Detailed Airborne Magnetic Survey of the Puna Geothermal Venture and the Lower East Rift Zone, Island of Hawai‘i

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Keywords

Geophysics, Aeromagnetic Survey, Pahoehoe, A'a, Puna Geothermal Venture, Lower East Rift Zone, Hawaii

ABSTRACT

A recently collected high-resolution airborne magnetic survey provides insight into the structural setting of the Puna Geothermal Venture (PGV) on the Island of Hawai’i. Previous magnetic investigations of the eastern flank of Kīlauea predominantly relied on the ‘Puna Forest’ airborne magnetic survey conducted by the United States Geological Survey in 1978. Those data revealed that the Lower East Rift Zone (LERZ) of the Kīlauea volcano is characterized by a magnetic high anomaly extending from Kīlauea’s summit down its southeastern flank. That feature makes a notable left step near PGV in an area with enhanced permeability in the geothermal system. Ormat’s 2024 airborne magnetic survey improves on that legacy survey by utilizing denser line spacing (100 m flight lines), as well as advanced magnetic detection equipment and processing techniques, to delineate smaller-scale fissures and fractures in and around PGV. The new magnetic data have been correlated, where applicable, with magnetic intensity measurements, lithologic interpretations from drilling, and paleointensity data previously collected across the area of interest.

The magnetic signatures captured by this survey reveal pronounced positive magnetic anomalies along the major N63°E LERZ trend, as well as with cross-cutting features that strike perpendicular to this regional LERZ trend. The N63°E-trending fissures and fractures have been well-characterized by drilling and can host permeability associated with production, however the location, orientation, and size of the cross-cutting geologic structures are not well understood. These structures were first hypothesized as an explanation for results from reservoir tracer studies which showed rapid tracer returns from certain production and injection wells. This implies permeable pathways trending approximately perpendicular to the structural grain of the LERZ. The existence of NW-SE trending fractures was recently confirmed by an acoustic borehole image log, but additional studies are required to quantify their contribution to field permeability (Spake

et al., 2024). In a geologically homogeneous environment, a largely uniform magnetic signature would be expected. However, the basalts deposited across the LERZ present a contrast of strong magnetic highs flanked by broad magnetic lows (±6000 nT). This paper discusses the results of the recently acquired magnetic survey and the implications to the magnetic and structural environment at PGV.

1. Introduction

The Island of Hawai'i is part of the Emperor-Hawaiian volcanic chain and is formed by a group of five shield volcanoes, each shaped by lava accumulations from eruptive events. Our understanding of the island's subsurface geology is largely derived from geophysical data and sparse drill hole data (Hildebrand et al., 1993). At Ormat's Puna Geothermal Venture, a dense cluster of drilling allows for the testing and refinement of magnetic interpretations.

Magnetic surveys can be effective at measuring magnetic variations in volcanic regions like Hawai'i (Gudmundsson et al., 1997). This is due, in part, to significant variations in rock magnetization across the island (Hildebrand et al., 1993). Previous magnetic studies on the island have demonstrated the effectiveness of magnetic surveys and have been able to identify rift features, volcanic vents, conduits, and areas of alteration. The United States Geological Survey (USGS) conducted magnetic surveys over Hawai'i's volcanic regions in the 1960's (Malahoff & Woollard, 1966), revealing correlations between magnetic anomalies and volcanic structures. The 1978 'Puna Forest' survey provided a comprehensive magnetic dataset fundamental in understanding the island's magnetic features (Godson et al., 1981).

This paper analyzes the results of a detailed airborne magnetic survey conducted over PGV and part of the Lower East Rift Zone (LERZ). The goal of this survey was to map lateral variations in magnetic intensity to better understand subsurface geologic structure and strengthen the conceptual model for the geothermal system. This detail-oriented survey, like its regional predecessors, demonstrates that airborne magnetic mapping can effectively image intrusive dike complexes as well as areas of complicated deposition or alteration. There is good correlation between anomalies detected in the survey and geologic observations from the geothermal field. Magnetic intensity measurements indicate strong variations in rock magnetization, which likely represents conditions during deposition or changes that the rock has undergone over time. We have utilized various transformation and filtration techniques to help visualize and analyze the total magnetic intensity of the project area.

