Advances in Large-N Seismic Measurements to Monitor Reservoir Behavior

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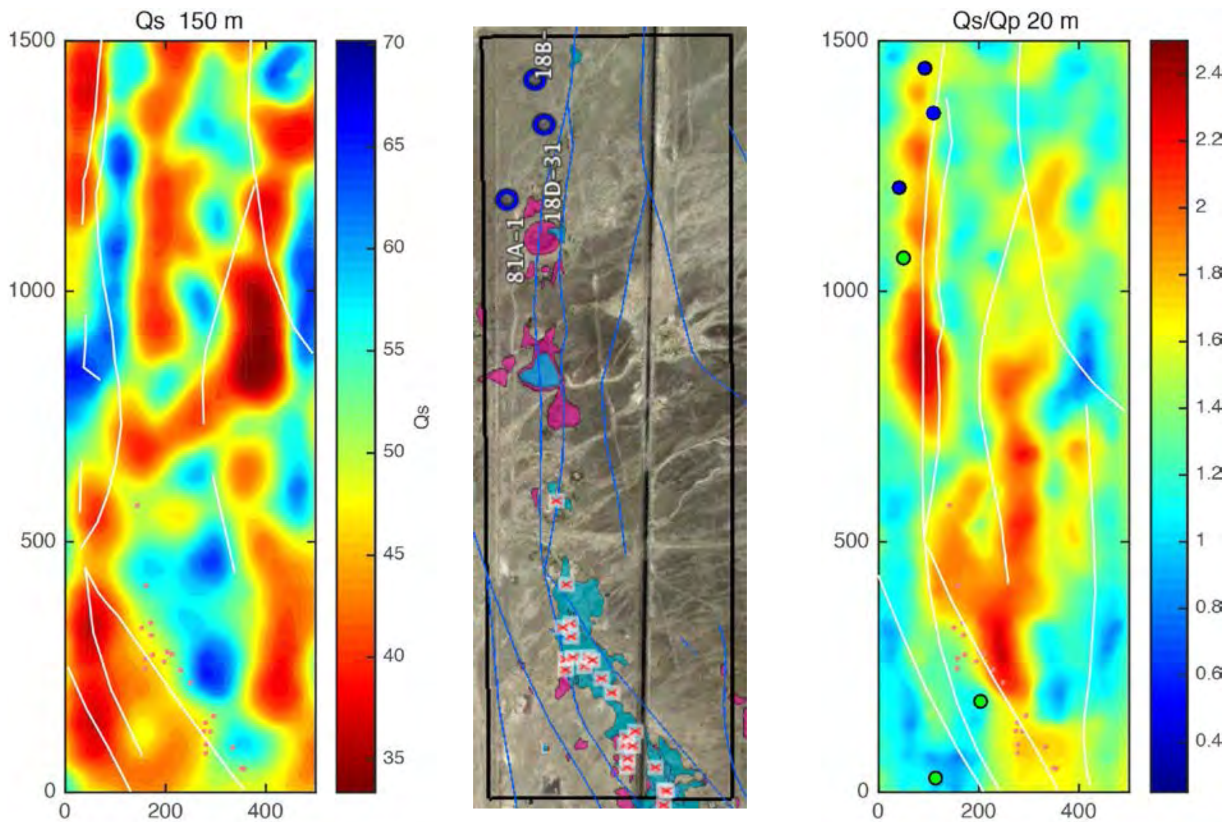


This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. The PoroTomo project was funded in part by the Office of Energy Efficiency and Renewable Energy (EERE), U.S. Department of Energy, under Award Numbers DE-EE0006760 and DE-EE0005510.

Project Overview

Award: FWP-FEW0191 (Susan Carroll PI)

Project Description

Tasks designed to advance the capabilities of analytical tools that will be needed to safely inject and store CO_2 in the subsurface.

Five tasks with specific technical focus:

Task 1 – CO_2 Storage Carbonate Reservoirs
Task 2 – Microseismic Toolset for Fault Detection and Seismicity Mitigation
Task 3 – Implications of Stress State Uncertainty on Caprock and Well Integrity
Task 4 – Industrial CO_2 Demonstrations
Task 5 – Novel Monitoring Techniques for CO_2 Storage Using Large-N Seismic Arrays

Project Benefits

Objective: Understand of the behavior of CO_2 injected underground for permanent storage, and detect it's effects.

- We want to be able to monitor the movement of CO_2 sequestered in the Earth.
- Need to ensure that CO2 sequestered in the ground will remain there, can be monitored over time and that the pressure field changes created don't fracture the seal or trigger induced events.

Technical methods/tasks

Technologies:

High-resolution characterization of the subsurface to obtain precise measurements on the evolving state of the storage reservoir through the CO_2 injection and post-injection monitoring.

High resolution of seismic velocities and attenuation can be used to infer porosity, permeability and fluid saturation.

Year 1 Tasks:

- Virtual Earthquake Methods (ANC,CWI,active and passive methods)
- Virtual Seismometer Method (VSM)

Upcoming Tasks:

- Fiber Optic Comparison
- Seismoelectric Effects

What is “Large” N

N :
number of seismometers
or
number of microquakes
at a site

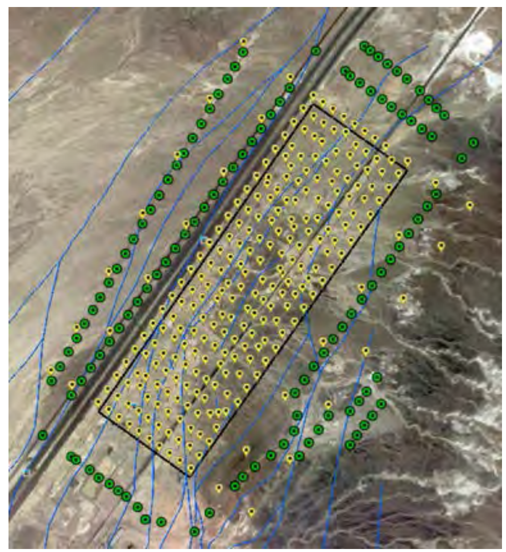
Large:

Newberry (25) : 300 correlations
Brady (239) : > 28,000
Long Beach (5200) : > 13 million

Differences in resolution

100’s to 1000’s of microquakes at active sites.

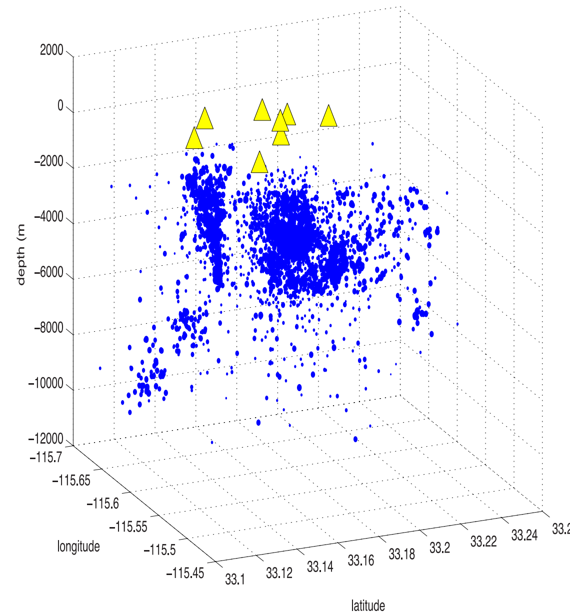
- Task 5.1: Assessment and pre-processing of available field datasets
  - Activities: Identify currently held / publicly available datasets particularly Large-N
  - Deliverables: Assessment of the most complete datasets for use in research tasks



PoroTomo experiment at Brady

- Large-N network
- Mix of instrument types including fiber
- Defined changes in subsurface fluid and pressure
- Terabytes of data in-house

(PI Feigl; Livermore lead Morency)

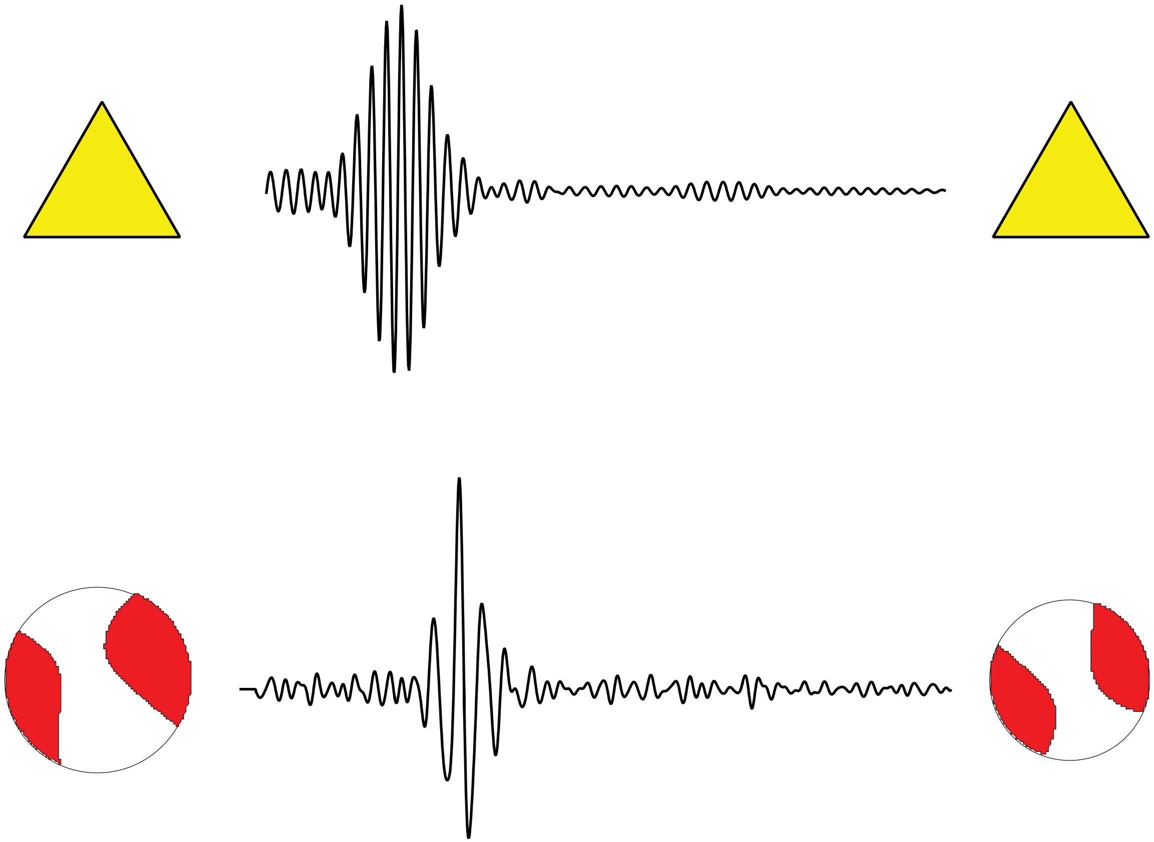


Salton Sea geothermal region

- Long term monitoring
- Thousands of cataloged microquakes
- Leverages work done for location identification 3D modeling, etc.
- Continuous and event data in-house

