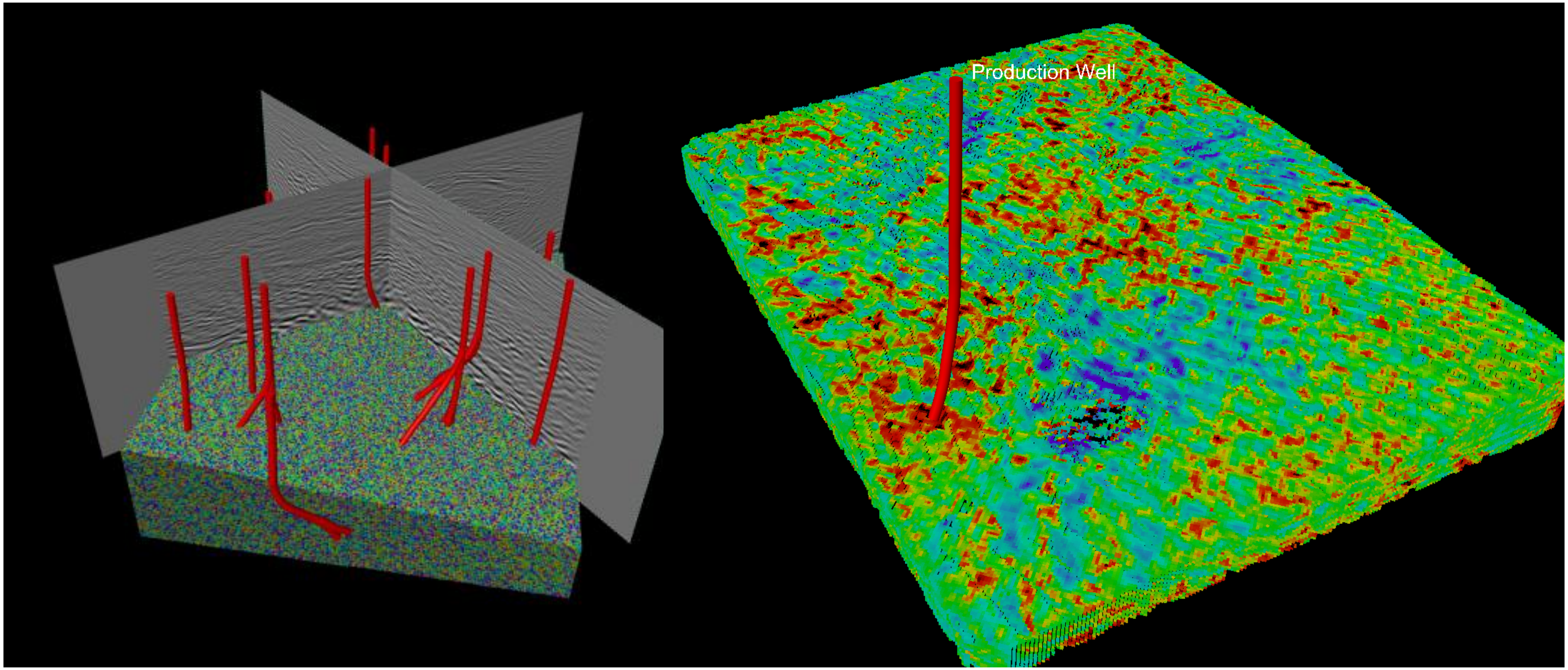


Identifying High Potential Well Targets with 3D Seismic, and Mineralogy

Project Officer: Eric Hass

Total Project Funding: $382,000

May 11, 2015

Principal Investigator: R. Mellors

Lawrence Livermore National Laboratory

HRC

Objective of project

- Detect zones of high temperature and permeability in a geothermal field using 3D seismic attributes
- Direct detection of high temperature and permeable zones within a geothermal field would reduce risk and save drilling costs.
- Uses 3D reflection seismic and techniques similar to those used and proven successful in the petroleum industry but must adapt for geothermal due to different geological setting and underlying rock physics.
- This project focuses on the technique in general and specific details relevant to Raft River will be kept proprietary.
- Success would result in fewer and more productive wells drilled in a production settings. Would likely also improve exploration success.

