

Improving a 2015 Map of Geothermal Resource Probability Across the State of Hawaii

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ABSTRACT

An initial Play Fairway analysis of geothermal resource potential across the State of Hawaii was completed in 2015. The results of this probability analysis, in addition to an evaluation of confidence in the probability value, as well as considerations of development viability, led to the identification of ten locations for exploration activities on the islands of Kauai, Oahu, Lanai, Maui, and Hawaii. With funding from the U.S. Department of Energy, the two main Phase 2 field activities currently ongoing are: i) geophysical (electromagnetic and gravity) surveys on Lanai and Haleakala's SW rift zone (Maui) - to explore for heated fluid and intrusive rocks, and ii) a groundwater sampling and analysis campaign in the ten locations of interest - to validate groundwater indications of geothermal activity and improve knowledge of groundwater flow paths. Non-field activities include the production of crustal stress models to better infer subsurface permeability, and the integration of new data into improved 2D and in specific locations a new 3D probability map. This paper will provide preliminary results of the main Phase 2 activities; namely the geophysical survey on Lanai, the groundwater sampling and analysis campaign, and the stress modeling.

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. Exploration for geothermal resources in Hawaii via this modern Play Fairway Analysis (PFA) method is timely for a number of reasons. The last statewide geothermal resource assessment, published in 1985 (Thomas, 1985), indicated potential prospects on all of the main Hawaiian Islands; however, little additional exploration work was completed for ~30 years. In 2013, our team members led a US Army funded drilling effort in search of groundwater, which found water at an elevated temperature (~140°C at 1.8 km depth with a 165°C/km gradient 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 our state's resource potential but also demonstrated that our understanding of Hawaii's geothermal resource potential is far from complete. Hawaii's economic and political environment is also highly favorable. Historically, Hawaii has had the highest electricity cost in the nation; which, in 2016 was 2.5 times the national average (U.S. EIA, 2016). 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 22%) over the past half-dozen years – primarily through expansion of intermittent (wind and solar) energy production. 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.

During Phase 1 of the Hawaii Play Fairway project existing data were compiled and integrated to produce a comprehensive assessment of geothermal resources statewide in Hawaii. The main accomplishments of Phase 1 were to: 1) identify, obtain, and rank all legacy and current geologic (location and ages of calderas, rift zones, vents, dikes, and faults), groundwater (temperature and chemistry), and geophysical (resistivity, gravity, seismicity, and geodetic strain) data relevant to the geothermal factors of heat (H), permeability (P), and fluid (F) across the state; 2) compile these data into a Geographic Information Systems (GIS) project; 3) develop a method for using diverse data types to produce probability maps of geothermal resources; 4) apply the method to Hawaii; and 5) identify prospective targets and exploration activities to improve the Phase 1 assessment. The Phase 1 methodology and results are detailed in a 3-paper series recently accepted (with 1 paper in revision) in *Geothermics* (Lautze et al, 2017a; Ito et al., 2016; Lautze et al., 2017b).

We are pursuing four project tasks in Phase 2. (1) Geophysics. To conduct magnetotelluric (MT), audiomagnetotellurics (AMT), and gravity surveys in areas where other data types suggest heat, and in locations where already available geophysical data suggest that a resource is likely but the data are inconclusive (2) Groundwater. To sample and analyze groundwater wells in key locations across the state in order to test earlier groundwater indications of geothermal activity and improve groundwater flow models. This will increase the spatial resolution of our resource probability maps and increase overall level of confidence in the play rankings. (3) Stress Modeling. To produce 3-D models of topographically influenced crustal stresses in order to better assess deep permeability structure across the state. (4) 2D and 3D Mapping. To integrate all new and existing data into 2 and new 3D probability maps to update and improve the Phase 1 PFA

2. PHASE 1 RESULTS

The datasets compiled in Phase 1, and their relative ranking in terms of subsurface Heat, Fluid, and Permeability (the qualities necessary for a resource to exist) are shown in Figure 1. Justification of the inclusion and ranking of such datasets is provided in Lautze et al., (2017a). The statistical methodology developed and applied to derive the probability map shown in Figure 2 is described in detail in Ito et al. (2016). The red boxes on Figure 2 highlight our Phase 2 focus areas. A 'Development Viability' criteria was applied in selecting

such areas, as described in Lautze et al., (2017b). This included consideration of: land use, vulnerability to natural hazards, perceived level of community acceptance, and ease of integration into the electrical grid.

