G Model
GEOT-1364; No. of Pages 17

ARTICLE IN PRESS

Geothermics xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Geothermics

journal homepage: www.elsevier.com/locate/geothermics

Play fairway analysis of geothermal resources across the State of Hawaii: 1. Geological, geophysical, and geochemical datasets

Nicole Lautze[a,*], Donald Thomas[a], Nicholas Hinz[b], Garrett Apuzen-Ito[a], Neil Frazer[a], David Waller[a]

[a] University of Hawaii at Manoa,1680 East West Road, Honolulu, HI 96822, USA
[b] Nevada Bureau of Mines and Geology, University of Nevada, Reno, NV 89557, USA

ARTICLE INFO

Article history:
Received 9 April 2016
Received in revised form 16 January 2017
Accepted 1 February 2017
Available online xxx

Keywords:
Hawaii
Play fairway
Geology
Groundwater
Volcano
Ocean island hotspot

ABSTRACT

Phase 1 of a Play Fairway Analysis (PFA) of geothermal resource potential across the State of Hawaii was recently completed. The final products of this work include a statewide geothermal resource probability map, a map of confidence in this probability, an assessment of the viability of development in areas of interest, and a prioritized list of recommended future exploration activities. The intersection of subsurface heat (H), permeability (P), and fluid (F) is necessary for an optimum geothermal play. This study: (1) identified and compiled all legacy and current data relevant to Hawaii's geothermal resource; (2) ranked these datasets in terms of their relevance to subsurface H, P, F; (3) developed a Bayesian statistical method to incorporate the data and their rankings, and produce a statewide resource probability map; (4) developed a method to assess confidence in the probability values; and (5) assessed what we term 'development viability' in resulting areas of interest across the state. This paper details the basic project workflow, and activities (1) and (2). It describes the rationale for including this study's datasets: surface geologic mapping data (calderas, rift zones, volcanic vents, dikes, faults), groundwater data (temperature, Chloride:Magnesium, SiO_2) and geophysical data (gravity, magnetotelluric, seismic, geodetic strain), and justifies their relative rankings in terms of H, P, and F. A second paper by Ito et al. (2016) describes activities (3) and (4) related to the statistical methodology, and a third paper (Lautze et al., 2017) describes activity (5), the development viability criteria, as well as our suggested roadmap for future exploration activities. Overall, we find that the likelihood of abundant of geothermal resources is highest on the youngest island of Hawaii, but groundwater indicators suggest there may also be resources on the other, older islands. The higher demand for renewable energy on the more populated islands of Maui and Oahu, as well as a high viability of development on Lanai, also motivate further exploration on these islands.

1. Introduction

Play Fairway Analysis (PFA), which originated in the oil and gas industry, involves identifying the characteristics necessary for a resource to exist; identifying and ranking the data that inform such characteristics in a given geographic area, or Fairway; and then systematically combining the disparate datasets to yield an internally consistent probability map of resource regions (Plays) that have a greater or lesser probability for a resource. The resource probability map is then used to define an assessment program that can most cost-effectively identify the viable resources within the Fairway. As defined by this project's funding agency (the US Department of Energy), the required elements for a viable geothermal Play are subsurface heat (H), permeability (P), and fluid (F). Heat is needed for the resource to exist, fluid is needed to transport heat from the resource to the surface, and permeability is required so that fluids can be extracted and replenished in the subsurface. The major undertakings of this project then, were to i) identify the datasets relevant to H, P, and F in Hawaii; ii) rank them in terms of their ability to inform each of H, P, and F in a way that is consistent with Hawaii's specific geologic, hydrologic, and structural conditions; iii) compile the data; iv) develop a systematic method of incorporating the data into an internally consistent resource probability map for the Hawaii Fairway; and v) devise an exploration plan for Plays deserving of more site specific resource analysis. The results of i)–iii) are the focus of this paper; the details of the probability modeling are presented in the second paper of this series (Ito et al., 2016); and the final step of developing a roadmap for future explo-

* Corresponding author.
E-mail address: lautze@hawaii.edu (N. Lautze).

http://dx.doi.org/10.1016/j.geothermics.2017.02.001
0375-6505/© 2017 Published by Elsevier Ltd.

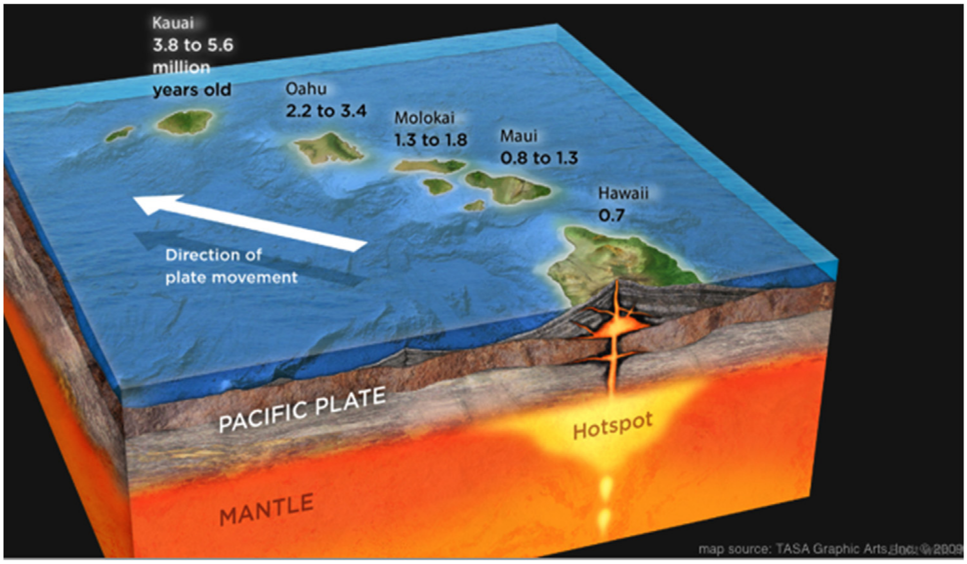

Fig. 1. Map showing the mantle hotspot origin of magma, which provides the heat for Hawaii's geothermal resource. The names of the state's five biggest islands and the average age of the shield building stage of volcanism are shown. Note this age increases to the northwest. (Map Source: TASA Graphic Arts, Inc.© 2009).

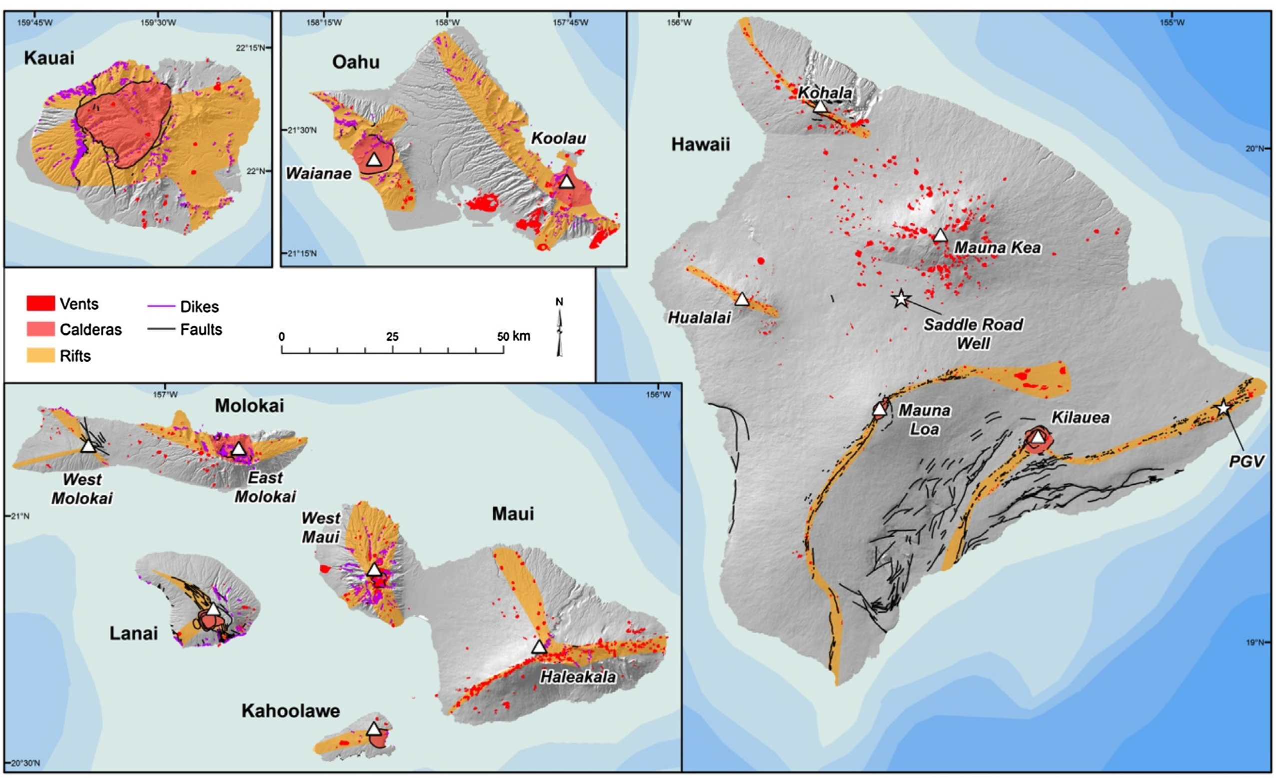

Fig. 2. Statewide map showing the seven islands that comprise the State of Hawaii. A white triangle designates the summit of each shield volcano. Surface geologic features including calderas, rift zones, volcanic vents, dikes, and faults were mapped following Sherrod et al. (2007) and other sources listed under “Geology” in Appendix A.

ration activities is the subject of the third and last paper in this series (Lautze et al., 2017).

There is timeliness to this Hawaii PFA. The Hawaiian Islands originate from a mantle hotspot (Fig. 1) such that subsurface heat can be expected; however, the last statewide geothermal resource assessment was published in 1985 (Thomas, 1985). The 1985 assessment indicated potential prospects on all of the main Hawaiian Islands, but little additional broadly focused exploration work has been done since. In 2013, team member D. Thomas led a U.S. Army-funded drilling effort in search of groundwater in Humu'ula Saddle region between Mauna Kea and Mauna Loa volcanoes (Fig. 2, ‘Saddle Road Well’) resulting in the discovery of water at an elevated temperature (~140 °C) at a depth of ~1.7 km – with a temperature gradient of 165 °C/km from ~1 km depth – in a location not previously recognized as a geothermal area of interest (Thomas et al., 2014). This discovery not only expanded the state's resource potential but also demonstrated that our understanding of Hawaii's geothermal resource is far from

Table 1
List of shield volcanoes on each island and the age of each stage of activity at each volcano. Data from sources listed under "Geology" in Appendix A.

Island	Volcano	Shield (Ma)	Post Shield (Ma)	Rejuvenation
Hawaii	Kilauea	0.275 to present	n/a	n/a
	Mauna Loa	0.75 to present	n/a	n/a
	Hualālai	1.0 to 0.15	0.15 to present	n/a
	Mauna Kea	0.9 to 0.25	0.25 to 0.0044 Ma	n/a
	Kohala	1.3 to 0.30	0.38 to 0.06 Ma	n/a
Maui	Haleakalā	1.6 to 0.6	0.6 Ma to 0.4 ka	none
	West Maui	2.3 to 1.3	1.3 to 1.1	0.61 to 0.39
Lanai	Lanai	2.1 to 1.1	None	none
Molokai	East Molokai	2.2 to 1.5	1.5 to 1.3	0.8 to 0.6 Ma
	West Molokai	2.5 to 1.7	1.4 to 1.7	none
Oahu	Koolau	3.2 to 1.8	None	1.1 to 0.08 Ma
	Waianae	>3.9 to 3.2	3.2 to 2.9	none
Kauai	Kauai	5.6 to ~3.9	~3.9–3.7	2.6 to 0.38 Ma

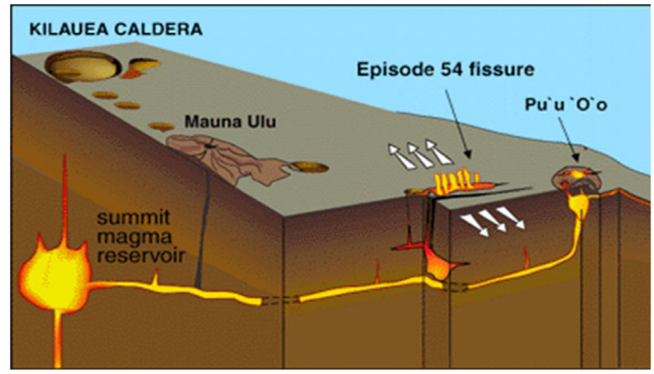

Fig. 3. Cartoon of subsurface relationships expected along Kilauea's east rift zone. Magma is channeled from a summit reservoir beneath the caldera into a rift zone within some kilometers of the earth's surface. Eruptions occur within the caldera and at individual vents along the rift zone. (Diagram by Johnson, 2000; https://hvo.wr.usgs.gov/kilauea/erz_xsec.html).

complete. Hawaii's economic and political environment is also extremely favorable. Historically, Hawaii has had the highest electricity price in the nation, which is currently more than double the national average (U.S. Energy Information Administration, 2015). As a result, the state has aggressively pursued renewable sources, such that the percentage of renewable power in the state has more than doubled (to >20%) over the past half-dozen years – primarily through expansion of intermittent (wind and solar) energy production (Department of Business, Economic Development and Tourism (DBEDT), 2015). Furthermore, in 2015 the state legislature mandated that 100% of Hawaii's electricity come from renewable sources by 2045. Hawaii's only cost-effective, base-load renewable energy source is geothermal. This work serves as a major step toward identifying viable geothermal resource areas – a key element for Hawaii's success in achieving its 100% renewable goals.

