Preliminary Ranking of Geothermal Potential in the Cascade and Aleutian and Volcanic Arcs, Part III: Regional Data Review and Modeling

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Cascade, Aleutian, volcanic, geothermal, potential, structure, arc, power density

ABSTRACT

As the third installment in a three-part series, this paper discusses methods of combining regional and local-scale data to predict geothermal potential at volcanic centers in the Aleutian and Cascade volcanic arcs. Local tectonic and structural settings were the primary drivers for assessing geothermal potential in these models, but the potential impact of new world models for strain style, plate motion, and crustal thickness was also assessed. In the case of strain style and plate motion, geodetically derived estimates of extensional and transtensional strain and arc-parallel plate velocities were found to correlate with power density and installed megawatts in producing arc-related geothermal systems. Local issues with global positioning system (GPS) station densities, locked plates, and magma movements increase local uncertainties of the geodetic models, but the observed correlations offer encouragement that with time, improved geodetic models can play an increasing role in geothermal predictions. A positive correlation was also identified between intermediate values of crustal thickness (25-40 km) and installed MWe in volcanic arcs. This relationship might be influenced by anthropogenic factors, because remote island arcs with thin crust and the high altiplano of South America with thick crust have seen relatively little geothermal development, but geologic factors such as uplift rates (high in the Andes), which influence the composition of reservoir host rock, may also exercise an important role.

Local and regional scale data were combined into predictive geothermal models using a play fairway concept with four principal tiers or geologic factors: heat source, permeability, fluid composition, and cap rock. Potential volcanic arc play types of 1) conventional arc systems, 2) strike-slip pull-apart systems, 3) extensional basin systems, and 4) other fault-dominant systems were incorporated into a single play fairway model using weighting factors appropriate to the specific structural setting of each. Subsequent to creation of the fairway models, direct evidence in the form of spring and well temperatures and geothermometry, as well as occurrences of fumaroles and surface mineral deposition (e.g. silica sinter) were used to refine the predictions. Degree-of-exploration was also incorporated by applying negative weights for the lack of positive direct evidence at volcanic centers where exploration was considered to have been significant.

The resulting preliminary fairway and favorability models predict elevated geothermal potential in several clusters of the central to western Aleutian Arc, the largest of which corresponds to the transition from oceanic crust to continental crust. In the Cascades, the best geothermal potential is predicted in the southern half of the arc, where transtensional to extensional tectonic process are more operative and Basin and Range extension overlaps with the active arc.

Introduction

This paper is the third in a three-part series discussing the preliminary results of predictive modeling of geothermal potential in the Aleutian and Cascade volcanic arcs. The first paper (Shevenell et al., 2015, this issue) discusses the scope of the project, data collection, and volcano-scale data analysis, and the second paper (Hinz et al., 2015, this issue) details the conceptualization and documentation of structural and tectonic settings, while the third paper reviews regional-scale data analysis and construction of preliminary predictive models. The results presented herein are preliminary because the project, funded by the Department of Energy (DOE), is approximately 50% complete as of the drafting of these papers. More complete data analyses and final predictive models will be presented after the project is completed later this year.

Data Analysis: Regional Relationships

Historically, the prediction of geothermal potential based on regional characteristics (e.g. such as subduction rate, magma composition) has proved challenging, and many geothermal explorationists have argued that the key to identifying geothermal resources lies in understanding the distribution of permeability and heat sources at a site-specific scale. Nevertheless it is recognized that certain regional-scale arc characteristics are favorable for geothermal potential; for example, the presence of significant amounts of active extension in New Zealand and Tuscany, Italy is associated with large clusters of geothermal power plants. Clusters of geothermal power plants occur elsewhere in active volcanic arcs, arguing for the influence of regional-scale favorable geologic conditions that extend beyond the scale of individual volcanic centers. It might be hypothesized therefore, that part of the difficulty in predicting geothermal potential on a regional basis could be caused by limitations in the quality and detail of regional-scale data, such as stress and strain rates, crustal motion parameters, and interactions between these parameters and pre-existing zones of weakness and lithologies.

The generation of world-wide databases of ever-increasing resolution and accuracy offer hope that regional-scale parameters relevant to geothermal potential can be better resolved. The scope of this study would not have been possible without two examples of such databases; Google Earth and the Smithsonian Global Volcanism Program database (Shevenell et al., 2015). Three additional databases utilized in this project are a world-wide geodetic plate motion and strain rate model (Kreemer et al., 2014) published in the fall of 2014, a world-wide crustal thickness model published during mid-2014 (Laske et al., 2013), and the World Stress Map (Heidbach et al., 2008). Shevenell et al. (2015) and Hinz et al. (2015) describe these databases, and an analysis of the data in a geothermal context is provided below.

Crustal Thickness Model

The digital format of the world crustal thickness model made it possible to assign crustal thicknesses to all arc volcanic centers, so that crustal thicknesses of geothermal producing and non-geothermal producing volcanic centers could be compared. In this project, a "geothermal producing" volcanic center is considered to be one in which installed geothermal electrical generation capacity either exists, is under construction, or has been demonstrated from well flow tests. Most geothermal production comes from arc segments with intermediate crustal thicknesses ranging from 25 to 40 km, and lower productivities are associated with crustal thicknesses of less than 25 km and greater than 40 km (Fig. 1).

This relationship may be influenced by anthropogenic factors. Crustal thicknesses of less than 25 km are generally associated with island arcs, as exemplified by the Aleutian Islands and the southwest Pacific islands between Papua New Guinea and New Zealand, which are relatively sparsely populated and/or poorly developed. Similarly, crustal thicknesses of greater than 40 km are largely limited to the South American altiplano, which is sparsely populated, remote, and has seen variable levels of geothermal development, in spite of world-class geothermal manifestations present at some locations (e.g., El Tatio, Chile; Rio Calientes, Peru; Laguna Colorada, Bolivia). Nonetheless, geologic factors might also influence the crustal thickness-productivity relationship. For example, high uplift rates in the Andes of South America may reduce the thickness of young volcanic rocks considered more favorable for hosting geothermal reservoirs and expose older rocks that have seen

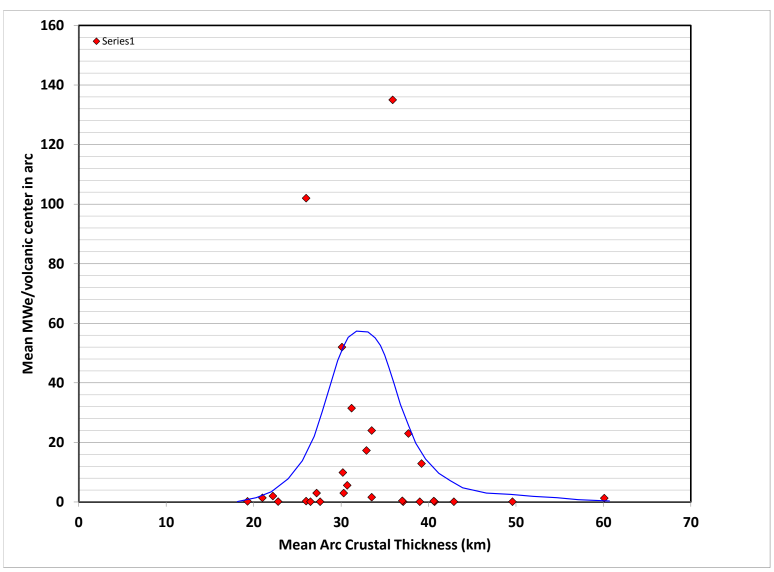

Figure 1. Mean installed MWe/volcanic centers for volcanic arc segments around the world, compared to corresponding mean crustal thickness. The blue line-of-fit is visually estimated and approximate.

greater degrees of burial-related consolidation. To evaluate possible geologic and anthropogenic factors further, we plan to estimate tectonic uplift rates for arc segments, assess play fairway indices relative to crustal thickness, and document the existing level of electricity infrastructure in these arc segments.

