Hawai‘i Statewide Geothermal Play Fairway Analysis: Final Phase Aqueous Geochemistry Results and Work in Progress

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ABSTRACT
Hawaii’s remote location, lack of fossil fuel resources, and need to address energy generation and pollution in the face of climate change, make it imperative to characterize its indigenous geothermal resources. The Department of Energy funded the Hawai‘i Play Fairway project to accomplish this task. Play Fairway analysis is an ideal, cost saving and risk-reducing methodology for subsurface resource exploration. The project is now in its third and final phase. This is the first statewide geothermal assessment since the 1970’s, and incorporates numerous advancements in technology and methods developed in the interim. In phase one, we compiled legacy geologic, geochemical, geophysical, structural, volcanic age, and cultural data to create a statistical probability model for blind geothermal resources. Phase two produced new data to enhance this model. The final phase seeks to test the model by investigating some of the identified high probability targets, and locate thermal anomalies. Noble gas, stable isotope, and common ions/metals analysis of well waters from sites on Kaua‘i, Lāna‘i, O‘ahu, Maui, and Hawai‘i are being undertaken to identify potential blind resources. Many traditional geochemical geothermal exploration techniques have proven to be of no value in Hawai‘i, however, Cl/Mg, dissolved SiO₂ concentration, sulfate concentration, carbonate concentration, δ¹³C-DIC, δ¹⁸O-H₂O, and ³He/⁴He are proven for identifying trends at Hawai‘i’s known geothermal resource locations, and in similar volcanic island settings globally. Six sites have been sampled on Kaua‘i, and 68 well sites have been identified on the other islands, though only a subset of these will ultimately be sampled due to issues with land access and operability of well pumps. Preliminary data from the Kaua‘i samples showed little direct indication of heat. However, an R/RA (³He/⁴He in sample over ³He/⁴He of the atmosphere) of ~7 was found in one well, suggesting either dilution of geothermal fluids with a magmatic heat source, or influence from deep structurally controlled fluid circulation. All other Kaua‘i wells showed an R/RA value of ~1. Given that the only sampled island thus far has a positive indicator for mantle heat, and that Kaua‘i is one of the farthest main Hawaiian Islands from the hot-spot, it is expected that some of the additional sites will also yield positive results.
1. Introduction

The Hawai‘i Play Fairway Analysis (PFA), is part of the Department of Energy (DOE) funded national Geothermal Play Fairway Analysis project (DE-FOA-0000841), for which work began in 2015 (award DE-EE006729.0000). In the two previous phases of work, compilation of legacy data relevant to a geothermal play in Hawai‘i was compiled and a resource and risk probability model was developed (Ito et.al. 2017, Lautze et.al. 2015, Lautze et.al. 2016a, Lautze et.al. 2017a, Lautze et.al. 2017b, Waller et.al. 2015), and then improved through the collection of new data (Lautze et.al. 2016b, Lautze et.al. 2018). Using the improved model from phase two, additional sampling sites were identified for targeting during phase three to validate the models efficacy. During this final phase of the project we will (1) drill to deepen two wells on Lana‘i, (2) complete new geophysical surveys in high resource probability locations, and (3) target well waters from 74 sites across five islands for aqueous geochemical analysis, of which six samples from one island have been completed as of 3/13/2019. Ultimately, we will sample only a portion of the wells due to land access issues for privately owned wells, and well maintenance issues in older wells. We discuss only the aqueous geochemistry portion of the project here.

2. Methodology and Site Selection

Building upon the work done during phase two (Lautze et.al. 2018, Tachera et.al. 2017), we began the phase three geochemical assessment by comparing the compiled phase one aqueous geochemical and temperature data to that obtained during phase two. This data is available through the Hawai‘i Groundwater and Geothermal Resource Center (HGGRC) as well as the Geothermal Collection on ScholarSpace (https://scholarspace.manoa.hawaii.edu/handle/10125/21320) and the Geothermal Data Repository (GDR)(http://repository.stategeothermaldata.org/repository/). Nearly 5500 data entries exist in the well database with varying quality and detail for well physical and chemical parameters. The vast majority of these have important missing data, such as temperature and/or depth information, thus requiring the incorporation of other play fairway data to narrow selections. Only roughly 800 sites had detailed enough geochemical data to be of use.

