PROCEEDINGS, 41st Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 22-24, 2016
SGP-TR-209

Hawaii Play Fairway Analysis: Discussion of Phase 1 Results

Nicole Lautze, Donald Thomas, Nicholas Hinz, Garrett Apuzen-Ito, Neil Frazer, David Waller

1680 East West Road, Honolulu, Hawaii 96822

lautze@hawaii.edu

Keywords: Hawaii, play fairway, modeling, probability

ABSTRACT

Phase 1 of a Department of Energy funded project to assess the probability of geothermal resource potential across the State of Hawaii was recently completed. This project: (1) compiled all legacy and current geological, geophysical, and geochemical data relevant to Hawaii's geothermal resource; (2) analyzed and ranked these datasets in terms of their relevance to geothermal heat, fluid, and permeability; (3) developed and applied a Bayesian statistical method to incorporate the ranks and produce probability models that map out Hawaii's geothermal resource potential; (4) developed a method to assess confidence in the probability values; and (5) assessed what we term development viability in areas of interest across the state. Here, we summarize the project methodology and present maps that highlight both relatively high prospect areas as well as areas that lack enough data (low confidence) to make an adequate assessment. This presentation will: discuss the rationale for using the datasets incorporated in the Hawaii play fairway analysis; show how the probability modeling can be adapted to other regions and other types of resources; and suggest a path for future exploration activities in Hawaii.

1. INTRODUCTION

Hawaii is an ocean island hotspot environment in which subsurface magma is the source of geothermal heat. The hotspot currently underlies the eastern portion of Hawaii Island (the Big Island), including the active shield volcanoes Mauna Loa and Kilauea. The age of volcanic activity in the state generally increases to the northwest, such that Kauai is the oldest of the main Hawaiian Islands. Each island is composed of one or more shield volcanoes. Typically each Hawaiian shield volcano exhibits four stages in a complete life cycle: a) pre-shield, b) shield building, c) post-shield, and d) rejuvenation. Across the state, there are volcanoes currently in each stage: the submarine offshore Loihi is in the pre-shield stage; Kilauea and Mauna Loa on Hawaii Island are in the shield building stage; Hualalai on Hawaii Island and Haleakala on Maui are in the post-shield stage; and several volcanoes can be considered to be in the rejuvenation stage. Direct evidence (e.g. well temperature) of thermal anomalies have been identified across most of the islands (Thomas et al., 1979; Thomas, 1985) indicating that all stages of volcanism may contribute geothermal heat to the upper crust.

Currently Hawaii has one producing geothermal system, the Puna Geothermal Venture (PGV) operated by Ormat Technologies, Inc. PGV is located along the SE rift zone of Kilauea volcano, and produces 38 MWe from >300 ℃ fluids at depths of up to 2.5 km. Outside of PGV and the Puna area, there are very few deep (~2 km) wells throughout Hawaii. Thus, from a geothermal perspective, the remainder of Hawaii is largely unexplored. Even still, from the few deep wells that do exist, it is clear that there is a high contrast between areas with recent hot intrusions and the established background geothermal gradient of ~18℃/km. This makes it such that targeting heat is one of the key elements in the Hawaii play fairway analysis.

Another important characteristic of geothermal resources in Hawaii is that they are largely blind. Surface manifestations are nearly hidden at PGV where upflow and outflow is diffuse > 1km depth through lavas that have high lateral permeability. There are some coastal warm springs down-gradient of the PGV area, and very mild warm vapor discharge from some of the deep pit craters within the area, however all other resources are blind. Given these facts, play fairway analysis provides an effective, low-risk exploration strategy that is needed in Hawaii.

2. PROJECT METHODOLOGY

Figure 1 is a flowchart that shows the overall project methodology. The Department of Energy's play fairway request for proposals defined the critical qualities of a geothermal play as Heat, Fluid and Permeability. Figure 1 depicts the key steps used by the Hawaii play fairway team. The method is general enough to be applied to any geologic setting; what makes the application relevant to a particular location is the choice and interpretations of the data types used.

