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Eric Matzel [3]
Robert J. Mellors [3]
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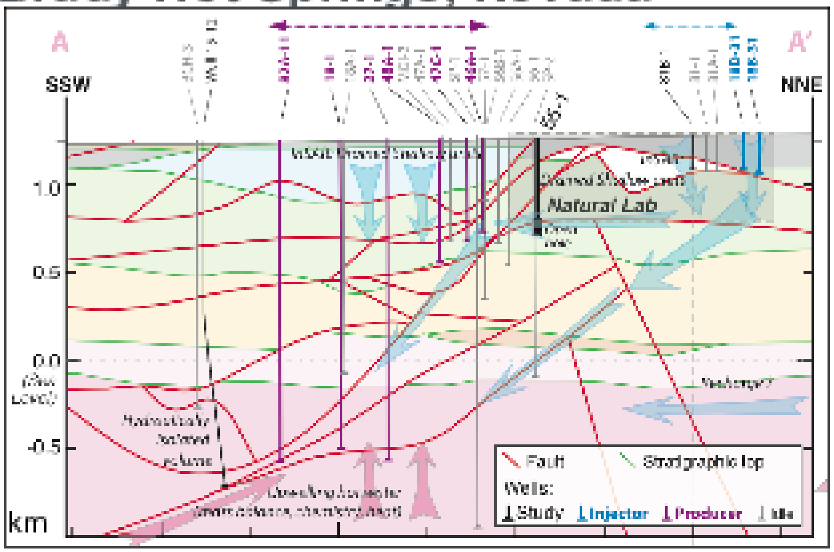
Michael Mondanos [6]
Christina Morency [3]
Jeremy Patterson [1]
Peter E. Sobol [1]
Paul Spielman [4]
Clifford Thurber [1]
W. Trainor-Guitton [3]
Herbert F. Wang [1]
Xiangfang Zeng [1]

Brady Hot Springs, Nevada



1. U. Wisconsin-Madison **(prime)**
2. Berkeley N.L.
3. Livermore N.L.
4. Ormat Technologies, Inc.
5. U. Nevada-Reno
6. Silixa Ltd.
7. Temple U.

Poroelastic Tomography by Adjoint Inverse Modeling of Data from Seismology, Geodesy, and Hydrology

inverse modeling:

- **adjoint**
- **Bayesian**

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

PoroTomo

Project Officer: Bill Vandermeer

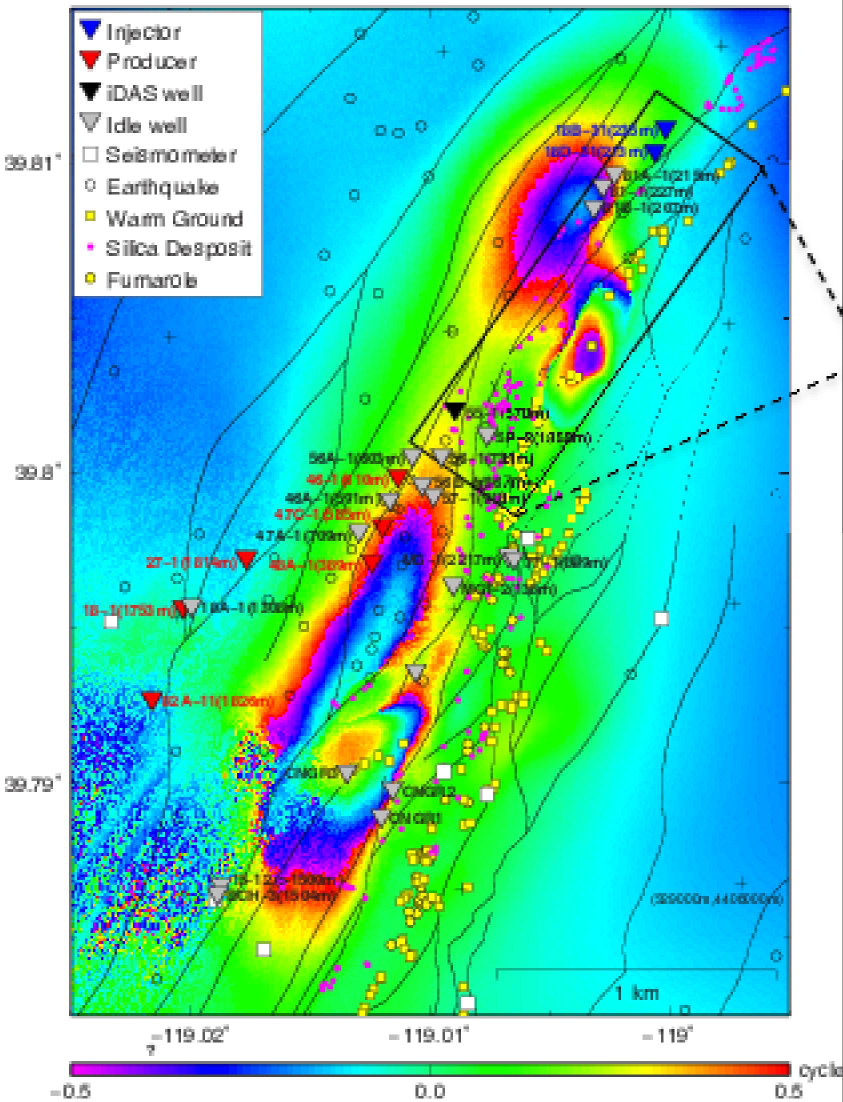
Total Project Funding: $2,319,973 (Govt. Share to UW)

November 13-15 2017

Kurt Feigl
University of Wisconsin

Track 4 EGS2

Brady Hot Springs, Nevada



Dec 24 2011 – Oct 27 2012; 1 cycle = 16 mm

Objective: assess an integrative technology to:

- characterize spatial distribution
- monitor temporal changes
- rock-mechanical properties of EGS reservoir
- in 3 dimensions
- spatial resolution better than 50 meters
- study volume: 1500 × 500 × 400 meters

Infer critically important parameters:

- ✓ Young's modulus
- ✓ Poisson's ratio
- ✓ density
- saturation
- porosity

Outcomes:

- ✓ Phase I: Proof of concept (existing data)
- ✓ Phase II: small-scale prototype (at Brady)

Impact:

technical specifications for full-scale deployment

Feigl, Cardiff, Fratta, Thurber, Wang University of Wisconsin-Madison

Methods/Approach

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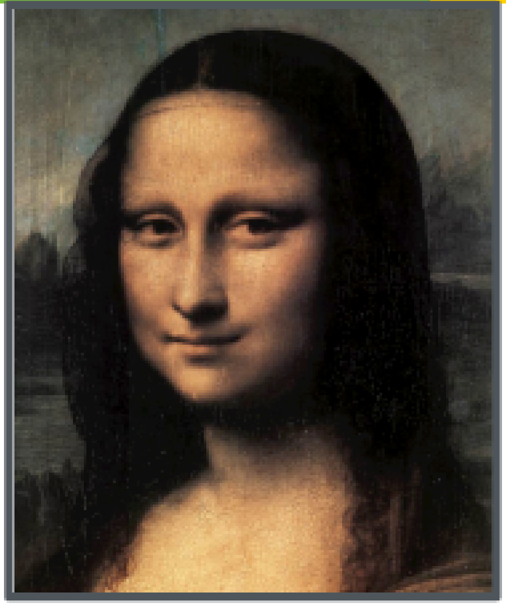
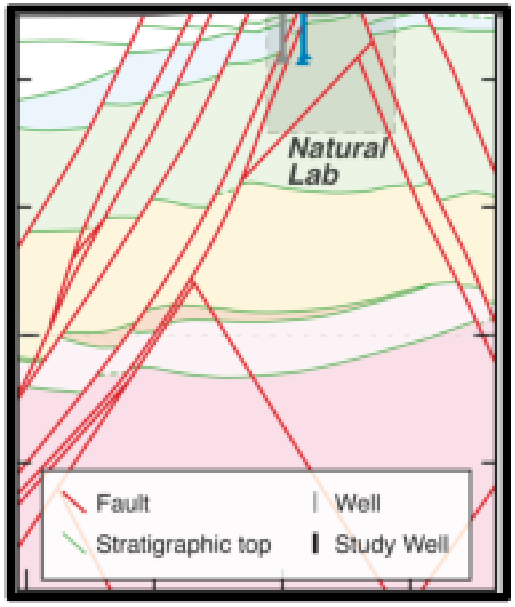




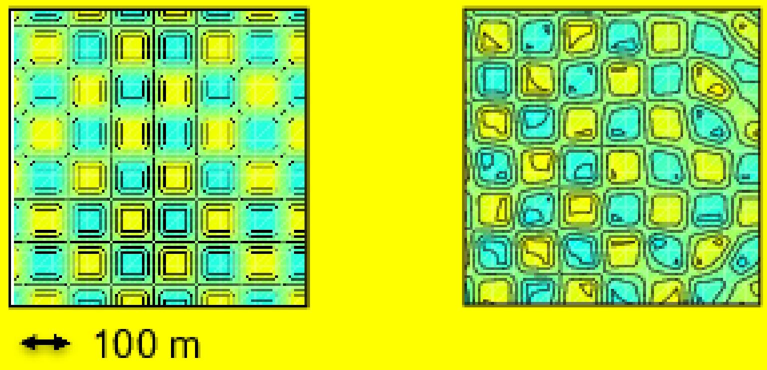
Adjoint tomography recovers rock-mechanical properties.

