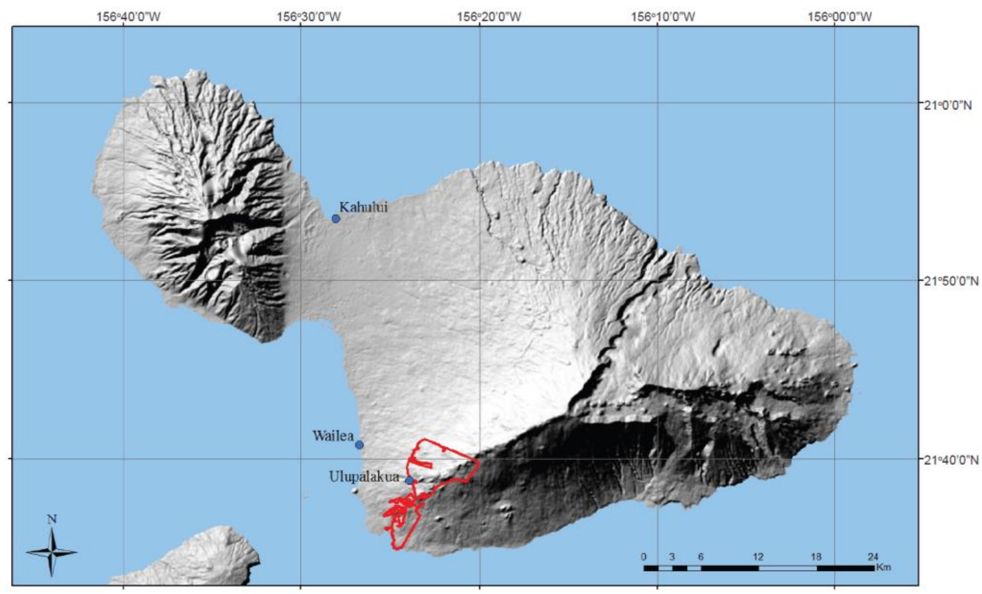
Maui Geothermal Exploration Project

Blind Geothermal System Exploration in Active Volcanic Environments; Multi-phase Geophysical and Geochemical Surveys in Overt and Subtle Volcanic Systems, Hawai'i and Maui

Final Report

DE-EE0002837



United States Department of Energy – Geothermal Technologies Program

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Executive Summary

Suites of new geophysical and geochemical exploration surveys were conducted to provide evidence for geothermal resource at the Haleakala Southwest Rift Zone (HSWRZ) on Maui Island, Hawai'i. Ground-based gravity (~400 stations) coupled with heli-bourne magnetics (~1500 line kilometers) define both deep and shallow fractures/faults, while also delineating potentially widespread subsurface hydrothermal alteration on the lower flanks (below approximately 1800 feet a.s.l.). Multi-level, upward continuation calculations and 2-D gravity and magnetic modeling provide information on source depths, but lack of lithologic information leaves ambiguity in the estimates. Additionally, several well-defined gravity lows (possibly vent zones) lie coincident with magnetic highs suggesting the presence of dike intrusions at depth which may represent a potentially young source of heat. Soil CO_2 fluxes were measured along transects across geophysically-defined faults and fractures as well as young cinder cones along the HSWRZ. This survey generally did not detect CO_2 levels above background, with the exception of a weak anomalous flux signal over one young cinder cone. The general lack of observed CO_2 flux signals on the HSWRZ is likely due to a combination of lower magmatic CO_2 fluxes and relatively high biogenic surface CO_2 fluxes which mix with the magmatic signal. Similar surveys at the Puna geothermal field on the Kilauea Lower East Rift Zone (KLERZ) also showed a lack of surface CO_2 flux signals, however aqueous geochemistry indicated contribution of magmatic CO_2 and He to shallow groundwater here. As magma has been intercepted in geothermal drilling at the Puna field, the lack of measured surface CO_2 flux indicative of upflow of magmatic fluids here is likely due to effective "scrubbing" by high groundwater and a mature hydrothermal system. Dissolved inorganic carbon (DIC) concentrations, δ13C compositions and 3He/4He values were sampled at Maui from several shallow groundwater samples indicating only minor additions of magmatic CO_2 and He to the groundwater system, although much less than observed near Puna. The much reduced DIC and He abundances at Maui, along with a lack of hotsprings and hydrothermal alteration, as observed near Puna, does not strongly support a deeper hydrothermal system within the HSWRZ.

Background

While the Haleakala Southwest Rift Zone (HSWRZ) on Maui Island, Hawai'i is considered geothermally "blind" (i.e., without surface manifestation of hot water), volcanism occurred as recently as 382 years ago with 200-500 year reoccurrence intervals (Sherrod, 2007), suggesting that magma is still actively being emplaced into the crust of Maui Island. Significant heat resources may therefore be available for geothermal production. The goal of this study was to assess previous geophysical surveys, conduct new geochemistry and soil gas flux studies at the well-characterized Puna geothermal field on the Kilauea Lower East Rift Zone (KLERZ), island of Hawai'i, determine lessons learned, and apply an integrated suite of geophysical, geochemical, soil gas flux, and remote sensing tools for exploration on the HSWRZ.

The Maui project is located on private lands leased from the Ulupalakua Ranch in December of 2008; adjacent land is either state or private. The project covers 7,462 acres along the ridgeline cut by the HSWRZ and ranges in elevation from near sea level at the SW end to an elevation of 6000 ft. at the NE end. While no gradient drilling has been done on Maui, geothermal researchers in the 1980's through 2005 concluded that the HSWRZ has the highest probability (15-25%) (Geothermex, 2005) of containing an active hydrothermal system on Maui (based on basic geologic models of hot-spot volcanism, soil gas chemistry and resistivity surveys). This is the highest ranking given for all non-Big Island prospects. Faults and fractures of the HSWRZ have served as conduits for the narrow zone of numerous young eruptive fissures and vents that define the Maui Project. Carbon-14 dating on post-shield Hana group Haleakala volcanics indicate a preponderance of ages less than 1000 years before present (Sherrod et al., 2007) and several flows of significant volume have an estimated ca. 1633 age. Thus on human time-scales, Maui is still active and has a significant chance of localizing a heat source at accessible depths beneath the HSWRZ. On the down side, there is a lack of surface hydrothermal activity within the HSWRZ and meteoric water input to support a rigorous hydrothermal system, which makes this project relatively high risk. In order to reduce this risk, a series of staged geophysical and geochemical surveys were recommended before advancing to exploration drilling.

