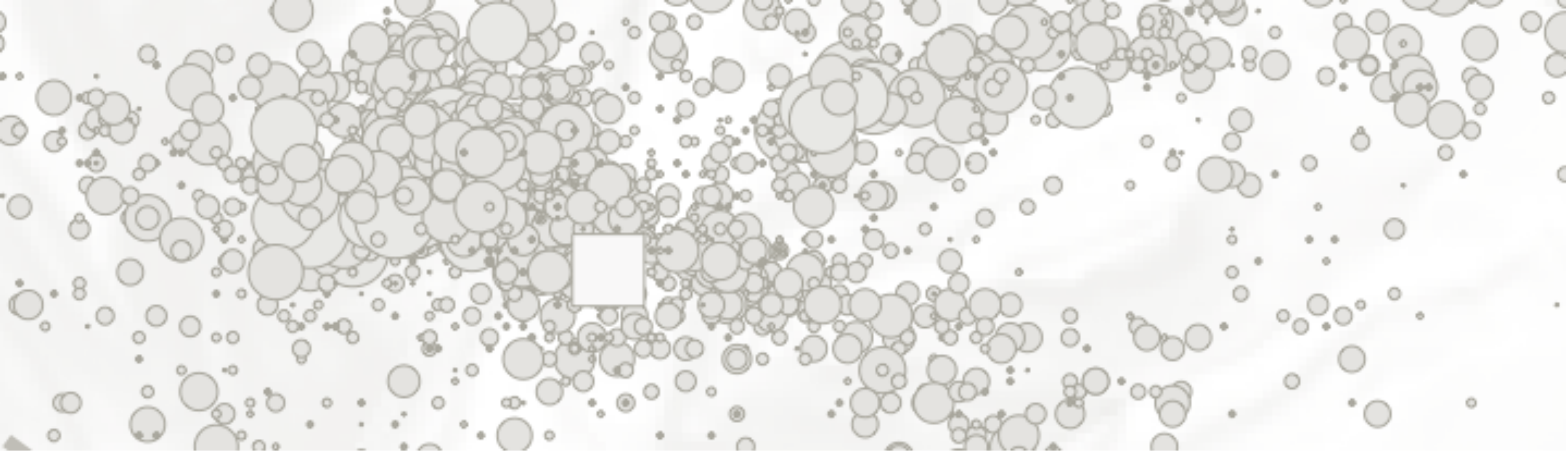


Microseismic processing for induced seismicity management at carbon storage sites

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

Project Number:
FWP-FEW0174-Task 1B & FWP-FEW0191-Task 2

Lawrence Livermore National Laboratory

Carbon Storage R&D Review Meeting, Pittsburgh, 18 August 2015

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.

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.

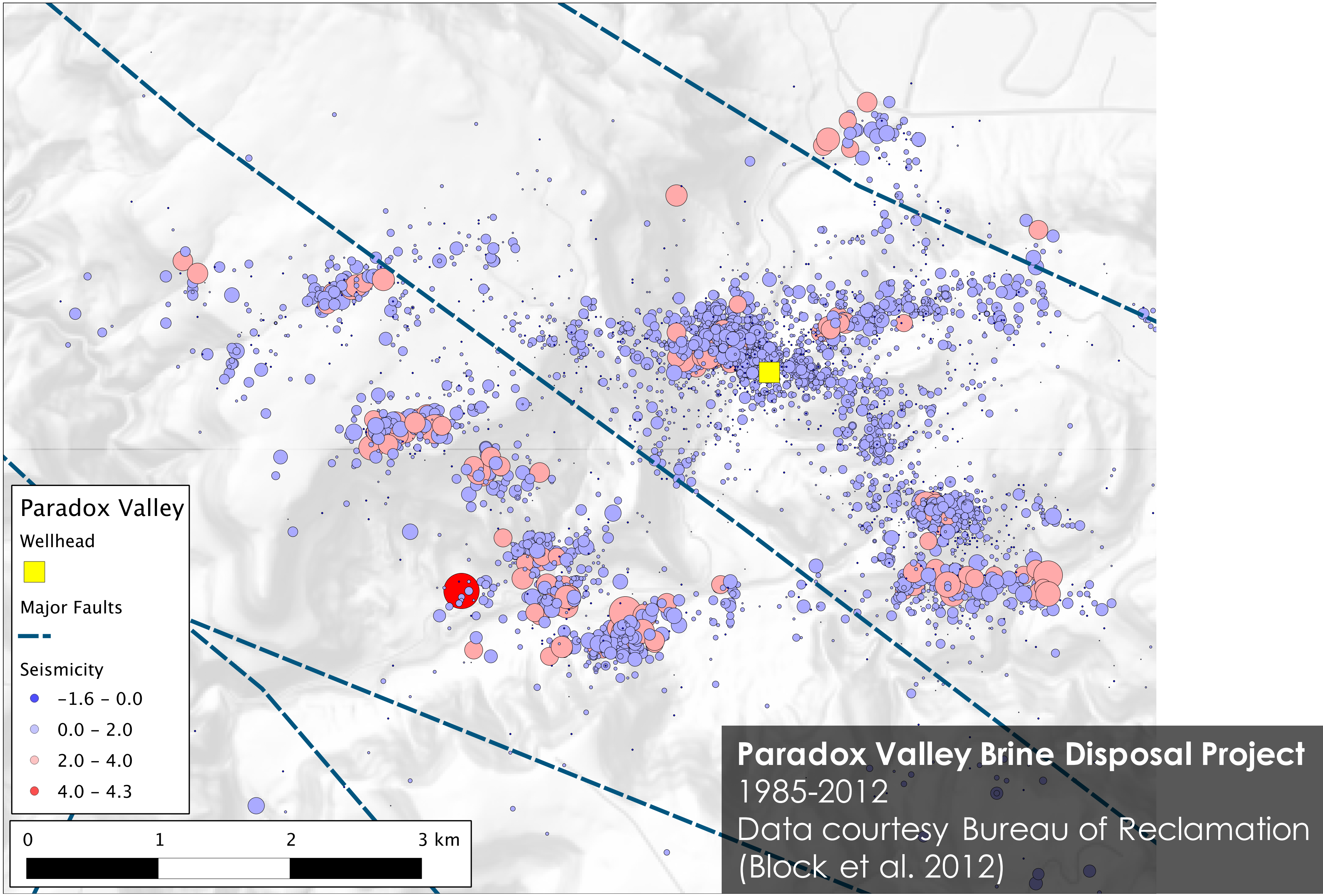
② The relationship between injection rate and seismic activity at a given site is complex.

