Induced Seismicity:

Can it be good for your field?

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Objectives

1) To present methods that can extract a wealth of information from induced seismicity regarding the reservoir and production operations that may result in:
   - Improved reservoir characterization
   - Improved performance
   - Reduced cost
   - Mitigated risk
   - Increased safety

2) To reason that induced seismicity does not deserve a bad reputation, as the benefits outweigh the risks.
   - Yes, problematic events do occur, but they are rare and can be mitigated
   - Very few sites have the capability to produce a magnitude 5 earthquake

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What is Induced Seismicity?

An earthquake caused by changes in the stress field due to human activity.

Magnitude	Description	Effect
M<2	**Microearthquake**	**Not felt by humans**
2≤M<3	Minor	Smallest event humans can feel
3≤M<4	Minor	Very minor structural damage possible at very close distances
M>=4	Small	Minor structural damage possible at close distances

The vast majority of induced seismicity is too small to be felt by humans.

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What is Induced Seismicity?

Stimulation-Induced Seismicity	Unintended-Induced Seismicity
❖ Cause: injecting fluid into a reservoir under high pressure to open new or pre-existing fractures to increase permeability and flow volume (hydraulic stimulation) ❖ A by-product of a **DESIRED** result! ❖ Typically very small and unfelt by the public	❖ Cause: fluid injection/ withdrawal (pressure or temperature change), underground mining, reservoir impoundment, etc. ❖ An unintended result ❖ Typically very small and unfelt by the public
Basel, Switzerland Mag 3.4: EGS reservoir stimulation, large events resulted in the project cancellation	The Geysers Mag 4.6: Probably the best example of IS in geothermal

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Problematic Induced Seismicity

In 2008, residents near the Dallas-Ft. Worth airport began experiencing minor earthquakes, including a magnitude 3.3. Event locations were found to be in close proximity to a recently initiated waste-water injection well.

Combined with the knowledge of an inactive fault nearby and an absence of prior seismic activity, researchers found it likely that water injection triggered induced seismicity.

The events caused no real damage, but they drew large public concern and media attention.

Lesson: Injection into any reservoir, no matter how innocuous, should be carefully planned and monitored.

This is particularly true for the geothermal industry where production from and injection into fault zones is often the goal.

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Monitoring the Field

- Installation of a seismic monitoring network is the only way to know if induced microseismicity is occurring.

- The network can consist of an array of (near-)surface sensors, an array of borehole sensors near the reservoir depth, or a combination.

- **Careful array design is the key to monitoring success!**

- Ideally, the network should be installed prior to any field development to provide a seismic baseline.

- Not only will a seismic network make the operator aware induced seismicity is being generated, but this information may allow improved reservoir characterization and performance.

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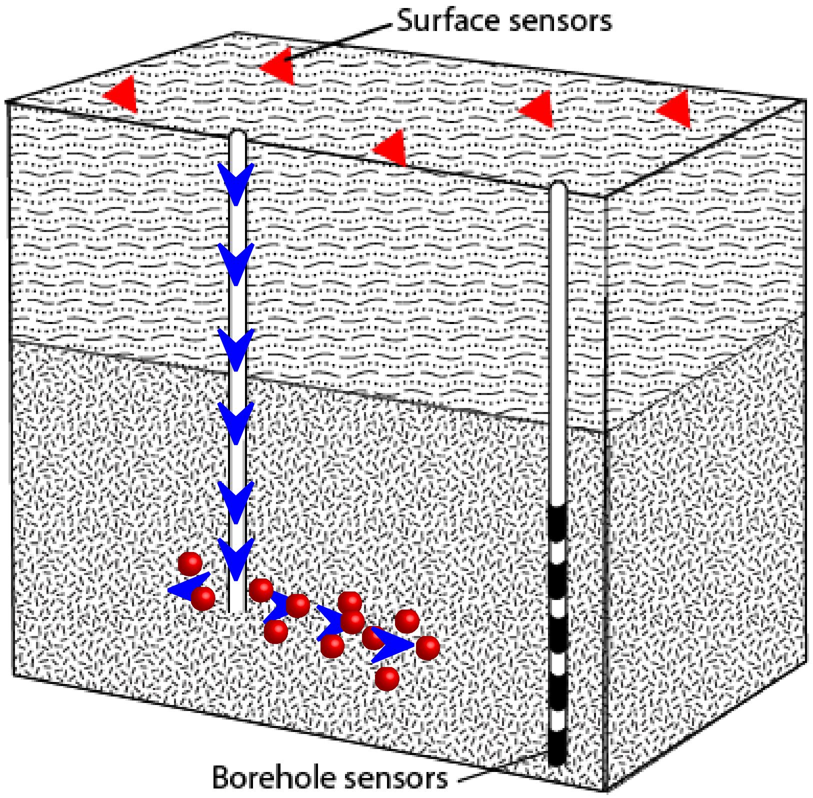
Making Induced Seismicity Work for You

