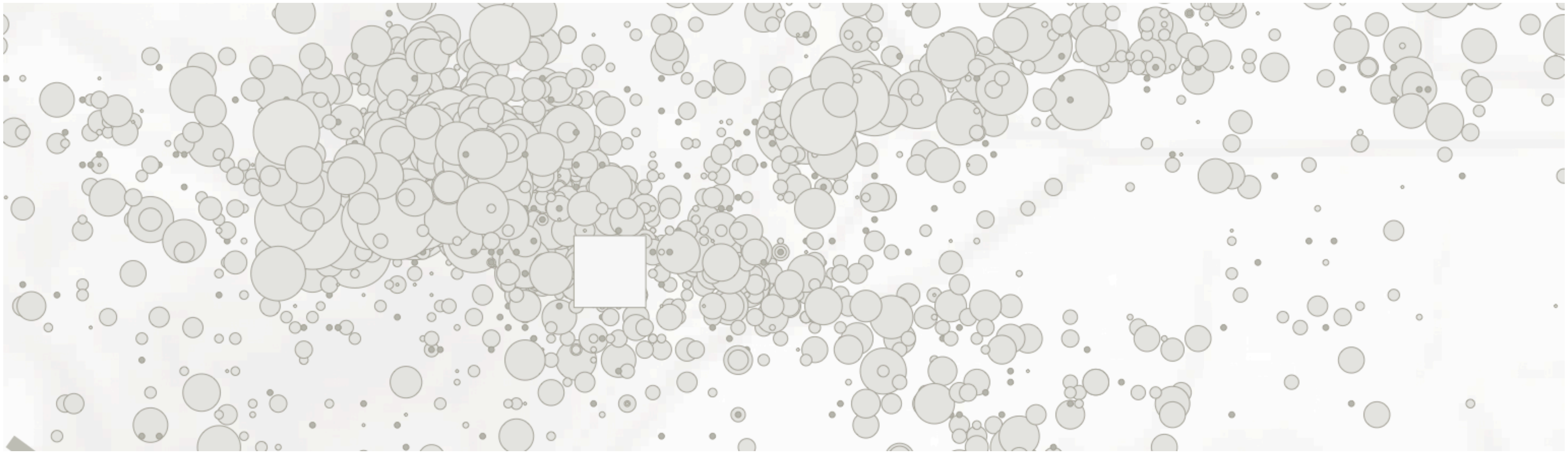

Microseismic processing for induced seismicity management at carbon storage sites

Eric Matzel, Christina Morency, Moira Pyle, Dennise Templeton, and Joshua White

Project Number:
FWP-FEW0191-Task 2

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

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	**Draft written, Final available Sept 30, 2016**

Staff

Seismology

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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.

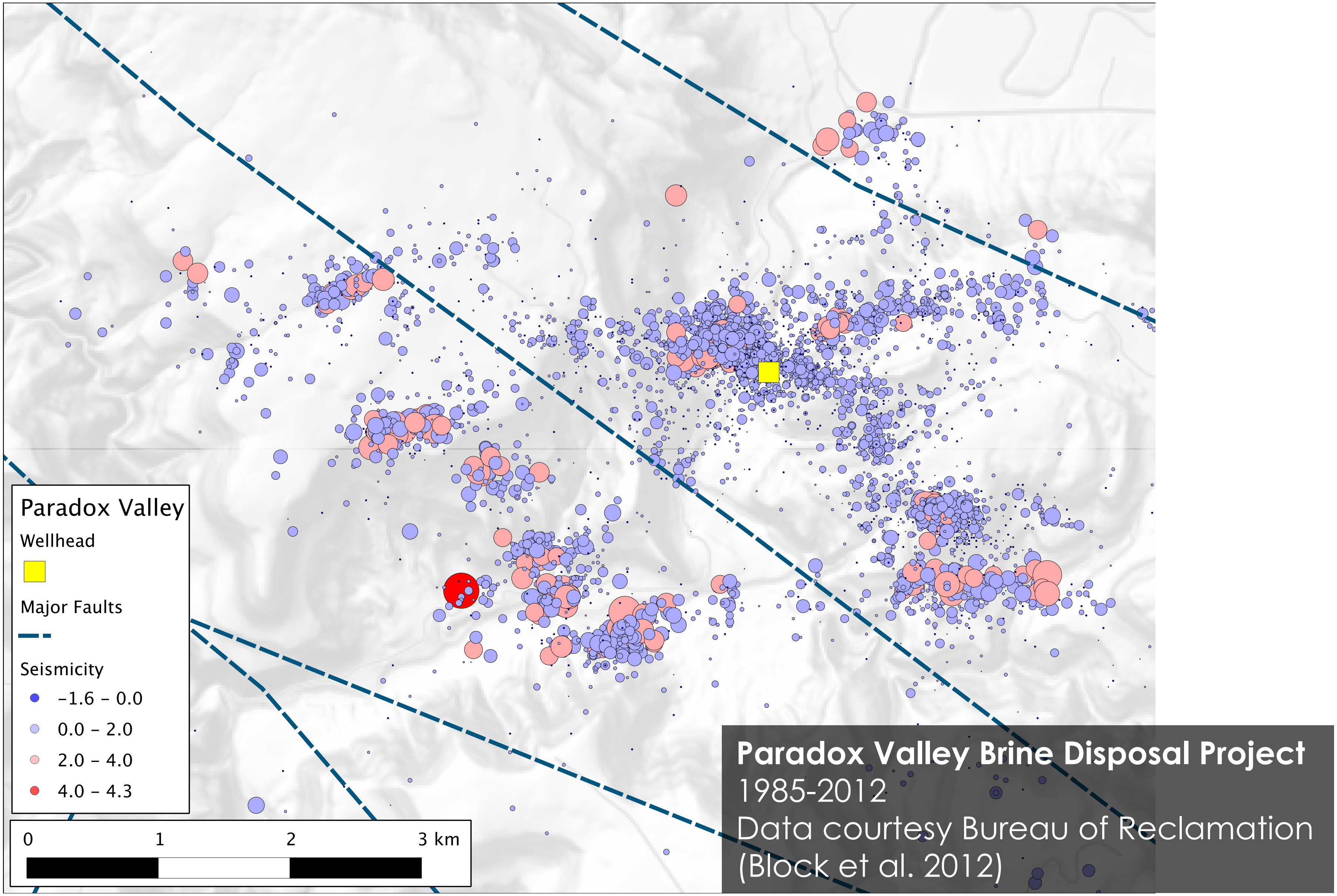
② The relationship between injection rate and seismic activity at a given site is complex.

