Future of Microseismic Analysis: Integration of Monitoring and Reservoir Simulation*

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Abstract

Monitoring of microseismic events induced by reservoir stimulation has become a key aspect in evaluation of hydraulic fractures and their optimization. Future developments of this technology are dependent on improvements in multiple discipline areas, two of which are discussed in this study: better quantification of event locations along with the velocity model, and improved understanding and calibration of the type of rock failure responsible for the seismic events.

Currently, locations of microseismic events are used to infer the geometries of hydraulic fractures. These locations are inverted from seismic signals recorded by sensors either distributed at the surface or in dedicated monitoring borehole(s). The accuracy and precision of the inverted locations depends on both the signal-to-noise ratios of seismic data and the spatial distribution of the receivers. While surface monitoring usually suffers from low signal-to-noise ratio, the ability to place receivers in multiple azimuths and offsets allows for precise event location. On the other hand, downhole monitoring provides robust detection due to a higher signal-to-noise ratio if an event is sufficiently close to the monitoring borehole; however, precise location of events might be difficult, especially in the case of a single monitoring well. Thus, integration of downhole and surface monitoring may be beneficial to both methodologies.

Observed seismic waves carry information about the reservoir properties and the mechanisms of microseismic sources, allowing determination of the type of rock failure in addition to using microseismic event to infer hydraulic fracture geometry. Fracture stimulation models are often based on generating tensile fractures parallel to the maximum stress direction in the reservoir but analyses of the observed microseismic events are dominated by shear failure mechanisms. An assessment of whether the shear failure represents creation of new fractures or reactivation of the existing ones is often based on conceptual models with little data for validation. Analysis of data obtained from a microseismic monitoring project where an image log was acquired in the treatment well allows validation of the model interpreted from the event locations and the inverted source mechanisms. Integration of source-mechanism analysis with information obtained from image logs leads to a better constrained reservoir model populated with fractures away from the wellbore.

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Summary

Part 1: Advances in event location accuracy

- Microseismic data acquisition methods
- Event location techniques

Part 2: Using microseismic data to create fracture models and reservoir flow properties

- Microseismic monitoring case study using surface acquired data
- Stimulated reservoir characterization
- Frac’d reservoir simulation

Part 3: The Future

- Where will improvements in the technology be?
- Other potential applications

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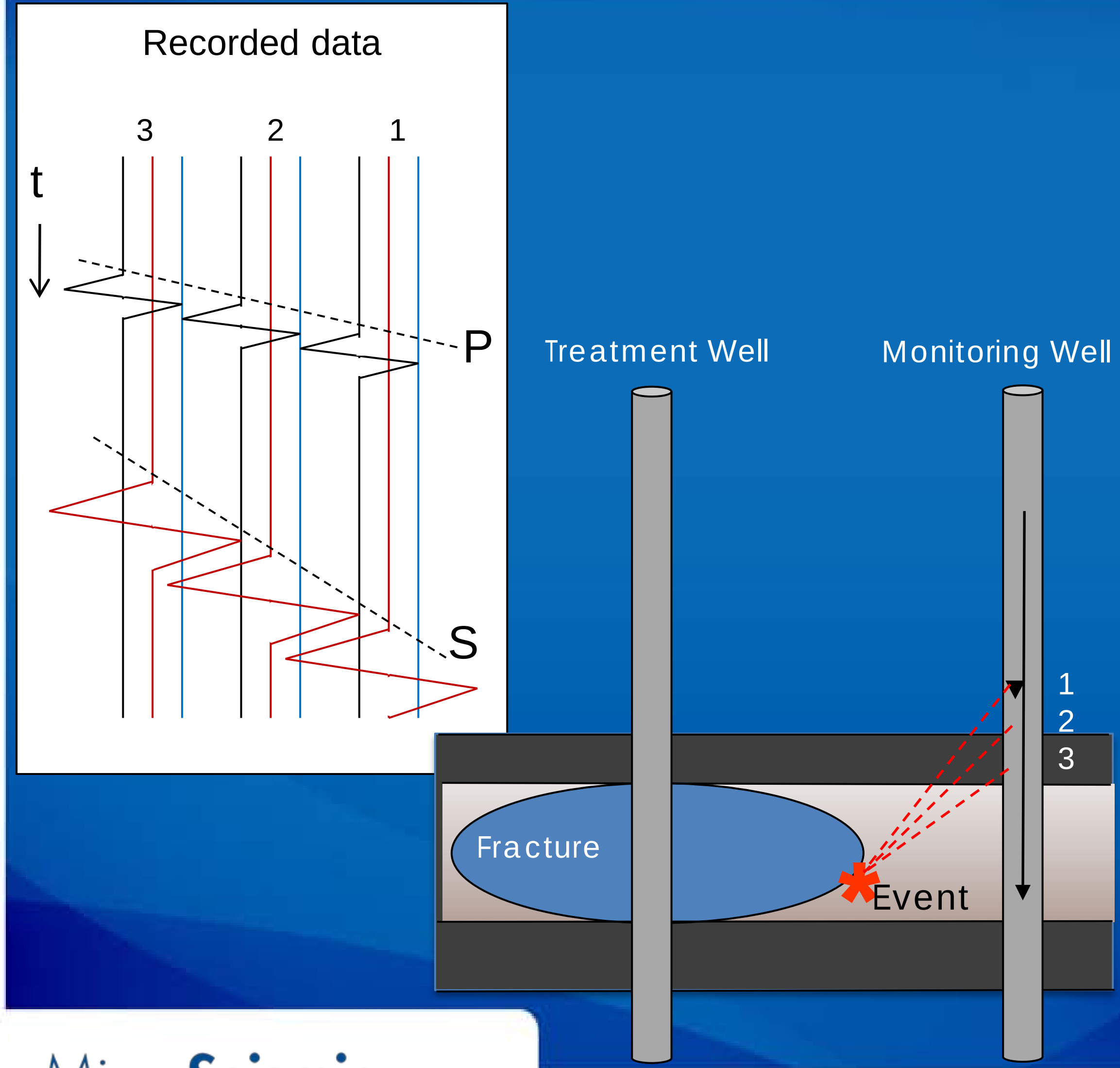
Microseismic Data Acquistion Methods

- Geophone array(s) in a nearby borehole(s)
- Geophone array on the surface above the well or reservoir
- Geophone array buried in the shallow subsurface above the well or reservoir

Geophone Array(s) In a Nearby Borehole(s)



Event identification method:

- Classic earthquake location
- First break processing
- Use P & S arrivals to determine range and elevation.
- Use P polarization to determine azimuth.

Implementation:

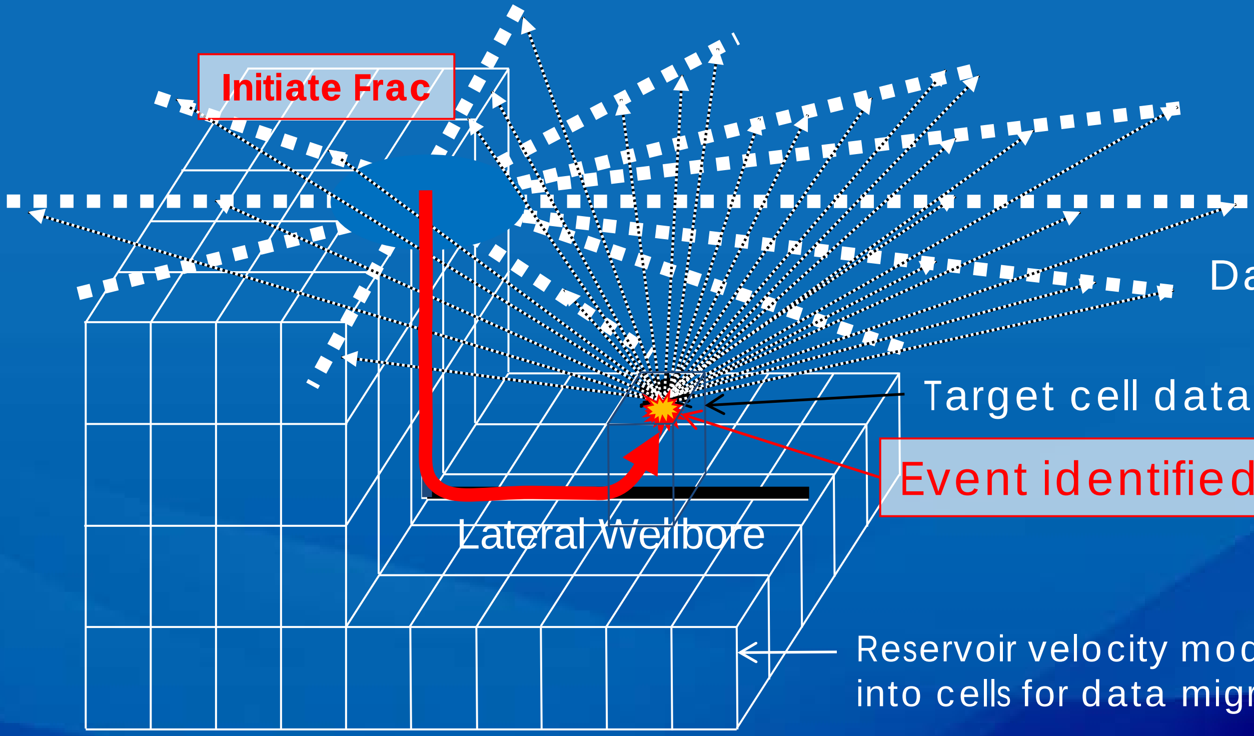
- 10 to 40 3C geophones in a wellbore close to reservoir
- Monitor well is less than 1000m from full frac pattern
- Listening well in addition to treatment well
- Can be used to augment a surface array

Geophone Array on the Surface

FracStar® Method

Entire dataset is migrated for each cell respectively then individual cell datasets are scanned for events

FracStar array deployed on the surface



Data acquired

Target cell data scanned

Event identified in target cell

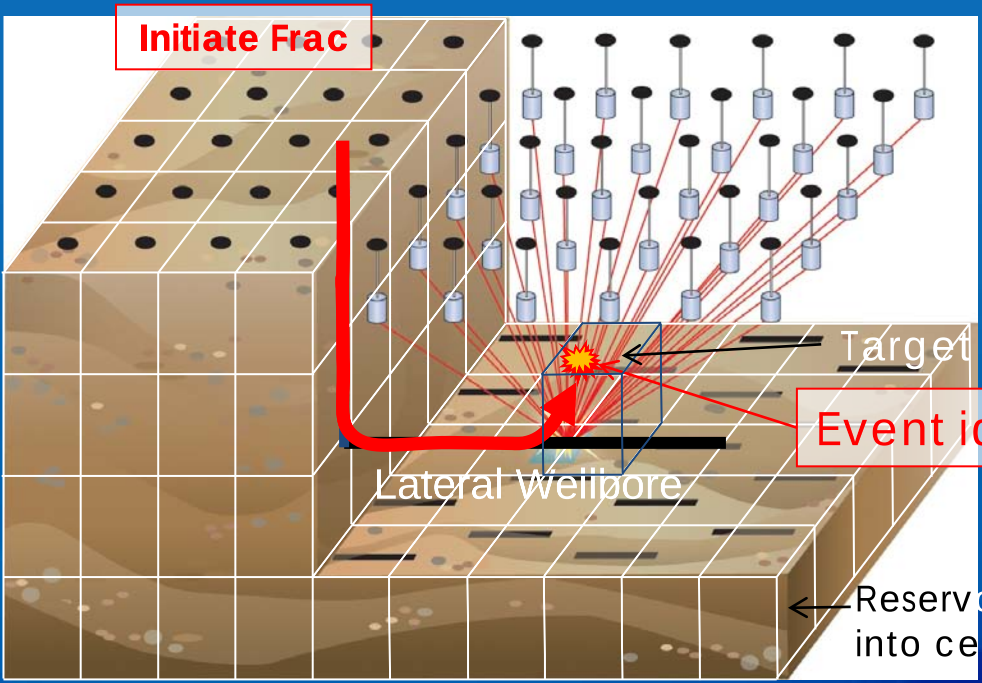
Reservoir velocity model subdivided into cells for data migration

Geophone Array Buried in Shallow Subsurface

BuriedArray^{TM} Method

Entire dataset is migrated for each cell respectively then individual cell datasets are scanned for events

Buried Array deployed on the surface



Data acquired

Target cell data scanned

Event identified in target cell

Reservoir velocity model subdivided into cells for data migration

Location Accuracy

Different methods have different location errors and advantages.

