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REGIONAL QUANTITATIVE PLAY FAIRWAY ANALYSIS: METHODOLOGY GLOBAL EXAMPLES AND APPLICATION FOR THE EAST AFRICAN RIFT SYSTEM

[1]Nicholas H. Hinz, [2]Mark Coolbaugh, [1]James E. Faulds, [2]Lisa Shevenell, and [3]Pete Stelling
[1]Nevada Bureau of Mines and Geology, University of Nevada, Reno, NV 89557, USA
[2]ATLAS Geoscience, Inc., Reno, NV 89509, USA
[3]Western Washington University, Bellingham, WA 98225, USA
nhinz@unr.edu

ABSTRACT

Most volcanic arcs and active rifts around the world host producing geothermal systems. Many undiscovered and/or undeveloped systems remain in each of these areas, including magmatic-heated systems, amagmatic extension-related systems, and blind resources lacking active surface manifestations in both types of settings. However, not all volcanic centers or extensional terranes have the same geothermal potential. For example, even when high heat flow is present, permeability is commonly a limiting factor to resource development. A tool recently adapted for the geothermal industry is play fairway analysis, which calculates the regional probability of power-capable resources based on the spatial coincidence of key geologic conditions. In a geothermal setting, these key geologic conditions are heat, permeability, and fluids. Higher enthalpy systems also benefit from suitable cap rock. These parameters can be assessed through multiple geologic, geochemical, and geophysical data sets and integrated quantitatively to produce a single geothermal play fairway map. Potential input data sets include but are not limited to: 1) tectonic setting; 2) structural setting; 3) faults attributed by recency of rupture and slip rate; 3) geodetic crustal stain models; 5) gravity; 6) earthquake distribution; 7) thermal models; 8) geochemistry from springs, wells, and fumaroles; 9) temperature from springs, wells, and fumaroles; 10) fumarole size and type; and 11) age of volcanism. Recent play fairway studies have been completed for volcanic arcs and the dominantly amagmatic, extensional Great Basin region, USA, but have yet to be applied to the East African Rift System (EARS). Previous estimates of total geothermal resource capacity in the EARS is ~20 GWe, but only three areas are currently in production as of 2015: Olkaria and Eburru in Kenya, and Aluto-Langano in Ethiopia for a total installed capacity of <0.7 GWe. Many more volcanic centers host potential resources. In addition, amagmatic and/or blind systems also have potential in the EARS. Play fairway analysis can highlight regions most prospective for geothermal resource development, help identify locations prospective for undiscovered resources, prioritize overall exploration and development efforts, and refine estimates for total undeveloped resource potential.

1. INTRODUCTION

Existing estimates of total geothermal energy potential for the EARS are ~20 GWe (IEA, 2011), with some estimates for the country of Kenya alone reaching 10 GWe (Omenda, 2012; Omenda and Simiyu, 2015). Currently, three areas have been developed in the EARS. These developed areas include Olkaria (659 MWe) and Eburru (2.4 MWe) in Kenya and Aluto-Langano (7.3 MWe) in Ethiopia. Together, they total ~669 MWe installed capacity. This equates to ~3.5% of the total projected resource capacity (Fig. 1).

For comparison, in the USA, the current installed capacity is ~3.7 GWe (GEA, 2016). The estimated cumulative resource capacity of all identified geothermal resources, both developed and undeveloped is ~9 GWe (Williams et al., 2009). Furthermore, the estimated total of unidentified resources in the USA is ~30 GWe (Williams et al., 2008), potentially providing for ~39 GWe of total geothermal potential. The ~3.7 GWe of installed capacity in the USA includes 34 resources that span a wide range of reservoir temperatures and geologic settings (Fig. 2). Production capacity ranges from < 1 to

5 MWe on the low end (e.g., Florida Canyon and Wabuska in Nevada, Oregon Institute of Technology in Oregon, Wendel and Amedee in California, Chena in Alaska, and Lightning Dock in New Mexico) to >700 MWe (e.g., the Geysers in California) for the most robust areas. These producing resources include both magmatic and amagmatic geothermal systems. A large number of these developed resources are also blind, the largest capacity of which is McGinness Hills at 72 MWe. Estimates are that ~75% of the total resources in the Great Basin alone are blind (Coolbaugh et al., 2007).