Technology Performance Metric:

resolution in meters

of a feature in the modeled 3-D distribution of a rock mechanical property as determined by the dimension of a visible checkerboard pattern at 200 m depth in a test using simulated data

Input ("true") | output ("recovered")



estimating more parameters

→ finer resolution

Feigl, Cardiff, Fratta, Thurber, Wang University of Wisconsin-Madison

Technical Accomplishments and Progress

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Milestone Summary Table

milestones (Mst.)
quarters (Q)
months (M)
from 2014/10/01

Number	Task Title, Milestone Description, or Go/No-Go Decision Criteria	Start (planned)	End (planned	End (extended)	Completion Month	Completion Quarter
1.0	**Coordination**	**1**	**36**	**51**		
Phase I	***Year 1 = FY '15***					
2.0	**Kickoff Meeting**	**1**	**1**	**1**	Oct. 2014	
	DOE Peer Review - score 8.4/10.0; ranked 3rd of 12 EGS projects				May 2015	
3.0	**Analysis of Existing Data**	**1**	**9**	**9**		
Mst. 3.1	Submit Metadata for existing data sets to NGDC				Dec. 2014	Q1
Mst. 3.2	Submit existing data sets to NGDC in unprocessed format				March 2015	Q2
Mst. 3.3	Submit existing data sets to NGDC in analyzed format				June 2015	Q3
4.0	**Design Deployment at Brady**	**6**	**12**	**12**		
Mst. 4.1	Uncertainty analysis				Sept. 2015	Q4
5.0	**Stage Gate Review #1**	**12**	**12**	**12**	Sept. 2015	
Go/No-Go #1	Resolution will meet minimum requirement for each of 3 data sets					Q4
Phase II	***Year 2 = FY '16***					
6.0	**Deploy Integrated Technology in Brady Natural Laboratory**	**13**	**24**	**24**		
Mst. 6.1	Plan (personnel, calendar dates, equipment list) for deployment drafted				Dec. 2015	Q5
Mst. 6.2	Plan for deployment confirmed				March 2016	Q6
Mst. 6.3	Submit metadata for deployment data sets to NGDC				June 2016	Q7
Mst. 6.4	Submit data for deployment data sets to NGDC in unprocessed format				Sept. 2016	Q8
7.0	**Stage Gate Review #2**	**24**	**24**	**24**	Aug. 2016	
Go/No-Go #2	Data were successfully collected according to plan					Q8
Phase II (cont'd)	***Years 3 and 4***					
8.0	**Analyze Data Collected During Deployment**	**25**	**30**	**48**		
Mst. 8.1	Preliminary data analysis completed				March 2017	Q10
	DOE Peer Review				Nov. 2017	
Mst. 8.2	Final data analysis complete				June 2018	Q15
9.0	**Inverse Modeling**	**36**	**36**	**48**		
Mst. 9.1	Preliminary inverse modeling				June 2018	Q15
Mst. 9.2	Final inverse modeling				Sept. 2018	Q16
10.0	**Final Review - at GRC meeting**	**36**	**36**	**51**	Oct. 2018	Q17
Mst. 10.1	Final report				Dec. 2018	Q17

*In March 2017, we were granted a no-cost extension of 15 months for our PoroTomo project to extend the performance period to **December 31st, 2018.**

Feigl, Cardiff, Fratta, Thurber, Wang University of Wisconsin-Madison

Research Collaboration & Technology Transfer

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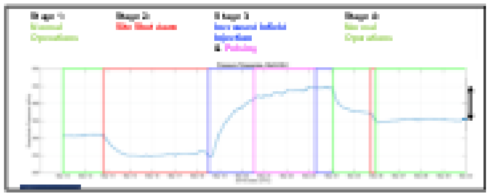
- PoroTomo Team includes 7 organizations:
  - 3 Universities:
    - University of Wisconsin-Madison hhttp://geoscience.wisc.edu/feigl/porotomo/
    - University of Nevada Reno
    - Temple Temple University
  - 2 Federally Funded Research Centers:
    - Lawrence Livermore National Laboratory (LLNL)
    - Lawrence Berkeley National Laboratory (Berkeley Lab)
  - 2 Industry Companies:
    - Silixa Ltd., experts in distributed sensing https://silixa.com/
    - Ormat Technologies, renewable energy expertise http://www.ormat.com/
- Transferring Technology:
  - Ormat is applying InSAR to other sites in California and Nevada
  - Both FORGE sites (Fallon NV and Milford UT) will apply InSAR
  - Silixa is applying techniques of DAS &DTS data analysis
    - other geophysical applications (e.g., CO2 sequestration)
  - InSAR data analysis is being applied at Raft River Idaho
    - Ali et al. (Stanford Geothermal Workshop 2016; submitted to *Geothermics*, 2017)

Deployment - March 2016

45 people
1500 × 500 × 400 meters
15 days in 4 stages:

1. Normal Operations
2. Shutdown
3. Re-inject all
4. Normal Operations



Active source (vibroseis):

at 240 locations
x (4 stages)
x (3 sweeps) x (P, S_T, S_L)

DAS + DTS in fiber optic cable:

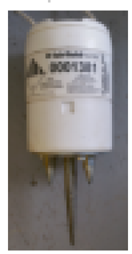
400 m in vertical borehole
9000 m in horizontal trench

246 seismometers:

240 Fairfield Nodal Zland 3-component sensors generously contributed by: Fan-Chi Lin (U. Utah), Amanda Thomas (U. Oregon), Marianne Karplus (U. Texas-El Paso)
plus 6 Reftek 3-component sensors from PASSCAL facility

5 borehole sensors:

Pressure
Temperature

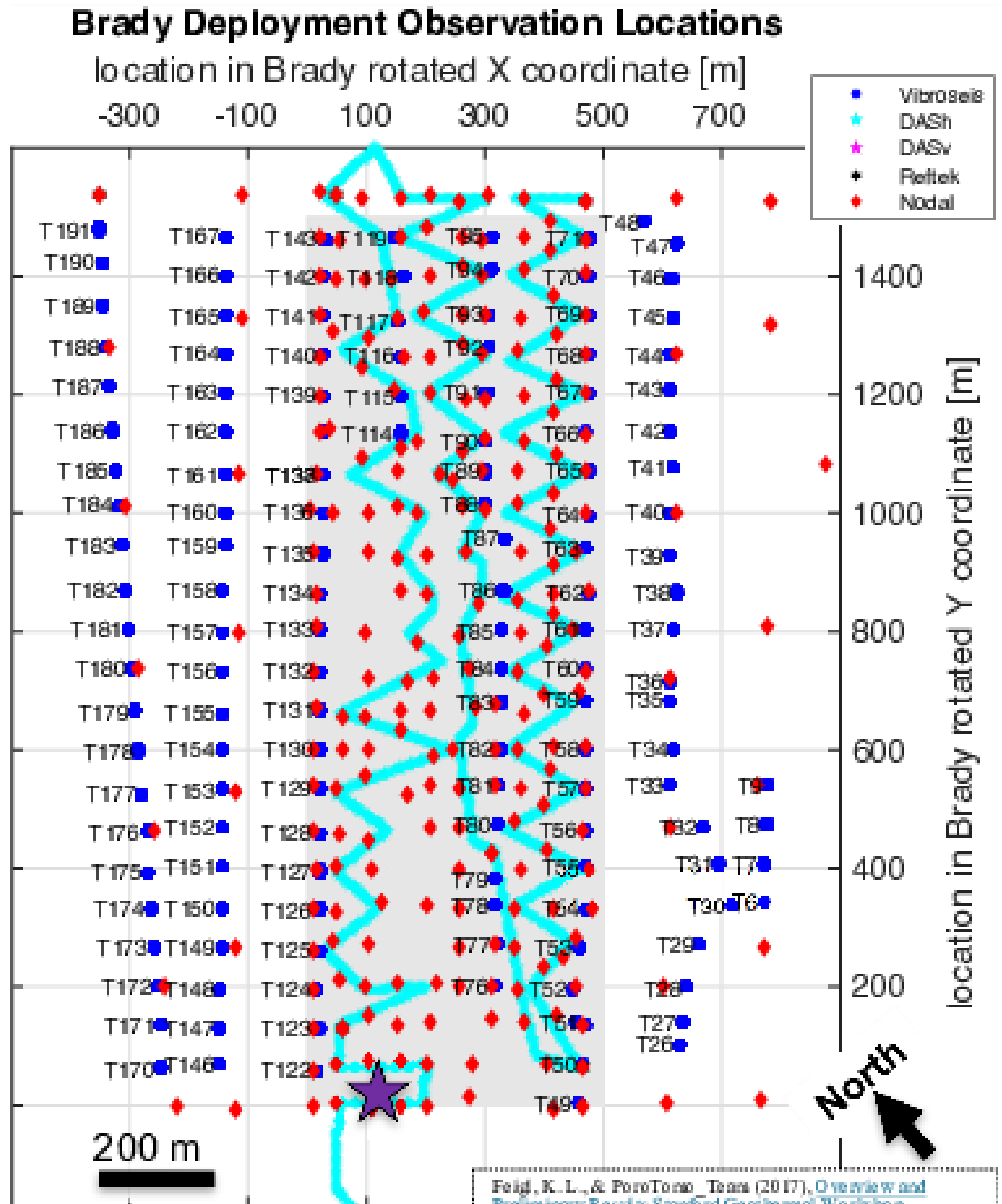


51 Terabytes of data:

ftp://roftp.ssec.wisc.edu/porotomo/

61 submissions to GDR:

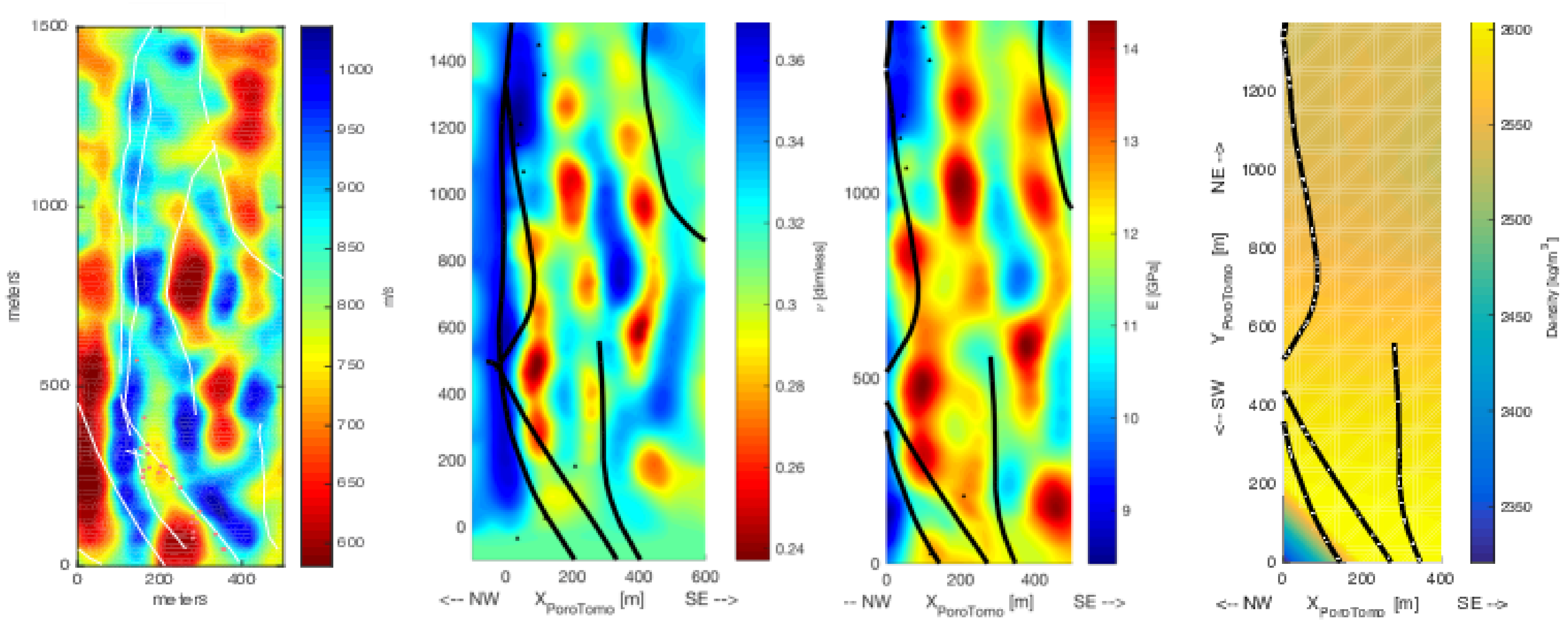
https://gdr.openei.org/



Feigl, K. L., & PoroTomo_Team (2017), Overview and Preliminary Results Stanford Geothermal Workshop.

Material properties from seismic tomography

Vs at 50 m depth [m/s] | **Poisson's ratio at 225 m depth** | **Young's modulus at 225 m depth [GPa]** | **density at 225 m depth [kg/m^3]**



Sweep interferometry using geophone recording of active seismic source:
Matzel, et al. (2017) https://pangea.stanford.edu/ERE/db/GeoConf/papers/SGW/2017/Matzel.pdf
Faults gridded from Jolie et al. 2015. https://doi.org/10.1016/j.geothermics.2014.10.003
Density from Witter et al. (2016) http://dx.doi.org/10.1186/s40517-016-0056-6

Subtask 8.3: Ambient noise tomography (Matzel, Thurber, Zeng, Peng, Morency)

