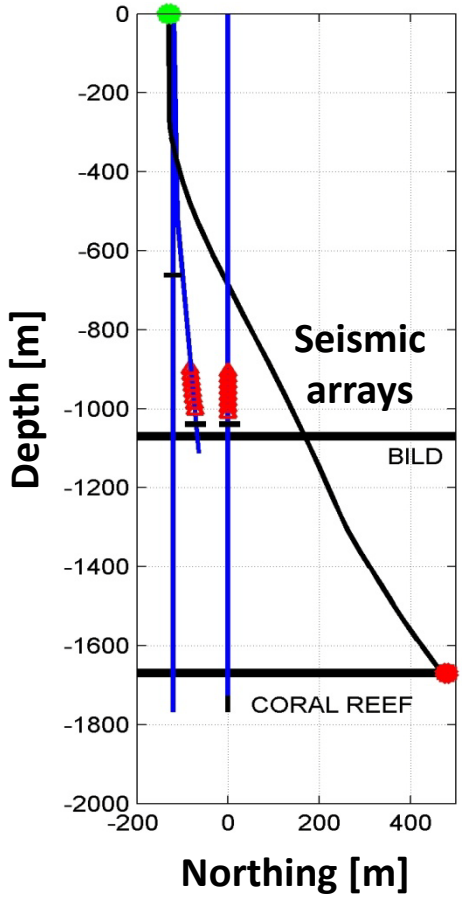
Project Overview

- Experiment is part of the Midwest Region Carbon Sequestration Partnership (MRCSP). Field Campaign carried out in collaboration with Engineering Seismology Group (ESG).
- Pilot Injection of 10,000 tons of supercritical CO_2 into the BILD formation during a period of 30 days (starting 8 Feb 2008).
- Deployment of two seismic arrays (8 3C sensors each) in two monitoring wells at 150 and 600 m distance to the injection point.
- CO_2 injection for EOR has been going on at the BILD site for 2.5 years into the Coral Reef at 1700 m depth.

Location of Injector and Monitoring Wells

Continuous seismic monitoring at 4000 Hz framing the injection period

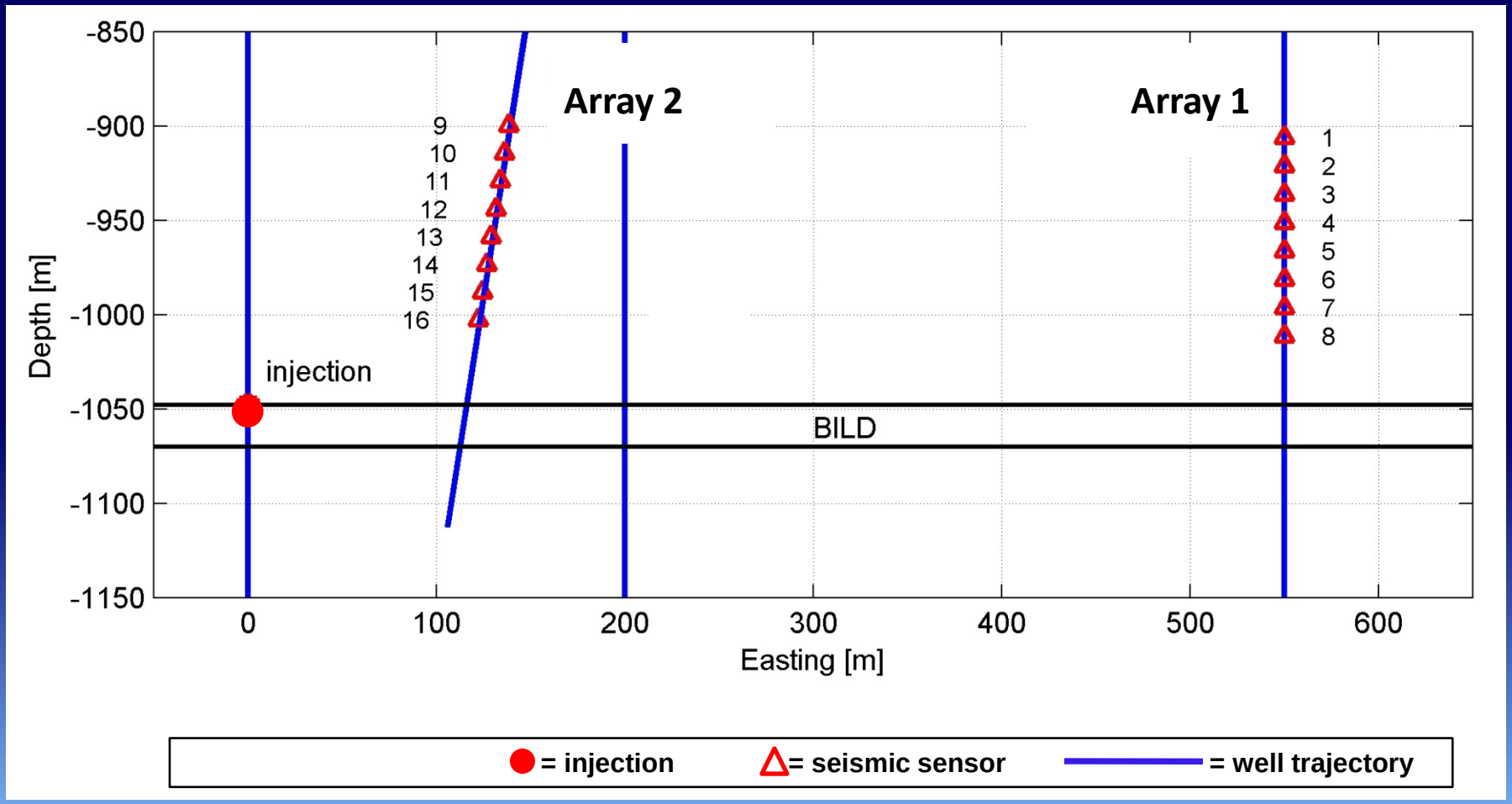




= well (surface) = injection = seismic sensor = well trajectory

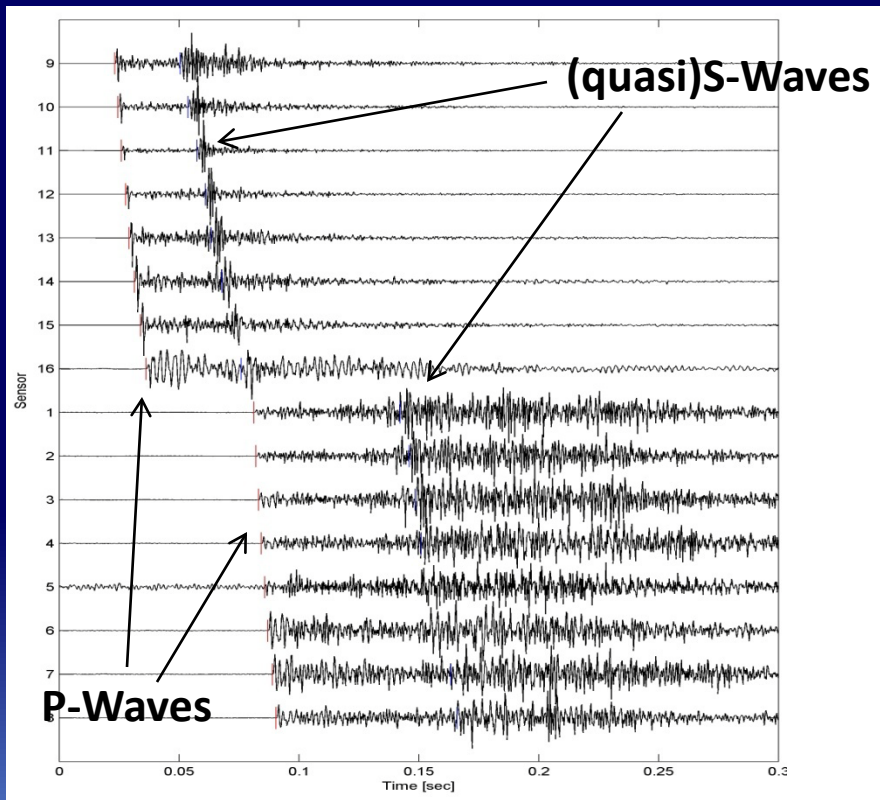
Downhole Seismic Arrays

Aperture of arrays: 105 m; Sensor spacing: 15 m
BILD injector drilled in 2006; Monitoring Wells drilled in 1970s

