Phase 2 Activities to Improve a 2015 Play Fairway Analysis of Geothermal Potential 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, coupled with considerations of development viability, led to the identification of ten locations for future exploration 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 planned are i) geophysical (electromagnetic and gravity) surveys in a few high priority areas, 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 will include the production of 3D crustal stress models to better infer subsurface permeability, and the integration of new data into improved 2D and new 3D probability maps. An introduction to, and description of, each activity is given below. A status update will be included in the presentation.

1. Introduction

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 currently in review at *Geothermics* (Lautze et al, 2016a; Ito et al., 2016; Lautze et al., 2016b).

Four project tasks will be pursued 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. These models will help rank plays according to their potential for developing a reliable geothermal fluid supply. (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 play fairway analysis.

This modern effort in play fairway analysis, and exploration for geothermal resources in Hawaii, is timely for a number of reasons. Published in 1985 (Thomas, 1985), the last statewide geothermal resource assessment indicated potential prospects on all of the main Hawaiian islands; however, little additional work has been done since. In 2013, our team members led a US Army funded drilling effort in search of groundwater, which found water at an elevated temperature (~140℃ at 1.8 km depth) in a location not previously recognized as a geothermal area of interest. 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 extremely favorable. Historically, Hawaii has had the highest electricity cost in the nation; it currently is more than twice the national average. 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.

2. Description of Planned Activities

2.1 Explore for Heated Fluid and Delineate its Distribution With New MT/AMT and Gravity Surveys

Motivation. Geothermal systems are often detected and defined using electromagnetic geophysical methods. MT and AMT provide estimates of electrical resistivity laterally and with depth. The ability of MT and AMT surveys to provide information over a broad depth range often allows both the delineation of the resource and also the causative underlying heat source.

In conducting MT and AMT surveys for groundwater exploration and subsequent drilling, UH researchers identified a previously unrecognized geothermal resource in the saddle between Mauna Kea and Mauna Loa on Hawaii Island (Lienert et al., 2014; Thomas et al., 2014). Consequently, UH has collected additional data on Hawaii Island, and surveys are ongoing. The dataset now includes 80 MT sites and 130 AMT measurements (Figure 1), as well as a statewide set of gravity data. Substantial relevant geophysical data exist for Hawaii Island (albeit with some gaps), but not for the other islands. Additional data for prospective regions on other islands will aid in (a) detecting and characterizing potential geothermal resources, and (b) identifying regions where further, more detailed exploration would be informative.

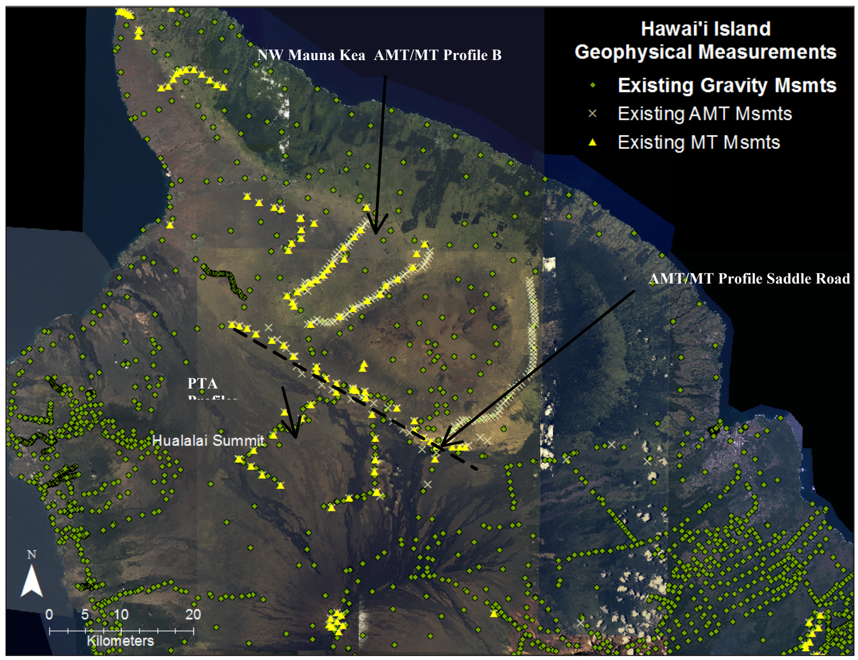

Figure 1. Location of existing gravity (green circles), MT (yellow triangles), and AMT (white crosses) data. Hualālai Summit, the location of the Saddle Resistivity Cross Section, and the AMT and MT profiles across NW Mauna Kea, are indicated on the map.