Accomplishments, Results and Progress

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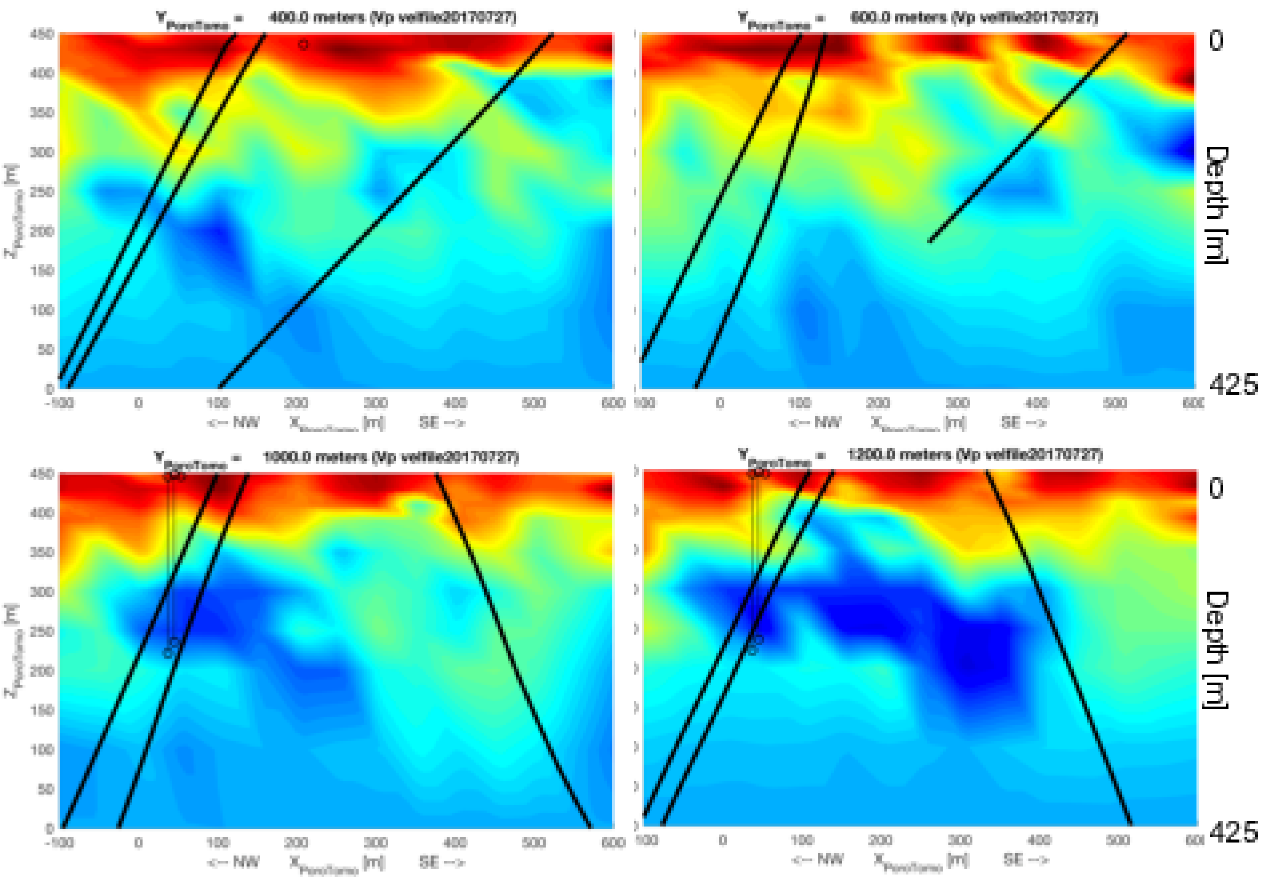
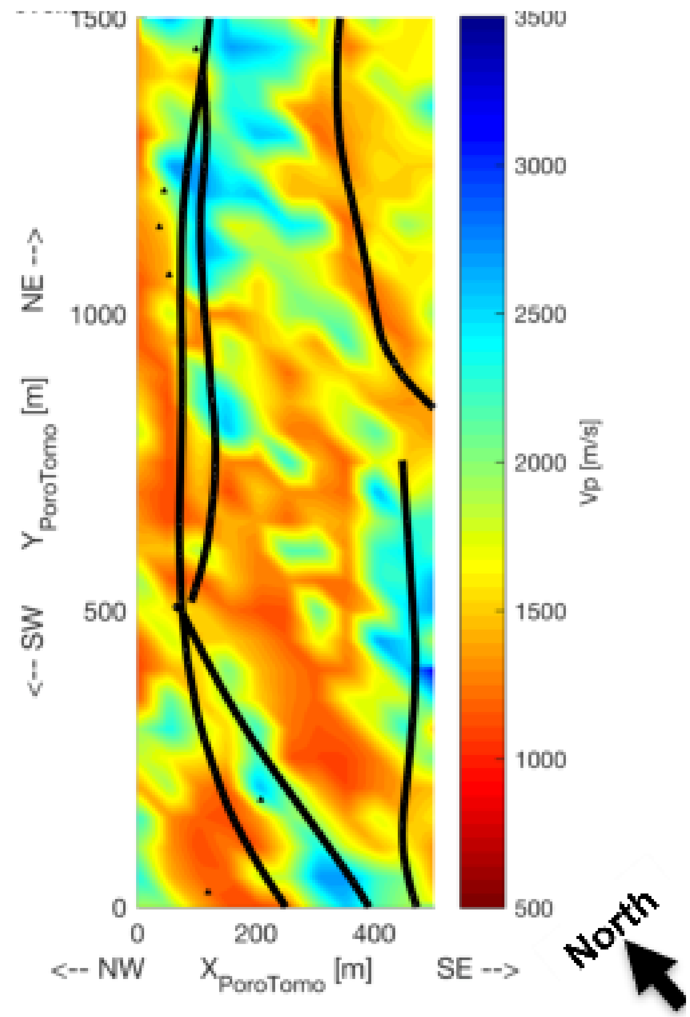
P-wave velocity from body-wave tomography

Vertical cross sections across strike



Horizontal slice at 35 m depth

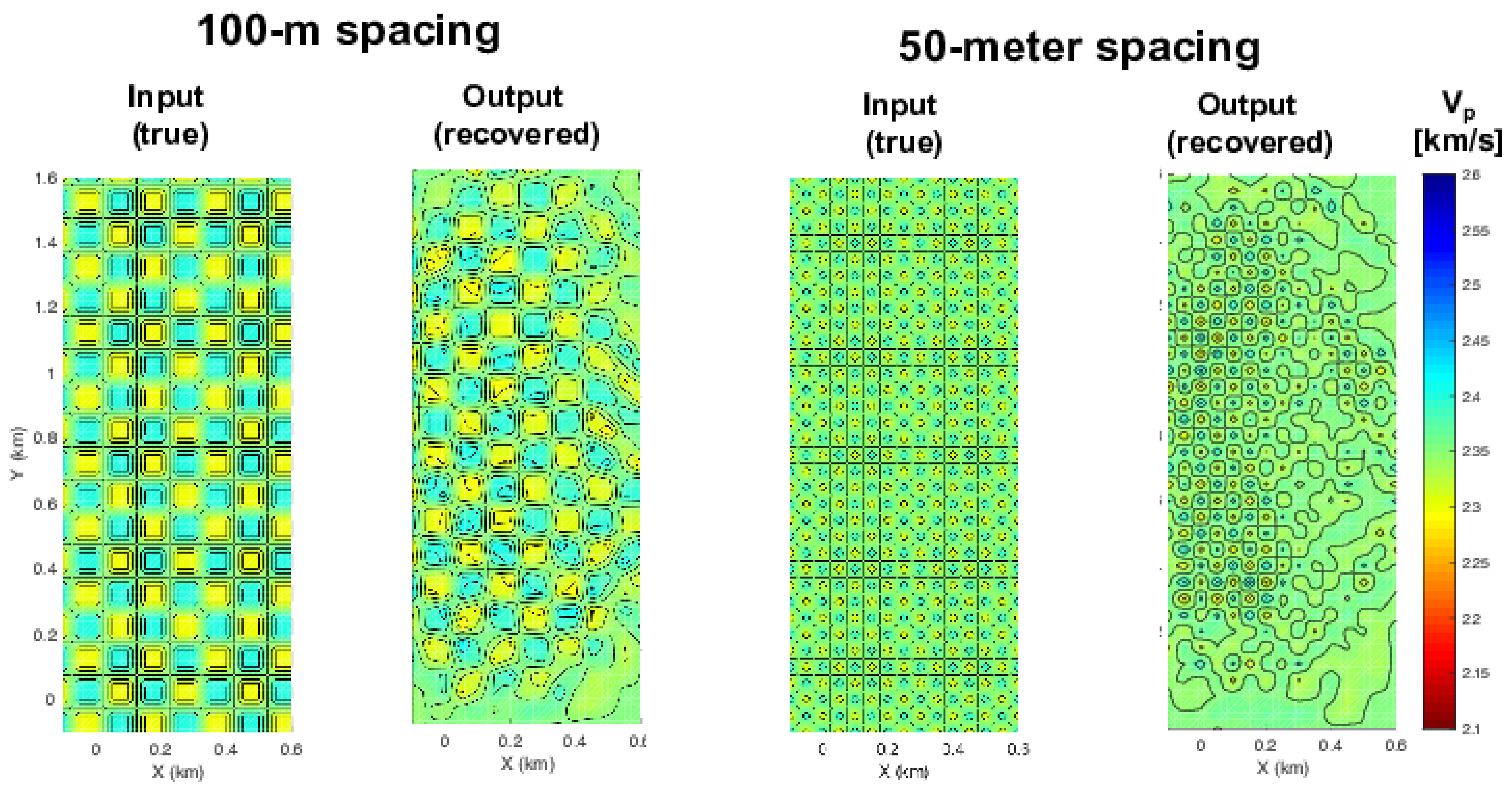


Parker, L. (2017), *Active Source 3D Seismic Tomography of Brady Hot Springs Geothermal Field, Nevada*, M.S. thesis, University of Wisconsin-Madison.