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

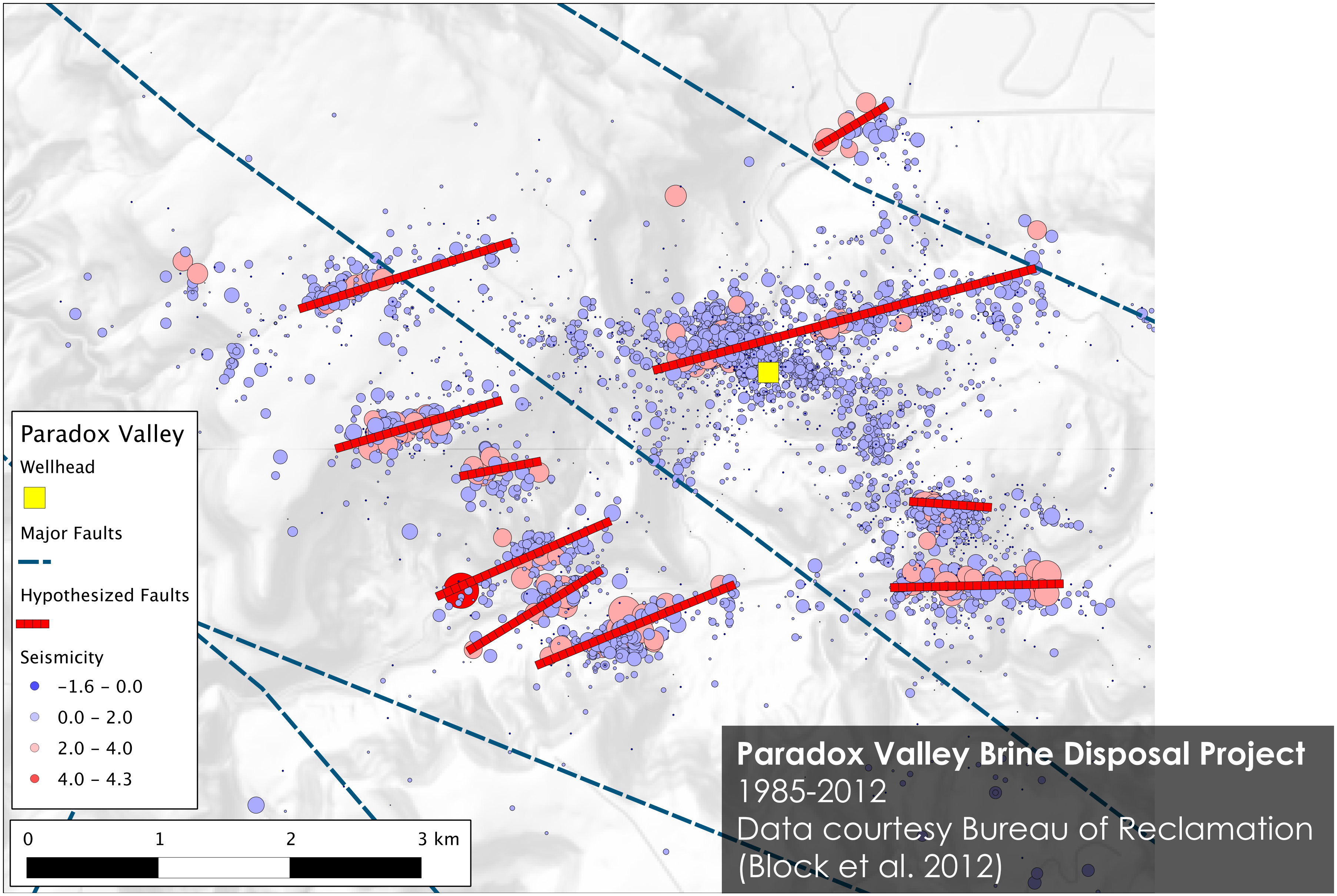
③ The knobs we can turn to reduce seismicity are limited.

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

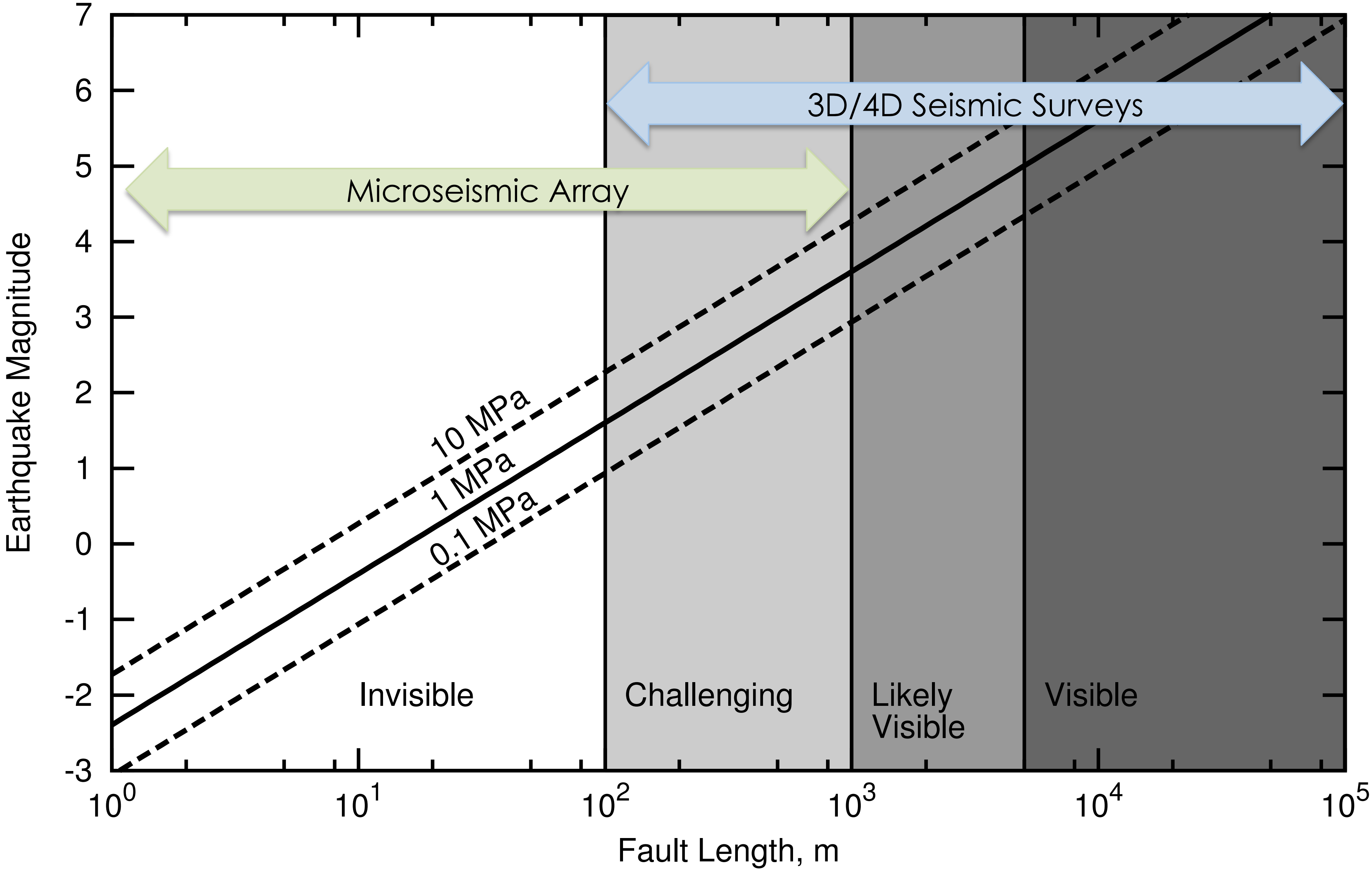
Faster detection of previously unobserved faults can help lower seismic risk



