Preliminary Ranking of Geothermal Potential in the Cascade and Aleutian Volcanic Arcs, Part II: Structural—Tectonic Settings of the Volcanic Centers

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ABSTRACT

As part of a Department of Energy funded project on Geothermal Play Fairway Analysis, this paper discusses the methodology and preliminary results of evaluating local structural and tectonic settings associated with permeability fairways in the Aleutian and Cascade arcs. Specific structural settings coupled with appropriate active strain and complementary stress fields are favorable for both the deep vertical permeability necessary for the roots of hydrothermal systems and the shallow permeability at depths economical for commercial development. Favorable structures include intersections of major faults, pull-aparts along strike-slip faults, step-overs between normal faults, fault terminations of normal or reverse faults, displacement transfer zones, accommodation zones, and dense networks of nascent faults or fault intersections. Some volcanic centers overlap with multiple separate individual or compound structures. Multiple supporting parameters are being collected to help characterize the favorability of these structural settings including strain rates, strain style (.e.g., extensional or compressional), Quaternary fault data, fault orientations, stress data, kinematic linkage of vents, and the degree of certainty for the principle parameters. These data will be combined with other data sets such as geochemistry, presence of active geothermal features, characteristics of magmatism and volcanism, and degree of exploration to produce overarching favorability analysis of the Cascade and Aleutian arcs as discussed in the two companion papers.

Introduction

This paper is part two of a three-part paper 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. This paper details the structural–tectonic settings of these volcanic centers as relevant to geothermal favorability. The third paper (Coolbaugh et al., 2015, this issue) 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.

Thus study covers 41 volcanic centers in the Cascades (37 in the USA) and 59 volcanic centers in the Aleutians. Currently there are no producing geothermal systems in the Cascade or Aleutian volcanic arcs, despite decades of exploration. Three of the Cascade volcanoes, Mount Meager in British Columbia, and Medicine Lake in California, have resources with collective proven capacities totaling 27+ MWe, but to date, development has been limited for one or more reasons in each area (e.g., Mount Lassen is in a National Park). To strengthen the favorability evaluation of the Cascade and Aleutian volcanic centers, metrics from other key volcanic arcs with 72 individual proven geothermal resources are also being compiled and evaluated as part of this study.

Background on Intra-Arc Tectonics

Much of the deformation associated with plate subduction is accommodated by crustal shortening in the overriding plate in the accretionary prism. In addition to large-magnitude compressional strain in the accretionary prism, most segments of modern day volcanic arcs around the world are actively accommodating other types of strain, including pure extension in the event of slab roll-back, transtension or transpression in the event of oblique subduction, or nearly pure compression where compressional forces from the colliding plates is transferred landward through the arc. Extension is typically accommodated by a combination of normal faults and intrusion of magma (e.g., Oregon Cascades, Sherrod and Smith, 2000; Kyushu, Japan, Mahony et al., 2011). Broad transtension is typically distributed across multiple kinematically linked strike-slip and normal faults (e.g., parts of the south Cascades and western Aleutians; Ave Lallemant, 1996; Ave Lallemont and Oldow, 2000), with magma intrusion locally accommodating some of the extension. Broad transpression is typically distributed across kinematically linked strike-slip faults and reverse or thrust faults and folds with magma intrusions generally more restricted to dilatational fault jogs if the intruding magma is kinematically linked (e.g., Washington Cascades, Smith, 1993). Intra-arc compression (shortening) can be accommodated by thrust faults, reverse faults, folds, and locally, arc-perpendicular normal faults and dikes (e.g., Honshu, Japan, Umeda et al., 2013). Large magnitude shear stress in arc segments is usually accommodated by large magnitude strike-slip faults (e.g. Grand Sumatra Fault, Indonesia, Yeats et al., 1997), especially in areas of higher lithospheric strength (Molnar and Dayem, 2010). Along with dynamics of the subducting plate, sediment flux in the accretionary wedge and related hydration of the mantel through subduction, characteristics of the overriding plate, these tectonic settings have been correlated with temporal and regional variation in magma production, volume of erupted material, and the geochemistry of volcanic systems (e.g., Smith, 1993; Mahony et al., 2011; Buurman et al., 2014).