Faults gridded from Jolie, Moeck, & Faulds (2015)
https://doi.org/10.1016/j.geothermics.2014.10.003

Subtask 8.2 Seismic travel time (Thurber, Parker, Fratta, Li, Ak, Zeng, Wang, Silixa)

Checkerboard tests of resolution of P-wave velocity at 200 m depth



Minimum requirement is met. Target requirement is feasible.

Subtask 8.2: Seismic tomography

Accomplishments, Results and Progress

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Shear-wave velocity in shallow layers

Multichannel analysis surface waves (MASW)
Noise Correlation Functions (NCF)
Distributed Acoustic Sensing (DAS)

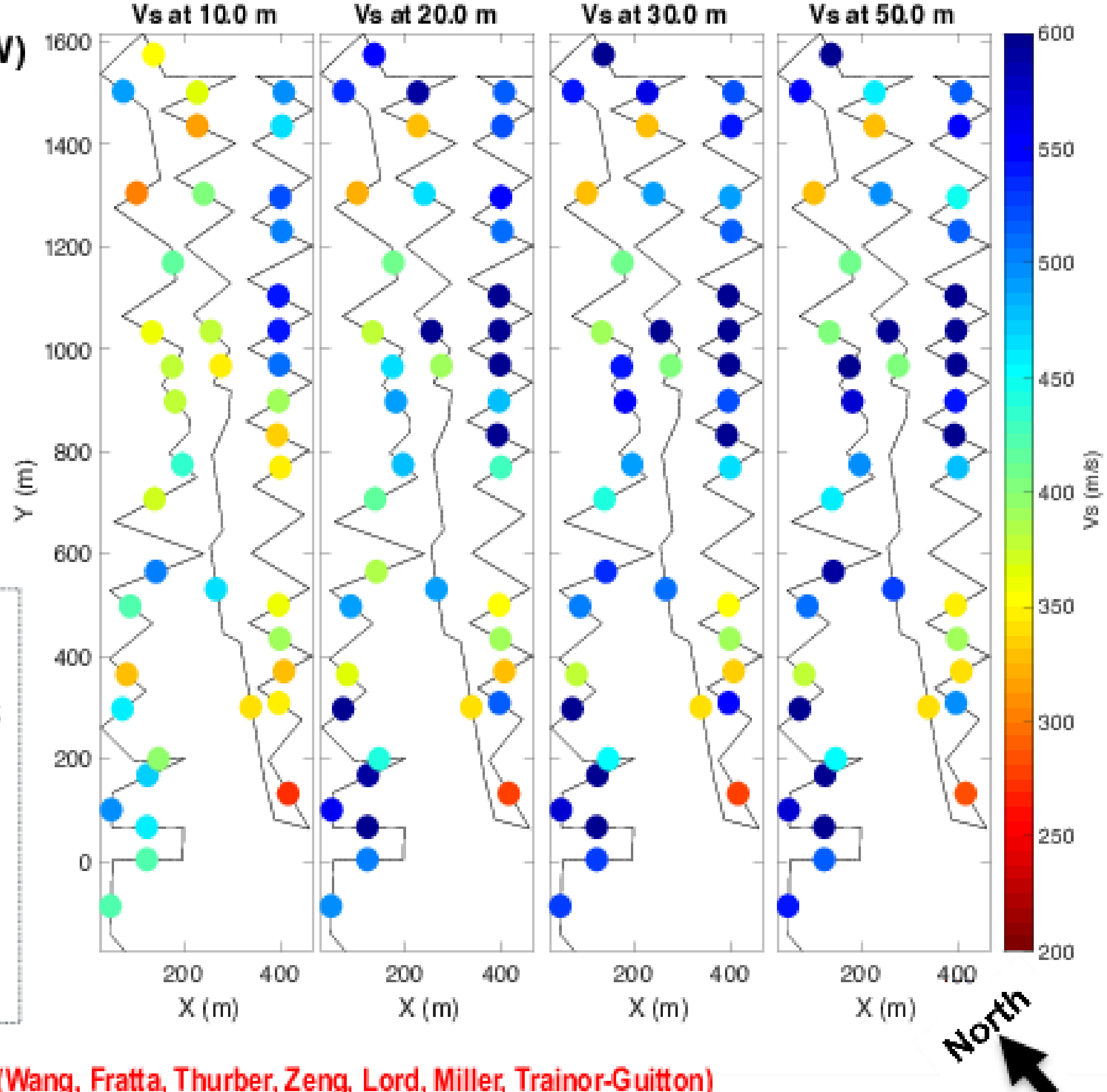
Local variations in:

- **shear velocity**
- **thickness**

Zeng, X., C. Thurber, H. Wang, D. Fratta, E. Matzel, and PoroTomo_Team (2017), High-resolution Shallow Structure Revealed with Ambient Noise Tomography on a Dense Array (#SGP-TR-212), in Proceedings, 42nd Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California. https://pangea.stanford.edu/ERE/db/GeoConf/papers/SGW/2017/Zeng.pdf

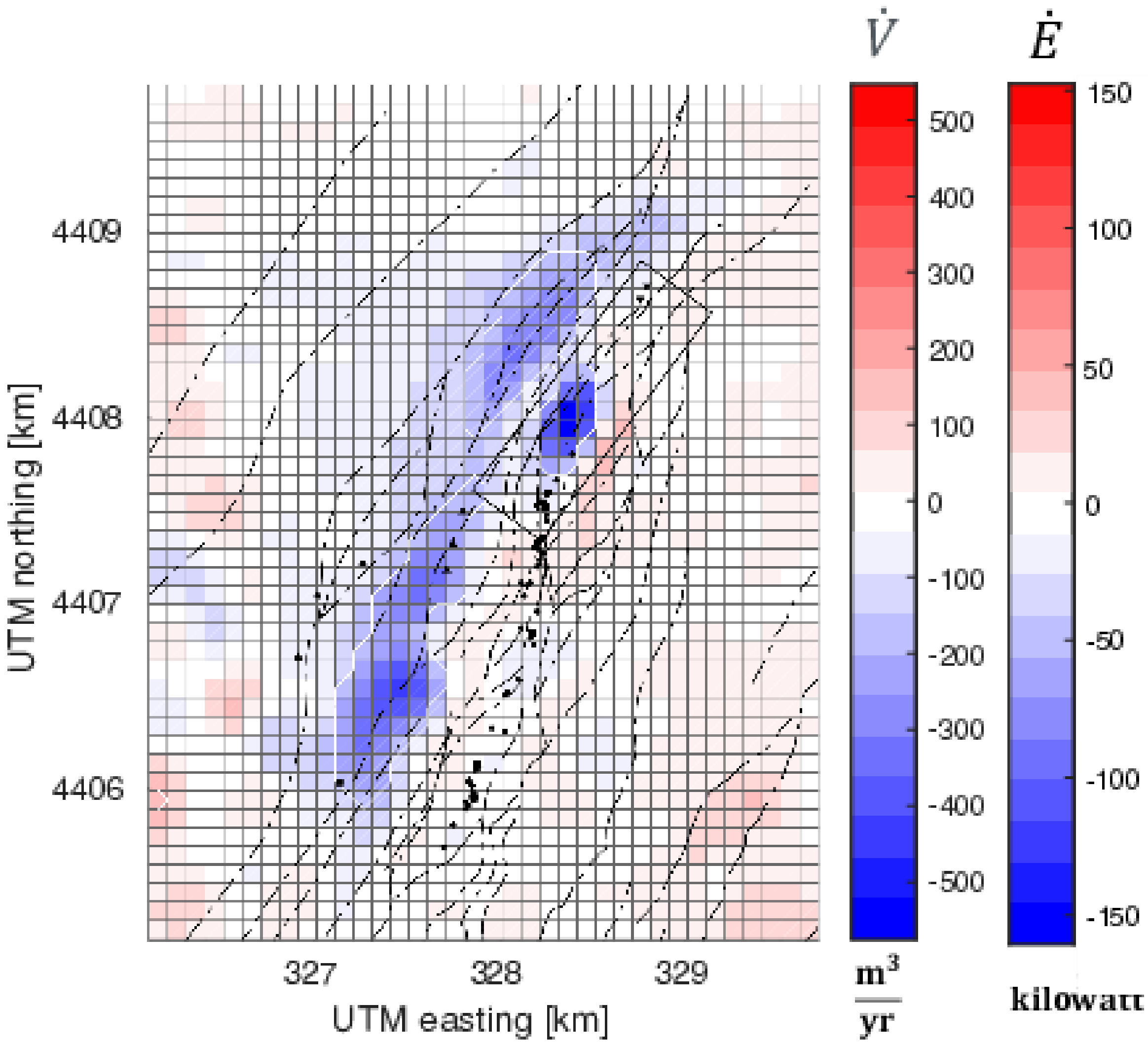
Wang, H., X. Zeng, D. Miller, D. Fratta, N. Lord, C. Lancelle, K. Feigl, C. Thurber, L. Parker, A. Chalari, and PoroTomo Ground Motion Response to a ML 4.3 Earthquake Using Co- Located Distributed Acoustic Sensing and Seismometer Arrays, submitted 2017/10/03 to *Geophys J Int.*

Map views at depth:



Subtask 8.1: Analyze DAS data collected during deployment (Wang, Fratta, Thurber, Zeng, Lord, Miller, Trainor-Guitton)

Inverse modeling of InSAR data spanning 2016-July-22 to 2017-August-22



(Reinisch, Cardiff, and Feigl, in prep.)