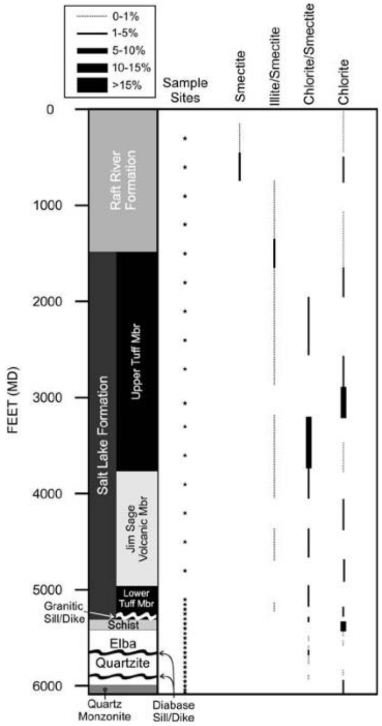
Scientific/Technical Approach

- Cooperation between Optim, Inc., Agua Caliente, LLC, Energy & Geoscience Institute at the University of Utah and Lawrence Livermore National Laboratory (Satish Pullammanappallil, John Casteel, Joseph Moore, Clay Jones).
- Identify known high productivity zones in field based on well and production data.
- Generate 3D seismic attributes and combinations of attributes.
- Statistically compare attributes and known high-productivity zones.
    - Crossplots between known value and attribute
    - Use neural net to automatically identify relationships by using available well data as 'training set' to associate attributes with productive areas
    - Once relationship defined, map productive areas through volume
- Validate results
    - Evaluate fundamental rock physics
    - Create synthetics where relevant
    - Predict results at well not used in original analysis
    - Future wells may be useful

Scientific/Technical Approach

How can 3D reflection seismic detect zones of geothermal productivity?

- Changes in lithology caused by alteration.
  - Known alteration at Raft River
  - Calibrate with borehole lithology
- Fracture detection and effects.
  - Scattering, anisotropy
  - Difficult to distinguish from small-scale structure or other heterogeneities.
- Attenuation
  - Causes changes in frequency and amplitude
- Attributes sensitive to subtle changes.



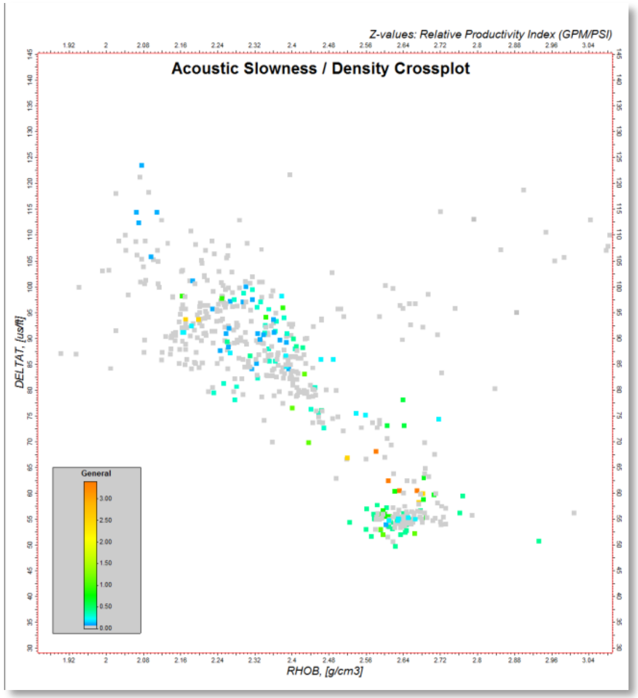
Scientific/Technical Approach

Use of reflection seismic for fracture detection.

- Vertical Seismic Profiles (VSP) used to detect fractures [e.g. Majer et al., 1988;Kim et al., 2013]. (*Note that VSP possesses much higher resolution than surface due to proximity and higher frequencies).

Reflection seismic attributes and neural nets widely used to map lithologies and fluid in petroleum datasets.