Geodetic Plate Motion and Strain Rate Model

Geodetic-based estimates of plate motion and strain rates have been used to corroborate and help quantify high rates of crustal extension observed at a number of productive geothermal areas, including Larderello and Mt. Amiata, Tuscany (Kreemer et al., 2014), the Salton Trough (Crowell, et al., 2013), Cerro Prieto (Glowacka et al., 2003), and Coso (Unruh et al., 2002). These relationships offer hope that new world geodetic models of crustal motion and strain rates based on geodetic measurements (e.g. Kreemer et al., 2014) could provide more widespread estimates of strain rates and plate motion useful for estimating geothermal potential, given that the world network of global positioning system (GPS) stations is growing rapidly. World geodetic models are still in their infancy, and significant challenges to accurate modeling of plate motion and strain styles remain, including the presence of locked plates, post-seismic deformation, deformation caused by magma motion, spatial resolution, and a lack of GPS stations in some areas.

Notwithstanding these challenges, the new Global Strain Rate Model (GSRM v 2.1) was merged with the arc volcanic center and power plant databases to evaluate possible relationships. The digital format of the GSRM made it possible to characterize relative tectonic plate motion vectors and strain rates and styles for the large majority of volcanic arc centers (both geothermal producing and non-geothermal producing) defined in this project. Dilatational and shear strain rates, and the second invariant of strain were calculated from the principal strain axes. A strain style index was calculated using the formulation of Kreemer et al. (2014) in which the style progressively changes from 1 (dilatation) through transtension (0.5) to pure shear (0), transpression (-0.5) and compression (-1). The relative plate motion vector of the subducting plate relative to the overriding plate was also estimated for the arc volcanic centers using the GSRM model. This vector was then compared with the orientation of each arc segment (azimuth or surface trend of each volcanic arc segment) to calculate arc-perpendicular and arc-parallel velocities. The azimuth of each arc segment was measured for each volcanic center in Google Earth based on the alignment of the trench (usually in areas of thicker continental crust) or the alignment of active volcanic centers (for some oceanic arcs), depending on which method appeared most reliable. In some areas, including Panama and the Molucca Sea, Indonesia, plate motion vectors were not calculated because the GSRM model was not sufficiently accurate and/or detailed.

One of the more distinctive associations identified is between geodetic strain style and the power density (MWe/km^2) of producing geothermal systems. Wilmarth and Stimac (2015) recently documented systematic relationships between power density, reservoir temperature, and tectonic setting (Fig. 2). For arc settings, two distinct trends or populations of power density are apparent, one with relatively low power densities, attributed by Wilmarth and Stimac (2015) to "compressional" arc settings, and the other with higher power densities, attributed to "more complex" structural settings. The strain style index provides corroboration of this relationship (Fig. 3). Compressional to transpressional values of the strain-style index are confined to relatively low power density systems, whereas dilatational, transtensional, and shear values of the index comprise the majority of high-density systems. The inference is that extensional, transtensional, and shear settings are more amenable to dilatational fracture permeability and widespread fracturing through shearing of larger volumes of rock, potentially forming fault-fracture meshes (Sibson, 1996), leading to high volumetric utilization (high power density) whereas in compressional settings, processes of fracturing are less efficient on a volumetric basis. Low-power-density geothermal systems might form in transtensional to dilatational settings if other factors (e.g., strain rate, lithology) are less favorable, but for the higher power density systems, a more favorable conjunction of strain style and other factors may be required.

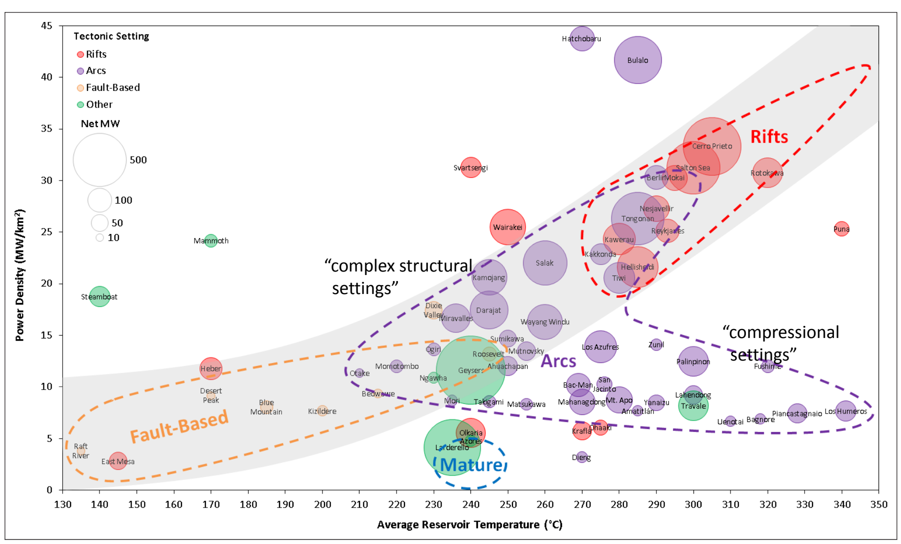

Figure 2. Power density in geothermal fields as a function of reservoir temperature and tectonic setting. Taken from Wilmarth and Stimac (2015).

A similar relationship is observed between power density and the arc-parallel velocity of the subducting plate (Fig. 4). Relatively low rates of arc-parallel motion are associated with low power density geothermal systems, whereas higher power densities are associated with higher arc-parallel velocities. Higher arc-parallel speeds could contribute to increased shearing in the volcanic arc, facilitate arc-parallel extension, and contribute to a greater structural complexity. These results are preliminary, and continued investigations are being made to clarify underlying relationships and identify the key independent parameters responsible for correlations.

The strain style index and the plate motion index were linearly combined through scaled addition (index = arc-parallel motion (mm/yr) + [125 x strain style]) to create a combined strain style/motion index. The scaling factor used to convert units between arc-parallel motion and strain style was determined from examination a scatter plot of the two indices. The cumulative distribution of this combined index for all volcanic arc centers reveals a strong correlation with producing geothermal systems (Fig. 5). The binary weights-of-evidence contrast statistic for this index is 0.94 +/- 0.26, with a statistically significant studentized contrast of 3.6. This suggests that plate motion characteristics and regional strain styles have a significant impact on geothermal potential, and that perhaps with continued improvements in GPS-station network densities and noise processing methodologies, that regional geodetic data may become more valuable in the future as a predictive tool. Currently however, high uncertainties characterize the GSRM at the scale of individual volcanic centers and some arc segments, and caution must therefore be exercised when using this parameter to predict local geothermal potential.

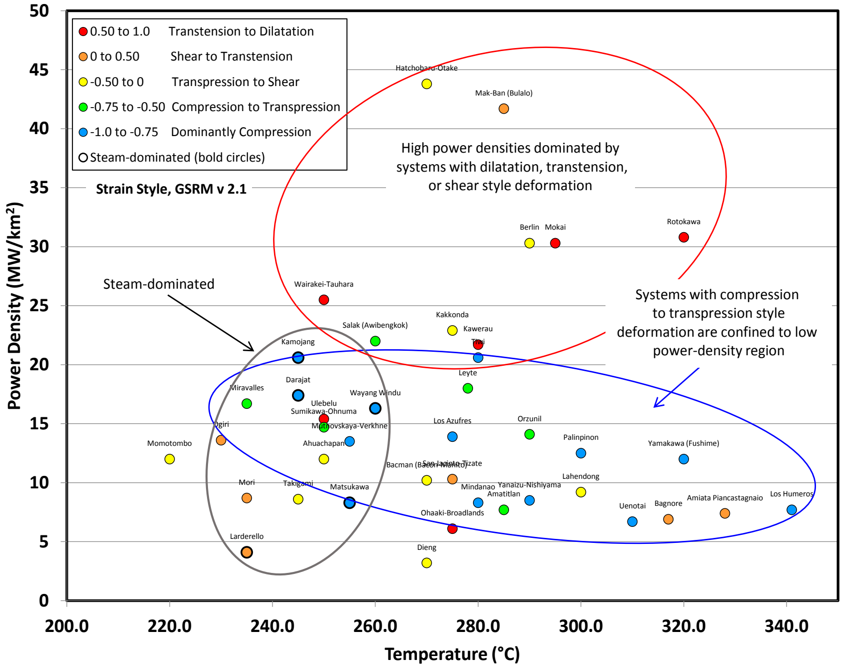

Figure 3. Relationship of power density to strain style measured from GSRM v. 2.1 for volcanic arc-hosted geothermal systems (see text for details). Power density data from Wilmarth and Stimac (2015).