Deformation field shows subsidence
Dislocation model for decreasing volume

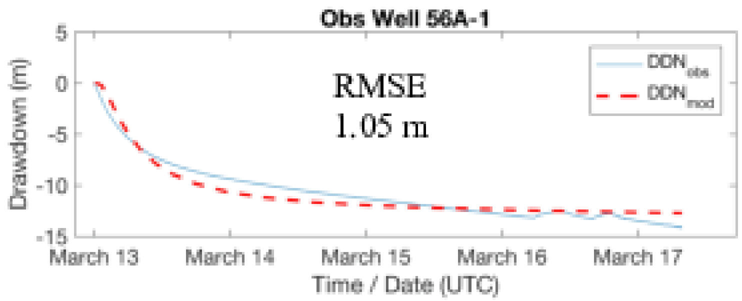
Driving mechanism:
Reject: decreasing pore fluid pressure
Favor: thermal contraction

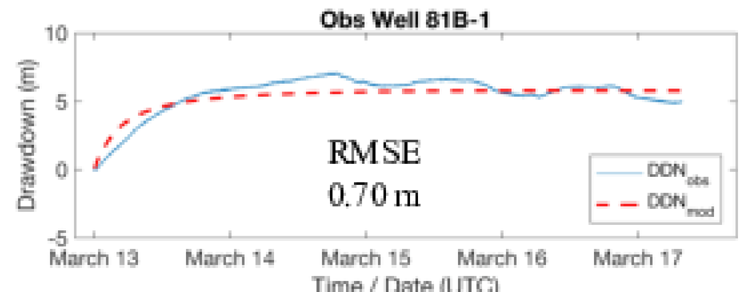
Thermal power $\dot{E}_{total}$:
89 to 132 Megawatt

Checkboard test for 100 m resolution
No significant difference between true values of model parameters and recovered parameters with 99% confidence

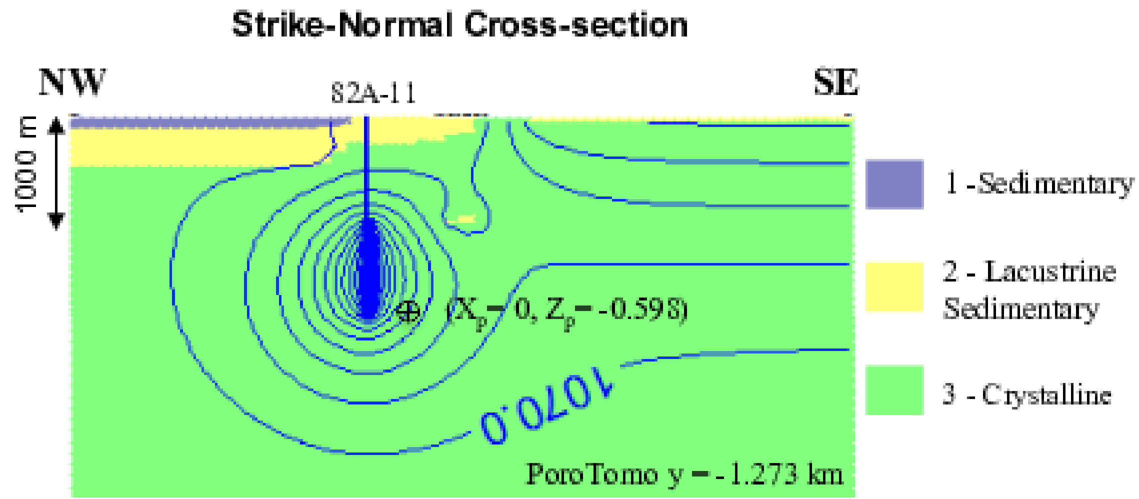
Subtask 8.3: InSAR (Reinisch, Feigl)

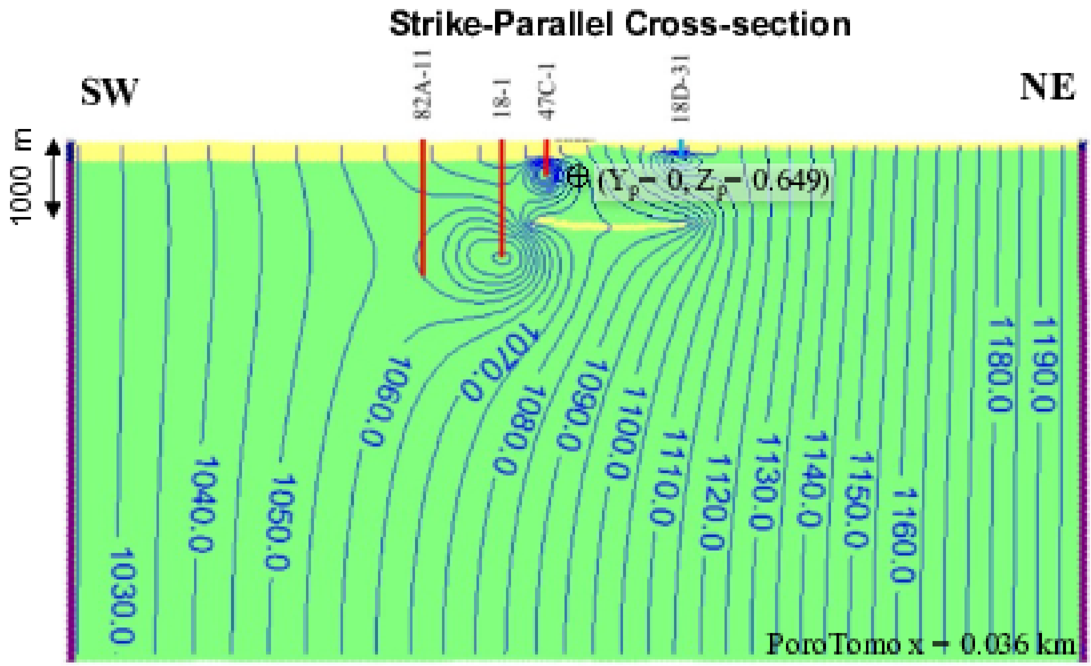
Pressure Data:
Analysis for Flow Properties





Rock type	Hydraulic conductivity K_{eff} (m/min)	Specific storage S_s (m^{-1})
1 - Sedimentary	1.4×10^{-2}	2.2×10^{-8}
2 - Lacustrine Sed.	3.8×10^{-2}	1.3×10^{-6}
3 - Crystalline	7.2×10^{-7}	1.1×10^{-6}