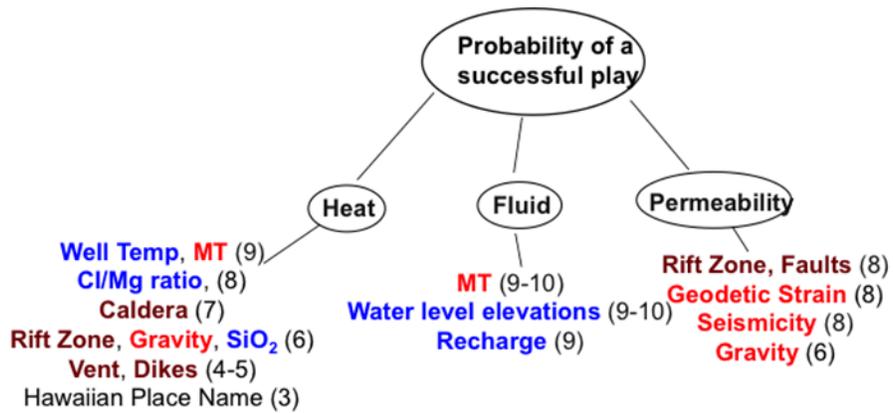


Figure 1: The data types used in the probability modeling to indicate the probability/likelihood of geothermal Heat, Fluid, and Permeability. The numbers in parentheses indicate the relative ranking of reliability, from 1 (low) to 10 (high). Data types are color-coded: brown for surface geologic features;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

