Developing an Integrated Exploration Program

Geothermal Resources Council Exploration Workshop
September 2014
Why are item nos. 1-4 important?
To successfully integrate geothermal exploration data, we need to:
- Identify the correct target
- Formulate a clear exploration plan
- Execute the plan systematically with clearly identified objectives
EXPLORATION CLASSIFICATION SYSTEMS

- Variety of Exploration Classification Systems in the literature
  - Temperature
  - Chemical Characteristics
  - Geologic Setting
  - Permeability
  - Heat Transport (Convection, Advection, Conduction)
  - Magmatic – Amagmatic
  - Hydrothermal – Enhanced Geothermal System
  - Resource Type

- The systems are not stand alone and many systems combine some of the elements indicated.
- Several of these classifications are discussed in more detail below.
EXPLORATION CLASSIFICATION SYSTEMS

Temperature based classification system (Williams et al. 2011).

Temperature

High
Intermediate
Low
Ultra High
Moderate
Low
Very Low
Non-Electrical
# EXPLORATION CLASSIFICATION SYSTEMS

<table>
<thead>
<tr>
<th>Exploration Setting</th>
<th>Topography</th>
<th>Depth to Resource</th>
<th>Surface Manifestations</th>
<th>Permeability</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Type A: Magma-heated Dry Steam Resource</strong> <em>(e.g., The Geysers, California, USA)</em></td>
<td>Rugged? Mountainous?</td>
<td>Usually deep (2.5-4km)</td>
<td>Restricted</td>
<td>Low to moderate fracture permeability (FP)</td>
</tr>
<tr>
<td><strong>Type B: Andesitic Volcanic Resources</strong> <em>(e.g., Philippines, Indonesia, Central &amp; South America)</em></td>
<td>Usually mountainous</td>
<td>Deep to moderate</td>
<td>Restricted depending on depth and shallow ground water</td>
<td>Low to moderate FP – often high</td>
</tr>
<tr>
<td><strong>Type C: Caldera Resources</strong> <em>(e.g., Medicine Lake, Valles Caldera, Yellowstone, USA)</em></td>
<td>Ring fractures; often rugged with gentle floor topography</td>
<td>Moderate to shallow</td>
<td>Common</td>
<td>Low to moderate FP – often think tuff units</td>
</tr>
<tr>
<td><strong>Type D: Sedimentary-hosted, Volcanic-related Resources</strong> <em>(e.g., Imperial Valley, California, USA)</em></td>
<td>Usually low topography</td>
<td>Usually deep (2.5-4km)</td>
<td>Very restricted</td>
<td>Variable?</td>
</tr>
<tr>
<td><strong>Type E: Extensional Tectonic, Fault-controlled Resources</strong> <em>(e.g., Great Basin, USA)</em></td>
<td>Rugged on upthrown block, low on valley floor</td>
<td>Usually deep (2.5-3.5km)</td>
<td>Usually restricted to fault traces</td>
<td>Dominantly fault controlled</td>
</tr>
<tr>
<td><strong>Type F: Oceanic Islands, Basaltic Provinces</strong> <em>(e.g., Hawaii &amp; Iceland)</em></td>
<td>Rugged to flat</td>
<td>Shallow (1-2 km)</td>
<td>Common</td>
<td>High horizontal permeability, variable vertical permeability</td>
</tr>
</tbody>
</table>

*Geologic Setting based* classification system (after Williams et al. [2011] from Brophy of EGS, Inc.)
**EXPLORATION CLASSIFICATION SYSTEMS**

