Fracture Imaging and Permeability Fairway Mapping*

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Abstract

In recent years, image logging in horizontal wells in the shale plays has documented that the rocks have large numbers of fractures. During the recent history of recognizing shale gas as a fundamental energy resource in the US, image logs have documented that the permeability structure of these reservoir is dominated by natural fault and fracture systems. Fracture networks consist of all of the fractures in the rock, both man-made in frac jobs and the natural systems that some frac stages intersect. The important fractures in the reservoir are those that are interconnected in natural fracture fairways and carry the pressure from the hydraulic fracturing (frac) point to locations that are at great distance from the well. These fractures make up the primary permeability of the rocks and provide the permeability fairway in the reservoir that controls producibility.

The process for generating images of fracture networks and fairways is described. The processing workflow uses microseismic recordings to compute semblance and coherence volumes. These volumes are combined over large time intervals to accumulate energy from the individual volumes, including energy from events much smaller than those normally detected by hypocenter methods. The seismic emissions that are persistent over time are combined and converted into the fracture network images called TFIs or Tomographic Fracture Images™.

The microseismic energy that is combined to make the fracture images contains the hypocenters that occur during the time interval used in the computation. However, the hypocenter energy is a very small portion of the total energy that is integrated. Das and Zoback (2011) describe a type of microseismic energy they call "LPLD" or Long Period, Long Displacement energy. These energy packets are generated in the same small sub-volume of the Earth, have a lower frequency band than hypocenters, and last for much longer periods of time. Occurrences have been documented to last for as long as a few seconds and up to a few minutes. This type of energy is observed in the microseismic trace data and examples will be shown. We believe that the bulk of the microseismic energy that is focused for TFI computation is the LPLD type of energy. Movies of the seismic emissions accumulated over the frac stage are made to show the time sequence of the fracturing process.

A primary objective for the completion engineers assessing frac jobs in shale gas systems is a measurement of the rock volume that has been stimulated to produce gas to the wellbore. The fracture imaging method is used to map the frac job near the perf zone as well as the natural fracture fairways that the frac intersects and allows measurements of the stimulated rock volume (SRV) and distance of fracture propagation.

References Cited

Das, Indrajit, and M.D. Zoback, 2011, Long period long duration seismic events during hydraulic stimulation of a shale gas reservoir: e-Poster, AAPG Annual Convention and Exhibition, Houston, Texas, USA, April 10-13, 2011.

Heffer, K., I.G. Main, and J. Greenhough, 2011, Monitoring geomechanical changes in naturally fractured reservoirs through rate correlation analysis: Proceedings EAGE Naturally and Hydraulically Induced Fractured Reservoirs Workshop: From Nanodarcies to Darcies, April 10-13, 2011, Nafplio, Greece, 5 p.

Zoback, M.D., A. Kohli, I. Das, and M. McClure, 2012, The importance of slow slip on faults during hydraulic fracturing stimulation of shale gas reservoirs, SPE #155476: SPE Americas Unconventional Resources Conferences, June 5-7, 2012, Pittsburgh, PA. 9 p. doi: 10.2118/155476-MS.

Fracture Imaging
and
Permeability Fairway Mapping

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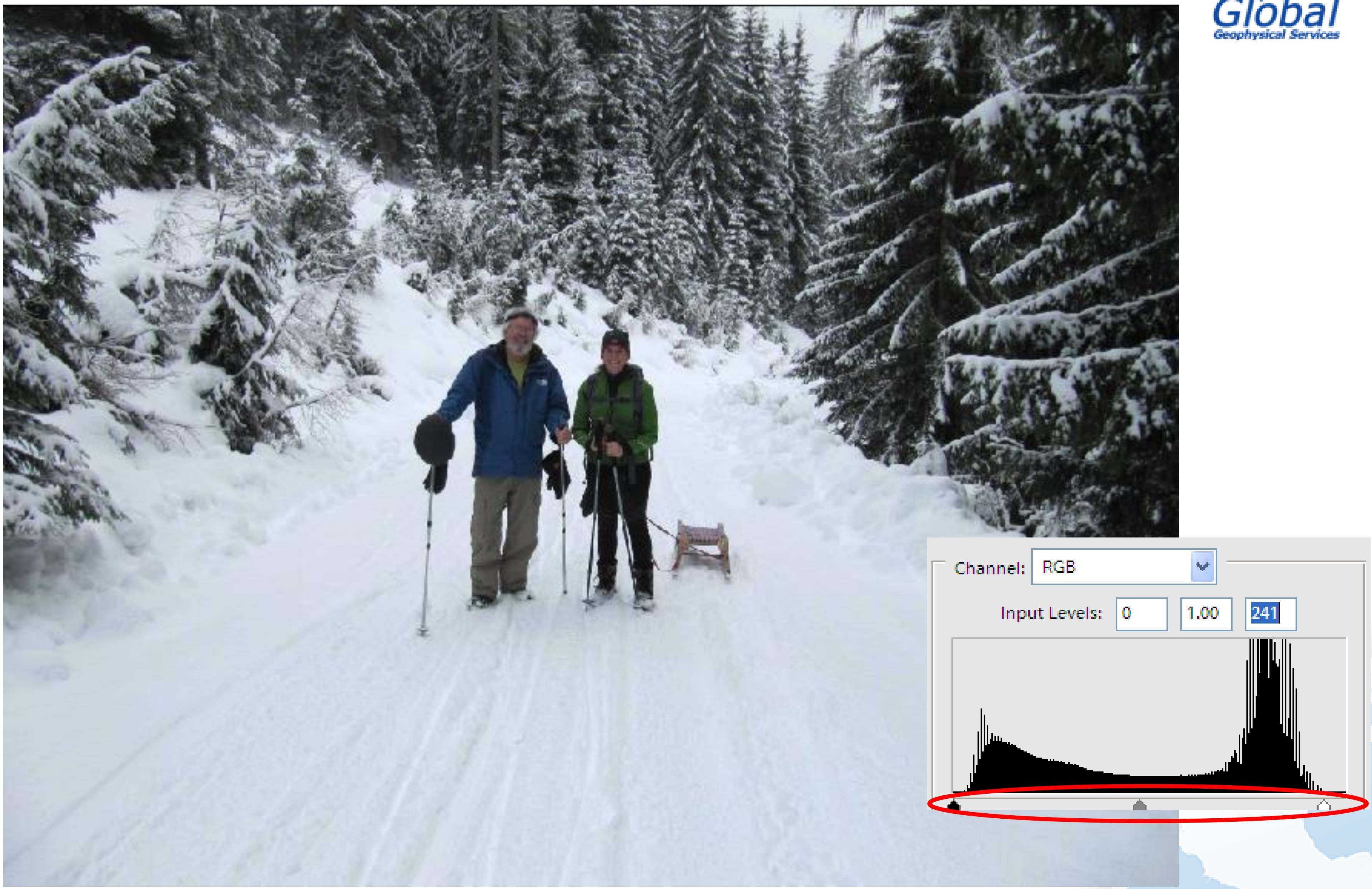
April, 2013

Global Microseismic Services

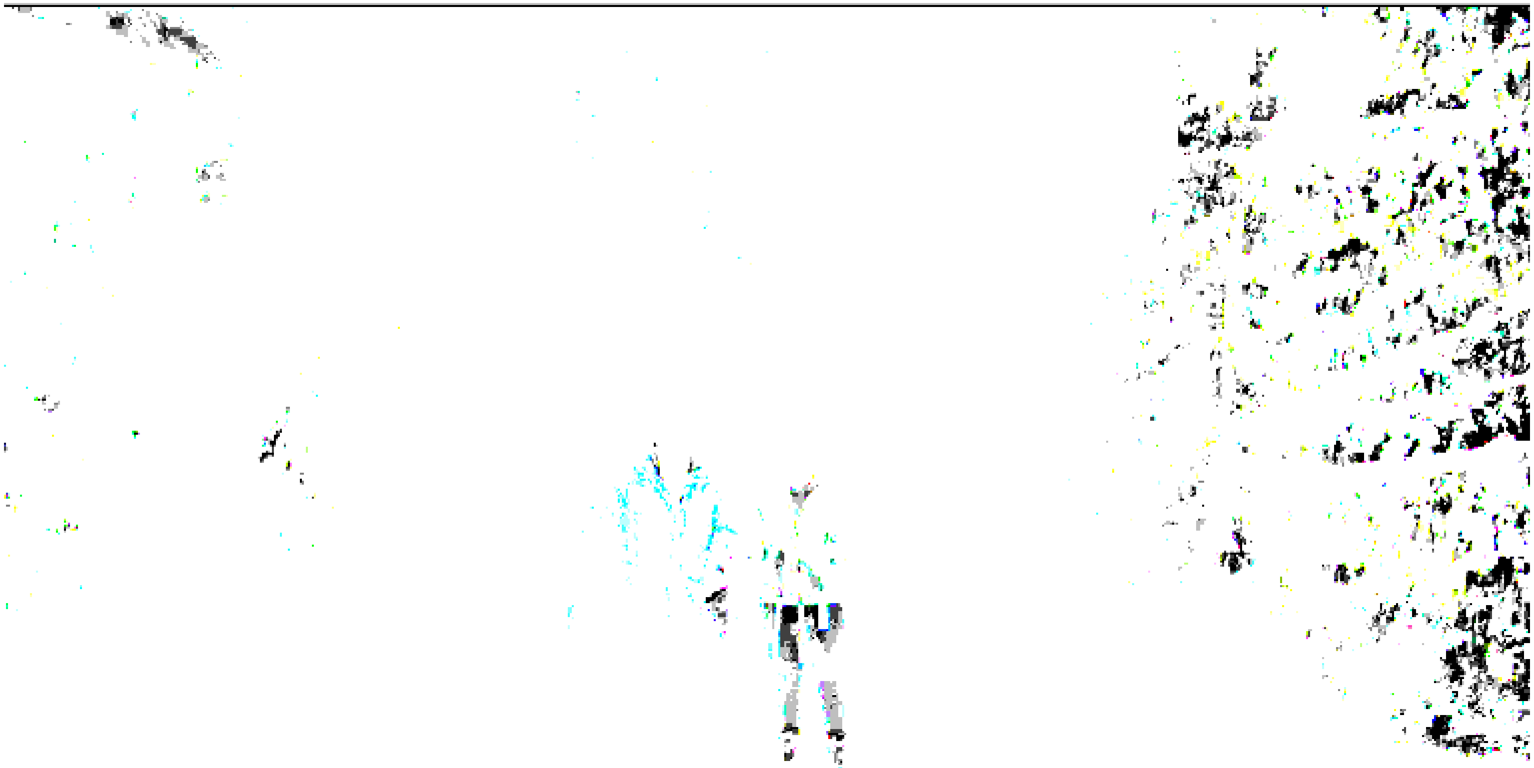
The Microseismic Value Proposition

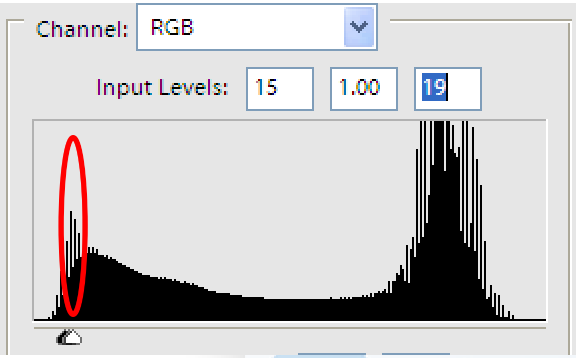
- ***Microseismic companies have been imaging only a small portion of what is going on during a frac or as a field is producing fluids.***
- **Micro-earthquakes are created by different processes**
- ***Imaging longer period events is critical to understanding reservoir structure***
- **Tomographic Fracture Images™ Provide**
  - **Maps of Reservoir-Wide Fracture Networks**
  - **Maps of Near Well Fractures Caused By Frac Pumping**
  - **Input to Reservoir Simulations and Modeling**
- **Mapping Of Fracture/Fault Zones Allows For Better Planning**
  - **Defines What Happened To Current Well**
  - **Helps Optimize Well Locations**
  - **Leads to Better Frac Planning**
  - **Defines Natural Fracture Systems Pre-drill**
- **Stress Direction Determination**

