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Presentation Outline

• Benefits to the Program & Project Overview
• Technical Status:
  – Field site
  – Installation
  – Test Plan
  – Video Data
  – Seismic Results
  – Distributed Acoustic Sensing (DAS) Results
  – Constant Pressure Test Results
  – Real-time Electrical Resistance Tomographic (ERT) Results
  – Joint Inversions
  – Inversion For Fracture Conductivity
  – Automatic Picking Results
• Accomplishments to Date
• Synergy Opportunities
• Concluding Remarks
• Questions
• Appendix
Benefit to the Program

Problem Statement:
Real time methods of characterizing fracture networks and monitoring fracture flow are required to provide actionable feedback during stimulation, injection, and extraction operations.

Current Limitations:
1. Data may be insensitive to small-scale fractures that are important to system function.
2. Data collection and processing times limit temporal and spatial imaging resolution.
3. Important fracture attributes (e.g. permeability) are not routinely estimated.
## Project Overview: Goals and Objectives

### Demonstrate geophysical imaging technologies that will characterize:

1. **3D extent and distribution of fractures stimulated from two explosive sources**
2. **3D fluid transport within the stimulated fracture network through use of a particulate tracer**

These data will also be used to:

1. **Develop methods of estimating fracture attributes from seismic data**
2. **Develop methods of assimilating disparate and transient data sets to improve fracture network imaging resolution**
3. **Advance capabilities for near real-time inversion of cross-hole tomographic data**

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<table>
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<tr>
<th>Subsurface Control for a Safe and Effective Energy Future</th>
<th>Adaptive Control of Subsurface Fractures and Fluid Flow</th>
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<td><strong>Wellbore Integrity &amp; Drilling Technologies</strong></td>
<td><strong>Subsurface Stress &amp; Induced Seismicity</strong></td>
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<td>Improved well construction materials and techniques</td>
<td>Measurement of stress and induced seismicity</td>
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<tr>
<td>Autonomous completions for well integrity modeling</td>
<td>Manipulation of stress and induced seismicity</td>
</tr>
<tr>
<td>New diagnostics for wellbore integrity</td>
<td>Relating stress manipulation and induced seismicity to permeability</td>
</tr>
<tr>
<td>Remediation tools and technologies</td>
<td>Applied risk analysis of subsurface manipulation</td>
</tr>
<tr>
<td>Fit for purpose drilling and completion tools (e.g. anticipative drilling, controls, monitoring)</td>
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<tr>
<td>HT/HP well construction / completion technologies</td>
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**Energy Field Observatories**

**Fit For Purpose Simulation Capabilities**
Field Site:

- Blue Canyon Dome, atop Socorro Peak west of Socorro, NM
- Weathered Rhyolite 0-30 ft below ground surface (bgs); Unweathered Rhyolite > 30 ft bgs
- 1 stimulation borehole (70 ft deep) surrounded by 4 monitoring boreholes (75 ft deep)
Installation - Fall 2015

Tremie Pipe
ERT Sensor
Fiber Optic Cable
ERT Installation
Fiber Loop & Deepest ERT Sensor
Field Campaign – April 2016

Seismic

- Angled CT (Logging)
- Campaign Seismic ML-CASSM
- Energetic Stimulation #1
- Continuous 4D ML-CASSM
- Pressure Tests & ZVI Injection #1
- Energetic Stimulation #2
- Pressure Tests & ZVI Injection #2
- Continuous 4D ERT
- Angled CT (Logging)
- Campaign Seismic ML-CASSM
- 3D ERT Baseline + 2 GPR baseline cross sections
- Active & Passive Recording
- 3D ERT + 2 GPR cross sections
Field Campaign
April 2016
Gantt Chart
Energetic Stimulation #2
Downhole Camera Footage

- Camera data is from post energetic stimulation #2
- Camera is located 50.0 ft below ground surface (bgs)
- Shot depths in both cases were 58-65 ft bgs
- Two near vertical fractures are visible
- Close examination appears to show that the fractures are self propped
- Along other sections of the borehole, more than 2 fractures were visible
Seismic Tomography

Acquisition
- 9 different vertical source-receiver offsets for each tube pair (0°, 15°, -15°, 30°, -30°, 45°, -45°, 60°, and -60°)
- Acquisition time for each one of these tests is only about 6.5 hours
- 1 week to pick the data and 2 days to perform the inversion.
- Each tomogram is constructed using approximately 25,000 picks over the 8x8x35 foot (2.44x2.44x10.7 m) volume.

Observations
- Big changes in coda
- Coherent (in depth) changes in arrival time
- Initial tomogram (pre-shot) shows similar structure to ERT
ML-CASSM

- **Goal**: map fracture time evolution & effects of fluid pressure
- Largest ML-CASSM system deployment to date (22 S x 72 R)
- Data recorded before/after fractures + continuously during pump tests & zvi injection
- System active for 1.5 weeks, recorded 55,000 gathers ~ 2000 tomographic datasets
- Challenges included: high wind noise levels, power instability, cable issues
ML-CASSM Data: Fracture Impact

West to North, source at ~21 m

Observations

- Baseline, excellent bandwidth (signal to 10 kHz and beyond)
- Fracturing induced significant attenuation change (visible in A & f)
- Higher order resonances of source particularly attenuated.
- Only small change in P-phase (velocity reduction)
- Big changes in coda
Distributed Acoustic Sensing (DAS) – Shot #1 Data Example

(Left) Gather after despiking, bandpass (top end at 50 khz), and trace balancing. Left is a large subset (700 traces) right is a zoom around first break in one of the wells. Data is temporally aliased.