(Wang, Templeton, Rhode and others)

Virtual Earthquakes and Virtual Seismometers



ANC, CWI

"virtual earthquake"

$CC = GF_{AB}$

VSM

"virtual seismometer"

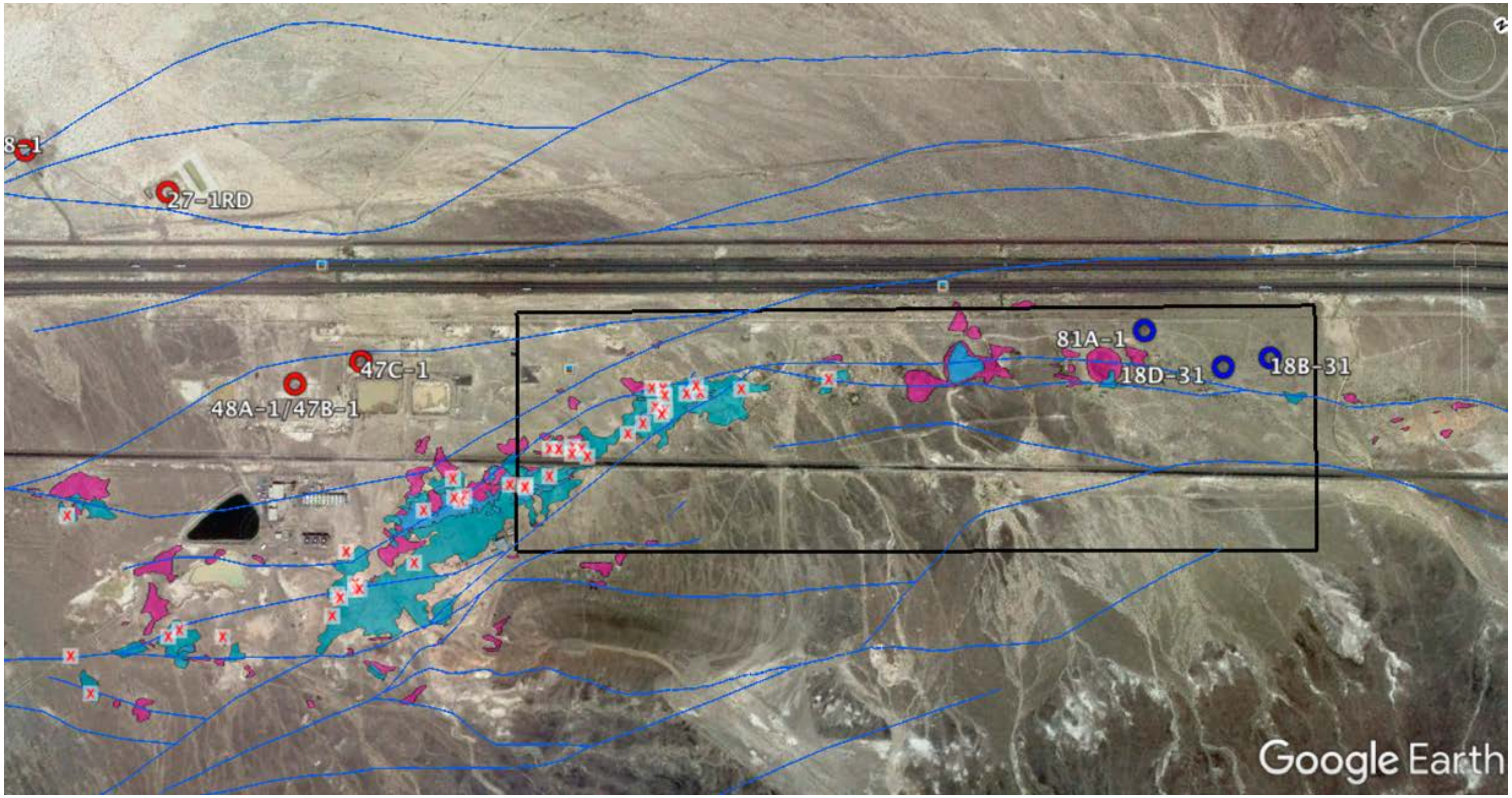
$CC = M_1\ M_2\ GF_{12}$

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

reference: Curtis et al. 2009

The PoroTomo "Natural Lab"

1500-by-500 meter natural laboratory at the Brady EGS field



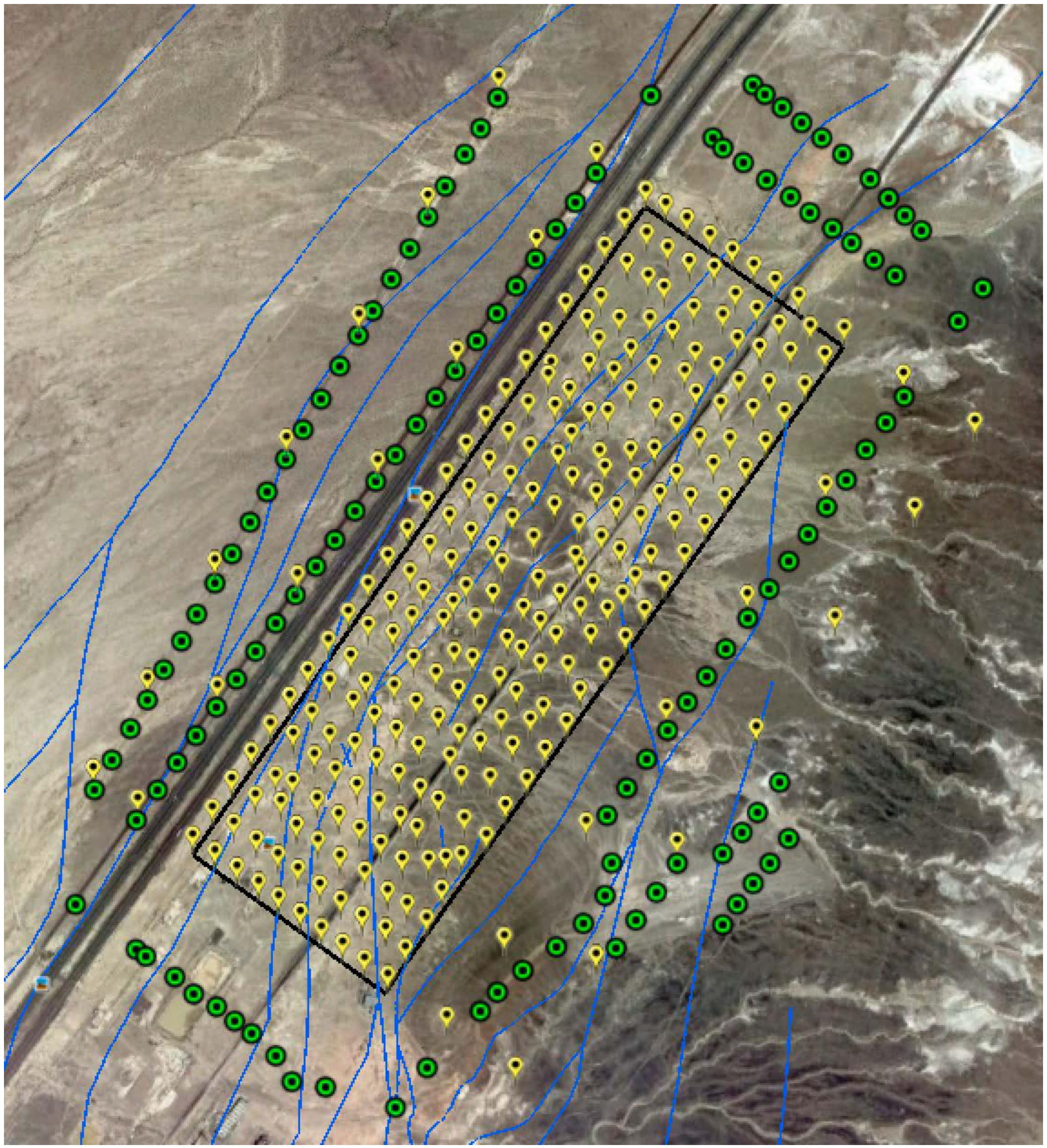
geologic obstacles by Coolbaugh

Designed to understand how fluids travel from shallow aquifers, through faults and fractures, to deep geothermal reservoirs.

Seismic, geodetic, and hydraulic technologies are applied to fully characterize the rock mechanical properties.

Feigl et al., SGW (2018)

Large network deployed during a period of changing fluid injection

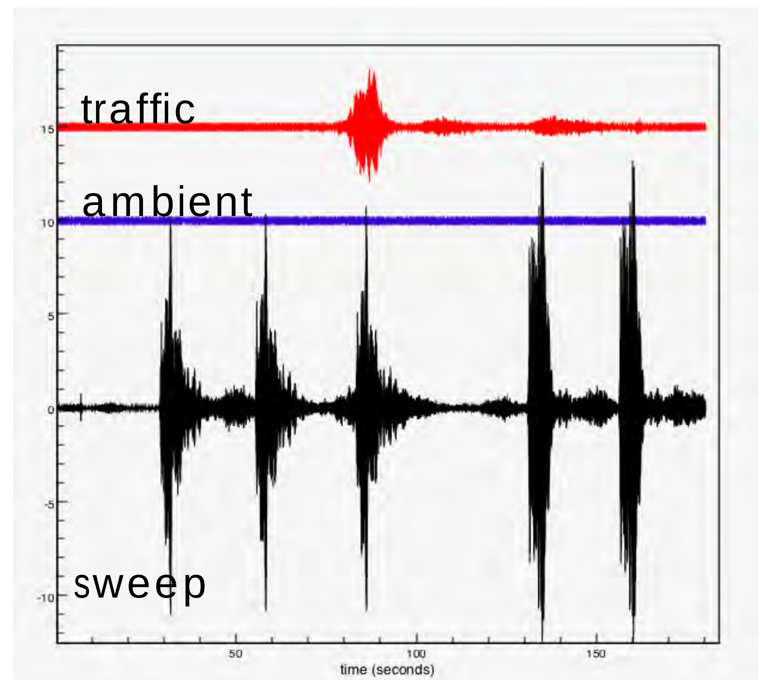


vibroseis points (green), geophones (yellow)
geologic obstacles from Coolbaugh, faults from Faulds

