Geothermal systems in volcanic arcs: Volcanic characteristics and surface manifestations as indicators of geothermal potential and favorability worldwide

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ABSTRACT

This paper brings a global perspective to volcanic arc geothermal assessments by evaluating trends and correlations of volcanic characteristic and surface manifestation data from world power production sites in subduction zone volcanic settings. The focus of the work was to evaluate volcanic centers individually and as a group in these arcs by correlating various geologic characteristics with known potential to host electricity grade geothermal systems at the volcanic centers. A database was developed that describes key geologic factors expected to be indicative of productive geothermal systems in a global training set, which includes all 74 subduction zone volcanic centers world-wide with current or proven power production capability. Importantly, this data set only contains data from subduction zone volcanoes and contains no negative cases, limiting the populations of any statistical groups. Regardless, , this is the most robust geothermal benchmark training set for magmatic-heated systems to date that has been made public. The work reported here is part of a larger project that included data collection, evaluation, correlations and weightings, fairway and favorability modeling and mapping, prediction of blind systems, and uncertainty analysis to estimate errors associated with model predictions. This first paper describes volcano characteristics, compositions and eruption ages and trends along with surface manifestation observations and temperatures as they relate to known power producing systems. Our findings show a strong correlation between the presence and size of active flank fumarole areas and installed power production. Additionally, the majority of volcanic characteristics, including long-held anecdotal correlations related to magmatic composition or size, have limited to no correlation with power production potential. Notable exceptions are correlations between greater power yield from geothermal systems associated with older (Pleistocene) caldera systems than systems hosted by Holocene calderas or non-caldera volcanic centers. Power-hosting volcanic centers that have erupted within the last 160 years supply 50% of the global installed geothermal power in subduction zones, and nearly all of these systems are generally mafic (basaltic or andesitic) in average composition. Volcanic centers erupting between 160 and 900 years ago are dominated by felsic volcanic systems, and provide 47% of the global power from volcanic arcs. Only 3% of geothermal power produced in subduction zones are hosted by volcanic center erupting more than 900 years ago. We anticipate that these results may be able to help guide future geothermal exploration efforts.

Keywords: world volcanic centers, geothermal potential, volcanic characteristics, fumaroles, power production, subduction zone volcanic arcs

1.0 Introduction

1.1 Background

Nearly 75% of productive and prospective geothermal power plants worldwide are associated with subduction zone volcanoes (Moeck, 2014). This is intuitive, as volcanoes are a substantial indicator of near-surface heat sources and volcanic arcs contain the greatest density of Pleistocene and Holocene subaerial volcanoes on Earth. Approximately 10% of the volcanic centers in world arcs are currently either producing electricity or have been shown to be power-capable, and the percentage could be much higher with additional exploration and access to power markets.

Although the United States is the largest geothermal power producer worldwide, none of the power produced in the U.S. currently comes from subduction-related volcano-hosted systems despite having two active volcanic arcs in the Cascades and Aleutians. The reasons for this anomalous trend in the US and Canada can be separated into two categories: societal factors, such as land use designations, population density and infrastructure; and geologic factors that dictate heat availability, fluid abundance and permeability that allow commercial-grade geothermal systems to form. Whereas commercial-grade geothermal systems can be exploited only when both societal and geologic conditions are favorable, the geologic conditions are more difficult to modify. In an effort to understand the most critical aspects of the geologic controls over geothermal system formation in subduction zones, we conducted an inventory of the significant geologic factors present at each of 74 volcanic centers that host productive and prospective geothermal systems in subduction zones across the globe (84 geothermal systems in total; Fig. 1). Data collected from these benchmark volcanic centers comprise a global training set on which we based a play fairway analysis for geothermal favorability in the Aleutians and Cascades volcanic arcs. Initial results of these investigations will be presented in this and subsequent

manuscripts, and have been initially described by Coolbaugh et al. (2015), Hinz et al. (2015; 2016), and Shevenell et al. (2015). While this data set represents the most comprehensive publically available data collection for geothermal systems hosted by subduction zone volcanoes, there are limitations for its use. First, this data set includes only data from subduction zone volcanoes, and application of the results of this study should be applied in other tectonic settings with caution. Second, due to limitations of data availability, the data set does not include any negative cases (volcanic centers where exploration was attempted but failed). Third, despite including all 84 productive or prospective geothermal systems in subduction zones worldwide, group populations are smaller than ideal and robust statistical analyses are challenging. Even considering these caveats, however, important initial conclusions can be drawn from this database we hope will aid in future geothermal exploration efforts.

Figure 1. Distribution of globally productive volcanic centers, symbolized by MWe. Base map from ESRI World imagery.

Although the objective of the project reported in Shevenell et al. (2015) was to develop play fairway models to be applied to the US volcanic arcs, the global training set used in the work represents a significant increase in our understanding of the geologic controls and manifestations of geothermal systems worldwide, and is the focus of this paper. This broad effort can be divided into three major components: the volcanic and surficial characteristics; the tectonic and structural characteristics; and the statistical analysis and Play-Fairway modelling that resulted from our efforts. This paper represents the first of these three components, with the other portions of the investigation to be presented in later papers. This paper describes the methods of a major data collection effort and justification for our approach, including important considerations for any future use of this dataset. We then present the results of a comparison between the inventoried volcanic characteristics and surface manifestations to geothermal productivity, particularly installed power (or the proven equivalent for systems with sufficient flow test or similar results). The paper concludes with a summary of important correlations and non-correlations between these geologic parameters and geothermal potential based on knowledge at global volcanic arc geothermal systems.

2.0 Methods

2.1 Selection of Volcanic Centers (VCs)

Thousands of volcanic centers exist in dozens of subduction zones around the world. In order to estimate the correlation between global VCs and geothermal potential, only those VCs associated with geothermal fields that are either currently producing electricity, have produced electricity in the past, or show productive potential (i.e., favorable flow tests) were considered as benchmark sites to assess the Aleutian and Cascade arcs. This limited the inventory effort to 15 subduction zones. Importantly, the restriction of only commercial grade resources indicates that no negative cases, where geothermal

exploration has occurred and failed, have been considered. This is largely due to the lack of such reported cases in the literature. To develop the global training set, we identified 84 commercial grade geothermal systems associated with 74 arc volcanic centers worldwide (Table 1).

Table 1. Geothermal power plants, associated VC, and installed power. Note that several VCs have multiple associated geothermal power plants.