Evolving models based on the new and existing data led us to divide the Maui project into 2 areas (Figure 7). The Makai area, located below Highway 37 and closest to the ocean at elevations from ~1800' to ~1100', hosts the most recent volcanism and appears to be cut by numerous fractures, faults and fault intersections. Ormat's conceptual geothermal model includes a shallow heat source (likely a basaltic intrusion of some kind) combined with deep-seated fractures inherent to the HSWRZ. However the flanks of Haleakala conduct large volumes of cold water from the summit and any hydrothermal activity is likely masked by this flow. The second area, Mauka, is predominately located above Highway 37 at elevations from ~1800' to ~3000'. Mauka also contains young volcanic centers and the presence of fractures, faults and fault intersections, however the elevations in this region will require much deeper drilling therefore is considered higher risk for exploration.

Ormat chose to propose the Ulupalakua, Maui prospect, located in the Makai area, for the DOE Innovative Technologies Program because of our history successfully developing the geothermal resource on Hawai'i Island and our unique ability to martial knowledge and development experience in this region. Furthermore, Maui provides us an opportunity to test geophysical and geochemical exploration techniques normally deployed in the Basin and Range geologic province. Assessment of these techniques in young, basaltic environments will provide us with a future best-practices roadmap for exploration in similar geologic environments, not least of which is additional locations within Hawai'i.

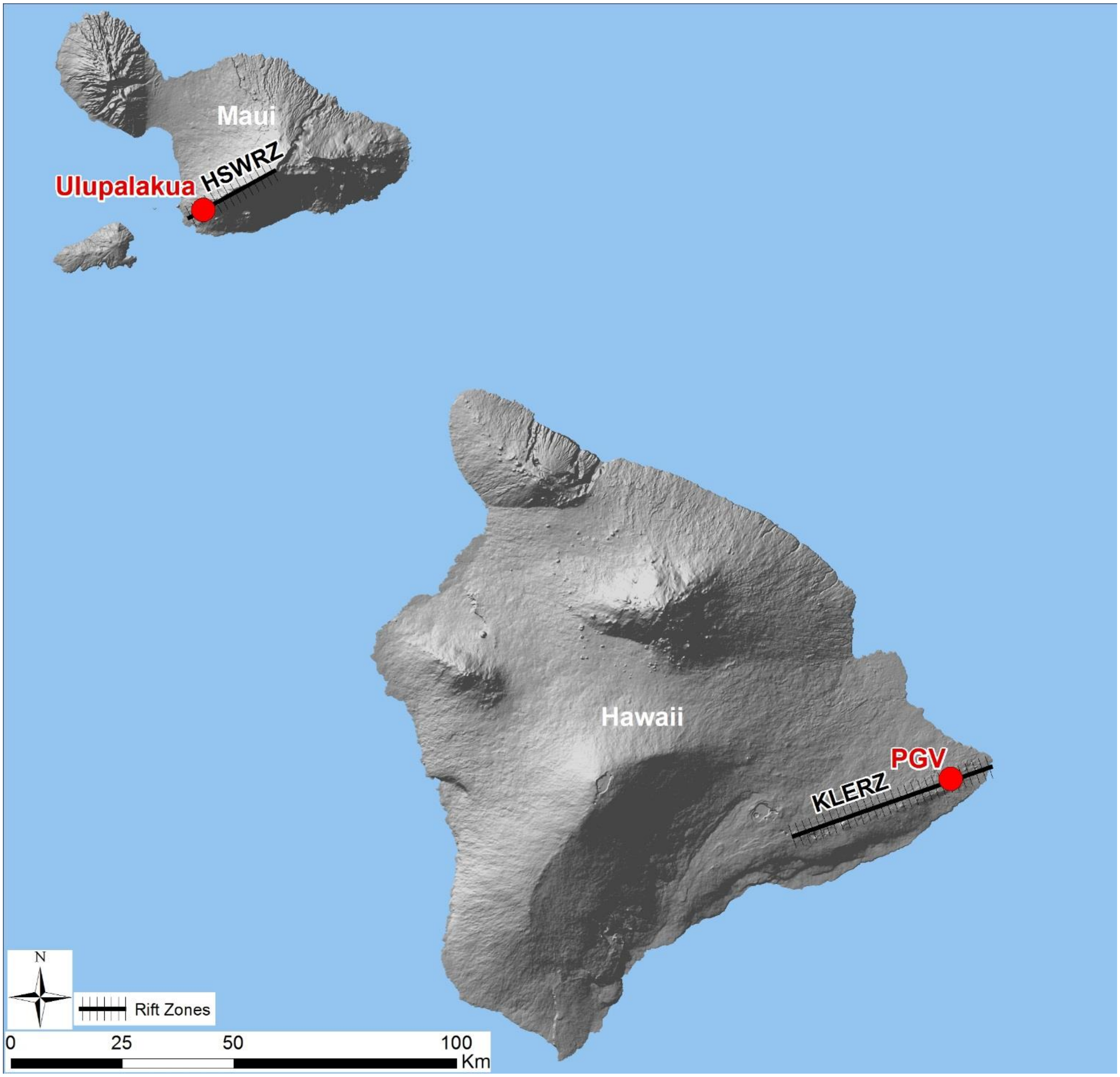

Figure 1. Overview map with shaded relief of Maui and Hawaii islands showing rift zones and study areas.

Gravity and Magnetic Studies

The ground-based gravity survey was collected covering approximately 284 km^2 and consisted of 400 gravity stations with 400 m spacing. Locations were derived with full DGPS. Station and line location, Complete Bouger Anomaly, first vertical derivative and horizontal gradient maps were calculated and produced (Figure 2). Finally, advanced modeling of the data was performed including 400m upward continuation and use of the LiDAR-derived elevation data. The upward continuation models what the data would look like if the sensors were 400m above the surface and helps to show broader and deeper structures. Horizontal gradient maps show where there is the greatest horizontal change in gravity and can be useful for indicating fault locations when two units of differing density are placed adjacent to each other through faulting. Faults/fractures were inferred based on spatially correlated high horizontal gradients in the Bouguer gravity (Figure 3).

Using a helicopter and a towed sensor array, the high-resolution aeromagnetic survey was carried out over the area of interest in Maui using primary survey lines spaced at 250-meter intervals with tie-line spacing of 1250 meters. Terrain clearance of the sensor averaged 401 meters. A total of 1253 line kilometers of aeromagnetic data were acquired. A reduced-to-pole grid was calculated for analysis and interpretation (Figure 4). Reduction-to-the pole calculates the field that would be observed if the survey area were located at the north magnetic pole. This transformation shifts the magnetic anomalies more nearly over the causative bodies.