We focused on wells located in the previously identified areas from the phase two improved model (Fig 1). These areas of study are the Līhu‘e Basin of Kaua‘i, the Waianae Caldera of O‘ahu, the Palawai Basin of Lana‘i, young volcanic areas in the Southwest of West Maui, and the Southwest Flank of Kohala Volcano on Hawai‘i. The Līhu‘e and Pālāwai Basins both bear striking similarity to calderas, as indicated by high gravity anomaly, ring fault structures, and dike orientations (Flinders et.al. 2013). A separate study undertaken on the Southwest Rift of Haleakala made additional exploration there unnecessary (Fercho et.al. 2015), though it did identify a potential resource. We will instead investigate the Northeast Rift of Haleakala in the Hana area, as this rift is among the longest on the Hawaiian Islands, which suggests a large volume flux of magma over the course of Haleakala’s life.
Figure 1: Adapted from Lautze et al. 2018. Phase two improved probability map, showing locations of phase three primary target sites. Note that some areas are crossed out, as these areas are no longer being targeted. This includes the Southwest Rift of Haleakala on Maui, most of Mauna Kea, and the Mauna Kea Saddle drilling site. They have been left here because they were identified by the model as primary targets.

For wells where the data is available, we consider the temperature of the waters to be of critical importance, but only when above ambient average summer surface temperatures for that location. This typically means well water temperature above 25-27°C, though there is substantial spatial variability. We accomplished analyzing this through the use of GIS mapping of the wells, symbolized to their temperatures, with a base-map of the average summer surface temperatures (Fig. 2). We did not exclude wells with temperatures below the 25-27°C threshold from consideration, but waters from cooler wells must show geochemical indicators that could be indicative of heat, such as a Cl/Mg ratio above 15, in order to be selected. In figure two, a number of wells are shown within the Līhu’e Basin of Kaua’i. Many of the wells show as having a 0°C temperature, which are the null value wells as listed in the database. Well temperatures in the Līhu’e Basin vary from around 20°C to 27°C. It is assumed that colder waters result from aquifers with higher elevation recharge, and no geothermal heat input. Warmer wells must stand out against the ambient surface temperatures to show as anomalous by this method. It is improbable that any existing well has been drilled directly into a thermal resource without being noticed previously. Thus all wells we are sampling are either diluted and vertically or horizontally distal from a heat source, or are not thermally influenced at all. The temperature comparison method serves as a highly conservative estimate of thermal anomaly. If a well is missed through this selection process, it is likely to be picked up by a geochemical indicator in another selection step. The NW Kilohana Well was an ideal target identified by this method, as it had a water temperature 4°C higher than the average August surface temperature. While it was promising, as a monitoring well we could
not sample the waters as no pump was in place. The nearest well we sampled was the Hanamaulu well, which was shallower, and had no geochemical or temperature data on record. We will likely face this, and numerous other complications in acquiring samples as the project continues.

