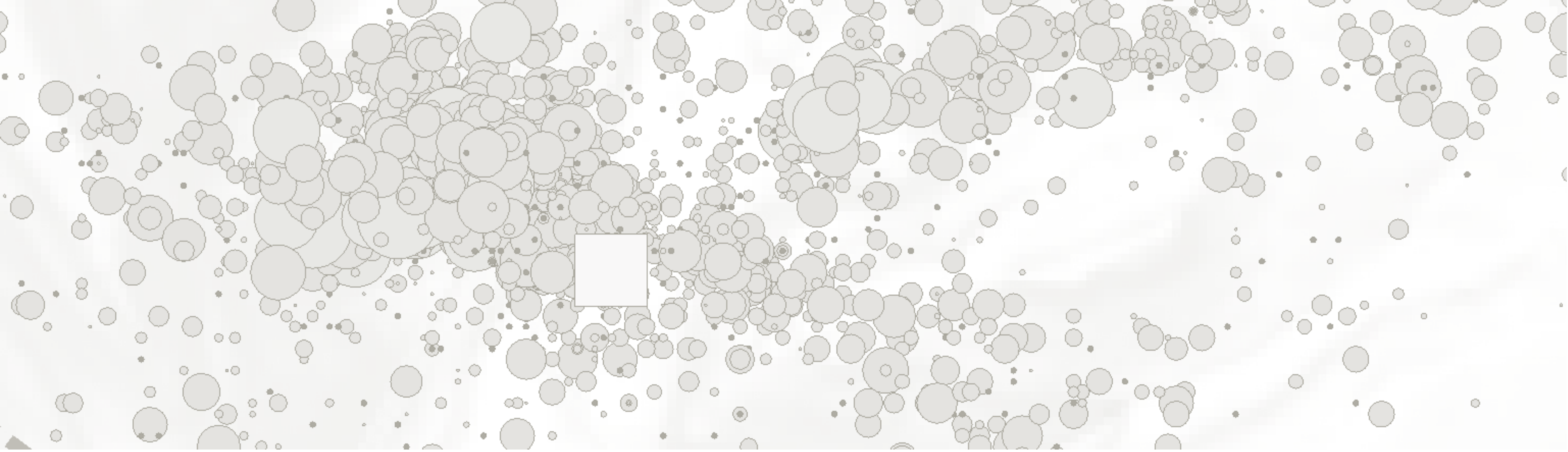

Microseismic Toolset for Fault Detection and Seismicity Mitigation

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LLNL-PRES-

Lawrence Livermore National Laboratory

Program Goal No. 4

- Develop Best Practice Manuals for monitoring, verification, accounting, and assessment; site screening, selection and initial characterization; public outreach; well management activities; and risk analysis and simulation.

Benefit Statement

- Induced seismicity hazards are a key concern for carbon storage.
- The goal of this project is to use advanced microseismic processing to better identify and characterize hazardous faults in the subsurface.
- If successful, this toolset can help operators rapidly respond to changing subsurface conditions. Timely identification and response is a key component of effective risk management.

Task Status

	Task	Status
1	Data-set acquisition and preprocessing	Complete
2	Active pressure management study	Complete
3	CCS-analog site studies	Complete
4	Illinois-Decatur site study (USGS data)	Complete
5	Best practices manual	Complete

Staff

Seismology

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- Christina Morency
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Reservoir Eng.

- Joshua White

Three key hurdles to effective seismicity management:

① Faults are pervasive, and we rarely know where they are prior to injection.

- Even after injection, we are often not very good at recognizing hazardous faults.

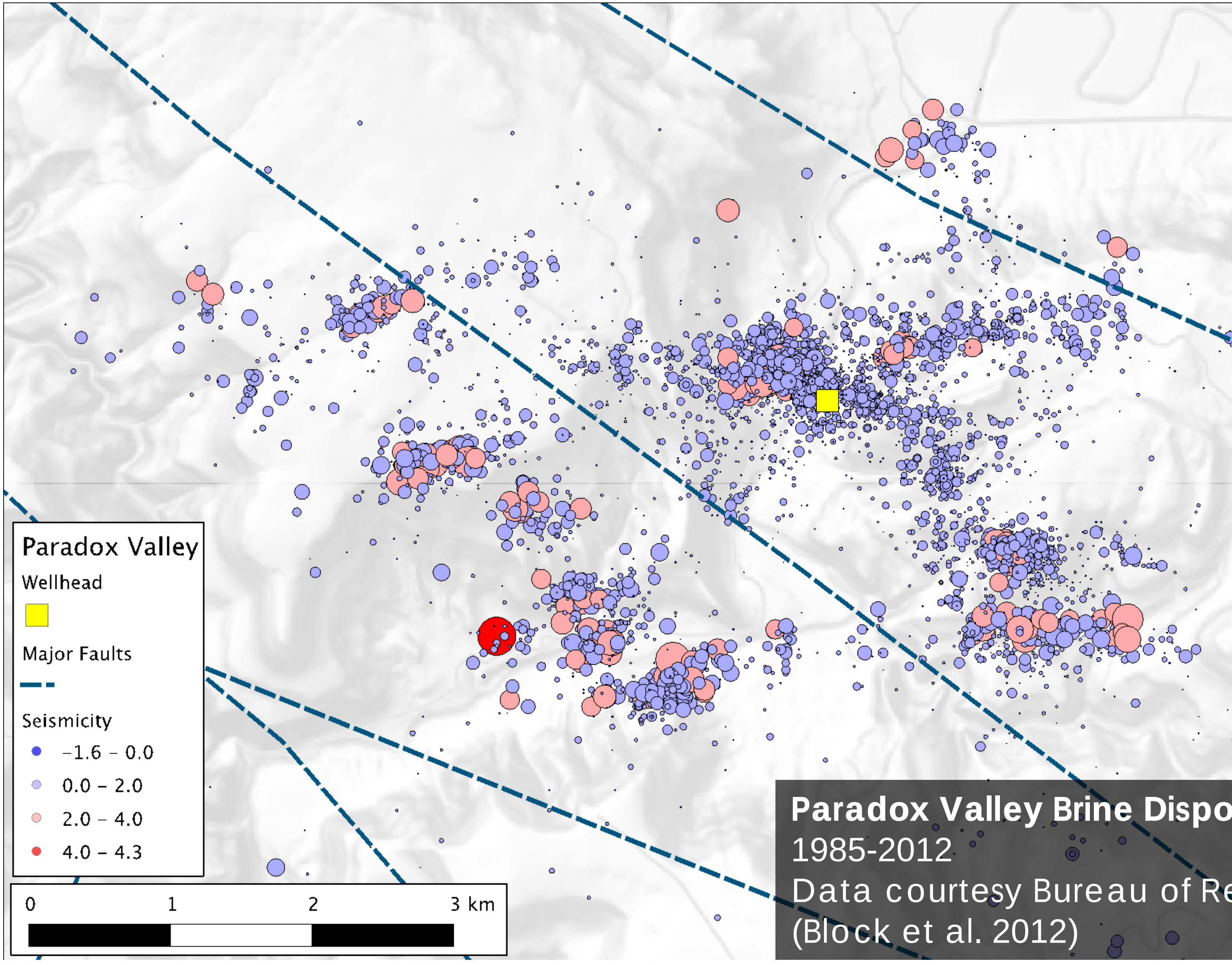
② The relationship between injection rate and seismic activity at a given site is complex.

- And we typically have very little time to figure it out.

③ The knobs we can turn to reduce seismicity are limited.