The two geophysical surveys have been processed to produce a preliminary two-dimensional gravity and magnetic model of the subsurface (Figure 5). The model delineates rift vent zones underlain by dike intrusions by adjusting contacts to fit the data in a process called forward modeling. The preliminary maps were used to guide CO2 flux mapping and other aquatic and gas geochemical sampling for the project.

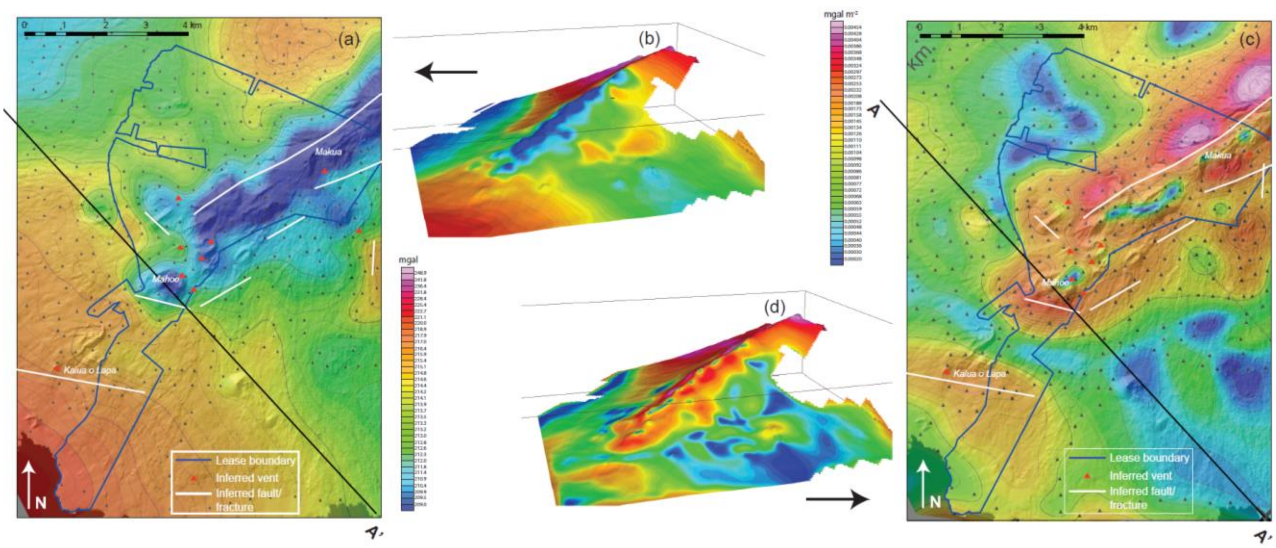

Figure 2. Maps of (a) Bouguer anomaly and (b) Bouguer anomaly draped over topography. Upward continuation (400 m) maps of (c) horizontal gradient in Bouguer anomaly and (d) horizontal gradient in Bouguer anomaly draped over topography. Faults/fractures inferred based on spatially correlated high horizontal gradients in Bouguer and magnetic (not shown) anomalies. Vent zones inferred based on spatially correlated low Bouger and high magnetic (Figure 4) anomalies.

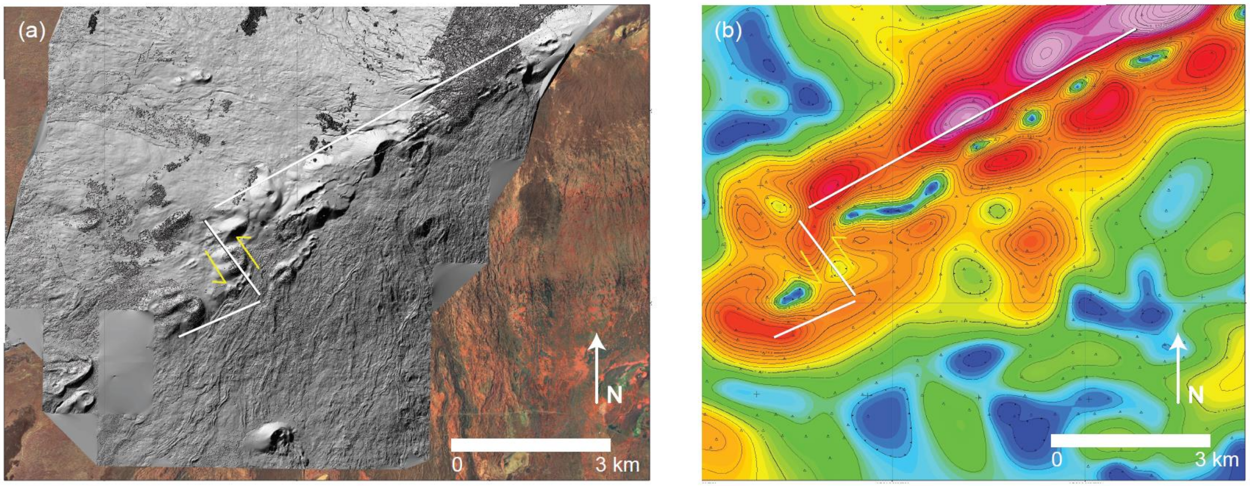

Figure 3. (a) Digital elevation model showing fault step-over inferred based on (b) upward continuation (400 m) map of the horizontal gravity gradient.