<table>
<thead>
<tr>
<th>RESOURCE TYPE</th>
<th>EXPLORATION METHODOLOGIES</th>
<th>Prospect Ranking</th>
<th>Exploration Well Targeting</th>
<th>Field Delineation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Regional Reconnaissance</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fault Circulation - Hot Spring</td>
<td>fluid geochemistry, satellite imaging, regional tectonics</td>
<td>shallow Temperature Gradient Holes (TGHs), gravity, airborne imaging</td>
<td>field geology, alteration mapping, area-specific geophysics</td>
<td>Drilling</td>
</tr>
<tr>
<td>Fault Circulation - Blind</td>
<td>satellite/airborne imaging, regional heat flow &amp; seismicity, tectonics</td>
<td>shallow TGHs, gravity, airborne imaging</td>
<td>field geology, alteration mapping, area-specific geophysics</td>
<td>Drilling</td>
</tr>
<tr>
<td>Magma Hydrothermal - Hot Spring</td>
<td>fluid/rock geochemistry, volcanic age/type</td>
<td>MT-TDEM, field geology, rock geochemistry &amp; age dating</td>
<td>Deep TGH, detail MT-TDEM, field geology, alteration mapping, area-specific geophysics</td>
<td>Drilling</td>
</tr>
<tr>
<td>Magma Hydrothermal - Blind</td>
<td>volcanic age/type, satellite imaging, airborne imaging/ EM</td>
<td>MT-TDEM, field geology, rock geochemistry &amp; age dating</td>
<td>Deep TGH, detail MT-TDEM, field geology, alteration mapping, area-specific geochemistry</td>
<td>Drilling</td>
</tr>
<tr>
<td>Magma Hydrothermal - Supercritical</td>
<td></td>
<td></td>
<td>Deep high-Temp fluid sampling (in known field)</td>
<td>Drilling</td>
</tr>
<tr>
<td>EGS - lithology</td>
<td>regional heat flow and basin analysis</td>
<td>heat flow, basin analysis, analogues</td>
<td>reflection seismic, sediment petrophysics</td>
<td>Reflection seismic</td>
</tr>
<tr>
<td>EGS - structure</td>
<td>heat flow, reflection seismic, satellite imaging, first-motion</td>
<td>heat flow, analogues</td>
<td>Deep heat flow, reflection seismic</td>
<td>Drilling</td>
</tr>
<tr>
<td>EGS – Hot Dry Rock</td>
<td>heat flow, reflection seismic, satellite imaging, first-motion</td>
<td>heat flow, analogues</td>
<td>Deep heat flow, reflection seismic</td>
<td>N/A</td>
</tr>
</tbody>
</table>

*Resource Type based classification system (after IPGT Exploration Working Group 2011).*

**Note:** Exploration methodology listing per stage is not complete.
### Exploration Classification Systems

<table>
<thead>
<tr>
<th>Resource Type Type</th>
<th>Exploration Methodologies</th>
<th>Prospect Ranking</th>
<th>Exploration Well Targeting</th>
<th>Field Delineation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sedimentary Basin – Geopressured</td>
<td>oil and gas drilling</td>
<td>heat flow, basin analysis, analogues</td>
<td>seismic studies</td>
<td>drilling, reflection seismic</td>
</tr>
<tr>
<td>Sedimentary Basin – Coproduction</td>
<td>oil and gas drilling</td>
<td>heat flow, basin analysis, analogues</td>
<td>seismic studies</td>
<td>drilling, reflection seismic</td>
</tr>
<tr>
<td>Sedimentary Basin – normally pressured, sediment hosted</td>
<td>heat flow and temperature gradient studies, oil and gas drilling</td>
<td>heat flow, basin analysis, analogues</td>
<td>seismic studies</td>
<td>drilling, reflection seismic</td>
</tr>
<tr>
<td>Sedimentary Basin – normally pressured, fracture hosted</td>
<td>heat flow and temperature gradient studies, oil and gas drilling</td>
<td>heat flow, basin analysis, analogues</td>
<td>seismic studies</td>
<td>drilling, reflection seismic</td>
</tr>
</tbody>
</table>

*Resource Type (cont’d) based* classification system (after IPGT Exploration Working Group 2011).

*Note:* Exploration methodology listing per stage is not complete.
### Heat Transport Type based classification

(from OpenEI [http://en.openei.org/wiki/Moeck-Beardsmore_Play_Types, after Moeck and Beardsmore [2014]])