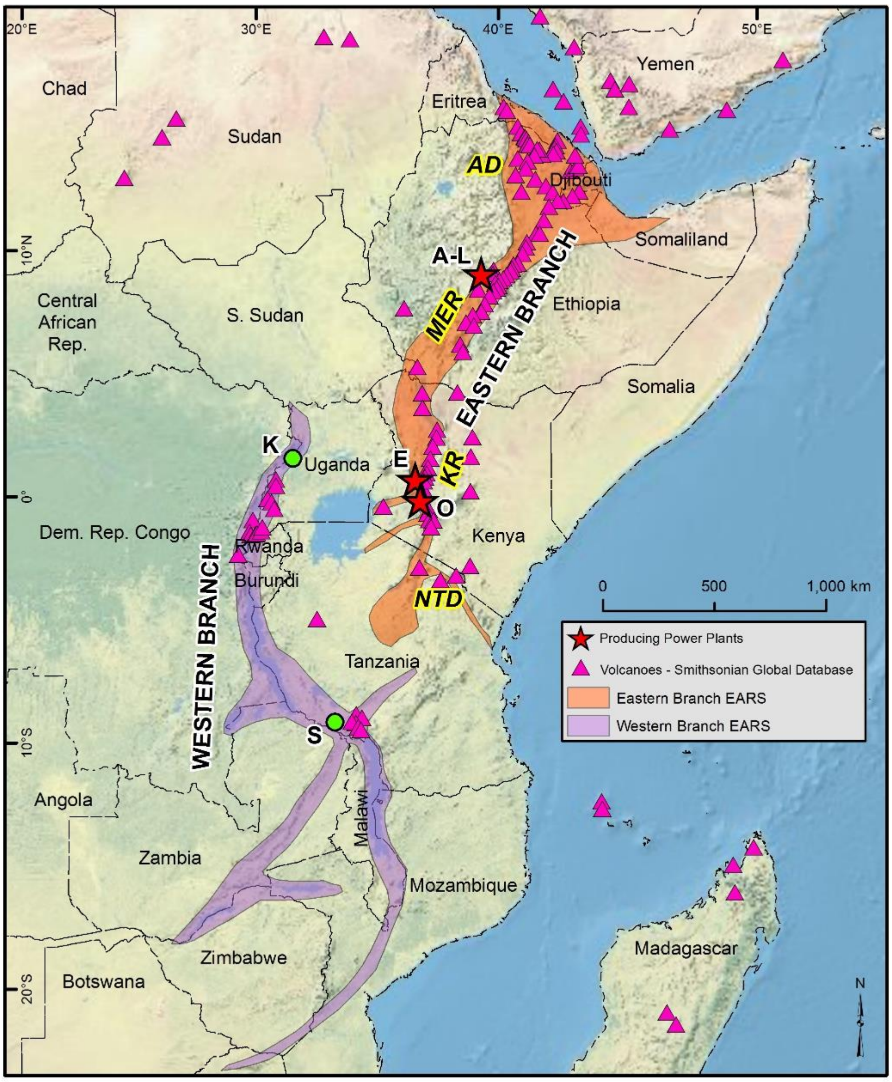

Figure 1. Map of the EARS with major volcanic centers and developed geothermal resources. Purple shading highlights rifts associated with the western branch of the EARS and orange shading highlights the rifts associated with the eastern branch of the EARS. All three producing geothermal systems are associated with volcanic centers: A-L, Aluto-Langano; O, Olkaria; and E, Eburru. Green circles represent locations of other geothermal areas referred to in the text: K, Kibiro; S, Songwe. Rift segments referred to in the text (yellow highlighted text): AD, Afar Depression; KR, Kenya Rift; MER, Main Ethiopian Rift, NTD, northern Tanzanian divergence.

In the EARS, USA, and other areas around the world such as Iceland, New Zealand, or the Philippines, there is substantial variation in resource size. For example, in global volcanic arcs, there are 74 power capable volcanic centers (actively producing or with successful flow tests), which have capacities of <1 MWe to >900 MWe, and approximate a logarithmic distribution (Shevenell et al., 2015). These 74 power capable volcanic centers equate to 10% of the volcanic centers in arc settings being power productive. Many of the non-productive arc volcanoes are located in remote locations, and the presence of geothermal resources is unknown. However, many arc volcanic centers reside in compressive or very low strain tectonic settings and are not subjective to local crustal extension that is inherent in most geothermal systems globally (e.g., Hinz et al., 2016). In continental and oceanic rifts, it is possible that a greater proportion of volcanic centers may host geothermal systems than in arcs simply because most of the volcanic centers are co-located in a region dominated by extensional strain. In summary, a linear approximation of MWe per late Quaternary volcanic center has limited utility in estimating total resource capacity for a given region. This conclusion is supported by the current ranges in resource size in the EARS (e.g., 2.4 MWe at Eburru, 7.3 at Aluto-Langano, and 669 MWe at Olkaria; Fig. 1).