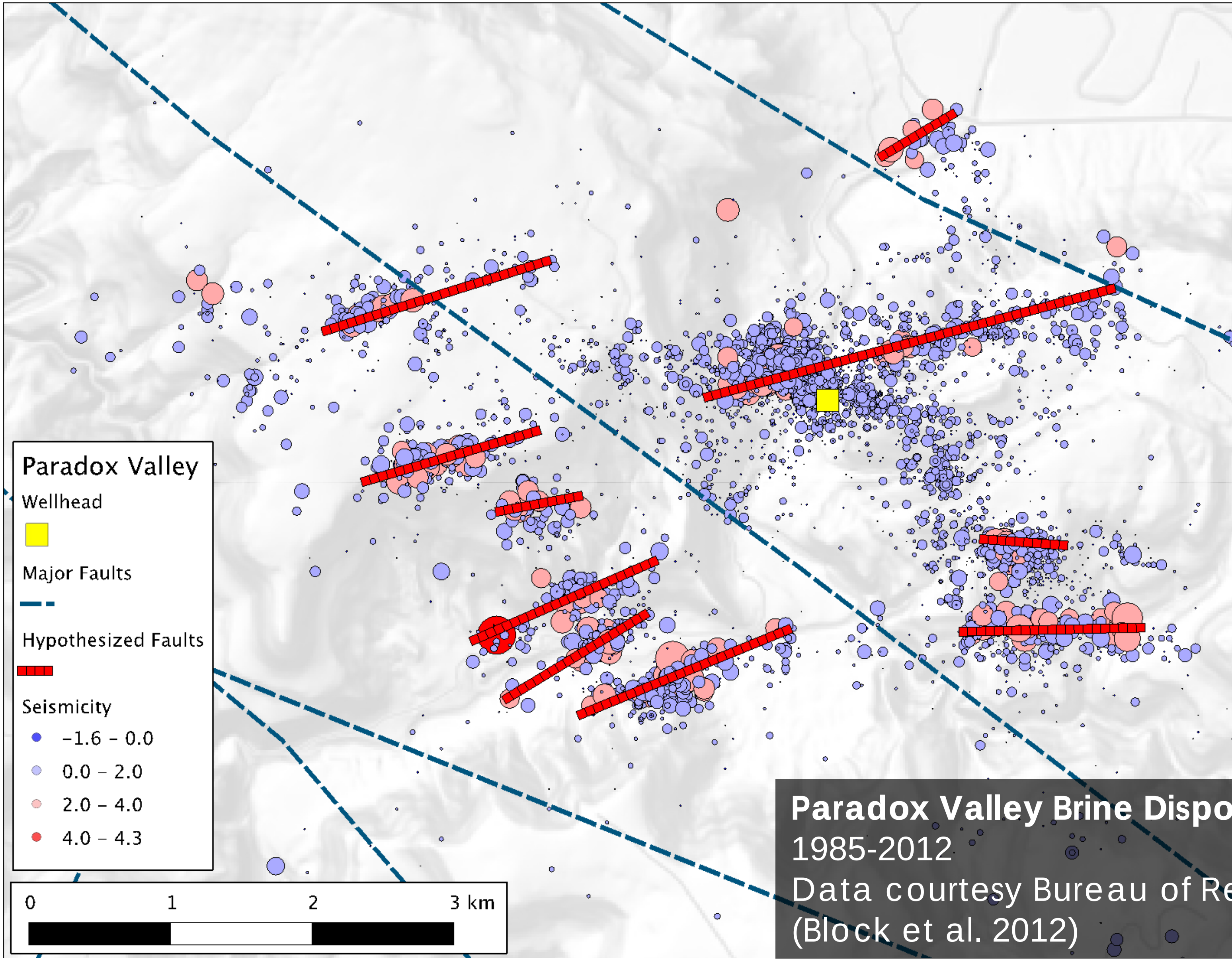
- And these often take significant time to have an effect.

Faster detection of previously unobserved faults can help lower seismic risk



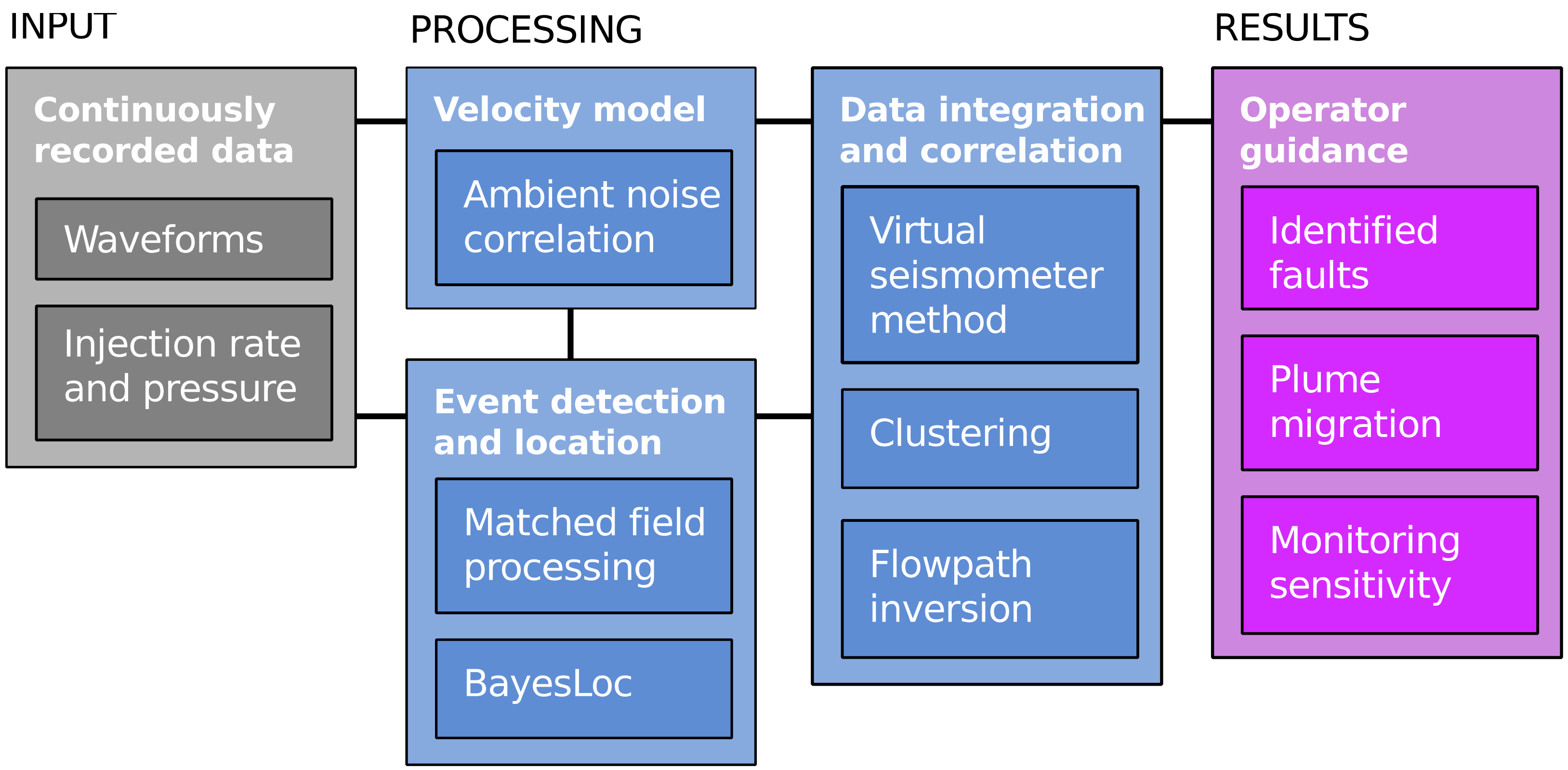
Paradox Valley Brine Disposal Project
1985-2012
Data courtesy Bureau of Reclamation
(Block et al. 2012)

Precise measurements are needed to identify faults hidden within the microseismic cloud



Paradox Valley Brine Disposal Project
1985-2012
Data courtesy Bureau of Reclamation
(Block et al. 2012)

Microseismic processing toolkit



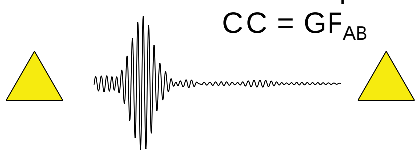
Key goal is to automate as much of this process as possible, to minimize the lag time between data aquisition and decision-making

Ambient Noise Correlation (ANC) has major advantages: precise Green's functions, perfect locations and times

ANC

- Perfect location and timing constraints
- Simple estimate of the GF.
- Slow - lots of continuous data needed (Typically months or longer)
- Frequency content defined by **background field** and instrument sensitivity

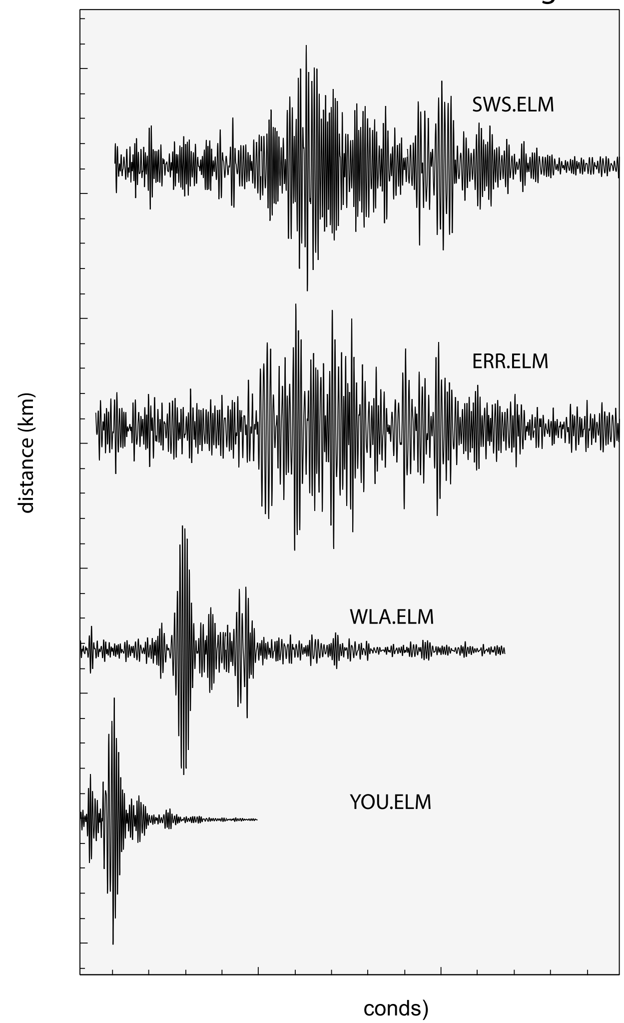
"virtual earthquake"
CC = GF_{AB}



Once the signal emerges from the noise, the GF is very stable.