2. Background

2.1. Hawaii's geologic setting

Hawaii is an ocean island hotspot environment in which subsurface magma is the source of geothermal heat. The hotspot currently underlies the southeastern portion of Hawaii Island (commonly known as '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 (Fig. 1). Each island is composed of one or more shield volcanoes (Fig. 2 and Table 1). Typically, each Hawaiian volcano exhibits four stages in a complete life cycle: a) pre-shield, b) shield building, c) post-shield, and d) rejuvenation, although not every volcano experiences each stage (Table 1). The pre- and post- shield stages occur just before and just after the shield building stage. The shield building stage is when the largest volume of magma is erupted to form the bulk of the volcanic edifice; during thit stage, most eruptions occur at a caldera that sits above the main conduit rising from the mantle plume, and along rift zones that extend outward from the caldera (Fig. 2). Magma is transported laterally from a shallow reservoir that resides below the caldera into a rift zone within a few kilometers of the surface (Fig. 3). More rarely during the shield stage, eruptions occur at 'satellite' vents, or vents not within the caldera or along rift zones. This contrasts with rejuvenation phase volcanism, whose vents most typically do not occur along any recognizable pre-existing structures (i.e. rift zones) or pattern of distribution. Rejuvenation phase volcanism occurs after a pause of 0.5–2 million years following the end of the shield stages of activity (Bizimis et al., 2013); for example, Ko'olau volcano's (Oahu) post shield activity ceased ~1.8 Ma, but the most recent rejuvenation activity occurred as recently as ~80 ka (Table 1). Rejuvenation phase eruptions are thought to be typically of short duration (days to weeks) and extrude a relatively small volume of magma. Whether an amount of subsurface heat adequate for a geothermal resource could be associated with rejuvenation activity remains an outstanding question.

Across the state, there are volcanoes currently in each stage: the submarine volcano Loihi is in the pre-shield stage; Kilauea and Mauna Loa on Hawaii Island are in the shield building stage; Hualālai and possibly Mauna Kea on Hawaii Island and East Maui volcano (commonly known as Haleakalā) are in the post-shield stage; and several volcanoes on the older islands can be considered to be in the rejuvenation stage. Direct evidence of thermal anomalies (e.g. in water wells) has been identified across most of the islands, including Kauai (Thomas et al., 1979; Thomas, 1985), which may indicate that all stages of volcanism can contribute geothermal heat to the shallow crust.

2.2. Hawaii's geothermal resource

Currently the Kilauea East Rift Zone (KERZ), on Hawaii Island, is the only geothermal system in the Hawaiian archipelago from which geothermal electric power is being produced. The Puna Geothermal Venture (PGV), operated by Ormat Technologies, Inc., produces up to 38 MWe from >300 °C fluids at depths of up to 2.5 km. This meets ~25% of Hawaii Island's and ~3% of the state's energy needs (DBEDT, 2015). Other than PGV and the Puna area, there are very few deep (~2 km) wells distributed among the major islands of the chain, such that, from a geothermal perspective, the remainder of Hawaii is largely unexplored. Nonetheless, from the few deep wells that do exist it is clear that there is a high contrast between areas with recent magmatic intrusions and the background geothermal gradient of ~18 °C/km (Büttner and Huenges, 2003). Therefore, heat is one of the key elements to identify in this Hawaii PFA.

Another important characteristic of geothermal resources in Hawaii is that they are mostly blind. Kilauea's lower east rift zone is the only area of Hawaii with known surface manifestations. These include warm springs along the Puna coast that are probably supplied by outflow from the rift zone (Fig. 4), and sparse, very weak fumaroles in some deep pit craters (Thomas 1987, 1989; Conrad et al., 1997). High lateral permeability in the first kilometer below ground surface (composed mainly of subaerial lava flows) does not allow for the formation of surface thermal features (e.g. hot springs, fumaroles, etc.) in other locations. Given these challenges, PFA pro-

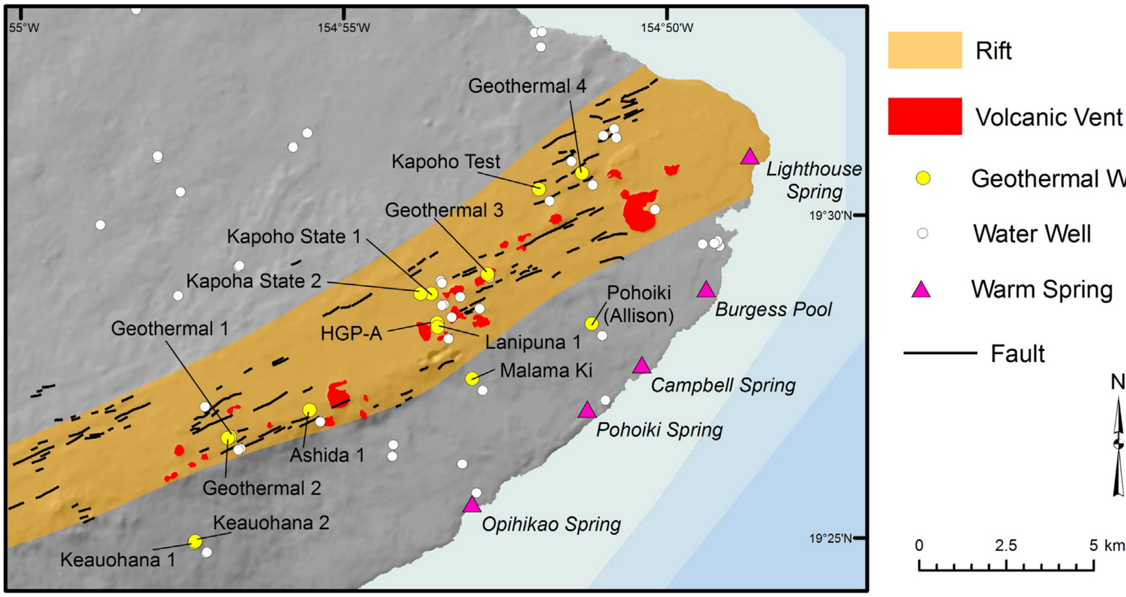

Fig. 4. Map of the Puna region of Hawaii Island highlighting Kilauea's lower east rift zone and near or offshore springs, some of which are warm. Note the number of faults and vents that occur within the rift zone. The Kapoho State wells are a part of Puna Geothermal Venture geothermal facility.

vides an effective, low-risk/cost exploration strategy that can guide future geothermal resource exploration in Hawaii.

3. Project methodology

The overall project methodology followed the workflow depicted in Fig. 5. Our first step was to identify datasets relevant to the necessary qualities (H, P, F) for a geothermal play in Hawaii. Of note, however, is that our basic project workflow and geostatistical methods are applicable to geothermal prospecting in any geologic setting, although the relevant datasets and their rankings will differ in other Fairways according to the regionally specific geologic, hydrologic, and structural conditions there. For example, in the case of continental fault-controlled geothermal systems, key datasets are likely to include Quaternary faulting as highly relevant to permeability, and heat flux as most relevant to heat.

Weekly meetings of the Hawaii Play Fairway Team facilitated smooth execution of the project. Outside experts at times participated in such meetings, including University of Hawaii professors John Sinton (Hawaiian Geology), James Foster (Geodesy/Deformation), and Steve Martel (Mechanics and Structural Geology), as well as Robert Whittier from Hawaii Department of Health (Groundwater Flow) and geologists from Ormat Technologies.

4. Hawaii geothermal datasets

The datasets relevant to geothermal heat (H) in Hawaii are directly linked to Hawaii's ocean island, hotspot volcanic setting, whereby magmatic intrusions supply the heat source. As lava erupted on the surface cools within minutes to days of extrusion, any resource heat will be derived from subsurface, or intrusive, magma. Volcanic features mapped on the surface serve as direct evidence of intruded subsurface magma (as not all magma is erupted) at some point in the geologic history of that area. Indirect evidence includes geophysical data and groundwater temperature and chemistry data. The datasets used in our analysis are shown in Fig. 6, and are grouped into 3 main data types: Surface Geology (brown) Geophysics (red), and Groundwater (blue). The numbers in parentheses indicate their ranking on a relative scale of 1–10, as derived by a method of 'expert elicitation', where experts included the authors of this paper and the others named in Section 3.

Data compilation involved a comprehensive search of public databases, reports, and peer reviewed literature. A list of the data sources, grouped by dataset, is provided in Appendix A. All data were submitted to the Department of Energy's National Geothermal Data System (NGDS). It is anticipated that the compiled data will be available from NGDS in the near future. One dataset included in Appendices A and B, but not discussed above is Land Use/Classification and Ownership. This was used in the assessment of Development Viability, as discussed in Lautze et al. (2017).

4.1. Hawaii datasets relevant to heat

4.1.1. Surface geologic data: caldera, rift zone, vent, dike

Subsurface magma is known to exist below volcanic features that can be mapped on the surface, including the **calderas** of each shield volcano, elongate **rift zones** that extend laterally outward from calderas, individual volcanic **vents** that can occur either on or remote from a caldera or rift, and **dikes** which outcrop in large volume along eroded calderas and rift zones (Fig. 2). The relative ranking of these mapped features is linked to the volume of subsurface magma anticipated. Calderas sit above the main conduit between the mantle plume and the surface. They therefore represent the locus of the most persistent intrusive activity over a volcano's pre-, post-, and shield stages of activity. Because of their elongate aspect ratio, rift zones are expected to lose heat more rapidly than calderas. Furthermore, changes in the stress regime on an island (e.g. due to growth of a sister volcano or to a mass wasting event) can shift the location of rift zones, such that the persistence of magma influx over time becomes less certain. Individual/isolated vents, with their relatively small size and ephemeral nature, suggest a lower volume of subsurface magma than do calderas and rift zones. Dikes mapped at the surface represent even smaller volumes of magma, although clusters of dikes can indicate the location of rift zones and calderas, especially in the older volcanoes.

4.1.2. Geophysical data: magnetotelluric, gravity

Magnetotelluric (MT) data indicate the resistivity of the subsurface. Based on existing studies in Hawaii, resistivity patterns

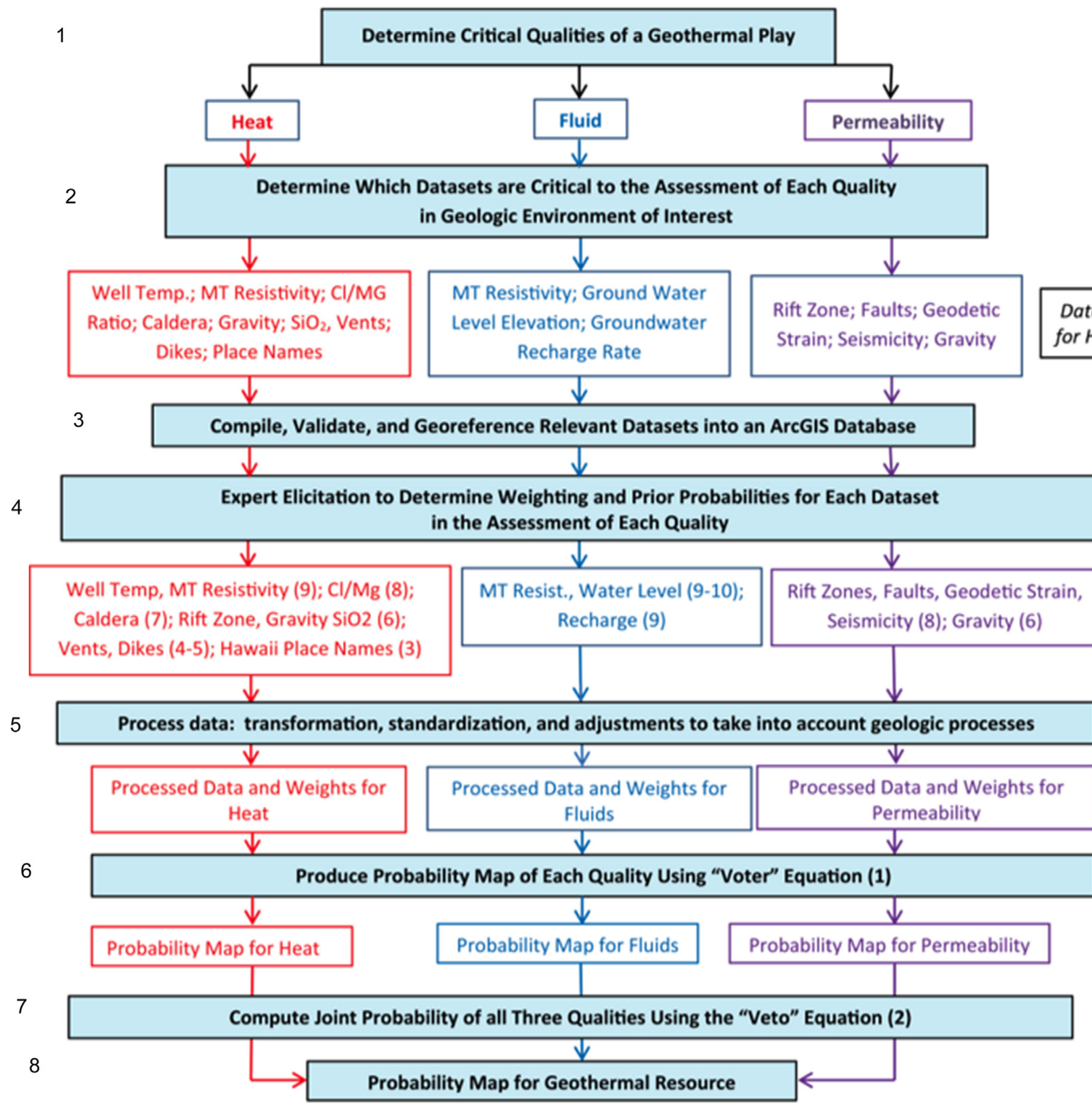

Fig. 5. Flowchart showing overall project methodology, applied to the assessment of a geothermal resource. The filled boxes, numbered 1–8, denote computational and/or decision-making steps, whereas the unfilled boxes represent the products of those computations/decisions. The datasets listed and the numbers in the boxes below step 4 refer to the relative weighting of the individual data sets (as discussed below). With appropriate modifications to the selection of data sets and weighting functions, this method is general enough to be applied to any geologic setting and resource type.