What's Really Happening



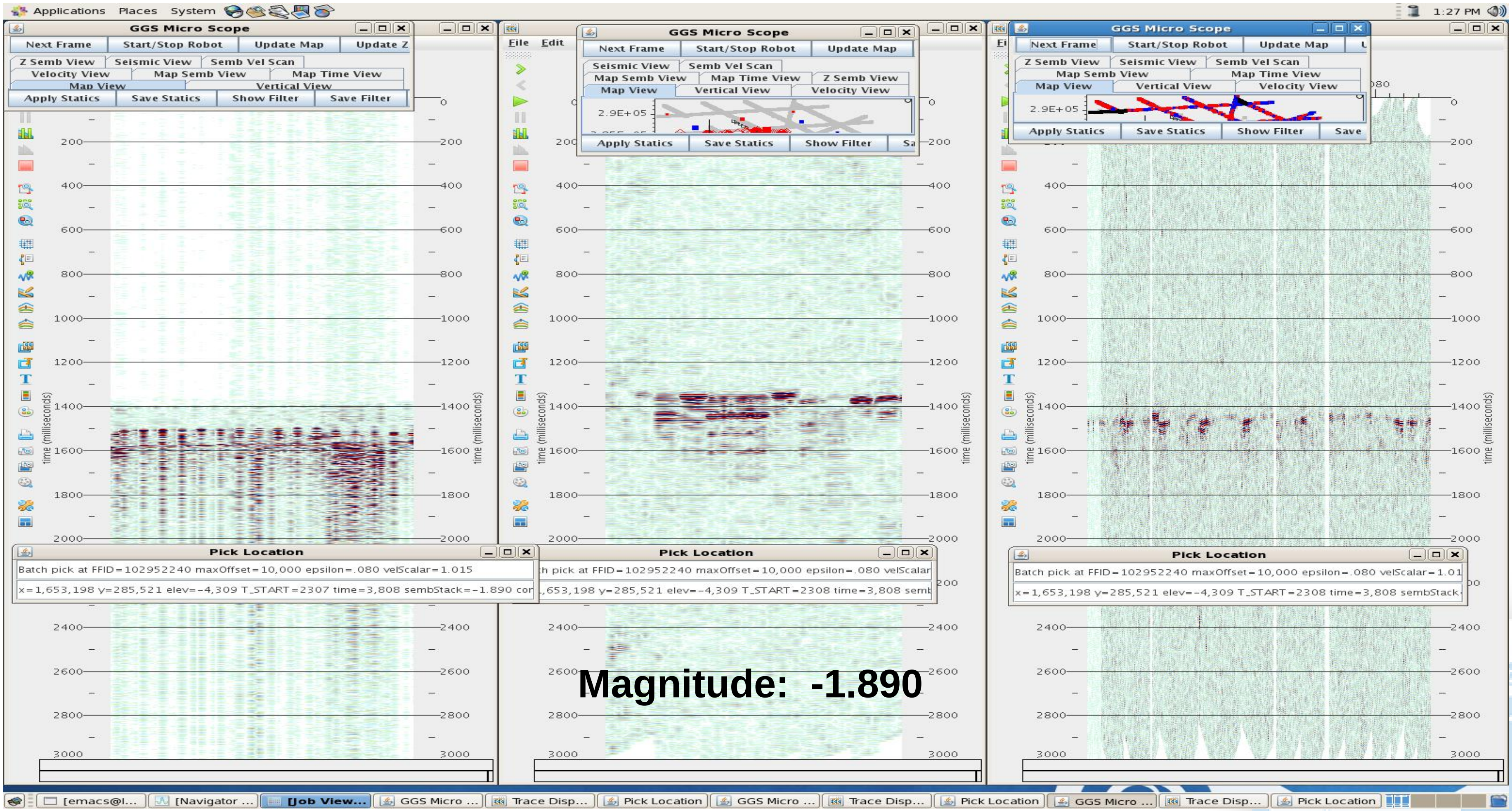
What Do Single Events Show You?





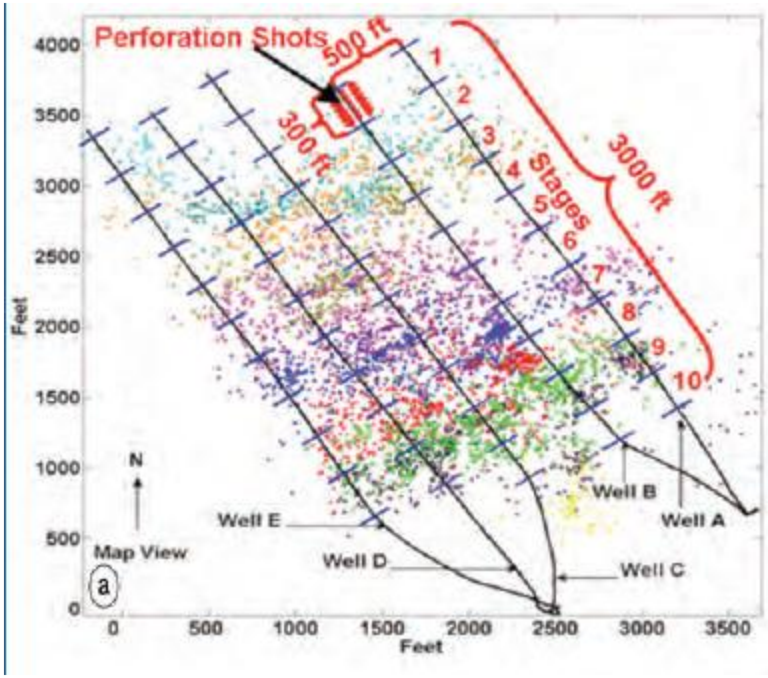
Some flavors of Microseismic data

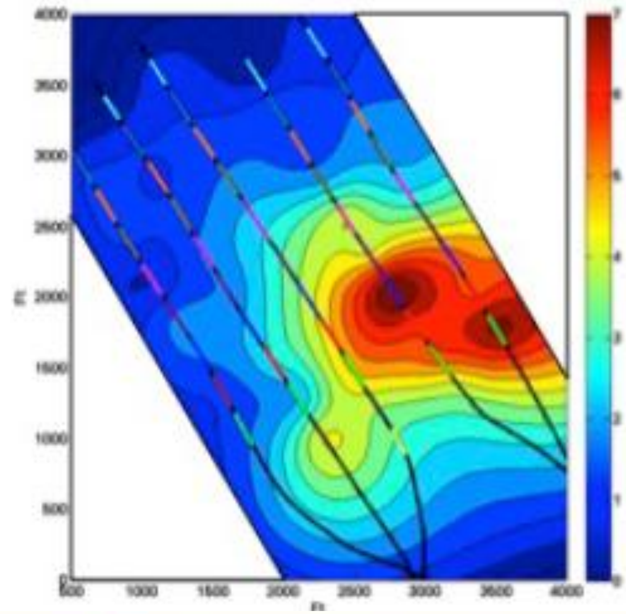
Bore hole **Buried sondes** **True surface**

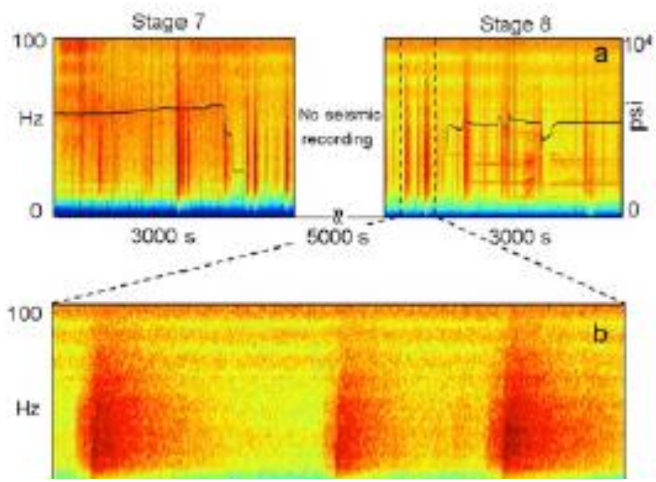


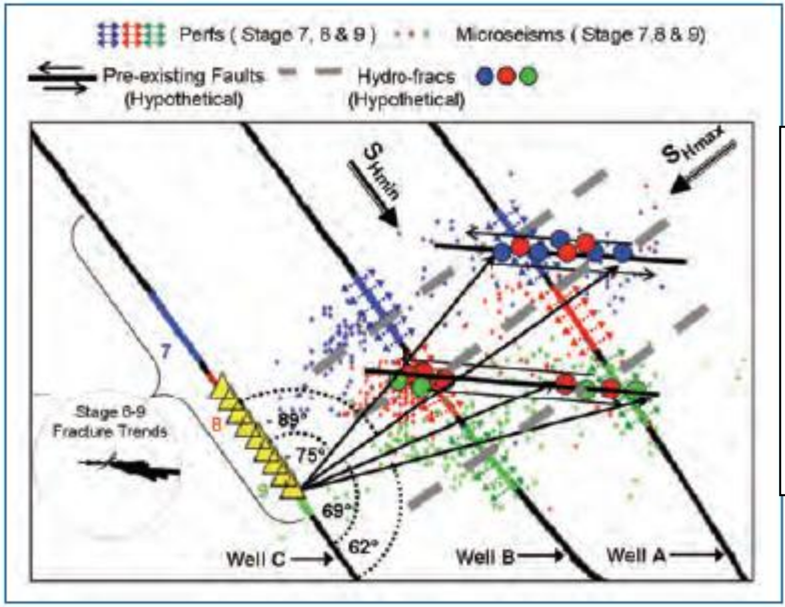
These data are only a SMALL portion of what's going on in the reservoir.

Zoback et al and LPLD Activity









Note that the Natural fault pathways are not in the same orientation as SH_{max}. This is the critical piece of data to image.

Zoback et al, 2012 SPE 155476

Micro-crack activity as illuminating the permeability field in a reservoir.

Global Geophysical Services

The Theory

The Earth's crust is a Self Organizing Critical system that is at frictional equilibrium with respect to brittle failure by slip on pre-existing fractures. This failure is in shear.

•Studies of stress drops associated with micro-seismicity indicate that **Δs of <0.01 bar can cause slip.**

When perturbed by either a positive or negative change in fluid pressure (a frac job, a producing well, an injector), the hydraulically conductive fractures of **the reservoir permeability field are illuminated.**

The Facts

•**Fluid pressure responses** are seen between wells km apart in a matter of minutes.

•A fluid pressure wave **(Pf) disrupts the frictional equilibrium** of the permeability field fracture/fault fairway system which consists of hydraulically conductive fractures.

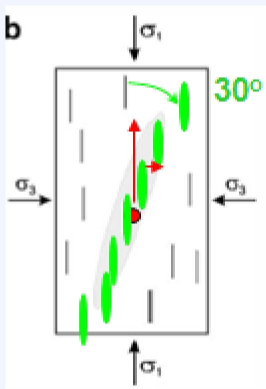
•Hydraulically conductive fractures are fluid filled and **oriented for shear failure** under *in situ* stress conditions and are therefore the weakest fractures.

•The re-adjustment of the micro-cracks in the permeability structure "light up" that structure – this is what we are imaging.

Fluid Pressure Connectivity

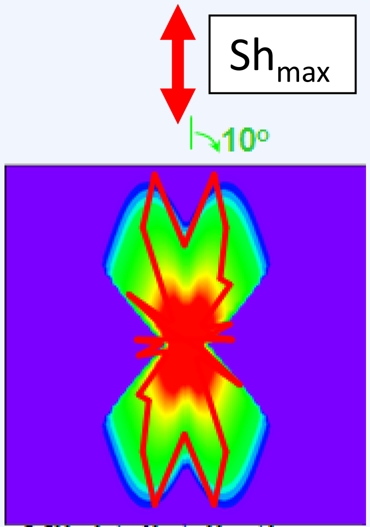
Flowstreams through interacting fractures in matrix of medium permeability

permeability



Healey et al, 2006

Fracture dilation



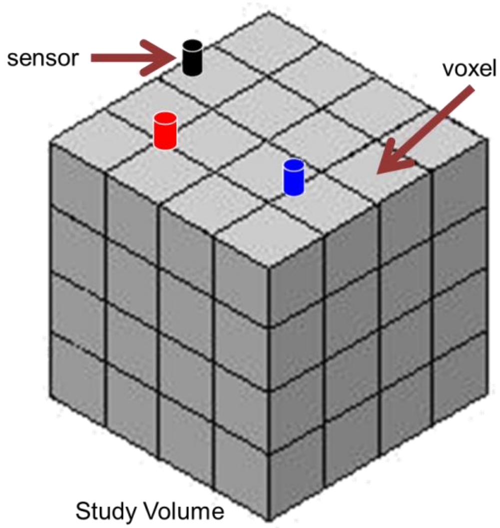
Time of flight distribution around a well ~ isobars of pressure field ~ normal to flowstreams and flood progression.

most favoured breakthrough directions for injected fluid in 47 'unfractured' fields worldwide

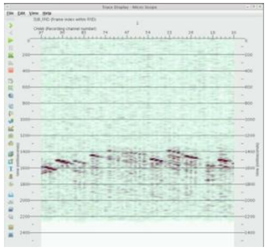
Kes Heffer, 2011

The contours show times of flight from constant injection or production at a central well, calculated assuming fracture permeability is proportional to the cube of the strain and matrix permeability is moderate. This pattern is present even in fields not recognized as being fracture dominated.

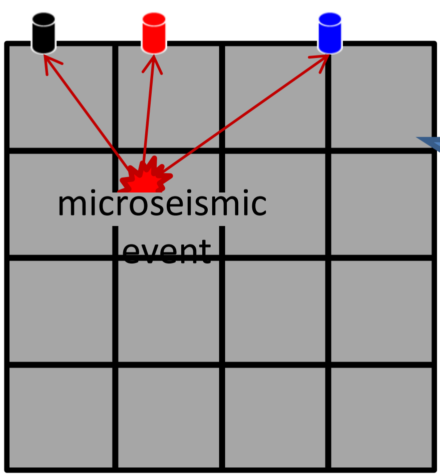
Make velocity model, then align records, compute semblance or other quantity



Semblance (**S**) is a measure of the coherence of acoustic emission for each voxel, over a selected time window (e.g. 1 sec.).

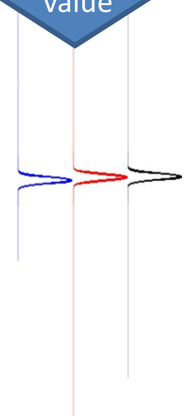


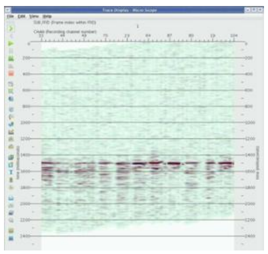
For the time window (1 sec., sampled at 1000 sps) the data are stacked, a semblance value is computed for each voxel.