- Even small variations in the GF are significant
- Allows precise imaging and 4D monitoring

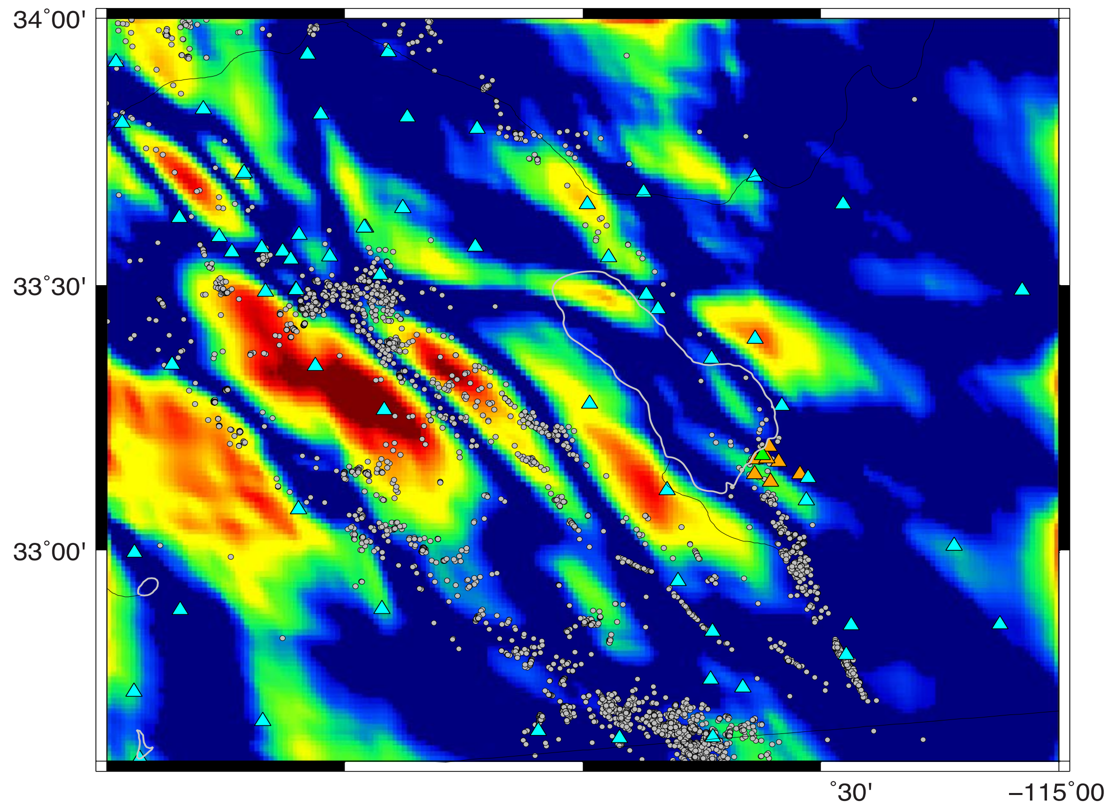
Southern California Virtual Seismograms



ANC allows sharp imagery of seismic velocity and attenuation at sites where good station geometry is available

