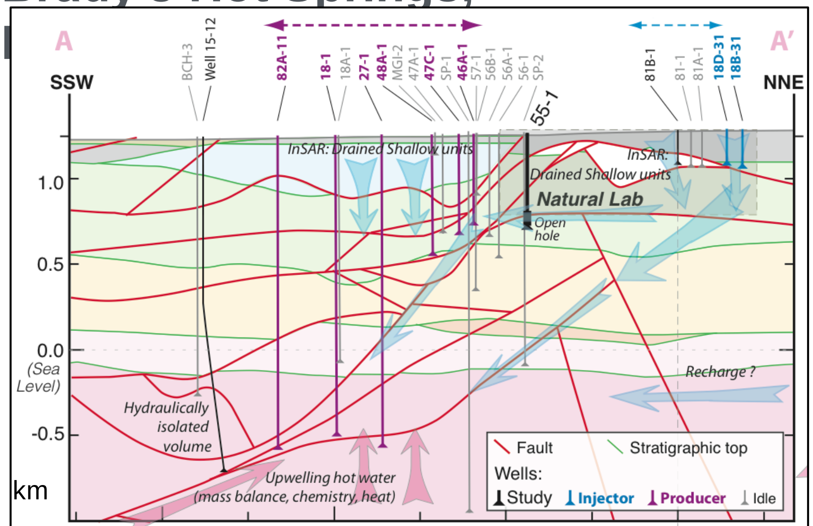
Kurt L. Feigl[1] **(PI)**
John Akerly [4]
S. Tabrez Ali [1]
Michael Cardiff [1]
Athena Chalari [6]
Thomas Coleman [6]
Nicholas C. Davatzes [7]
William Foxall [2]
Dante Fratta [1]
Joe Greer [6]
Corné Kreemer [5]
Neal E. Lord [1]
Janice Lopeman [4]
Eric Matzel [3]
Robert J. Mellors [3]
Michael Mondanos [6]
Christina Morency [3]
Peter E. Sobol [1]
Paul Spielman [4]
Clifford Thurber [1]
W. Trainor-Guitton [3]
Herbert F. Wang [1]
Xiangfang Zeng [1]

## Brady's Hot Springs,




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.**

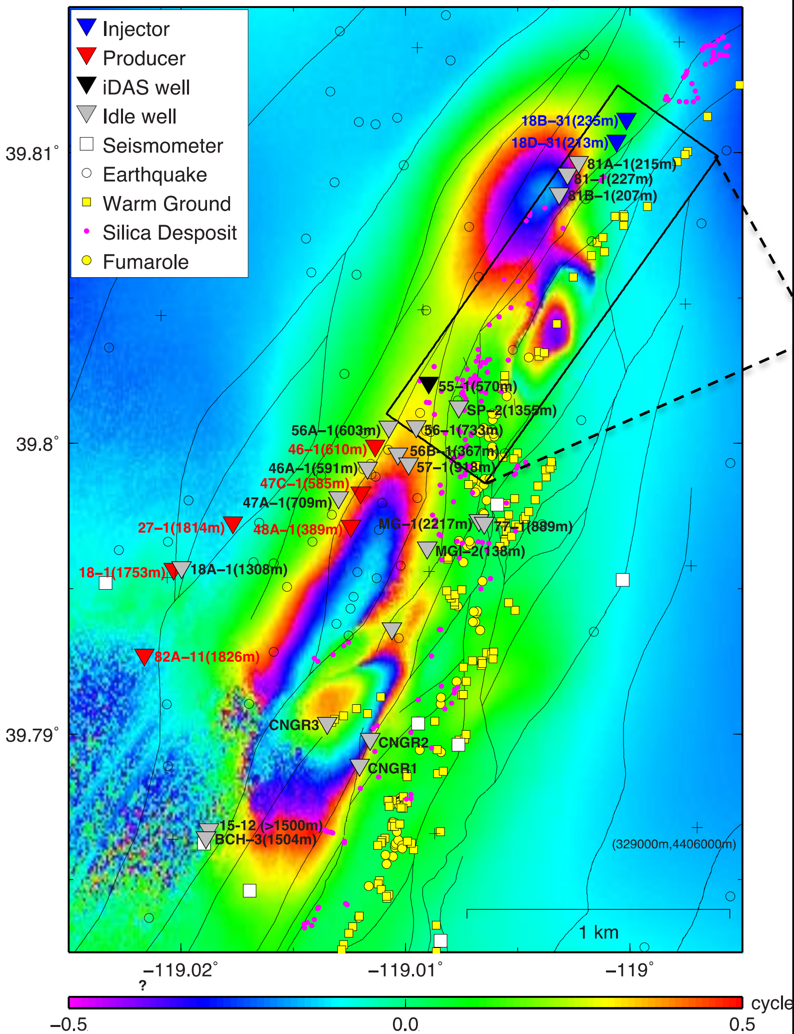
# PoroTomo

Project Officer: Bill Vandermeer
Total Project Funding: $2,319,973 (Govt. Share to UW)
May 12, 2015

**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
- saturation
- porosity
- density

**Expected outcomes:**

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

**Impact:**

**technical specifications for full-scale deployment**



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# Scientific/Technical Approach

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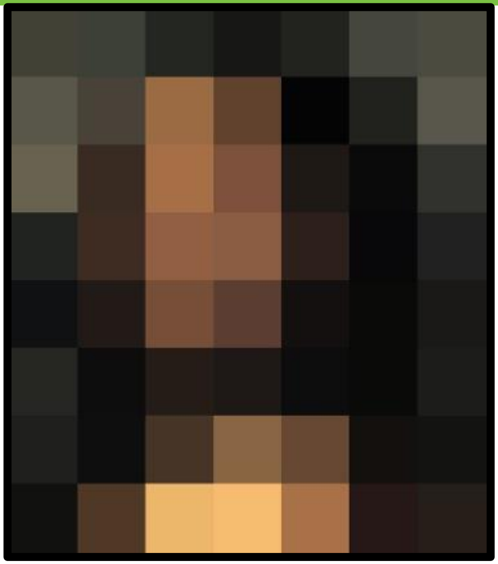
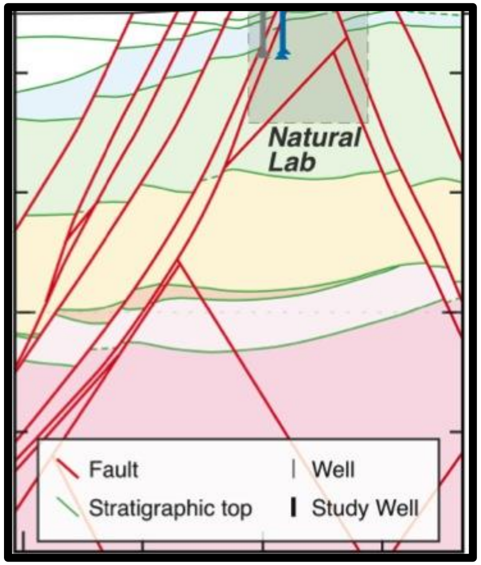
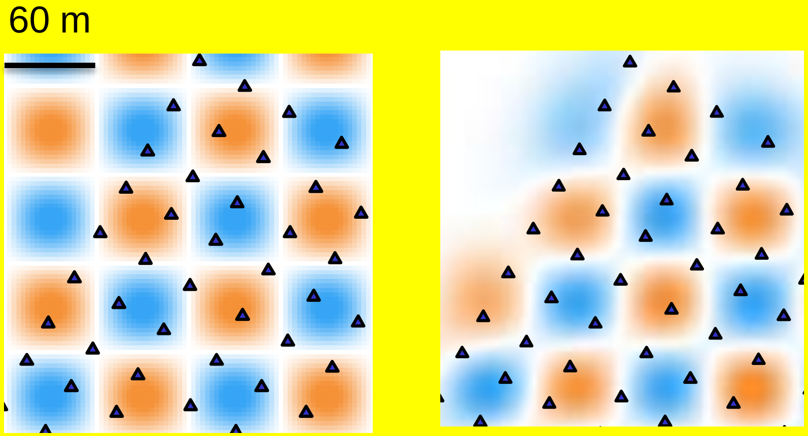





