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Push-pull well testing using CO_2 with active source geophysical monitoring

Project Officer:
William Vandermeer
Total Project Funding: $750,000
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Track Three

This presentation does not contain any proprietary confidential, or otherwise restricted information.

Relevance to Industry Needs and GTO Objectives

- **Motivation**
  - **Enhanced Geothermal Systems (EGS) benefit from the ability to control fracture flow and fracturing**
  - **In order to control, need ability to characterize faults and fractures**
  - **Natural and induced faults/fractures are hard to image.**
  - **Seismic and electrical contrast are small for water-filled faults/fractures**
  - **Gas injected into faults/fractures enhances contrast**
- **Objective**
  - **Develop and demonstrate (by modeling) a new technology for characterizing faulted/fractured geothermal systems involving**
    - **CO_2 push-pull and related pressure-transient testing**
    - **Active-source seismic imaging**
    - **Well logging**

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Relevance to Industry Needs and GTO Objectives

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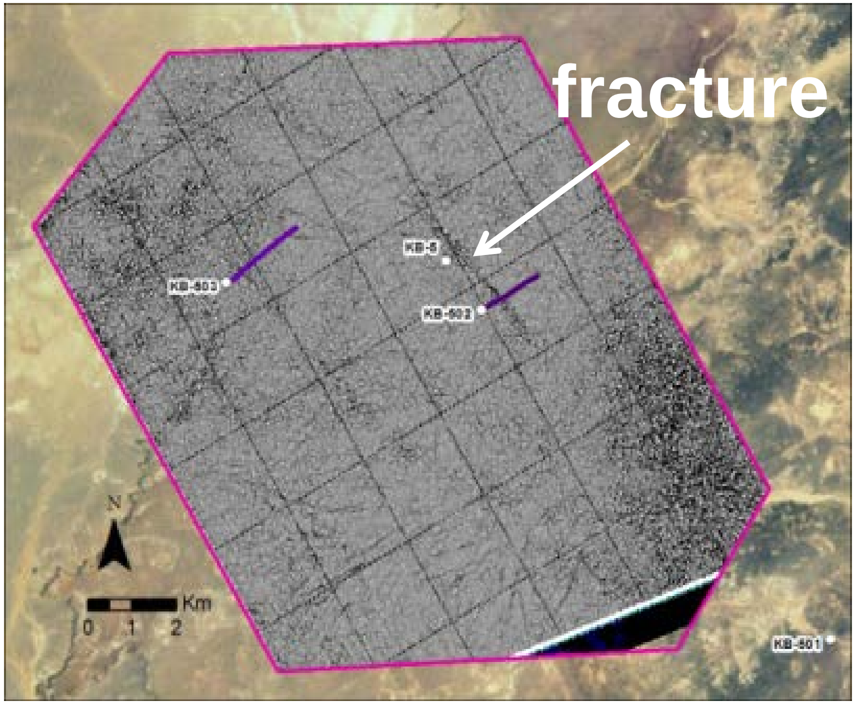
- **Key idea: Inject CO_2 into fault or fracture zone to enhance imaging of the fault or fracture**
  - **CO_2 has been shown to enhance seismic detection of a large fracture zone**
  - **CO_2 is non-wetting (capillarity holds water in matrix) so it has strong preference for flowing in faults and fractures**
  - **$scCO_2$ is relatively dense diminishing upward buoyancy effect**
  - **$scCO_2$ has low viscosity which allows it to flow in fracture/fault**
  - **There is lots of experience with $scCO_2$ from geologic carbon sequestration research**



Zhang, R., Vasco, D., and Daley, T.M., 2015. Study of seismic diffractions caused by a fracture zone at In Salah carbon dioxide storage project. International Journal of Greenhouse Gas Control, 42, pp.75-86.