(Right) Top: raw trace; Middle: after despiking and filtering; Bottom: amplitude spectrum
DAS - Seismic Interferometry

1. Cross-correlate ambient noise recordings between channels
2. Stack to increase signal-to-noise ratio
3. Measure relative velocity variations \((dv/v)\) based on delay in phase arrivals

\(\text{END GOAL} = \text{Detect temporal and spatial changes in seismic velocity}\)
Constant-Rate Injection Testing

• Analysis of pressure falloff data section for quantitative estimates of hydraulic conductivity (K)
• Comparison of successive tests provides a measure of change in K associated with stimulations
• Agarwal (1980) time transformation applied to allow analysis of pressure falloff response using standard analytical well-function models
• Pressure falloff data fit to a vertical fracture model (Gringarten and Witherspoon, 1972)
• Difference in hydraulic response for three borehole conditions tested was readily apparent
Constant–Rate Injection Test Analysis

- Fit of pressure and pressure derivative (diagnostic) data to a vertical fracture model

<table>
<thead>
<tr>
<th>Hydraulic Conductivity (ft/d)</th>
<th>Permeability (md)</th>
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<tbody>
<tr>
<td>Baseline</td>
<td>7E-5 to 3E-9</td>
</tr>
<tr>
<td></td>
<td>(book value range)</td>
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<tr>
<td>Post-Shot #1</td>
<td>0.087</td>
</tr>
<tr>
<td></td>
<td>32</td>
</tr>
<tr>
<td>Post-Shot #2</td>
<td>0.25</td>
</tr>
<tr>
<td></td>
<td>92</td>
</tr>
</tbody>
</table>
Pre-fracture Baseline ERT Image

- Low electrical conductivity (EC) with high variability (2 orders of magnitude)
- Steeply dipping EC structure
- Highly resistive rock deep in the section (more competent?)
Real-time 4D imaging during ZVI injection

- Injection time: 3 hrs
- Injection vol: 110 gal
- Image frame rate: 15 min.

NOTES:
- Post detonation camera log shows multiple dominant vertical fractures.
- ZVI solution appears to migrate primarily into the east/west trending fracture.
- ZVI reaches outer boundaries of imaging zone, likely beyond...
Fly-around view of ZVI-filled fracture zone
Joint Inversion Development

- Enables ERT and Seismic/Radar data to be jointly inverted
- Leverages assumption that fractures induced changes in geophysical properties are co-located.
- Joint constraints significantly improve resolution.
- **Goal**: ‘Real-time’ joint inversion of large-N travel time and ERT data for fracture characterization and/or flow monitoring.

Algorithm Development
- Highly scalable parallel modeling/inversion
- Side by side forward simulations
- Unstructured tetrahedral mesh (finite element for ERT, fast marching method for travel time)
- Advanced a priori constraints
- Fresnel Volume Sensitivity
- Status: Complete (Simulated), Testing (Field)
Inversion for fracture conductivity

- Remote sensing of fractures
- How can we extract the most information? Permeability?
- Move beyond empirical rules
  - Self-consistent
  - Predictive

Pristine fracture  Fracture containing precipitated pillars

Asperity $i$

Precipitated pillar

Aperture distribution (m)

Normal stress/compliance index

$M_i^1$  $M_i^2$  $M_i^1$
Our approach: Improvements that deliver results early and can be extended to a next-generation capability

- **Current effort:** Apply a modified version of Sayers and den Boer (2012) workflow
  - Utilize latest models coupling geophysics-mechanics and conductivity (Morris et al., 2016)

- **Future:** Introduce additional self-consistent fracture models to develop a next-generation workflow:
  - Predictive – Different geological settings
  - Extensible – Different geophysical attributes
Automatic Picking Results

- The automatic first arrival time estimates are mostly reliable.

- Misestimated first arrival times are identifiable by their large changes in velocity from their neighbors.

- S-wave arrivals are more problematic, but, for low angle offsets and in undamaged rock, the estimates provide a meaningful constraint to the velocity structure of the rock.

- The amount of time required to perform the analysis is short (less than 10 s for 120 traces).
Accomplishments to Date

- **Demonstrated:**
  - Successful multi-organizational (FFRDC, private industry, and academia) scientific collaboration and field execution
  - High resolution (spatial and temporal) geophysical imaging
  - Real-time imaging of fracture generation and tracer migration
  - Dense multi-disciplinary data acquisition

- **Developed and/or Improved:**
  - Joint inversion of geophysical data
  - Inversion for fracture conductivity
  - Automatic picking of high frequency seismic data
  - 3D change detection imaging using DAS technology
Synergy Opportunities

Wellbore Integrity
- LANL: Novel 3D Acoustic Borehole Integrity Monitoring System
  - SNL, ORNL, NETL
- ORNL: Ultrasonic Phased Arrays and Interactive Reflectivity Tomography
  - LANL, Purdue Univ., SNL

Subsurface Stress/Induced Seismicity
- SNL: Imaging Fracture Networks
  - LLNL, LBNL, PNNL

Permeability Manipulation

New Subsurface Signals
- LBNL: Intermediate-Scale Hydraulic Fracture and Stimulation (SURF)
  - INL, \(^1\)WGSS, \(^2\)SDSMT
  - LANL, PNNL, LLNL, NETL

Funded collaborations
Unfunded collaborations

\(^1\) WGSS: University of Wisconsin, Golder Associates, Stanford University, SNL
\(^2\) SDSMT: South Dakota School of Mines & Technology
Questions?

National Lab Team
April 2016 Fracture Test
Publications & Presentations