**Technology Performance Metric:**
***resolution in meters***
of a feature in the modeled 3-D distribution of a rock mechanical property as determined by the dimension of a visible checkerboard pattern at 200 m depth in a test using simulated data




Go/No-Go decision at Stage Gate Review:

If the expected values of the metrics are equal to or better than the minimum requirements, then the project will proceed.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# Scientific/Technical Approach

## Adjoint tomography can recover rock-mechanical properties

- estimating many parameters → finer resolution
- monitor $CO_2$ injection from cross-well seismic experiment (4 sources, 20 receivers)
- estimate bulk density

**forward wave field:** $\rho \partial_t^2 \mathbf{s} = \nabla \cdot \mathbf{T} + \mathbf{f}$

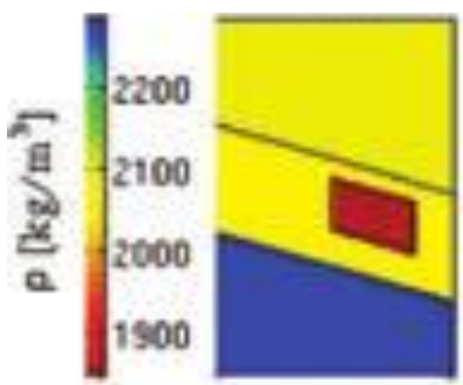
**adjoint wave field:** $\rho \partial_t^2 \mathbf{s}^\dagger = \nabla \cdot \mathbf{T}^\dagger + \mathbf{f}^\dagger$

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

$$\delta\chi = \int_\Omega [K_\rho \delta ln\rho + K_{\rho_f} \delta ln\rho_f + K_m \delta lnm + K_\eta \delta ln(\eta/k) + K_B \delta lnB + K_C \delta lnC + K_M \delta lnM + K_{\mu_{fr}} \delta ln\mu_{fr}] d^3\mathbf{x}$$

bulk density [kg/m³]

model used to ***generate*** simulated data set




model ***estimated*** from simulated data set

*(after Morency et al, GJI 2011)*

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

# Scientific/Technical Approach

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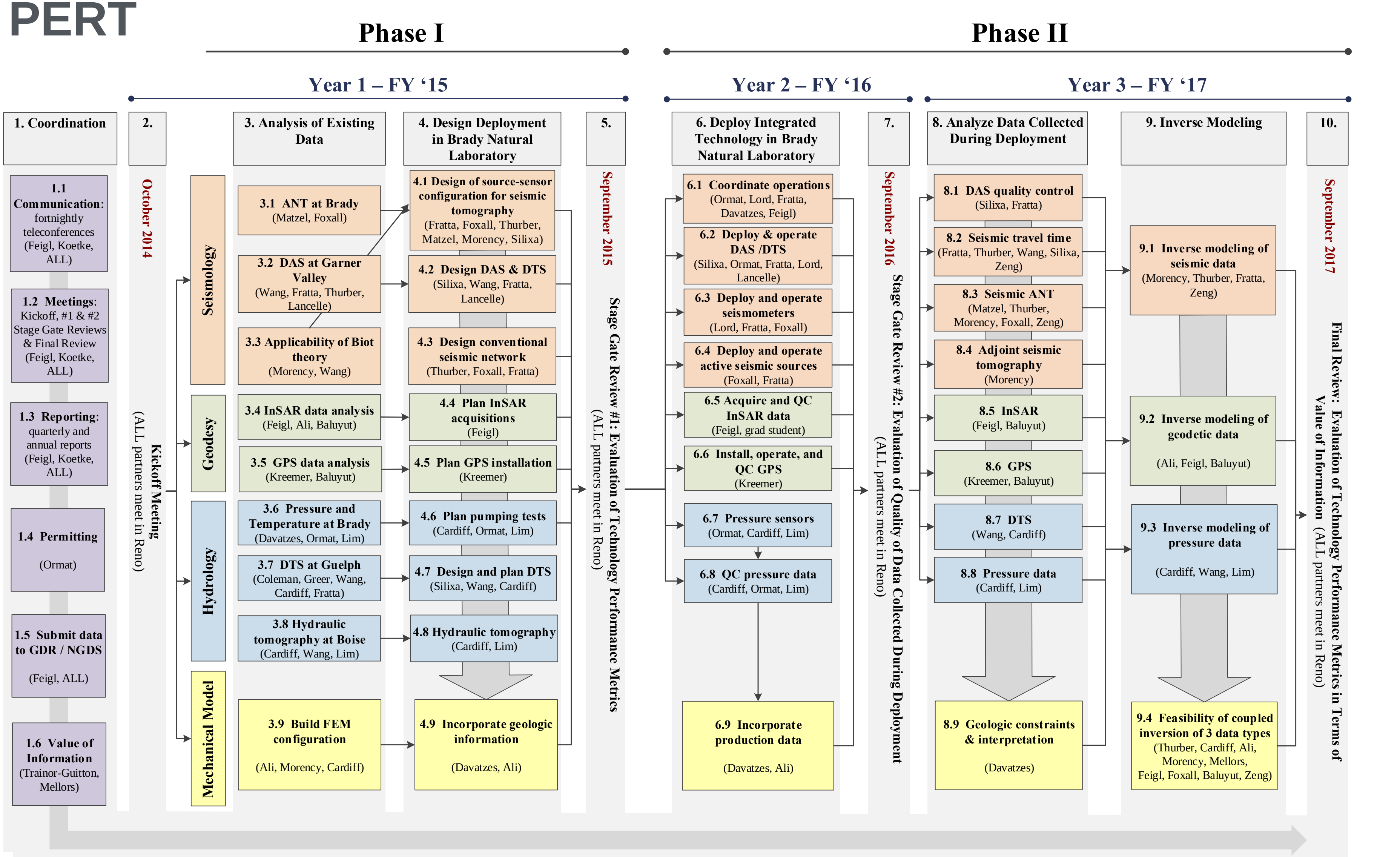
## PERT