Aleutian and Cascade Arc Geologic Settings

In the Aleutian arc, the angle of plate convergence between the North American and Pacific plates varies steadily from sinistral oblique convergence at the far eastern end, near-perpendicular convergence in the east central part, dextral oblique convergence for much of the western half, and a nearly pure transform motion at the far west end of the arc (e.g., Buurman et al., 2014). Oblique subduction drives translocation of the entire western half of the arc along arc-parallel strike-slip faults and arc-parallel extension accommodated by a complex system of normal and strike-slip faults (Ave Lallemant, 1996; Ave Lallemont and Oldow, 2000). As obliquity of subduction increases from east to west along the Aleutian arc, so do the magnitude of dextral shear along intra-arc dextral strike-slip faults. The Aleutian arc also straddles a passive oceanic-continental crustal boundary, with the western half subducting beneath oceanic crust forming an oceanic arc, and the eastern half subducting under continental crust forming a continental arc.

The Cascade arc is undergoing clockwise rotation resulting from oblique plate convergence in combination with arc translation related to slab role-back and back-arc extension (Wells and McCaffrey, 2014). South of the Oregon-Washington border the arc is dominated by extension and transtension while north of the Oregon-Washington border the arc is dominated by transpression and compression. As a result of compression, the northern portion of the arc is also undergoing arc-perpendicular shortening and arc-parallel extension (McCaffrey et al, 2013). In contrast to the Aleutian arc, the Cascade arc is entirely a continental arc.

Arc Play Fairway Analysis – Structural and Tectonic Related Permeability

The objective of the DOE-funded Geothermal Play Fairway Analysis is to identify play fairways across a given region and evaluate relative favorability by mapping the combined distribution of key component geologic factors. In this volcanic arc project, the key geologic factors are considered to comprise heat, permeability, fluid composition, and cap rock. The net permeability of the crust associated with each volcanic area is the sum of the primary stratigraphic permeability and secondary permeability associated with faults and fractures that have formed through tectonism, magma buoyancy, gravitational collapse, and/or fracturing of country rock around intrusive bodies during emplacement. Many of these volcanic centers have formed in association with active tectonic structures that predate the volcanic centers by hundreds of thousands or millions of years and continue to co-evolve with the volcanoes, yielding a strong kinematic linkage between the regional structural framework and the structure of the magmatic system associated with each volcanic center. The focus for phase 1 (year 1) of this play fairway study is to develop a workflow module to singularly evaluate the tectonic-induced structural permeability and effectively integrate this key factor into the overarching play fairway analysis.

The inflation of volcanic edifices (e.g., Mount Peulik, Alaska; Lu et al., 2002) is highly temporal, fluctuating annually or decadal and is not addressed in this study. Fractures around intrusions can only be evaluated through identifying intrusive bodies in the subsurface and is also not addressed in this study. Large-scale gravitational collapse of volcanic edifices through mega-landslides and normal faults (e.g., Hawaii) or sackungen (e.g., Mount Meager, British Columbia, Canada; Friele et al., 2008) develop at a large enough scale and can evolve over a relatively long timeframe (1000s of years) and contributes to dilation of the shallow crust, in similar fashion to crustal-scale tectonic-driven extension. Gravitational collapse structures are noted in this study, but are addressed separately from the tectonic-driven deformation in the play fairway analysis.

