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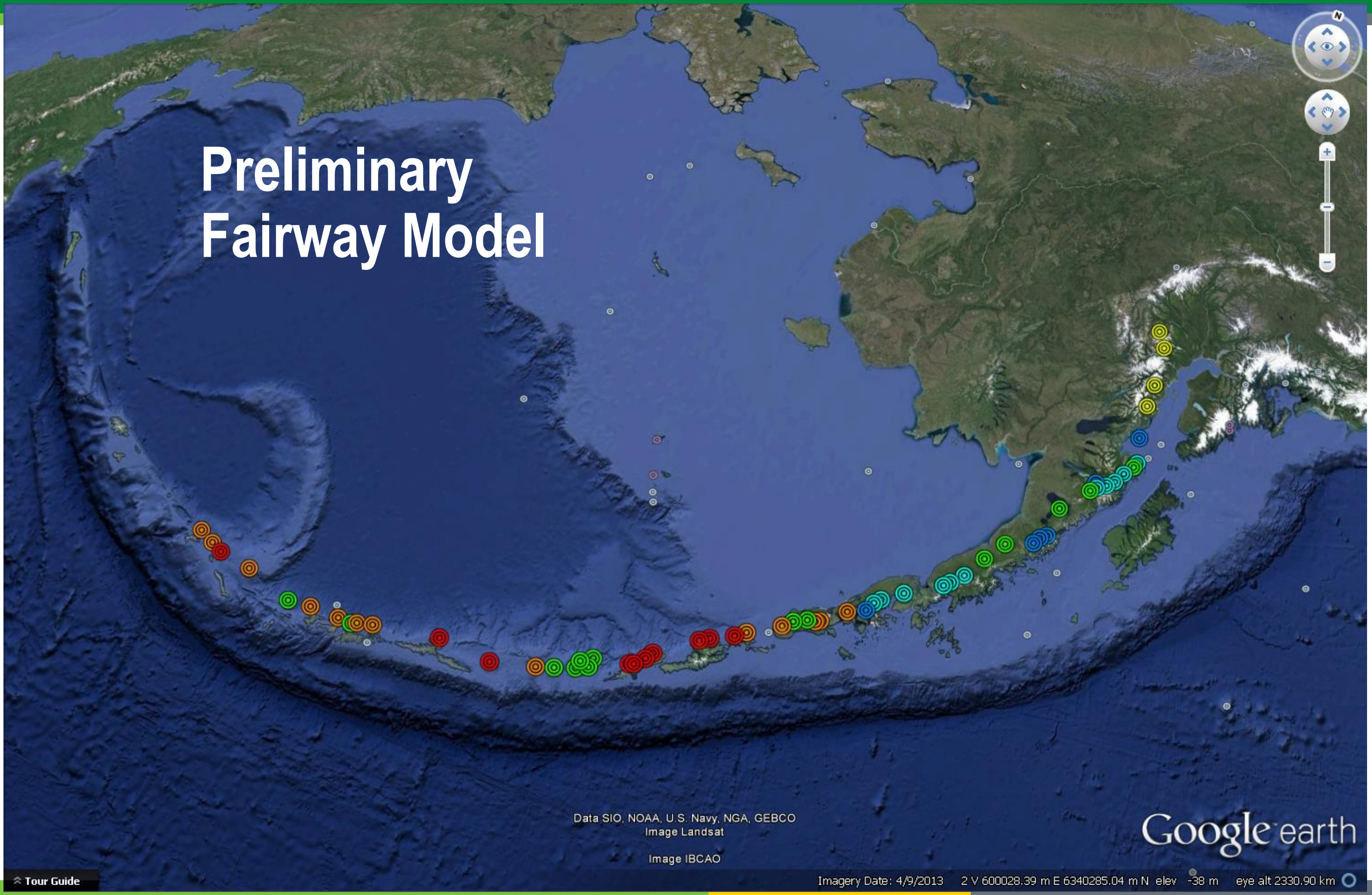

Cascades and Aleutians – Ranking

PI: Lisa Shevenell

Presenter: Mark Coolbaugh

ATLAS Geosciences Inc

Track Name: HRC

Project Officer: Eric Hass

Total Project Funding: $343,262

May 11, 2015

Relevance/Impact of Research

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 hierarchal 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

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Online Library Resources	Digital Data Sets
AVO & CVO	Nevada Geodetic Laboratory
GeoRef	NGDS
Geothermics	Smithsonian
GRC	Laske, 2014 -Crustal Thickness
IGA	
OSTI	

Original Planned Milestone/ Technical Accomplishment	Actual Milestone/Technical Accomplishment	Date Completed
Background Data Evaluation	Documentation of selection & use of relevant data types	12/31/14
Preliminary Data Compilation	Tables of Arcs, Data Types, Power Plants	12/31/14

Accomplishments – Data Gathering

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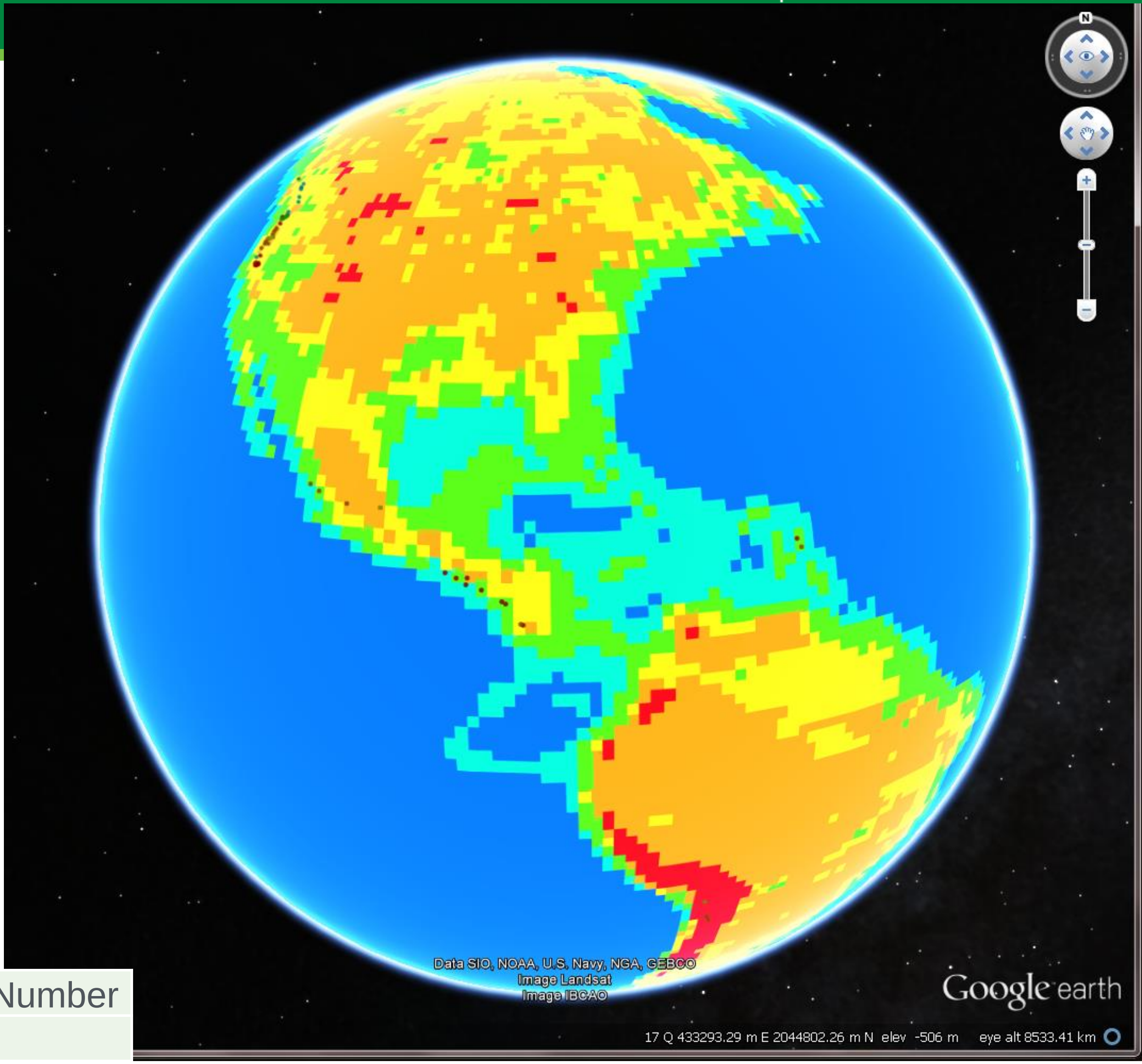
Local Datasets

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

As of 3/31/15

Regional Parameters

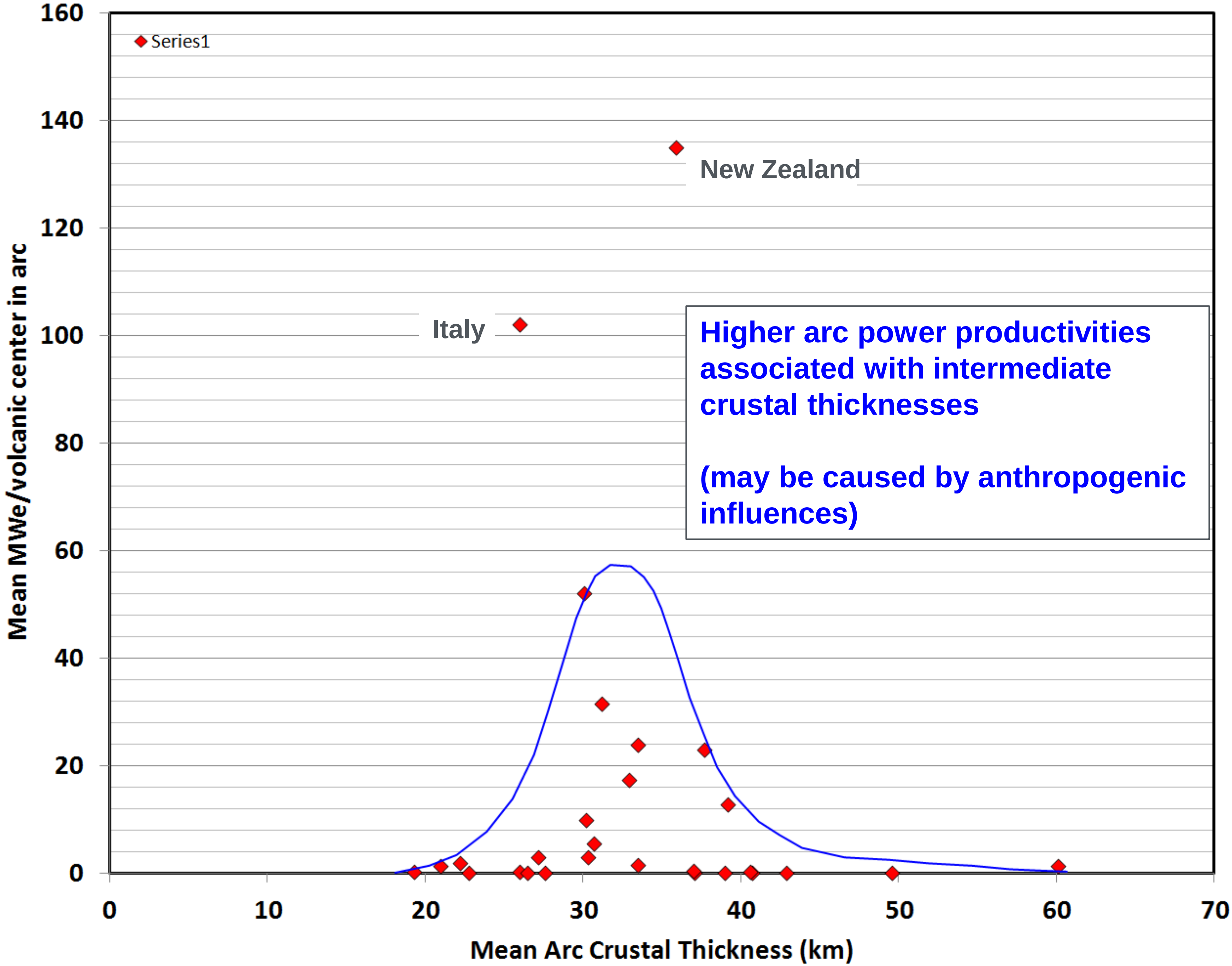
- arc volcanic center database
- arc power plant database
- world strain rate model
- volcanic center database
- world crustal thickness
- tectonic setting characterization