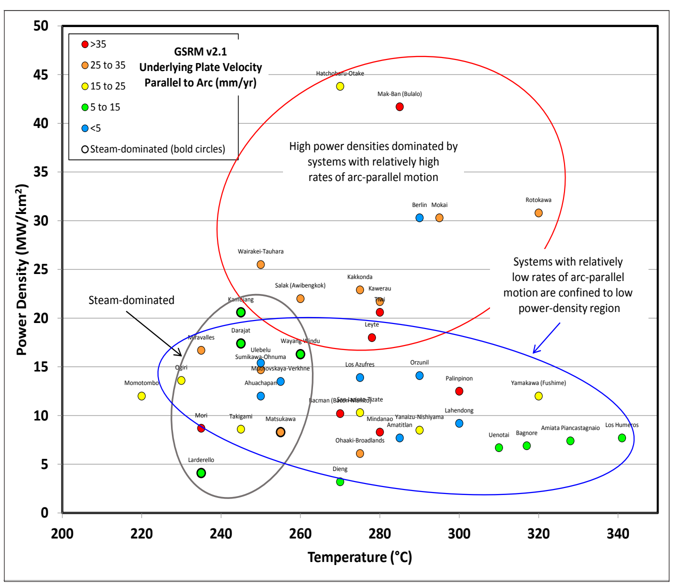

Figure 4. Relationship of power density to arc-parallel subducted plate velocities measured from GSRM v. 2.1 for volcanic arc-hosted geothermal systems (see text for details). Power density data from Wilmarth and Stimac (2015).

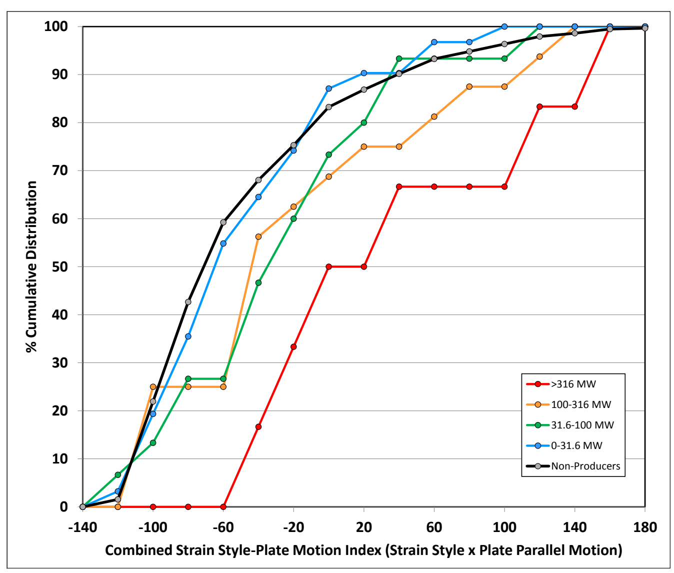

Figure 5. Cumulative distribution of an additively combined strain style-arc-parallel plate motion index for arc volcanic centers (see text for formula). Black line represents the distribution for non-producing volcanic centers, and colored lines represent distributions for the specified installed megawatt categories of geothermal systems associated with volcanic centers. Weights-of-evidence W+ = 0.47, W- = -0.47, contrast = 0.94 +/- 0.26 (student contrast = 3.6).

Model Construction

The preliminary predictive geothermal models utilize the play fairway concept originally developed for petroleum exploration. In the play fairway approach, a set of key geological factors (Fugelli and Olsen, 2005) or principal hierarchical tiers (Doust, 2010) define required components or conditions considered essential for the development of resources. In the case of petroleum exploration, these tiers might consist of, for example, 1) a petroleum charge (source rocks, a maturation window, and a migration pathway), 2) a reservoir rock, 3) a topseal or caprock, and 4) suitable traps (Allen and Allen, 2005).

In the case of geothermal plays in arc terrains, four key component geological factors or hierarchical tiers are considered in this project; they are: 1) heat source, 2) permeability, 3) viable fluid chemistry, and 4) cap rock. The first component, a heat source, is commonly present to varying degrees at suitable depths beneath most active arc volcanic centers. As such, it isn't always the most critical component, though clearly the presence of high heat flow related to large cooling magma bodies or intrusions at relatively shallow depths can have a significant impact on the heat content and size of a resource. The third component, a viable fluid composition, is also usually available in most arcs where moderate-salinity, near-neutral pH meteoric hydrothermal systems develop within or marginal to intrusive centers. In some cases, however, low-pH fluids with magmatic input, or other fluids that pose difficult-to-resolve challenges related to corrosion or mineral precipitation in well bores, can make economic exploitation difficult.

It might be argued that the fourth component, a cap rock, is not necessary for the development of hydrothermal circulation in a geothermal system; however, most successfully developed systems show well established caps (Faca and Tonani, 1967; Grant and Bixley, 2011). It may be that in order to achieve *economic* viability, some type of cap rock helps constrain the natural rate of energy release into the environment. Geothermal reservoirs are inherently more dynamic than petroleum reservoirs in the sense that, if they are not sustained by an ongoing influx of heat, they will dissipate their stored energy by conduction within a few tens of thousands of years if impermeable and much more quickly by convection if permeable. Economically viable conventional geothermal resource development requires high permeability, which would result in the rapid dissipation of a reservoir's available heat energy to the surface or near-surface environment if a cap rock was not present.

It could also be argued that clay caps commonly form in volcanic environments where geothermal systems are present, thus the presence of a clay cap might be assumed in many cases, and will not usually comprise a critical missing component. However, the ability of a clay cap to form might be complicated by an unsuitable host rock (e.g. quartzite) or hindered by the presence of alteration minerals formed during earlier periods of alteration that are resistant to the transformation into clay (e.g. hornfels?). At some locations, clay caps have initially formed, but have since been breached by rapid rates of erosion related to high topographic gradients, high uplift and/or high precipitation rates, glaciation, or volcanic sector collapse. Such breaching is interpreted to have caused significant damage to reservoirs at Karaha Bodas, Indonesia (Moore et al, 2002) and Tolhuaca, Chile (Melosh et al, 2012; Melosh, verbal communication, April, 2015). Hoagland and Bodell (1990) described a cap failure event during production that was devastating at Tiwi, Philippines. In these cases, lack of an intact cap constitutes a negative indicator.

The remaining component, permeability, is considered by many as the most critical factor for geothermal resource development (Faulds et al., 2010, Melosh, 2015, Hinz et al., 2011), from the perspective of its relative scarcity compared to the other factors mentioned above. Economic levels of permeability can be challenging to predict, and are influenced by structural and tectonic settings, lithology (as it influences both primary and secondary permeability) and lithologic diversity (Melosh, 2015), as well as geologic history. Accordingly, permeability has received the greatest attention in the geothermal modeling processes described herein.