Detecting and locating induced seismicity can aid:

- Mapping zones of fluid flow
- Identifying fluid flow pathway problems
- Determining proper injection pressures
- Reducing the likelihood of a problematic event
- Visualizing time-lapse (4-D) changes in the reservoir



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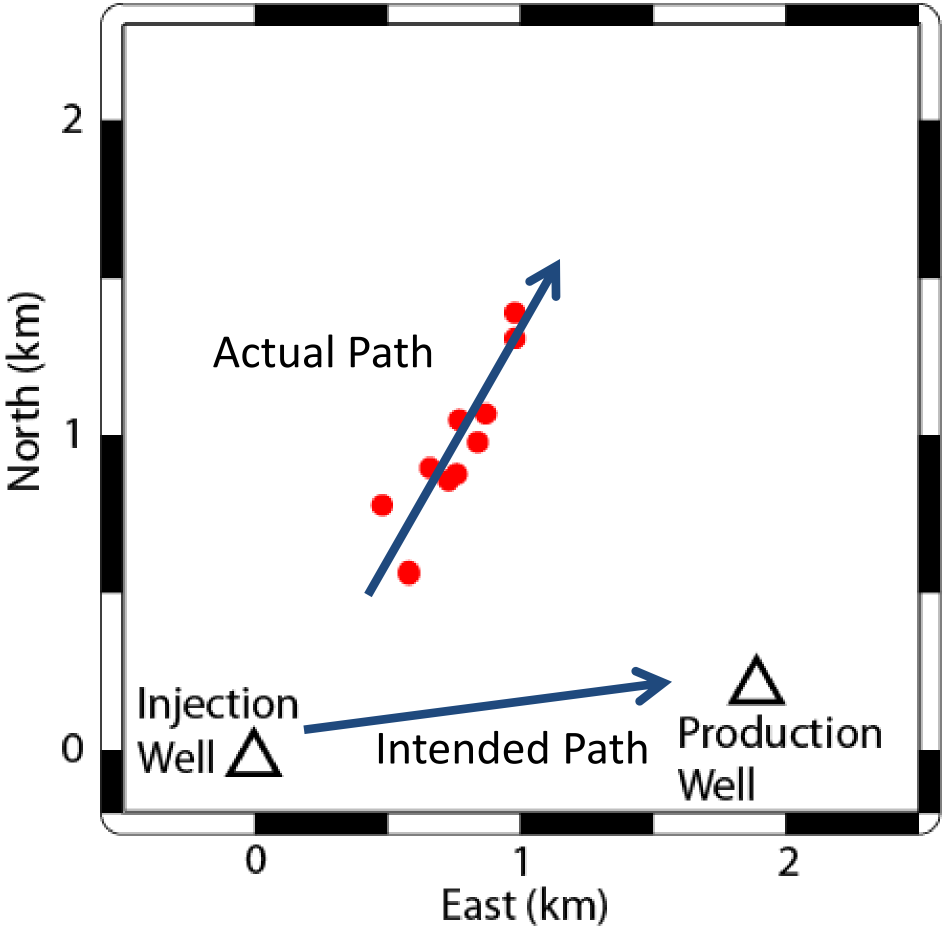
Detecting and Locating Seismicity



- Mapping induced seismicity can show fluid flow pathways.
- It can also identify a fluid flow pathway problem.