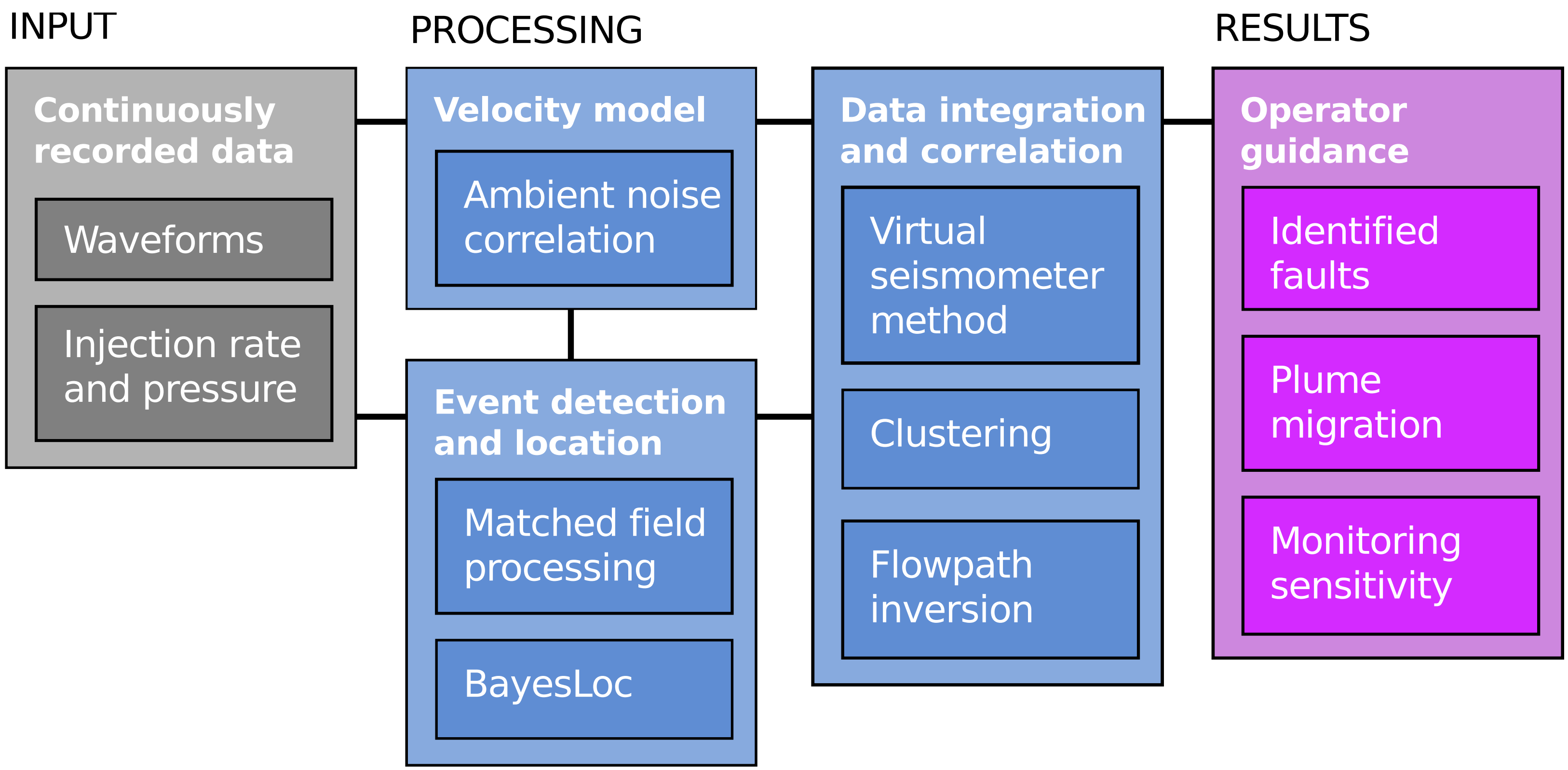
Precise measurements are needed to identify faults hidden within the microseismic cloud



At any site, there are two fault populations—known faults and unknown faults—that must be managed differently



Microseismic processing toolkit



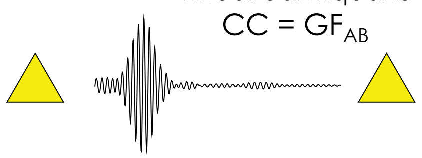
Key goal is to automate as much of this process as possible, to minimize the lag time between data aquisition and decision-making

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

ANC

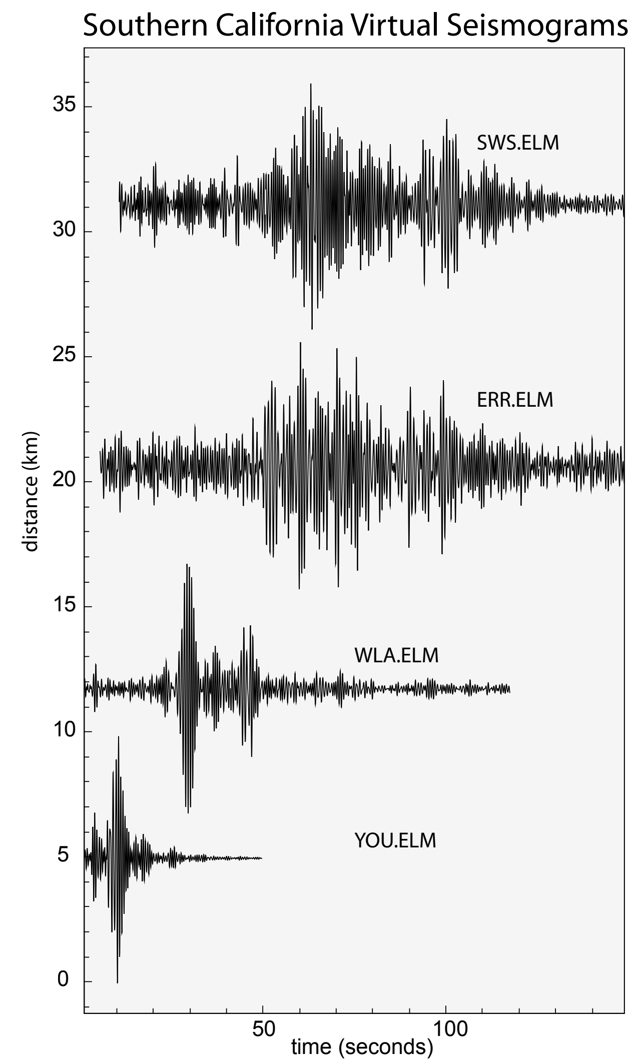
- Perfect location and timing constraints
- Simple estimate of the GF.
- Slow - lots of continuous data needed (Typically months or longer)
- Frequency content defined by **background field** and instrument sensitivity

"virtual earthquake"
$CC = GF_{AB}$

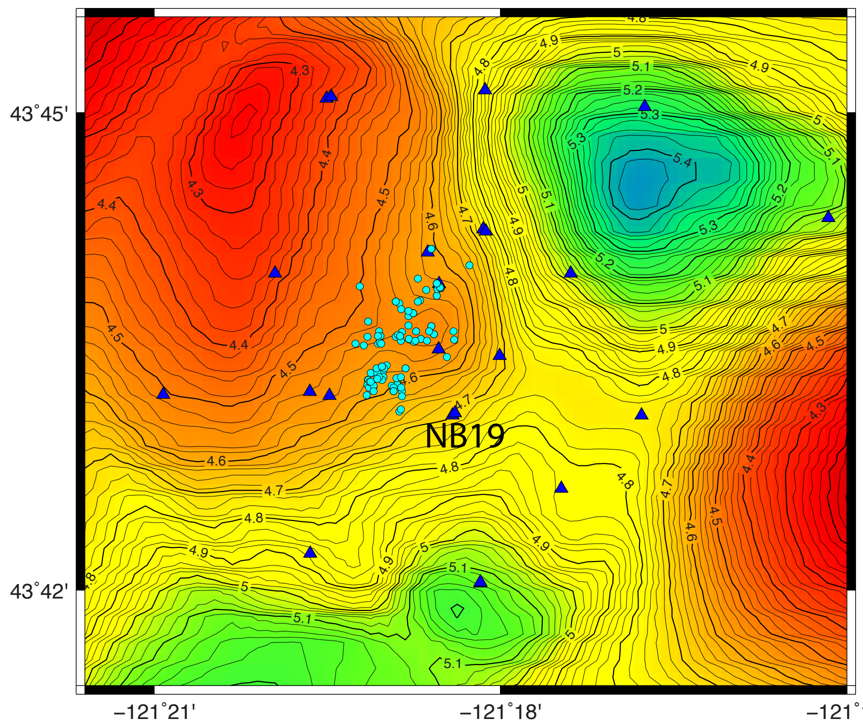


Once the signal emerges from the noise, the GF is very stable.