Play Types

Most geothermal occurrence models and play type classification systems prominently include volcanic arc settings (Sabin et al., 2004; Walker et al., 2005; Moeck and Beardsmore, 2014; Moeck, 2014), but subdivisions with volcanic arcs are less clearly defined. The inclusive approach to defining volcanic arcs we have employed herein does include geothermal systems classified differently by others. For example, Moeck (2014) considers Larderello as "plutonic", which is not unreasonable considering the weak development of subduction, and Wilmarth and Stimac (2015) classify New Zealand geothermal systems as rift-related. And although not explicitly stated in some publications, most researchers would recognize strike-slip pull-apart settings within volcanic arcs (e.g., Leyte, Philippines; Sarulla block, Sumatra, Gunderson et al., 2000) as a discrete play type akin to the Salton Trough and Cerro Prieto.

Clues to the occurrence of multiple play types in volcanic arc settings can be seen in a graph of installed megawatts of producing systems versus distance to the nearest Holocene volcanic center (Fig. 6). It should be noted that volcanic centers defined in this graph only include Holocene vents at least 500 meters in height (excluding calderas); a Holocene age threshold was chosen because of the geographic completeness of the Smithsonian Holocene volcanic database affords less bias in more remote arcs.

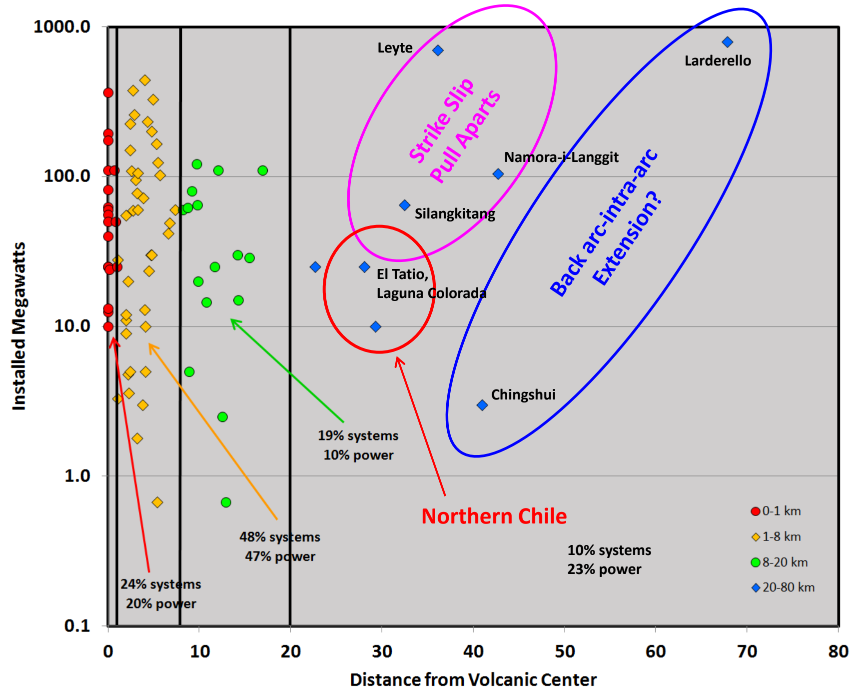

Figure 6. Installed MWe for producing and power-capable geothermal systems compared to distance to the nearest Holocene volcanic vent at least 500 meters in height. Distances based on data from Smithsonian Global Volcanism Program database and inspection in Google Earth.

Not surprisingly, Figure 6 illustrates that approximately 72% of producing geothermal systems in arc settings, and a similar percentage of the total installed power (67%) are found within 8 km of a Holocene volcanic edifice ≥500 m in height. At greater distances of 8-20 km, an additional 19% of producing systems account for only an additional 10% of installed power. The reduced ratio between installed power and number of systems in this category likely indicates that lower enthalpy-content peripheral outflow zones are present in some of these systems.

The trend reverses at distances greater than 20 km, where 10% of the arc systems contain 23% of installed power, including some of the more productive geothermal systems (e.g. Larderello, Leyte). Although small Holocene or Pleistocene volcanic centers lie closer to these geothermal fields than the ≥500-meter-tall Holocene edifices shown here, these geothermal systems appear distinct from most other arc systems, and the high productivities associated with some of them may suggest that different geologic controls are operative and therefore that different play types may be present.

Perhaps most clearly representative of a different play type in Fig. 6 are the strike-slip pull-apart geothermal systems at Leyte, Philippines and the Sarulla block, Sumatra. Additional strike-slip pull-apart systems could occur at distances less than 20 km from Holocene volcanic centers and not be distinguishable in Fig. 6, but the graph illustrates the potential for such plays to occur well outside conventional distances between arc volcanic centers and associated geothermal systems. A second play type might be represented by Larderello and Chingshui, Taiwan; they might be classified as back-arc or intra-arc extensional plays based on the back-arc position of the former and the high extension rates and geologic setting of the latter. A third potential play category includes a group of geothermal systems with demonstrated power potential in northern Chile, including El Tatio, Laguna Colorada, and Apacheta. These systems are associated in part with sinistral, transtensional Quaternary grabens oriented obliquely to the arc trend (Tassi et al., 2010; Lanza et al., 2013) and local development of silicic domes. Structural preparation appears important in these systems, similar to some geothermal systems of the Great Basin, USA.

The potential play types described above have been incorporated into the preliminary model by recognizing their associated structural and tectonic settings, and assigning appropriate weights to them in the permeability model (see discussion below).

Fairway Model

The predictive models currently comprise two stages (Fig. 7): a fairway model and a favorability model (additional model stages illustrated in Fig. 7 will be added when the final model is completed later this year). The first stage is the fairway model; it represents the combined occurrence of the four geologic factors or hierarchical tiers considered necessary for an economic geothermal system to form, and as such, constitutes the "fairway" when plotted on maps. The fairway model does not consider any direct evidence of geothermal activity (e.g. hot springs). Direct evidence is added later in the favorability model (see on the following page).

In the modeling process, the four hierarchical tiers or principal geologic factors described above (see initial section on "Model Construction") were assigned numerical values that qualitatively indicate the probability that each key component is present at each volcanic center. The numerical range for each component is from 0 to 1. These probability assignments are non-quantitative in part because the scale of the project and data availability and quality issues for less well-explored volcanic arcs prevented accurate characterization of geologic factors in non-producing volcanic arc segments around the world (Shevenell et al., 2015). The probability assignments for each of the four hierarchical tiers were then multiplied together to form a fairway prediction (Fig. 7), in accordance with the play concept that each of these key factors should be present in order for a viable geothermal system to form.

In the preliminary model, sufficient data has not been gathered to differentiate between the quality of heat source, fluid chemistry, or cap rock for each of the Aleutian and Cascade volcanic centers. In the final model, this may change, at least in the case of cap rock, but for now, default probabilities have been assigned to these three tiers or geologic factors. These default probabilities are high, ranging from 0.9 to 0.95 (Fig. 7), reflecting the expectation that at most active arc volcanic centers, these three factors are either present or could develop in response to geothermal activity.