In 2004 and 2008, UH researchers, the USGS, and the US Army Corps of Engineers collected AMT and MT data across Saddle Road on Hawaii Island (*Pierce and Thomas*, 2009). Locations are marked on Figure 1. The purpose of the survey was to explore for high elevation groundwater underlying the Humuʻula Saddle region and, if evidence of accessible water was found, to identify drilling sites for an exploration well for the US Army Pohakuloa Training Area (PTA). The site for the PTA exploration well was chosen based on a published resistivity model (Figure 2) showing an area with low resistivity (units of Ohm-meters, Ωm), which indicates groundwater, and a lack of high resistivity, which indicates higher permeability. The water table elevation in the groundwater well at the eastern edge of the profile (near MT station KM01 in Figure 2) corresponds to the 1100 Ωm contour, consistent with the resistivity for basalts saturated with freshwater (*Zohdy and Jackson*, 1969). At depth, the thermal gradients approached 165℃/km and a bottomhole temperature of 140°C where resistivities were interpreted to be 20 Ωm and lower.

We are now analyzing MT and AMT data recently collected from PTA and NW Mauna Kea using the three-dimensional inversion program of *Siripunvaraporn et al.* (2005) as well as 1D and 2D inversions (*Rodi and Mackie*, 2001). Figure 3 shows contoured 1-D inversion results along two profiles acquired at PTA. The profiles agree well where they intersect in the upper 2000 m, but disparate resistivity values at greater depths demonstrate that 2- and 3- D inversion are necessary for a robust result.

The results of the published MT/AMT studies, our findings to date, and drilling data from the Saddle area point to the existence of geothermal resources in previously unanticipated locations. These results demonstrate the necessity of MT/AMT studies in Hawaiian geothermal resource evaluation.

Methods. *Top two sites.* Our highest priority sites for new geophysical surveys are the *Island of Lanai* and the *SW Rift of Haleakala* (Maui). These islands lack MT/AMT data, but if a resource is identified at either site the viability of geothermal development is very high.

Lanai. A system of roads developed for plantation access reduces the cost of a 3D geophysical survey on Lanai (a luxury not present on Hawaii Island, where road access is much more limited), and we already have support for land access. The Lanai survey will cover as much of the island as allowable, enabling a 3D study and analysis of 30-50 soundings to identify and characterize both the near surface resource system and the underlying heat source. This will allow for accurate mapping and interpretation of the structure of the island, providing insight into other locations not currently volcanically active. The 3D modeling of Lanai will also provide a framework to better understand the 2D models obtained from MT surveys on Hawaii and Maui where 3D surveys are not logistically possible but the structure is expected to be 3D. Modeling in 2D and 3D will be completed using the NLCG (Rodi and Mackie, 2001) and HexMT algorithms (*Kordy et al.*, 2015a, & *Kordy et al.*, 2015b) respectively. HexMT is a recently developed 3D finite element approach, employing a deformable mesh that allows a smooth topography representation rather than the block stair step representation of other 3D finite difference approaches. The ability to accurately and realistically represent topography is essential for obtaining accurate results in ocean island settings such as Hawaii.

Haleakala Southwest Rift (Maui). Both geography and land development (anthropogenic noise) limit where high quality data are expected to be collected. A 2D transect will be conducted to characterize the geothermal resource above the coast (which is heavily developed) and beneath the relatively steep western flanks of Haleakala.