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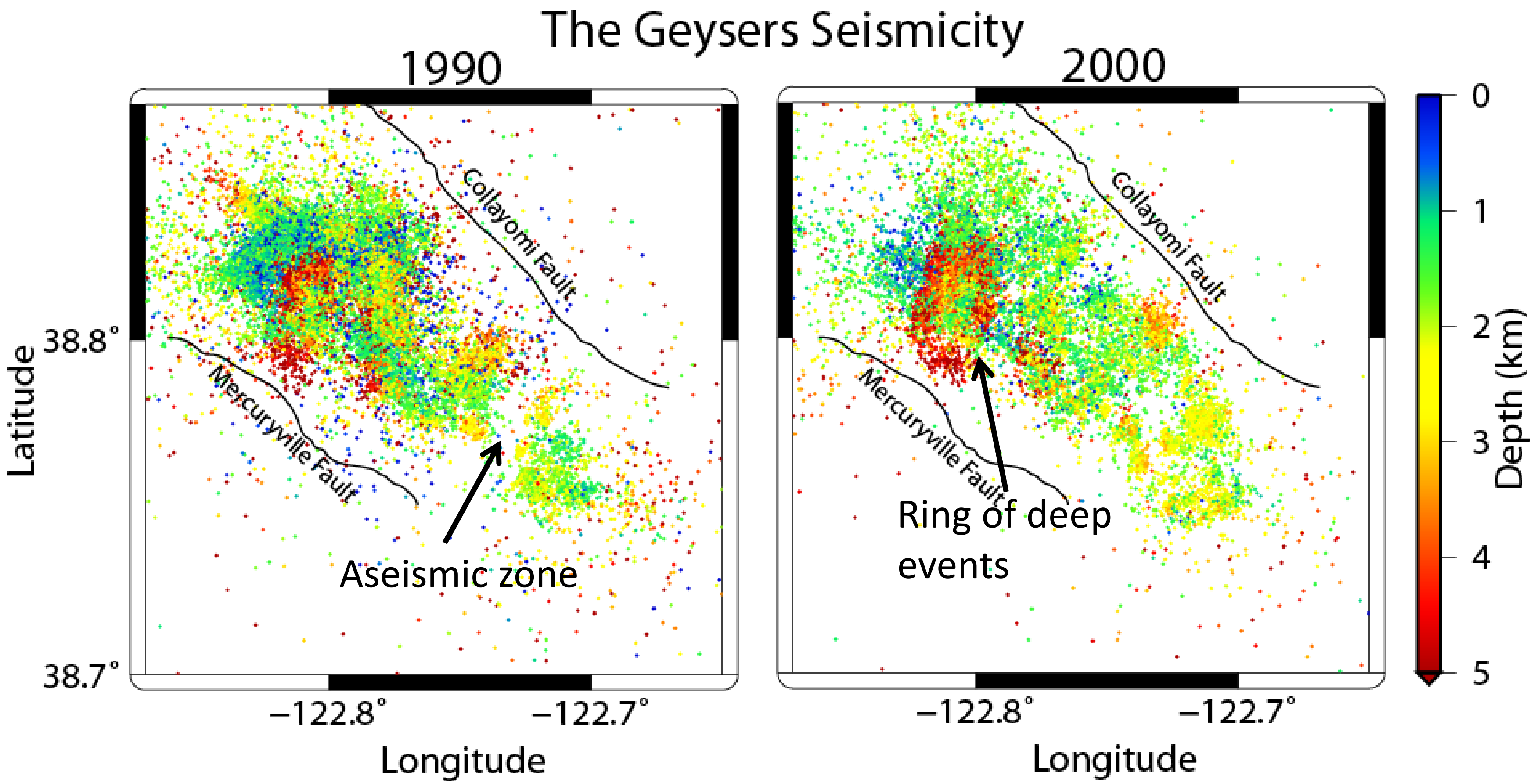
Detecting and Locating Seismicity



- Seismicity patterns and depths show variations from 1990 to 2000.
- Significant number of events occurring within close proximity to major faults.