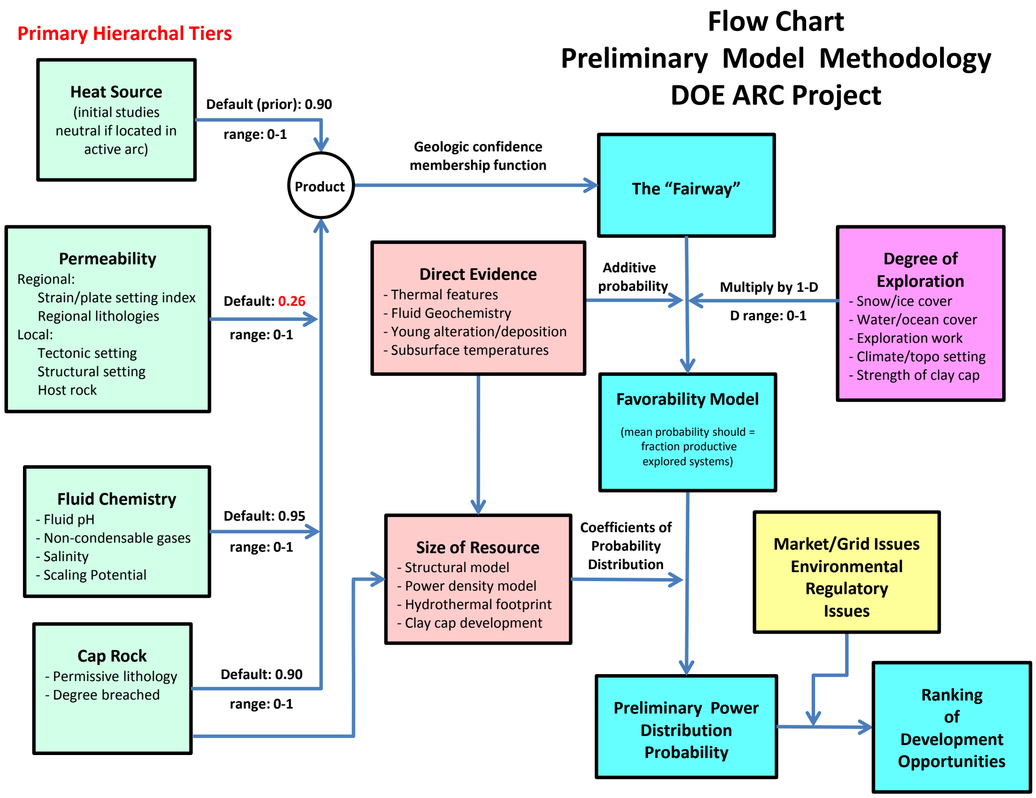

Figure 7. Overall flow chart of predictive model methodology. The preliminary model included calculation of the fairway and favorability models. The Preliminary Power Distribution model and Ranking of Development Opportunities will be completed at the end of the project.

A mean default probability value for the permeability component of the model was chosen such that the resultant mean value for the play fairway equaled the expected fraction of arc volcanic centers that can ultimately host conventional economic geothermal resources. In other words, in the current model, approximately 730 arc volcanic centers have been defined (around the world), and 10% are known to host productive geothermal systems. If one assumes that half of the world's suitable arc systems have been developed to date, this number could double to 20%, yielding a mean fairway probability prediction of 0.2 (prior probability). Calculation of the mean permeability probability based on this number, and based on the default probabilities assigned for the other three hierarchical tiers, yields a mean permeability value of 0.26 (so that 0.26 (mean permeability) x 0.90 (mean heat source) x 0.95 (mean fluid chemistry) x 0.90 (mean cap rock) = 0.20). We emphasize there is no attempt at this point to justify a mean fairway probability of 0.2, the true value could be higher or lower. The intention is to work with plausible probabilies, so that when other similarly scaled components are added to the model, the resulting output is more likely to be weighted properly.

Permeability

The permeability component constitutes the core of the preliminary fairway model, based on its demonstrated importance in determining geothermal potential. Permeability is influenced by many factors that include lithologic as well as structural/tectonic parameters. We are evaluating methods of systematically including lithology in the model. Because of challenges in accurately representing subsurface lithology at reservoir depths on a regional basis, it has not yet been added. One possible means of indirectly incorporating lithology involves the use of tectonic uplift rates as a measure of predicting the thickness of preserved young volcanic rocks (considered more likely to host permeable reservoirs) and the corresponding depth to older rocks less prone to develop distributed fracture permeability. This will be investigated in the final stage of this project later this year.

The preliminary permeability model consists of three components (Fig. 8); tectonic setting, structural setting, and the strain style-plate motion index. Together the tectonic and structural settings comprise approximately 80% of the weight of the permeability layer. The remaining 20% is comprised by the strain style-plate motion index, which was rescaled in probability space to a range of 0.11, reflecting an approximate equivalent probability contribution based on its calculated weight-of-evidence contrast statistic of 0.94.

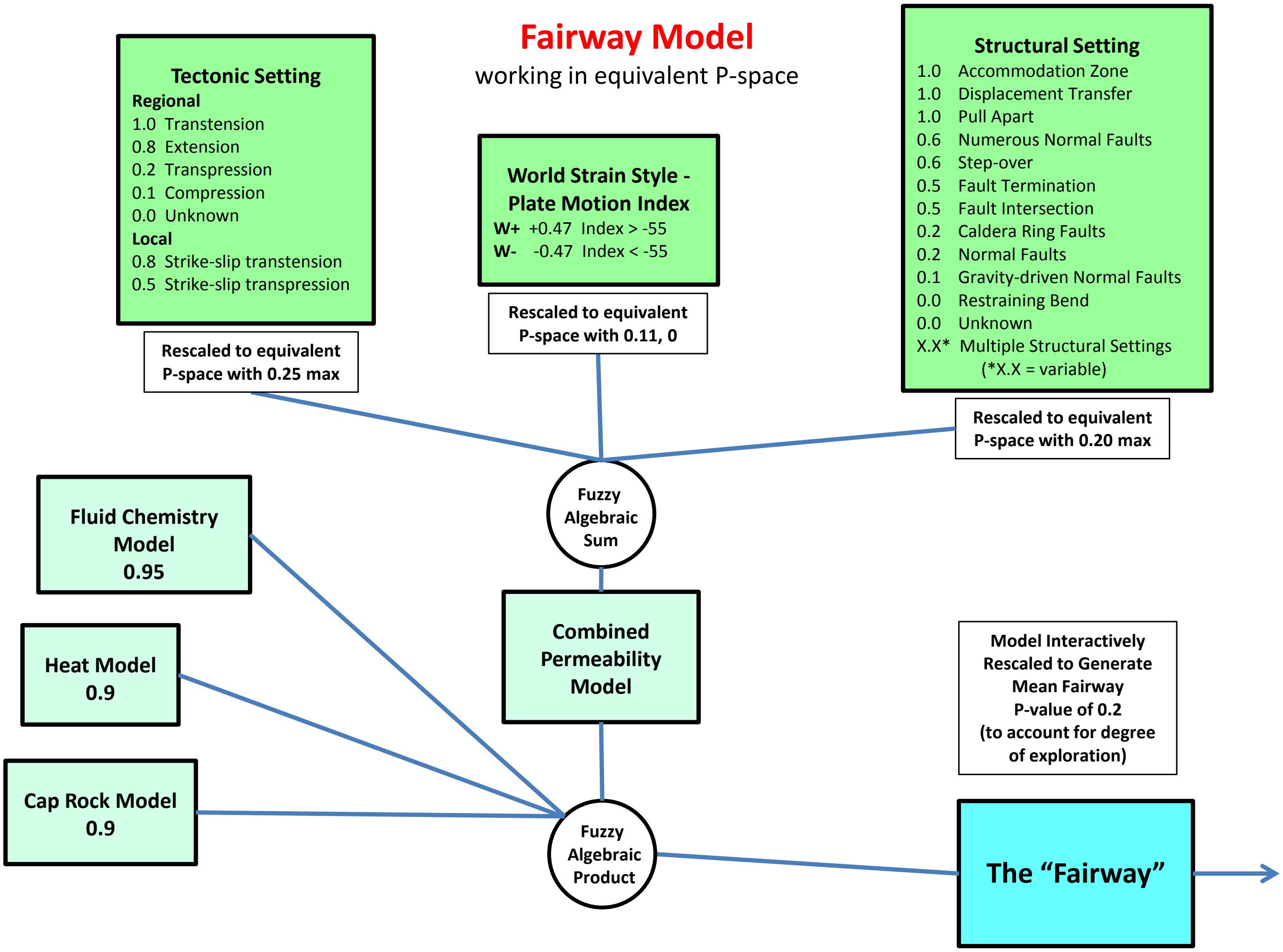

Figure 8. Flow chart for construction of the fairway model.