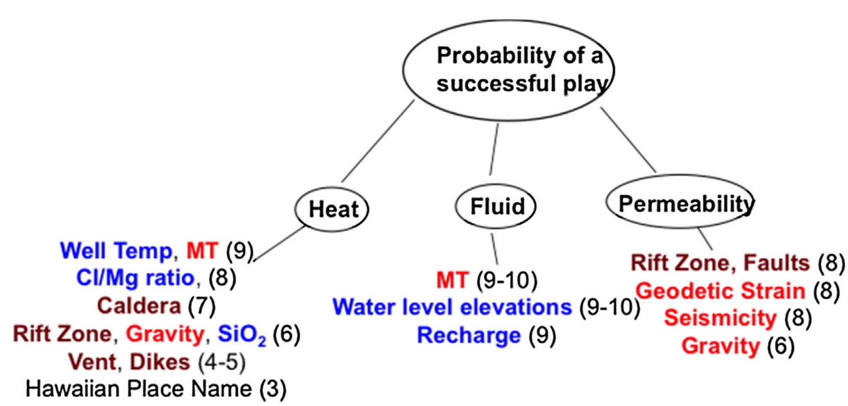

Fig. 6. The data types used in the probability modeling to indicate the probability/likelihood of geothermal Heat, Fluid, and Permeability. The numbers in parentheses indicate the relative ranking of reliability, from 1 (low) to 10 (high). Data types are color-coded: brown for surface geologic features; red for geophysical data; and blue for groundwater data. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Please cite this article in press as: Lautze, N., et al., Play fairway analysis of geothermal resources across the State of Hawaii: 1. Geological, geophysical, and geochemical datasets. Geothermics (2017), http://dx.doi.org/10.1016/j.geothermics.2017.02.001

are most affected by rock porosity, the degree of saturation, and the temperature and salinity of groundwater in rock (Pierce and Thomas, 2009; Thomas et al., 2014). Unlike other high temperature volcanic settings where very low resistivity may indicate a clay cap above a hydrothermal reservoir (Johnston et al., 1992; Anderson et al., 2000; Cumming, 2009), prominent clay caps have not been documented in association with Hawaiian resources (Evans et al., 1992a,b,c,d,e,f,g; Trusdell et al., 1993). Although alteration mineralogy does not have a large impact on resistivity signatures of hydrothermal resources, the combination of thermal fluid and elevated salinity in saturated rocks corresponds to moderately low resistivity in reservoirs. For example, in the Humuʻula "Saddle Road Well" (Fig. 2), where groundwater exploration drilling found hot water, MT data indicate an order-of-magnitude lower resistivity in basalts saturated with thermal fluid, compared to ambient-temperature freshwater (Pierce and Thomas, 2009). Resistivity estimates are therefore a key geophysical data type indicative of subsurface heat in Hawaii, particularly when interpreted in the context of other, regionally appropriate, sources of increased/decreased resistivity (e.g., Ussher et al., 2000). MT data currently exist for only a small percentage of Hawaii Island, and no other islands. Hence, in Hawaii, we have no means of assessing the relative effects of aging, weathering, and long-term thermal decline on the modeled MT resistivity signatures over older geologically favorable geothermal prospects.

Gravity surveys have proven useful in Hawaii for identifying dense intrusive magmatic centers, which are the primary source of geothermal heat in Hawaii. Gravity data have been used to map the extent and distribution of magmatic centers beneath rift zones and summit dike complexes, and a recently published re-analysis of Hawaii's gravity data (Flinders et al., 2013) identified potential dike complexes that were previously unrecognized and show few surface manifestations. The Humu'ulu 'Saddle Road Well' coincidentally confirmed the presence of a higher–than-expected dike frequency and significant thermal activity in that location (Fig. 7; Thomas et al., 2014). Gravity data can therefore invaluably supplement geologic map data by indicating intrusive activity that may not be evident at the surface.

MT data are ranked more highly than gravity/density data because, in Hawaii, the former typically measure present-day conditions whereas the latter are indicative of prior events (magmatic intrusions) that, with time, lose heat.

4.1.3. Groundwater data: well temperature, Chloride:Magnesium ratio, silica concentration

Elevated **groundwater** temperature is a direct indicator of a heat source at or somewhere upgradient of the measurement location. Many areas of Hawaii have high rates of rainfall that filters through highly permeable surface layers into a permeable shallow groundwater system. Geothermal fluids discharging into the shallow groundwater system therefore have a high likelihood of being diluted and transported far (tens of kilometers) from their source. Elevated temperatures measured in wells are therefore considered to be conservative and diagnostic signatures of geothermal influence. Fig. 8 shows the water well temperature results, calculated as the difference between water and annual mean surface/air temperatures. Note that anomalously high ($\Delta T \geq 5$) water well temperatures occur on all islands except Molokai.

Less reliable, but still valuable, are ***groundwater chemical variations*** associated with thermal fluids. A **Cl/Mg** ratio above that of seawater (i.e >15) strongly suggests Mg depletion has occurred within a hydrothermal system. All groundwater in Hawaii has sea-salt present, either through mixing with the underlying seawater, or as a result of sea-salt aerosol deposition on land that seeps into the groundwater system. The chloride ion is relatively non-reactive in groundwater and its concentration is relatively stable whereas the magnesium ion is extremely sensitive to removal by geothermal processes (removed as secondary clays; Thomas, 1987). In the vicinity of Hawaii's proven geothermal system (PGV, Figs. 2, 7 and 8), thermal saline water mixes with shallow groundwater, and most wells have distinctly elevated Cl/Mg values (Table 2). Hence, this chemical signature in shallow groundwater can indicate a nearby heat source with minimal ambiguity. Results of this analysis are shown in Fig. 9, where the limited number of wells, as compared to Fig. 8, illustrates a limitation in available groundwater chemistry data.

Table 2
Examples of Cl/Mg and SiO_2 compositions and reference water types.

Location or Water Type	Cl/Mg Ratio	Silica (ppm by weight)	Silica Z value
Typical Sea Water	15	4	n.a.
Rainwater	7.2	Nil	n.a.
Geothermal Production Fluids (Puna Area, Hawaii)	42,000	561	n.a.
Hawaii Geothermal Project Well–A (Hawaii)	1150	501	13.4
Kapoho State 1 (Hawaii)	1050	2000	22.6
Kapoho State 2 (Hawaii)	80	1100	18.6
Kapoho State 3 (Hawaii)	827	1581	21.0
Malama Ki (Hawaii)	18.2	101	2.9
Allison (Hawaii)	18.7	24	−6.6
Kapoho Crater(Hawaii)	5.5	58	−0.8
Paauilo Shaft North Flank Mauna Kea(Hawaii)	22.9	27	−5.8
Pohakuloa Training Area Well No. 1 (West Saddle Area, Hawaii)	20.4	104	3.1
Punahou Springs Haleakalā East Rift (Maui)	16	18	−8.5
Maui High Well Haleakalā Northwest Rift (Maui)	21.3	53	−1.3
Puuloa Road Well South Shore Koolau (Oahu)	413	28	−5.5
Lualualei Well (2508-07) Waianae Caldera (Oahu)	16.4	186	6.9

Silica is abundant in rocks and has a temperature-dependent solubility; therefore elevated silica in groundwater has been widely used as a thermal indicator. Elevated silica can also be attributed to irrigation, making it a less reliable indicator than elevated Cl/Mg in agricultural regions. Also, the dilution of thermal water with shallow groundwater has a greater effect on the silica concentrations than on the Cl/Mg ratios. To mitigate such complications, we screened for anomalous silica values within individual watersheds. Using the Hawaiʻi Department of Health aquifer designations for the state (Mink and Lau, 1990), we standardized (i.e., took the deviation from the median on the scale of the median absolute deviation) the silica values within the watersheds and used the standardized (Z) values to detect outliers. Wells with Z-values ≥ 1 were used in the probability modeling.

The groundwater data were compiled from legacy and current state water wells. Given that most groundwater in Hawaii is highly mobile, any geothermal signature found in these data was likely sourced some distance away from the well that was sampled. To account for this, we used groundwater flow models to estimate the flow paths as the set of possible locations from which the geothermal signature originated. In doing so, we considered evidence for both a currently active heat source (i.e. groundwater indicators) and indirect data (i.e. location of volcanic features) in our analysis. This is explained in more detail in paper 2 of this series (Ito et al., 2016).

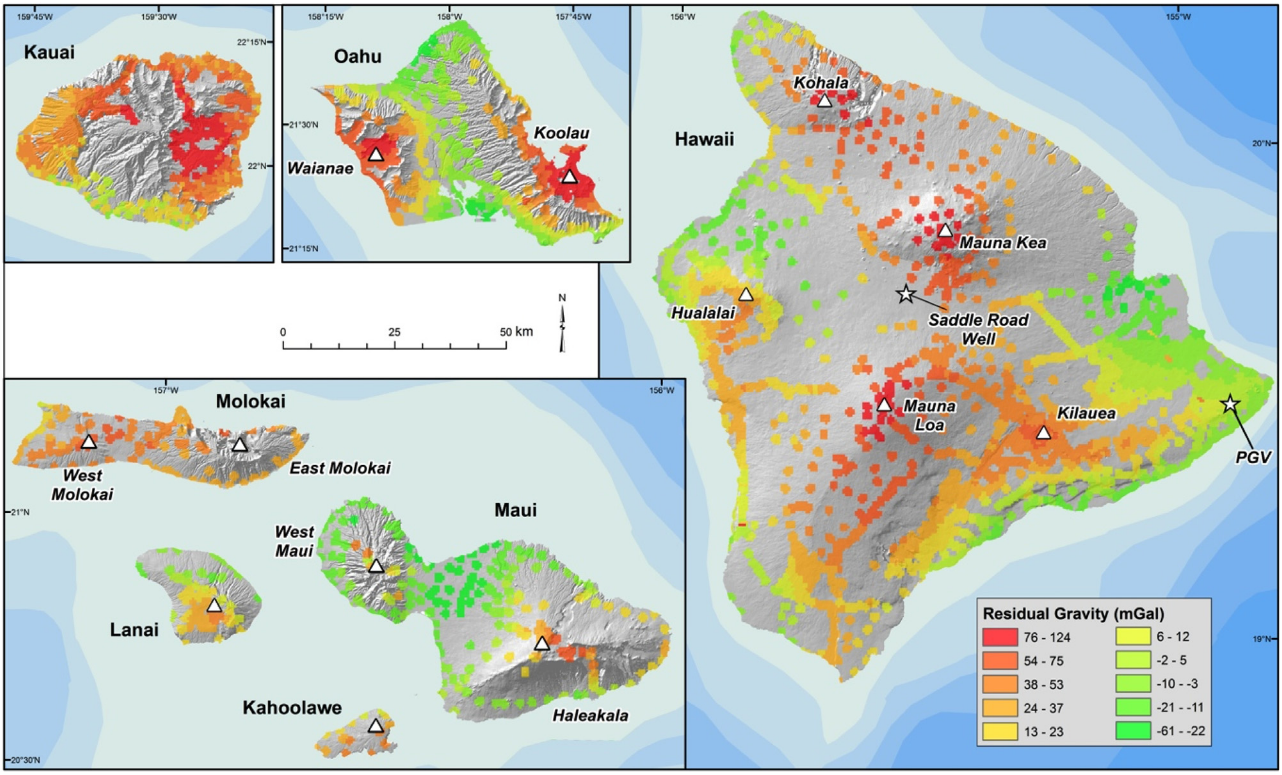

Fig. 7. Statewide map of gravity from Flinders et al. (2013). The map shows residual gravity anomaly, which is the complete Bouguer anomaly minus the attraction of the crust-mantle interface, assuming it conforms to the shape of an elastic lithospheric plate being flexed downward by the weight of the volcanoes. The map therefore reflects primarily variations in crustal density with high residual gravity indicating dense intrusive magma.