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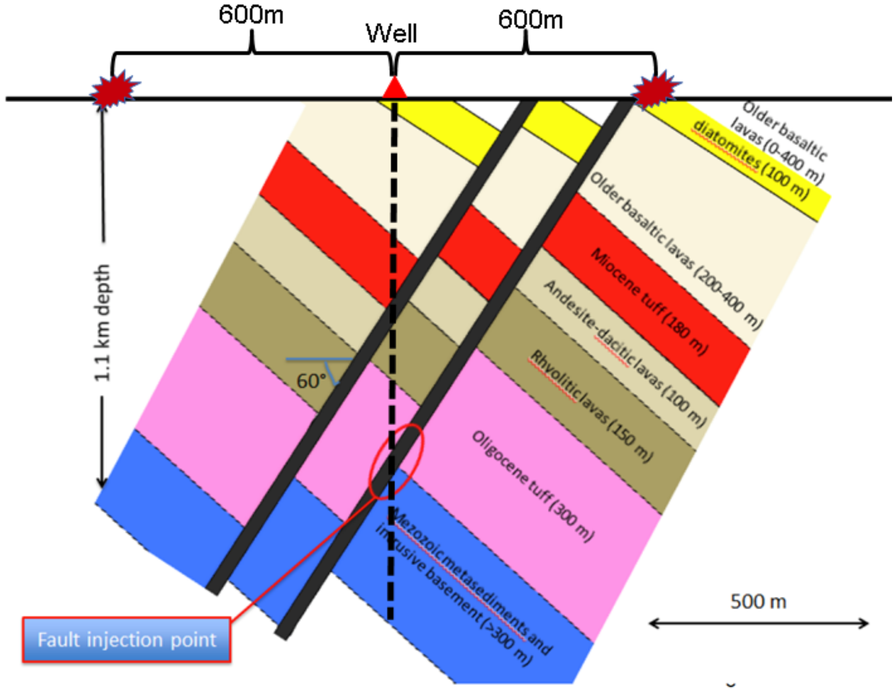
- **Define prototypical EGS site based on Brady's Hot Springs system**
- **Simulate CO_2 injection using TOUGH2/ECO2N V.2**
- **Simulate active seismic monitoring**
- **Simulate well logging**
- **Simulate pressure-transient analysis**
- **Carry out sensitivity and data-worth analysis**
- **Combine the modeled results to infer fault properties**



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Methods/Approach

- Excellent collaborative team
  - Flow modeling and simulation, well-testing (LBNL)
  - Well logging, geophysics simulation (Schlumberger-Doll Research)
  - Seismic modeling (LBNL and Univ. Louisiana, Lafayette)
- Step-by-step approach
  - Selection of prototypical site and characteristics
  - Flow modeling to establish expected, P, T, X, and saturation
  - Simulation of well logging and seismic imaging
  - Well test simulation and inverse modeling
- Key issues
  - Extent of CO_2 flow in fault zone (e.g., gouge), recovery, etc.
  - Extent to which CO_2 can be imaged by logging and seismic methods
- Over three years, we investigated these issues and more.

Technical Accomplishments and Progress

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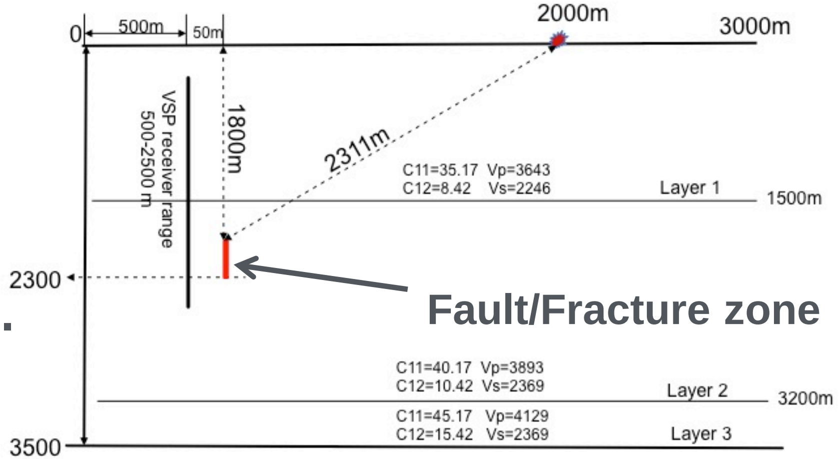
- Developed and tested by simulation the concept of using CO_2 as a contrast enhancement fluid for EGS fault charaterization
- Simulated multiple scenarios of CO_2 injection into a prototypical fault zone
- Estimated effectiveness of well-logging tools to image injected CO_2
- Simulated well tests and sensitivity of fault properties to CO_2 injection for use in inversion
- Simulated seismic monitoring of various kinds (Surface, VSP, Cross-well)
- Inverted for fault location from cross-well seismic simulated data
- Developed draft test plan for field testing

We use an anisotropic finite difference code based on SPICE with fracture compliance models to simulate active seismic monitoring in time-lapse mode.