<i>Plant_Name</i>	<i>Volcano Name</i>	<i>Country</i>	<i>Region</i>	<i>Class*</i>	<i>Installed MWe**</i>
<i>Meager</i>	Meager	Canada	Canada	Flow	4.8
<i>Medicine Lake</i>	Medicine Lake	United States	USA (California)	Flow	25.0
<i>Domo de San Pedro</i>	Ceboruco	Mexico	Mexico	Flow	25.0
<i>Cerritos Colorados</i>	Primavera, Sierra la	Mexico	Mexico	Flow	10.0
<i>Los Azufres</i>	Azufres, Los	Mexico	Mexico	Plant	195.0
<i>Los Humeros</i>	Humeros, Los	Mexico	Mexico	Plant	40.0
<i>Las Pailas</i>	Rincon de la Vieja	Costa Rica	Costa Rica	Plant	42.0
<i>Miravalles</i>	Miravalles	Costa Rica	Costa Rica	Plant	165.5
<i>Ahuachapan</i>	Apaneca Range	El Salvador	El Salvador / Honduras	Plant	95.0
<i>Berlin</i>	Tecapa-El Tigre	El Salvador	El Salvador / Honduras	Plant	109.4
<i>Orzunil</i>	Santa Maria	Guatemala	Guatemala	Plant	28.0
<i>Cerro Blanco</i>	Ixtepeque	Guatemala	Guatemala	Plant	5.0
<i>Amatitlan</i>	Pacaya	Guatemala	Guatemala	Plant	24.0
<i>San Jacinto-Tizate</i>	Telica	Nicaragua	Nicaragua	Plant	72.0
<i>Momotombo</i>	Momotombo	Nicaragua	Nicaragua	Plant	77.5
<i>Roseau Valley</i>	Watt, Morne	Dominica	West Indies	Flow	11.0
<i>La Bouillante</i>	Soufriere Guadeloupe	France	West Indies	Plant	15.0
<i>Puchildiza</i>	Isluga	Chile	Northern Chile	Flow	10.0
<i>Pabellon (Apacheta)</i>	Azufre-Pabellon	Chile	Northern Chile	Flow	20.0
<i>El Tatio</i>	La Torta-Cerros Tocorpuri	Chile	Northern Chile	Flow	25.0
<i>Laguna Colorada</i>	La Torta-Cerros Tocorpuri	Chile	Northern Chile	Flow	30.0
<i>Chillan</i>	Chillán, Nevados de	Chile	Central Chile	Flow	5.0
<i>Tolhuaca</i>	Tolguaca	Chile	Central Chile	Flow	12.0
<i>Copahue</i>	Copahue	Chile-Argentina	Central Chile	Plant	0.7
<i>Okeanskaya</i>	Sashiusudake [Baransky]	Japan (Russia)	Kuril Islands	Plant	3.6
<i>Mendeleevskaya</i>	Raususan [Mendeleev]	Japan (Russia)	Kuril Islands	Plant	1.8
<i>Dolina Geizerov</i>	Uzon	Russia	Kamchatka Peninsula	Thermals	25.0
<i>Paratunskaya</i>	Barkhatnaya Sopka	Russia	Kamchatka Peninsula	Plant	0.7
<i>Mutnovskaya-Verkhne</i>	Mutnovsky	Russia	Kamchatka Peninsula	Plant	62.0
<i>Pauzhetskaya</i>	Diky Greben	Russia	Kamchatka Peninsula	Plant	14.5
<i>Mori</i>	Nigorikawa	Japan	Hokkaido	Plant	25.0
<i>Sumikawa-Ohnuma</i>	Hachimantai	Japan	Honshu	Plant	59.5
<i>Matsukawa</i>	Iwatesan	Japan	Honshu	Plant	23.5

<i>Kakkonda</i>	Akita-Komagatake	Japan	Honshu	Plant	80.0
<i>Uenotai</i>	Kurikomayama	Japan	Honshu	Plant	28.8
<i>Onikobe</i>	Onikobe	Japan	Honshu	Plant	12.5
<i>Yanaizu-Nishiyama</i>	Numazawa	Japan	Honshu	Plant	65.0
<i>Hachijojima</i>	Hachijojima	Japan	Izu, Mariana Islands	Plant	3.3
<i>Suginoi Hotel</i>	Yufu-Tsurumi	Japan	Ryukyu Islands	Plant	3.0
<i>Hatchobaru-Otake</i>	Kujusan	Japan	Ryukyu Islands	Plant	124.5
<i>Takigami</i>	Kujusan	Japan	Ryukyu Islands	Plant	25.0
<i>Ogiri</i>	Kirishimayama	Japan	Ryukyu Islands	Plant	30.0
<i>Yamakawa (Fushime)</i>	Ibusuki Volcanic Field	Japan	Ryukyu Islands	Plant	30.0
<i>Chingshui</i>	Kueishantao	Taiwan	Taiwan	Plant	3.0
<i>Mak-Ban (Bulalo)</i>	San Pablo Volcanic Field	Philippines	Luzon	Plant	442.8
<i>Maribarara</i>	San Pablo Volcanic Field	Philippines	Luzon	Plant	20.0
<i>Tiwi</i>	Malinao	Philippines	Luzon	Plant	330.0
<i>Bacman</i>	Pocdol Mountains	Philippines	Luzon	Plant	150.0
<i>Leyte</i>	Mahagnao	Philippines	Central Philippines	Plant	700.0
<i>NNGP (Mambucal)</i>	Kanlaon	Philippines	Central Philippines	Plant	49.0
<i>Palinpinon</i>	Cuernos de Negros	Philippines	Central Philippines	Plant	232.5
<i>Mindanao</i>	Apo	Philippines	Mindanao	Plant	106.0
<i>Lahendong</i>	Tondano Caldera	Indonesia	Sulawesi	Plant	62.5
<i>Sibayak</i>	Sibayak	Indonesia	Sumatra	Plant	13.2
<i>Namora-i-Langgit</i>	Sibualbuali	Indonesia	Sumatra	Flow	105.0
<i>Sibualbuali</i>	Sibualbuali	Indonesia	Sumatra	Flow	9.0
<i>Silangkitang</i>	Sibualbuali	Indonesia	Sumatra	Flow	65.0
<i>Muara Laboh</i>	Kerinci	Indonesia	Sumatra	Flow	110.0
<i>Lempur Kerinci</i>	Kunyit	Indonesia	Sumatra	Flow	10.0
<i>Lumut Balai</i>	Lumut Balai, Bukit	Indonesia	Sumatra	Flow	55.0
<i>Rantau Dedap</i>	Patah	Indonesia	Sumatra	Flow	110.0
<i>Ulubelu</i>	Hulubelu	Indonesia	Sumatra	Plant	110.0
<i>Salak (Awibengkak)</i>	Salak	Indonesia	Java	Plant	377.0
<i>Kamojang</i>	Guntur	Indonesia	Java	Plant	200.0
<i>Patuha-Cibuni</i>	Patuha	Indonesia	Java	Plant	60.0
<i>Wayang Windu</i>	Wayang-Windu	Indonesia	Java	Plant	227.0
<i>Dieng</i>	Dieng Volcanic Complex	Indonesia	Java	Plant	60.0
<i>Karaja-Telaga Bodas</i>	Galunggung-Talagabodas	Indonesia	Java	Flow	13.0
<i>Darajat</i>	Papandayan-Kendang	Indonesia	Java	Plant	260.0
<i>Ulumbu</i>	Poco Leok	Indonesia	Lesser Sunda Islands	Plant	5.0
<i>Mataloko</i>	Inerie	Indonesia	Lesser Sunda Islands	Plant	2.5
<i>Lihir</i>	Lihir	Papua New Guinea	New Ireland	Plant	56.0
<i>Rotorua</i>	Rotorua	New Zealand	New Zealand	Thermals	50.0
<i>Kawerau</i>	Okataina	New Zealand	New Zealand	Plant	122.2
<i>Reporoa-Waiotapu</i>	Reporoa	New Zealand	New Zealand	Thermals	50.0
<i>Ohaaki-Broadlands</i>	Reporoa	New Zealand	New Zealand	Plant	103.0

<i>Wairakei-Tauhara</i>	Maroa	New Zealand	New Zealand	Plant	364.0
<i>Rotokawa</i>	Maroa	New Zealand	New Zealand	Plant	175.0
<i>Ngatamariki</i>	Maroa	New Zealand	New Zealand	Plant	82.0
<i>Mokai</i>	Maroa	New Zealand	New Zealand	Plant	111.0
<i>Orakeikorako</i>	Maroa	New Zealand	New Zealand	Thermals	25.0
<i>Larderello</i>	Larderello	Italy	Italy	Plant	795.0
<i>Amiata Piancastagnaio</i>	Amiata	Italy	Italy	Plant	60.0
<i>Bagnore</i>	Amiata	Italy	Italy	Plant	60.0

*Class categories are "Plant" = power from installed plant; "Flow" = viable flow test from one or more wells demonstrates ability to produce electricity; "Thermals" = abundant high-temperature surface manifestations used to assume viability (four cases). **Installed Power includes nameplate power and demonstrated power.

To develop a systematic approach for characterizing VCs, uniform criteria were established in order to develop a database of "qualifying" volcanic centers. For this purpose, a "volcanic center" is different from a "volcanic vent", given that there may be many vents associated with one "volcanic center." In order to ensure consistency in the designation of a viable volcanic center, each VC must have the following characteristics:

- 1) Most proximal vent to a productive geothermal system.
- 2) The most recent eruption must have occurred less than 500,000 years ago
  - a. In the absence of dates, age can be inferred based on geomorphology
  - b. In absence of dates, the presence of persistent fumaroles with temperatures within 10°C of boiling.
  - c. In absence of dates, documented earthquake swarm(s) with strongly suspected volcanic cause.
  - d. In absence of dates, significant measured volcanic-related deformation is measured (through InSAR or geodetic techniques).
- 3) Be composed of a composite cone, crater/caldera, or dome complex >500 meters in height
- 4) Can include more eroded subjacent sister volcanoes within 8 km.
- 5) Adjacent vents located at a distance of ≤8 km from the main vent were generally grouped into one VC.