2. Geologic Setting

The Puna Geothermal Wellfield lies within the Lower East Rift Zone of the Kīlauea volcano (Figure 1). The LERZ hosts volcanic vents, craters, fissures, and fractures along a N63°E regional trend, mapped by Moore and Trusdell, in 1991. These volcanic features can act as conduits for both magma and hydrothermal fluids (Kenedi et al., 2010; Moore and Trusdell, 1991; Tilling & Dvorak, 1993). The PGV site is located in an area where eruptive vents appear to shift northward, suggesting the presence of north-south trending transform faulting (Moore, 1992; Spielman et al., 2006). This area is characterized by a magnetic high anomaly extending from Kīlauea's summit down its southeastern flank, with a notable left step in the magnetic field near PGV. This magnetic discontinuity may be an indicator of left-step transform faulting (Trusdell et al., 2009; Neal et al., 2019).

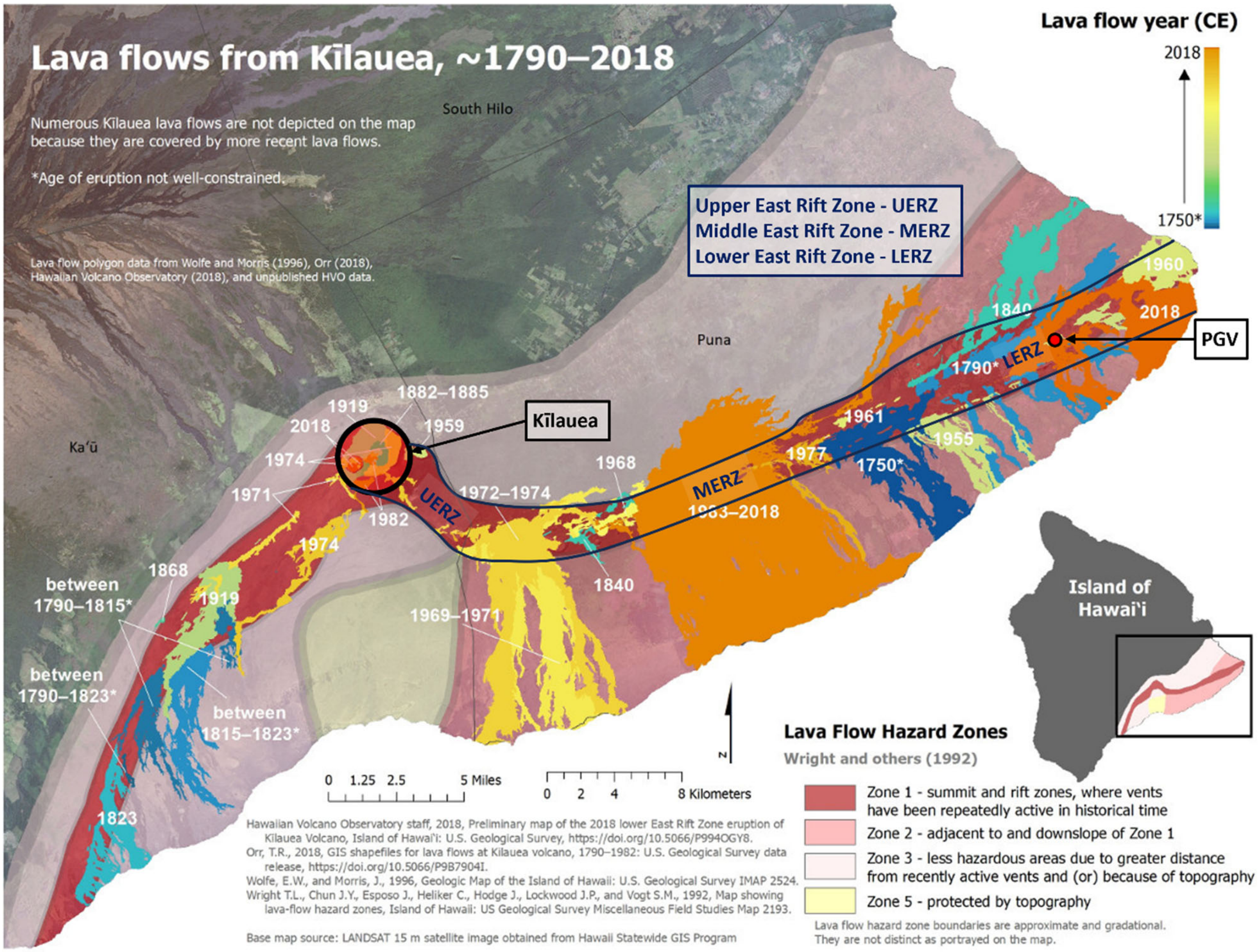

Figure 1: Annotated map showing the subaerial extents of lava flows and explosive deposits from Kīlauea, 1790–2018. Lava flow hazard zones, districts of the County of Hawai'i, the Upper, Middle, and Lower East Rift Zones are also depicted. Modified from Mulliken et. al, HVO (2024).