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

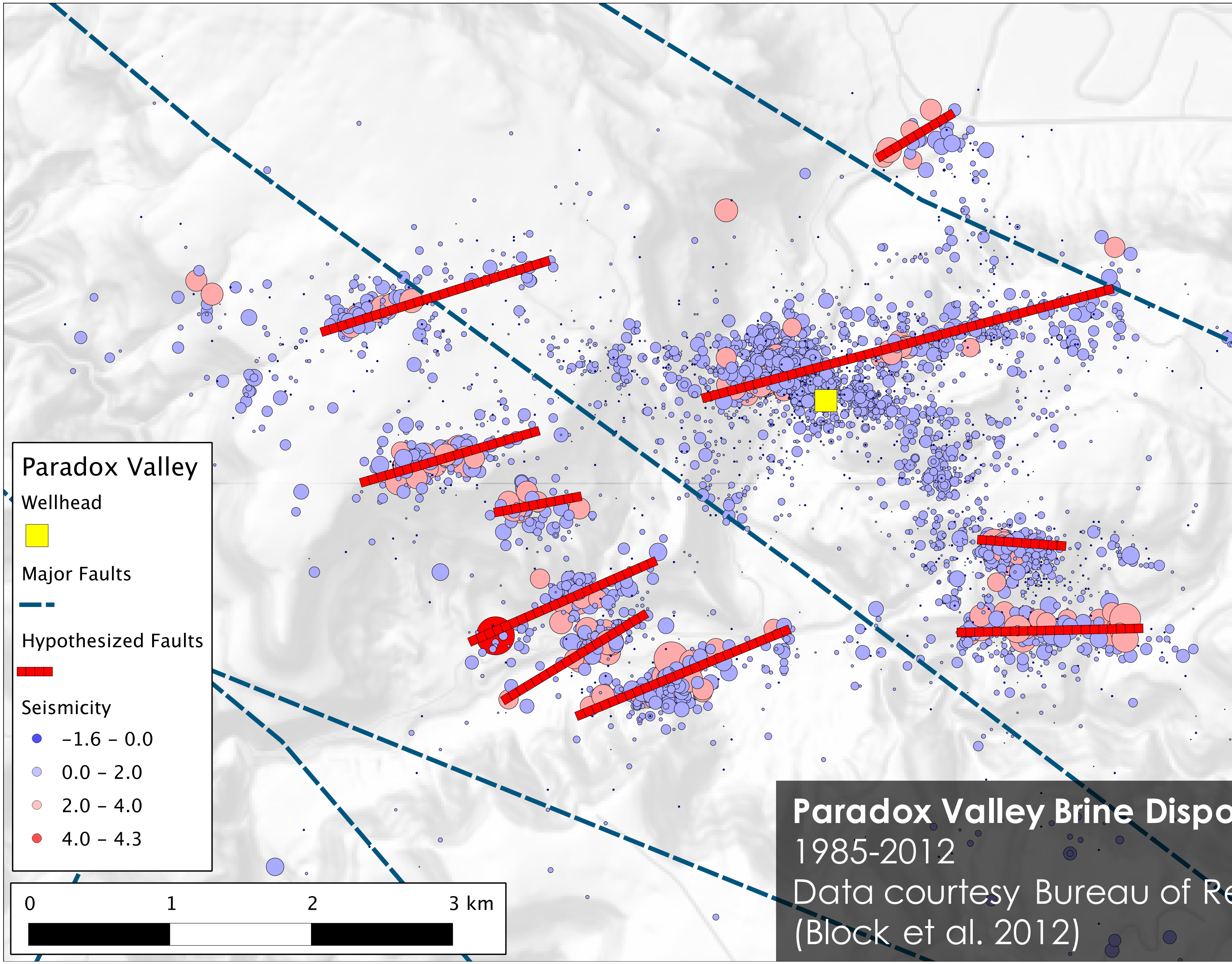
③ The knobs we can turn to reduce seismicity are limited.