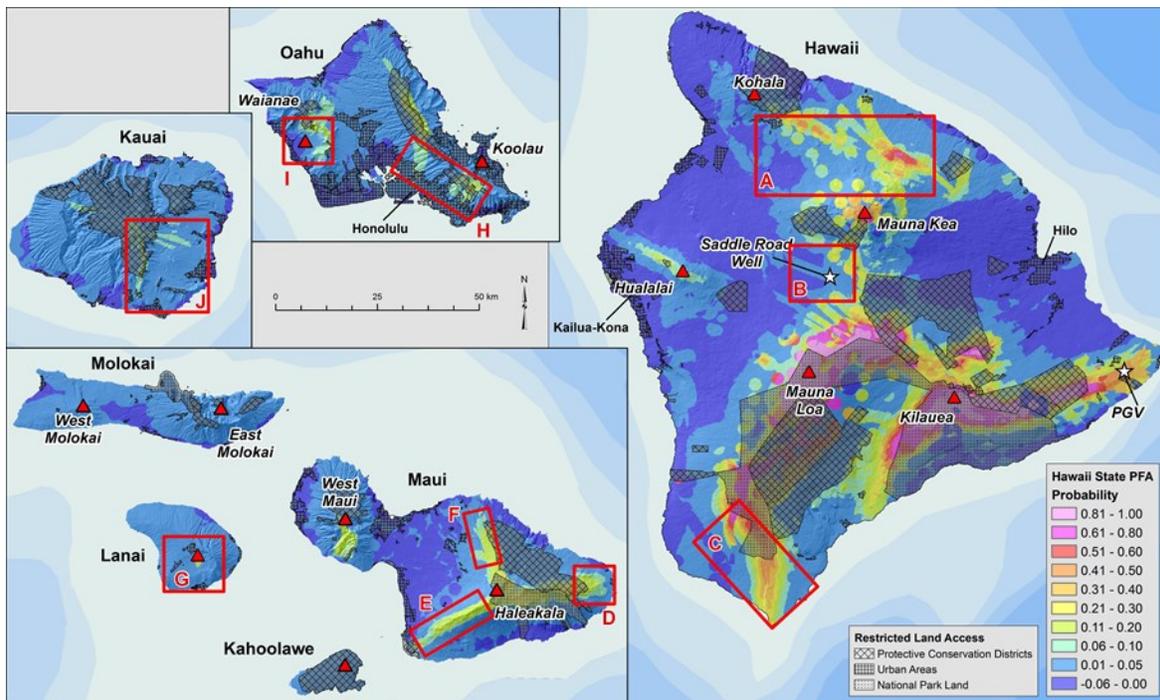


Figure 2: Results of the DOE Phase 1 geothermal play fairway probability analysis for the State of Hawaii. Probabilities of a geothermal resource are colored. Areas with restricted land access are shown in stippled and crosshatch patterns (e.g., National Park lands, protective conservation districts, and urban areas). Red boxes outline areas proposed for Phase 2 study. Red triangles indicate the calderas of the main shield volcanoes. White stars mark the locations of the Saddle Road well and Puna Geothermal Ventures (PGV).

2. PHASE 2 RESULTS TO DATE

2.1 Groundwater Temperature

The figure below shows the location and measured temperature of water wells sampled during Phase 2. Note that anomalously warm wells occur in some locations of the Big Island, on Lanai, in the region of Waianae's caldera on Oahu, and along the SW rift zone of Haleakala (Maui). We plot the difference between the measured well water and surface temperature (*Giambelluca et al., 2014*). We consider this a conservative approach, as the well water will be sourced from higher elevation and therefore colder than the surface temperature at the well location. We are exploring, and open to feedback, as to whether this is the best approach.

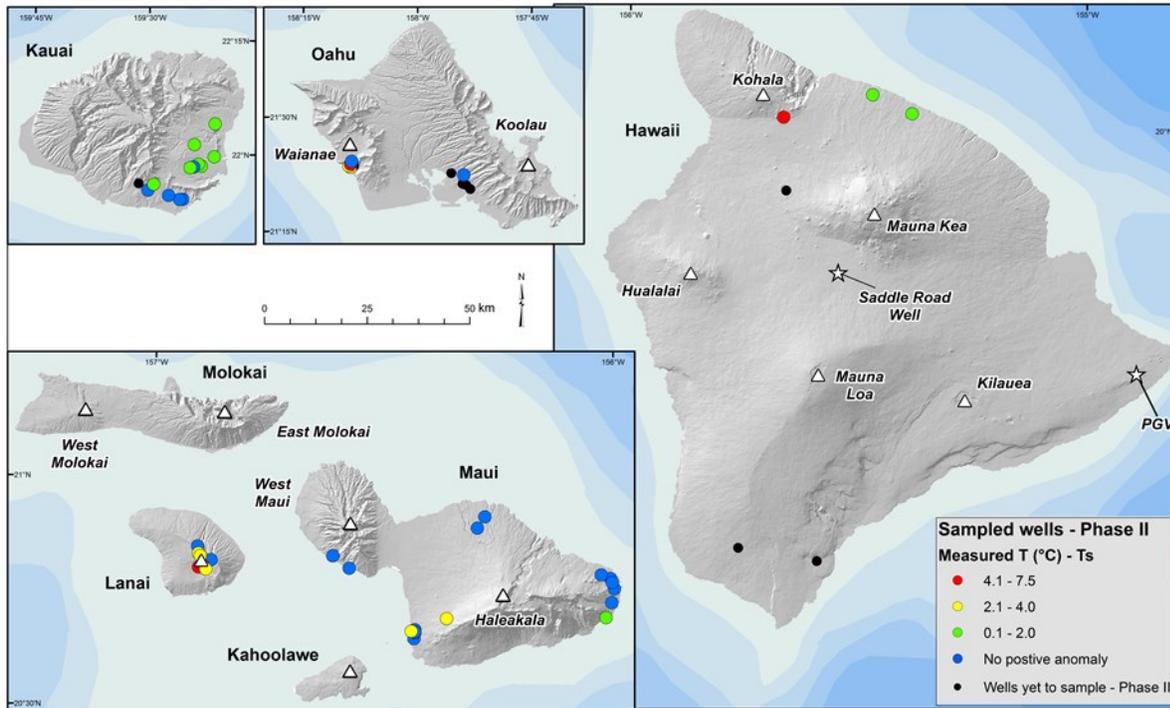


Figure 3: Results of the DOE Phase 1 geothermal PFA analysis for the State of Hawaii. Probabilities of a geothermal resource are colored. Areas with restricted land access are shown in stippled and crosshatch patterns (e.g., National Park lands, protective conservation districts, and urban areas). Red boxes outline areas proposed for Phase 2 study. Red triangles indicate the calderas of the main shield volcanoes. White stars mark the locations of the Saddle Road well and Puna Geothermal Ventures (PGV).

