Integration of Data in a Play Fairway Analysis of Geothermal Potential Across the State of Hawaii

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ABSTRACT

The execution of this project can be divided into three main tasks: (1) the compilation of both historical and current geologic, geophysical, and geochemical data for Hawaii that is relevant to geothermal resources into a single Geographic Information System (GIS) project; (2) the systematic analysis and ranking of these datasets in terms of their relevance to the three primary properties of a viable geothermal resource: heat (H), fluid (F), and permeability (P); (3) the application of geostatistical methods to the ranked data to produce Play Fairway (PF) maps for Hawaii's. Here, we summarize the project methodology and present preliminary maps that highlight both high prospect areas as well as areas that lack enough data to make an adequate assessment. We suggest a path for future exploration activities in Hawaii, and discuss how this method of analysis can be adapted to other regions and other types of resources.

Introduction

Hawaii offers the opportunity to gain knowledge and develop geothermal energy on the only oceanic hotspot in the U.S. As a remote island state, Hawaii is more dependent on imported fossil fuel than any other state in the U.S., and energy prices are 3 to 4 times higher than the national average (Hawaii State Energy Office, 2013). The only known resource, located in Puna (on Hawaii Island's active Kilauea volcano), is a region of high geologic risk; other regions of probable resource exist but lack adequate assessment.

The last comprehensive statewide geothermal assessment occurred in 1983 and found a potential resource on all islands (Hawaii Institute of Geophysics, 1983). Since then a substantial volume of new geochemical, geological, and geophysical data have been gathered. A high density of surface/structural geology (e.g. Sherrod et al., 2007), water well (temperature and chemistry) and gravity (e.g. Flinders et al., 2013) data and analyses are available across the state. These, along with more site-specific magnetotelluric (MT; e.g. Pierce and Thomas, 2009), seismic (e.g. Matoza et al., 2013), and geodetic data were integrated into our PF analysis for Hawaii.

Our initial goal was to identify and compile these diverse datasets into a single GIS project. Each dataset was assessed for its quality, reliability, and relevance to one or more critical properties of a viable geothermal resource. The PF analysis was performed using the combined datasets to develop internally-consistent maps of geothermal prospects statewide (in Hawaii, nearly all of which qualify as "blind", with no active surface manifestations), and a gap analysis was conducted to assess which data types can most cost- effectively improve the reliability of our inferences regarding each prospect. Hence the intended products of this effort consist of: state-wide resource potential maps; guidance on the next steps to validate one or more of the resource(s); and a structured, novel method for formally assessing geothermal resources that can be adapted to other geologic settings.

Methods - Conceptual Framework

PF analysis can be characterized generally as an effort to formally assess where and how an exploration program should be deployed to maximize the probability of positive return on expenditures. Return can be characterized as dependent on three primary properties of heat, fluid, and permeability, however in our conceptual framework we expand this to consider five properties: the presence of a heat source (HS); the temperature of the resource (T); the ease with which heat can be extracted (permeability P and fluid availability F); the scale of the heat source (S); and its geometric (G) configuration (depth and aspect ratio). Geological, geophysical, and geochemical data types measure specific attributes of these five properties. Table 1 lists a subset of "data types" relevant to volcanically hosted geothermal systems (column 1) with the "property" to which it most pertains (column 2). The most significant or useful information each data type can provide about one or more properties, as well as other potential but less relevant information, is given in column 3 ("Information Re- turned"). However, most of the data types listed are subject to uncertainties as to the true origin of the measured signals. Consequently, the reliability of each data type for identifying the primary property(s) is conditional upon specific circumstances of its location or other geologic information (column 4; "Reliability and Weighting Conditional on"). Also, in many cases the information required to quantify the reliability of an inference is poorly known, unknown, or unknowable (non-uniqueness). Hence, we are also incorporating "Uncertainties and Ambiguities" in development of quantitative probabilities. Expert knowledge about these conditions, uncertainties, and ambiguities controls how significantly the attributes derived from the data influence the final estimates of probability of the 5 properties considered (H, T, P&F, S and G).