Tectonic and structural classes were qualitatively assigned based on detailed analysis at each volcanic center, as described in parts I and II companion papers (Shevenell et al., 2015; Hinz et al., 2015). Numerical weights for each class were based on their expected favorability for geothermal potential (at this point they are preliminary and mainly illustrative in nature). These weights were then rescaled into pseudo-probability space (Fig. 8) such that their mean algebraic sum, when combined with the strain style-plate motion index, equaled 0.26 (see discussion above). The fuzzy algebraic sum is represented by the following formula:

$$\text{Fuzzy Algebraic Sum} = 1 - [(1-p_1) * (1-p_2) * (1-p_3)] \qquad (1)$$

where p_1, p_2, and p_3 represent the component weights of tectonic setting, structural setting, and strain style-plate motion index. Two key characteristics of the fuzzy algebraic sum are 1) the output probability increases when any of the input probabilities increases (multiple favorable factors are better than one favorable factor), and 2) the sum can never exceed a value of 1.

Favorability Model

A second stage favorability model was built upon the fairway model by adding “direct evidence” and “degree-of-exploration”. Direct evidence includes thermal manifestations (e.g., fumaroles and hot springs), well data, and surface deposits (e.g. silica sinter), whose presence and character (e.g., geothermometry) can significantly impact the geothermal potential of a given volcanic center. Degree-of-exploration is a qualitative indicator of how well explored a given area is for geothermal resources.

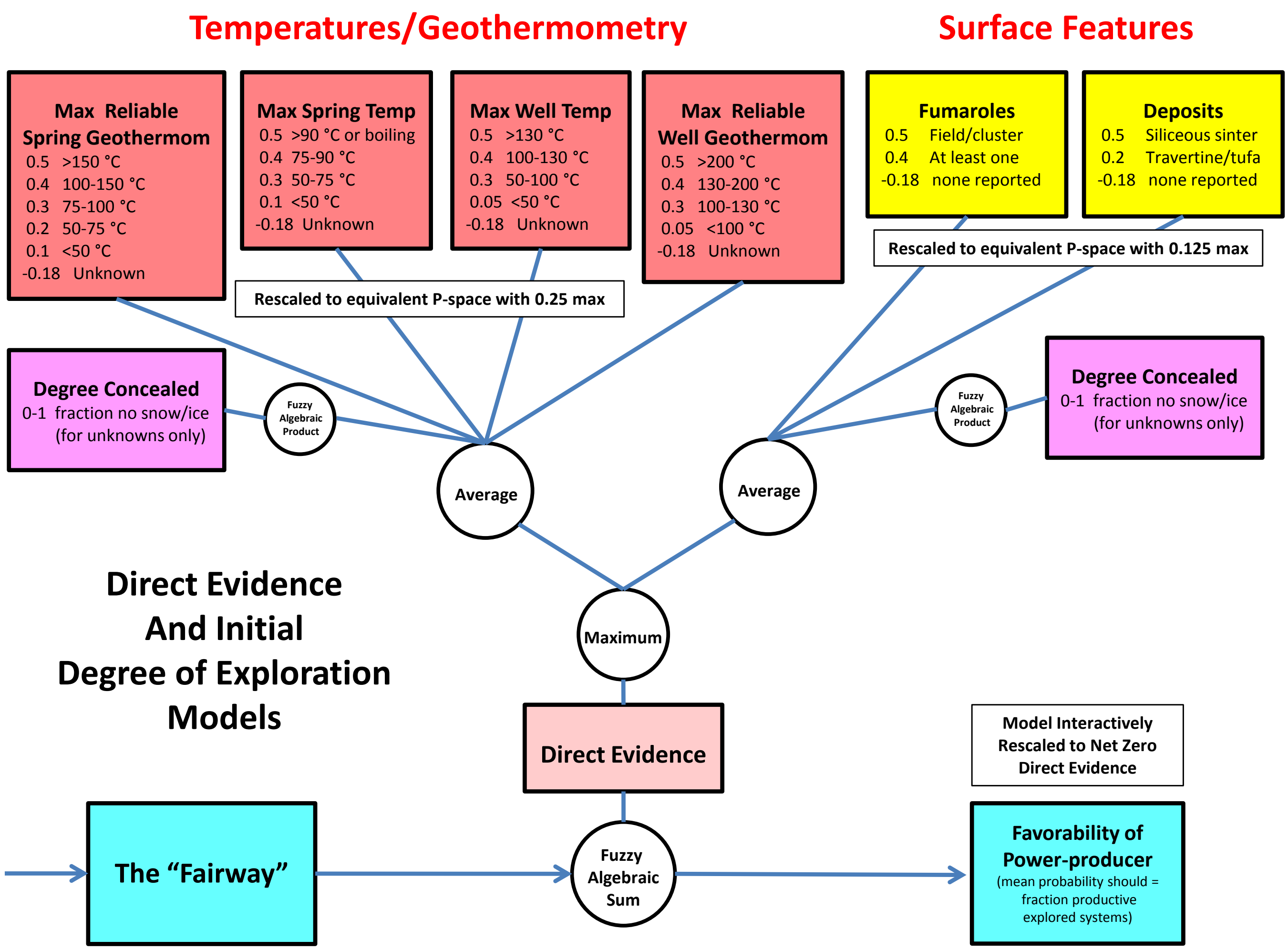

Figure 9. Flow chart for construction of the favorability model with input from direct evidence and degree-of-exploration.

Direct Evidence

Direct evidence incorporated into the preliminary model includes well and spring temperatures, well and spring geothermometry (including gas and liquid geothermometers), and presence of fumaroles and mineral deposits (e.g. silica sinter) (Fig. 9). Methods of compiling these parameters and assigning relative weights are described in the part I companion paper (Shevenell et al., 2015). The preliminary weights assigned to these parameters and the rescaled pseudo-probabilities (Fig. 9) represent efforts to qualitatively characterize the probability of occurrence of economic geothermal activity given the presence of these features.

Degree-of-Exploration

The degree-of-exploration index is designed to qualitatively characterize the thoroughness of geothermal exploration at each volcanic center. If thorough exploration has not yielded a ‘discovery’, it is less likely that an economic geothermal system exists. The degree-of-exploration index also attempts to account for the ability of a geothermal system to remain blind or hidden. If the potential for a blind system is considered high, the degree-of-exploration will be lower. Degree-of-exploration is scaled in probability space from 0 (no exploration) to 1 (complete exploration). Degree-of-exploration is difficult to estimate because many factors play a role, including geomorphic factors related to surface manifestations, climate/vegetation, population density, drilling, geological, geochemical, and geophysical surveys, and ease of access. An example of the use of degree-of-exploration is provided by Coolbaugh et al. (2007) who used this index to revise geothermal evidence weights in Nevada and estimate the magnitude of undiscovered resources. Incorporated into the Coolbaugh et al. (2007) model were data on 1) water table depth, 2) depth and type of wells drilled, 3) presence or absence of a carbonate aquifer.

Consideration was given to including a ‘rain curtain’ effect in the degree-of-exploration model which would account for the often quoted tendency of geothermal manifestations in the Cascade and Aleutian Arcs to remain concealed or disguised to due high rates of precipitation and shallow cold groundwater flow, which, it is envisioned, could capture and entrain rising thermal fluids. However, many arc volcanic settings in similarly wet, mountainous climates in the southwestern and western Pacific show strong surface geothermal manifestations, and surface water mass balance calculations in the Cascades do not reveal significant rates of hidden geothermal contributions to streams and rivers (Muffler and Guffanti, 1995). For this reason, a rain-curtain effect was not included.

At this preliminary stage of model construction, the only factor incorporated into the degree-of-exploration index was the percentage ice cover. Glacial ice covers large portions of some volcanic centers in the easternmost Aleutian Arc and the northernmost Cascade Arc in Canada, and clearly hinders exploration in those areas. Percentage ice cover was estimated in Google Earth for each volcanic center and proportionately converted into a degree-of-exploration index ranging from 0 (100% ice cover) to 1 (0% ice cover). Such an assignment overestimates degree-of-exploration in non-ice covered areas, because degree-of-exploration for geothermal resources has never reached 100% in the broad area associated with a volcanic center. The degree-of-exploration factor will be refined in the final model, but for now it serves as a demonstration of how the factor can be incorporated into a favorability model (see below).