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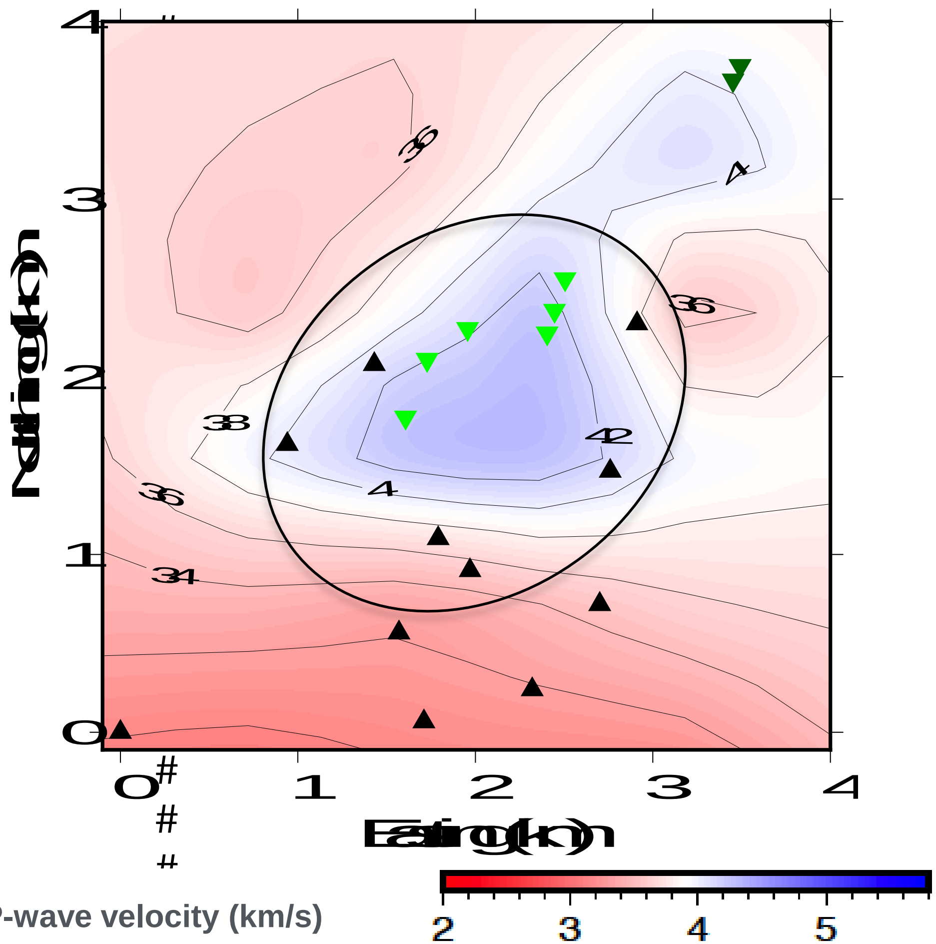
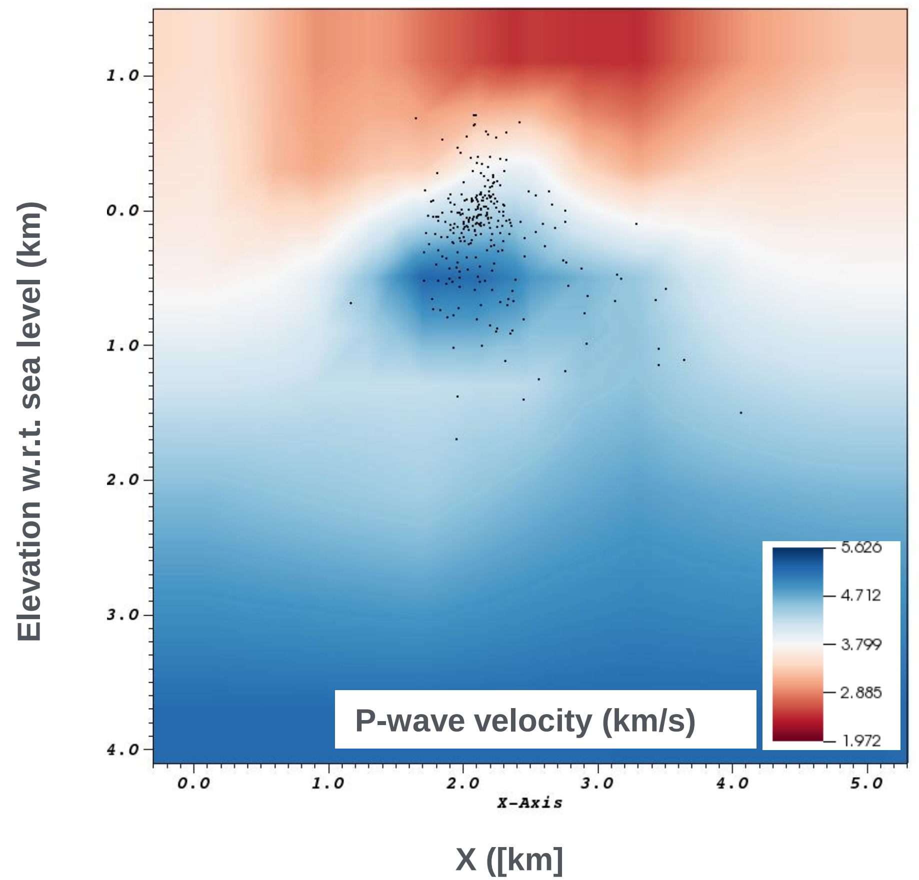
# 3D velocity structure and relocation of hypocenters