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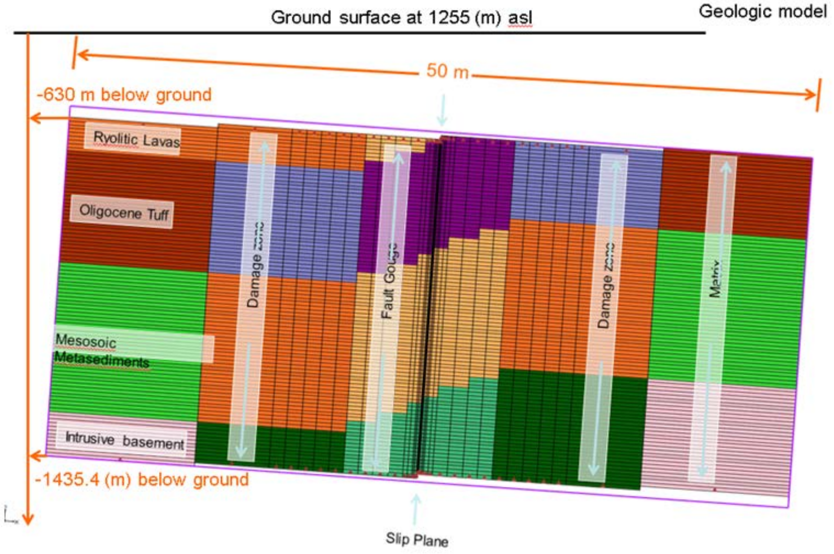
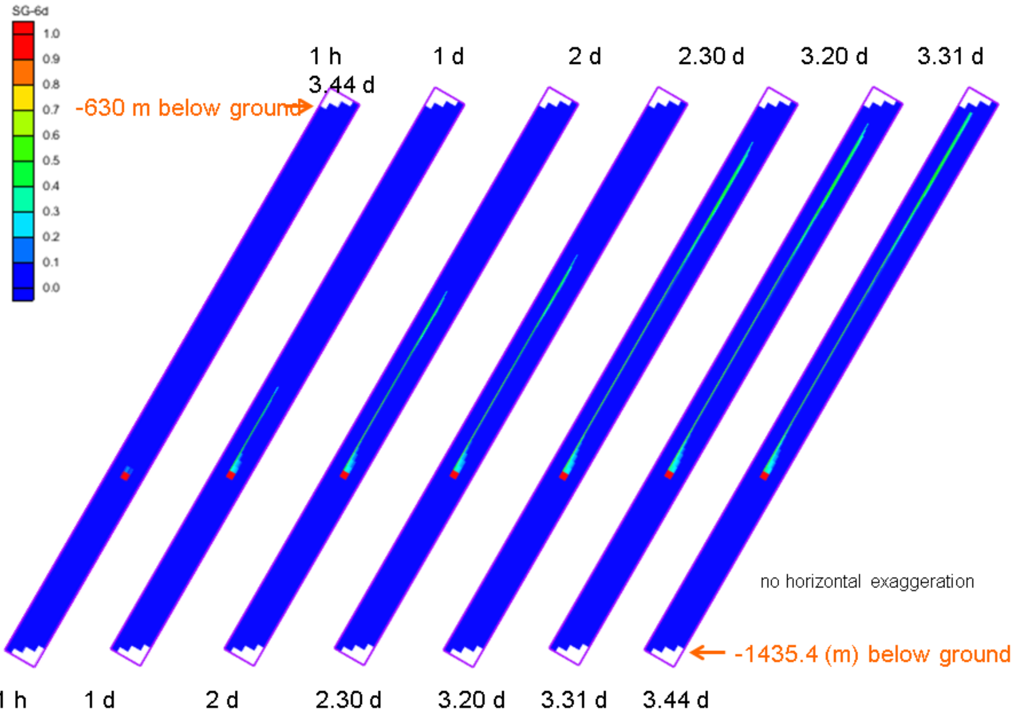
Technical Accomplishments and Progress



- **Faults comprise slip plane, gouge, and damage zone.**
- **Prototype system is based on Desert Peak (Bradys)**



- **Despite relatively high density of CO_2, buoyancy leads to upflow during push and difficulty recovering CO_2.**
- **During pull, tend to get mostly water production.**

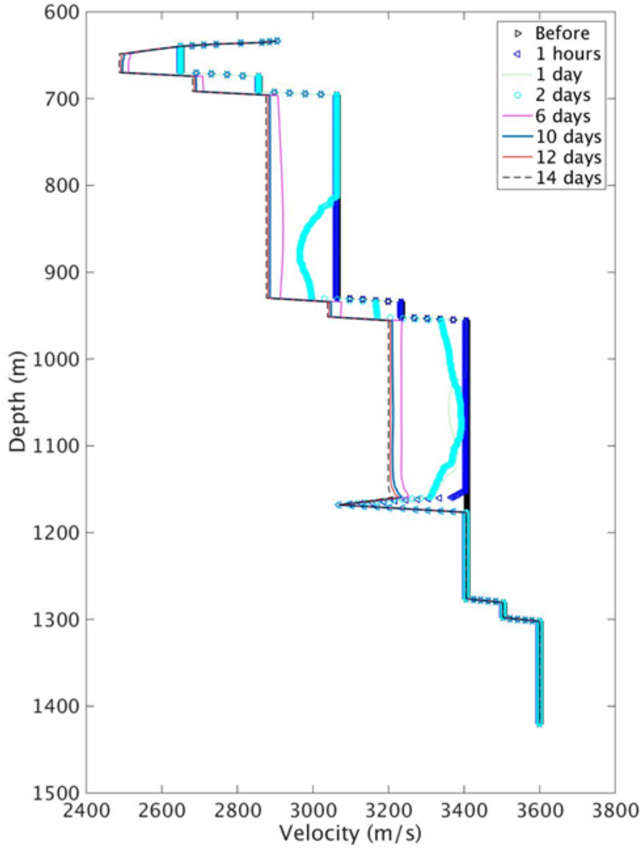
Limited set of logging tools is available for EGS environment due to high temperature

