Continuous Seismic Monitoring of CO2 injection projects

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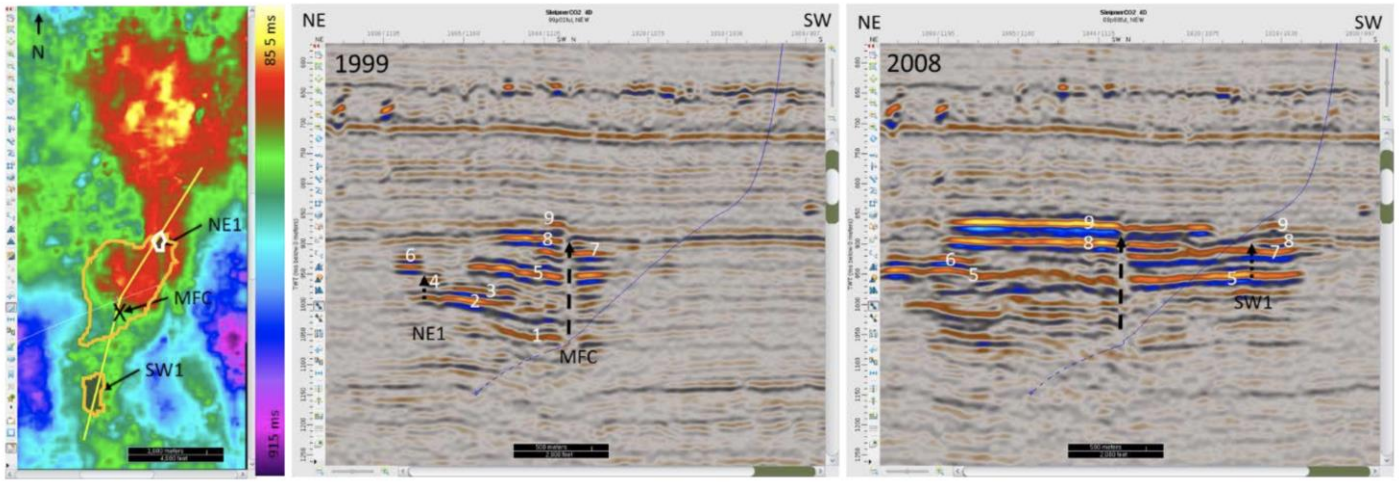
with contributions by *Ariel Lellouch, William L. Ellsworth, and Siyuan Yuan*

Stanford Exploration Project

Geophysics Department

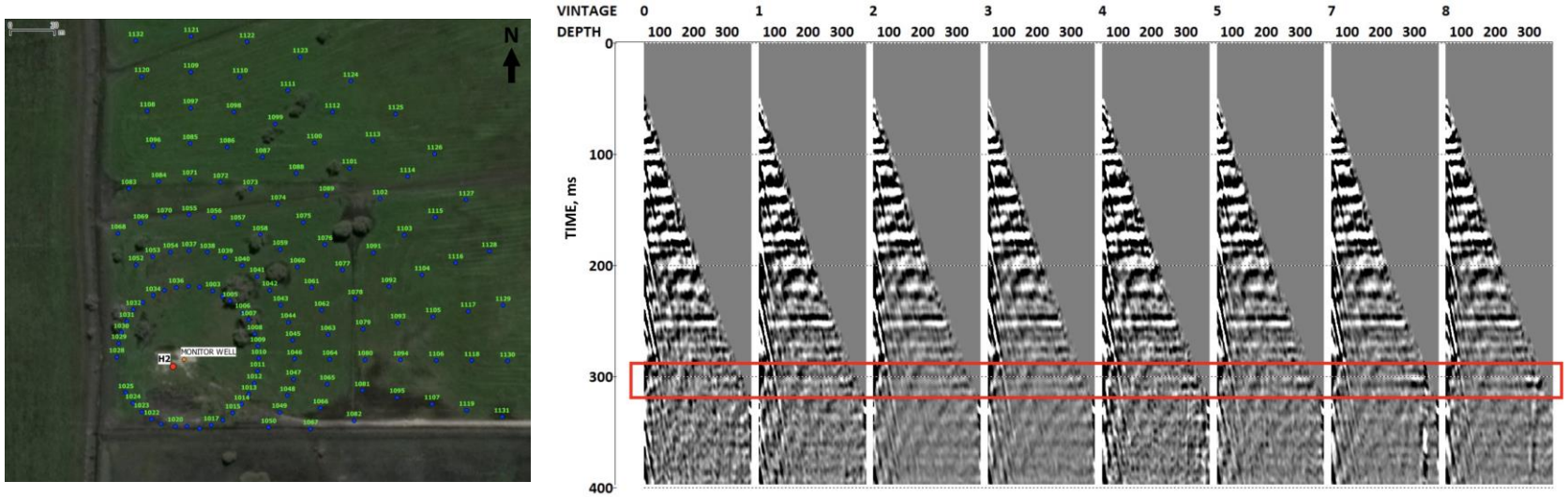
Stanford University

Periodic active seismic monitoring



4D surface seismic

Sleipner (Norway)

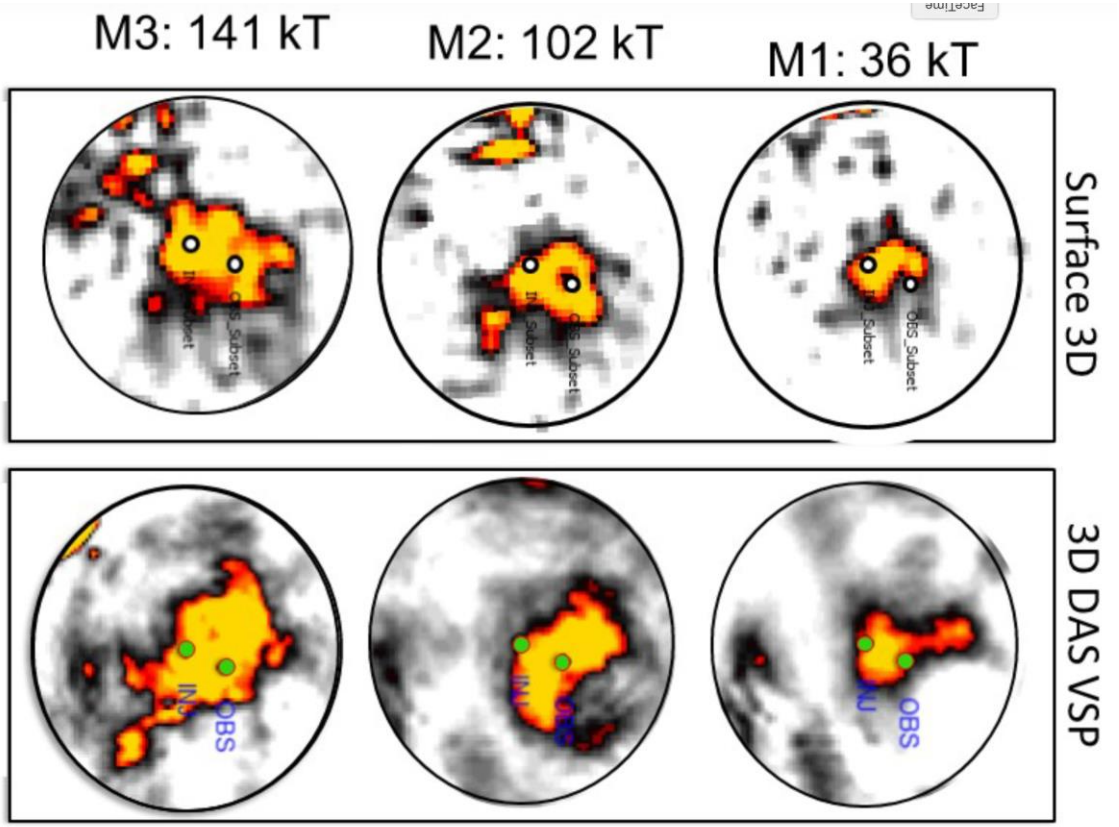


4D DAS-VSP

South West Hub (Australia)

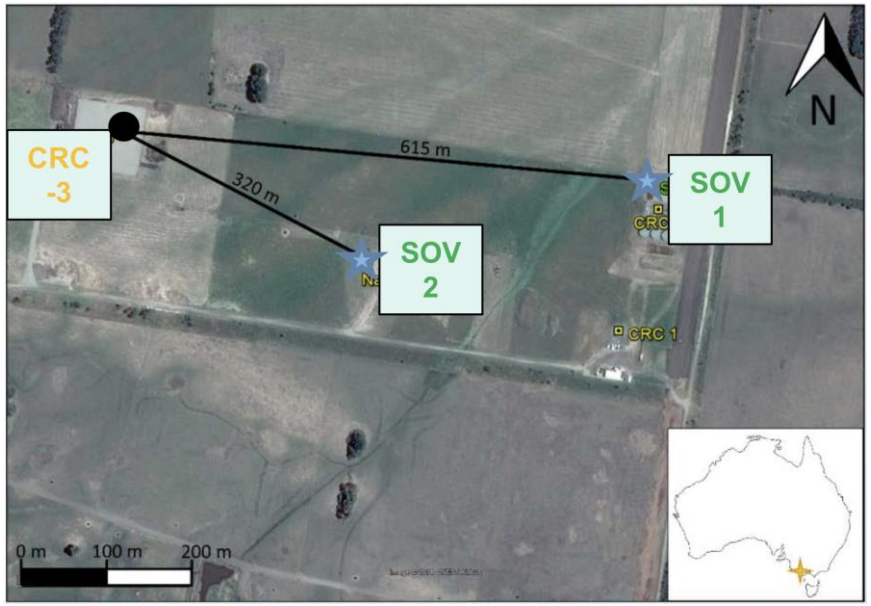
Periodic active seismic monitoring

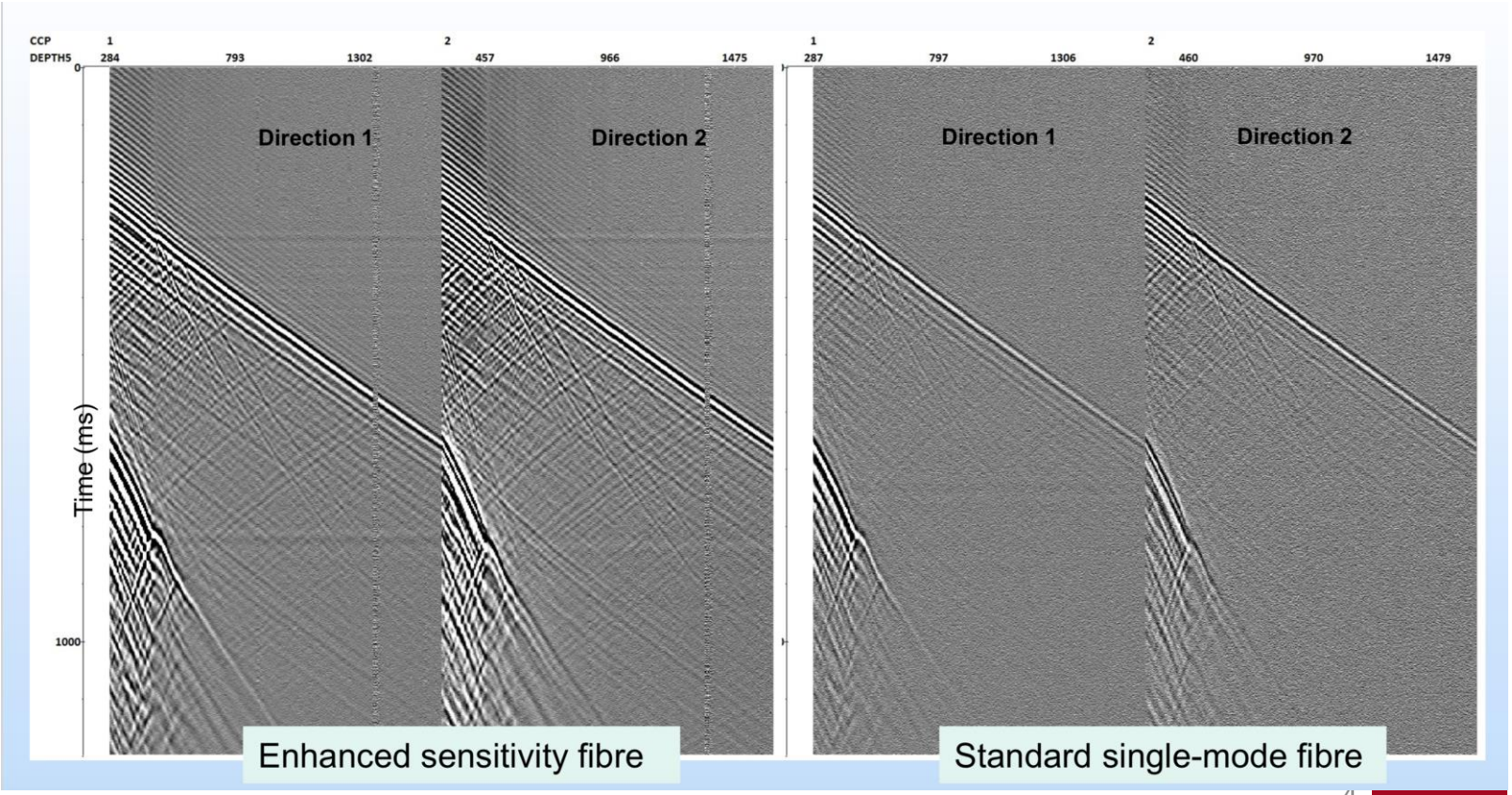
4D surface seismic & 4D DAS-VSP
Aquistore (Canada)



Continuous active seismic monitoring

4D DAS-VSP with Surface Orbital Vibrator (SOV) sources
Otway (Australia)