6) Submarine and island volcanoes <5 km in diameter were excluded from the analysis.

A listing of 74 benchmark VCs included in the global training set, as well as 59 Aleutian VCs and 41 Cascade VCs for application of the developed model, appears in Appendix I which is a subset of data available on-line at <http://gdr.openei.org/submissions/662>. The unique identifier for each VC (VC_Num) is listed in each data tab. Vents that were grouped based on criteria #4 and #5 above are listed in the fourth column (Linked_Centers) of the World_Volcanoes tab.

2.2 Inventory methods for volcanic characteristics

Data collected for global volcanic features includes information about the physiography, eruptive history, eruptive styles and composition (Table 2). Physical information, including size, number, and distances between volcanic features, was collected initially from Google Earth and was heavily augmented with the written and tabulated data from the Smithsonian and Google Earth databases (Table 2). Compositional information was collected from a combination of Smithsonian and GeoROC (<http://georoc.mpch-mainz.gwdg.de/georoc/>) databases.

Table 2. Volcanic features inventoried for all qualifying VCs in this study. *Data sources: G.E. =Google Earth; Smith. =Smithsonian Global Volcanism Network Database; V.O. = Alaska and/or Cascades Volcano Observatory.

Category	Characteristics inventoried	Data Source*
Ice	Presence, extent (based on historical imagery)	G.E.
Alteration	Presence, extent (based on coloration in imagery)	G.E.
Primary Vents		
Stratocone	Number, age, footprint, most recent eruption	G.E., Smith., V.O.
Shield volcano	Number, age, footprint, most recent eruption	G.E., Smith., V.O.
caldera	Number, age, footprint, most recent eruption	G.E., Smith., V.O.
Subsidiary vents		
Cinder cones	Number, age, orientation/clustering	G.E.
Domes	Number, age, orientation/clustering	G.E.
Topology		
Tectonic	Distance, azimuth to trench; arc-trench gap	G.E.
Along arc	Distance, angle to next VC; distance from main volcanic arc	G.E.
Intervent features		
Non-VC Pleistocene vents	Number	G.E., Smith., V.O.
Non-VC Holocene vents	Number	G.E., Smith., V.O.
shield	Number	G.E., Smith., V.O.
caldera	Number	G.E., Smith., V.O.
Cinder cones	Isolated, field, lineament	G.E.
domes	Number	G.E.
Alteration	Presence	G.E.
Lava flows	Presence	G.E.
Ocean cover	Presence (affects degree of exploration)	G.E.
Erupted Composition	Whole rock SiO ₂ content	GeoROC

142 2.2.1 Physical parameters

143 Using Google Earth, all VCs were inventoried for a wide variety of physical parameters (Table 2; a full list
144 of categories can be found in Appendix 1). Due to the abundance of high-quality imagery for most areas
145 inventoried, the majority of measurements have a high degree of confidence. These include the number
146 and footprint of all volcanic features and topology (distance and azimuth between various volcanic
147 features). Rather than attempting to estimate the volume of volcanic features, which would introduce
148 unnecessary error by assuming a conical form using radius and total relief, the footprint of volcanic
149 features (domes, stratocones, shield volcanoes and calderas) was used as a proxy for volcano size. The
150 footprint area was estimated by a combination of the extent of volcanic features (e.g., lava flows), the
151 geomorphic break in slope and written descriptions in the various databases. Similarly, data collected
152 regarding the presence and extent of ice, based on the minimum extent of iced and crevassed areas in
153 the historical imagery, has a high confidence level. In areas for which high-resolution imagery was not

available (e.g., portions of Indonesia, Philippines, Alaska), physical measurements are somewhat less precise but still have high reliability.

Although Google Earth is well suited for the measurement of the physical aspects of volcanic features, reliability of other aspects of the collected data are limited. For instance, the extent of alteration present, based on discoloration of the ground surface, is strongly affected by image quality and ground cover, particularly in forest/jungle areas. Even in areas above tree line, the interpretation of altered ground is somewhat subjective, and the values recorded are regarded with less certainty. Other limitations are present when trying to correlate datasets outside of reliable Google Earth imagery. In particular, combining Google Earth imagery with text-based external data sets (e.g., the Smithsonian database, Google Earth written descriptions) is challenging. For example, for cases in which rhyolite domes are mentioned in the Smithsonian database, it is commonly not possible to distinguish which of several domes present might be rhyolitic, and typically, not all vents visible in Google Earth are noted in the Smithsonian database, making correlations additionally difficult. For cases in which the correlation between complementary datasets were easily recognizable (e.g., “A large, rhyolite flow is present on the northeast flank of the volcano”), these features were separated by chemical composition. However, these cases were rare enough that this additional discrimination was not useful.

2.2.2 Ages

The age of volcanic centers was estimated using the Smithsonian and Cascade and Aleutian Volcano Observatory databases. Initially our team intended to report the ages of volcanic features in categories of <1,000 years, 1,000-5,000 years, Holocene and Pleistocene. Data contained within the various text-based external data sets, however, were not sufficiently specific to allow this level of age resolution for individual volcanic features. We were therefore forced to eliminate the finer-resolution age categories

from our original compilation, and broad age divisions of Holocene and Pleistocene were used. The Holocene vs. Pleistocene determinations were based fundamentally on Volcano Observatory and Smithsonian databases, with subsequent age determination based on morphology observed in Google Earth using glaciated and otherwise heavily eroded surfaces to indicate pre-Holocene VCs. Several calderas were identified as “inter-vent,” or located between the VC of interest and an adjacent VC. Because these calderas are absent from the Smithsonian database of Holocene volcanoes, these were interpreted to be Pleistocene in age. In cases where only Pleistocene and Holocene age determinations were possible, or if no information could be determined, no numeric age was assigned. These features were therefore not included in analyses based specifically on numeric ages, but were included in the broader categorization.

Eruptive frequency was determined based on the Smithsonian database of Holocene volcanoes. The number of Holocene eruptions for each VC was summed and the time period between the oldest recorded eruption and the publication date of the database (2015 for the online database) was tabulated. Forty seven of 74 benchmark VC (64%) have these data available. Using these data, the number of eruptions per 100 years was calculated.

2.2.3 Eruptive Compositions

The compositions of erupted material from each VC were compiled from two main resources: Smithsonian and GeoROC. Information regarding the composition of the most recent eruption from each VC was collected from the Smithsonian database, which provided data for 51% of the VCs in the global training set, 62% of the Aleutian VCs and 91% of Cascades VCs. Published comprehensive compositional histories are available for very few volcanoes in the world. However, chemical analyses of eruptive products from many of the VCs in this study have been made. These analytical results are

reported in several geochemical clearinghouses (GeoROC, <http://georoc.mpch-mainz.gwdg.de/georoc/>; EarthChem, www.EarthChem.org; GERM, www.earthref.org/GERM/, Volcano Observatory databases, and others). There is a small amount of duplication between these databases. Because GeoROC contained the most complete inventory of analyses for the VC in this study, only this database was used. GeoROC was queried for volcanic and plutonic whole rock analyses from each of the volcanic arcs represented in the global training set. This resulted in over 94,000 whole rock geochemical analyses, of which 11,000 from >3,400 scientific publications were related to the VCs inventoried. This data set includes data for the majority of VCs in this study (80% of global training set VCs, 86% of Aleutian VCs, 62% of Cascades VCs).

Although the GeoROC database is the most complete global data set for igneous rock chemistry, it is by no means complete. The database is populated by researchers voluntarily submitting their data in the interest of public distribution. Thus, there is a reporting bias toward more heavily studied volcanoes and for more intensely studied eruptions. For example, of the 319 samples listed for Mt. St. Helens, Washington State, USA, 99 (31%) are from the 1980 eruption. In comparison, the three large dacitic Plinian eruptions from Glacier Peak volcano (also in Washington State) between 13,000 and 11,000 years ago have only a single entry in the database among them. Thus, the GeoROC database (and all other igneous geochemical clearinghouses) is skewed toward volcanoes and deposits that have piqued scientific interest. Regardless, GeoROC represents the most complete dataset for the VCs inventoried in this study, and data are available for 77% of the VCs studied.