<table>
<thead>
<tr>
<th>Type</th>
<th>Geologic Setting</th>
<th>Heat Source</th>
<th>Dominant Heat Transport Mechanism</th>
<th>Storage Properties of Reservoir</th>
<th>Regional Topseal or Caprock</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CV-1: Magmatic</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CV-1a: Extrusive</td>
<td>Magmatic Arcs, Mid Oceanic Ridges, Hot Spots</td>
<td>Active Volcanism, Shallow Magma Chamber</td>
<td>Magmatic-hydrothermal Circulation</td>
<td>---</td>
<td>Extensive Low Permeability Clay-rich Layers</td>
<td>Java</td>
</tr>
<tr>
<td>CV-1b: intrusive</td>
<td>Magmatic Arcs, Mid Oceanic Ridges, Hot Spots</td>
<td>Active Volcanism, Shallow Magma Chamber</td>
<td>Magmatic-hydrothermal Circulation, Fault Controlled</td>
<td>---</td>
<td></td>
<td>Taupo Volcanic Zone</td>
</tr>
<tr>
<td><strong>CV-2: Plutonic</strong></td>
<td></td>
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</tr>
<tr>
<td>CV-2a: Recent or Active Volcanism</td>
<td>Convergent Margins with Recent Plutonism (&lt; 3 Ma), Young Orogens, Post-orogenic Phase</td>
<td>Young Intrusion + Extension, Felsic Pluton</td>
<td>Magmatic-hydrothermal Circulation, Fault Controlled</td>
<td>---</td>
<td></td>
<td>Larderello</td>
</tr>
<tr>
<td>CV-2b: Inactive Volcanism</td>
<td>Convergent Margins with Recent Plutonism (&lt; 3 Ma), Young Orogens, Post-orogenic Phase</td>
<td>Young Intrusion + Extension, Felsic Pluton, Heat Producing Element in Rock</td>
<td>Hydrothermal Circulation, Fault Controlled</td>
<td>---</td>
<td>Low Permeability Caprock</td>
<td>The Geysers</td>
</tr>
<tr>
<td><strong>CV-3: Extensional Domain</strong></td>
<td>Metamorphic Core Complexes, Back-arc Extension, Pull-apart Basins, Intracontinental Riffs</td>
<td>Thinned Crust + Elevated Heat flow, Recent Extensional Domains</td>
<td>Fault Controlled, Hydrothermal Circulation</td>
<td>---</td>
<td></td>
<td>Basin and Range, Soultzeren, Forêts</td>
</tr>
</tbody>
</table>
**Exploration Classification Systems**

<table>
<thead>
<tr>
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<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Conduction Dominated</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>CD-1: Intracratonic Basin</strong></td>
<td>Intracratonic/Rift Basins, Passive Margin Basins</td>
<td>Lithospheric Thinning and Subsidence</td>
<td>Litho/Biofacies Controlled</td>
<td>High Porosity/Low Permeability Sedimentary Aquifers</td>
<td>---</td>
<td>North German Basin</td>
</tr>
<tr>
<td><strong>CD-2: Orogenic Belt</strong></td>
<td>Foreland Basins within Fold-and-thrust Belts</td>
<td>Crustal Loading and Subsidence Adjacent to Thickened Crust</td>
<td>Fault/Fracture Controlled, Litho/Biofacies Controlled</td>
<td>High Porosity/High Permeability or High Porosity/Low Permeability Sedimentary Aquifers</td>
<td>---</td>
<td>Southern Canadian Cordillera, Molasse Basin</td>
</tr>
<tr>
<td><strong>CD-3: Crystalline Rock - Basement</strong></td>
<td>Intrusion in Flat Terrain</td>
<td>Heat Producing Element In Rock, Hot Intrusive Rock</td>
<td>Hot Dry Rock, Fault/Fracture Controlled</td>
<td>Low Porosity/Low Permeability Intrusive Rock (Granite)</td>
<td>Insulating Caprock</td>
<td>Fenton Hill</td>
</tr>
</tbody>
</table>

*Heat Transport Type (cont’d) based classification continued from previous slide*
EXPLORATION CLASSIFICATION SYSTEMS

Indonesian Geothermal Systems (modified after Suryantini (2013))

- No Particular Classification for the Geothermal System.
- Common classification used are:
  - Based on Reservoir Temperature (Hochstein, 1990; Hochstein and Browne, 2000);
    - High Temperature/High Enthalpy (>225°C)
    - Medium Temperature/Medium Enthalpy (125°C – 225 °C)
    - Low Temperature/Low Enthalpy (<125 °C)
  - Based on fluid chemistry (related to heat source) (Hochstein and Browne, 2000);
    - Volcanic System (or Volcanic Hydrothermal System)
    - Non Volcanic System
- Potential Classification is based on the result of G-G-G Survey (Stage of Geothermal Development according to Indonesian Law UU No 27 / 2003)
EXPLORATION CLASSIFICATION SYSTEMS

- Variety of Classification Systems
  - Temperature
  - Chemical Characteristics
  - Geologic Setting
  - Permeability
  - Heat Transport (Convection, Advection, Conduction)
  - Magmatic – Amagmatic
  - Hydrothermal – Enhanced Geothermal System
  - Resource Type

Example Generalized Conceptual Models

Choice of classification system will depend on such considerations as company objectives and the geothermal environment/province being explored.