- Accuracy of microseismic event locations array is dependent on the signal to noise ratio and the distribution of the receiving sensors
  - Surface array –
    - o location accuracy of events located by inversion is improved by sensors placed in multiple azimuths away from the monitored borehole
  - Downhole array –
    - o location accuracy of events located by inversion is improved by being close to the monitored borehole (high signal to noise ratio)
  - Surface array –
    - o location accuracy of events located by stacked imaging is improved by increasing the stack power and by receivers placed in multiple azimuths away from the monitored borehole

Location Accuracy

- All acquisition methods have reasonable errors in most applications (on the order of 10 – 50 meters for good quality data)
- High location accuracy is critical for thin shale reservoirs, so improvements are still needed
- Discrete fracture network modeling of using event locations also benefits from improved location accuracy
- Combining two of the existing inversion acquisition methods is one way to improve location accuracy

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Trade-offs by Acquisition Method

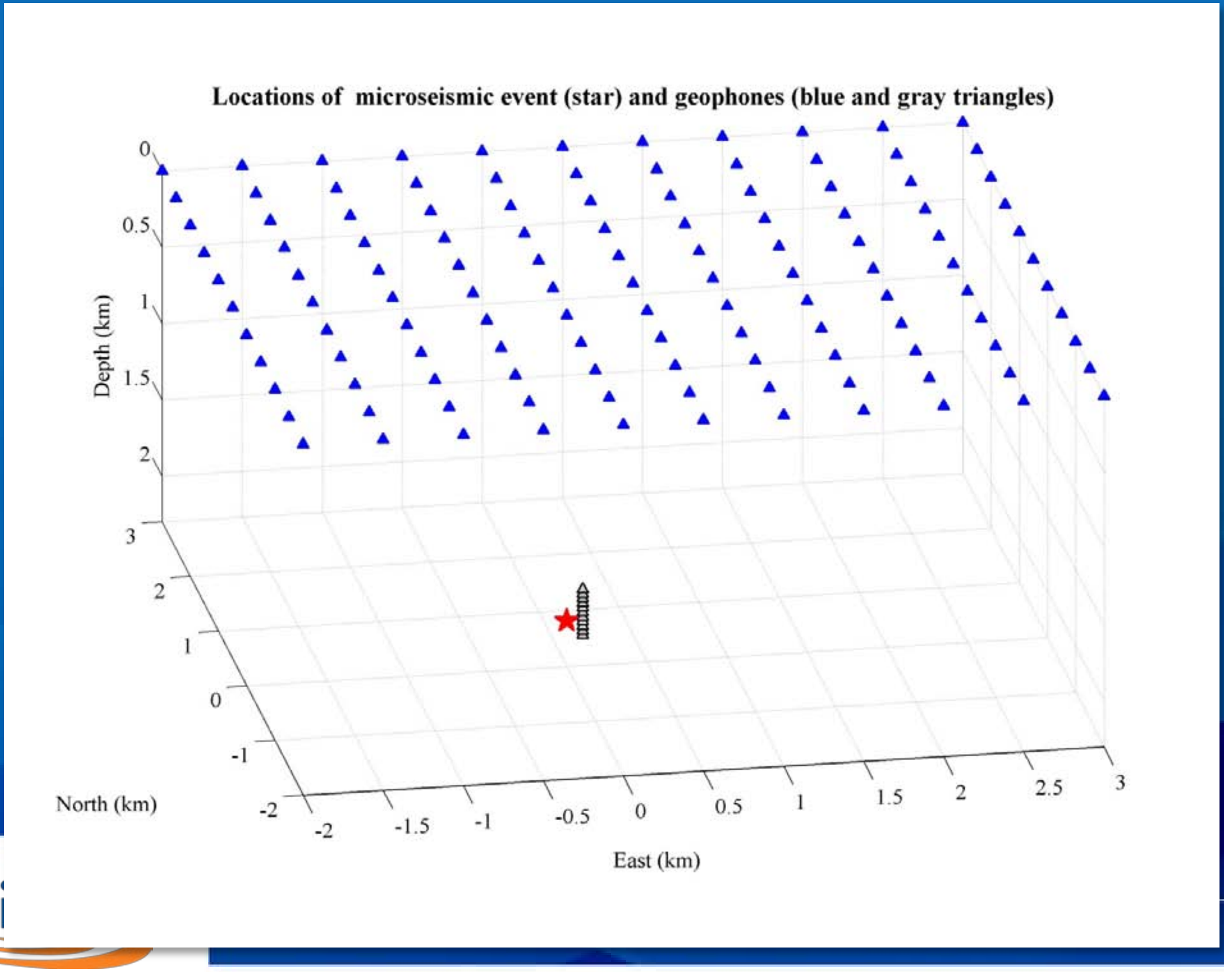
Downhole Acquisition

- Optimal viewing area is close to monitor well
- Good detectability of smaller microseisms and larger events
- Location error increases with distance from array

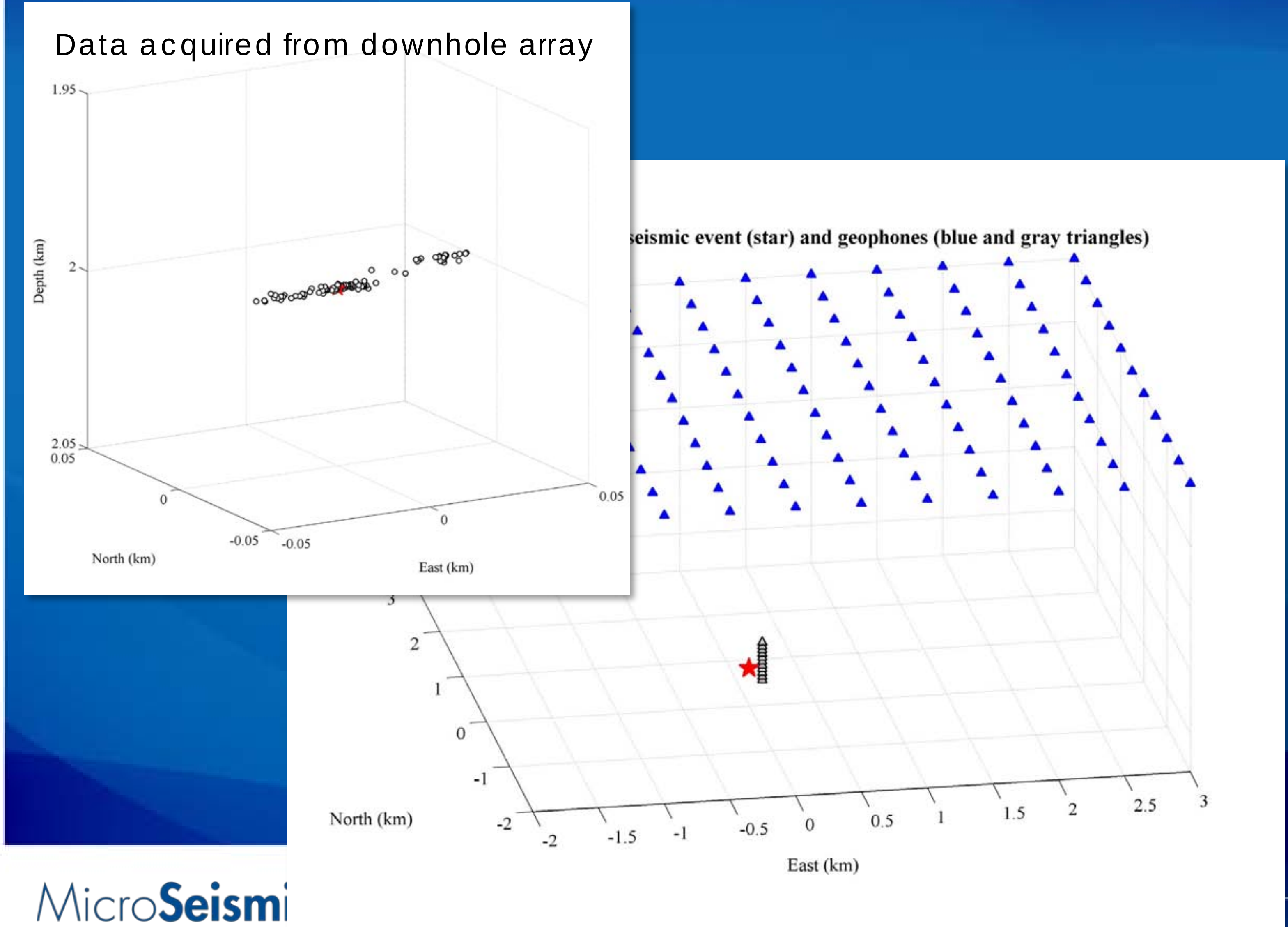
Surface Acquisition

- Wide azimuth viewing area above treatment well
- Detection very good for larger events
- Location error is small for large events and high SNR

Theoretical Model of Event locations



Theoretical Model of Event locations



Data acquired from downhole array

seismic event (star) and geophones (blue and gray triangles)

