

Hawai‘i Play Fairway, Phase 3 Update

Nicole Lautze and Donald Thomas

University of Hawai‘i at Mānoa

Keywords

Geothermal, Hawai‘i, groundwater, geophysics, Play Fairway

ABSTRACT

A three-phase project funded by the U.S. Department of Energy, the Hawai‘i Play Fairway Project transitioned from Phase 2 to Phase 3. Phase 1 focused on collecting existing geologic, groundwater, and geophysical datasets. A statistical methodology was developed to rank and then integrate the collected data into a resource probability map and identified 10 regions of interest across the state of Hawai‘i. Phase 2 was then designed to collect new groundwater data in the regions of interest, gather new geophysical data on Lāna‘i, Maui, and Hawai‘i, and model topographically induced stresses to further characterize permeability. These Phase 2 data were then re-incorporated into an updated statewide resource probability and confidence maps. Phase 3 encompasses more high-investment exploratory work, including drilling a temperature observation well, continued geophysical surveys, and noble gas groundwater sampling in areas of highest probability and confidence. This paper summarizes a subset of the Phase 2 results and how that was considered when choosing the well drilling site, along with the current status of the Hawai‘i Play Fairway Project.

1. Introduction

The primary goal of Budget Phase (BP) 3 is to validate the Play Fairway (PF) methodology established in the earlier 2 phases through drilling a test hole in one of the project’s established regions of high probability and confidence. However, because drilling in Hawai‘i is logistically challenging, the selection of BP3 drill targets has also taken into account: anticipated regulatory timelines, landowner interest, scientific impact, and the viability of development (likely private-sector investment). Four locations in the state were investigated intensively enough during BP2 to warrant a go/no-go on exploratory drilling (Ito et al., 2017; Lautze et al., 2017a; Lautze et al., 2017b). These are: the north, east, and south flanks of Mauna Kea volcano (Hawai‘i Island); Haleakalā volcano’s SW rift zone (Maui); and Lāna‘i’s summit caldera and rift zones.

Additional exploratory work targeted the caldera region of Lāna‘i volcano. The probability for a resource in this area at an accessible depth is supported by gravity, resistivity, and groundwater temperature data collected as part of BP2. The landowner is committed to the development of renewable energy for this island and has expressed strong support for further geothermal exploration and development on the island. The regulatory burdens on a drilling project at this location have been significantly ameliorated by prior environmental work as well as prior land use of the prospective drilling location. Further, the results of test drilling in this location,

whether positive or negative, will play a crucial role in Hawai‘i’s future geothermal development strategy.

2. Background

Of the four sites, and for reasons outlined below, Mauna Kea’s south-southeast flank and Lāna‘i’s caldera region rose to the top for BP3 drilling targets, with Lāna‘i’s caldera region being ultimately selected. Below are descriptions of the target sites, with more attention on the selected Lāna‘i caldera region.

2.1 Mauna Kea Prospect

Mauna Kea is the third-youngest volcano on Hawai‘i Island. It last erupted between 4 and 6 ka and is in its post-shield phase of activity. The younger volcanoes, Kīlauea and Mauna Loa are in their shield building stage, whereas Mauna Kea’s shield stage ended ~150,000 years ago. The project’s assessment of Mauna Kea’s resource potential aims to identify areas with evidence of geologically recent intrusive activity (e.g. elevated gravity, reduced resistivity, groundwater anomalies).

Mauna Kea has been the focus of a substantial amount of recent research led by D. Thomas under non-DOE funding. This research includes magnetotelluric (MT) and audio-frequency magnetotelluric (AMT) surveys on all flanks except the volcano’s northeast (some of this data had not been analyzed at the start of BP2) (Pierce and Thomas, 2009) and drilling of 2 deep (1.8 km) boreholes with downhole fluid sampling on the south-southwest and west flanks (Thomas et al., 2017). Geophysical results on the southeast flank during BP2 encouraged the attainment of additional gravity and groundwater data (beyond what was originally planned).

Multiple factors including the newly discovered corroborating evidence provided by the geophysical data and the project’s probability analyses pointed to the southeast flank of Mauna Kea as a high-priority target for BP3 drilling (**Fig. 1**). In this location, both elevated gravity and reduced resistivity suggest thermal activity at favorable resource depths. The gravity signature is interpreted to be part of a robust dike system that extends across the Humu‘ula Saddle region between Mauna Loa and Mauna Kea (Flinders et al., 2013). While the reduced resistivity values could be attributed to a variety of factors (including secondary mineralization, clay formation, saltwater intrusion), several factors strongly suggest warm fluid as the primary source for the low resistivity in this location. In particular, 1 of the 2 deep boreholes, located approximately 12 km to the northwest, identified high-elevation (>1000 m amsl) fresh and hot groundwater. Results of the completed well included water with temperatures of 140 °C at a depth of 1760 m and a temperature gradient of 165 °C/km as the electrically conductive formations were approached. Hence, heat as well as the fluid components of a resource are likely present in this top-priority BP3 drilling target. According to the project’s modeling of permeability, the BP3 target site would have similar permeability as the completed test well. The deep formations in the test well were not flow tested due to its small diameter, but the borehole did show evidence of internal flow from depth up into the shallower formations (resulting in sealing of the deep section of that hole with dense drilling mud to protect the upper aquifer from contamination).