A growing body of evidence from around the world has shown that specific structural settings coupled with appropriate active strain and a complimentary stress field are favorable for both the deep vertical permeability necessary for the roots of hydrothermal systems and the shallow permeability at depths economical for commercial development. A global survey found that thermal springs are generally concentrated near the ends of faults or at fault intersections (Curewitz and Karson; 1997). In the Taupo volcanic zone of New Zealand, Rowland and Sibson (2004) noted that most of the geothermal systems were structurally controlled and that nearly two thirds were associated with accommodation zones. In Iceland, high temperature geothermal activity is generally focused near the intersections of the rifts with the volcanic centers (Siler et al., 2015a), and geothermal areas in east Africa may follow a similar pattern to those in Iceland. In Hawaii, deep permeability (at 2-3 km) is greater within a subtle step-over along the axis of the southeast rift of Kilauea (Spielman et al., 2006). Most of the >400 known geothermal systems in the Great Basin region of the western United States are associated with specific structural settings, such as terminations of major normal faults, step-overs in range-front faults, major fault intersections, accommodation zones, pull-aparts in strike-slip faults, or displacement transfer zones, rather than central segments of major normal faults with maximum displacement (Faulds et al., 2011; Faulds and Hinz, 2015). The Aegean extensional province in western Turkey exhibits structural controls similar to those of the Great Basin (Faulds et al., 2009).

These structural settings share several important characteristics that individually and synergistically favor relatively long-term development of dense networks of critically stressed, dilation-prone, fault breccia-dominated faults and fractures that are conducive to deep hydrothermal circulation. Complex fault termination splays, intersections, and linkages between faults typically correspond to rupture arrest areas, which have been associated with elevated permeability (Sibson, 1987; Micklethwaite and Cox, 2004). In contrast to segments of faults that rupture during earthquakes and experience a drop in tectonic stresses, rupture arrest areas accumulate above-background levels of tectonic stress (e.g., Siler et al., 2015b). The rupture arrest areas are typically dominated by breccia rather than clay gouge. Fault breccia is more permeable then clay-rich fault gouge, resists sealing, and helps to set up a positive feedback for continued permeability by maintaining a state of critical stress (Sibson, 1994; Barton et al., 1995; Townend and Zoback, 2000). Additionally, the numerous fault and fracture intersections associated with these structural settings weaken the crust such that heterogeneous stress fields enable dilation and enhanced permeability in these areas.

Structural framework is only part of the structural-tectonic equation driving relative geothermal favorability between volcanic centers. Tectonic strain rates and in particular, extensional strain rates have been shown to correlate favorably with geothermal activity (e.g., Faulds et al., 2012). For example, a pull-apart along a strike-slip fault constitutes a highly favorable structural setting, but generally less so if the local faults are no longer active, and especially less so if the greater region is tectonically inactive. Relative weighting factors for the structural and tectonic settings identified in this work and used in the preliminary model (Coolbaugh et al., 2015) are reported in Shevenell et al. (2015).

Methodology

A review of existing data on the structural and tectonic controls of geothermal systems around the world indicates that three primary structural-tectonic characteristics are paramount for geothermal favorability: 1) type of structure and overall structural complexity, 2) extensional strain, and 3) strain rate. To assist in assessing these characteristics along volcanic arcs, we have assembled a list of geologic parameters to be populated for each volcanic center. Principally, this process involves the identification of the structural setting(s) associated each volcanic center (e.g. fault intersections or pull-aparts) along with additional local (e.g., stress orientations or Quaternary fault characteristics) and regional parameters (e.g., tectonic setting) that facilitate favorability ranking of these structures. Most local parameters were populated from data within a 10 km radius of each volcanic center, based on the observation that roughly 80% of the geothermal areas associated with volcanic centers in arcs around the world are located within 10 km of a significant volcanic vent (Coolbaugh et al., 2015, this issue). These data were collected from published geologic maps, databases, papers, reports, and thorough cross-checking against structures visible in available imagery available through Google Earth, ArcGIS, and Bing Maps.

The degree of certainty is also being compiled for many of these categories so that the absence of available data for a given volcanic center will not translate to negative favorability. This degree of certainty will be based on one or more attributes, including (1) volcanic centers that are largely covered with permanent snow fields/glaciers, (2) are heavily vegetated with locally poor image quality, (3) are isolated islands with minimal regional geology exposed subaerially, or (4) are not covered by existing published studies that provide any local or detailed structural data. Specific statistical weighting factors for each category in each parameter are still being refined and are not covered in this paper.