Tholeiitic basalts make up the overwhelming majority of the rock volume on the Island of Hawai'i and dominate the geology around PGV (Clague and Dalrymple, 1989). Notably, 80% of the LERZ is covered by basalt flows erupted within the last 500 years (Teplow et al., 2009). Most of the flows visible at the surface were deposited by eruptions in 1790, 1955, and 2018, all sourced from Pu'uhonuaula and Ahu'ailā'au craters (Figure 2). These events have resulted in ground deformation and changes in the subsurface, including fracture dilation, contraction, and reactivation of previously sealed fractures (Kauahikaua & Trusdell, 2020). The 2018 eruption was impactful, producing substantial changes in the landscape of the LERZ (Neal et al., 2019).

Subsurface lithology at PGV consists of four main units: subaerial basalts, a transitional sequence dominated by hyaloclastites, submarine basalts, and dike complexes intruded into basaltic host rock. Steeply dipping dacitic and diabase dikes associated with fissure eruptions have been linked to areas of high permeability (Teplow et al., 2009). The reservoir's permeability is influenced by en echelon, fracture systems oriented N63°E and dipping 85° to the NW. The intricate and long-lived nature of the geothermal system is evident from mineralogic studies of the reservoir rock (e.g., Iovenitti and D'Olier, 1985), which identify alteration due to contact metamorphism, low-temperature interaction with magma, and hydrothermal processes.

