Fracture Network and Fluid Flow Imaging for EGS Applications from Multi-Dimensional Electrical Resistivity Structure

Principal Investigator: Philip E. Wannamaker
University of Utah
Energy & Geoscience Institute

May 18, 2010

This presentation does not contain any proprietary confidential, or otherwise restricted information.
• Project Context:
  – Timeline
    • Project start date: January 6, 2010
    • Project end date: January 6, 2013
    • Percent complete: 5%
  – Budget
    • Total project funding: $699,863
    • DOE share: $559,485
    • Awardee share: $140,378
    • Funding for PY10 (total): 244,331
  – Barriers
    • Lack of available and reliable resource information
    • High exploration risks
    • Inadequate site selection, characterization, resource assessment
  – Partners
    • ENEL North America (ENA) Ltd. (informal)
    • Virginie Maris (Post-Doctoral Scholar, beginning June)
    • Michal Kordy (Ph.D Student, arriving August)
Versatility and Efficiency in Imaging Fluid Flow via Electrical Resistivity

• 1), Develop a 3-D code for simulating EM responses at the surface of the earth with topographic variations. To start, two platform choices will be pursued to determine the superior approach.

• 2), Incorporate the selected simulation code and the inversion parameter jacobians that follow from it into an existing inversion algorithm for imaging and monitoring and improve its efficiency.

• 3), Parallelize the inversion code on new-generation multi-core workstations to achieve fast calculations within a single, cost-efficient, shared memory processing (SMP) box.

• 4), Apply the final algorithm to two important geothermal field MT data sets, one from an extensional system and one from an andesitic system.
Relevance/Impact of Research

Coso Geothermal Field, California
3-D Inversion Slices, East Flank MT Survey
(Maris, in prep.)
Relevance/Impact of Research

Coso Geothermal Field, California
3-D Inversion Slices, East Flank MT Survey
(Maris, in prep.)
Relevance/Impact of Research

Inversion slices compared to production/lost circ (Maris, in prep.)

(production/lost circ redrawn after Newman et al., 2008; temperature contours after Adams et al., 2000)
Scientific/Technical Approach

Electromagnetic Simulation and Inversion with Conformal Receiver Surfaces (Topography)

MT3DI

Finite Difference Topo Model

Loki-3D

Deformable Mesh Cutout View

Madden et al., Newman et al., Siripunvaraporn et al., Sasaki

Sugeng, Wilson, Annetts, Raiche

Graphics after Art Raiche
Scientific/Technical Approach

Influence of Topography/Errors When Ignored
Scientific/Technical Approach

Evaluate Two Independent Approaches
Select Superior Approach for Further Development

\[ \oint H \cdot ds = \iint \sigma E \cdot ds \]
\[ \oint E \cdot ds = \iint \mu \omega H \cdot ds \]

Finite Difference Staggered Grid

- Difference eq’ns originated from integral forms of Maxwell’s eq’ns
- Generalize to cell vertex positions from heights, widths

\[ \frac{E_{xt} - E_{xb}}{\Delta z} \cdot (\frac{E_{zr} - E_{zl}}{\Delta x}) \cdot i\omega \mu H_y = \]

Finite Element Deformable Mesh

- Topography already incorporated
- Only solves for H at present
- Need to derive E through double spatial derivatives
Scientific/Technical Approach

Cove Fort, UT
(~800 m elevation change)

Karaha, Java, Indonesia
(~1000 m elevation change)
Scientific/Technical Approach

Multi-Core Workstation Parallelization of 3D FD MT Inversion
(Maris and Wannamaker, 2010, C&G, in press)

Modified Cholesky
Parameter Step
(Excellent Scalability,
Preserves $N^3$ ops.)