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

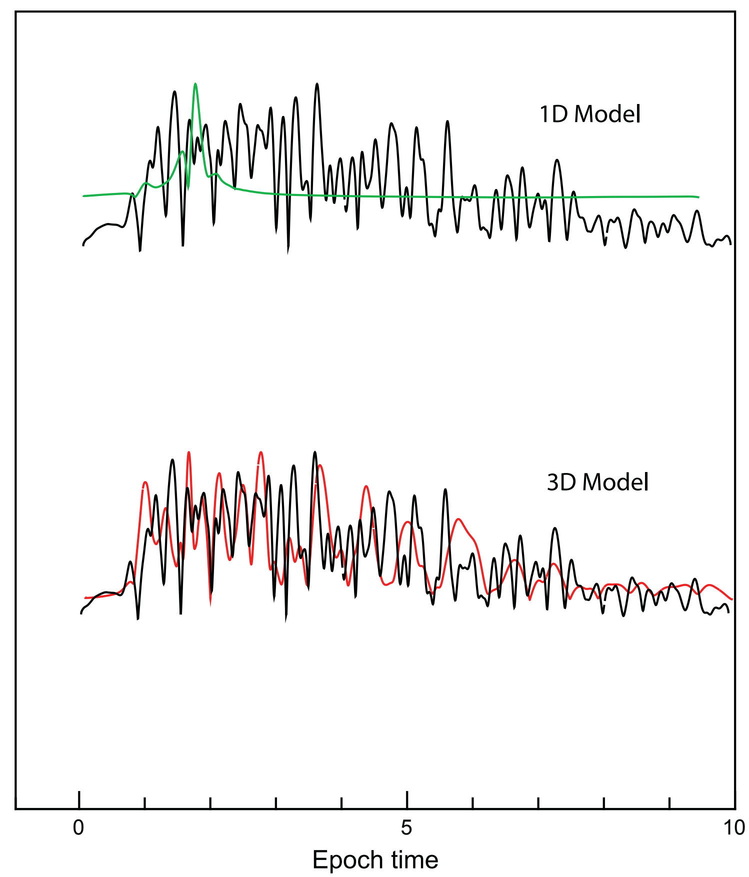


ANC allows sharp imagery of seismic velocity and attenuation at sites where good station geometry is available



Newberry Geothermal P-velocity model at 2.5 km estimated using 1 month of recorded noise.

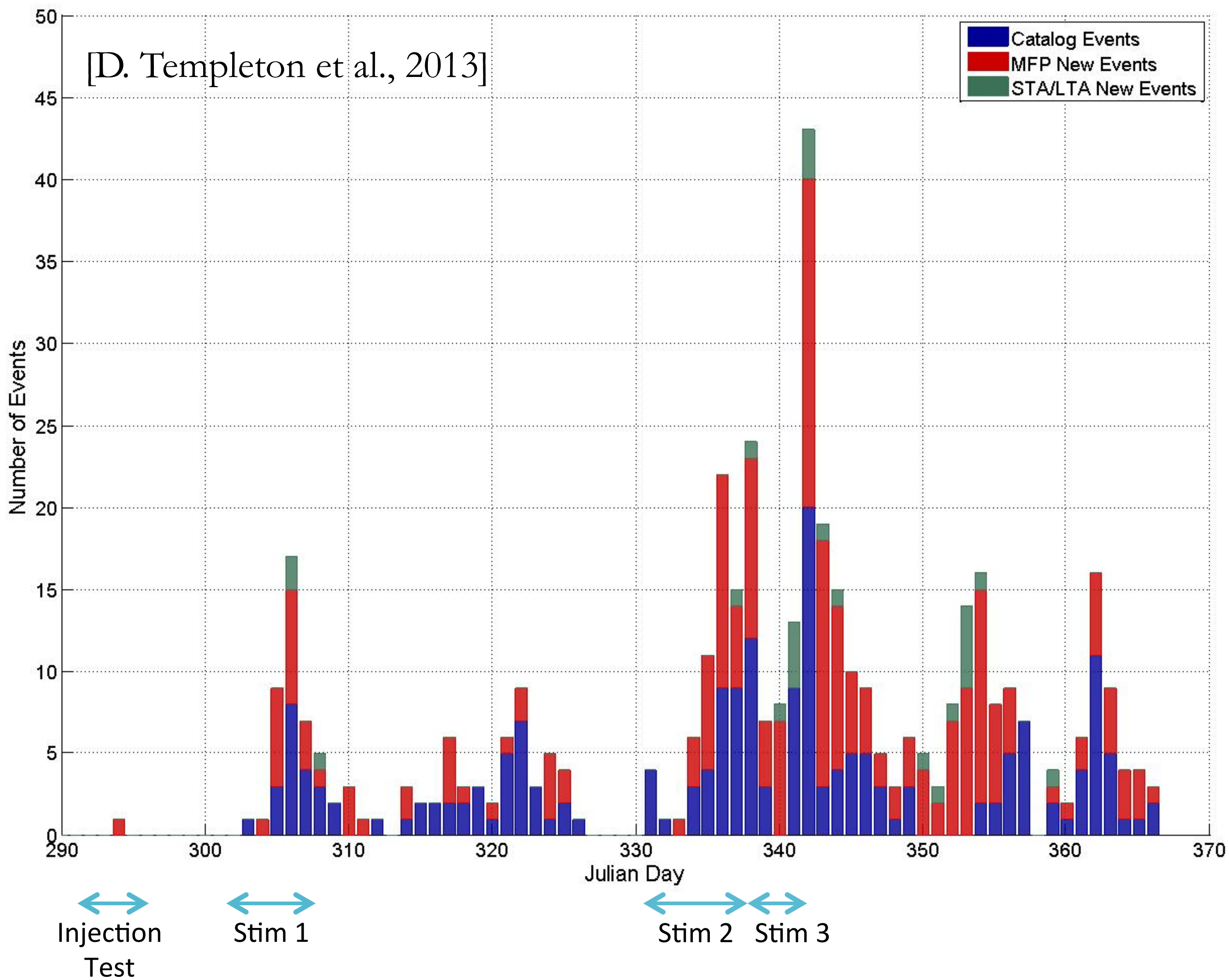
Newberry data vs 3D model synthetics



These images allow us to predict synthetic seismograms to aid in identifying the microseismicity.

The repeatability of the waveform allows 4D monitoring.

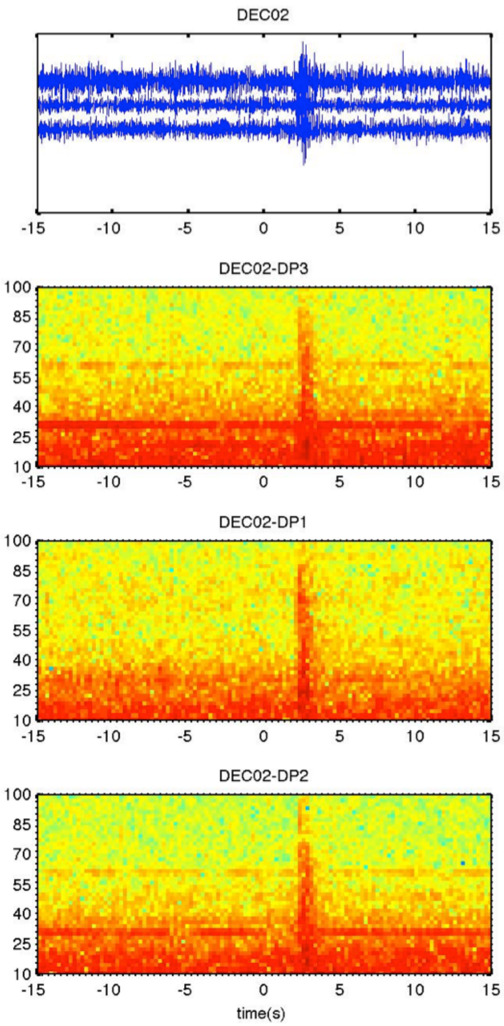
Matched field processing can improve small event detection in noisy data



