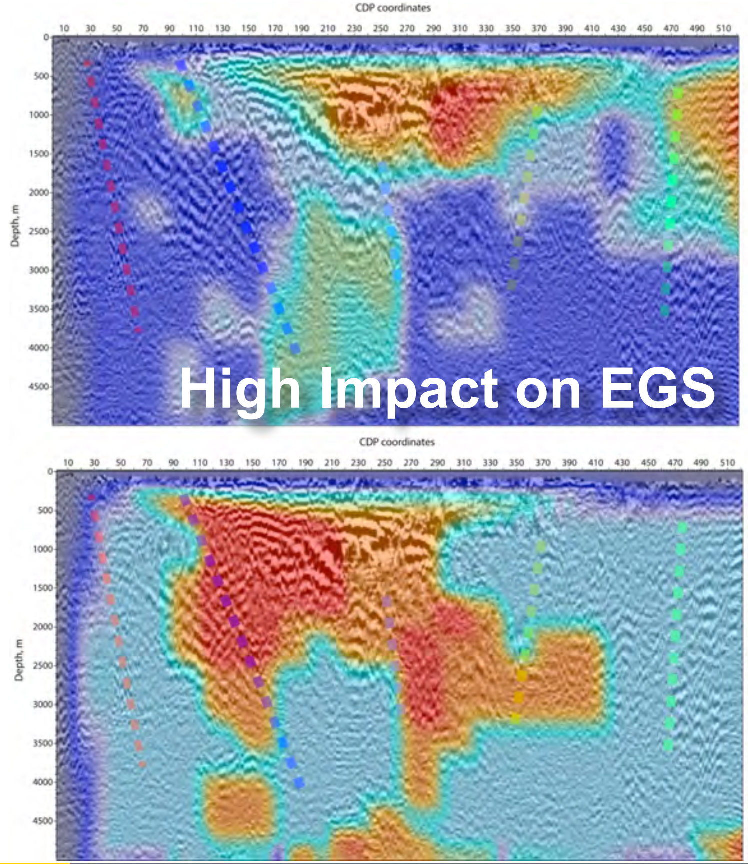

Quantifying EGS Reservoir Complexity with an Integrated Geophysical Approach

Project Officer: Sean Porse

Total Project Funding: $408,195

November 15, 2017

Prof. John N. Louie

University of Nevada, Reno

Track 3 EGS Tools

Relevance to Industry Needs and GTO Objectives

Primary Goal: Improved resolution (2 km → 0.1 km, to 3 km depth) of seismic interferometry-estimated parameters relative to prior work on the Dixie Valley Geothermal Wellfield (DVGW). Assess the possibility of using seismic analysis in combination with other geophysical techniques for EGS target identification, and characterize subsurface.

EGS Industry Challenges Addressed:

- Can ambient seismic noise identify structure in the subsurface, seismic parameters such as seismic attenuation, temperature and lithology at depth that can be used to identify EGS drilling sites?

Impact on EGS Industry Costs and Performance:

- Adapting methods designed for conventional geothermal analysis to larger-scale and different EGS requirements, while preserving the low cost of the technique, will allow lower-cost EGS resource assessments, and less risk to developers.

Relevance to Industry Needs and GTO Objectives

Innovative Project:

- New exploration technology includes application of seismic interferometry and seismic array signal processing techniques, developed for nuclear monitoring, to geothermal seismic-reflection surveys at the EGS scale.