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

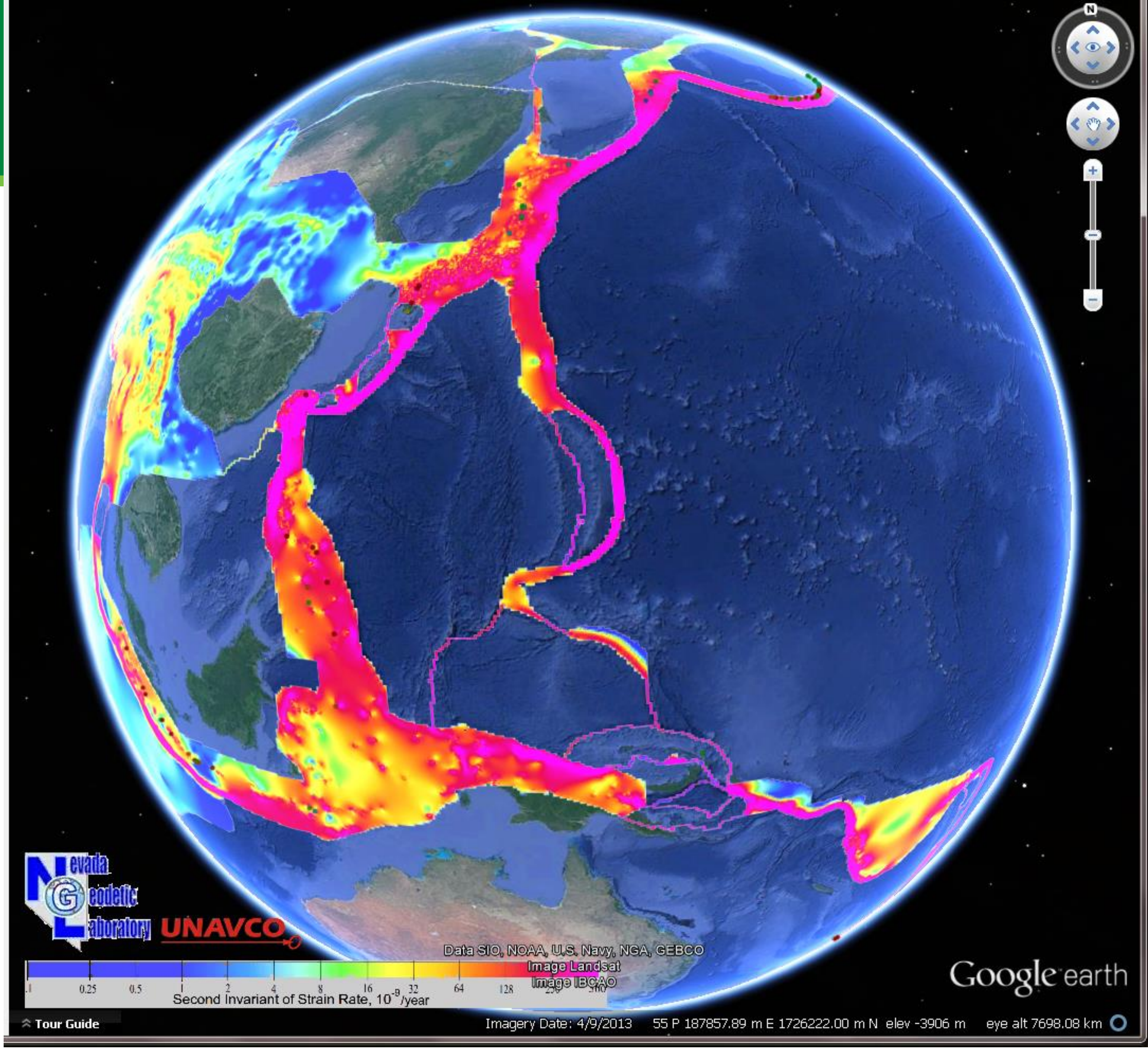
All data entries linked by common Volcano Number
160 Unique data fields per record (VC)

Laske, G., Masters., G., Ma, Z. and Pasyanos, M., Update on CRUST1.0 - A 1-degree Global Model of Earth's Crust, Geophys. Res. Abstracts, 15, Abstract EGU2013-2658, 2013. (made available Aug. 2014).


Series1
New Zealand
Italy
Higher arc power productivities associated with intermediate crustal thicknesses
(may be caused by anthropogenic influences)
Mean MWe/volcanic center in arc
0
20
40
60
80
100
120
140
160
Mean Arc Crustal Thickness (km)
0
10
20
30
40
50
60
70

Accomplishments

New Global Plate Motion and Strain Rate Model (GSRM v2.1) available Oct., 2014



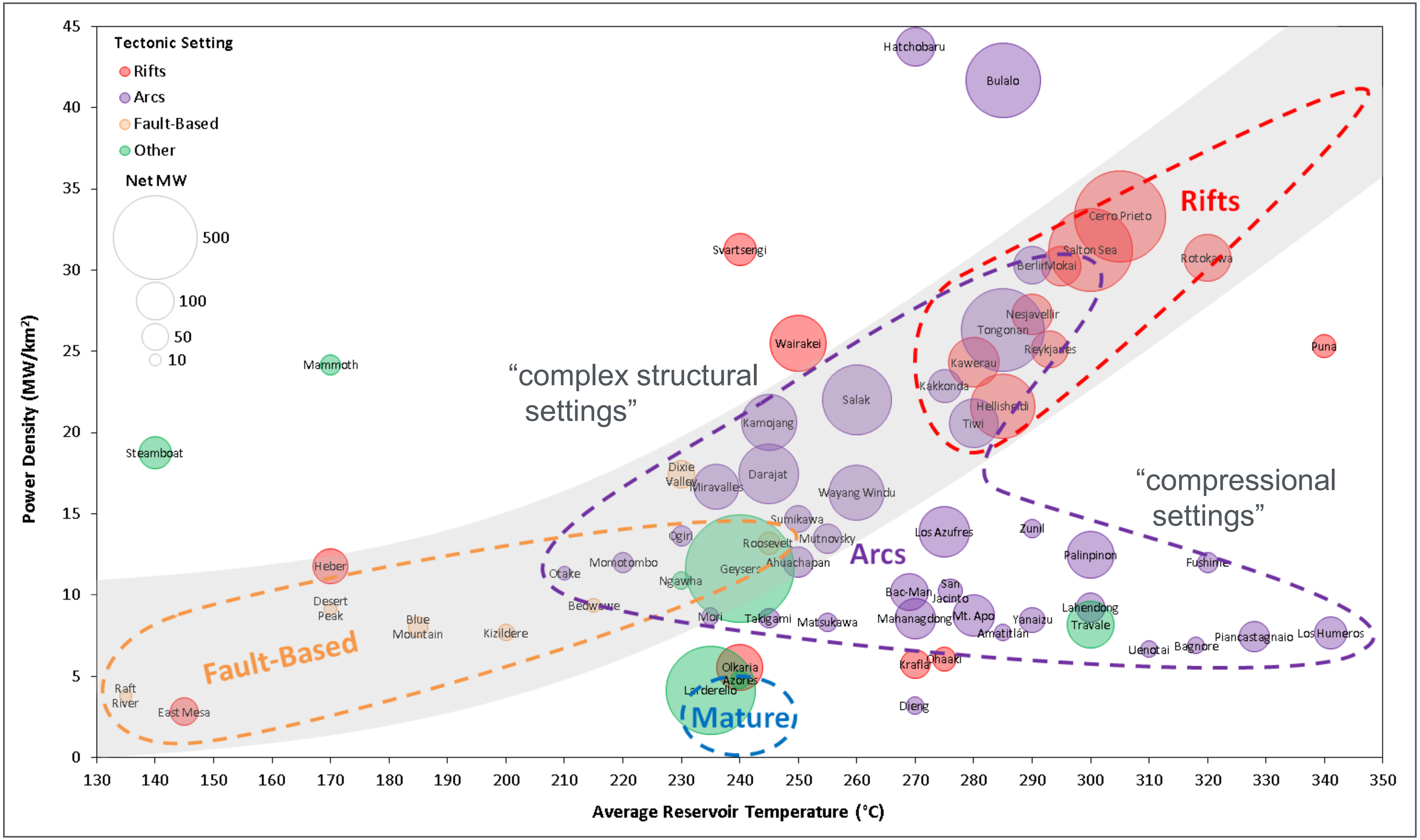
Key Points:

- 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

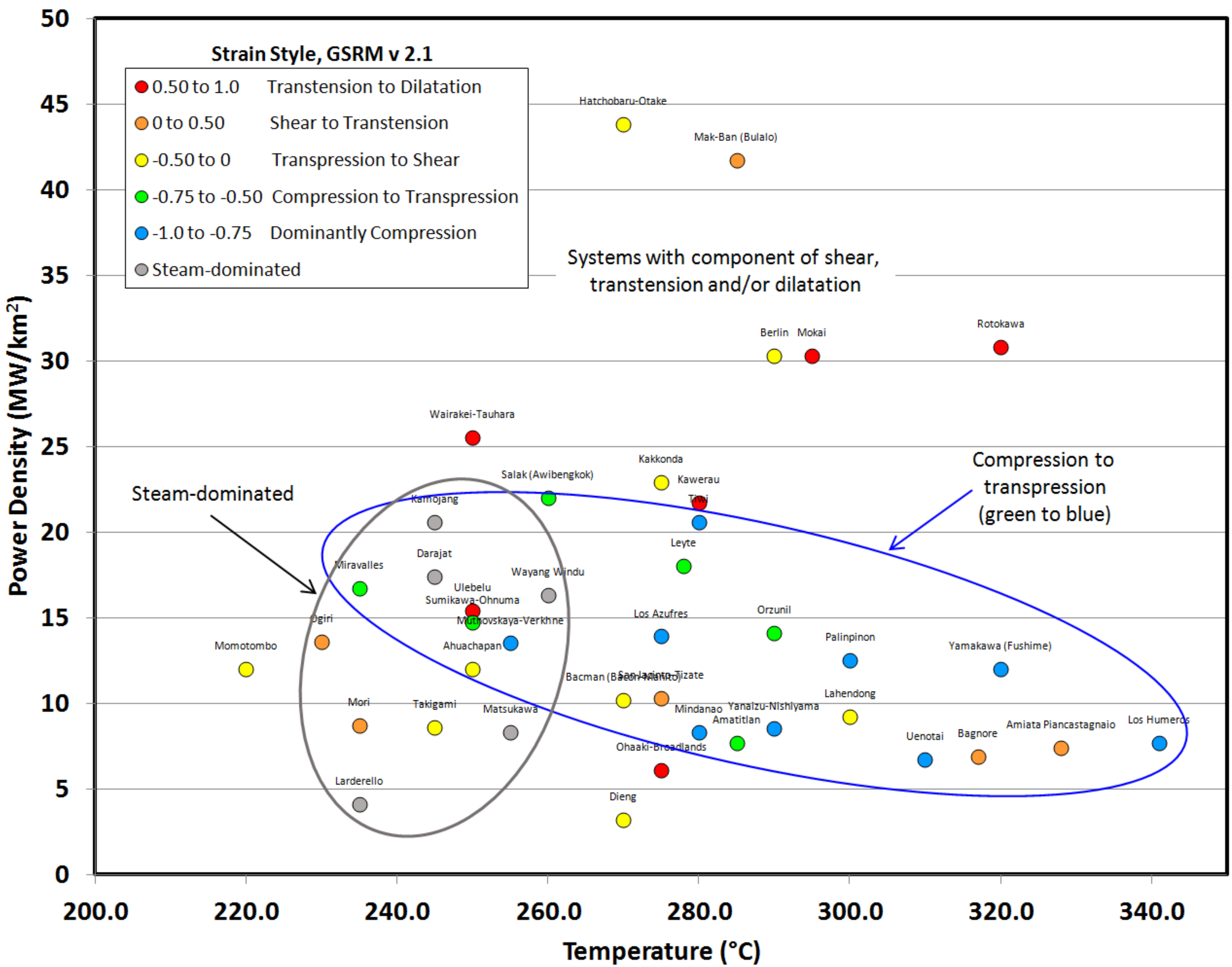
Kreemer, C., Blewitt, G., and Klein, E.C., 2014, A geodetic plate motion and global strain rate model: Geochemistry, Geophysics, Geosystems, v. 15, p. 3849-3889.

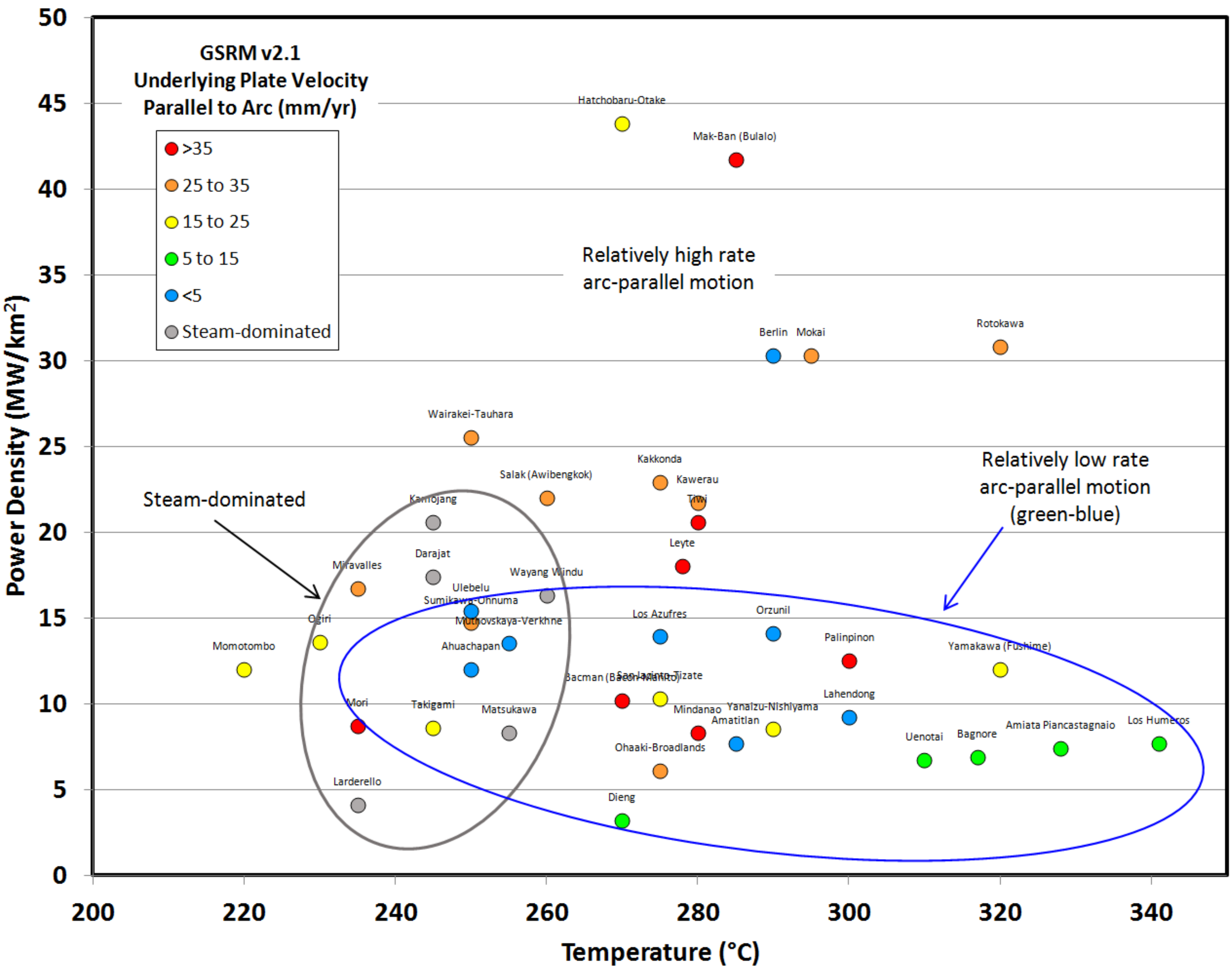
World compilation of productive geothermal field power densities

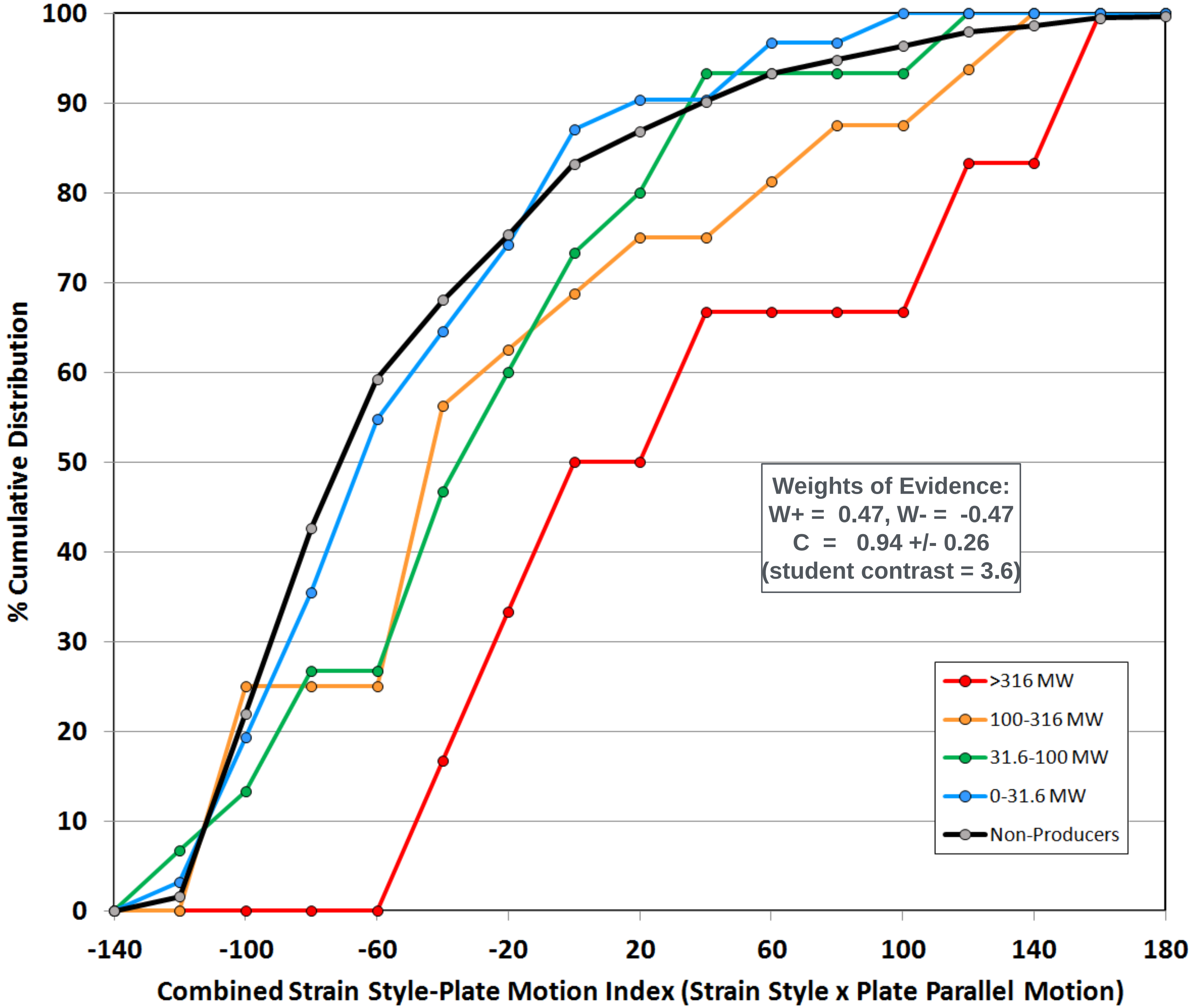
Max Wilmarth and James Stimac, published April, 2015



Wilmarth, M. and Stimac, J., 2015, Power density in geothermal fields: World Geothermal Congress 19-15 Apr 2015.