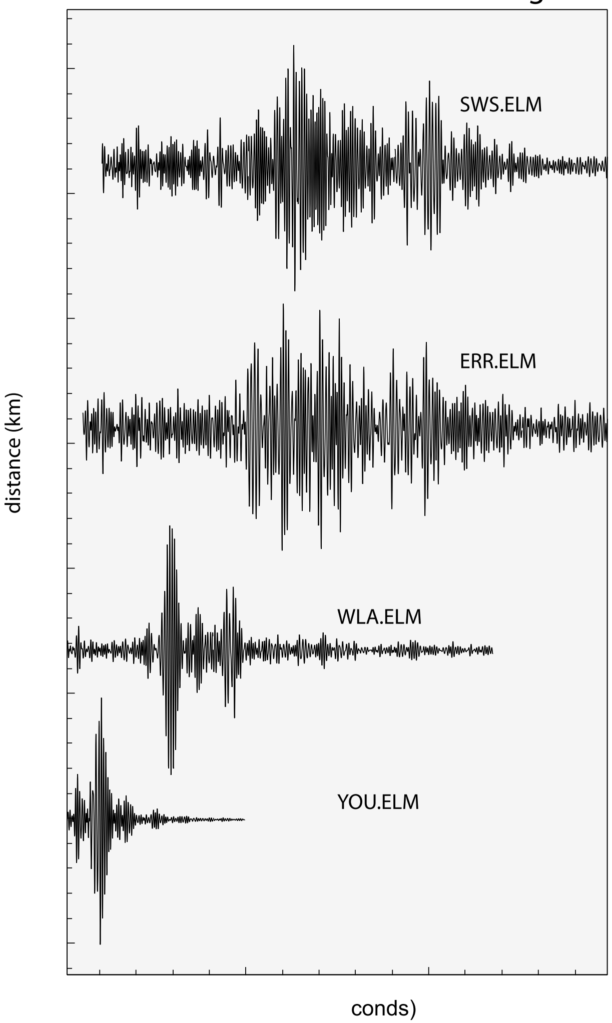
Southern California

Lateral velocity contrasts at 9 km depth

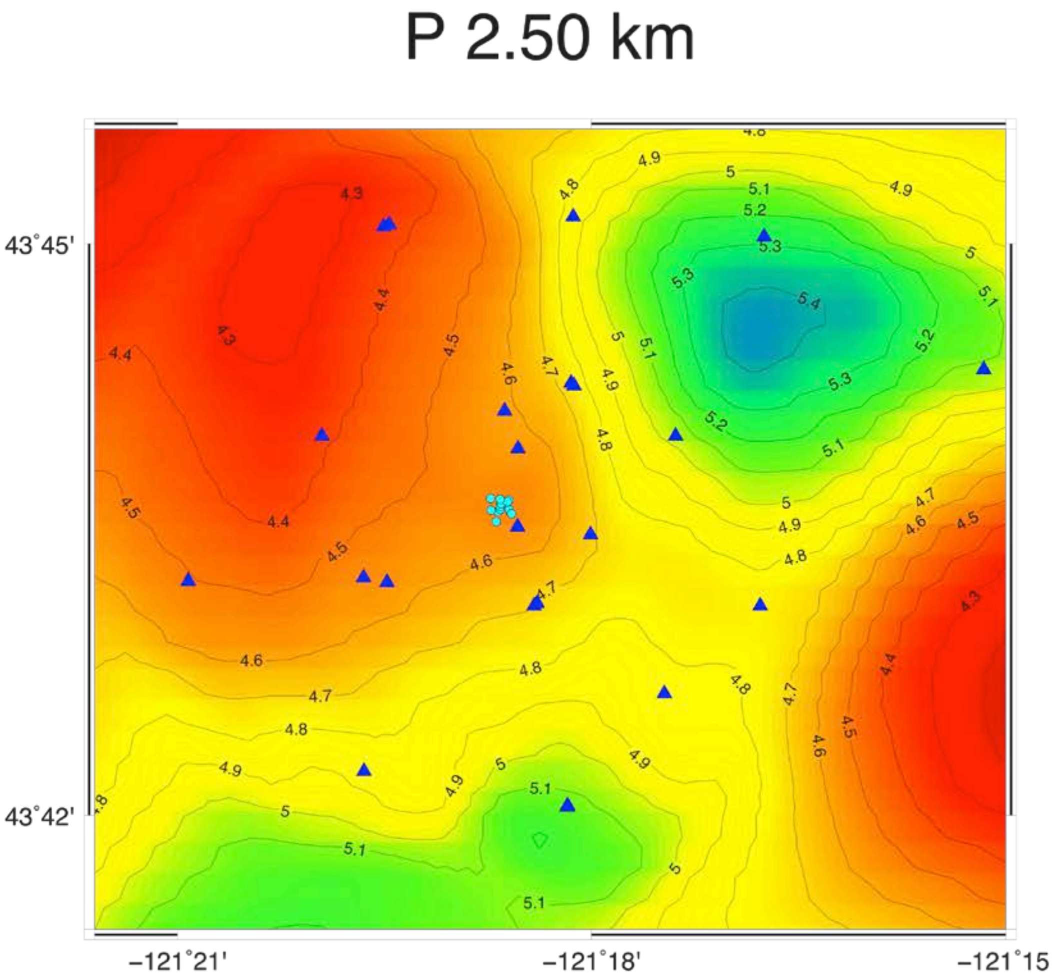


Seismicity from Hauksson

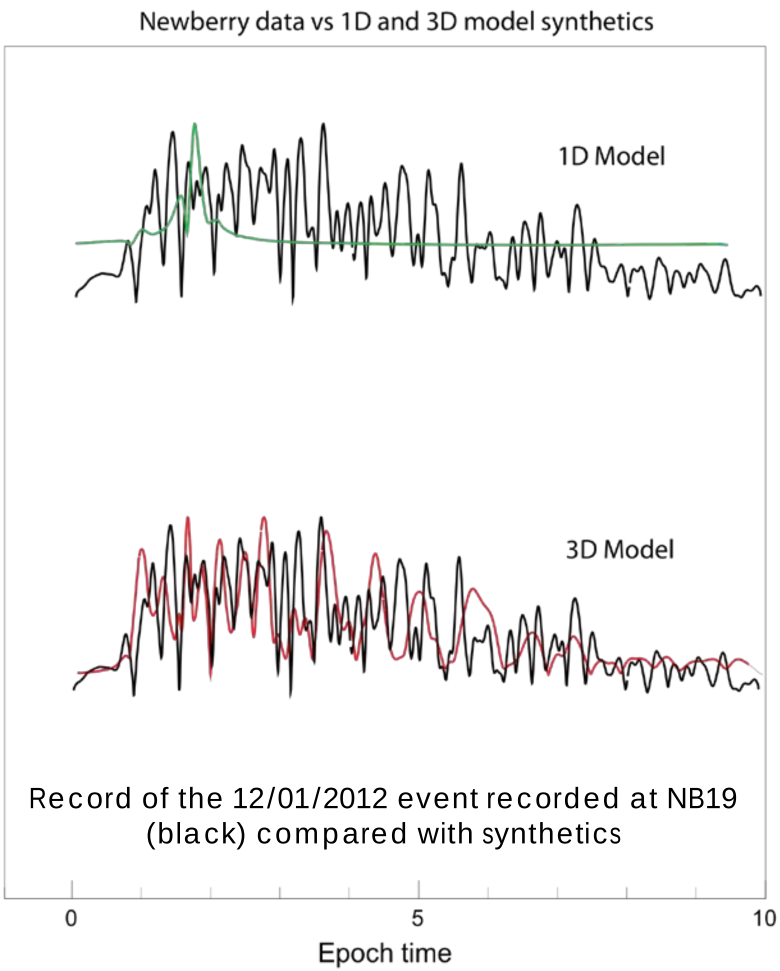
Southern California Virtual Seismograms



ANC: 3D models precise enough to capture much of the complexity seen in the seismic records.



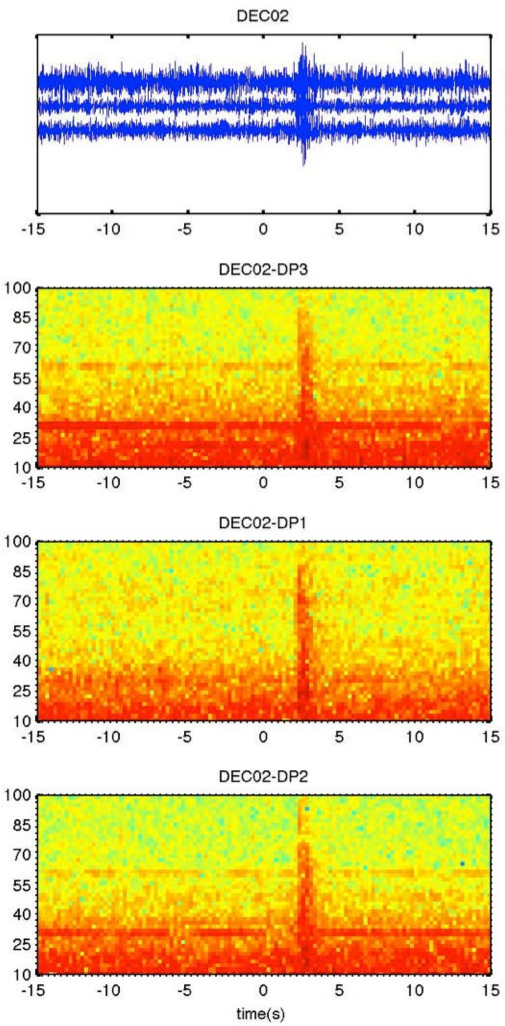
Newberry geothermal seismic array (AltaRock)



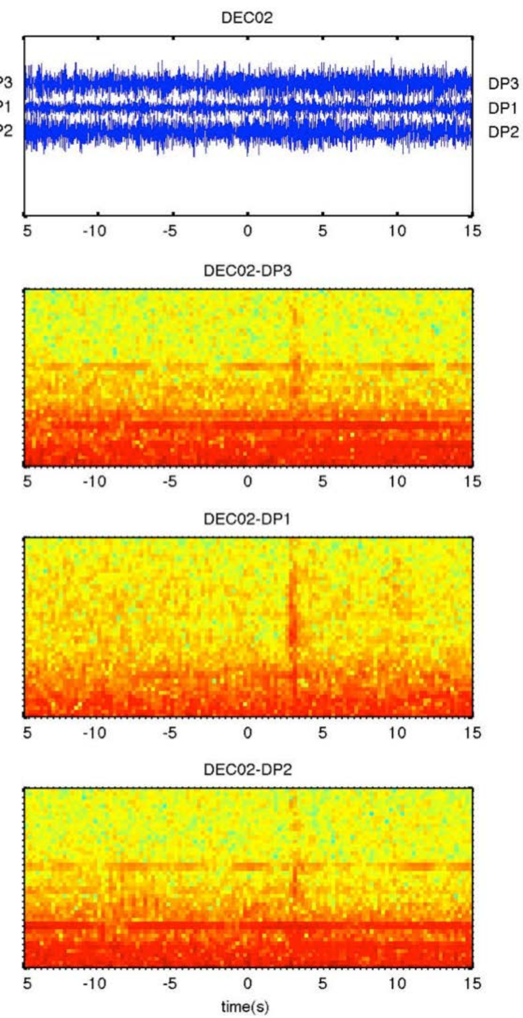
Record of the 12/01/2012 event recorded at NB19 (black) compared with synthetics

Recommendation: Even a short term deployment of passive seismic arrays can greatly improve the characterization of a site.