Types of data:
ambient noise, coda, active sources

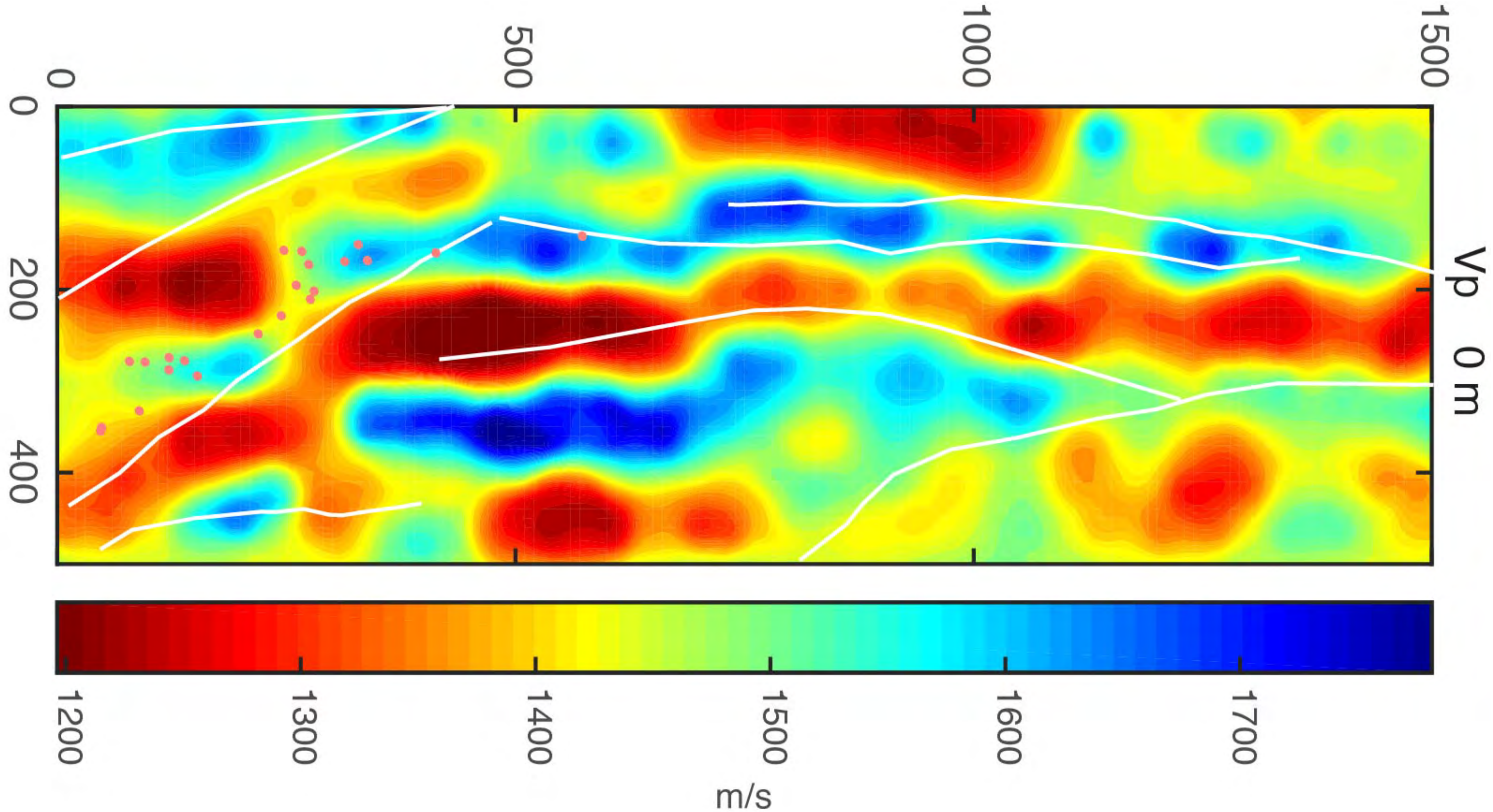
Fiber optic, & geophone data

4 stages of operation over a 15 day experiment



Seismic Velocities and Attenuation:

Can be used to infer porosity, permeability and fluid saturation



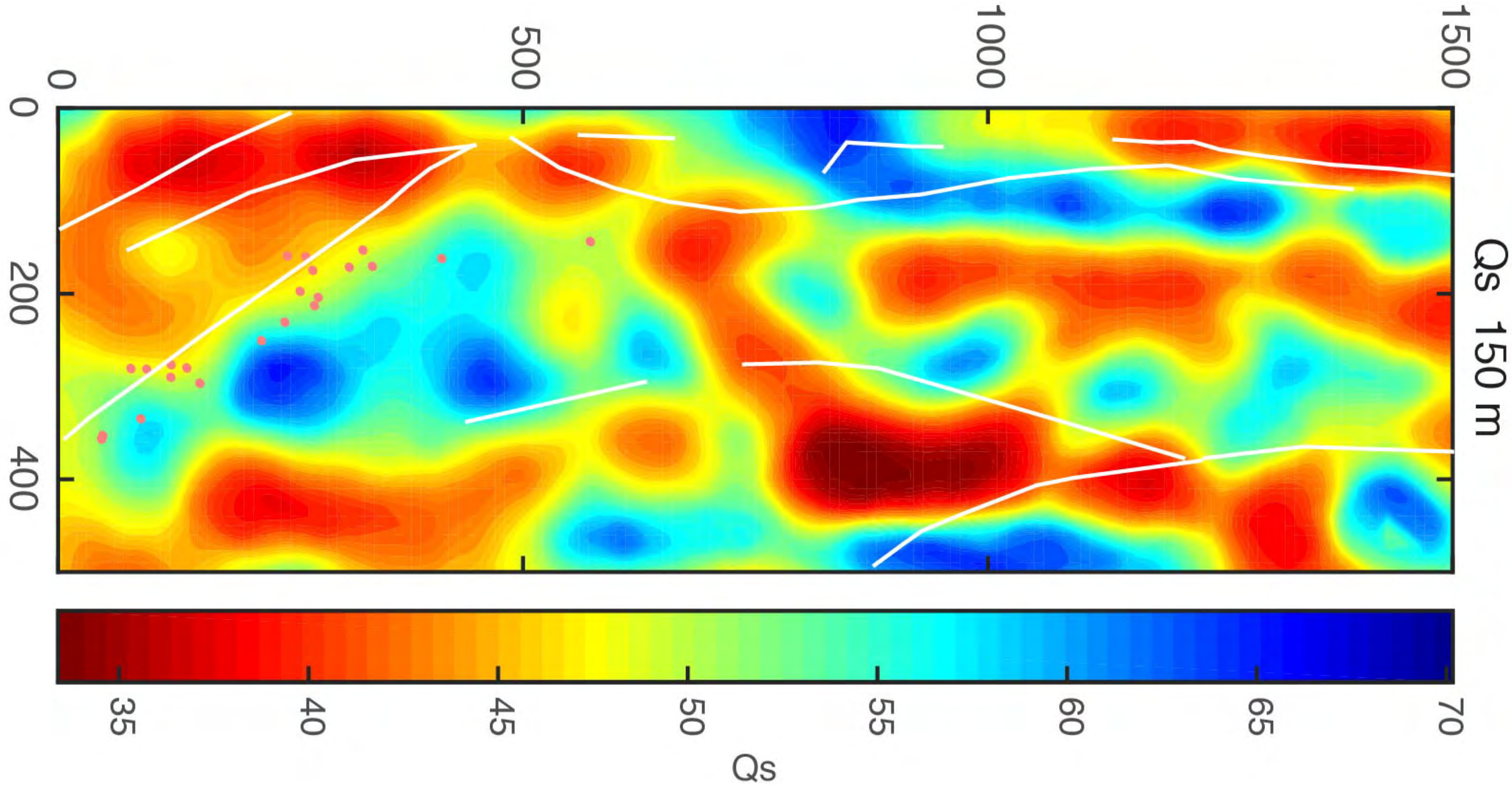
Vp (surface)

surface expression of faults in white,
fumaroles (orange circles)

geologic obstacles from Coolbaugh, faults from Faulds

- Inverted for Vp, Vs, Qs, Qp
- At the surface Vp varies by more than 50%.
- Anomalies align with mapped hotspots and faults.

Attenuation of seismic energy increases in regions that are hot or heavily fractured.



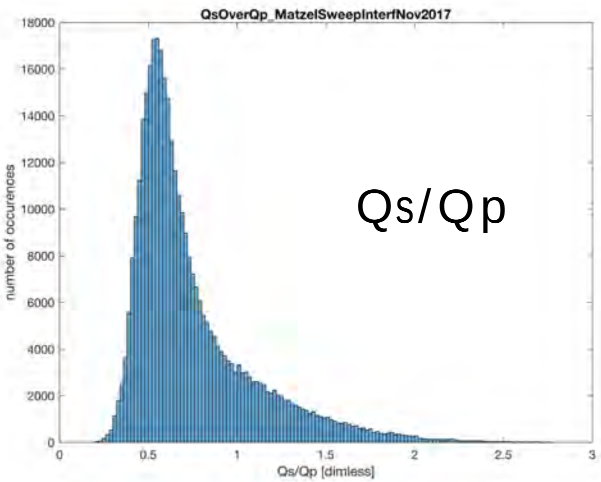
Qs (150 m)

150 m depth of faults in white, fumaroles (orange circles)

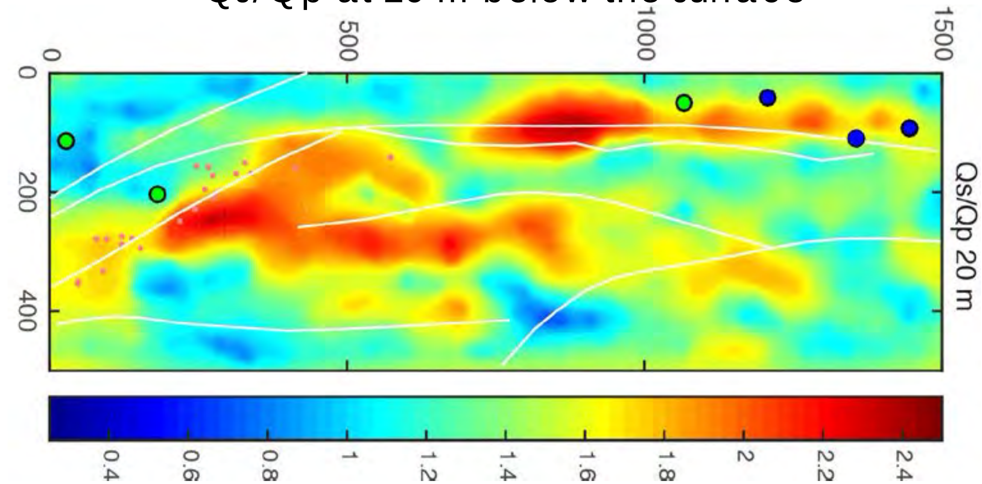
geologic obstacles from Coolbaugh, faults from Faulds

- Inverted for Vp, Vs, Qs, Qp
- Each has different sensitivity to material properties (temperature, porosity, fluid content and composition.)