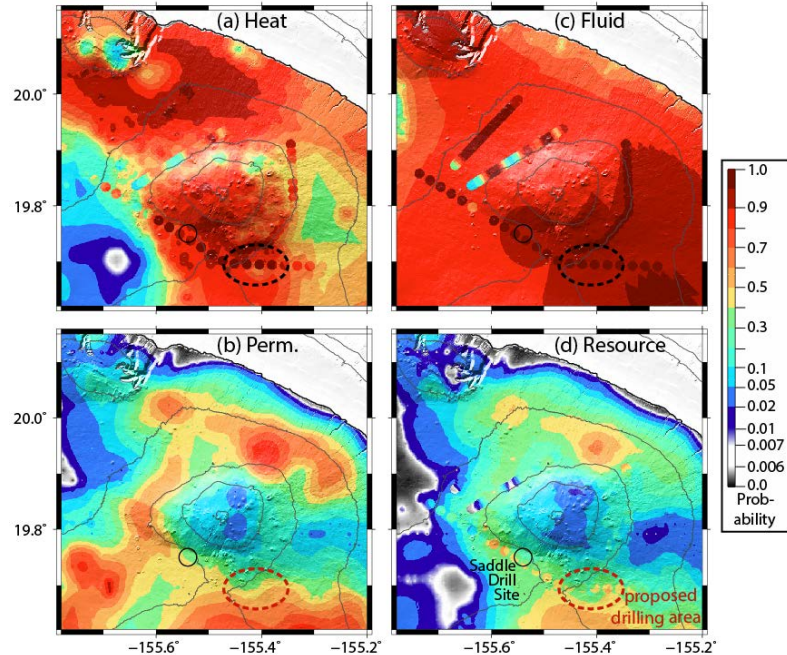


Figure 1: Local probabilities for Mauna Kea of (a) heat, (b) permeability, (c) fluid, and (d) a geothermal resource. BP3, the highest-priority drill site, is marked by the dashed oval.

A number of other factors contributed to the selection of Mauna Kea as a top BP3 target. The organization that manages this land, the Department of Hawaiian Home Lands (DHHL) enjoys a favorable regulatory status in terms of their compliance with environmental requirements and County zoning rules. Also, DHHL will receive 100% of State royalties from geothermal revenues. The Hawaiian Homes Commission, which establishes policy for the Department and provides guidance on new initiatives to Department staff, has supported prior geothermal exploration work on their lands and, when the results of the project's exploration were presented at a recent Commission meeting, a very favorable response from the Commissioners was received. Also, an inquiry for additional information from a private-sector developer was received less than 24 hours after the project delivered an oral presentation.

As another advantage to this site, D. Thomas is very familiar with this region. Thomas managed the groundwater exploration program that was done in the Humu'ula Saddle. This work included development of an environmental assessment (EA) for two test borehole sites, acquisition of a drill rig and support equipment, and oversight of the drilling program for 2 slim holes drilled to ~1.8 km. Much of the environmental documentation done for those previous sites will be directly applicable to the selected site and should shorten the overall regulatory review process. Notably, both prior EAs were published with few to no public comments and a determination of "No Significant Impact" was made without challenge.

The selected site would be logistically challenging but tractable. No production wells currently exist within the Humu'ula Saddle, so the drilling project would need to contract for water delivery from Hilo (approximately 40 km distant).

2.2 Lāna‘i Prospect

Lāna‘i is the third smallest of the eight main Hawaiian islands (West et al., 1992). The main mountain range of the island stretches in the northwest direction and contains three known rift zones (West et al., 1992). Pālāwai basin is thought to be the remnant caldera of the island, which is 7 kilometers in diameter (Walker, 1990). It is formed by a single shield volcano, now extinct, estimated to be 1.3 Ma and active from approximately 2 Ma to 1 Ma. This Hawaiian volcano apparently stopped erupting during its shield stage, as inferred from missing alkalic cap and post erosional lavas (Walker, 1990). Growth of Lāna‘i is thought to have begun during the Tertiary and ceased ~1 Ma (Stearns et al., 1940; Herrero-Bervera et al., 2000). The Lāna‘i Volcanics is an igneous geologic unit that comprises all the volcanic rock units forming the island. All known lavas of Lāna‘i are tholeiitic (Walker, 1990). The bioclastic Hulopoe Gravel is a carbonate-cemented gravel on the southern slopes of the island, with competing theories of origin, including sea level rise and megatsunamis. A rift zone extends from the northwest to the southeast of the island, radiating from the caldera of Pālāwai Basin. An additional rift zone extends southwest from the caldera. Both are marked by dike complexes.

The combined probabilities for heat, fluid, and permeability indicate several locations on Lāna‘i that could host a resource at the depths of interest for geothermal production (**Fig. 2**). The area of greatest interest is within the Pālāwai Basin, where a high gravity signature and reduced resistivities at depth are co-located. Notably elevated groundwater temperature are also located near this area.