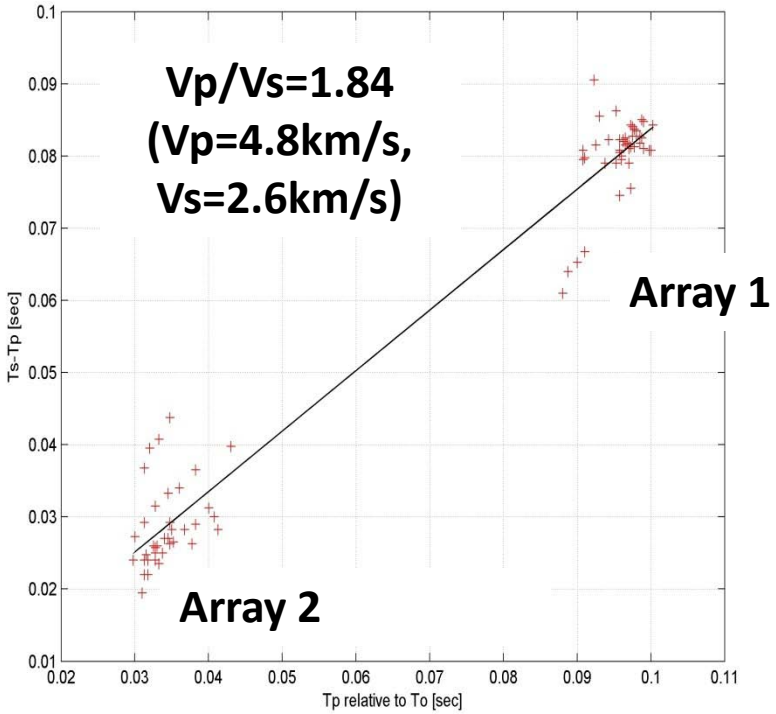


Waveform Recordings of Calibration Shots

Calibration Shot Seismogram



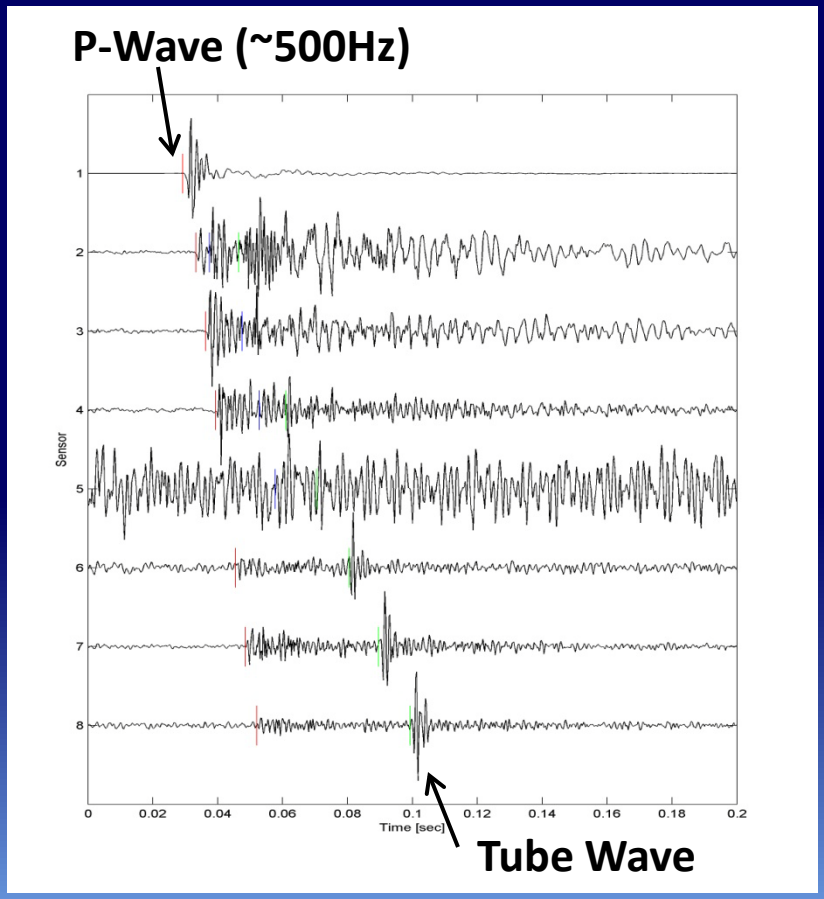
Wadati-Diagram

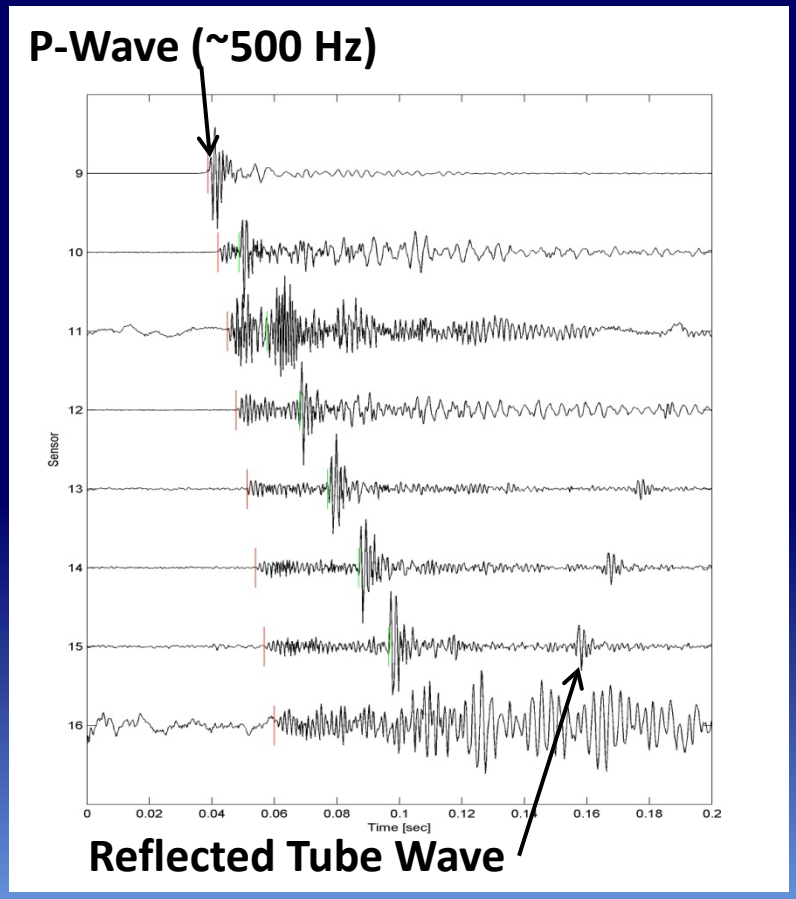


→ all 7 shots were located with a precision of 10-15 m

Observed Seismic Signatures

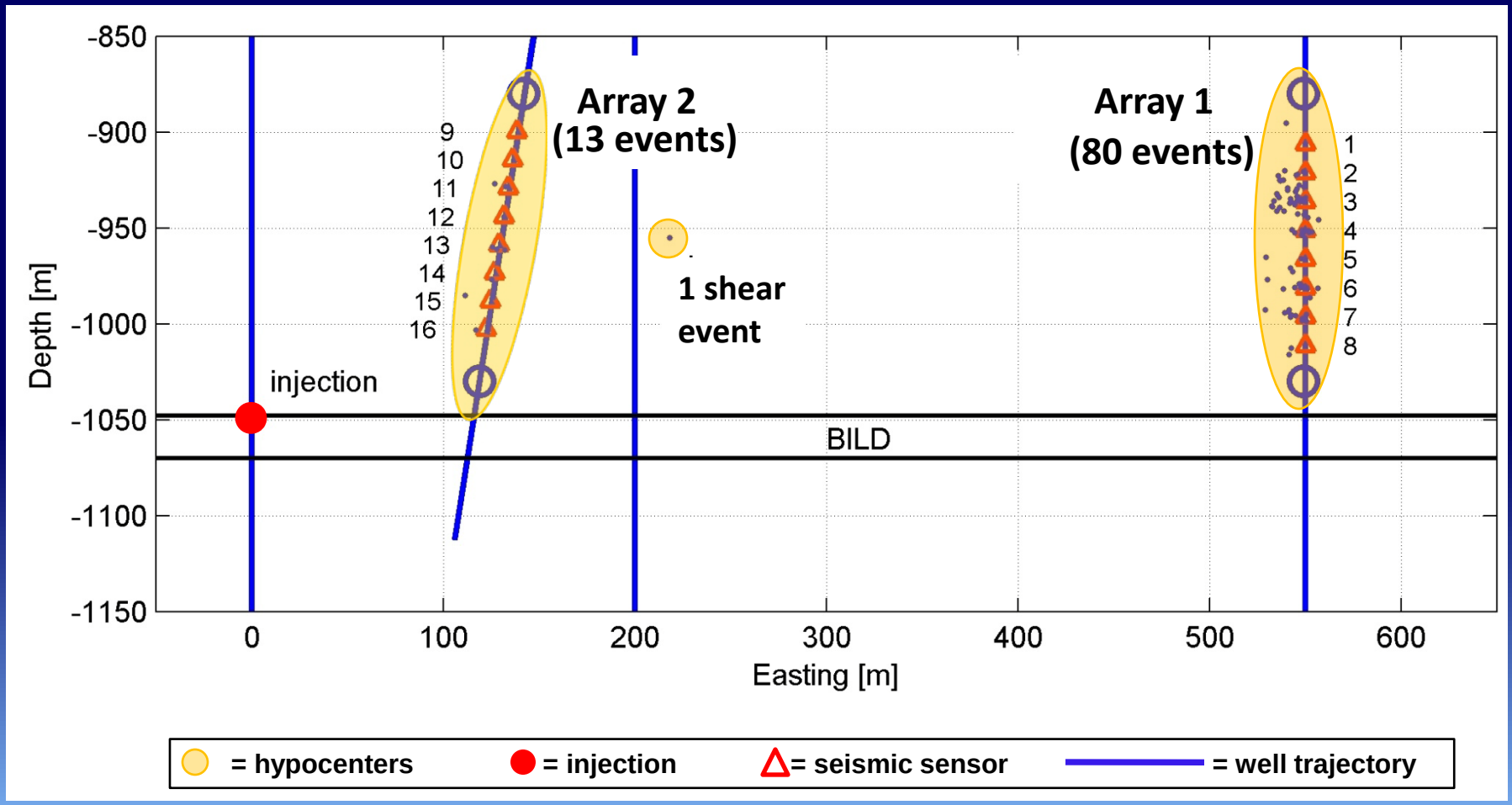
A total of 225 events were detected of which 94 can be precisely located
Almost none of the events contained shear waves but instead tube waves!