This paper broadly explains the utility and the ranking of datasets used in the Hawaii specific play fairway analysis i.e. the steps above "Process Data" in Figure 1. The statistical methodology, i.e. "Process Data" through "Compute Joint Probability" is touched upon in section 4, with details in a separate paper (Ito et al., in prep).

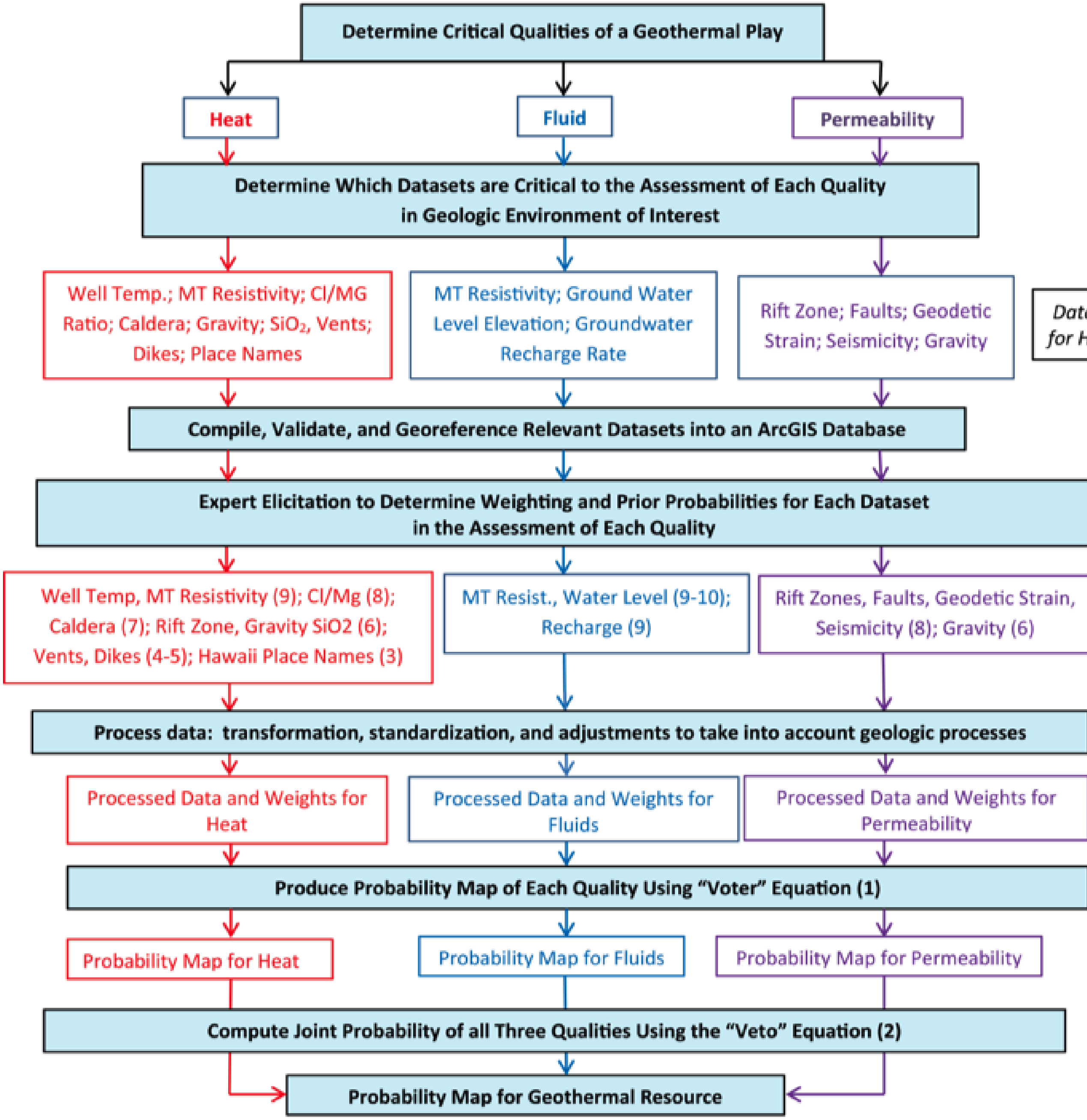

Figure 1. Flowchart showing overall project methodology applied to the assessment of a geothermal resource. The filled boxes denote computational and/or decision-making steps, whereas the unfilled boxes represent the products of those computations/decisions. Note that the datasets listed and their relative rankings are the only aspect of the methodology that is specific to Hawaii.