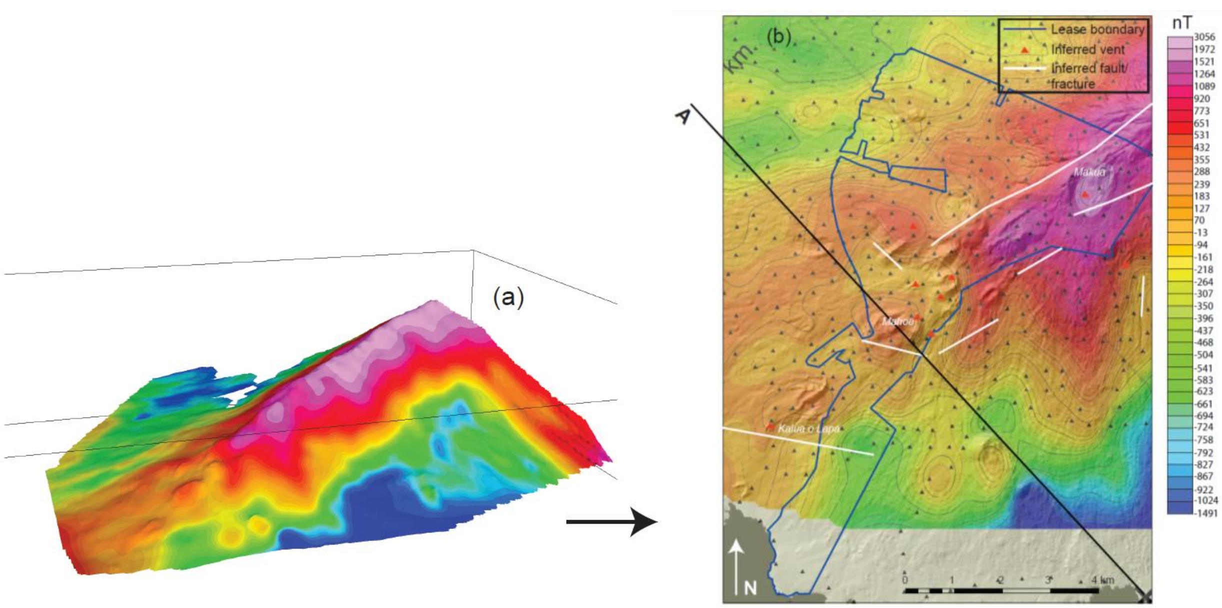

Figure 4. Maps of (a) reduced to the pole magnetic anomaly draped over topography and (b) reduced to the pole magnetic anomaly.

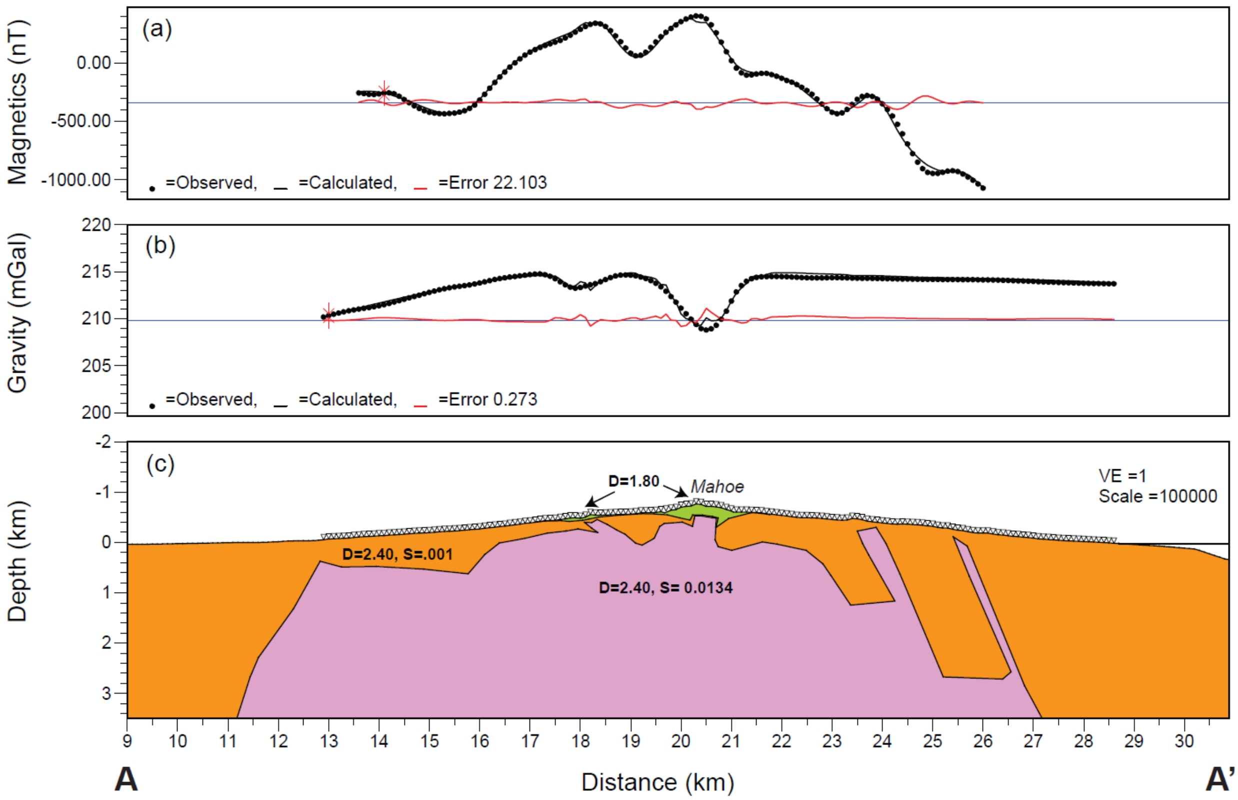

Figure 5. Preliminary two-dimensional gravity and magnetic model of subsurface (cross-section A-A' shown in Figures 2-4). Field data and synthetic curves shown in (a) and (b). (c) Modeled vent zones (green) underlain by dike intrusions (pink).

Geochemical Studies

Soil CO_2 Flux and Temperature

We conducted soil CO_2 flux and temperature surveys on the islands of Hawaii and Maui July 12-21, 2010. Similar to the surveys conducted in April 2010, average soil temperatures were measured over 10 cm depth using a hand-held thermocouple. Soil CO_2 fluxes were measured using a portable accumulation chamber instrument.

Hawaii

Soil CO_2 flux and temperature measurements were made during April and July 2010 on the Puna Geothermal Venture (PGV) property. In July, surveys were conducted on the PGV property and included 100 measurements of soil CO_2 flux and 41 measurements of soil temperature (Figure 6). Measurements along the traverse were made within natural soils with grasses as the dominant vegetation type. Soil temperatures ranged from 24 to 27°C, with an average of 26°C. CO_2 fluxes ranged from 15 to 48 g m^{-2} d^{-1}, with an average of 30 g m^{-2} d^{-1}. No spatial trends in soil CO_2 fluxes and temperatures were observed that would be suggestive of geothermal fluid/heat upflow and values were considered typical of background values for tropical vegetation. Fluxes were typically highest in areas with dense vegetation and lowest where sparse vegetation was present. CO_2 fluxes measured around wells KS-5, KS-6, and on the expansion pad ranged from <1 to 9 g m^{-2} d-1, with an average of 2 g m^{-2} d^{-1} and were not considered anomalous.