Figure 2a: Līhu'e Basin, Kaua'i Mean August Surface Temperature Map. Point locations are wells. NW Kilohana Monitoring Well shows a 4°C difference between its water temperature and the surface temperature. Hanamaulu well, which had no temperature data was ultimately the nearest well to NW Kilohana that we could sample during phase 3. Surface temperature map from Giambelluca et.al. 2014. Kaua'i Hillshade map from State of Hawai'i Office of Planning http://planning.hawaii.gov/gis/download-gis-data/.
Geochemical parameters used in the site selection process are selected from calibration locations with similar geologic conditions as the Hawaiian Islands. The only known geothermal resource on the Hawaiian Islands is the Kapoho geothermal district, which is the location of Puna Geothermal Venture (PGV), which is the only operational geothermal power plant in the state of Hawai‘i. PGV, owned and operated by Ormat Technologies Inc., is located on the East Rift of Kilauea, the youngest and most active subaerial volcano on the Hawaiian Islands. There are numerous sources for geochemical data related to PGV (Thomas 1987, Evans et.al. 2015, Hilton et.al. 1997, Fercho et.al. 2015, Sorey and Colvard 1994, and others), which, when combined with data within the GDR for PGV allowed for an extensive calibration data set. We added additional calibration sites from the Azores (Cruz and Franca 2005), Indian Ocean ‘Black Smokers’ (Gamo et.al. 2001), the Reykjanes Peninsula, Iceland (Arnorsson 1978, Berehannu 2014), Ladolam-Lihir, New Guinea (Simmons and Brown 2006), and Hawaiian seawater. From this set of known resources we looked at Cl/Mg ratio (Thomas 1987), dissolved SiO$_2$, and SO$_4$, and compared them to wells across the state of Hawai‘i. Cl/Mg is known to increase as thermal waters in the presence of basalt precipitate out Mg mineral phases, while Cl is either conservative or being enhanced from volatiles in the heat source. SiO$_2$ has a well understood heat-dependent, normal solubility. SO$_4$ can be representative of magmatic volatiles being carried by thermal waters. Numerous other parameters would have been useful, but are not available broadly enough to draw comparative conclusions.
In figure 3a, the relationship of Cl/Mg ratio to temperature can be seen. While variability is high at lower temperatures, for Cl/Mg >100 the water samples come from geothermal systems without exception. Lower Cl/Mg wells can still be warm, but for the Hawaiian sample set and for our calibration points, very few wells had a Cl/Mg less than seawater at ~15 and still an above ambient temperature. Further, due to dilution of thermal waters with colder meteoric waters, a Cl/Mg >15 occurs in some cold waters. The Cl/Mg can in principal be largely preserved during dilution, though Mg bearing cold waters will suppress the signal. Figure four is a zoomed in portion of figure three, where we can see the trends possibly representative of dilution of thermal waters, as may be present in some of our target systems, and is expected to be encountered in exploration of blind resources. These lower temperature, elevated Cl/Mg wells make prime candidates for additional geochemical sampling (Fig. 3b).

![Figure 3a: Cl/Mg and Temperature plot for calibration sites and a set of selected wells from Hawai'i. The relationship between a high Cl/Mg ratio with elevated temperature can be seen. No high temperature well has a Cl/Mg less than that of seawater.](image-url)
Figure 3b: Cl/Mg Ratio and temperature for selected HI wells, and relevant calibration wells for the temperatures below boiling and more moderate Cl/Mg ratios. Wells from four of the target areas appear as unique populations.

SiO₂ is not conservative as a tracer, however the rate of precipitation from cooling water is slow, allowing supersaturation to be preserved temporarily. As such, SiO₂ may be suggestive of heat within the groundwater discharge. As such, even water some distance from a heat source can preserve an elevated dissolved SiO₂ content, so long as that water is not significantly diluted. Unfortunately, it is expected that given the high volume of rainfall and groundwater flux on the Hawaiian Islands that SiO₂ values will decline rapidly with distance from the site of geothermal outflow. Nevertheless, it is still possible to find anomalies, and when correlated to the Cl/Mg ratio, a trend can be established (Fig. 4).
SO\textsubscript{4} proved a more complicated signal. While SO\textsubscript{4} can be a representative of magmatic sulfur, it can also be a contaminant from industrial and agricultural activities, and can be introduced through mixing of freshwater and seawater. Among the highest SO\textsubscript{4} samples from our database is the Ala Moana Blvd well. Ala Moana is an area of brackish water mixing, as well as a substantial urban drainage for Honolulu on O'ahu, and is a prime example of SO\textsubscript{4} contamination. Because SO\textsubscript{4} is present in seawater, it is also present in freshwaters on the Hawaiian Islands, being brought inland as a volatile in rainwater, and in sea-spray. Normal waters fall on a mixing line between a low SO\textsubscript{4}, low Cl/Mg freshwater, and a high SO\textsubscript{4} seawater with Cl/Mg of 15. Thermal waters look more like seawater in terms of SO\textsubscript{4}, though none are as enriched in it as seawater (Fig. 5).