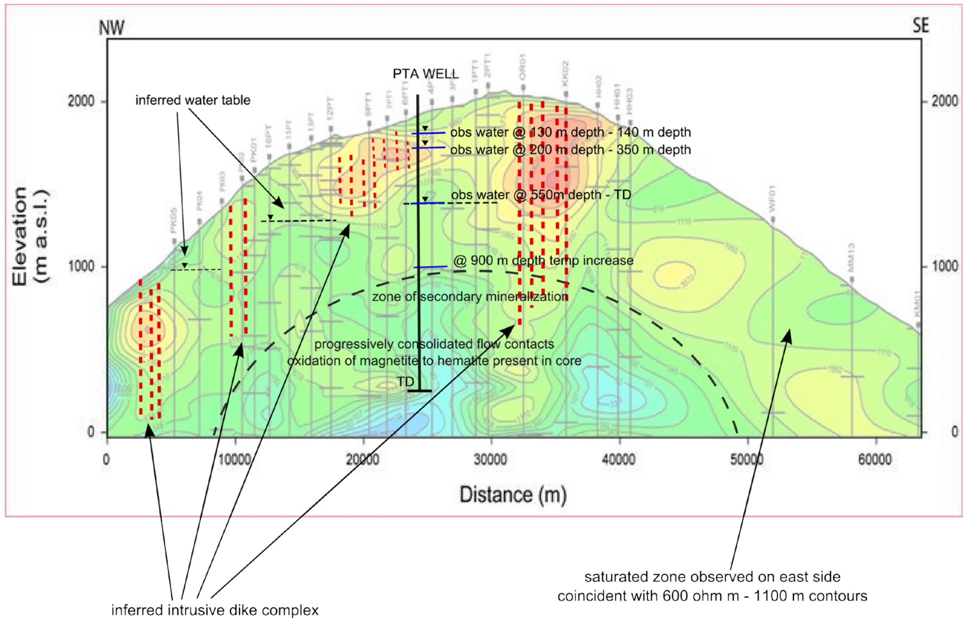

Figure 2. Cross section of electrical resistivity through the Humuʻula Saddle of Hawaii Island (Pierce and Thomas, 2009), produced from 23 MT stations (locations shown in Fig. 1). This model was used to target the drill site at Pohakuloa Army Training Area (PTA).

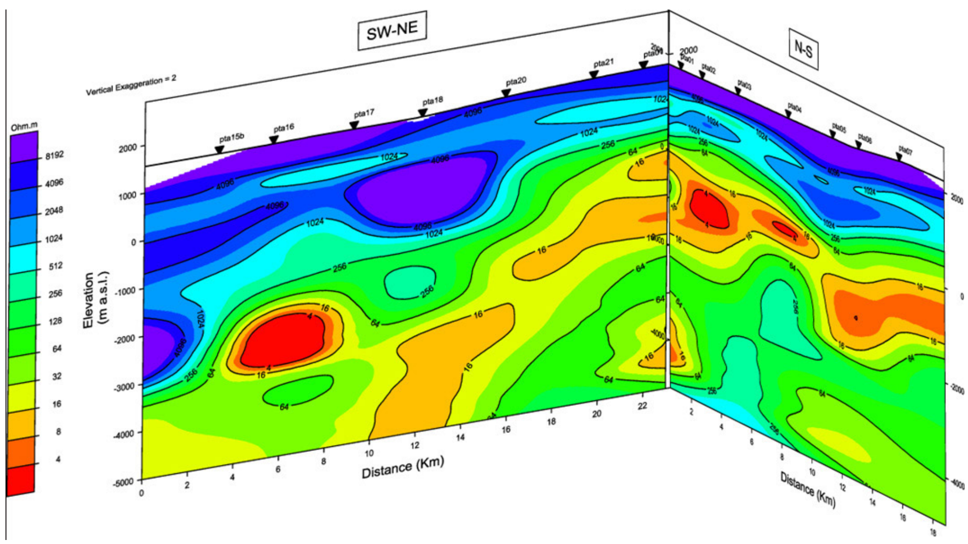

Figure 3. Contours of 1-D Occam models along the SW-NE and N-S profiles shown in Fig. 1. The image was produced from 1-D inversions beneath the individual stations along the two profiles separately. The disagreements at depth indicates that 2-D and 3-D inversion are needed for a robust result. The numbers on the contour lines are resistivity values in Ohm-m. The PTA-1 well is at the approximate intersection of these two profiles.