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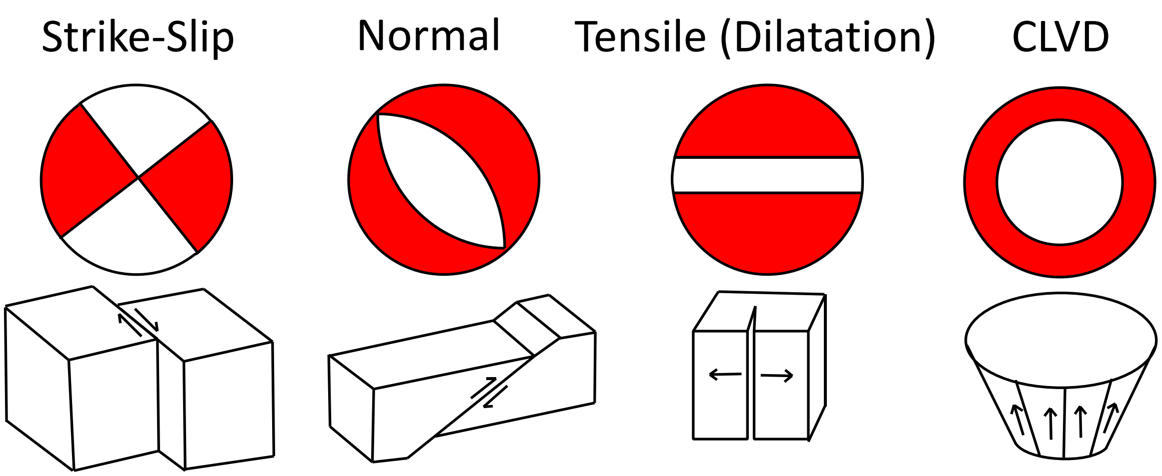
Moment Tensors & Focal Mechanisms

A moment tensor is a symmetric rank 2 tensor with 6 independent observations that represent the source function (e.g. motion along the fault) and event magnitude.

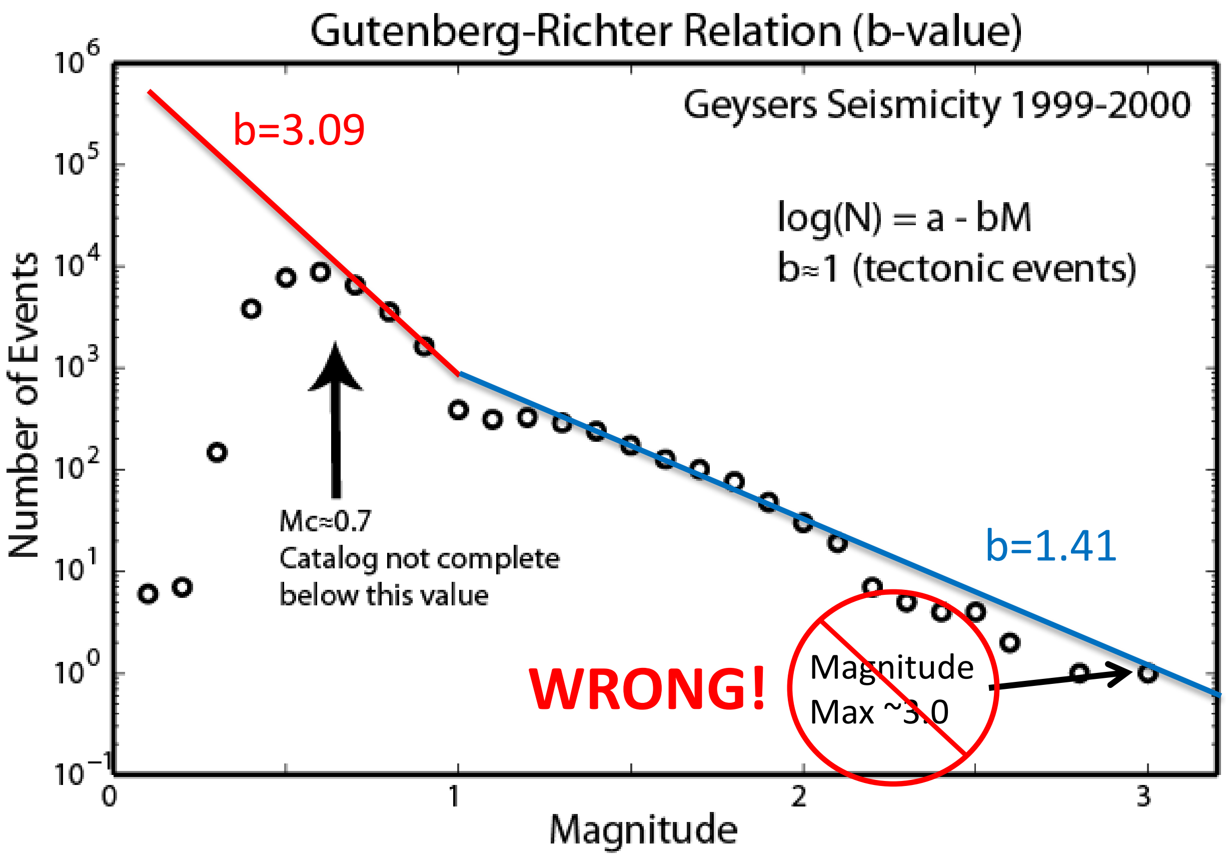
$$M = M_0 \begin{bmatrix} Mxx & Mxy & Mxz \\ Myx & Myy & Myz \\ Mzx & Mzy & Mzz \end{bmatrix}$$, where M_0 is the Seismic Moment.