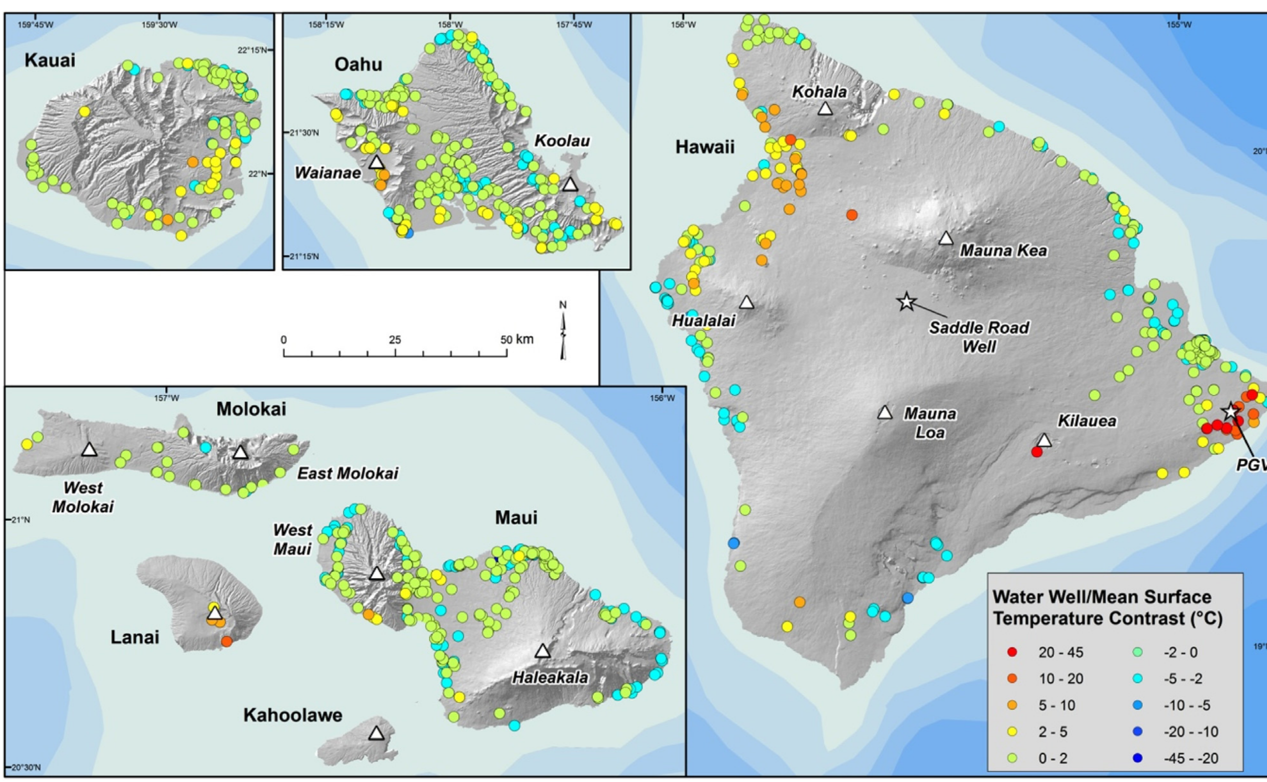

Fig. 8. Statewide map of water well temperatures (shown as the difference between water and surface air temperature). From database of Hawaii's Department of Land and Natural Resources Commission of Resource Water Management, and other sources listed under "Well Temperature" in Appendix A.

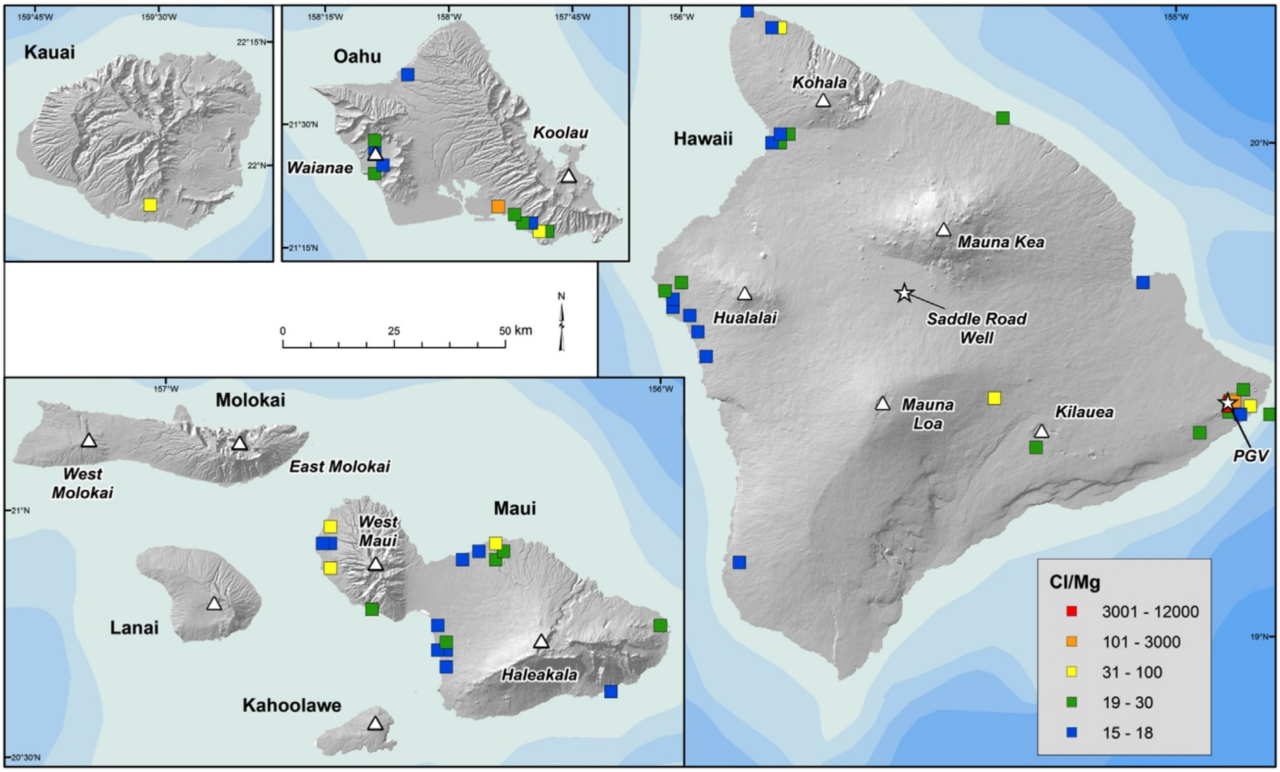

Fig. 9. Statewide map showing wells with anomalous Cl/Mg values. Data sources listed under "Cl/Mg and SiO_2 Well Values" in Appendix A.

4.1.4. Other: hawaiian place names

Finally, in recognizing the Native Hawaiian practice of integrating historical and descriptive information into Hawaiian place names and oral histories, as well as the very long tenure of Polynesian residence in Hawaii, we screened Hawaiian location names throughout the state for references to thermal or recent volcanic activity. This dataset is weighted lowest because many of the descriptive references are allegorical in nature and often non-unique; for example Hawaiian words that describe hot or warmth include wela, hahana, and iki'iki (wehwehe.org). These can be incorporated into a place name that refers to a hot climate instead of warm groundwater. Section 4 describes these results.

4.2. Hawaii datasets relevant to fluid

4.2.1. Geophysical data: MT

Electrical resistivity (or MT) measurements of the crust can serve as a sensitive indicator of saturation, temperature, and salinity of fluids 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 more than an order of magnitude lower. In the Humu'ula Saddle region, where resistivity and subsurface temperature data exist contemporaneously, the resistivity of formations saturated with high-temperature fluids were found to be an order of magnitude lower than rocks saturated with ambient freshwater (Pierce and Thomas, 2009). Thus resistivity can be a reliable indicator of the state of saturation in subsurface rocks in Hawaii in both thermal and non-thermal areas. Analysis of the resistivity data also takes into account the potential for low resistivity associated with seawater saturation and variations in lithology.

4.2.2. Groundwater data: water table elevation, recharge

4.2.2.1. Groundwater elevations. Accepted models of ocean island hydrology assume universal seawater saturation below a floating basal groundwater lens derived from freshwater recharge. Given the generally high permeability of Hawaii's basaltic lava flows, and anticipated resource depths of 2–3 km, it is reasonable to assume, where hydraulic flow paths are continuous, that fluids are present at resource depth so long as the water table (hydraulic head) elevation is at or above that predicted by prevailing models. Recent data, including that from the Saddle Road well, suggest this is indeed the case. ***Groundwater Recharge Rates*** are often proportional to hydraulic head, such that, for the same reason as just stated, recharge data are informative, especially in locations where groundwater elevation data are lacking (i.e. where no wells exist).

Although access to fluid is probable in most areas of the state, more favorable conditions are expected to be in areas of elevated water table and high rates of groundwater recharge. This is for two primary reasons: First, prior studies (e.g. Seyfried and Bischoff, 1979) have shown that fresh and saline waters behave very differently in basaltic hydrothermal systems: seawater intruding into a hydrothermal system causes deposition of several minerals which substantially lowers the pH of the intruding fluids and brings about rapid breakdown of the primary basaltic minerals and deposition of secondary minerals that can *occlude formation permeability*. Analyses of fluids from saline thermal wells in Puna have confirmed this process given both highly altered saline chemistry and pH values below 3 (Thomas, 1987 and references therein). Freshwater-derived thermal fluids are less aggressive in altering the native basalt minerals and have more benign pH values, and consequently constitute a more ideal resource fluid.

A second consideration relevant to availability of water for Hawaii's geothermal systems is that, to date, there has been little evidence suggesting that pressure and temperature within these systems are controlled by an overlying clay cap (Evans et al., 1992a,b,c,d,e,f,g; Trusdell et al., 1993). More typically, temperatures observed in deep wells appear to be controlled by the hydrostatic head of the overlying groundwater system: measured temperatures and steam saturation pressures in deep wells rarely exceed the hydrostatic pressure for the depth of the measured temperature. Hence, in the interior of the islands, a highly elevated regional groundwater table allows elevated temperatures to reach higher values at shallower depths below ground surface.

In areas where groundwater elevation is higher and/or high rates of recharge occur, the overlying freshwater typically displaces seawater to substantial depths below sea level, thus making the ideal combination of shallower elevated temperatures and lower salinity thermal fluids more likely.

4.3. Hawaii datasets relevant to permeability

The distribution of subsurface permeability within the islands at geothermal reservoir depths is not well documented given that very few deep test holes outside of Puna (Fig. 4) have been drilled. An exception – the Hawaii Scientific Drilling Project – drilled a 3.5 km-deep research hole into the near-shore flank of Mauna Kea, which showed that subaerial basaltic lava flows maintain 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 maximum depths (Thomas and Haskins, 2013). There are little to no data on how compaction is expressed in the older volcanic systems.

Given the absence of ground truth data outside of Puna, this PFA analysis used the following structural and geophysical datasets to inform the quality of permeability:

4.3.1. Surface geologic data: rift zones and faults

Faults are zones of crustal fracturing and are therefore associated with elevated permeability. Most faulting in Hawaii is caused by stresses due to the weight of a volcano, and/or magmatic processes within a volcano rather than by plate tectonic stresses. The most intensively faulted regions in Hawaii involve normal faults associated with areas of caldera formation, flank subsidence, and dike intrusion (e.g. Kilauea caldera, the Hilina fault system of Kilauea, and the southwest flank of Mauna Loa).

4.3.2. Geophysical data: geodetic strain, seismicity, gravity

4.3.2.1. Geodetic strain. Ground surface motion using the Global Positioning System (GPS) 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 insights into the distribution of deformation rates over much of the island. Less extensive coverage is available for the older islands.

4.3.2.2. Seismicity. Seismicity in volcanic environments indicates an elevated probability of permeability either through fracturing around dikes or through faulting. Hawaii Island hosts one of the densest seismic networks in the United States. An abundant data resource is available from this network dating back to the early 1900s. The older islands have substantially less coverage but a long history of seismic data exists there as well; see Appendix A.

4.3.2.3. Gravity. 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. Also, regions of elevated gravity are often associated with higher rates of subsidence (i.e. increased rates of subsidence beneath rift zones and calderas) and crustal deformation, which may also be associated with elevated levels of fault generated permeability.

5. Hawaiian place names associated with volcanism or geothermal characteristics

In recognizing that many location names across the State of Hawaii originate from the Hawaiian language, and that the Hawaiian place names are highly descriptive in nature, we screened Hawaiian named locations across the state for indications of hot or warm fluid, and/or other characteristics that might be associated with thermal activity (e.g. odors, recent volcanism, etc.). We include our preliminary results here and in Table 3, although Hawaiian place names were not weighted highly in the Hawaii PFA analysis.

Ancient Hawaiians (circa 1200–1300 CE; Wilmshurst et al., 2010) believed that each natural phenomenon had a personality. The fire goddess Pele and her siblings were associated with volcanism and related geologic phenomena and are among the best-known figures in Hawaiian mythology. Pele's family members included Kamoho Ali'i (Pele's brother and a shark god), who was associated with steam; Kane hekili, associated with thunder; Kane Pohaku ka'a, associated with earthquakes; Kane hoa lani, associated with fire making; and Kane huli honua, associated with turning earth upside down. Our survey of Hawaiian place names explored whether those names alluding to Pele, her family members, and/or environmental conditions (i.e. words for "hot") might indicate subsurface thermal phenomena.

Fig. 11 and Table 2 show the results of this analysis. Not surprisingly the highest density of findings exists in the vicinity of the active Kilauea volcano. Some examples from the Puna region include *Ke awa o Pele* ("the landing place of Pele"), *Puhi a Pele* ("blown out by Pele"), *Keahi a Laka* ("the tame fire of Laka, Pele's sister"), Pu'u Pilau ("stinking hill"), Pu'u Kukai ("dung hill"), and Waiwelawela ("warm water,"). Kilauea's Southwest Rift Zone includes two sites associated with Pele along the shoreline: Wai Wela Point ("warm water point") and Wai o Pele Bay ("water of Pele Bay"). The former is known to host a warm coastal brackish spring; we have no data on the other.

On Mauna Loa, only two place names were identified as references to volcanic activity and no place names suggested warm water. *Na'alehu*, a small town near South Point, translates to "the volcanic ashes", and *Mana Ka'a* Point is named for a stone offshore that was reputed to have been named by family grieving after their father that was turned to stone by Pele (the point is part of an extensive coastal lava flow that recent work has dated to 3000 to 5000 years before present (Sherrod et al., 2007)). On Hualālai, *Makole a* translates to "glowing red eye", and *Puhi a Pele* to "blown out by Pele." Both locations are associated with Hualālai's 1801 eruptive event. On Mauna Kea, *Pu'u Ka Pele*, "Pele's hill," and *A'ahu wela*, "hot garment/mantle," refer to Pele and heat, respectively. On Kohala volcano, *Ha'ena*, translates to "red hot" but, as no thermal or volcanic features exist in this region, its hot dry climate may explain its name.