Gravity Surveys will accompany the MT/AMT surveys. Existing gravity data are adequate for characterizing the island-scale crustal density structure, but more closely spaced measurements would better suit geothermal exploration. The gravity data will be reduced using standard methods (*Flinders et al.*, 2013) to produce the Bouguer and residual gravity results. To produce the 3D density structure the residual gravity anomalies will be inverted using the GRAV3D 2007 algorithm. The gravity modeling will identify the depths and distributions of the dense, intrusive (hot) source rock. To address the inherent non-uniqueness of gravity inversions, multiple solutions for each study area will be calculated to show the range of probable depths and distributions of potential heat sources. The co-located gravity and MT/AMT surveys will provide complementary constraints on the 2D and 3D distributions of dense source rock (gravity), conductive geothermally altered regions indicative of the presence of hot fluid (MT/AMT), versus cool porous crust (gravity & MT/AMT).

Outcomes. The data collected will provide a better understanding of the exploitable geothermal resources present on Lanai, and Maui, as well as a more thorough understanding of the deep structure and underlying heat source responsible for geothermal systems in Hawaii in general. We will develop 3D models of the full range of geologically plausible and geologically probable density structure, and 2D and 3D models of electrical resistivity of Lanai.

2.2 Validate the Groundwater Indications of Geothermal Activity and Improve the Constraints With Analyses of New Water Samples

Motivation. Circulation of groundwater through a geothermal reservoir imparts a temperature and chemical signature that is carried with the groundwater as it flows down gradient. In Phase 1 of the project, a groundwater temperature and chemistry database was compiled from sources at the USGS, Hawaii's water utilities, Hawaii's Department of Land and Natural Resources (DLNR), the Hawaii Department of Health (HDOH), and the Hawaii Institute of Geophysics and Planetology (HIGP) at the University of Hawaii. In order to evaluate the origin of the water exhibiting elevated temperatures and/or the characteristics of geothermal alteration, flow vector fields were created from groundwater models produced by the HDOH's Source Water Assessment Program (SWAP). The groundwater data used in Phase 1 demonstrate their value to the play fairway (PF) analysis and overall assessment of Hawaii's geothermal resources.

Some drawbacks of the existing Hawaii groundwater data are that: a) the chemistry data are limited to Ca, Na, K, Cl, Mg, Si, pH, and carbonates; some valuable chemical indicators are lacking (e.g., trace metals and isotopes); b) many of the samples were collected prior to 1980; analysis techniques have greatly improved since then; c) the geographic availability of data is far from comprehensive; several of the Play Fairway modeled areas of interest (e.g., Haleakala's rift zones) have very sparse groundwater data; and d) the groundwater flow paths are not well established.

The goal of this Phase 2 task is to remedy these shortcomings. Sampling and analyzing groundwater is relatively low cost, low risk, and straightforward to do, making it a logical next step in Hawaii's geothermal resource assessment program.

Methods. We will collect groundwater samples from key areas where Phase 1 results indicate that a geothermal resource probably exists, and where development is viable. Three such areas are on Hawaii Island, three on Maui, one on Lanai, two on Oahu, and one on Kauai. We will identify strategic sampling points and (where possible) collect 10 to 25 samples from each area. To the extent possible, sampling will be coordinated with the routine data collection efforts of county water utilities and state agencies. Some trace element analyses will be conducted to determine whether anomalous values are apparent, however, prior work has generally indicated that the strongest indicators of anomalous chemistry are associated with silica and sulfate concentrations as well as modifications to dissolved inorganic carbon isotopes.

Geothermal resources are commonly located substantial distances from available sampling points. However, groundwater often retains signatures of geothermal alteration as it flows down the hydraulic gradient. To track groundwater that exhibits chemical characteristics of geothermal alteration back to the most probable source area, the flow path trajectories and water table heights were estimated by groundwater modeling in Phase 1. Oxygen & hydrogen (O&H) isotope data will be collected and used to validate or correct these paths in Phase 2. Previous research has shown that a predictable (but island- and mountain-specific) relationship exists between the precipitation elevation and the O&H isotopic composition of that precipitation (*Scholl et al.*, 1996 and 2002; *Fackrell and Glenn*, 2014; and *Tillman et al.*, 2014). Since the spatial distribution of the isotopic composition of precipitation/recharge can be predicted with reasonable accuracy (as a function of elevation), and since the isotopic composition changes little during infiltration and flow, O&H isotopes can be used to validate or improve existing groundwater flow paths.