Choice of classification system will impact the details of a conceptual model developed for the prospect/project.
WHAT DO WE NEED TO KNOW!

- Geology
  - Structure
  - Stratigraphy
  - Stress

CONCEPTUAL MODEL
As soon as we have some data, we want to build a conceptual model and modify it as we learn more about the system.

CONCEPTUAL MODEL is a qualitative and quantitative document / depiction of what is believe to be true of the system being investigated.
Consider the statement in an earlier presentation at this workshop and I paraphrase, “IQ gets you to the area of interest through geoscientific data synthesis and integration, NQ (drilling) makes the discovery.”

Is exploring by drilling only, with no geoscience framework, a good idea?
This is one of many different exploration schema. But they are all essentially the same. Other example schema will be presented and cross-correlated with this one. The key is to progress from the least expensive methods to the most expensive ones based on sound, geoscientific data and your conceptual model.
**Exploration Schema**

**Exploration**: a Structured Methodology

Data is collected, synthesized and integrated.

It is an iterative process requiring a continuous refinement of the prospect’s conceptual model which is fundamental for risk reduction.

“Exploration” occurs during all stages of a project.
EXPLORATION SCHEMA

Steps to Delineating a Geothermal Resource

Regional Reconnaissance
- Geophysics
  - Regional Seismicity
- Remote Sensing, Aerial Photos
  - JoSAT
  - Satellite Image Analysis
- Geology, Structure, Tectonics
  - Literature Search
  - Data Collection and Analysis
- Mineralogy, Petrology
- Geochemistry
- Petrophysics, Rock Mechanics

Prospect Identification
- Preliminary Resource Assessment (Phase 1)
  - Literature search pertains to all disciplines with relevant data and information
- Resource Assessment (Phase 2)
  - Geology Synthesis
  - Detailed Tectonic and Geologic Setting
  - Groundwater and Hot Spring Analyses
  - Characterization

Project Appraisal
- Resource Capacity Assessment (Phases 3 and 4)
  - Field Surveys
  - Field Mapping
  - Geology Synthesis
  - Fluid Flow
  - Stress/Strain Analysis

Figure modified after Walker et al. (2005)
EXPLORATION SCHEMA

Phase 1 - Preliminary Resource Assessment

Phase 2 - Resource Assessment

Also referred to as a Pre-Feasibility Assessment

Phases 3 & 4 - Resource Capacity Assessment

**EXPLORATION SCHEMA**

**Phase 1 - Preliminary Resource Assessment**

**Phase 2 - Resource Assessment**

**Phases 3 & 4 - Resource Capacity Assessment**

**Figure after IFC (2013)**
DEVELOPMENT SCHEMA

- Drill project area to develop sufficient production capacity for a commercial project
  - Primarily involves full-size geothermal wells

- Drill project area for injection, address production/injection issues, obtain deep fluid chemistry and determine reservoir properties

“Exploration activities” continue in development drilling but it is now focused on reservoir characterization (i.e., permeability continuity and controls). It also continues to be a data collection, integration and iteration process requiring a continuous refinement of the development project’s conceptual model and reduction of risk.
PRODUCTION PROCESS

- Drill make-up wells to maintain production
- Monitor and drill additional injection wells (as required)
- Locate and drill for additional injection water (as required)

“Exploration activities” continue in production but now it is entirely focused on reservoir maintenance and improvement (and continues to be a data integration and iterative process requiring a continuous refinement of the production project’s conceptual model.)
GEOTHERMAL “EXPLORATION” SUCCESS – PRIMARY RISK

- “Exploration” and drilling accounts for 40-60% of overall geothermal project costs.
- Despite development at a large number of sites across the western US, exploration success has not improved markedly in the past ~20 years and remains around 25%.
- Future research and development in exploration technologies should focus on those factors that most affect project success rates.
- Flow (and injection) rate per well, controlled by permeability, is the single most important factor in determining success of production and injection wells.

