Integrated 3D Geophysical Inversion and Geological Modelling for Improved Geothermal Exploration and Well Targeting

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The Geothermal Exploration Process

Only one thing matters…
The Geothermal Exploration Process

Finding the right place to drill!
The Geothermal Exploration Process

Acquire Property

There is an economic resource!

You can’t find it

You do find it

- Collect right kind of data
- Collect right amount of data
- Interpret data correctly
- All data informs selection of drill targets
- DRILL IN RIGHT PLACE!

There is not an economic resource!
The Geothermal Exploration Process

1. Acquire Property
   - If there is an economic resource:
     - You can’t find it
       - Collect right kind of data
     - You do find it
       - Collect right amount of data
       - Interpret data correctly
     - You keep exploring
     - All data informs decision to abandon project
   - If there is not an economic resource:
     - You abandon project
Geothermal Exploration in the 21st Century

- Geothermal exploration is difficult
- Technology transfer from other industries
- Mineral industry has much to offer geothermal exploration
- Geologic environment is very similar
  - Volcanic-hosted geothermal systems
  - Deep circulation fault-hosted systems
Geothermal Exploration in the 21st Century

• To reduce resource risk, we **must** explore better

• How?
Case Study:
McCoy Geothermal Prospect
Central Nevada

3D Temperature Modelling
3D Gravity, Magnetic, and MT Inversion Modelling
3D Geological Modelling and Targeting
McCoy Geothermal Prospect – Central Nevada

“3D Earth Model” Volume
GEOLOGY – 3D model

Place cross-sections in 3D space

2x vertical exaggeration
GEOLOGY – 3D model

Add surface geologic map.

Make sure it’s consistent with cross-sections.

2x vertical exaggeration
Place cross-sections in 3D space

2x vertical exaggeration
GEOLOGY – 3D model

Add mapped faults and extend them to depth

2x vertical exaggeration
GEOLOGY – 3D model

Add top of the Havallah sequence (Pumpernickel formation)

2x vertical exaggeration
GEOLOGY – 3D model

Add top of the Dixie Valley Formation

2x vertical exaggeration
GEOLOGY – 3D model

Add top of the Favret Formation

2x vertical exaggeration
GEOLOGY – 3D model

Add top of the Augusta Mountains Formation

2x vertical exaggeration
GEOLOGY – 3D model

Add top of the Tuff of Hole-in-the-wall

2x vertical exaggeration
GEOLOGY – 3D model

Add top of the Edwards Creek Tuff

2x vertical exaggeration
GEOLOGY – 3D model

Add topography

Geologic model built with an implicit modelling engine

2x vertical exaggeration

New data? → Update model
How do we combine this...

...with this...

...to generate value?
Traditional geophysical data interpretation is insufficient for today’s exploration challenges.
Traditional geophysical data interpretation is insufficient for today’s exploration challenges

- Traditional, map-based geophysical interpretation doesn’t extend into 3D
Traditional geophysical data interpretation is insufficient for today’s exploration challenges

- Traditional, map-based geophysical interpretation doesn’t extend into 3D
- Traditional, 3D geophysical inversion modelling is “unconstrained” and outputs blobby 3D models that lack geological realism
## Rock Physical Properties – the critical link between geology and geophysics

<table>
<thead>
<tr>
<th>Formation</th>
<th>Age</th>
<th>Rock type</th>
<th>Gravity</th>
<th>Magnetics</th>
<th>MT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Density (g/cm³)</td>
<td>Magnetic Susc. (S.I.)</td>
<td>Resistivity (ohm-m)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Average</td>
<td>Average</td>
<td>Min.</td>
</tr>
<tr>
<td>Tuff of McCoy Mine</td>
<td>Tertiary</td>
<td>Rhyolite tuff</td>
<td>2.35</td>
<td>0.0011</td>
<td>no data</td>
</tr>
<tr>
<td>Edwards Creek Tuff</td>
<td>Tertiary</td>
<td>Rhyolite tuff</td>
<td>2.35</td>
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<td>Rhyolite tuff</td>
<td>2.35</td>
<td>0.0011</td>
<td></td>
</tr>
<tr>
<td>Augusta Mtns Formation</td>
<td>Triassic</td>
<td>Fossiliferous limey mudstone</td>
<td>2.45</td>
<td>0.00013</td>
<td>20</td>
</tr>
<tr>
<td>Favret Formation</td>
<td>Triassic</td>
<td>Fossiliferous limey, sandy mudstone</td>
<td>2.50</td>
<td>0.00013</td>
<td>50</td>
</tr>
<tr>
<td>Dixie Valley Formation</td>
<td>Triassic</td>
<td>Conglomerate, sandstone &amp; siltstone</td>
<td>2.55</td>
<td>0.000249</td>
<td>20</td>
</tr>
<tr>
<td>Havallah Sequence (Pumpernickel Formation)</td>
<td>Pennsylvanian</td>
<td>Siliceous siltstone and chert</td>
<td>2.55</td>
<td>0.000225</td>
<td>no data</td>
</tr>
</tbody>
</table>

*Note: MT data not available for all formations.*
Constraints for Geophysical Modelling

- Major Lithologic Boundaries
- Physical Properties of Major Rock Types (measured or from rock property database)
- Downhole Geophysical Logs
- Hard or Soft Constraints

Put it all together → 3D Earth Model
McCoy Geothermal Gravity dataset

Unconstrained Inversion
McCoy Geothermal Gravity dataset

Starting geologic model assigned with densities and faults.
McCoy Geothermal Gravity dataset