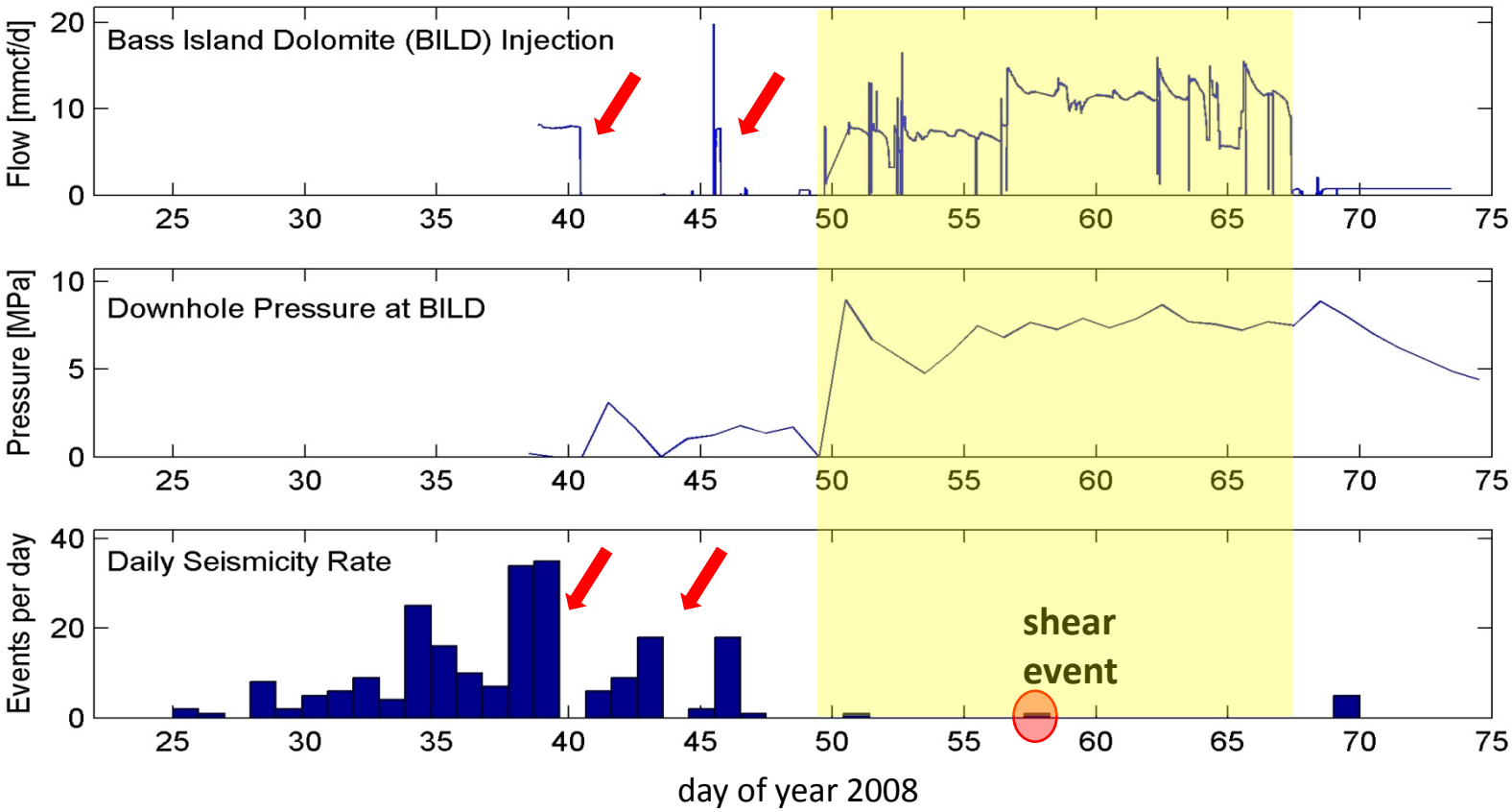


Hypocentral Distribution of Induced Seismicity

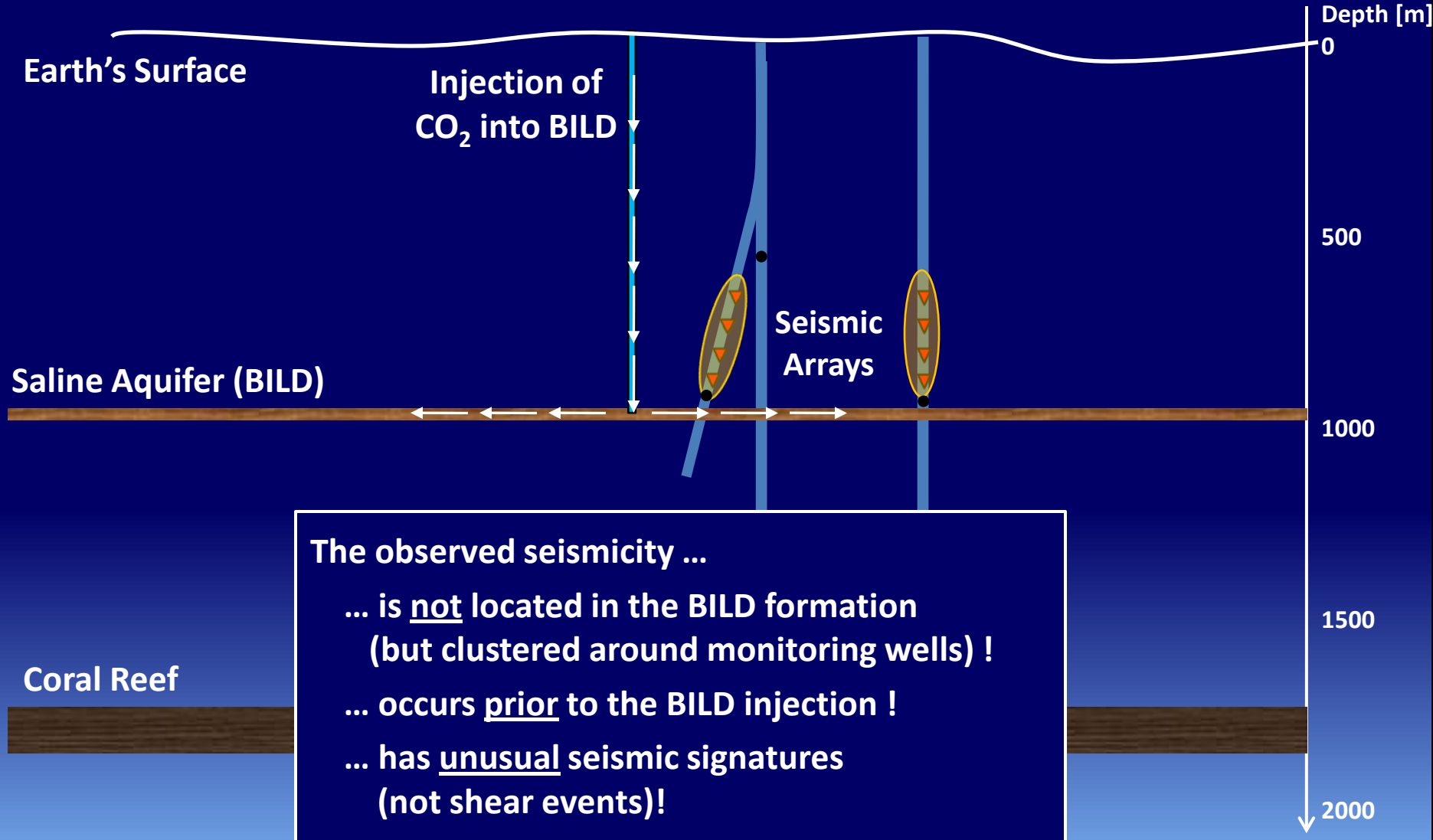
A total of 225 events were detected of which 94 can be precisely located
All events (except 'the' shear event) are located close to the respective array