Each of the identified trends, when taken alone, are not definitive. However, when combined and overlapping, a blind geothermal resource may be present within the groundwater flow path. We took the geochemical information, along with the PFA probability of resource to select wells that would be targeted in phase three. Because the PFA used structural, geophysical, and volcanic age information in its model, we did not need to re-evaluate those methods here.
3. Preliminary Results and Planned Work

From 5500 plus wells in the state of Hawai‘i, we made a down-selection to 74 candidates for geochemical analysis in phase three through the above methods. The primary analytes are δ\(^{13}\)C-DIC, \(^{3}\)He, and \(^{4}\)He. These are of interest because the ultimate heat source for Hawaiian systems will be mantle heat, rising with the hot-spot plume, or along structural features related to it. In addition, we sampled for Ne, Ar, Kr, Xe, \(\delta^{18}\)O-H\(_2\)O, \(\delta^{D}\)H\(_2\)O, As, B, Ba, Be, Br, Ca, Cd, Cl, Co, Cr, Cu, Fe, F, K, Li, Mg, Mn, Mo, N, Na, Ni, P, Pb, Re, Sb, Se, SiO\(_2\), Sr, U, V, Zn, and SO\(_4\), in order to look for any other systematics, and improve the depth and volume of geochemical data available for the Hawaiian Islands. At this time, we have only analyzed samples from Kaua‘i, and of those δ\(^{13}\)C-DIC is not yet completed.

The isotope \(^{3}\)He is generally considered mantle helium, or primordial helium. Because this isotope is not produced radiogenically, and is unlikely to be produced in quantity at depth by other processes, the source of it must primarily be related to the mantle reservoir and is an inherited value. Conversely, nearly all \(^{4}\)He is produced radiogenically through uranium and thorium decay. Because of the light weight of both isotopes, they eventually escape to space after reaching the atmosphere. The flux into and out of the atmosphere results in a steady state where the atmospheric ratio of \(^{3}\)He/\(^{4}\)He is roughly 1.399\times10^{-6} (Ozima and Podosek 2002). The atmosphere is used as the common standard of comparison for noble gas measurements. The notation R/RA expresses the ratio of \(^{3}\)He/\(^{4}\)He in a sample to that of the atmosphere. Atmospheric values will be approximately one R/RA, crustal values with ingrown \(^{4}\)He will be less than one R/RA, and samples with mantle influence and excess \(^{3}\)He will typically be greater than one R/RA. In some cases a ratio near or below one can be observed when ingrown \(^{5}\)He is present alongside excess \(^{3}\)He, suppressing the R/RA value. As a result, it is important to look at both isotopes independently.