2.2.4 Processing of Rock Geochemistry Data

The compositions obtained from GeoROC were separated into four broad categories (basalt, andesite, dacite, rhyolite) based on SiO₂ wt%. From this, the number of entries for volcanic samples of each

compositional group were tabulated. A weighted average for the number of samples in each category was calculated, where basalt = 1, andesite = 2, dacite = 3, rhyolite = 4, and no data = 0, and the average composition was separated into groups (basalt=1-1.75, andesite=1.75-2.5, dacite=2.5-3.25, rhyolite=3.25-4). For example, Los Azufres Volcano, Mexico, has 31 basaltic samples, 50 andesitic samples, 11 dacitic samples and 56 rhyolitic samples, yielding a weighted average of 2.62, equivalent to an average composition of andesite. The diversity of eruptive products was also calculated by adding the number of different compositional categories that occurred. Volcanoes that erupted only basalt would receive a compositional diversity score of one. For the example above, Los Azufres received the highest possible compositional diversity score of four.

2.3 Inventory Methods for Fluid Geochemical Characteristics

2.3.1 Techniques for obtaining fluid geochemical data and characteristics

Data for the VCs outside of the US were obtained almost exclusively through data entry from published sources. Name searches for geochemical data by primary and secondary volcanic center and geothermal field names were conducted in the following source databases: Geothermal Resources Council library (GRC), International Geothermal Association conference database (IGA), US Office of Scientific and Technical Information (OSTI), Geothermics, GeoRef, Cascades and Aleutian Volcano Observatories (CVO and AVO). Over 200 publications were reviewed from which data were entered and compiled, some of which contained information on multiple geothermal fields or volcanic centers. A list of references used to construct the database appears in Appendix I in the document at <http://gdr.openet.org/submissions/681>. Additional geochemical data were obtained for arc VCs in South America from a digital database of published data maintained by co-author Glenn Melosh.

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250 Raw data were compiled whenever available such that geothermometers could be calculated for as
251 many sites as possible. For all VCs, both a representative well and spring (both highest temperature
252 available) were included when both were located for a particular VC. However, many VCs had no
253 published geochemical analyses, but had notations of one or more geothermometer values in the
254 publications. These data are included in the data set, as were maximum spring, well and field
255 measured temperatures. When possible, preferred data to be included in the database had a
256 complete analysis with a charge balance $<5\%$, and $\text{pH} > 5.5$. This condition could not be met at all
257 sites, and the less reliable analyses were weighted lower during the modeling phase of this work (to
258 be discussed in companion papers and reported in Shevenell et al., 2015).

259

260 2.3.2 Processing of Geochemical Data

261 One analysis, one set of geothermometer calculations, and one measured temperature was
262 compiled for both a spring and deep well (where available) for each site in an attempt to obtain
263 geochemical and geothermometer data from springs, as well as potential or actual reservoir fluids.
264 When multiple spring or well data were available for a particular volcanic center, one
265 representative sample was included in the master geochemical data set such that one entry per
266 volcanic center would be included in modeling. The highest temperature spring or well sample with
267 the most complete analysis and best charge balance was selected when a choice of samples was
268 available. In many cases, only one complete analysis was available for a particular VC (although
269 most had good charge balances of $<5\%$). Low pH samples were avoided when possible as their
270 chemistry would lead to unreliable calculated geothermometer temperatures due to a variety of
271 factors including leaching of soluble SiO_2 near discharge.

272

273 In many cases (World VCs as well as Cascades and Aleutian VCs), only minimal information could be
274 gleaned from published literature, such as a single temperature or geothermometer value without
275 an accompanying full chemical analysis to evaluate. Although the quality of these data could not be
276 directly ascertained via methods such as charge balances, the data were retained in the master data
277 set to maximize the amount of information available for the evaluation. For these cases without full
278 chemical analyses, and only a notation of a geothermometer value, the value was listed in a Best
279 Estimate column regardless of whether the geothermometer was obtained from a water or gas
280 sample or if it was unstated by what method the source of the estimate was made. It is recognized
281 that a “Best Estimate” for a particular VC is not necessarily a good estimate, only the best available.
282 These digital data are available for download at <http://gdr.openei.org/submissions/662>.

283

284 2.3.3 Geothermometer Calculations

285 Estimated subsurface temperatures were calculated using all compiled water analyses using the
286 following geothermometers: K-Mg (Giggenbach, 1988), Na-K (Giggenbach, 1988), Na-K-Ca (Fournier
287 and Truesdell, 1973), Na-K-Ca, Mg corrected (Fournier and Potter, 1979), Quartz (Fournier, 1981),
288 Chalcedony (Fournier, 1981), Quartz-Adiabatic cooling (Fournier, 1981), SiO₂-Gigg (Giggenbach,
289 1992), and SiO₂-Mariner (Mariner et al., 1983). Each geothermometer was calculated in a
290 spreadsheet along with a column for the average of the Na-K-Ca, Mg-corrected and SiO₂-Mariner
291 geothermometer values. The SiO₂-Mariner temperature is based on a threshold in which the quartz
292 geothermometer is used if the Mg-corrected Na-K-Ca temperature is $\geq 100^{\circ}\text{C}$, and the chalcedony
293 temperature is used if this temperature is $< 100^{\circ}\text{C}$.

294

295 One “representative” geothermometer value was selected for each record based on the following
296 criteria. If the record had multiple geothermometers in agreement ($\leq 20^{\circ}\text{C}$ variance), the
297 approximate average of the geothermometers was selected within $\pm 5^{\circ}\text{C}$. If the record had both a
298 SiO_2 and Na-K-Ca, Mg-corrected geothermometer in agreement, the average was taken as the
299 geothermometer for that sample (again, reporting geothermometers in 5°C increments). If the
300 record only reported SiO_2 and no cation data, the SiO_2 -Gigg geothermometer was selected as the
301 value for that record. When either or both the Na-K-Ca, Mg-corrected and SiO_2 geothermometers
302 were lacking or unrealistically low, the K-Mg geothermometer was selected as the sample was most
303 likely from a lower temperature source for which this geothermometer is preferred. When SiO_2 was
304 either lacking or unrealistically low (e.g., negative numbers), the Na-K-Ca geothermometer was
305 recorded for the record. However, when the maturity index (MI) for a samples was >2.5 , the Na-K-
306 Ca geothermometer was selected in preference to the quartz, although in many cases, when
307 $\text{MI} > 2.5$, the quartz and Na-K-Ca geothermometers were in good agreement, particularly for the
308 non-US sites. When the MI was <2 , the best estimate of the sample was based on the quartz
309 geothermometer for higher temperature systems, and chalcedony for the lower temperature
310 systems ($<120^{\circ}\text{C}$). As noted, low pH waters were avoided but were used in some cases when those
311 were the only analyses available. The “best” analysis was picked in this case based on what
312 appeared most reasonable from the various SiO_2 and Na-K-Ca geothermometers availability and MI.

313

2.4 Inventory methods for surface manifestations

2.4.1 Techniques for obtaining surface manifestation characteristics

The same published sources used to collect geochemical data were also searched for notations of the presence or absence of fumaroles, sinters and travertines, and summaries compiled (digital data reported at <http://gdr.openei.org/submissions/662>). Notations of surface manifestations in the Smithsonian database were also included in this compilation. Relatively few notations were located in the literature relating to the presence or absence of sinters and travertines, although these were included into the master data set where available.

Data on flank fumarole presence and temperatures from the published literature were compiled, including a few MW estimates from heat loss calculations. Most data sources did not specify fumarole temperatures, chemistries or manifestation sizes. A visual search for fumaroles was then initiated in Google Earth to locate fumarole fields associated with world volcanic centers to estimate size of the surface expression of the fumarole fields. The search focused on locating flank fumaroles rather than summit fumaroles under the assumption that flank fumaroles are more likely to be associated with hydrothermal activity, whereas summit fumaroles are more likely to be, at least in part, a surface manifestation of magmatic degassing. Thus, summit fumaroles are likely not indicative of an active, producible hydrothermal system.