- Some previous example of seismic attributes in geothermal so far:
  - Kaelin et al., 2006 [energy and frequency]
  - Luschen et al., 2014 [coherence, dip, AVOA: fractures, lithology]
  - Khair et al., 2012 [curvature: fractures]
- We see relationships between data from Raft River using data from well logs; should extend to seismic data also.



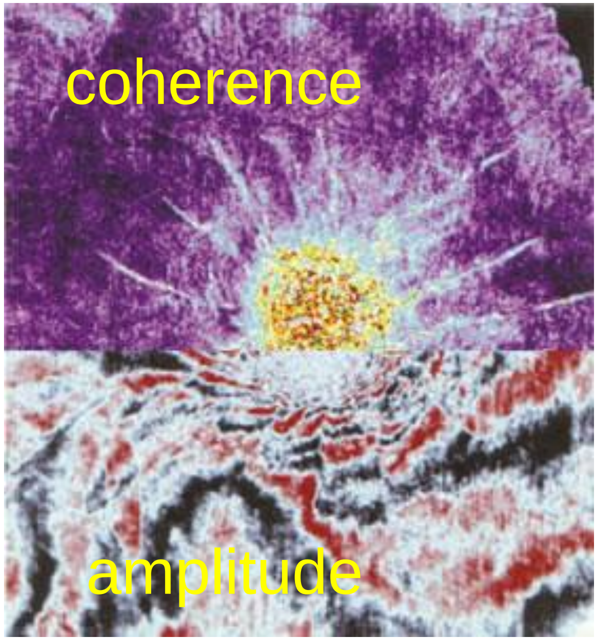
Acoustic slowness

Density

Crossplot of data from Raft River (from well logs) showing roughly linear relationship.

Scientific/Technical Approach

- "*quantitative measure of a seismic characteristic*"
- Many attributes exist:
  - Single-trace attributes, which depend only on a single trace
  - Multiple-trace attributes, which require 2 or more traces to calculate
  - Composite, composed of two or more attributes
  - Pre or post-stack
- Widely used in petroleum industry
  - Useful for mapping faults
  - Inferring lithology
  - Identifying areas of possible high fracture density
- This study: 3D seismic of Raft River
  - 7.64 square miles; xline:660 ft; inline: 165; vibroseis; depth migrated



Example showing illumination of fractures using coherence from Gulf Coast salt dome.

Accomplishments, Results and Progress

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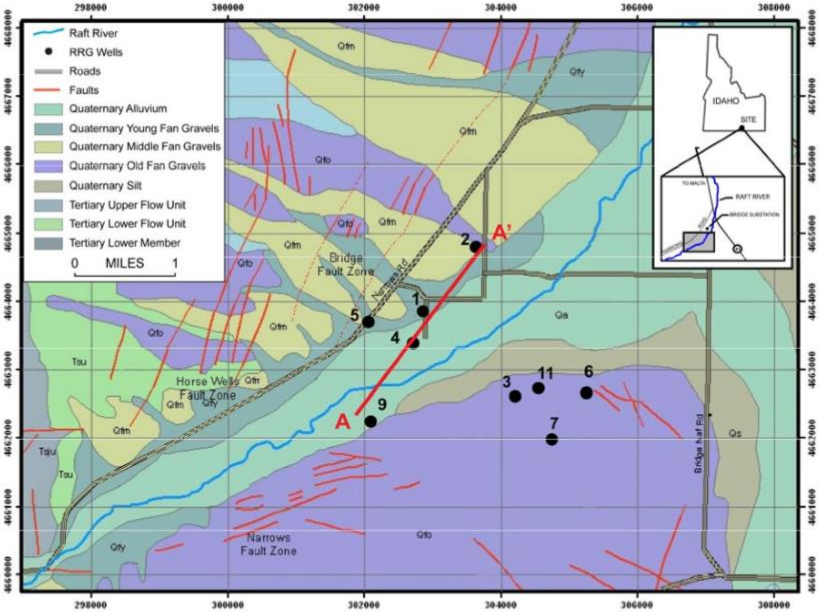
- Accomplishments/Progress to date.
  - Attributes calculated for 3D volume (Raft River) using both automated code and commercial interpretation package.
  - Well data (lithology and well logs) collected for wells inside area of 3D survey.
  - Relationships between seismic attributes and geothermal productivity are estimated (in progress).
  - Performance schedule delayed due to delays in receiving funds from DOE and in processing sub-contracts.
  - Costs as are planned.
  - We show attributes calculated using Petrel here but can also calculate using separate algorithms.