Exploration methods aimed at identifying and understanding features (structures, formations, etc.) controlling permeability at depth can most quickly benefit and improve exploration success and minimize risk.

Slide text after Iovenitti and Petty (2012)
INTEGRATION OF EXPLORATION DATA

- Dixie Valley Geothermal System, Nevada
  - Most highly characterized system in the Basin and Range in the public domain.
  - It has a considerable amount of geoscience data including well results.
  - Will use the EGS Exploration Methodology Project using the Dixie Valley Geothermal System, Nevada as a Calibration Site to exemplify exploration data integration.
    - Project results were focused was on EGS; however, many of the results and methodologies uses are also applicable to hydrothermal systems.
    - Data and information presented from:
      - Baseline (existing data) Conceptual Model (AltaRock Energy Inc., 2014a)
      - Enhanced (existing and new data) Conceptual Model (AltaRock Energy Inc., 2014b)

Calibration Area ~170km²

Project Area is 50x50km
INTEGRATION OF EXPLORATION DATA

- Regionally, the Project Area
  - Has extensive Quaternary hydrothermal alteration along range front and in certain areas of the footwall block.
  - Has hot springs exist along range-front fault and in the valley
  - Has fumarolic areas and evidence of paleo-hot springs (sinter deposits) along the range-front fault and in its footwall block.

[Image: Hydrothermal silica seam in colluvium on the footwall block of the range-front fault in Dixie Valley.]
Regionally, the Project Area

- Has extensive Quaternary hydrothermal alteration along range front and in certain areas of the footwall block.
- Has hot springs exist along range-front fault and in the valley
- Has fumarolic areas and evidence of paleo-hot springs (sinter deposits) along the range-front fault and in its footwall block.
- Lies within the Central Nevada Seismic Belt, a zone of focused contemporary seismicity with a NNE trend extending from the Walker Lane into central Nevada and has had the largest earthquakes ($M_w > 6-7$) recorded in Nevada over the last century.
INTEGRATION OF EXPLORATION DATA

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  - Lies within the Central Nevada Seismic Belt, a zone of focused contemporary seismicity with a NNE trend extending from the Walker Lane into central Nevada and has had the largest earthquakes ($M_w > 7$) recorded in Nevada over the last century.
  - Lies in the lowest topographical valley in western NV.
  - Occurs within an area of highest heat flow in the Great Basin, the Battle Mountain heat flow high.
Regionally, the Project Area

- Has extensive Quaternary hydrothermal alteration along range front and in certain areas of the footwall block.
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- Lies in the lowest topographical valley in western NV
- Occurs within an area of highest heat flow in the Great Basin, the Battle Mountain heat flow high.
- Coincides with a major lithospheric boundary separating thinner crust and lower surface elevation to the west from thicker crust and higher surface elevation to the east.
INTEGRATION OF EXPLORATION DATA - Geology

- **Stratigraphy** divided into 8 formations (7 major and 1 minor) based on field occurrence and EGS potential (also important for hydrothermal systems:
  1. **Q-Tbf** — Basin-filling sediments
  2. **Tmb** — Miocene basalt
  3. **Tv** — Oligocene silicic volcanics
  4. **Jz** — Humboldt Igneous Group
  5. **Jbr** — Boyer Ranch quartzite (minor formation)
  6. **Tr** — Triassic meta-sediments
  7. **Kgr** — Cretaceous-Tertiary (?) Granodiorite
  8. **Pz** — Paleozoic meta-sediments

Geoscience details are important in understanding a geothermal system. Knowing how to integrate and generalize these details is critical for a successful exploration program, and subsequent development and production.
INTEGRATION OF EXPLORATION DATA - Geology

Natural and Induced (primarily mine explosions) seismicity from 1900 to 2010 located by UNR within 100km (62mi) of the Dixie Valley project area. The depth range is zero to 19km (~12mi). Earthquakes in the Dixie Valley area are listed by USGS (PDE-current catalog-562 earthquakes, USHIS-historical catalog-123 earthquakes) and UNR catalogs and explosions identified at UNR (298 events). Faults are represented as yellow lines.