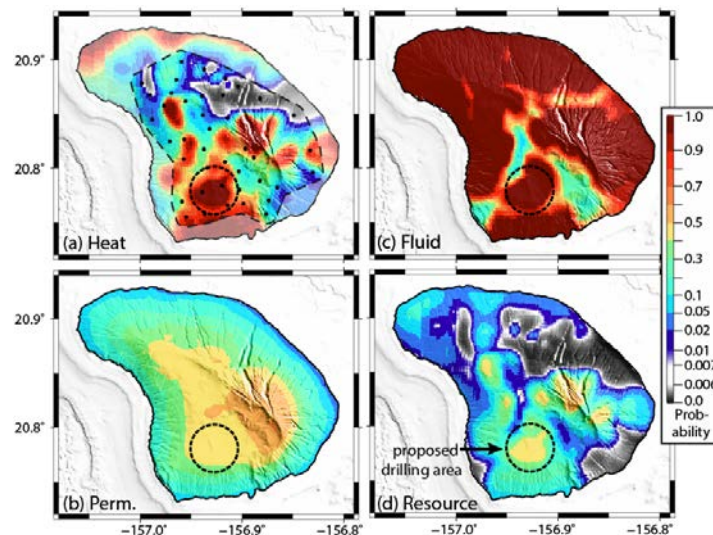


Figure 2: Local probabilities for Lāna‘i of (a) heat, (b) permeability, (c) fluid, and (d) a geothermal resource. The reliable area for the MT results is contained within the footprint (outlined by dashed lines) of the MT stations (dots), both due to data coverage as well as the likelihood that salt water is highly conductive probably intrudes the crust near the shorelines.

The BP2 gravity data clearly delineates the dike complex associated with Lāna‘i volcano’s central magma conduit. Less clearly evident in the gravity data or density models is the dike complex associated with the rift system, located to the northeast of the Lāna‘i caldera and striking in a generally northwest-southeast direction (**Fig. 3**). That rift system has been mapped in detail through surface exposures of dikes as well as through drilling for high-level dike-impounded groundwater in this location.

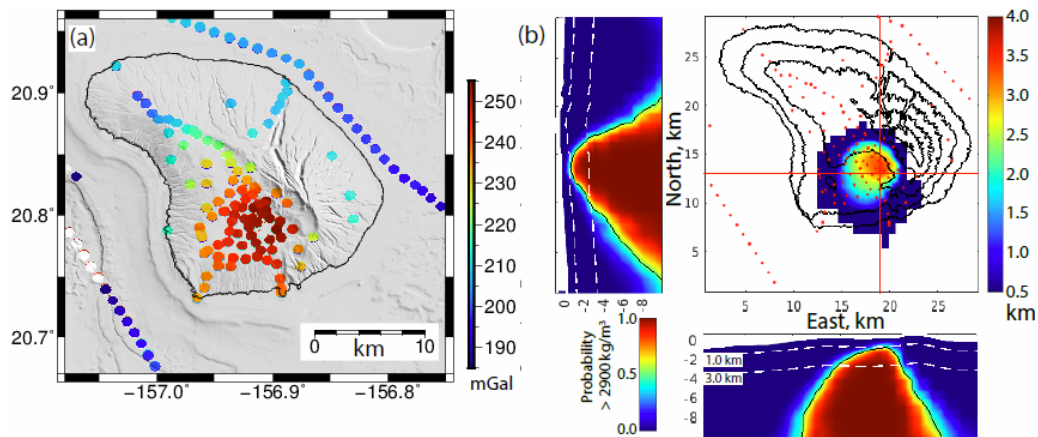


Figure 3: (a) Local complete Bouguer anomaly of Lāna‘i using $\rho_0 = 2600$ kg/m³ (colored patches at measurement locations). Topography is illuminated from the NE and the shoreline outlined. (b) Map of the depth below the surface to 90%-probability of densities ≥ 2900 kg/m³. Subaerial topography is contoured (100 m intervals), and gravity stations are marked with red dots. (c) East-west and (d) vertical cross sections along the lines in (b) showing probability of density > 2900 kg/m³; black contour is for median density of 2900 kg/m³. Vertical axis is elevation relative to sea level.

The 3-D resistivity modeling shows a complex distribution of resistivity values across the island and at depth, which requires a correspondingly complex interpretation (**Fig. 4**). It is appropriate to discount all of the low resistivity features around the distal edges of the island as due to seawater. Similar to the situation with Haleakalā volcano, Lāna‘i has, since the end of its shield building stage of activity, subsided by about 2 km, such that the formerly subaerial and permeable lavas are now saturated with seawater. Shallow groundwater drilling in most of the coastal areas of the island further substantiate this inference and has found either (a) a very thin freshwater basal aquifer or (b) an aquifer that is entirely brackish to saline. Hence, the near-shore conductive features are of no interest to the PF investigations. The project concludes, however, that the intrusive complex associated with the central magma conduit of Lāna‘i volcano can serve as an effective barrier to infiltration of seawater to the interior of the caldera. Further, the presence of high-level (~ 300 m asl) groundwater within the caldera region of the island likely further impedes seawater intrusion into the complex. Based on this analysis, the conductive feature that extends from about 1 to 3 km depth located at the 16 km mark in the resistivity cross section shown in **Fig. 4** represents the resistivity anomaly least likely to be the result of seawater saturation. Notably, this feature is flanked by much more resistive formations, which may reflect a low permeability dike complex.