Jones et al., 2011

Accomplishments, Results and Progress

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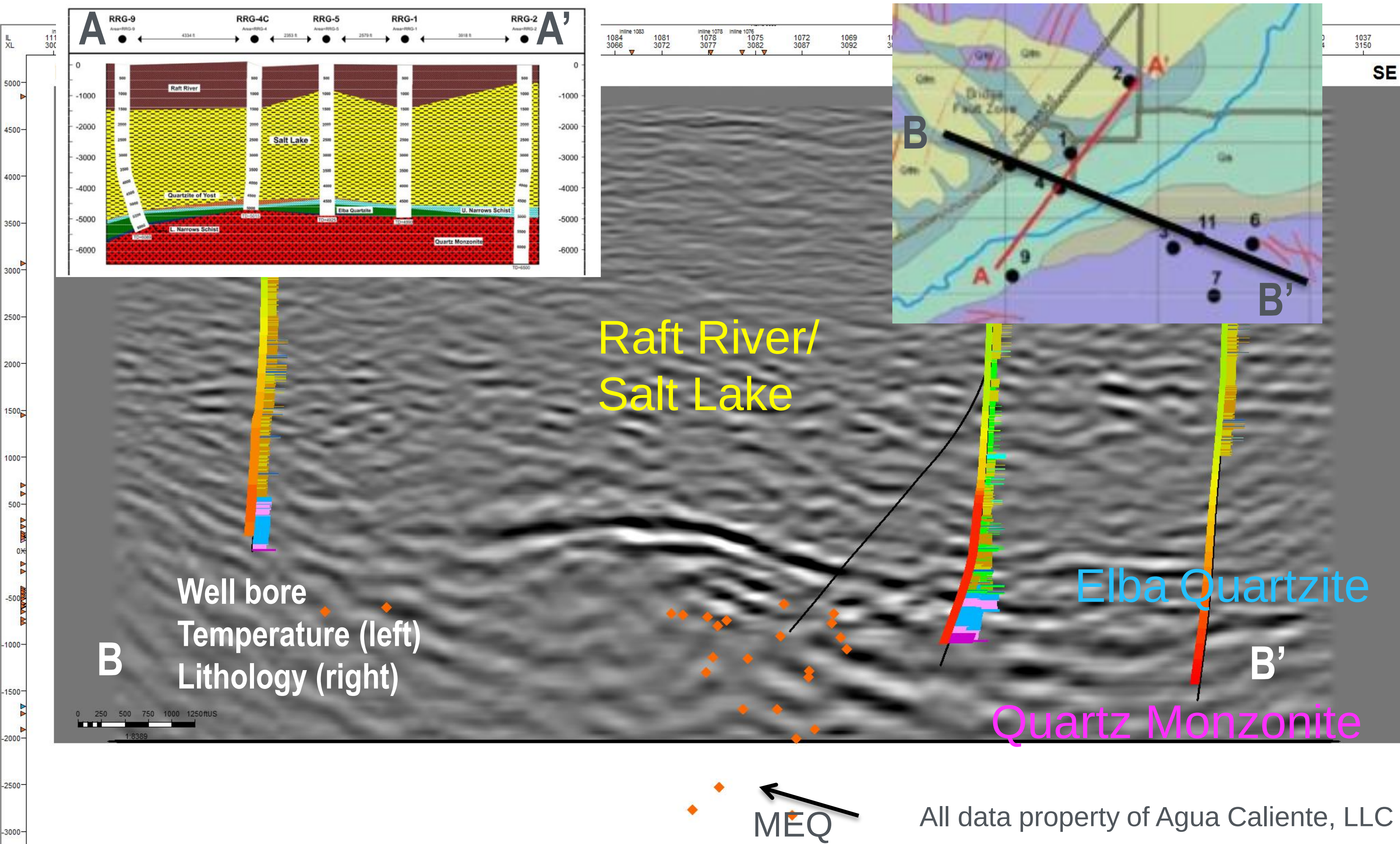
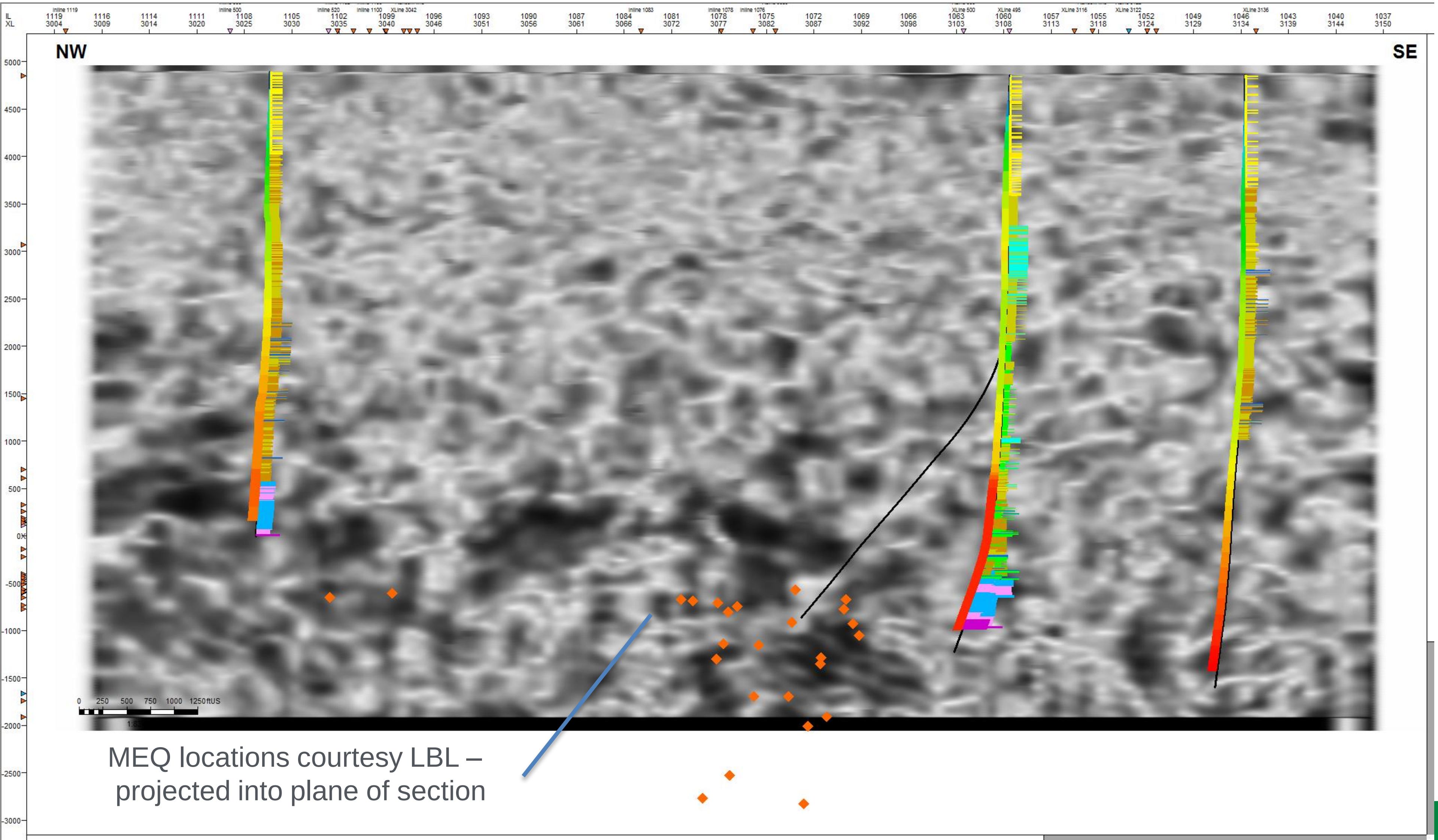