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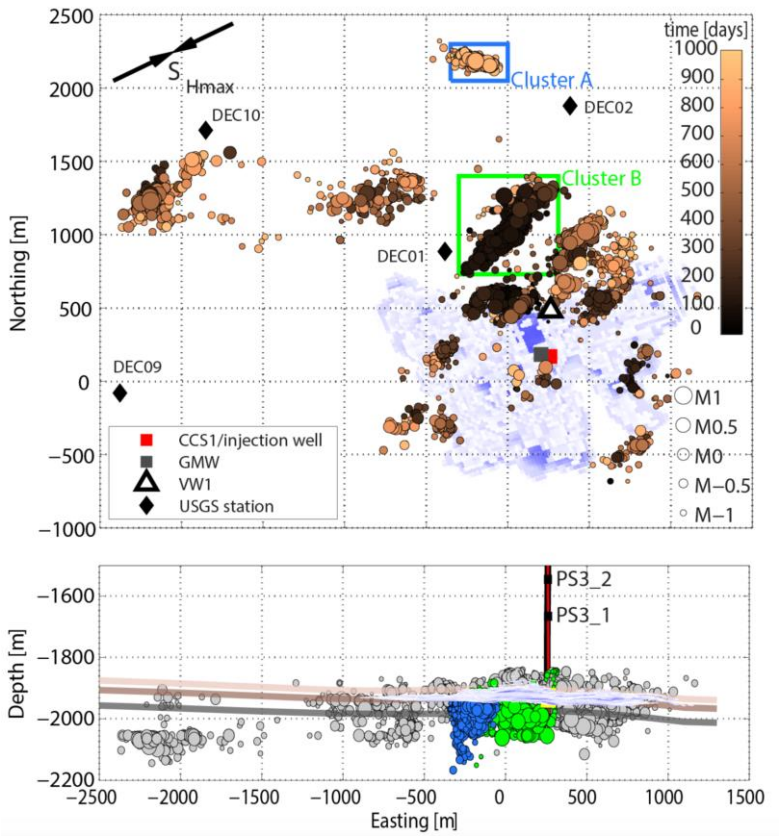
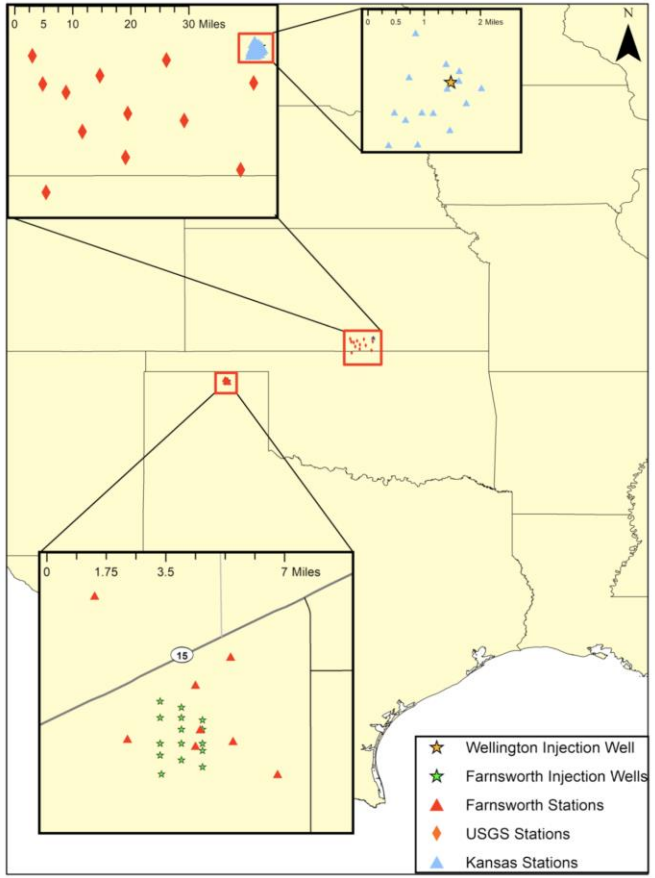
Continuous passive seismic monitoring

Induced seismicity monitoring by arrays of seismometers

Decatur (CCS)

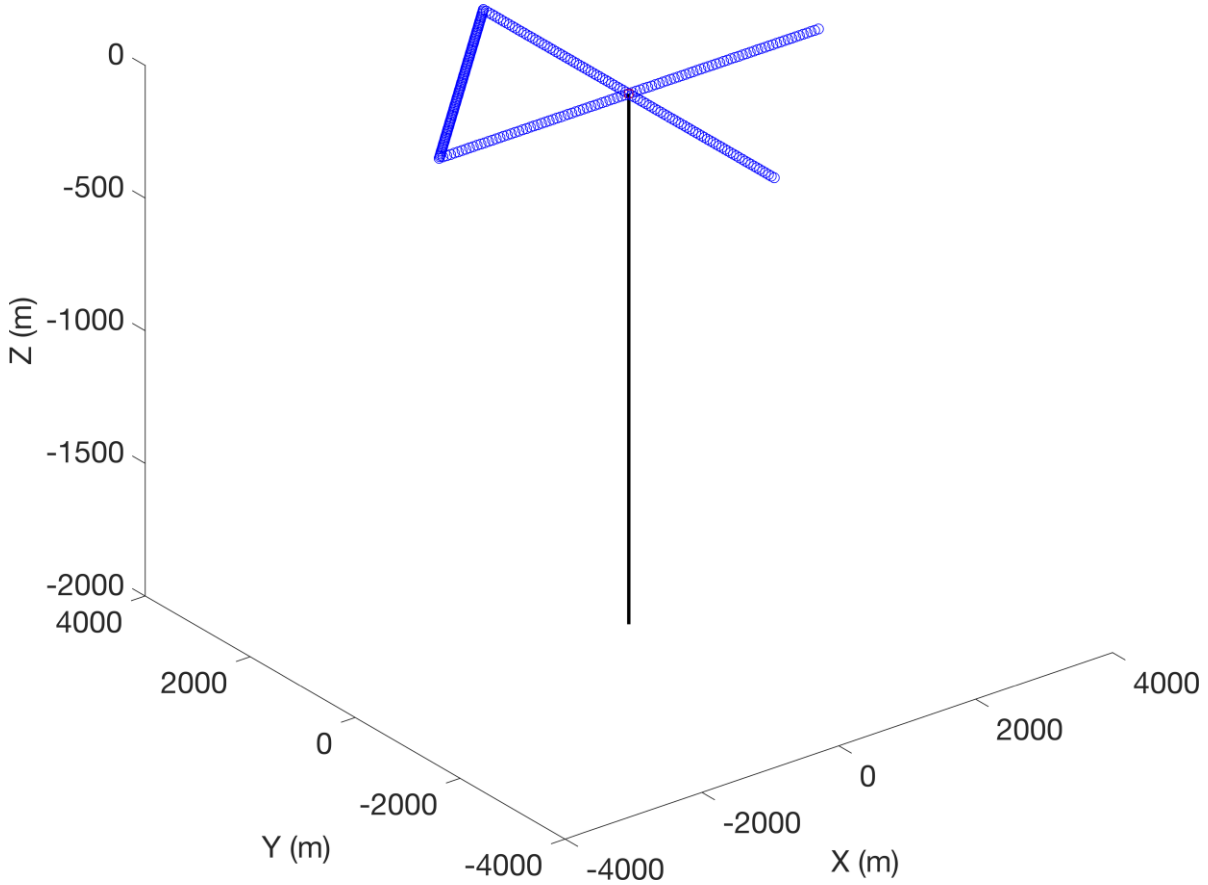


Wellington & Farnsworth (EOR)

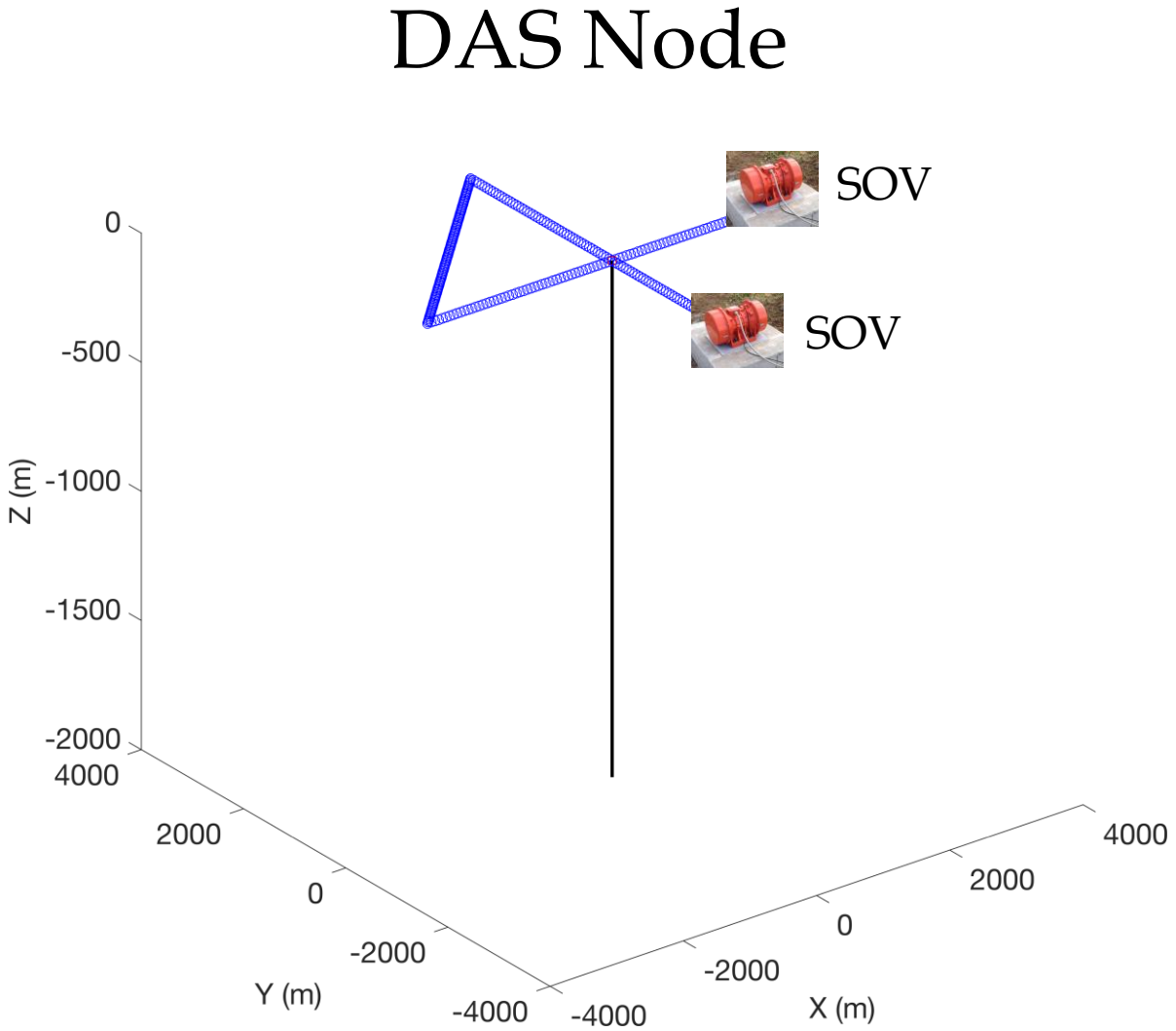


Continuous passive seismic monitoring by a DAS Node

DAS Node

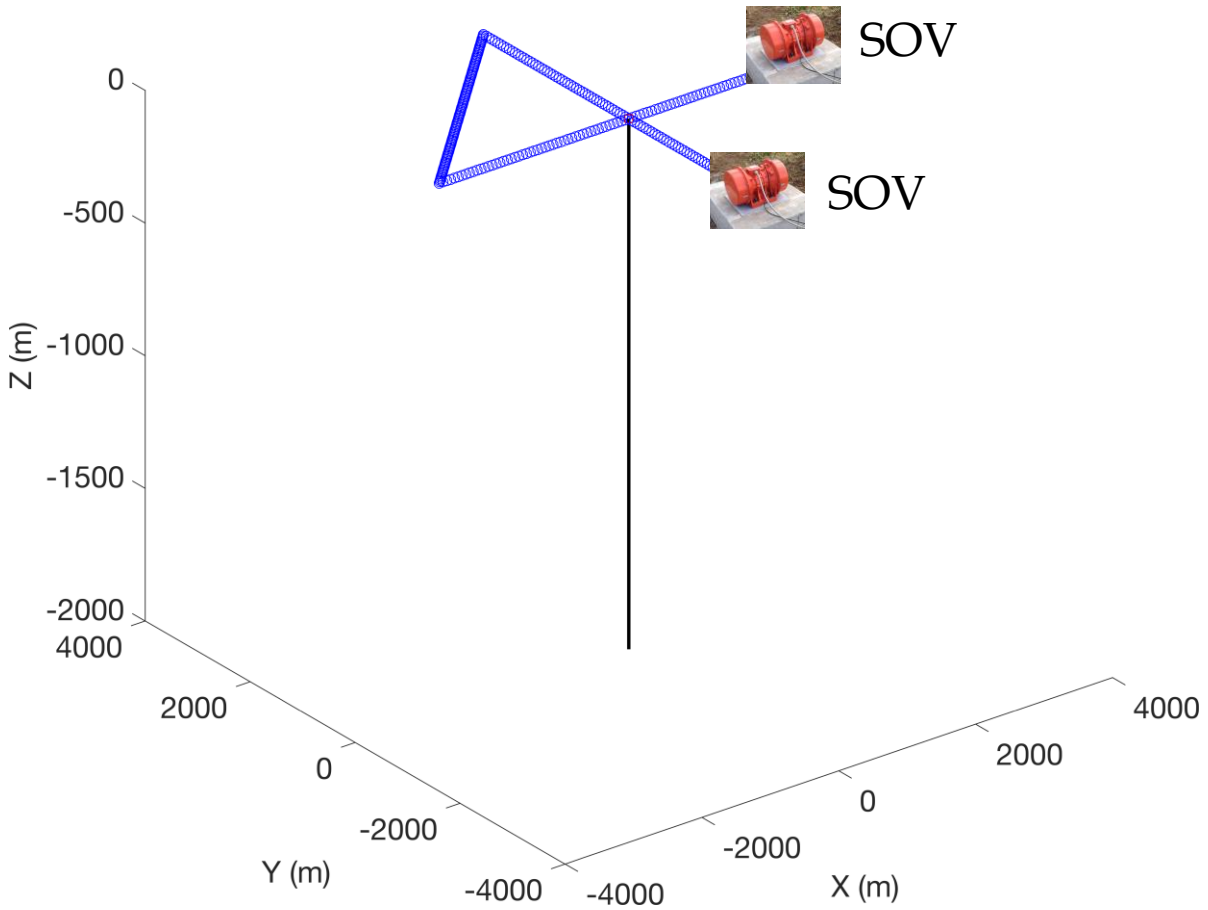


Continuous passive and active seismic monitoring by a DAS Node

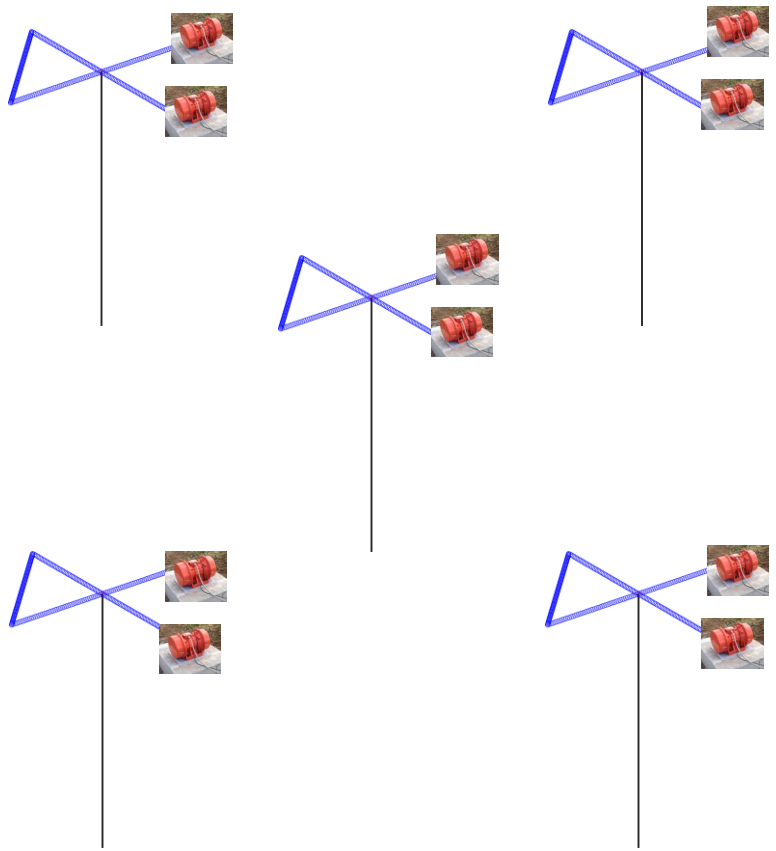


Continuous passive and active seismic monitoring by a DAS Net

DAS Node



DAS Net



Ideal continuous passive seismic monitoring systems

- Cost-effective long-term operations
  - Low-maintenance
  - Durability of field equipment
  - Reliable and high-bandwidth data telemetry of recorded waveforms
  - Stable coupling with the ground
- Requirements for induced seismicity monitoring
  - Detection of weak events
  - Accurate source location
  - Reliable magnitude estimation
  - Source mechanism characterization?