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

Faster detection of previously unobserved faults can help lower seismic risk

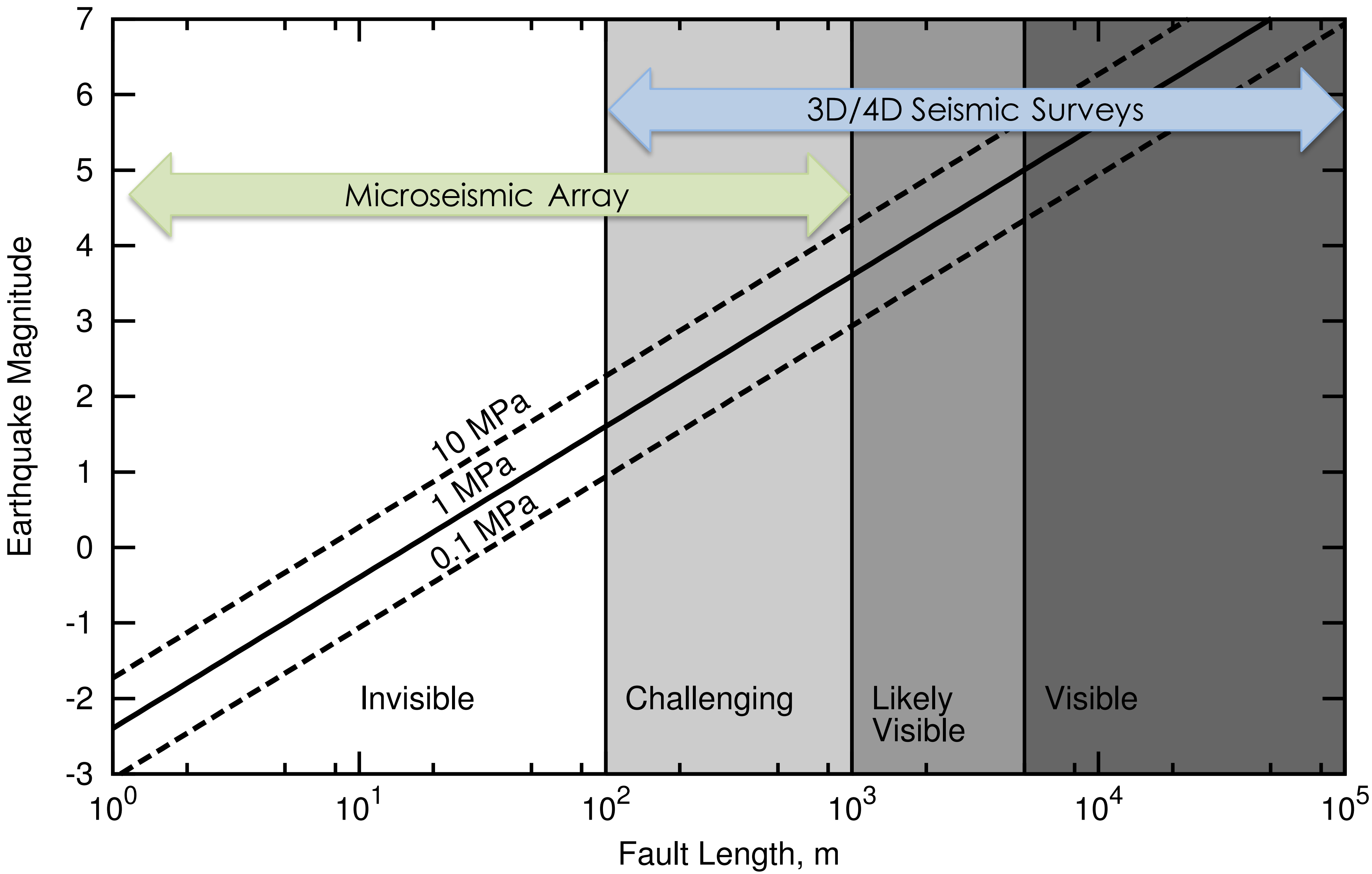


Faster detection of previously unobserved faults can help lower seismic risk

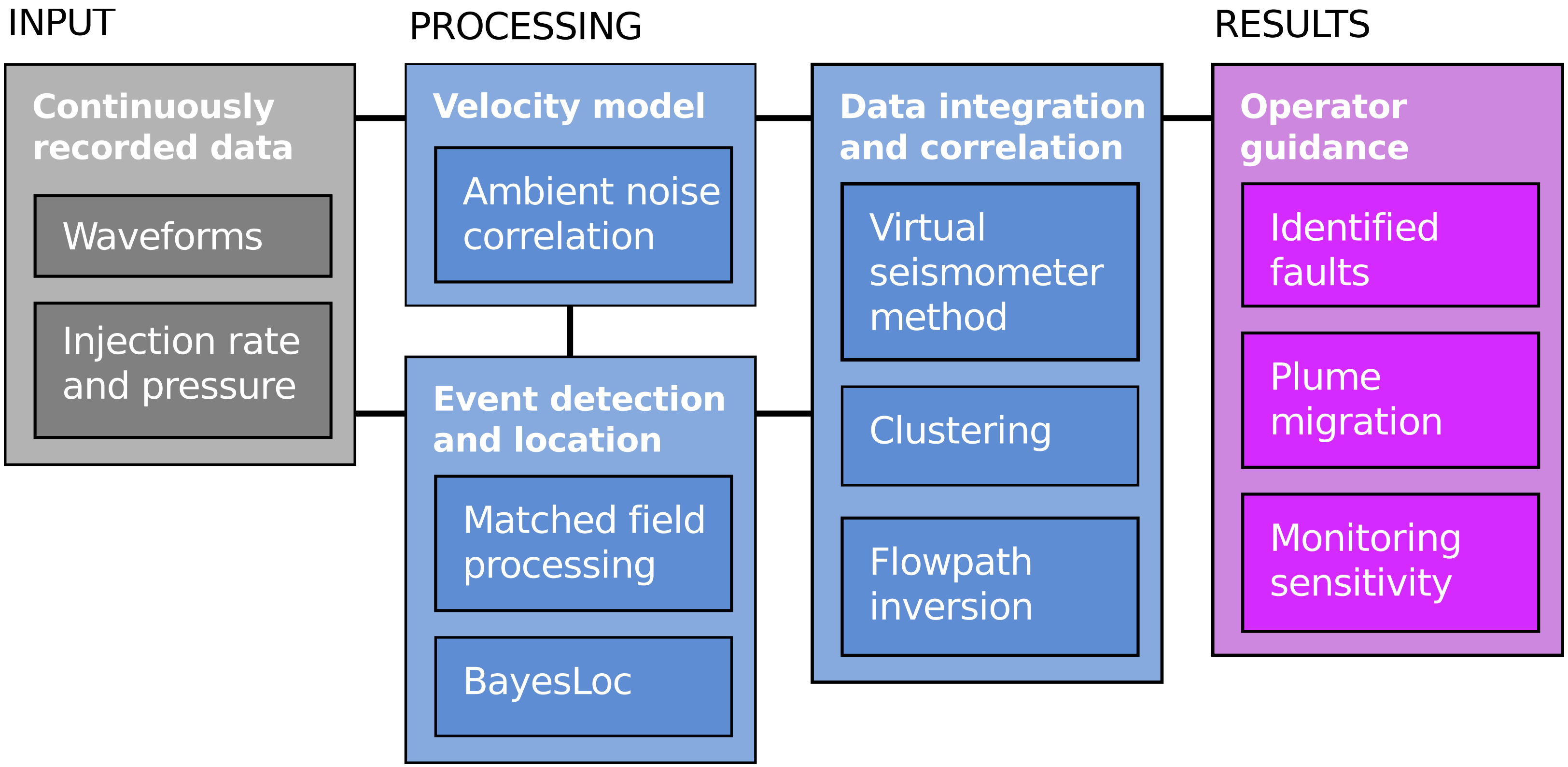


Paradox Valley Brine Disposal Project
1985-2012
Data courtesy Bureau of Reclamation
(Block et al. 2012)

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

Task Status

① Data-set acquisition and preprocessing	**Complete**	
② Active pressure management study	**Complete**	
③ CCS-analog site studies	**90%**	Tool Development
④ Illinois-Decatur study (USGS data)	**15%**	Tool Development
⑤ Toolset packaging and deployment	**FY16 + FY17**	

Staff

Seismology

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- Moira Pyle
- Dennise Templeton

Reservoir Eng.

- Joshua White

Ambient Noise Correlation

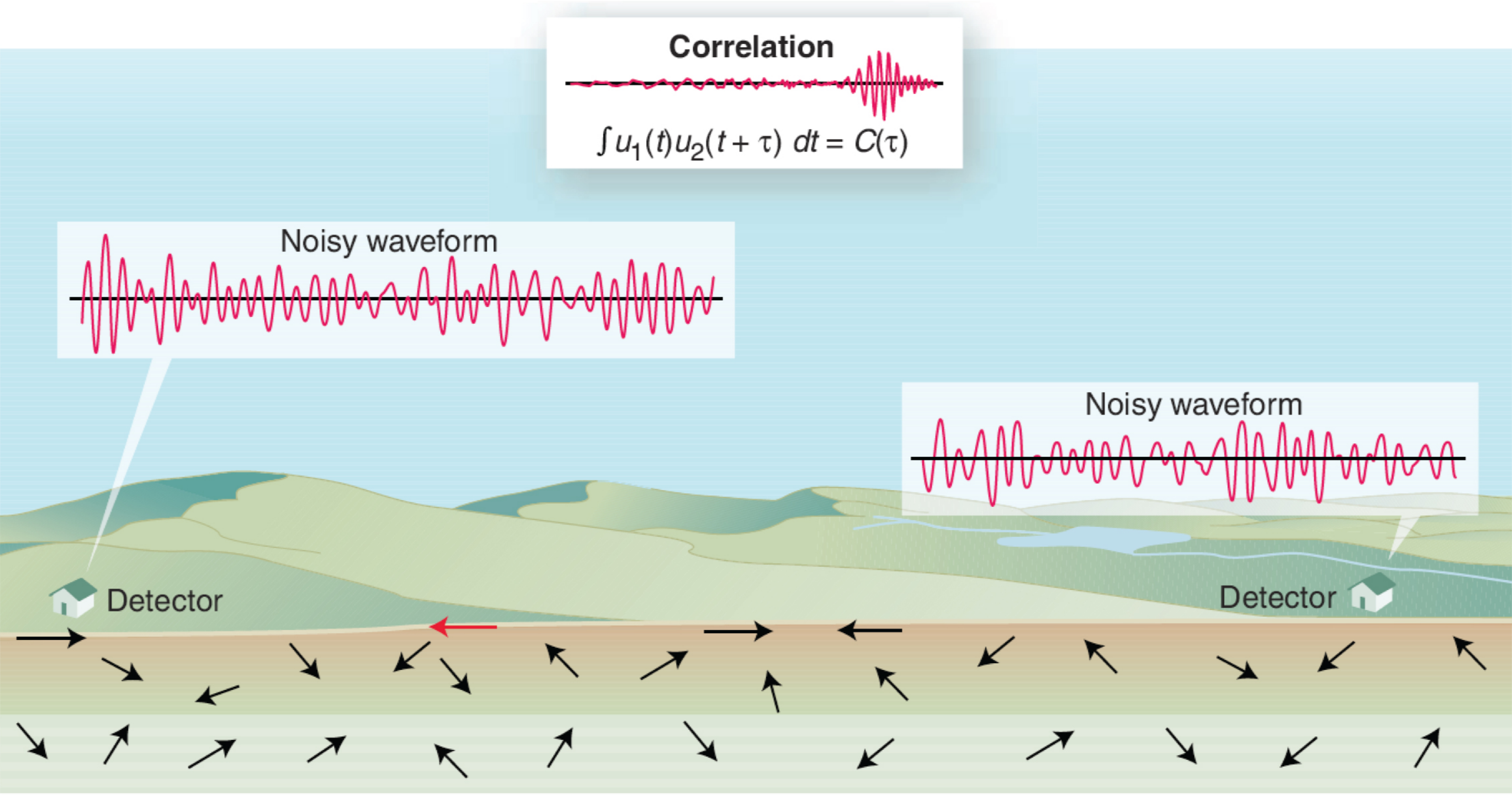
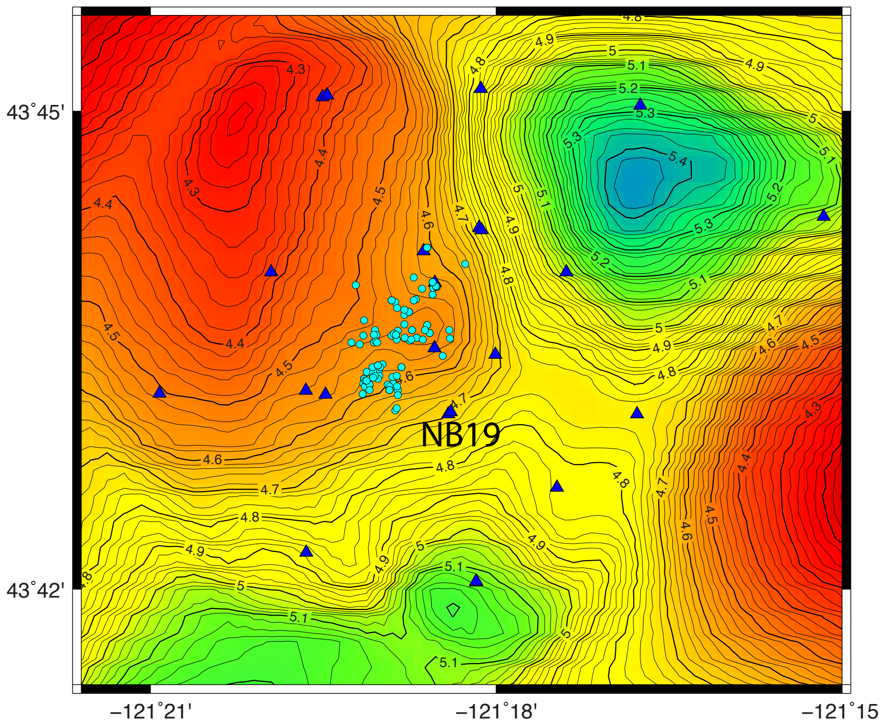
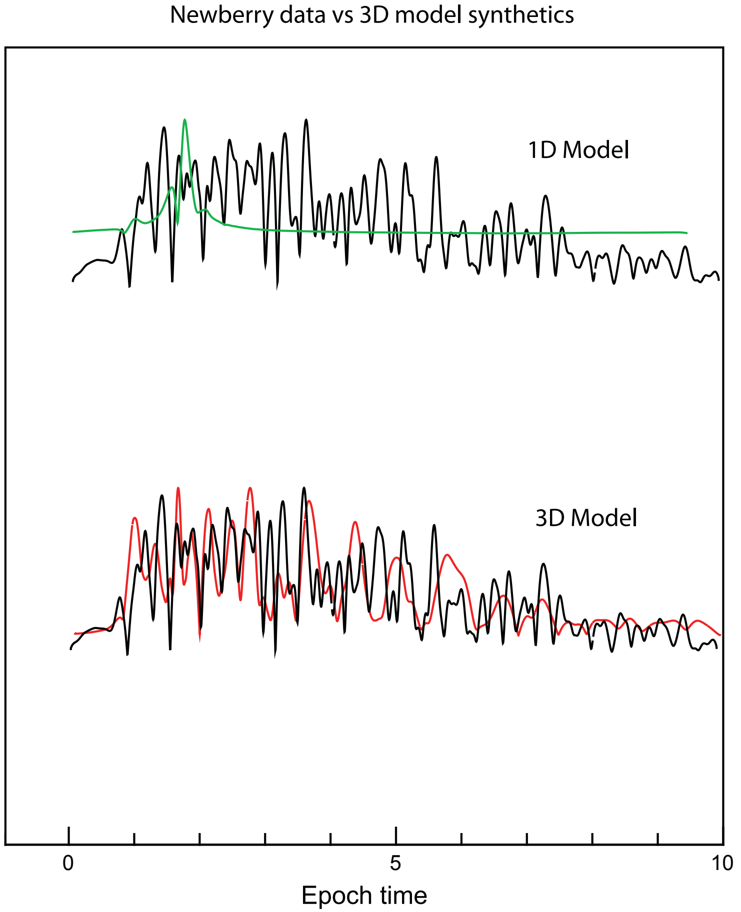