Not all geothermal systems have an elevated R/RA. Systems in continental settings can have substantial uranium and/or thorium can have a heat source related to radioactivity. The age of reservoir rocks can also simply suppress the geothermal signal through ingrown \(^{4}\)He so long as they are releasing their volatiles to the reservoir through water-rock interaction. Cold crustal fluids from the Basin and Range of Nevada and Utah have a value of ~0.02 R/RA, structurally controlled geothermal systems had a value of >0.2 to 2, while mantle influenced fluids globally range from ~6 to 35 R/RA (Kennedy and Van Soest 2007). An elevated R/RA is typically associated with areas of higher heat flow, even when water temperatures are suppressed by distance from resource or dilution with colder groundwater (Dobson et.al. 2015). Active serpentinization can also generate an elevated R/RA with values of ~4 (Abrahano et.al. 1990). Diffusion of helium from rocks and volcanic glass happens, but values would be expected to be elevated throughout basaltic systems if this route played a major role, which the data from this work shows is not the case and a background of atmospheric value is dominant. Fracturing of rock through earthquakes is also likely to release helium, but this could not be sustained past a short window after an earthquake. It is important to note, that the relationship between temperature and R/RA is not direct, and helium alone is not a geothermometer: the hottest waters in a system do not always have the highest R/RA, but will have an elevated value compared to cold, local groundwater. However, helium as it related to heat and heat flow is a clearly evidenced association.
Measured values for $R/R_a$ at PGV are approximately 15, and for the Southwest Rift of Haleakala, Maui, are a maximum of 8 (Fercho et al. 2015, Hilton et al. 1997). Of our six samples from the Līhu'e basin area on Kaua'i, four show an atmospheric value. One sample, from the deepest well, has an $R/R_a$ of 2, and the final sample from the Hanamaulu well, near the center of Līhu'e Basin and the Kilohana Crater, has an $R/R_a$ 7. This value comes as something of a surprise, as the youngest flows on Kaua'i are the Koloa rejuvenation volcanics, as young as 0.15 m.a. to 0.5 m.a. (Garcia et al. 2010). Rejuvenation volcanics are not generally voluminous enough to be thought to have a large underground magma system associated with them, though Kaua'i does have an extensive and long-lived rejuvenation phase. The Hanamaulu well had no chemical or temperature data for it during site selection, but was instead chosen based on the nearby NW and NE Kilohana Monitoring wells, maintained by the USGS. In well logs from drilling NW Kilohana, 32°C water was encountered at 1004 ft. (Gingerich and Izuka 1997). The NE Kilohana well log indicated extensive alteration, including a thick layer of green clays, and amygdaloidal basalts, but only temperatures of about 25°C (Izuka and Gingerich 1997). The combination of warm waters in one well and alteration phases in another made the area a target, but without pumps the USGS wells are difficult to sample for noble gas analysis, thus we chose Hanamaulu, as it was the nearest pumped well. If as expected the magma which supplied rejuvenation volcanics is not the source of heat and volatiles, it is instead possible that an island bounding normal fault (Fig. 6a, Sherrod et al. 2015), is allowing for deep fluid circulation and outgassing of mantle volatiles, which then flow out through the Līhu'e Basin/Caldera (Fig 6b, Reiners et al. 1998). This would also allow for some anomalous heat but it is unclear how much. Unfortunately, no correlating geochemical signatures are seen in the Hanamaulu well that would also indicate thermal anomaly, and its temperature was ambient, at 24.5°C. Additional work in the vicinity is clearly warranted. It is planned that by using specialized sampling tubes, able to be deployed down a well and then activated, we will eventually be able to sample the USGS wells on Kaua'i. Geophysical survey is also planned for this area.
Figure 6a: Structural map of Kaua‘i Island, showing N-S striking normal fault bounding the entire island, and intersecting the Līhu‘e Basin/Caldera. From Sherrod et.al. 2015.
The remaining 68 wells lie primarily in calderas or in conjunction with rejuvenation volcanics, with the exception of the Kohala area on Hawai‘i. The sites on Lāna‘i will be sampled between March and April 2019, and Hawai‘i will be sampled between May and June 2019. O‘ahu and Maui do not yet have hard dates, as access is currently being worked out, but will ideally be done during the summer months.

4. Conclusions

While the final phase of the PFA is still in progress, it is clear that our model has been able to identify low temperature anomalies on Lāna‘i and Kaua‘i. There is a high likelihood that the elevated temperatures seen at the remaining sites along with their chemical anomalies and structural associations will result in the discovery of additional helium anomalies. Helium has proven an invaluable technique for exploration, as R/Ra anomalies are unambiguously associated with heat sources and dilution and cooling of thermal waters does not heavily impact the values.

That a blind anomaly has been located on even the oldest subaerial volcano, suggests that the state of Hawai‘i may have undiscovered developable geothermal resources on every island. While it is not possible through this work to establish the quality of these resources for direct use or electrical generation, additional components of the PFA phase three will better characterize the resource on Lāna‘i, and yield some additional information about Kaua‘i.
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REFERENCES