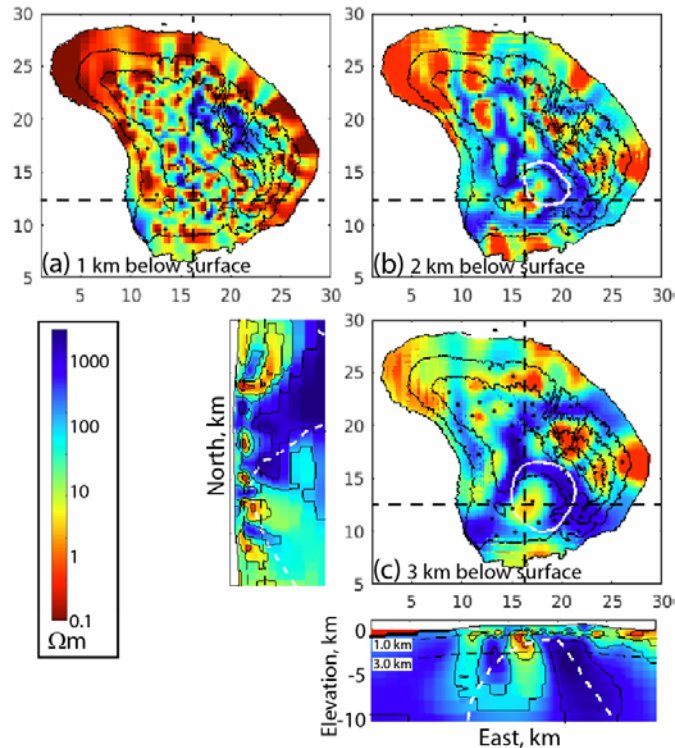


Figure 4: 3D resistivity structure from inversions of MT data shown at (a) 1 km, (b) 2 km, and (c) 3 km below the surface. Vertical sections along dashed lines are shown. White curves outline a median density of 2900 kg/m^3 from the gravity inversions.

In addition to the Pālāwai Basin feature just described, there are two additional low-resistivity features located to the northeast and north-northeast, within the dike complex of Lāna‘i volcano’s rift zone. The resistive formations separating these features from seawater saturated rocks flanking the island are less compelling. Hence, the likelihood of non-thermally induced conductivity is somewhat reduced, and these features are of secondary interest. Further work on these features could be pursued (outside of PF) if a heat source was confirmed within the Pālāwai Basin.

As with the other resistivity datasets, the project recognizes the potential for the conductive features present in Lāna‘i’s dike complex to reflect secondary mineralization and clay formation in a now-exhausted hydrothermal system. However, the presence of elevated groundwater temperature suggests residual heat remaining within Lāna‘i’s magma conduit.

The Pālāwai Basin site is attractive to the project for additional, non-geologic reasons. N. Lautze and D. Thomas have had extensive discussions with the landowner and managers of the island (Pūlama Lāna‘i), and there is very strong interest in and support for the work that the project has been conducting. The landowner is working to develop the island as a “green” resort destination and has committed to the use of renewable resources wherever possible. Pūlama Lāna‘i, the corporate entity that manages the owner’s lands and development efforts, has been in discussion with private-sector geothermal development interests (Thermal Energy Partners) regarding exploratory drilling on the island. Project team members have met with the CEO and key

members of TEP's team – and have a very cordial and cooperative relationship with them. They are interested in the project's BP2 data and have expressed a willingness to facilitate and integrate the project's resource investigations into a potential future drilling program – should their negotiations with Pūlama Lānaʻi proceed as such.

As private-sector discussions were not successful, the University of Hawaiʻi (the project) took the lead on drilling of a slim hole – a regulatory review found extensive environmental, cultural, and land use documentation has already been done by Pūlama Lānaʻi for much of the island. A second relevant element is that the area proposed for drilling is located in a part of Lānaʻi that had been used by prior corporate owners for pineapple agriculture for several decades and hence poses little likelihood of hosting threatened or endangered plants or animals that might be impacted by the project's proposed work. Likely, any resource found on Hawaiʻi's older volcanoes will have temperatures more compatible with binary power generation rather than flash-steam generation and therefore will have significantly fewer impacts and lower visibility in the community.

The project's interest in recovering deep thermal information on Lānaʻi is augmented by the fact that it will be the first time insight into the long-term rates of cooling of the cores of Hawaiʻi's volcanoes is gained. All geothermal exploratory drilling to date has taken place on the youngest of island in the state: Hawaiʻi Island. Successful identification of a viable thermal source within Lānaʻi volcano can encourage deep investigations on even older volcanic systems on Maui, Oʻahu (where the vast majority of the energy market resides), and Kauaʻi. Conversely, failure to find evidence of useable residual heat on Lānaʻi will strongly indicate that, if geothermal heat were to provide electrical power to Hawaiʻi, the majority of that power will have to be generated on Hawaiʻi Island.