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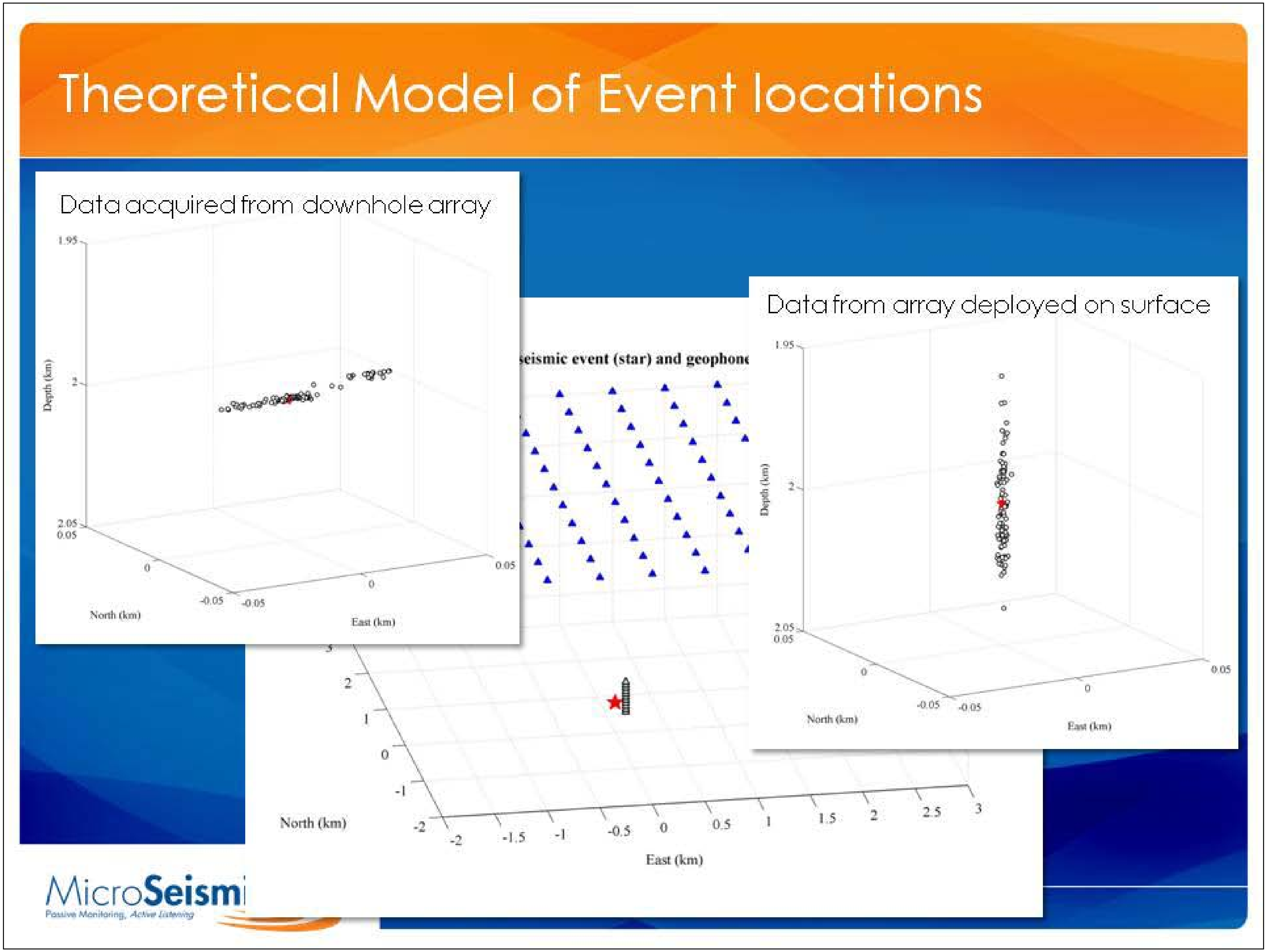

Theoretical Model of Event locations

Data acquired from downhole array

seismic event (star) and geophone

Data from array deployed on surface

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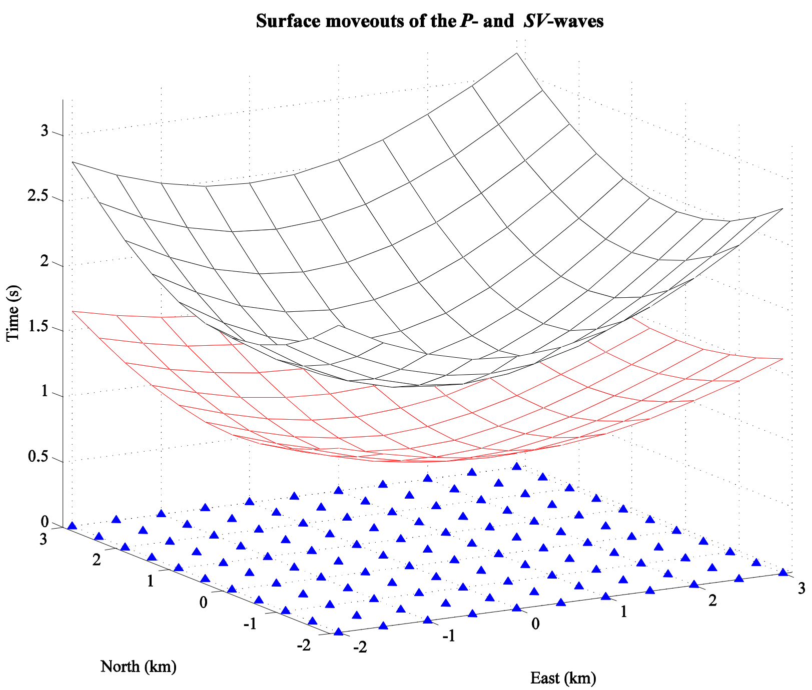
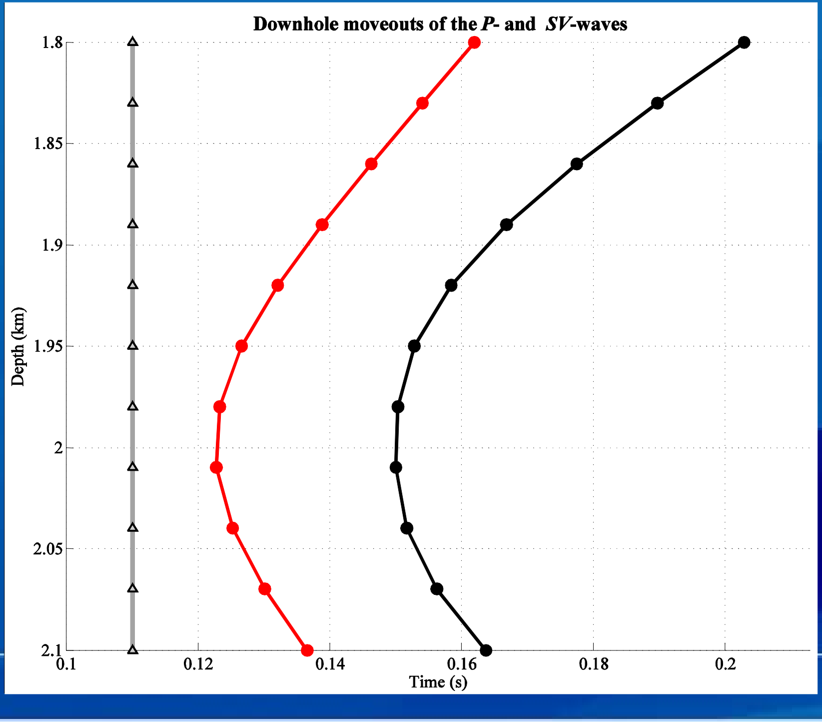
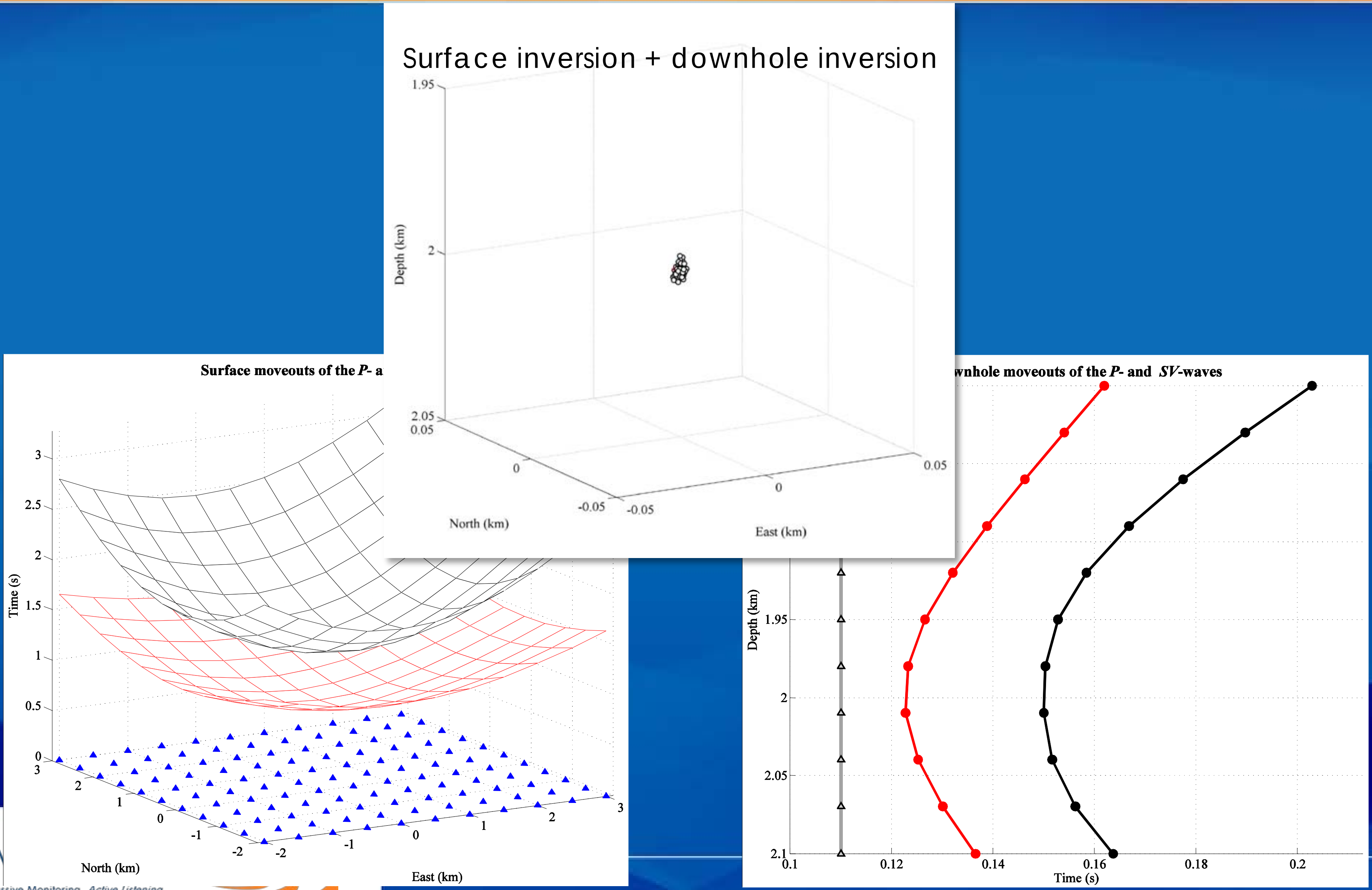
Notes by Presenter: The error on the downhole acquisition is larger in the horizontal, and for the surface array it’s larger in the vertical direction. In both cases, the error is not terrible, about ± 50 meters.