Observed Microseismicity Preceedes BILD Injection!



How to Explain the Spatiotemporal Pattern?



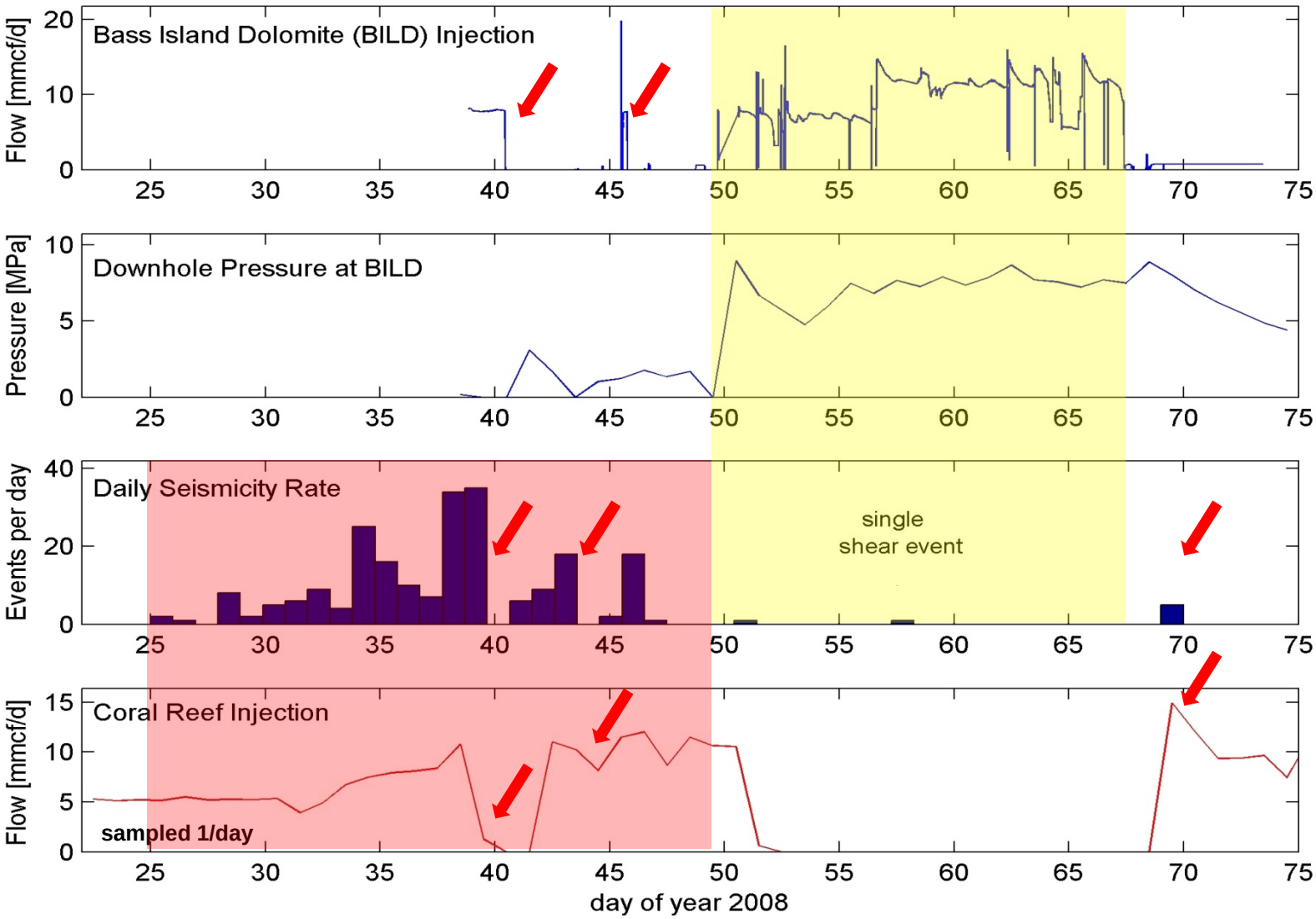
The observed seismicity …

… is <u>not</u> located in the BILD formation (but clustered around monitoring wells) !