Qs and Qp:
Seismic amplitudes are sensitive to fluid saturation

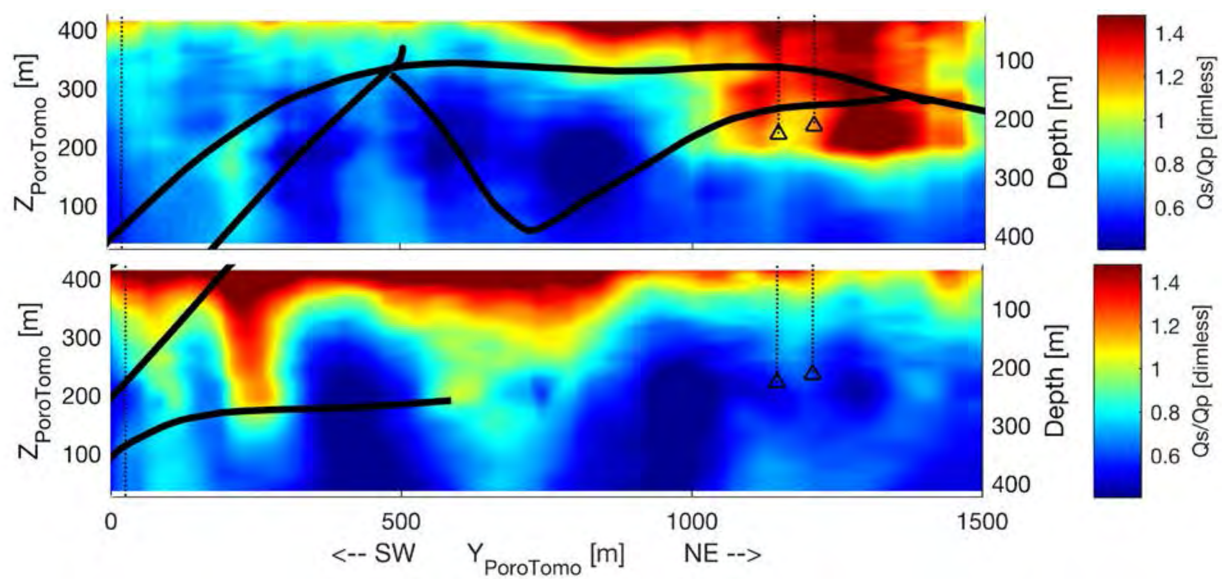


Qs/Qp at 20 m below the surface

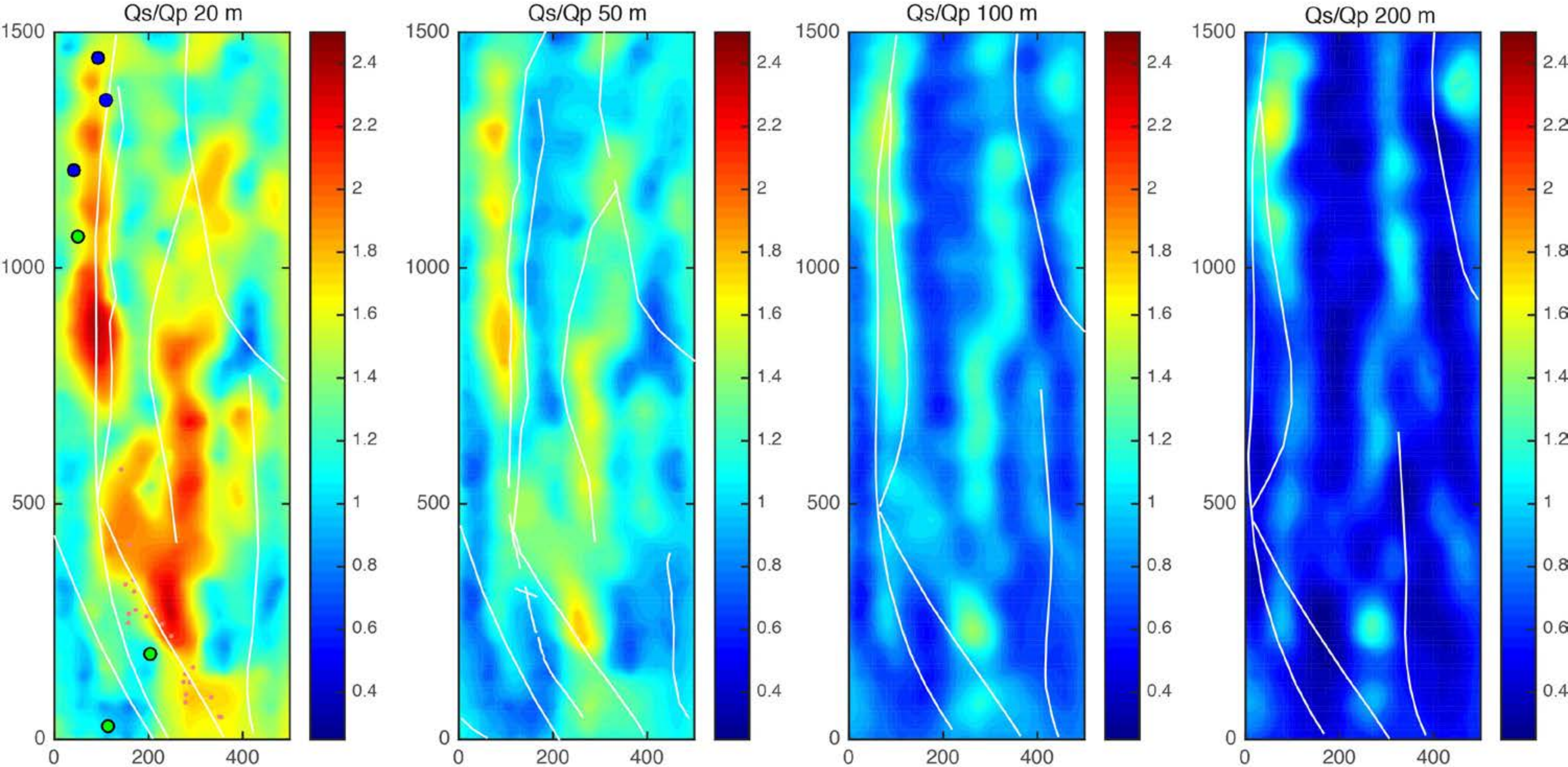


Cross section through injection point
x= 50m

Cross section through fumaroles
x=270m



Qs/Qp illuminates fluid pathways.



At Brady: highly permeable conduits along faults channel fluids from shallow aquifers to the deep geothermal reservoir

geologic obstacles from Coolbaugh, faults from Faulds

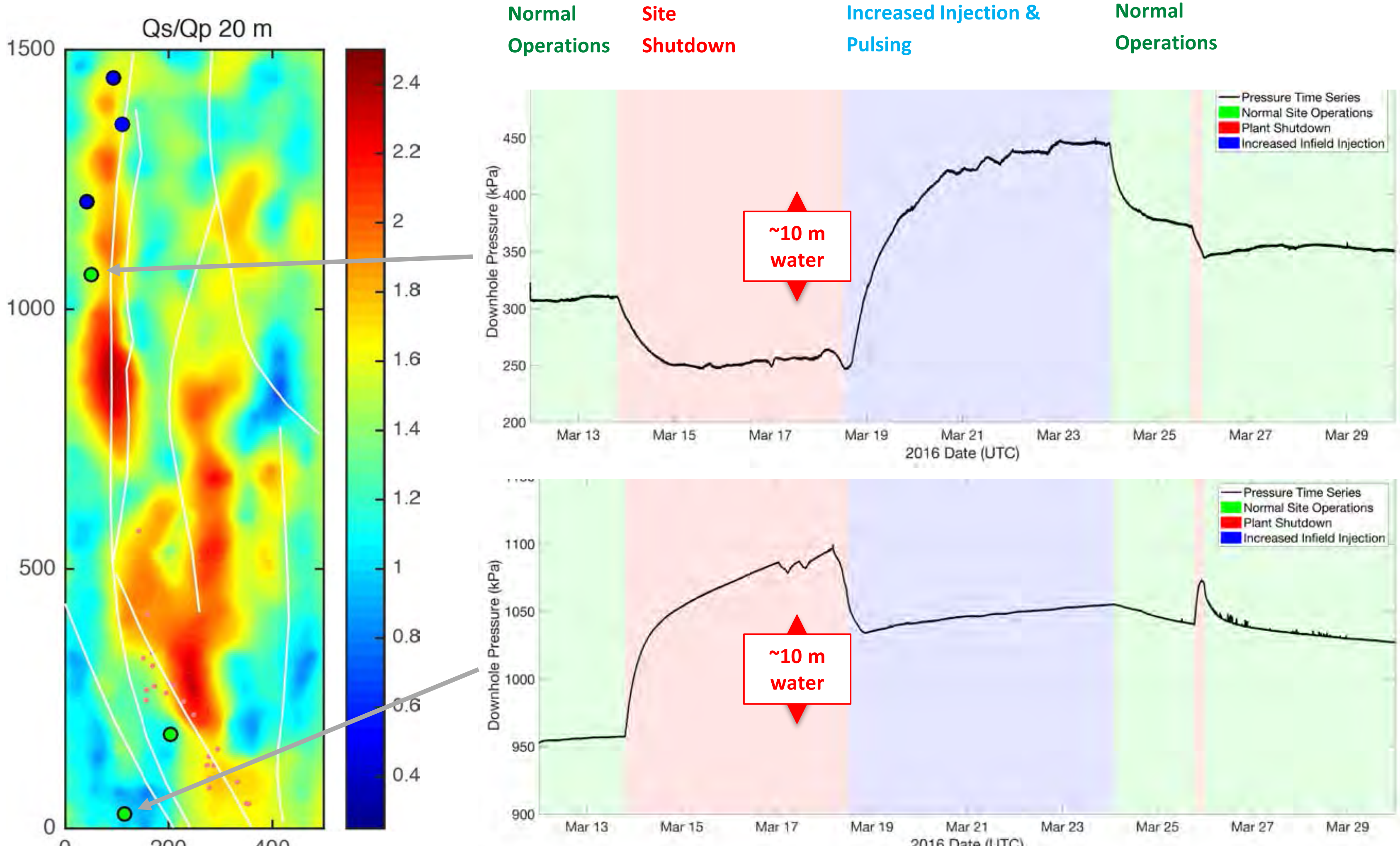
Pressures were changed in four stages over the two week experiment.