Theoretical Joint Location Technique Error





Theoretical Joint Location Technique Error



Surface inversion + downhole inversion

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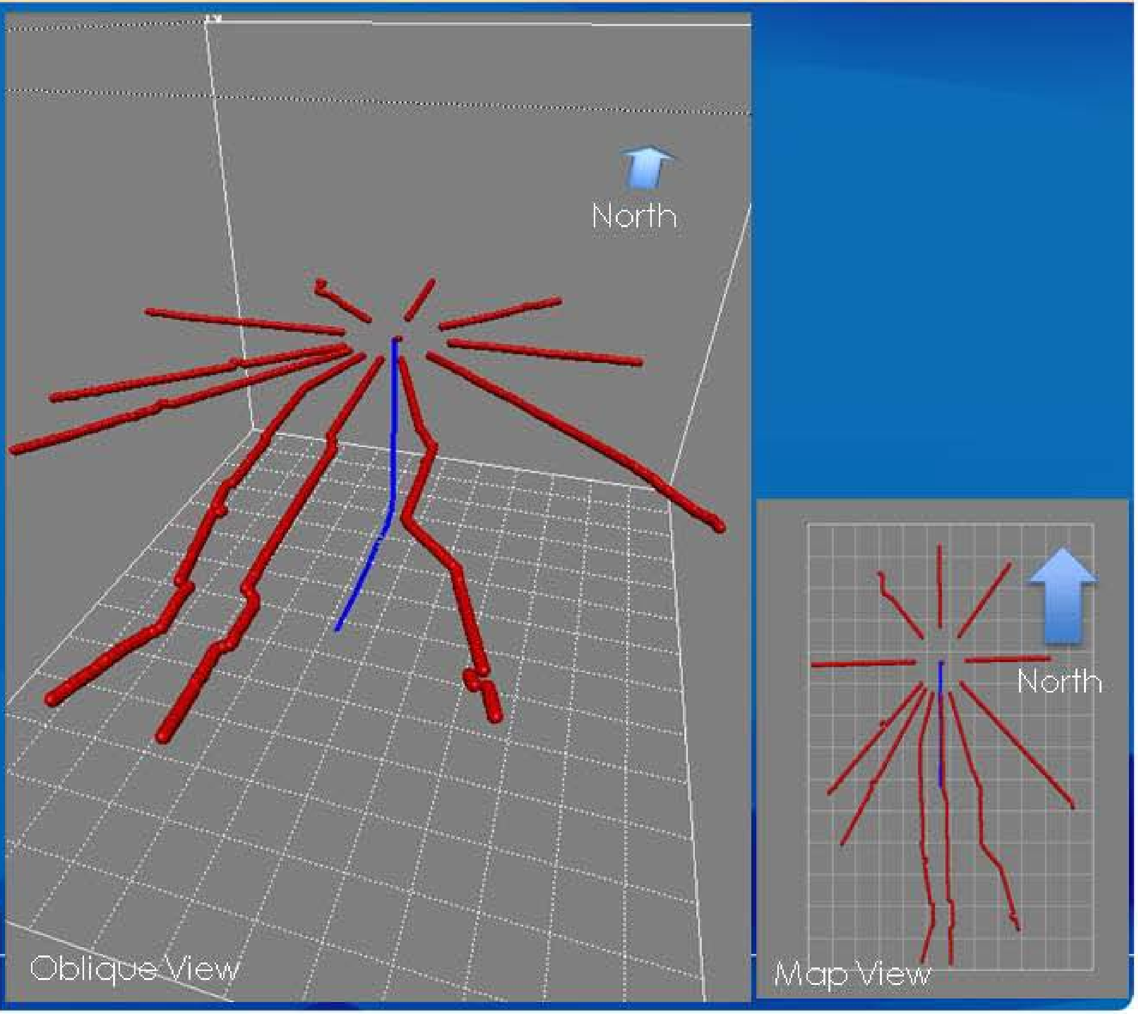
FracStar Surface Array Configuration

Horizontal Well
deviated due south



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Notes by Presenter: By finding the intersection of the event locations by both methods, the error is less than 10 meters in all directions. This method does require the synchronization of the timing for both methods to be a fraction of a millisecond. An additional advantage to this method is that the velocity model is also constrained by joint location of the events. Neither method can uniquely resolve the event location and the velocity, so the trade off between event location, origin time, and velocities is eliminated.

Joint Location Method - Implications

- This method requires the synchronization of the timing for both methods to be a fraction of a millisecond.
- Besides improved location accuracy, an additional advantage to this method is that the velocity model is also constrained by joint location of the events.
- Downhole inversion alone or surface inversion alone cannot uniquely resolve the event location and the velocity
- The trade off between event location, origin time, and velocities is eliminated.
- The wide aperture of the surface array provides additional information that can be used to determine the failure mode of the rock
- Failure mode models have direct application to discrete fracture network models

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Case Study:
Frac'd Reservoir Characterization

- Treatment well located in mid-continent USA
- Microseismic monitoring result indicated natural fracture reactivation
- Fracture planes were explicitly identified by source mechanisms and image log
- In-situ stress indicators from image log and from source mechanisms agree
- Implications for fracture modeling and reservoir characterization

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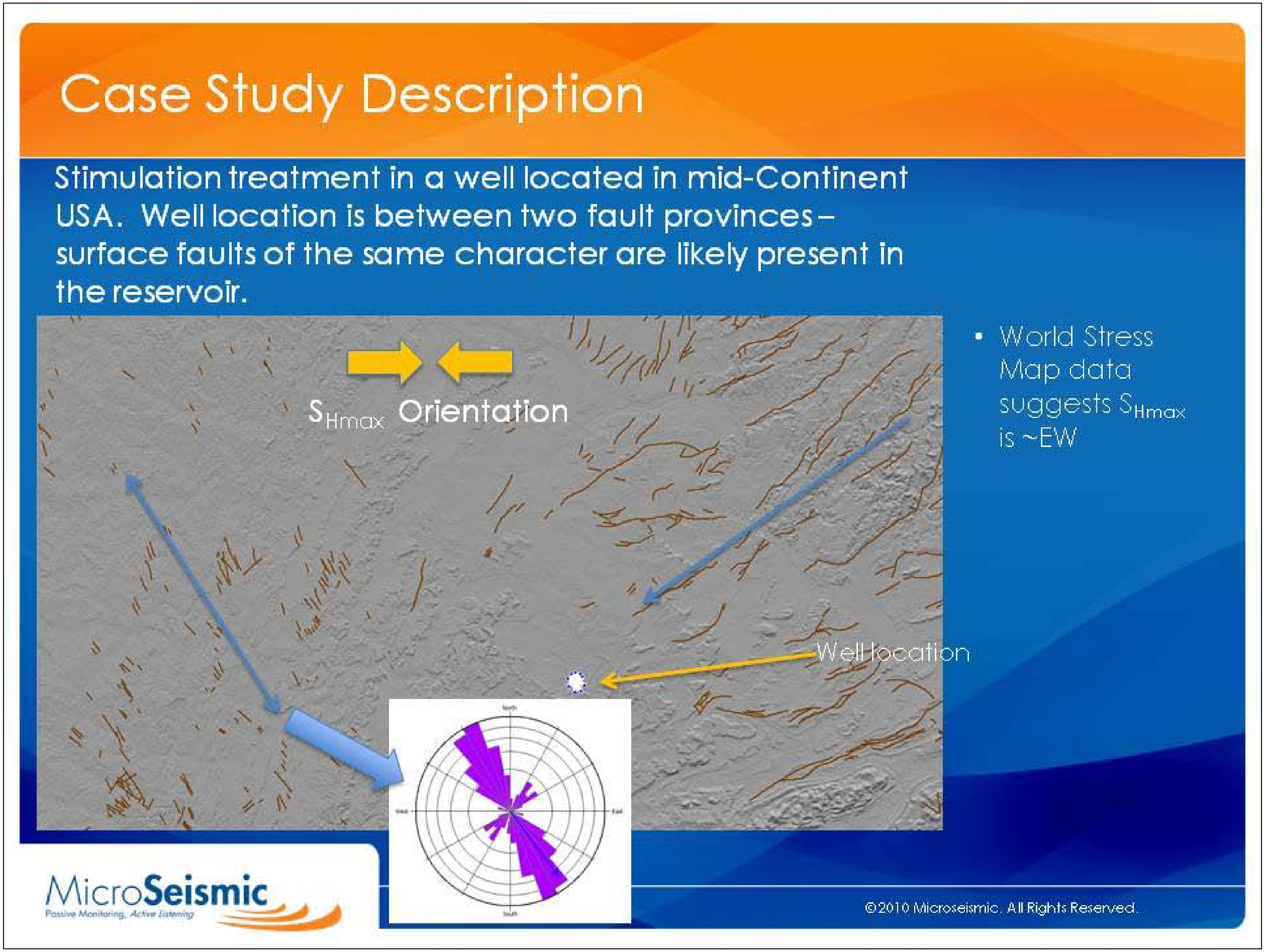

Case Study Description

Stimulation treatment in a well located in mid-Continent USA. Well location is between two fault provinces – surface faults of the same character are likely present in the reservoir.

- World Stress Map data suggests S_{Hmax} is ~EW

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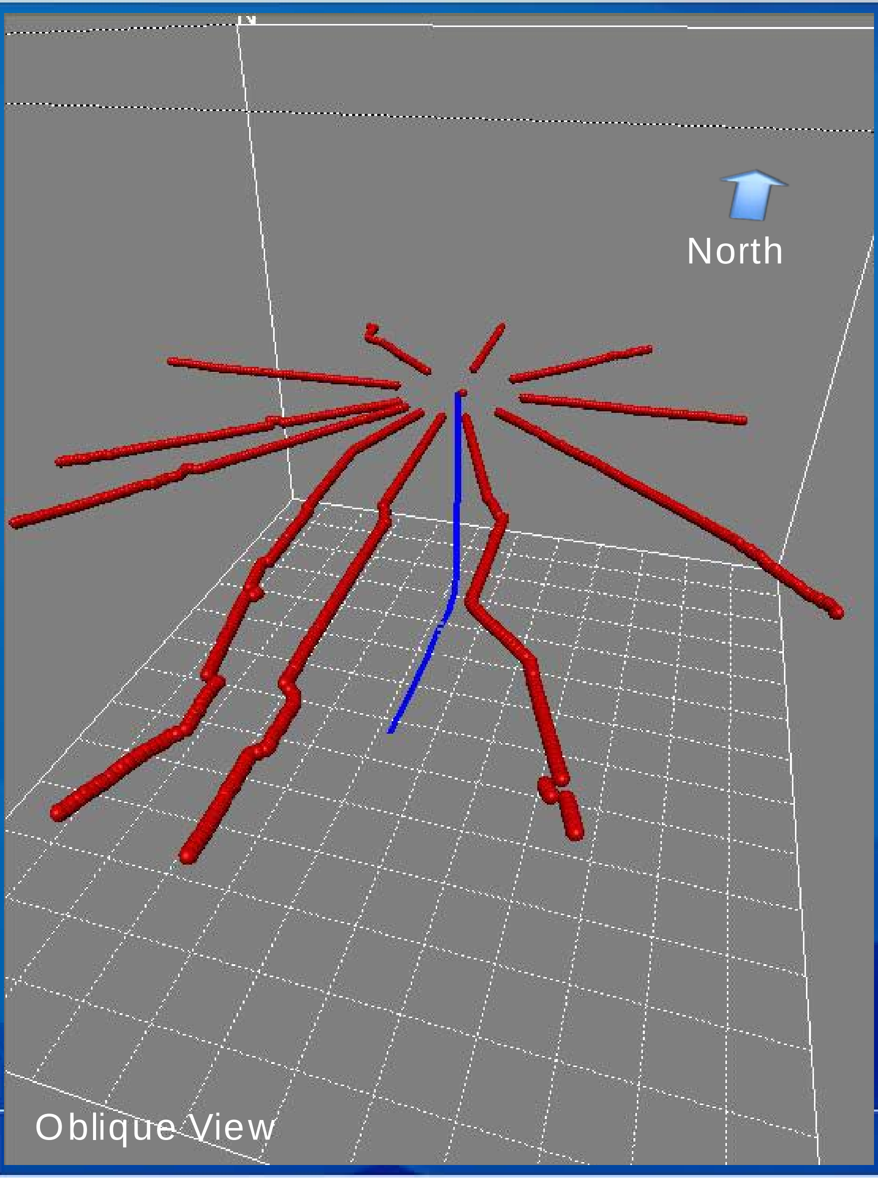
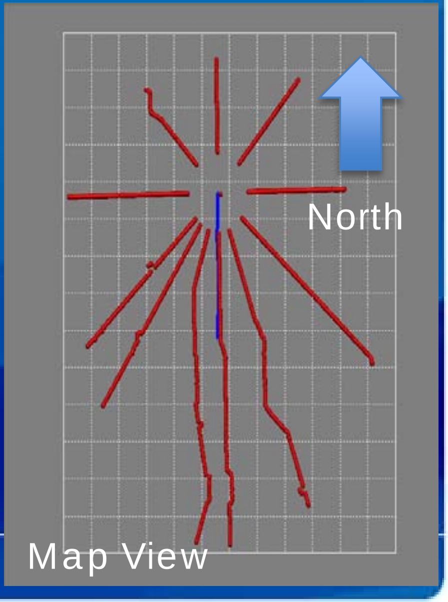
Notes by Presenter: Surface faults are in Pennsylvanian sediments, reservoir is in Mississippian sediments, so deformation is post Pennsylvanian and it had to have deformed the older rocks, too.