3. HAWAII GEOTHERMAL DATASETS

The datasets of relevance to geothermal heat (H), fluid (F), and permeability (P) in Hawaii are directly linked to Hawaii's ocean island, hotspot magma setting**.** Those used in our analysis are shown in Figure 2, and grouped into 3 main data types: Surface Geology (brown) Geophysics (red), and Groundwater (blue). Here, we discuss how each of these dataset groups relates to H, F, and P within Hawaii's unique geologic setting, including the relative rankings shown in parenthesis in Figure 2.

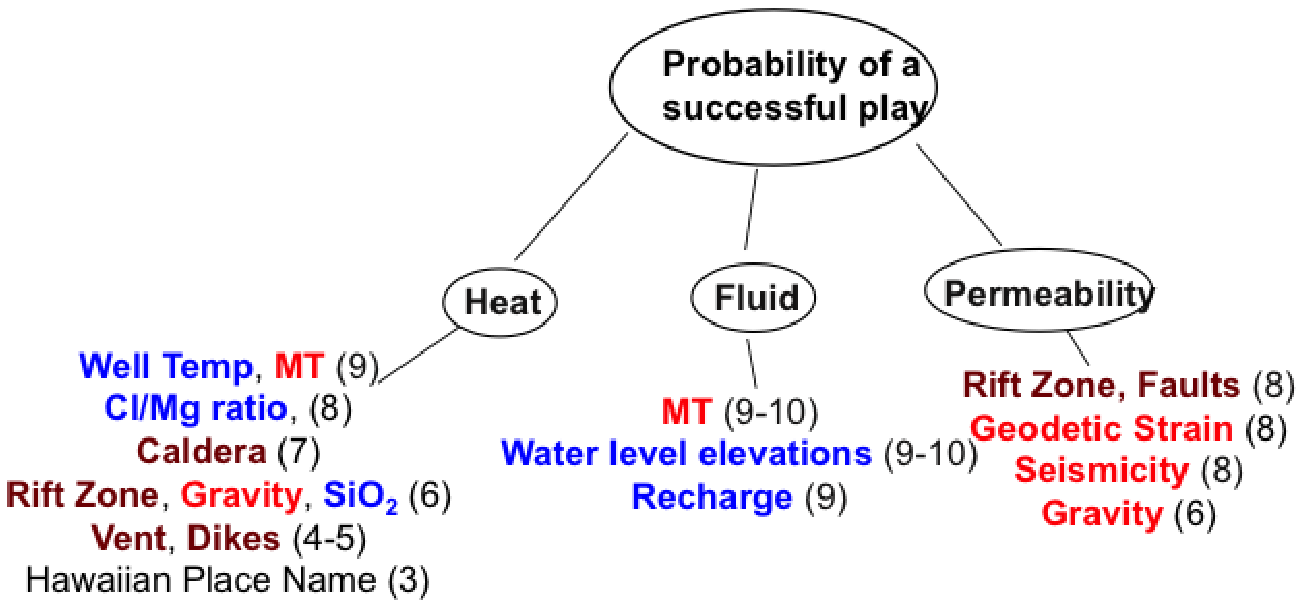

Figure 2. The data types used in the probability modeling to indicate geothermal Heat, Fluid, and Permeability. The numbers in parentheses indicate the relative ranking of importance from 1 (low) to 10 (high). Data types are color coded: brown for surface geologic features; red for geophysical data; and blue for groundwater data.