Horizontal slice at 1400 m depth




Vertical slice striking SW-NE




**Subtask 3.1: Ambient noise tomography (Matzel, Foxall, Singh)**



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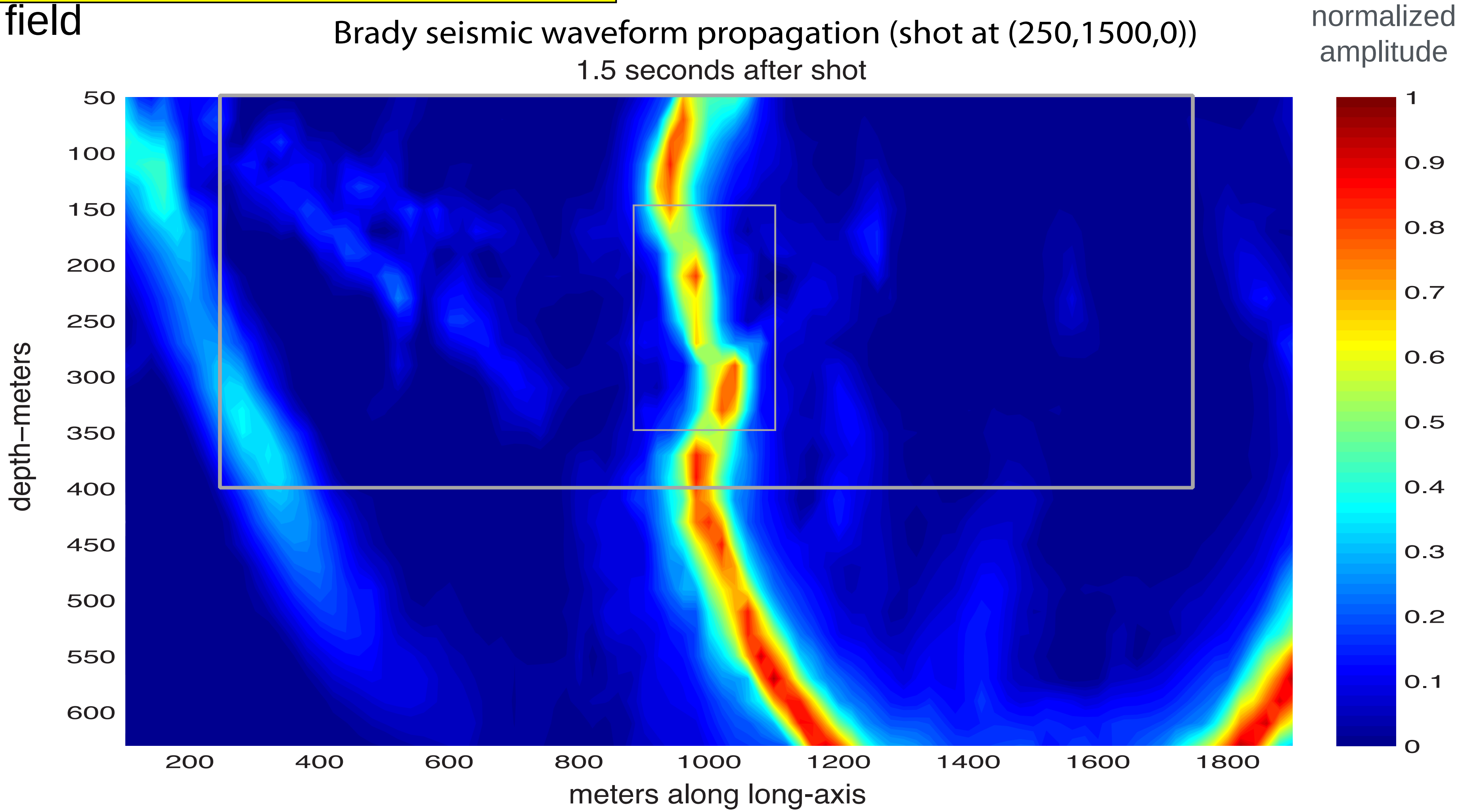
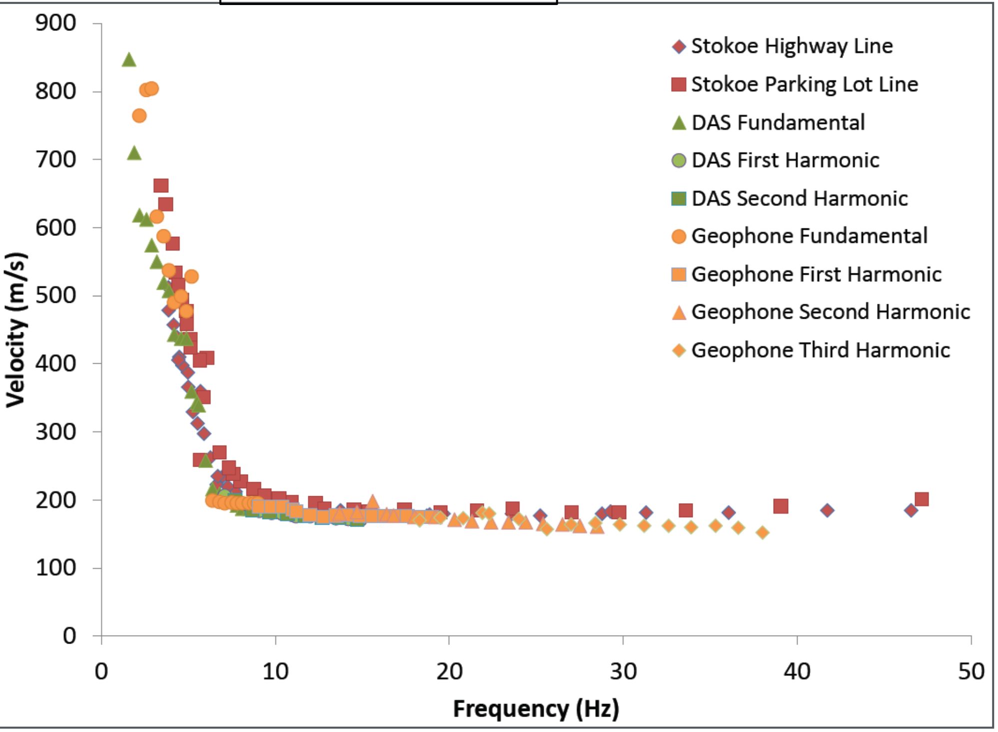
## Simulation of seismic wave field

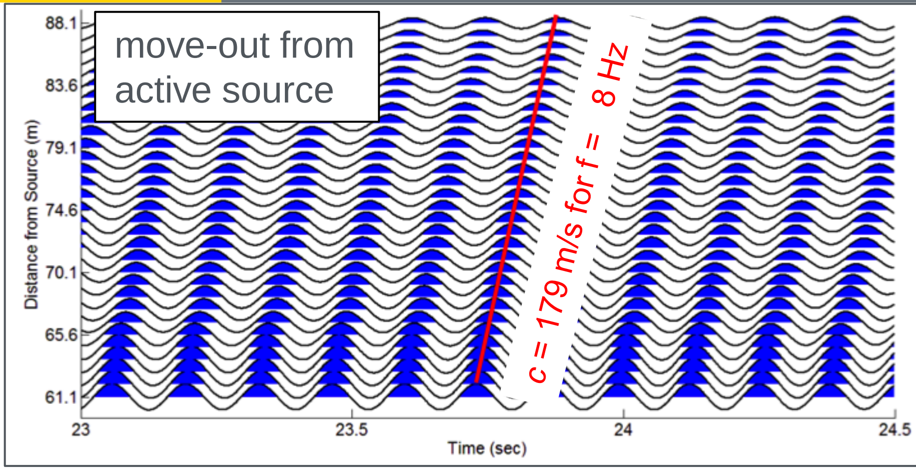



**Subtask 4.1: Design of source-sensor configuration for seismic tomography (Fratta, Foxall, Thurber, Matzel, Morency, Greer, Coleman, Zeng)**

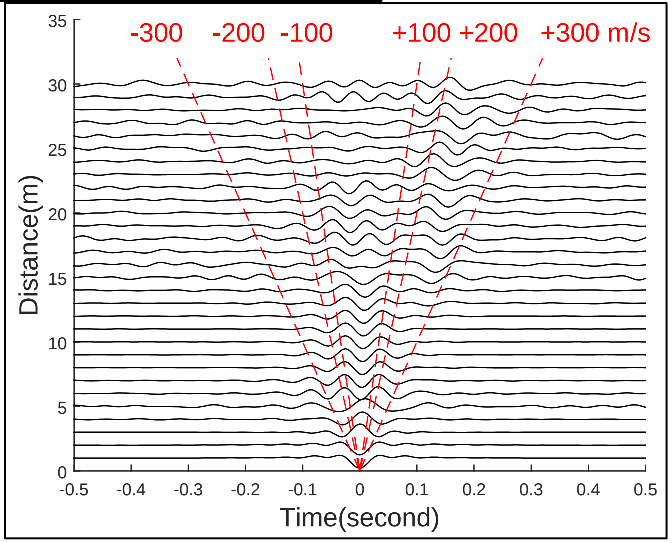
# Distributed Acoustic Sensing (DAS)