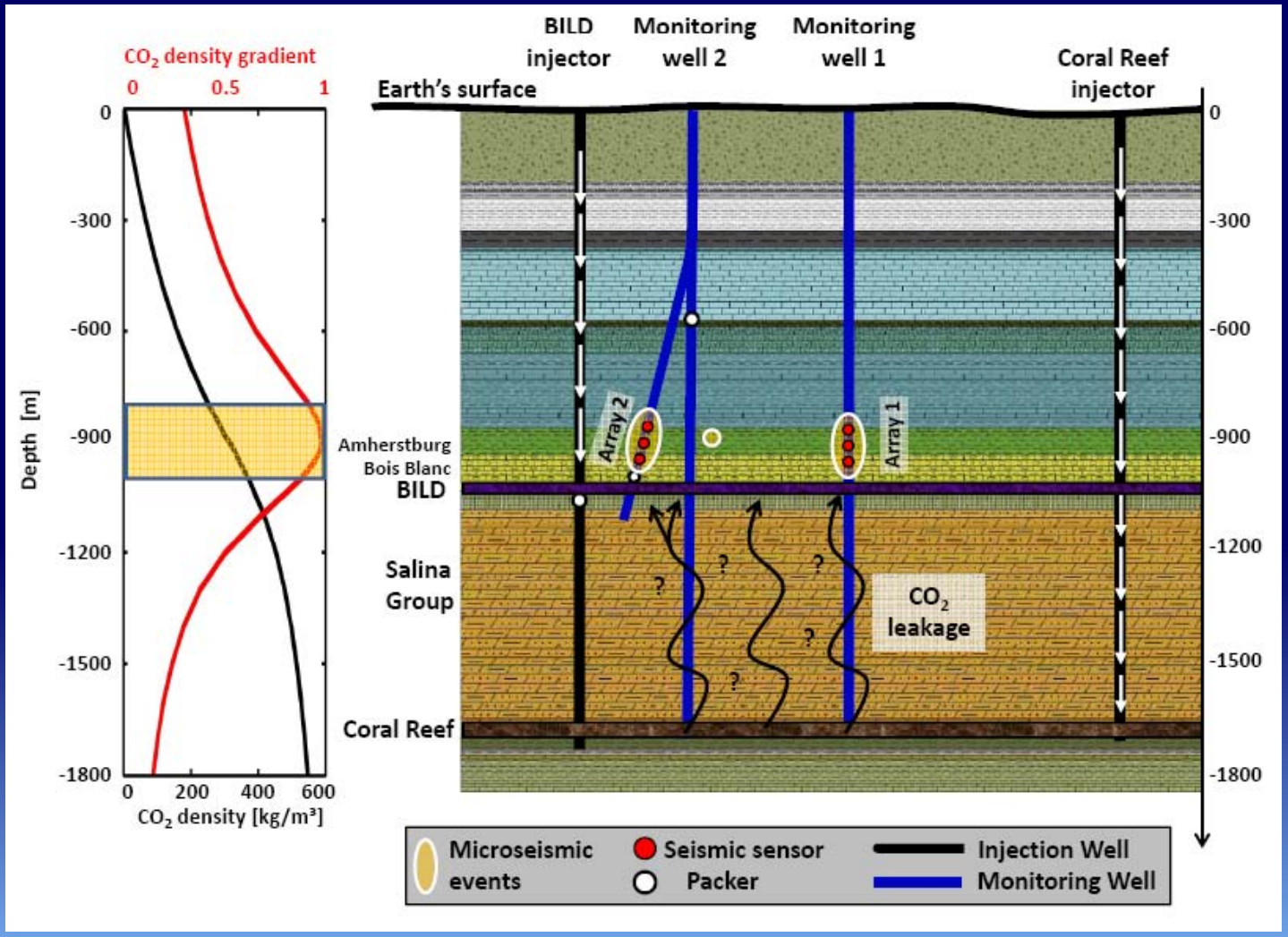
… occurs <u>prior</u> to the BILD injection !

… has <u>unusual</u> seismic signatures (not shear events)!

Hydraulic Parameters and Seismicity Rate



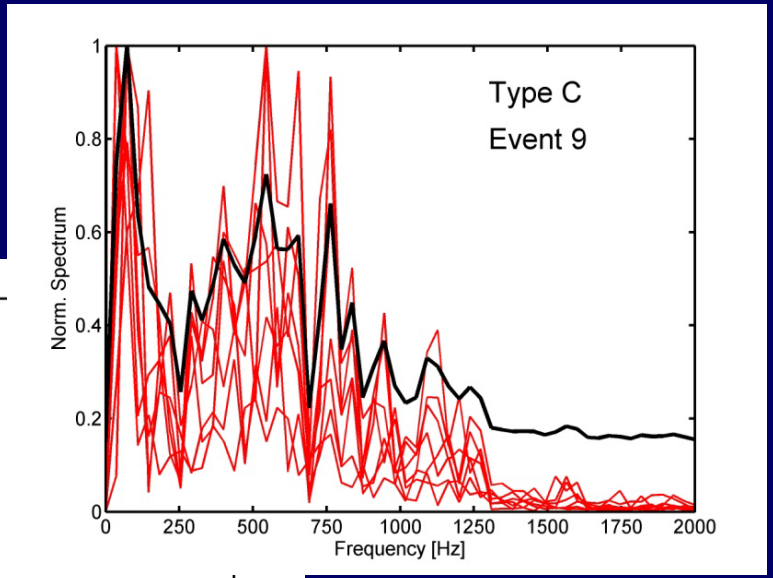
Summary of Observations



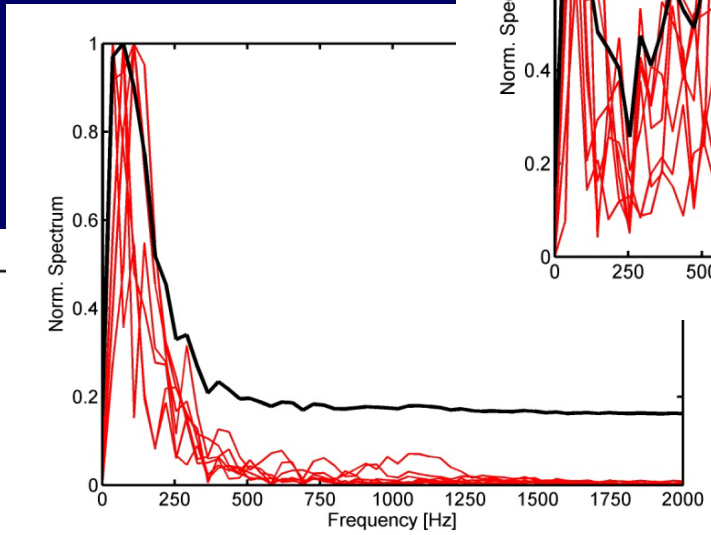
Bohnhoff et al., IJGGC (2010)