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Data Type	Property ¹	Information Returned ⁴	Reliability & Weighting Conditional on:	Ambiguities or Uncertainties
Volcanic structures				
Vents, Rift systems, dike systems	t, HS,s,g	Pa intrusion	Age, duration, source, depth dist.	How well is age & dist. known
Fracture systems				
Faults, grabens, dilational fracture	P, s, g	Pa/C P/HS	Tectonic/volcanic; age	Age, extent, fault expression
LIDAR (lineaments)	P, s, g	Pa Faults/Perm.	Relevance to heat source	Source of features
Mineral deposits				
Sinter, exposed fracture fill	HS, t, f, p, s	Pa/C T, P	Age; extent; present at all?	Age/Duration/preservation/ scale
Soil geochemistry	HS, f, s	Pa Hydroth.	Age; extent; duration	Age and duration; preservation
Geophysical Data				
Resistivity surveys				
AMT, TDEM (shallow); MT	T, P, F, s, g	C TDS/T/Alt; Pa Alt.	penetration; uniqueness; noise	gw salinity; alteration; ash
Seismic				
Macro seismic data	P, s, g	C Perm. Prod.	Distribution; duration and	Threshold sensitivity
Micro seismic data	t, P, f, s, g	C P/active hydroth.	Distribution	Threshold sensitivity
Gravity surveys (Intrusives, rifting)	HS, S, G	C/Pa HS	Age; age distribution; depth	Data limitations; adequacy of model
Heat flow/temp. gradient	T, s, g	C HS	Hydrol. effects; climatic effects; depth	Depth of heat source
SP	t, P, F, s	C P; implied hydroth	GW effects; depth of sensitivity	subsurface hydrology
Multi-spectral (mineralogy/bio)	HS, p, f	C/Pa hydroth.	Hydrol. conditions; non-uniqueness	Age and relevance
Geodetic INSAR	T, P, S, g	C T/P/S/G	Relevance to heat source	Overall relevance to deformation
GPS geodesy (active deformation	t, hs, P, s, g	C. Perm/Scale/	Whether related to heat source	Magnitude and history of feature
Hydro Geochemical				
Spring/Well Temperatures	T, P, s	C hydroth.	Mag. of anomaly; hydrologic cond.	QC of data; hyd. cond.; recharge
GW Chem: Silica, Cation Geotherm.	T, f, p, s	C Hydroth.	Hydrol. Proc.; re-equilibration; contam.	Deg. of contamination; hydro. proc.
Tracers (Rn, CO ₂ , SO ₄ , He, etc.)	HS, P, f, s	Pa/C Hydroth.	SW cont.; chemical variation of lavas;	Sources of tracers
Qual. geotherm. (Cl/Mg ratios)	T, p, f, s	C Hydroth.	Seawater contamination	Ssources of chemical
				cont./alteration
lsotopic tracers ($\delta^{18}O, {}^{14}C$)	T, p, f	C Hydroth.	Natural variability locally;	Uncertainty of hydrologic flow
				paths
Soil Gas Tracers (Rn, CO ₂ , He, etc.)	P, f	C Hydroth./P	Scale to anomaly; non-uniqueness	Dynamics of soil gas transport
Other				
Botanical	hs, f, s	C/Pa Hydroth.	Non-uniqueness; "visibility"	
Traditional/cultural/historical	hs, s	Pa Hydroth.	Imputed age of observations	Fidelity to true history

Table 1. ¹T, HS, P,F, S, G = Temperature, Heat Source, Permeability, Fluids, Scale, Geometry as primary relevance ¹t, hs, p, f, s, g = Temperature, Heat Source, Permeability, Fluids, Scale, Geometry as secondary/minor relevance ² T,P,F as above; C = current, Pa = Past, TDS = total dissolved solids/salinity

Methods – Bayesian Statistical Modeling

In modeling there is always a hierarchy of levels of sophistication, and it is often the case that parsimonious models are more reliable than complex models. Here we present a relatively simple and computationally fast method that can be applied to the whole state relatively quickly.

The three primary properties or *desiderata* of a successful geothermal play are the presence of *heat* (*H*), the presence of *fluid* (*F*), and the appropriate *permeability* structure (*P*). The value $a_i(\vec{\mathbf{x}})$ of scaled data type *i* at location $\vec{\mathbf{x}}$ quantifies the evidence for (if > 0) or against (if < 0) the presence of each critical property there. The importance of the evidence associated with data type *i* for resource quality $j \in \{H, F, P\}$ is the *weight* w_{ij} assigned to the scaled data value $a_i(\vec{\mathbf{x}})$. The probability of a given quality of a resource is thus a function of the a_i 's. For example, we map the probability of *heat* (*H*) using a generalized linear model with probit link function (expit inverse-link function):

$$\Pr(H|\mathbf{\vec{x}}) = \left[1 + \exp\left(-w_{0H} - \sum_{i=1}^{n} w_{iH} a_i(\mathbf{\vec{x}})\right)\right]^{-1}.$$
(1)

In this illustrative example, we estimate the probability of a heat source across Hawai'i Island.