2.2 Lanai Gravity

The raw gravity data were corrected for instrument drift and then converted to absolute gravity. Complete Bouguer anomalies (CBA) were then computed by removing the gravity of the WGS84 reference ellipsoid, and correcting for elevation as well as the attraction of the crust between the measurements and sea level using a reference density of 2600 kg/m^3 . The resulting anomaly thus reflects subsurface density variations that deviate from 2600 kg/m^3 .

The most notable feature is in the Palawai Caldera in the southern half of the island where the CBA is 50-60 mGal higher than near the coasts in the northern part of Lanai. CBA is also elevated in the areas of the southwest and southeast rift zones where dikes are exposed. The CBA decreases rapidly to the north of the caldera and, surprisingly, is relatively low over most of the topographic ridge of the northwest rift zone. Initial inversions of the CBA to produce models of subsurface density were done using GRAV3D [*UBC Geophysical Inversion Facility, Univ. British Columbia, Vancouver*].

One model shown in the figure above demonstrates that beneath the caldera, there is a voluminous mass of rock with densities between 2900 kg/m^3 and the maximum density allowed by the inversion of 3000 kg/m^3 . These densities are expected for intrusive dikes and gabbro containing olivine cumulates. The possibility that these intrusions are still hot is suggested by water sampled in 3 wells in the area (circles) with temperatures of 5.5-14°C above the annual mean surface temperature.