Impacting These GTO Goals:

- Improving processes of identifying, accessing, and developing geothermal resources – *Cost-effective seismic exploration.*
- Mitigating risk – *Statistically proven assessment of EGS favorability.*
- Solving environmental permitting and subsurface data challenges – *Seismic exploration without heavy vehicles or intrusive sources.*
- Accelerating a commercial pathway to and securing the future of EGS – *An exploration & assessment technology designed for EGS.*
- Supporting early-stage R&D – *Research team has decades of experience with commercial geothermal developments.*

Methods/Approach

- Summary of Scientific/Technical Approach – Phase I:
  1. Design an innovative seismic deployment, including an unprecedented combination of broadband (BB), short period (SP), and high frequency sensors for ambient noise;
  2. Modify the seismic interferometry data processing technique to shorten the duration of the experiment from 21 days to 6-9 days, while obtaining the same seismic image resolution;
  3. Identify and quantify multiple seismic parameters (velocity, attenuation, waveform complexity, heterogeneity, stress drop, stress orientation) to improve characterization of lithology, temperature, and fault location and orientation;
  4. Evaluate the best method to circumvent effects of the seismic noise directionality when assessing P/S velocity and attenuation.

Methods/Approach

- Summary of Scientific/Technical Approach – Phase II:
  1. Update the AltaRock Energy Inc. (2014) Dixie Valley Conceptual Model for the new seismic results with respect to predicted temperature and lithology at depth.
  2. Investigate geostatistical relationships between all variables, especially modeling of temperature, lithology, EGS favorability, and hydrothermal productivity.
  3. Generate new EGS favorability/trust maps for Dixie Valley Geothermal Wellfield, using the extant EGS favorability/trust maps as a base case.
  4. Prepare Final Scientific Report, presentations/papers for conferences/workshops, market transformation and commercialization plan, and GDR data transfer.

Methods/Approach

- *Rigor of scientific/technical research methods*
  - Basis of team's data-collection and analysis processes vetted in peer-reviewed journal publications (e.g., Pullammanappallil & Louie, 1997; Tibuleac et al., 2011) and reviewed results of prior GTO projects (Tibuleac et al., 2015). Results will be submitted for peer-reviewed publication.
  - Project team includes both academics and industry experts to ensure both rigor and industry applicability.
- *Logic and reasonableness of milestones and steps*
  - Results of Tasks 1, 2, 3 reviewed by GTO at Go/No Go gateway decision in May 2017. Go decision to proceed with Tasks 4, 5, 6.
- Technical feasibility
  - Use of very portable and flexible PASSCAL "Texan" recorders allowed reconfiguration of data collection in the field to match severe weather conditions, schedule and funding constraints.