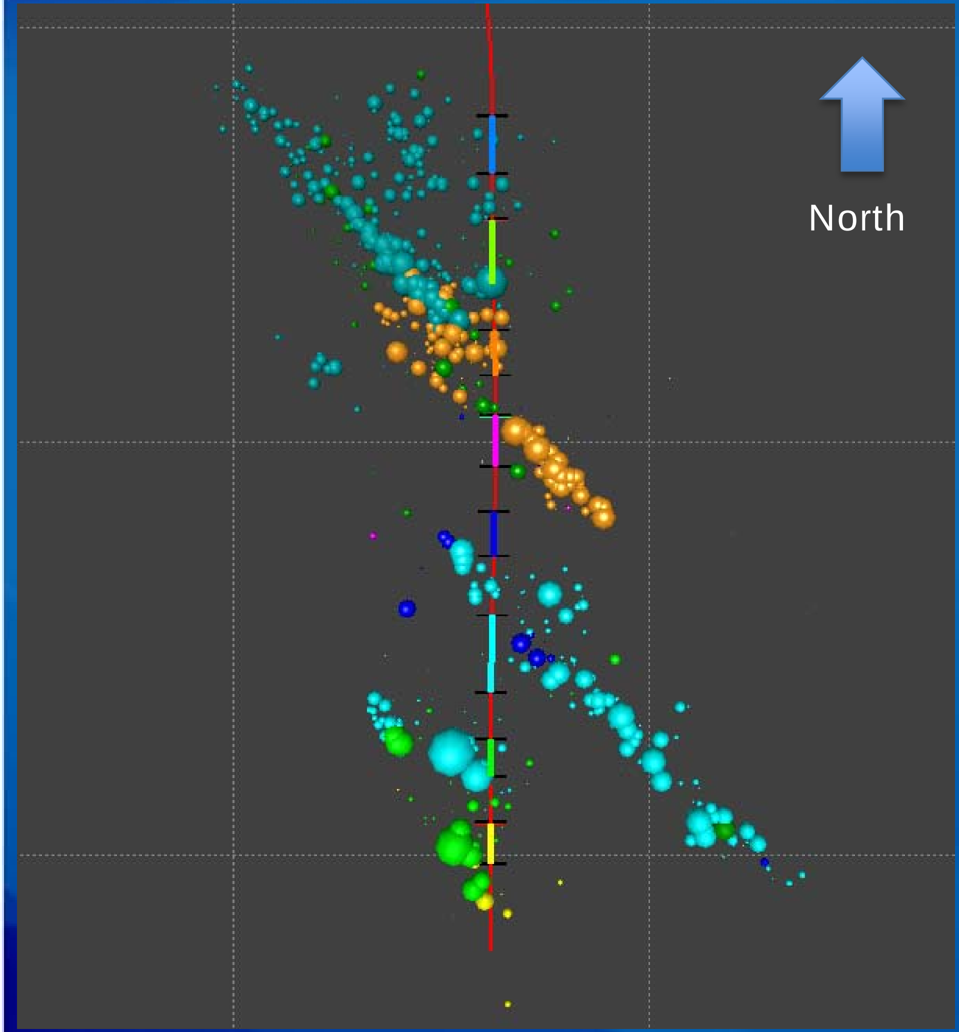
FracStar Surface Array Configuration

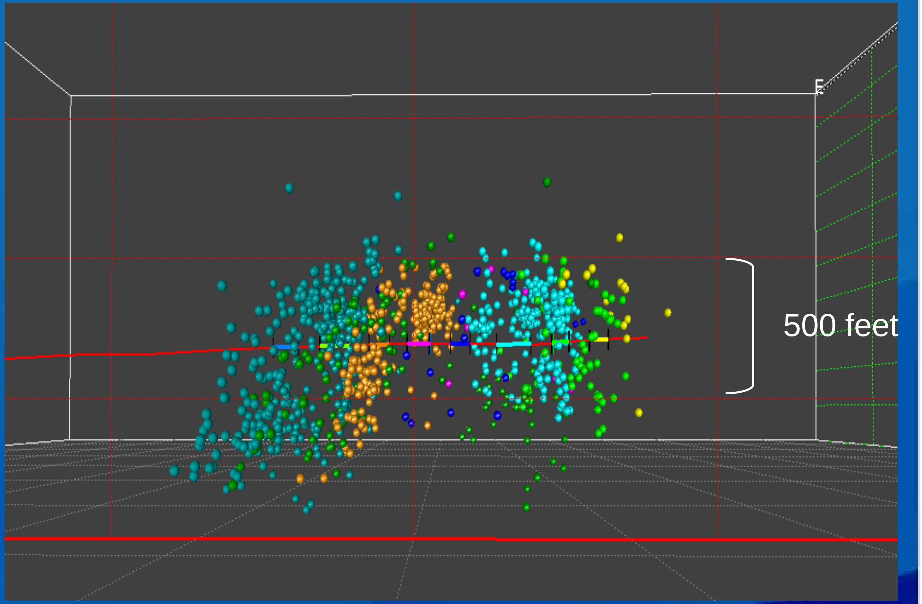
Horizontal Well
deviated due south





Induced Microseismicity During Treatment





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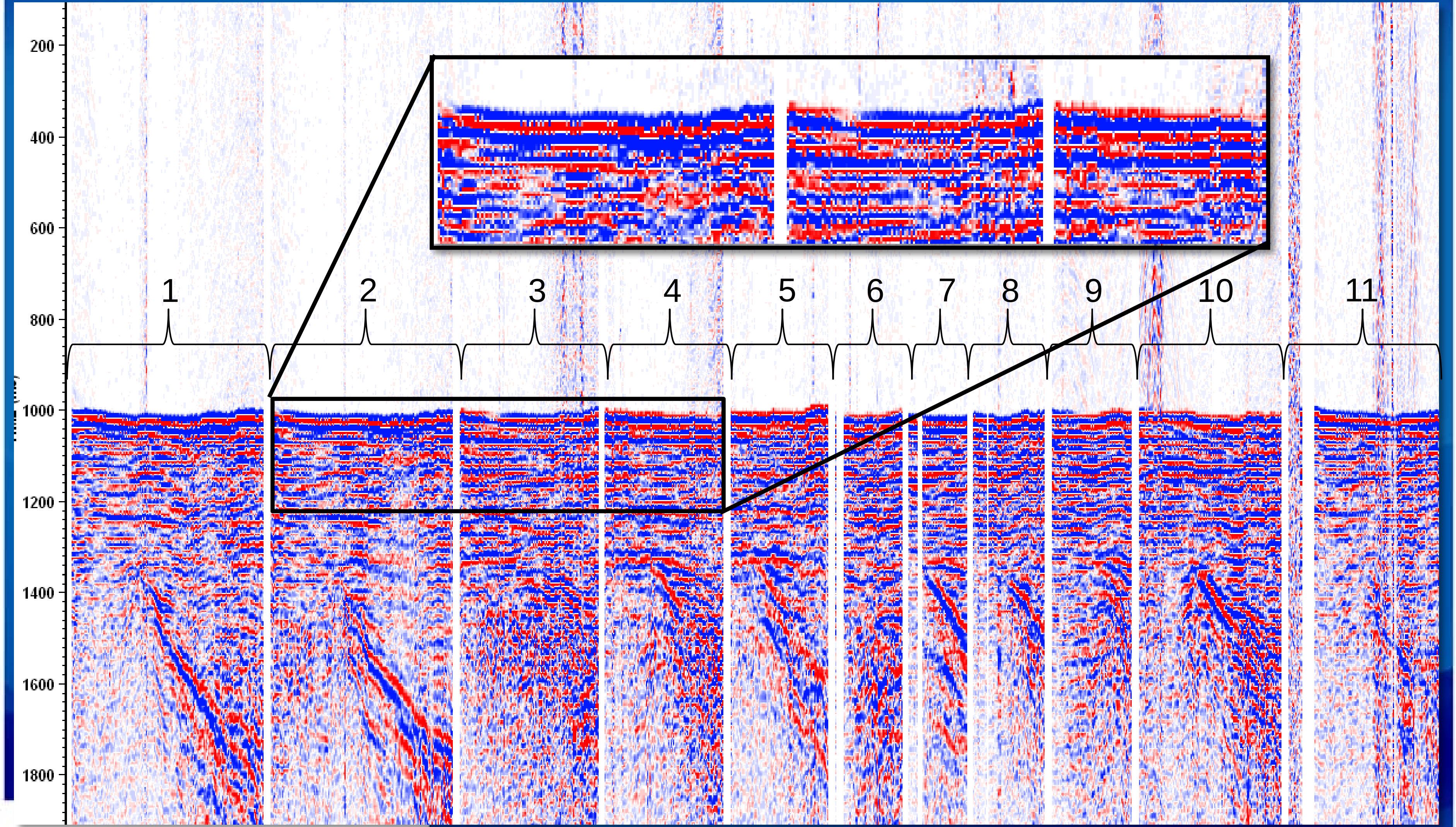
Seismic Data