For the given velocity model, travel time is computed for each voxel recording-site pair.

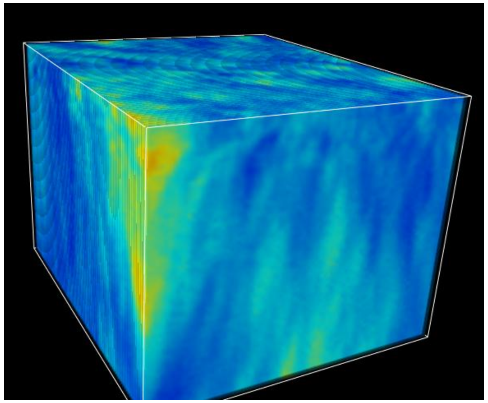
a weak but coherent signal results in a high semblance value





$$S = \frac{\sum_{j=0}^{T} \left[\sum_{i=0}^{K} f_{ij}(\tau_i) \right]^2}{\sum_{j=0}^{T} \sum_{i=0}^{K} f_{ij}^2(\tau_i)}$$

Constructing a Tomographic Fracture Image



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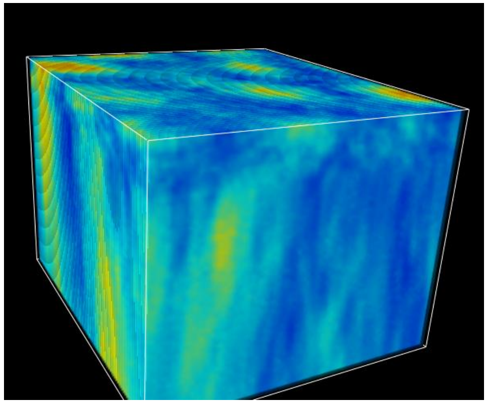

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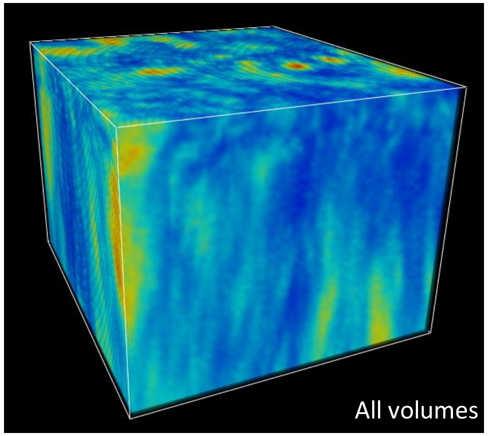
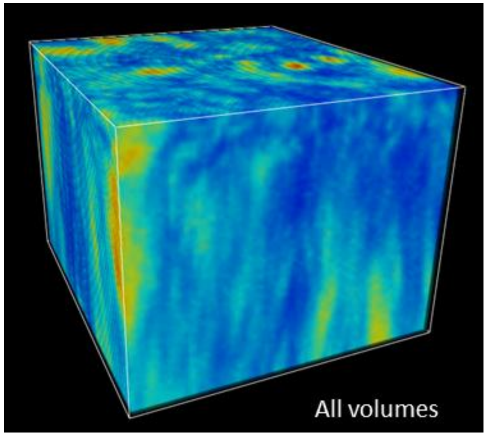


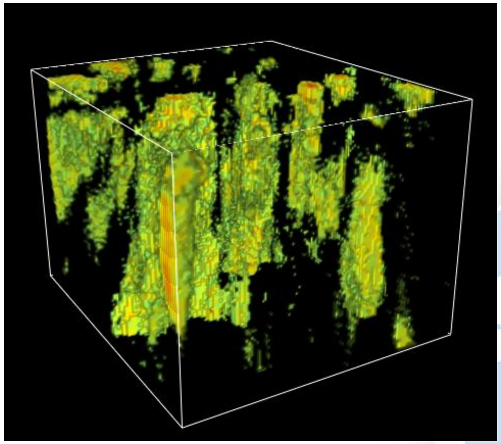
Semblance Variables

Timing, Window Length, Sample Frequency, Semblance Values, Semblance Persistence, Other Temporal and Morhologic Features

