Time-lapse Joint Inversion of Geophysical Data and its Applications to Geothermal Prospecting - GEODE

Project Officer: Mark Ziegenbein
Total Project Funding: $635,000

Principal Investigators:
Andre Revil & Mike Batzle (Colorado School of Mines)
Ezra Zemach (ORMAT)
Objectives of the project

• Geologically-constrained geophysical inversion + specific attributes
• Joint inversion (stochastic/deterministic) for ground water flow imaging
• Combined passive and active geophysical methods + time lapse
• Application to Pagosa Springs to explain the plumbing system
• Application to Jersey Valley (Nevada, 10 MW) to reinject water

Impact on costs (consistent with Geothermal Technologies Office’s goals)

• Decrease of the costs of drilling through better characterization of targets
• Better management of existing fields through time lapse geophysics
• Methodologies can be easily transferred to other DOE test sites
• ORMAT can use the new approaches for both exploration/production
  (see issue with the reinjection of water at Jersey Valley, NV)
Scientific/Technical Approach

**PHASE 1**
(2011-2013)
- Task 1: Assemble & Assess Data (Stromboli, Pagosa, Jersey)
- Task 2: Formulate Joint Inversion Model
- Task 3: Establish Database
- Task 4: Rock Samples Gathered from Jersey Valley
- Task 5: Testing of the Electromagnetic System
- Task 6: Acquisition Planning (Pagosa + Jersey)

**PHASE 2**
(2014-2015)
- Task 7/13: Permitting
- Task 8: Utilize Jersey Valley Data in Initial Inversion
- Task 9: Jersey Valley Data Set 1
- Task 10: Joint inversion of Jersey Valley data set 1
- Task 11: Interpret inversion results with geologic information provided
- Task 12: Acquisition Planning
- Task 14: Second Joint Inversion Model for Jersey Valley
- Task 15: Collect Jersey Valley Data Set 2
- Task 16: Joint inversion of Jersey Valley Data 2
- Task 17: Interpret inversion results w/geologic information
- Task 18: Commercialization
- Task 19: Document Software for Public Release
Scientific/Technical Approach

a. Image-guided inversion and interpolation

- Raw resistivity data
  - Gauss-Newton inversion
  - Resistivity tomogram

- Geological information
  - Expertise from a Geologist
  - Geological cross-section

- Revised geological cross-section
  - Image-guided inversion
  - Revised resistivity tomogram
    - Interpolation
    - Revised resistivity tomogram
      - Image-guided inversion
      - Revised geological cross-section

b. Data fusion

(Revil et al., JVGR, 2015)

- Tomogram 1
  - Attribute 1
  - $0 \leq \mathcal{I}_1 \leq 1$

- Tomogram 2
  - Attribute 2
  - $0 \leq \mathcal{I}_2 \leq 1$

- Combined image
  - $\mathcal{I} = \mathcal{I}_1 \mathcal{I}_2$

- Combined attributes
Scientific/Technical Approach

Application to Pagosa Springs (CO)

(Zhou et al., GJI, 2014)

Image-guided inversion: Improved tomograms and updated geological models
S/T Approach

Initial geology

Updated geology

Definition of new faults
Not visible at the surface because of the Mancos shale

Pagosa Springs (CO)
Geologically-constrained geophysical inversion

Joint inversion with facies optimization and petrophysical clustering

1) Application to the inversion of gravity and resistivity (MT)
2) Going from prior to posterior geological models (faults, facies)
3) Can be used with normalized attributes to refine targets
Scientific/Technical Approach

Joint inversion of Gravity and resistivity (galvanometric / MT)

Petrophysical clustering

Limitation: Only 2D so far!

Work submitted to “Geophysics”
Accomplishments, Results and Progress

a) Develop a new approach for the time-lapse joint inversion of geophysical data: Done
b) Develop a preliminary technique of image-guided inversion of geophysical data: Done
c) Develop geologically-constrained joint inversion using the level set technique: Done
d) Perform the 3D tomography of Stromboli using gravity and resistivity data: Done
e) Large-scale self-potential survey can be used to assess the geometry of a geothermal field: Done
f) Application to Pagosa Springs to understand its plumbing system: Done
g) Application to Jersey Valley to understand the hydrogeology & assist ORMAT: in progress

Jersey Valley (4 years ago and now)

1210 gravity stations, and 221 MT stations
The valley is bordered by a set of faults, which exhibit upward and downward flow.
Accomplishments, Results and Progress

3D model (be used for ground water flow modeling)

1210 gravity stations, and 221 MT stations

18 profiles total to build a 3D model
Accomplishments, Results and Progress

1) Negative anomalies: areas of downward flow
2) Reinjection should be done in this areas

1435 SP stations

Power Plant
Publications (11 peer-reviewed)


Award: A. Revil just received the Nishida award from Japan Geoscience Union
Future Directions

May (1) Ground water flow model performed (steady state) (2) Computation of the associated self-potential field. (3) Perturbation of the ground water flow model consistent with the measured self-potential data. End of April and in preparation of the presentation for the DOE meeting in Westminster.

June (1) DOE meeting and presentation of the results. (2) Field camp of Geophysics at Pagosa Springs (3) Acquisition of additional data (mostly MT and gravity) at Pagosa Springs (see description in the last report) to demonstrate the proof of concept on another target. (4) Final attempts to produce a geological model and a hydrogeological model consistent with all available geophysical data (SP, MT, gravity) and geological knowledge of the area. (5) Try to extend in 3D the codes.

July-August. (1) Finish and submit the last papers a) Stromboli (we never submitted the paper on Phase 1 regarding the 3D inversion of resistivity). b) Paper on the hydrogeology of Jersey Valley. (2) Finish the final report for DOE.

<table>
<thead>
<tr>
<th>Milestone or Go/No-Go</th>
<th>Status &amp; Expected Completion Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>End of the project</td>
<td>August 2015</td>
</tr>
</tbody>
</table>
Summary

- New techniques for the joint inversion of geophysical data
- Geologically-constrained geophysical inversion
- Self-potential can be used to track ground water flow
- Normalized attributes to delineate geothermal targets

- Successful application to volcanic systems (Phase 1)
- Delineation of the plumbing system of Pagosa Springs
- Determination of upflow/downflow in Jersey Valley