Preliminary searches for flank fumaroles in Google Earth indicate data from these evaluations could be quite subjective, as well as incomplete due to the variation of image quality among areas.

However, extensive international experience and site visits by Glenn Melosh and Bill Cumming (co-

authors), and Tom Powell, helped identify the locations of many fumarole fields throughout the world. However, fumarole areas could not be estimated for VCs in all countries (e.g., Japan), making this dataset incomplete.

2.4.2 Processing Data

From the fumaroles located in Google Earth, a polygon was drawn around the altered areas or areas of known acid-sulfate mud pot occurrence, and the areas (in m²) of the polygons were calculated in ArcMap. Areas of altered ground around springs were not included in the calculations. When more than one fumarole area was located for a particular VC, the areas were summed to obtain a total surface area of fumarole manifestations. Note that this is substantially different than summing a larger alteration area outlined by bicarbonate springs, for example. Figure 2 shows one example site at Salak, Indonesia where two power plants (yellow push pins) and four fumarole areas (red outlines with white fill) are within the extent of the figure. In this case the areas for each of the four fumarole manifestations were calculated, summed, and attributed to the Salak VC. The summed fumarole areas for all VCs were then plotted and compared against known power production, geothermometer values, and structural and tectonic characteristics.

Figure 2. Google Earth image of the Salak VC area showing four fumarole areas identified and outlined by project team members (red outline with white fill, white text). Yellow push pins and text indicate geothermal power plants. The summit of Salak VC is just out of the frame to the upper right.

3.0 Results

A preliminary analysis of interrelationships among the various data sets was completed using graphs, scatter plots, cumulative distribution curves, and statistics. A more comprehensive analysis, including the use of multivariate statistics and other statistical treatments was completed after the final data collection task in association with the construction of the numerical play fairway models (Coolbaugh et al., 2015, Shevenell et al., 2015, and subsequent papers in preparation).

3.1 Physical Geographic parameters

Physical geographic characteristics of volcanoes were compared to installed power hosted by each VC for the global training set (n=74) in order to identify meaningful trends. The majority of characteristics, including several previously understood to be strong predictors of geothermal potential, show little to no correlation with installed power.

3.1.1 Important non-correlations of physical characteristics

3.1.1.1 Size of Volcanic Features

One of the physical parameters evaluated is the size of the volcanic edifice, with the assumption that a larger edifice would represent a larger, potentially longer lived magmatic system that would have greater potential to heat a larger subsurface volume. The longevity of a magmatic system has been suggested to be related to geothermal potential (Smith and Shaw, 1979). Plots of these relationships (stratocone footprint, caldera surface area) showed no correlation with installed power (Fig. 3).

Figure 3. Areal footprint of major volcanic features (base of stratocone or caldera rim) vs. installed power. Holocene and Pleistocene VCs are plotted, and separation of Pleistocene and Holocene features showed similar results. No obvious correlation exists for either parameter.

3.1.1.2 Flank vents, cinder cones and domes

Prior to data collection, the presence and abundance of flank vents (cinder cones and domes) was anticipated to yield a strong correlation with geothermal productivity. In part, this stemmed from the presence of rhyolite domes at several successful geothermal fields (e.g., Japan, (Ishikawa, 1970); Coso, (Bacon et al., 1980); Rotorua, (Wood, 1992)) and have been suggested as potential indicators of geothermal potential (Wohletz and Heiken, 1992). The abundance of flank vents was hypothesized in two opposing arguments: a larger number of flank vents would suggest a denser fracture network that could promote permeability; or, conversely, that a larger amount of flank vent volcanism would allow greater stress accommodation by magma injection rather than brittle failure, effectively decreasing permeability. The data reveal no statistical trends to support either of these arguments (Fig. 4a).

Specific tests of correlations between the presence of felsic domes and geothermal potential are difficult. The composition of volcanic features is challenging to constrain, so the occurrence of rhyolite domes specifically cannot be addressed with the current data set. However, using the area of domes present on and around VCs would include the rhyolite and non-rhyolite domes, and also include a factor related to the volume of material erupted. Also, domes were identified in Google Earth in part by their steep-sided morphology. Because the higher viscosity of rhyolite promotes the formation of steep-sided lava domes, this category likely includes the majority of rhyolite domes. A plot of dome area vs. installed power revealed no correlation (Fig. 4b). The ambiguity in the data collection, however, diminishes the confidence in this conclusion.

Figure 4. Flank vent characteristics vs. installed power. VCs without flank vents are not plotted. (A) Number of flank vents (cinder cones and domes). (B) Dome area, or footprint, separated by age. Each data point represents the sum of the areas for all domes associated with each VC. VCs without domes are not plotted. No significant correlation was observed.

3.1.1.4 *Inter-vent Features*

An inventory was made of all volcanic features located between the VC associated with a productive geothermal system and the nearest volcanic center. Only the presence of these so-called inter-vent features were noted; they were not counted or measured. These features include lava flows, various occurrences of cinder cones (isolated, distributed fields or lineaments), small poly-genetic Pleistocene and Holocene vents that were too small to be included in the VC list, areas of alteration, and more (Fig. 5). Several calderas were observed, which were interpreted to be Pleistocene in age because they did not appear in the Smithsonian database of global Holocene volcanic centers. 92% of the global training set VCs have some sort of inter-vent feature, and 60% have multiple types. Visually, Fig. 5 shows that inter-vent shield volcanoes and Holocene vents are associated with lower power yields, but the population of these groups is too low to support a statistically significant correlation.

Figure 5. Inter-vent volcanic features vs installed power. The vertical blue line separates cumulative data (left) and data for individual features (right). Data for “Power with multiple inter-vent features” duplicates many of the data points separated out on the right side. Numbers across the top indicate the number of data points in each column and the percentage of the global VCs that contain each individual inter-vent feature.

3.1.2 Statistically significant correlations of physical characteristics

3.1.2.1 Caldera-hosted systems

The strongest correlation between installed power and physical volcanic characteristics is the occurrence of productive geothermal systems located within or near calderas. This was in part anticipated, as several reports have suggested that large volumes of un-erupted silicic material commonly associated with calderas are capable of releasing substantial heat for millions of years after

the last eruptive activity (Kolstad and McGetchin, 1978; Wohletz and Heiken, 1992). Of the 74 global arc-related VCs that host power-producing geothermal systems, approximately 60% are associated with calderas (Fig. 6). Further exploration of this relationship reveals that, although Pleistocene caldera volcanoes host only 26% of all power-producing systems in the global training set, they produce 36% of the power, an average of 140 MWe/system. In comparison, systems hosted by Holocene calderas represent 31% of power producers, yet yield 19% of the power (average 61 MWe/system). Non-caldera geothermal systems represent 45% of all systems and yield 43% of the power (average 108 MWe/system). Formal statistical tests of the difference between means using log-normalized populations indicate that systems associated with Pleistocene calderas have higher average energy output compared to systems in Holocene calderas or non-caldera systems (p values = 0.02 and 0.03, respectively).

Figure 6. Global geothermal systems separated by their association with calderas. More power-producing systems are associated with calderas, and those associated with Pleistocene calderas tend to have greater power yields on average.

3.1.2.2 Recency of Eruption and Eruptive Frequency

Relationships between installed power and time since the last eruption were examined, with the hypothesis that the more recently active volcanoes would have proportionally greater heat flow into the surrounding shallow crust. Data are available for 48 benchmark VCs, or 65% of the global training set. Of this subset of the training set, volcanic centers with eruptions within the last 900 years account for 97% of installed power (Fig. 7), indicating that relatively recent eruptive activity is an important characteristic for volcano-hosted geothermal systems. Interestingly, cumulative installed power constrained by the time since last eruption is in large part controlled by the average composition of the VC hosting the geothermal system. Of the energy produced from VCs erupting in the last 160 years, which accounts for 50% of all installed power on VCs worldwide, 98% is hosted by mafic volcanoes (those with average erupted compositions less than 63 wt% SiO₂ based on data from the GeoROC database; see section 2.3.2). Alternatively, energy produced from VCs erupting more than 160 years ago is dominated (90%) by felsic VC productivity. Caveats regarding these correlations are important to consider, notably that 29% of total installed power cannot be included in Fig. 7, either because eruptive dates or compositional data are not available (seven mafic VCs (11% of total installed power) and 14 felsic VCs, (6% of the total installed power) do not have eruptive dates; 14 VC (13% of total installed power) do not have compositional data). However, considering that historical eruptions are more likely to be reported than older eruptions, the eruptive dates for these VCs are likely to fill in the older portion of the plot and increase the compositional separation shown in Fig. 7. Although VC average composition does not appear to have significant direct control over power production (see section 3.2), if the recency

of eruptive activity is considered in the assessment of a geothermal prospect, the average composition of the host VC is a critical factor.