Frequency Characteristics of the Seismic Events

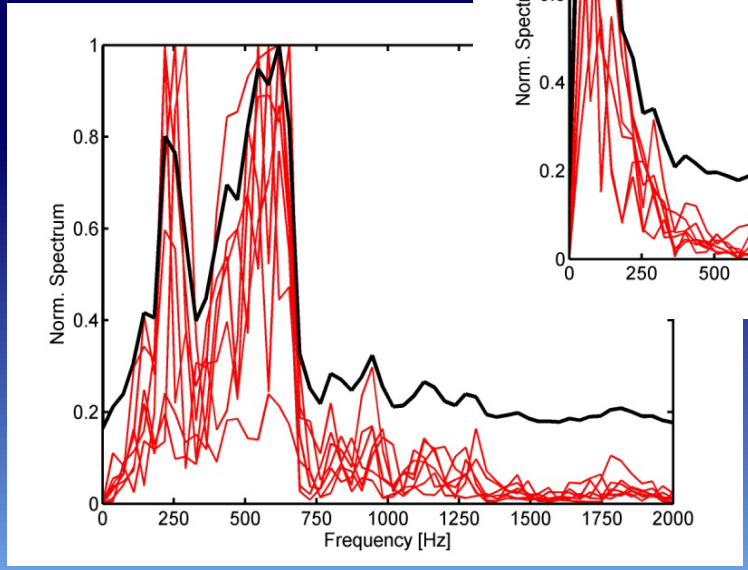
Type C events



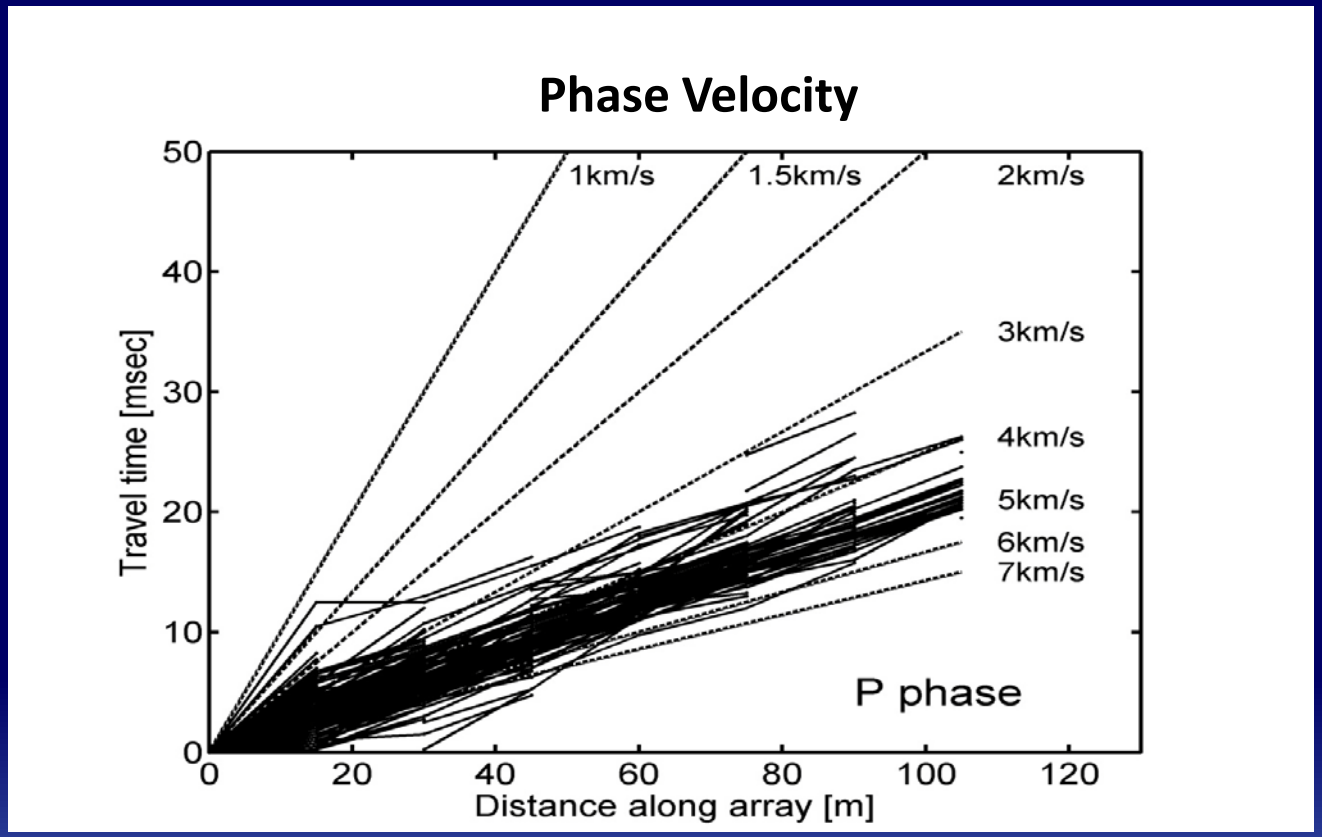
Type B events

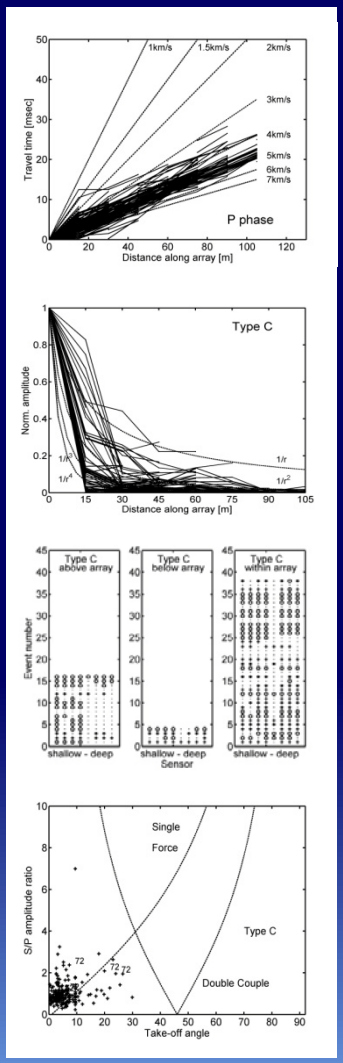


Type A events



Seismic Source Process ?