3.1 Hawaii Datasets relevant to Heat

3.1.1 Surface Geologic Data: Caldera, Rift Zone, Vent, Dike

Because a successful geothermal play in Hawaii requires heat derived entirely from magma injected below the ground surface, a geothermal system requires subsurface intrusive activity. As described above, intrusive activity plays an important role in the geologic environments, including the **calderas** of each volcanic system, the elongate **rift zones** that extend out from those calderas, and individual **vents** either on or remote from a caldera or rift. As for the relative "importance" of these mapped features, calderas are thought serve as the locus of the most persistent deposition of subsurface heat over a volcano's active life. Rift zones are slightly less so because changes in the stress regime on an island (e.g. due to growth of sister volcano) can affect them. Furthermore, because of their aspect ratio, rift zones are thought to lose heat more rapidly than caldera systems. Likewise, not associated with a caldera or rift, individual vents are thought to be associated with significantly less subsurface heat due to their activity's ephemeral nature. Thus, we gave a lesser weight to individual vents in our analysis.

3.1.2 Geophysical Data: Resistivity, Gravity

Gravity surveys are useful for identifying dense subsurface rocks. They have been used successfully to map the extent and distribution of rift zones and summit dike complexes. A recently published reanalysis of Hawaii's gravity data (Flinders et al., 2013) has identified potential dike complexes that were previously unrecognized and show no surface manifestation. A groundwater exploratory drilling program coincidentally confirmed the presence of a higher–than-expected dike density in one such location – which also demonstrated significant thermal activity (*Thomas et al.,* 2014). Hence, gravity data invaluably supplement the surface geologic mapping and indicate intrusive activity not evident at the surface.

3.1.3 Groundwater Data: Well Temperature, Cl/Mg ratio, SiO_2

Elevated **groundwater** temperature (relative to mean annual air temperatures) is a direct indicator of a near-by heat source. Hawaii's rocks contain relatively high shallow hydraulic conductivity, and high rainfall recharge is present over many areas of interest in Hawaii. Hence, elevated temperatures in shallow groundwater wells are considered somewhat "conservative" because thermal fluids discharged into the shallow groundwater table have a high likelihood of being heavily diluted by the time a shallow groundwater well intercepts them. Therefore, deeper higher temperatures serve as the gold standard for demonstrating a heat source.

Less reliable, but still valuable, are the **groundwater chemical variations** associated with discharge of thermal fluids. Because of Hawaii's proximity to the ocean, all of Hawaii's groundwater has sea-salt contamination either through mixing with the underlying seawater or as a result of sea-salt aerosol deposition on the land that seeps into the groundwater system. It has been shown that chloride ion concentrations are relatively stable, but the magnesium ion is extremely sensitive to removal by geothermal processes. Hence, a **Cl/Mg** ratio that is substantially higher than that of seawater strongly suggests Mg depletion within a hydrothermal system. In Hawaii's one known geothermal system (in Lower Puna) hydrothermal activity extensively mixes underlying thermal saline water with shallow groundwaters, and most wells in that district have elevated Cl/Mg values. Hence, this chemical signature in shallow groundwaters can a nearby heat source with minimal ambiguity.

Due to its temperature-dependent solubility, elevated **silica** concentrations have served as a widely used indicator for thermal fluid mixing into groundwaters worldwide, including Hawaii. However, we could not as heavily rely on this thermal tracer for the Cl/Mg ratios for two reasons. First, the dilution of thermal water with shallow groundwater has a greater effect on the silica concentrations than on the Cl/Mg ratios. Second, groundwater silica values have been found to be affected by the use of agricultural irrigation, which, on its return to the groundwater table, raises silica concentrations into the range of values seen for thermally affected groundwater. One potential manner by which to account for the affect of irrigation is to identify anomalous silica values within individual watersheds.

3.1.4 Other: Hawaiian Place Names

Finally, we recognized the much longer term of Polynesian occupancy of Hawaii than of western residency and the Native Hawaiian practice of integrating historical and descriptive information into Hawaiian place names and oral histories. Therefore, we conducted a survey of traditional Hawaiian place names throughout the state to determine whether they indicated past thermal volcanic activity not recorded in the more modern datasets. This dataset is weighted lowest because many of the descriptive references are allegorical in nature; hence, a given place name could be a reference to any natural condition at that place (e.g. hot climate or hot water/rock).