Figure: Schematic illustration of noise correlation principle from Weaver [2005].

We can use ANC to develop 3D velocity and attenuation models at sites where good station geometry is available



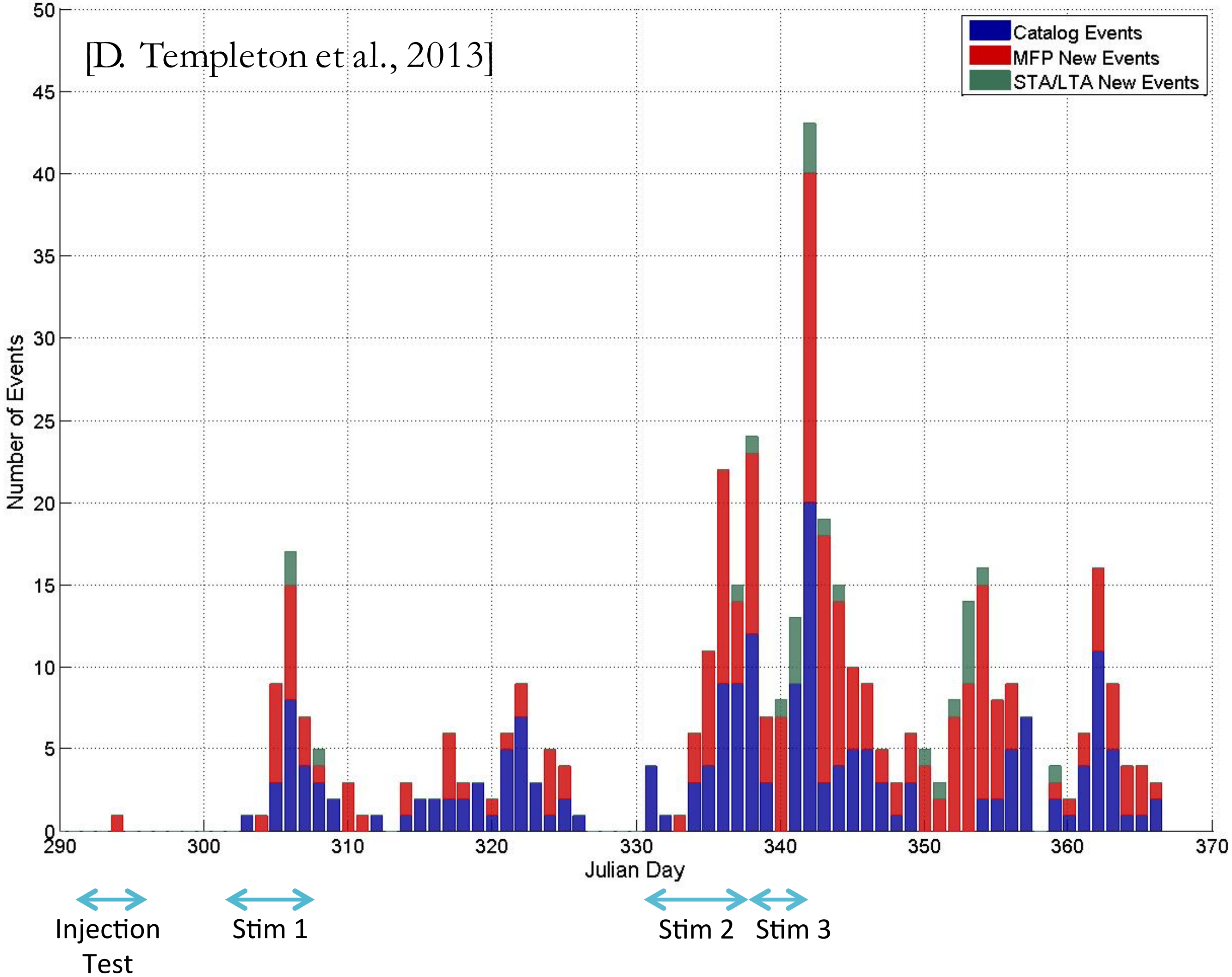
Newberry Geothermal P-velocity model at 2.5 km estimated using 1 month of recorded noise.



Current focus: We are developing a 3D velocity model for Illinois-Decatur Project using data from the USGS surface / shallow borehole array.

Also exploring 4D potential of the method.