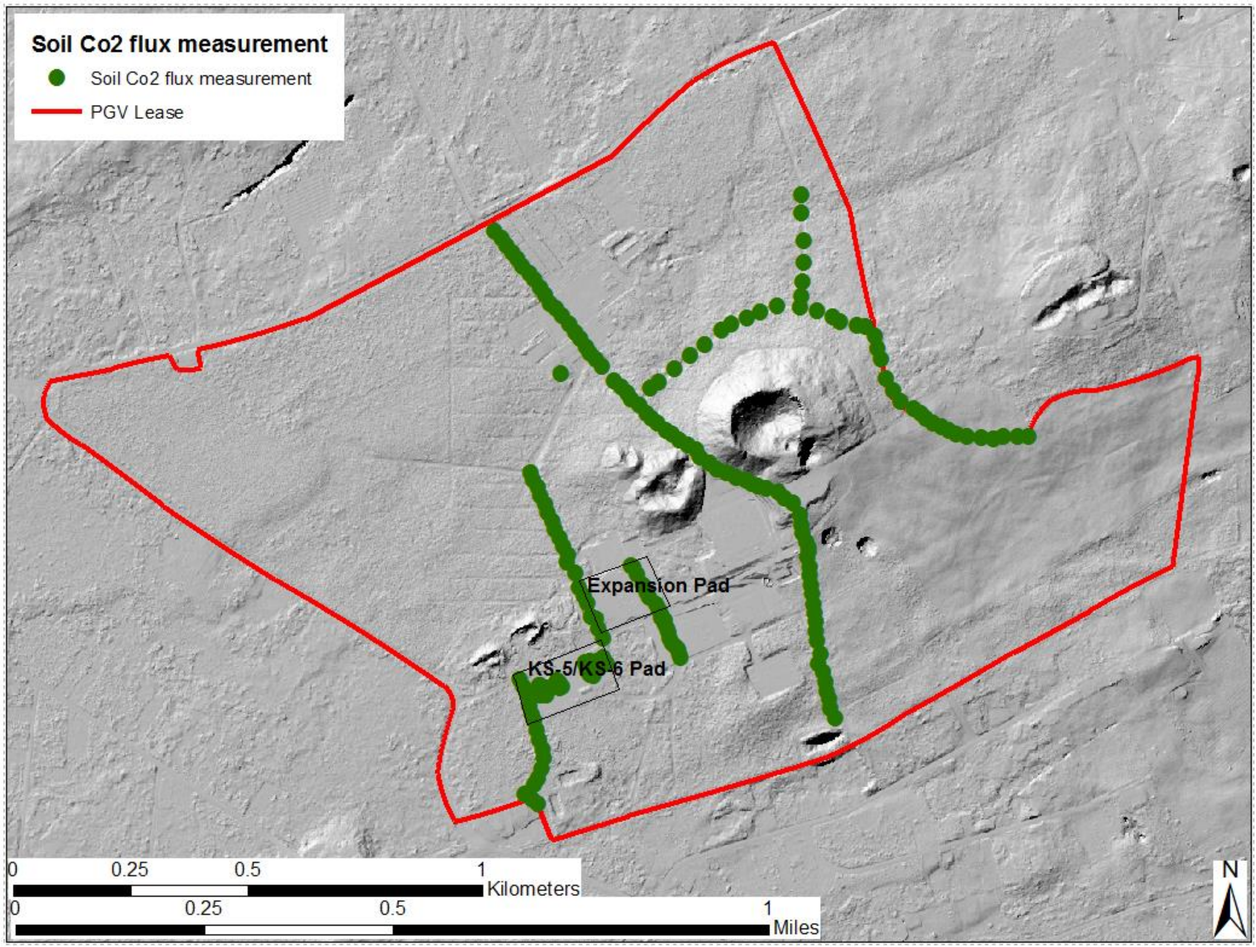

Figure 6. Map showing locations of the soil CO^2 flux measurements at PGV.

Maui

Soil CO_2 flux and temperature surveys were conducted in July 2010 along the Haleakala Southwest Rift Zone on the Ulupalakua Ranch and within the Ahihi Kinau Natural Area Reserve (Figure 7). Measurements were focused near a young vent (Kalua o Lapa) and in areas on the Ulupalakua Ranch designated for investigation based on preliminary results of aeromagnetic and gravity surveys (Figure 2). We made 170 soil temperature and 224 CO_2 flux measurements in July 2010. Soil temperatures ranged from 18 to 27°C, with an average of 23°C. CO_2 fluxes ranged from <1 to 42 g m^{-2} d^{-1}, with an average of 13 g m^{-2} d^{-1}. As noted for April 2010 surveys, soil CO_2 fluxes measured in the Ulupalakua Ranch area of Maui were, on average, lower than those measured at PGV, likely due to the relatively dry climate and sparser vegetation there, resulting in lower soil CO_2 respiration rates. Fluxes were typically higher in areas with dense vegetation and low where little to no vegetation was present. With the exception of those measured around Kalua o Lapa, values and spatial distributions of soil temperatures and CO_2 fluxes did not suggest geothermal fluid/heat upflow and were not correlated with geophysical anomalies.

Almost no vegetation was present and soil development was poor to non-existent on Kalua o Lapa, the youngest vent on the Haleakala Southwest Rift Zone. Soil CO_2 fluxes were generally undetectable here, with the exception of several areas around the vent where evidence of mineral alteration/deposition, hydrothermally or otherwise derived, was present. Slightly elevated (up to 20 g m^{-2} d^{-1}) soil CO_2 fluxes were measured in these altered zones in April and July 2010, The lack of significant soil development on young lavas here prevented soil gas sampling for isotopic analysis and soil temperature measurements.

Noble Gases and DIC-δ^{13}C

Hawaii

PGV Wells: Samples of non-condensable gas were collected using a mini-separator from five PGV production wells (Table 1) to characterize deep primary fluids produced from the KS5 Fracture (KS-5 and KS-6), the KS8 Fracture (KS-9 and KS-10) and the "Dilation zone" (KS-14). At each well, samples were collected for carbon isotopes and noble gases. The helium isotopic compositions (R/Ra) corrected for air and/or air saturated water range from 14.5 to 15.1, consistent with earlier data reported by Sorey, 2008 (internal report for Ormat). For the one sample for which we can make direct comparisons (KS-9) our helium isotope compositions (14.4 MS; 14.6 LBNL) and He/Ne ratios (26.9 MS; 21.1 LBNL) compare very well. However, the MS sample has about 10 times more argon than our sample, consistent perhaps with the large N2 abundance (77.8%) reported in Sorey (2008) suggesting significant air contamination. Carbon isotope compositions from PGV production wells ($\delta^{13}C$ = -0.80 to -2.9‰) support CO_2 contributions from an entirely magmatic source. Shallow monitoring wells at PGV were also sampled in the liquid phase for $\delta^{13}C$ and He isotopes. DIC-carbon isotopes averaged -4.1‰ and R/Ra values of 8.9 (Table 1), suggesting that a majority of the dissolved gases from these monitoring wells were derived from a deeper mantle source. Plots of magmatic vs biogenic $\delta^{13}C$ -DIC sources suggests that less than 0.05-0.25mmol/L (or <12% of the total DIC) is derived from a biogenic source, indicating little mixing. While the R/Ra values are still quite high, the relative He-abundances [F(^{4}He)] are quite low (Figure 8) suggesting efficient scrubbing of the magmatic volatiles and strong dilution in a large reservoir of shallow groundwater.