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Pros and cons of DAS for permanent seismic monitoring

+ Cost per “virtual” receiver
+ Receiver density => Exploit moveouts => Back propagate wavefields
+ Possibility of placing receivers in otherwise inaccessible locations
+ Power and connectivity needed by interrogators but not by receivers
+ Receiver durability and resilience in harsh environments
- Receiver sensitivity is lower than geophones and highly directional

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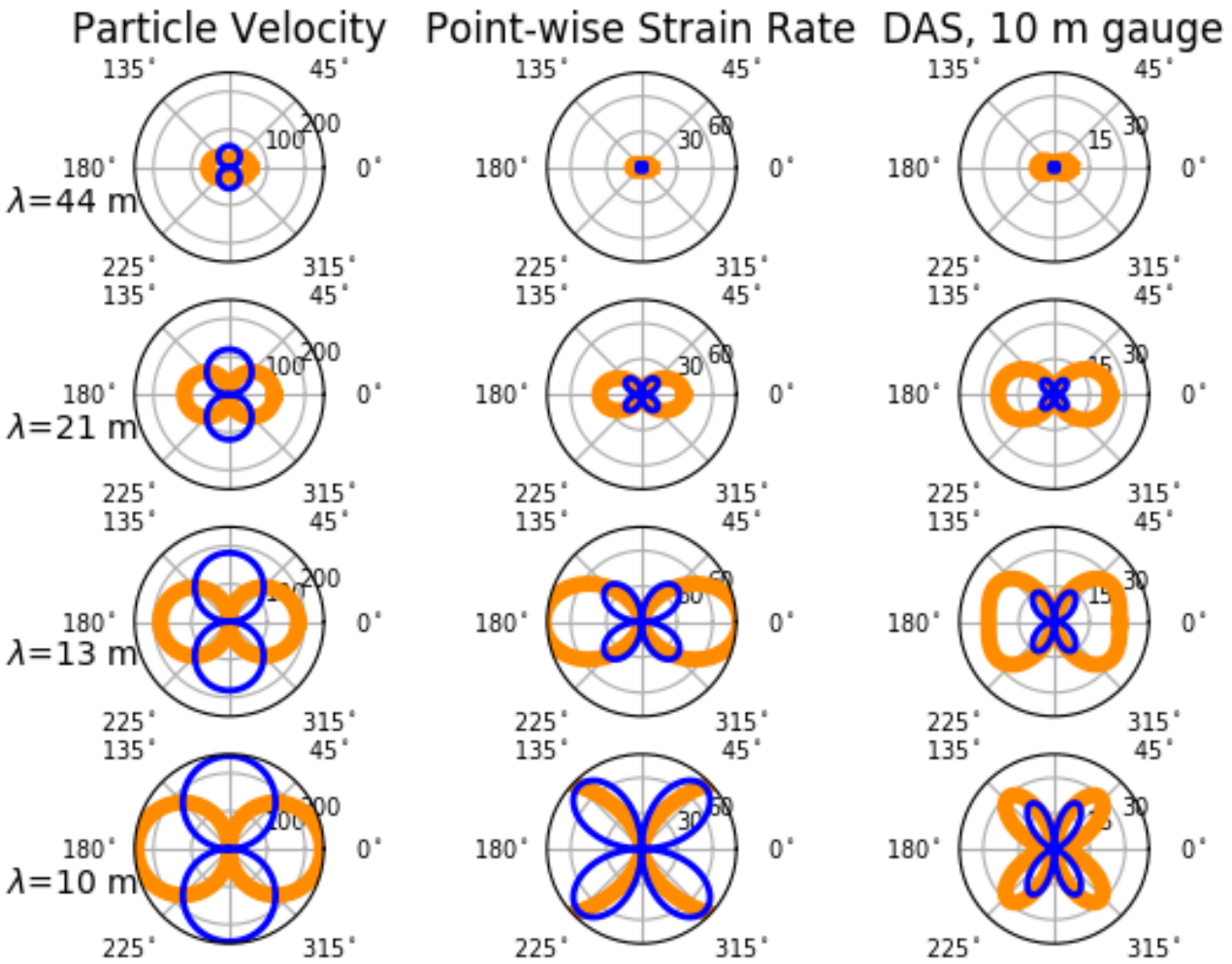
Sensitivity of seismometer vs. vertical DAS



Sensitivity to body waves recorded in vertical borehole

1) incidence angle

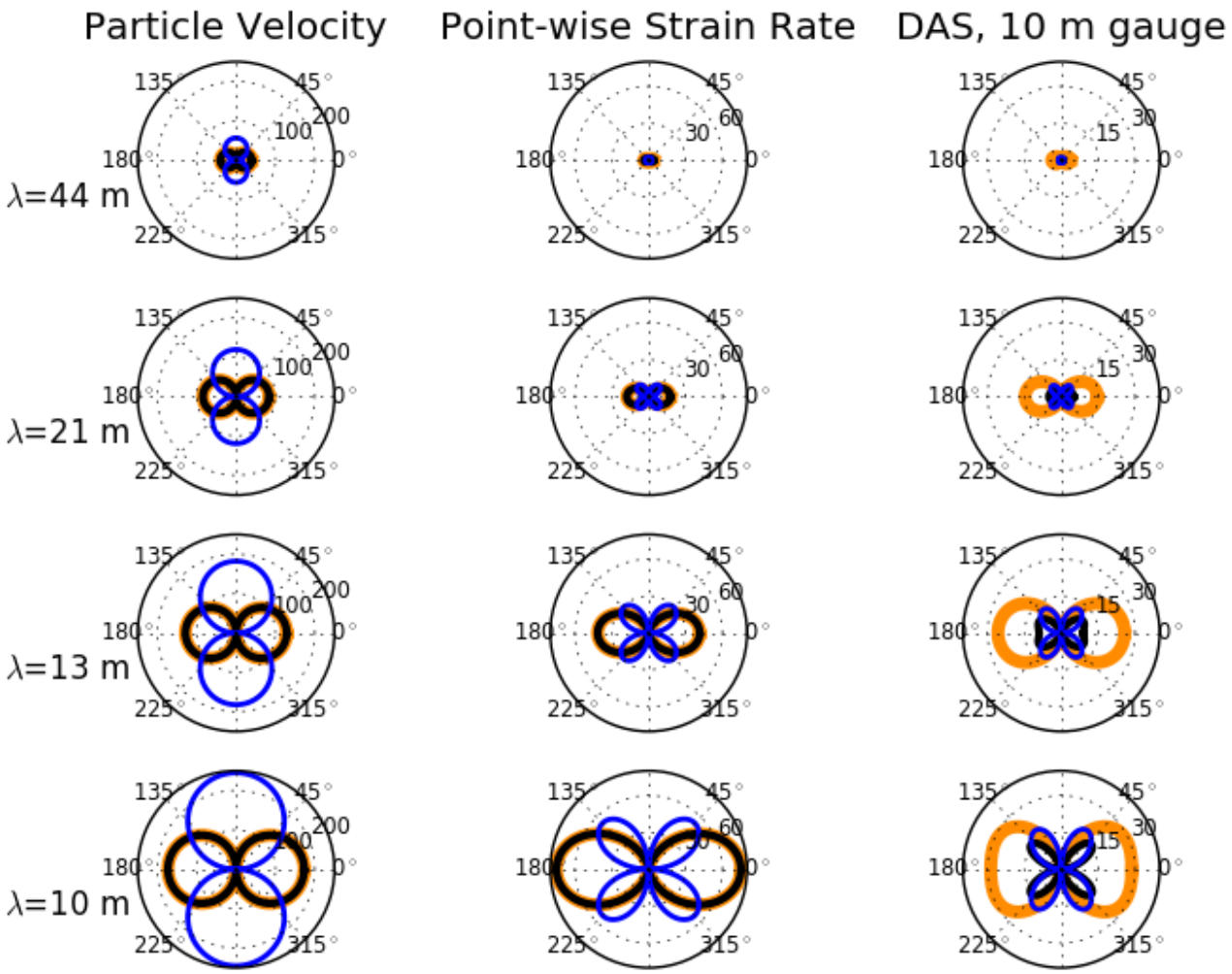
2) wavelength

-P waves

-SV waves

Eileen Martin's Ph.D. thesis - May 2018

Sensitivity of seismometer vs. horizontal DAS



Sensitivity to body waves emerging at 45° as a function of:

1) azimuth angle

2) wavelength

-P waves

-SH waves

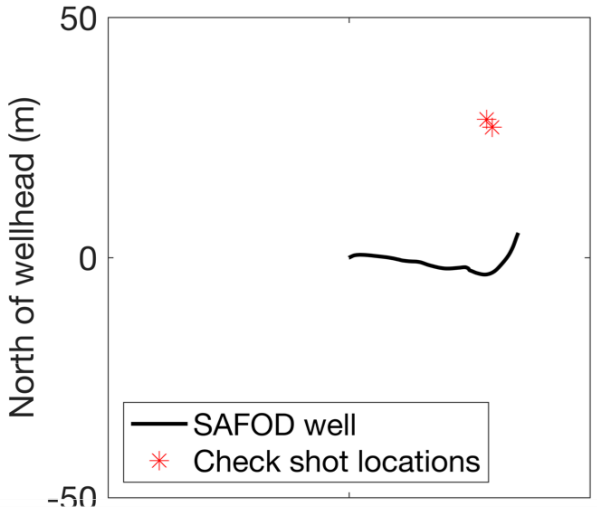
-SV waves

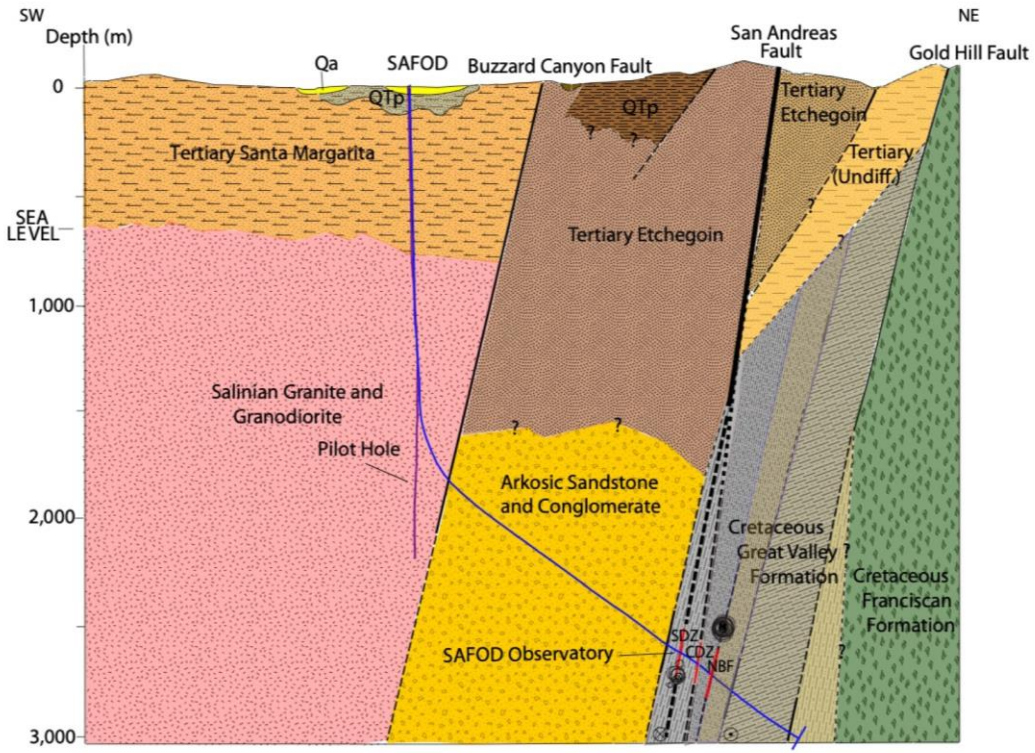
Eileen Martin's Ph.D. thesis - May 2018

SAFOD fiber array

In place for ~13 years before acquisition

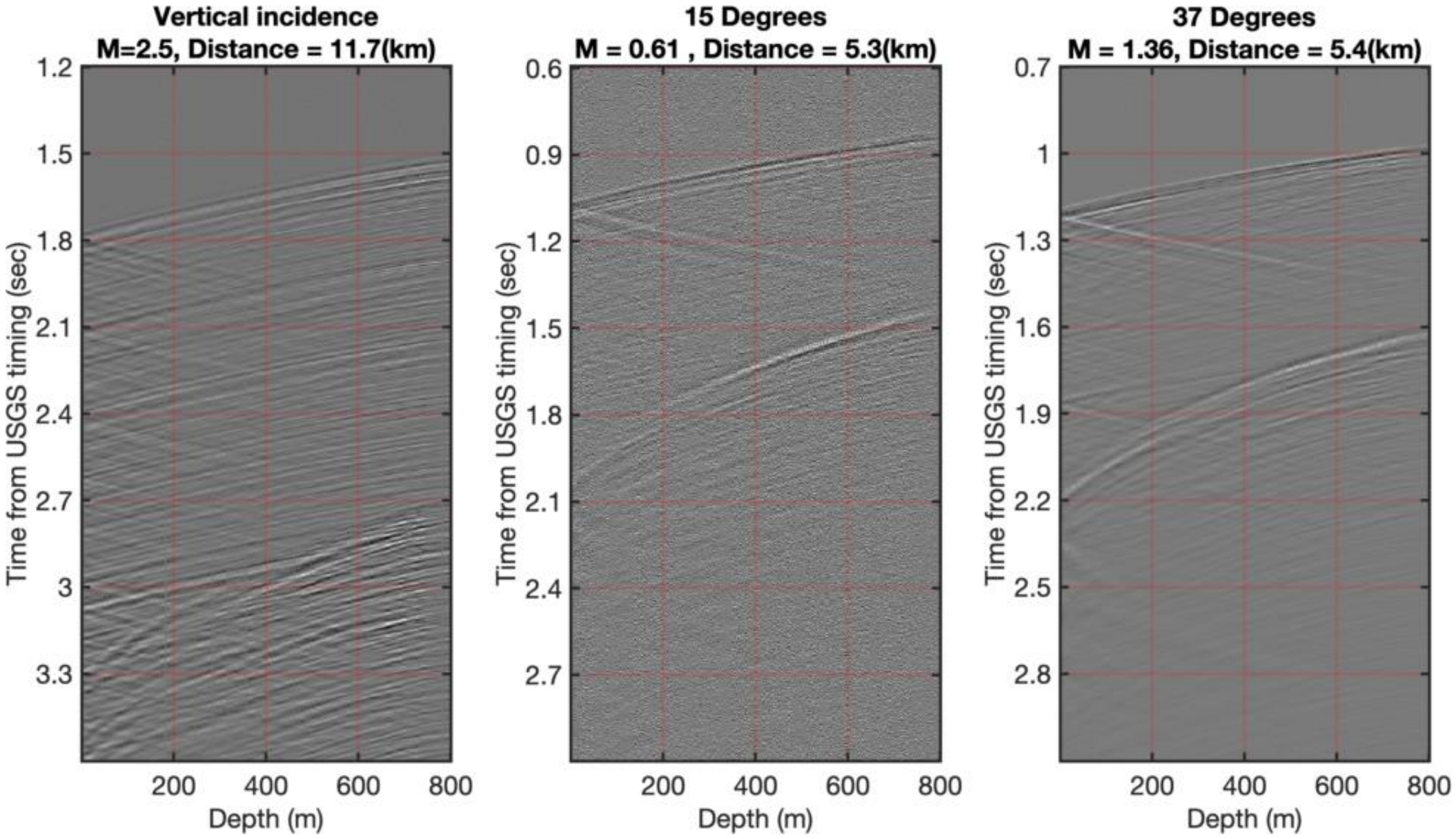
Richard et al, 2013



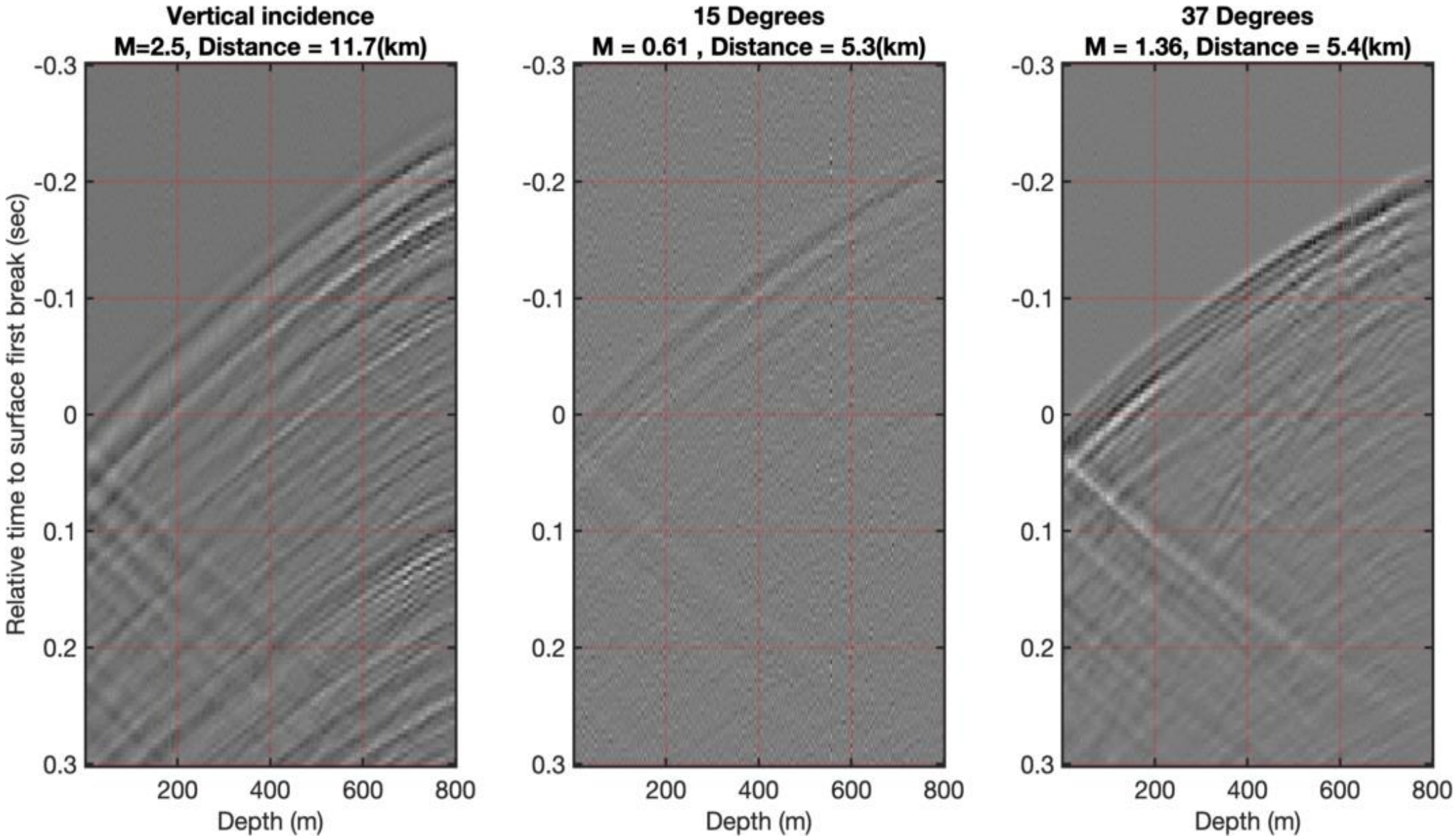


About 20 days of recording, June-July 2017

Three local quakes recorded by SAFOD DAS

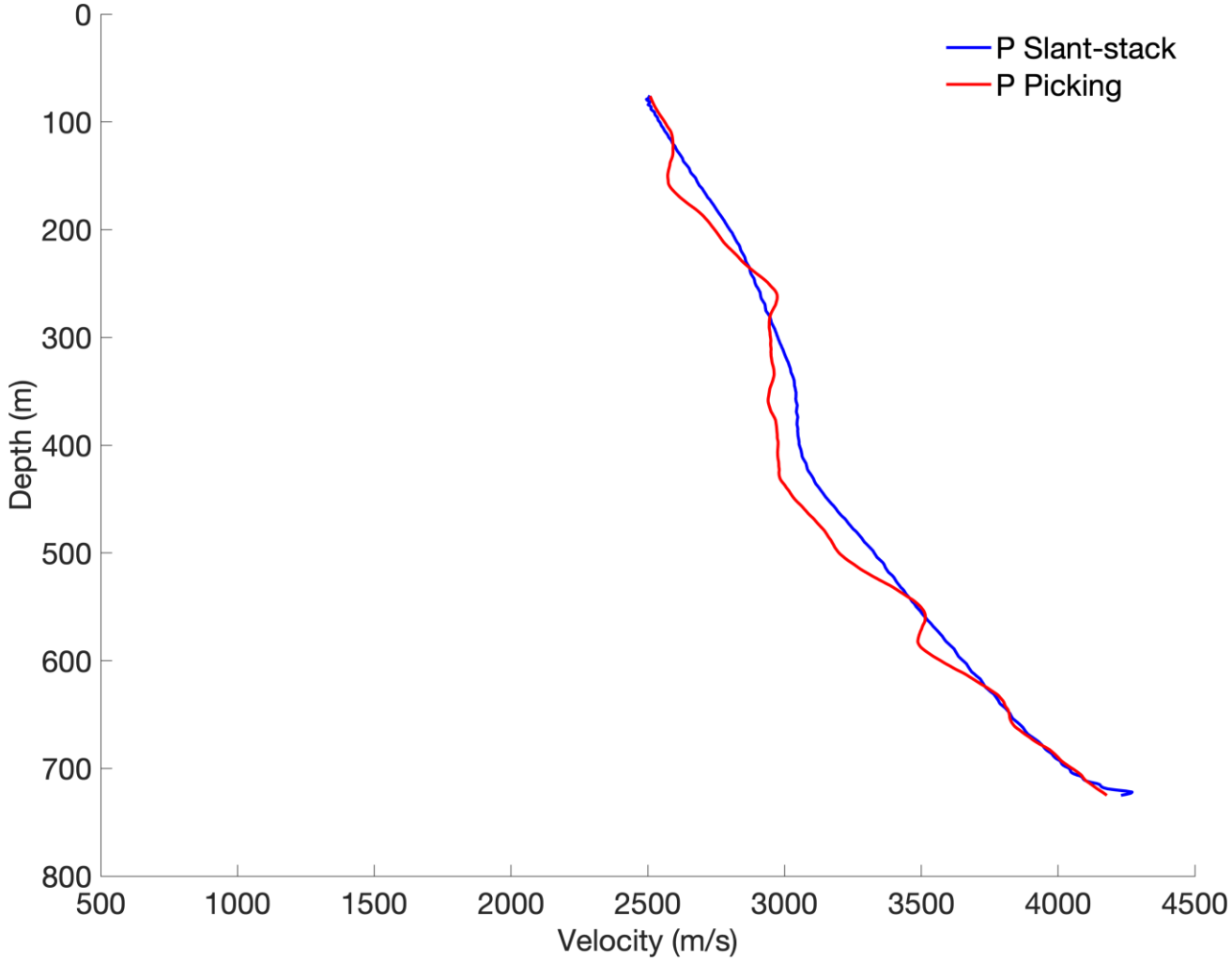


P arrivals from same three local quakes



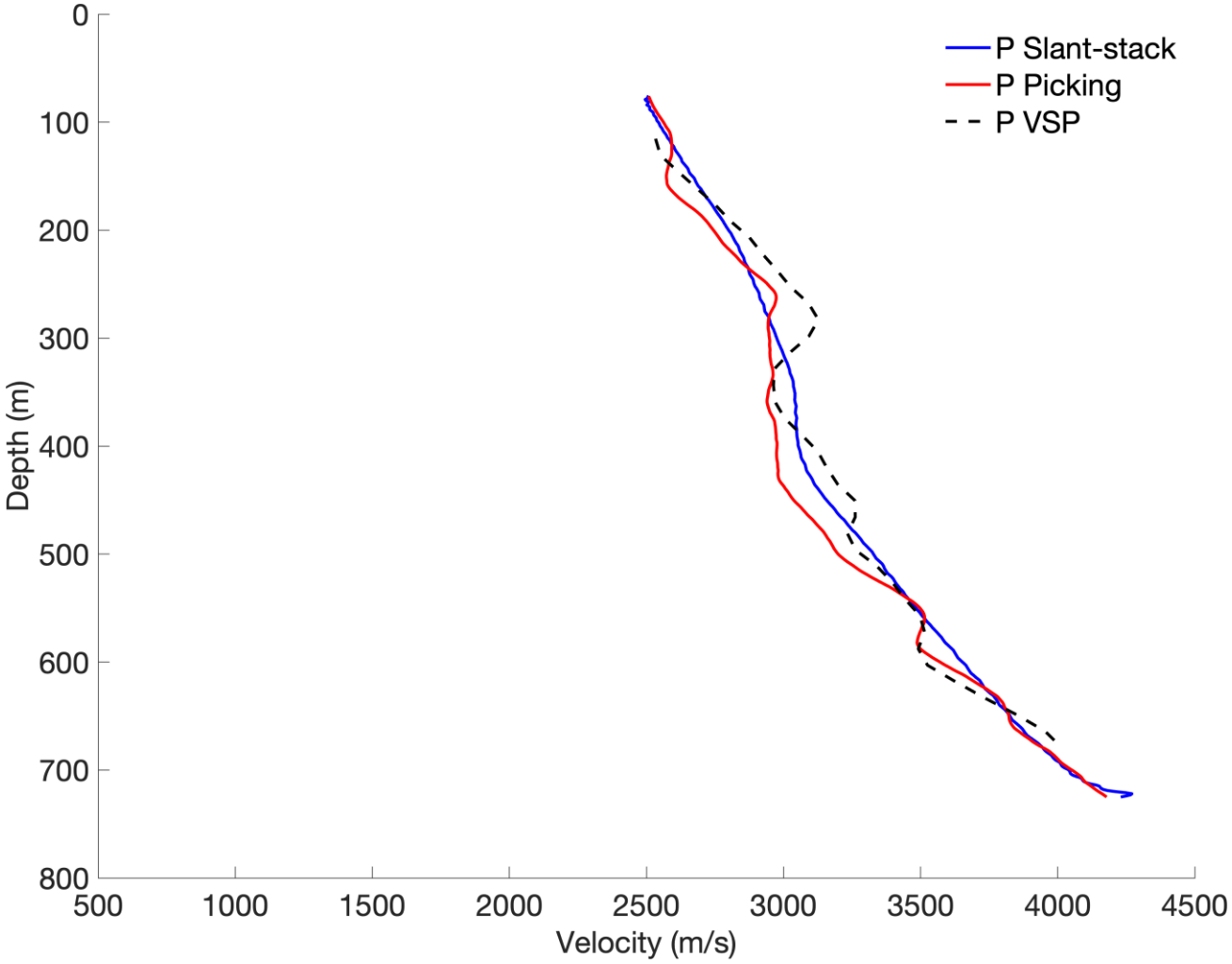
Estimated P velocities from DAS

- Good agreement between picking and slant-stacks



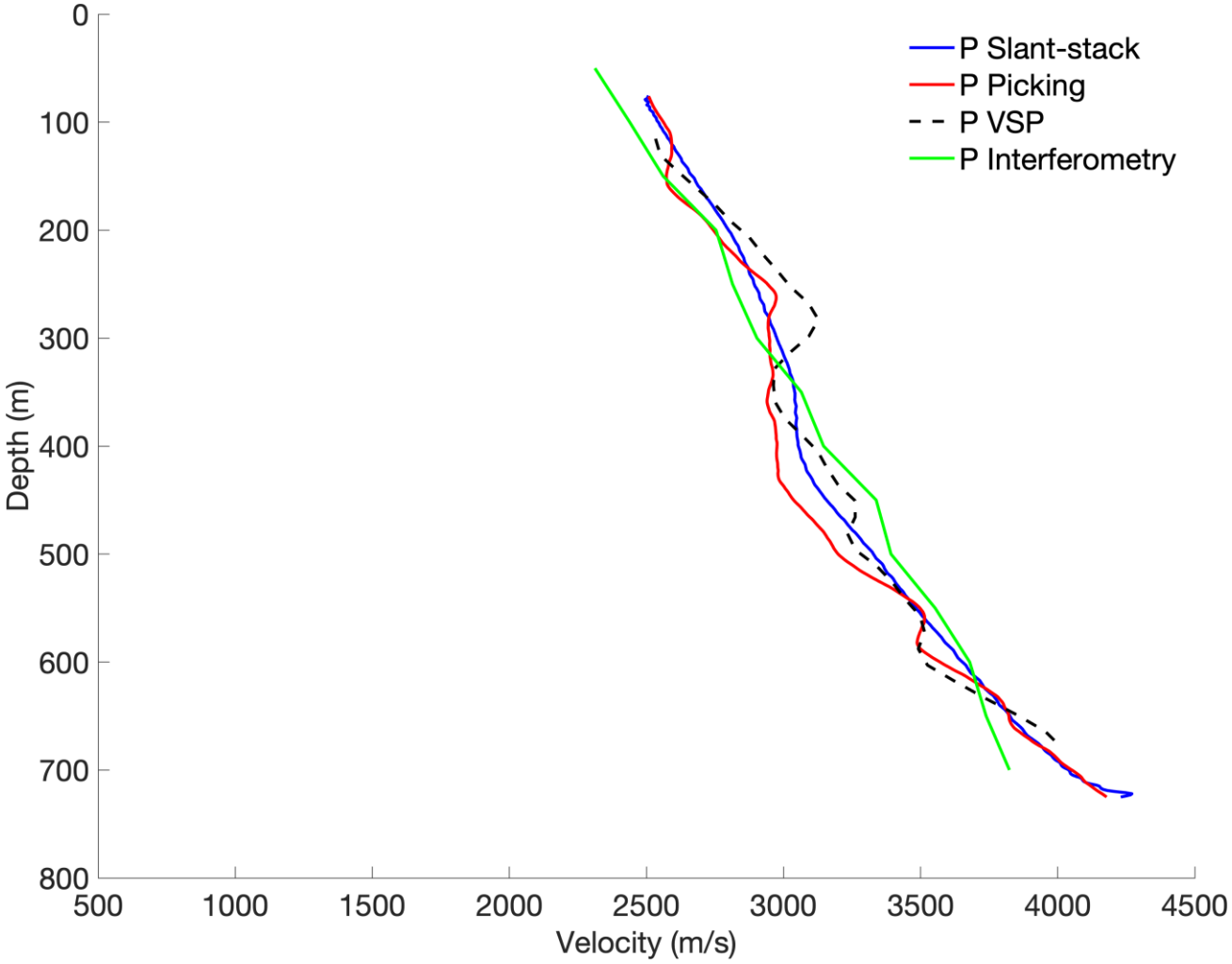
Estimated P velocities from DAS & VSP

- Good agreement between picking and slant-stacks
- Matches check-shot processing
- Geological structure