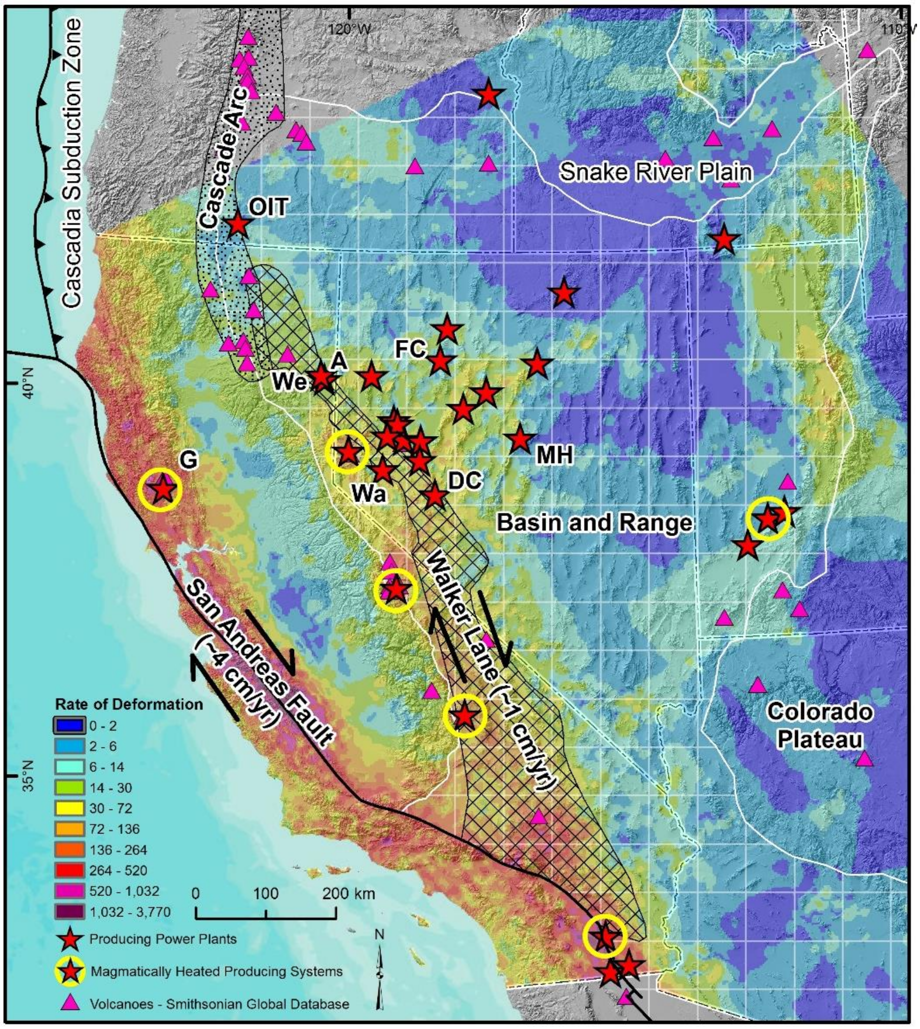

Figure 2. Map of the southwestern USA with major volcanic centers and developed geothermal resources, modified from Faulds et al. (2012). Base map shows the second invariant strain rate tensor model (10-9/yr; Kreemer et al., 2012). Thirty-one of the 34 producing geothermal systems in the USA are shown in this figure. The remaining three that reside outside this map extent include: Lightning Dock in New Mexico, Chena in Alaska, and Puna in Hawaii. Geothermal areas referred to in the text: A, Amedee, DC, Don Campbell; G, Geysers; FC, Florida Canyon; MH, McGinness Hills; OIT, Oregon Institute of Technology; Wa, Wabuska, We, Wendel.

In order to help improve the effectiveness of exploration for undiscovered resources and provide similar base-level information for both known and undeveloped resources, particularly the blind resources, the U.S. Department of Energy (DOE) initiated a funding program called Play Fairway Analysis (PFA) in 2014. The PFA approach was adapted from the petroleum industry for the geothermal industry. The results of these ongoing PFA studies have been to produce new maps of the probability of economic grade resources, including magmatic and/or amagmatic as relevant to a given region, and also blind versus not blind resources. Given current power plant technology and locations, economic-grade resources are generally considered those with reservoir temperatures greater than about 130°C (e.g., 19 MWe capacity Don Campbell power plant, 129 °C reservoir; Fig. 2). This same PFA methodology can be applied to the EARS as a whole, at a country-wide scale, or a rift branch or rift segment scale.

2. PLAY FAIRWAY ANALYSIS METHODOLOGY

Play Fairway Analysis has been a cornerstone of the petroleum industry for a couple decades (e.g., Rose, 2001; Doust, 2010) and involves analyzing the co-location of reservoir, trap, and seal in 3D space. More recently, PFA has been adapted for geothermal resources (e.g., Siler and Faulds, 2013). Play Fairway Analysis can be particularly practical for guiding exploration and reducing risk for initial exploration holes for the discovery of new resources. Adaptation of PFA for the geothermal industry swapped in heat, permeability, and fluids as the primary geologic conditions. All three of these parameters are needed for a hydrothermal system to develop. A potential fourth category is the seal above a reservoir, which not only keeps warm fluids in, but minimizes the influx of cool shallow fluids directly down into the center of a system. For simplicity, these initial geothermal play fairway studies have thus far centered on the three parameters of heat, permeability, and fluids.

The U.S. DOE funded 11 separate geothermal PFA projects beginning 2014 that cover multiple types of geologic settings including the extensional Basin and Range province, volcanic arcs, deep hot sedimentary basins, and mid-ocean plate hot spot volcanism (Hawaii). Each of these PFA projects were designed around an overall common workflow that organizes publically available, digital data sets into categories based on whether the respective dataset is indicative of heat, permeability, or fluids. The input data sets are integrated in probability space and weighted according to analysis of benchmarks and/or expert opinion. For each PFA project, quantitative modeling was accomplished in one or more software programs such as ArcGIS, MATLAB, and MS Excel. Given the variability in data sets available and variability in the geologic settings, these projects provide a wide range of templates that can be adapted to other regions in the world.

The geothermal systems currently producing power in the EARS are associated with volcanic centers in the eastern branch of the EARS (Fig. 1). The eastern branch of the EARS is known to host a number of geothermal systems associated with volcanic centers, many of which have been locally evaluated but not yet developed. It is probable that economic-grade amagmatic resources are also present within the eastern branch (e.g., Basin and Range style fault-hosted resources) and could be considered in future resource assessments. The western branch of the rift is associated with substantially less volcanism relative to the eastern branch. No resources have yet been developed in the wester branch, but initial assessments suggest that both volcanic (e.g., Ngozi, Tanzania; Delvaux et al., 2015) and amagmatic geothermal resources are probably present (e.g., Songwe, Tanzania; Delvaux et al., 2015; Kibiro, Uganda; Mawejje et al., 2015; Fig. 1).