Stage 1: Normal Operations

Stage 2: Site Shutdown

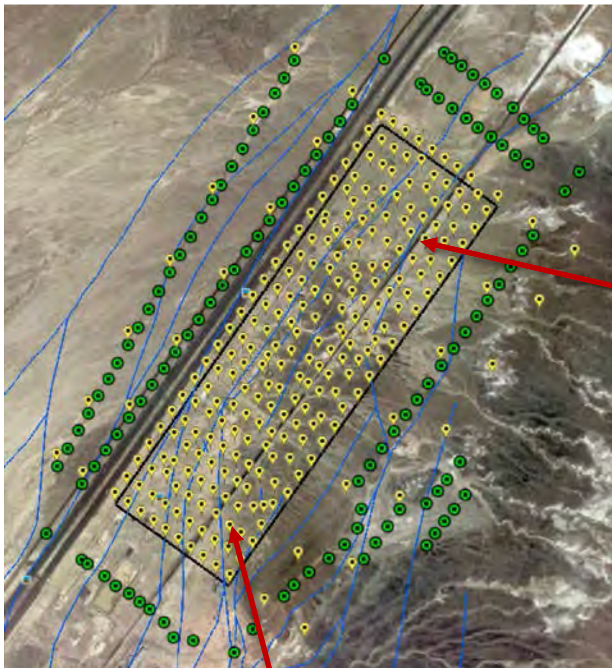
Stage 3: Increased Injection & Pulsing

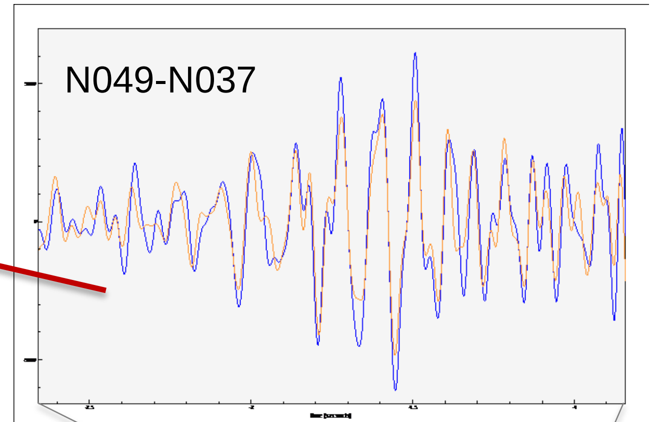
Stage 4: Normal Operations



Time series of pressure records showing the response to four stages of pumping operations at recorded in three monitoring boreholes (Feigl, 2017)

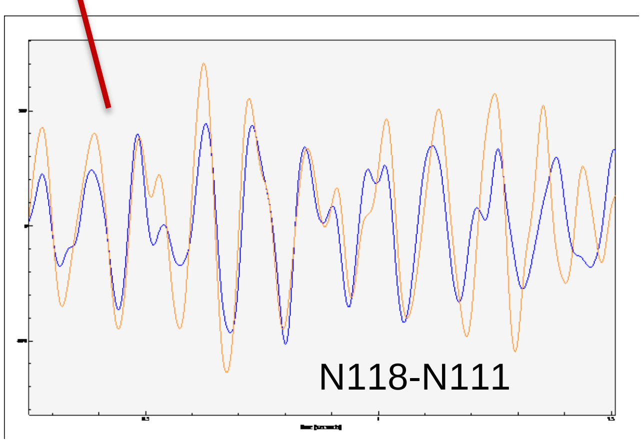
Phase arrival times are nearly identical, but amplitudes changed measurably after site shutdown



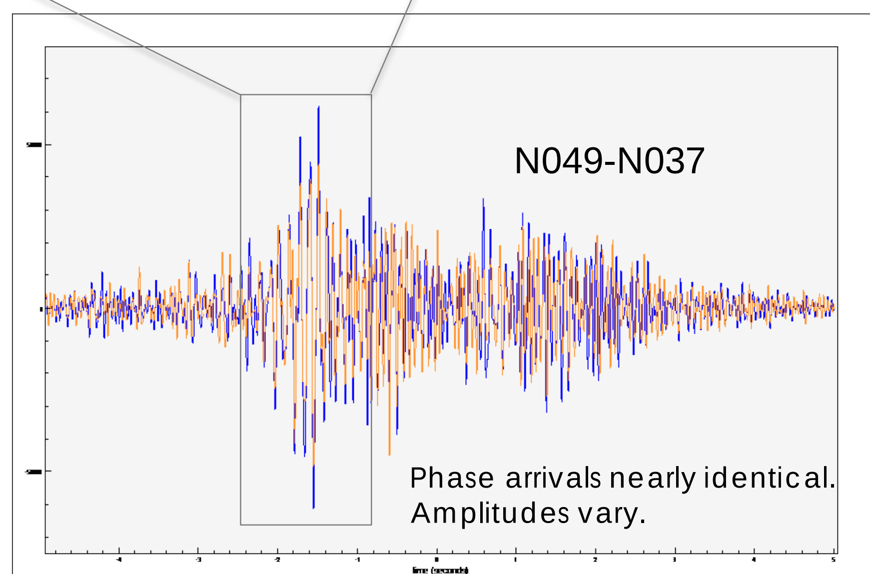


Amplitudes in the North decreased after shutdown

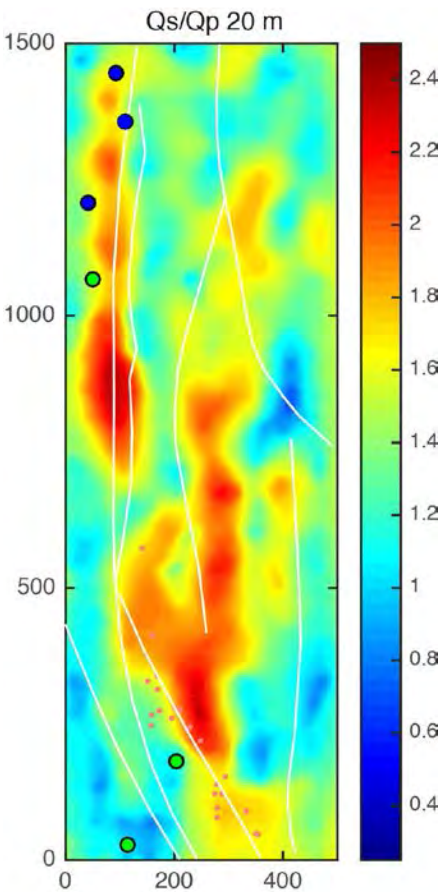
Normal Ops: Blue
Site Shutdown: Orange



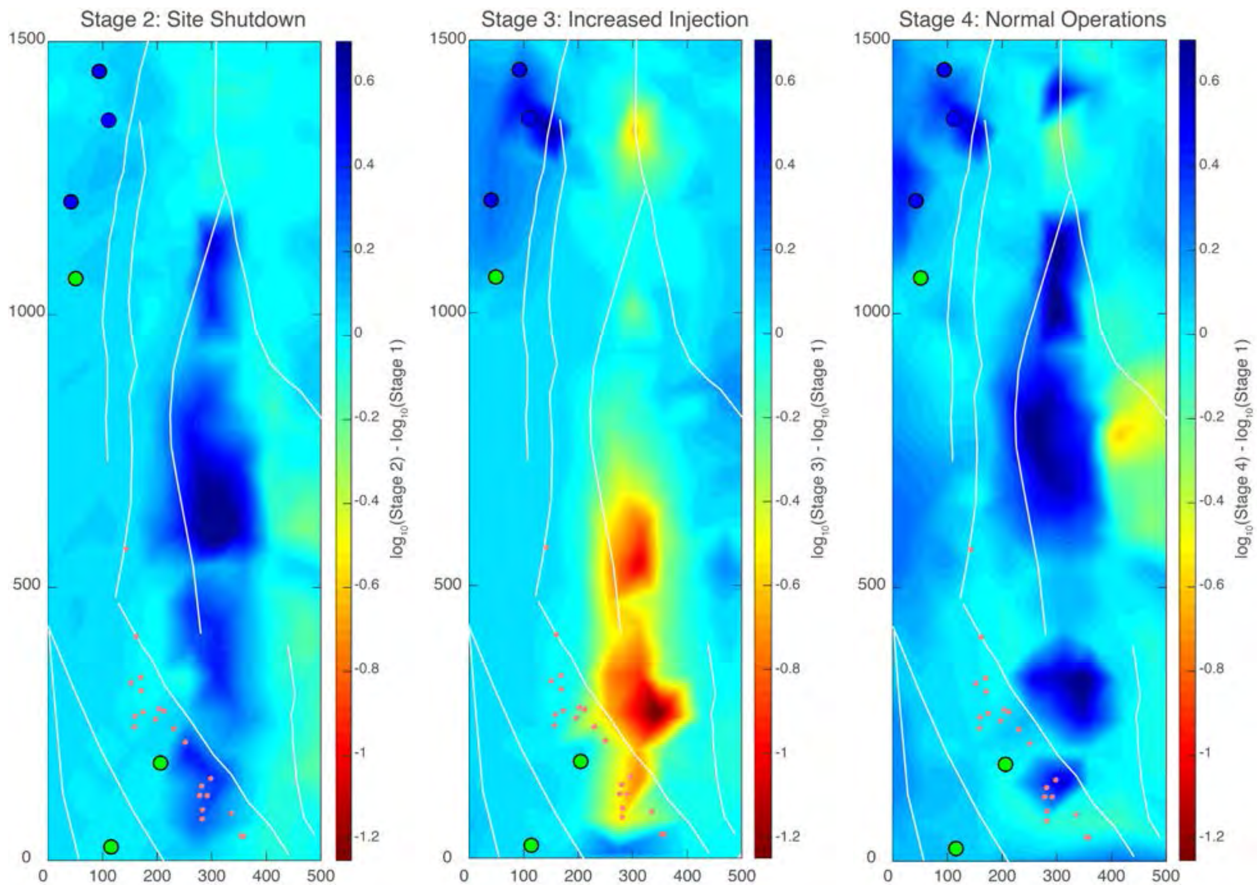
Amplitudes in the South increased after shutdown



Changes in amplitude are concentrated in fault bounded blocks.