Five place names on Maui may refer to thermal activity. On Haleakalā's East rift zone are *Ka iwi* o *Pele/Na iwi o Pele* ("Pele's bones"), *Ma'ino/Pali Pilo* ("stinking cliff"), and *Pu'u Haoa* ("hot hill"), and on Haleakalā's NW rift zone is *Pa'u Wela* Point ("hot soot"). On West Maui Volcano, *Ka Pilau*, "stinking ridge," is located above the Iao Valley area.

On the island of Kaho'olawe, *Kahuahale-o-Kamoho Ali'i*, "foundation of the house of Kamoho Ali'i" (Pele's brother) is situated within the general area of the island's least weathered and most likely youngest cinder cone.

Molokai Island hosts *Ka holo a Pele*, ("Pele's Landslide"), *Kapuai a Pele* ("Pele's fireplace"), and *Kauha Ko* ("intestine"). The latter two are located on the Kalaupapa peninsula where Pele was reputed to have come to dig her home on Molokai. The Kalaupapa Peninsula is the site of the most recent volcanism on Molokai.

Table 3
Hawaiian Place Names Associated with Volcanism or Identifiable Geothermal Characteristics. Latitude and Longitude in WGS 1984. Data sources listed under "Hawaiian Place Names" in Appendix A.

Place Name	Translation	Island, Place	Associated Feature	Lat_DD	Lon_DD
Mana Ka'a Point	Stone	Hawaii, Ka'u	Landmark stone where Pele turned a man named Mana Ka'a to stone; located near relatively recent lava flow from Mauna Loa.	19.02538056	−155.571328
Na'a Lehu	Volcanic ashes	Hawaii, Ka'u	On Mauna Loa SW rift zone; close proximity to geologically recent vents and flows; may be reference to cinder or spatter from one of those eruptions.	19.06096389	−155.582797
Wai o Pele Bay	Water of Pele	Hawaii, Ka'u	Embayment at terminus of Kilauea SW rift zone	19.15823611	−155.442158
Wai Wela Wela Point	Warm water	Hawaii, Ka'u	Warm coastal spring along Kilauea SW rift zone	19.19615278	−155.387942
Ka'ena	Heat	Hawaii, Puna	Ka'ena Point; common term; may refer to climate conditions in this location.	19.27299444	−155.135008
Pauahi	Destroyed by fire	Pit crater on Kilauea east	rift zone	19.37183611	−155.224839
Puhi mau	Ever smoking (steaming)	Hawaii, KERZ	Pit crater on the upper east rift zone; steam production at the bottom	19.393925	−155.248739
Ha'akuula manu	Like a bird's gathering place	Hawaii	Sulphur Banks fumarole area (bad smells and white ground)	19.43203889	−155.260869
Malama Ki	Bright ti plant	Hawaii, Lower Puna	Where ancient Hawaiians honored Kamoho Ali'i (Pele's brother); near a large pit crater where steam is occasionally visible.	19.46173889	−154.880033
Ke awa o Pele	Awa of Pele	Hawaii, Lower Puna	Known as the first place Pele came to on Hawaii, and she reportedly dug pit craters here and along the LERZ.	19.46503889	−154.891122
Keahi a Laka	Fire made by Laka the hula Goddess; also the tame or beneficent fire	Hawaii, Lower Puna	Craters near Leilani Estates	19.46510556	−154.908272
Pu'u Pilau	Stinking hill	Hawaii, Puna	Located adjacent to HGP-A site, at the discovery well for the Puna geothermal field.	19.474275	−154.886528
Pu'u Honua 'ula	Red place of refuge	Hawaii, Lower Puna	Cinder cone on ERZ; at the Puna Geothermal Venture	19.48057222	−154.887614
(Ka) Wai o Pele	Water of Pele	Hawaii, Lower Puna	Former name of Green Lake; may be duplicate of Ke awa o Pele	19.50245278	−154.839186
Pu'u Kukae	Dung hill	Hawaii, Lower Puna	Small cinder cone estimated to be 400–750 years old	19.51151944	−154.831464
Wai Wela Wela	Warm water	Hawaii, Lower Puna	Warm ponds in lower Puna covered by 1960 lava flows	19.51327222	−154.829036
Puhi a Pele	Blown out by Pele	Hawaii, Hualalai West Rift	Lower vent of 1801 lava flow	19.76156667	−155.975067
Pu'u ka Pele	Pele's Hill	Hawaii, Pohakuloa area	Cinder cone on SW flank of Mauna Kea, just below Pu'u Ke'e Ke'e; young, cinder cone minimally eroded; common name for young intact cinder cones; recent drilling in this area indicates that residual heat is present in this area further supporting its young age.	19.76653333	−155.634417
Makole a	Glowing red eye	Hawaii, Keahole Pt.	Likely reference to the 1801 lava flow on this site	19.77559722	−156.046492
A'ahu-wela	Hot garment	Hawaii	East slope of Mauna Kea; likely referring to string of (mostly) red cinder cones on east flank of Mauna Kea.	19.87069722	−155.399533
Ha'ena	Red hot	Hawaii	Kohala area; used frequently; may refer to climate rather than geothermal activity.	20.21681111	−155.844169
Kahuahale-o-Kamohoalii	Foundation of the house of Kamoho Ali'i (Pele's brother)	Kahoolawe	One of the youngest and least weathered cinder cones on Kahoolawe	20.53135	−156.652053
Ka iwi o Pele/Na iwi o Pele	Pele's bone	Maui, Hana	Recent Cinder Cone, Haleakalā ERZ	20.73749722	−156.001719
Ka Pilau	Stinking ridge	Maui, Wailuku	Ridge above Iao Valley	20.8668	−156.548253
Pa'u Wela	Hot soot	Maui, NE rift of Haleakalā	Source of name is unclear; on Haleakalā NE rift zone; relatively recent cinder cones up rift of the point.	20.94569167	−156.296578
Ka holo a Pele	Pele's landslide	Molokai	Peak/ridge between Kumu'eli and Wailau	21.11592222	−156.873517
Kapuai a Pele	Pele's Fireplace	Molokai, Kaunakakai	N. Coast of Molokai, west of Kalaupapa Pn.	21.18041667	−157.004111
Kauha Ko	Intestines	Molokai, Kaunakakai	Kalaupapa Pn. The first pit dug by Pele on Molokai (youngest volcanism on Molokai). She then left this location and moved to Maui.	21.18798889	−156.966142
Maeaea	Stench	Oahu, Waialua	Not clear what this refers to; may be a more modern name associated with sugar cultivation.	21.60284444	−158.106822
Pua Ena	Issue hot	Oahu, Waialua	Pele reportedly lived at Waialua Bay before going to Hawaii.	21.60421944	−158.105414
Makahuena Point	Eyes overflowing with heat	Kauai, Poipu	South Poipu; leeward Kauai – maybe climatic reference	21.87103333	−159.445019
Nomilu	[No translation]	Kauai, South Shore	Fishpond within geologically young crater; allegedly gave off sulfur smell during volcanic activity on Hawaii Island.	21.88498611	−159.527978

Please cite this article in press as: Lautze, N., et al., Play fairway analysis of geothermal resources across the State of Hawaii: 1. Geological, geophysical, and geochemical datasets. Geothermics (2017), http://dx.doi.org/10.1016/j.geothermics.2017.02.001

Table 3 (*Continued*)

Place Name	Translation	Island, Place	Associated Feature	Lat_DD	Lon_DD
Maka o Kaha'i	Pele's older sister	Kauai, Ko-loa District	near, down slope of late stage cinder cone	21.88565278	−159.530033
Mahana Loa	Very warm	Kauai, Kula NAR	May refer to climatic conditions – leeward Kauai; rain shadow.	22.14027778	−159.704167
Ma'ino/Pali Pilo	Stinking cliff	Maui, Hana	Unknown location; unknown source of name		
Mo'a Ula	Cooked red by Pele's fires	Hawaii, Molokai	Commonly used name for red rocks; several locations all associated with geologically recent lava flows.		
Pu'u Haoa	Hot hill	Maui, Kipahulu	Possibly mistaken reference – Haou was found, not Haoa.		

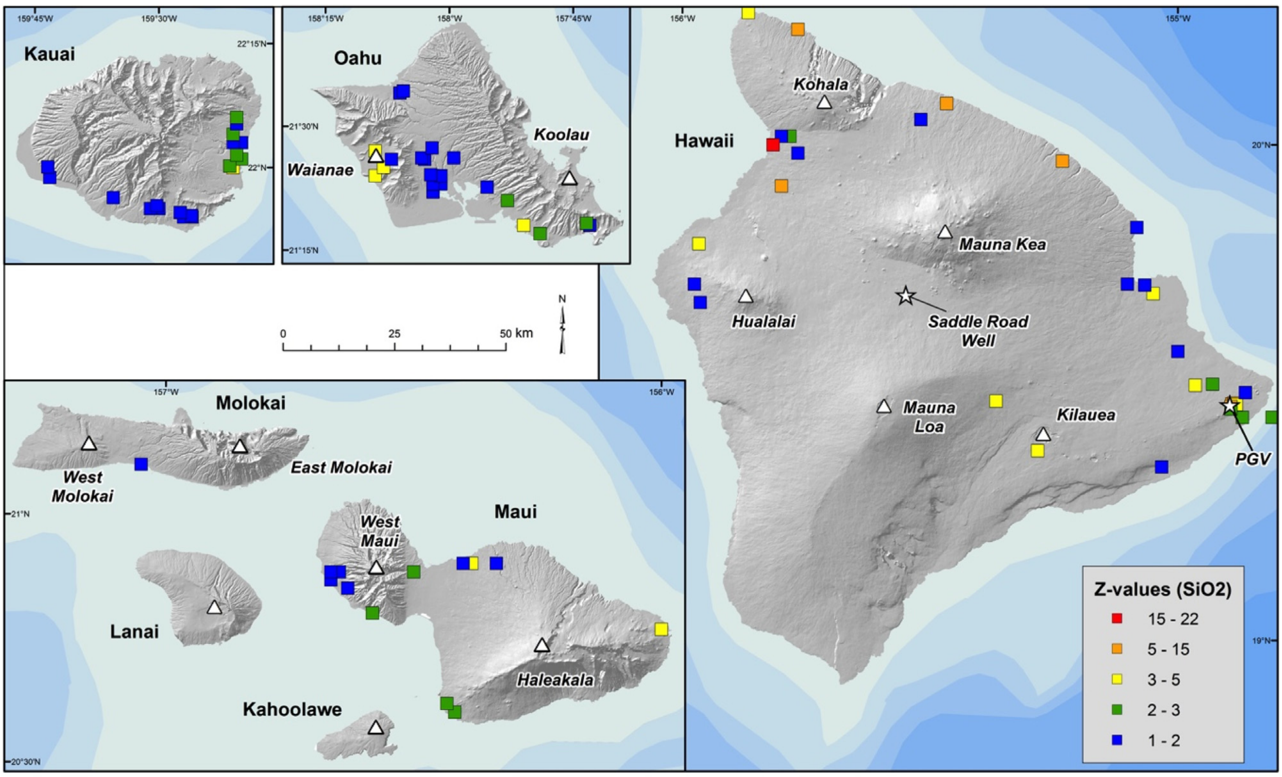

Fig. 10. Statewide map of SiO_2 data. Data compiled from sources listed under "Cl/Mg and SiO_2 Well Values" in Appendix A.

Oahu hosts *Ma'ea'ea*, "stench", and *Pua Ena*, "issue hot." Both sites are located in close proximity to each other and to Wailua Bay, an area that Hawaiian oral history recognizes as a former home for Pele when she came to Oahu.

Kauai hosts *Mahana Loa*, "very warm," and *Makahuena* Point, "eyes overflowing with heat" with unclear sources that may refer to climactic conditions, and *Maka o Kaha'i*, which is immediately downslope of a geologically young cinder cone and *Nomilu* Cone which appears to be a young maar produced by an eruption very close to the current shoreline.

6. Initial findings

6.1. Evidence for elevated heat

Several indicators of hot source rock are shown in Figs. 2, 7–10. The residual gravity anomaly has been corrected for the effects of surface topography (i.e., free-air and Bouguer corrections) as well as the base of the crust (assuming topography is compensated regionally by lithospheric flexure; Flinders et al., 2013), and therefore mostly reflects density variations within the crust. With that, Fig. 7 illustrates the well-known coincidence of dense intrusive rock beneath the large shield volcanoes, especially beneath the volcanic calderas and rift zones. These are the most probable locations of elevated heat. However, while this excess heat is known to be present beneath the active volcanoes, Mauna Loa and Kilauea in the southern part of Hawaii island, it is not well known to what extent the heat has been lost with time in the older volcanoes.

Fig. 8 shows where groundwater was measured to be unusually warm; Figs. 9 and 10 respectively show where Cl/Mg ratios and SiO_2 content of groundwater are unusually high and thus suggest interaction with geothermal fluid. A cluster of these indicators of heat is found near Kilauea's lower east rift zone, which reflects the known geothermal activity. In addition, groundwater indications of heat occur in clusters on the west flank of the older Hualālai volcano (shield stage ended 0.15 Myr ago) as well as southwest of Kohala volcano (shield stage ended ~0.38 Myr ago) and Mauna Kea volcano (shield stage ended ~0.25 Myr ago). Such data suggest the presence of geothermal activity on or near these three older volcanos on Hawaii Island, which is consistent with findings at the PTA-1 drill site located in the Humu'ula Saddle.