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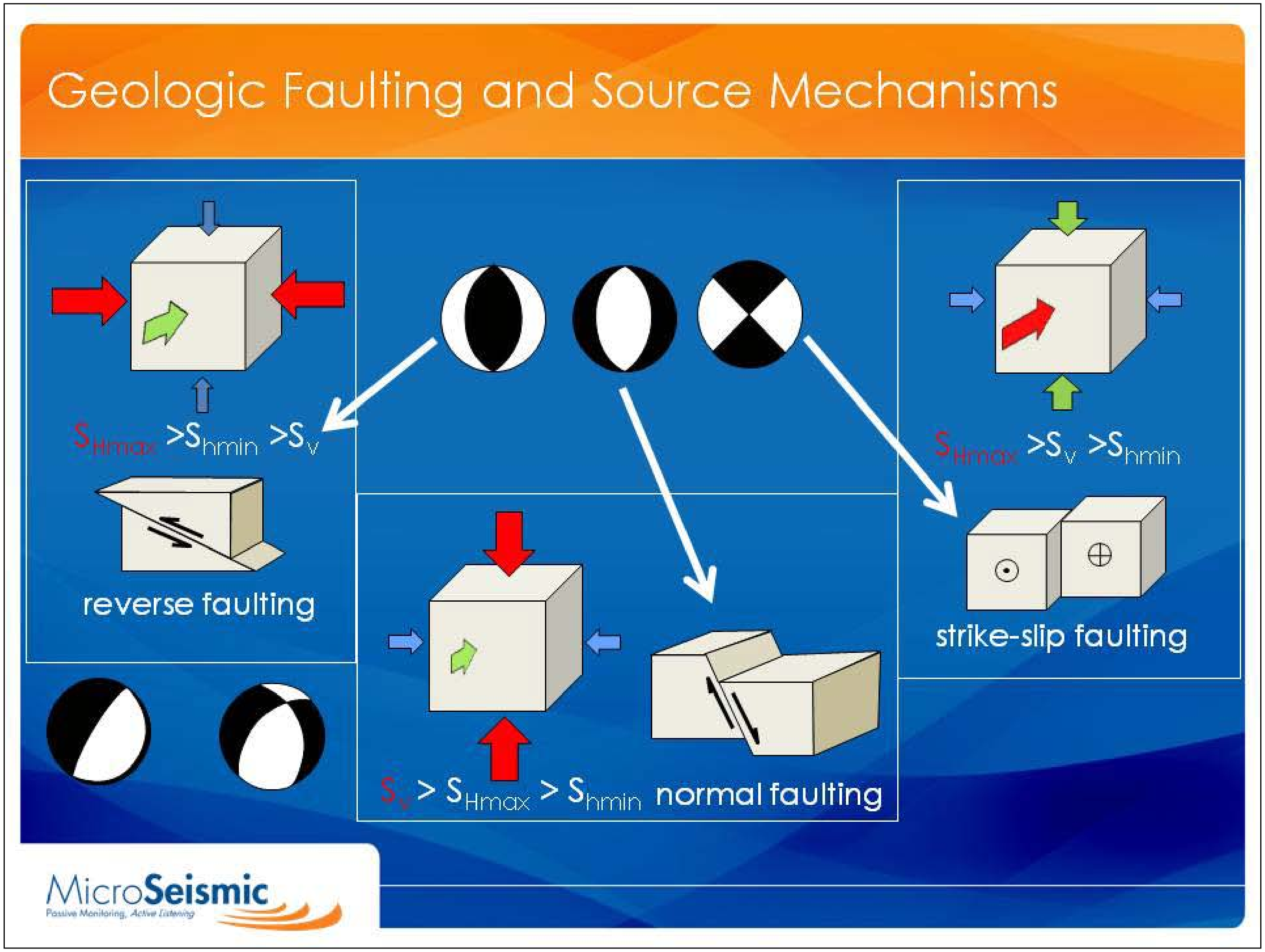

Geologic Faulting and Source Mechanisms

$S_{Hmax} > S_{hmin} > S_v$

reverse faulting

$S_{Hmax} > S_v > S_{hmin}$

strike-slip faulting

$S_v > S_{Hmax} > S_{hmin}$

normal faulting

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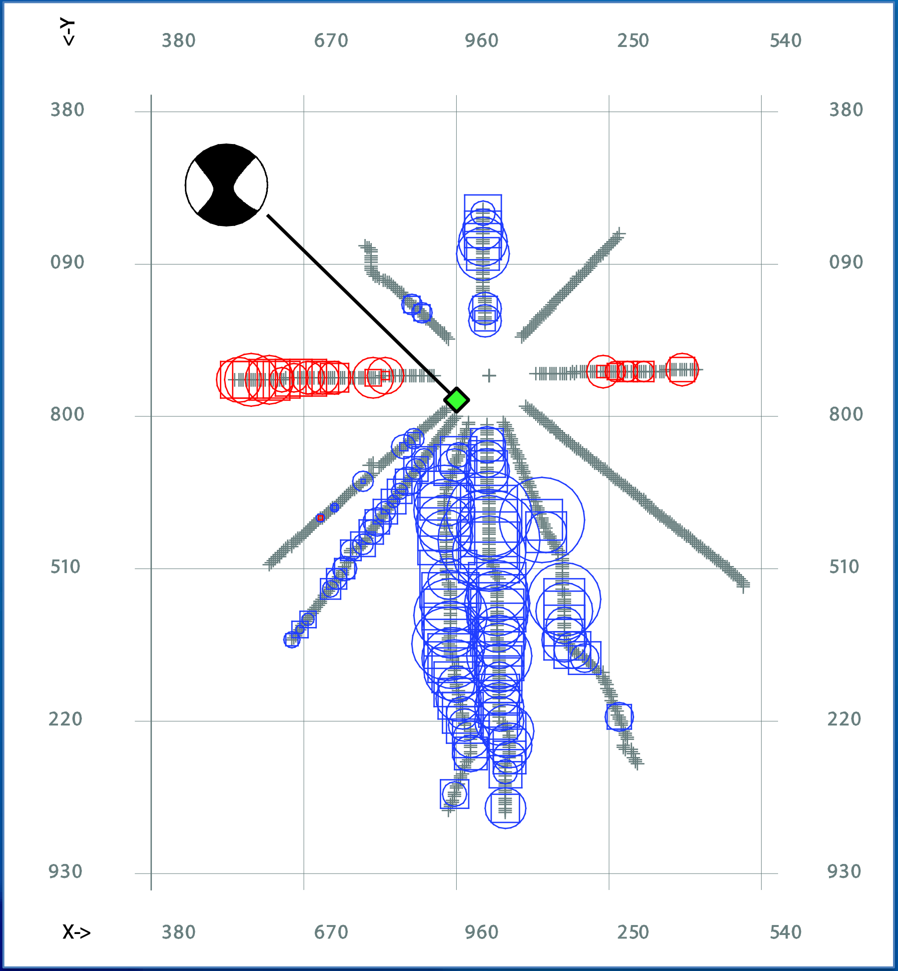
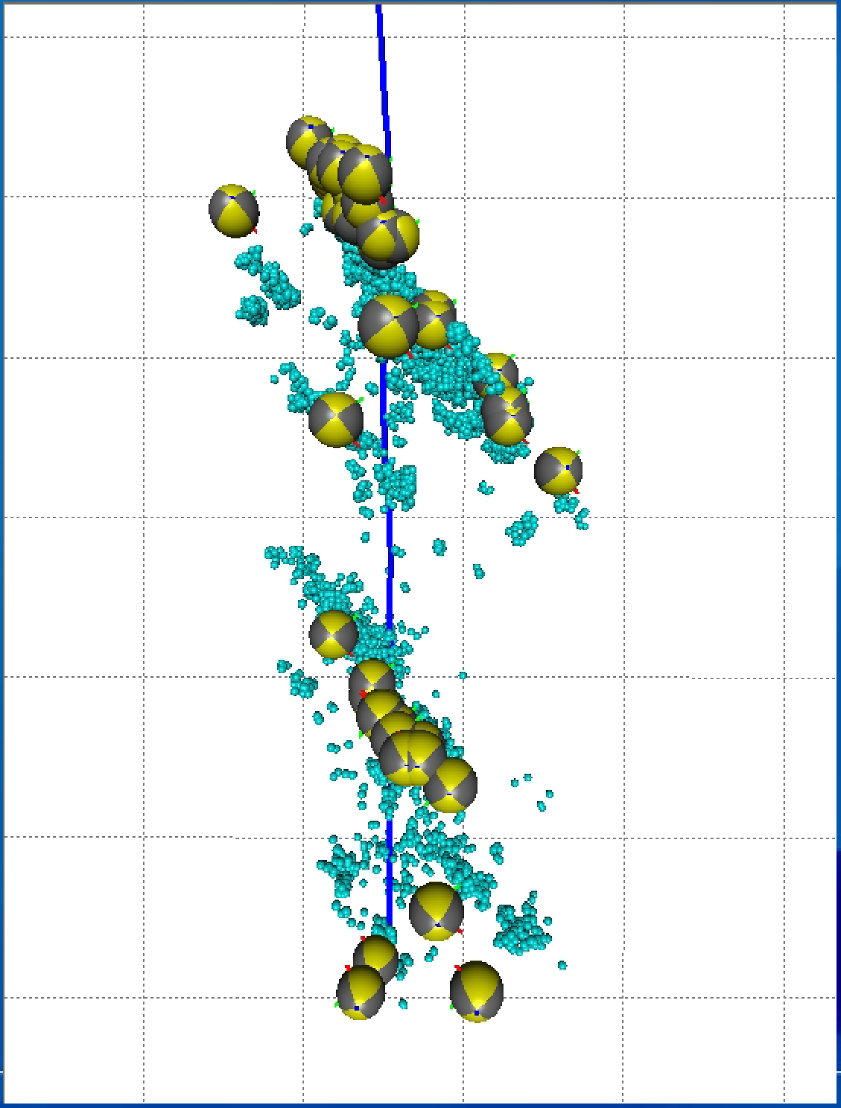
Notes by Presenter: Double couple source mechanism solutions are commonly shown for earthquakes – these are the solutions based on slip on a fault plane. The solution tells you the orientation of the fault (2 possible orientations, as the solution is non-unique, and I'll explain that later) and the directions of slip on that fault plane. The beach balls have 4 quadrants colored to indicate tension (black) or compression (white) in the energy radiation patterns of the earthquakes.

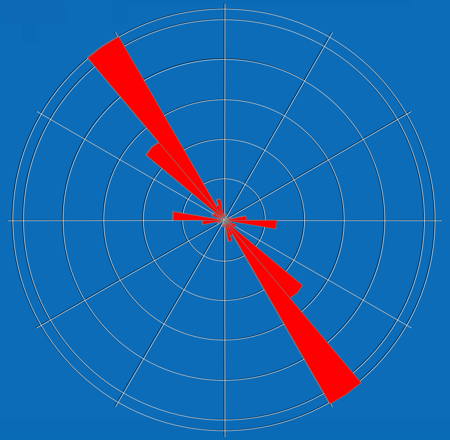
The pure strike-slip, reverse dip-slip and normal dip-slip beach balls are the top three in the diagram, and they relate to the three end member fault mechanisms in the block diagrams. The more general cases, where there the slip is oblique (not pure dip slip, but includes a strike slip component), are represented by the bottom two beach balls.