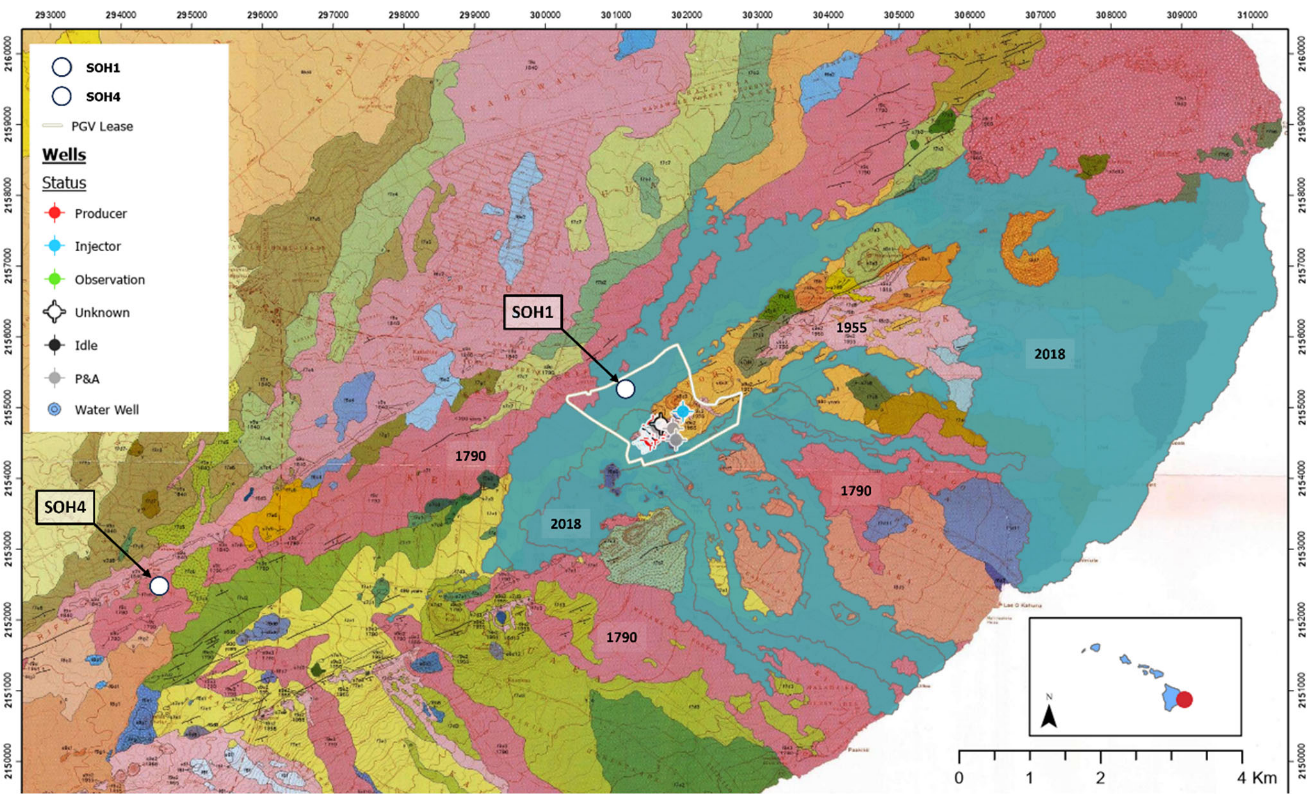

Figure 2: Annotated Map of the LERZ highlight recent impactful depositional events and Scientific Observation Holes SOH1 and SOH4. Modified geologic map from Moore and Trusdell, (1991). 2018 flow geospatial data from Zoeller et al, 2019.

Inflated pāhoehoe sheet flows, as found on the island and in the LERZ, can form when lava is injected beneath an existing, solidified crust (Self et al., 1998). Often, inflated sheet flows form in low-relief areas and can be the result of fluid pressure building within a cooling shell, as lava is injected into the interior of the flow (Holcomb, 1980; Hon and Kauahikaua, 1991). These flows cool relatively slowly, which likely has an effect on the quantity, distribution, and grain size of magnetic material within the flows (Audunsson et al., 1992). During the prolonged cooling process, ferromagnetic minerals like titanomagnetite have more time to align with the paleomagnetic field. This results in higher measured magnetic intensities compared to surrounding rocks.

‘A’ā lava flows, as characterized by MacDonald in 1953, form fragmented, rough surfaces, with clinkers often overlying an auto-brecciated base. The lava cools quickly and clasts topple along the flanks of the flow forming clinkers as a result of differential motion and shearing of the molten interior (Harris et al, 2016). This flow behavior results in a surface morphology that transitions from spiny fragments near volcanic conduits to loose, rubbly flow-breccia as the flow moves further away from the source (MacDonald, 1953). The irregularity and fragmented nature of these flows may affect the distribution, direction, and grain size of magnetic minerals, potentially leading to more variable magnetic signatures compared to other flow types (Hildebrand et al., 1993). ‘A’ā clasts that have tumbled and have varying magnetic orientation could lead to a mixed or suppressed measured magnetic intensity compared to pāhoehoe flows. The magnetic minerals in these clasts may not have sufficient time to align with the magnetic field before rapidly cooling, creating a mixed domain state within the rock (Bücker et al., 1999).

3. Magnetic Data

The ‘Puna Forest’ airborne magnetic survey, (Figure 3), was conducted in 1978 by the USGS and has been integral to the design and justification of this survey. The USGS survey was predominantly flown at a height of 305m with 1600m spacing with lines oriented N27°W (Godson et al., 1981) and perpendicular to the main rift trend, at N63°E (Flanigan et al., 1986). The data provide a total magnetic intensity map suitable for regional analysis.