Groundwater indications of elevated heat on Haleakalā may be associated with extended post-shield activity that included 12–15 eruptions in the last 1500 years (the most recent ~400 years ago) or older shield stage (≥0.6 Ma) activity (Table 1). West Maui residual heat may be related to post shield or to late shield stage activity 2–1.4 Ma. Lanai Island (shield stage ended ~1.1 Ma; no post-shield) also shows elevated temperatures. On Oahu, groundwater indicators of elevated heat occur on the south and east shores of the Koolau shield volcano, near areas of relatively young (~80–100 ka)

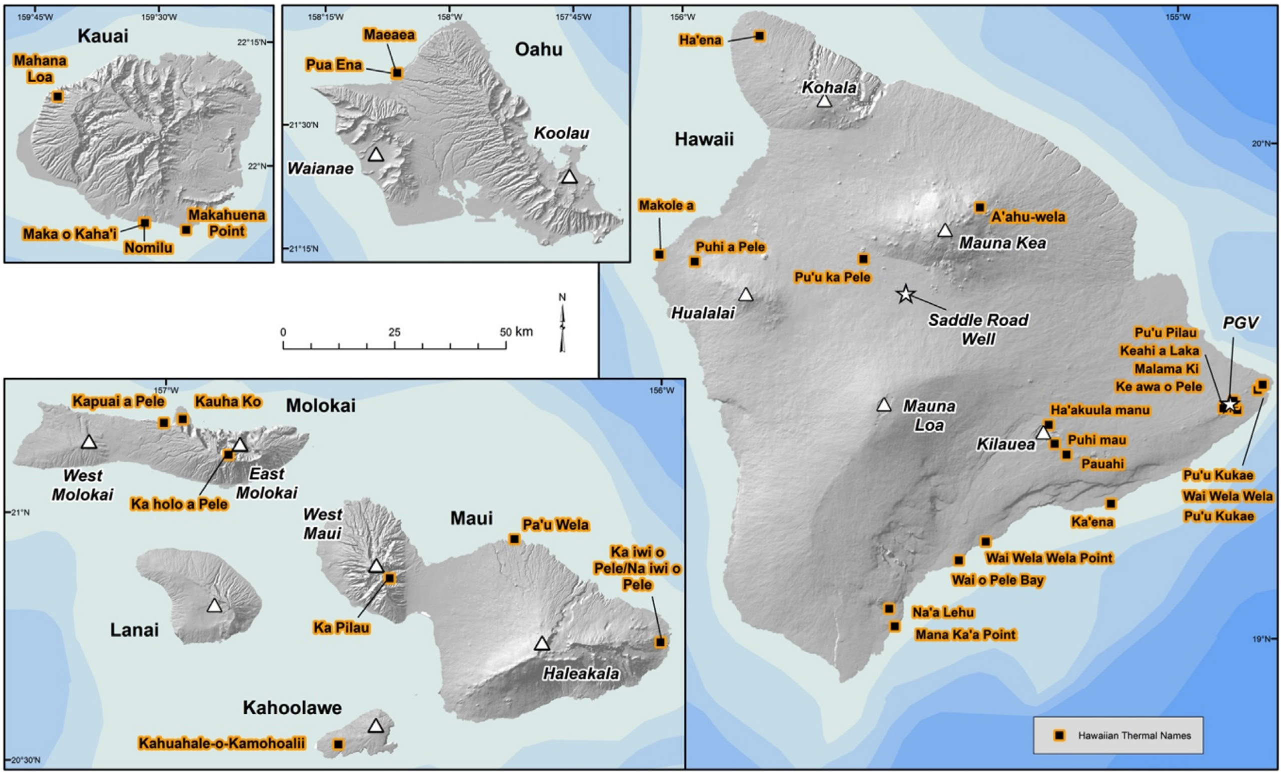

Fig. 11. Map showing results of the Hawaiian place names analysis highlighted in yellow.

rejuvenated volcanic features. There are also groundwater indications of elevated heat in the vicinity of the caldera of Waianae volcano whose post-shield activity ended ~3 Myr ago (no rejuvenated volcanism has been recognized). On the still older island of Kauai, there are a few groundwater indications of thermal activity in the southwest part of the island. Kauai's shield stage ended ~4 Ma but it has the largest volume and longest duration of rejuvenated volcanism of the Hawaiian islands, with eruptions having occurred in the past 500 ka (Garcia et al., 2010).

6.2. Evidence for elevated fluid content and permeability

More favorable fluid conditions are expected in areas of high water table and rapid groundwater recharge. The water table tends to be higher beneath areas of higher elevation and the rate of recharge tends to be higher on the northeast and windward sides of the islands. On Hawaii island, relatively high values of both indicators occur on the east side of the island on the flanks of and between Mauna Loa and Mauna Kea. On Maui, the two properties are relatively high on West Maui and on the northeast side of the Haleakalā volcano. On Lanai, recharge is relatively low but data suggest the water table is elevated. On Oahu the water table and recharge rates are relatively high over the Koolau and Waianae mountain ranges. On Kauai they are relatively high where the surface is elevated over the central and northwest areas of the island.

The permeability structure of the islands at depths of more than 1 km is not well defined since so few wells have been drilled to those depths. On Hawaii island, elevated permeability is indicated by elevated seismicity and geodetically measured surface deformation, which are largely confined to the active Mauna Loa and Kilauea volcanoes. On all of the islands, areas near rift zones, calderas, and faults (Fig. 2) are more likely to have greater permeability, but like heat, permeability in these areas probably decays with time due to weathering. Nonetheless, given what is known to date, these areas are more likely than elsewhere to have greater permeability.

6.3. The coincidence of heat, fluid, and permeability for geothermal resources

Our preliminary and qualitative assessment of where elevated heat, fluid content, and permeability coincide is based on four primary considerations: (i) the indicators of elevated heat; (ii) that groundwater is likely to be present at depths of the heat source on all of the islands; (iii) the tendency for permeability to be relatively high near calderas, rift zones, and mapped faults; and (iv) the fact that elevated permeability associated with those features and the heat associated with intrusive magmatism decreases with age. These four considerations confirm the presence of geothermal resources on the active Kilauea volcano, and suggest a high likelihood of resources on the less active Mauna Loa volcano. Resources are also possible, although less likely, near the summits and rift zones of the older (Hualālai, Kohala and Mauna Kea) volcanoes on Hawaii Island. The favorabilility of resources is reduced on Lanai and Maui due to their greater ages, but groundwater data suggest geothermal activity exists. A possible heat source for East Maui (Haleakalā) is the recent activity associated with prolonged post-shield volcanism. Resouce favorability on Oahu and Kauai is reduced further due to their greater ages, but groundwater data suggest thermal fluids are still present. On the Koʻolau range of Oahu, and on Kauai, the relatively recent rejuvenated volcanism is a possible source of heat.

Although geothermal resources are expected to be most prominent on the young island of Hawaii, the population of this island is relatively low, and nearly half of its demand for electricity is already supplied by renewable sources, including geothermal. The demand and viability of geothermal energy production may be greater on the more populated islands of Maui and Oahu; therefore exploration efforts on or near (i.e., Lanai) these islands is highly desirable. More discussion of viability issues is presented in Lautze et al. (2017).

Please cite this article in press as: Lautze, N., et al., Play fairway analysis of geothermal resources across the State of Hawaii: 1. Geological, geophysical, and geochemical datasets. Geothermics (2017), http://dx.doi.org/10.1016/j.geothermics.2017.02.001

7. Conclusions

This Hawaii Play Fairway Analysis provides the first comprehensive statewide geothermal resource assessment in Hawaii in over three decades, and is the first to produce a quantitative resource probability model (Ito et al., 2016). As part of this Hawaii PFA, the authors made a concerted effort to be inclusive of any and all existing datasets that may indicate subsurface Heat, Permeability, and Fluid—the three qualities necessary for a geothermal resource. Such datasets were identified and ranked in terms of their importance to indicate each of three qualities through a process of expert elicitation. This paper justifies the inclusion and ranking of each dataset, provides maps of much of the data, and gives the references from which the data were obtained. It is expected that the data incorporated in this analysis will soon be available from the DOE's National Geothermal Repository.

The next paper on this project by Ito et al. (2016) details the development and application of our geostatistical method, which is universally applicable but was used here to produce an updated statewide geothermal resource probability map for Hawaii, as well as a quantification of confidence in the resource probabilities that were computed. A third paper by Lautze et al. (2017) describes the development viability criteria that were the 3rd aspect (in addition to probability and confidence) used to develop a prioritized roadmap of future exploration activities.

This PFA finds that the likelihood of abundant geothermal resources is highest on the youngest island of Hawaii, but groundwater indicators suggest that a significant likelihood for resources also exists on the older islands. Development viability criteria, including demand for renewable energy and anticipated levels of community acceptance, motivate further exploration across the state. This Hawaii PFA, and in particular the data types described in this paper, are likely to be most directly applicable to other mid-ocean plate hotspot settings in the world, such as American Samoa, the Comoros Islands (Africa), and the Galapagos Islands (Ecuador). The approach and methodology applied in this PFA can be adapted to the evaluation of geothermal prospects in a global array of geologic settings – through an appropriate selection and weighting of regionally specific datasets.

Acknowledgements

We thank the U.S. Department of Energy's Geothermal Technologies Program for providing funding and management of this project, under award number DE-EE6729. Local expert researchers, including John Sinton, James Foster, Stephen Martel, Robert Whittier, and Ormat geologists, willingly shared their knowledge throughout this project. We also thank thesis student Hannah Schuchmann and GIS wizard Mahany Lindquist for their enthusiastic participation.

Appendix A. Hawaii play fairway data sources, 2016

(a) Geology

Calderas, rift zones, vents and dikes are sites where hot intrusive rocks were emplaced and might still contain heat. Rift zones are also locations where extension may have created permeability for fluid flow.

Bianco, T.A., Ito, G., Becker, J.M., and Garcia, M.O., 2005, Secondary Hawaiian volcanism formed by flexural arch decompression: Geochemistry Geophysics Geosystems, v. 6, p. 1–24, doi: 10.1029/2005GC000945.

Garcia, M.O., Hanano, D., Flinders, A., Weis, D., Ito, G., and Kurz, M.D., 2012, Age, geology, geophysics and geochemistry of Mahukona Volcano, Hawai'i: Bulletin of Volcanology, v. 74, p. 1445–1463, doi: 10.1007/s00445-012-0602-4.

Sherrod, D.R., Sinton, J.M., Watkins, S.E., and Brunt, K.M., 2007, Geologic map of the State of Hawai'i: U.S. Geological Survey, Open-File Report 2007-1089, scales 1:250,000 and 1:100,000, http://pubs.usgs.gov/of/2007/1089/ (accessed October 2015).

Sinton, J.M., 2015, His input at team meetings: Honolulu, University of Hawai'i at Mānoa.

Sinton, J.M., n.d., Lecture notes from his graduate-level course in Hawaiian geology: Honolulu, University of Hawai'i at Mānoa.

U.S. Geological Survey, 2006, Quaternary fault and fold database for the United States: http://earthquake.usgs.gov/hazards/qfaults/ (accessed 2013).

(b) Gravity

Team member Ito has provided grids of residual gravity anomalies as well as 3D models of density anomalies produced by geophysical inversion.

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

Kauahikaua, J.P., 1993, Geophysical characteristics of the hydrothermal systems of Kilauea volcano, Hawaii: Geothermics, v. 22, p. 271–299, doi:10.1016/0375-6505(93)90004-7.

Kauahikaua, J.P., Duarte, K., and Foster, J., 1998, A preliminary gravity survey of the Kailua-Kona area, Hawaii, for delineation of a hydrologic boundary: U.S. Geological Survey Open-File Report 98–110, 21 p., http://pubs.usgs.gov/of/1998/0110/report.pdf (accessed October 2015).

(c) Magnetotelluric (MT)

The data from recent surveys are currently being processed.

Bartel, L.C., and Jacobson, R.D., 1987, Results of a controlled-source audiofrequency magnetotelluric survey at the Puhimau thermal area, Kilauea Volcano, Hawaii: Geophysics, v. 52, p. 665–677, doi: 10.1190/1.1442334.

Jackson, D.B., and Sako, M.K., 1982, Self-potential surveys related to probable geothermal anomalies, Hualalai Volcano, Hawaii: U.S. Geological Survey Open-File Report 82–127, 20 p., http://pubs.usgs.gov/of/1982/0127/report.pdf (accessed October 2015).

Kauahikaua, J.P., 1981, Interpretation of time-domain electromagnetic soundings in the east rift geothermal area of Kilauea Volcano, Hawaii: U.S. Geological Survey Open-File Report 81–979, 25 p., http://pubs.usgs.gov/of/1981/0979/report.pdf (accessed October 2015).

Kauahikaua, J.P., 1990, The location and mapping of hydrologic regimes and thermal waters in Hawai'i: The use of electrical geophysical techniques, *in* Transactions, 1990 International Symposium on Geothermal Energy, Kailua-Kona, Hawaii: Davis, CA, Geothermal Resources Council, v. 14, no. 2, p. 1489–1492, http://pubs.er.usgs.gov/publication/70015944 (accessed October 2015).

Mattice, M.D., 1981, Geothermal and ground water exploration on Maui, Hawaii, by applying D.C. electrical soundings [M.S. thesis]: Honolulu, University of Hawai'i at Mānoa, 102 p., http://hdl.handle.net/10125/21686 (accessed October 2015).

Pierce, H.A., and Thomas, D.M., 2009, Magnetotelluric and audiomagnetotelluric groundwater survey along the Humu'ula portion of Saddle Road near and around Pohakuloa Training Area, Hawaii: U.S. Geological Survey Open-File Report 2009-1135, 160 p., http://pubs.usgs.gov/of/2009/1135/pdf/ofr2009-1135.pdf (accessed October 2015).

Zablocki, C.J., 1976, Some electrical and magnetic studies of Kilauea Iki lava lake, Hawaii: U.S. Geological Survey Open-File

Report 76–304, 19 p., http://pubs.er.usgs.gov/publication/ofr76304 (accessed October 2015).