Paul Otellini, CEO Intel,
holds 80-core chip wafer
(PBS News Hour archive)

Bi-conjugate
Gradient
Forward,
Jacobians
(Likely limited by
processor-RAM bus speeds)

Dual quad-core
Xeon 5355 2.66 GHz
16 GiB RAM
Accomplishments, Expected Outcomes and Progress

Initial Efforts:
• Obtained Loki-3D algorithm, reviewed code structure with developer Dr. Glenn Wilson, compiled and ran test examples.
• Completed publication, now in press, on parallelization of inversion code on multi-core, single-box workstations.
• Continued exercising limits of existing inversion code at workstation level using Coso MT data set.
• Investigated relationship between seismicity and resistivity structure while concluding Ph.D thesis research of Maris.

Plans:
• Incorporation of plane-wave sources into Loki-3D, verification of magnetic field responses.
• Experiment with various interpolation approaches for spatial derivatives to yield the electric field.
• Generalize finite difference equations for arbitrary prism geometries based upon integral forms of Maxwell’s equations.
• Select superior forward problem module for inversion platform development.
Seismicity tends to cluster along conductor-resistor margins. Fluidized conductive zones are soft, don’t support stress. Conductive zones can provide fluids to trigger eq’s in resistors.
Model slices with seismicity overlay (Maris, in prep.).
Correlation between seismicity and conductor margins good.
### Table 1. Time Line of Research Tasks

<table>
<thead>
<tr>
<th>Task</th>
<th>Year 1</th>
<th>Year 2</th>
<th>Year 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loki-3D Recon</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FD Cmpl., CF flat inv.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Loki E-fields, Maris FD deform</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FE/FD choice</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Parameter Sensitivities</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inverse Integration</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SMP Inverse Parallelization</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Deformed Mesh Topo &gt; Stepped Mesh</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cove Fort Final Topo Inv.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Karaha Final Topo Inv.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Final Writeup and Submission</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Graduate Student Supervision</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Table 2. Cost Profile for Project Tasks

<table>
<thead>
<tr>
<th>Task</th>
<th>Year 1</th>
<th>Year 2</th>
<th>Year 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loki-3D Recon</td>
<td>$56,083</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FD Cmpl., CF flat inv.</td>
<td>$93,471</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Loki E-fields, Maris FD, w/s purch.</td>
<td>$94,777</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Year 1 Total</strong></td>
<td>$244,331</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Parameter Sensitivities</td>
<td>$92,528</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inverse Integration</td>
<td>$92,528</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SMP Inverse Parallelization</td>
<td>$37,011</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Year 2 Total</strong></td>
<td>$222,067</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cove Fort Final Topo Inv.</td>
<td>$77,822</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Karaha Final Topo Inv.</td>
<td>$58,366</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Final Writeup and Submission</td>
<td>$97,277</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Year 3 Total</strong></td>
<td>$233,465</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Total for Project</strong></td>
<td>$699,863</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Rules for Activity Intervals:
- Gray segments indicate the activity interval.
- A yellow circle marks the decision point.

1. 3-D Forward Problem Development
2. Inverse Integration/Parallelization
3. Post-Doc/Grad Student Supervision
4. Inversion of Geothermal Data Sets
Future Directions

- **PY10:** Augmentation of the Loki-3D algorithm for plane-wave source H-fields, test interpolation schemes for E-field, verify topography. Embark on generalizing finite difference platform for deformable mesh cells, verify topography.
- **PY11:** Decision point- Choice of superior forward platform for topographic simulation. Installation of jacobians into chosen platform, initial inverse testing. Parallelization of inverse on multi-core workstation.
• Electrical resistivity emerging as key indicator of physical state, fluid distributions in geothermal systems.
• MT is the method of choice for depths beyond 1-2 km.
• Image accuracy with rugged terrains requires explicit accounting of receiver x-y-z distributions.
• Useful inversion capability affordable by many is becoming possible with multi-core architectures.
• Need to train young professionals to achieve state-of-the-art, and beyond.
Publications Receiving Support from this Grant:

Coso California Geothermal Field, MT Station Map