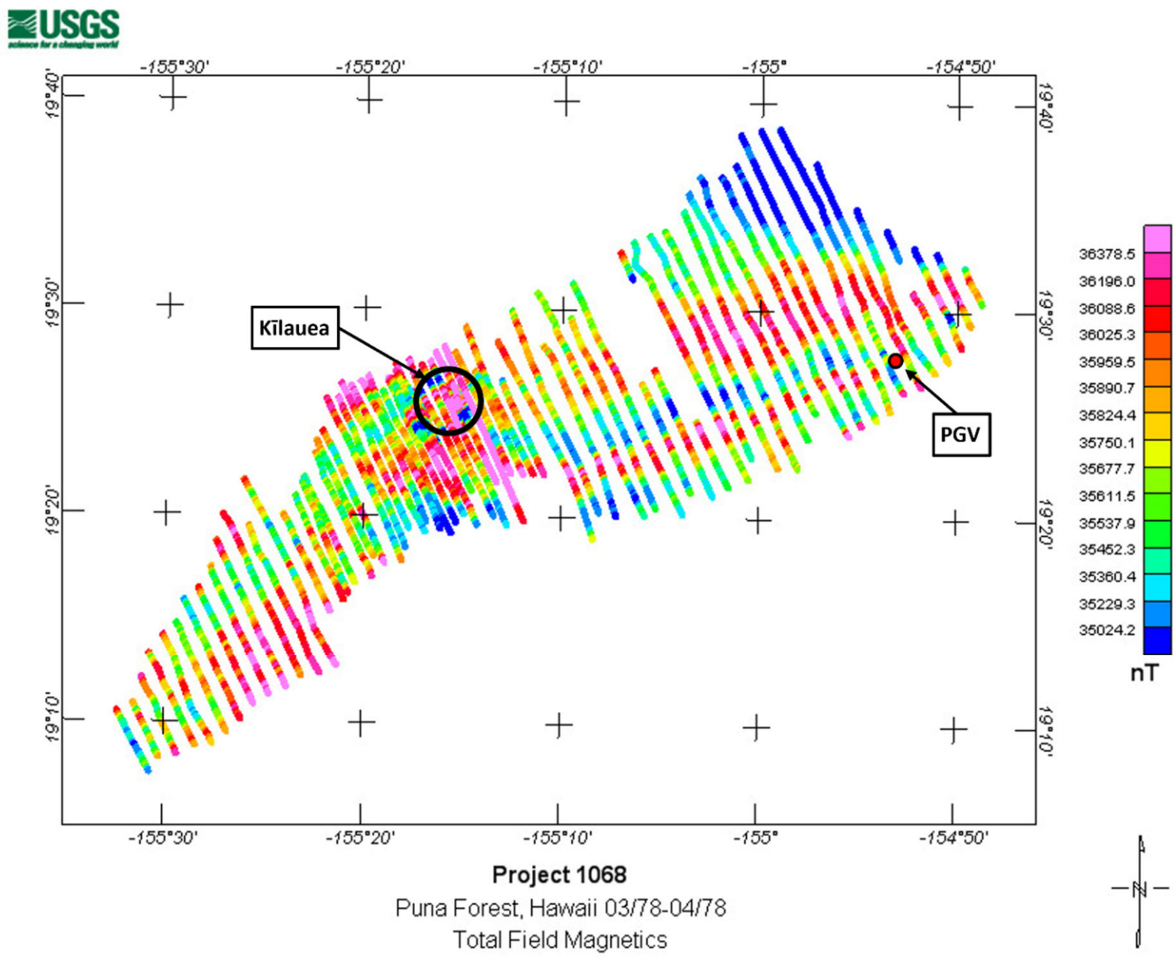

Figure 3: Map of the 1978 USGS ‘Puna Forest’ airborne magnetic survey with flight lines overlain with Total Field Magnetics.

In 2024, Ormat Technologies contracted MWH Geo-Surveys to collect an unmanned aerial system (UAS) magnetic survey covering 36 km² over PGV and the surrounding area (Figure 4). Total magnetic field data were collected using the Geometrics MagArrow, a laser-pumped cesium magnetometer specifically designed for UAS surveys with a sensitivity of 0.0005 nanotesla (nT).

Main flight lines for this survey, spaced 100 m apart and bearing N27°W, were flown perpendicular to the main LERZ trend, totaling 344 line-km. Tie-lines, flown perpendicular for leveling and enhancing possible rift-perpendicular structures (Figure 4), covered 88 line-km, bearing N63°E and spaced 400 m apart. Flights were conducted at 140 m above ground level (AGL) to minimize localized magnetic effects from anthropogenic sources and highly magnetic fresh lava flows prevalent in the LERZ. Flight line drape was planned using a 1 m DEM model from the USGS, in an attempt to minimize terrain effect on the data.