Constrained Inversion

Turned unconstrained inversion result on its head!
McCoy Geothermal Gravity dataset

Unconstrained vs. Constrained Inversion
Turned unconstrained inversion result on its head!
McCoy Cross-Section B-B’

Geology

Mira Geoscience...modelling the earth
McCoy Cross-Section B-B'

Unconstrained Gravity Model

Density
McCoy Cross-Section B-B’

Geology

Mira Geoscience...modelling the earth
McCoy Cross-Section B-B’

Constrained Gravity Model

Density
Quantitative Models not Conceptual Models

- Concepts aren’t convincing to skittish investors
- Quantitative evidence is convincing
- What should we make instead of conceptual models?
Quantitative Models not Conceptual Models

- Data-rich, 3D geothermal exploration models
- Built from multiple lines of independently-derived, quantitative evidence

- Robust, 3D architecture
  - Define 3D exploration volume
  - Build surfaces (rock contacts and faults)
  - Discretize lithologic blocks into cells
  - Populate cells with information (rock type, temp, density, etc.)

(Our friends in O&G and mining do this... Shared Earth Model, Common Earth Model etc.)
Historic Drillholes

52 Shallow temperature gradient wells (30-100 m deep)

6 Intermediate depth exploration wells (594-765 m deep)
Historic Drillholes

52 Shallow temperature gradient wells (30-100 m deep)

6 Intermediate depth exploration wells (594-765 m deep)
DRILLHOLES in 3D space

- Downhole Geology Tests Geologic Model
- Visualize Downhole Temperature within 3D Geologic Model
Temperature Gradient Map in Plan View

3D Temperature Iso-surfaces Derived from Downhole Temperature Profiles in Shallow Wells

Topography

40 °C
30 °C
20 °C

Mira Geoscience
...modelling the earth
Analysis of Temperature Interpolated Between Wells to Identify Zones of Thermal Upwelling
Select and Rank Drill Targets Based Upon Quantitative Evidence

- Deciding where to drill…
- Secret to reducing resource risk…
- We need better tools to select better drill targets

(Mining industry already has these tools…)
Select and Rank Drill Targets Based Upon Quantitative Evidence

- Quantitative targeting methods
  - Knowledge-driven
  - Data-driven (weights-of-evidence)

- Define exploration criteria
  - What is important to me to help me find what I’m looking for?
    
    e.g. Distance to faults
         Distance to fault intersections
         Distance to a high temperature portion of a well
         Within a specific, permeable rock type
         Below a high conductivity (clay) layer
         Distance to geologic contact
         etc.
... 3D Geothermal Potential Mapping

- fault intersection proximity
- fault proximity
- rock type
- geologic contact proximity
- temperature
- MT resistivity

Mira Geoscience
...modelling the earth

3D geothermal potential index
## Exploration Targeting

<table>
<thead>
<tr>
<th>Exploration Criteria</th>
<th>Targeting property on 3D voxet</th>
<th>Weight</th>
<th>Classes</th>
<th>Scores</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proximity to permeable geologic contact</td>
<td>Distance to Tertiary-Triassic boundary</td>
<td>2</td>
<td>0 m - 100 m, 100 m - 200 m, 200 m - 500 m, 500 m - 1000 m, &gt;1000 m</td>
<td>4, 3, 2, 1, 0</td>
</tr>
<tr>
<td>Proximity to fault intersection (likely permeable)</td>
<td>Distance to fault intersections</td>
<td>4</td>
<td>0 m - 100 m, 100 m - 200 m, 200 m - 500 m, 500 m - 1000 m, &gt;1000 m</td>
<td>4, 3, 2, 1, 0</td>
</tr>
<tr>
<td>Proximity to NE-SW oriented fault (most likely orientation to be dilatant)</td>
<td>Distance to NE-SW fault surfaces</td>
<td>4</td>
<td>0 m - 100 m, 100 m - 200 m, 200 m - 500 m, 500 m - 1000 m, &gt;1000 m</td>
<td>4, 3, 2, 1, 0</td>
</tr>
<tr>
<td>Proximity to any known fault (possibly permeable)</td>
<td>Distance to fault surfaces</td>
<td>2</td>
<td>0 m - 100 m, 100 m - 200 m, 200 m - 500 m, 500 m - 1000 m, &gt;1000 m</td>
<td>4, 3, 2, 1, 0</td>
</tr>
<tr>
<td>Distance to well water samples with high geothermometry temperatures</td>
<td>Distances to wells 66-8 and 28-18</td>
<td>5</td>
<td>0 m - 100 m, 100 m - 200 m, 200 m - 500 m, 500 m - 1000 m, &gt;1000 m</td>
<td>4, 3, 2, 1, 0</td>
</tr>
</tbody>
</table>

\[
\text{GPI} = \frac{\sum_{i}^{n} S_{ij} W_{i}}{\sum_{i}^{n} W_{i}}
\]
Exploration Targeting

High Geothermal Potential Index (red)

Highest Ranked Targets (spheres)

Slice through GPI model at ~1300 m asl
Select and Rank Drill Targets Based Upon Quantitative Evidence

- Use geostatistics to rank drill targets based upon a rigorous synthesis of all the available exploration data
Select and Rank Drill Targets Based Upon Quantitative Evidence

- Prioritize drill targets from best to worst
- Independent, mathematical approach which makes for a good comparison with subjective expert opinion
Thank you!