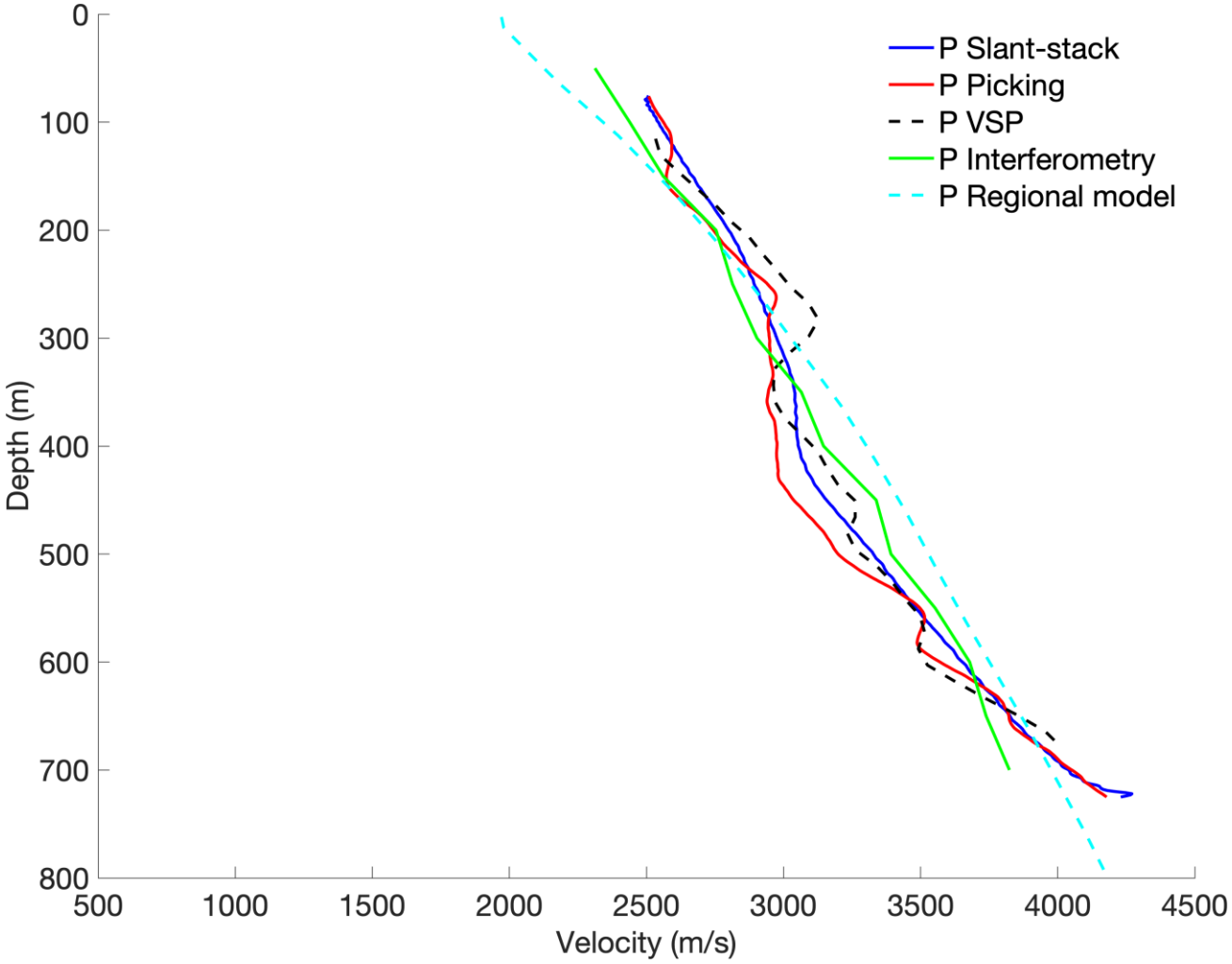
Estimated P velocities from DAS, VSP & Interferometry

- Good agreement between picking and slant-stacks
- Matches check-shot processing
- Geological structure



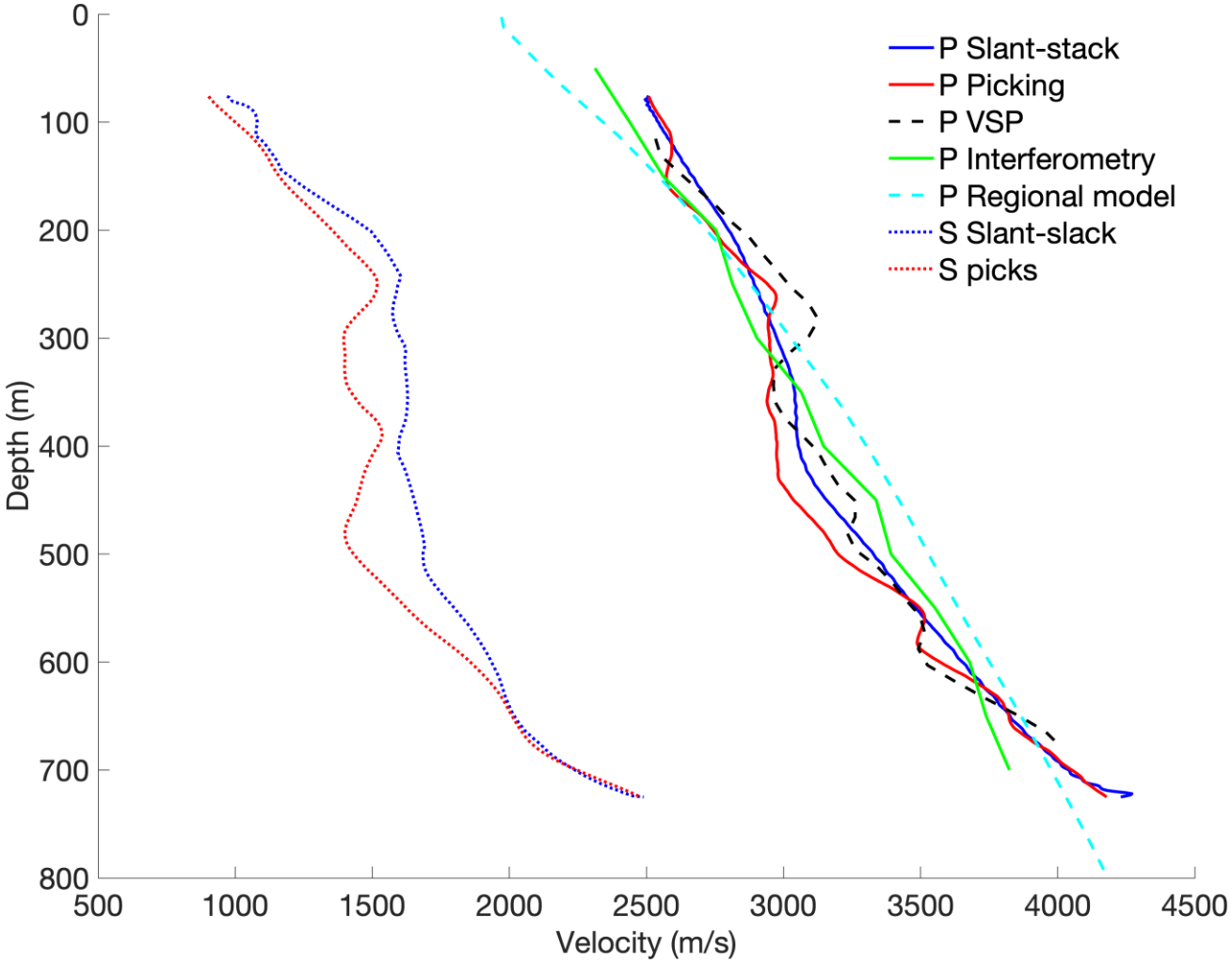
Estimated P velocities from DAS, VSP, Interferometry & surface seismic

- Good agreement between picking and slant-stacks
- Matches check-shot processing
- Geological structure



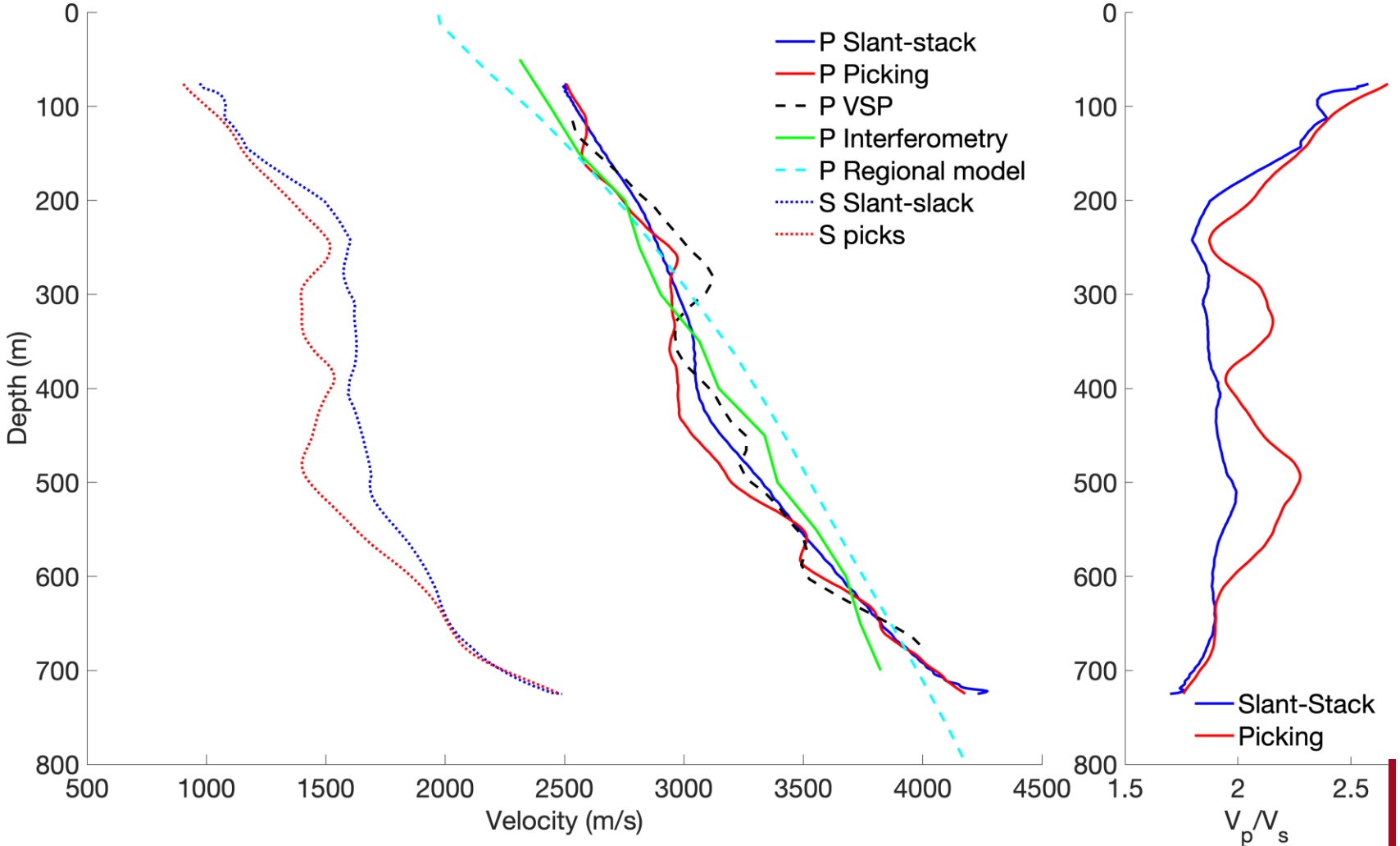
Estimated S velocities from DAS

- Good agreement between picking and slant-stacks
- Matches check-shot processing
- Geological structure
- S follows same structure