$$M_w = \left(\frac{\log M_0}{1.5}\right) - 10.73$$, where M_w is the Moment Magnitude.

A focal mechanism, often called a beach ball diagram, is the most commonly presented solution. It represents only the motion along the fault. **The local stress field and hydraulic stimulation fracture type can be determined from this information.**



Maximum Magnitude



- Can help infer event type and largest possible event magnitude (Risk Management).
- Recent work indicates b-value can highlight fluid flow pathways as b-values decrease with distance from the injection point.
- Inverse relationship to differential stress, with largest magnitude events occurring in regions of low b-value.

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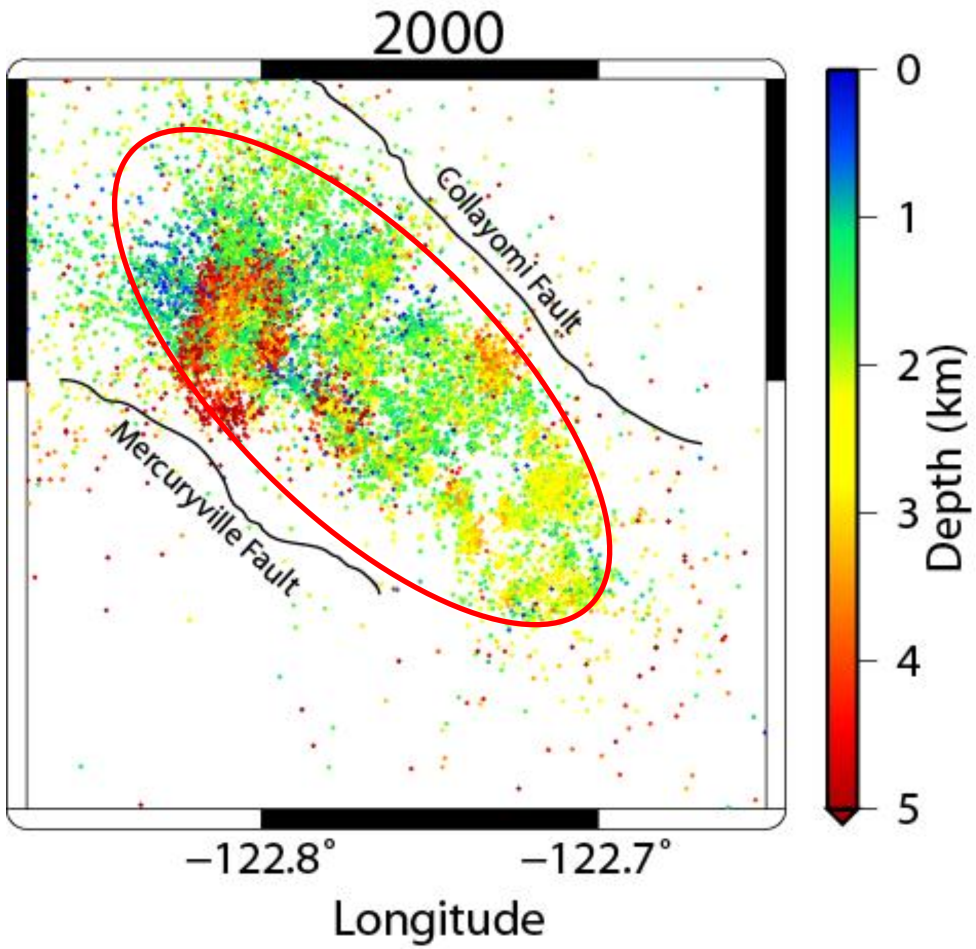
Maximum Magnitude