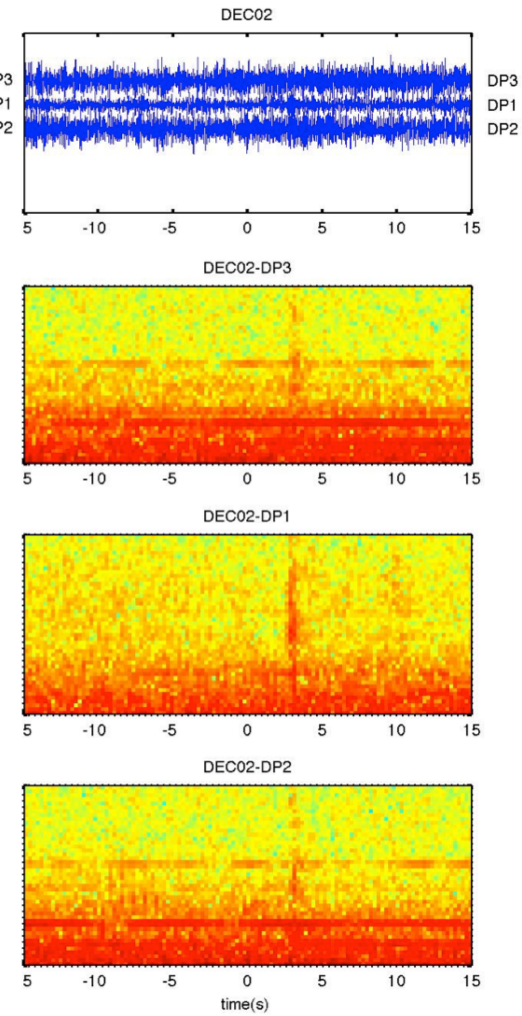
206 catalog events
217 MFP new events
24 STA/LTA new events

Figure: Detected microseismic events during Newberry Geothermal stimulation. Matched field processing (MFP) was able to identify twice as many events as industry-standard techniques.

Matched field processing can improve small event detection in noisy data

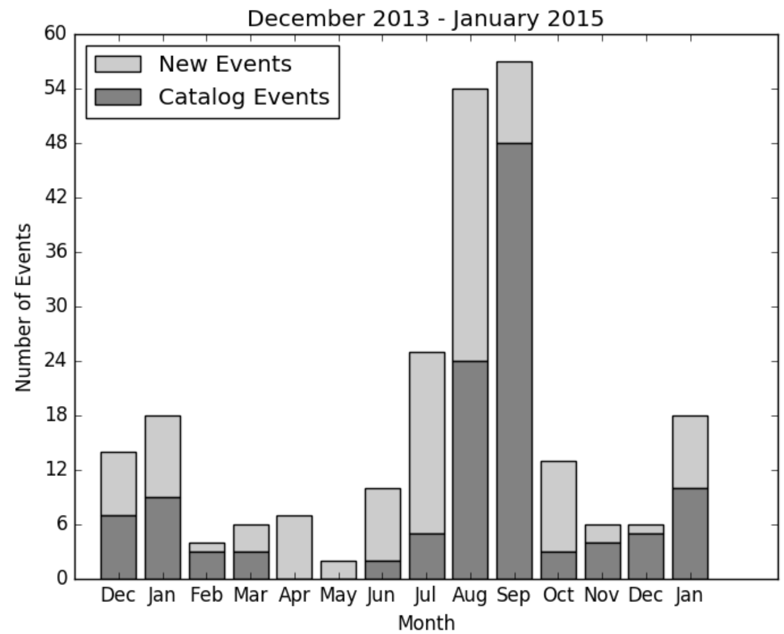


An event detected by threshold triggering



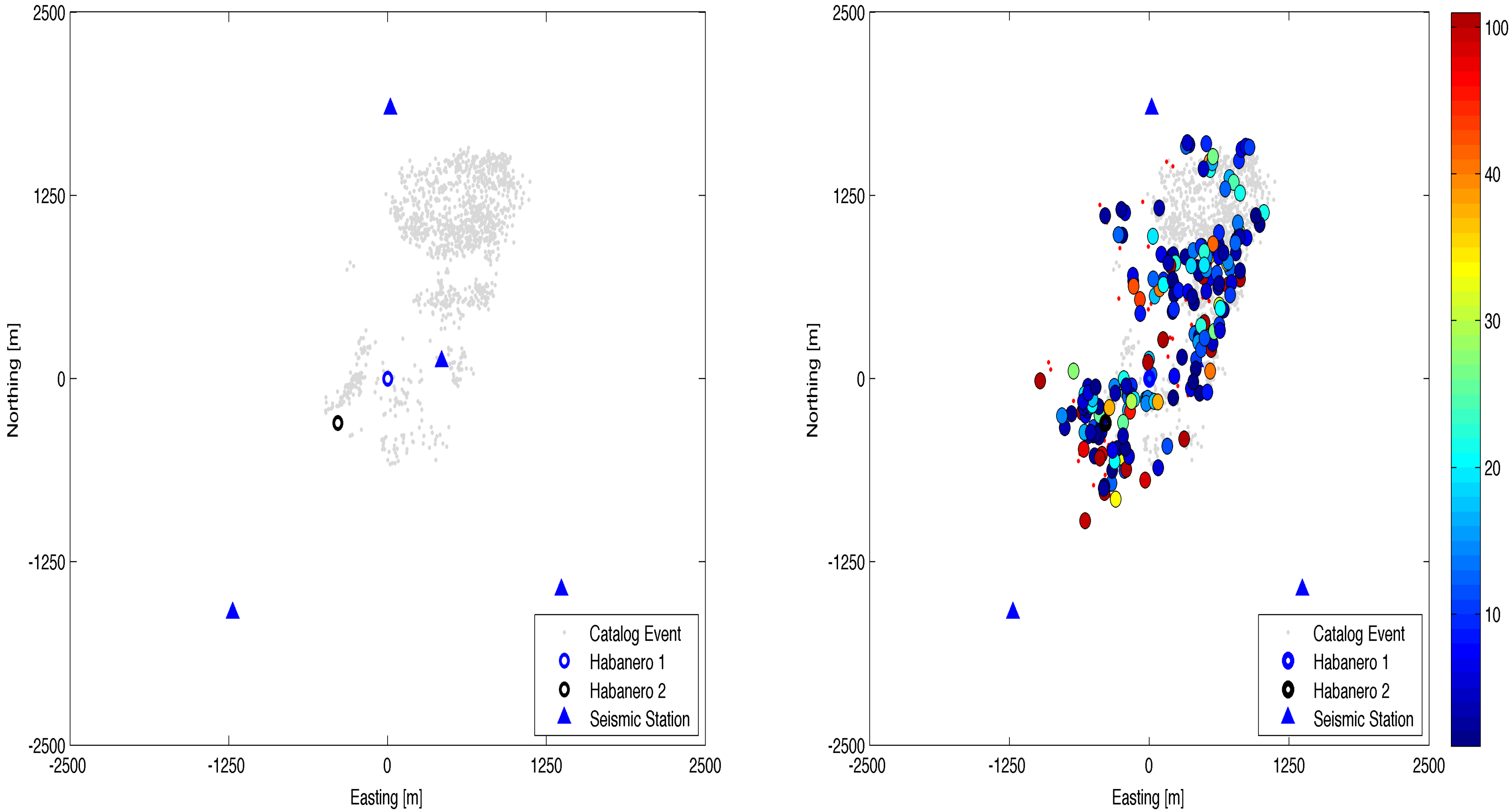
An event detected by MFP.

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.