All data property of Agua Caliente, LLC

Accomplishments, Results and Progress

Example attribute "B" – (same section)

Well tracks (projected into section)



MEQ locations courtesy LBL – projected into plane of section

Accomplishments, Results and Progress

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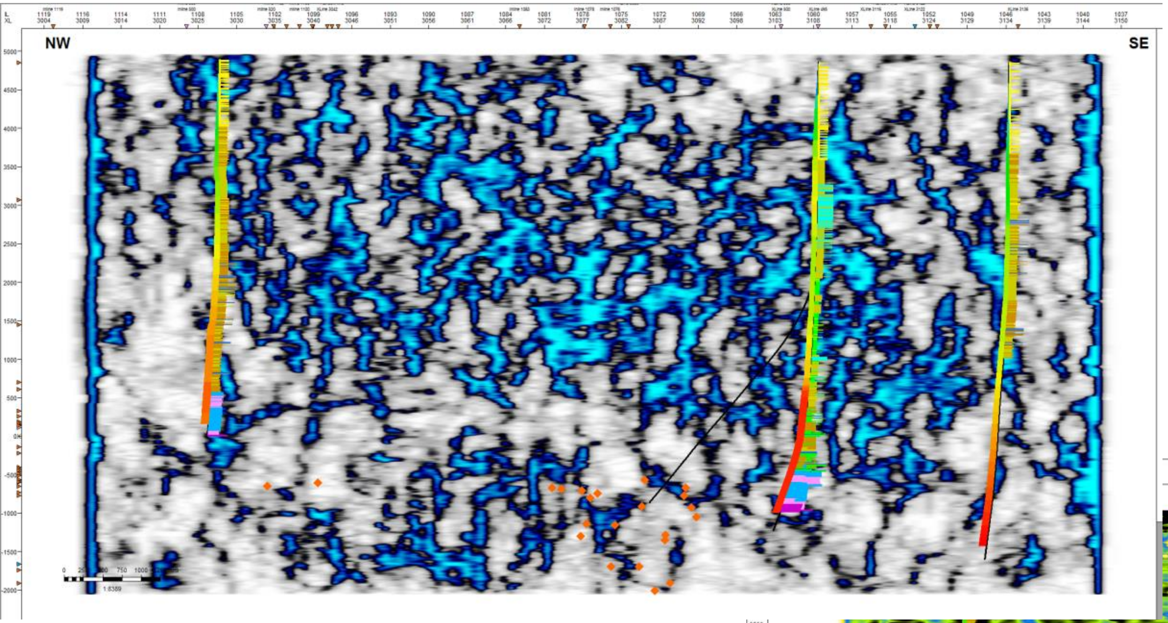
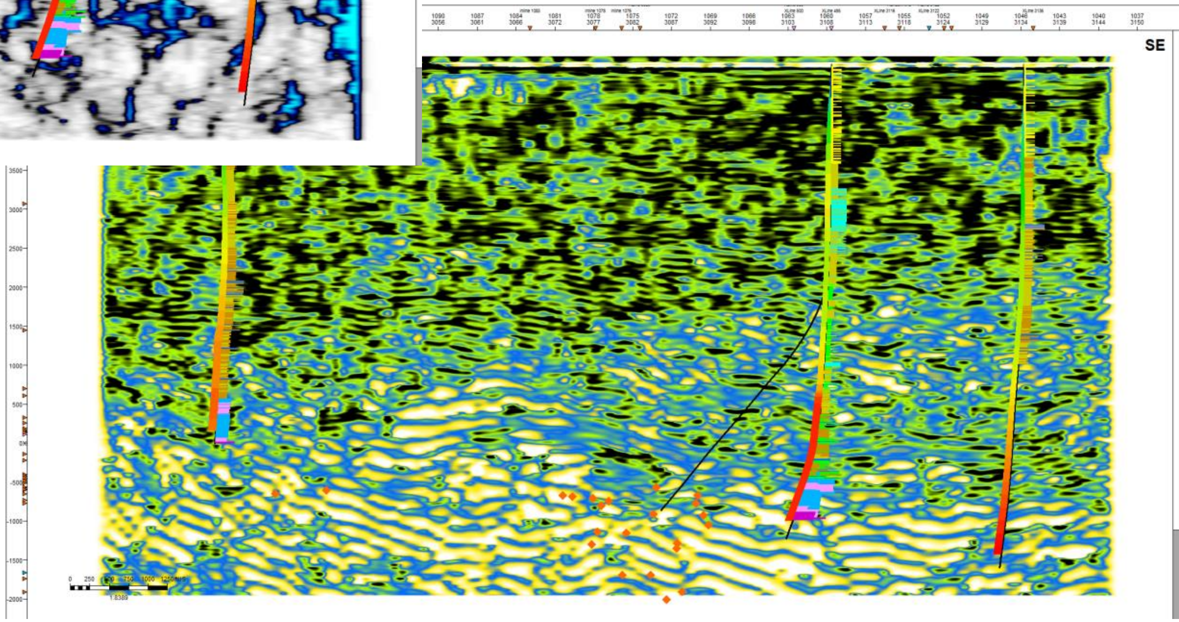
Example attribute: Attribute "C"