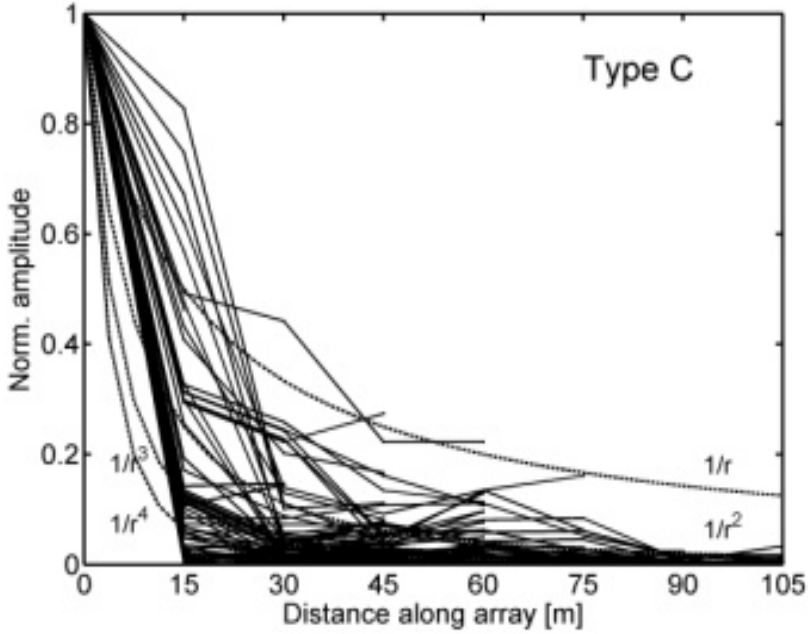


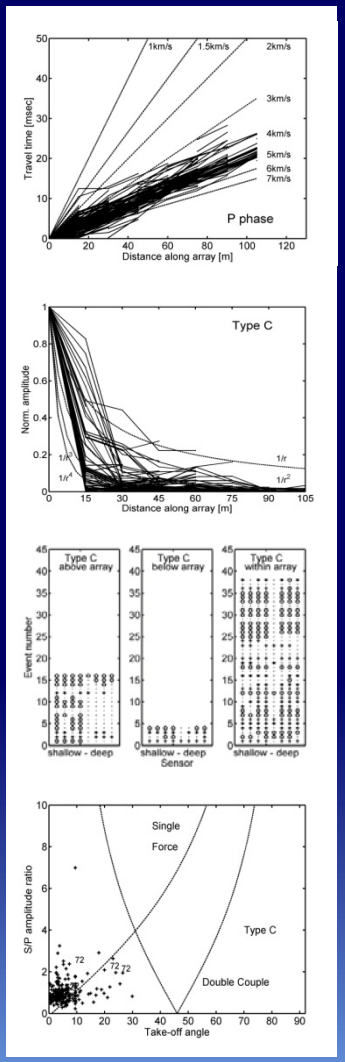
Isotropic Source: Not permitted by pol., not supported by ampl. ratios
Double Couple: Not permitted by pol., not permitted by ampl. ratios

Single Force: Supported by polarities and amplitude ratios

Seismic Source Process ?

Amplitude decay





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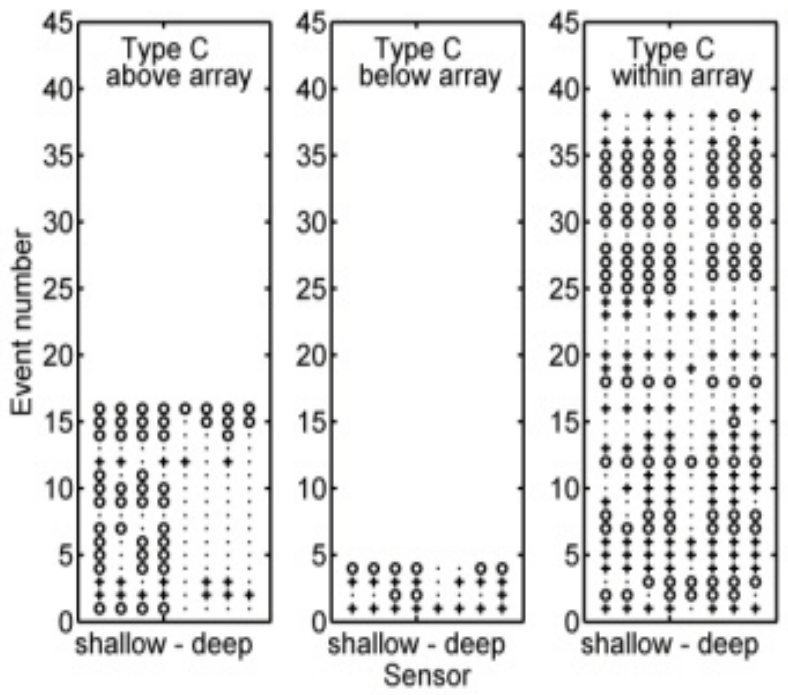
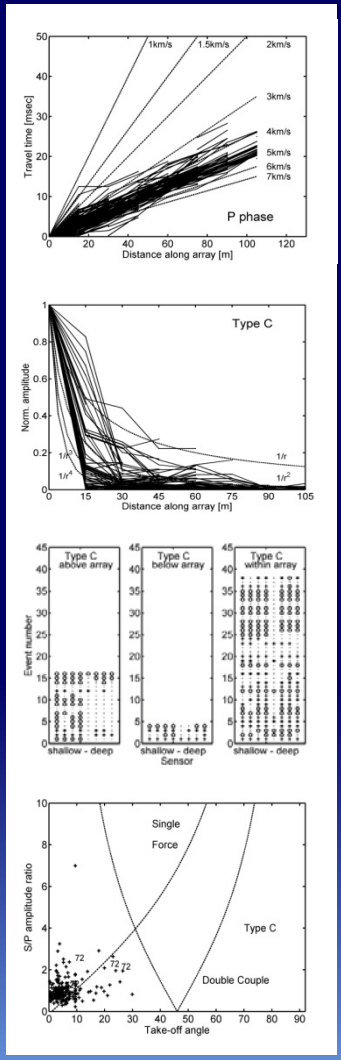
Seismic Source Process ?





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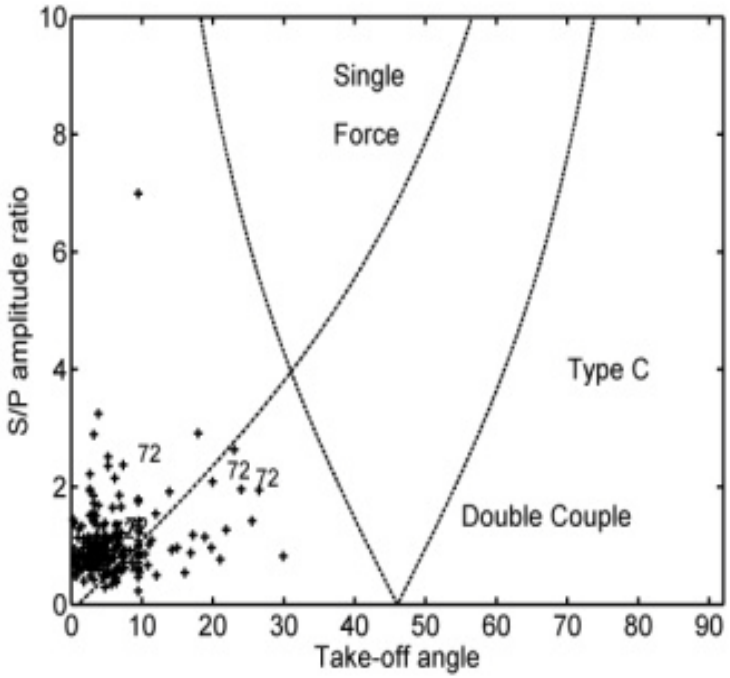
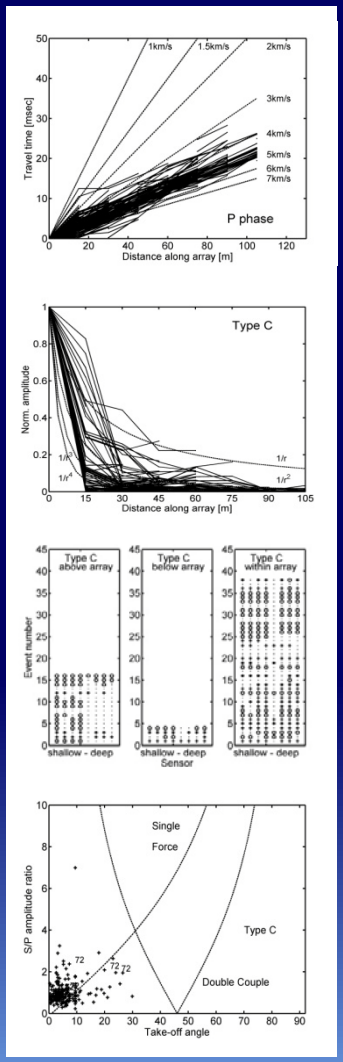
Seismic Source Process ?