2.1.1 Lānaʻi Drill Sites

The project proposes to extend the well present at each drilling location by digging deeper into the subsurface for new geologic and hydrologic insights to groundwater systems of Lānaʻi. The proposed drilling sites are located within the Pālāwai Basin on Lānaʻi, a remnant of the unfilled caldera, in the central and southern region of the island of Lānaʻi, near Lānaʻi City. While a single landowner now owns ~98% of Lānaʻi, Lānaʻi has large amounts of undeveloped land that remain as fallow or active agricultural land. Northeast of the Pālāwai Basin, a wet forest covers the ridges of Lānaʻihale, the highest point on the island at >1,000 m. Lānaʻi Well #10 (20.765278°, -156.919444°) is the primary target of the study, located on the southern rim of Pālāwai Basin. Lānaʻi Well #9 (20.8180820°, -156.914048°) is the secondary target of the study as far as resources allow. Both of the proposed drill sites, Wells #10 and #9, exist within land designated as “cropland and pasture” by the State of Hawaiʻi Office of Planning (State of Hawaiʻi, 1992; State of Hawaiʻi, 1993).

With the introduction of agriculture and grazing by goats and deer on Lānaʻi, wind erosion has increased soil loss. The majority of the soil in Pālāwai Basin near the drill site at Lānaʻi Well #9 is a vertisol, a clay-rich material. The soil at drill site Lānaʻi Well #10 at the edge of the basin is an oxisol, defined by its highly weathered minerals and oxidized subsurface layer. Both of these soils played an important role in Lānaʻi's pineapple production (Deenik et al., 2014).

Lānaʻi has a subtropical climate, with Lānaʻi City at 1,620 feet in elevation and an average annual temperature of 68.1° F. Lānaʻi experiences the northeasterly trade winds and is partly sheltered by West Maui and East Molokaʻi. Lānaʻi falls within the rain shadow of Maui, decreasing the importance of orographic rainfall caused by those northeasterly trade winds. Average annual rainfall is as low as 10 inches at the coast to 38 inches at the summit, but will vary greatly year to year. Rainfall also varies within the year, with a dry season and wet season; this wet season is marked by the presence of southerly Kona storms in addition to the regular orographic rainfall that approach the island unmitigated from the south. Heavy rains in a Kona storm can account for a large portion of the annual rainfall, sometimes as much as 80% in arid regions. Naulu storms are also sudden, and heavy rainfall events form off the south or west coast of Lānaʻi during periods of hot weather (Stearns et al., 1940).

There are two types of groundwater on Lānaʻi: basal groundwater near the coast and high-level groundwater inland in the rift zone and caldera complex. Coastal basal groundwater a few feet above sea level is often too brackish for human consumption. High-level inland groundwater is contained by dike-impounded reservoirs or perched aquifers, sustained by an impermeable soil bed at the base of the alluvium layer. Where the land has been eroded to intersect these dike complexes, groundwater would flow freely as perennial springs (Stearns et al., 1940). These springs have since stopped after tunnels diverted the water sources; there are no perennial streams on the island. Lānaʻi's sustainable groundwater yield is estimated to be 6 million gallons per day, most of which comes from the Central aquifer encompassing portions of the Pālāwai Basin and rift zone. In 2008, total withdrawals from the central aquifer system were approximately 2.2 million gallons per day, coming from six primary wells. Well #10 is near the proposed boundary between Kealia and Leeward Central aquifer; Well #9 is within the Leeward Central aquifer as proposed by Mink and Lau, 1993.

The impact of the drilling activity on any groundwater resources below the Pālāwai Basin lands will be temporary and insignificant. There are no known prospective potable water sources in the area surrounding either proposed drill location at Lānaʻi Well #10 and Lānaʻi Well #9. Nonetheless, the non-toxic drilling materials have been selected to protect against possible impacts to unknown resources. The project will use a conventional water-well drilling fluid composed of bentonite clay and polymer. All the materials that will be used during the drilling are typically used for potable water well drilling and are considered to pose a minimal risk of degrading the water quality in the formations being drilled. Additionally, as part of the completion work on the well, the project will use fluid bailers to remove as much of the drilling fluids from the bore as is possible to enable the project to collect clean samples of formation water for the planned chemical analysis of and evolution of water quality. A secondary impact on water resources may come from the use of water during drilling, which is estimated to be less than or equal to 25,000 gallons per day. To minimize the project's use of the potable water resources of the island of Lānaʻi, the project will be using brackish water for the drilling fluids.

3. Methods

The project plans to drill a single, temperature gradient hole to a depth of 1.5 km to 2 km below the ground surface using diamond wireline core drilling techniques. The project recognizes that much shallower temperature gradient drilling over a broad grid is the preferred exploration method at this stage of investigation in the western states, but doubt that this type of drilling will

be productive in Hawai'i. In Hawai'i, the known and anticipated resource depth is considerably deeper than on the mainland. This is due to the permeability of shallow subaerial lavas, which do not allow the formation of surface thermal features (e.g. hot springs, fumaroles, geysers) except in extremely high heat flow areas. Also, prior experience indicates that thermal fluids typically mix very rapidly with fresh groundwater systems, and that any residual thermal or chemical signature is dissipated very rapidly in the porous vadose zone. Recent core drilling in Saddle region of Hawai'i Island has shown that numerous confining layers (e.g. ash beds, soil intervals, alluvial fans) allow for the formation of multiple thin confined aquifers that will further impede the movement of thermal fluids into the shallow environment.

