Preliminary Fairway Model

Cascades and Aleutians – Ranking

Project Officer: Eric Hass
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ATLAS Geosciences Inc
Track Name: HRC

This presentation does not contain any proprietary confidential, or otherwise restricted information.
**Objective** - Quantifiably rank the geothermal potential of each of the young volcanic centers in Cascades and Aleutians

- **Challenges/barriers** – Lack of geothermal development in US Arcs
- **Impact** – Identify most promising prospects for development
- **Innovative Aspect** - Systematically and regionally assessing the underlying physiochemical favorability for geothermal production
  - Multiple data types (geologic, geophysical, geochemical, volcanologic)
  - Comparison with power-producing Arc systems world-wide
- **Solving GTO Goals** - Accelerate near-term geothermal development by identifying the systems most likely to be productive
  - Lead to refinements in our understanding of the conditions necessary for geothermal systems to form and what size they are likely to attain
- **Phases II and III** of this project would use the ranking of this Phase I work to select systems requiring more detailed work (including drilling) to better explore geothermal potential of selected volcanic centers
Scientific/Technical Approach (1)

- Systematic and regional assessment of the underlying physiochemical favorability for geothermal production
- Interpret geothermal potential in the context of play fairway analysis
  - Key hierarchical tiers (component characteristics) assembled in a statistical framework
  - Quantify geothermal potential and optimize future exploration through the definition of “play fairways”
  - Focus future exploration efforts in underdeveloped area of the US: Cascade and Aleutian Arcs
### Accomplishments – Data Gathering

#### Online Library Resources

<table>
<thead>
<tr>
<th>AVO &amp; CVO</th>
<th>Nevada Geodetic Laboratory</th>
</tr>
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<tbody>
<tr>
<td>GeoRef</td>
<td>NGDS</td>
</tr>
<tr>
<td>Geothermics</td>
<td>Smithsonian</td>
</tr>
<tr>
<td>GRC</td>
<td>Laske, 2014 -Crustal Thickness</td>
</tr>
<tr>
<td>IGA</td>
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<td>OSTI</td>
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#### Digital Data Sets

<table>
<thead>
<tr>
<th>Original Planned Milestone/Technical Accomplishment</th>
<th>Actual Milestone/Technical Accomplishment</th>
<th>Date Completed</th>
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<tbody>
<tr>
<td>Background Data Evaluation</td>
<td>Documentation of selection &amp; use of relevant data types</td>
<td>12/31/14</td>
</tr>
<tr>
<td>Preliminary Data Compilation</td>
<td>Tables of Arcs, Data Types, Power Plants</td>
<td>12/31/14</td>
</tr>
</tbody>
</table>
## Volcanic Centers

<table>
<thead>
<tr>
<th></th>
<th>World Arcs</th>
<th>Aleutian</th>
<th>Cascades</th>
<th>Data Categories</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geochemistry</td>
<td>65</td>
<td>63</td>
<td>37</td>
<td>30</td>
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<tr>
<td>Geothermometry</td>
<td>65</td>
<td>63</td>
<td>37</td>
<td>32</td>
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<tr>
<td>Surface Expressions</td>
<td>53</td>
<td>22</td>
<td>35</td>
<td>5</td>
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<tr>
<td>Structural Setting</td>
<td>72</td>
<td>59</td>
<td>37</td>
<td>12</td>
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<tr>
<td>Power Plants</td>
<td>84</td>
<td>0</td>
<td>0</td>
<td>6</td>
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<tr>
<td>Eruption Freq/Comp</td>
<td>624</td>
<td>63</td>
<td>37</td>
<td>20</td>
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<tr>
<td>Vent Types</td>
<td>6</td>
<td>49</td>
<td>23</td>
<td>10</td>
</tr>
<tr>
<td>Power Density</td>
<td>41</td>
<td>--</td>
<td>--</td>
<td>1</td>
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<tr>
<td>General (name, loc.)</td>
<td>633</td>
<td>63</td>
<td>37</td>
<td>10</td>
</tr>
</tbody>
</table>

As of 3/31/15
Regional Parameters

- arc volcanic center database
- arc power plant database
- world strain rate model
- volcanic center database
- world crustal thickness
- tectonic setting characterization

New world-wide crustal thickness model (August, 2014)

All data entries linked by common Volcano Number
160 Unique data fields per record (VC)

Higher arc power productivities associated with intermediate crustal thicknesses (may be caused by anthropogenic influences)
New Global Plate Motion and Strain Rate Model (GSRM v2.1) available Oct., 2014

Key Points:
- A data set of 22,500 horizontal geodetic velocities compiled
- Geodetic plate motions for 36 plates estimated
- A new velocity gradient tensor field for plate boundary zones modeled

Weights of Evidence:
\[ W^+ = 0.47, \quad W^- = -0.47 \]
\[ C = 0.94 \pm 0.26 \]
(student contrast = 3.6)
Accomplishments – Preliminary Evaluation