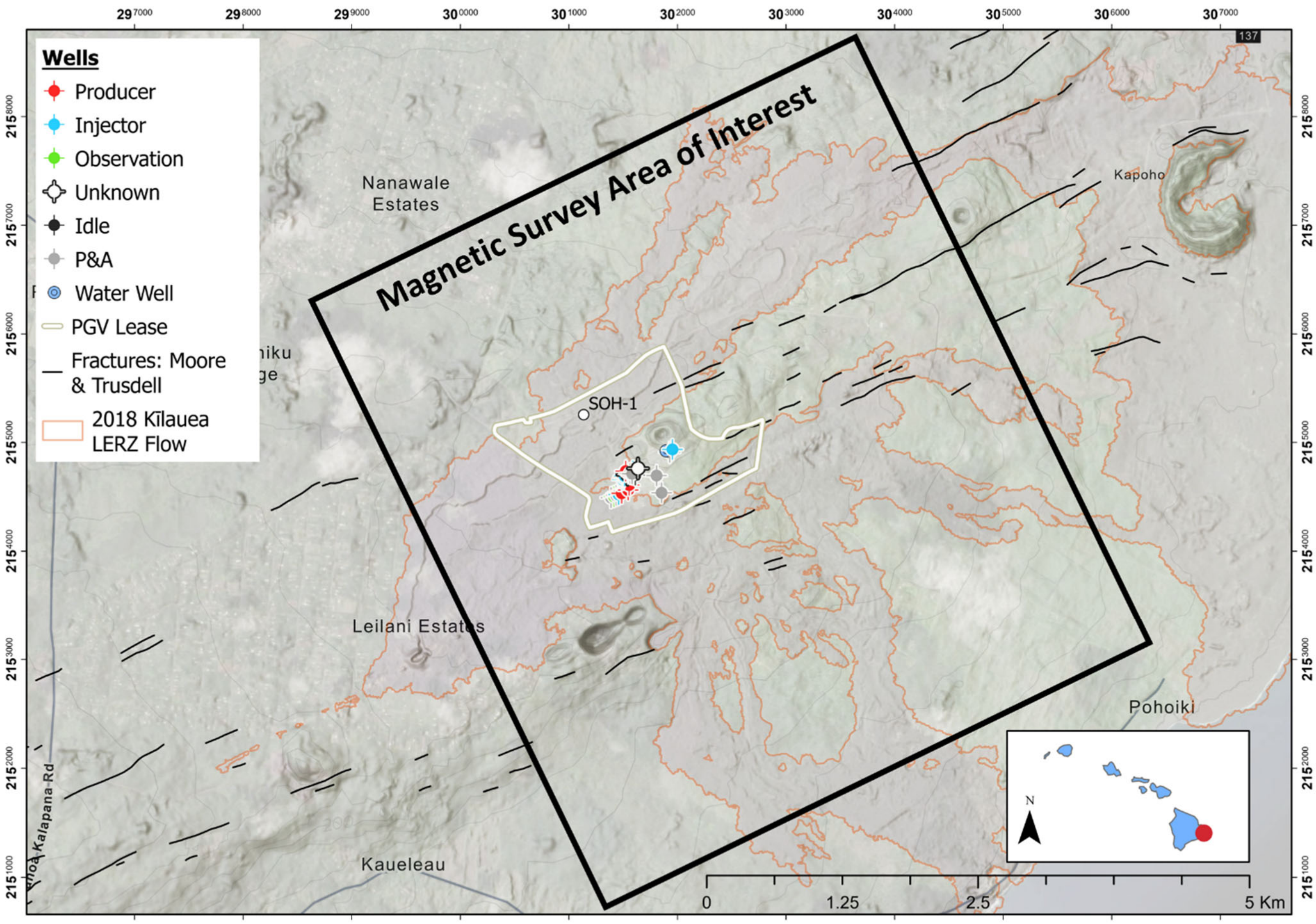

Figure 4: Survey AOI from the 2024 Ormat UAS magnetic study, flight lines spaced 100 m, with tie-lines every 400 m.

Total magnetic intensity (TMI) data were processed using minimum curvature gridding and reduced to the pole (RTP) (Figure 5) with a magnetic inclination of 36.5° and a declination of 9.5°. A map of total magnetic intensity, reduced to the pole reveals distinct magnetic anomalies interpreted to be associated with intrusive dike complexes, slowly cooled pāhoehoe basalt flows, ‘a’ā flows, and areas of possible alteration.

4. Data Analysis

Total Magnetic Intensity (TMI) was calculated for the high-resolution magnetic dataset by adding the International Geomagnetic Reference Field (IGRF), approximate value 34,302 nanotesla for the survey date and location, to the diurnally corrected magnetic data. Standard line-to-line leveling resolved herringbone effects, while tie-line leveling adjusted data values based on mis-tie values at line/tie-line intersections, ensuring consistency in the final maps.