3.1 Drilling Program

The drilling program will follow the same general procedure that the project followed with the two groundwater exploration holes drilled on the Army training base in the Saddle (in addition to the 'Saddle well,' a second slim hole was drilled 10km to the West – both on the Army's Pohakaloa Training Area): installation of a shallow conductor casing; coring with a PQ (4.8" dia.) sized bit to a depth of ~3000'; installation of a shallow 4.5" diameter casing string; continue coring to total depth of ~ 6600'. The drilling depth may, however, be constrained by the temperatures encountered. The project is proposing here to drill a temperature observation well, not a geothermal test well. The latter would require a substantially higher level of engineering and regulatory review that would not be possible with the available budget or in the time that is available to complete the project. In the project's prior groundwater exploration hole, the project terminated drilling at a temperature of 100 °C. Perhaps that temperature could be exceeded somewhat in the proposed hole, but that would require negotiation with staff of the Commission on Water Resources Management and their approval. Drilling at temperatures above 100°C also would likely require more intensive monitoring of downhole conditions during and after drilling in order to ensure that thermal fluids were not migrating up the hole and contaminating drinking water aquifers.

Based on the drilling experience in the prior two holes, the project estimates that drilling would require between 90 and 120 operating days. The prior project at the Saddle operated the drill rig 24 hours per day with two shifts for about 40 continuous days of operation. A two-week break for the crews during which maintenance and repairs to the rig were made as needed; followed by another 40-day campaign. The project estimates an additional two-week period prior to the initiation of drilling to allow site preparation, wellhead slab installation, construction of water storage tanks and a drilling sump. The project anticipates that the drilling operations could be reasonably completed within 180 days.

Over the course of the drilling, the project will measure "dynamic" temperature using a memory temperature logger installed inside the core tube; this method was used in the prior drill holes and found to indicate rising temperatures. Downhole temperature surveys would be conducted during drilling breaks after allowing the borehole temperatures to equilibrate. Formation fluid samples would be collected as the borehole fluid chemistry approaches equilibrium with the formation fluids.

The University of Hawai'i owns a complete drilling rig. This includes both PQ and HQ drill rods; a containerized field shop; mud mixing equipment; a 20 KW diesel gen-set for off-grid electrical power and most of the tools that would be needed to conduct the drilling. The project

also has an electric wireline unit fabricated by Comprobe Inc. as well as a variety of sampling tools. Geophysical logging tools would have to be rented from commercial suppliers. Densities of the rock cores will be measured and logged and then used to refine the density model to further characterize the site.

4. Results

4.1 Phase 3 Accomplishments

Several major objectives of PF BP3 have been completed in the last half of 2018, and these accomplishments are described below.

The project lowered a state-owned camera down Lānaʻi Well #10 and obtained video from a similar exercise conducted on Lānaʻi Well #9 in June 2016. The Hawaiʻi Commission on Water Resource Management (CWRM) owns a down well camera. The project coordinated with CWRM and Pūlama Lānaʻi to lower this camera down Lānaʻi Well #10 as an inexpensive and relatively simple exercise to ensure this well did not have any unexpected blockages and was straight enough to justify performance of a gyroscopic log. Pūlama Lānaʻi had a camera lowered down Lānaʻi Well #9 in June 2016, and the project obtained this video from them.

A major component of the PF BP3 work was to prepare an EA and submit to the Hawaiʻi Department of Health (HDOH) Office of Environmental Quality Control (OEQC). The Draft EA was submitted on Sept 19, 2018, and public comments were received at the end of the posting period. Pūlama Lānaʻi representation and University of Hawaiʻi Office of General Counsel were consulted for appropriate legal responses. Pūlama Lānaʻi Conservation Directors and the Pacific Fish and Wildlife Office were consulted for biological survey information to create a system of mitigation measures for the project, particularly focusing on Hoary Bats and Hawaiian Petrels. A Final EA and Finding of No Significant Impact (FONSI) were submitted to the HDOH OEQC and published on Dec 23, 2018. Now ongoing is the completion of the ensuing National Environmental Policy Act (NEPA) Review Process required for the proposed action.

A gyroscopic log and deviation survey was provided for Lānaʻi Well #10 from December 2 to 9, 2018. The results of the gyroscopic log determined the well to be suitable for successful coring using the University of Hawaiʻi (UH)-owned truck-mounted drill rig. Due to differences in the design of core drilling pipe, it was less flexible in a bending mode than is conventional rotary drilling pipe. Hence, straightness of the hole was a critical factor in assessing the feasibility of deepening this borehole. Competitive quotes were solicited; Frontier Logging Corporation was selected to complete the project. Full results and interpretations were returned to the PI on Dec 20, 2018, for analysis. Upon consulting with the drilling supervisor, the deviations yielded little concern to the overall drilling target.