Two PFA studies conducted in the USA that are particularly applicable to the EARS include the Cascade-Aleutian Arc PFA, which focuses on volcano hosted geothermal resources (Shevenell et al. 2015), and the Nevada PFA study in the Great Basin region, which focuses on amagmatic, fault hosted resources (Faulds et. al., 2015). Both of these PFA studies incorporated substantial training data from power productive resources in the respective geologic settings to help establish weights and/or prior probabilities relative to individual datasets. The individual datasets that were used to model heat, permeability, and fluids for each of these two projects are listed in Figure 3. Rationale as to why these datasets were selected and how they relate to heat, permeability, or fluids, respectively, is discussed in the following subsections.

Datasets for Heat

Data inputs for heat fall into two principal categories, direct and indirect. Direct evidence includes measured spring and well temperatures, and spring and gas geochemistry (Faulds et al., 2015; Shevenell et al., 2015). Indirect evidence for heat can come from broad crustal conductive heat-flow models (e.g., Blackwell et al., 2011) or from inference of the potential for upper crustal magmatic heat by identifying and characterizing volcanic centers. For the Nevada PFA project area, there is no known Quaternary upper crustal magmatism and the sole heat input for the study was a conductive thermal model of the temperature at 3 km depth spanning the entire state (Coolbaugh et al., 2005). This thermal model was computed using well temperatures from deep wells that have purely conductive thermal profiles. For the Cascade-Aleutian Arc PFA, there was insufficient data to produce a large conductive thermal model. In contrast to the Nevada PFA project, where all resources are amagmatic, most of the hydrothermal activity within the Cascade and Aleutian Arcs are heated by upper crustal magmatism. In the Cascade-Aleutian Arc PFA study, the probability of heat was modeled by identifying and characterizing late Quaternary volcanic centers (Shevenell et al., 2015).

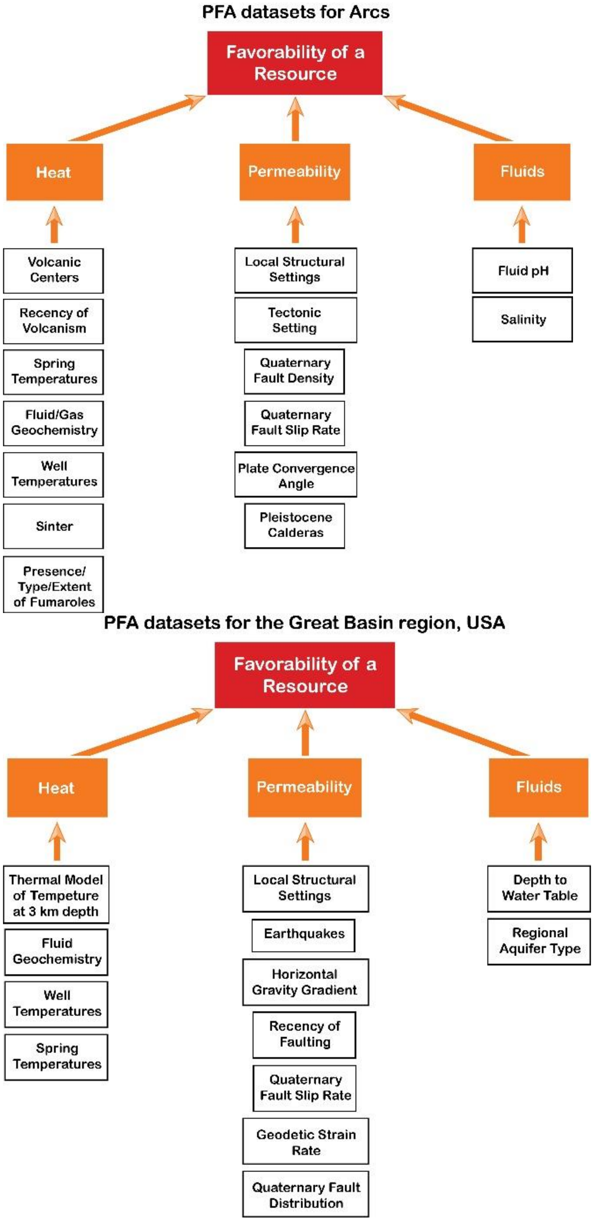

Figure 3. Data inputs for heat, permeability, and fluids for PFA models of Arc settings (left side of figure), and the Great Basin region, USA (right side of figure). Detailed descriptions of these data inputs can be found in Shevenell et al. (2015) for the Arc PFA study and in Faulds et al. (2015) for the Nevada PFA study.

Volcanic centers can be characterized according to many attributes including, but not limited to: age of most recent eruption, composition, erupted volumes, type of edifice, or number and distribution of vents. For age, a cutoff of 0.5 Ma for the most recent eruption was used in the Cascade-Aleutian Arc

PFA study. The availability of heat is linked to the age of volcanism, but it is also related to the volume of magma stored in the upper crust. A small volume of upper crustal intrusion that is only 0.1 Ma old or less might be too cool by present time to drive hydrothermal convection simply because the initial heat input into the crust was too small. For this scale of study a common level cutoff was needed because we do not know exact volumes or depths of magma to run specific heat loss calculations for each volcanic center.