Kona Water District: Water samples for noble gas analyses were collected from six wells within the Kona Water District (Table 1). The wells were selected to provide a traverse into the Hualalai Rift Zone. Four of the samples are from wells within the rift (HR-1, HR-3, HR-4 and HR-5) and two wells are located outside of the rift (Kalaoa and Hualalai). Preliminary work reported by Sorey (2008) indicated a possible increase in the He content of the well waters towards the central portion of the rift and a very recent eruption cone; whereas wells outside the rift contained much lower He concentrations, as expected.

To date we have analyzed all of the Kona samples. The relative abundances of the noble gases [F(i) values] and concentration of ^{36}Ar were found to be consistent with water saturated with air at ~10 ^{o}C and containing a small amount of air (~10% of the ^{36}Ar), either injected into the water during recharge of the aquifer or introduced as a contaminant during sampling.

The helium isotope [(R/Ra)m] and relative abundance [F(^{4}He)] data demonstrate a well-defined trend (Figure 8), consistent with the preliminary data presented by Sorey (2008). On the assumption that the water wells are all producing from the approximate same depth, then the trend indicates an increase in the magmatic helium flux in the rift, with the highest flux occurring near the central portion of the rift and the area of recent magma extrusion. The high DIC concentrations for these wells and magmatic $\delta^{13}C$ values of -1.7 to -2.5‰ (Figure 9; Table 1) also support this heavy flux of magmatic gases from a nearby heatsource, yet suggest little scrubbing or dilution with a deep hydrothermal system or shallow water-table.

Maui

Maui Water Wells: Three wells were sampled for noble gas and carbon isotope analysis in Maui. One was collected from a water well (Horse Well) in the vicinity of the most recent eruption (Kalua o Lapa vent) within the SW rift zone of Haleakela; the remaining pair were collected off of the rift approximately 6km to the north (Figure 7). Abundances of total helium for the Horse well were quite high, however the He-isotopic signature were [(R/Ra)c = 3.15], were quite mixed, suggesting a significant contribution of gases from a circulating groundwater source containing non-magmatic helium (He-4). Similar trends were observed in the carbon isotope suite, indicating high DIC concentrations and d13C values intermediate between mantle CO2 and biogenic carbon (Figure 9). Off-rift samples in Maui (Wailea #1 and #2) have similar He abundances [F(^{4}He)] and R/Ra values as the Kona-rift samples, suggesting very minor scrubbing of the He gases by a proximal shallow water table. In all cases of the Maui water samples, we can surmise that a magmatic heat source is still present, however much less vigorous than that observed in Puna (LKERZ). In addition, we do *not* witness efficient scrubbing of the noble gases and magmatic CO_2 as we do in the monitoring wells over a prolific hydrothermal system like PGV which has both high rates of meteoric precipitation and a thick overlying condensate cap.

Geochemical Summary

The geochemical data sets, including both the CO_2 flux surveys and fluid isotopic analysis, provide a comprehensive understanding of both the robustness of magmatic heating and degree of hydrothermal circulation or 'maturity' over these volcanic geothermal prospects. Unlike Basin and Range-type systems, we can only attribute helium abundances to magmatic input as very little radiogenic helium (He-4) is available over these young basaltic terrains to dilute the He-3 ratios.

Similarly DIC input can be fairly well limited to either magmatic or biogenic (C-3 or C-4 plant) sources. Mature hydrothermal systems over young magmatic heat-sources such as Puna exhibit magmatic-δ13C and R/Ra (He-isotope) signatures, as well as efficient scrubbing of these gases near the surface, as demonstrated by a lack of CO2 soil flux values and low DIC and relative He abundances. We understand well from hotsprings discharging near the shorelines around Puna that CO_2 gas is entrained in the shallow condensate waters; similar hotsprings are not found along the shores beneath the HSWRZ (Maui) or Kona .

Kona district wells indicate both low abundances of DIC and He input as well as magmatic d13C and R/Ra signatures suggesting a fresh magmatic heat source but lack of hydrothermal circulation to buffer the entrainment of gases to the surface.

Maui appears more similar to the Kona system than to the Puna system. CO_2 soil gases are limited in Maui, with the exception of the young Makai area where there is no vegetation and some hydrothermal alteration. This may be attributed to either a limited input of magmatic CO_2 from the deep magmatic heat-source or efficient scrubbing by near-surface groundwaters. Helium isotope and carbon isotope signatures of the rift-well (Horse well) indicate a measurable magmatic input in addition to a significant mixing with biogenic carbon or shallow non-geothermal CO_2. Relatively low He and DIC abundances in Maui, combined with a limited level of rainfall (similar to Kona), do not support efficient scrubbing of magmatic gases by shallow groundwaters. It is more likely that a deep magmatic heat source is present, although waning, and that a vigorous geothermal system is either not present or influencing the near-surface geochemistry.