Matched field processing: detecting small events in noisy data

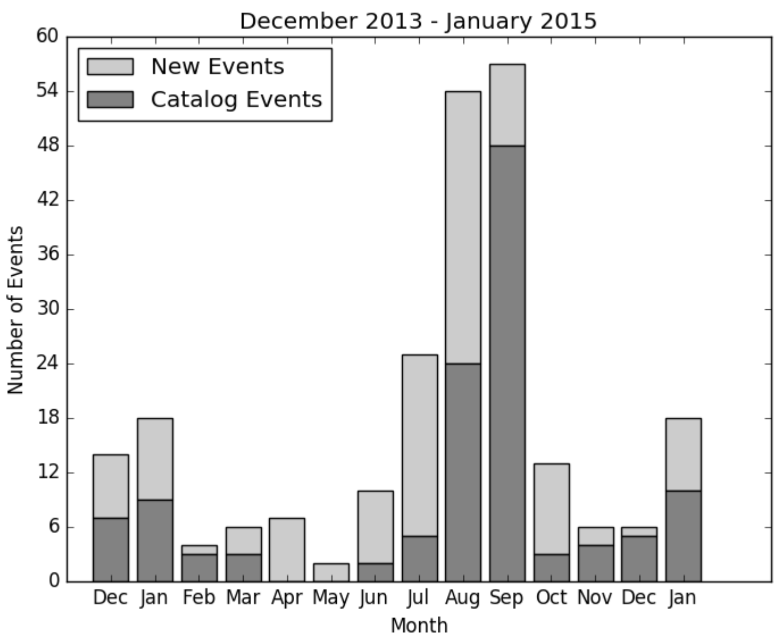


An event detected by threshold triggering



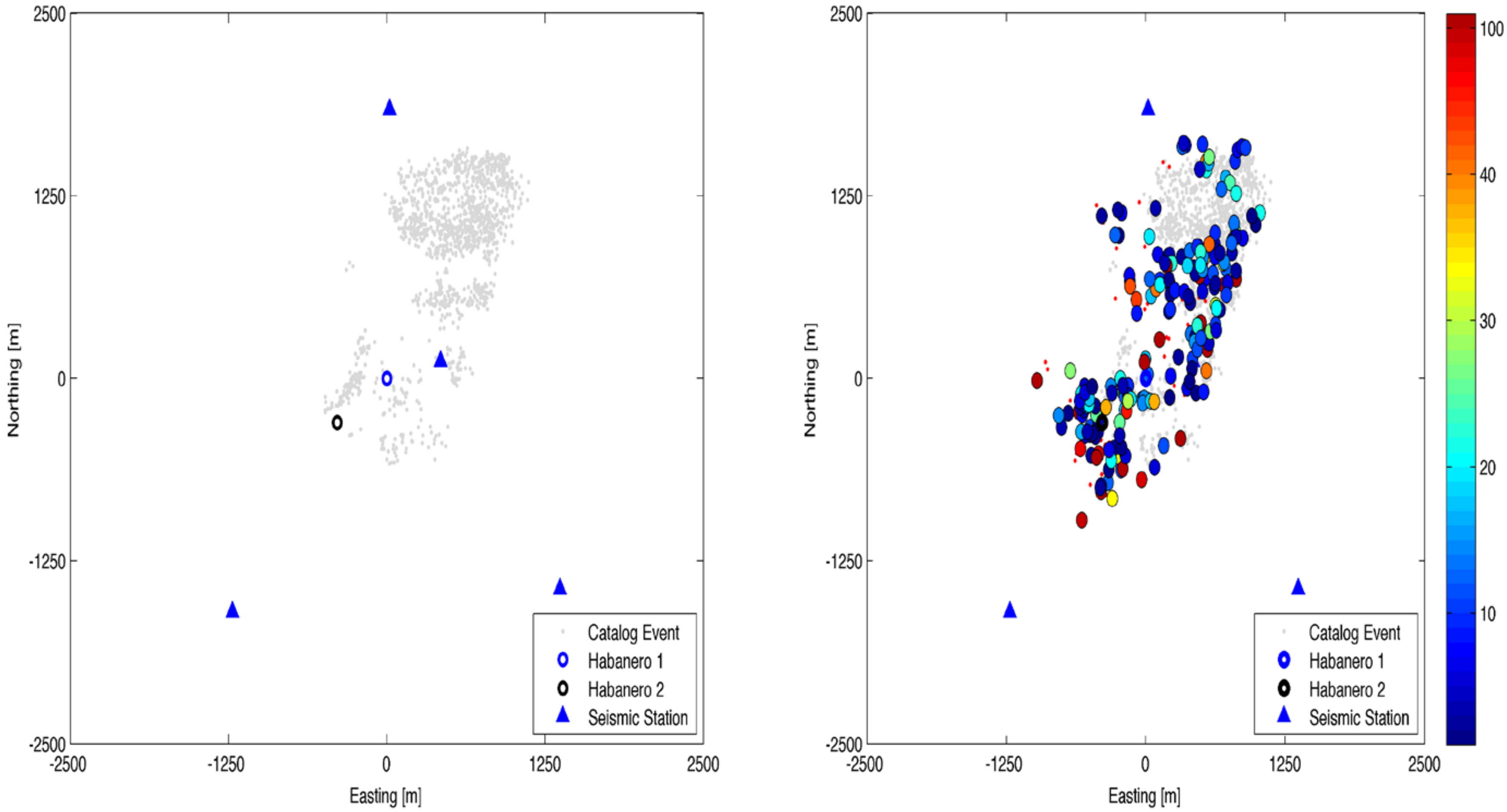
An event detected by MFP.

Data from the USGS shallow borehole recording at the Illinois-Decatur Project.



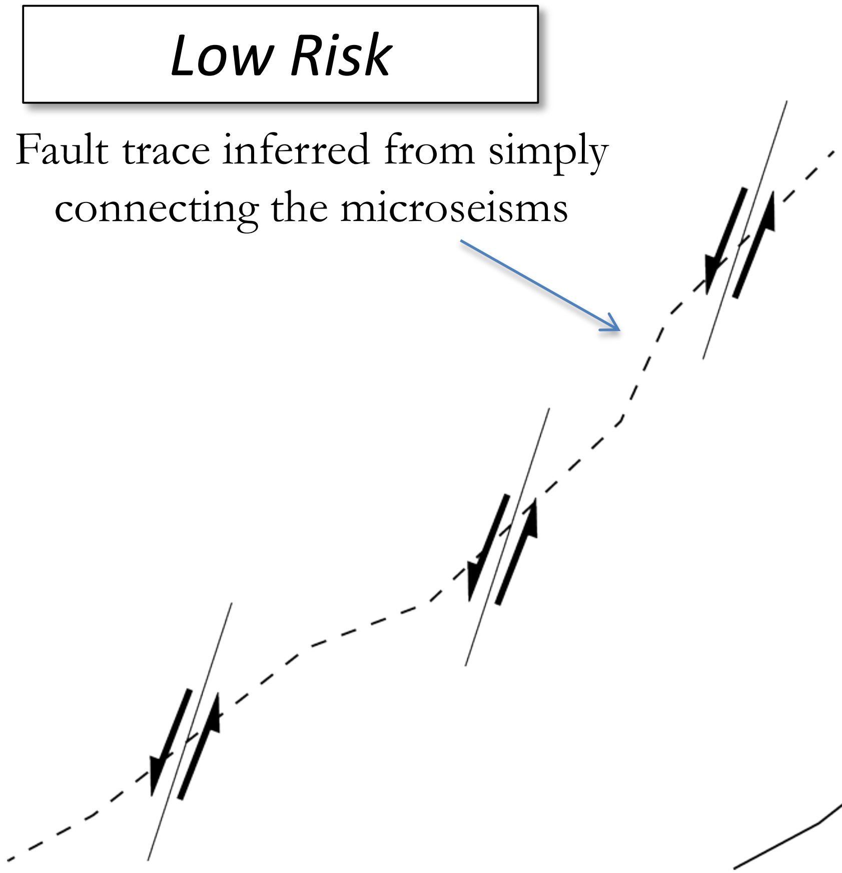
December 2013 – January 2015: 123 events in the original catalog, 117 new events identified by MFP.

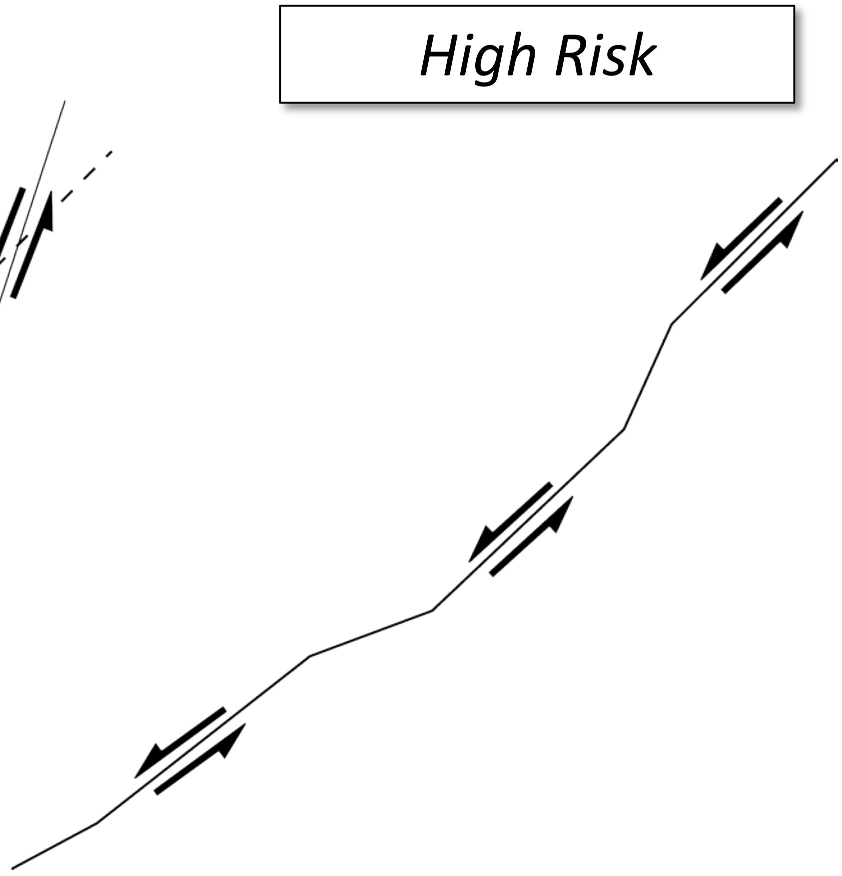
Increasing the sensitivity of the network: Regions that appear quiet may actually be quite active.