Strain Style, GSRM v 2.1
0.50 to 1.0 Transtension to Dilatation
0 to 0.50 Shear to Transtension
-0.50 to 0 Transpression to Shear
-0.75 to -0.50 Compression to Transpression
-1.0 to -0.75 Dominantly Compression
Steam-dominated
Systems with component of shear, transtension and/or dilatation
Compression to transpression (green to blue)
Steam-dominated
Power Density (MW/km²)
Temperature (°C)
Hatchobaru-Otake
Mak-Ban (Bulalo)
Berlin
Mokai
Rotokawa
Wairakei-Tauhara
Kakkonda
Kawerau
Tiwi
Salak (Awibengkok)
Kamojang
Leyte
Darajat
Miravalles
Wayang Windu
Ulebelu
Sumikawa-Ohnuma
Mutnovskaya-Verkhne
Ogiri
Momotombo
Ahuachapan
Los Azufres
Orzunil
Palinpinon
Yamakawa (Fushime)
Bacman (Bacon-Manito)
San Jacinto-Tizate
Mori
Takigami
Matsukawa
Mindanao
Yanaizu-Nishiyama
Amatitlan
Lahendong
Ohaaki-Broadlands
Uenotai
Bagnore
Amiata Piancastagnaio
Los Humeros
Larderello
Dieng
50
45
40
35
30
25
20
15
10
5
0
200.0
220.0
240.0
260.0
280.0
300.0
320.0
340.0


GSRM v2.1
Underlying Plate Velocity
Parallel to Arc (mm/yr)
>35
25 to 35
15 to 25
5 to 15
<5
Steam-dominated
Relatively high rate
arc-parallel motion
Relatively low rate
arc-parallel motion
(green-blue)
Steam-dominated
Hatchobaru-Otake
Mak-Ban (Bulalo)
Berlin
Mokai
Rotokawa
Wairakei-Tauhara
Kakkonda
Kawerau
Tiwi
Salak (Awibengkok)
Kamojang
Leyte
Darajat
Miravalles
Wayang Windu
Ulebelu
Sumikawa-Ohnuma
Mutnovskaya-Verkhne
Ogiri
Los Azufres
Orzunil
Palinpinon
Momotombo
Ahuachapan
Yamakawa (Fushime)
Bacman (Bacon-Manito)
San Jacinto-Tizate
Mori
Takigami
Matsukawa
Mindanao
Yanaizu-Nishiyama
Lahendong
Amatitlan
Uenotai
Bagnore
Amiata Piancastagnaio
Los Humeros
Ohaaki-Broadlands
Larderello
Dieng
Power Density (MW/km²)
Temperature (°C)
0
5
10
15
20
25
30
35
40
45
50
200
220
240
260
280
300
320
340



% Cumulative Distribution
100
90
80
70
60
50
40
30
20
10
0
-140
-100
-60
-20
20
60
100
140
180
Combined Strain Style-Plate Motion Index (Strain Style x Plate Parallel Motion)
Weights of Evidence:
W+ = 0.47, W- = -0.47
C = 0.94 +/- 0.26
(student contrast = 3.6)
>316 MW
100-316 MW
31.6-100 MW
0-31.6 MW
Non-Producers

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

Flow Chart Preliminary Model Methodology

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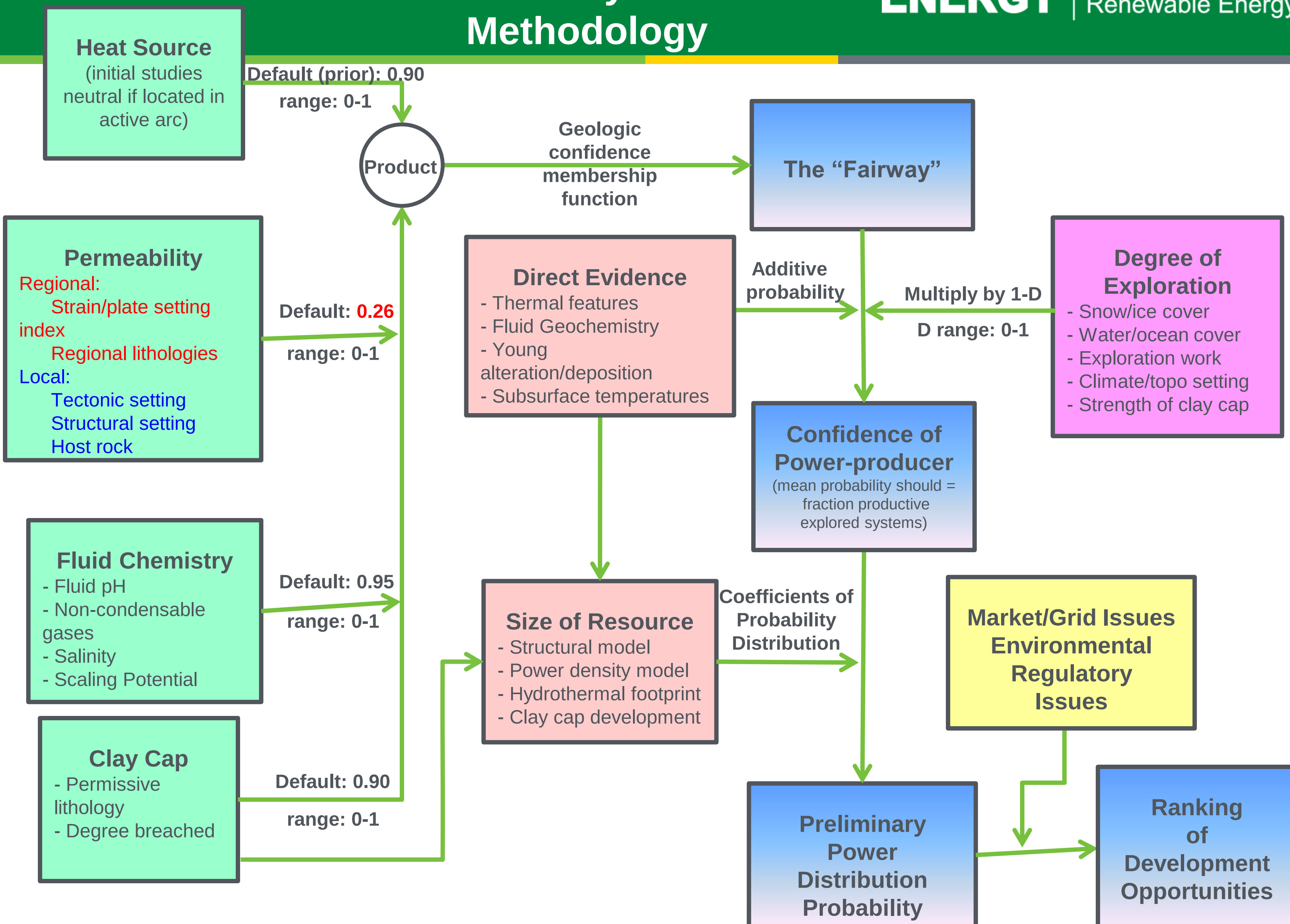
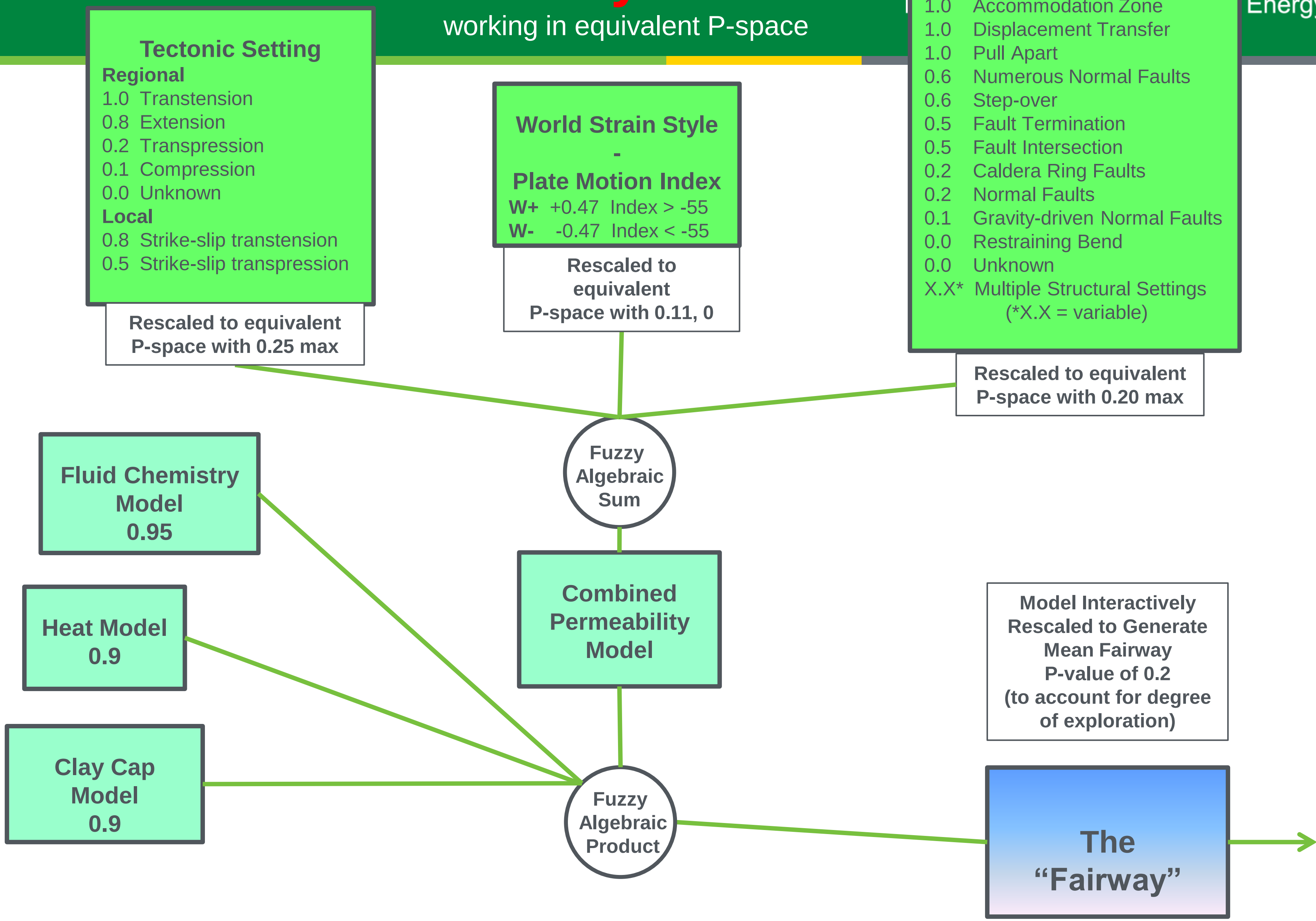
Primary Hierarchal Tiers