To help select which physical volcanic features were relevant to potential heat flow, training data from 74 power-capable volcanic centers located in arcs globally were analyzed to evaluate each individual physical volcanic characteristic versus MWe of power production (Shevenell et al., 2015; Stelling et al., 2016). The presence of flank fumaroles (versus summit fumaroles) and the size of flank fumarole fields, if known, correlated favorably with power production. The age of the most recent eruption also correlates favorably with power production. Volcanic centers dominated by Pleistocene calderas also correlate more favorably than Holocene calderas, possibly because the volcanic strata have had more time to undergo structural preparation (more fractures and faults). In contrast, the eruptive composition, eruptive style, compositional diversity, composition of the most recent eruption, edifice size, inter-vent features, and flank cinder cones and domes show no significant correlations with MWe production.

Datasets for Permeability

Volcano-hosted geothermal resources are commonly characterized by larger physical reservoir size with greater distributed permeability than fault-hosted amagmatic resources. In part this is due to the reservoir residing in Plio-Pleistocene volcanic rocks with limited fault maturation relative to fault-controlled systems that might be hosted in Miocene or older bedrock, where structures have had a longer amount of time to mature and focus fluid flow. Despite the differences in expression of the reservoirs between volcano-hosted resources and amagmatic fault hosted resources, many of the same structural-tectonic datasets correlate favorably with the magnitude of energy production in each setting.

In both the Cascade-Aleutian Arc PFA project and the Nevada PFA project, local structural settings (e.g., fault terminations or fault step-overs), regional geodetic extensional strain rate models, local geologic strain rates of individual Quaternary faults, recency of faulting on respective faults, active extensional or transtensional strain (versus transpression or compression), all contribute favorably to permeability and power production in the training sets. These patterns are also reported in published literature on permeability patterns in the crust relative to stress, strain, and structures (e.g., Sibson, 1987, 1994; Barton et al., 1995; McGrath and Davison, 1995; Curewitz and Karson, 1997; Townend and Zoback, 2000; Cox et al., 2001; Kim et al., 2004; Rowland and Sibson, 2004; Micklethwaite and Cox, 2004; Micklethwaite, 2009; Hinz et al., 2014; Faulds et al., 2012, 2013; Faulds and Hinz, 2015).

The average MWe/geothermal system generally increases positively with extensional strain rates that have been modeled geodetically, geologically, or both (Faulds et al., 2012; Hinz et al., 2016). For example, most of the faults in the Basin and Range province are accommodating <1 mm/yr, and many accommodate <0.1 mm/yr. The Basin and Range is host to numerous geothermal systems and more than two dozen producing power plants, with installed capacities averaging near 20 MWe and ranging from <1 MWe to about 100 MWe. In the Walker Lane, slip rates on individual faults increase to 1 to 5 mm/yr and geothermal systems (e.g., Coso) can produce 100-300 MWe (Faulds et al., 2012). Furthermore, in association with pull-parts along the San Andreas, where local strands accommodate upwards of 10 to 40 mm/yr, some geothermal systems are capable of producing upwards of 300 to 700 MWe (e.g., Salton Sea, Cerro Prieto, and the Geysers). The 74 power product volcanic centers around the world follow a similar trend between MWe produced and the strain rate on faults. Many of the larger geothermal systems associated with arc volcanic centers are located in pull-aparts or displacement-transfer zones (e.g., Faulds and Hinz, 2015) with relatively high strain rates such as in the Philippines, Sumatra, or West Java, or are in high strain rate intra-arc rifts such as New Zealand, Nicaragua, or Costa Rica (Hinz et al., 2016). The key is that extensional strain is needed. For example, a fast moving purely strike-slip fault will not provide dilatant fractures for convective fluid flow.

Another key correlation is defined by the recency of faulting vs the probability of a commercial resource. Nearly all the commercial-grade resources, both developed and undeveloped in the Great Basin region are associated with faults that have last ruptured in the late Pleistocene or Holocene. Faults that have last ruptured in the middle or early Pleistocene or pre-Quaternary have a much lower probability of a commercial-grade resource (Faulds et al., 2016a).

Datasets for Fluids

Simply put, geothermal power production requires hot steam and/or hot fluids. A primary predictor for fluid availability is the depth to water table, where data are available in any given area. Fluid depth and regional aquifer characteristics also provide key parameters to pair with temperature and geothermometry data for modeling heat. General geochemical characteristics of aquifers and aquifer host rocks can affect geothermometry calculations per a given region (e.g., aquifers residing in carbonate, basalt, or crystalline metamorphic rocks). The rate of conductive heat transfer is much slower in the vadose zone versus the saturated zone, and thus the heat modeling part of PFA is optimized when accounting for well temperature measurements that terminate above versus below the water table.