- **Structure**: Synthesis of volcanic arc structural settings is clarifying regional differences in geothermal potential
- **Strain**: Positive relationship between crustal deformation style (extension and shear) and power density and size of geothermal resources is being demonstrated
- **Clay Caps**: Cap integrity and its relationship to the magnitude of geothermal resources is being demonstrated
- **Volcanism**: Recentness of eruption, composition and style of eruption, trench-arc gap, depth to subducting plate, etc. being compiled and evaluated for information predictive for geothermal potential
- **Permeability/Lithology**: Lithologic diversity produces rheological contrasts which can enhance fracturing and fluid flow, and relatively young rocks have had fewer opportunities for burial-related compaction and reduction in primary porosity and permeability
- **Geochemistry**: Facilitating predictions of reservoir temperatures in underexplored portions of the Cascade and Aleutian arcs
- **Surface Manifestations**: Springs, fumaroles, sinters, travertines – qualitative indicators of elevated temperatures
Primary Hierarchal Tiers

Heat Source
(initial studies neutral if located in active arc)

Permeability
Regional:
- Strain/plate setting index
- Regional lithologies
Local:
- Tectonic setting
- Structural setting
- Host rock

Fluid Chemistry
- Fluid pH
- Non-condensable gases
- Salinity
- Scaling Potential

Clay Cap
- Permissive lithology
- Degree breached

Direct Evidence
- Thermal features
- Fluid Geochemistry
- Young alteration/deposition
- Subsurface temperatures

Size of Resource
- Structural model
- Power density model
- Hydrothermal footprint
- Clay cap development

The “Fairway”

Confidence of Power-producer
(mean probability should = fraction productive explored systems)

Size of Resource

Confidence of Power-producer
Multiply by 1-D

D range: 0-1

Product

Geologic confidence membership function

Ranking of Development Opportunities

Market/Grid Issues
Environmental Regulatory Issues

Degree of Exploration
- Snow/ice cover
- Water/ocean cover
- Exploration work
- Climate/topo setting
- Strength of clay cap

Default (prior): 0.90
range: 0-1

Default: 0.26
range: 0-1

Default: 0.95
range: 0-1

Default: 0.90
range: 0-1

Default: 0.26
range: 0-1

Coefficients of Probability Distribution

Direct Evidence
Additive probability

Confidence of Power-producer
Fairway Model
working in equivalent P-space

**Tectonic Setting**
- Regional
  - 1.0 Transtension
  - 0.8 Extension
  - 0.2 Transpression
  - 0.1 Compression
  - 0.0 Unknown
- Local
  - 0.8 Strike-slip transtension
  - 0.5 Strike-slip transpression

**World Strain Style**
- Plate Motion Index
  - W+ +0.47, Index > -55
  - W- -0.47, Index < -55

**Structural Setting**
- 1.0 Accommodation Zone
- 1.0 Displacement Transfer
- 1.0 Pull Apart
- 0.6 Numerous Normal Faults
- 0.6 Step-over
- 0.5 Fault Termination
- 0.5 Fault Intersection
- 0.2 Caldera Ring Faults
- 0.2 Normal Faults
- 0.1 Gravity-driven Normal Faults
- 0.0 Restraining Bend
- 0.0 Unknown
- X.X* Multiple Structural Settings
  (*X.X = variable)

**Rescaled to equivalent P-space with 0.25 max**

**Fluid Chemistry Model**
- 0.95

**Heat Model**
- 0.9

**Clay Cap Model**
- 0.9

**Combined Permeability Model**

**Fuzzy Algebraic Sum**

**Fuzzy Algebraic Product**

**Model Interactively Rescaled to Generate Mean Fairway P-value of 0.2**
(to account for degree of exploration)

**The “Fairway”**

**Rescaled to equivalent P-space with 0.20 max**
### Direct Evidence And Initial Degree of Exploration Models

**The “Fairway”**

- **Fuzzy Algebraic Product**
  - Rescaled to Net Zero Direct Evidence
  - Rescaled to equivalent P-space with 0.125 max

**Surface Features**

- **Fumaroles**
  - 0.5 Field/cluster
  - 0.4 At least one
  - 0.18 None reported

- **Deposits**
  - 0.5 Siliceous sinter
  - 0.4 Travertine/tufa
  - 0.18 None reported

**Degrees Concealed**
- 0-1 fraction no snow/ice (for unknowns only)

### Temperatures/Geothermometry

#### Average Maximum Fuzzy Algebraic Product

- **Max Reliable Spring Geothermometer**
  - 0.5 >150 °C
  - 0.4 100-150 °C
  - 0.3 75-100 °C
  - 0.2 50-75 °C
  - 0.1 <50 °C
  - 0.18 Unknown

- **Max Reliable Well Geothermometer**
  - 0.5 >200 °C
  - 0.4 130-200 °C
  - 0.3 100-130 °C
  - 0.05 <100 °C
  - 0.18 Unknown