Microseismicity during the 2005 Habanero EGS Simulation in the Cooper Basin of South Australia. Matched Field Processing identified hundreds of events that were missed by the catalog.

Improvements in focal mechanism estimation can help identify higher-risk scenarios and constrain state-of-stress

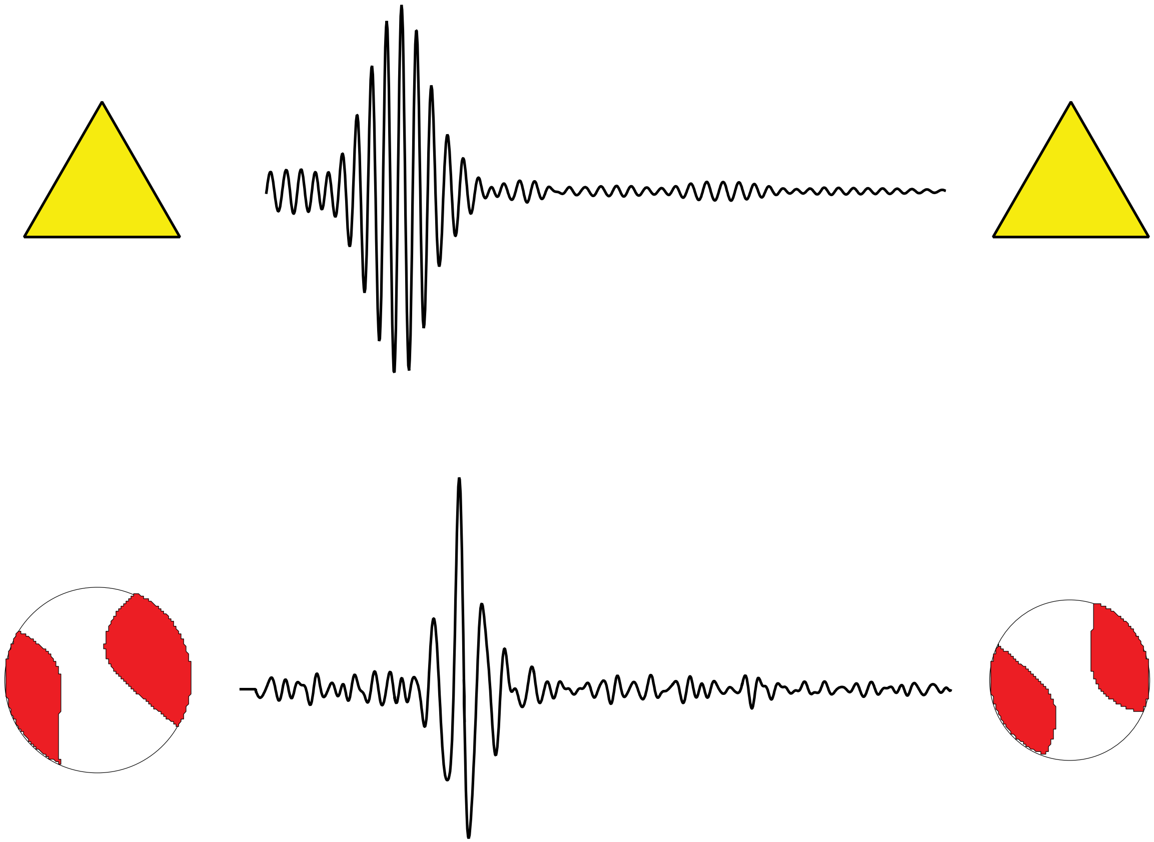




Focal mechanisms indicate a series of shorter *en echelon* fractures, not a single feature

Focal mechanisms reveal slip direction parallel to the inferred fault trace, supporting a single feature

Virtual seismometers: Flip the geometry used in ANC to focus on the structure between pairs of earthquakes.



ANC, CWI

"virtual earthquake"

$CC = GF_{AB}$

VSM

"virtual seismometer"