Combination of Direct Evidence and Degree-of-Exploration to Form Favorability Model

Direct evidence was combined with degree-of-exploration to produce an overall "direct evidence index". First, individual well and spring temperature and geothermometer indices were rescaled to pseudo-probability space (maximum value of 0.25) and fumaroles and surface deposits were rescaled to a maximum value of 0.125. The average of the four well/spring indices was then compared to the average of the two surface feature indices and the maximum value adopted as a direct evidence index (Fig. 9).

Within each of the six indices mentioned above, a negative 0.18 weight corresponds to unknown data (no information). The negative weight was then multiplied by the degree-of-exploration, such that areas with a high degree of exploration incorporate a negative weight for lack of data, whereas areas with little exploration have minimal negative weights assigned for missing data. For example, a lack of known thermal manifestations is considered a negative factor only if surface exploration has been sufficiently detailed to find them. As mentioned above, the degree-of-exploration index as currently employed in the preliminary model is considered to be rated higher than it really is. This results in underestimated values of 'direct evidence'. The degree-of-exploration index will be refined when the final model is completed later in the year.

The combined 'direct evidence' index was then combined with the fairway model using a fuzzy algebraic sum (see form of equation 1) to create an overall favorability model (Fig. 9). Probability rescaling and negative weights for lack of information were designed so that the net mean contribution of direct evidence into the model was zero. That is, the contributions of direct evidence and degree-of-exploration approximately balance each other when averaged over the entire model. From one volcanic center to another, however, the effects are much different. Some volcanic centers with positive evidence of high-temperature geothermal activity see their predictive indices rise considerably with the addition of direct evidence (e.g., Mt. Lassen, CA), whereas others considered to be explored, but without favorable direct evidence, see their predictive indices decline (e.g., Magee Peak, CA).

Preliminary Model Results

Preliminary fairway and favorability model results for the Aleutian and Cascade arcs are respectively depicted in Fig. 10-13. In the Aleutian Arc, several elevated clusters of fairway potential are predicted in the western and central portions of the arc (Fig. 10). A review of input data reveals that high predictions in the Aleutians are driven primarily by complex/favorable structural settings. Interestingly, the largest cluster of elevated potential occurs where the oceanic portion of the arc joins the continental shelf, in the vicinity of Akutan and Makushin, the two most explored areas in the Aleutians. Perhaps a change in crustal thickness produces a more complex structural response to oblique subduction in this area. It should be noted that the fairway model itself does not incorporate any direct evidence of geothermal activity. The preliminary favorability model of the Aleutians (Fig. 11), which does include direct evidence and degree-of-exploration, highlights most of the same areas shown in the fairway model (Fig. 10). This indicates good agreement between favorable tectonic/structural settings and direct evidence of geothermal activity.

The fairway model for the Cascade arc (Fig. 12) indicates progressively higher potential in more southerly portions of the arc, broadly consistent with observations by Muffler and Guffanti (1995). The Cascade favorabilities are driven by 1) tectonic setting, 2) structural setting, and 3) strain style/plate motion index, all three of which are in broad agreement with each other. In general, the southern Cascades are characterized by a transtensional to extensional environment, in which Basin and Range extension overlaps with parts of the active arc, whereas the northern Cascades appears more uniformly compressional in character. Relatively high favorabilities are reported for the Mt. St. Helens area in southern Washington. The strain style component of the permeability index in the immediate area of Mt. St. Helens may be unduly influenced

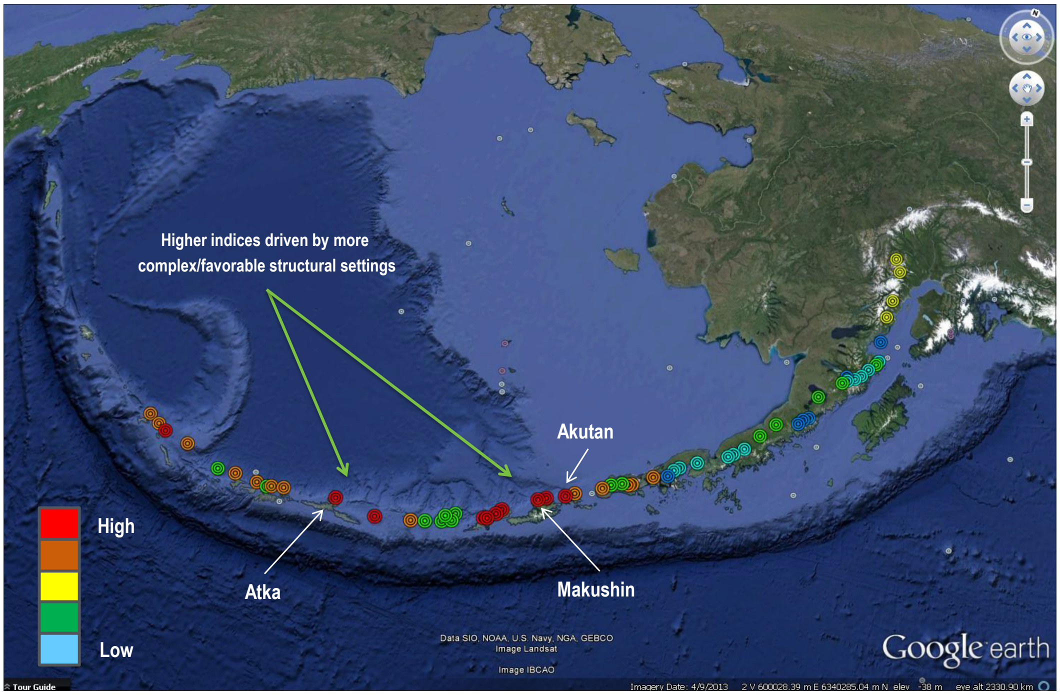

Figure 10. Aleutian Arc preliminary fairway model. Warmer colors represent progressively higher values of the predictive index. Known geothermal features were not included in this fairway model. The largest cluster of elevated potential occurs where the oceanic portion of the arc joins the continental shelf, in the vicinity of Akutan and Makushin. Perhaps a change in crustal thickness produces a more complex structural response to oblique subduction in this area, enhancing permeability and development of geothermal systems, as shown by direct evidence of geothermal activity in this same area (see Fig. 11).