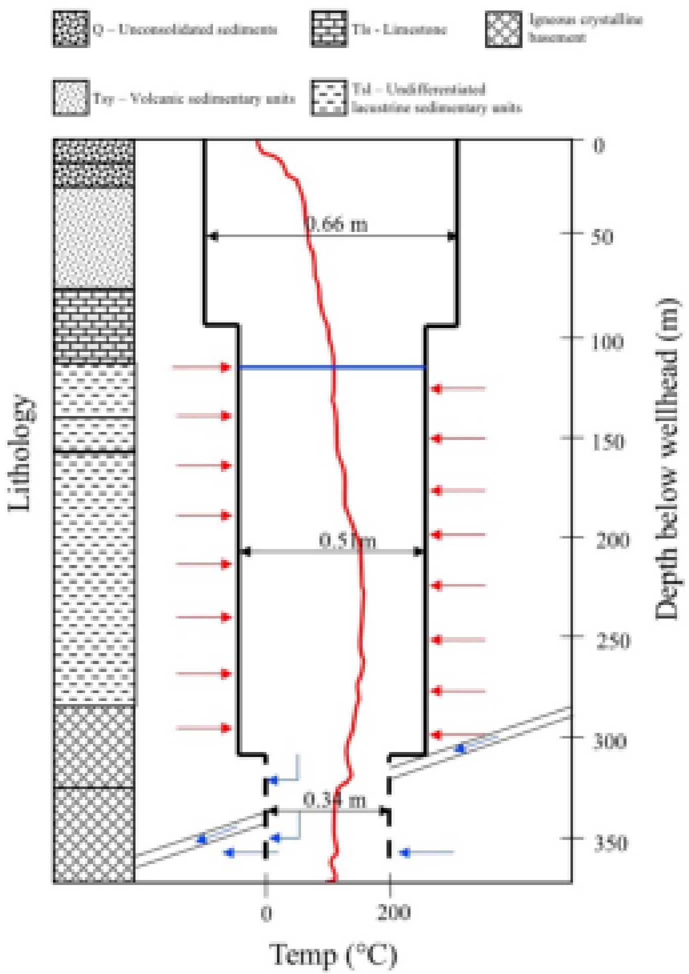




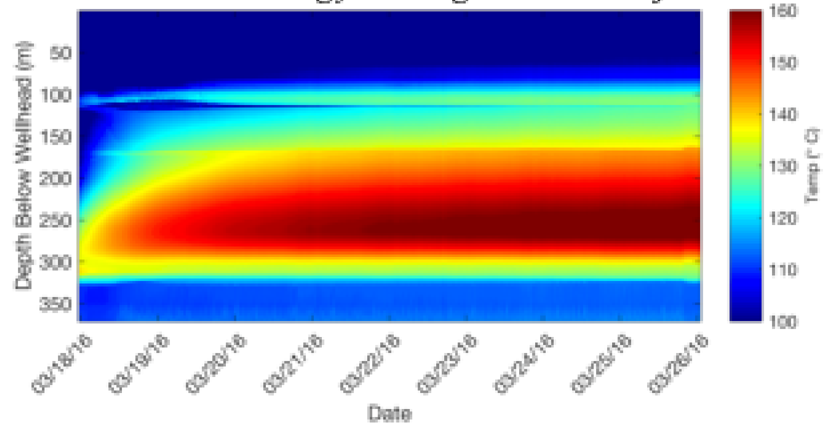
Subtask 8.8 Pressure Data (Patterson, Cardiff, Lim)

Distributed Temperature Sensing (DTS) Data: Analysis for Thermal Properties

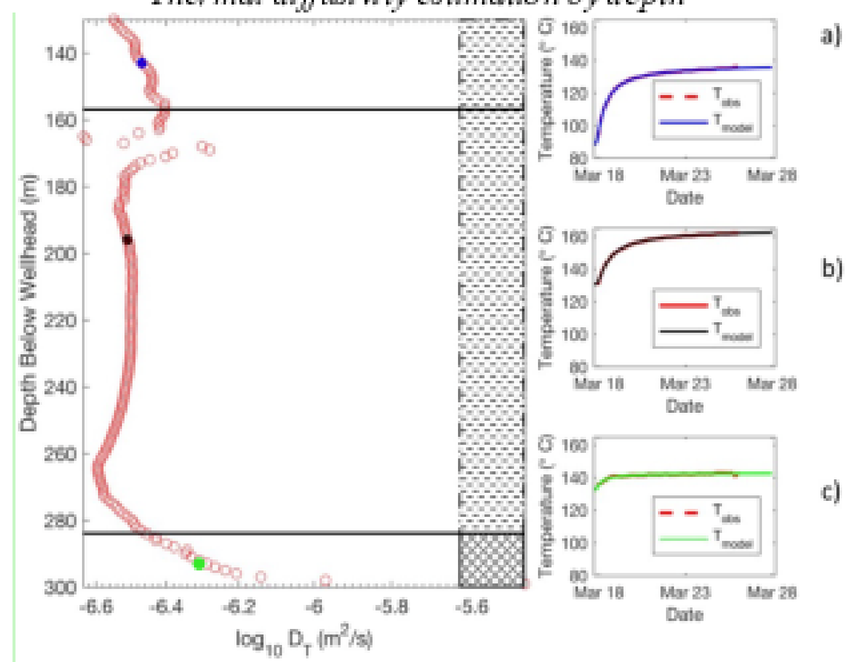
Well 56-1 Schematic and temperature profile



Borehole warming following cold water injection



Thermal diffusivity estimation by depth



Patterson et al. (2017-in review) "Geothermal reservoir characterization using Distributed Temperature Sensing at Brady Geothermal Field, Nevada", The Leading Edge

Subtask 8.7: Analysis of DTS data (Patterson, Cardiff, Coleman, Wang)

We have submitted 61 data sets to the GDR.

All of the data are publically available at on a file server at UW-Madison: ftp://roftp.ssec.wisc.edu/.

The complete data set includes more than 50 Terabytes in volume.

Several of the data sets are larger than the storage capacity of the GDR.

They are only available on the UW server.

This service will continue until the end of 2018 or the failure of the disk drives on the server, whichever comes first.