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

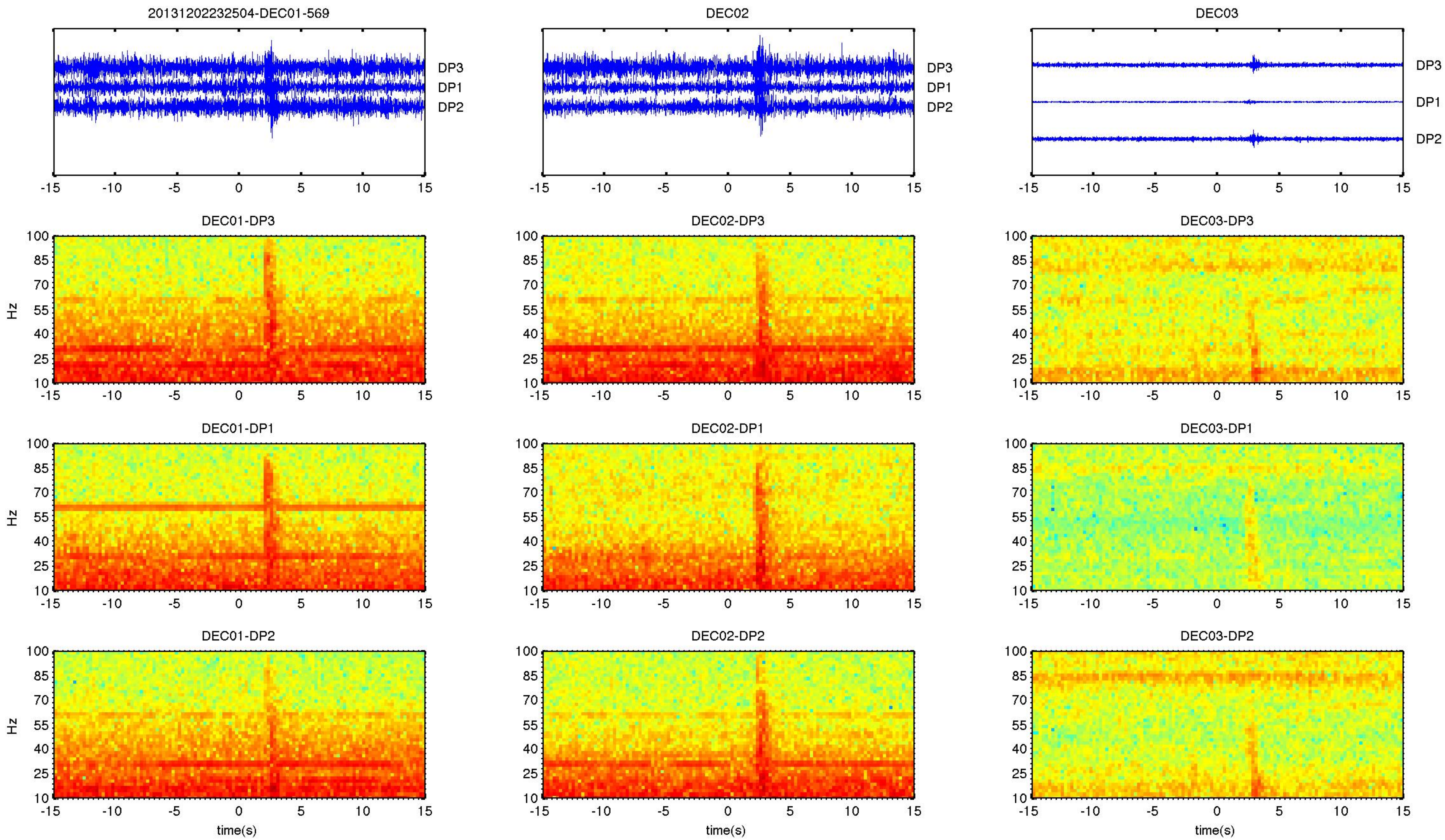


Figure: Waveform data from USGS shallow borehole recording at the Illinois-Decatur Project. This event was large enough to be detected by both threshold triggering and template matching.

Matched field processing can improve small event detection in noisy data

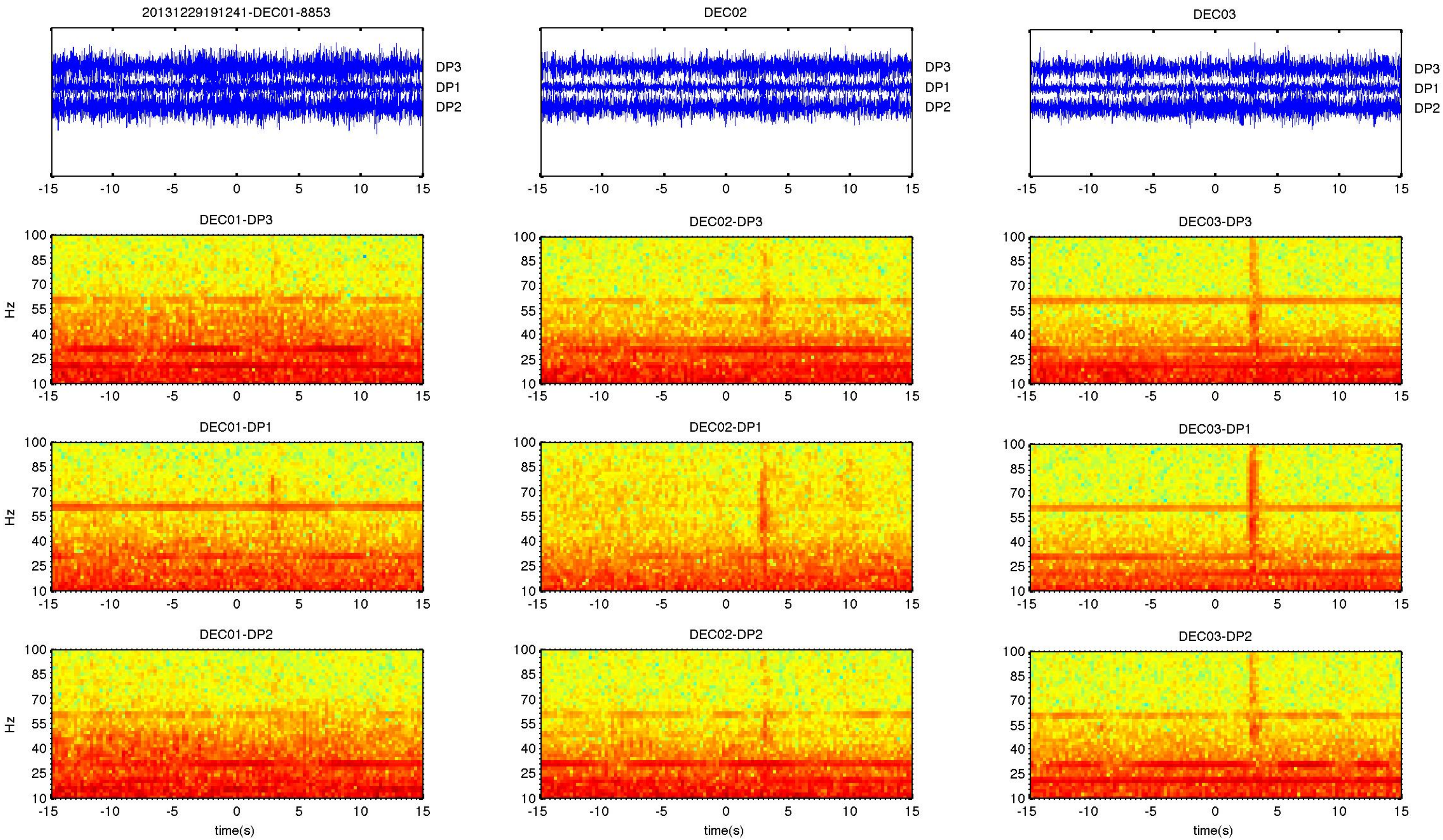
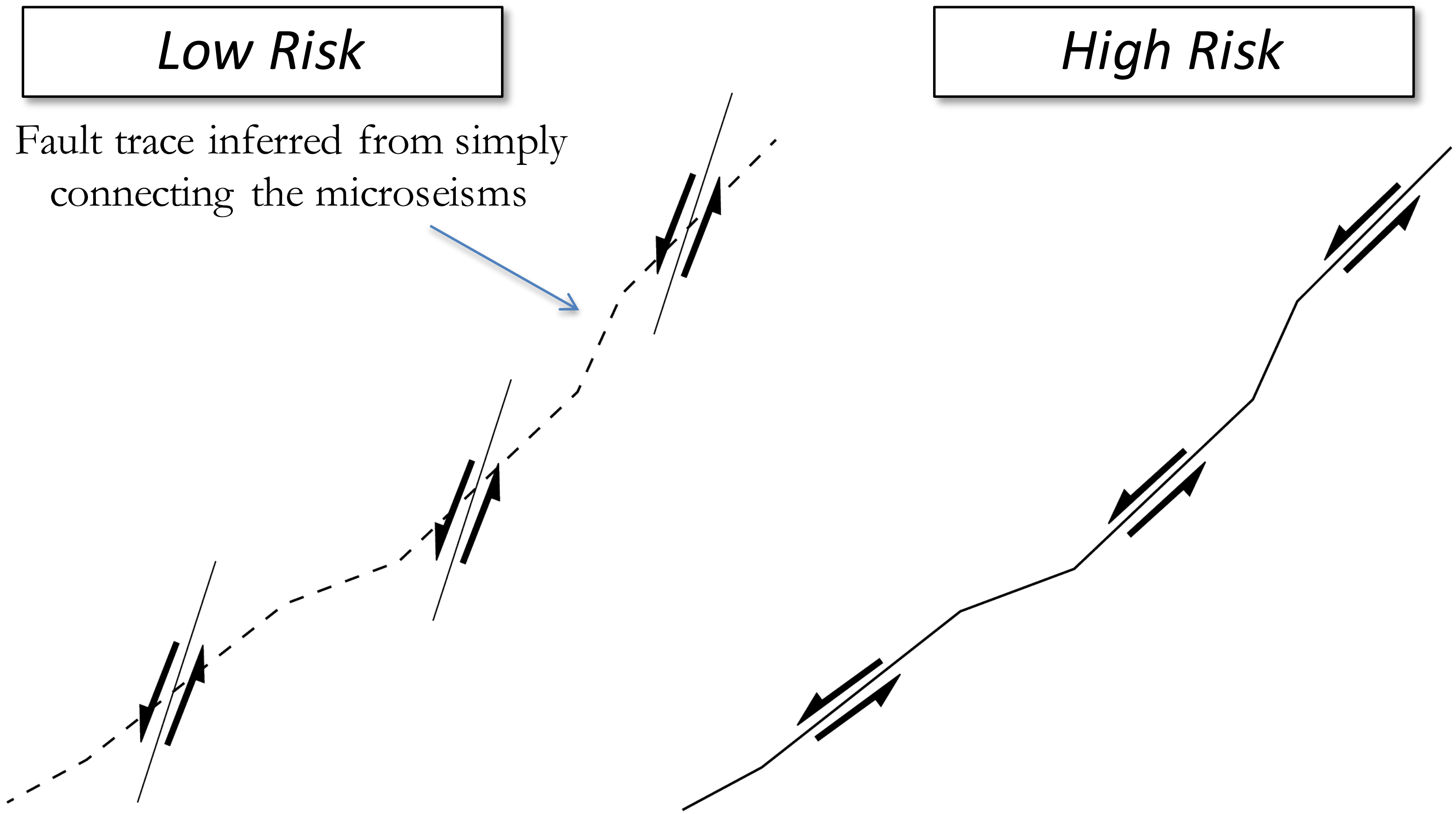