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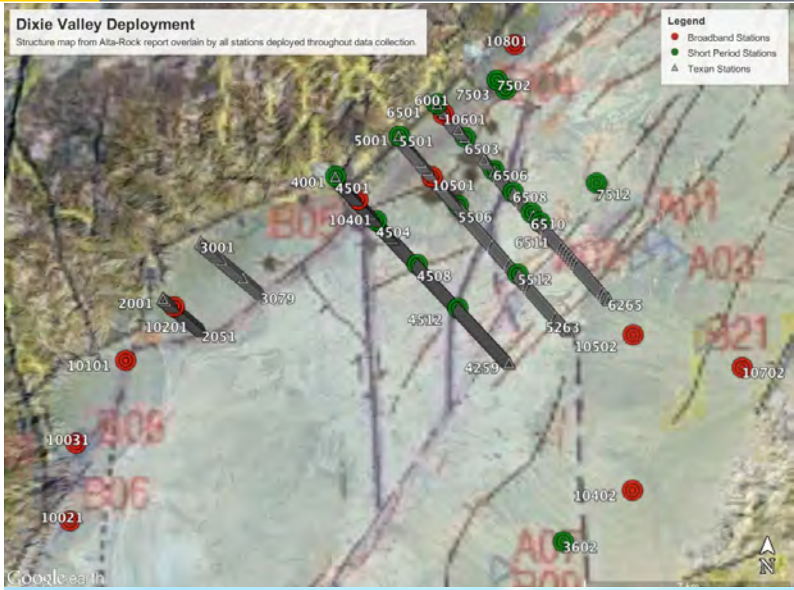
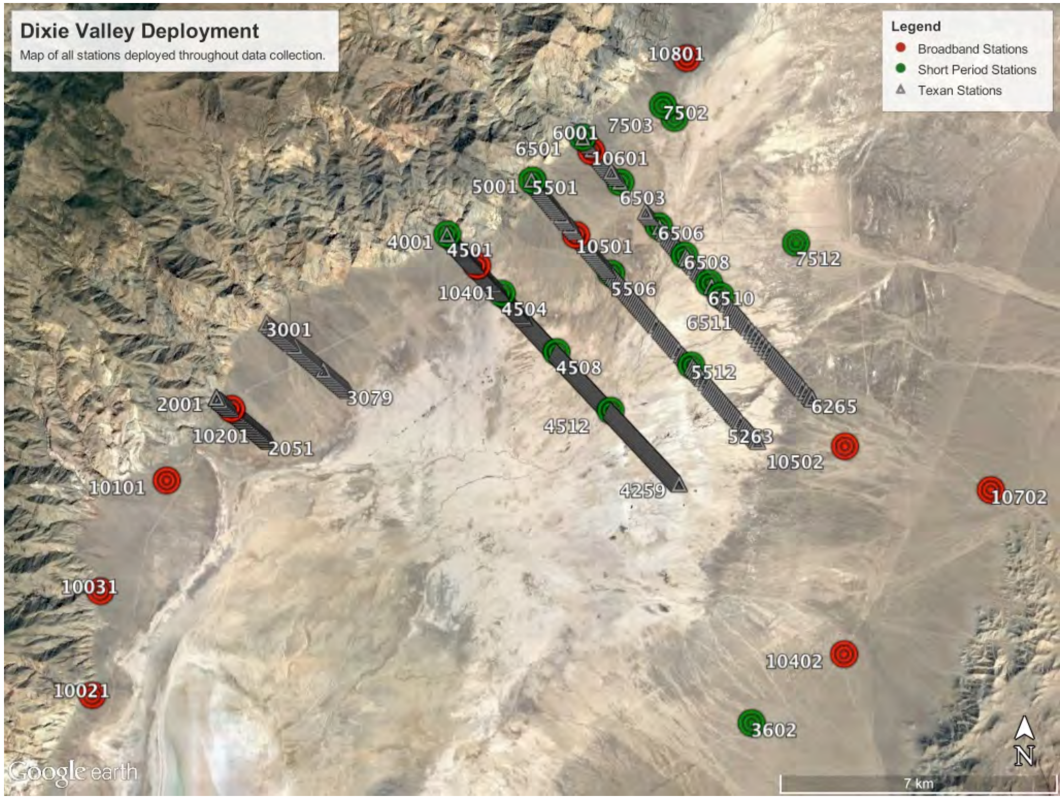
- Key Issues:
  - Extremely difficult weather conditions limited battery life and demanded re-configuration of the field experiment.
  - New job for Dr. Tibuleac is driving faster transfer of technology to students and industry participants.
- Despite difficulties, all needed data were collected, and Phase II of the project was approved and has begun. The team works together well.



Technical Accomplishments and Progress

Seismic Equipment Installation:

- 550 PASSCAL Texans with 4.5 Hz vertical geophones, in 5 arrays with spacing as close as 34 m (triangles).
- 12 broadband (BB) 3C (red)
- 15 short-period (SP) 3C (green)
- Included 6-9 days or more of ambient-noise recording on all sensors.