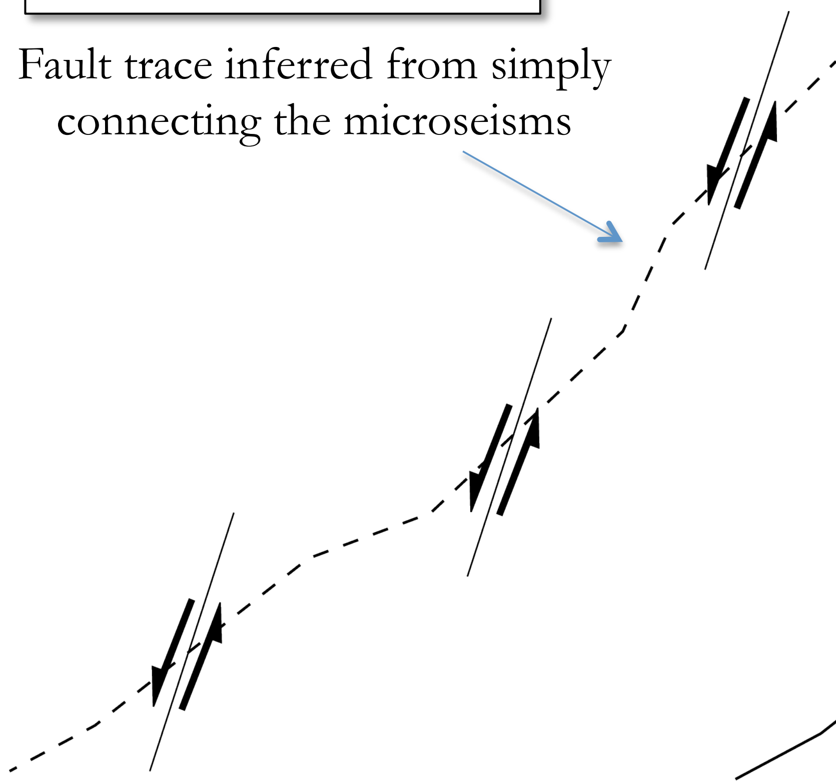
Increasing the sensitivity of the network: Regions that appear quiet may actually be quite active.



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.

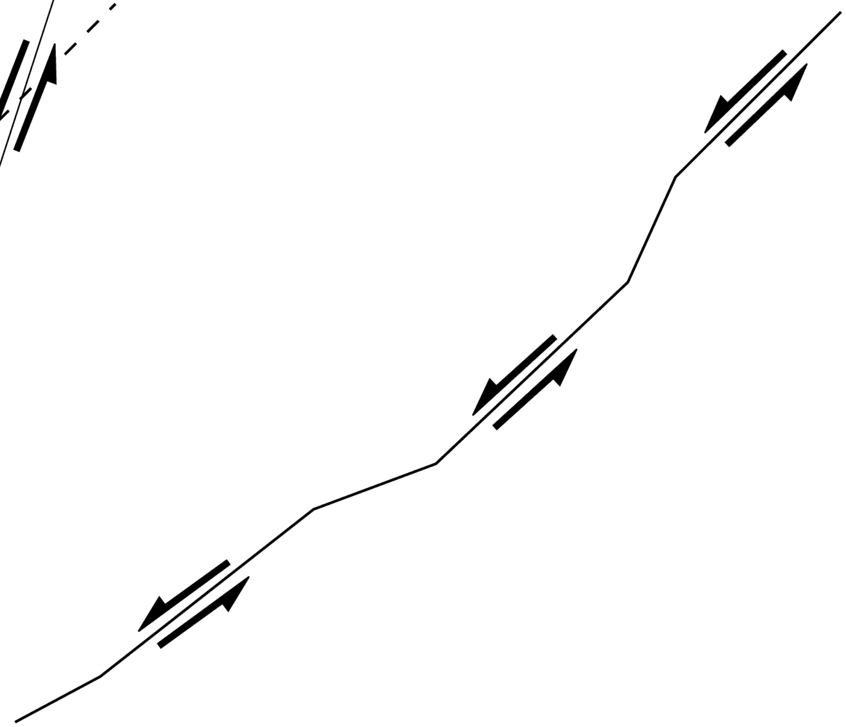
Improvements in focal mechanism estimation can help identify higher-risk scenarios and constrain state-of-stress

Low Risk



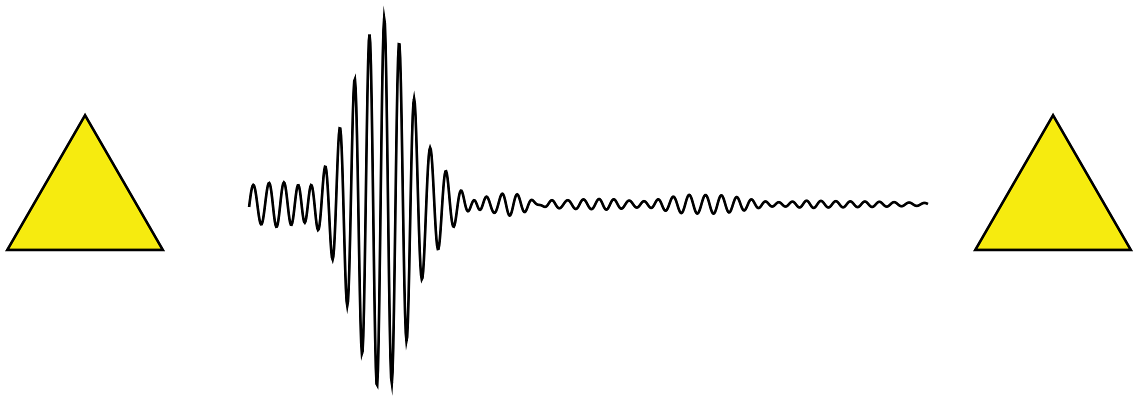
Focal mechanisms indicate a series of shorter *en echelon* fractures, not a single feature

High Risk



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

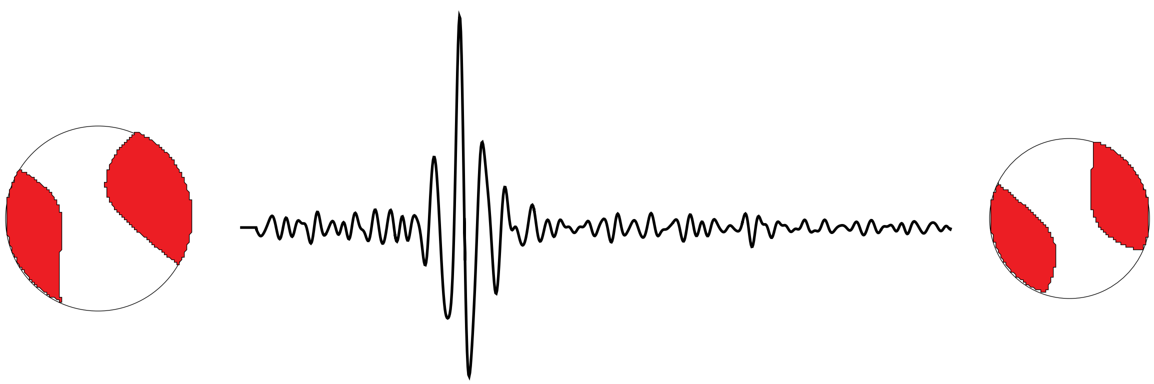
Virtual seismometers: Flip the geometry used in ANC to focus on the structure between pairs of earthquakes.



ANC, CWI

"virtual earthquake"

$CC = GF_{AB}$



VSM

"virtual seismometer"