Figure: Waveform data from USGS shallow borehole recording at the Illinois-Decatur Project. This event was missed in the original USGS processing, but detected by MFP.

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

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

1. Record microevents x_1^j and x_2 at the (surface) seismometers
2. Cross-correlate waveforms of every source x_1^j with x_2
3. Calculate strain rates of each event x_1^j as recorded by x_2
4. Invert for moment tensor of x_2

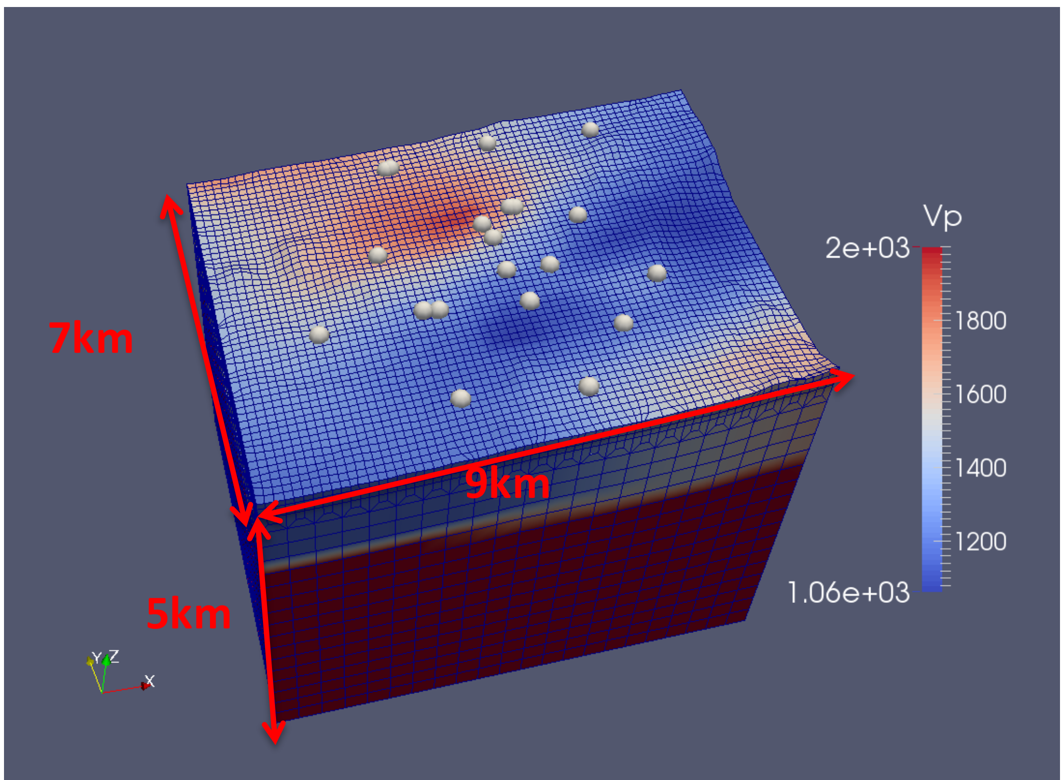
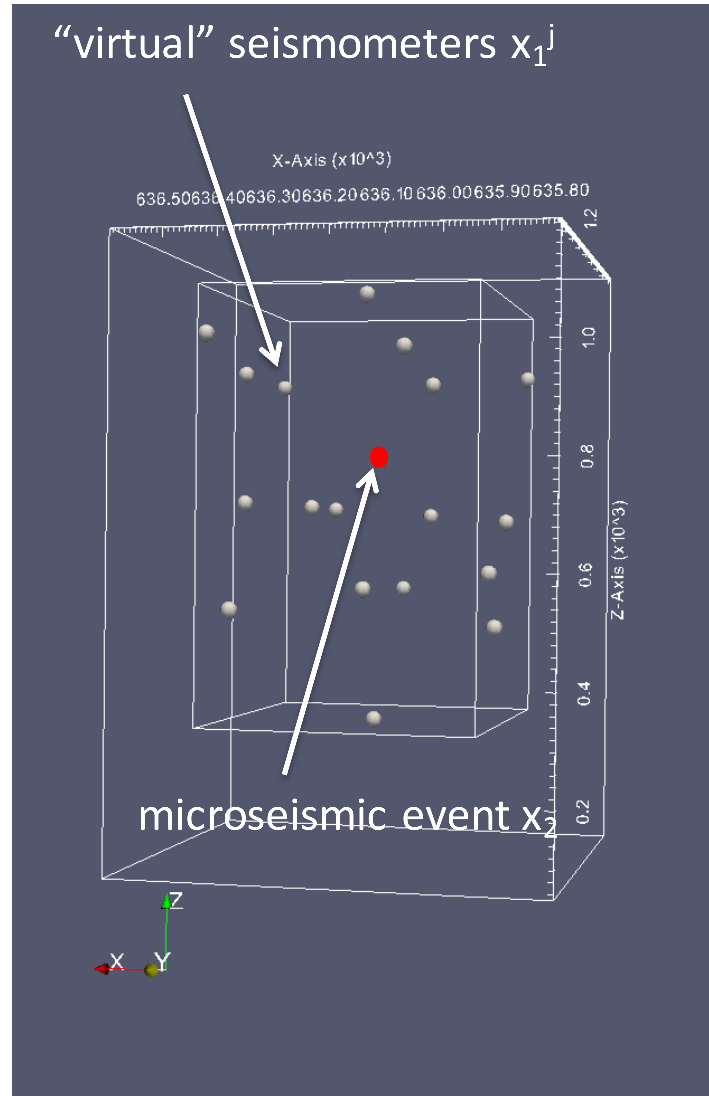


Figure: SpecFEM model of Newberry Geothermal Field



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 (possibly 4D) velocity and attenuation models (ANC)
  - Re-processed event catalogs (MFP)
  - Re-located events with location uncertainties (BayesLoc)
  - Moment tensor analyses (VSM + AI)

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 **Ultimate goals:**

- Integrate microseismic and rate / pressure data into a "real-time" processing toolkit to support Adaptive Risk Management.
- Think ahead to "Large-N" monitoring deployments.
- Help us get to gigatonne-scale storage safely and responsibly!