Final Volume

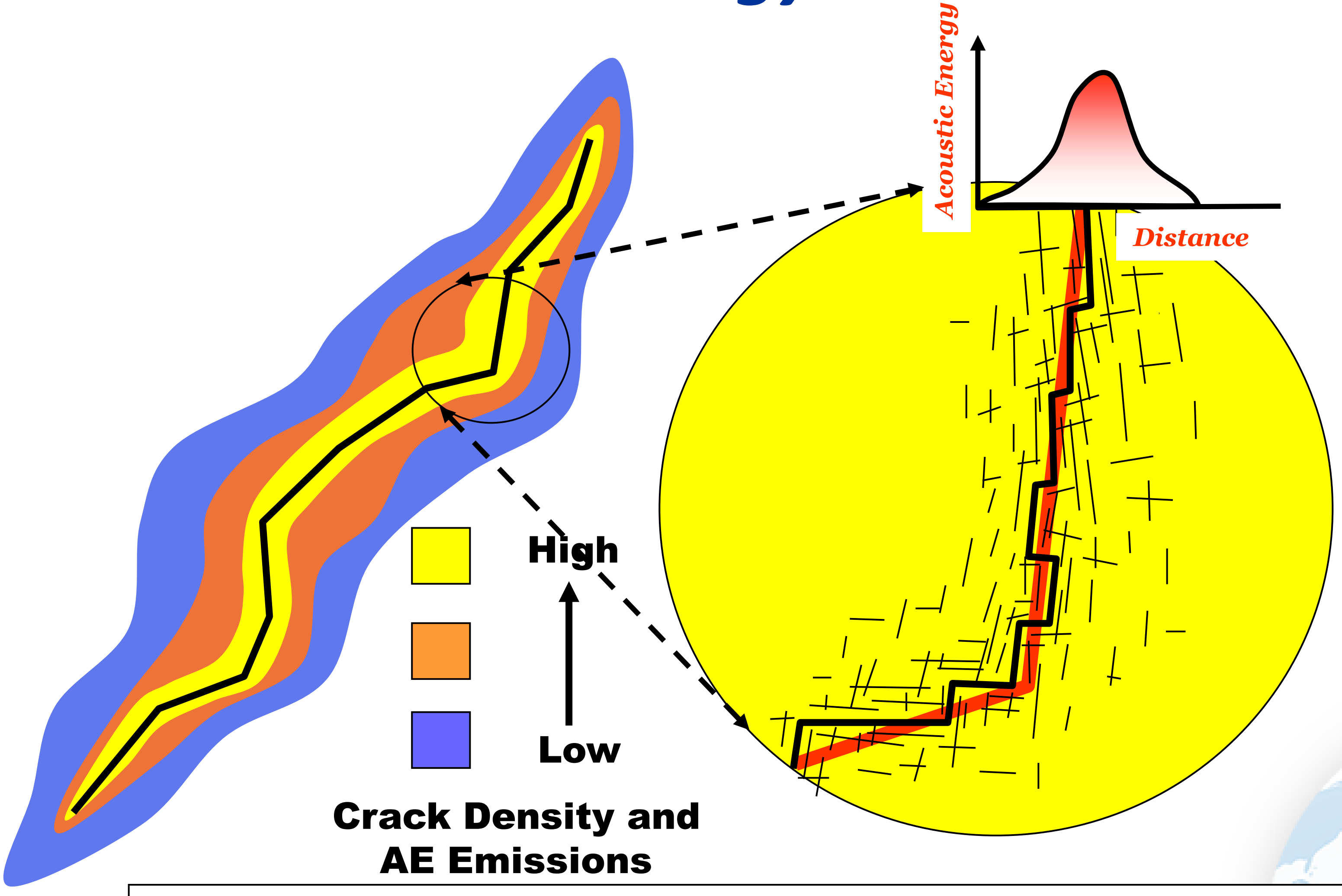


Analyze Data and Select Methods



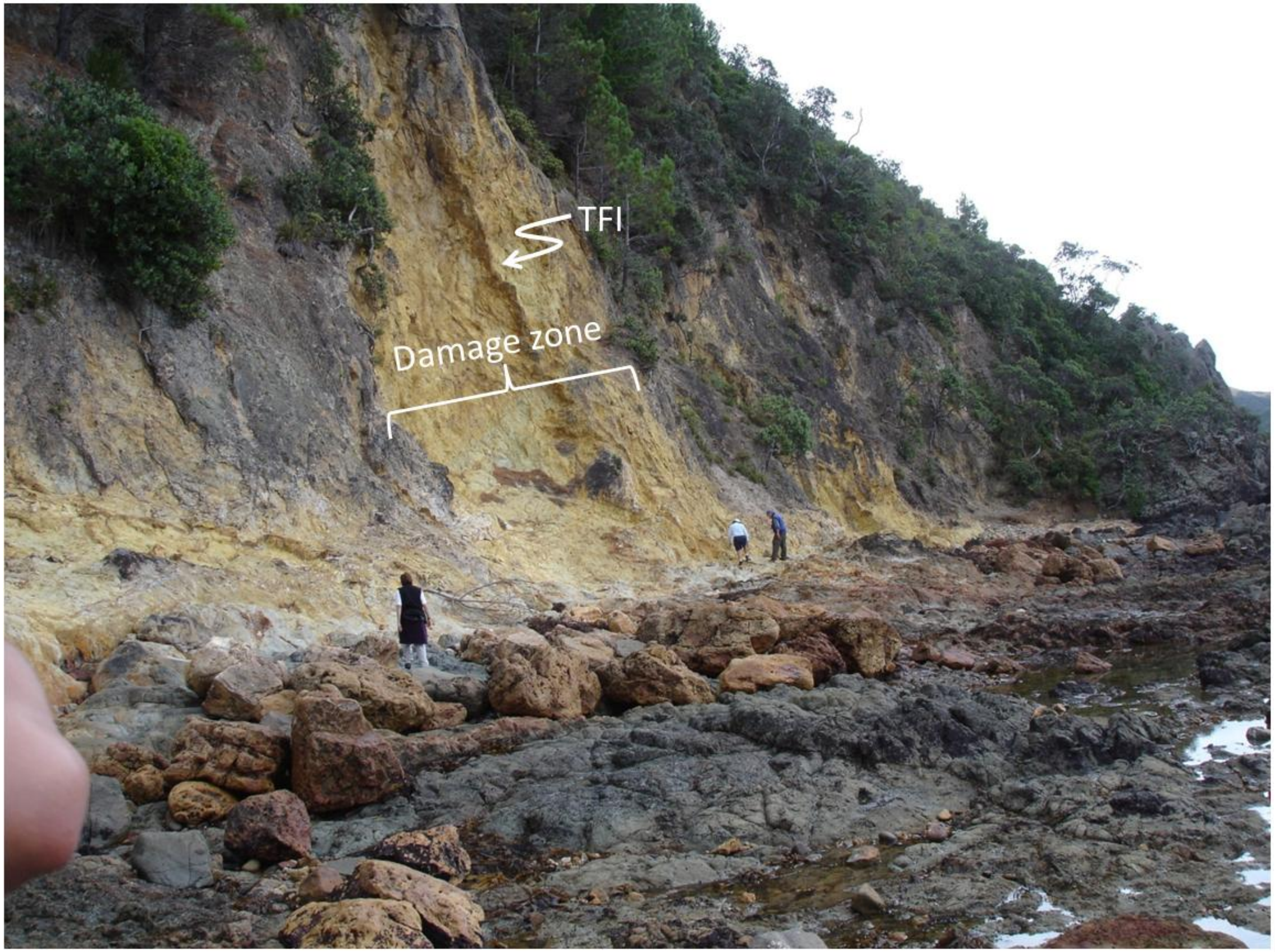
TFI Volume

Relation of Fault/Fracture Fairways to Acoustic Energy Emission



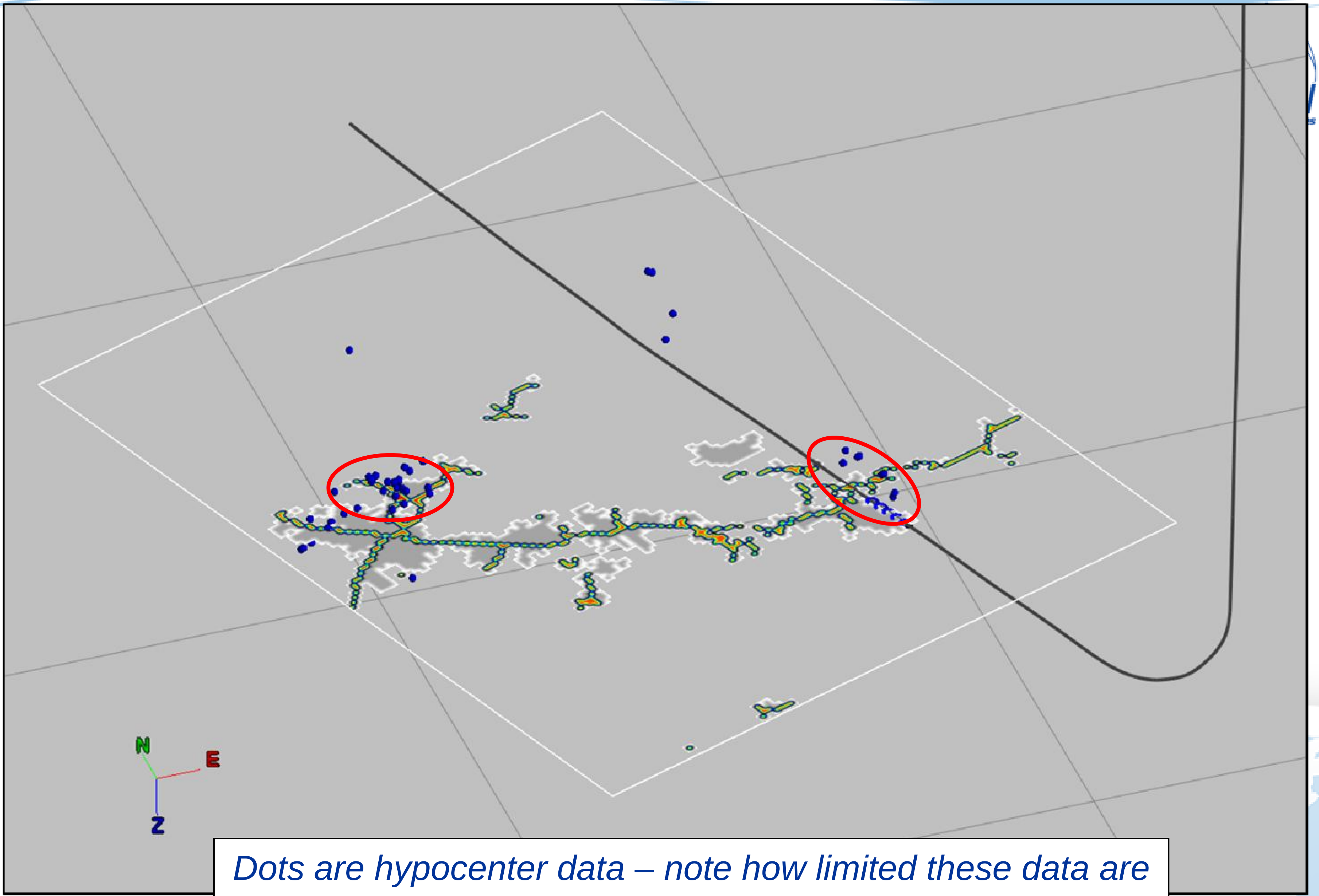
The density of microcracks is MUCH higher close to a fault.
LPLD activity takes place as these cracks readjust to pressure changes.

Fault/Fracture Fairway
Outcrop Example



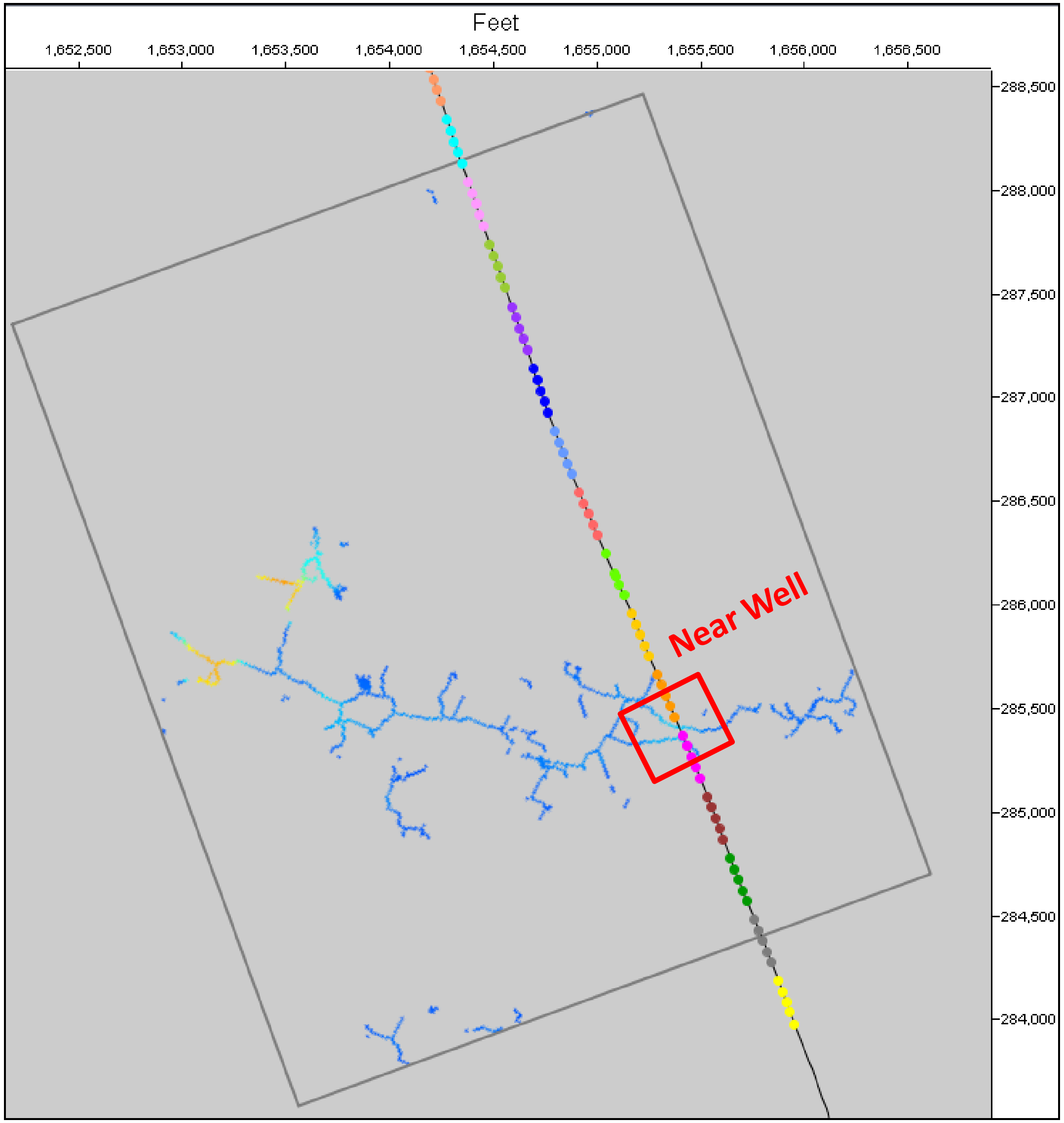
Graywacke reservoir exposure of Coromandel Formation: New Zealand

Color change is due to fluids moving through the fault damage zone. TFIs image these damage zones as permeability corridors.



Dots are hypocenter data – note how limited these data are compared to the TFI data that show the fracture fairway.