Figure 7. Cumulative installed power for mafic VCs (n=34), felsic VCs (n=11), all VCs with compositional and eruptive date information vs years since the last eruption. Data labels for mafic and felsic groups indicate the percentage of cumulative power from each compositional group. Data labels for total cumulative power indicate percentage of all installed power, including data not plotted. Compositional groups based on bulk compositions for each VC from GeoROC database. Additional data that plot beyond 1,000 years: *mafic VCs*: 2300 years, 4.8 MW; 3500 years, 42.0 MW; *Felsic VCs*: 1100 years, 30 MW; 1600 years, 14 MW; 2000 years, 5 MW; 4500 years, 65 MW.

Our team hypothesized that high eruptive frequency would correlate with greater geothermal productivity as the greater magmatic throughput would allow higher heat flow into the surrounding crust. Additionally, we hypothesized that because mafic magma systems tend to erupt more frequently (White et al., 2006), the greater magma flux will transmit more heat into the surrounding crust and support hydrothermal systems. Alternatively, the long residence time of felsic systems allows the magma to transmit a greater percentage of its total heat into the surrounding rock. To test these hypotheses, eruptive frequency was plotted against installed power (Fig. 8).

Approximately 42% of the VCs have eruptive frequencies below 0.2/100 years (one eruption every

500 years). Although this group contains most of the >100 MW VCs, the majority of these low eruptive frequency systems produce less than 100 MW. This implies that an unexplored VC with a low eruptive frequency is not any more or less likely to host a >100 MW geothermal system, making this characteristic of relatively little value in terms of greenfield exploration.

Figure 8 also separates out compositional groups. As expected, the VCs with the greatest eruptive frequency, including all VCs with eruptions more frequent than one per 100 years, are all basaltic. The most frequently erupting felsic (dacitic and rhyolitic) VC has an eruption every ~262 years (Ibusuki Volcanic Field, Japan; frequency score of 0.382). This is consistent with volcanological concepts regarding the less frequent eruptive character of silicic magmas and more frequently active mafic magmas (White et al., 2006). However, the lack of correlation between compositional groups, eruptive frequency and installed power do not support or refute any of the working hypotheses.

Figure 8. Eruptive frequency (number of eruptions per 100 years) vs. installed power (MWe), classified by VC composition. Vertical dashed line denotes one eruption per 100 years. Eruptive history data from the Smithsonian database.

3.2 Eruptive Composition parameters

Overall, no strong correlations have been established between eruptive composition alone and installed power in our global training set. Graphical tests of relationships between the composition of the most recent eruption, compositional diversity of erupted products and the average composition of volcanic material have been made. However, most of the compositional data evaluated are based on the GeoROC database, which is not comprehensive (see section 2.2.4). This adds ambiguity to the importance of these conclusions.

3.2.1 Average VC composition and composition of the most recent eruption

One of the strongest anecdotal correlations in geothermal exploration is the link between silicic volcanism and highly productive geothermal resources (Wohletz and Heiken, 1992). Based on the data collected from the GeoROC database (section 2.2.4), the average composition of each VC was calculated. As discussed in section 2.2.4, using the GeoROC database adds substantial sampling bias, and the results of these analyses should be interpreted with caution. With that in mind, initial conclusions can be drawn based on the data available. Plots of average VC composition vs installed power (Fig. 9) indicates very little control exerted by magmatic composition over the productivity of associated resources. Formal statistical tests indicate no significant difference in installed power between basaltic, andesitic, dacitic and rhyolitic groups at the $p=0.05$, $p=0.1$ and even $p=0.5$ significance levels. Similarly, mafic (basalt + andesite) and felsic (dacite + rhyolite) compositional groups show no statistical difference at these significance levels. These statistics exclude the 17 VCs (~23%) that do not have compositional data in GeoROC ("unk" in Fig. 9). Compositional data for these VCs, along with more comprehensive compositional data for the other VCs, could affect these statistics. However, given that 77% of VCs are represented, and that an average of ~192 analyses for each VC was used to define

average compositions, it would require a substantial addition of new data to produce statistically significant differences between these groups.

The composition on the most recent eruption was also considered (Fig. 9). These data are based on text entries (e.g., “basalt”) in the Smithsonian Holocene eruption database, and therefore are assigned default “average” compositions rather than being determined by whole rock SiO₂ wt% as in the case of GeoROC data. Youngest eruption compositional data exist for just over half of the global training set of VCs. These data suggest a weak relationship between most recent andesitic and phreatic eruptions and the potential for higher power yield (>100 MWe). Similarly, no geothermal systems with installed power >100 are associated with VCs that have most recently erupted basalt. Importantly, as with average VC compositions, no statistically significant correlation exists between higher silica content (more felsic) eruptive composition and installed power, as has been anecdotally suggested. Although the sample population is small, our conclusion, based on the existing data, is that magmatic composition has very little bearing on the likelihood of hosting a productive geothermal system.

Figure 9. Average VC composition and composition of the most recent eruption vs. installed power. Average composition is based on the average SiO₂ wt% of all entries for each VC in the GeoROC database. Compositions of youngest eruption are based on text entries in the Smithsonian database and are therefore only assigned a generic compositional value plotting in the center of the colored compositional regions. Phreatic category is an eruptive style with no compositional meaning, and only refers to most recent eruptions. Unk=unknown.

3.2.2 Eruptive Diversity

An anecdotal relationship made by members of our team suggests that smooth-sided, well-formed stratovolcanoes are often somewhat far away from productive geothermal fields. Whereas the smoothness of each VC was not estimated, the morphology of “idealized” stratovolcanoes is largely due to the dominance of basaltic eruptions (Karátson et al., 2010), and volcanoes with a broader compositional diversity are less likely to have these idealized shapes. Furthermore, the lack of compositional diversity suggests limited fractionation and evolution of magma in a shallow chamber. Thus, these volcanoes are interpreted to have small magma chambers with very rapid magma flow-through and short magma residence time in the shallow crust (Bertagnini et al, 2003). A correlation between low eruptive diversity and poor geothermal conditions would be consistent with a relatively low heat supply from a rapidly migrating magmatic system.

To test this hypothesis, we plotted eruptive diversity (see section 2.2.4) against installed power (Fig. 10). All diversity categories appear to be equally likely to host moderate to low yield (<150 MWe) geothermal systems. Volcanic Centers erupting only a single composition appear to be less likely to host high-yield (>150 MWe) geothermal systems, with 10-30% of the VCs in each diversity category hosting >150 MWe. Formal statistical tests indicate that these differences are not significant at 0.05 or $p=0.1$ significance levels, however. Additional data from future geothermal development in new areas will improve these statistical populations.

Figure 10. Eruptive diversity vs. installed power. A maximum diversity score of 4 indicates that samples from all four compositional groups (basalt, andesite, dacite and rhyolite) are present for that VC in the GeoROC database; a score of 0 means no compositional data were available. Symbol color indicates average VC composition. Bold horizontal line highlights 150 MWe gridline

3.3 Fluid geochemical characteristics

Temperature, geothermometer and fumarole data have been compared with installed power from the 74 world VCs representing power producing systems in arc environments. Geochemical data entered and used to calculate geothermometers and best geothermometer estimates by field were selected for incorporation into a master geochemical data file and several plots and maps were made. Either spring or well chemistry (or both when available) were included for 97 (spring) and 63 (well) samples from the 172 volcanic centers (59 Aleutian, 41 Cascade and 74 global benchmark sites (which includes the 2 power capable systems in the Cascades).