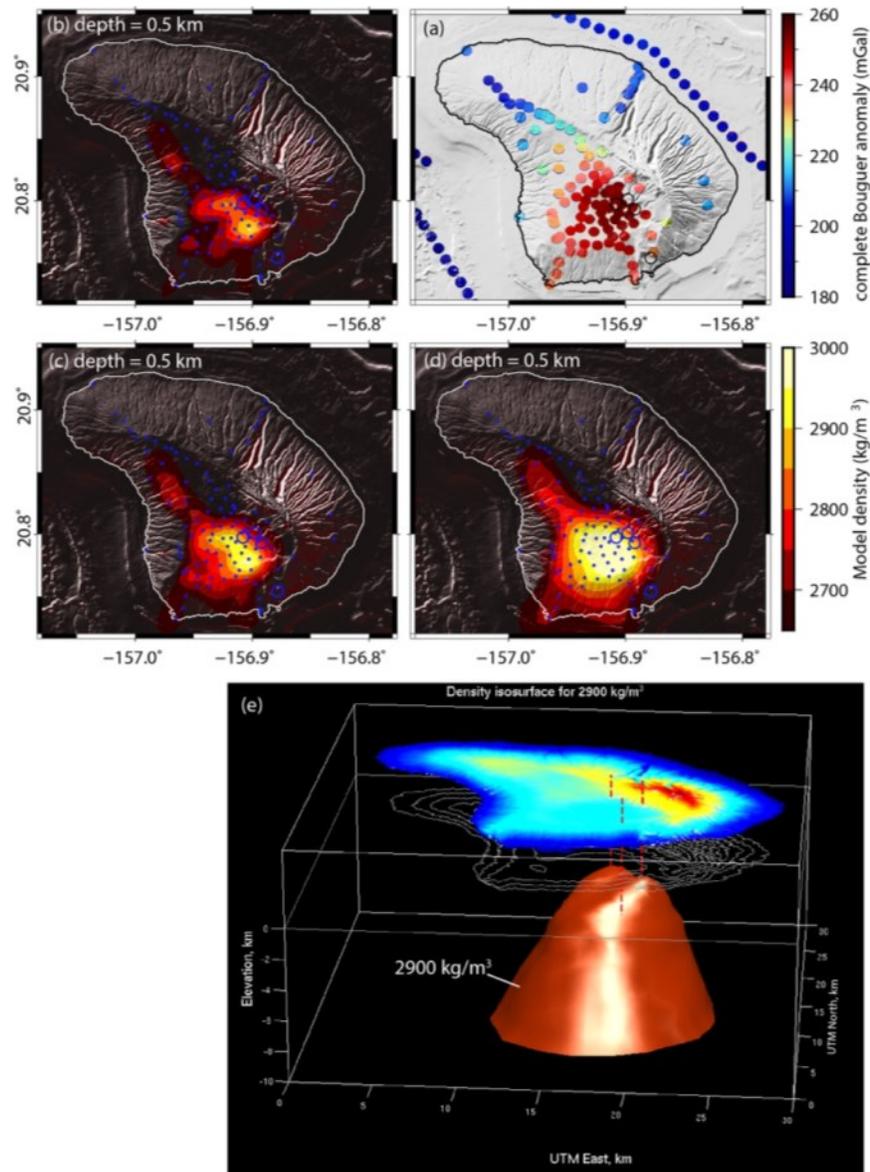


Figure 4. Panel (a) shows map of complete Bouguer gravity anomaly (CBA) at individual stations on and around Lanai (topography illuminated from the northwest). (b),(c), and (d) show cross sections of a density model produced by inverting the CBA at depths of 0.5, 1.0, and 2.0 km below sea level, respectively. Blue dots are station locations and circles mark locations of elevated well water temperatures. (e) 3D perspective view of the 2900 kg/m³ isosurface (red). 100-m contours of elevation are shown at zero elevation. Colored topography is shown on a plane 3 km above sea level for visualization purposes.

2.3 Lanai MT

Data from 44 MT sites were collected over 5 weeks in Sept/Oct 2016 using modern Phoenix Geophysics equipment, which can collect short to long period data. The data have been edited and processed into .edi files. The data will be inverted using a 3D algorithm developed by P. Wannamaker and a 2D open source code MARE2DEM (<http://mare2dem.ucsd.edu/>). Even though longer period data was collected, due to the coast affect and other 3D effects data longer than 2-300 seconds will not be used for this project.

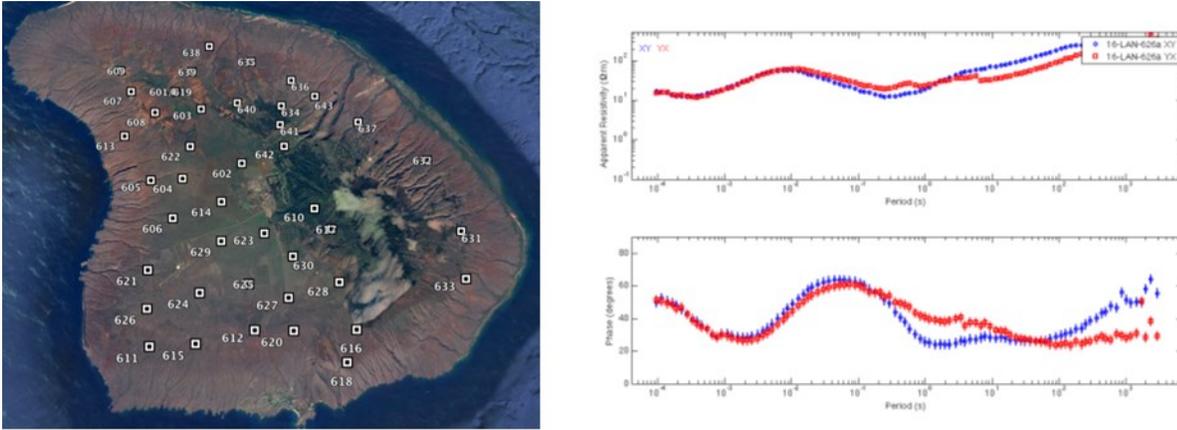


Figure 6. On left is a map showing locations of MT sites on Lanai. On right is the apparent resistivity and phase from site 626. This site is of high quality and is largely representative of the data found on Lana'i. The interesting thing on a small island that the dataset is largely 1D with some structure around .1-10s. The period of 1s has a skin depth of approximately 300m in this environment.