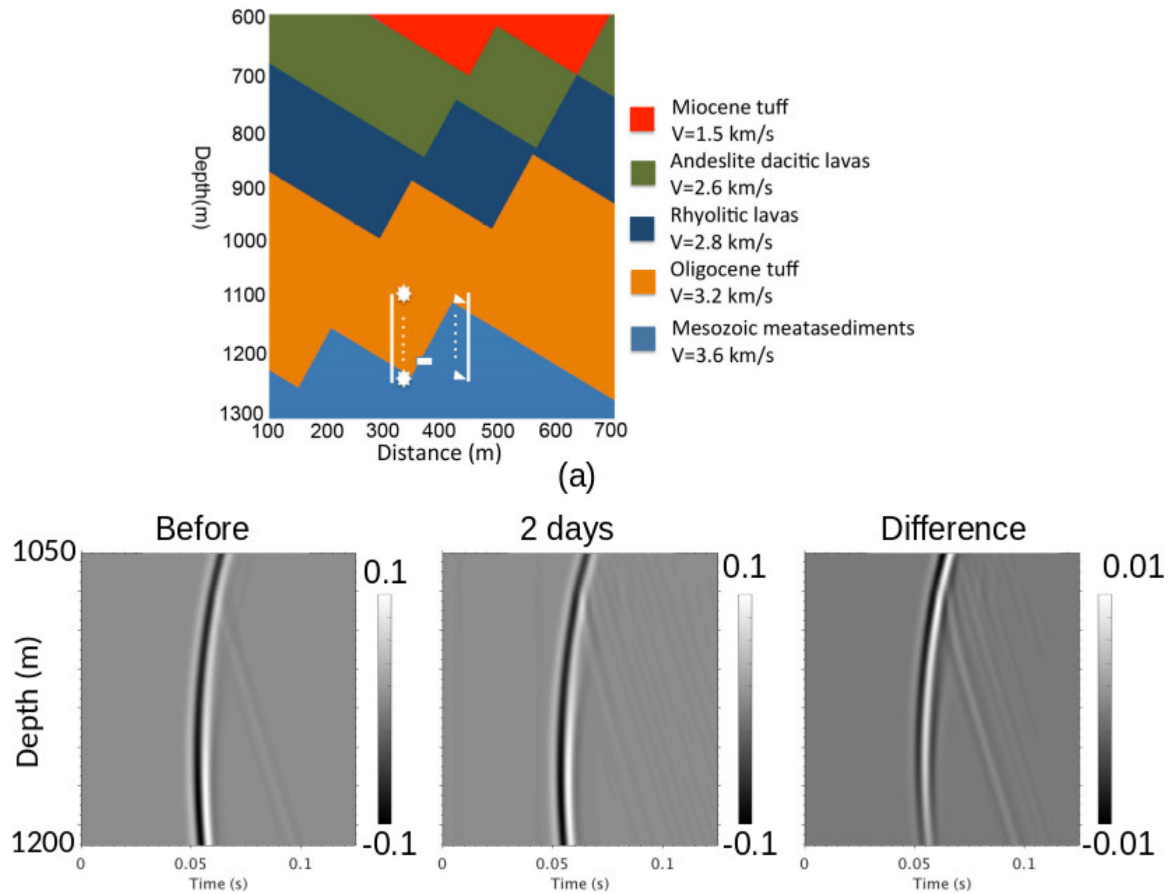
- **Neutron capture (HAPS) monitoring might be feasible for fault gouge (and limited for slip-plane and damage zone), provided enough salinity contrast (or pre-flush with high-salinity brine). This is a <u>shallow measurement</u> (5-10" into formation).**

Tool	Effective Property	Matrix	Damage zone	Fault gouge	Slip plane
HLDS	bulk density				
HSLT	elastic properties				
HIT	conductivity				
HAPS	capture cross-section				

feasibility possible limited no

FD simulation of cross-well seismic using simulated saturations in the Desert Peak prototype produce time-lapse differences of approximately 10%.