Surface manifestations in Table 3 include VCs at which either or both sinter and travertine were noted in the literature searches. The large number of data for fumaroles in the Aleutians is a result

of a specific notation of the presence or absence of fumaroles on Alaska VCs by Schaefer et al. (2014). No other area includes comprehensive information on the absence of fumaroles at particular VCs. Many of the data gaps apparent in geothermometer and measured temperatures are due to the inability to locate data for a particular volcanic center in the literature. Although it is known that geochemical and temperature data exist for many of these geothermal fields, the information is currently held proprietarily. The exception to this trend is seen in the Alaska data in which the low number of well temperatures and geothermometers occurs because there are very few VCs drilled in the Aleutians. Hence, much of the “missing” data for VCs can be attributed to Alaska where geochemistry for wells is only available at two of the 59 volcanic centers, and for springs at 21 of the centers as many of the islands have not been explored to any great extent.

Table 3. Summary of available data from geothermal manifestations along with the percent of coverage of each data type over all VCs included in this study. The number of volcanic centers containing data for the individual columns is listed, as are the number of productive systems (which include successful flow tests and power plants). Entries are included for all VCs in the Aleutian and Cascade arcs (100 VCs total, including 2 potential power producers) and only power producing VCs (72) in other global arcs.

	Total Number of VC	Productive Systems	Meas Spring Temp	Spring Geotherm ometer	Measured Well Temp	Well Geotherm ometer	Fumarole	Surface Manifesta tion
<i>US Volcanic Arcs</i>								
Aleutians	59	0	22	21	2	2	45	8
Cascades	41	2	18	16	7	5	11	5
<i>World Volcanic Arcs</i>								
Central America	13	13	8	8	12	9	8	6
Europe	2	3	1	1	3	2	1	1
Indonesia	17	19	14	15	9	7	17	6
Japan	12	13	8	8	10	10	4	1
New Zealand	4	9	2	9	6	9	2	4
Papua New Guinea	1	1	0	0	1	1	1	0
Philippines	7	8	3	4	8	7	7	1
Russia	6	6	4	5	3	3	3	0
South America	7	7	7	7	4	5	6	2
Taiwan	1	1	1	1	1	1	0	0
West Indies	2	2	1	2	2	2	1	0
Totals:	172	84	89	97	68	63	106	34
% Aleutian with data			37%	36%	3%	3%	76%	14%
% Cascades with data			44%	39%	17%	12%	27%	12%
% World with data (excluding US)			68%	83%	82%	78%	69%	29%

Water pH was compiled along with other geochemical data and many of the producing, world VCs have a low pH zone in their geothermal fields, but not within the production zone. Hence, low pH of surface manifestations does not eliminate a geothermal system from further evaluation based on corrosive considerations. Low pH zones are often indicative of a high temperature system within a VC as they are indicators of boiling. Low pH can also be an indication of magmatic contributions, which isn't necessarily an indicator of power producing systems.

3.3.1 Temperatures

As with other data types compiled for this project, many plots of various data groupings were constructed to evaluate trends and data interrelationships. A summary of world maximum temperatures by region appears in Fig. 11 which shows that the maximum, known temperatures of US systems are typically less than those in other areas of the world in volcanic arc environments. The highest temperature systems in both the north and south Cascades (Meager and Newberry) are both known to be of low permeability (Thompson, 2010), with Newberry being an active site for EGS studies (Cladouhos et al., 2015).

Figure 11. Summary of maximum known temperatures from geothermal systems around the world in arc settings. For each arc or arc segment, the VC providing the highest temperatures is listed above the data.

Temperatures range from 190-353°C (average: $281 \pm 48^\circ\text{C}$) for all world arc power plant systems (excluding Aleutians and Cascades), whereas the maximum temperatures in the Aleutians is 220°C (geothermometer estimate at Makushin) and Cascades is 288°C (measured at Glass Mountain, Medicine Lake). Thus, maximum known temperatures in the Aleutians are lower than the average global value at producing power systems, but slightly higher in the southern Cascades. Average measured temperatures from all US VCs is $190 \pm 70^\circ\text{C}$ show there is a wide range of temperature variability in US systems, with most being lower than the global average in arc settings. In contrast, the well geothermometer temperatures from the world power producing sites are similar to measured temperatures (average of $276 \pm 31^\circ\text{C}$, compared to 281°C average measured temperature). In the Cascades and Aleutians, well geothermometer temperatures suggest somewhat higher values than measured temperatures at $211 \pm 48^\circ\text{C}$ (compared to 190°C average measured temperature).

The temperature data were investigated to evaluate various relationships including local and regional trends. Figure 12 illustrates the best estimate of spring geothermometer temperatures versus the maximum measured well temperatures at the sites. As expected, nearly all sites worldwide have higher measured temperatures relative to those indicated by geothermometer temperatures obtained with spring chemistry. Spring chemistry apparently provides an indication of elevated temperatures at depth, but typically not an accurate reservoir temperature. In 90% of the cases for which data are available, measured temperatures are greater than those indicated by spring geothermometer temperatures obtained from the highest temperature spring. Thus, reservoir temperatures obtained from spring chemistry geothermometry can be expected to underestimate reservoir temperatures from drilling

results, with only 8% of sites in this data set indicating higher spring geothermometer temperatures than have been encountered thus far during drilling.

Figure 12. Plot of spring geothermometer temperatures versus maximum measured well temperatures for geothermal systems in volcanic arcs. Note that the well (68-8) with the maximum measured temperature at Medicine Lake of 288°C (Glass Mountain; Cumming and Mackie, 2007) is not included because there is no corresponding spring geothermometer available for this area.

The low spring geothermometer estimates result because the spring waters often undergo variations in chemistry (mixing, precipitation, dissolution, etc.) prior to sample collection, thus indicating lower than actual deep temperatures. Although geothermometer temperatures obtained from deep wells may not reflect true reservoir temperatures, because these fluids are less influenced by re-equilibration they better reflect temperatures at reservoir conditions as expected.

3.3.2 Fumaroles

In compilations of fumarole and acid-sulfate mud pot features, summit fumaroles (presumed to be magmatic) are distinguished from flank fumaroles/features (presumed to be hydrothermal). Discussions in this paper are exclusively made with reference to flank fumarole data, and calculations of fumarole area only refers to the sum of altered surface area directly related to hydrothermal (e.g., non-magmatic) fumarolic activity (section 2.4.2). Fumarole occurrences show a strong correlation with power producing

systems. Although fumaroles could not be located at all sites investigated, they may yet occur, especially in Japan for which fumarole occurrence is notably under reported. Even though fumarole areas were not documented for all power-producing VCs in all countries, 70% of the world power producing systems have known flank fumaroles, with the occurrence of flank fumaroles being unknown in the remaining 30%. Nevertheless, 86% of all power produced in total MWe at world arc VCs are from systems with known flank fumaroles, demonstrating the strong correlation of power production with flank fumarole occurrence. Thus, one factor to consider in any early exploration effort should include the mapping of flank fumarole occurrences.

3.3.3 Correlations

Numerous charts were constructed to evaluate relationships among data types and facilitate correlations. Figure 13 shows fumarole area (rows) and well geothermometer temperatures (columns, in °C). The numbers within the box represent the average MWe per producing system within the particular data categories. For instance, the red box with the average of 437MW/system in the upper right corner represents 3 systems producing a total of 1310 MW, with the three VCs in this case being Mahagagdong and Palinpinon (Philippines) and Salak (Indonesia). In this figure, only one system with an installed 2 MW plots in the 150-200°C geothermometer range at the >100,000 m² fumarole area size (Mendeleev, Russia). Nevertheless, there is a general trend of higher mean MW for systems with larger flank fumarole areas at higher temperatures.

The heavy box in the upper right corner outlines the systems with the higher average MW values. The numbers along the horizontal axis show average MW increases with increasing well geothermometer temperature whereas the right vertical axis shows generally increasing average MW with increasing flank fumarole areas, with the <10,000 m² row being somewhat anomalous at an average of 112

MW/system. As can be seen, there are very few low temperature (<200 °C) VCs with significant power production.