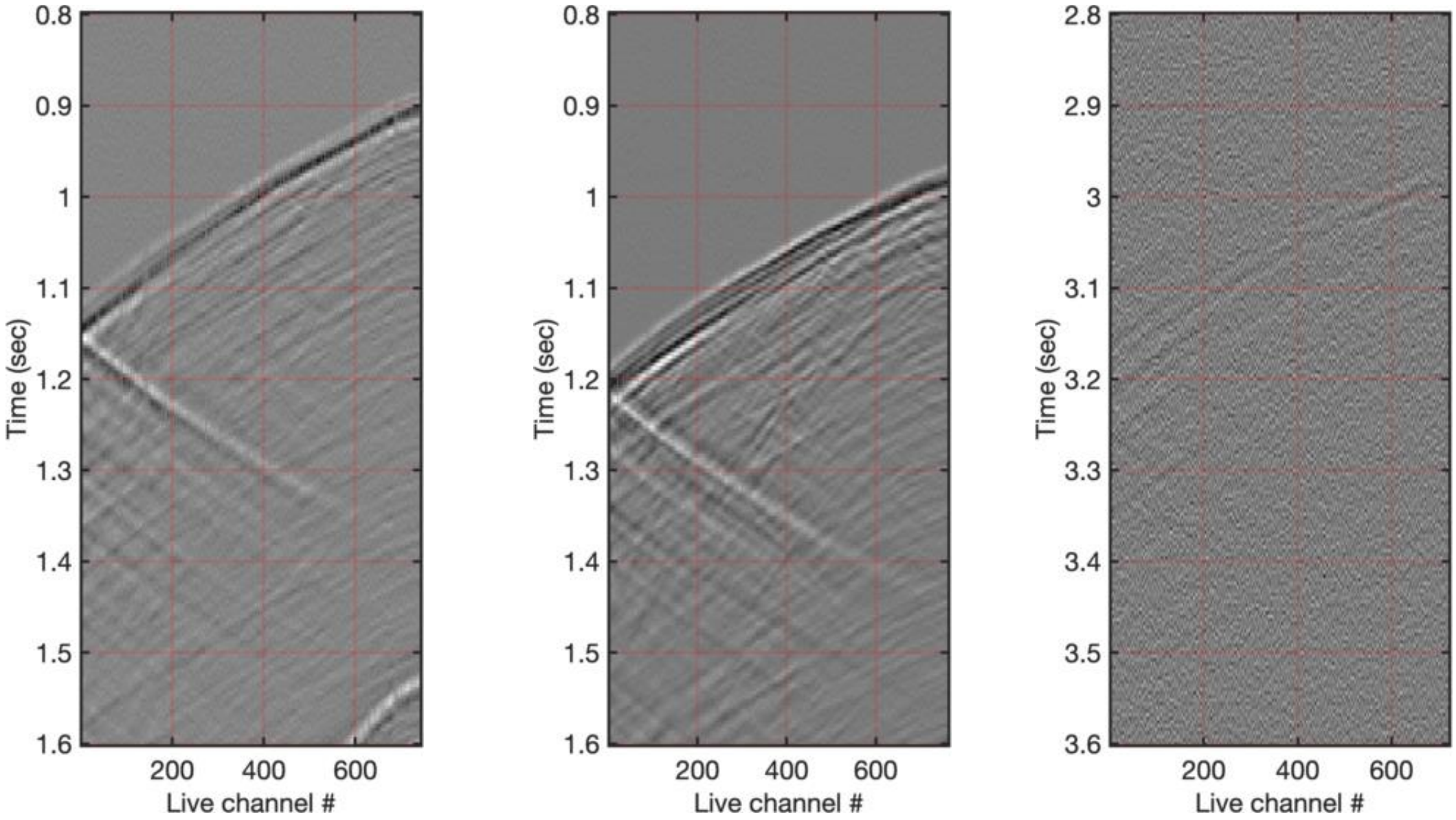


Estimated P/S velocity ratio from DAS

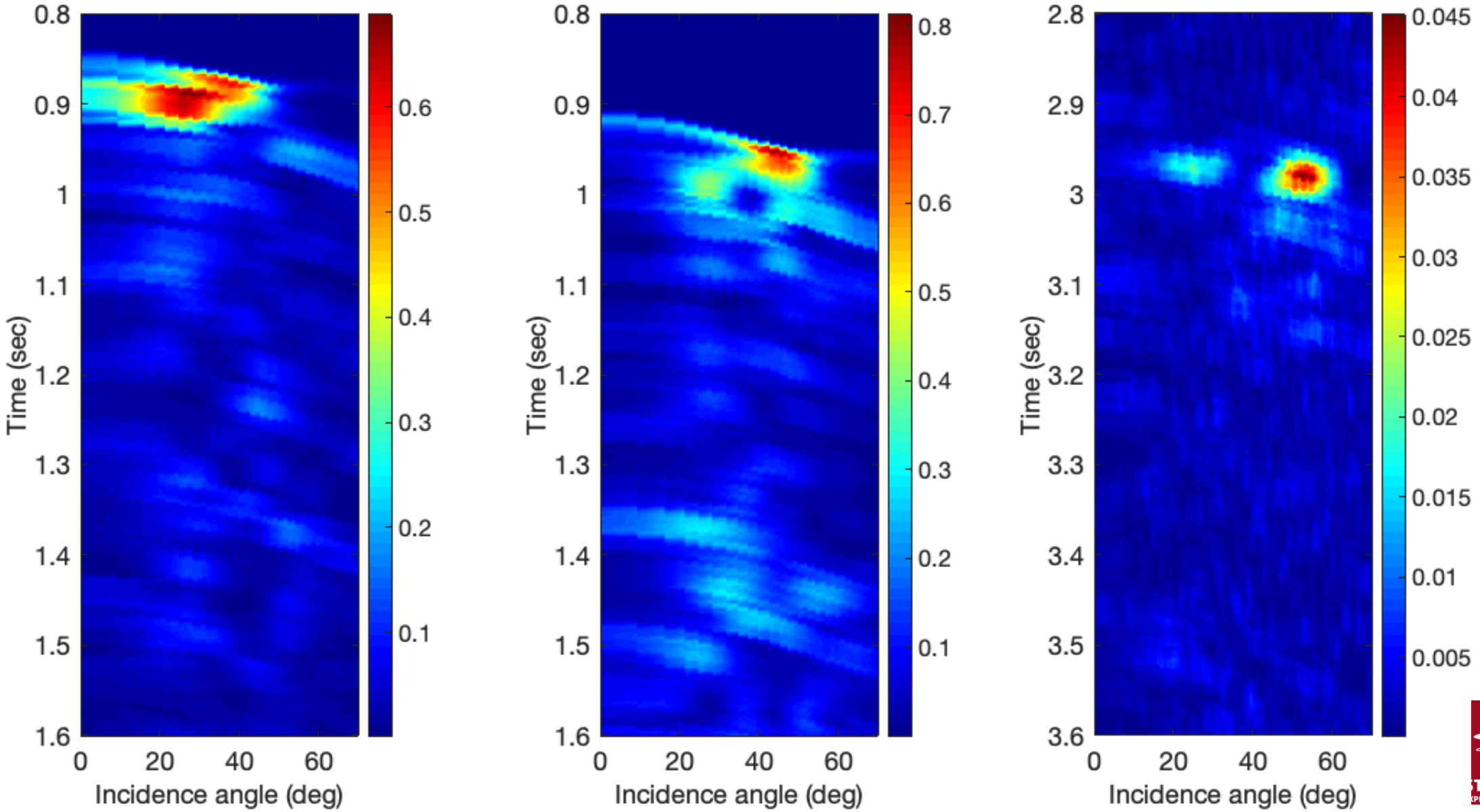
- Good agreement between picking and slant-stacks
- Matches check-shot processing
- Geological structure
- S follows same structure
- "Normal" V_P/V_S