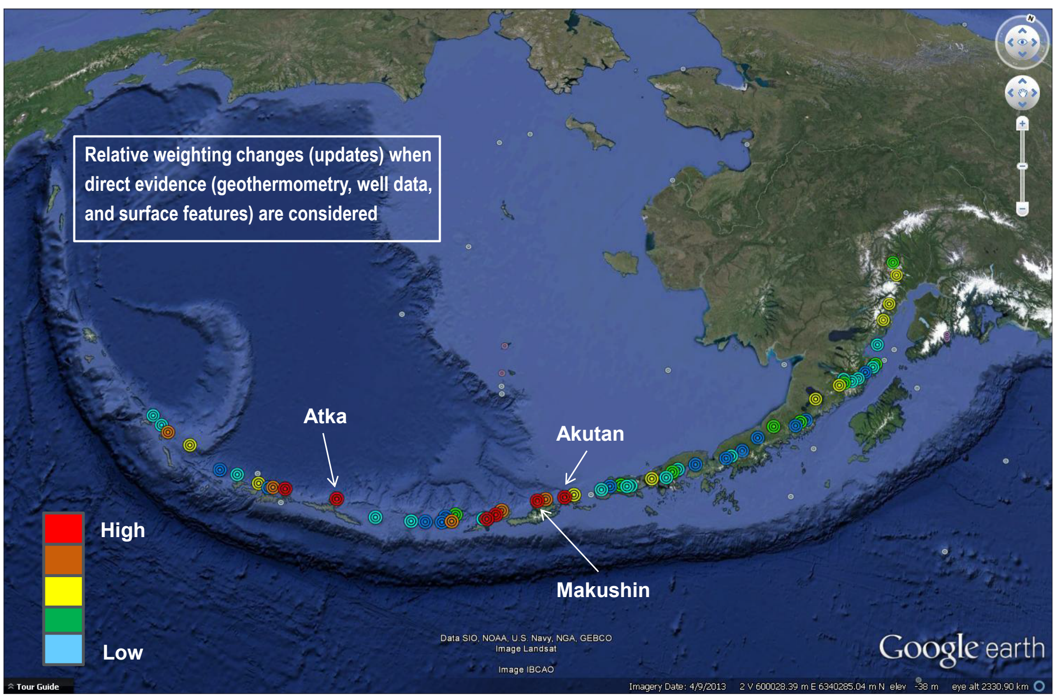

Figure 11. Aleutian Arc preliminary favorability model after addition of direct evidence and degree-of-exploration. Direct evidence reflected in this model generally collaborates the predictions of the fairway model shown in Fig. 10.

by active magmatic injection here, but the overall effect on the indices should be minor. This region will receive further investigation in the latter part of this project.

With the addition of direct evidence (Fig. 13), the favorability model of the Cascades becomes more focused into specific areas, notably including Mt. Lassen and Medicine Lake, where viable geothermal systems are either likely or known to occur, and also at Mt. St. Helens, and to a lesser extent, Newberry, Mt. Hood and Mt. Meager.

Conclusions and Future Work

The preliminary models are predicting elevated geothermal potential in several clusters in the western and central Aleutians, and in the southern Cascades. Geothermal potential predicted by the fairway models is generally consis-

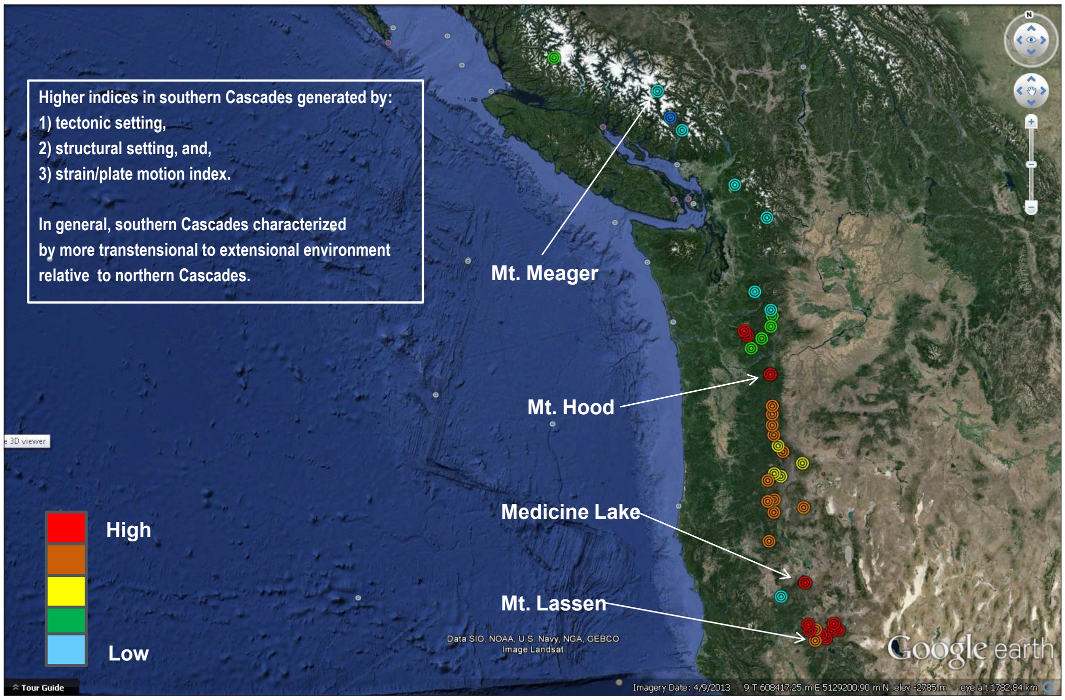

Figure 12. Cascade Arc preliminary fairway model. Warmer colors represent progressively higher values of the predictive index. Known geothermal features were not included in the fairway models.

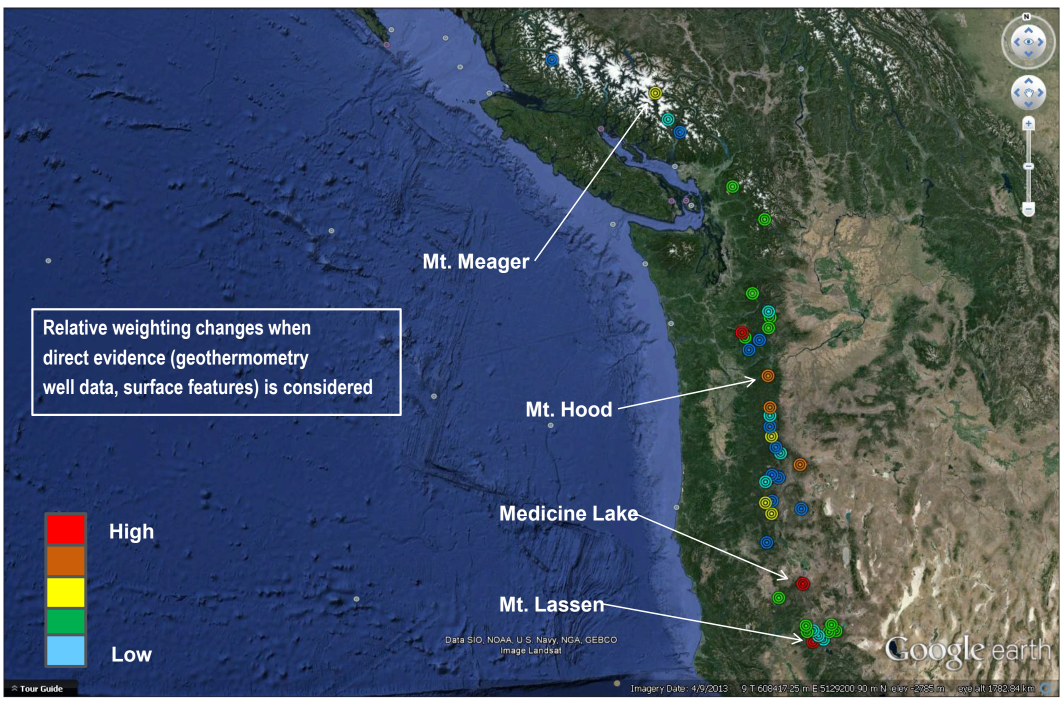

Figure 13. Cascade Arc preliminary favorability model after addition of direct evidence and degree-of-exploration. Relative weighting changes when direct evidence (geothermometry, well data, surface features) is considered.

tent with geothermal potential predicted by the favorability model, indicating a degree of corroboration between the permeability index (the primary driver of the fairway model) and observed geothermal features (the primary driver of the favorability model).

The predictive models will be refined during the second half of the research project, scheduled to be completed in the latter part of 2015. These refinements will include more detailed interpretations of tectonic and structural settings, and an assessment of the role tectonic setting (e.g. uplift rates) exercises on potential reservoir host rock composition. Play types will be more formally defined and potential resource magnitudes will be addressed. A more formal process of identifying weighting and scaling parameters will be adopted, and degree-of-exploration will be merged with direct evidence in a more integrated manner. Ultimately, the final models will be overlain with power infrastructure, population density, markets, and land use designations to help identify sites where the greatest benefit from development of geothermal energy could be realized.

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