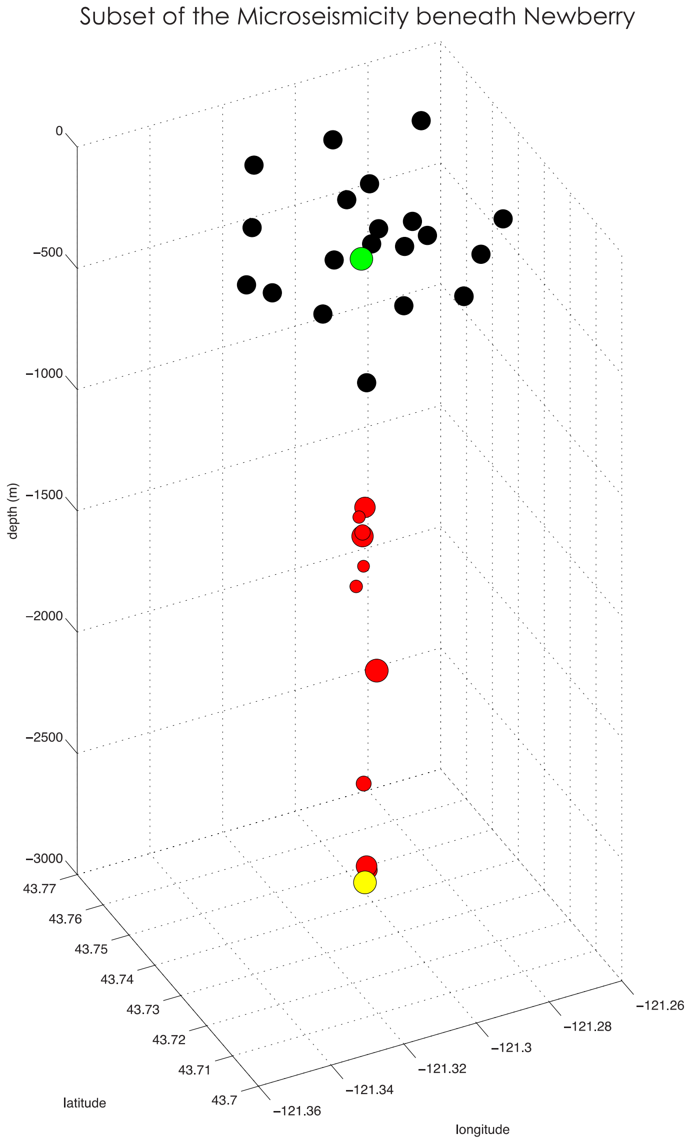
$CC = M_1\ M_2\ GF_{12}$

Both methods: Ncorrelations = N*(N-1)/2

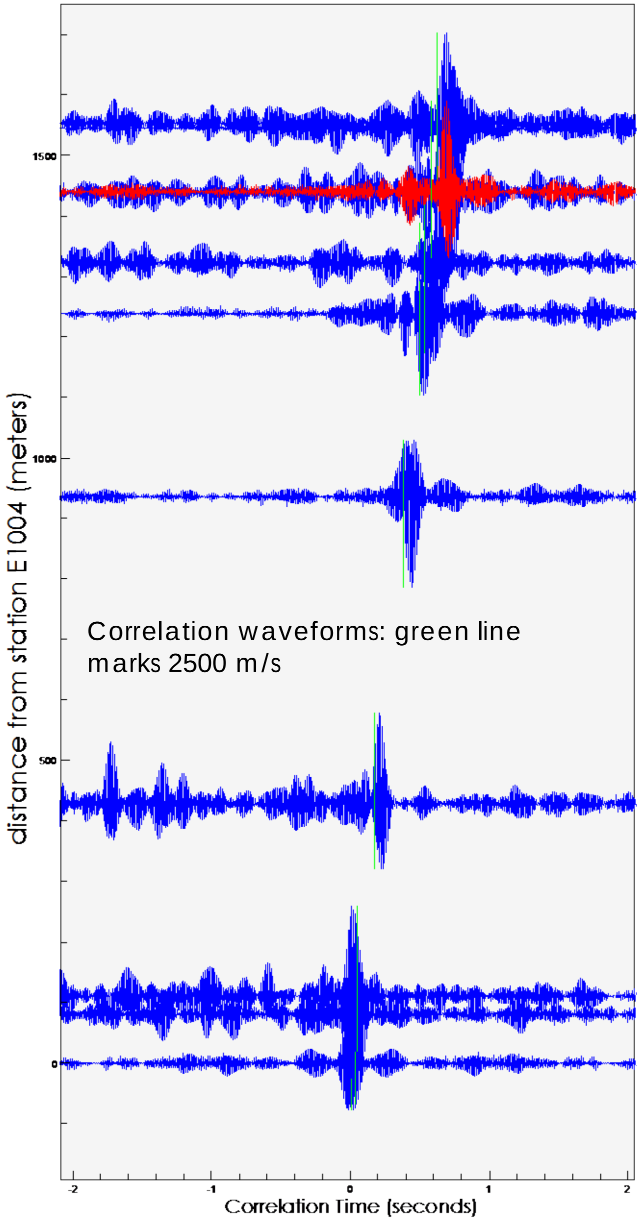
reference: Curtis et al. 2009

Allows fine measurements within the seismically active zone

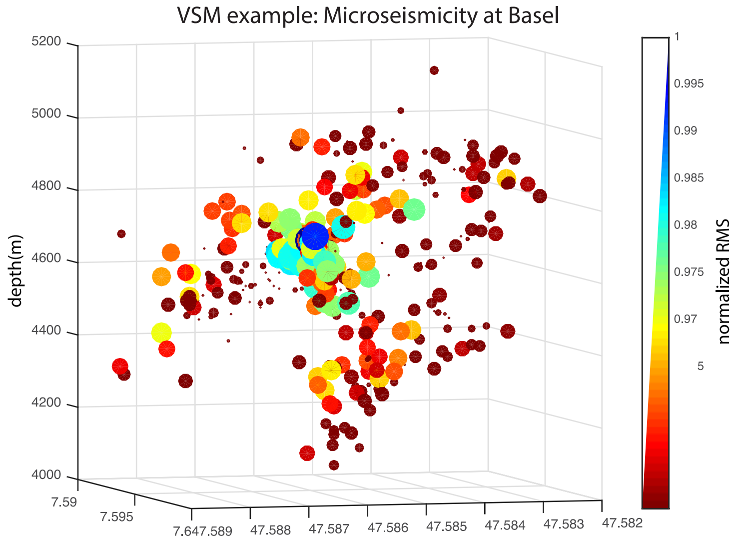
Example of a microquake as a virtual seismometer



E1004 (yellow) as the reference virtual seismometer recording events along a line pointing towards NN24

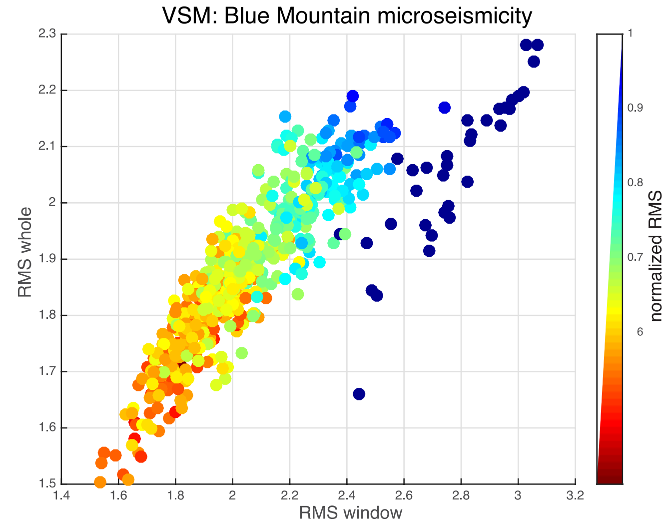


VSM: Amplitude and shape measurements sort the events in space and track evolution of microseismicity in time.



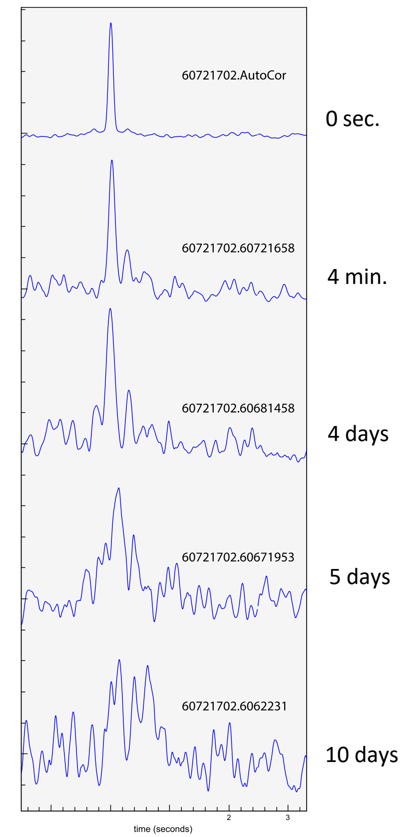
(Basel):

- VSM amplitudes and similarity functions are highly sensitive to relative 3D locations



VSM amplitudes for local microseismicity at Blue Mountain. High RMS values indicate closely spaced events.

Virtual Seismograms at Blue Mountain



Above: the evolution of the VSM envelopes over time suggests an evolving pressure field.

VSM collapses the computational scale: often by several orders of magnitude.

Enables fast, full waveform inversion of source focal mechanism, structure and wave propagation