Static image of attenuation during normal operations (Stage 1)



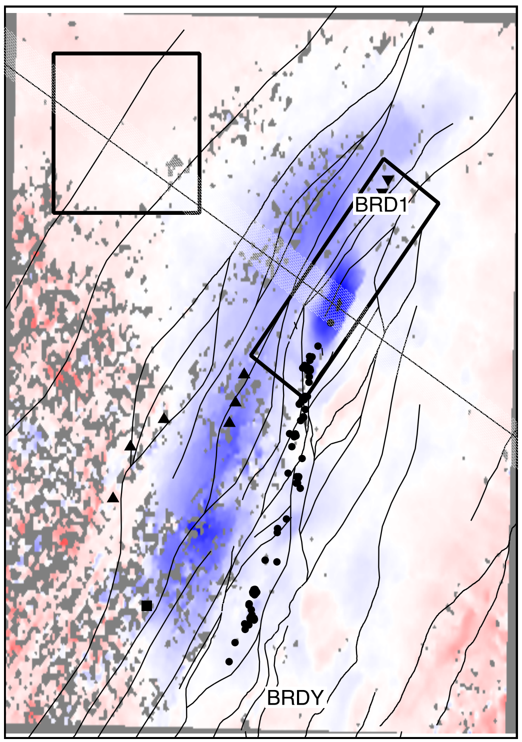
Dynamic changes in seismic amplitudes as operations changed

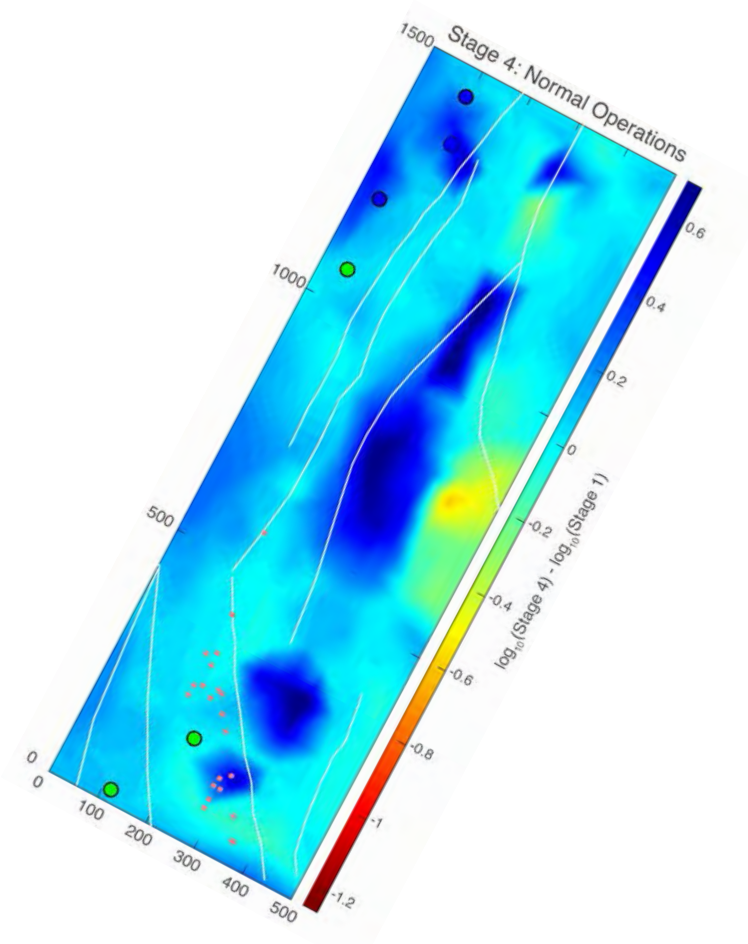
- blue: more efficient propagation
- red: more attenuated

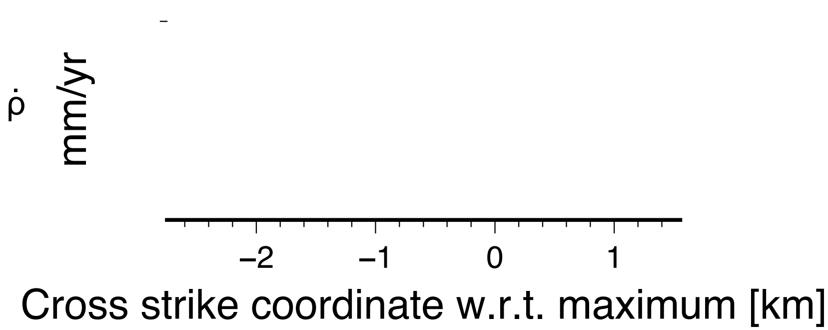
Comparison with InSAR image.

Observed seismic anomaly matches a region of high subsidence

$\dot{\rho}$







Reinisch et al., *Characterizing Volumetric Strain at Brady Hot Springs, Nevada, USA Using Geodetic Data, Numerical Models, and Prior Information*, GJI, 2018

Accomplishments to Date

- Interferometric techniques provide high-resolution characterization of the subsurface and allow precise measurements on the evolving state of the storage reservoir

- High resolution of seismic velocities and attenuation can be used to infer porosity, permeability and fluid saturation.

- Qs/Qp illuminates fluid pathways.

- Changing fluid pressures appear immediately in the seismic amplitudes, concetrated in fault bounded blocks.

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Future Work

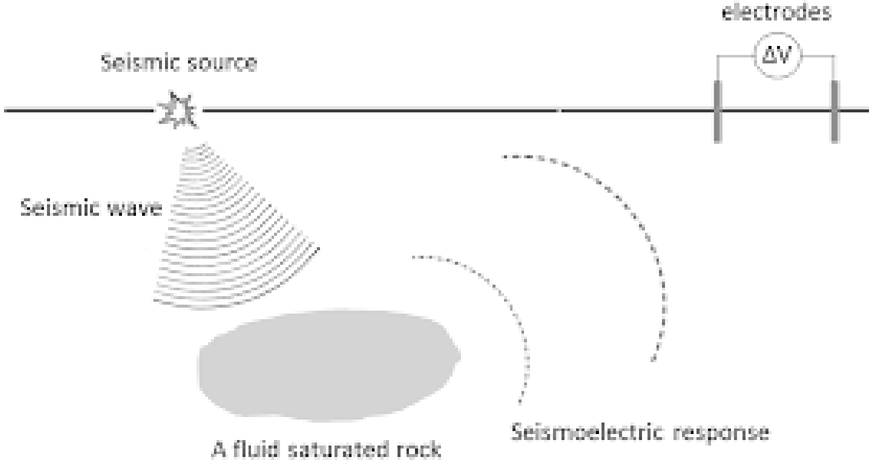
Subtasks to begin in Year 2

Fiber Optic Comparison

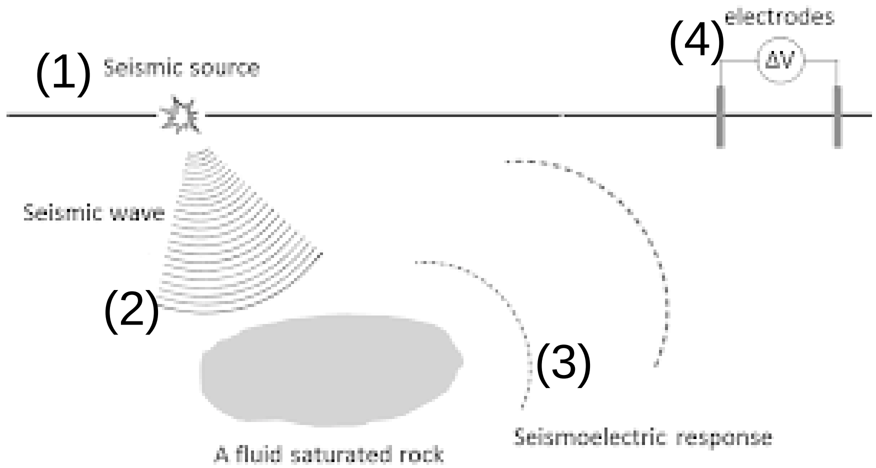
- Inexpensive.
- Can be used in place of individual geophones, significantly reducing the associated costs.
- Notable differences in sensitivity need to be understood to adapt the new technology.

Seismoelectric Effects

- Techniques will enable mapping of fluid in a saturated fracture network, and improve our understanding structural and fluid properties.



Future Work : Seismoelectric effects



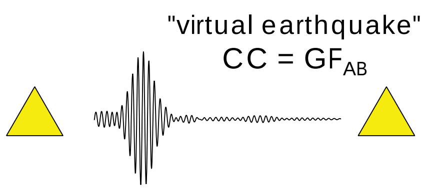
A seismic source (1) triggers a seismic wave (2), which propagates in a porous medium, where charges are put in relative motion between grain surfaces and pores, generating an electric dipole, which triggers an electromagnetic field (3), which can be recorded at electrodes (4).

- The coupled poroelastic Biot equations & EM Maxwell's equations have been implemented in a spectral-element code to mimic the seismoeletric effects.
- We will test the sensitivity of CO2 plume and leakage detection to
  - (a) pure seismic approach,
  - (b) pure EM approach, and
  - (c) coupled seismic-EM approach (seismoelectric effects).

A major advantage: no longer require earthquakes or artificial sources.