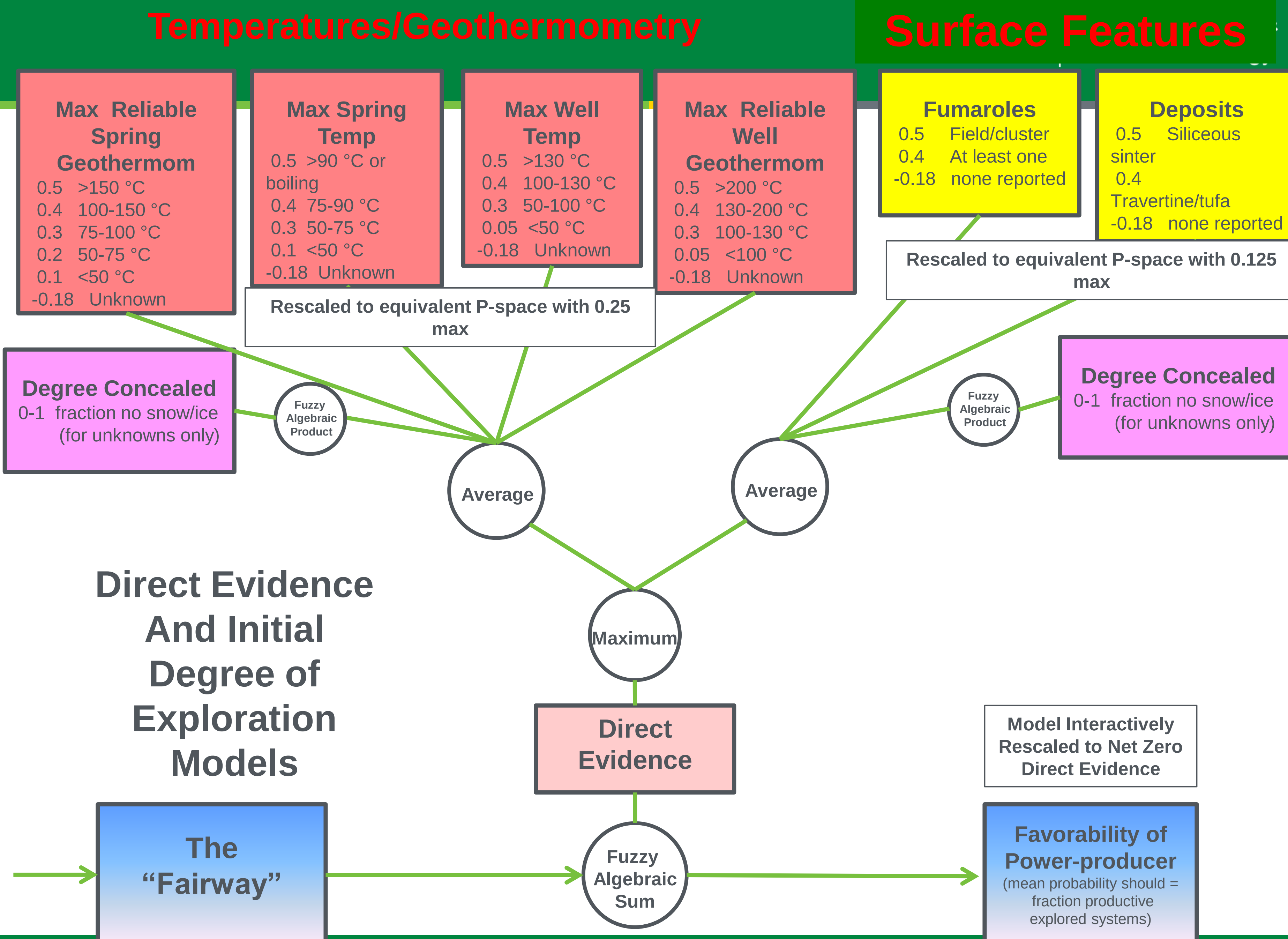


Fairway Model

working in equivalent P-space



Direct Evidence And Initial Degree of Exploration Models



Accomplishments – Challenges

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- 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

Original Planned Milestone/ Technical Accomplishment	Actual Milestone/Technical Accomplishment	Date Completed
Preliminary Modeling	VC Ranking, weighted favorability maps	3/30/15
Go/No Go	Verified Feasibility of Methodology	3/30/15

Aleutian Arc Preliminary Fairway Model

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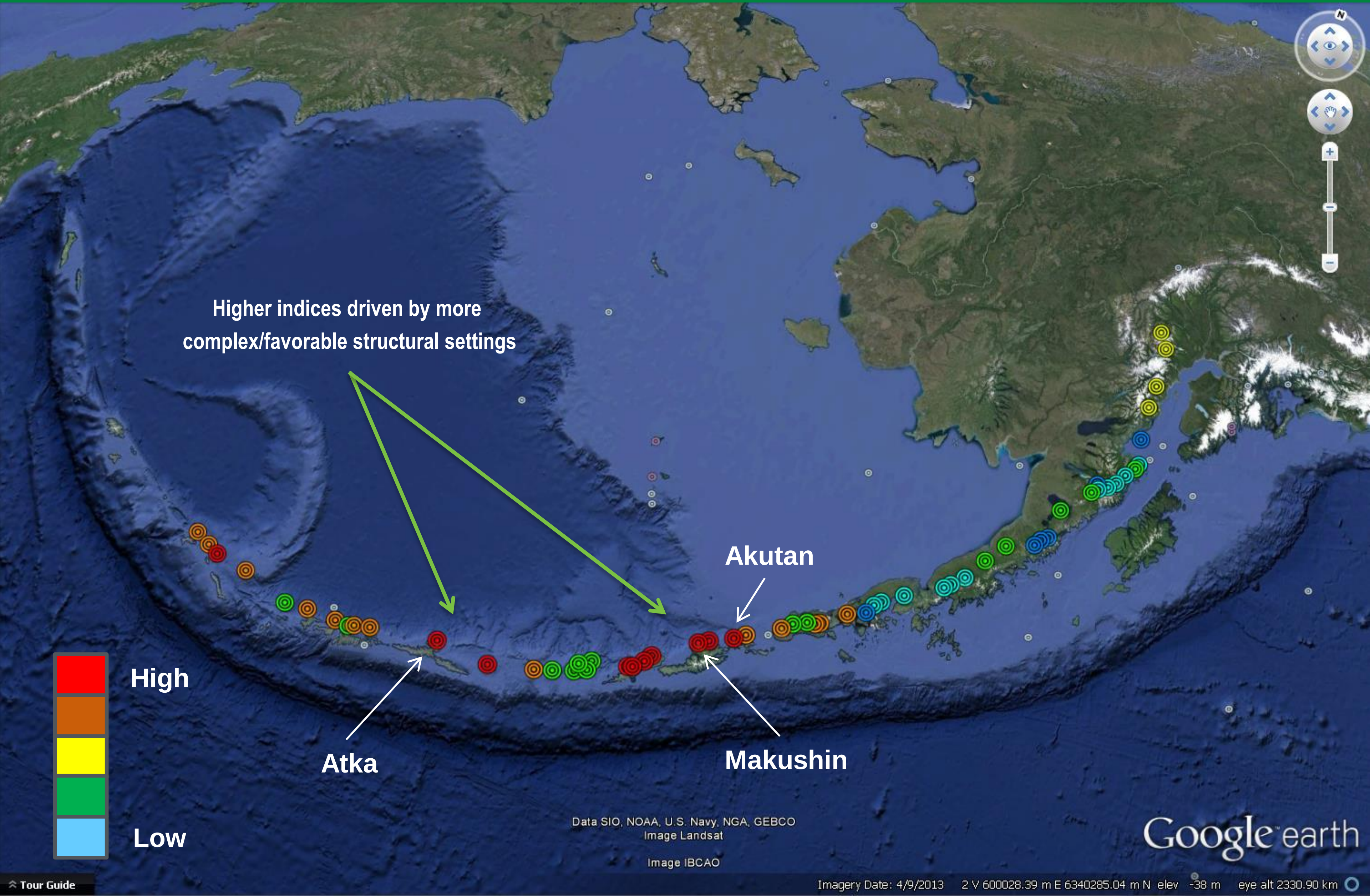