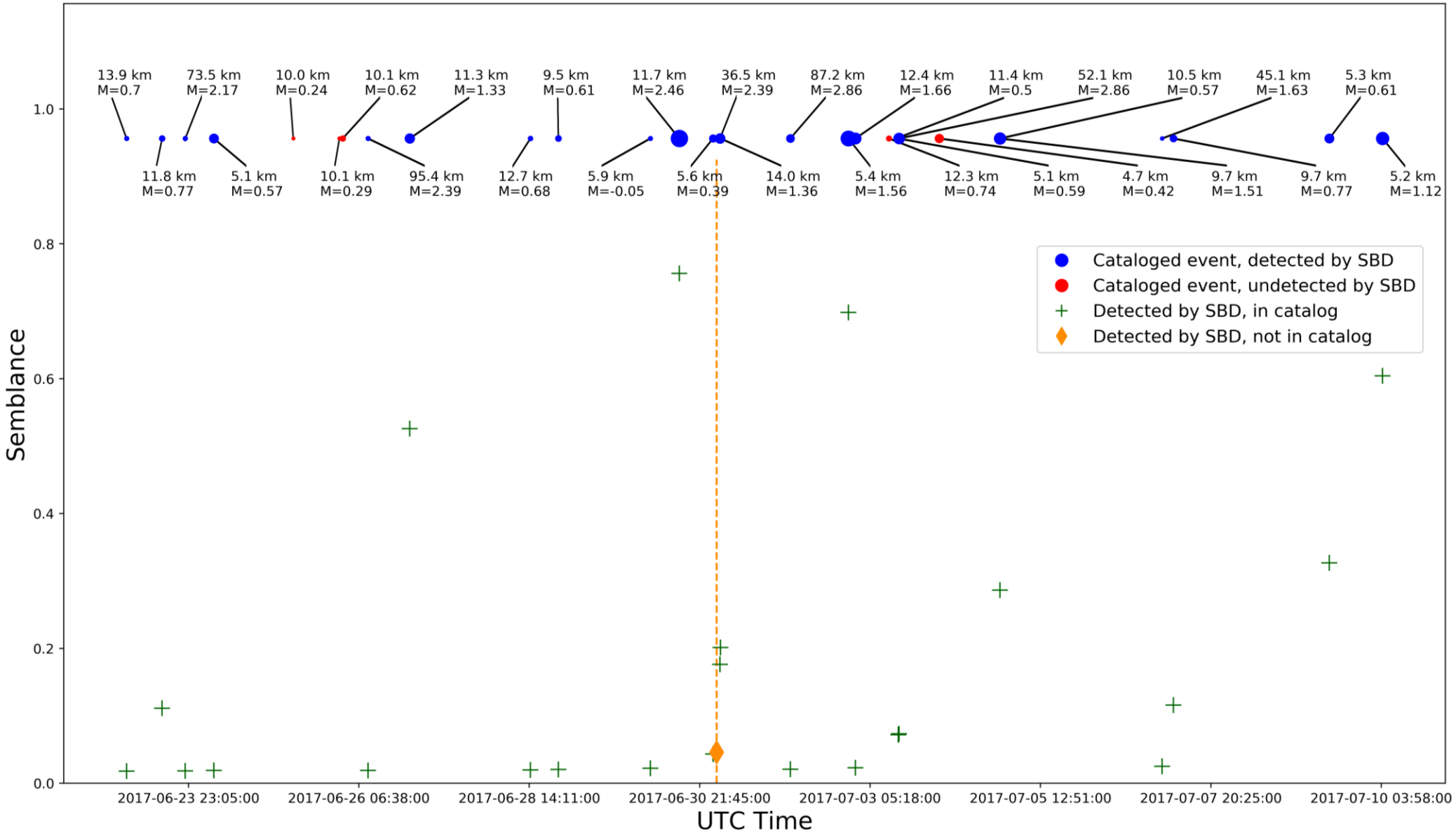
Incidence-angle estimation: input data

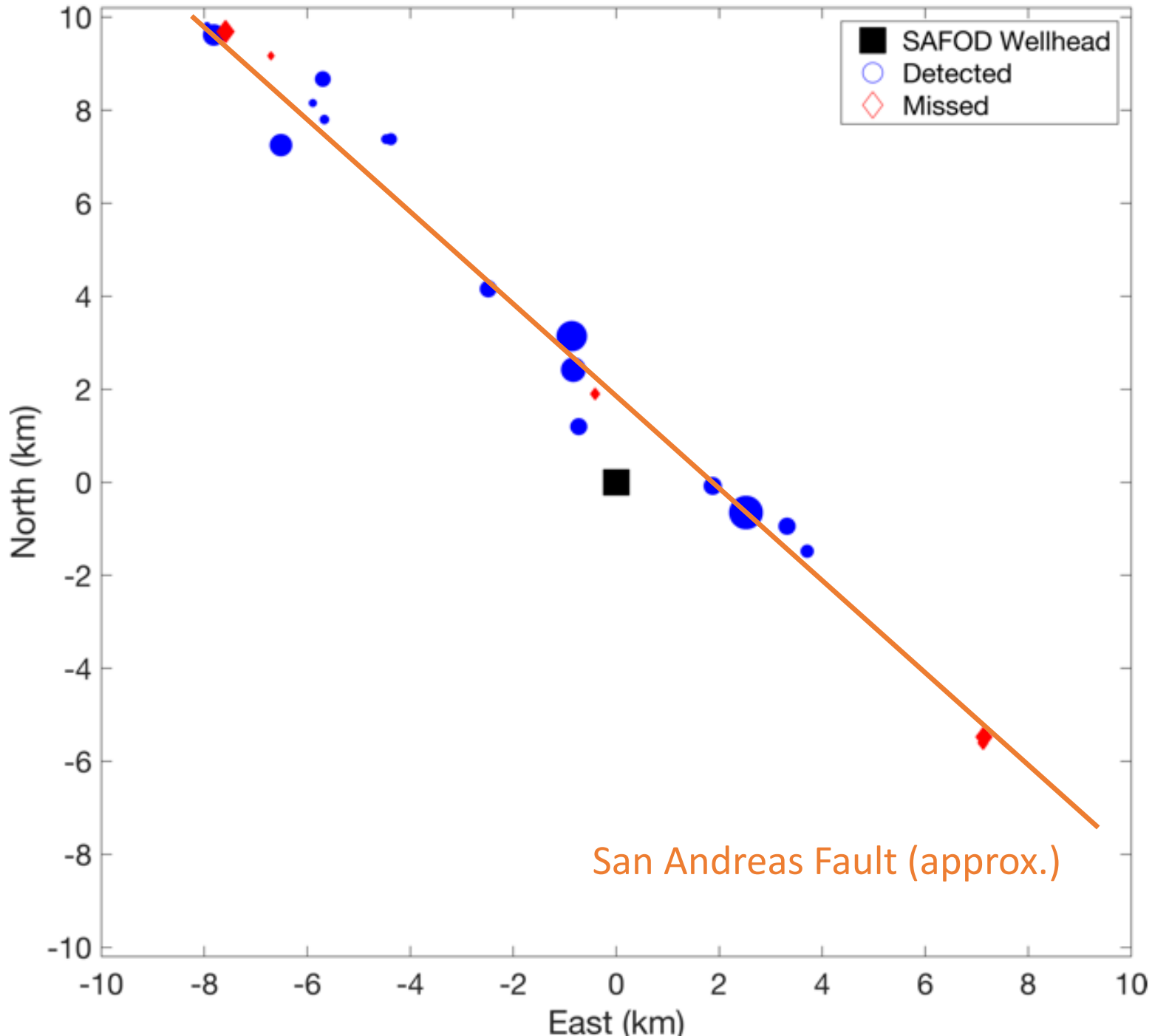


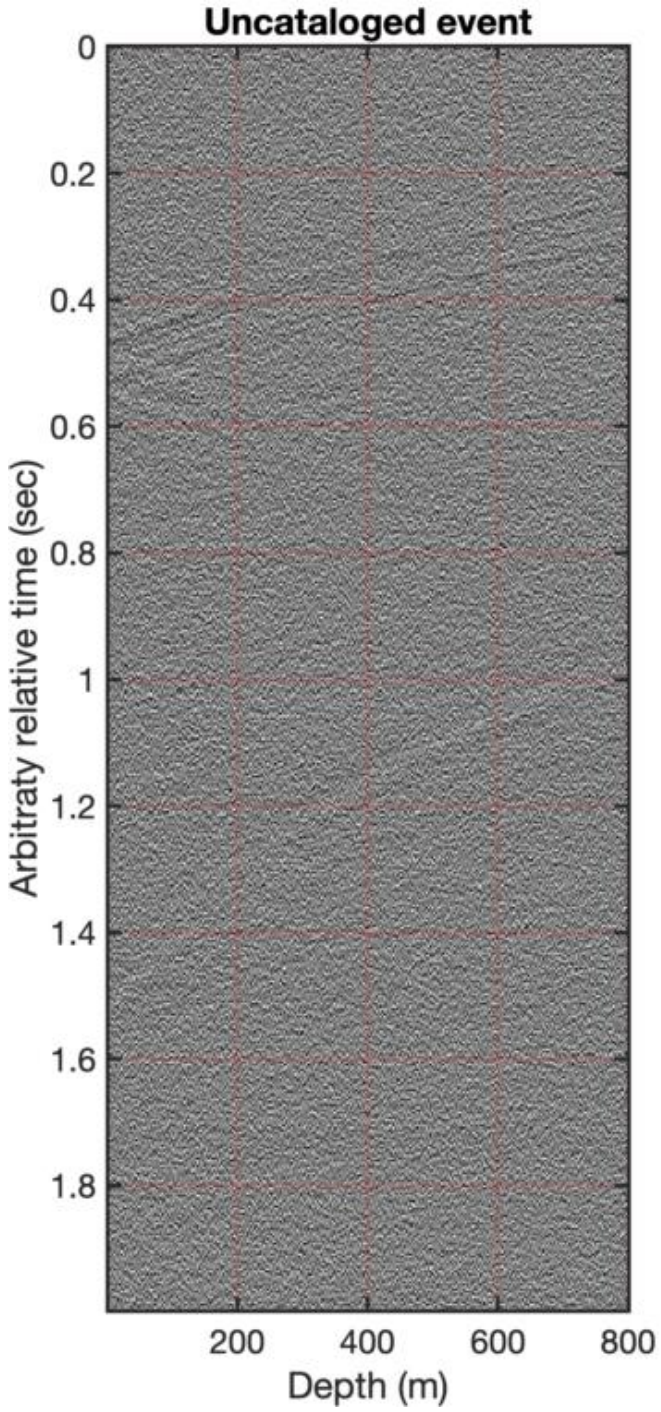
Incidence-angle estimation: angle scans



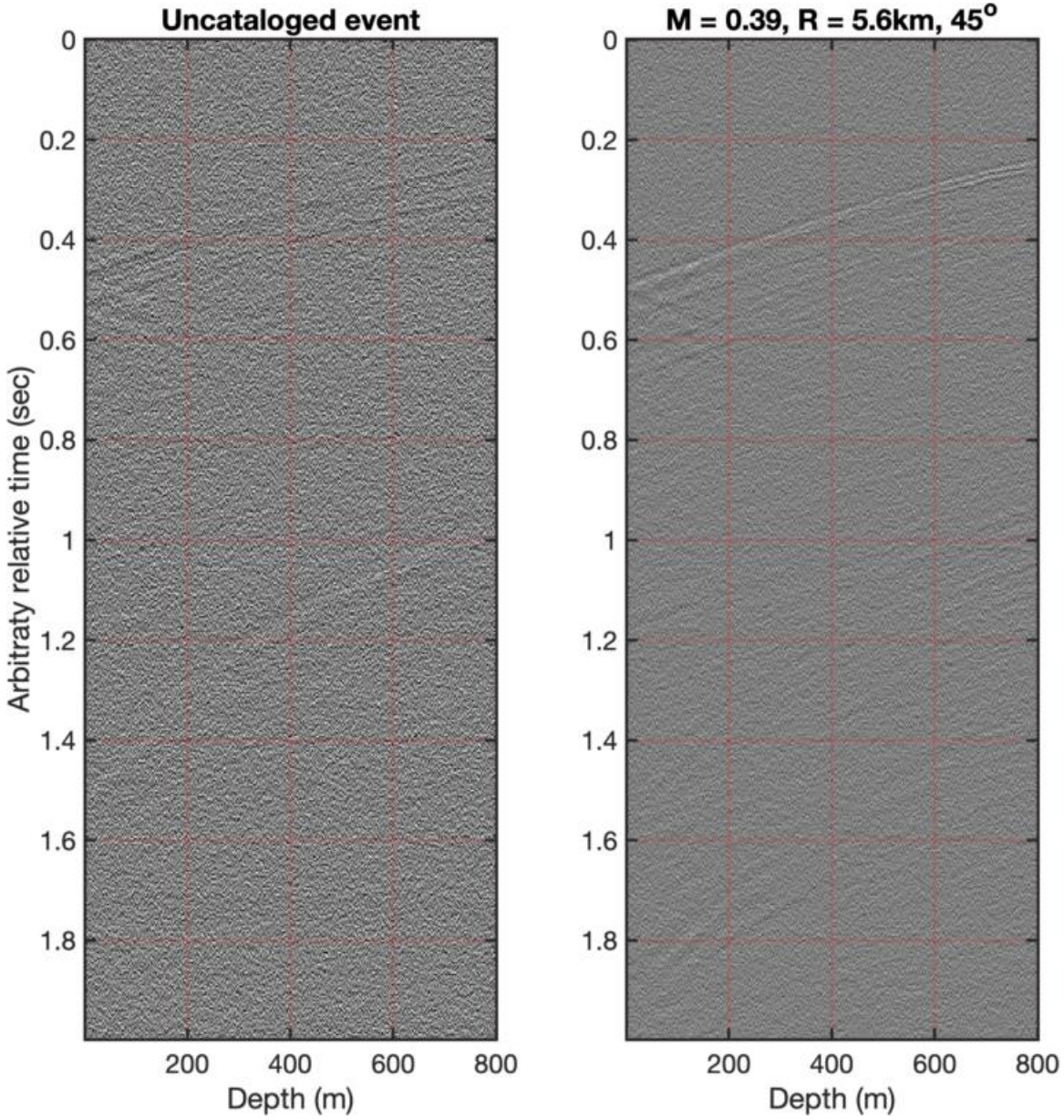
Event-detection results



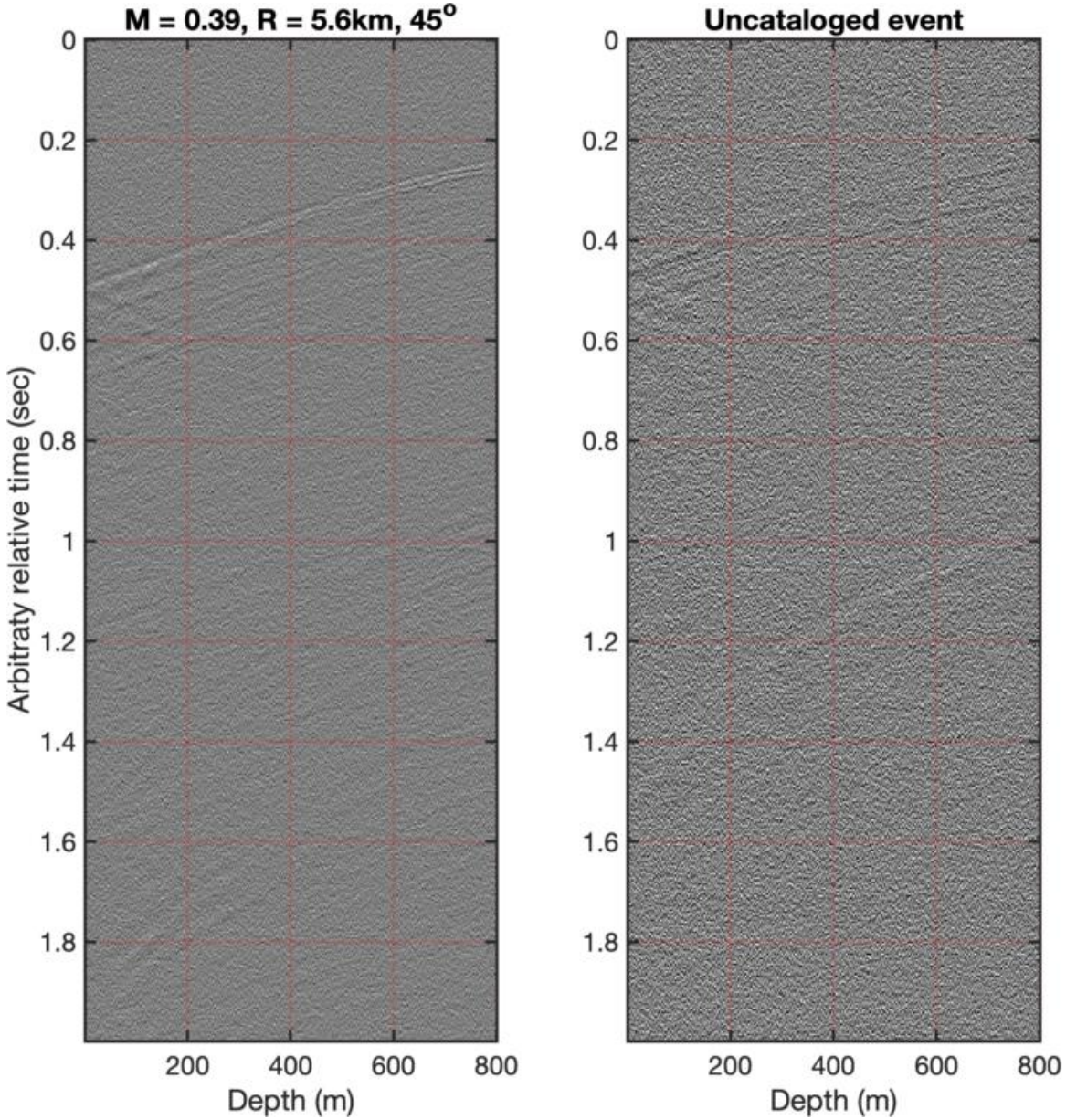

SAFOD Wellhead
Detected
Missed
San Andreas Fault (approx.)
North (km)
East (km)
10
8
6
4
2
0
-2
-4
-6
-8
-10
-10
-8
-6
-4
-2
0
2
4
6
8
10


Uncataloged event
Arbitraty relative time (sec)
Depth (m)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
200
400
600
800

Uncatalogued event similar to a catalogued one



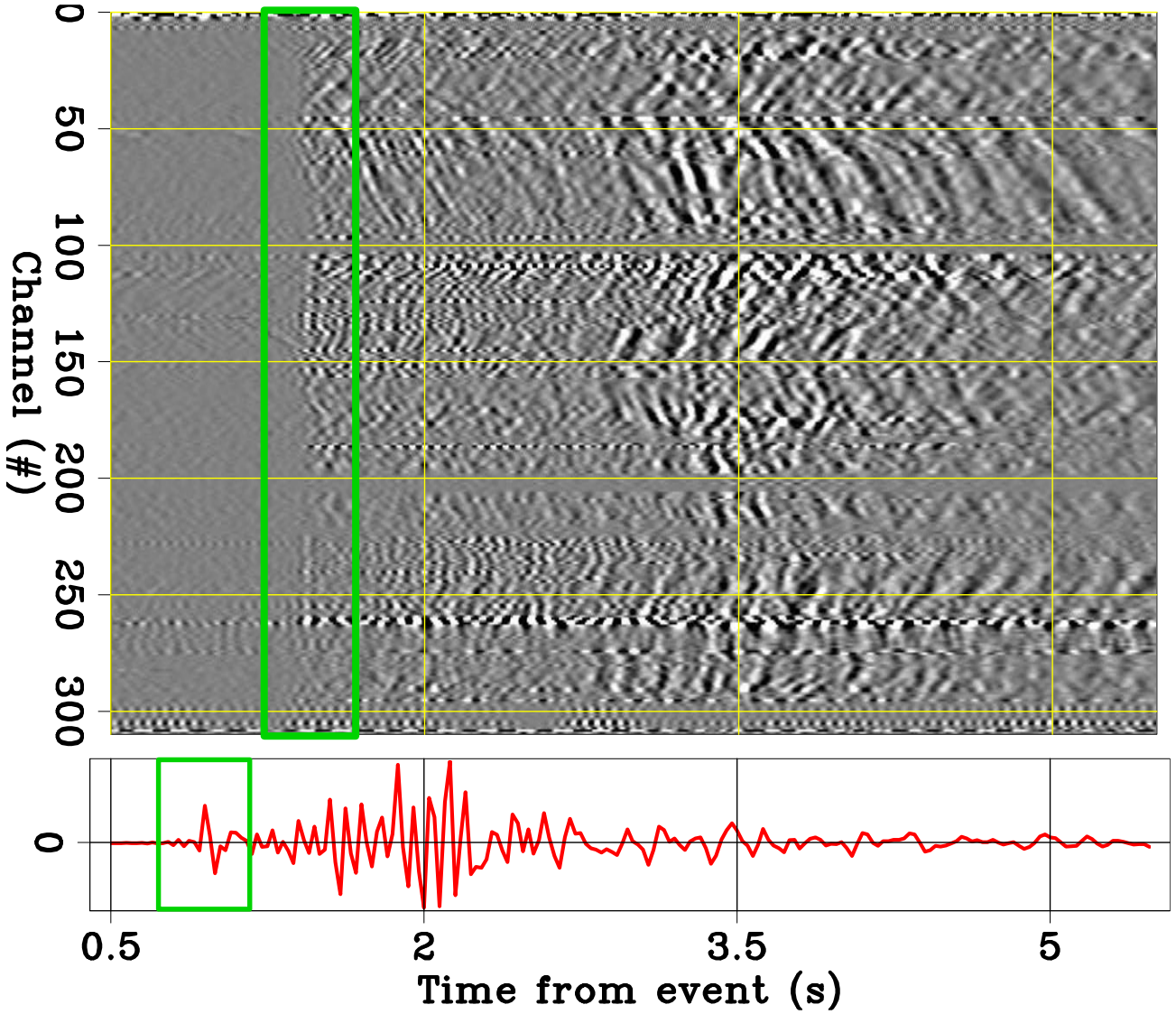
Uncatalogued event similar to a catalogued one



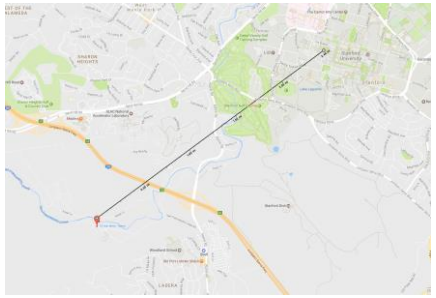
- Low signal-to-noise
- Visible P and S phases
- Short P-S difference => close event (5-7km)
- M< -.5
- Definitely it is an earthquake


0.0 seconds
+4.1424e6
+5.726e5
West UTM (m)
East UTM (m)
0
100
200
300
400
500
600
700
Campus Dr
Panama St
Via Ortega
Via Palou Mall
Via Pueblo Mall
Serra Mall
N Service Rd
N South Axis
Roth Way
Searsville Rd
S Service Rd
Governors Ave
Santa Teresa St
Samuel Morris Way
Lomita Mall
Escondido Mall
Welch Rd
Oak Rd
Stock Farm Rd
Los Arboles Ave
Palm Dr
The Oval

P-waves arrivals – DAS vs. Broadband Z-comp



Ladera EQ M 1.8



DAS data

vs.

Broadband Z-comp

Distance 3.8 km
Depth 3.6 km
7:50 pm

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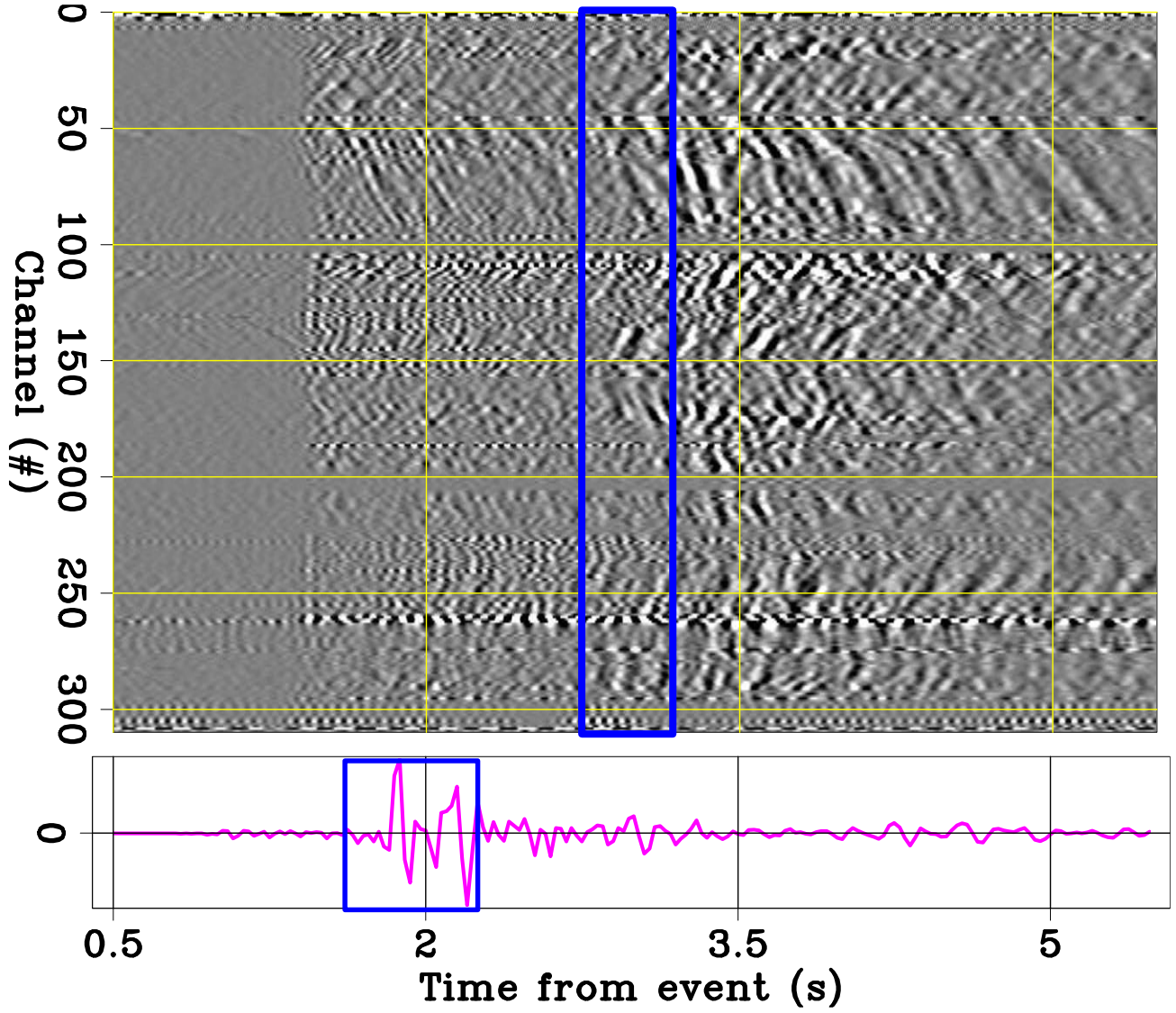
P-waves arrivals – DAS vs. Broadband N-comp