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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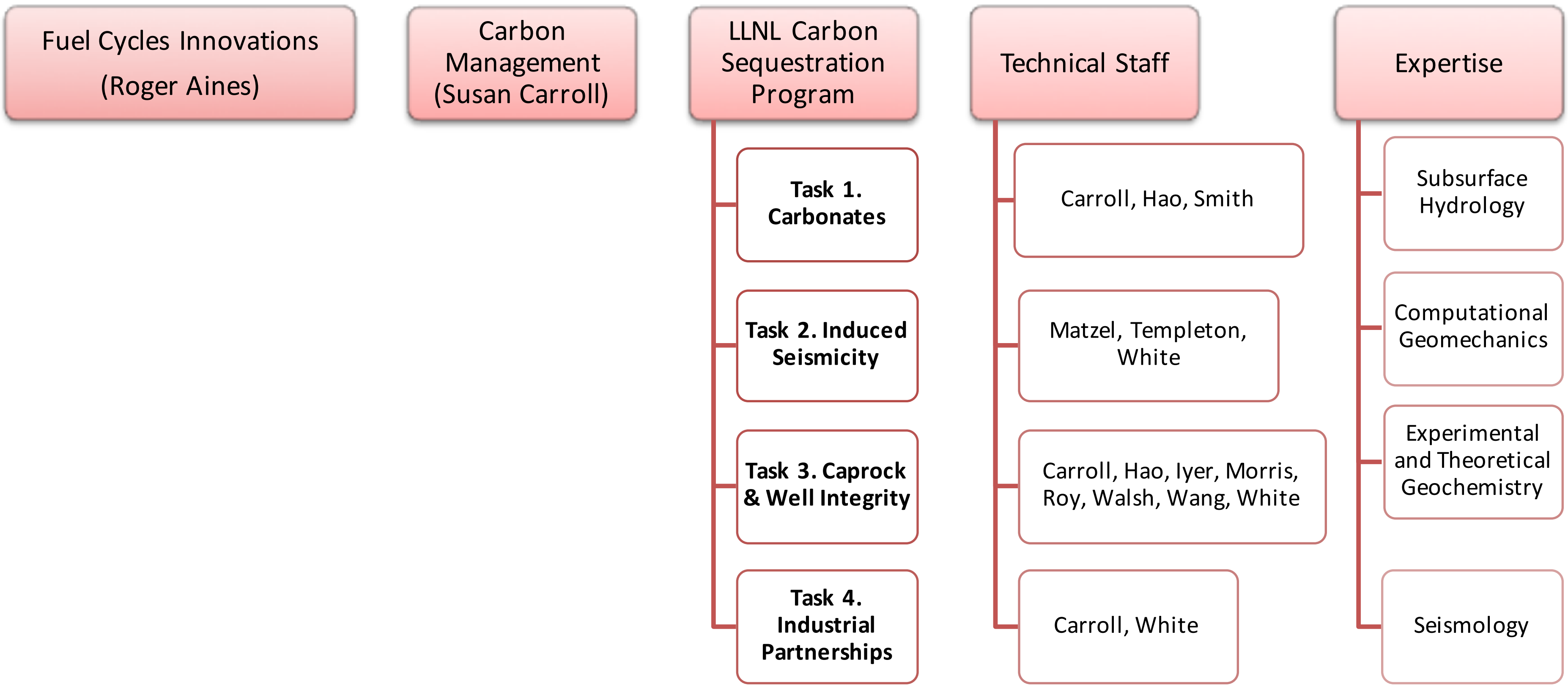
Appendix: Program Management

Org Chart



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

Basel EGS Data

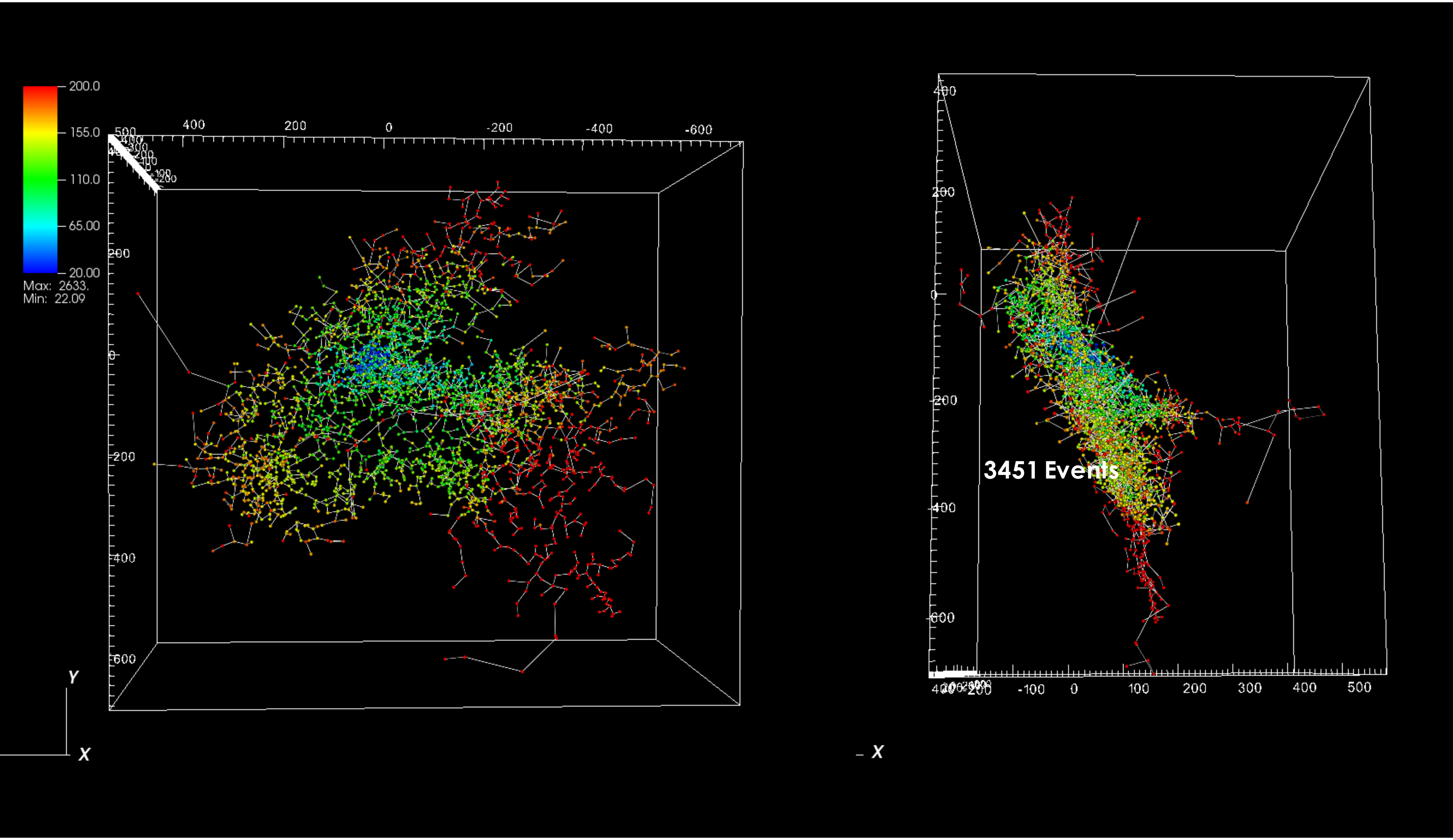


Figure: Seismicity reveals several linear (fault) structures in the Basel EGS dataset.