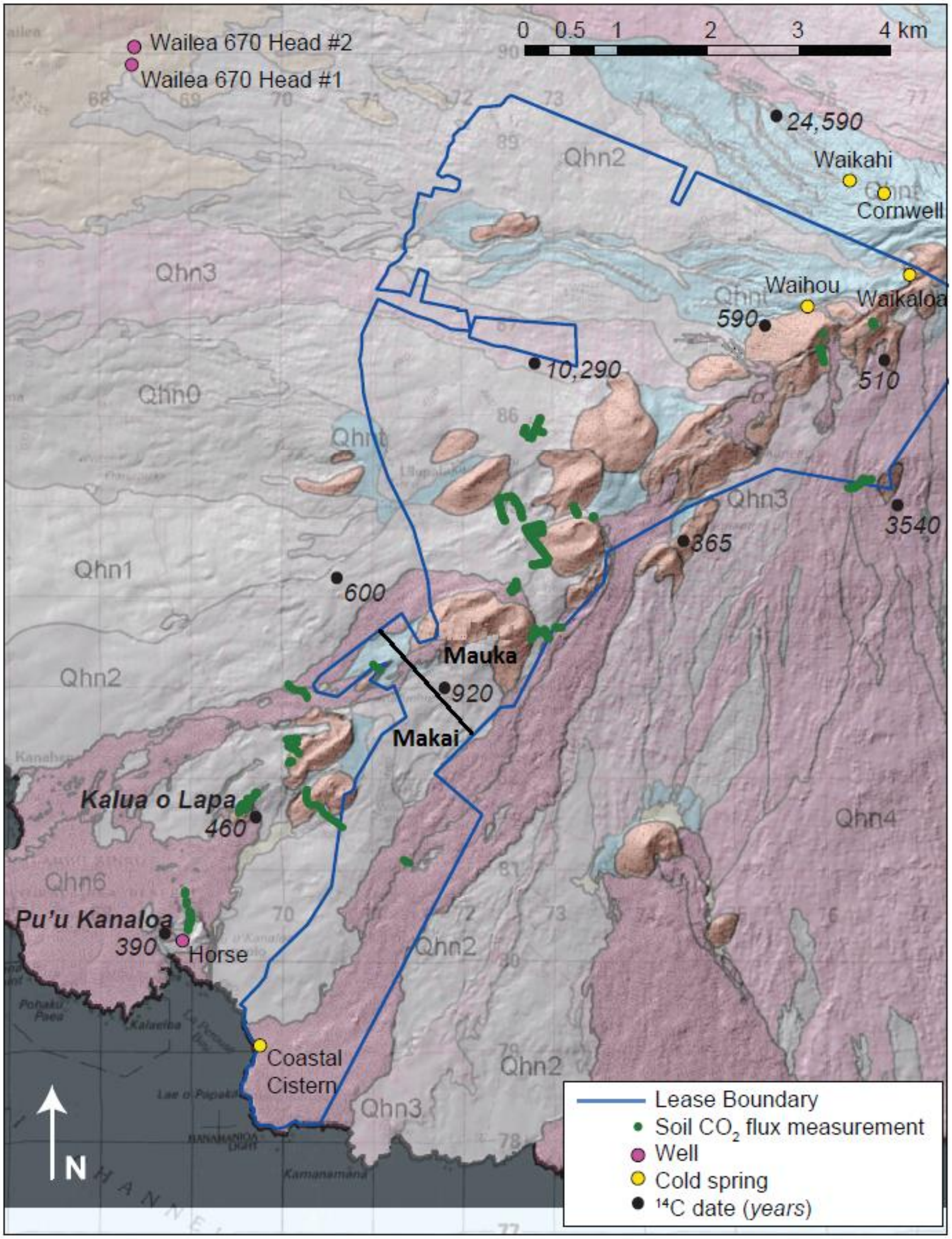

Figure 7. Map showing the Maui study area with geology [Sherrod et al., 2007], Ulupalakua lease boundary, and locations of soil CO2 flux measurements (n = 406) and sampled wells and springs. Black line delineates the Makai (seaward) and Mauka (mountain) areas. Fluxes were measured near young lava flows and vents (selected 14C dates shown in years [Sherrod and McGeehin, 1999]), plant stress identified in hyperspectral imagery, and geophysical anomalies.

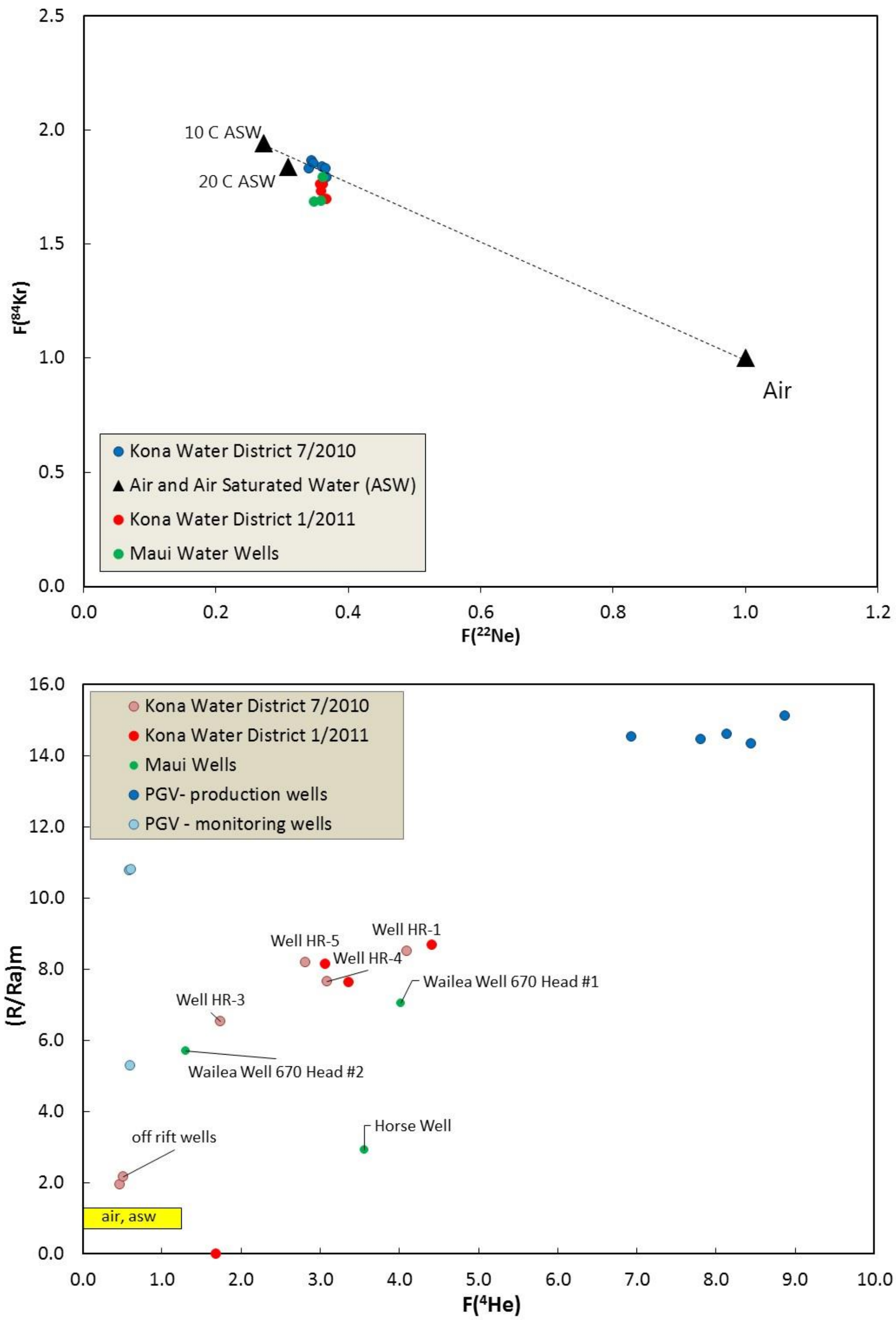

Figure 8. (a) Relative abundances of noble gases in waters compared to air-saturated water at 10 and 20°C and air. (b) Measured helium isotopic compositions [$(R/Ra)_c$] in waters as a function of the 4He enrichment factor [F(^{4}He)]. Data trend for Hualalai and Wailea samples is consistent with mixing a magmatic helium enriched components with air-saturated water.