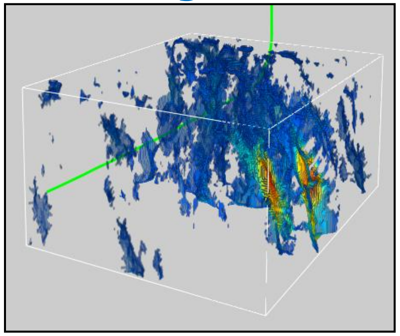
Reservoir-scale fracture fairways



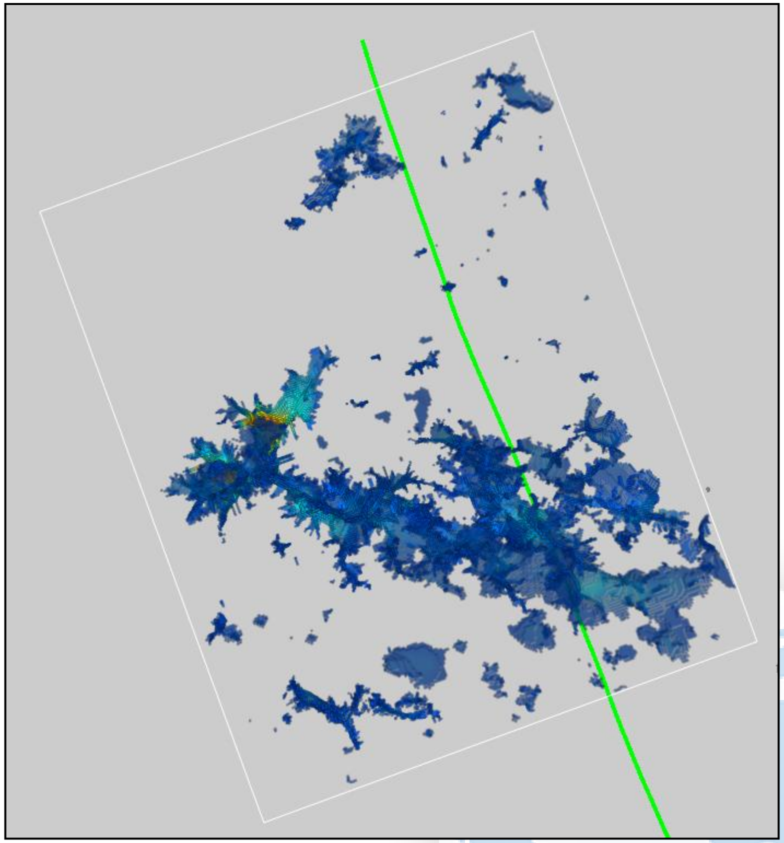
Map view at perf depth

A large TFI segment is located at the stage 12 perf location

Pumping into this fracture activates a pre-existing fairway to the NW

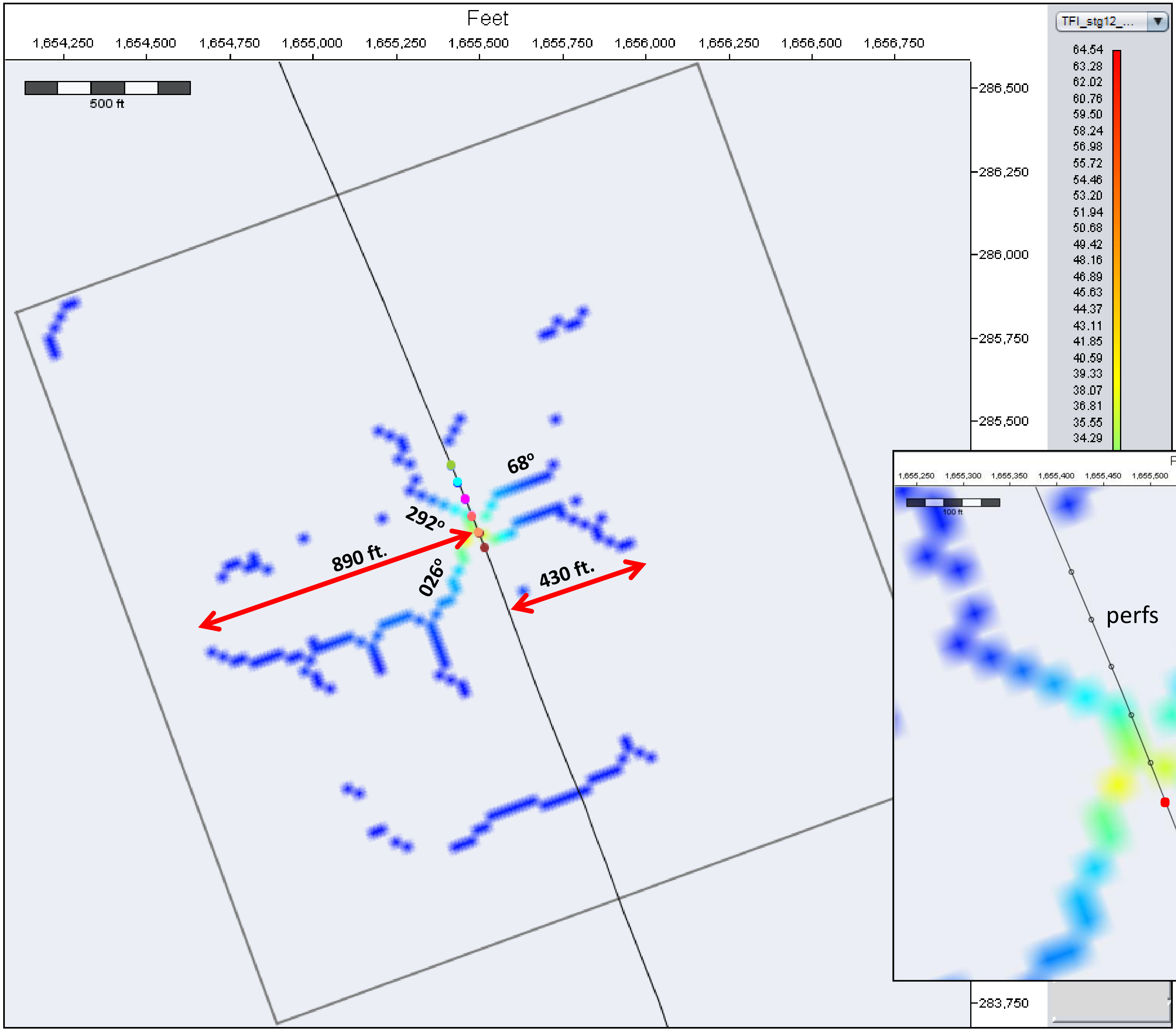


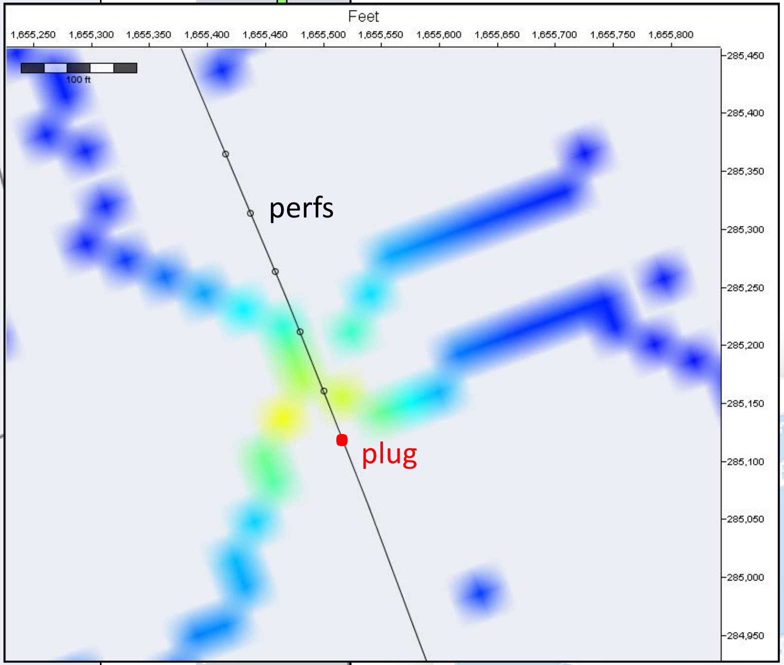
3D TFI viewed from NW



3D TFI viewed from above

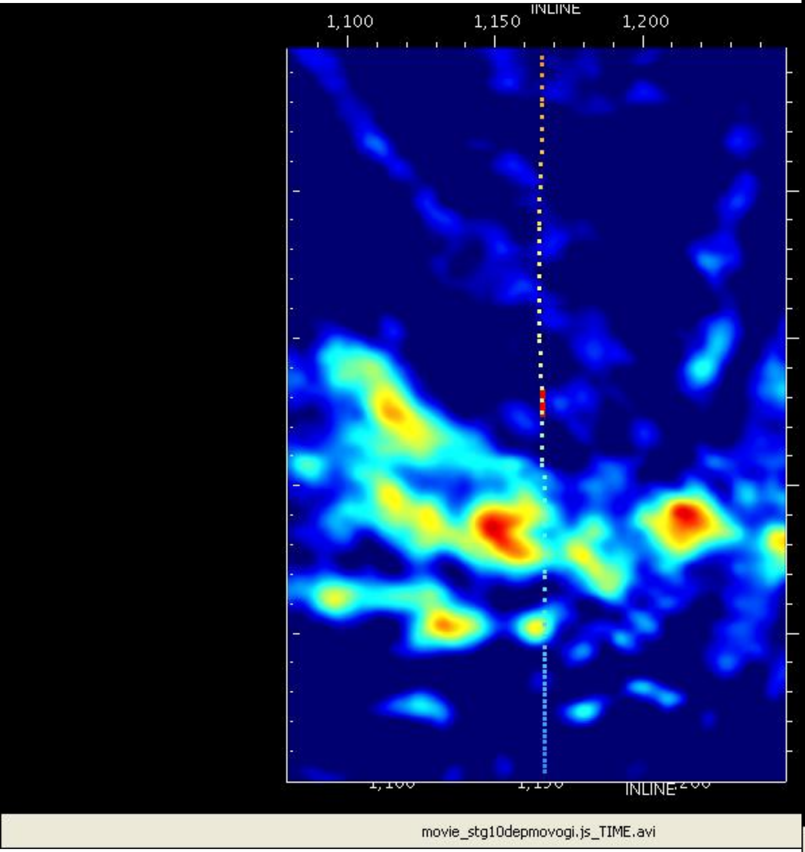
Near-well stage location activity

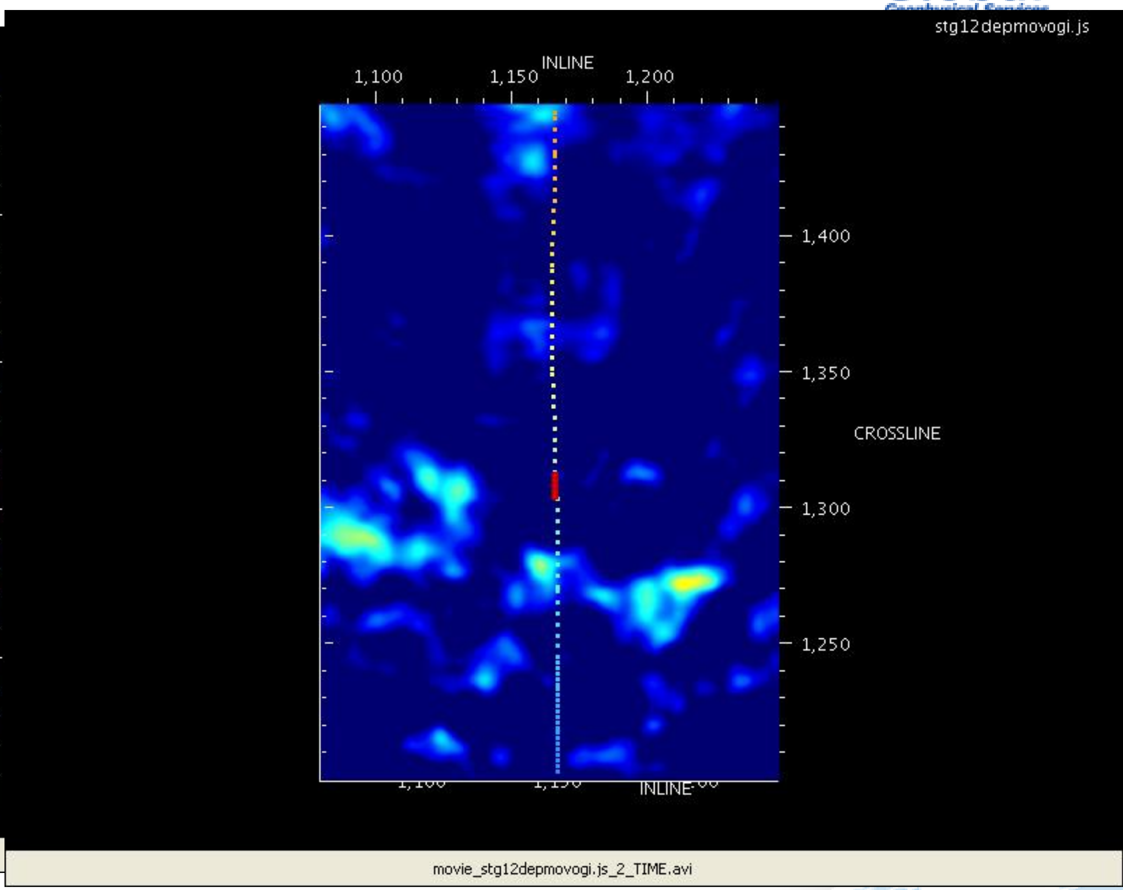




All activity directly connected to the perf shot locations for stage 12 frac stage (3.75 hrs.)

Fracture Imaging – 2 Stages





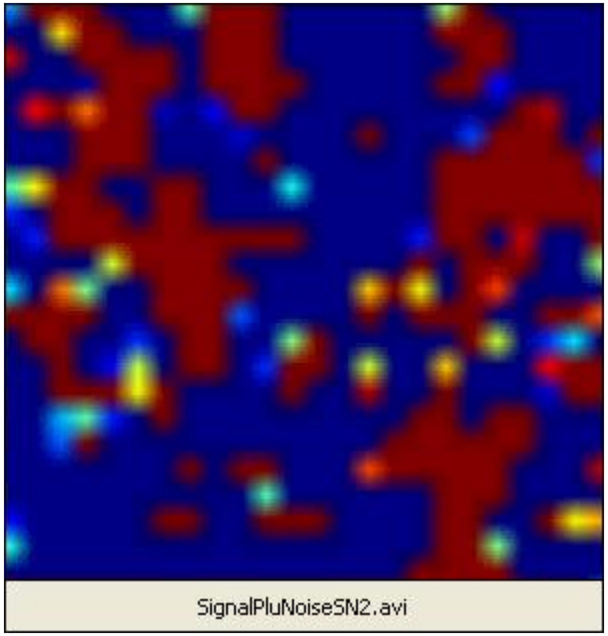
Stage 10

Stage 12

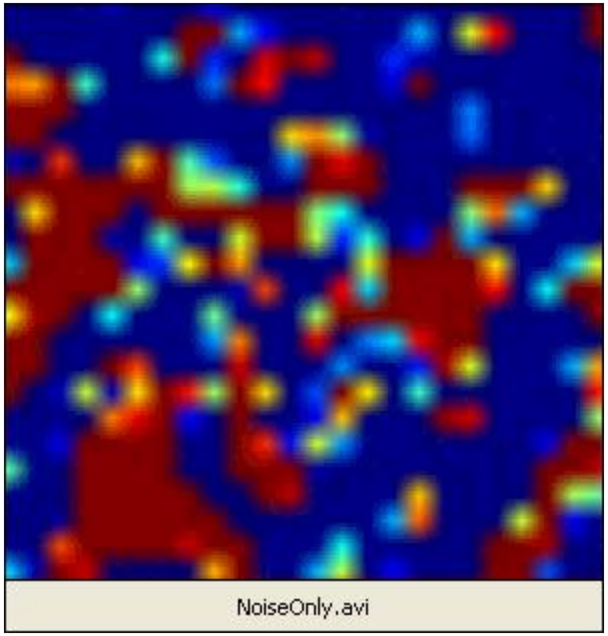
The interaction of frac pressures with *in situ* permeability is complex.
Spatially stable activity mapped as TFIs can give a detailed image of fluid responses.

Fracture Imaging
Building Up Signal, Suppressing Noise

Fracture Image With Noise



Noise Only

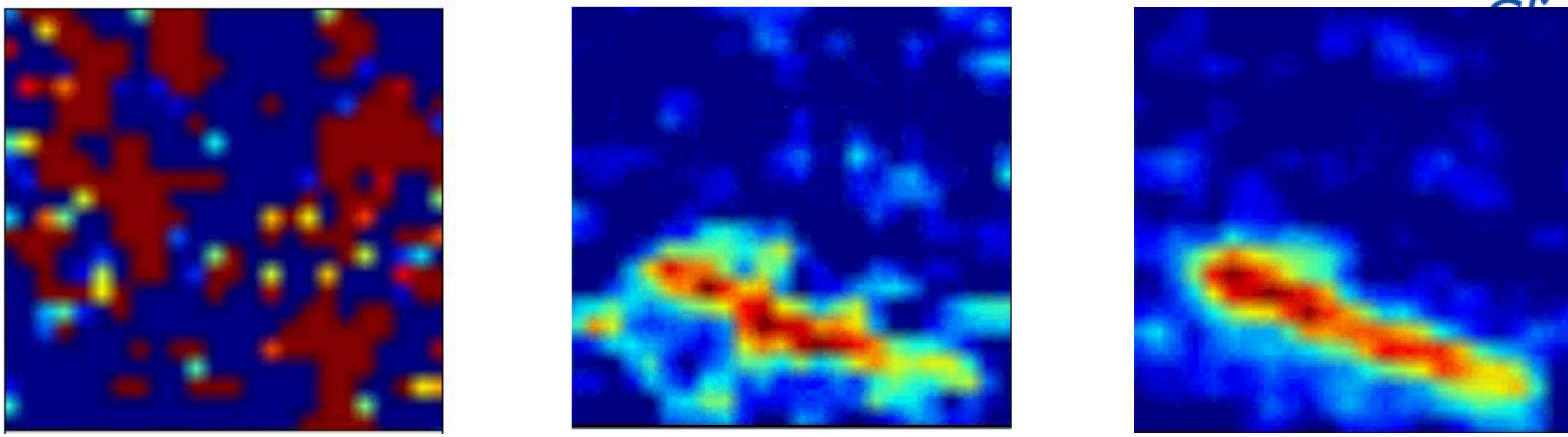


Spatially stable activity through time emerges and is mapped as TFIs

Random noise stacked through time fades into the background.