3.2 Hawaii Datasets relevant to Fluid

3.2.1 Geophysical Data: Resistivity

Electrical resistivity of the crust serves as a sensitive indicator of the fluids' presence in subsurface formations. In Hawaii, dry basalts have resistivities in the range of 20,000 ohm-m and higher, whereas freshwater saturated basalts have resistivities that are more than an order of magnitude lower. Where we have contemporaneous resistivity and temperature data, in the Humu'ula Saddle region, we found that resisitivities of thermal fluids can be another order of magnitude lower than that for rocks saturated with ambient freshwater. Hence, data on resistivity distributions within thermal prospects that can reliably indicate that formation's state of saturation.

3.2.2 Groundwater Data: Water table height, Recharge

Groundwater Elevations: Our general concept for Hawaii's geothermal systems is that they are not confined by clay caps. This is based on observations made in the Puna geothermal wells, where temperatures almost always conform to the boiling point with depth (or hydrostatic head) relationship, as well as in recognition of the generally high permeability of Hawaii's basalts. Hence, if significant elevations of fresh groundwater exist above a geothermal prospect, then most likely, the presence of permeability in the resource zone will indicate the presence of water. For resources below sea level, we can likewise assume that the presence of formation permeability will indicate fluid in the geothermal reservoir. This characteristic is particularly important where we have prospects occurring at high elevations such as the Humu'ula Saddle region of Hawaii Island. At this location, high groundwater elevations allow us to infer that fluids are present in the inferred prospect at accessible depths.

***Groundwater Recharge Rates**:* Groundwater recharge rates are typically associated with a higher subsurface freshwater head. Hence, their relationship of recharge to fluid availability within the geothermal reservoir is similar to that for groundwater elevations.

3.3 Hawaii Datasets relevant to Permeability

The distribution of subsurface permeability within the islands at geothermal reservoir depths is not well documented. Very few deep test holes have been drilled into the islands outside of the Puna geothermal field. The Hawaii Scientific Drilling Project drilled a 3.5 km-deep research hole into the near-shore flank of Mauna Kea; that borehole showed that subaerial basalts maintained their porosity and permeability to at least 1 km depth. The Humu'ula Saddle boreholes, extending to depths of 1.5 and 1.7 km, show moderate compaction of subaerial lava flows at their total depths. We have few-to-no data on how compaction is expressed in the older volcanic systems.

Given the absence of ground truth data outside of Puna we have elected to rely on four data sets to provide guidance on the likelihood of finding deep permeable formations:

3.3.1 Surface Geologic Data: Rift Zone, Faults

In continental environments, **Faults** are zones of crustal fracturing and, therefore, associated with elevated permeability. In Hawaii, faulting mostly, if not entirely, associated with stresses developed within the island mass rather than in association with the underlying crustal plate. The most intensively faulted regions of Hawaii are associated with volcanic **rift zones** (which are extensional settings), in areas of flank subsidence, above dikes, and/or in response to changing topographic stresses (e.g., as a volcano is constructed or eroded). Fault systems are also associated with mass wasting events where sea-ward flanks of the volcanic edifice become mobile and sporadically fail (e.g. the Hilina fault system).

3.3.2 Geophysical Data: Geodetic Strain, Seismicity, Gravity

Geodetic Strain: GPS geodetic strain measurements can be used to model both the dilatational and shear components of active strain. Crustal permeability correlates strongly with extensional strain. Hawaii Island has an extensive GPS network for monitoring ground motion associated with magma intrusion into its active volcanoes and provides us with insights into the distribution of deformation rates over much of the island. Less extensive coverage is available for the older islands.

Seismicity: In volcanic environments, earthquakes result from active tectonic deformation and/or dike intrusion. The active deformation may indicate elevated permeability either through fracturing around dikes or through faulting. Hawaii Island hosts one of the densest seismic networks in the United States and an abundant data resource is available from that network that dates back to the early days of the founding of the Hawaiian Volcano Observatory. The older islands have substantially less coverage but extensive seismic data sets are available for them as well.