Tectonic Setting This was a qualitative characterization based on synergistic integration of local and regional structural data, stress data, and strain data. Categories include extensional, transtensional, transpressional, compressional, or dominated by a single major strike-slip fault zone. This category is useful for evaluating broad trends in the data sets, as well as providing favorability weighting based on regional data, especially where the local structural setting cannot be identified due to absence of data (e.g., unmapped and/or covered by snow).

Structural Setting This was also a qualitative characterization based on evaluation of faults within a 10 km radius of each volcanic center. Structural setting categories include, but are not limited to accommodation zones, pull-aparts, displacement transfer zones along strike-slip faults, terminations of major normal faults, step-overs in normal faults, or major fault intersections between normal faults, strike-slip faults, or high-angle reverse faults. In many cases, volcanic centers are associated with 2 or 3 major structural settings, acting singly on separate parts of the volcanic center or in direct overlapping and compound fashion. Up to three structural settings are being noted in this study for individual volcanic centers.

The type of structural setting contributes to the relative geothermal potential of a structural target area. Recent research shows that structural settings with greater complexity (e.g., accommodation zones) have greater geothermal potential to host a viable geothermal resource than those with less structural complexity (e.g., fault termination). The relatively more complex structural settings may correspond to greater bulk permeability which can facilitate larger commercial reservoir volumes and provided more efficient conduits for conductive heat transfer through the crust to drive the geothermal system (Faulds et al., 2013; Faulds and Hinz, 2015; Siler et al., 2015b).

Volcanic Vents Kinematically Linked Categories include yes, maybe, no, or unknown and were evaluated within a 10 km radius of each volcanic center. Coupled with the relative density of quaternary fault scarps, this category helps assess the amount of extension locally accommodated by magma intrusion versus brittle faulting. Magma intrusion can plug and seal open fractures and limit the magnitude of faulting if much of the extension is accommodated by intrusion. Intrusions can create some permeability at dike tips and around other intrusive bodies, but the volume and degree of permeability is less than that associated with complex fault systems.

Relative Density of Quaternary Fault Scarps Categories include high, moderate, low, none, or unknown within a 10 km radius of each volcanic center. This category assess the relative number of Quaternary faults associated with each volcanic center. Faults and structures active in the Quaternary demonstrate a positive relationship with geothermal activity (e.g., Bell and Ramelli, 2007).

Fault Slip Rate(s) Generally, higher strain rates provide greater geothermal favorability, by increasing the rate at which fractures form and open (e.g., Faulds et al., 2012). Therefore, distinguishing strain rates associated with specific faults that make up the structural settings associated with specific volcanoes is important for predicting relative favorability. This category is populated from the USGS Quaternary Fault and Fold Database for CA, OR, and WA (USGS, 2010). Paleoseismic and GPS geodetic data will be used to populate this field for other areas. For some areas in this study, local fault slip rates will not be available.

Recency of Faulting Similar to fault slip rates, recency of fault activity along faults that make up the structural settings associated with specific volcanoes provides relative favorability. This category is populated from the USGS Quaternary Fault and Fold Database for CA, OR, and WA (USGS, 2010). Paleoseismic data will be used to populate this field for other areas. For some areas in this study, recency of faulting will not be available.

Fault Orientations Azimuth of primary, secondary, and tertiary (when present) fault sets in a 10 km radius of each volcanic center are being recorded. Faults at higher angles to S_{Hmin} are more favorable for dilation and enhanced permeability.

S_{Hmin} (azimuth of least principle horizontal stress). Stress data are compiled from published data local to each volcanic center or estimated from regional data available in the World Stress Map (Heidbach et al., 2008). The least principle horizontal stress will be compared against the fault orientations. Presence of faults oriented at high angles to S_{Hmin} are more favorable for dilation then those at low angles to S_{Hmin}.