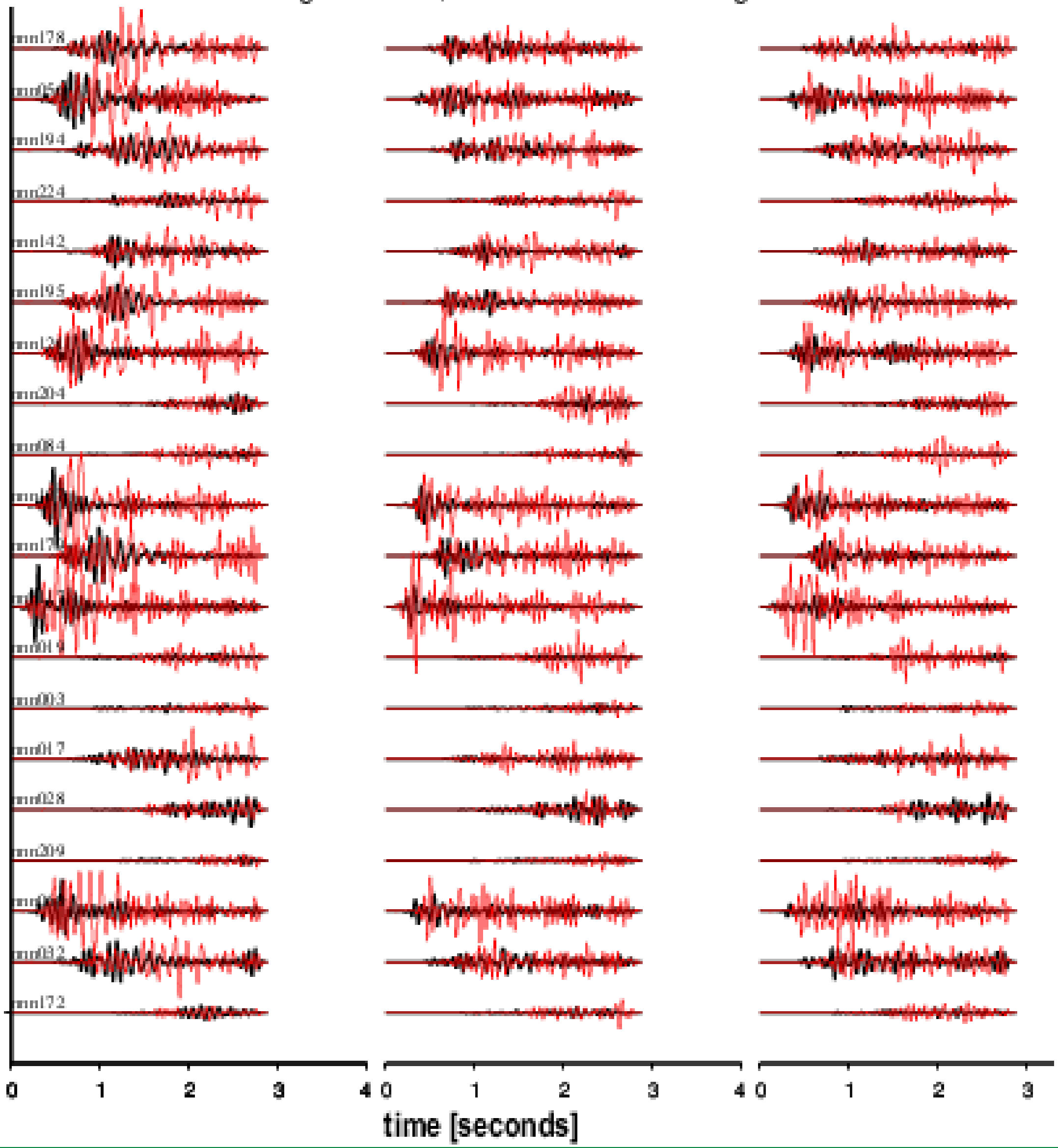
Data Stream	Deployment Subtask	Analysis Subtask	URL	Quantity metric	Quality metric (criterion)	Volume (raw) in Terabytes (TB)	metadata submitted to GDR (June 2016)	raw data submitted to GDR (Sept. 2016)	analyzed data submitted to GDR (Sept. 2017)
Geology	6.9	8.9	https://gdr.openei.org/			0.001			
Production	6.8	8.8	https://gdr.openei.org/		TBD	0.001			
Pressure and Temperature	6.7		https://gdr.openei.org/		stddev(noise) ~ 10 kPa	0.001			
INSAR (56 mm wavelength)	6.5	8.5	https://scihub.copernicus.eu/		GPS-InSAR < 5 mm			ESA	roftp
INSAR (32 mm wavelength)	6.5	8.5	https://winsar.unavco.org/		GPS-InSAR < 5 mm			WINSAR	roftp
GPS	6.6	8.6	ftp://data-out.unavco.org/pub/rinex/obs		GPS-InSAR < 5 mm				
Vibroseis	6.4		https://gdr.openei.org/		four criteria	0.012			
Nodal Seismometers	6.3	8.2	https://gdr.openei.org/		SNR ≥ 2	2.138		roftp	roftp
DAS - horizontal in trench	6.2	8.1, 8.2	ftp://roftp.ssec.wisc.edu/porotomo/		SNR ≥ 2	45.843		subset	roftp
DAS - vertical in borehole	6.2	8.1, 8.2	ftp://roftp.ssec.wisc.edu/porotomo/		SNR ≥ 2	1.053		subset	roftp
DTS - vertical in borehole	6.2	8.7	ftp://roftp.ssec.wisc.edu/porotomo/		paired T diff < 1 deg C	0.011		roftp	roftp
*DTS - horizontal in trench	6.2	8.7	ftp://roftp.ssec.wisc.edu/porotomo/		paired T diff < 1 deg C	0.005		roftp	roftp
**permaseis*	LBNL	8.2	http://www.ncedc.org/		TBD			NCEDC	
**UAV*	UNR		http://ctemps.org/						
** value added by partnerships*									
Legend			As planned						
			In progress						
			Quantity less than planned						

- Body-wave seismic tomography achieved target resolution of 50 meters of P-wave velocity at 200 m depth for much of the natural lab using P-wave arrival times picked from DAS and geophones.
- Seismic sweep interferometry using data recorded by geophones during active source sweeps estimated a 3-dimensional model of Vs, Vp, Q, and Poisson's ratio with a resolution of the order of ~100 m at a depth of 200 m.
- Deploying DAS effectively doubled the number of seismic sensors, provided DTS capability simultaneously, and proved the integrated technology for seismic characterization of a reservoir.
- Shear-wave velocities estimated from surface wave dispersion curves based on Noise Correlation Functions (NCF) from DAS data show horizontal variations with resolution ~100 m and vertical variations with resolution of ~ 10 m at depths less than 50 m.
- InSAR data spanning 2004-2017 at Brady have been analyzed to estimate the rate of volume decrease to be $(29 \pm 1) \times 10^3$ m^3/yr in a dislocation model of multiple cubic sinks buried in an half space with uniform elastic properties.
- GPS data at 3 stations BRDY, BRAD and BRD1 from 2016 through 2017 have been collected, archived, distributed, and analyzed to yield time series of daily estimates of relative, 3-dimensional position.
- Structured parameter estimation on pump testing data estimates hydraulic conductivity and storage coefficient with a spatial resolution comparable to the 500-meter distance between sensors.
- The Temperature Sensing (DTS) data set has been analyzed to characterize heat flow within the reservoir during production and injection with a vertical resolution of the order of 0.1 meter.
- An initial model of rock mechanical properties incorporates geologic information.
- Bayesian, adjoint tomography will recover rock-mechanical properties with fine resolution.
- Data on pressure, temperature, production, and injection at Brady for the time interval 2004-2014 are being analyzed to test three competing hypothesized models to explain the deformation field observed by geodetic data:
  - **Hypothesis 1: Injecting cooled water causes thermal contraction** ***[FAVORED]***
  - Hypothesis 2: Changes in pressure and saturation causes poroelastic compaction ***[rejected]***
  - Hypothesis 3: Dissolution in water flowing through fractures removes minerals from rock ***[rejected]***

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

Future Directions

Comparison of **Z, X, Y** components of synthetic waveforms at 20 seismometers.
Black waveforms: using 3D model; Red waveforms – using 1D model.



(Bayesian) adjoint seismic tomography
Recover rock-mechanical properties

- **Finer spatial resolution**
- **Detecting temporal changes**

Forward wavefield: $\rho\partial_t^2\mathbf{s} = \nabla\cdot\mathbf{T} + \mathbf{f}$

Adjoint wavefield: $\rho\partial_t^2\mathbf{s}^\dagger = \nabla\cdot\mathbf{T}^\dagger + \mathbf{f}^\dagger$

waveform adjoint source:

$$\mathbf{f}^\dagger(\mathbf{x}) = \sum_{r=1}^{N}[\mathbf{s}(\mathbf{x}_r, T-t) - \mathbf{d}(\mathbf{x}_r, T-t)]\delta(\mathbf{x}-\mathbf{x}_r)$$

- Interaction of both waveforms
- Fréchet derivatives in iterative inversion
- Refine frequency content of modeled signal

Subtask 9.1: Inverse modeling of seismic data (Morency, Thurber, Fratta, Zeng)

PoroTomo has achieved its goal in resolution:

seismology: 100 m

geodesy: 100 m

hydrology: 500 m

Technology performance metric is *resolution in meters* of a feature in the modeled 3-D distribution of a rock mechanical property (e.g., Poisson's ratio), as determined by the dimension of a visible checkerboard pattern at 200 m depth in a test using simulated data

	Resolution			
	Seismology	Geodesy	Hydrology	Combined
Current state of the art at Brady	200 m[(a)]	~500 m[(b)]	—	—
Minimum requirement: improve resolution to	100 m (Achieved)	500 m	500 m (Achieved)	200 m
Target: improve resolution to	50 m (Feasible)	250 m	250 m	50 m (Feasible)
Beyond ("over") target: improve resolution to	25 m	100 m (Achieved)	100 m	25 m

(a) Approximate resolution of seismic reflection survey (Queen et al., 2010, Lin et al., 2011).
(b) Inverse modeling of InSAR data elastic properties (Ali et al., 2014a)

Solid box: Achieved

Dotted box: Feasible

Thank you!

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Figure 1. PoroTomo team on a hill overlooking the natural laboratory, including (from left to right), Dante Fratta1, David Lim1, Neal Lord1, Kurt Feigl[1], Janice Lopeman[2], Joe Greer[3], Thomas Coleman[3], Mike Cardiff[1], Christina Morency[6], Michelle Robertson[7], John Akerly[2], Eric Matzel[6], Bill Foxall[7], Bret Pecorora[4], Chelsea Lancelle[1], Corné Kreemer[4], Martin Schoenball[5], Paul Spielman[2]. The PoroTomo team includes scientists and engineers from:(1) University of Wisconsin-Madison Department of Geoscience, (2) Ormat Technologies, Inc., (3) Silixa Ltd., (4) University of Nevada-Reno, (5) Temple University, (6) Lawrence Livermore National Laboratory, (7) Lawrence Berkeley National Laboratory [Photo by Dan Koetke using Neal Lord's camera 2014/10/16]