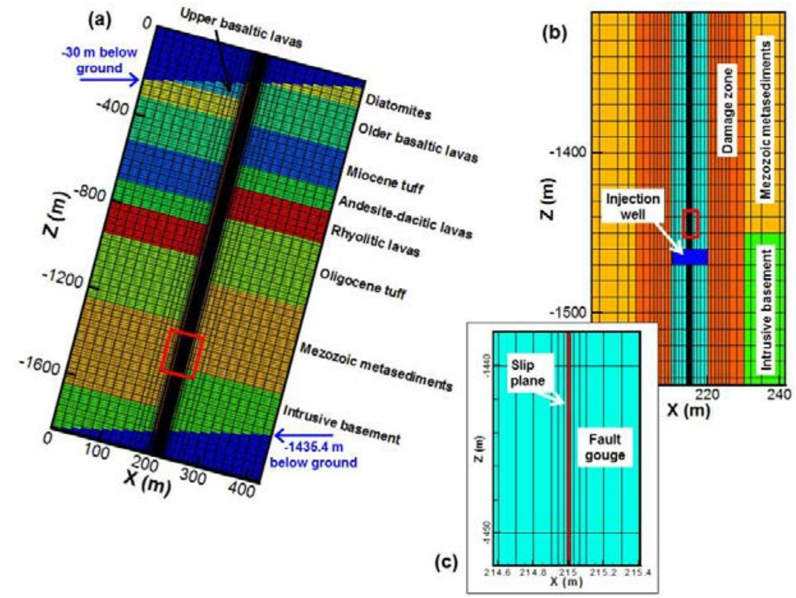


(a)

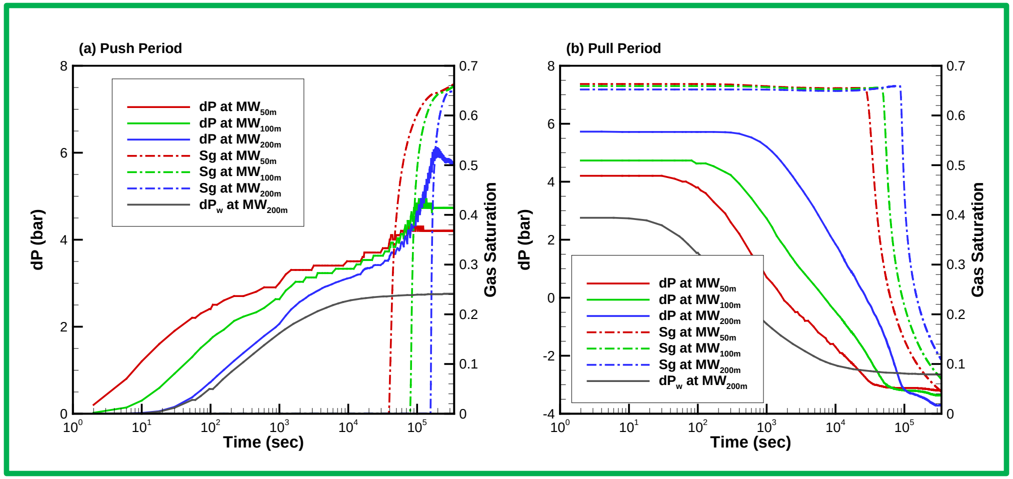
(b)

Technical Accomplishments and Progress

- **Goal:** Evaluate feasibility of using pressure transient monitoring during CO_2 push-pull tests to complement active seismic and wireline well logging for EGS characterization
- Create **2D model** of a single fault based on the Desert Peak geothermal field
- The **fault zone** consists of slip plane, fault gouge, and damage zone, and is bounded by the surrounding country rocks



- The **pressure transient** at the monitoring wells in the fault gouge shows unique traits due to the multiphase flow conditions developed by CO_2 injection, and varies sensitively on the arrival of the CO_2 plume
- **Sensitivity analysis**
  - Pressure transient is most sensitive to the fault gouge permeability
  - Optimal monitoring well location is 200 m above injection point
- Fault gouge permeability can be best estimated with the pressure transient data



Technical Accomplishments and Progress

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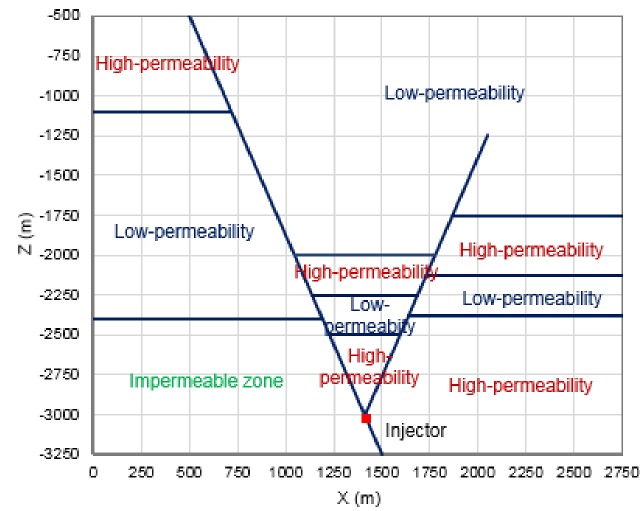
Dixie Valley is another promising geothermal site: QUESTION: What are the optimal measurements during CO_2 push-pull to characterize the faults?