Figure 13. Mean MW per system (in colored boxes) in the 74 world power producing sites in volcanic arc settings, grouped by their respective fumarole areas (vertical) and well geothermometer temperatures (horizontal in °C). Numbers in parentheses indicate the number of VC in each category. Note that Color coding of average MW size are included on these plots as follows: Largest – Red; Large – Orange; Medium – Yellow; Small – Green; Smallest – Blue. Numbers horizontally across bottom indicate percentage of power produced (top row) and average installed power per VC (bottom row) from each well thermometer category. The relationship depicted here may vary markedly in other geothermal settings (e.g., rift basalt settings).

A similar trend is obtained when considering spring geothermometer temperatures, although few suggest temperatures in excess of 300°C (Fig. 14). Systems with the largest flank fumarole areas and highest spring geothermometer temperatures have the highest average MW, (although the box in the most extreme upper right has only one system (Leyte)). The next highest average MW per system is 428 MW which is the average of Dieng (60 MW) and Larderello (795 MW). Both of these have relatively large flank fumarole occurrence areas (>30,000 m²), but low temperatures indicated by spring geothermometers.

Figure 14. Mean MW per system (in colored boxes) in the 74 world power producing sites grouped by their respective fumarole areas (vertical) and spring geothermometer temperatures (horizontal in °C). Numbers in parentheses indicate the number of VC in each category. Colors as in Fig. 13.

Additional plots correlating fumarole areas with tectonic setting and regional strain rate were evaluated that show similar trends (increasing potential in the upper right of the plots). Each of these characteristics show reasonably consistent trends. Figure 15 shows fumarole occurrence along with regional strain rate (described in detail by Hinz, et al., 2015, 2016; and Nick Hinz in Shevenell et al., 2015). The higher strain rates >5 mm/yr are associated with larger MW production and account for 61% of all power production in arc settings. The largest MW are represented by two areas, the Whakamaru region in New Zealand and Larderello, Italy (Hinz et al., 2015; 2016), averaging 729 MW per area at the highest strain rates with accompanying largest surface area of fumarole manifestations. Similarly, the largest power producers are associated with the extensional environments (Hinz et al., 2015; 2016) that also exhibit large areas of surface manifestations (two red boxes of Fig. 14; Whakamaru, New Zealand (361,101 m² with 757 MW); Larderello, Italy (85,087 m² with 795 MW)).

Figure 15. Regional strain rate versus fumarole area. Regional strain rate is calculated as extension rate over a 50 km of arc length centered on the VC. Average MW per producing system noted in each colored box. Numbers in parentheses indicate the number of VC in each category. Colors as in Fig. 13.

Similarly, Fig. 16 shows that the highest MW producers plot in the region of extensional to transtensional tectonic settings with large fumarole areas.

Figure 16. Tectonic setting versus fumarole area. Average MW per producing system noted in each colored box. Numbers in parentheses indicate the number of VC in each category. Colors as in Fig. 13. Comp=compression; transpress. =transpressive; SS refers to Strike-Slip dominant transtension, EX refers to extension dominant transtension.

4.0 Discussion

Investigations of the collected data have yielded several important observations that affect our understanding of arc volcano hosted hydrothermal systems. One of the most important of these is the link between the presence of flank (as opposed to magmatic) fumaroles and geothermal productivity. More than 70% of all VCs hosting electricity producing geothermal systems have mapped flank fumaroles and flank fumaroles may be present at many of the remaining 30% of productive systems but are not currently documented. This represents at least 86% of the electricity generated in volcanic arcs worldwide. Moreover, the size of the fumarole field is generally proportional to the amount of power produced by the associated geothermal system.

Other important observations arose from the lack of correlation between the majority of volcanic characteristics and geothermal productivity. Many characteristics such as dominant eruptive compositions, compositional diversity, composition of the last eruption, edifice size, inter-vent features and flank cinder cones and domes show no significant correlations with MW production in the global training set. Relationships regarding average composition are slightly less reliable as these data are derived from the GeoROC database which is not comprehensive and may not be an accurate representation of average volcanic compositions. Despite the sampling bias inherent in using these data, the non-correlations observed are reasonably robust. These results are surprising, as many of these characteristics have been commonly assumed indicators of geothermal potential.

Two correlations were observed between physical characteristics of VCs and the power yield from the geothermal systems they host. A strong correlation exists between installed power from mafic VCs that have erupted in the last 160 years, and felsic VC dominate the contribution from VCs erupting between 160 and ~1000 years ago. Less than 3% of the installed geothermal energy in subduction zones occur from VCs without an eruption in the past 1000 years. Additionally, the relationship between older (Pleistocene) calderas and greater average installed power is important, although not fully understood. Because the distribution of installed geothermal power in volcanic arcs appears to obey a power-law distribution, systems with installed power >100 MWe are relatively uncommon (<30% of the global training set). Thus, a surface characteristic that can help identify prospective regions with potential for higher energy yield, such as the presence of Pleistocene caldera, could be a valuable exploration tool. The specific controls over these relationships are not fully understood and will be the subject of additional research.

The intent of the volcanic inventory was to estimate the quality and contribution of the heat source at each of the benchmark sites, and many of the volcanic parameters measured were intended to address

specific physical volcanic processes that were anticipated to affect heat flow. Results show that productive geothermal systems can occur in a broad range of eruptive compositions, eruptive styles (calderas, stratovolcanoes, dome fields, etc.) and locations. Whereas this diversity is encouraging in terms of the ability of economic systems to form in a broad range of volcanic environments, it complicates efforts to predict geothermal potential based solely on volcanic characteristics. The general lack of correlation between the majority of volcanic characteristics and geothermal production suggests that, while it is certain that heat flow is much more complex than modeled here, heat availability is not a primary obstacle to the development of geothermal systems at or around arc volcanoes. Strong positive correlations between installed power and structural parameters and tectonic setting suggest that controls over secondary permeability are more dominant factors. This is supported by clear relationships identified between fumarole presence and size and geothermal productivity.

5.0 Conclusions

This work describes some of the most relevant observations of relationships between key geologic factors and global production of geothermal electricity in volcanic arcs. All 74 volcanic centers worldwide that support current power production or are capable of doing so based on successful flow tests, were included. The project consisted of a large data compilation and collection effort using existing digital databases and data entry from hundreds of published sources. We have developed a combined inventory of volcanic, geothermal, and geochemical information that, to our knowledge, is the largest and most complete compilation publically available. This paper focuses on the volcanic, fumarolic and geochemical aspects of the database. Details of the structure, tectonics and statistical modeling of this work will be presented in subsequent papers.

Most volcanic characteristics cannot be definitively used as a primary predictor of the geothermal potential of a particular volcanic center in an arc environment. The data set presented here dispels

some commonly held beliefs that power production potential may be correlated with readily obtained volcanic characteristics. Several criteria were tested, including the size of each volcanic edifice, the presence and number of domes and other flank vents, average erupted composition or compositional diversity. None of these characteristics were found to have a direct correlation with geothermal production. Not all commonly held beliefs were dispelled, however. Moderate correlations were found between installed power and systems hosted by calderas, with significantly greater average power per VC for systems hosted by older (Pleistocene) calderas and lower average power per VC for Holocene calderas or systems not associated with a caldera at all. Additionally, the majority of geothermal systems (and installed power) in volcanic arcs worldwide are hosted by VC with eruptions within the past 1000 years. Of these, power generated by VCs erupting the past 160 years are almost exclusively mafic in average composition, while power generated by VCs most recently erupting between 160 and 1000 years ago is almost entirely derived from felsic VCs. Thus, both correlated and uncorrelated criteria in this study will provide guidance for geothermal exploration efforts worldwide.

The strong correlation of the presence and size of flank fumaroles on volcanoes can be used as an initial exploration tool to identify centers most likely to host high temperature, power producing geothermal systems. Additionally, the long-used exploration technique of high spring, fumarole and well temperatures and fluid geothermometers is strongly supported by our statistical investigation of global volcanic arc data. Although our investigation has been limited to subduction zone volcanic centers, it is quite possible that these thermal characteristics are applicable in other tectonic settings as well. However, explorationists should exercise great caution extrapolating these conclusions to ocean island (e.g., Iceland, Hawaii), rift zones (e.g., East Africa), or other tectonic settings.

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