The N-S structure is important because if re-activated, the structural intersection of N/S- and NE-trending faults will form dilatation and compression zones promoting or restricting the upward flow of geothermal fluids.
INTEGRATION OF EXPLORATION DATA - Structure

- Identify all known / inferred faults and compile a structure map.
- N-trending faults related to an early Basin & Range extension (~8 mya):
  - These structures show apparent strike-slip motion under current stress field.
- Complex structural interactions at major intersections of N- and NE-trending faults are evident.

Note: Wells 45-14 and 66-21 are discussed in the “Basin and Range - Geophysical Case Study” presented in this workshop.
Intersection of N-trending (pre-8 mya B&R) and NE-trending (post-8 mya B&R) structures result, in the current stress regime, form:

- zones of compression
- zones of dilatation
- Dilatation zones are coincident with shallow thermal anomalies (right figure) along the bounding faults on both sides of the Stillwater Range.
INTEGRATION OF EXPLORATION DATA – Structure & He R/Ra Values

All available producers (to this project) occur in dilation zones (yellow areas) and show a magmatic He R/Ra signature. All available injectors occur in a dilation or “other” structural zone. Most available non-producer sub-commercial wells occur in a compression and “other” structural zone type.
### INTEGRATION OF EXPLORATION DATA – Well Lithology, Permeability and Structural Zone

<table>
<thead>
<tr>
<th>Well Type</th>
<th>Well ID No.</th>
<th>Permeable Interval</th>
<th>Permeable Interval Formations</th>
<th>Fault Zone Encountered</th>
<th>Bottom-Hole Formation</th>
<th>Geologic Formations above 200°C</th>
<th>Compression / Dilatation / Other Zone</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Injectors</strong></td>
<td>65-18</td>
<td>2500-2800</td>
<td>Tmb, Jz</td>
<td>X</td>
<td>Jz</td>
<td>Tmb, Jz</td>
<td>Other</td>
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<tr>
<td></td>
<td>32-18</td>
<td>2000-2275</td>
<td>Tmb, Jz</td>
<td></td>
<td>Tmb</td>
<td>Tmb</td>
<td>Other</td>
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<tr>
<td></td>
<td>52-18</td>
<td>2200-2250</td>
<td>Tmb</td>
<td></td>
<td>Tmb</td>
<td>Tmb</td>
<td>Other</td>
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<td>2200-2250</td>
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<td>SWL-2</td>
<td>1950-2250</td>
<td>X</td>
<td>Kgr</td>
<td>Tmb, Kgr</td>
<td>Dilatation</td>
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<tr>
<td></td>
<td>SWL-3</td>
<td>1950-2250</td>
<td>X</td>
<td>Kgr</td>
<td>Tmb, Kgr</td>
<td>Dilatation</td>
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<tr>
<td></td>
<td>41-18</td>
<td>2500</td>
<td>Jz</td>
<td>NA</td>
<td>Jz</td>
<td>NA</td>
<td>Other</td>
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<tr>
<td></td>
<td>38-32</td>
<td>500-1000</td>
<td>Jz, Jbr</td>
<td>X</td>
<td>Tr</td>
<td>Tr</td>
<td>Other</td>
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<tr>
<td></td>
<td>27-32</td>
<td>200</td>
<td>Jbr</td>
<td>NA</td>
<td>Jbr</td>
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<td>NA</td>
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<tr>
<td></td>
<td>25-5</td>
<td>1800-1900</td>
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<td>X</td>
<td>Kgr</td>
<td>Kgr</td>
<td>Dilatation</td>
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<tr>
<td></td>
<td>45-5</td>
<td>1650-1900</td>
<td>Tmb</td>
<td>X</td>
<td>Kgr</td>
<td>Kgr</td>
<td>Dilatation</td>
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<td><strong>Producers</strong></td>
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<td>Tr, Kgr</td>
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<td>Compression</td>
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<td>Dilatation</td>
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</table>
INTEGRATION OF EXPLORATION DATA – Qualitative Geoscience Correlations

- Cross-sections constructed parallel & perpendicular to the range front in Calibration Area.
- Correlations identified among the following data:
  - geology
  - seismic reflection profiles
  - magnetotellurics
  - thermal
  - gravity-magnetics
  - P-wave velocity (Vp)
Baseline serial sections of all data sets looking N45°E, approximately parallel to the mountain range.