The expit function, which is an instance of the logistic function, has the required property that it is restricted to values between 0 and 1. Here it also includes the prior probability—the probability of heat in the absence of any information,

$$\pi_{H} = \left[1 + \exp(-w_{0H})\right]^{-1}.$$
⁽²⁾

Once the prior probability π_H is estimated, the parameter w_{oh} is set. The probability of a resource at location $\vec{\mathbf{x}}$ is then the joint probability of the *desiderata*, which (in the independence approximation useful for point-wise processing of large areas), is approximately equal to the product of the marginal probabilities

$$\Pr(H, F, P | \mathbf{\vec{x}}) \approx \Pr(H | \mathbf{\vec{x}}) \Pr(F | \mathbf{\vec{x}}) \Pr(P | \mathbf{\vec{x}}).$$
(3)

To indicate prospects where more information about fluid, say, would be helpful, we will generate the partial product map $Pr(H|\mathbf{x}) Pr(P|\mathbf{x})$ in areas where fluid data are absent or ambiguous, and similarly for the other two partial products.

In some regions of the world the prior probabilities and weights on each data type can often be estimated from locations where geothermal resources are known to exist or known not to exist. Such a "training dataset" in Hawaii is small and insufficient (only one active geothermal plant and one other location with hot water). We are therefore assigning weights using "expert elicitation". This is conducted during team meetings, at which participants discuss and rate the relevance of Hawaii data types and quantitative ranges to the presence of the essential properties. These discussions are informed by the literature of other, analogous geothermal areas, such as Iceland. For example, we have found that geochemical geothermometers developed for Iceland seem to perform better in Hawaii than geo-thermometers designed for other regions.

Preliminary Results

Gravity is a data type that remotely senses dense intrusive rock, which is the source of heat for geothermal systems in Hawaii. The residual gravity anomalies on the Island of Hawaii of *Flinders et al.* [2013] are normalized by the median value to produce the scaled data values $a_i(\vec{x})$ within 1.5 km of each measurement point. These values were then converted to probability for using Eq. (1), assuming a prior probability of p0H=0.1 and $w = w_{0H}$. Preliminary results show elevated probabilities around the summits of the main shield volcanoes as well as along the Kilauea East Rift Zone and the Mauna Loa SW Rift Zone (in the southeast, Fig. 1(a), (b)). Data are sparse in various areas between the shield volcanoes, including around of Hualalai in the northwest, near where MT surveys are currently ongoing.

Volcano Age is an important indicator of heat because the intrusive rock cools with time. For simplicity, the age at any given location is equal to the youngest dated shield-stage, surface lava from the associated volcano. We assign age in this manner to represent the time since the volcano's rift zone(s) were last active. The age is scaled base on the form of the solution for 1-D conductive cooling of an initially hot intrusion

$$a_{age} = C_I \exp(-(age/t)) + C_0. \tag{4}$$

Here, t is the diffusion time scale, which relates thermal diffusivity k and the thickness scale of the intrusion, D, emplaced at a uniform excess temperature relative to the surrounding (infinite) crust,

$$t = D^2/k.$$
 (5)

The ages are shown in Fig. 1(c) and the corresponding probabilities of heat are shown in in Fig. 1(d) for t = 0.5, $C_1 = 1.5$, $w = 0.5w_{0H}$. The predicted probabilities are highest for the active Mauna Loa and Kilauea volcanoes in the southeast and decrease (with age) to the northwest.

Proximity to a Rift Zone is a third indicator for potentially hot intrusive rock. Geologic data and the DEM were used to pick the locations of the major rift zones. Then the scaled distances were computed as a smooth decay function over a distance of 8 km away from each rift zone (Fig. 1(e)). From the scaled distances map, the probabilities of heat solely

associated with proximity-torift zone were produced, using weighting factor $w = 0.75w_{0H}$ (Fig. 1(f)).