Outcomes. This task will update and greatly expand the groundwater temperature and chemistry database in Hawaii. Collecting data to improve the groundwater flow models is an essential element of this task, as it will enable us to more confidently track geothermally altered water from the sample location (i.e., well or spring) to the origin of the alteration (i.e., the geothermal resource). At relatively low cost, the final products will develop more accurate maps of resource probability and confidence on all the islands.

2.3 Provide New Information About Permeability Structure Using 3D Crustal Stress Models

Motivation. A lack of information on the subsurface permeability structure is a major shortcoming of our knowledge about geothermal systems in Hawaii. The permeability of many geothermal fields is strongly controlled by the structural geology (*Moeck*, 2014; *Moeck et al,* 2010; *Faulds et al.,* 2011). In volcanically active settings, numerous geologic features associated with magmatism influence the permeability structure of the shallow crust (*Ingebritsen and Scholl*, 1993; *Faybishenko et al.*, 2000; *Kuntz et al.*, 2002; *Martel and Langley,* 2006; *Kaven and Martel,* 2007; *Lau and Mink,* 2006). As volcanism wanes and ceases, the permeability evolves with mass wasting, weathering, mineralization, and especially changes in the crustal stress field. For example, the stress field can cause near-surface fractures either to squeeze shut, thus reducing their permeability, or to open or slip (*Pollard and Segall,* 1987), which locally increases their permeability (*National Research Council,* 1996). Topography is an important influence on the crustal stress field. As our target sites are in areas with large changes in topography and where deformation due to active magmatism is subdued or has ceased (with the exception of Mauna Loa's SW rift zone), topography-induced stresses are likely to be a dominant influence on the permeability structure.

Recent findings support our inference that topography can influence crustal permeability. *St. Clair et al.* (2015) have shown that two geophysical signatures of fluid-filled fractures, low P-wave speeds and low electrical resistivity, correspond remarkably well to the 3D elastic stress response to topography at three different sites (Figure 4). One measure of the response is failure potential (ϕ), which is proportional to the difference between the maximum and minimum compressive stresses and reveals the tendency for fractures to slip and indirectly increase permeability (Figure 4A-C). A second measure of the response to topography is the least compressive stress (σ_{1c}), which reveals the tendency for fractures to open and directly enhance the permeability. Failure potential is computed as being high and the least compressive stress is computed as being low in areas where P-wave speeds and resistivity are low and indicate elevated fluid content (Figure 4). These results reveal a close relationship between the topographically influenced stress field and the subsurface permeability structure.

Methods. We will model the topographically perturbed gravitational elastic stresses in 3D for each of the Hawaiian Islands using two methods. The first is a fast approximate solution based on the Boussinesq solution for the stresses arising from a concentrated vertical force on the surface of a half-space (*Sadd*, 2009). Research in progress shows that this solution can be used to evaluate stresses beneath a topographic surface of arbitrary shape, provided that the slopes are gentle (<11°), as they are in Hawaii. The second is the more accurate, but slower, technique of *St. Clair et al.* (2015), which uses the boundary element code POLY3D (*Thomas*, 1993) and is better suited for steeper topography. This method is an extension of a 2-D technique (*Martel*, 2000; *Martel and Muller*, 2000) devised to examine the interaction of subsurface structures with topographically modified stresses (*Muller and Martel*, 2000). We will calculate both total stresses and effective stresses based on the digital elevation (and bathymetric) data we have collected as well as various estimates of the level of the groundwater table. We will also perform some exploratory work using POLY3D to investigate how (a) slip along a fault near the base of a volcano, and (b) dike intrusion along rifts would alter the total stress field.