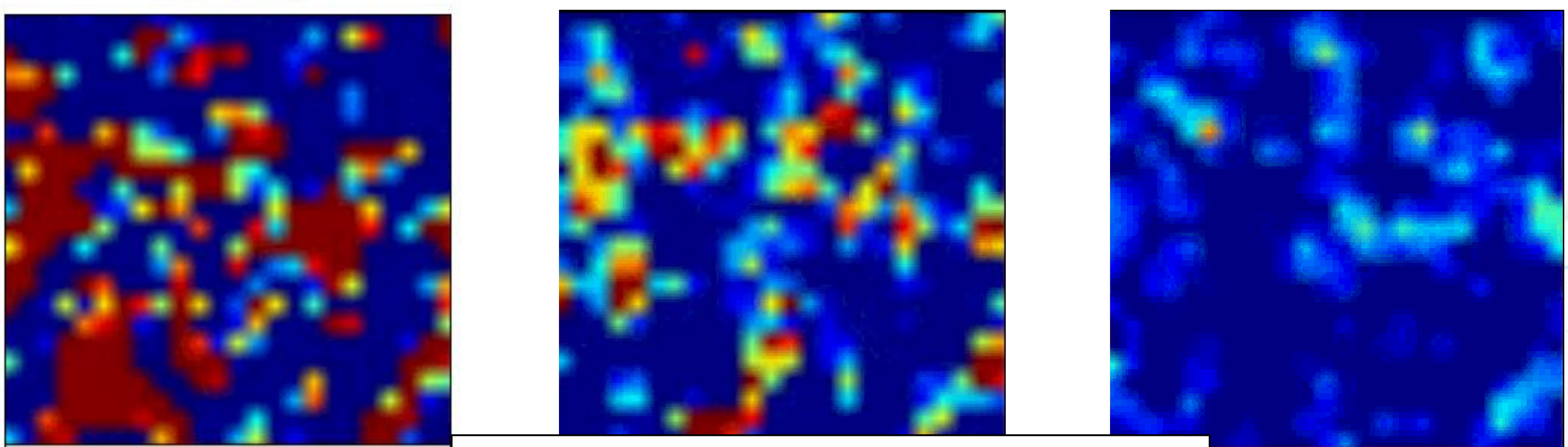
Fracture Imaging
Building Up Signal, Suppressing Noise

Fracture Image With Noise



Spatially stable activity through time emerges and is mapped as TFIs

Noise Only



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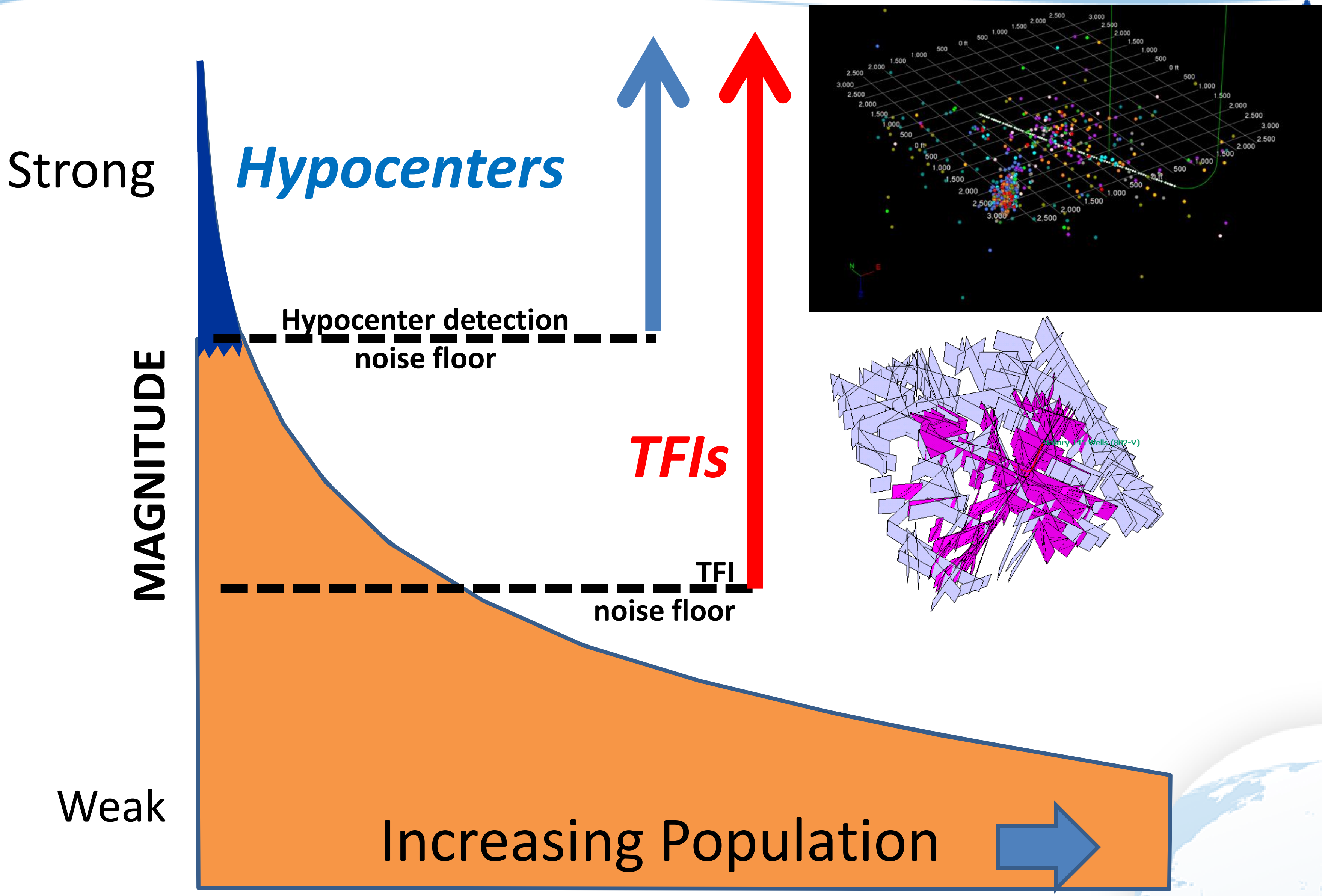


By stacking tens of thousand of events through time, we image spatially stable locations of the permeability structure of the reservoir.

GMS Experience by Basin or Play

Domestic

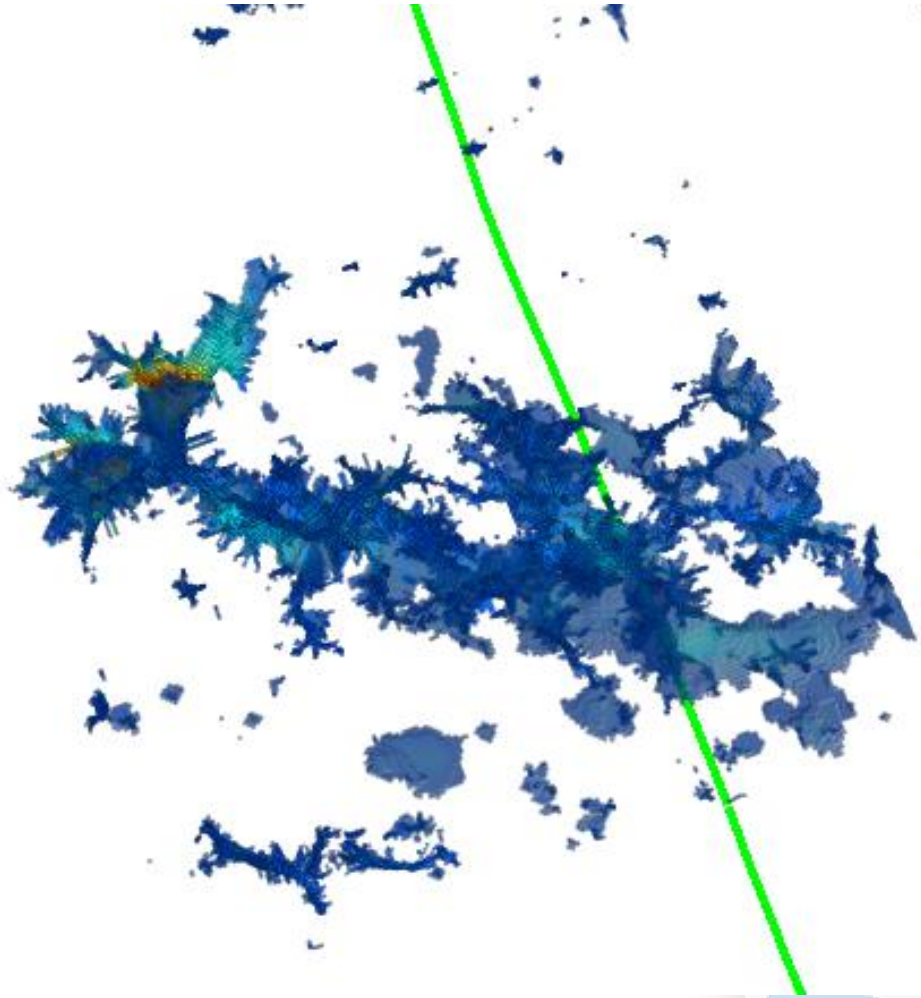
- ✓ Eagle Ford
- ✓ Marcellus
- ✓ Haynesville
- ✓ Niobrara
- ✓ Permian
- ✓ Bakken
- ✓ Olmos

International

- ✓ Argentina
- ✓ Mexico
- ✓ China
- ✓ Canada

New Areas/awards

- ✓ Utica



Experience

TOTAL

bp

RANGE RESOURCES

COMESA

Apache CORPORATION

MARATHON

EQT

Where energy meets innovation.

Lewis Energy Group

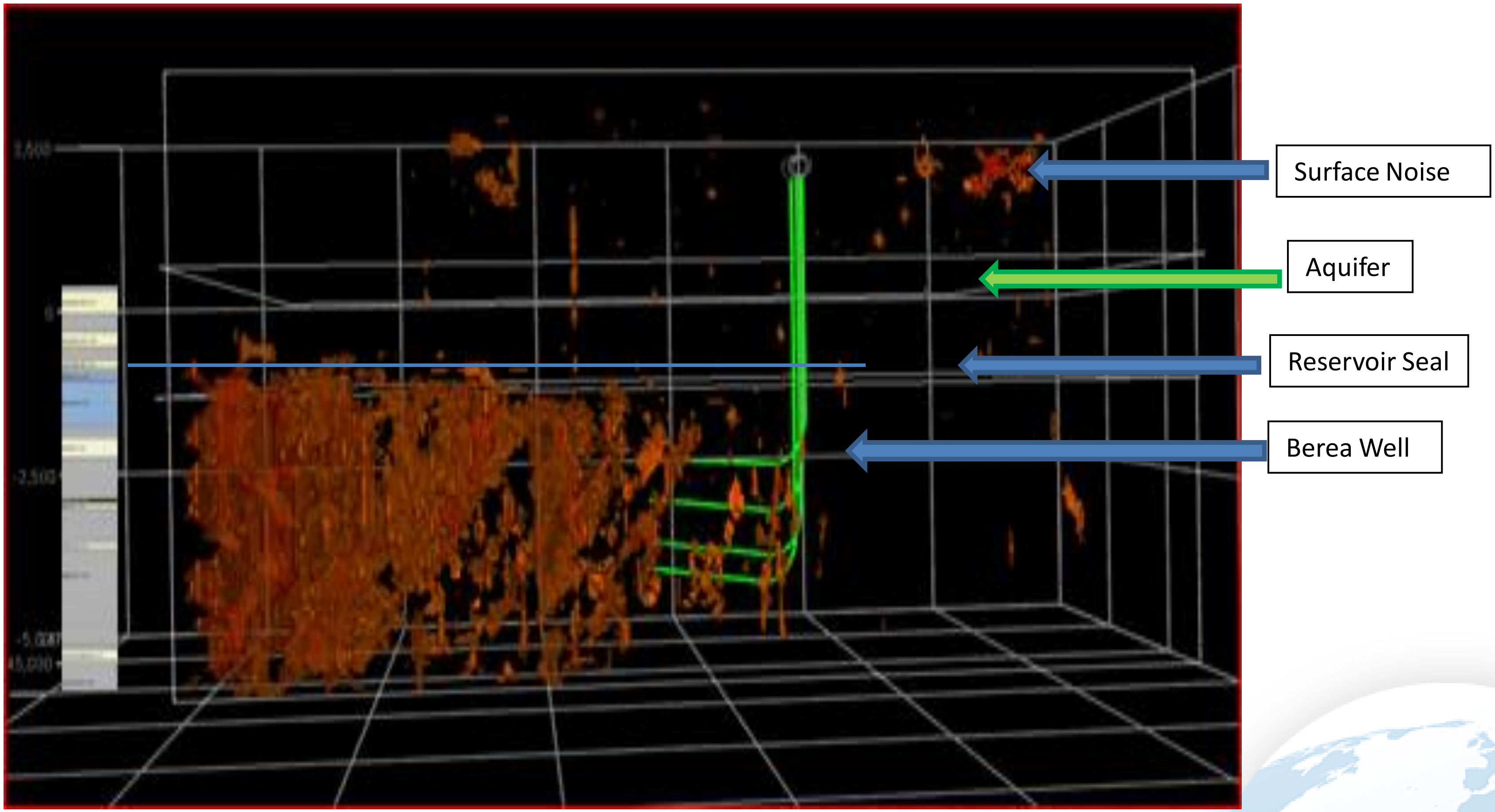
Fasken Oil and Ranch, Ltd.

BLACKBRUSH OIL & GAS, L.P.