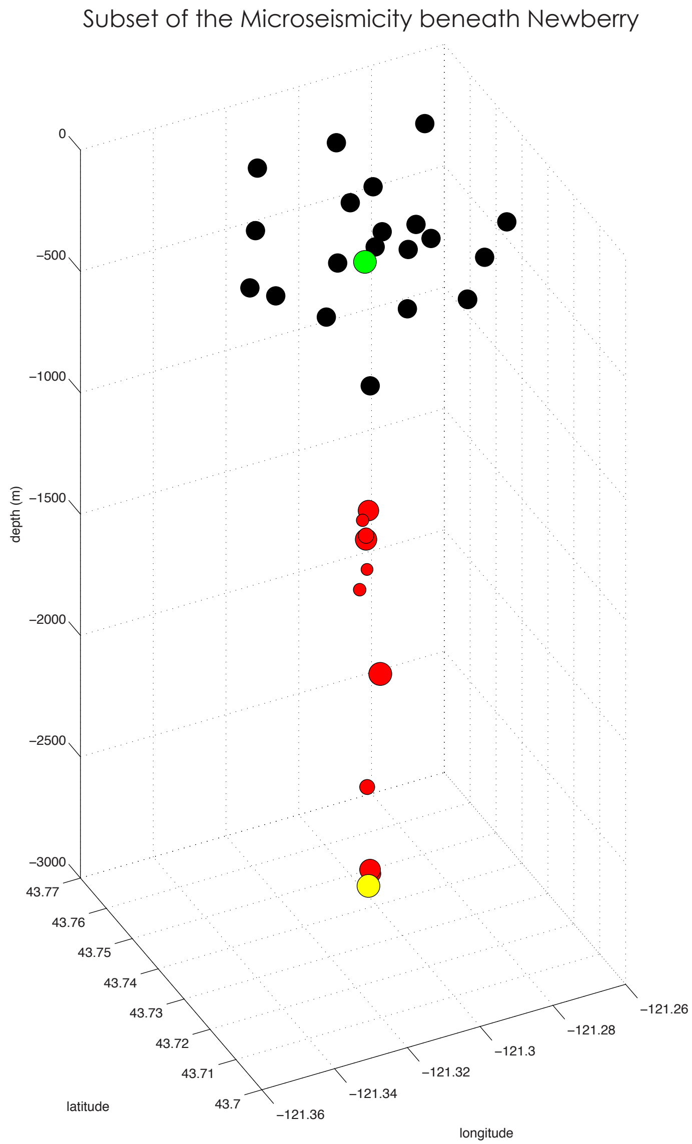
$CC = M_1 M_2 GF_{12}$

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

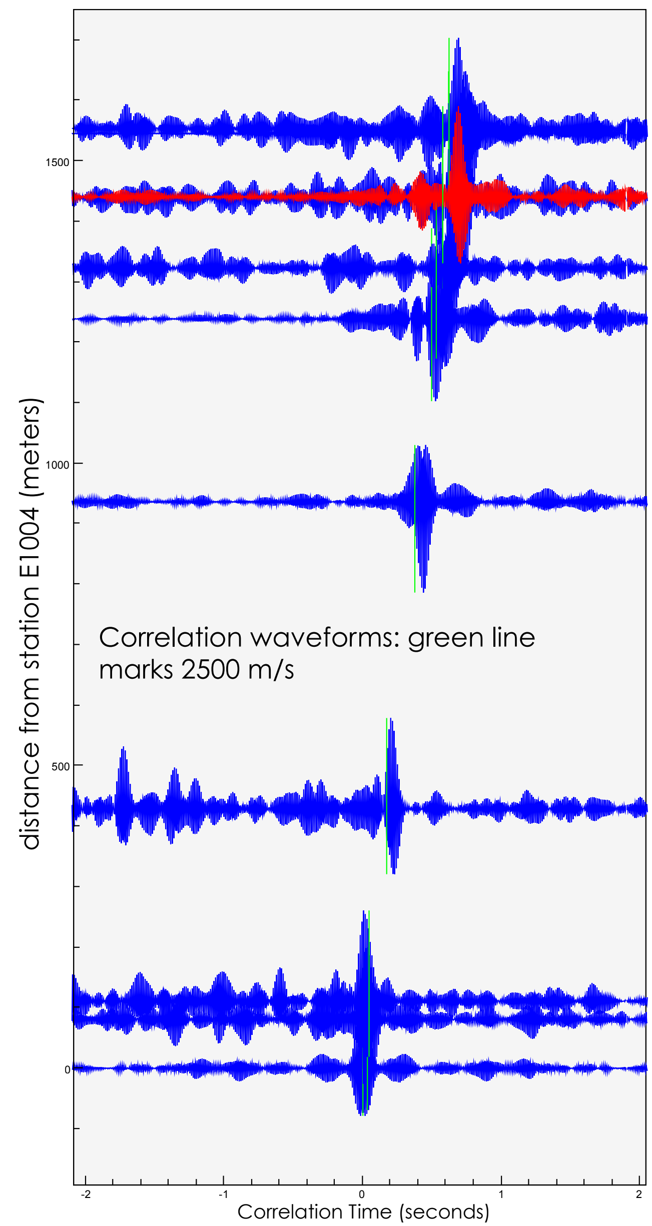
reference: Curtis et al. 2009

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



We are combing the Virtual Seismometer Method with Adjoint Inversion to improve moment tensor estimation

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

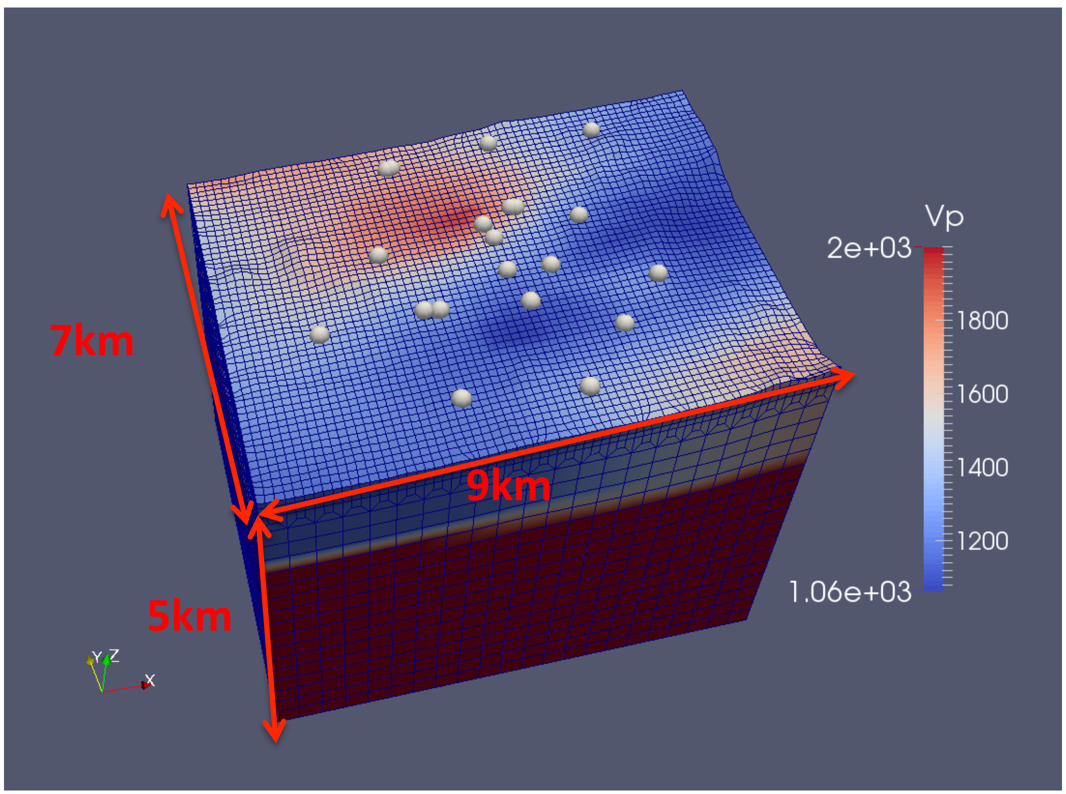
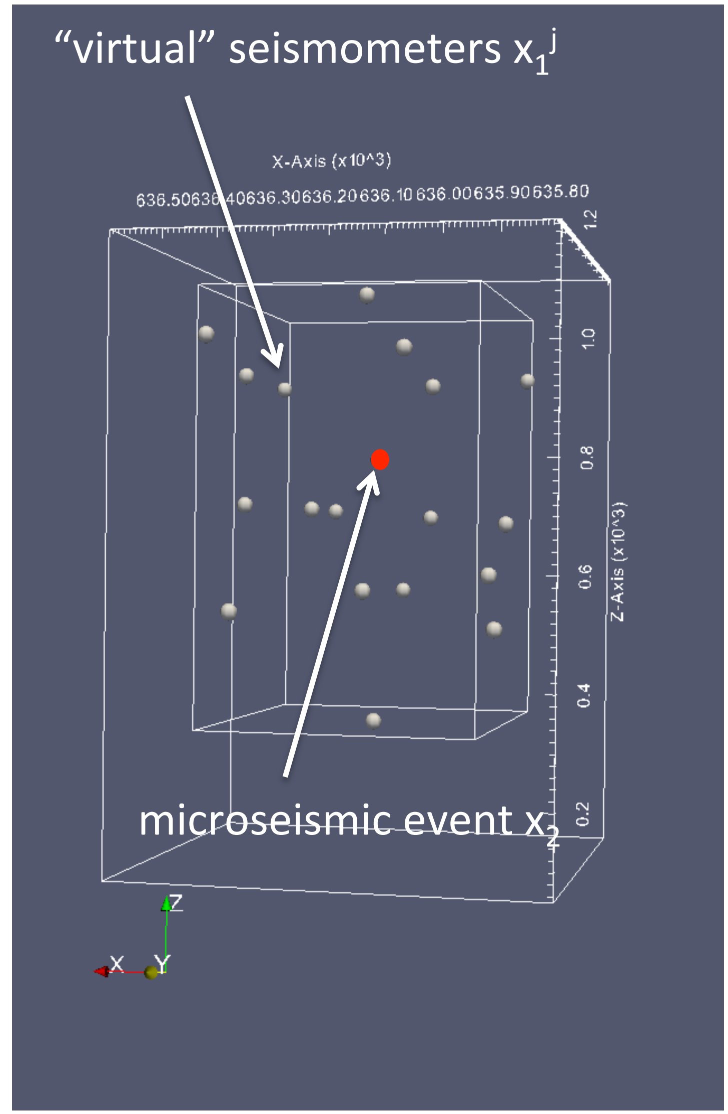