***Gravity*:** Because dikes are denser than surface lava flows, in Hawaii, high gravity implies dike intrusion (elevated heat) and, because an intrusion must break existing rock, there is an elevated probability of permeability forming around the intrusion. Furthermore, the horizontal stresses arising from dike intrusions can reasonably be expected to express themselves in seismicity and readjustment of the stress field surrounding the intrusion. Finally, regions of elevated gravity are thought to be associated with higher rates of subsidence (i.e. differential rates of subsidence beneath rift zones and calderas) and crustal deformation; these processes may also be associated with elevated levels of faulting.

4. OVERVIEW OF PROBABILITY AND CONFIDENCE CALCULATIONS

The first building block of our method of estimating probability is generalized linear model (e.g., *McCullagh and Nelder*, 1983) in which the influence of each data type is weighted and summed in the logistic link function,

$$\Pr(\mathbf{x}) = \left[1 + \exp\left(-w_0 - \sum_i w_i z_i(\mathbf{x})\right)\right]^{-1}. \tag{1}$$

Here Pr(**x**) is the probability of one of the qualities (elevated heat *H*, permeability *P*, fluid *F*) at location **x** on the map; $z_i(\mathbf{x})$ is the standardized form of data type *i* at that location; and w_i is weight that reflect the relative importance and meaning of data type *i*. This equation also includes a reference probability, or prior probability $\Pr_0$. This is the probability in the absence of data and is recovered when w_0 is the only term in the exponent.

We refer to Eq (1) as the "voter equation" because it allows each data type to influence the outcome (positively or negatively) depending on its weight w_i. For example, suppose z_1 represents the gravity anomaly at location **x** and z_2 represents a measure of electrical resistivity beneath the ground at **x**. Because high positive values of gravity are interpreted as indicating dense intrusive source rock the associated weight w_1 will be positive. In contrast, unusually low resistivity is associated with hot rock and therefore w_2 will be negative. Thus, a large positive value of $\Sigma = w_0 + w_1 z_1 + w_2 z_2$ indicates a high favorability of elevated heat. Clearly as more (positive) data types contribute to the sum, the sum increases monotonically. But if, for example, there are five strong positive indications of elevated heat from five different data types, then adding a sixth positive data type does not provide much more new information. This aspect is taken into account with the logistic link function, $\Pr = \text{expit}(\Sigma) = e^{\Sigma} / [1 + e^{\Sigma}] = [1 + e^{-\Sigma}]^{-1}$, which spans 0 to 1 as does a true probability. If in another location Σ is large and negative, the probability of heat will be small and close to zero. If in yet another location there are no data, the data votes will be zero, but the probability will not be; it will equal the prior probability $\Pr_0 = \text{expit}(w_0) = [1 + e^{-w_0}]^{-1}$. The probabilities of elevated permeability and fluid are computed in the same way.

With the probabilities of all three qualities computed ($\Pr_H, \Pr_P, \Pr_F$) the probability of a viable resource, Pr_R, is the joint probability of all three qualities,

$$\Pr_R(\mathbf{x}) = \Pr_H(\mathbf{x}) \Pr_P(\mathbf{x}) \Pr_F(\mathbf{x}) \tag{2}$$

This equation is based on the second building block of our method: a conditional independence assumption that has demonstrated robustness in Bayesian learning as well as strength in its simplicity and generality (e.g., *Domingos and Pazzani*, 1997). We refer to Eq. (2) as the "veto equation" because the absence of any one quality will indicate the absence of a viable resource.

Figure 3 shows the results of Eq. 1 (a-c) and Eq. 2 (d) for Hawaii Island.

We account for confidence (C) in the calculated probability such that, $0 \le C \le 1$ increases with the number of different types of data and their quality,

$$C = \text{expit}(w_0 + w'_1 q_1 + w'_2 q_2 + \ldots w'_n q_n) \tag{3}$$

Here, the quality for data type *i* is quantified as $0 \le q_i \le 1$, with $q_i = 0$ when data are absent. For example, the association of residual gravity anomaly with dense intrusive rocks is straightforward and well established, so the data quality is estimated at $q_1 = 0.75$. In contrast, approximating z_2 for Cl/Mg as being uniform along groundwater flow paths leads to a poorer quality of $q_2 = 0.25$. The quality factors are weighted according to modified weights, $w'_i = n w_i Z^*_i / (w_1 Z^*_1 + w_2 Z^*_2 + \ldots w_n Z^*_n)$, where Z^*_i is the standardized form of the "promising" data value D^*_i used during expert elicitation. Thus, each probability computed by our method has an associated confidence. For example, if a given location has many types of high quality data, and none of those data types suggest a resource, the probability of a resource at that location will be small, but our confidence in that probability will be high.