2.4. Lanai Failure Potential Model

To compute topographic stresses for Lanai we interpolated the digital elevation model to 100 m grids in a 30 km x 30 km area encompassing the whole island, approximately centered over the Pawalai Caldera. Each grid locates the origin of a Green's function for a square patch of downward traction on the shear traction-free horizontal surface of a 3D half-space. The downward traction at each grid is proportional to the reference crustal density (2600 kg/m^3) and surface topographic height above (positive load) or depth below (negative load) datum, which here, is sea level. The effects of each square patch are summed to give the total perturbation to each component of the 3D stress tensor due to topographic loading at a given location in the crust. The full stress solutions are the stress perturbations plus lithostatic pressure. A measure of the potential for fracture permeability is the failure potential [Martel 2000],

$$\Phi = \frac{(\sigma_1 - \sigma_3)}{\tau_0 + |(\sigma_1 + \sigma_3)|} \quad (1)$$

where σ_1 and σ_3 are the least, and most compressive stresses respectively, and τ_0 is a constant (here 20 MPa). The numerator is differential stress, greater values of which promote fracturing and faulting. The denominator is a general proxy of the rock's brittle strength, which increases with pressure (including lithostatic pressure) $|(\sigma_1 + \sigma_3)|$ above the reference strength τ_0 .

Results show an overall trend of increasing failure potential Φ with depth in the first few km below sea level, and then decreasing below that. Failure potential is predicted to increase with depth in the uppermost 0 – 2 km, relevant to a geothermal resource, thus tending to partially counter-act the effects of increasing lithostatic pressure to close pore-space and reduce permeability at these depths. Topographic loading is thus predicted to increase the likelihood of fracture permeability at depths where intrusive (potential heat source) rocks are more likely to be present, as suggested by the gravity inversions.