Ground Motion Measured at Permanent GPS stations were used to compute the horizontal component of divergence, as a possible source of crustal permeability. Mean velocities at each station were estimated for the time the stations were active (5 -18 years). Most of the stations are on Kilauea's East Rift zone, on the summit of Mauna Loa, and on Mauna Loa's eastern and southern rift zones. There are a handful of stations around the perimeter of the island to the north. The velocities were interpolated onto a regular grid and then the gradients of the east and north velocities $(\partial v_r / \partial x)$ and $\partial v_y / \partial y$ were computed. The sum

$$\Delta \equiv \partial v_x / \partial x + \partial v_y / \partial y \quad (6)$$

is the horizontal part of the divergence, which indicates where the surface is horizontally expanding (>0) or contracting (<0). Such deformation probably indicates where permeability is being actively created in the crust (Fig. 1 (g)). The absolute value of horizontal divergence was normalized by a reference value D_0 (=5 Myr¹) to yield scaled values. From this, the probability of permeability



Figure 1. (left column) Maps of data values (a) gravity anomaly, (c) volcano age (Myr), (e) proximity to rift zones, and (middle column) what they inform about the probability of heat (b, d, and f, respectively). Bottom row shows (g) horizontal divergence and (h) the associated probability of permeability. The right column shows (i) the joint probability of heat and (j) the joint probability of heat and permeability from the shown data types. White colors of probability indicate where there are no constraints or where the probability is unchanged from the prior probability. Gray shades indicate where probability is reduced from the prior and thus where geothermal resources are least likely to exist.

is computed (Fig. 1(h)). Results show that permeability is most likely to be actively created on the deforming summits of the two active volcanoes and the rift zones of Kilauea in the southeast.

The Probability of Heat as the joint probabilities derived from gravity, volcano age, and proximity to a rift are shown in Fig. 1(i) using Eq. (3). This map shows the highest probabilities over the summits and rift zones of the youngest and active Mauna Loa and Kilauea volcanoes. Probability is moderately over Mauna Kea (central) and Hualalai (NW), but moderately high over Kohala, mostly due to its high gravity and proximity to its NW-SE rift zone. The star in the SE locates the active plant by Puna Geothermal Ventures (PGV); the star in the center of the island locates the drill site of the ongoing Humu'ulu Groundwater Research Project, in the saddle region where anomalously elevated water temperatures were found.

The Joint Probability of Heat and Permeability (Fig. 1(j)) is produced by multiplying the field shown in Fig. 1(i) by that in Fig. 1(h). Compared to the probability of heat, the joint heat-permeability map shows relatively high values that are mostly restricted to the summits and rift zones of the active Mauna Loa and Kilauea volcanoes. The PGV area is predicted to have only a moderate probability. The saddle drill site is predicted to have low probability for both permeability and heat.

Next Steps

The above preliminary results show progress we have made on three indicators of heat and only one indicator of permeability. Our future and ongoing efforts are directed toward incorporating information about water temperature and water chemistry as heat indicators. This will involve making simplistic models of well-water capture zones by estimating groundwater flow paths from the well up the volcanoes where the hydraulic head is elevated. In computing the scaled chemical attribute values $a_i(\vec{x})$, the simplest implementation would have these values be directly proportional to the key indicators themselves (Cl/Mg, Si, SO₄/Cl, well water temperature). In a higher level of sophistication the attribute values can be corrected for factors such as rainfall, agriculture, distance from coast, hydraulic head height, and date the chemical analysis was performed (because later analyses are thought to be more accurate). In yet another level of sophistication, the attribute values become geo-thermometers from the literature or that we will be developing on our own.

Further considerations will also be made for permeability and fluids. Seismicity for example is another indicator of active deformation and the creation of permeability, but may also indicate areas of risk. Proximity to rift zones as well as topography will be considered as evidence for high stresses, which pertains to permeability. Rainfall data and hydraulic head will inform the probability of fluid. We will incorporate and model all essential data for the big island of Hawaii first, and then progressively move up the chain to the other islands, eventually modeling the whole state.

Conclusions

Hawaii is the only ocean island hotspot environment in the U.S. Approximately 90% of Hawaii's energy is sourced from imported oil at a cost to the state of > \$ 5 billion a year, resulting in the highest energy costs in the nation. The only proven resource, in the Puna region of Hawai'i Island, is a region of extreme geologic hazard. The last integrated state-wide resource assessment was conducted in 1983 and suggested a potential resource on all islands, but little additional exploration was conducted in subsequent years – until recently. Here, we will present the results of Phase 1 of this Play Fairway project and suggest a path for future geothermal exploration across the State of Hawaii.

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