dispersion curves



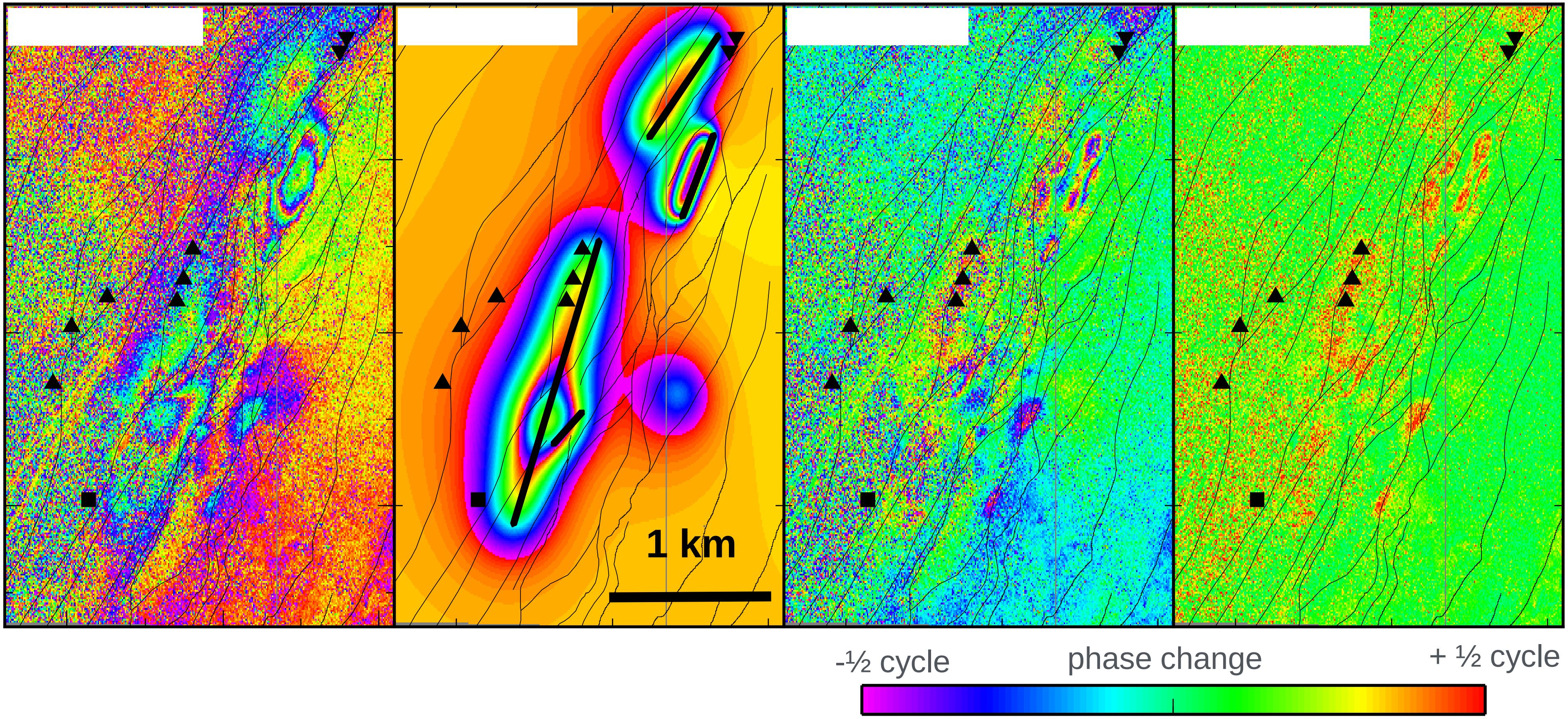

noise correlation functions




**Subtask 3.2: DAS at Garner Valley (Wang, Fratta, Thurber, Lancelle, Zeng, Lord)**

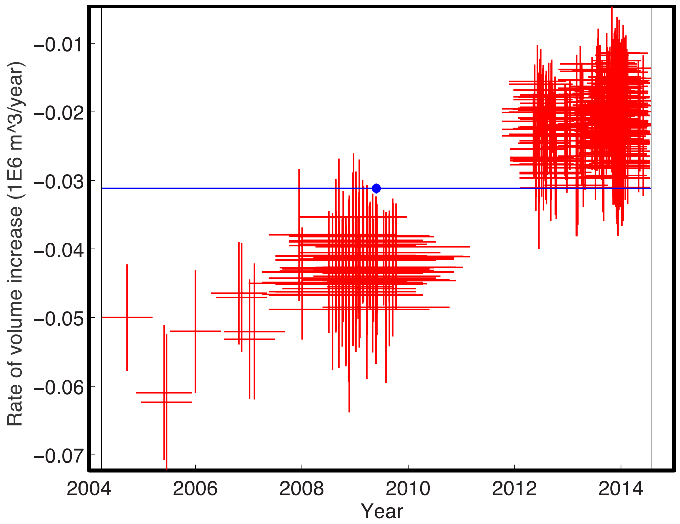
# InSAR data spanning 2013-May-13 to 2014-May-11

wrapped phase in 16-mm cycles



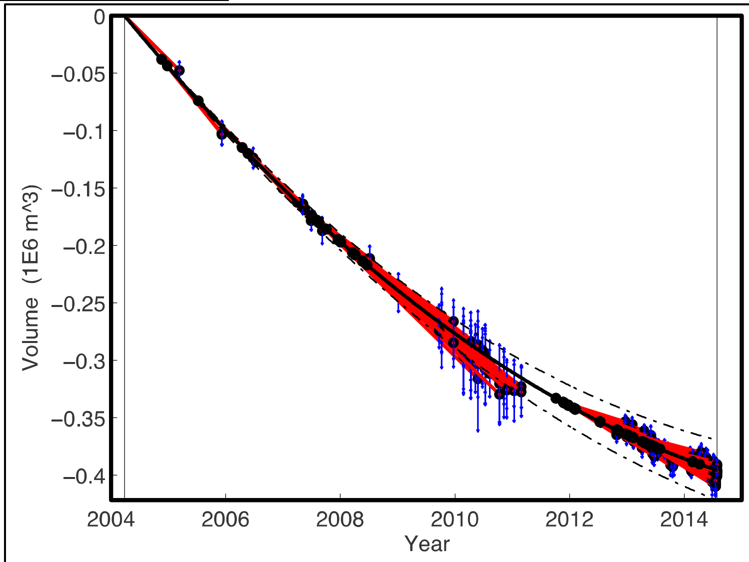

**Subtask 3.4: Analysis of existing InSAR data (Feigl, Ali, Baluyut)**

Data: InSAR data spanning 2004-2014 at Brady
Model: dislocation sink buried in an elastic half space
Estimated parameter: rate of volume decrease of the order of ~3 liters/second




$$Rate = \frac{dV}{dt} = \dot{V}$$

temporal adjustment




$$Total\ V = \int \dot{V}\, dt$$

average rate of volume change dV/dt

= $-31 \pm 0.1 \times 10^3\ m^3/yr$
≅ –1 liter/second
≅ –16 gallon/minute

quadratic function of time

total change in volume since 2004

= –380 ± 20 × 103 m3
≅ –400 Megaliter
≅ –100 million gallons

**Subtask 3.4: Analysis of existing InSAR data (Feigl, Ali, Baluyut)**

# Hydraulic tomography from pumping tests

Boise Hydro-geophysical Research Site pumping tests

- stimulate flow

measure pressure

- fiber optic transducers

estimate in each grid cell:

- hydraulic conductivity K
- storage coefficient

Resolution ~ sensor spacing:

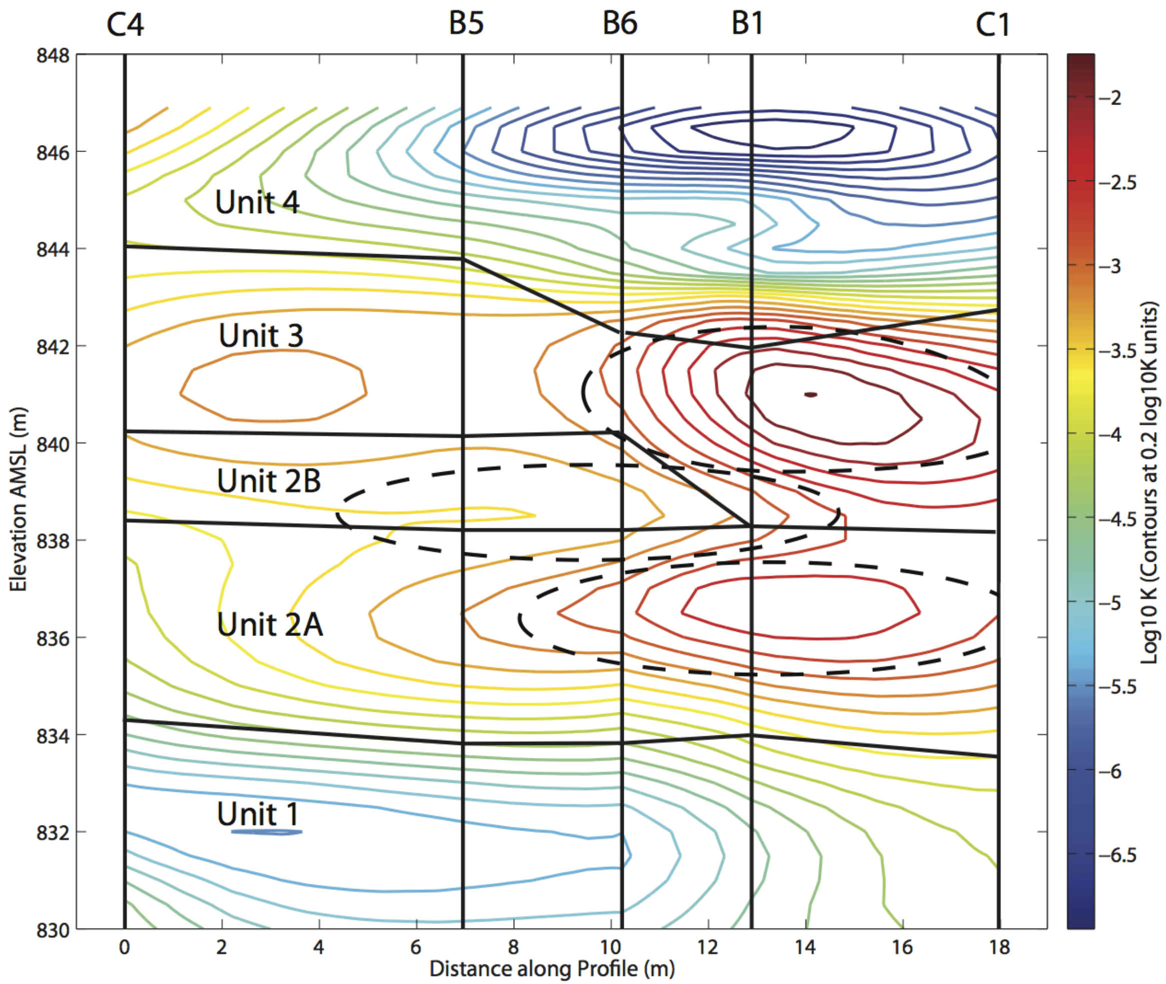
Boise:

1 m vertical

5 m horizontal

Brady:

300 to 500 m horizontal

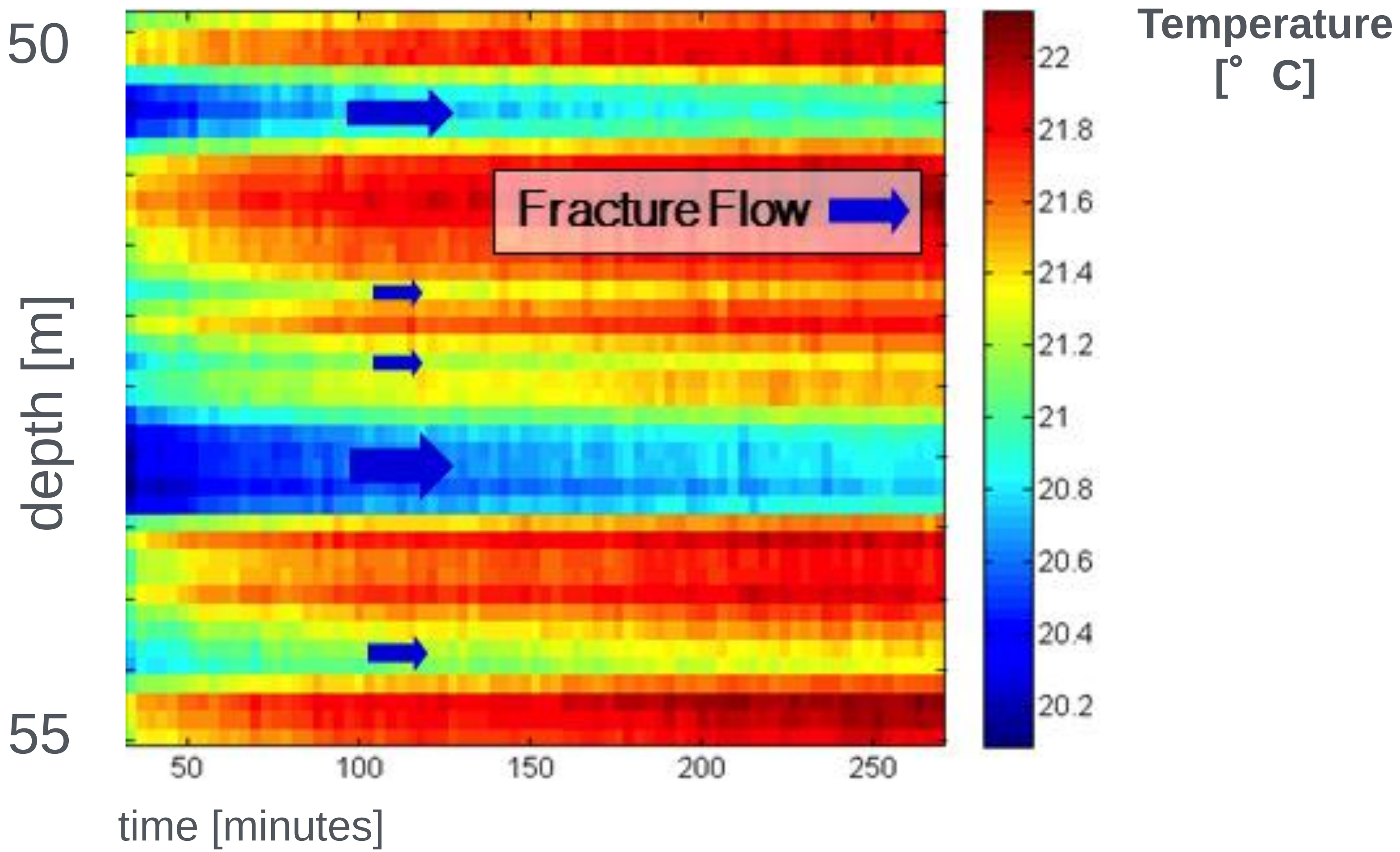



**Subtask 3.8: Development & application of hydraulic tomography at Boise (Cardiff, Wang, Lim)**

# Distributed Temperature Sensing (DTS)

fiber optic cable

vertical resolution ~ 0.1 m




**Subtask 3.7: Analysis of existing DTS data at Guelph (Coleman, Greer, Wang, Cardiff, Fratta)**

# Accomplishments, Results and Progress



- Bayesian, adjoint tomography can recover rock-mechanical properties with fine resolution.
- Ambient noise tomography (ANT) at Brady estimated a 1-dimensional model of seismic velocity and attenuation with a vertical resolution of the order of ~100 m at a depth of 200 m.
- Analysis of previously collected DAS data at Garner Valley led to: (a) invention of a Time-Frequency Filter (TFF) to remove traffic noise and source harmonics, (b) measurement of directivity and sensitivity of DAS response, (c) measurement of near-surface Rayleigh-wave velocity dispersion from a swept-frequency, active source, and (d) noise correlation functions between pairs of receiver points.
- InSAR data spanning 2004-2014 at Brady have been analyzed using inverse modeling to estimate the rate of volume decrease of the order of ~3 liters/second of a dislocation sink buried in an elastic half space.
- Data on pressure, temperature, production, and injection at Brady for the time interval 2004-2014 are being analyzed to distinguish between hydro-mechanical and thermo-elastic models.
- GPS data at stations BRDY and BRAD for the time interval from 2009 through 2014 have been collected, archived, distributed, and analyzed to yield time series of daily estimates of relative, 3-dimensional position.
- Hydraulic tomography on pump testing data estimates hydraulic conductivity and storage coefficient with a spatial resolution comparable to the distance between sensors.
- A Distributed Temperature Sensing (DTS) experiment at Guelph has been analyzed to characterize flow through fractures under natural and forced conditions with a vertical resolution of the order of 0.1 meter.
- An initial model of rock mechanical properties incorporate geologic information.

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

- **Hypothesis 1: Injecting cooled water → thermal contraction**
- **Hypothesis 2: Changes in pressure and saturation → poroelastic compaction**
- **Hypothesis 3: Dissolution in water flowing through fractures removes minerals from rock**



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# Future directions

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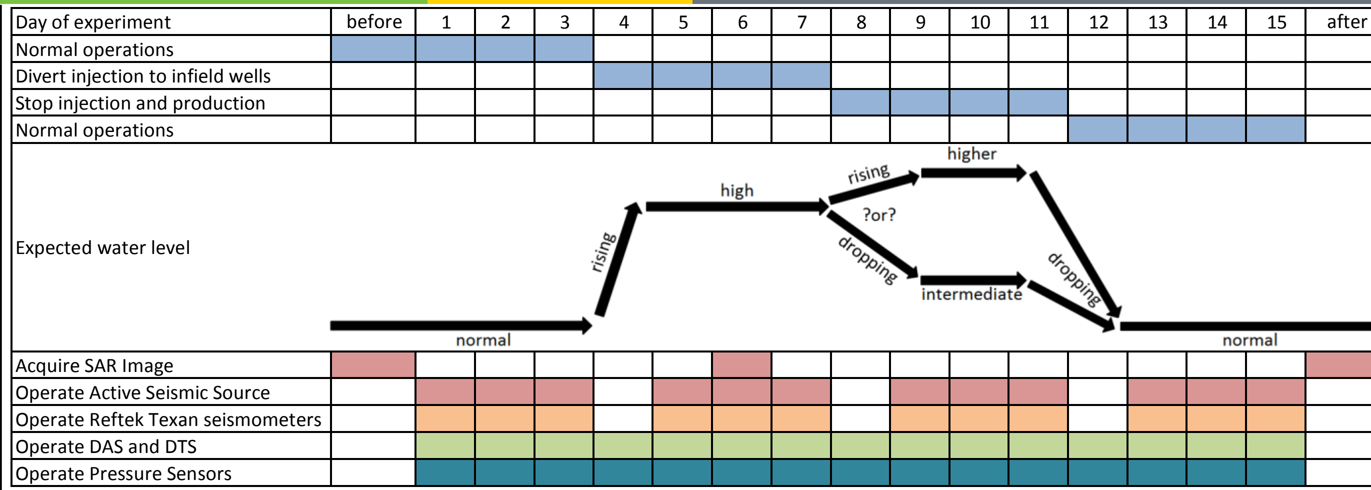
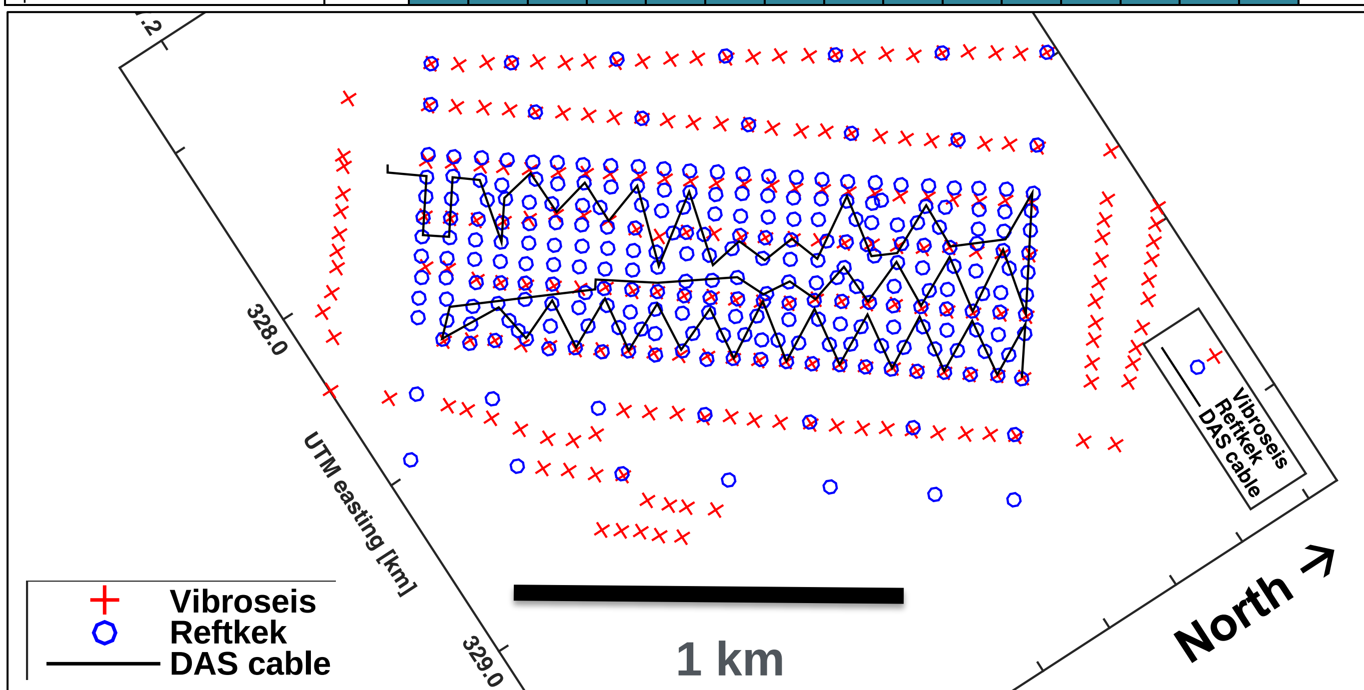
Issues:
- Value of information
- Software licensing

Stage Gate Review:
- 24-25 Sept. 2015
- evaluate metrics

Phase II:
- demo prototype
- analyze data

deployment plan
- March 2016
- 4 obs. intervals
- 9000 m DAS
- 400 m DTS + DAS
- 240 seismometers
- 240 vibroseis
- 5 P & T sensors





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## PoroTomo project is on track

- "The EERE project team has assigned a Green overall project health indicator." (based on first quarterly report, Jan. 2015)
- Analysis of existing data in Phase I will evaluate the technology performance metric at Stage Gate Review in September 2015.