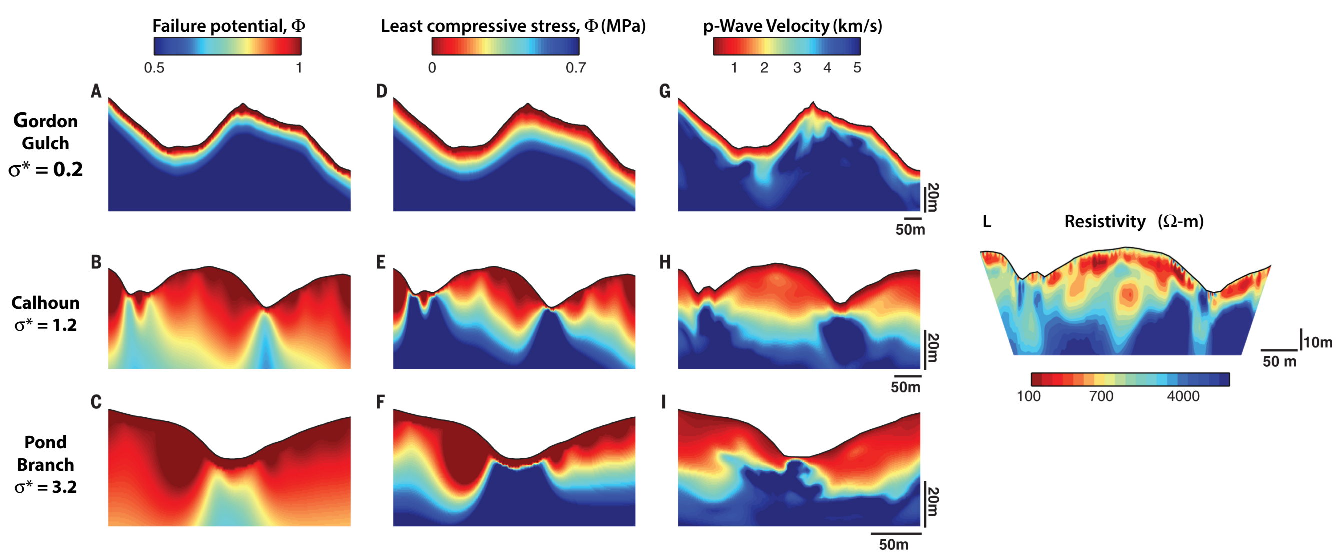

Figure 4. Modeled failure potential (A-C), least compressive stress magnitude (D-F), and measured P-wave velocity (G-I) for profiles (A,D,E) at Gordon Gulch, Colorado (vertical exaggeration = 3.6x), (B,E,H) Calhoun, South Carolina (vertical exaggeration = 3.7x), and (C,F,I) Pond Branch, Maryland (vertical exaggeration = 2.3x). The term σ* is the ratio of the horizontal tectonic stress acting perpendicular to the valley to a characteristic vertical compressive stress that scales with the topographic relief. From *St. Clair et al.* (2015).

Outcomes. The products will be 3D maps of the topographically perturbed gravitational stresses, failure potential, and least compressive stress for each of the Hawaiian Islands. The results will be interpreted in terms of variations in permeability and will be used in the 2D and 3D probability modeling during the final data integration and interpretation phase of the project.

2.4 Integrate All Data and Produce Improved 2D and New 3D Probability Maps

The culminating activity that will integrate the results of the new geophysical surveys, water sampling and analyses, and stress modeling will be improved 2D probability models and new 3D models. Regarding the 2D models, the results of the water sampling and stress modeling will be used to refine our statewide maps of probability and confidence. These improved maps will not only be a check on our rankings of prospects, but will also be of high value in the long-term, as the range of economically viable resource types expands with improved engineering technology. As noted above, our methodology easily incorporates new data, allowing maps to change rapidly as Phase 2 data accumulate.

The 3D models will be most important for delineating the subsurface structure of target areas. We will apply the same methodology that we developed and applied in Phase 1, but in three dimensions. We will also use modern software (e.g., Paraview www.paraview.org) to interactively visualize the data and probability models in 3D.

3. Conclusion

The 2015 Hawaii Play Fairway Analysis provided the first comprehensive geothermal resource assessment since 1985. That study integrated all existing data relevant to Hawaii's geothermal resource into a probability model. The probability model and considerations of the viability of development in the areas of elevated probability were used to prioritize additional attention in 10 areas across the state, including on the islands of Kauai, Oahu, Maui, Lanai and Hawaii. With Department of Energy funding, Phase 2 activities in 2016-7 will consist of geophysical surveys on Lanai and Maui, groundwater sampling and analysis in the 10 focus areas, crustal stress modeling, and improved 2D and new 3D imaging.

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