Figure: SpecFEM model of Newberry Geothermal Field



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.
- Think ahead to "Large-N" monitoring deployments and novel monitoring technologies.

Acknowledgements

- This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. Funding was provided by the DOE Office of Fossil Energy, Carbon Sequestration Program.

- 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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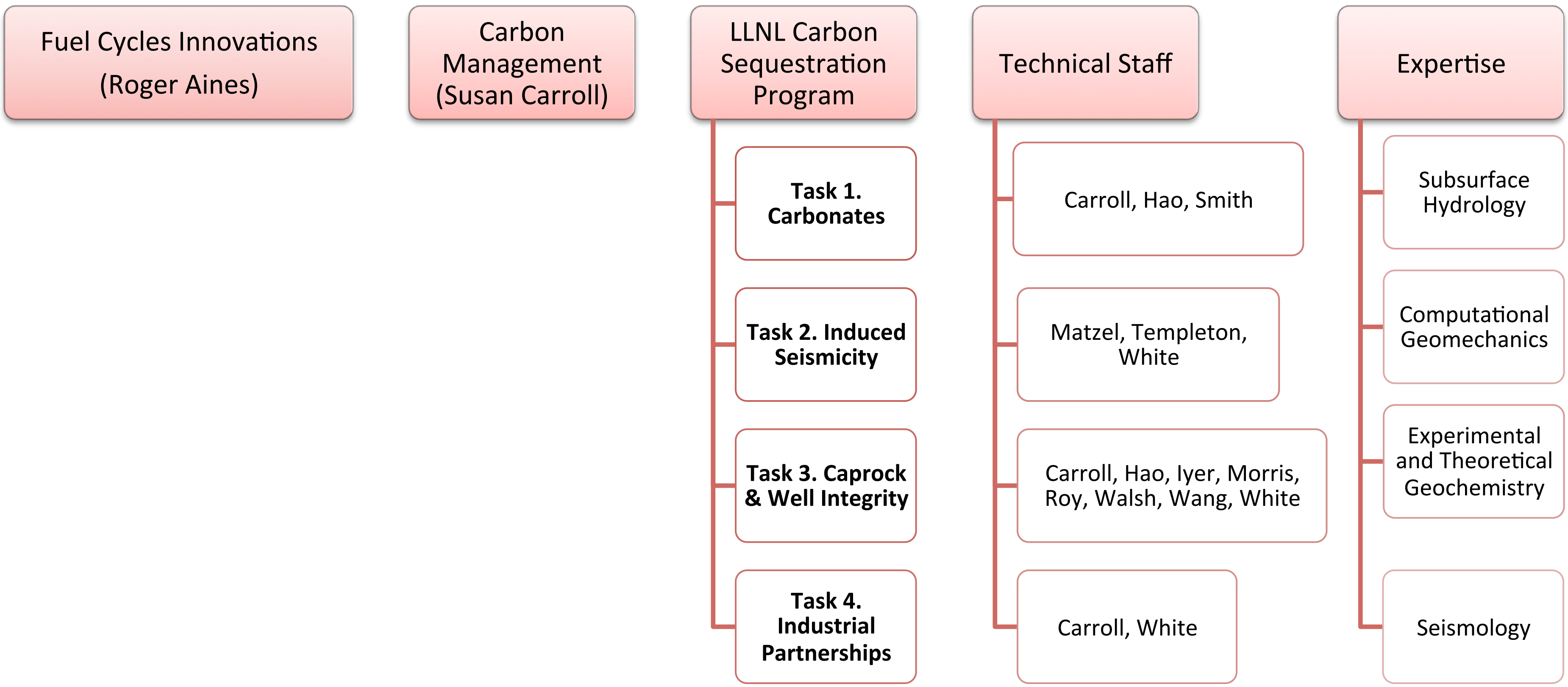
Appendix: Program Management

Org Chart


Fuel Cycles Innovations (Roger Aines)
Carbon Management (Susan Carroll)
LLNL Carbon Sequestration Program
Technical Staff
Expertise
Task 1. Carbonates
Task 2. Induced Seismicity
Task 3. Caprock & Well Integrity
Task 4. Industrial Partnerships
Carroll, Hao, Smith
Matzel, Templeton, White
Carroll, Hao, Iyer, Morris, Roy, Walsh, Wang, White
Carroll, White
Subsurface Hydrology
Computational Geomechanics
Experimental and Theoretical Geochemistry
Seismology

Project Timeline for FEW0191

Task	Milestone Description*	Project Duration	Start : Oct 1, 2014				End: Sept 30, 2017							Planned Start Date	Planned End Date	Actual Start Date	Actual End Date	Comment (notes, explanation of deviation from plan)
		Project Year (PY) 1				PY 2				PY 3								
		Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12					
1.1	Calibrate Reactive Transport Model						x							1-Oct-14	30-Mar-15			
1.2	Calibrate NMR Permeability Estimates						x							1-Oct-14	30-Mar-15			
1.3	Scale Reactive Transport Simulations from the core to reservoir scale										x			1-Jul-15	28-Feb-17			
1.4	Write topical report on CO2 storage potential in carbonate rocks												x	1-Dec-16	30-Sep-17			
2.1	Algorithm development and testing				x									1-Oct-14	30-Sep-15			
2.2	Array design and monitoring recommendations								x					1-Oct-15	30-Sep-16			
2.3	Toolset usability and deployment												x	1-Oct-16	30-Sep-17			
3.1	Analysis of monitoring and characterization data available from the In Salah Carbon Sequestration Project				x									1-Dec-14	30-Sep-15			
3.2	Wellbore model development				x									1-Oct-14	30-Sep-15			
3.3	Analysis of the full-scale wellbore integrity experiments										x			1-Mar-14	28-Feb-17			
3.4	Refining simulation tools for sharing with industrial partners												x	1-Oct-16	30-Sep-17			
4.1	Engage with industrial partnerships		x											1-Oct-14	28-Feb-15			Future tasks pending discussions with industrial partners
4.2	Develop work scope with industrial partners				x									1-Mar-14	30-Sep-15			

* No fewer than two (2) milestones shall be identified per calendar year per task

Bibliography

① Matzel et al. [2014] Microseismic techniques for managing induced seismicity at carbon storage sites. Energy Procedia 63:4297-4304.

② White and Foxall [2014]. A phased approach to induced seismicity risk management. Energy Procedia 63:4841-4849.

③ Buscheck et al. [2014]. Pre-injection brine production for managing pressure in compartmentalized reservoirs. Energy Procedia 63.

Appendix: Backup Slides