Maximum magnitude error due to:

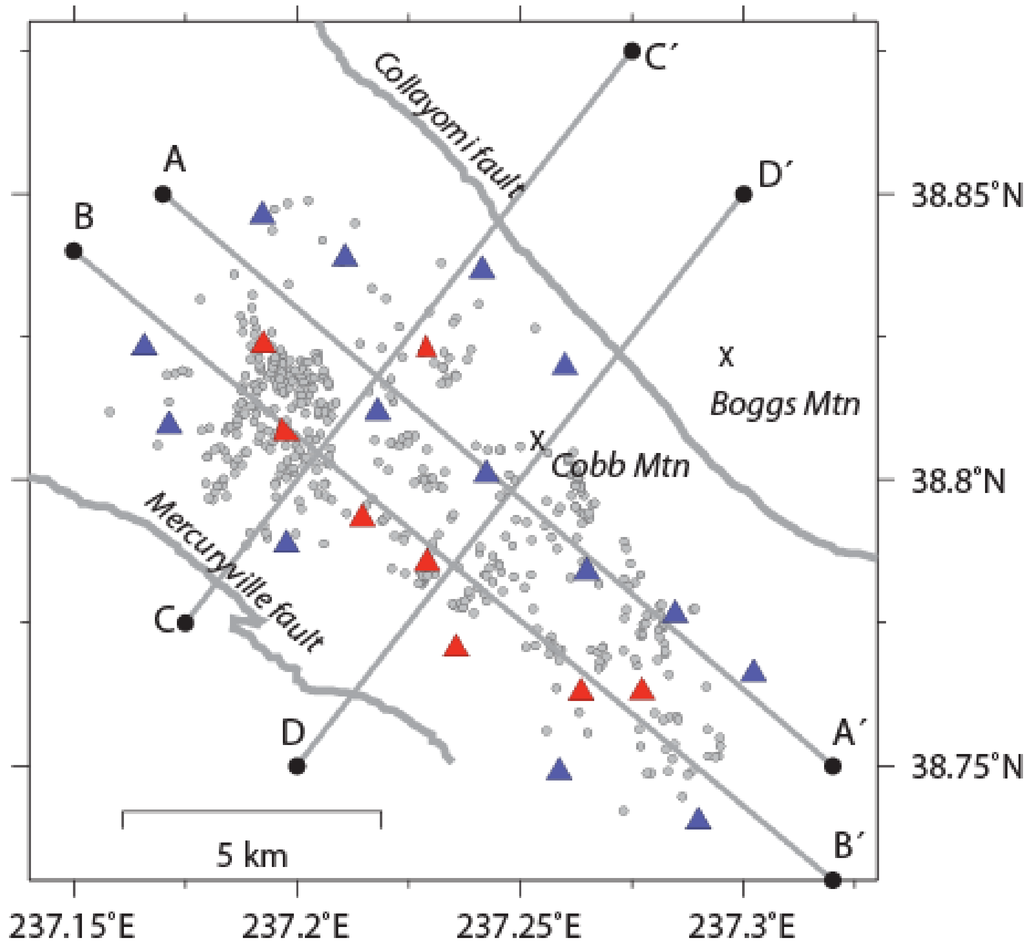
- Using only 1 year of seismic events (larger events occur less frequently)
- Only examining events from the reservoir (should examine regional events to include larger potential faults)
- **Bad science is more dangerous than no science!**

Geophysical Field Imaging

Subset of largest and best located induced seismic events (circles) in year 2000 and the monitoring array (triangles).