Original Planned Milestone/ Technical Accomplishment	Actual Milestone/Technical Accomplishment	Date Completed
2.1 Seismic Equipment Installation	550 Texan, 12 BB, 15 SP	2/2016
2.3 Seismic Data Interpretation	As proposed	3/2017

Technical Accomplishments and Progress

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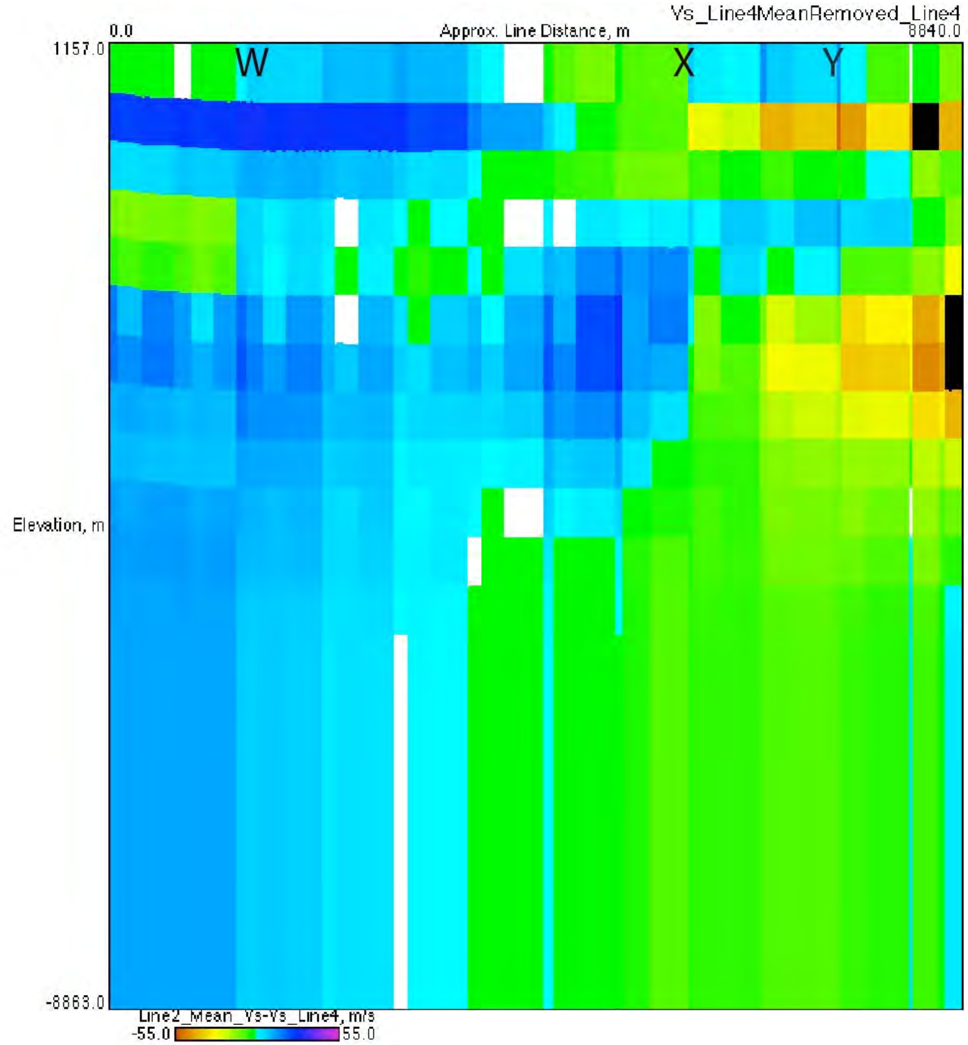
Seismic Velocity Results, Other Parameters:

- Seismic interferometry produced cross-correlated empirical Green's function seismograms between every pair of sensors.
- $(550+12+15)^2$ = 0.33 million pairs. Each produced a Rayleigh group-velocity dispersion curve, Vs(z) profile, many more parameters.
- Resulted in Vs, other maps and sections for DVGW. At right, Line 4 Vs deviation from average at each depth.