**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 | 500 m | 500 m | 200 m |
| Target: improve resolution to | 50 m | 250 m | 250 m | 50 m |
| Beyond ("over") target: improve resolution to | 25 m | 100 m | 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)

# 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]

**The slides following this one may be useful for answering questions during the 10-minute Q & A period.**

**I am not planning to show the following slides during the 20 minutes allowed for presentation.**

# Submissions to DOE Geothermal Data Repository

Brady's Geothermal Field Seismic Network Metadata (Subtask 3.1),
http://gdr.openei.org/submissions/469

Brady Geothermal 1D seismic velocity model (Subtask 3.1),
http://gdr.openei.org/submissions/472

Metadata for DAS at Garner Valley (Subtask 3.2),
http://gdr.openei.org/submissions/465

Poroelastic references (Subtask 3.3),
http://gdr.openei.org/submissions/463

Analysis of existing InSAR data (Subtask 3.4),
http://gdr.openei.org/submissions/471

Individual raw GPS data for GPS stations BRAD and BRDY (Subtask 3.5),
http://gdr.openei.org/submissions/467

Daily estimates of position for GPS stations BRAD & BRDY (Subtask 3.5),
http://gdr.openei.org/submissions/466

Metadata for active DTS at Guelph (Subtask 3.7),
http://gdr.openei.org/submissions/468

Metadata for Boise Hydro-geophysical Research (Subtask 3.8),
http://gdr.openei.org/submissions/470

# Scientific/Technical Approach

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

- **Hypothesis 1: Injecting cooled water → thermal contraction**
- **Hypothesis 2: Changes in pressure and saturation → poroelastic compaction**
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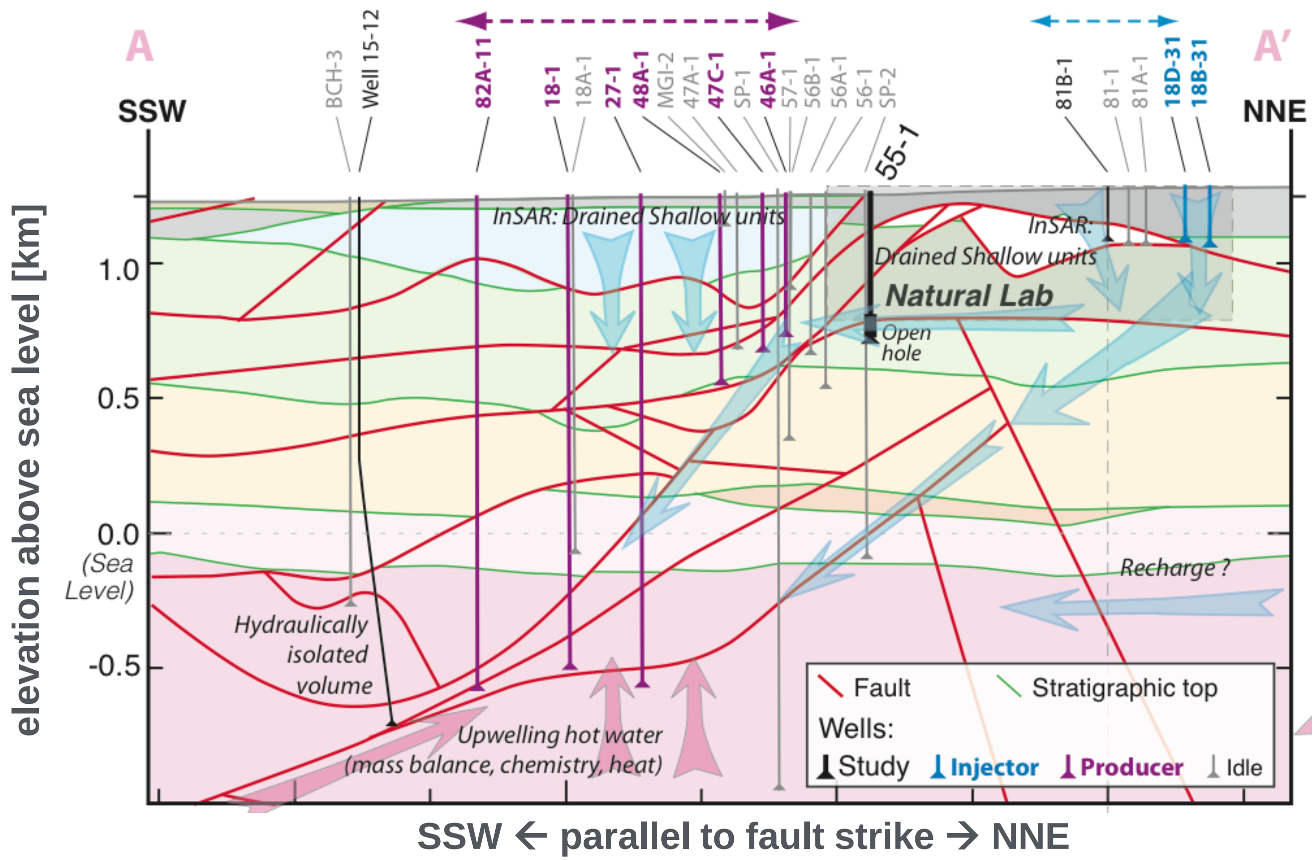



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# Accomplishments, Results and Progress

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***Milestone Summary Table***

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

| Task or Milestone Number | Description | Start Month M | End Month M | Quarter |
|---|---|---|---|---|
| **1.0** | **Coordination** | **1** | **36** | |
| ***Phase I*** | ***Budget Period 1 = Year 1 (FY '15)*** | | | |
| **2.0** | **Kickoff Meeting** | **1** | **1** | |
| **3.0** | **Analysis of Existing Data** | **1** | **11** | |
| Mst. 3.1 | Metadata for existing data sets submitted to GDR | | | Q1 |
| Mst. 3.2 | Existing data sets submitted to GDR in unprocessed format | | | Q2 |
| Mst. 3.3 | Existing data sets submitted to GDR in analyzed format | | | Q3 |
| **4.0** | **Design Deployment at Brady** | **1** | **11** | |
| Mst. 4.1 | Uncertainty analysis | | | Q4 |
| **5.0** | **Stage Gate Review #1** | **12** | **12** | |
| Go/No-Go #1 | Resolution expected for Phase II will meet minimum requirement | | | Q4 |
| ***Phase II*** | ***Budget Period 2 = Year 2 (FY '16)*** | | | |
| **6.0** | **Deployment of Integrated Technology in Brady Natural Lab.** | **13** | **23** | |
| Mst. 6.1 | Plan (personnel, dates, equipment) for deployment drafted | | | Q5 |
| Mst. 6.2 | Plan for deployment confirmed | | | Q6 |
| Mst. 6.3 | Metadata for deployment data sets submitted to GDR | | | Q7 |
| Mst. 6.4 | Data from deployment submitted to GDR in unprocessed format | | | Q8 |
| **7.0** | **Stage Gate Review #2** | **24** | **24** | |
| Go/No-Go #2 | Data were successfully collected according to plan | | | Q8 |
| ***Phase II cont'd*** | ***Budget Period 3 = Year 3 (FY '17)*** | | | |
| **8.0** | **Analysis of Data Collected During Deployment** | **25** | **30** | |
| Mst. 8.1 | Preliminary data analysis | | | Q9 |
| Mst. 8.2 | Final data analysis completed and data sets submitted to GDR | | | Q10 |
| **9.0** | **Inverse Modeling** | **30** | **35** | |
| Mst. 9.1 | Preliminary inverse modeling | | | Q11 |
| Mst. 9.2 | Final inverse modeling | | | Q12 |
| **10.0** | **Final Review** | **36** | **36** | |
| Mst. 10.1 | Final report | | | Q12 |


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