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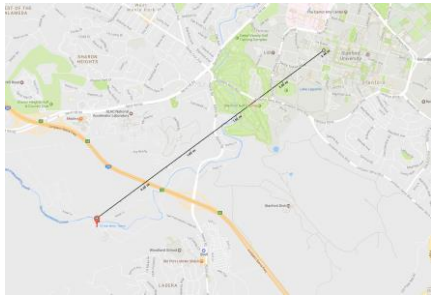


DAS data

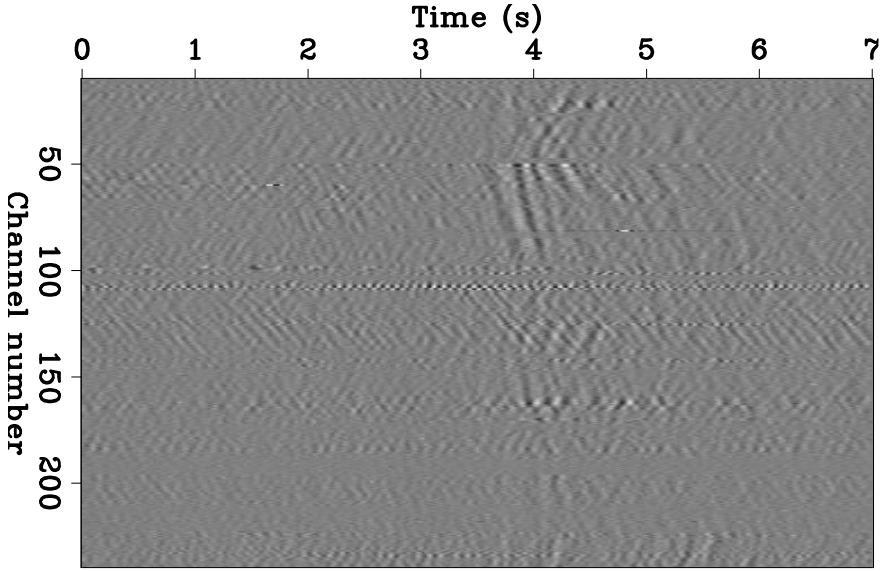
vs.

Broadband N-comp

Distance 3.8 km
Depth 3.6 km
7:50 pm

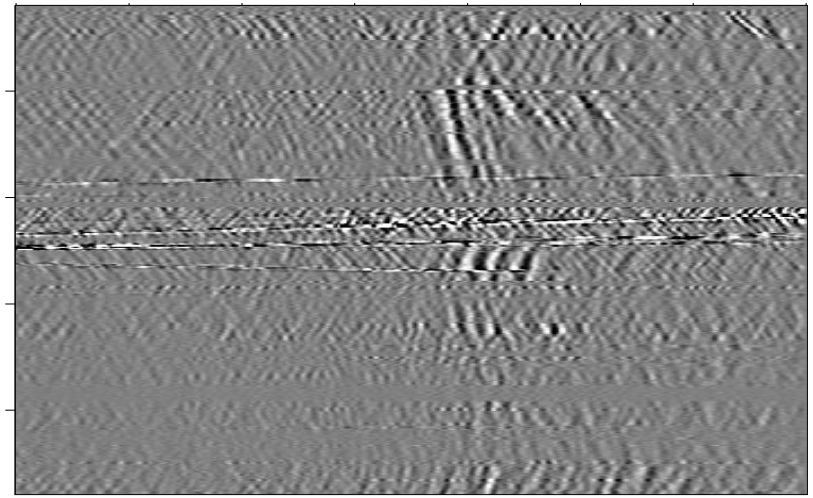
Detection of weak EQs not detected by conventional seismometers networks

Detected precursor



Mag ≈ 0.1
May 10th, 2017

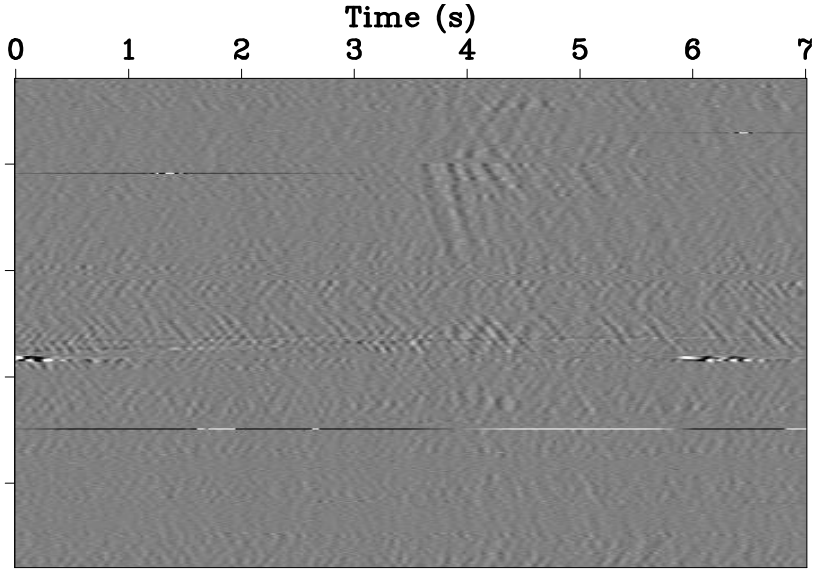
Main E.Q.
in USGS catalogue



Mag 1.35
July 12th, 2017

Distance 4.0 km
Depth 3.2 km

Detected aftershock



Mag ≈ -0.1
July 13th, 2017

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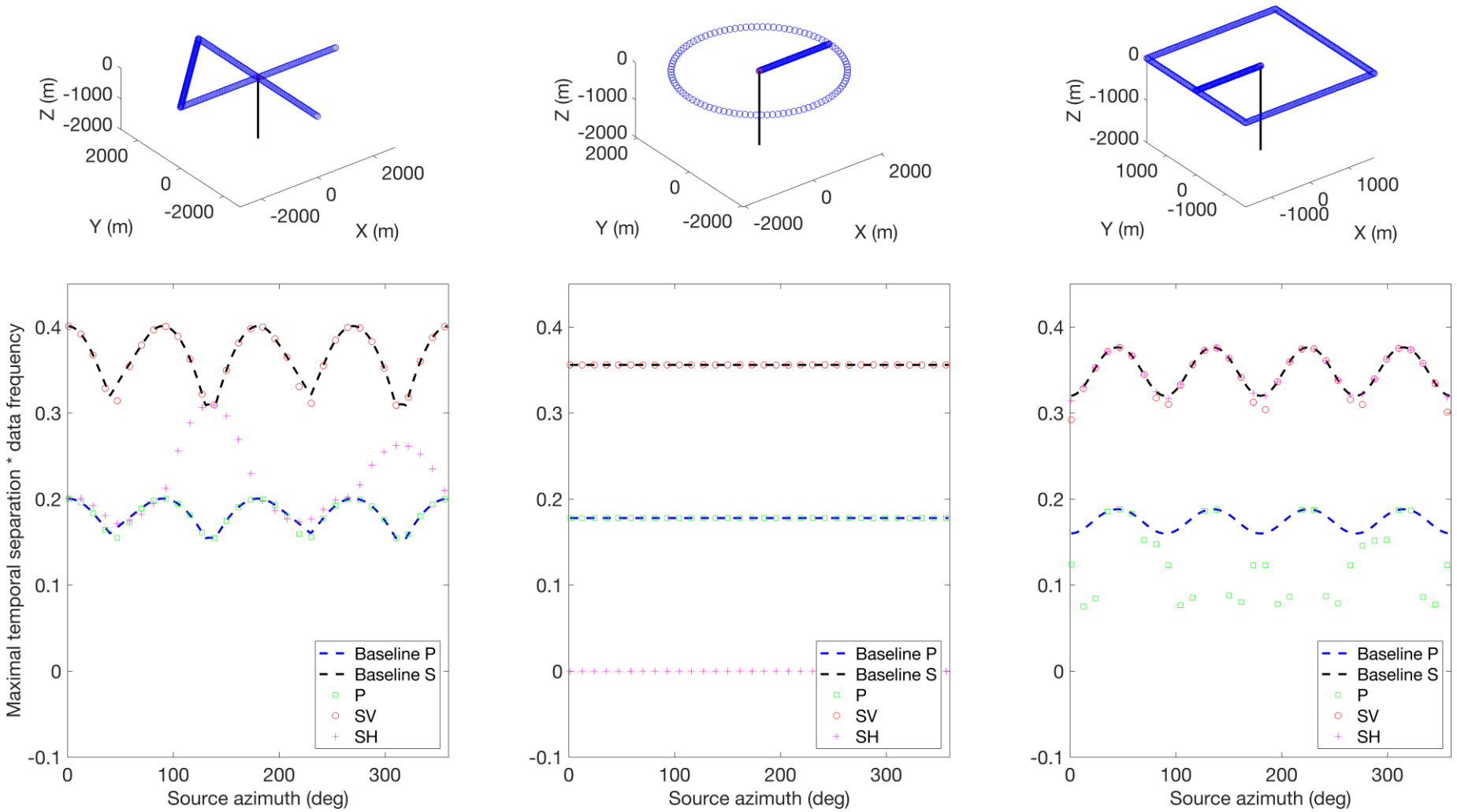
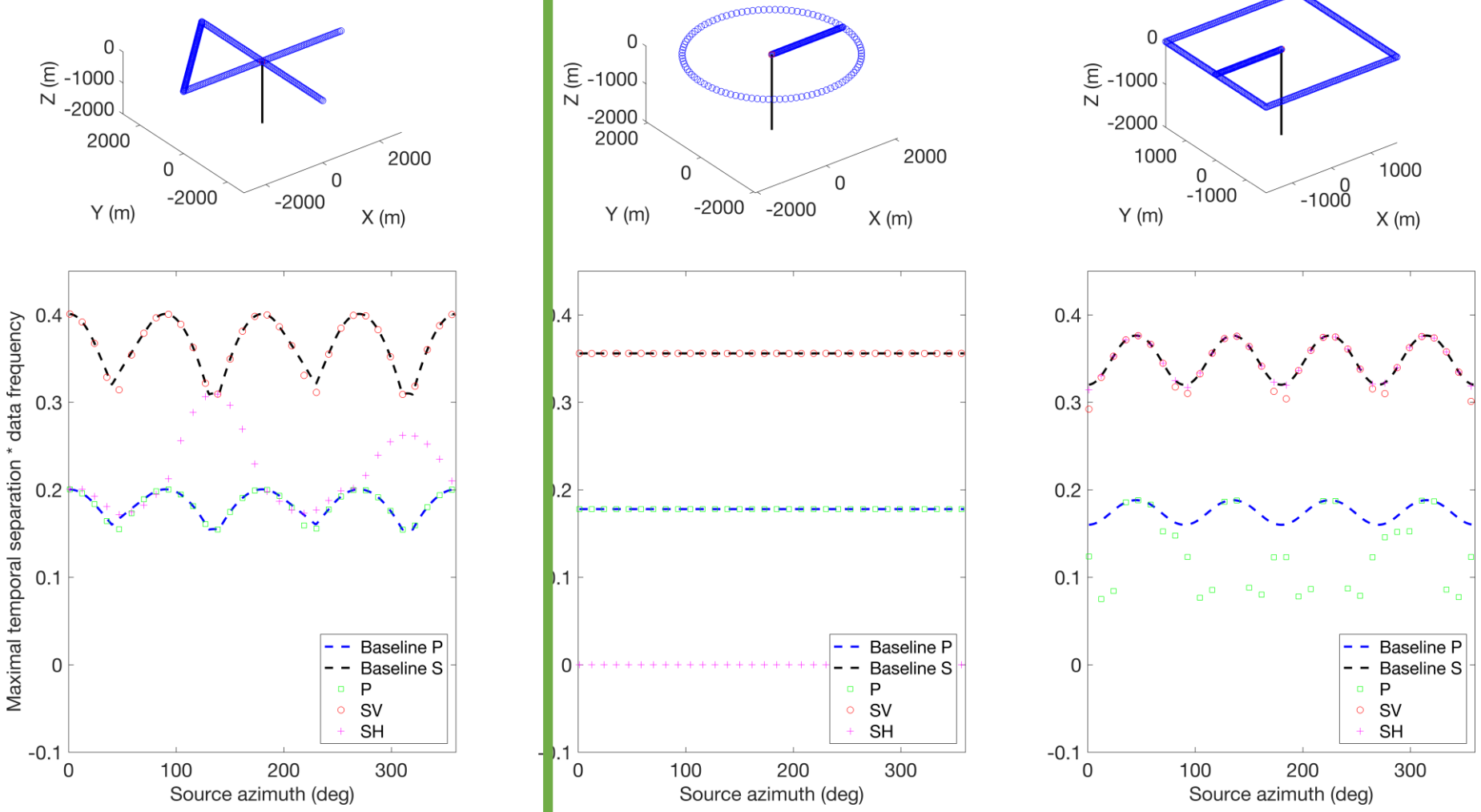
Modeling azimuthal resolution of DAS Nodes



- Fiber length: 17 km
- Event depth: 2 km
- Event distance from well: 0.5 km
- Arc length resolution: 10 m (source depth and distance from well assumed known)
- Data frequency: 50 Hz
- DAS sensitivity threshold (receivers below that value are discarded): 40%

Modeling azimuthal resolution of DAS Nodes



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Current Developments of DAS technology

- New generation of interrogator improve sensitivity by 10-20 db
- Shorter gauge length
- Engineered cables for:
  - Improved sensitivity
  - "Omnidirectional" sensitivity
  - "Discrete" or "distributed" multi-component sensors
- Wireline systems have been successfully tested in unconventional deviated wells; they provide flexibility for temporary and/or unplanned deployments.

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Conclusions

- DAS Nodes can be cost-effective for long-term continuous monitoring of:
  - CO2 plumes by active seismic imaging (4D VSP + surface-to-surface)
  - Induced seismic events (detection, localization and magnitude estimation)
- As CO2 plume grows, DAS Nodes can be added as needed to make a modular DAS Net.
- Active seismic monitoring by DAS in vertical boreholes is becoming a standard, but passive monitoring of CO2 injection by a DAS Node has not been tested yet. Any interest in a pilot project?

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Acknowledgments

- OptaSense for providing DAS interrogator for both SAFOD and Stanford Array experiments.
- Affiliate members of the Stanford Exploration Project (SEP) for financial support.
- Affiliate members of the Stanford Center for Induced and Triggered Seismicity (SCITS) for financial support.