Results

Preliminary results document a variety of structural settings among volcanic centers in the Cascade and Aleutian volcanic arcs (Figs. 1, 2). The most common structural settings associated with the 41 Cascade volcanic centers are associated with fault intersections (34%), normal fault step-overs (24%), accommodation zones (17%), pull-aparts (15%), other (5%), and unknown (5%). The 59 Aleutian volcanic centers are associated with fault intersections (37%), other categories (5%), and unknown (58%). The assessment of 74 arc volcanic centers in the world that have installed geothermal power plants or successful flow tests is in the early stages. Preliminary results document structural settings that include fault intersections (29%), step-overs (11%), pull-aparts (11%), displacement transfer zones (8%), other categories (21%), and unknown (20%).

A number of volcanic centers are associated with multiple and/or compound structural settings. Of the 39 Cascade volcanic centers with known structural settings, 38% were associated with two structural settings and 13% were associ-

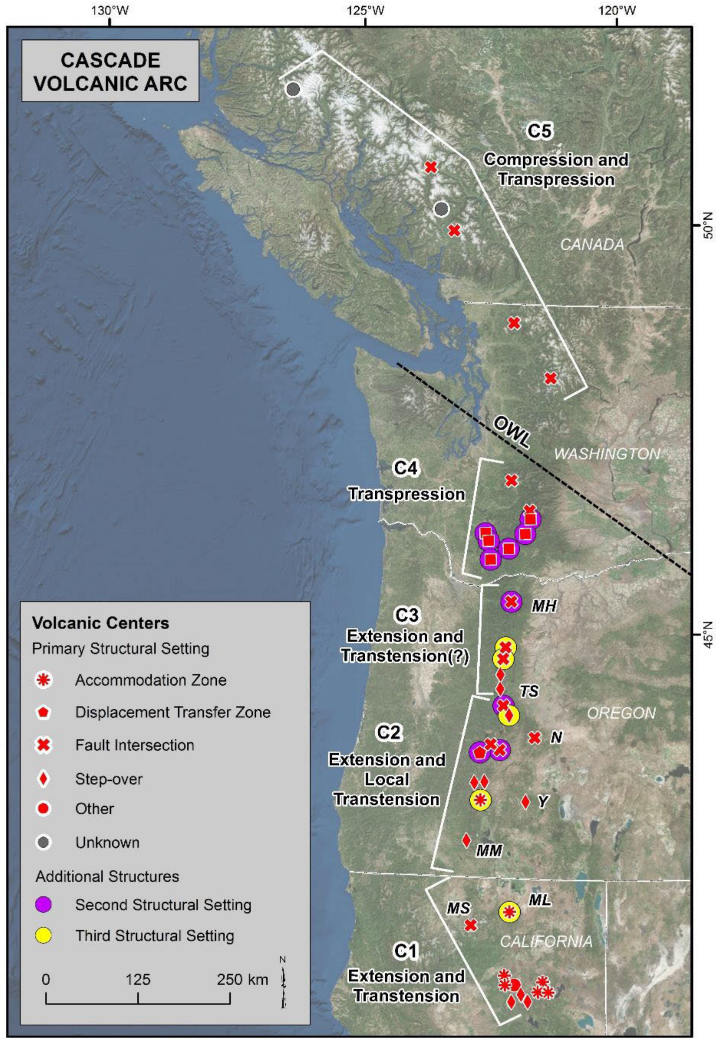

Figure 1. Structural-tectonic settings of the Cascade volcanic centers, based on preliminary analysis of available data and imagery. Second and third structural settings refer to volcanic centers associated with multiple structural settings. Arc segments C1, C2, etc., correspond to Table 1. Volcano names used in text: MH, Mount Hood; ML, Medicine Lake; MM, Mount McLoughlin; N, Newberry; OWL, Olympic-Wallowa Lineament; TS, Three Sisters; Y, Yamsay.

ated with three structural settings. Of the 25 Aleutian volcanic centers with known structural settings, 36% were associated with two structural settings and none with three structural settings. Relative to the Cascade arc, analysis of the Aleutian volcanic centers is more limited by the locally poor image quality and/or snow cover for specific volcanoes, the generally minimal existing detailed maps for most of the arc, and limited subaerial exposures of the western Aleutian arc.