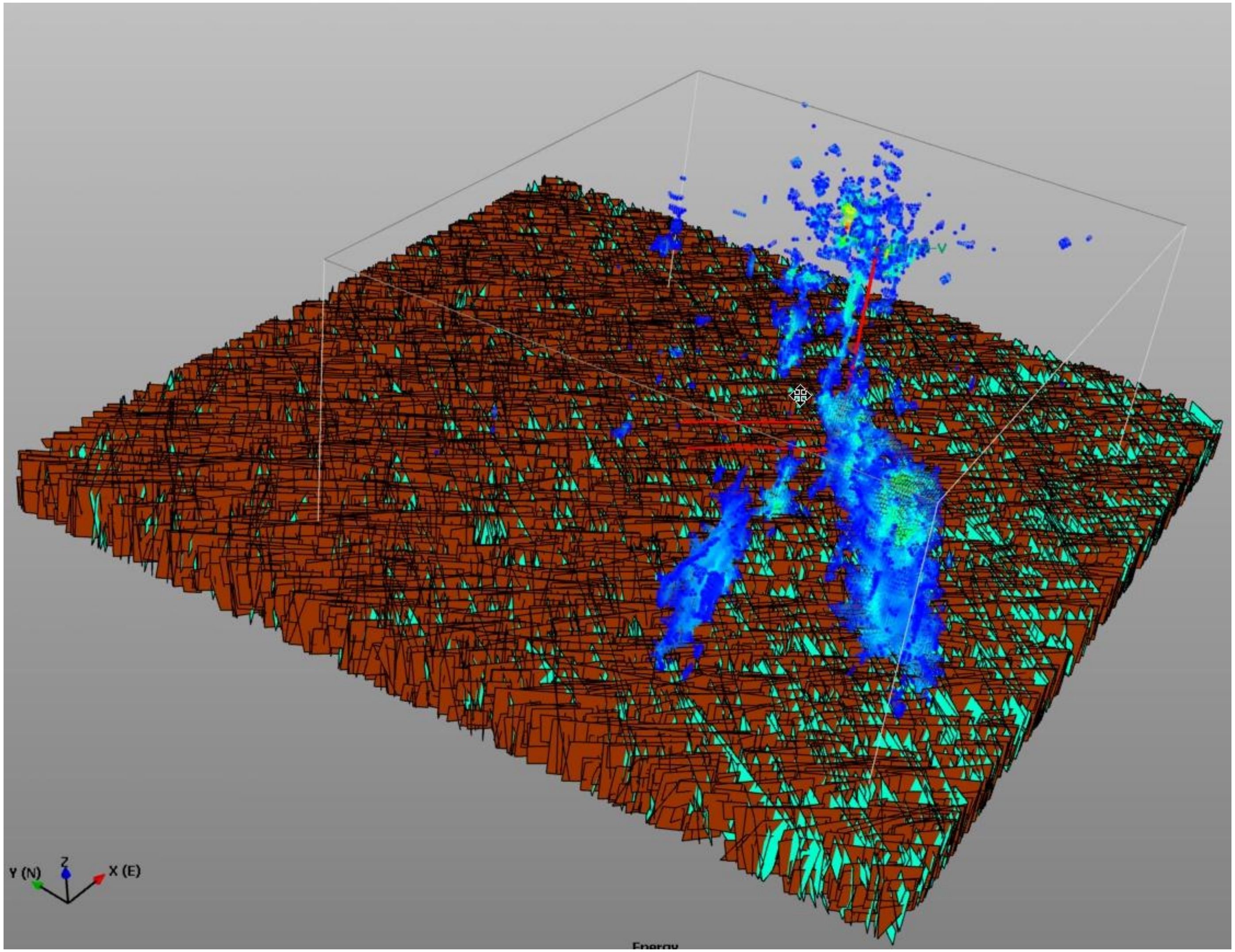
PEMEX

NEWFIELD

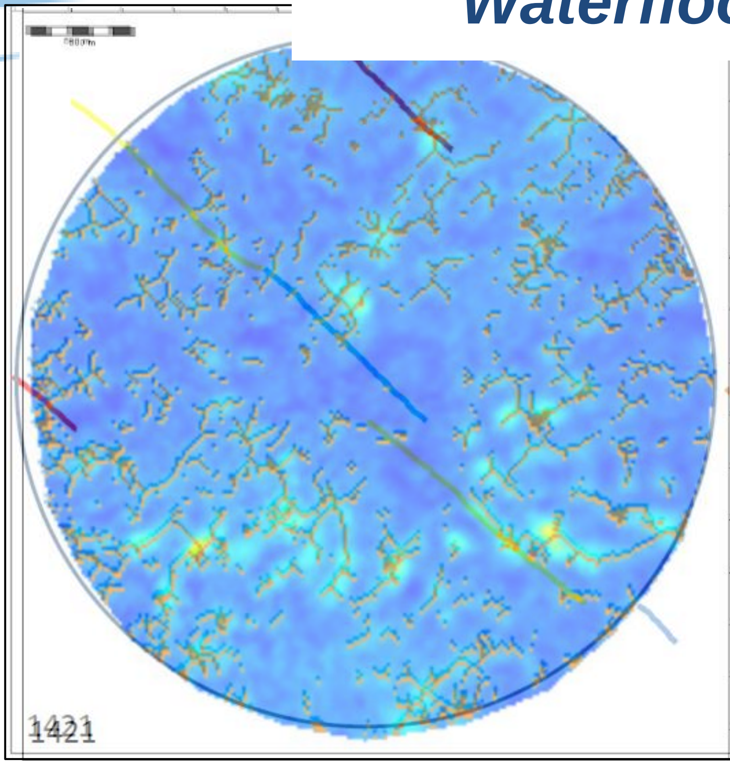
Additional Value: by imaging the entire rock volume, frac energy can be mapped in 3D to evaluate impact on aquifers.



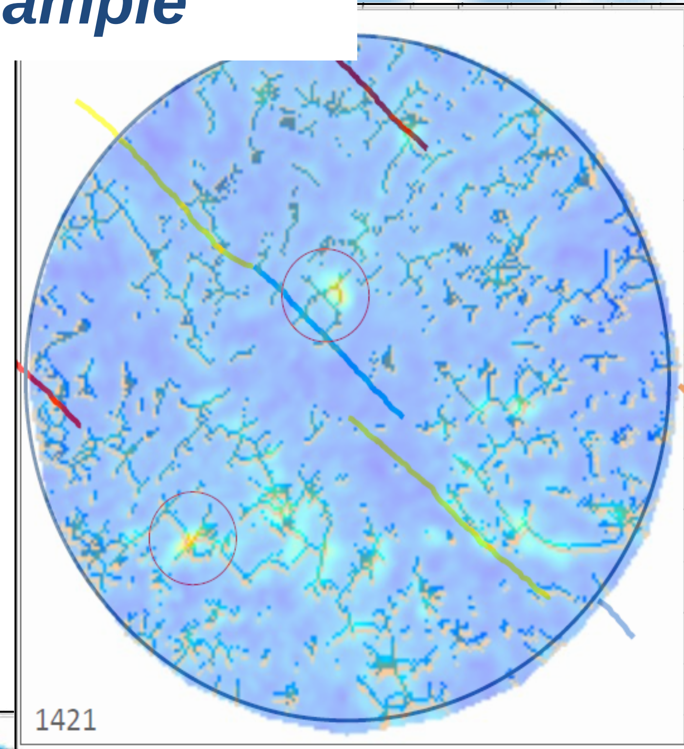
TFIs Used to Populate a Discrete Fracture Network Model



Waterflood Example

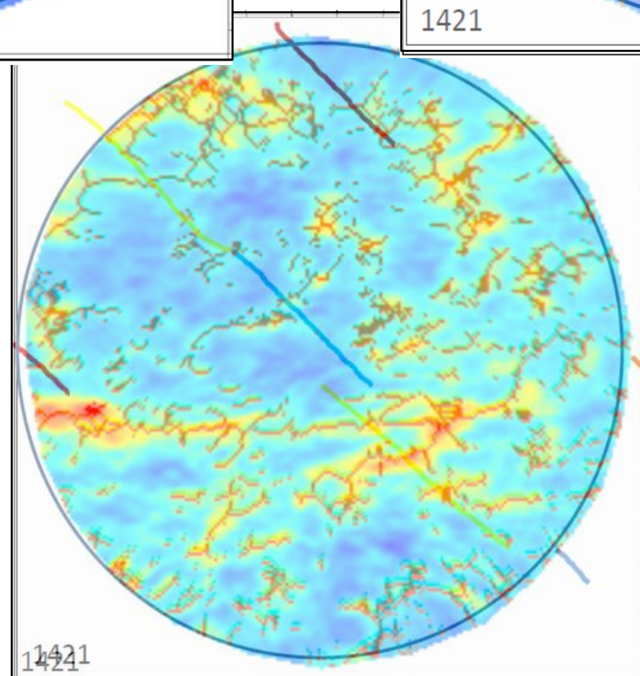


Pre-Injection



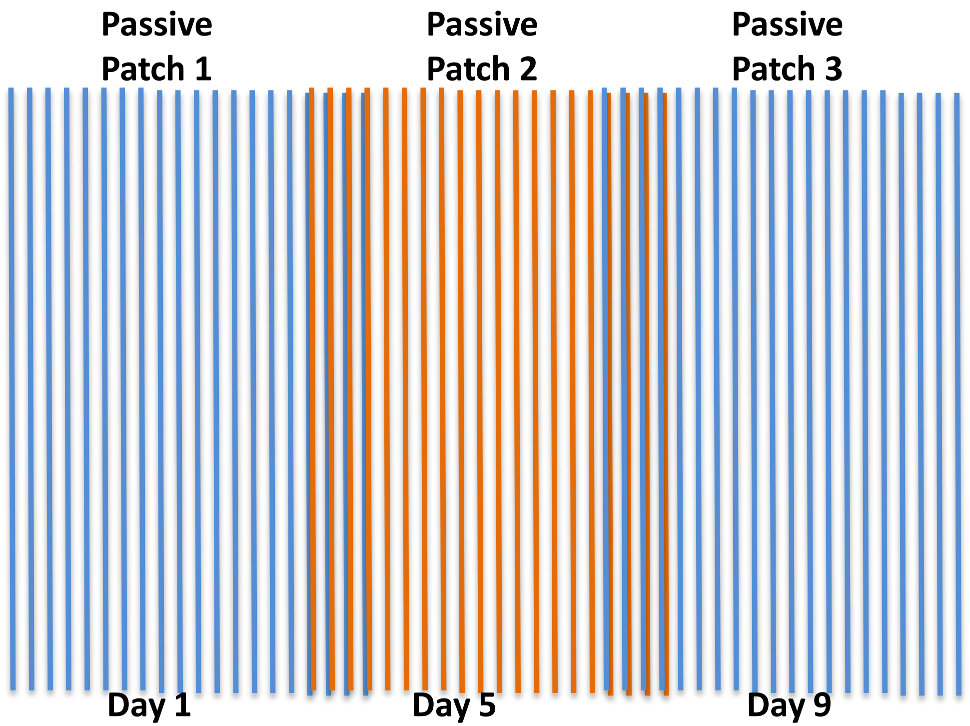
Water Injection

Details of pressure responses ID fluid thief zones in reservoir.