Figure 4 shows the results of the confidence calculation for Hawaii Island.

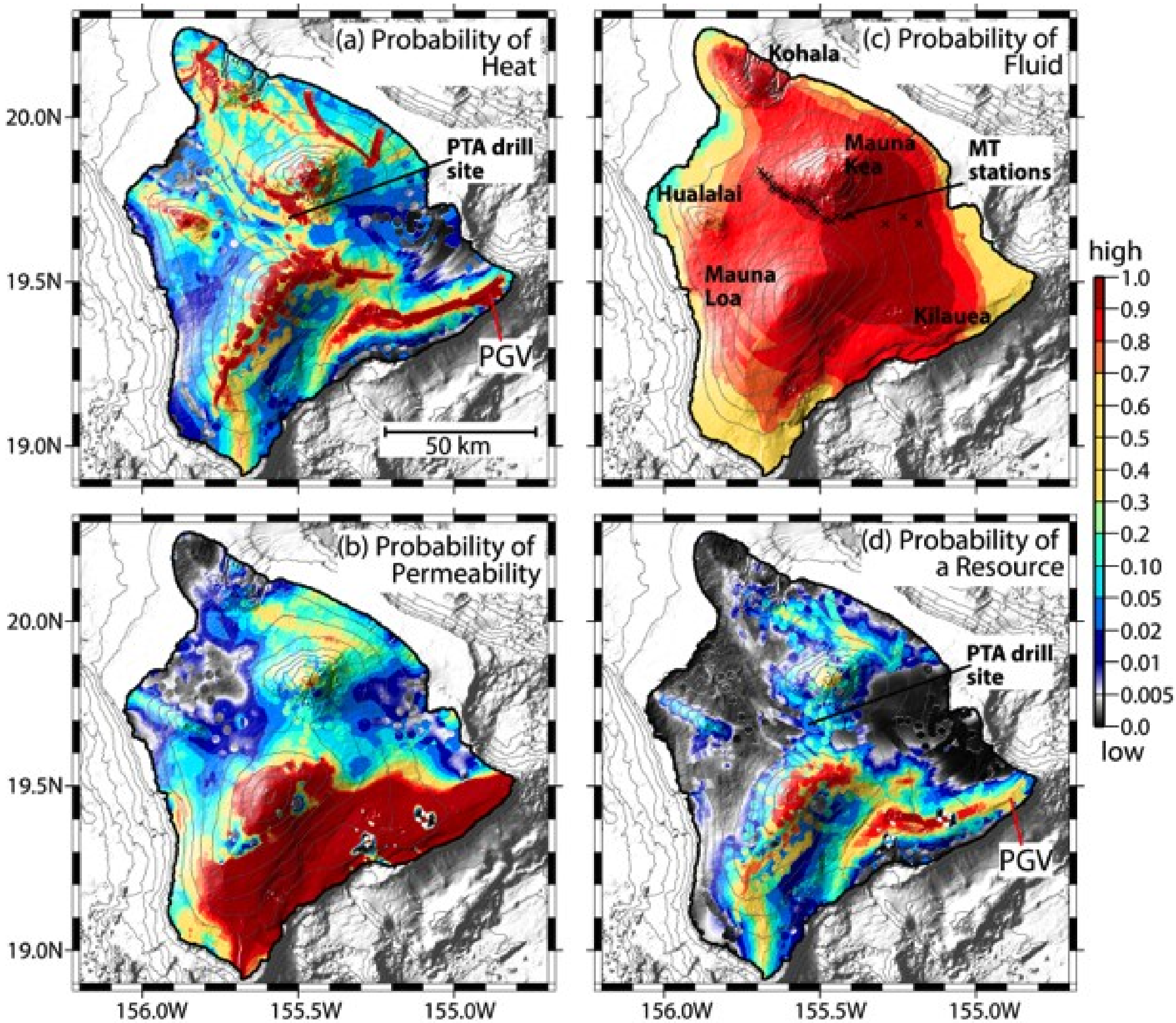

Figure 3. Results for the Island of Hawaii. Probability of (a) heat (b) permeability and (c) fluid. (d) The product of the former probability fields, using the veto equation (2), yields the joint probability of all three qualities, or the probability of a resource.

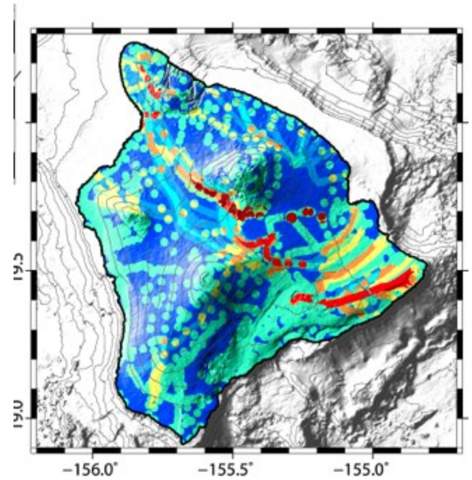

Figure 4. Confidence in the calculations of the probability of a resource for Hawaii Island.

5. ROADMAP FOR PHASE 2 ACTIVITIES

Using the results of the probability and confidence modeling, together with considerations of the viability of development (Lautze et al., in prep.), we identified four main activities for Phase 2. (1) *Groundwater*. We will sample and analyze water sources in key locations across the state to validate groundwater indications of geothermal activity and improve groundwater flow models. This will enable us to better constrain our resource probabilities and increase our overall level of confidence in the play rankings. (2) *Stress Modeling*. We will produce 3-D models of topographically-influenced crustal stresses in order to better assess deep permeability structure across the state. These models will help us rank plays according to their potential for developing a reliable geothermal fluid supply. (3) *Geophysics*. MT/AMT and gravity surveys are proposed in areas where other data types show favorable characteristics for heat, and in locations where already available geophysical data suggest that a resource is likely but the data are inconclusive. (4) *2-D and 3-D Mapping*. All new and existing data will be integrated into 2- and new 3-D probability maps therein updating and improving the Phase 1 play fairway analysis.