Technical Accomplishments and Progress

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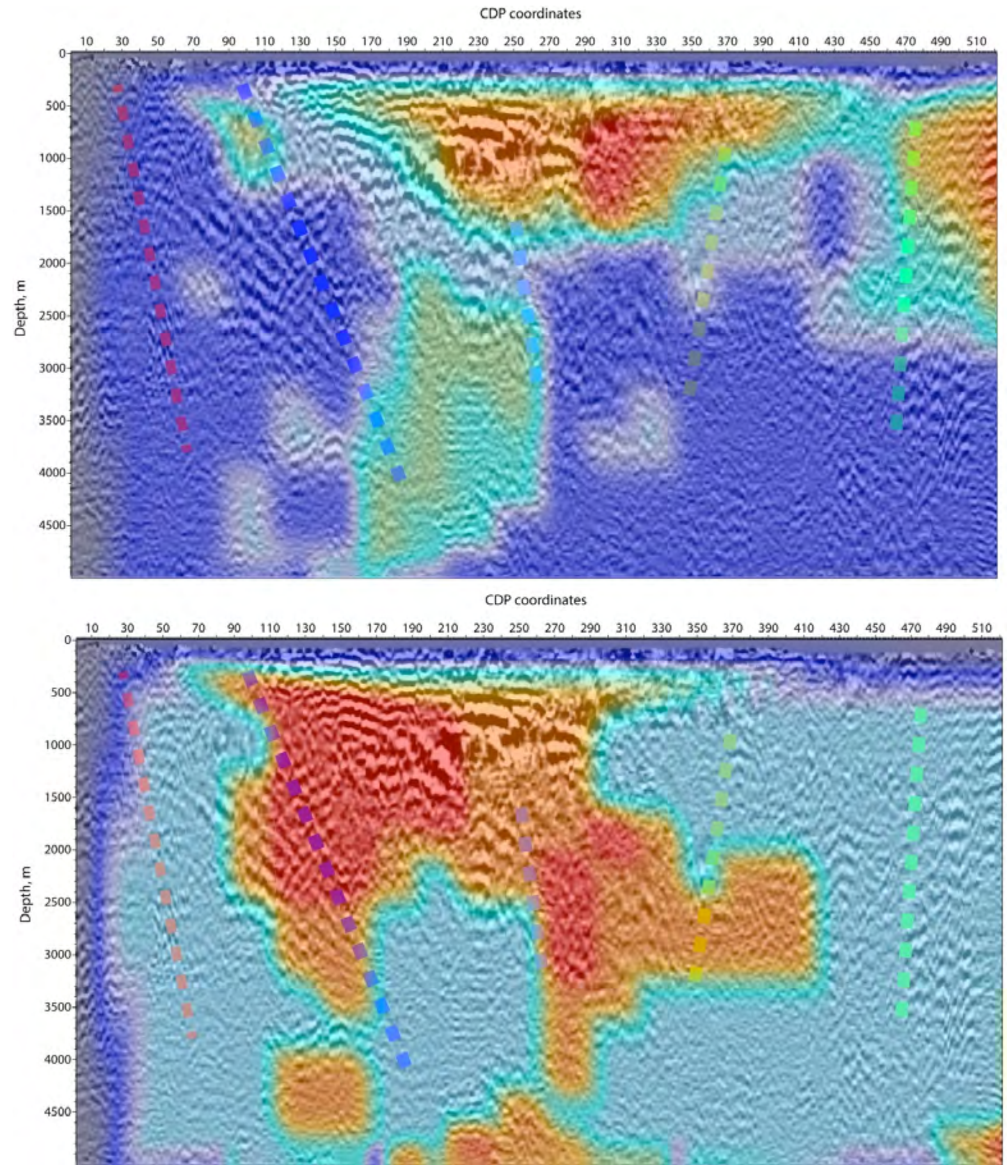
Seismic Imaging Results:

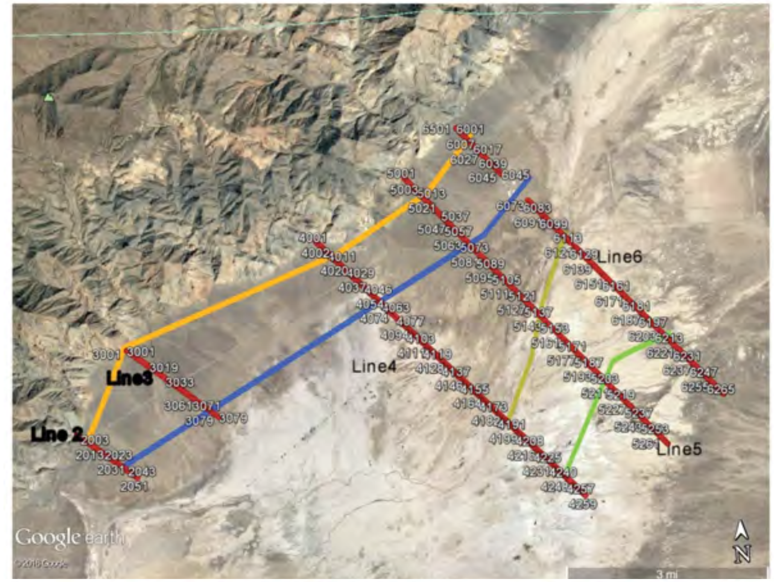
- Velocity results input to Advanced Seismic Imaging reflection-coherency optimization process (Pullammanappallil & Louie, 1997).
- Resulting prestack migrated reflection depth sections show basin floor and sediments, bedrock structures to EGS depths >4 km - deeper than any prior surveys.
- Faults interpreted into deep basement from fault-plane images, reflection terminations, velocity boundaries, low correlation (upper), or high Hurst number (lower).



Technical Accomplishments and Progress

Fault Interpretation Results:

- (upper) Colored lines correlate faults between the detailed reflection sections of the Large-N Texan lines.
- (lower) The new fault interpretation from high-resolution, deep seismic interferometry closely matches the fault map from prior work (AltaRock, 2014).
- Faulting of the deep basement must be assessed for EGS projects. Faults play both a positive and negative role in EGS development and as such, must be considered in the selection of drilling targets.
- With knowledge of faulting geometry, EGS drilling and fracking operations can be planned with more certainty.



Research Collaboration and Technology Transfer

- *Academic Engagement:*
  - **University of Nevada, Reno (UNR)** – Project lead is Prof. Louie with Dr. Tibuleac in an advisory role since Sept. 2016; originated Tibuleac's seismic interferometry and Louie's advanced seismic imaging technologies further developed for this project; Phase I results will be submitted for publication in a peer-reviewed journal.
  - **University of California, Berkeley** – Subaward to Prof. H. Ibser; developing and testing geostatistical assessments of subsurface geological, geophysical, and hydrothermal parameters.
  - **New Mexico Institute of Mining and Technology** – Hosts the PASSCAL Instrument Center of the Incorporated Research Institutions for Seismology (IRIS), supported by the National Science Foundation and DOE; supplied the Large-N seismic array of portable "Texan" instrumentation, and data-archiving services, at cost of staff travel. Requires recorded data to be open.
  - **University of Texas, El Paso** – Host of some PASSCAL staff.

Research Collaboration and Technology Transfer

- *Technology Transfer:*
  - **Joe Iovenitti** – Consulting geoscientist with subaward on the project; brings experience from AltaRock projects including Dixie Valley; research management role in project; integrating the seismic results from this project with the non-seismic geoscience datasets presented in AltaRock Energy Inc. (2014) as well as providing geoscience support to the geostatistical analysis of the data collected; advising on future markets for the seismic-interferometry technology and identifying clients for future DOE opportunities.
  - **Optim** – Geophysical software and services company with subaward on the project; Dr. Pullammanappallil brings 20 years experience with multiple hydrothermal and EGS clients, plus an extensive toolbox of proven as well as developing technologies; completed all Phase I advanced seismic imaging work; consulting on Phase II; has successfully commercialized UNR technologies.