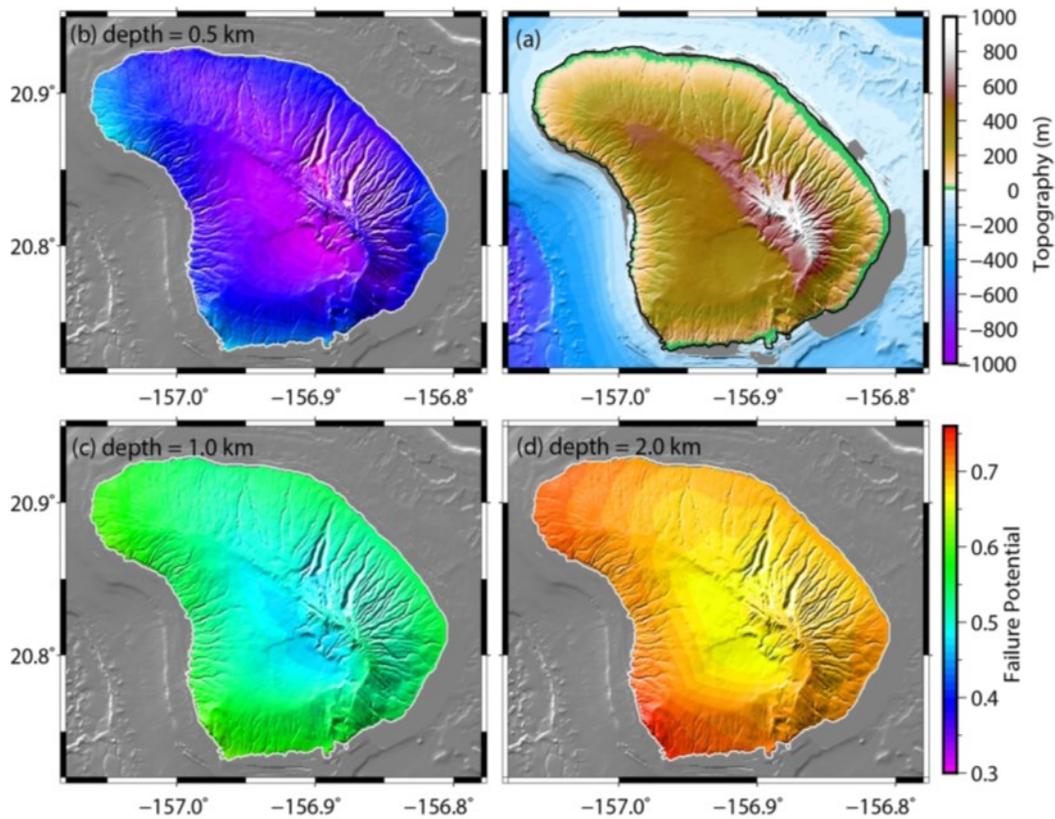


Figure 6. Topography of Lanai, illuminated from the northwest. (b), (c), and (d) show failure potential Φ at depths of 0.5 km, 1.0 km, and 2.0 km respectively.

2.5 Mauna Kea Geophysics

Separately funded MT/AMT surveys conducted on the east flank of Mauna Kea have provided a significant new addition to the for Hawaii Island dataset. Initially, this work was intended to further investigate conductivity anomalies identified on State-owned (Department of Hawaiian Home Lands - DHHL) property that had been identified during geophysical surveys conducted in search of shallow groundwater in the Humu'ula Saddle region (Pierce and Thomas, 2009). The more recent surveys covered a much broader region of the Mauna Kea flank and recovered data that suggests that there may be extensive thermal discharges from the core of Mauna Kea at depths of two to three km below ground surface beneath the 56,000 acres encompassed by the DHHL lands. Further, data within the central eastern flank of the mountain are strongly suggestive of a previously unconfirmed east rift zone of Mauna Kea; resistivities within this rift are consistent with the presence of an active hydrothermal system.

These are the first modern data supporting the presence of an east rift zone for Mauna Kea and further support the previously collected data in the Humu'ula Saddle that significant residual heat is present within this recently active volcanic system. The geophysical data are consistent with elevated GW temperature and anomalous chemistry identified in Phase 1 as an elevated resource probability in this location.

We have presented the results of our findings to the interested agencies and recommended additional geophysical and drilling exploration to confirm the presence of a prospective geothermal system there. Discussion of strategies for conducting that work are continuing.



Figure 7. This figure shows the locations of the Mauna Kea survey line for the survey of DHHL lands. The sites in red are those located over the interval showing the lowest resistivity values.