Analysis, Uncertainty, and Geothermal Potential Maps

Final PFA analysis for both the Cascade-Aleutian Arc and the Nevada projects was accomplished in simulated probability space (Coolbaugh et al., 2015; Faulds et al., 2015; Shevenell et al., 2015). An example of the order of data integration and relative weighting of individual data sets and intermediate composite models is shown for the Nevada PFA project in Figure 4. The Cascade-Aleutian Arc and Nevada projects covered different scales, had different data availability, and focused on two different outputs (Fig. 5). The entire Cascade and Aleutian Arcs cover a very large area with limited consistent coverage of digital GIS data relevant for quantitative analyses. For the Arc PFA study, analysis was accomplished entirely in MS Excel and focused on overall PFA analysis of individual volcanic centers as a whole, such that volcanic centers could be compared directly to each other. For the Nevada PFA study, analysis was accomplished with ArcGIS using raster grid formats. This second method produces a single, final probability grid for the entire study area.

Both the Cascade-Aleutian Arc PFA and the Nevada PFA studies incorporated uncertainty calculations. This is important for multiple reasons, one of which has to do with data density and extent of existing exploration. For example, in an area with numerous deep wells and equilibrated, static, down-hole temperature logs, the uncertainty in the local thermal regime is low. Conversely, in an area with no local spring or well data, the local thermal regime is not well characterized and has a relatively high degree of uncertainty meaning it could be hot, warm, or cool. In the Cascade-Aleutian PFA and Nevada PFA studies, uncertainty was quantified for each individual data set and combined at the end to produce an overall degree of uncertainty in the geothermal potential models. The methods for calculating uncertainty are described in detail in Faulds et al. (2015) and Coolbaugh et al. (2015).

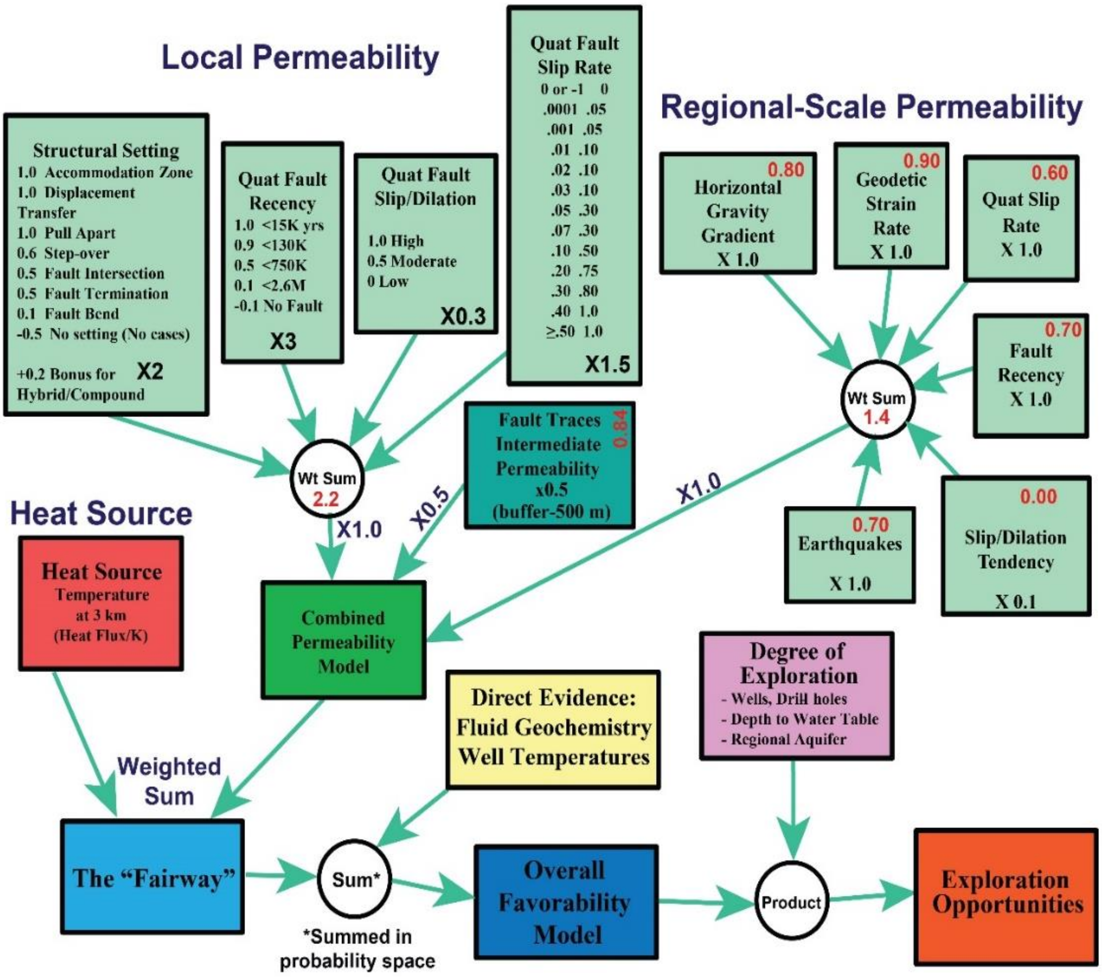

Figure 4. Example of data integration for the Nevada/Great Basin PFA, with sub-categories per parameter and internal weighting of sub-categories and relative weighting between categories. This figure is from Faulds et al. (2015, 2016a), and the methodology and parameters are described in detail in Faulds et al. (2015).