The volcanic centers in both the Aleutian and Cascade arcs are spread across a wide spectrum tectonic settings (Table 1, Figs. 1, 2). The Aleutian arc spans three tectonic domains that from west to east include dextral transtension, compression and transpression, and extension plus sinistral transtension, respectively. The Cascade arc spans two primary tectonic domains, extension and transtension in the south and transpression and compression in the north. Both halves of the Cascade arc are further subdivided into five total tectonic domains, three in the south half (C1, C2, C3; Table 1; Fig. 1) based on variations in the distribution and rate of transtensional strain accommodated across regional structures, and two in the north half based on the distribution of near pure compression (C4, C5; Table 1; Fig., 1).

Volcanic centers in both the south Cascades (segments C1, C2, C3, Fig. 1) and western Aleutians (A1, Fig. 2) exhibit greater variety of structural setting types and a greater proportion of volcanic centers being associated with two or three structural settings relative to the other segments of these arcs. These same segment divisions, C1, C2, C3, A1, and A2 are associated with extension and transtension whereas segments C4, C5, and A2 are

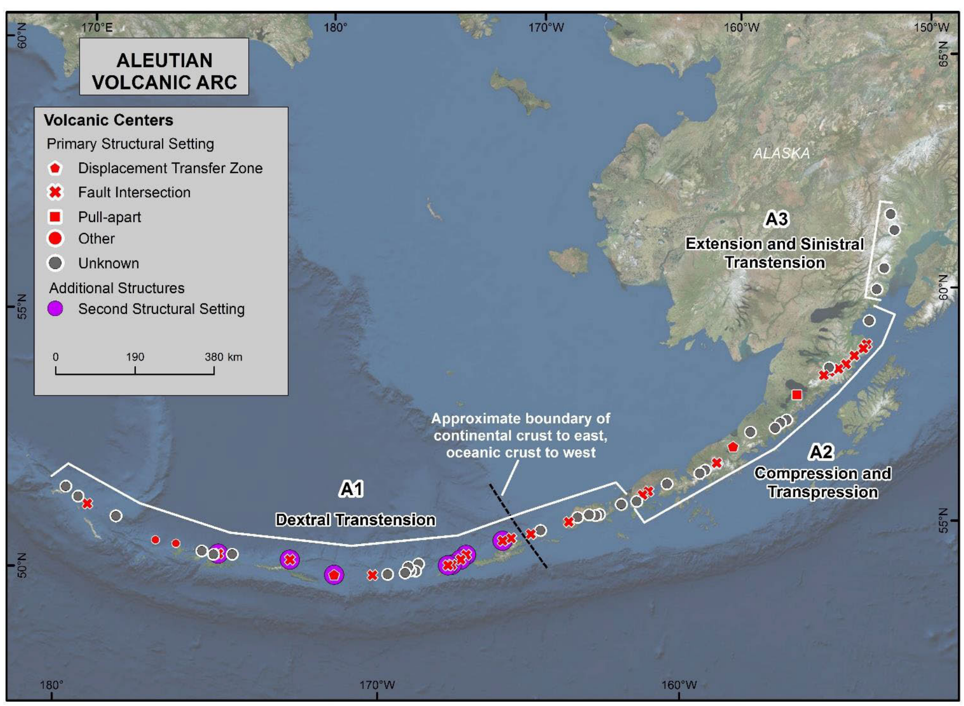

Figure 2. Structural-tectonic settings of the Aleutian volcanic centers, based on preliminary analysis. Second and third structural settings refer to volcanic centers associated with multiple structural settings. Arc segments A1, A2, etc., correspond to Table 1.

Table 1. Regional structural and tectonic trends of the Aleutian and Cascade Arcs. Arc segments A1, A2, etc., correspond to Figures 1 and 2.