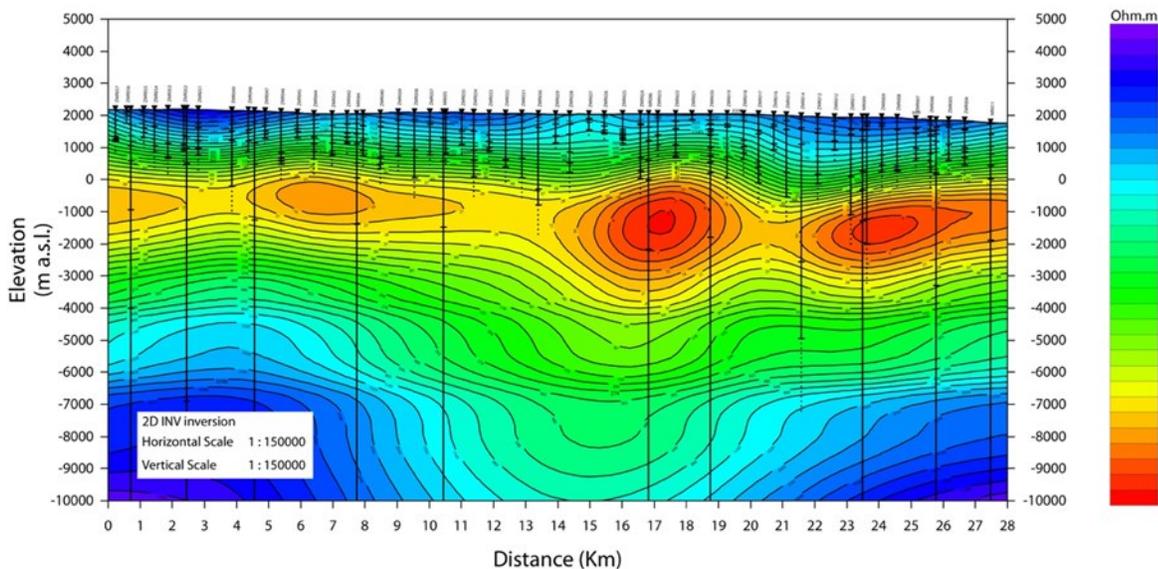


Figure 8. Conductivities at and below sea level are consistent with the presence of thermal fluids at these depths; the lowest resistivities are co-located with concentrations of cinder cones on the flank of Mauna Kea. The central resistivity low, between the 11 km and 21 km interval of the transect, based on the deep penetration of the resistivity low, is interpreted as the Mauna Kea east rift zone.

2.6 Back-Propogation of Water Well Data

Team member Frazer is working on a method to improve our back-propagation of well water temperature and geochemical signals. This is an interesting problem, not only because of the large number of unknowns and uncertainties, but also because of the computational challenge—in order to be practical in a reconnaissance situation a method must be fast enough to run in minutes not days. Our work is based on the principle that the transpose of an operator is a low-resolution, relative-amplitude approximation to the inverse of that operator. It is not yet clear whether this work will be an improvement on our present method of back propagation, which has the virtue of forcing the interpreter to consider the local geology.

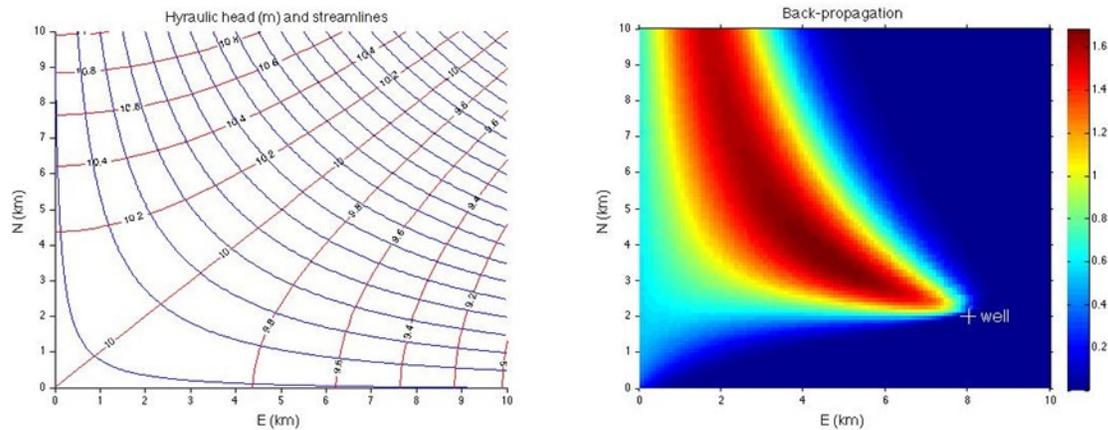


Figure 9. Left panel: Contours of hydraulic head (red) and streamlines (blue). Right panel: back propagation of a positive geochemical signal from the well located at '+'. The color bar indicates the relative probability of a geothermal resource, assuming that (as in Hawaii) geothermal waters are heated at depths ≥ 2 km.

3. CONCLUSION

The Phase 1 PFA was a success, and Phase 2 is progressing nicely. Plans for next quarter include: to perform a geophysical survey on the SW rift of Haleakala volcano (Maui; pending NEPA and landowner approval), to complete sampling of water wells on Oahu and Big Island, to analyze groundwater samples for geothermal anomalies and improve flow models, to perform topographic stress modeling for the rest of the Phase 2 study areas, and to obtain groundwater samples and gravity data on the DHHL land east of Mauna Kea (as feasible). Our ultimate goal is to bring all data into an improved statewide resource probability map, and outline a plan for Phase 3.

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