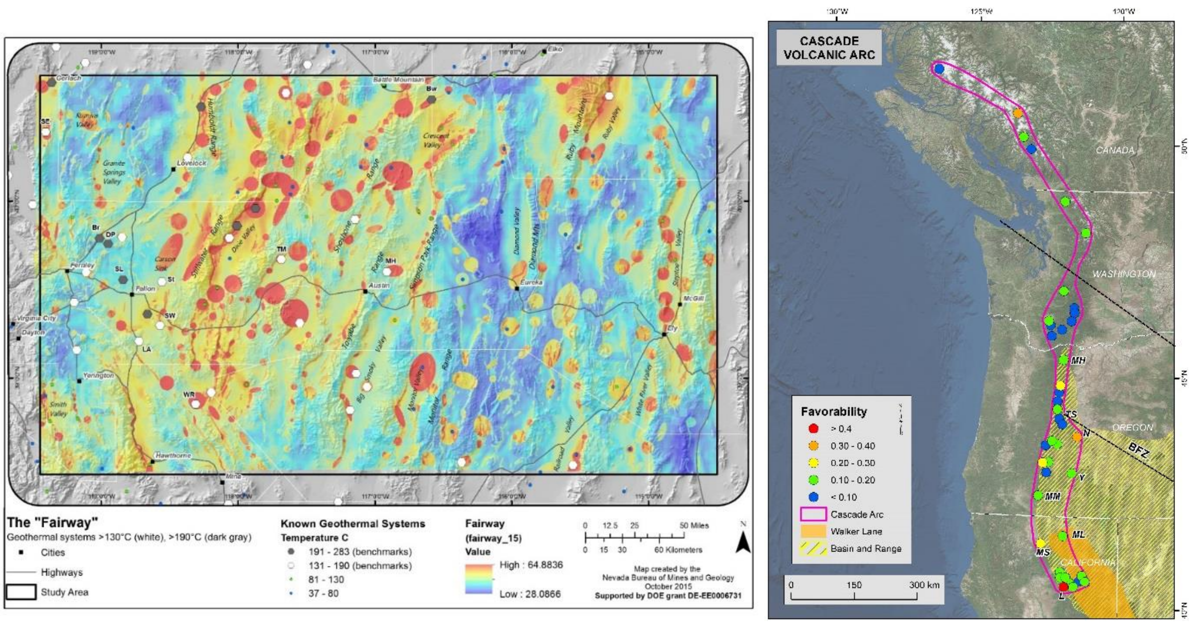

Figure 5. Example of geothermal potential maps from the Nevada/Great Basin PFA study (left, Faulds et al., 2015, 2016a) and the Arc PFA study (right, Shevenell et al., 2015).

3. PLAF FAIRWAY ANALYSIS FOR THE EARS

Many of the data sets used in the Cascade-Aleutian Arc PFA study and the Nevada/Great Basin PFA study are relevant and practical as inputs for a PFA study of the EARS (Figs. 4, 6). For example, most of the Quaternary faults for Ethiopia are publically available as GIS data from Corti et al. (2013). Included with this Quaternary fault database are a population of age-attributed faults for which Corti et al. (2013) have acquired ^{14}C dates on surficial deposits cut by these faults. Many of the faults for Kenya are available for download as a digital data set compiled by Guth and Wood (2013). The Kenya faults are not attributed by age, but ages could be estimated in part using the youngest age of volcanics cut by the faults, and/or with the use of expert opinion of scarp morphology.

Although there are limited GPS geodetic strain data for the EARS, multiple models do exist and could be adapted to make a grid for analysis in GIS. The model by Stamps et al. (2008) provides key modeled velocities at nearly regular points along both the western branch and the eastern branch of the EARS. In this model the eastern branch decreases steadily from ~6 mm/yr in northeastern Ethiopia to ~3 mm/yr at the Ethiopia/Kenya boundary. Strain rates continue decreasing to the south along the Kenya Rift and drop to ~0.1 mm/yr in the north Tanzanian divergence zone (Fig. 1). The modeled extension rate along the western branch of the EARS peaks at about 3 to 4 mm/yr along the central western border of Tanzania and decreases steadily to the north and south along the western branch to ~1.5 mm/yr just prior to the termination.

As with the Cascade-Aleutian Arc PFA projects, volcanic data can be gathered from the Smithsonian global database, as well as from the publically available published journal articles and reports on the geology, volcanology, and geothermal resources of the EARS. Data may also be acquired through the ARGeo AGID database (The UNEP ARGeo Geothermal Inventory Database System, http://agid.theargeo.org/index.php#), the GRMF database http://www.grmf-eastafrica.org/gis, or with national geologic surveys.

One additional key characteristic that could be incorporated in an EARS PFA study is the current evolutionary stage of rifting for each rift segment of the western and eastern branches. As endmembers, these are mechanical or magmatic (e.g., Morley, 1988; Ebinger and Casey, 2001; Keir et al., 2010). During the initial tectonic stage of rifting, strain is concentrated along border faults bounding the rift segments and control the evolution of detachment faults (e.g., Lake Malawi). In the early stages of rifting, asthenospheric upwelling and upper crustal magmatism is spatially and temporally limited relative to the more evolved magmatic rift stage. Magmatic rift segments are narrow and focused along the axes of the overall rifts relative to the border faults, and have been shown to accommodate >80% of the extension in a given rift segment (Bilham et al., 1999). Magmatic rifting involves more upwelling of asthenosphere (e.g., Bonavia et al., 1995), which in turn helps drive increased melt production and upper crustal magmatism. The axial dike intrusion along with focused axial faulting accommodate the upper crustal extension in these rift segments. Key takeaways from evaluating the stage of rifting for PFA studies is that magmatic rift segments have overall greater heat flow than tectonic rift segments, and extensional strain is focused along the rift axes rather than the border faults. The distribution of Quaternary magmatic provinces could be pulled directly from publically available literature such as Keir et al. (2011). Furthermore, analogs for evaluating geothermal potential with magmatic rifting in Iceland could also be integrated in a PFA study of the EARS (e.g., Siler et al., 2015).