Case Study Source Mechanism Result

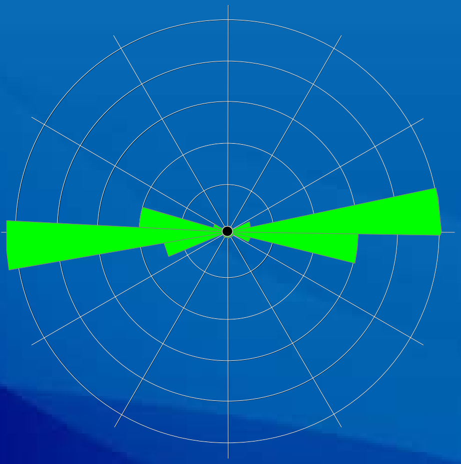




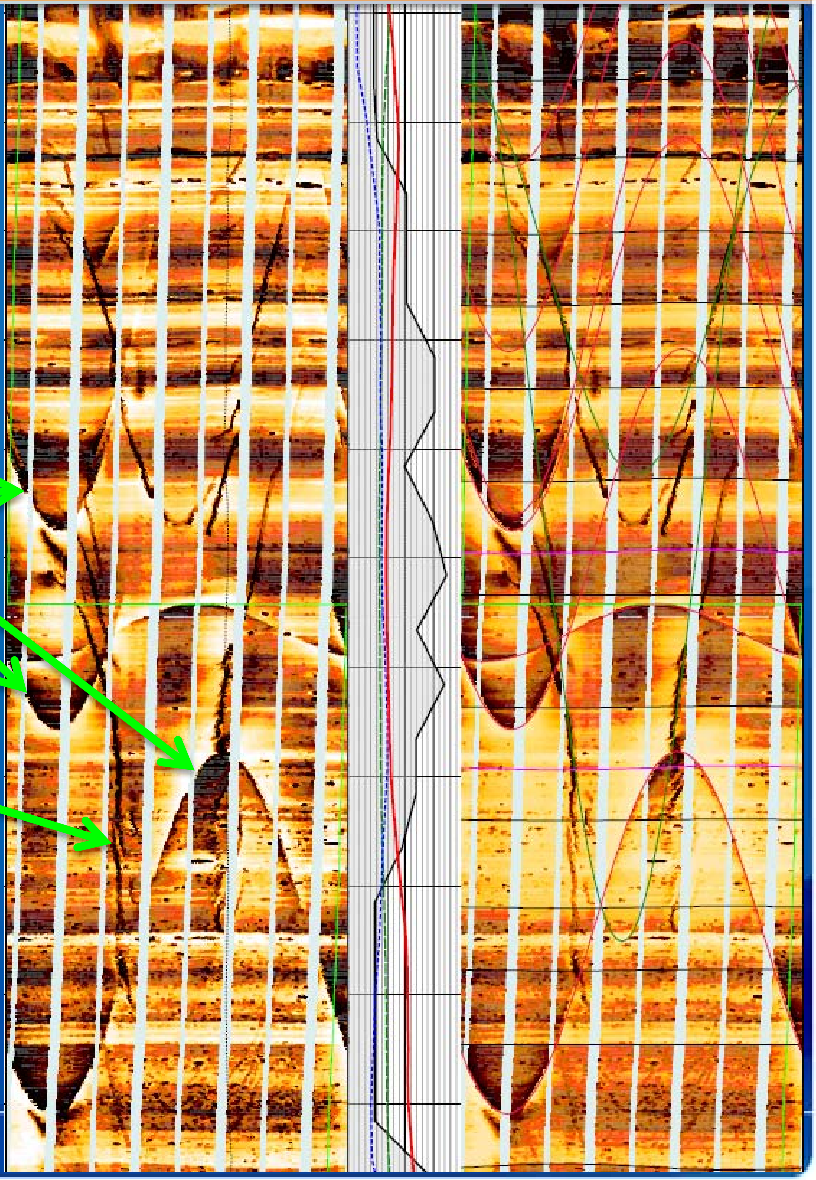
Correlation with Conductive Fractures in FMI Log

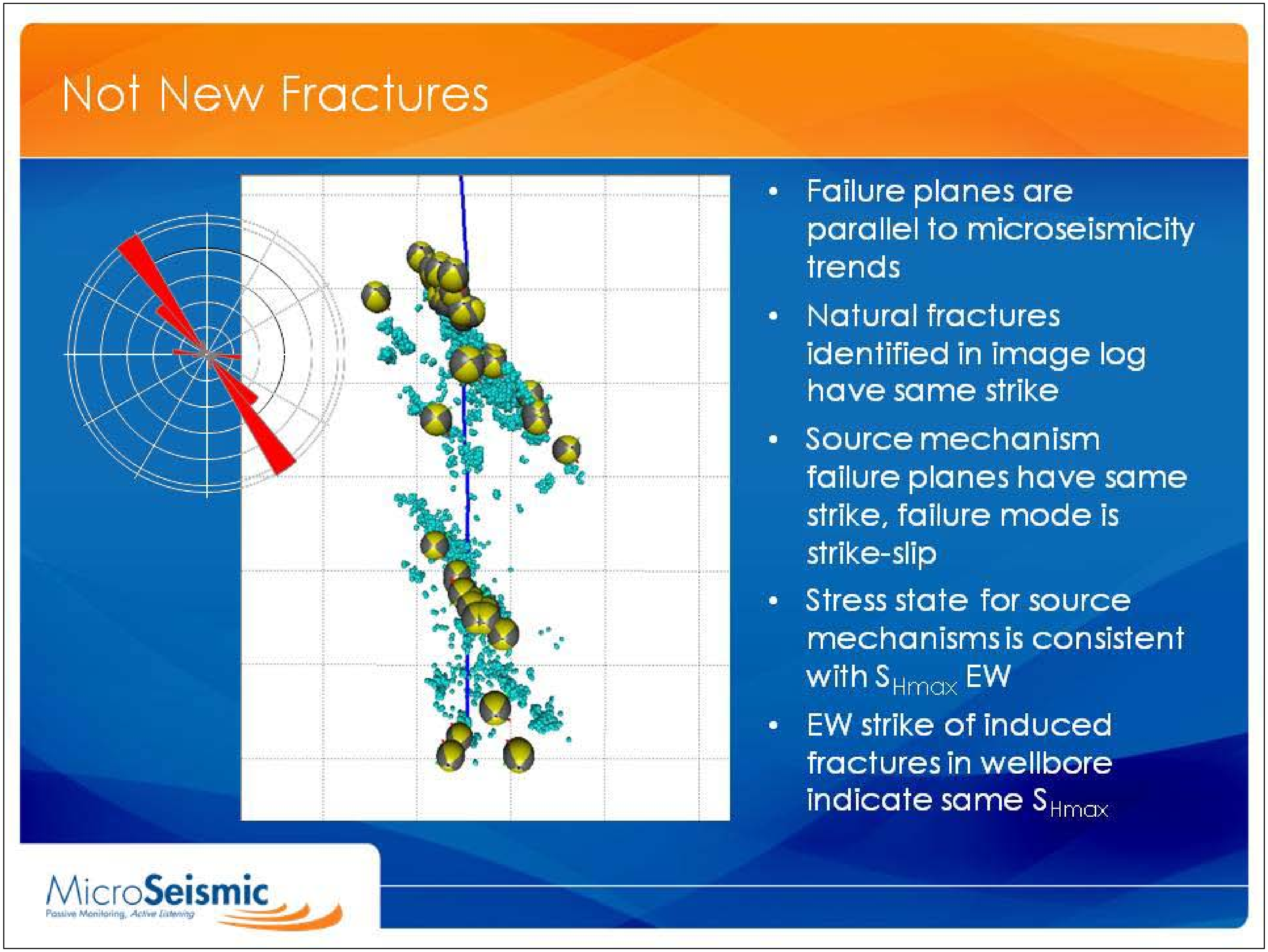


Existing conductive natural fractures. This orientation is reactivated in strike-slip failure by the stimulation treatment



Drilling Induced Fractures. These fractures strike parallel to the maximum horizontal stress





Not New Fractures

- Failure planes are parallel to microseismicity trends
- Natural fractures identified in image log have same strike
- Source mechanism failure planes have same strike, failure mode is strike-slip
- Stress state for source mechanisms is consistent with S_{Hmax} EW
- EW strike of induced fractures in wellbore indicate same S_{Hmax}

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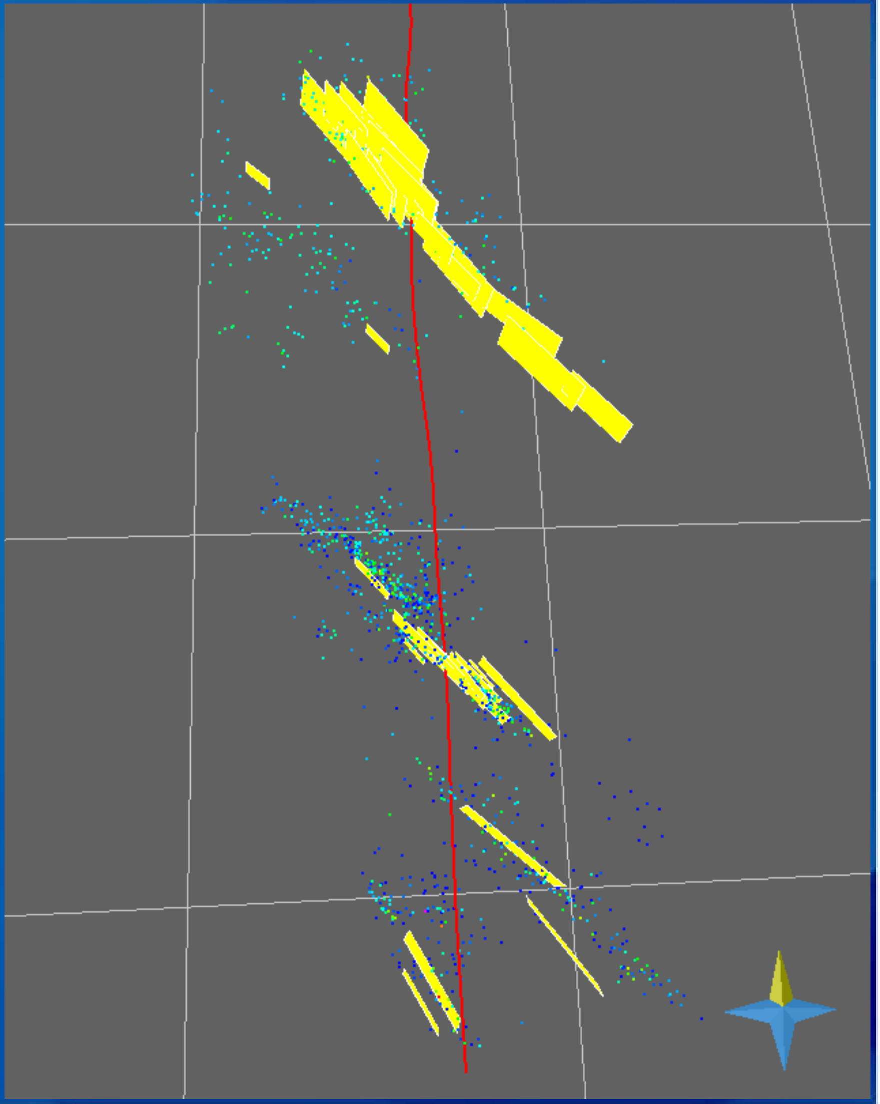
Notes by Presenter: A) Natural fracture data from Etna Well Image log. Stereonet of natural fracture dips (left), and rose plot of natural fracture strikes (right). Mean Dip Orientation is 84.2°/46.5°, and rose plot strike interval is at 10°; B) Source mechanism based fracture data. Stereonet of fracture dips (left), and rose plot of fracture strikes(right). Mean Dip Orientation is 85.94°/231.86°, and rose plot strike interval is at 10°; C) Stochastic DFN data. Stereonet of fracture dips (left), and rose plot of fracture strikes(right). Mean Dip Orientation is 84.52°/38.94°, and rose plot strike interval is at 10°.