Example attribute: Attribute "D"



Accomplishments, Results and Progress

Compute attribute

Extract values (e.g. well)

Statistics & Analysis Discover Relationships

Use neural network using existing wells as training data and apply throughout volume.

Evaluation and testing (e.g. omit one well; predict)

Attributes calculated in two ways:
- Self-developed algorithms
- Commercial 3D seismic reflection software package.

Accomplishments, Results and Progress

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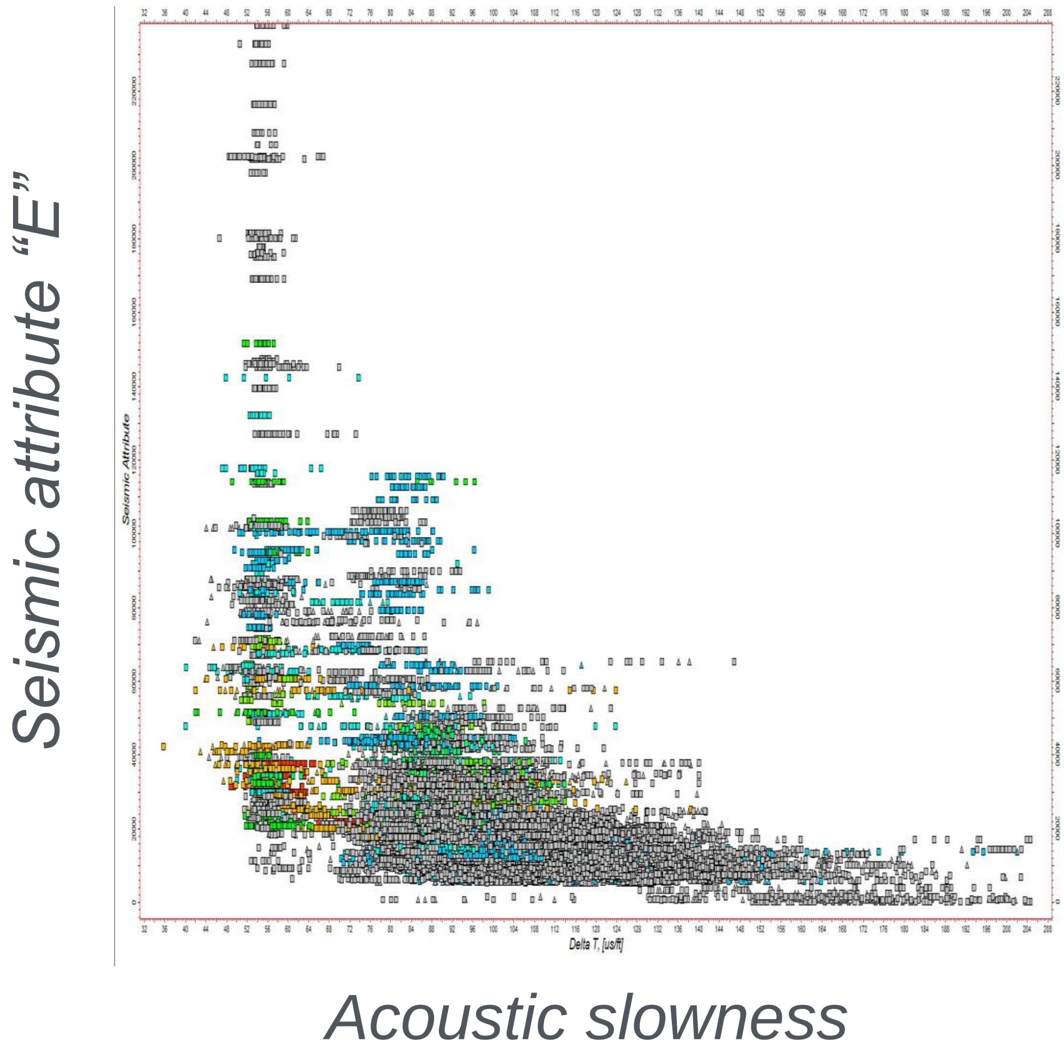
Example crossplot from Raft River. Color denotes mapped permeable zones. Permeable zones tend to 'group' together.