In the near future, the project will ship the UH drill rig to Lānaʻi, purchase preliminary supplies, and ship them to the site. The first steps in the drilling portion of the project will be to procure a temporary casing string and ship it, along with the UH-owned drill rig, from its current location on Hawaiʻi Island to Lānaʻi. Additionally, other equipment must be inventoried and shipped, or otherwise purchased or rented for the project. Site modification and lodging must be prepared for the duration of the project. Appropriate permits for well modification must be submitted to the

CWRM, air quality monitoring to the HDOH, and vehicular drill rig registration to UH and state must be completed. To date, preliminary site visits to Lāna‘i were conducted with PI Nicole Lautze, Co-I Don Thomas, and Drill Supervisor Ron Fierbach, and they assessed site access, power supply, water supply, lodging, and shipping logistics, among other items. Drafts of all well modification permits, noncovered source permits, and drill rig registration items are in review. PI Lautze and Co-I Thomas met with a representative of the CWRM to discuss the process of submitting a well modification permit for both Lāna‘i Well #9 and #10 and have since submitted their permit application for Well #10. Upcoming action items include submission of the Temporary Noncovered Source permit to the HDOH and registration of the truck-mounted drill rig as a UH vehicle with the state, finalizing lodging and personnel requirements, and completing all site modification and preparation work so that drilling can commence in April 2019.

4.2 Remaining Phase 3 Objectives

The project plans to install temporary casing in Lāna‘i Well #10. During the drilling effort, the temporary casing will stabilize the walls of the existing borehole to ensure that the formation will not collapse in or around the drill string (collapsing can result in the loss of the drill string). This will soon be succeeded by the deepening of Lāna‘i Well #10 along with the collection of core and fluids. Thus far, the project has begun site preparations and mobilized drilling crew to conduct drilling using the project’s existing HQ coring string. Recovered core will be cleaned and boxed on site and shipped to a core processing facility at the University of Hawai‘i at Hilo on a weekly basis for documentation and analysis. At the conclusion of the drilling exercise, the project will perform temperature logs in the borehole during its equilibration and recovery period, and samples of fluids will be recovered from the deeper interval of the borehole. If temperature surveys indicate internal circulation of fluids from depth, then the project will be able to collect relatively pristine formation fluid samples; if not, the project will attempt to stimulate circulation using compressed air (air lifting) to draw deep fluids into the wellbore. Based on the results of these analyses, the project will consult with the well owner as well as the staff of CWRM as to whether this well will be maintained as a long-term monitoring well or if they prefer to plug and abandon the well. At the completion of any further downhole work required by that decision, the project will withdraw the temporary casing and demobilize the drill rig from the Lāna‘i site and return it to Hawai‘i Island.

The project has scheduled downhole Geophysics on Lāna‘i Well #10. The project will contract to perform downhole geophysics including but not necessarily limited to: resistivity, acoustic velocity, gamma log, borehole tele-viewer, and spinner log. These will provide insights into: present downhole stress conditions (from borehole breakouts) within the caldera region as well as any variations in those conditions with depth; formation fracture density and permeability; *in situ* formation resistivities; the degree of secondary mineralization; presence of internal flow and variations in hydrostatic heads within the dike complex; and *in situ* seismic velocity variations with depth and evolving physical properties of the dike complex.

The drill core will be analyzed for rock type (i.e. dike, pahoehoe, a‘a), hydrothermal minerals, and fracture orientation to lend insight into the volcanic and hydrothermal history of Lāna‘i. The project is currently considering candidates to be hired for logging and analyzing recovered drill core and will soon hire a candidate to oversee proper cataloguing, storage, and shipment of the core.

With available time and funding, additional geophysical and groundwater data collection will occur elsewhere in the state of Hawai'i. South Point Hawai'i Island, East Rift Haleakalā, and Kaua'i Island were BP2 targets for groundwater analyses, the results of which indicate a subsurface resource. The three locations also have relatively low infrastructure noise. The project will work with landowners on access permissions in order to pursue magnetotelluric and gravity surveys in up to all three of the locations. The project obtained Helium isotope data for two areas in Hawai'i from previous work funded by DOE under ARRA. These informative data suggest that more Helium data statewide will improve the project's PF probability and confidence maps. As part of BP3, the project will seek to collect groundwater samples for Helium isotope analyses in the BP2 target areas. Thus far, the project has initiated contact with land and well owners for site access permissions and permitting and corresponded with selected labs to coordinate plans for future groundwater sample collection and analysis. The project has also begun a review of BP2 data to complete a down-select for targeted wells for groundwater sampling in BP3. The next immediate step is to obtain land access permissions and the necessary NEPA review to begin groundwater sampling and geophysical surveys.

One of the major results of this PF BP3 will be to refine and improve PF BP2 probability and confidence models. The project will strive to obtain other new exploratory data and/or make improvements to its models in order to refine, improve, and, where possible, validate its BP2 probability and confidence maps. Ultimate products of the upcoming work include integration of results into improved conceptual model of Lāna'i's geothermal resource, an updated BP3 probability and confidence maps, and a report detailing the new findings.