Aleutian Arc Preliminary Favorability Model

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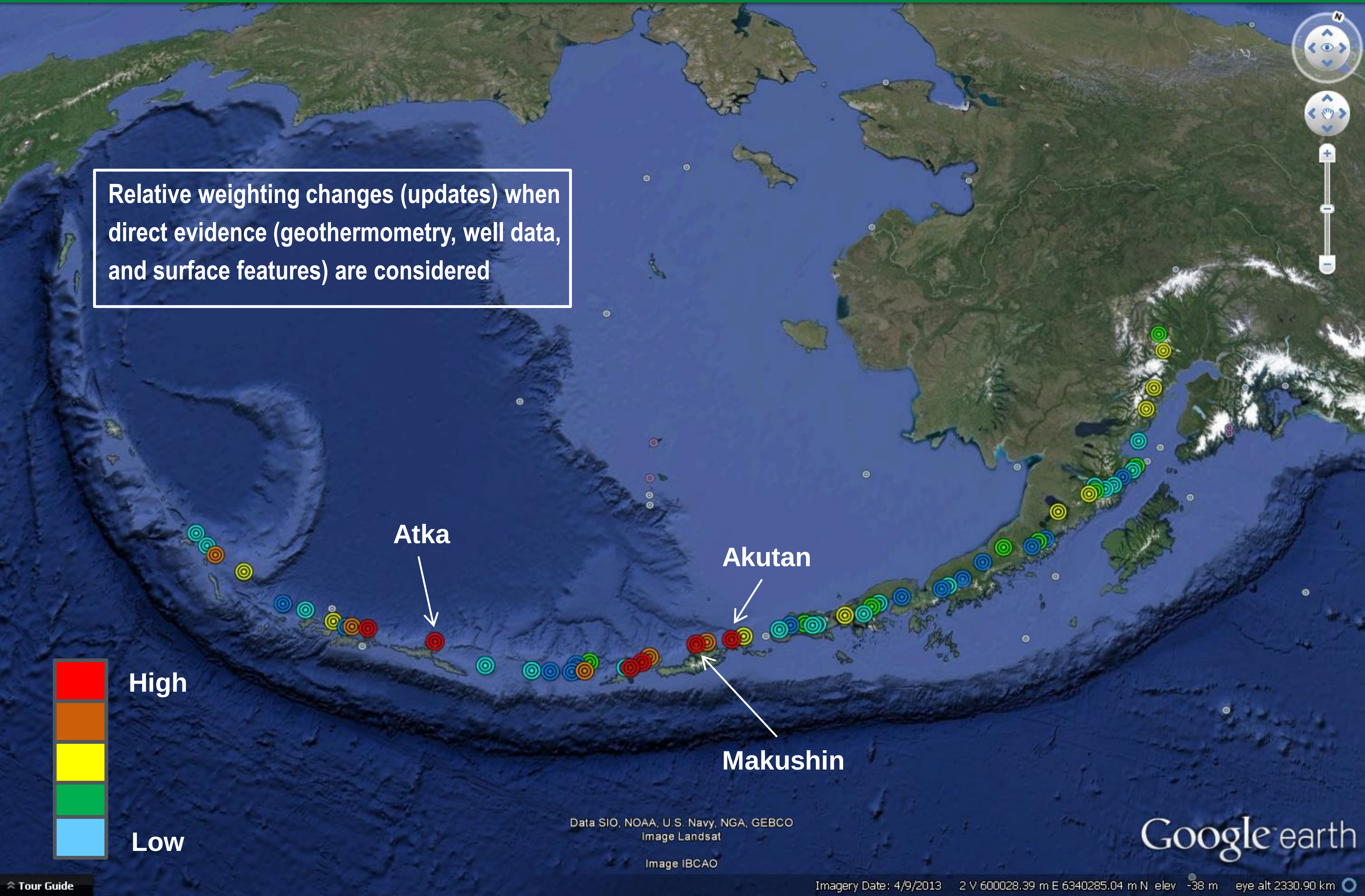

Cascade Arc Preliminary Fairway Model

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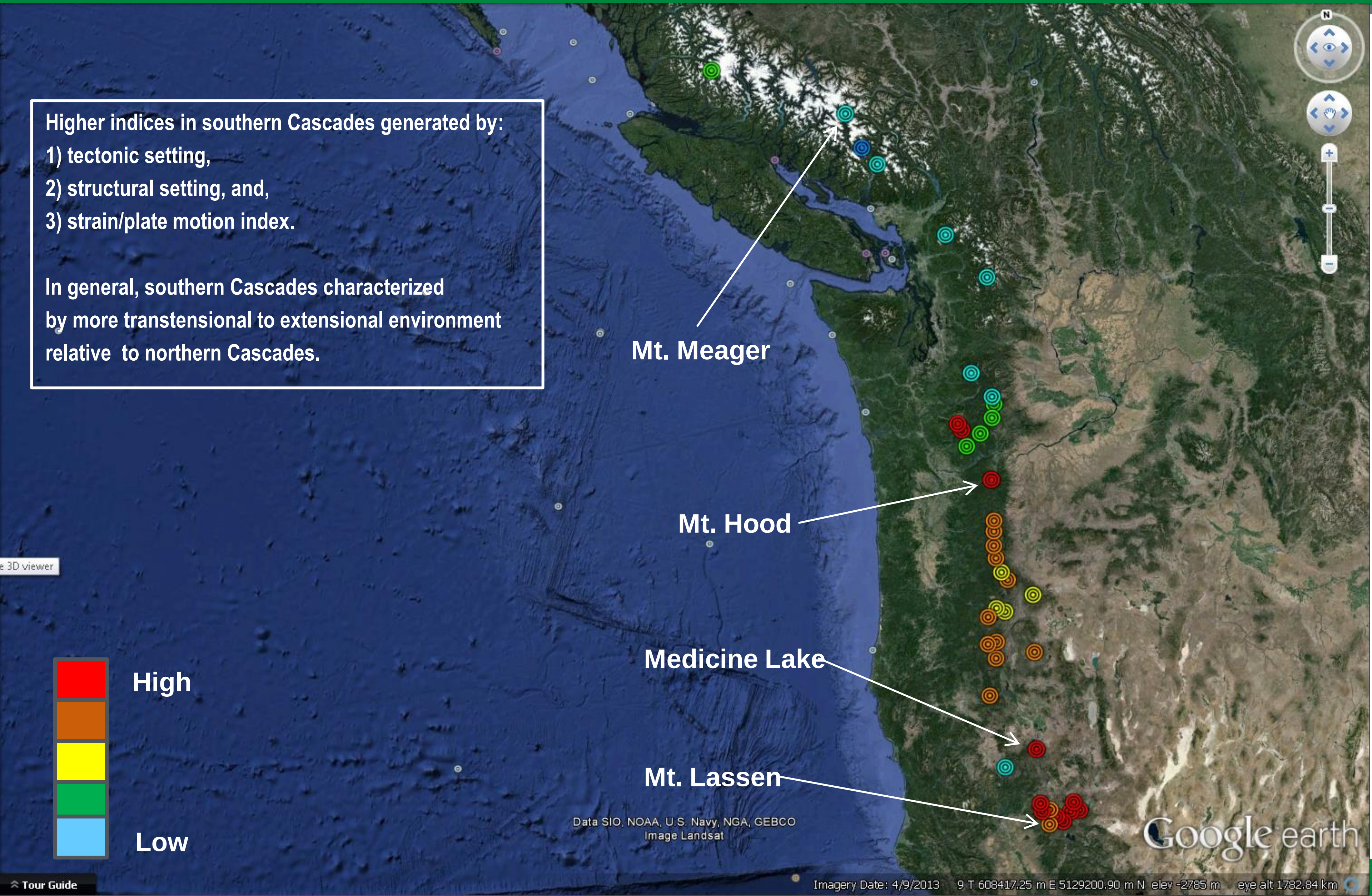
Higher indices in southern Cascades generated by:
1) tectonic setting,
2) structural setting, and,
3) strain/plate motion index.

In general, southern Cascades characterized by more transtensional to extensional environment relative to northern Cascades.