Sections F-F’ and E-E’ discussed more detail in the next slides.
Dixie Valley Fault Zone (DVFZ) is a complex fault zone consisting of:
- a range-front fault
- piedmont fault (Blackwell et al., 2005)
- Additional faults are also indicated between the range-front and piedmont faults in some of the sections.

Production is from the piedmont fault.

Excellent correlation between the geology and gravity-magnetic models.

Excellent correlation between the MT and geology models.

Highest subsurface temperature in Basin and Range (285°C) measured in 36-14 at ~3km bgs and is associated with the range-front fault.

Producing reservoir temperatures are ~240°C at 2.5-3km bgs and are associated with the piedmont fault.

The range-front and pediment fault segments of the DVFZ appear to host different geothermal cells.
Intermediate resistivity occurs in the footwall of the range-front fault, an unexpected finding:
  ○ High resistivity (>5000 Ω-m) does not occur until about the center of the mountain range along this section

• Possible explanations for discontinuous magnetic Jg rocks may be areas where they:
  ○ Have been rifted apart by N-S faulting
  ○ Have been hydrothermally altered
  ○ Were never present and/or non-magnetic Jg sub-units may be present
### INTEGRATION OF EXPLORATION DATA – Geologic Formations at Reservoir Depth, Stress and Structural Zone

<table>
<thead>
<tr>
<th>Well Type</th>
<th>Well ID No.</th>
<th>Permeable Interval (m)</th>
<th>Permeable Interval Formation</th>
<th>Bottom Hole Formation</th>
<th>Stress Conditions$^2$</th>
<th>Compression / Dilatation / Other Zone$^3$</th>
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</thead>
<tbody>
<tr>
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<td>Injectors</td>
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<td>37-33</td>
<td>2600-2800</td>
<td>Jz, Jbr</td>
<td>Kgr</td>
<td>Optimal</td>
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<td><strong>73-7</strong></td>
<td>2650-2700</td>
<td>Jz</td>
<td>Jz</td>
<td>Optimal</td>
<td>low critically stressed</td>
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<tr>
<td></td>
<td><strong>74-7</strong></td>
<td>2600-2700</td>
<td>Jz</td>
<td>Jz</td>
<td>Optimal</td>
<td>critically stressed</td>
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<td>Sub-Commerical</td>
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<td><strong>Tr</strong></td>
<td>Mis-oriented</td>
<td>low</td>
<td>not critically stressed</td>
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<tr>
<td>Dry Holes</td>
<td><strong>66-21</strong></td>
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<td><strong>Tr</strong></td>
<td>Optimal</td>
<td>high</td>
<td>not critically stressed</td>
</tr>
<tr>
<td></td>
<td><strong>82-5</strong></td>
<td>---</td>
<td>Optimal &gt; 2.7km</td>
<td>NA</td>
<td>NA</td>
<td>Compression</td>
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</table>

$^1$Bottom Hole Formations: Tmb-Miocene basalt, Tv-Cz silicic volcanics, Jz-mafic rocks, Tr-metasediments, Kgr-granodiorite

$^2$Stress Conditions from Hickman et al. (1998, 2000)

$^3$Relative to bottomhole permeable interval; Other Zone indicates the well is completed in neither a zone of compression nor dilatation
INTEGRATION OF EXPLORATION DATA – Baseline Qualitative Geoscience Correlations

- High level of correlation between Generalized Geology, Gravity-Magnetic inferred Lithology Model, Seismic Reflection and MT Profiles.

- The discontinuous nature of a magnetized Jurassic unit (Jg) in the Gravity-Magnetic model sections correlate in some areas with lower resistivity possibly suggesting hydrothermal alteration at depth in the valley and within the Dixie Valley Fault Zone (DVFZ), bounded by the range-front fault on the northwest and the piedmont fault on the southwest, and with N-trending structures.
  - Further assessment of these areas is required to determine the relationships

- Very high resistivities found below the Stillwater Range in the MT sections likely correlate to the presence of relatively unfractured Cretaceous-early Tertiary granodiorite.