Dynamic seismic forecasting and hazard assessment

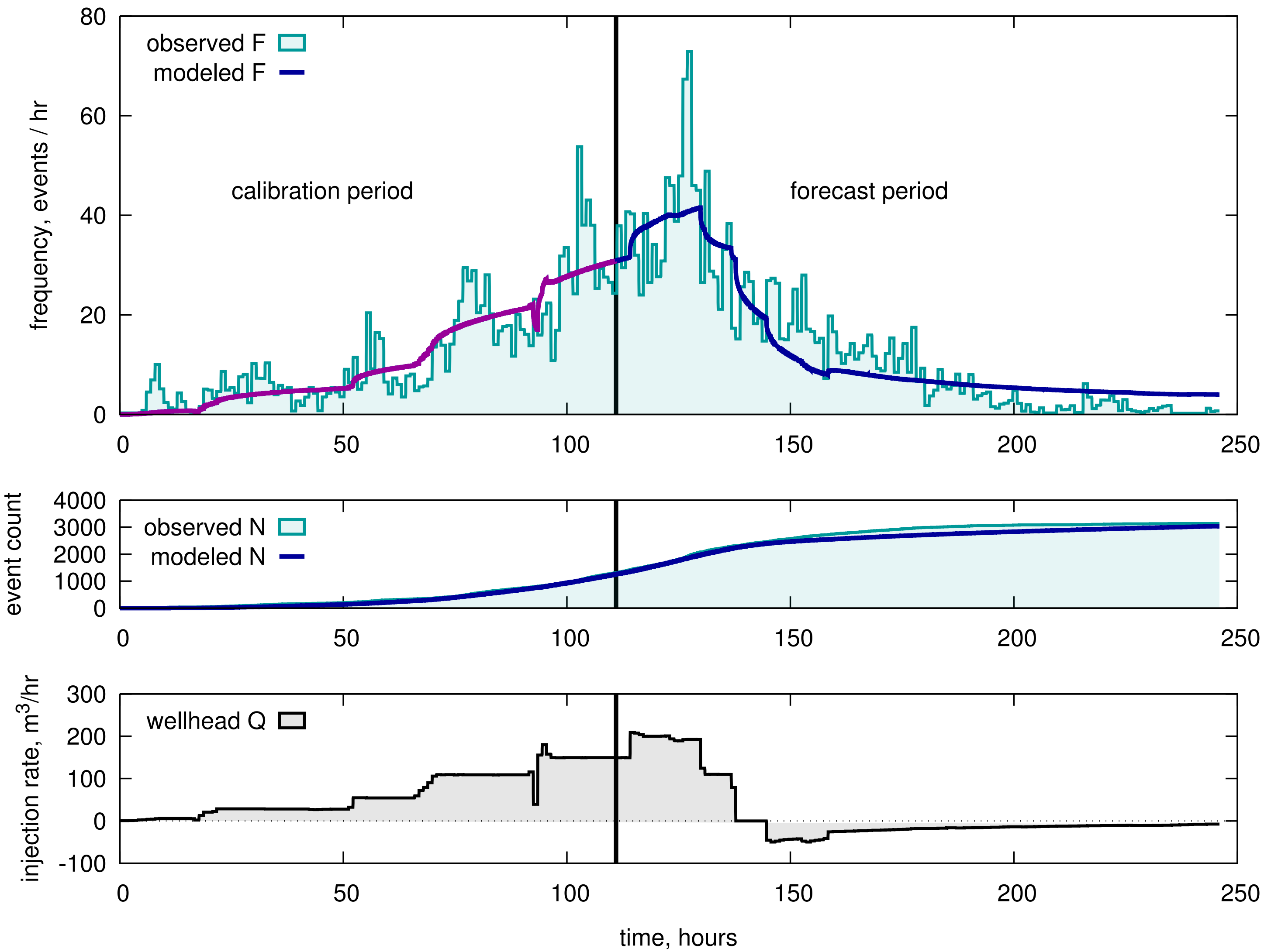
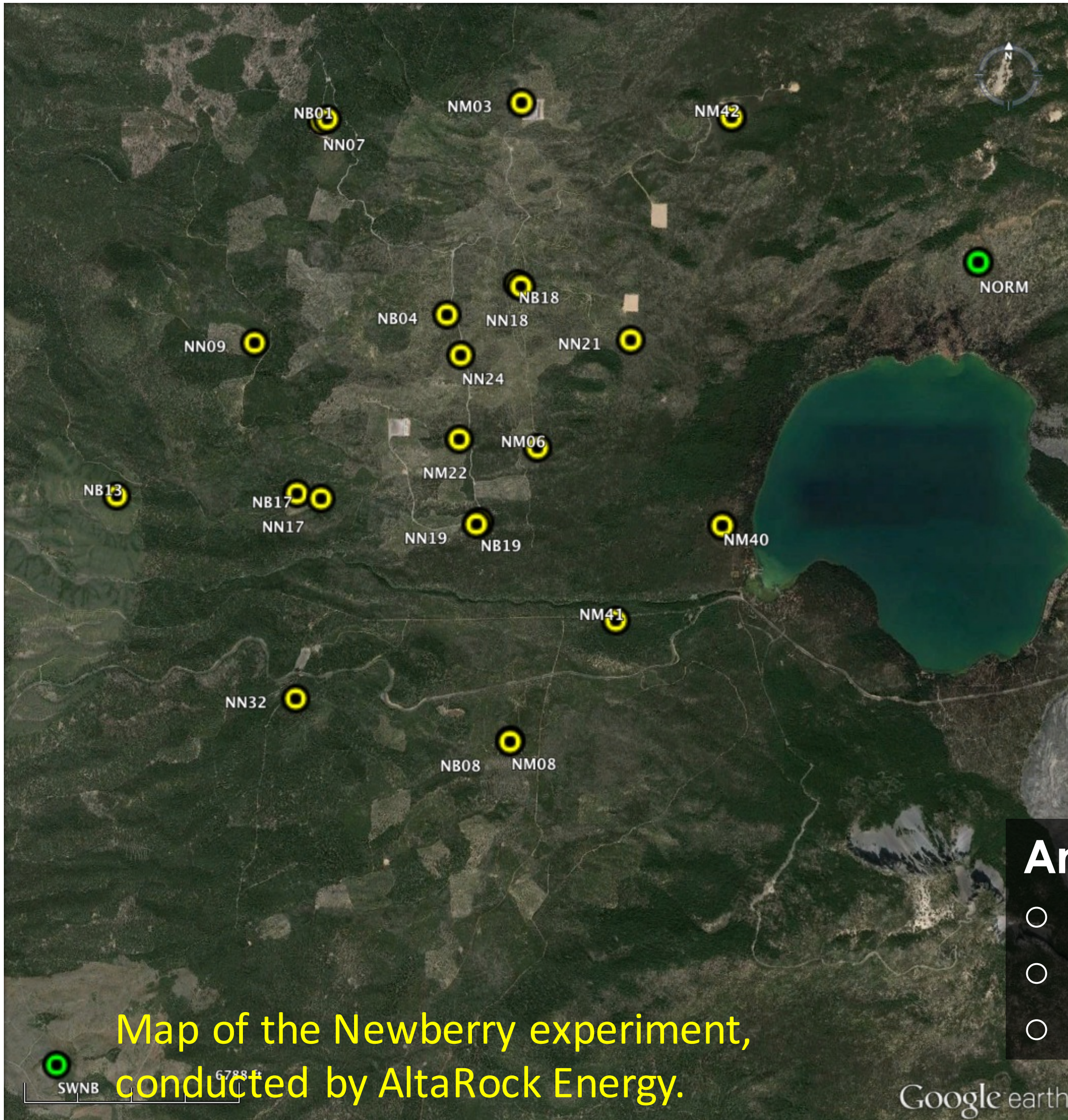


Figure: Tool to estimate future event frequency as a function of injection rate. Dataset from the Basel Enhanced Geothermal Project.

Creating a 3D model of the Newberry Geothermal Site



Map of the Newberry experiment, conducted by AltaRock Energy.

Ambient noise correlation

- 1 month of data
- Depth resolution ~ 5 km
- Vp, Vs, estimate of Qs