Cascade Arc Preliminary Favorability Model

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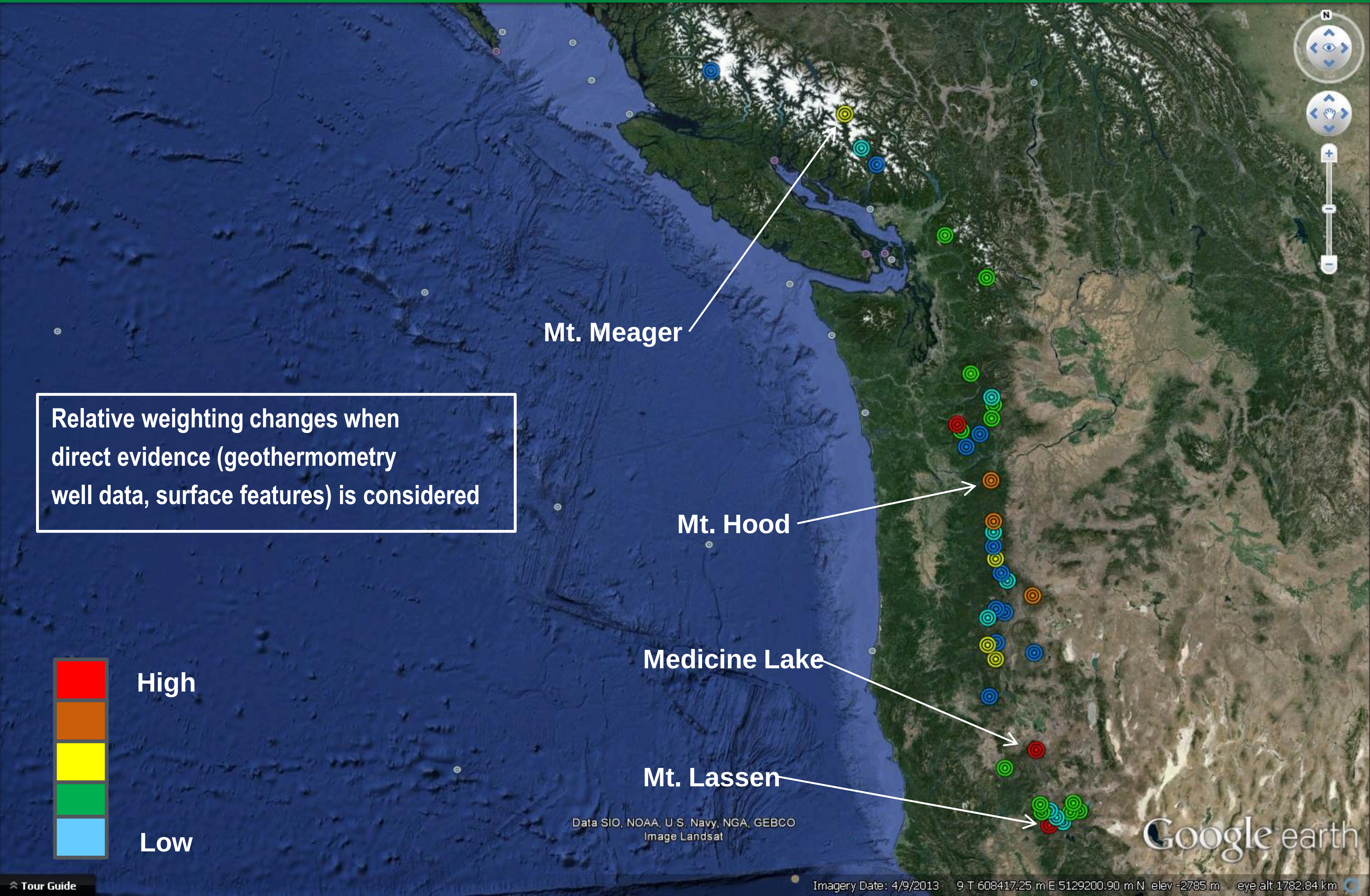
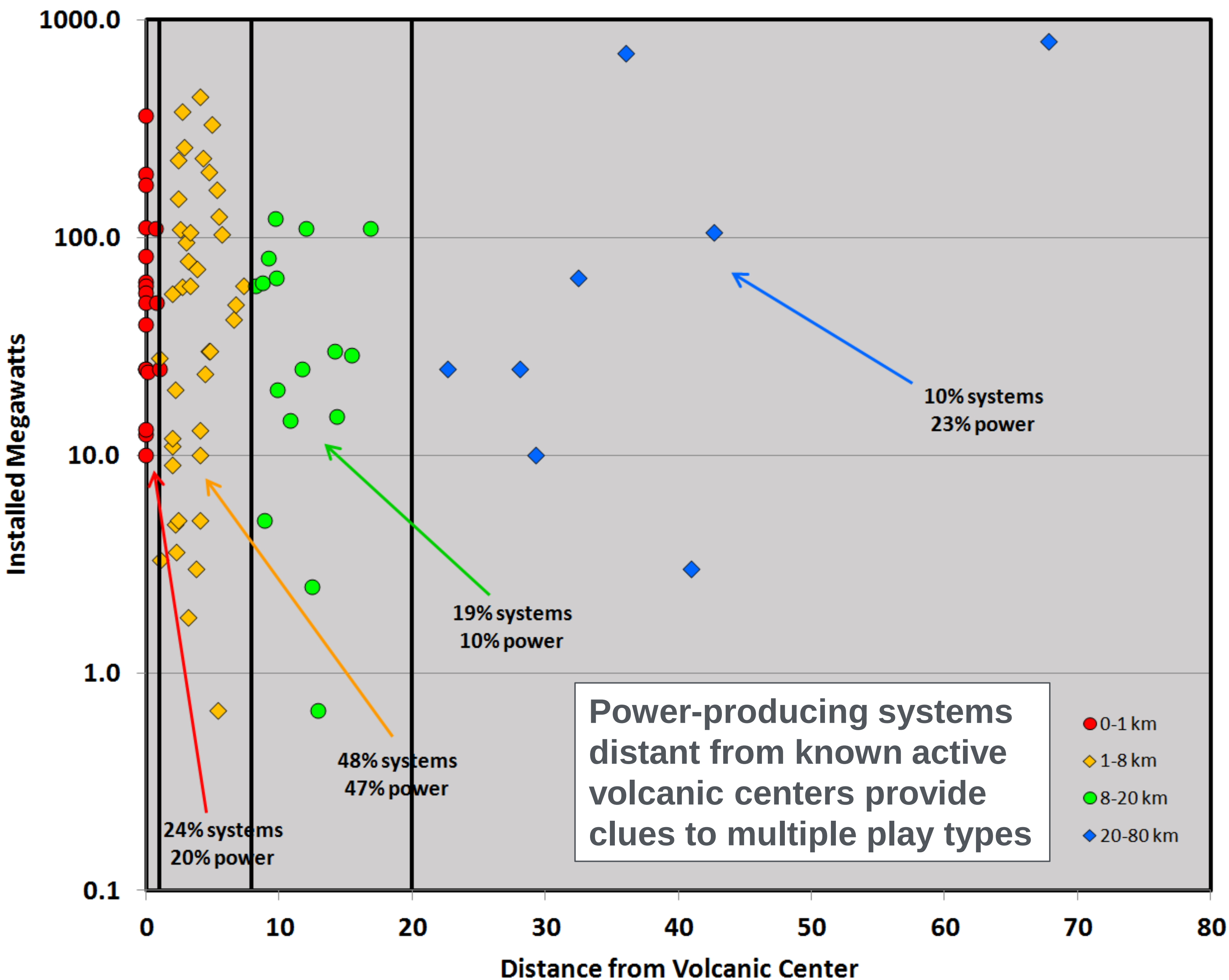
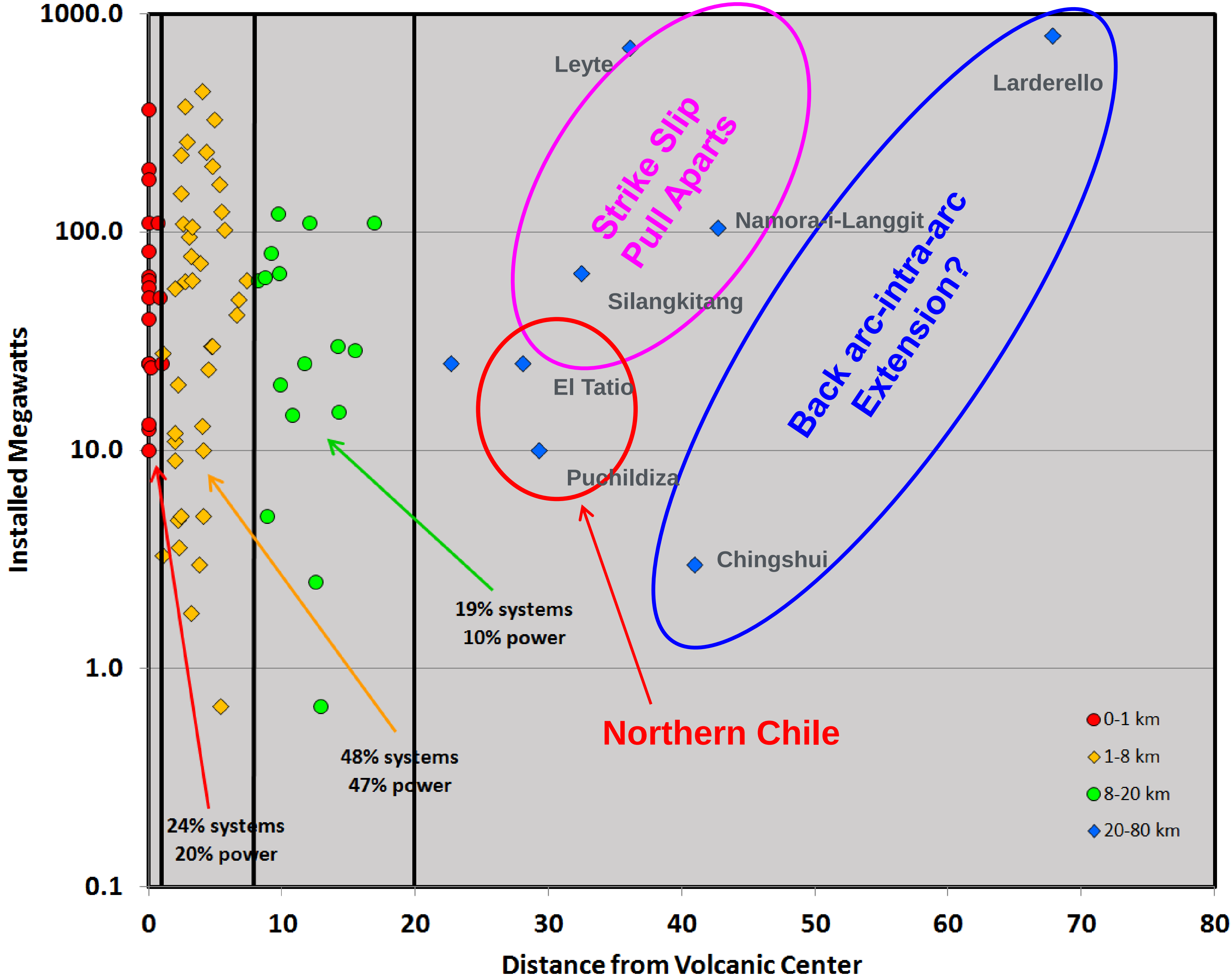
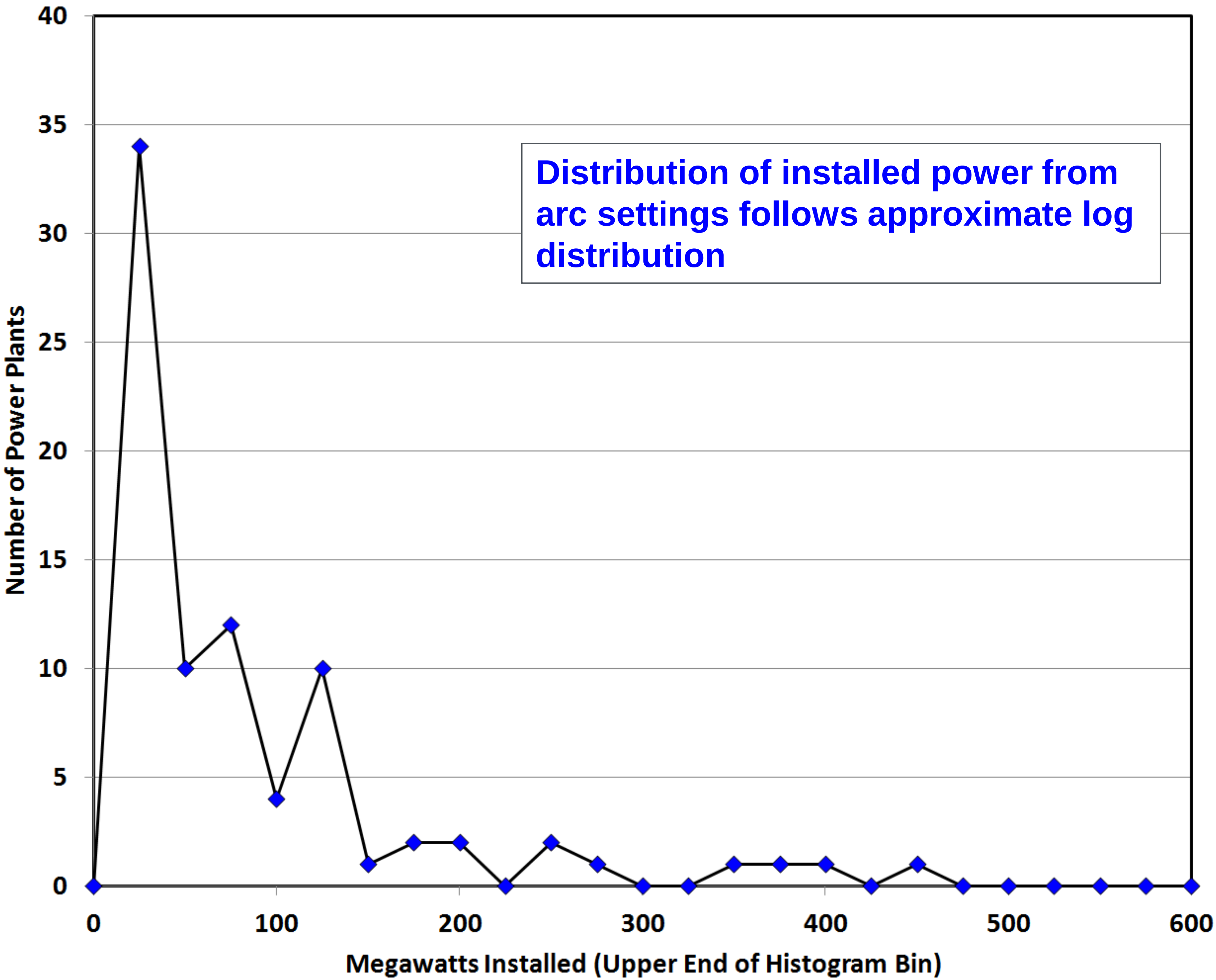