Category/Arc Segment	Characterization
ALEUTIAN ARC	
A1 - Western Aleutians	
Tectonic Setting	Dextral transtension
Structural Framework	Complex arrays of strike-slip, oblique-slip, and normal faults with numerous fault intersections
Length	1425 km
Number of Volcanic Centers	33
Proven Geothermal Resources	0 MWe
Average Crustal Thickness	28 km
A2 - East-Central Aleutians	
Tectonic Setting	Transpression and compression
Structural Framework	Complex region of strike-slip, reverse, and thrust faults with minor normal faulting, numerous fault intersections
Length	775 km
Number of Volcanic Centers	22
Proven Geothermal Resources	0 MWe
Average Crustal Thickness	39 km
A3 - Far Eastern Aleutians	
Tectonic Setting	Extension and sinistral transtension
Structural Framework	Not yet compiled
Length	225 km
Number of Volcanic Centers	4
Proven Geothermal Resources	0 MWe
Average Crustal Thickness	39 km
ALEUTIAN ARC SUMMARY	Active Arc is 2,425 km long, 59 volcanic centers, 0 MWe
CASCADE ARC	
C1 - Northeast California	
Tectonic Setting	Dominated by intra-arc and back-arc extension with a component of broadly distributed dextral transtension
Structural Framework	Normal faults, normal-oblique faults, and minor strike-slip faults
Other Notes on Volcanoes	Most volcanic centers are situated entirely in extensional/transtensional regions (e.g., Medicine Lake) and some volcanic centers are situated on the boundary between Basin and Range extension and compression to the west in the Klamath Mountains region (e.g., Mount Shasta)
Length	200 km
Number of Volcanic Centers	11
Proven Geothermal Resources	25+ MW at Medicine Lake (flow tests, no active production)
Average Crustal Thickness	36.8 km
C2 - Southern Oregon	
Tectonic Setting	Back-arc and intra-arc extension with localized dextral transtension
Structural Framework	Dominantly normal faults, possible kinematic linkage with strike-slip faults, minor dextral shear distributed across much of this region, with greater amounts localized along Modoc, Eugene-Denio, and Brothers fault zones
Other Notes on Volcanoes	Most volcanic centers are situated near margin of active back-arc extension region (e.g., Mount McLoughlin), some volcanic centers situated in region of back-arc extension (e.g., Yamsay)
Length	250 km
Number of Volcanic Centers	11
Proven Geothermal Resources	0
Average Crustal Thickness	41 km
C3 - Northern Oregon	
Tectonic Setting	Back-arc extension with localized dextral transtension
Structural Framework	Cascade graben, extending from north of the Three Sisters volcanic area to the OR-WA border, also Mio-Pliocene NW-striking faults locally re-activated(?) to accommodate dextral shear
Length	160 km
Number of Volcanic Centers	5
Proven Geothermal Resources	0 MWe
Crustal Thickness	41 km average crustal thickness
C4 - Southern Washington (south of the Olympic-Wallowa Lineament)	
Tectonic Setting	Transpression
Structural Framework	Regional intersecting system of NW, NNE, and ENE to NE-striking faults, active Quaternary faults within the arc have not been documented, seismicity does support that some faults may be active
Other Notes on Volcanoes	Most volcanic centers associated with right step in NW-striking faults, step across NNE faults, dextral transpression facilitates pull-aparts along these structures, largely associated with kinematically linked vents
Length	190 km
Number of Volcanic Centers	8
Proven Geothermal Resources	0 MWe
Average Crustal Thickness	43 km
C5 - Northern Washington and British Columbia	
Tectonic Setting	Compression and transpression
Structural Framework	Active Quaternary faults within the arc have not been documented, complex basement structures throughout region
Length	600 km
Number of Volcanic Centers	6
Proven Geothermal Resources	2 MWe at Meager (flow tests, no active production)
Average Crustal Thickness	37 km
CASCADE ARC SUMMARY	1,400 km long, 41 volcanic centers, 27+ MWe (flow tests only)

associated with transpression and compression. Although the data is not reported in this paper, slip rates on individual Quaternary-active faults in the Cascade arc are higher in the south half then the north half. Slip rates associated with intra-arc faults in the Aleutians are not well constrained.