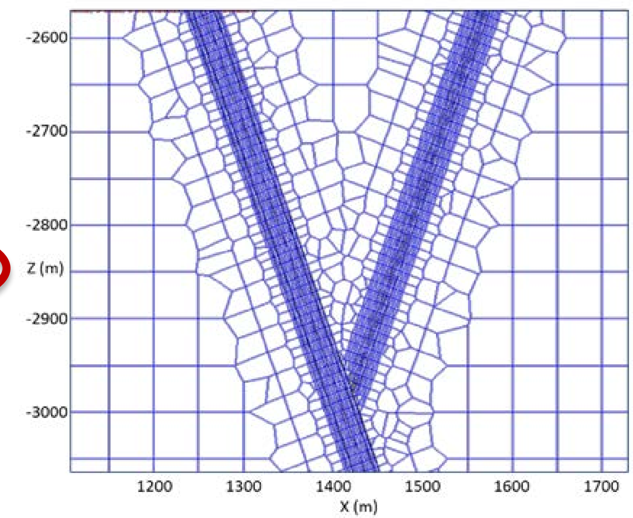


Approach: Data-worth analysis for 30-days of CO_2 push

- **Perturb 8 most-controlling unknown parameters:**
  – Slip plane (K, S_{lr}), Fault gouge (K, S_{lr}, λ, $1/P_0$), Damage zone (K, $1/P_0$) – 8
- **Observe for 20 days, 12 most-sensitive measurable responses:**
  – Pressure (main & conjugate fault @ 2925, 2520, 2100 m) - 6
  Gas saturation (main & conjugate fault @ 2925, 2520 m) - 4
  Temperature (conjugate fault @ 2520, 2100) - 2
- **Predict the CO_2 distributions in the fault zones after 30 days.**
  – S_G and X_CO_2(A) at main & conjugate fault @ 2925, 2520, 2100 m) - 6

Evaluate data-worth, as an increase of prediction uncertainty caused by removal of observation data

Measurement	DWA (%)
Main Fault Pressure @2925 m	5.2
Main Fault Pressure @2520 m	17.18
Main Fault Pressure @2100 m	11.47
Conjugate Fault Pressure @2925 m	3.59
Conjugate Fault Pressure @2520 m	31.44
Conjugate Fault Pressure @2100 m	30.55
Main Fault Sg @2925 m	0.18
Main Fault Sg @2520 m	0.07
Conjugate Fault Sg @2925 m	0.21
Conjugate Fault Sg @2520 m	0.11
Conjugate Fault Temperature @2520 m	0
Conjugate Fault Temperature @2100 m	0



Technical Accomplishments and Progress

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Original Planned Milestone/ Technical Accomplishment	Actual Milestone/Technical Accomplishment	Date Completed
M1.2. Powerpoint summarizing end-member fractured reservoir characteristics	Developed ppt showing topologies of different fault/fracture sets, orientations, and intersections	12/31/2014
M2.1. Powerpoint summarizing simulations of CO2 well tests in fractured reservoirs	Developed ppt showing TOUGH2/ECO2N V.2 simulations of push-pull tests	3/31/2015
G2. Go/No-Go: Must show through simple models or empirical results that typical expected CO2 saturations in fractures can be imaged by active seismic and/or well logging approaches.	Developed ppt showing preliminary results of CO2 impact on seismic velocity change and neutron capture logging	9/30/2015
M3.1. Powerpoint summarizing design of geophysical monitoring scenario	Go/No-Go presentation was not held until late Ocotober, and Go decision was not conveyed until Nov. 23, 2015 so could not start these tasks on 10/1/15.	3/31/16
M3.3. Powerpoint summarizing design of well logging scenario	See above.	3/31/2016
M4. Powerpoint summarizing simulation of well logging	We demonstrated simulation of neutron capture well logging and showed its sensitivity for detecting CO2 especially for highly saline systems.	9/30/2016
G4. Go/No-Go: Demonstrate ability to simulate seismic imaging of CO2 in a fractured reservoir	We have demonstrated ability to simulate imaging in the 2D Brady's system.	9/30/2016
M5.1. Powerpoint summarizing inversion of virtual hydrologic well test data	We carried out inversion and data-worth analysis. Powerpoint is included in Q2 FY17 quarterly report.	3/31/2017
M5.2. Powerpoint summarizing inversion of virtual geophysical data	We carried out reverse-time migration.	10/30/2017
G5. Go/No-Go: Demonstrate ability to jointly invert well-test, geophysical, and well logging data to estimate fracture locations and properties	We inverted synthetic seismic and well-test data. Joint inversion was secondary importance to individual inversion which consumed the available time and budget.	10/30/2017
M6. Written final report	We assembled the final report from various conference proceedings, one published journal article, and three other journal articles in prep.	10/30/2017