- MT sections show resistivity structures that correlate with known zones of faulting within the Stillwater Range and in the DVFZ.

- Complex faulting and relatively low resistivity zones in the DVFZ and into the Stillwater Range along MT array C, which goes through the geothermal producing area.

- Varying resistivity structure exists along the Stillwater Range (footwall) of the range front segment of the DVFZ.
Two hydrothermal cells are evident in the thermal sections.
- High temperature zone (285°C) related to the range-front fault in the area of 36-14.
- Relatively moderate high temperature zone (240°C) related to the piedmont fault and the producing geothermal reservoir.

The structural intersection of N-trending and NW-trending faults results in dilatation and compression zones.
- Dilatation (or dilated) zones promote the upwelling of geothermal fluids.

The baseline data integration presented here met the objectives of the project conducted.

However, it does not complete the process for what is required for a successful exploration program:
- Need to cross-correlate the position and dips of the faults identified by surface and subsurface geologic mapping and those identified by gravity-magnetic modeling
- Need higher resolution gravity, MT and seismic (enhanced) data
  - Enhanced gravity and MT data collected (see AltaRock Energy Inc. (2014b))
  - Enhanced ambient noise seismic data was also collected but it did not have the resolution of the other data sets:
    - A new US Department of Energy project will be conducted to collect very high resolution ambient noise seismic data
EGS parameters of interest (temperature, lithology and stress) were gridded across the Calibration Area (~170km) by subdividing the region into 500m by 500m cells from +1km above sea level (asl) to -4km asl in 0.5km increments.

Hard data (temperature, lithology, geochem, etc.), modeled data (seismic, grav-mag, resistivity, etc.) and inferred/interpolated data.

For Baseline Conceptual Model, geoscience data gridded along cross-sections extrapolated across the Calibration Area.

Well data provided hard data.

Data input used to generate the EGS Favorability / Trust Maps.

Purpose of EGS Favorability Maps (gridding the integrated data sets):
- To have a systematic approach to identifying potential drilling targets

Purpose of Trust Maps:
- To have a systematic approach to identifying the confidence in the data being used
INTEGRATION OF EXPLORATION DATA – Gridding the Data Sets

Creating map view slices of geoscience parameters of interest

**EXCEL** template for the Calibration Area, with 500m² cells designated as either derived from a cross-section (light blue) or a well (outlined and labeled).

Example **EXCEL** spreadsheet representing plan view of the thermal model at 2.5km below sea level. Bolded values represent measured data in wells.
The key parameters for EGS were defined as (1) temperature, (2) rock type, and (3) stress. What parameter should be added to evaluate the hydrothermal system?

![Table showing favorability values](image-url)

Favorability and weight values assigned based on Subject Matter Expert Team input.
INTEGRATION OF EXPLORATION DATA – Defining Favorability and Trust Values

Favorability
1 (least favorable) through 9 (most favorable)
- Good range
- Allows for true neutral value (5)

Trust
1 (most trust) through 9 (least trust)
- Encompasses many different different data sources
- Better understanding of favorability sources

\[ F_v = (d_0 \times w_0) + (d_1 \times w_1) + (d_2 \times w_2) + \cdots + (d_n \times w_n) \]

where \( F_v \) is the favorability value for a cell, \( d_0 \) through \( d_n \) is the favorability value of a cell’s geoscience parameter data, and \( w_0 \) through \( w_n \) is the weight for a particular data set.
INTEGRATION OF EXPLORATION DATA – Favorability and Trust Maps

**Favorability Maps** – the warmer the color the more favorable the 500m² cell.

**Trust Maps** – the shading represents data reliability with white being hard data and the darker the gray shading, the less reliable the composite data is.

Besides displaying favorable area for future assessment, the trust maps equally display areas where additional data should be collected for a more definitive assessment and action.
REFERENCES


REFERENCES


IPGT Exploration Working Group, 2011, IPGT Exploration Whitepaper.


Suryantini (2013), IGA workshop in “Developing Best Practice for Geothermal Exploration and Resource/Reserve Classification”, Essen, Germany, 14 November.


Thank you for your attention!

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E-mail: jiovenitti@comcast.net