Discussion and Conclusions

Preliminary modeling using some of the initial results of the structural-tectonic analysis indicate a positive correlation between extensional strain, relative structural complexity, and geothermal potential (Coolbaugh et al., 2015), which is in line with previous studies (e.g., Faulds et al., 2012). Fault intersections between major faults are the most common structural setting in the Cascades, Aleutians, and at productive arc centers around the world (not necessarily by MWe total, just by sheer number of volcanic centers). Most of the structural settings associated with the 72 global productive systems fit with typically complex intra-arc tectonics accommodating some component of extension and often a large component of extension, facilitating dilation of faults and fractures and the deep circulation of fluids necessary for reservoirs. This relationship fits with broad observations that many orogenic belts undergo orogen parallel extension (e.g., Dewey, 1988; Dewey and Lamb, 1992), and that oblique subduction drives arc-translation and arc-parallel extension through a system of kinematically linked strike-slip and normal faults (e.g., Ave Lallemant and Oldow, 2000).

Further insights will be gained into relative geothermal favorability between arc segments by systematically comparing characteristics of specific Cascade and Aleutian arc segments with other similar segments around the world. For example, extensional slip rates on intra-arc Quaternary faults in the south Cascades are <0.2 mm/yr (USGS, 2010) whereas extensional slip rates on intra-arc faults in the Taupo Volcanic Zone (TVZ) in New Zealand or in the Beppu-Shimabara and Kagoshima grabens in Honshu, Japan range 0.1 to 3 mm/yr (Villamor and Berryman, 2001; Nicol et al., 2006; Wallace et al., 2009). Relatively high slip rates along major intra-arc strike-slip faults such as the Grand Sumatra Fault (6-27 mm/yr, Sieh and Natawidjaja, 2000) and the Philippine Fault (20-35 mm/yr, Galgana et al., 2007) impart similarly high extension rates across normal faults in pull-aparts along these strike-slip faults. Geothermally productive areas in southwest Japan, TVZ, Sumatra, and the Philippines are largely associated with extensional structures (grabens and pull-aparts) with greater extension rates than for the structures associated with volcanoes in the southern Cascades which have no current producing resources. While intra-arc extension rate cannot solely predict geothermal favorability, these trends are compelling.

Another example is comparing crustal thickness and lithospheric strength between the western Aleutians and Sumatra. Both arc segments are associated with dextral-oblique subduction and dextral intra-arc transtension. However, strain is largely focused along a single through-going strike-slip fault (the Grand Sumatra Fault) in Sumatra, which contrasts the way that strain is distributed over a complex region of strike-slip, oblique-slip, and normal faults in the Aleutians (Ave Lallemant and Oldow, 2000). The western Aleutians are an oceanic arc with crustal thickness average 27 km, whereas the Sumatra crust averages 31 km thick (Coolbaugh et al., 2015). The differences in these crustal thicknesses are not that great, but the continental crust is much stronger. Globally, regions accommodating shear strain across strength lithosphere correlate with the generation of single, large strike-slip faults rather than a mesh of many smaller ones (Molnar and Dayem, 2010). Shear strain that is focused along major strike-slip faults can translate to high extensional strain across pull-apart structures. In contrast, shear strain distributed across many structures will yield a lower slip rate per individual structure. Further assessment of these and other trends will be assessed both quantitatively and qualitatively to evaluate potentially meaningful relationships between geothermal activity and structure, tectonics, crustal thickness, type of crust, style and type of volcanism, geochemistry, and proven resources as the project moves towards its final stages later this year.

One additional utility of the structural-tectonic analyses of these volcanic centers that has not yet been employed in this study is to help assess exhumation rates. 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. One such example of high erosion rates is with Mount Akutan in the Aleutians where geophysics and geology both indicate that the cap over the modern active system in Hot Springs Bay Valley is deeply eroded by multiple Pleistocene glaciations (Stelling et al., 2015). Several other examples from arc settings outside the USA are discussed by Coolbaugh et al. (2015). In all of these cases, lack of an intact cap constitutes a negative indicator. This process does not have to completely marginalize a system, but may contribute to a reduced resource size.

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