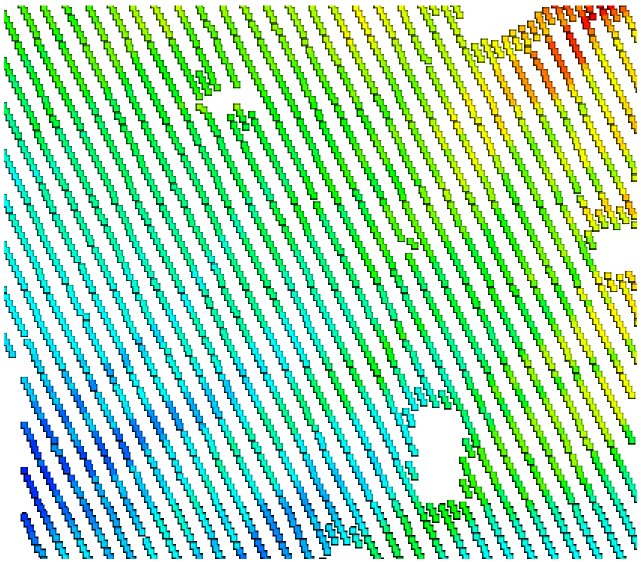


On Production

Passive Recording During Active Acquisition



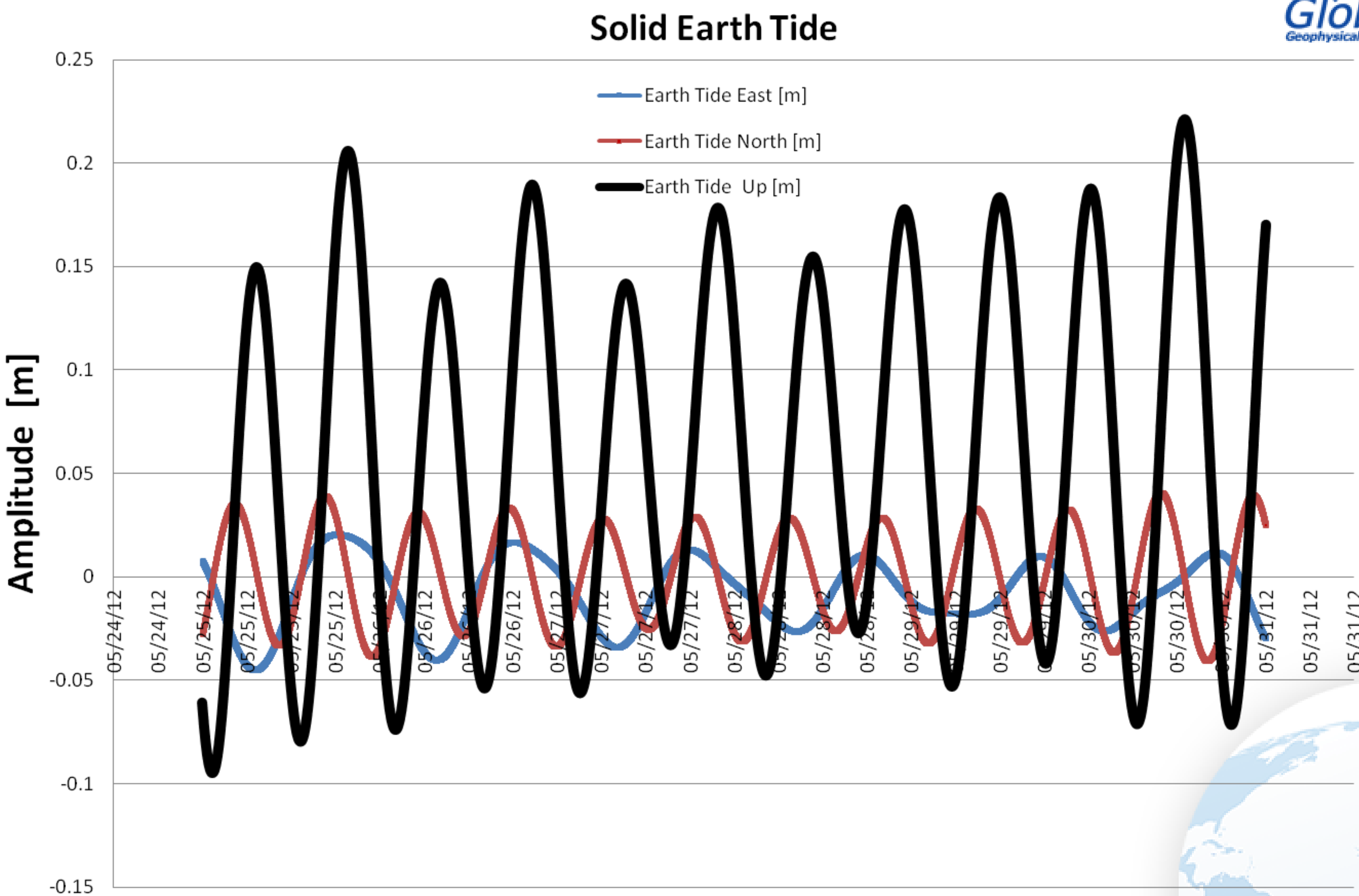
Rolling the Receivers



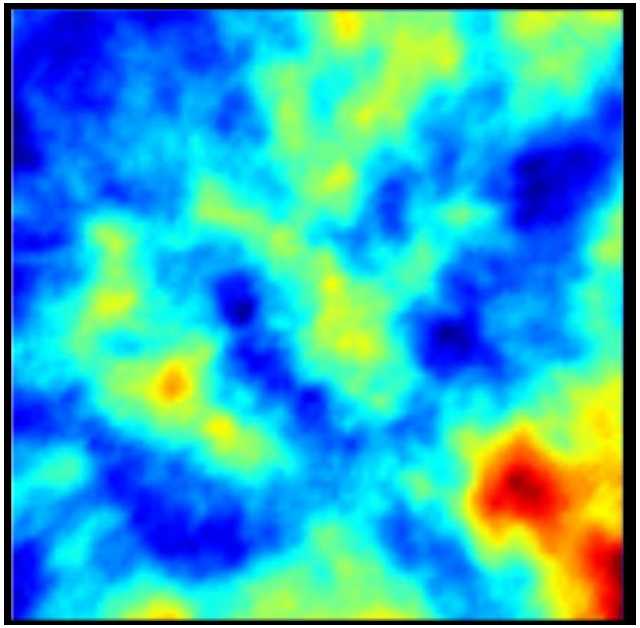
Receivers Fixed for Entire Active Shoot

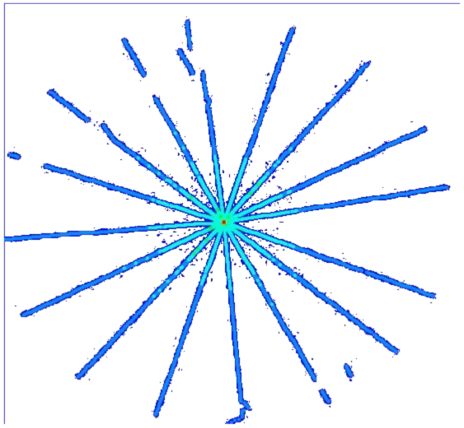
Active acquisition records every day, all day but stops for passive recording time
Passive records every Nth day, at night or other quiet time

Earth Tides
Passive Recording

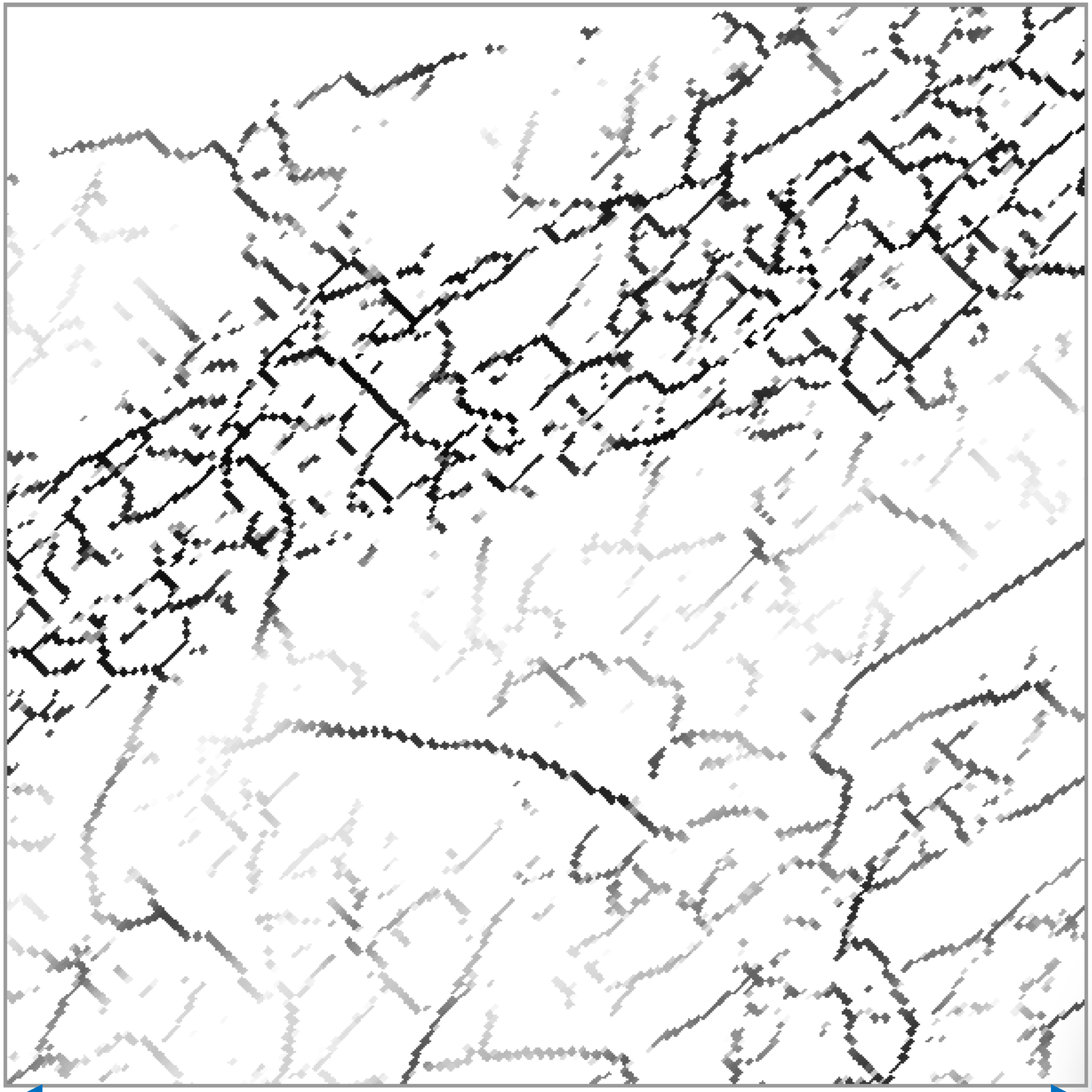


Passive Recording
TFI From 3 Minutes of Data



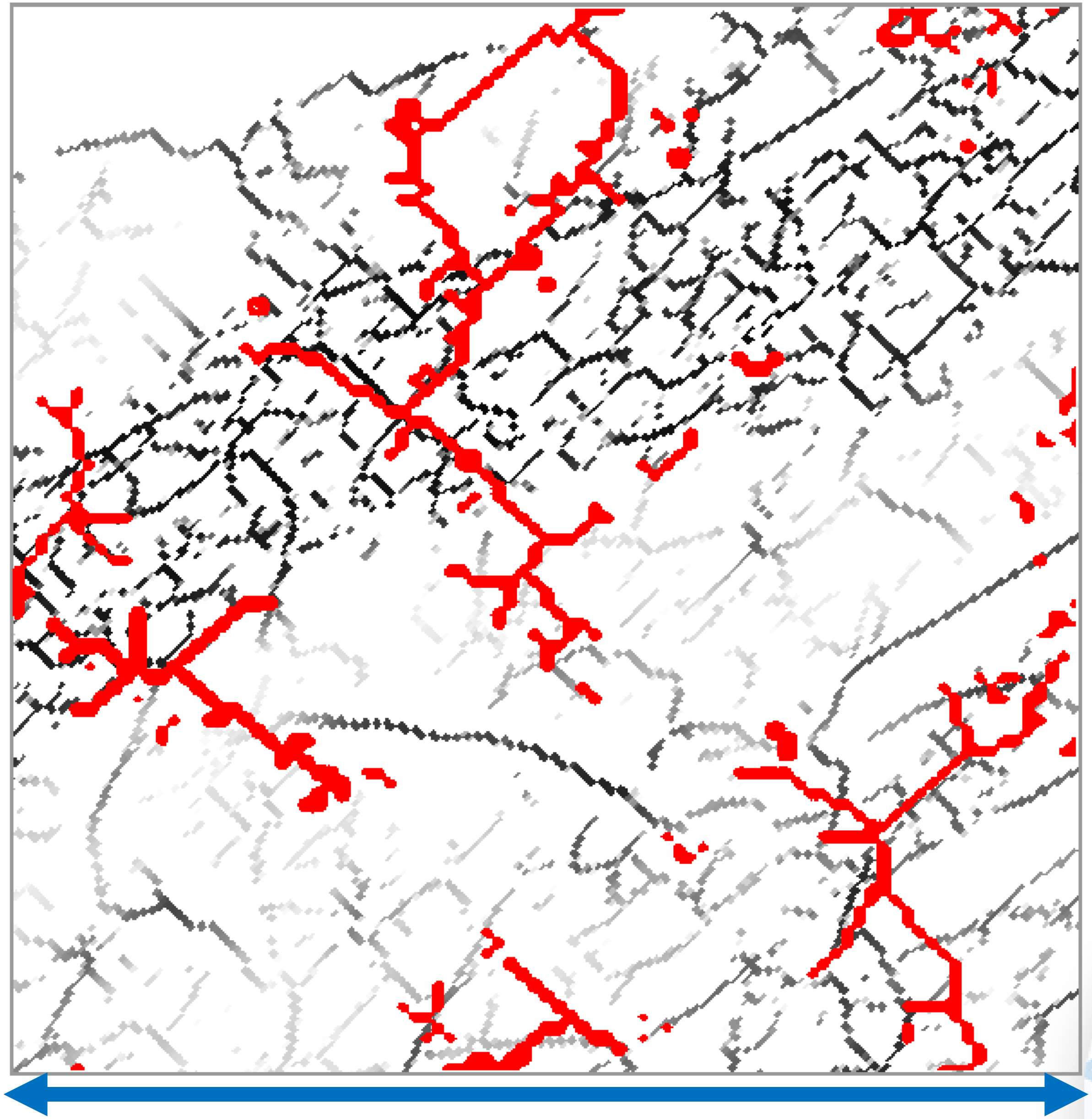


FAULT SCAN



10,000 feet

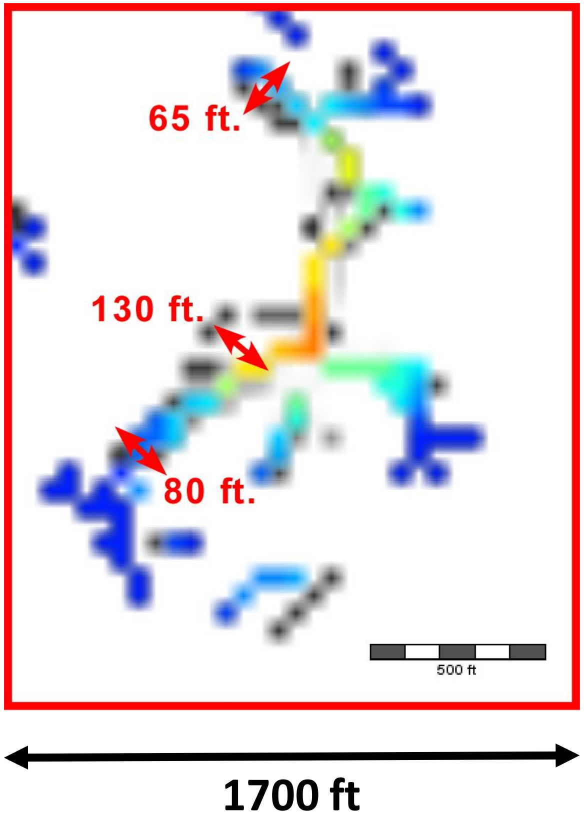
FAULT SCAN WITH TFI



10,000 feet

Passive Recording During Active Acquisition Confidence

Compute Independent TFI Volumes For Separate Time Windows
Time Windows for 4 Separate Days are Overlaid Here



Tomographic Fracture Imaging™ and Microseismic Value

- **TFI Benefits**
  - Hypocenters are not the most important information
  - Long Period data are critical for understanding reservoir fluid structure
  - Images Are Computed For
    - Fractures Created By The Pumping
    - Natural Fractures That Serve As Fluid-Flow Pathways
  - Defines What Happened To Current Well
  - Helps Plan Future Well Locations
  - Defines Natural Fracture Systems Pre-drill
    - Leads To Better Frac Planning
  - Maps the Permeability Fairways
  - Fractures Are Imaged As Complex Surfaces And Networks

Tomographic Fracture Imaging™ and Microseismic Value

- **TFI Reports**
  - **Surface array, well locations & field infrastructure**
  - **Full processing documentation**
  - **Images Are Computed For**
    - **Fractures Created By The Pumping**
    - **Natural Fractures That Serve As Fluid-Flow Pathways**
    - **Pre-and post-frac ambient data**
  - **Hypocenter location and timing**
  - **Mechanical stratigraphy affected by the frac**
  - **Focal mechanisms for field geomechanics**

Tomographic Fracture Imaging
Pushing the Envelope on Fractured Reservoirs

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