6. CONCLUSION

Phase 1 of the Hawaii Play Fairway project compiled and integrated existing data to produce the first statewide assessment of geothermal resources since 1985. Our main accomplishments were to: 1) identify, obtain, and rank all legacy and current geologic, geochemical, and geophysical data relevant to the geothermal qualities of heat (H), permeability (P), and fluid (F) across the state; 2) develop a method for using diverse data types to produce probability as well as confidence maps of geothermal resources; 3) apply the method to Hawaii; and 4) identify prospective targets with quantified risk to pursue exploration in Phase 2. Phase 2 activities will include groundwater and geophysical surveys, modeling of topographic stresses, and improved 2-D as well as 3-D mapping.

REFERENCES

Flinders, A.F., Ito, G., Garcia, M.O., Sinton, J.M., Kauahikaua, J.P., and Taylor, B., 2013, Intrusive dike complexes, cumulate cores, and the extrusive growth of Hawaiian volcanoes: *Geophysical Research Letters*, v. 40, p. 3367–3373, doi:10.1002/grl.50633.

Thomas, D.M., 1985, Geothermal resources assessment in Hawaii: Final report: *Hawaii Institute of Geophysics Technical Report HIG-85-2*, 115 p.

Thomas, D.M., Cox, M.E., Erlandson, D., and Kajiwara, L., 1979, Potential geothermal resources in Hawaii: A preliminary regional survey: *Hawaii Institute of Geophysics Technical Report HIG-79-4*, 185 p., http://hdl.handle.net/10125/20122 (accessed October 2015).