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- Task 3 – Dixie Valley EGS Conceptual Model
  - *Task Summary:* This task involves updating the AltaRock Energy Inc. (2014) Dixie Valley Conceptual Model for the new seismic results with respect to updated seismic parameters and predicted temperature and lithology at depth. At the end of this task, UNR will organize a meeting with team members to discuss the results.
  - Task Lead: *Joe Iovenitti*, Consulting Geoscientist.
  - Ongoing. Completion scheduled for March 31, 2018.
  - Subtask 3.1 Update Conceptual Model - Five sections across DVGW originally shown in AltaRock Energy Inc. (2014) will be updated per the new seismic results.
  - Subtask 3.2 Conceptual Model Expert Evaluation – by key team members in a webinar.
  - Subtask 3.3—Updated Conceptual Model Report – finalized by task leader.

- Task 4 – Geostatistics
  - *Task Summary:* UNR will investigate relationships between all variables, especially modeling of temperature, lithology, EGS favorability, and hydrothermal productivity. A report will be drafted by the Task Leader, reviewed by key team, and finalized by the Task Leader.
  - Task Lead: *Prof. Hank Ibser*, Univ. of California, Berkeley.
  - Ongoing. Completion scheduled for March 31, 2018.
  - Subtask 4.1—Exploratory Data Analysis - Initial includes bivariate analysis, then more detailed modeling and prediction analysis using multiple regression and CART on temperature, lithology as defined by well data, lithology defined by gravity-magnetic modeling, EGS favorability, and hydrothermal productivity. Additional analysis after the effect of depth is removed.
  - Subtask 4.2—Exploratory Data Analysis Expert Evaluation – via webinar with project team.

Future Directions

- Task 5 – EGS Favorability/Trust Mapping
  - *Task Summary:* Generate new EGS favorability/trust maps for DVGW, with extant EGS favorability/trust maps as a base case.
  - Task Lead: *Joe Iovenitti*. Starting 12/1/17; completion 5/31/18.
  - Subtask 5.1—Generate New EGS Favorability/Trust Maps.
- Task 6 – Project Reporting
  - *Task Summary:* Prepare quarterly and Final Scientific Reports, presentations/papers for conferences/workshops, market transformation and commercialization plan, GDR data transfer, and project audits.
  - Task Lead: *John Louie*. Ongoing; completion 6/30/18.
  - Subtask 6.1 Conference/Workshop Presentations.
  - Subtask 6.5 Market Transformation and Commercialization Plan.
  - Subtask 6.6 NGDS/GDR Data Transfer.

Future Directions

- Factors requiring no-cost time extension of project completion date to June 30, 2018:
  - Subtask 2.1 Seismic Equipment Installation and Data Acquisition could not be completed until February 2016.
  - Dr. Tibuleac moved from UNR to Air Force Technical Application Center in September 2016. With Prof. Louie approved as project lead, completion of Task 2 and the Seismic Report for the Go/No Go review had to be delayed to March 25, 2017.
  - The Go decision for Phase II was rendered on May 30. Spending re-authorization was officially received by UNR on July 20, 2017.

Completion Milestone	Status & Expected Completion
Task 3 – Dixie Val. EGS Conceptual Model	In progress for completion 3/31/18
Task 4 – Geostatistics	In progress for completion 3/31/18
Task 5 – EGS Favorability/Trust Mapping	Starting 12/1/17; completion 5/31/18
Task 6 – Project Reporting & Tech. Transfer	In progress for completion 6/30/18

Mandatory Summary Slide

- Met primary goal of Phase I: Improved resolution (2 km ➔ 0.1 km, to 3 km depth) of parameters estimated by "Large-N" seismic interferometry at Dixie Valley Geothermal Field.
- Further improved and applied a new cost-effective and noninvasive exploration method for EGS resources.
- Developed a procedure for initial fault identification.

- Phase II will statistically quantify advantages of seismic analysis, together with other geological and geophysical techniques, for EGS target identification.