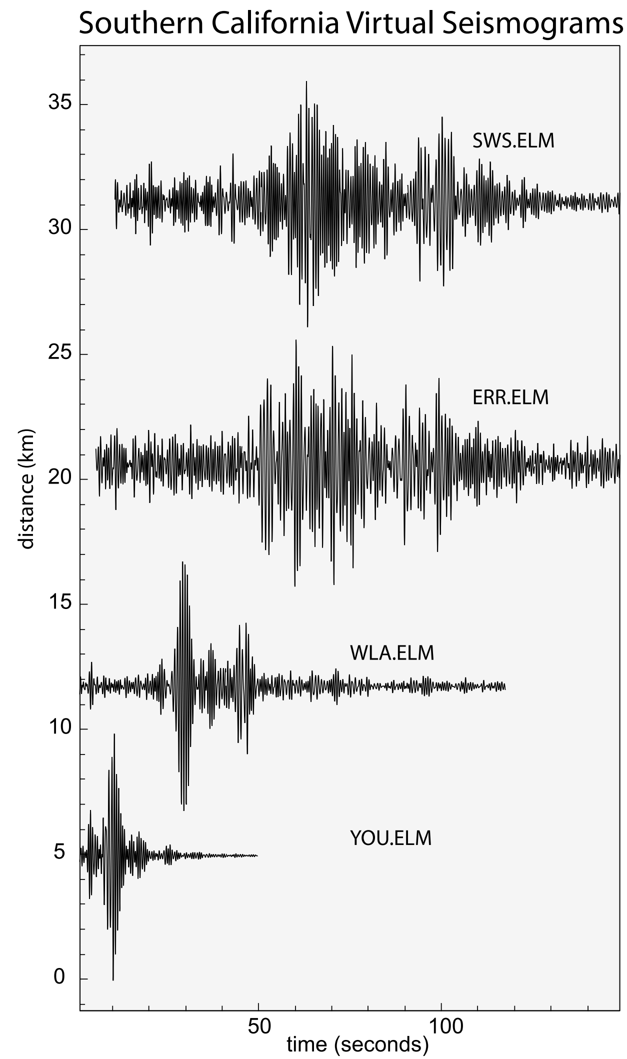
Virtual earthquake method

- 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

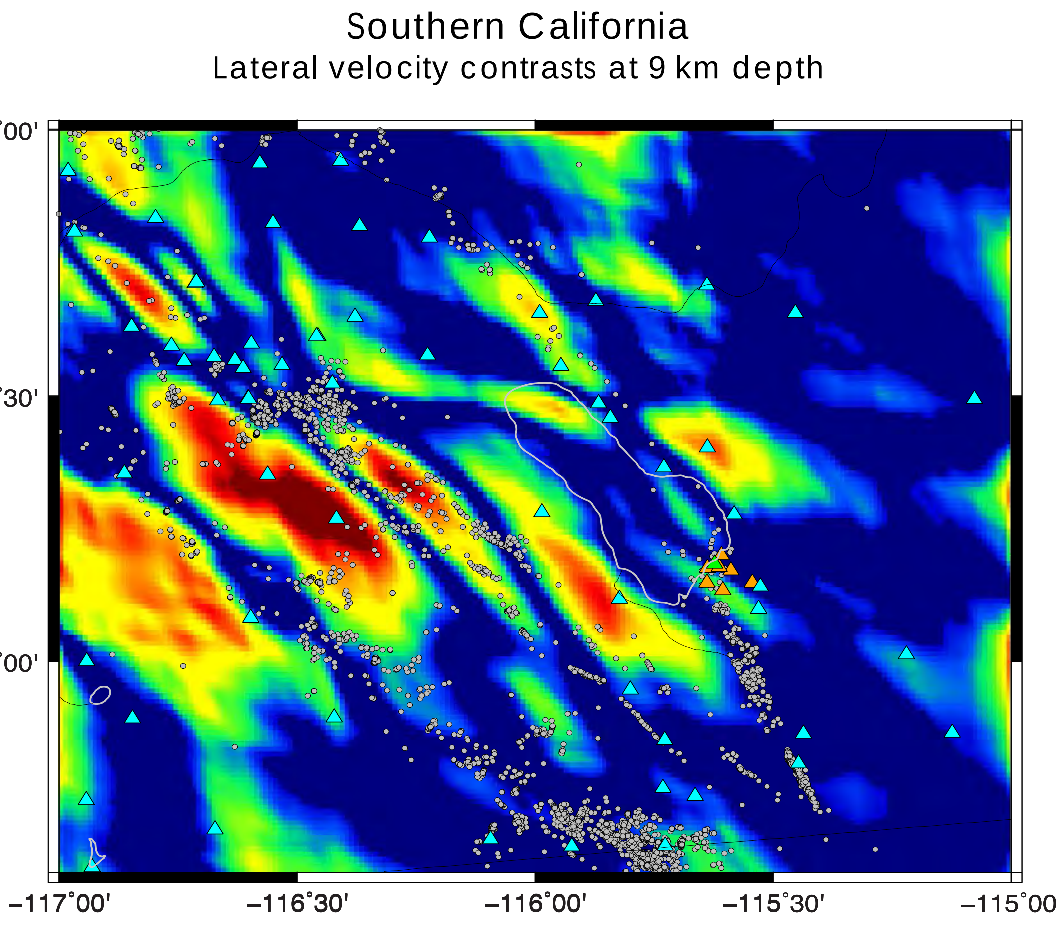


Once the signal emerges from the noise, the GF is very stable.

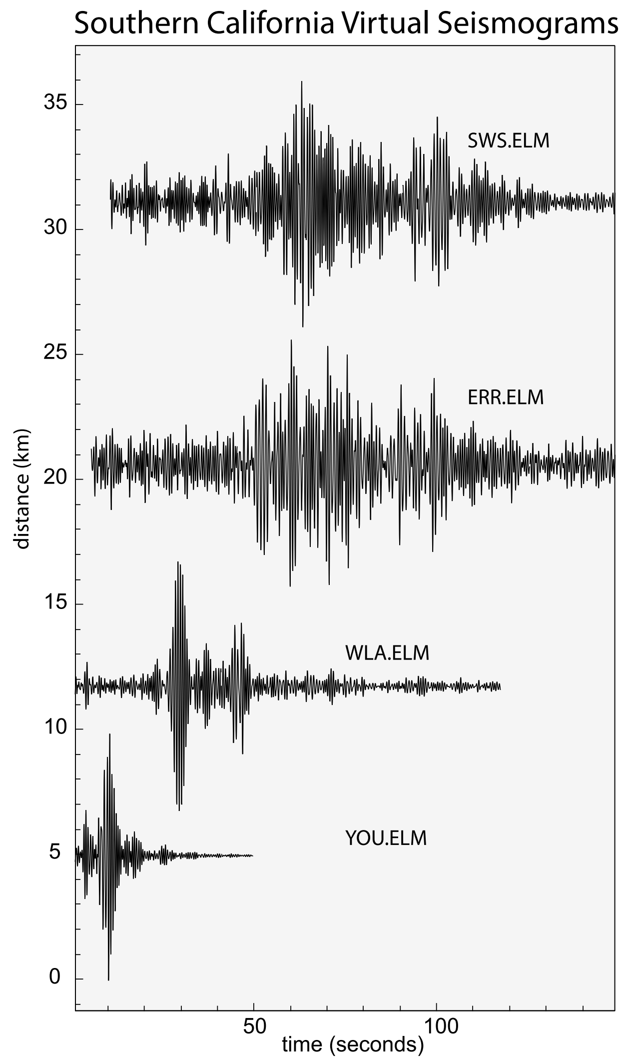
- Even small variations in the GF are significant
- Allows precise imaging and 4D monitoring



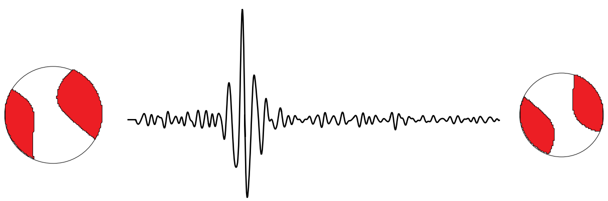
Ambient noise correlation: enables sharp imagery of the Earth.



Seismicity from Hauksson



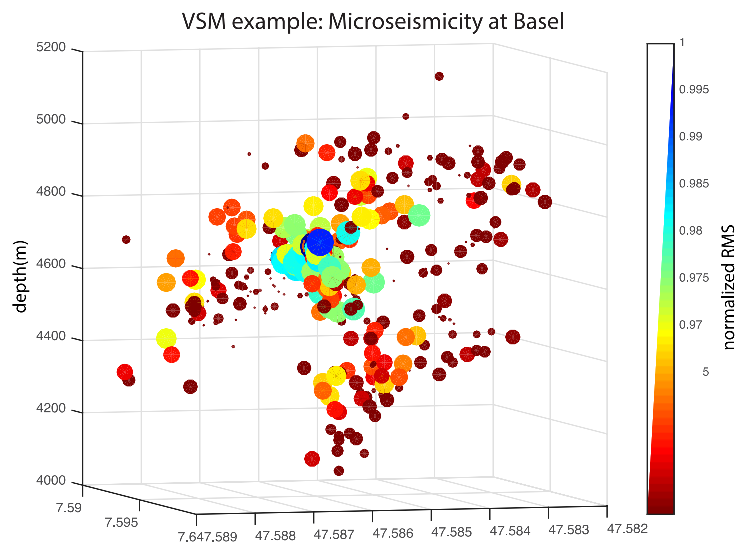
VSM significantly increases resolution of tectonically active features



VSM

"virtual seismometer"

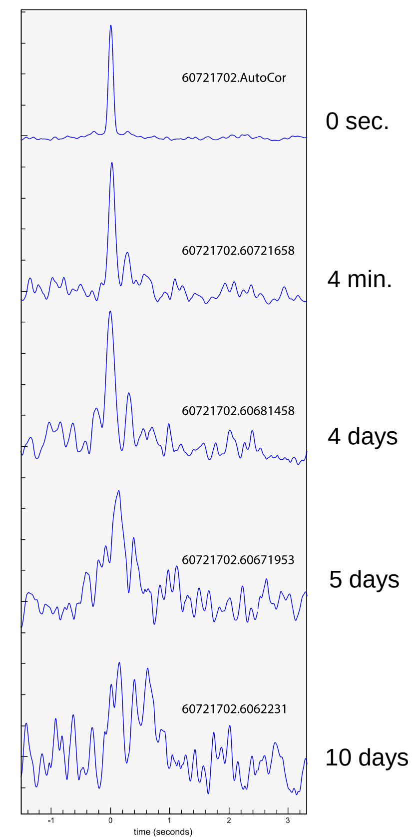
$$CC = M_1 M_2 GF_{12}$$



(Basel):