A tomographic inversion produced a 3-D seismic velocity model that is shown along 4 cross sections in following slides.

Object is to improve reservoir characterization, improve production, reduce cost and risk.



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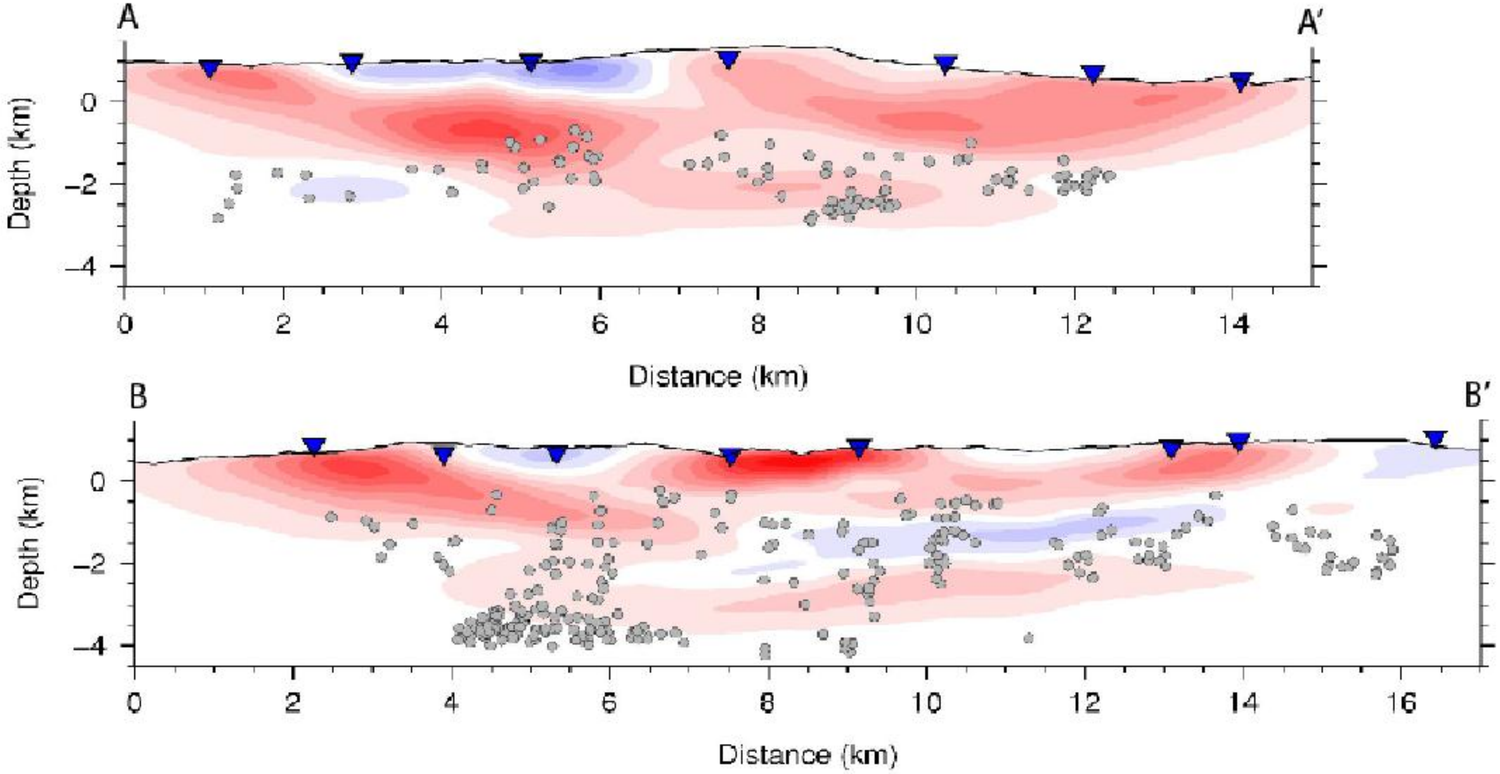
Geophysical Field Imaging