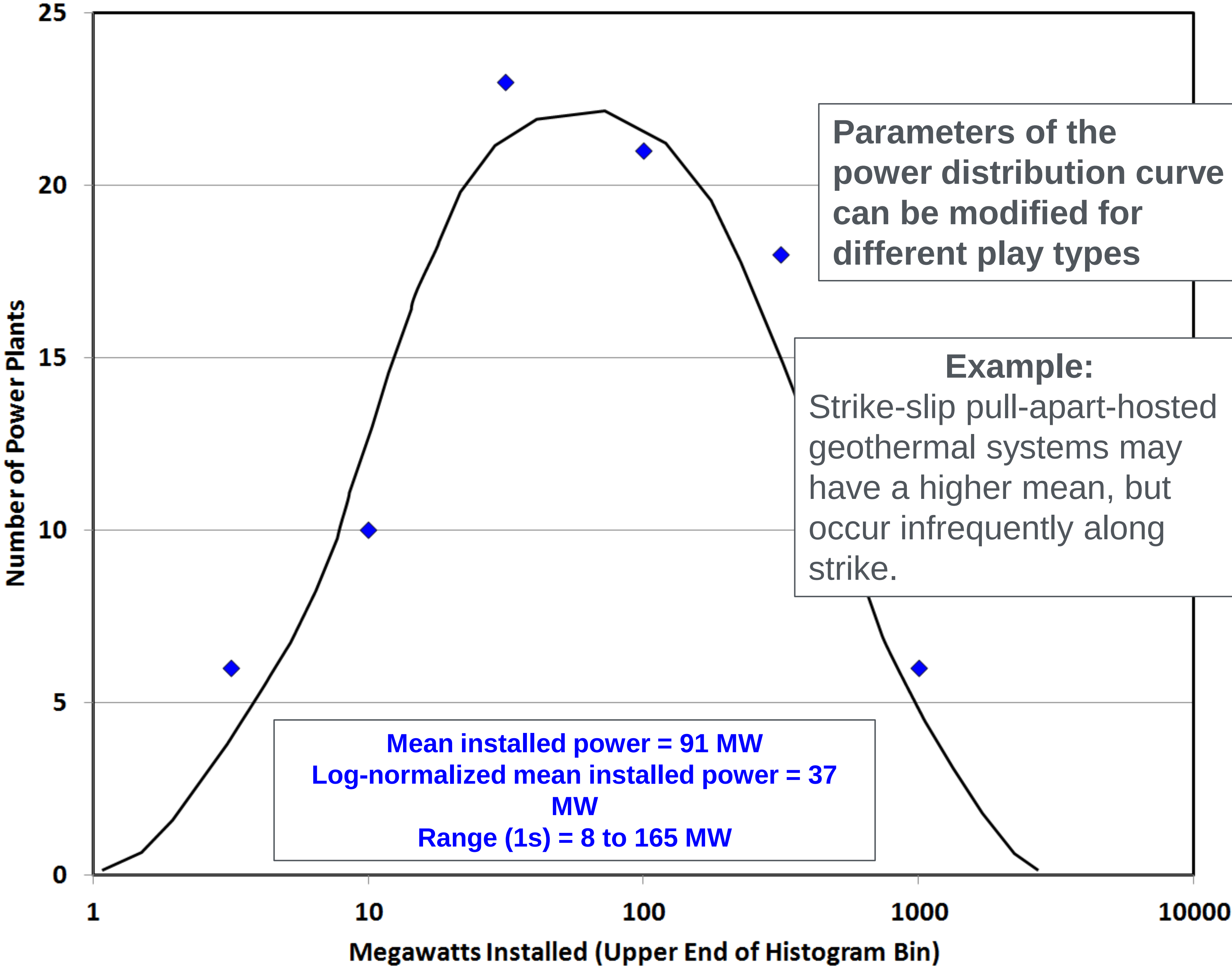
Relative weighting changes when direct evidence (geothermometry well data, surface features) is considered


1000.0
100.0
10.0
1.0
0.1
Installed Megawatts
0
10
20
30
40
50
60
70
80
Distance from Volcanic Center
10% systems
23% power
19% systems
10% power
48% systems
47% power
24% systems
20% power
Power-producing systems distant from known active volcanic centers provide clues to multiple play types
0-1 km
1-8 km
8-20 km
20-80 km



Installed Megawatts
1000.0
100.0
10.0
1.0
0.1
0
10
20
30
40
50
60
70
80
Distance from Volcanic Center
Leyte
Larderello
Strike Slip
Pull Aparts
Namora-i-Langgit
Silangkitang
Back arc-intra-arc
Extension?
El Tatio
Puchildiza
Chingshui
Northern Chile
19% systems
10% power
48% systems
47% power
24% systems
20% power
0-1 km
1-8 km
8-20 km
20-80 km


Distribution of installed power from arc settings follows approximate log distribution
Number of Power Plants
0
5
10
15
20
25
30
35
40
0
100
200
300
400
500
600
Megawatts Installed (Upper End of Histogram Bin)



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

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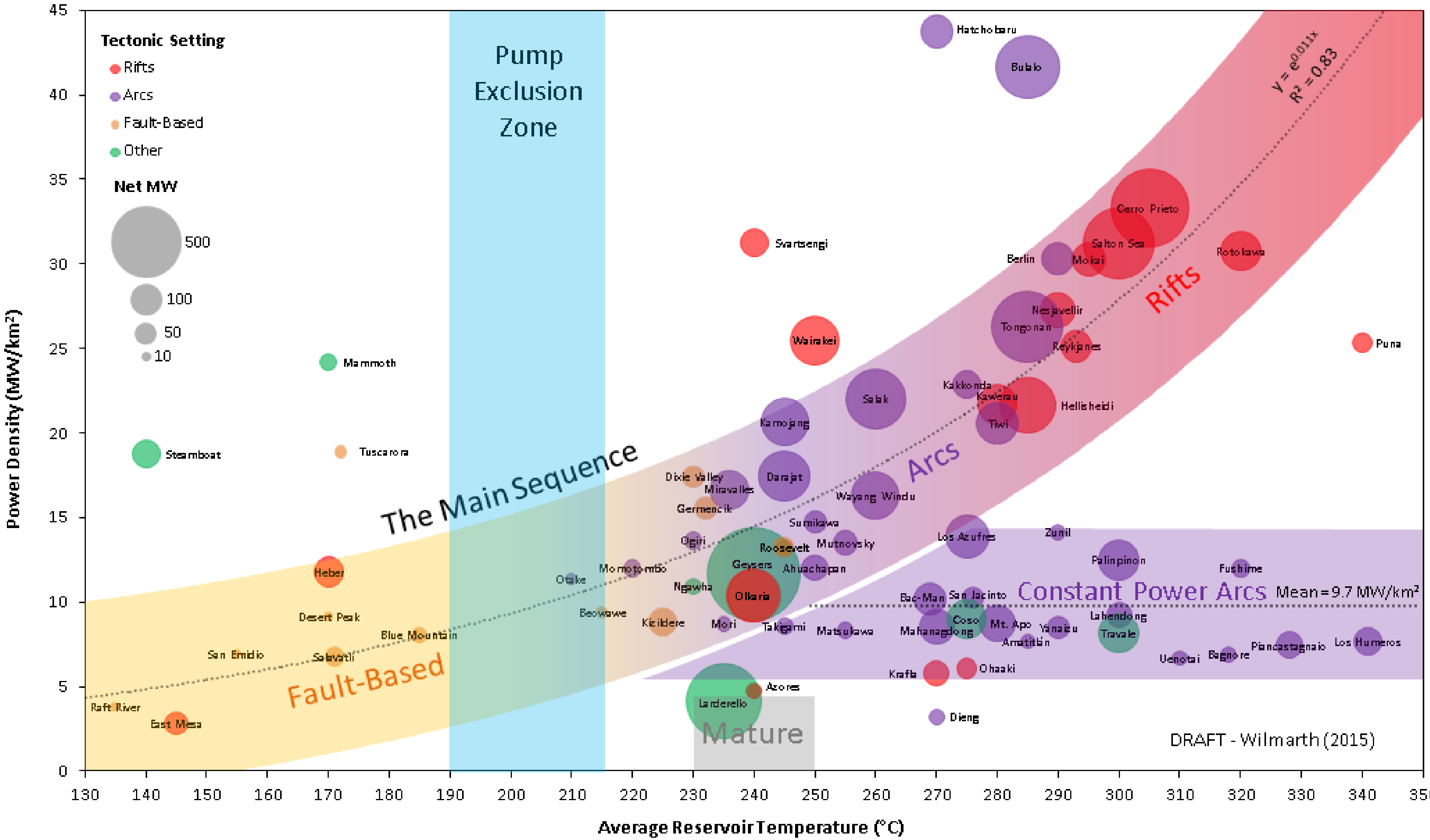
- Detailed evaluation of preliminary modeling results
- Final data compilation
- Assessment of weighting factors and relevant data ranges
- Adjustment of model parameters
- Final modeling
- Maps, tables and report preparation
- Presentation of results (GRC)

Milestone or Go/No-Go	Status & Expected Compl. Date
Final Stage Data Compilation	Initiated; Complete 6/30/15
Final Model; Generation of Predictive Indices	Planned: 10/31/15
Ranking of Volcanoes; Reporting; Commercialization	Planned: 10/31/15

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


Tectonic Setting
Rifts
Arcs
Fault-Based
Other
Net MW
500
100
50
10
Pump Exclusion Zone
The Main Sequence
Fault-Based
Arcs
Rifts
Constant Power Arcs
Mean=9.7 MW/km²
y = e^{0.011x}
R² = 0.83
Mature
DRAFT - Wilmarth (2015)
Power Density (MW/km²)
Average Reservoir Temperature (°C)
Hatchobaru
Bulalo
Cerro Prieto
Svartsengi
Salton Sea
Berlin
Mokai
Rotokawa
Nesjavellir
Tongonan
Wairakei
Reykjanes
Puna
Mammoth
Kakkonda
Kawerau
Salak
Hellisheidi
Kamojang
Twi
Steamboat
Tuscarora
Darajat
Dixie Valley
Miravalles
Wayang Windu
Germencik
Sumikawa
Ogiri
Los Azufres
Zunil
Roosevelt
Mutnovsky
Geysers
Ahuachapan
Palinpinon
Fushime
Heber
Otake
Momotombo
Ngawha
Olkaria
Bac-Man
San Jacinto
Beowawe
Lahendong
Coso
Desert Peak
Kizildere
Mori
Takigami
Matsukawa
Mahanagdong
Mt. Apo
Yanaizu
Blue Mountain
Amatitlan
Tiwi
San Emidio
Salavatli
Uenotai
Bagnore
Piancastagnaio
Los Humeros
Krafla
Ohaaki
Azores
Raft River
Larderello
East Mesa
Dieng