Research Collaboration and Technology Transfer

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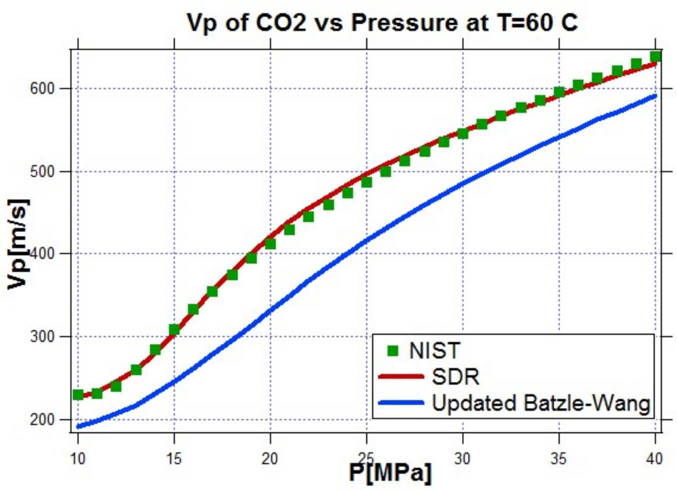
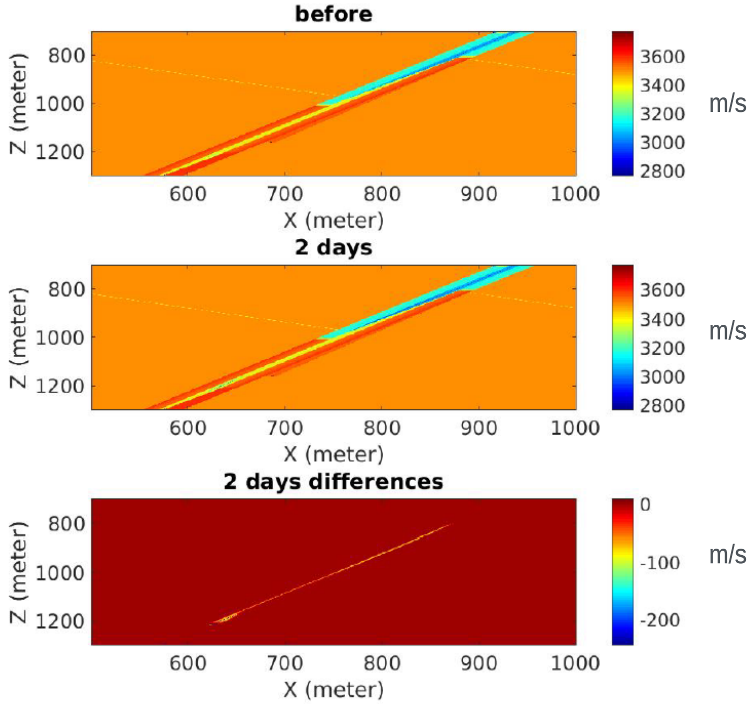
- This project was carried out with Schlumberger-Doll Research (SDR) and the University of Louisiana, Lafayette
- We discussed approaches and methods on regular weekly screen-share telecons over three years
- SDR provided valuable assistance with modeling of geophysical monitoring using CO_2 which will lead to improvements in the seismic modeling code.





Future Directions

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- We evaluated potential sites in the U.S. for a field demonstration.
- We have written a field test plan for Desert Peak (excerpts below).

Table 1. Potential sites for developing the ASCO experiment. Highlighted: yellow → best; green → good.

Properties ↓ Locations →	Brady's	Desert Peak	San Emidio	Dixie Valley	SURF
Depth of fault intersections	500-2000	500-2000	500-1500	500-1500	1478
Temperature °C	160-180	200-230	140-160	230-250	35
Lithology	metasediments	metasediments	metasediments	metasediments	phyllite and amphibolite
Known transmissive faults	yes	yes	yes	yes	no
Gouge or damage present	good	good	good	good	no
Open fractures within fault	very good	good	excellent	good	no
Sealed system	poor	good	poor	poor	yes
Complexity of structures	complex	relatively simple	highly complex	complex	yes
well geometry for seismic monitoring	excellent	very good	good	probably good	
Wells intersecting faults	yes	yes	yes	yes	not known currently
Availability of wells	probably many	good	probably few	probably few	numerous
Partnering potential	good	good	very good	very good	excellent
Degree of characterization	very good	very good	very good	very good	very good

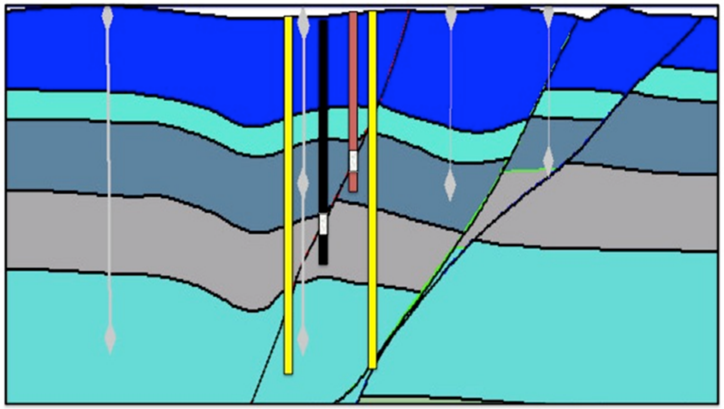

Fig. 3. Proposed fault experiment borehole geometry. The black borehole is an injection well perforated in the white interval, and the red borehole is a geochemical sampling well perforated in the white interval. The yellow wells are dedicated geophysical monitoring wells. The monitoring well spacing would ideally be 30-50 m from the injection well.