Zohdy, A.A.R., and Jackson, D.B., 1969, Application of deep electrical soundings for groundwater exploration in Hawaii: Geophysics, v. 34, p. 584–600, doi:10.1190/1.1440033

(d) GPS Geodesy

Time series of displacements at permanent Global Positioning System (GPS) stations on the Island of Hawaii were used to produce models of land surface motion and then horizontal divergence, which may create permeability.

Brooks, B.A., Foster, J.H., Bevis, M., Frazer, L.N., Wolfe, C.J., and Behn, M., 2006, Periodic slow earthquakes on the flank of Kīlauea volcano, Hawaiʻi: Earth and Planetary Science Letters, v. 246, p. 207–216, http://www.soest.hawaii.edu/pgf/Publications/brooks_etal_epsl_06.pdf (accessed October 2015).

Pacific GPS (Global Positioning System) Facility, University of Hawaiʻi at Mānoa, 2015, Horizontal velocities data: Pacific GPS Facility, University of Hawaiʻi at Mānoa.

(e) Seismicity

Seismicity can act as a source of permeability as well as a hazard.

U.S. Geological Survey, n.d., U.S.G.S. Advanced National Seismic System (ANSS) catalog of seismic events for the State of Hawaii region: http://earthquake.usgs.gov/earthquakes/search/(accessed October 2015).

(i) Water Wells, Geothermal Wells, and Springs

(i)Well Temperature

State of Hawaii, Department of Land and Natural Resources, Commission of Water Resource Management; 2015, Well index database: http://dlnr.hawaii.gov/cwrm/groundwater/wellinfo/ (accessed July 14, 2014).

Hawaii Institute of Geophysics, University of Hawaiʻi at Mānoa; National Geophysical Data Center, National Oceanic and Atmospheric Administration for the Geothermal and Hydropower Technologies Division, U.S. Department of Energy; 1983, Geothermal resources of Hawaii, 1983: National Geophysical Data Center, National Oceanic and Atmospheric Administration for the Geothermal and Hydropower Technologies Division, U.S. Department of Energy; scale 1:500,000, 1 sheet.

(ii) Cl/Mg and SiO_2 Well Values

City and County of Honolulu, Board of Water Supply; 2015, Mineral analysis data for Hawaii's water supply (via email dated March 6, 2015, from BWS geologist Nancy Matsumoto).

County of Hawaii, Department of Water Supply; 2014, Mineral analysis data (accessed November 2014).

Cox, M.E., and Thomas, D.M., 1979, Chloride/magnesium ratio of shallow groundwaters as a regional geothermal indicator in Hawaii: University of Hawaiʻi at Mānoa, Hawaii Institute of Geophysics Report 3, HIG 79-9, 51 p., http://hdl.handle.net/10125/20124 (accessed October 2015).

Cox, M.E., Sinton, J.M., Thomas, D.M., Mattice, M.D., Kauahikaua, J.P., Helstern, D.M., and Fan, P-f., 1979, Investigation of geothermal potential in the Waianae caldera area, Western Oahu, Hawaii: Hawaii Geophysical Institute, University of Hawaiʻi at Mānoa, Assessment of Geothermal Resources in Hawaii 2, HIG-79-8, 84 p., doi:10.2172/5197537, http://hdl.handle.net/10524/47109 (accessed July 1, 2015).

GeothermEx, Inc., 1994, Annual report: Geothermal resource assessment: Richmond, CA, GeothermEx, Inc., 310 p., http://hdl.handle.net/10524/23406 (accessed October 2015).

Thomas, Donald. "Geothermal Resource Assessment in Hawaii." *Geothermics* 15(1986): 435–514.

U.S. Geological Survey, 2015, U.S.G.S. water-quality data for Hawaii: National water information system: http://waterdata.usgs.gov/hi/nwis/qw/(accessed March 10, 2015).

Hawaii Department of Health. UIC Report Geothermal Production Fluids dated June 14, 2014.

(iii) Other

D'Olier, W.L., and Iovenitti, J.L., 1984, Drilling and testing geothermal wells in an active volcanic domain, Puna Geothermal Field, Hawaii, USA, *in* Proceedings, ASEAN (Association of Southeast Asian Nations) Geothermal Workshop, Bandung, Indonesia, May 1, 1984: Jakarta, Indonesia, 7 p., http://hdl.handle.net/10524/12318 (accessed October 2015).

Epp, D., and Halunen, A.J., Jr., 1979, Temperature profiles in wells on the island of Hawaii: Hawaii Institute of Geophysics, University of Hawaiʻi at Mānoa, Geothermal Resources Exploration in Hawaii 7, Technical Report HIG-79-7, 31 p., http://hdl.handle.net/10125/20123 (accessed October 2015).

Gardner, M.C., and Klein, C.W., 1984, Drilling history and geology of the Lanipuna no. 6 geothermal test, Lanipuna prospect, Hawaii: Richmond, CA, GeothermEx, Inc., for Barnwell Industries, Inc., 41 p., http://hdl.handle.net/10524/12322 (accessed October 2015).

GeothermEx, Inc., 1994, Annual report: Geothermal resource assessment: Richmond, CA, GeothermEx, Inc., 310 p., http://hdl.handle.net/10524/23406 (accessed October 2015).

GeothermEx, Inc., 2000, Development opportunities for geothermal spas in the State of Hawaii: Richmond, CA, GeothermEx, Inc., 5 p., http://hdl.handle.net/10524/48060 (accessed October 2015).

Gingerich, S.B., 1995, The hydrothermal system of the lower east rift zone of Kilauea volcano: Conceptual and numerical models of energy and solute transport [Ph.D. thesis]: Honolulu, University of Hawaiʻi at Mānoa, 215 p., http://hdl.handle.net/10125/9868 (accessed October 2015).

Iovenitti, J.L., 1990, Shallow ground water mapping in the lower east rift zone Kilauea Volcano, Hawaii: Geothermal Resources Council, Transactions, v. 14, part 1, p. 699–703, http://pubs.geothermal-library.org/lib/grc/1001947.pdf (accessed October 2015).

Iovenitti, J.L., and D'Olier, W.L., 1985, Preliminary results of drilling and testing in the Puna geothermal system, Hawaii, *in* Proceedings, Tenth Workshop on Geothermal Reservoir Engineering, Stanford University, January 22–24, 1985: Stanford, CA, Stanford University, p. 65–71, http://hdl.handle.net/10524/23372 (accessed October 2015).

Kroopnick, P.M., Lau, L-k.S., Buddemeier, R.W., and Thomas, D.M., 1978, Geochemistry of a Hawaii geothermal well: HGP-A: Geothermal Resources Council, Transactions, v. 2, p. 375–377, http://hdl.handle.net/10125/21072 (accessed October 2015).

Stone, C., 1977, Chemistry, petrography, and hydrothermal alteration of basalts from Hawaii Geothermal Project Well-A, Kilauea, Hawaii [M.S. thesis]: Honolulu, University of Hawaiʻi at Mānoa, 84 p., http://hdl.handle.net/10125/21054 (accessed October 2015).

Thomas, D.M., A geochemical model of the Kilauea east rift zone, chap. 56 *of* Decker, R.W., Wright, T.L., and Stauffer, P.H., eds., Volcanism in Hawaii: U.S. Geological Survey Professional Paper 1350: Volcanism in Hawaii, v. 2, p. 1507–1525, http://hdl.handle.net/10125/23623 (accessed October 2015).

Tilling, R.I., and Jones, B.F., 1991, Composition of waters from the research drill hole at summit of Kilauea Volcano and of selected thermal and non-thermal groundwaters, Hawaii: U.S. Geological Survey Open-File Report 91–133-A, 28 p., http://pubs.usgs.gov/of/1991/0133a/report.pdf (accessed October 2015).

Tilling, R.I., and Jones, B.F., 1996, Waters associated with an active basaltic volcano, Kilauea, Hawaii; variations in solute source, 1973–1991: Geological Society of America Bulletin, v. 108, no. 5, p. 562–577, doi:10.1130/0016-7606(1996)108<0562:WAWAAB>2.3.CO;2.

Trusdell, F.A., Novak, E., Evans, S.R., and Okano, K., 1999, Core lithology from the State of Hawaii Scientific Observation Hole 1, Kilauea Volcano, Hawaii: U.S. Geological Survey Open-File Report 99–389, 67 p., http://hdl.handle.net/10125/21548 (accessed October 2015).

University of Hawaii, 1976, Hawaii Geothermal Project: Progress report on the drilling program: Honolulu, University of Hawaii, 12 p., http://hdl.handle.net/10125/22352Geothermics_Datasets_submission.docx (accessed October 2015).

Visher, F.N., and Mink, J.F., 1964, Ground-water resources in southern Oahu, Hawaii: U.S. Geological Survey Water-Supply Paper 1778, 133 p., http://pubs.er.usgs.gov/publication/wsp1778 (accessed October 2015).

Waibel, A., 1983, A review of the hydrothermal mineralogy of Hawaii Geothermal Project Well-A, Kilauea, Hawaii: Geothermal Resources Council, Transactions, v. 7, p. 205–209, https://www.geothermal-library.org/index.php?mode=pubs&action=view&record=1001066 (accessed October 2015).

(g) Groundwater Flow Models

Oahu

Rotzoll, K., and El-Kadi, A.I., 2007, Numerical ground-water flow simulation for Red Hill fuel storage facilities, NAVFAC Pacific, Oahu, Hawaii: Water Resources Research Center, University of Hawaiʻi at Mānoa; 86 p., ftp://ftp.soest.hawaii.edu/krotzoll/pub/ROTZOLL_%282007%29_RedHill_FlowModel.pdf (accessed October 2015).

Whittier, R.B., and El-Kadi, A.I., 2009, Human and environmental risk ranking of onsite sewage disposal systems: Final: Department of Geology and Geophysics, University of Hawaii at Manoa, 142 p., http://health.hawaii.gov/wastewater/files/2015/09/OSDS_OAHU.pdf (accessed October 2015).

Whittier, R.B., Rotzoll, K., Dhal, S., El-Kadi, A.I., Ray, C., Chen, G., and Chang, D., 2008, Hawaii source water assessment program report, vol. 7: Island of Oahu: Water Resources Research Center, University of Hawaiʻi at Mānoa.

All Neighbor Islands

Whittier, R.B., and El-Kadi, A.I., 2014, Human health and environmental risk ranking of on-site sewage disposal systems for the Hawaiian islands of Kauai, Molokai, Maui, and Hawaii: Final: Department of Geology and Geophysics, University of Hawaiʻi at Mānoa, 257 p., http://health.hawaii.gov/wastewater/files/2015/09/OSDS_NI.pdf (accessed October 2015).

Kauai

Whittier, R.B., Rotzoll, K., Dhal, S., El-Kadi, A.I., Ray, C., Chen, G., and Chang, D., 2015, Hawaii source water assessment program report, vol. 4: Island of Kauai: Water Resources Research Center, University of Hawaiʻi at Mānoa, prepared for the State of Hawaii, Department of Health, Safe Drinking Water Branch.

Molokai

Whittier, R.B., Rotzoll, K., Dhal, S., El-Kadi, A.I., Ray, C., Chen, G., and Chang, D., 2008, Hawaii source water assessment program report, vol. 6: Island of Molokai: Water Resources Research Center, University of Hawaiʻi at Mānoa, prepared for the State of Hawaii, Department of Health, Safe Drinking Water Branch.

Lanai

Whittier, R.B., Rotzoll, K., Dhal, S., El-Kadi, A.I., Ray, C., Chen, G., and Chang, D., 2010, Hawaii source water assessment program report, vol. 3: Island of Lanai: Water Resources Research Center, University of Hawaiʻi at Mānoa, prepared for the State of Hawaii, Department of Health, Safe Drinking Water Branch.

Maui

Whittier, R.B., Rotzoll, K., Dhal, S., El-Kadi, A.I., Ray, C., Chen, G., and Chang, D., 2008, Hawaii source water assessment program report, vol. 5: Island of Maui: Water Resources Research Center, University of Hawaiʻi at Mānoa, prepared for the State of Hawaii, Department of Health, Safe Drinking Water Branch.

Hawaii

Whittier, R.B., Rotzoll, K., Dhal, S., El-Kadi, A.I., Ray, C., Chen, G., and Chang, D., 2008, Hawaii source water assessment program report, vol. 2: Island of Hawaii: Water Resources Research Center, University of Hawaiʻi at Mānoa, prepared for the State of Hawaii, Department of Health, Safe Drinking Water Branch.

(h) Groundwater Recharge

All of the Islands Listed Below

Whittier, R.B., and El-Kadi, A.I., 2014, Human health and environmental risk ranking of on-site sewage disposal systems for the Hawaiian islands of Kauai, Molokai, Maui, and Hawaii: Final: Department of Geology and Geophysics, University of Hawaiʻi at Mānoa, 257 p., http://health.hawaii.gov/wastewater/files/2015/09/OSDS_NI.pdf (accessed October 2015).

Hawaii

Oki, D.S., 1999, Geohydrology and numerical simulation of the ground-water flow system of Kona, island of Hawaii: U.S. Geological Survey Water-Resources Investigation Report 99–4073, 70 p., http://pubs.er.usgs.gov/publication/wri994073 (accessed October 2015).

Oki, D.S., 2002, Reassessment of ground-water recharge and simulated ground-water availability for the Hawi area of North Kohala, Hawaii: U.S. Geological Survey Water-Resources Investigation Report 02-4006, 62 p., http://pubs.usgs.gov/wri/wri02-4006/ (accessed October 2015).

Lanai

Hardy, W.R., 1996, A numerical ground-water model for the Island of Lanaʻi, Hawaii: Honolulu, State of Hawaii, Department of Natural Resources, Commission on Water Resources Management; CWRM Report No. CWRM-1, 270 p., http://files.hawaii.gov/dlnr/cwrm/publishedreports/CWRM-1.pdf (accessed October 2015).