Deterministic Fractures

- Deterministic fractures -
    - Location is known
    - Orientation is know
    - Size is known.
- These fractures are placed explicitly in a geologic model
- Good location accuracy is required to model these fractures



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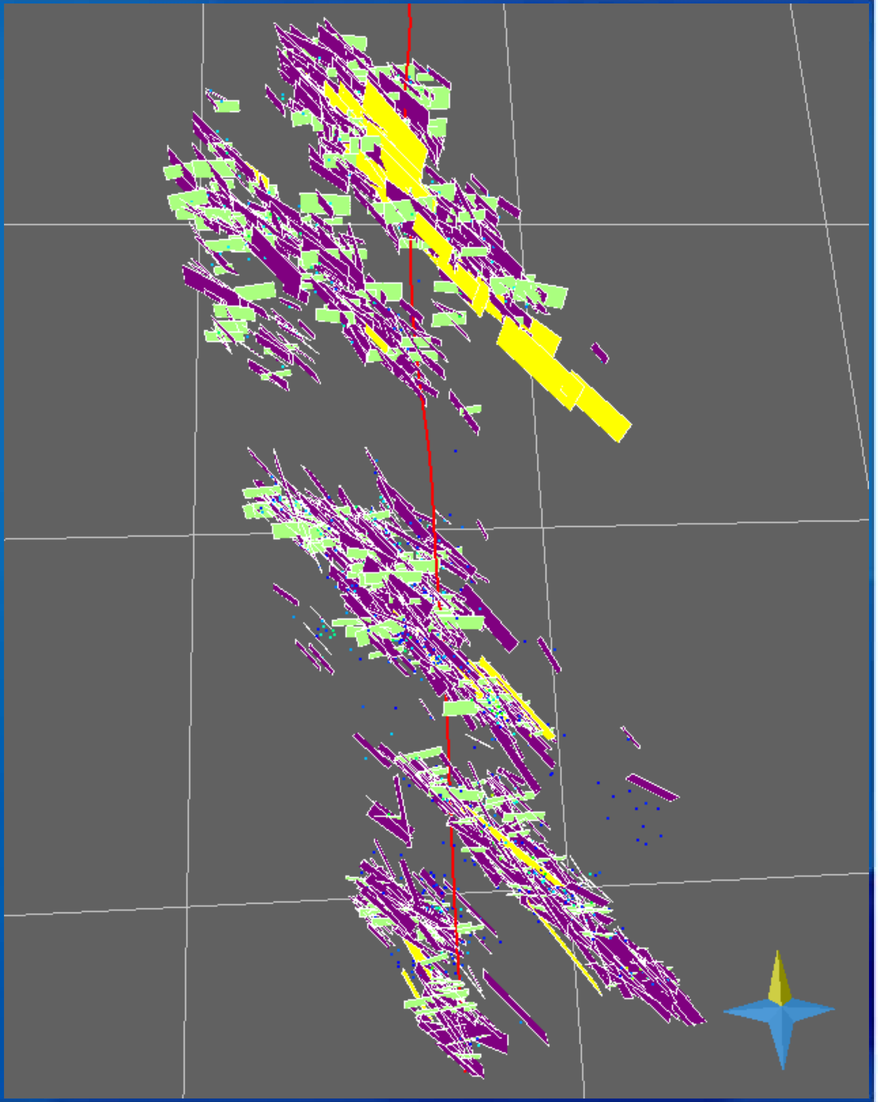
Stochastic (Natural and Induced) Fractures

- Deterministic fractures -
  - Location is known
  - Orientation is know
  - Size is known.
- These fractures are placed explicitly in a geologic model
- Good location accuracy is required to model these fractures
- Two additional fracture sets are stochastically generated
  - Natural fracture set using orientation statistics from image log
  - Fractures with EW strike representing tensile fractures



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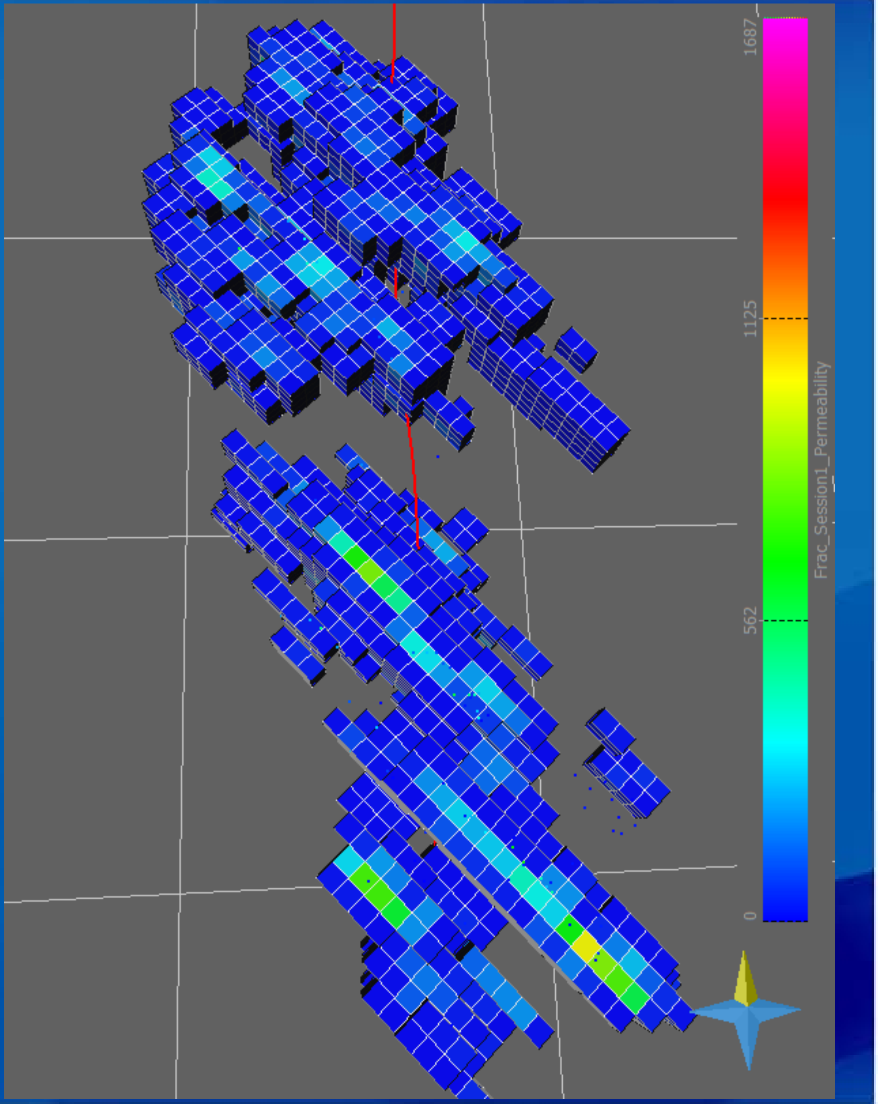
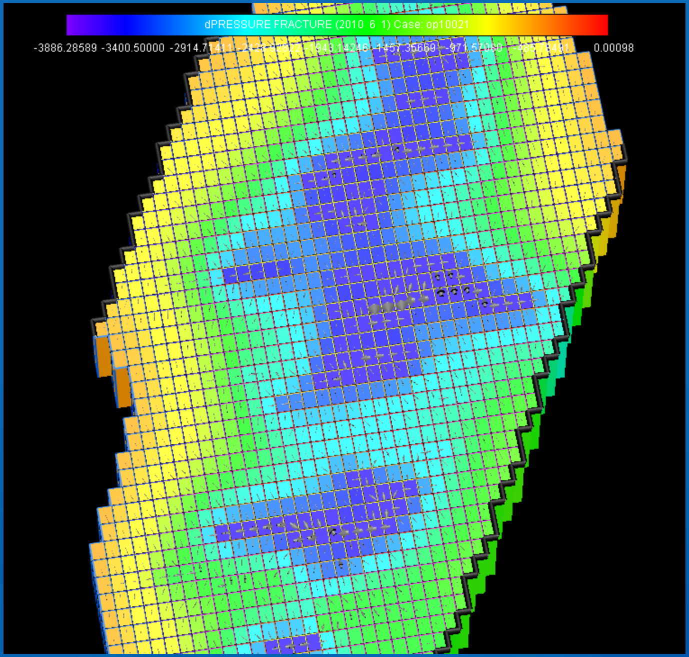
Fracture Flow Property Output

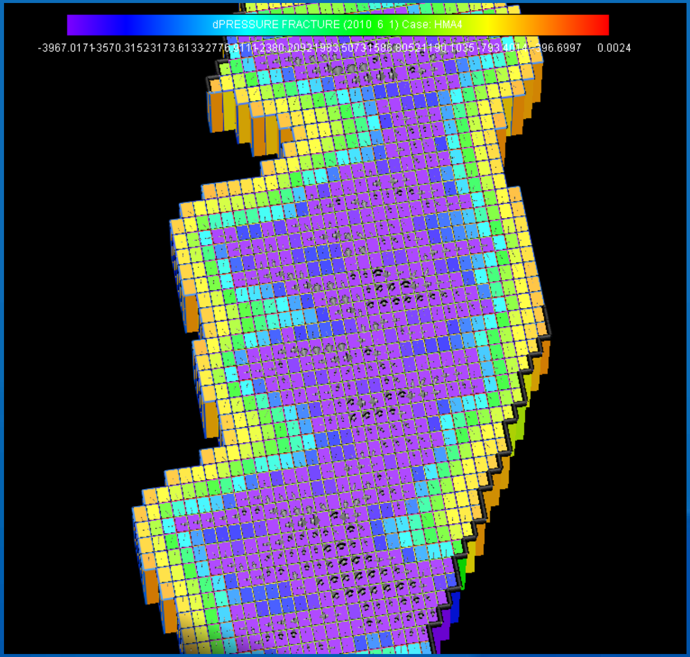
- Geocellular model is populated with flow properties calculated from fractures in the DFN
- Output permeabilities in the model represent zones of stimulated reservoir
- Combined with reservoir matrix rock properties flow models improve predictions of reservoir performance



Reservoir Simulation: Dynamic Calibration Process Example

Williston Basin Bakken Example showing fracture delta P after 24 months of production of a stimulated reservoir comparing two different DFNs





History matching calibrates parameters of Discrete Fracture Network model, leading to more accurate EUR

The Future - Applications

- Energy Industry
  - Improved stimulated reservoir definition
  - Better understanding of the fracture mechanics for better frac design
  - Reservoir simulation, more accurate EUR estimates
  - Reservoir monitoring, optimal reservoir exploitation
- Environmental applications
  - CO_2 sequestration
  - Preventing water supply contamination
  - Induced earthquake monitoring

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Notes by Presenter: These are the current type of applications of the technology that can be applied now. The environmental applications both concern fault seal – monitoring microseismicity of reservoir injections can show when and where faults are intersected that are potentially leaky. Induced earthquakes related to fluid injection is also a big concern, and we will hear more about in couple of other talks in this meeting. Permanent array installations would be a good technology for these applications.

The Future – Technology Areas

- Improvements in technology:
  - Better location accuracy
  - Faster processing
  - More sensitive detection of microseismic events
  - Calibration of source mechanisms with failure plane size
  - Better prediction of rock fracturing behavior for different lithologies, basins, stress regimes
  - Improvements in real-time event detection and for long-term production monitoring

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