Future research related to this project:

- Better characterization of actual fault zones for modeling
- Full wave-form inversion
- Coupled active fracturing and imaging using CO_2 to account for aperture and elastic rock property changes
- Design of seismic survey to maximize imaging CO_2 in fault zone
- Other prototypical systems (e.g., highly fractured systems)

Mandatory Summary Slide

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- **Simulations show that CO_2 can be injected into fault zones (gouge) for push-pull well testing and as contrast fluid for geophysical monitoring.**
- **CO_2 buoyancy causes CO_2 to rise causing poor recovery during pull.**
- **Simulations of seismic monitoring using anisotropic FD code are sensitive to CO_2-water saturation in the gouge zone of a fault.**
- **Depending on seismic monitoring configuration, differences from pre-injection (no CO_2) to post push (CO_2 injection) produce time-lapse differences on the order of 1-10% percent.**
- **Detection of 1-10% difference will require very high-quality data.**
- **The HAPS logging tool response for neutron capture cross-section (Σ) is expected to perform well based on modeling by Schlumberger.**
- **Simulations and sensitivity studies of CO_2 push-pull in systems based on Desert Peak and Dixie Valley show that pressure change in the fault is the most valuable field measurement for characterization because it is sensitive to gouge properties.**

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- Publications arising from this project:

Borgia, A., Oldenburg C.M., Zhang R., Pan L., Finsterle S., Ramakrishnan T.S., 2015. **Simulations of CO_2 push-pull in fractures to enhance geophysical contrast for characterizing EGS sites**. PROCEEDINGS, TOUGH Symposium 2015, Lawrence Berkeley National Laboratory, Berkeley, California, September 28-30, p. 109-115.

Borgia, A., Oldenburg C.M., Zhang R., Jung Y., Lee K.J., Doughty C., Daley T.M., Altundas B., Chugunov N., Ramakrishnan T.S., 2017a. **Simulations of Carbon Dioxide Injection, Seismic Monitoring, and Well Logging for Enhanced Characterization of Faults in Geothermal Systems**. PROCEEDINGS, 42nd Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California, February 13-15, SGP-TR-212.

Borgia, A., Oldenburg C.M., Zhang R., Pan L., Daley T.M., Finsterle S., Ramakrishnan T.S., 2017b. **Simulation of CO_2 injection into fractures and faults for improving their geophysical characterization at EGS Sites**. Geothermics, , v. 69, p. 189-201, http://dx.doi.org/10.1016/j.geothermics.2017.05.002.

Jung, Yoojin, Christine Doughty, Andrea Borgia, Kyung Jae Lee, Curtis M. Oldenburg, Lehua Pan, Thomas M. Daley, Rui Zhang, Bilgin Altundas, Nikita Chugunov, T.S. Ramakrishnan, **Pressure transient analysis during CO2 push-pull tests into faults for EGS characterization**, in prep.

Lee, Kyung Jae, Curtis M. Oldenburg, Christine Doughty, Yoojin Jung, Andrea Borgia, Lehua Pan, Rui Zhang, Thomas M. Daley, Bilgin Altundas, and Nikita Chugunov, **Simulations of Carbon Dioxide Push-Pull into a Conjugate Fault System Modeled after Dixie Valley—Sensitivity Analysis of Significant Parameters and Uncertainty Prediction by Data-Worth Analysis**, *Geothermics*, in review.

Oldenburg, C.M., Daley, T.M., Borgia, A., Zhang, R., Doughty, C., Ramakrishnan, T.S., Altundas, B., Chugunov, N., 2016. **Preliminary Simulations of Carbon Dioxide Injection and Geophysical Monitoring to Improve Imaging and Characterization of Faults and Fractures at EGS Sites**. PROCEEDINGS, 41st Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, February 22-24, 2016, SGP-TR-209.

Zhang, Rui, Andrea Borgia, Thomas M Daley, Curtis M. Oldenburg, Yoojin Jung, Kyung Jae Lee, Tieyuan Zhu, Christine Doughty, Bilgin Altundas, Nikita Chugunov, T.S. Ramakrishnan, **Time-lapse multi-scale seismic modeling of injected CO_2 in a fault zone for enhanced characterization of permeable flow paths in geothermal systems**, in prep.

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