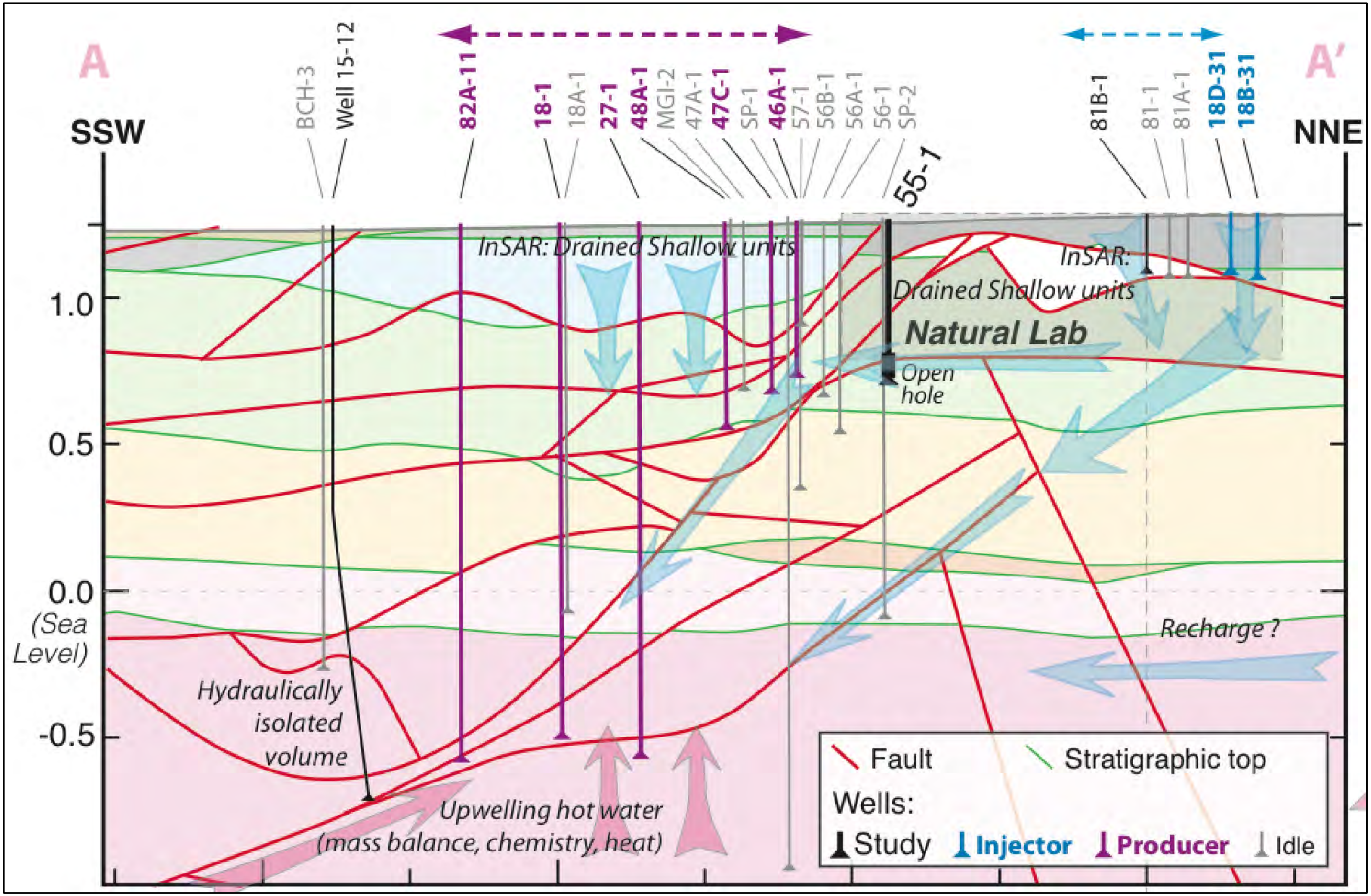
- VSM amplitudes and similarity functions are highly sensitive to relative 3D locations

Virtual Seismograms at Blue Mountain

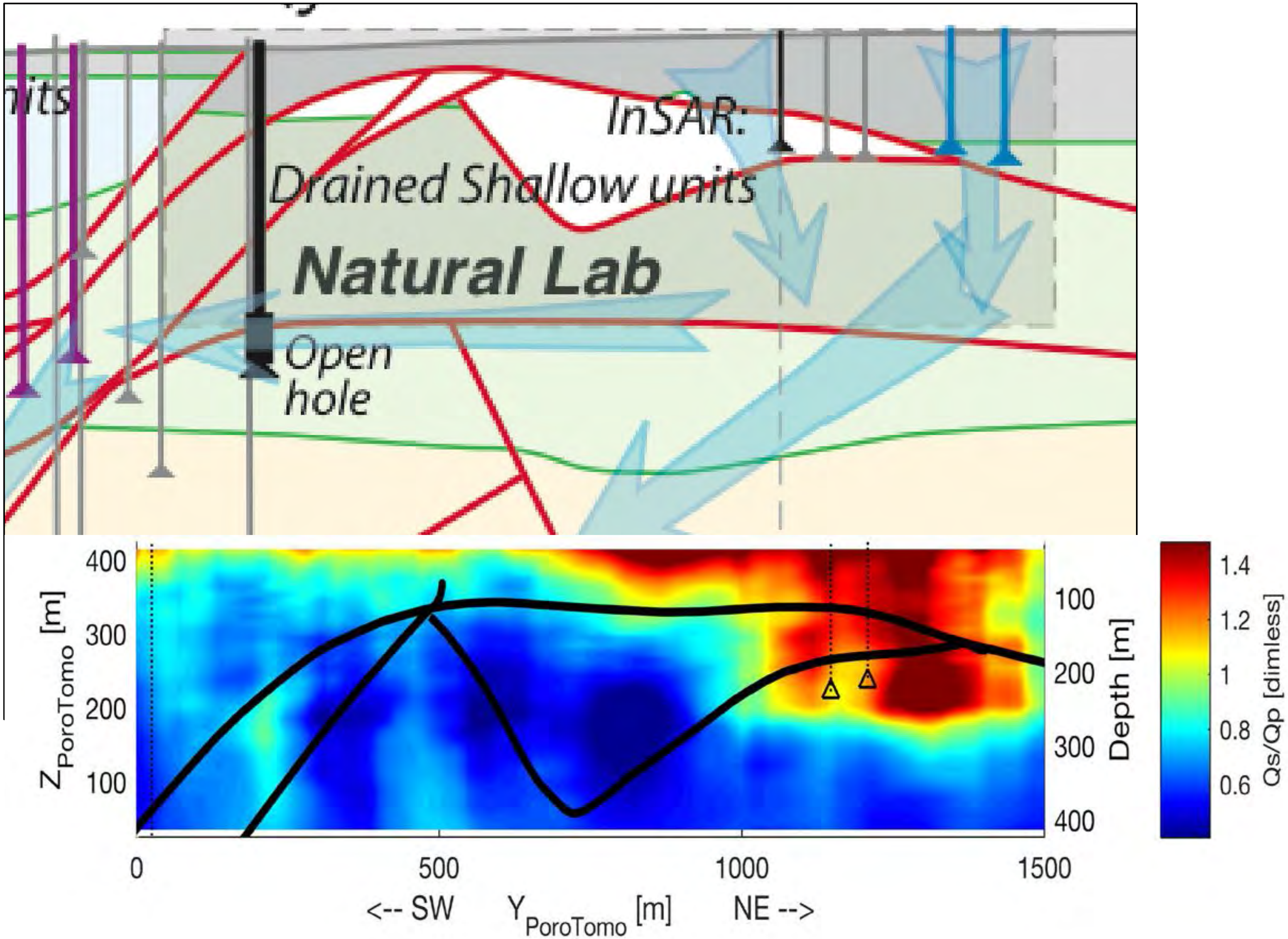


Above: the evolution of the VSM envelopes over time suggests an evolving pressure field.

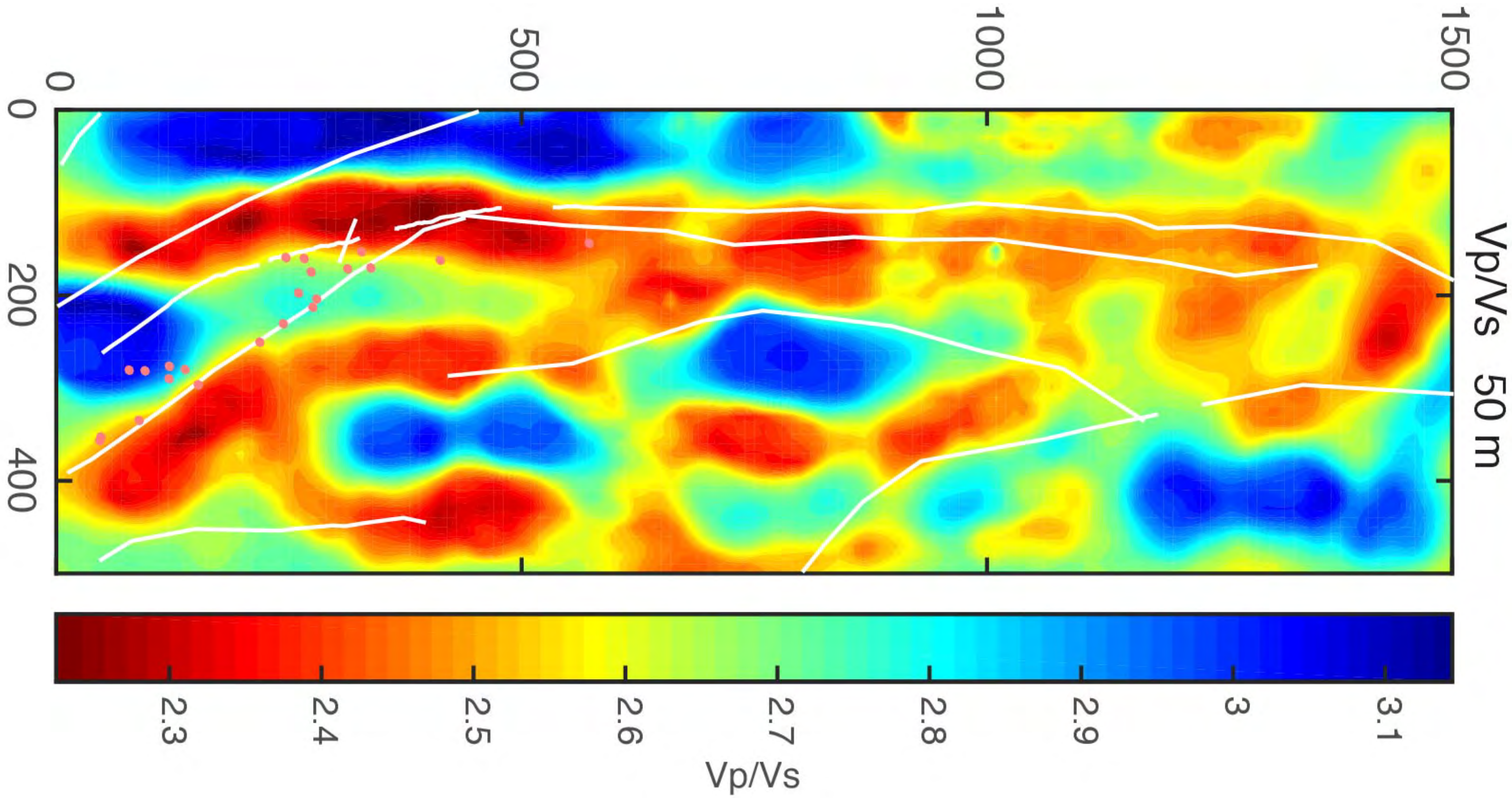
Conceptual model: Highly permeable conduits along faults channel fluids from shallow aquifers to the deep geothermal reservoir tapped by the production wells.



Comparison with conceptual model



Vp/Vs contrasts appear to map subsurface fabric



Vp/Vs (50 m)

50 m depth of faults in white, fumaroles (orange circles)

geologic obstacles from Coolbaugh, faults from Faulds

- Inverted for Vp, Vs, Qs, Qp
- Max Vp/Vs decreases rapidly with depth in the top 100 m.
- Surface Vp/Vs varies between 3.5-7.