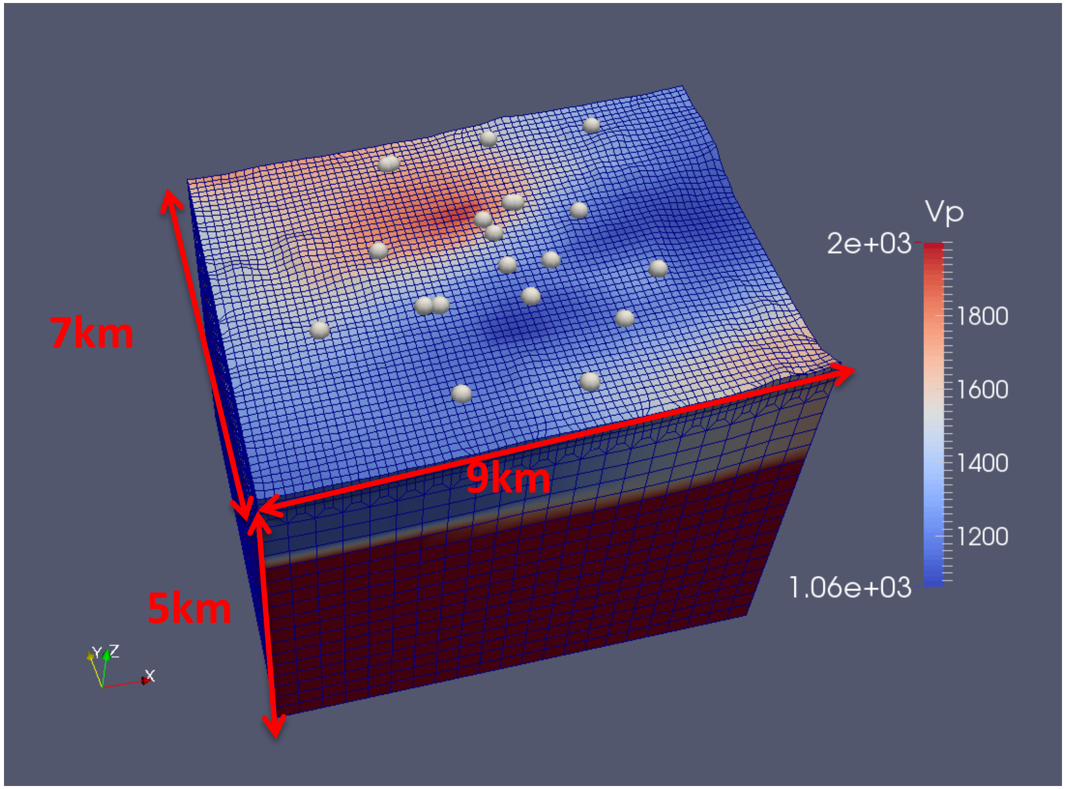
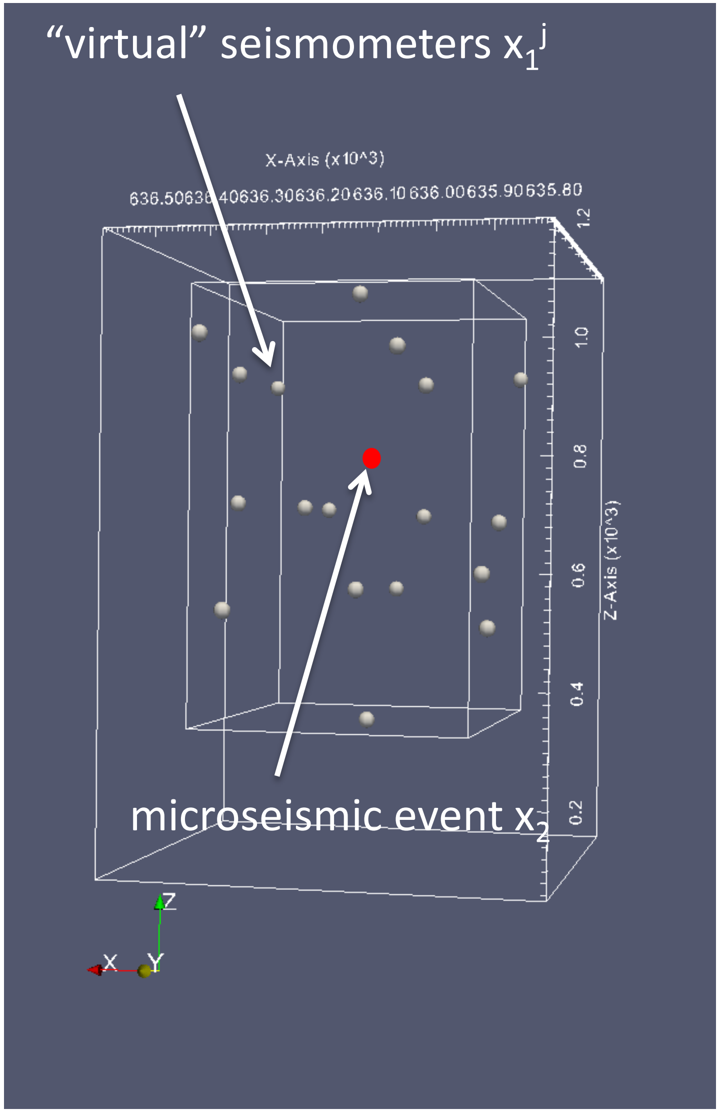
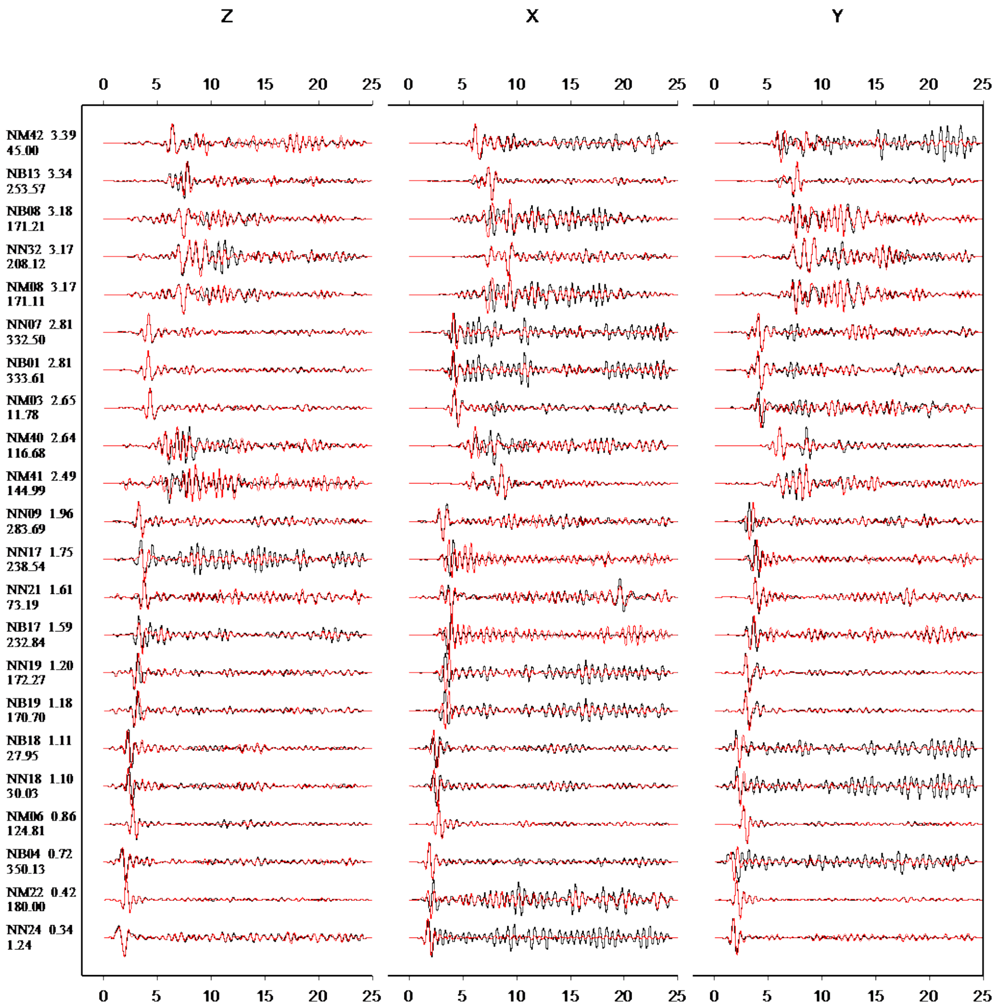
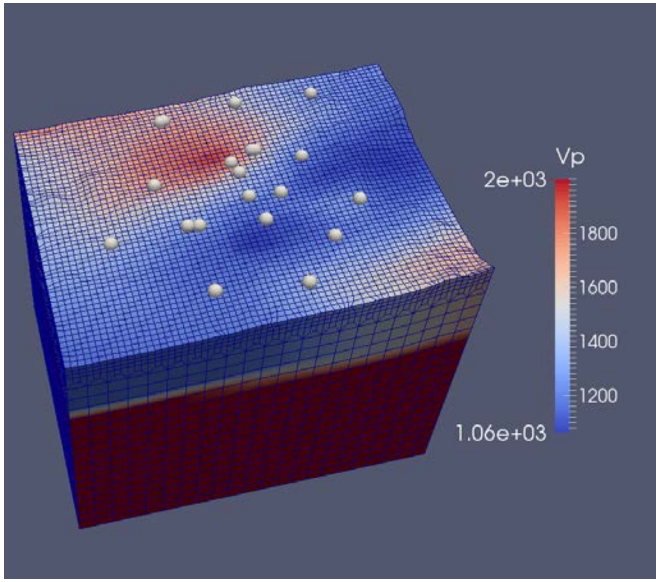


Figure: SpecFEM model of Newberry Geothermal Field



We can precisely match the records of the surface stations using the inverted Moment Tensor result.





Synthetics calculated using the MT estimate (red) match the originally recorded waveforms (black).

Recommendations

1. Observational data is key to understand the seismic behavior of CO_2 injection sites. This data be ideally be broadly-accessible to independent research groups to solicit the best analysis and insight available.

2. Microseismicity provides direct information about smaller faults not visible in 3D active seismic surveys. Better techniques are necessary for rapidly determining the site-specific relationship between injection rate at one or more wells and seismic frequency.

3. The types and quality of microseismic analyses that can be performed generally improve with the extensiveness of the microseismic array (both laterally and with depth). Larger arrays typically provide better spatial coverage and sensitivity. Collection of "big data" opens up new analysis opportunities.

4. A high priority should be placed on encouraging technologies that can lower the cost and improve the practicality of deploying such "Large-N" arrays.

Matzel, E., Morency, C., Pyle, M. Templeton, D. and White, J. (2016), A Microseismic Workflow for Managing Induced Seismicity Risk at CO2 Storage Projects, LLNL-TR-678691

Accomplishments to date

We have demonstrated the usefulness of several microseismic processing algorithms for carbon storage sites:

① Improved velocity and attenuation models via **Ambient Noise Correlation**

② Lowered event detection thresholds via **Matched Field Processing**

③ Better event locations and location uncertainty via **Bayesian Location**

④ Novel focal mechanism analysis via the **Virtual Seismometer Method**

⑤ Improved prediction of seismic frequency via **Empirical Forecasting**

Synergistic Opportunities

① Several demonstration projects are now collecting high-quality passive seismic data, providing new partnering opportunities.

② Potential for two-way benefits:

- Opportunity for us to improve our analysis algorithms.
- We can potentially provide back to operators:
  - 3D velocity and attenuation models and 4D monitoring (ANC)
  - Re-processed event catalogs (MFP)
  - Re-located events with location uncertainties (BayesLoc)
  - Moment tensor analyses (VSM)

Summary

① Microseismic monitoring is essential to identifying and reacting to seismic hazards.

② **Our recent work** has focused on new tools for extracting information about earth structure, state-of-stress, and fault behavior from noisy waveform data using state-of-the-art signal processing algorithms.

③ **Long term goals:**

- Integrate microseismic and injection data into a “real-time” processing toolkit to support Adaptive Risk Management.
- Begin work applying to “Large-N” monitoring deployments and novel monitoring technologies.

Acknowledgements

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- We are grateful for data sharing and technical input from colleagues at the Bureau of Reclamation, the U.S. Geological Survey, AltaRock Energy, and many other industrial and academic partners.

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