5. Conclusion

BP1 of the Hawai'i Play Fairway project led to the identification of 10 priority locations for BP2 activities. BP2 involved the collection of new groundwater data in 10 areas statewide and magnetotelluric and gravity data on Lāna'i, Haleakalā Volcano's SWRZ (Maui), and central Hawai'i Island. The project also modeled topographically induced stress in order to better characterize subsurface permeability during BP2. Ultimately, all data were incorporated into updated resource probability maps for the State of Hawai'i.

Work in BP3 is designed to validate the Play Fairway (PF) methodology established in BPs 1 and 2. To complete this, the primary objective of BP3 is to drill a temperature observation well with additional geophysical surveys and noble gas groundwater sampling. In addition to complying with the updated BP2 probability and confidence maps, drilling prospects had to account for anticipated regulatory timelines, landowner interest, scientific impact, and the viability of development. Four locations in the state were investigated extensively during BP2 to warrant a decision on exploratory drilling, with Lāna'i's summit caldera being ultimately selected for the test well. Gravity, resistivity, and groundwater temperature data collected as part of BP2 suggests a resource in this area at an accessible depth. The results of test drilling in this location will determine the future geothermal development strategy of Hawai'i.

Acknowledgement

This project was funded by the DOE EERE – Geothermal Technologies Grant as part of the Play Fairway Project, award number DE-EE0006729.0000. The authors thank their collaborators from all three phases of the Play Fairway Project, especially Neil Frazer, Nicholas Hinz, Garrett Ito, Steve Martel, Graham Hill, Phil Wannamaker, and Thomas Martin for previous and ongoing contributions.

REFERENCES

- Deenik, J., Miura, T., Yost, R., Dorman, N., Silva, J., and Connor, W., 2014, Hawai'i Soil Atlas, <http://gis.ctahr.hawaii.edu/SoilAtlas>, accessed September 2018.
- Flinders, A.F., Ito, G., Garcia, M.O., Sinton, J.M, Kauahikaua, J., and Taylor, B., 2013, Intrusive dike complexes, cumulate cores, and the extrusive growth of Hawaiian volcanoes: *Geophysical Research Letters*, v. 40, p. 3367-3373.
- Herrero-Bervera, E., Margas-Vinueta, J., and Valet, J-P., 2000, Paleomagnetic study of the ages of lavas on the island of Lanai'i, Hawai'i: *Journal of Volcanology and Geothermal Research*, v. 104, no. 21-31.
- Ito, G., Frazer, N., Lautze, N.C., Thomas, D.M., Hinz, N., Waller, D., Whittier, R., and Wallin, E., 2017, Play Fairway Analysis of Geothermal Resources across the State of Hawaii: 2. Resource Probability Mapping: *Geothermics*, v. 70, no. 393-405, doi: 10.1016/j.geothermics.2016.11.004.
- Lautze, N.C., Thomas, D.M., Hinz, N., Ito, G., Frazer, N., and Waller, D., 2017a, Play Fairway Analysis of Geothermal Resources across the State of Hawaii: 1. Geological, geophysical, and geochemical datasets: *Geothermics*, v. 70, p. 376-392, doi: 10.1016/j.geothermics.2017.02.001.
- Lautze, N.C., Thomas, D.M., Waller, D., Hinz, N., Frazer, N., and Ito, G., 2017b, 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*, v. 70, p. 406-413, doi: 10.1016/j.geothermics.2017.07.005.
- Mink, J.F., and Lau, L.S., 1993, Aquifer identification and classification for Lāna'i: groundwater protection strategy for Hawai'i: Water Resources Research Center, Technical Report, no. 190.
- Pierce, H.A., and 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. Geological Survey Open-File Report 2009–1135, 160 p., <https://pubs.usgs.gov/of/2009/1135>.
- State of Hawai'i, Commission on Water Resource Management, 1992, Lanai Well #9 Well Completion Report: Department of Land and Natural Resources, Division of Water Resource Management, 161 p.

- State of Hawai'i, Commission on Water Resource Management, 1993, Lanai Well #10 Well Completion Report: Department of Land and Natural Resources, Division of Water Resource Management, 79 p.
- Stearns, H.T., Macdonald, G.A., and Swartz, J.H., 1940, Geology and ground-water resources of the islands of Lanai and Kahoolawe, Hawaii: Advertiser Publishing Co., no. 6.
- Thomas, D.M., Pierce, H.A., and Lautze, N.C., 2017, Integrated Geophysical and Drilling Results for Mauna Kea Volcano: Hydrologic Implications: Abstracts with Programs, GSA Annual Meeting, Geological Society of America, Seattle, WA, v. 49, no. 6, doi: 10.1130/abs/2017AM-308419.
- Walker, G.P.L., 1990, Geology and Volcanology of the Hawaiian Islands: Pacific Science, v. 44, p. 315-347.
- West, H. B., Garcia, M.O., Gerlach, D.C., and Romano, J., 1992, Geochemistry of tholeiites from Lanai, Hawaii: Contributions to Mineralogy and Petrology, v. 112, p. 520-542.