- **Max Spring Temperature**
  - 0.5 >90 °C or boiling
  - 0.4 75-90 °C
  - 0.3 50-75 °C
  - 0.1 <50 °C
  - 0.18 Unknown

- **Max Well Temperature**
  - 0.5 >130 °C
  - 0.4 100-130 °C
  - 0.3 50-100 °C
  - 0.05 <50 °C
  - 0.18 Unknown

- **Surface Features**
  - **Deposits**
    - Siliceous sinter
    - Travertine/tufa
  - **Fumaroles**
    - Field/cluster
    - At least one
  - **Degree Concealed**
    - 0-1 fraction no snow/ice (for unknowns only)
Accomplishments – Challenges

• The greatest **Challenges** faced by the project are
  – The large amount of data search and compilation required,
  – The incomplete and uneven nature of data availability for individual arc volcanic centers.

• **Resolutions:**
  – Data search and compilation has progressively focused on the most relevant and complete data types
  – The number of volcanic centers for which detailed data is solicited outside the Cascade/Aleutian arcs has been focused from nearly 600 to the roughly 80 centers with demonstrated economic potential (Power Production).
  – Degree of exploration factor is used partly to account for uneven data distribution/availability

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<thead>
<tr>
<th>Original Planned Milestone/Technical Accomplishment</th>
<th>Actual Milestone/Technical Accomplishment</th>
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</thead>
<tbody>
<tr>
<td><strong>Preliminary Modeling</strong></td>
<td>VC Ranking, weighted favorability maps</td>
<td>3/30/15</td>
</tr>
<tr>
<td>Go/No Go</td>
<td>Verified Feasibility of Methodology</td>
<td>3/30/15</td>
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</tbody>
</table>
Higher indices driven by more complex/favorable structural settings.
Relative weighting changes (updates) when direct evidence (geothermometry, well data, and surface features) are considered.
Higher indices in southern Cascades generated by:
1) tectonic setting,
2) structural setting, and,
3) strain/plate motion index.

In general, southern Cascades characterized by more transtensional to extensional environment relative to northern Cascades.
Relative weighting changes when direct evidence (geothermometry, well data, surface features) is considered.
Power-producing systems distant from known active volcanic centers provide clues to multiple play types.
Distribution of installed power from arc settings follows approximate log distribution
Mean installed power = 91 MW
Log-normalized mean installed power = 37 MW
Range (1s) = 8 to 165 MW

Parameters of the power distribution curve can be modified for different play types

Example:
Strike-slip pull-apart-hosted geothermal systems may have a higher mean, but occur infrequently along strike.
Measures of Certainty (errors of estimate)

1) Lack of data from non-producing geothermal systems complicates calculation of quantitative weights and errors

2) Exceptions are data for crustal strain, plate motion, and crustal thickness
   - Weights of evidence with estimate of error calculated for strain index
   - However, world strain model is still in infancy, and errors on a volcano by volcano basis will be higher

3) Much regional exploration data used herein has relatively high uncertainties

4) Quality indices and corresponding estimates of uncertainty being developed for geochemical data

5) Comprehensive evaluation of detailed databases can be used to constrain uncertainties, but much of these data are not publically available

6) Expert guidance will be used to help constrain probabilities and estimates of certainty
Future Directions

- Detailed evaluation of preliminary modeling results
- Final data compilation
- Assessment of weighting factors and relevant data ranges
- Adjustment of model parameters
- Final modeling
- Maps, tables and report preparation
- Presentation of results (GRC)

<table>
<thead>
<tr>
<th>Milestone or Go/No-Go</th>
<th>Status &amp; Expected Compl. Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Final Stage Data Compilation</td>
<td>Initiated; Complete 6/30/15</td>
</tr>
<tr>
<td>Final Model; Generation of Predictive Indices</td>
<td>Planned: 10/31/15</td>
</tr>
<tr>
<td>Ranking of Volcanoes; Reporting; Commercialization</td>
<td>Planned: 10/31/15</td>
</tr>
</tbody>
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Summary

- On Schedule; 80% of data gathering complete

- **Structure**: A synthesis of volcanic arc tectonic and structural settings is clarifying and documenting regional differences in geothermal potential.

- **Strain**: Analyses of newly available world crustal motion and strain rate data yield predictive information supporting, and helping to quantify, a relationship between extension, shear, and geothermal potential.

- **Predictive Maps**: Structure & strain data are beginning to define geothermal “fairways” in the Cascade and Aleutian Arcs characterized by more complex structural settings and more favorable extension/transtension tectonics.

- **Clay Caps**: Cap integrity and its relationship to the magnitude of geothermal resources is being demonstrated.

- **Permeability/Lithology**: Lithologic diversity produces rheological contrasts that can enhance fracturing and fluid flow, and relatively young rocks have had fewer opportunities for burial-related compaction and reduction in primary porosity and permeability.

- **Surface Manifestations & Geochemistry**: As anticipated, fumaroles, sinters, and fluid geothermometry are qualitative indicators of elevated temperatures.