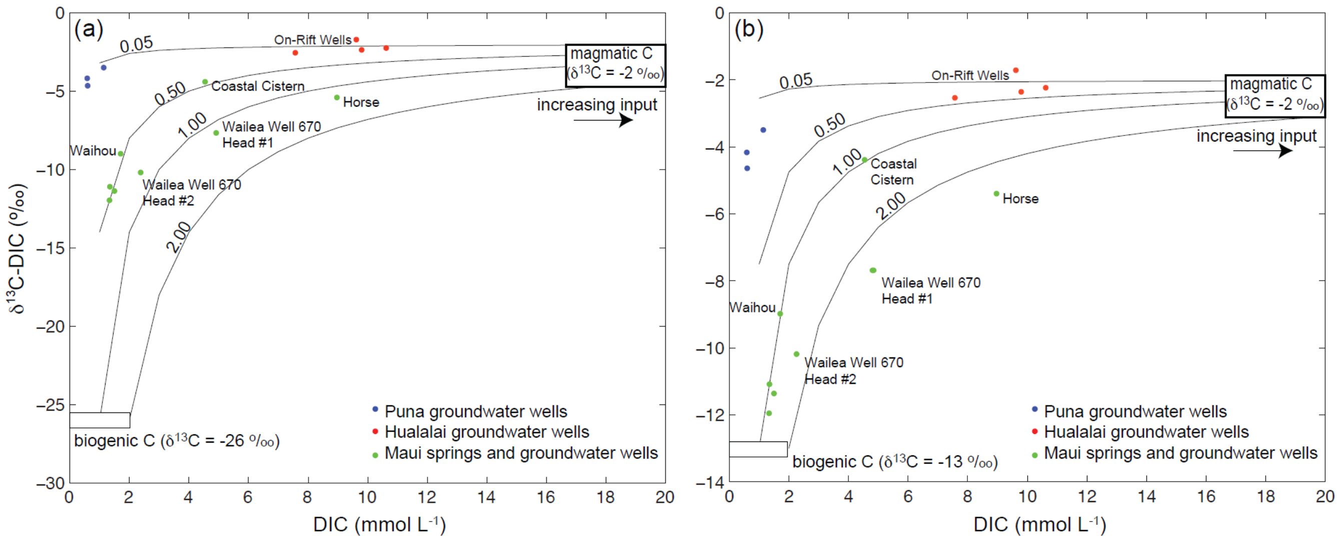

Figure 9. δ13C-DIC versus DIC concentration (in liquid) diagrams for groundwater and spring samples from LKERZ (Puna), Hualalai (Kona), and HSWRZ (Maui). [after Chiodini et al., 2000]. Theoretical curves of mixing between (a) biogenic C-3 carbon with δ13C = -26 ‰ and magmatic carbon with δ13C = -2 ‰ and (b) biogenic C-4 carbon with δ13C = -13 ‰ and magmatic carbon with δ13C = -2 ‰ are shown for initial concentrations of biogenic carbon = 0.05, 0.50, 1.00, and 2.00 mmol L^{-1}.

Well/Spring	Name	$\delta^{13}C$-DIC (°/oo, PDB)	$(R/Ra)_c$
Puna Production	KS-6	-2.90	14.34
Puna Production	KS-5	-2.60	14.52
Puna Production	KS-14	-1.50	14.46
Puna Production	KS-10	-0.80	15.13
Puna Production	KS-9	-1.70	14.61
Puna Groundwater	MW-2	-3.49	10.77
Puna Groundwater	MW-1	-4.17	5.28
Puna Groundwater	MW-3	-4.64	10.81
Hualalai Groundwater	On-Rift	-2.24	8.53
Hualalai Groundwater	On-Rift	-1.71	9.20
Hualalai Groundwater	On-Rift	-2.54	8.02
Hualalai Groundwater	On-Rift	-2.36	9.27
Hualalai Groundwater	Off-Rift	ND	4.53
Hualalai Groundwater	Off-Rift	ND	4.47
Maui Groundwater	Horse	-5.40	3.15
Maui Spring	Cornwell	-11.37	ND
Maui Spring	Waikahi	-11.08	ND
Maui Spring	Waihou	-8.98	ND
Maui Spring	Waikaloa	-11.95	ND
Maui Groundwater	Wailea 670 Head #1	-7.74	7.63
Maui Groundwater	Wailea 670 Head #2	-10.22	7.43

Table 1. Stable carbon and air-corrected helium [$(R/Ra)_c$] isotopic compositions for springs and wells sampled on LKERZ (Puna), Hualalai Rift Zone, and HSWRZ.

Summary

Locations and geometries of faults/fractures, vent zones, and dike intrusions within the HSWRZ were inferred based on ground based gravity coupled with heli-borne magnetics and LiDAR datasets. Soil CO_2 flux measurements typically did not reveal upflow of magma-derived CO_2 to the surface within the HSWRZ and KLERZ. Spatial variations in flux were instead correlated with vegetation type and density and soil development. Noble gas and carbon geochemistry indicated come contribution of magmatic helium and carbon to shallow groundwaters within the HSWRZ, Hualalai Rift Zone, however these were well mixed and not nearly as high as those found in shallow monitoring wells or

deep production wells near Puna in the KLERZ. After comparing results from Maui, Puna and Kona, we feel that groundwater geochemistry may be a more successful indicator of magmatic fluid upflow than soil CO_2 flux measurement in areas with high groundwater flow, relatively deep vadose zone, and/or dense vegetation that may mask upflow of magmatic volatiles to the surface. Despite evidence for a magmatic heatsource and geophysically-defined structures which may provide permeability, we have determined that the risk for finding a robust hydrothermal system on Maui is still very high.

A 3D Leapfrog model has not been developed due to delays in state permitting, which currently restricts movement forward on this project.

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