- Velocity model cross-sections showing relative difference between current velocities and starting model.
- Variations in seismic velocities could indicate differences in temperature, fracture density, fluid saturation, etc.

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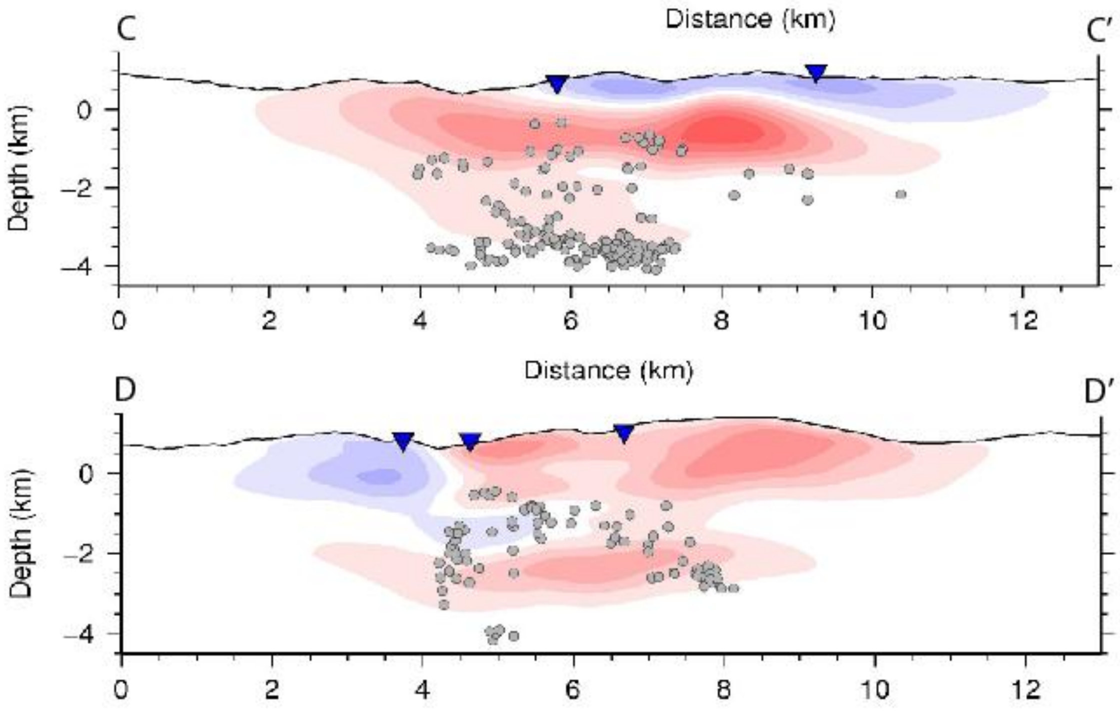
Geophysical Field Imaging



- Difference maps can be produced at specified time intervals to look for changes in the field.
- Can be combined with active source measurements to generate higher resolution maps.

Conclusions

- ✓ **Monitoring induced seismicity can aid reservoir characterization, improve performance, reduce cost, alert the operator of potential issues, improve safety, and reduce risk.**
- ✓ Induced seismicity often has a negative connotation, but the vast majority goes unnoticed. With a seismic monitoring network, the seismicity could provide a low-cost wealth of information not otherwise available.
- ✓ Although monitoring induced seismicity may not answer all questions directly, it can provide relevant information to help infer the answers to questions and raise new questions.
- ✓ There are numerous analysis methods, in addition to those introduced here, that can be performed to gain more field information.

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