While outliers exist, the permeable zones tend to group in the lower left.



Accomplishments, Results and Progress

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Original Planned Milestone/ Technical Accomplishment	Actual Milestone/Technical Accomplishment	Date Completed
2D map inline and xline	Complete (Optim)	FY14 Q2
3D automated mapping	Complete (Optim)	FY15 Q3
FD waveform synthetics	Shot gathers generated (LLNL)	FY14 Q3
X-ray analysis of well cuttings	Two wells X-ray and analysis (Utah)	FY15 Q1
FY14 final report	Complete (LLNL)	LLNL FY15 Q1
Include well data in analysis	In progress (Optim, Agua Caliente)	In progress
Calculate attributes using neural net	Delayed. FY15 funding arrived in FY15 Q2. (Optim, Agua Caliente)	In progress
MEQ locations and 3D seismic	In progress	FY15 Q3
Final report		FY15 Q4

Future Directions

- By the end of FY15, we expect to evaluate how well 3D seismic attributes correlate with key geothermal parameters.
  - Additional seismic attributes and combinations of attributes calculated.
  - Attributes correlated with specific geothermal parameters derived from well data using automated (neural net) means.
  - 3D seismic attributes and structure compared with micro-earthquakes.
  - Delayed funding issue has been resolved and we anticipate completion on time.

Milestone or Go/No-Go	Status & Expected Completion Date
Include well data in analysis/validation	In progress (Optim, Agua Caliente) **6/1/15**
Calculate attributes using neural net	Delayed. FY15 funding arrived in FY15 Q2. (Optim, Agua Caliente) **6/1/15**
MEQ locations and 3D seismic	6/30/15
Final report on 3D attributes.	9/30/15

Mandatory Summary Slide

- Use of attributes is a promising technique borrowed from the petroleum industry.
- Success in application to geothermal prospects would be a major breakthrough.
- The Raft River dataset offers a unique opportunity that strongly leverages industry assets and cooperation.
- Technical aspects
  - Dataset quality is sufficient for most, but not all, attributes due to lack of well-defined continuous horizons.
  - Automated extraction and assessments is underway.
  - Validation is planned.
- Results look promising but it remains a challenging problem.

Additional Information

References:

Jones, C. J. Moore, W. Replow, and S. Craig, 2011, Geology and hydrothermal alteration of the Raft River geothermal system, Idaho, PROCEEDINGS, Thirty-Sixth Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California, January 31 - February 2, 2011, SGP-TR-191

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