S to P amplitude ratios





Isotropic Source: Not permitted by pol., not supported by ampl. ratios
Double Couple: Not permitted by pol., not permitted by ampl. ratios

Single Force: Supported by polarities and amplitude ratios

Seismic Source Process: Single Force

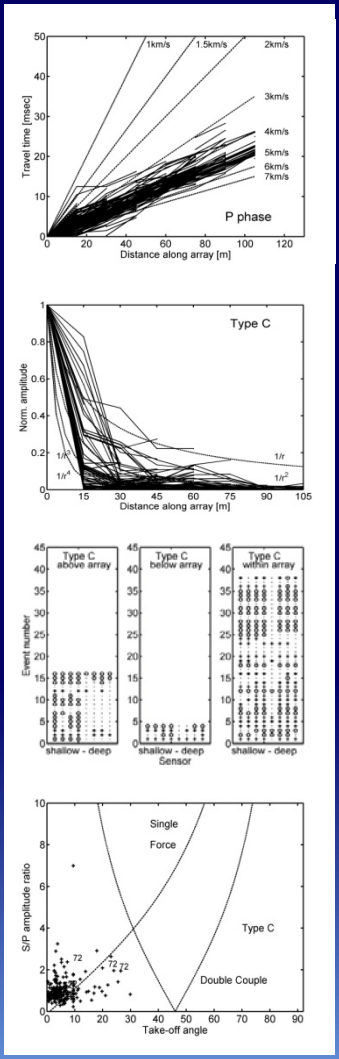
1. Hypocenters:
   Located in direct vicinity to the observation wells

2. Phase velocity:
   4.8 km/s P waves and 1.6 km/s for Tube Waves

3. Amplitude decay and non-linearity of particle motion:
   Events were observed in seismic near-field

4. P-wave Polarities:
   Uniform polarities per event; both upward (65%) and downward (35%) first motion → source cannot be isotropic

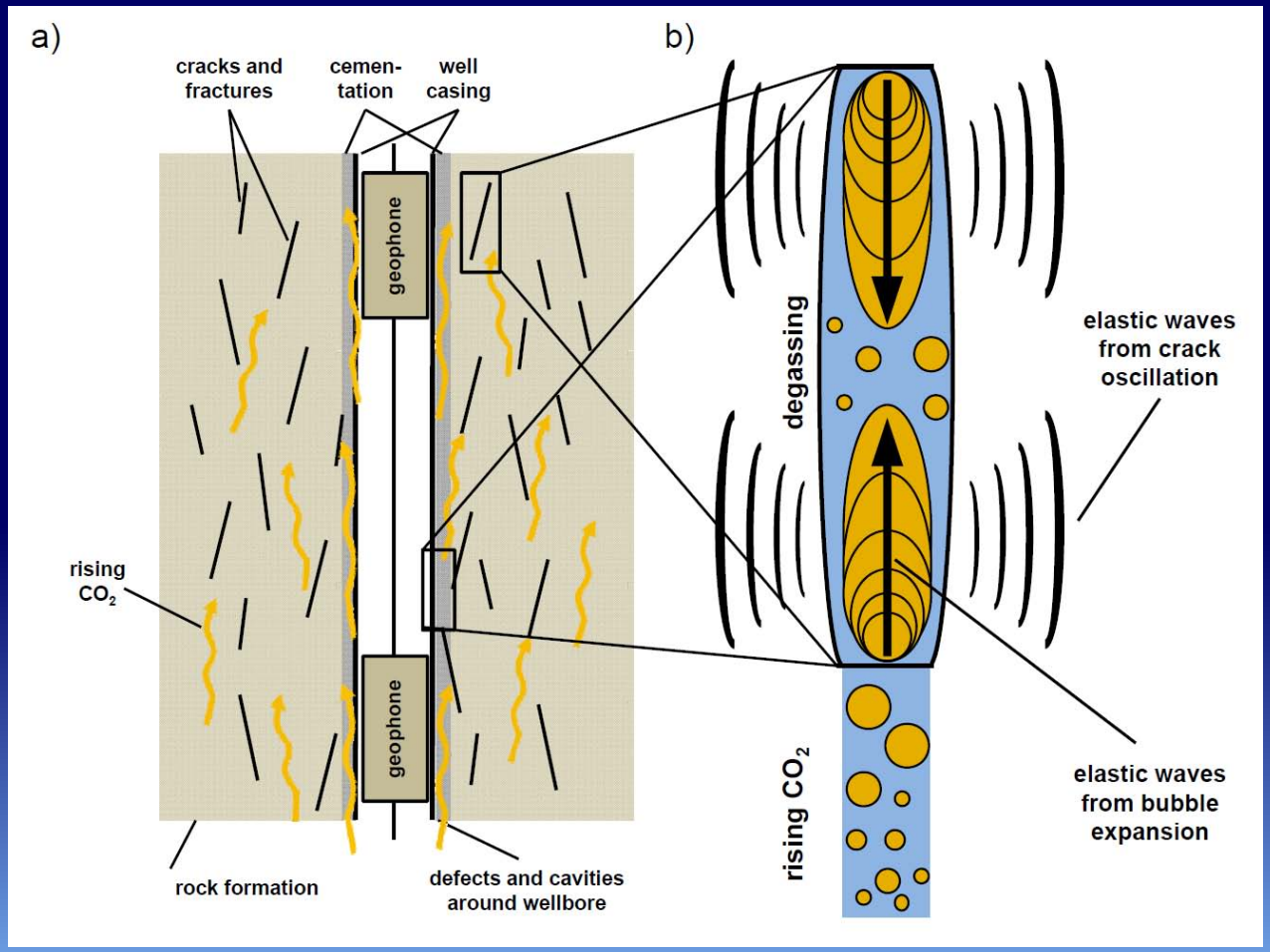
5. S to P amplitude ratios (restricted to far field):
   indicative of single force; some events with weak shear waves



Isotropic Source:	Not permitted by pol., not supported by ampl. ratios
Double Couple:	Not permitted by pol., not permitted by ampl. ratios
Single Force:	Supported by polarities and amplitude ratios

Conceptual Model of the Observed Source Process During Leakage of CO_2 along Monitoring Wellbores

(Bohnhoff & Zoback, JGR, 2010)



<u>Source:</u>
Volume increase of CO_2 during rise from reservoir towards the surface along wellbores

<u>Resonator:</u>
Fluid-filled cracks and fractures as well as defects and cavities (e.g. caused by corrosion) around the monitoring wellbore

Summary and Conclusions

- Supercritical CO_2 was injected into a Saline Aquifer at 1050 m depth during a break of EOR-related CO_2 injection into the Deeper Coral Reef.
- A total of 225 seismic events were detected by a downhole seismic array. The events occurred along the annulus of the monitoring wells but not within the BILD or Coral Reef reservoirs.
- The temporal evolution of the seismicity shows a clear correlation with the Coral Reef injection, not with the BILD injection. Modeling of CO_2 transition from supercritical to gaseous based on local P and T conditions indicates that the volume increase occurs to a large portion at the depth where the seismic events were observed.
- The seismic events are interpreted to reflect leaking CO_2 along or near the annulus of two monitoring wells. Amplitude ratios and polarity pattern suggest a single force source mechanism pointing to oscillation of fluid-filled cracks triggered by volume expansion of the CO_2.

Implications

- This is the first known observation of seismic events indicating CO_2 leakage along pre-existing wells in oil/gas reservoirs considered for CO_2 sequestration. Further experiments to validate this observation are planned (collaborations welcome!).
- Given the large number of $>10^6$ pre-existing wells on the North American continent, of which a large number would be used to sequester 1 GT Carbon/yr, this observation is critically important to further develop CCS in the near future.
- This case study stresses the relevance of downhole (and therefore near-source) passive seismic monitoring

  1. to monitor wellbore and caprock integrity and the elastic response of reservoirs during and after CO_2 storage (same for hydrocarbon and geothermal reservoirs).
  2. to potentially detect and analyze yet undetected types of earthquakes.

Thank you for your Attention !