Finally, Play Fairway Analysis of the EARS could take many forms. It could involve only volcanic centers, similar to the Cascade-Aleutian PFA study, or alternatively could be done on a grid format as with the Nevada PFA (Fig. 5). Both studies are regional in scale and do not substitute for the local detailed studies of individual geothermal resources that are necessary for developing property-scale conceptual models and selecting specific well targets (e.g. Cumming et al., 2016). However, the regional PFA study can help identify broad regions as well as individual geothermal fields of under-developed geothermal potential (e.g., Faulds et al., 2016b), provide general estimates for potential ranges of resource capacities, and streamline local exploration and development.

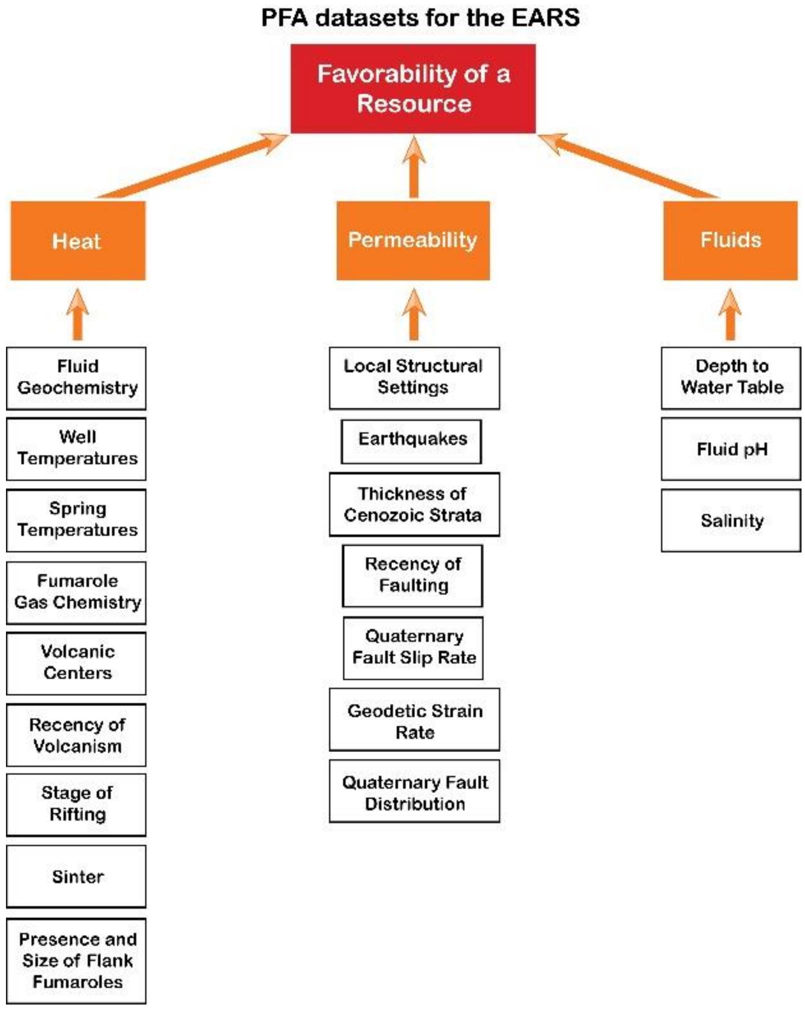

Figure 6. Potential data sets relevant to heat, permeability, and fluids within the EARS.

4. CONCLUSIONS

There is a large potential for growth in the energy sector in Sub-Saharan Africa, and the EARS has huge potential for geothermal energy development. For comparison, based on data published in 2011, the North African countries, including Egypt, Tunisia, Algeria, Libya, and Morocco collectively use 52 GWe spread across a population of ~170 million with a per-capita consumption of 1,120 kWh. The country of South Africa alone uses 44 GWe, and with a population of ~50 million has a per-capita consumption of 5,350 kWh. In contrast, Sub-Sahara Africa, with >50 countries collectively uses only 33 GWe spread across a population of ~790 million with a per-capita consumption of only 140 kWh (IEA, 2011). Play Fairway Analysis of the entire EARS, or individual branches, or at country-wide levels could help guide exploration and reduce risk, thereby potentially increasing the leverage of funding for exploration and development. Furthermore, regional assessments can identify key patterns in resource characteristics inherent to a given region such as average resource size, cap development and/or preservation, or presence/absence of surface manifestations. This would facilitate the creation of a catalogue of amagmatic vs magmatic and/or blind vs not blind geothermal play types customized for the EARS (e.g., Moeck and Beardsmore, 2014; Hinz et al., 2016), which would recognize different stages of rift evolution and current volcano-tectonic characteristics.

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