Molokai

Oki, D.S., 1997, Geohydrology and numerical simulation of the ground-water flow system of Molokai, Hawaii: U.S. Geological Survey Water-Resources Investigation Report 97–4176, 62 p. http://pubs.er.usgs.gov/publication/wri974176 (accessed October 2015).

Kauai

Izuka, S.K., and Oki, D.S., 2002, Numerical simulation of ground-water withdrawals in the southern Lihue Basin, Kauai, Hawaii: U.S. Geologic Survey Water-Resources Investigations Report 01-4200, 54 p., http://pubs.usgs.gov/wri/wri014200/#pdf (accessed October 2015).

Shade, P.J., 1995, Water budget for the island of Kauai, Hawaii: U.S. Geologic Survey Water-Resources Investigations Report

95–4128, 25 p., http://pubs.er.usgs.gov/publication/wri954128 (accessed October 2015).

(j) Land Use/Classification and Ownership

National Park Service, U.S. Department of the Interior; 2009, National park boundaries: https://catalog.data.gov/dataset/national-park-boundariesf0a4c (accessed October 2015).

State of Hawaii, Office of Planning, 2015, Downloadable layers, 015–Cadastral and land descriptions (Conservation district subzones and State land use districts): http://planning.hawaii.gov/gis/download-gis-data/(accessed October 2015).

(k) Hawaiian Place Name

These place names indicate heat (Native Hawaiian student Kamahana Kealoha compiled them). Appendix E describes the research results.

Bier, J.A., 2011, Map of Hawai'i, the Big Island: Full color topographic (8th ed.): University of Hawai'i Press, scale 1:260,000, 1 sheet.

Bliss, J.D., 1983, Hawaii, basic data for thermal springs and well as recorded in GEOTHERM: U.S. Geological Survey Open-File Report 83–430, http://pubs.er.usgs.gov/publication/ofr83430 (accessed October 2015).

Hawaiian Ethnological Notes, Water Holes: Honolulu, Bishop Museum Library, v. 1, p. 1108–1109, http://data.bishopmuseum.org/HEN/index.php (accessed October 2015).

Hoku o Hawaii, 1930, March 11, Kupunakane and Kupunawahine Springs, *cited in* Sterling, E.P., and Summers, C.C., compilers, 1978, Sites of Oahu: Honolulu, Bernice P. Bishop Museum, p. 247.

Kanahele, C., 1970, Clinton Kanahele interviewing Gus Kaleohano June 11, 1970, at Laie, Oahu, Hawaii (interview transcript and translation): Clinton Kanahele Collection, Brigham Young University–Hawaii, 26 p., https://library.byuh.edu/sites/library.byuh.edu/files/archives/img/Clinton%20Kanahele%20Interview%20PDFs/Gus%20Kaleohano%20Interview.pdf (accessed January 29, 2015).

Kirch, P.V., 2001, Hawaii, ancestral Polynesia: An essay in historical anthropology: Cambridge, New York, Cambridge University Press, 375 p.

Luciano, M., Enos, K., LaFrance, L., Scanlan, J., and Williams, H.T., 2005, Pāpōhaku Dunes cultural and natural resource preservation plan, Kaluako'i, Moloka'i, Hawai'i: Honolulu, Department of Urban and Regional Planning, University of Hawai'i at Mānoa, various paging.

Pukui, M.K., 1983, 'Ōlelo no'eau: Hawaiian proverbs & poetical sayings: Honolulu, Bishop Museum Press, Bernice P. Bishop Museum Special Publication No. 71, 351 p.

Pukui, M.K., and Elbert, S.H., 1971, Glossary of Hawaiian gods, demigods, family gods, and a few heroes, *in* Hawaiian dictionary; Hawaiian-English, English-Hawaiian: Honolulu, University of Hawai'i Press, p. 381–398.

Pukui, M.K., and Elbert, S.H., 1986, Hawaiian dictionary: Hawaiian-English, English-Hawaiian (Revised and enlarged edition): University of Hawai'i Press, http://ulukau.org/elib/cgi-bin/library?c=ped&l=en (accessed October 2015).

Pukui, M.K., Elbert, S.H., and Mookini, E.T., 1976, Place names of Hawaii (Revised and expanded edition): University of Hawai'i Press, 289 p., http://ulukau.org/elib/cgi-bin/library?c=pepn&l=en (accessed October 2015).

Reeve, R.B., 1993, The place names of Kaho'olawe: A study of those place names known from the island of Kaho'olawe: Kaho'olawe Island Conveyance Commission, Kaho'olawe Island Conveyance Commission consultant report No. 16, 259 p.

Sherrod, D.R., Hagstrum, J.T., McGeehin, J.P., Champion, D.E., and Trusdell, F.A., 2006, Distribution, ^{14}C chronology, and paleomagnetism of latest Pleistocene and Holocene lava flows at Haleakala volcano, Island of Maui, Hawai'i: A revision of lava flow hazard zones: Journal of Geophysical Research: Solid Earth, v. 111, doi:10.1029/2005JB003876, http://onlinelibrary.wiley.com/doi/10.1029/2005JB003876/full (accessed October 2015).

Sherrod, D.R., Sinton, J.M., Watkins, S.E., and Brunt, K.M., 2007, Geologic map of the State of Hawai'i: U.S. Geological Survey Open-File Report 2007–1089, scale 1:250,000, 8 sheets, http://pubs.usgs.gov/of/2007/1089/(accessed October 2015).

Sterling, E.P., and Summers, C.C., compilers, 1978, Sites of Oahu: Honolulu, Bernice P. Bishop Museum, 352 p.

Taylor, C., 1954, August 18, Hapu'u and Kalaihauola, Honolulu Star-Bulletin, *cited in* Sterling, E.P., and Summers, C.C., compilers, 1978, Sites of Oahu: Honolulu, Bernice P. Bishop Museum, p. 324–325.

Woodruff, J.L., 1987, Geothermal spas in Hawaii: A new tourist industry? (A preliminary report): Honolulu, Hawaii Natural Energy Institute, University of Hawai'i at Mānoa, 71 p., http://hdl.handle.net/10125/21057 (accessed October 2015).

References

Anderson, E., Crosby, D., Ussher, G., 2000. Bulls-eye! Simple resistivity imaging to reliably locate the geothermal reservoir. In: Proceedings World Geothermal Congress 2000, Kyushu – Tohoku, Japan, pp. 909–914, May 28–June 10.

Bizimis, M., Salters, V.J.M., Garcia, M.O., Norman, M.D., 2013. The composition and distribution of the ejuvenated component across the Hawaiian plume: Hf-Nd-Sr-Pb isotope systematics of Kaula lavas and pyroxenite xenoliths. Geochem. Geophys. Geosyst. 14, 4458–4478, http://dx.doi.org/10.1002/ggge.20250.

Büttner, Grit, Huenges, Ernst, 2003. The heat transfer in the region of the Mauna Kea (Hawaii)—constraints from borehole temperature measurements and coupled thermo-hydraulic modeling. Tectonophysics 371 (1), 23–40.

Conrad, M.E., Thomas, D.M., Flexser, S., Vanneman, T.W., 1997. Fluid flow and water-rock interaction in the East Rift Zone of Kilauea Volcano, Hawaii. J. Geophys. Res. 102 (B7), 15 (021-11,037).

Cumming, W., 2009. Geothermal resource conceptual models using surface exploration data. In: Proceedings, Thirty-Fourth Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California, p. 27 (Department of Business, Economic Development and Tourism, 2014 Hawaii Energy Facts & Figures November 2014).

Department of Business, Economic Development and Tourism, 2015. State of Hawaii Energy Resources Coordinator's Annual Report 2015, 77.

Evans, S.R., Novak, E.A., Trusdell, F.A., 1992a. Scientific Observation Hole Project, SOH 1 Well, Visual Core Descriptions, Volume 1A, February 1991. Puna Research Center, Pahoa (HI).

Evans, S.R., Novak, E.A., Trusdell, F.A., 1992b. Scientific Observation Hole Project, SOH 1 Well, Visual Core Descriptions, Volume 2A, February 1991. Puna Research Center, Pahoa (HI).

Evans, S.R., Novak, E.A., Trusdell, F.A., 1992c. Scientific Observation Hole Project, SOH 1 Well, Visual Core Descriptions, Volume 3A, February 1991. Puna Research Center, Pahoa (HI).

Evans, S.R., Novak, E.A., Trusdell, F.A., 1992d. Scientific Observation Hole Project, SOH 4 Well, Visual Core Descriptions, Volume 1A, September 1990. Puna Research Center, Pahoa (HI).

Evans, S.R., Novak, E.A., Trusdell, F.A., 1992e. Scientific Observation Hole Project, SOH 4 Well, Visual Core Descriptions, Volume 1B, September 1990. Puna Research Center, Pahoa (HI).

Evans, S.R., Novak, E.A., Trusdell, F.A., 1992f. Scientific Observation Hole Project, SOH 4 Well, Visual Core Descriptions, Volume 2A, September 1990. Puna Research Center, Pahoa (HI).

Evans, S.R., Novak, E.A., Trusdell, F.A., 1992g. Scientific Observation Hole Project, SOH 4 Well, Visual Core Descriptions, Volume 2B, September 1990. Puna Research Center, Pahoa (HI).

Flinders, A.F., Ito, G., Garcia, M.O., Sinton, J.M., Kauahikaua, J.P., Taylor, B., 2013. Intrusive dike complexes, cumulate cores and the extrusive growth of Hawaiian volcanoes. Geophys. Res. Lett. 40, 3367–3373, http://dx.doi.org/10.1002/grl.50633.

Garcia, M.O., Swinnard, L., Weis, D., Greene, A.R., Tagami, T., Sano, H., Gandy, C.E., 2010. Petrology, geochemistry and geochronology of Kaua'i lavas over 4.5 Myr: implications for the origin of rejuvenated volcanism and the evolution of the hawaiian plume. J. Petrology 51 (7), 1507–1554.

Ito, G., Frazer, N., Lautze, N.C., Thomas, D., Hinz, N., Waller, D., Whittier, R., 2016. Play Fairway Analysis of Geothermal Resources across the State of Hawaii: 2. Resource Probability Mapping, http://www.sciencedirect.com/science/article/pii/S0375650516301407 (in press).

Johnston, J.M., Pellerin, L., Hohmann, G.W., 1992. Evaluation of electromagnetic methods for geothermal reservoir detection: Geothermal Resources Council. Transactions 16, 241–245.

Lautze, N.C., Thomas, D., Waller, D., Hinz, N., Frazer, N., Ito, G., 2017. Play Fairway Analysis of Geothermal Resources across the State of Hawaii: 3. Use of Development Viability as one criteria to prioritize future exploration activities. Geothermics (in revision).

Mink, J.F., Lau, S., 1990. Water Resources Research Commision Tehcnical Report No. 179 Aquifer Identification and Classification for Oahu , Groundwater protection strategy for Hawaii.

Pierce, H.A., Thomas, D.M., 2009. Magnetotelluric and audiomagnetotelluric groundwater survey along the Humu'ula portion of Saddle Road near and around the Pohakuloa Training Area. Hawaii, U.S. Geol. Survey Open File Report 2009-1135, 164.

Seyfried, W.E., Bischoff, J.L., 1979. Low temperature basalt alteration by seawater: an experimental study at 70 °C and 150 °C. Geochim. Cosmochim. Acta 43, 1937–1947.

Sherrod, D.R., Sinton, J.M., Watkins, S.E., Brunt, K.M., 2007. Geologic map of the State of Hawaii. U.S. Geological Survey Open-File Report 2007-1089, scale 1:250,000, 8 sheets (accessed October 2015) http://pubs.usgs.gov/of/2007/1089/.

Thomas, D.M., Haskins, E., 2013. Analysis of Hydrologic Structures Within an Ocean Island Volcano Using Diamond Wireline Core Drilling AGU Fall Meeting H11l-1263.

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

Thomas, D., Wallin, E., Lautze, N.C., Lienert, B., Pierce, H., 2014. A blind hydrothermal system in an ocean island environment: Humu'ula Saddle, Hawaii Island. AGU Fall Meet., V21A–4731.

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

Thomas, D.M., 1987. A geochemical model of the Kilauea East Rift Zone, chapter 56 in U.S. Geological Survey Professional Paper 1350. In: Decker, R., Wright, T., Stauffer, P. (Eds.), Volcanism in Hawaii. , pp. 1507–1525.

Thomas, D.M., 1989. Hydrothermal systems in Hawaii, contributed to chapter 12, the Hawaiian-Emperor chain, of vol. N. The Eastern Pacific Ocean and Hawaii, Geological Society of America Series, Decade of North American Geology, 271–277.

Trusdell, F.A., Novak, E.A., Evans, R.S., 1993. Core Lithology State of Hawaii Scientific Observation Hole 4 Kilauea Volcano, Hawaii. U.S. Dept. of the Interior, U.S. Geological Survey, Menlo Park (CA).

U.S. Energy Information Administration, 2015. Electric Power Monthly (accessed 6.04.2015) https://www.eia.gov/state/?sid=HI.

Ussher, G., Harvey, C., Johnstone, R., Anderson, E., 2000. Understanding the resistivities observed in geothermal systems. In: Proceedings World Geothermal Congress 2000, Kyushu – Tohoku, Japan, pp. 1915–1920, May 28–June 10.

Wilmshurst, J.M., Hunt, T.L., Lipo, C.P., Anderson, A.J., 2010. High-precision radiocarbon dating shows recent and rapid initial human colonization of East Polynesia. Proc. Nat. Acad. Sci. U. S. A. 108, 1815–1820 http://www.pnas.org/content/108/5/1815.full.