At Hawai‘i’s low magnetic latitude, total magnetic intensity anomalies can present as dipolar in shape, with circular intrusions manifesting as magnetic highs closely flanked by magnetic lows, often in a north-south orientation. This can result in east-west oriented gradients that can be misleading in interpretation. The Reduction-to-Pole (RTP) transformation (Figure 5a) corrects for this by shifting positive anomalies over their sources (Bhattacharyya, 1965). For visualization and interpretation, magnetic data were gridded at 40 m intervals and contoured at 200 nT increments to accommodate high-quality data with very steep magnetic gradients.

5. Results

The magnetic data collected in this survey offer valuable insights into the magnetic and structural characteristics of the LERZ and PGV. The UAS magnetic survey highlights N63°E trending fissures and fractures as intermediate to low magnetic anomalies, which correlate well with the fissures and fractures mapped by Moore and Trusdell (1991). Cross-cutting anomalies are also apparent in this dataset, with the most significant rift-perpendicular lineament located east of PGV. Broad magnetic low anomalies are more common to the south of PGV and the highest amplitude magnetic low anomalies coincide with mapped craters (Figure 5b).

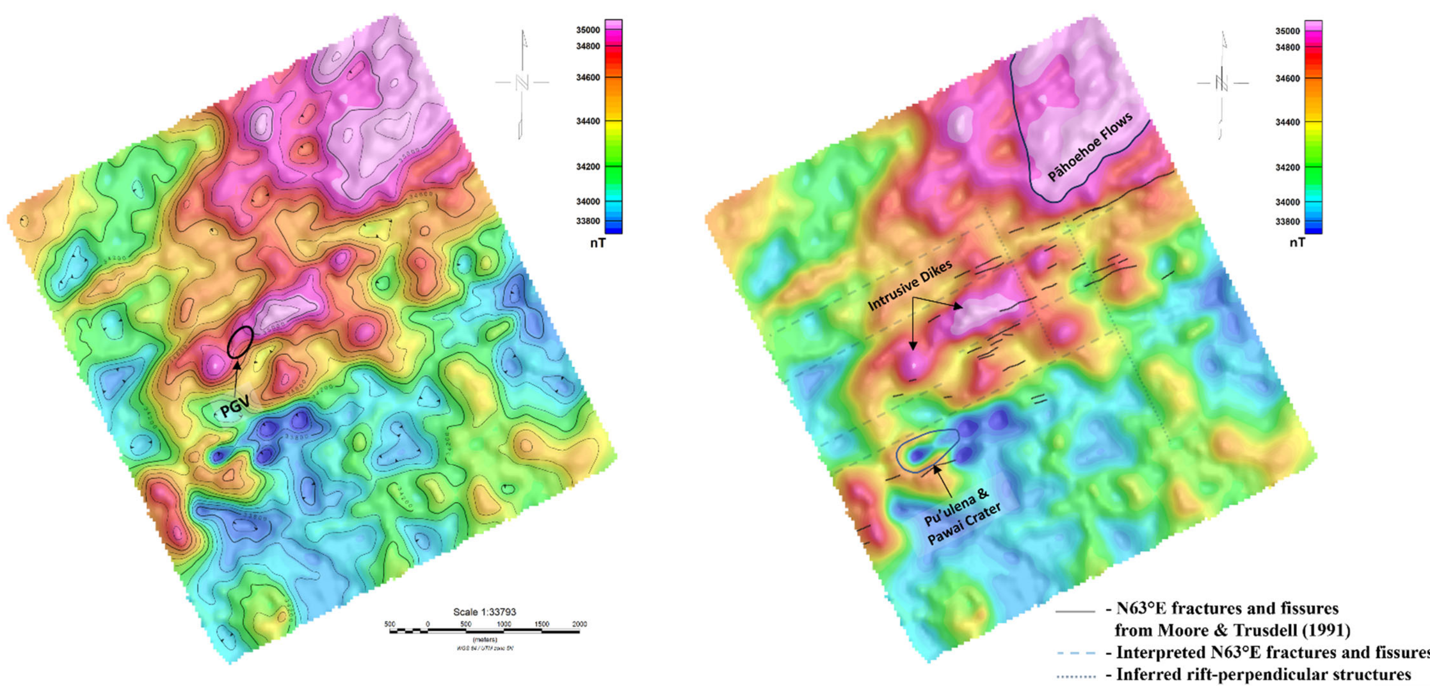

Figure 5: a.) Reduced-to-Pole (RTP) magnetic data with contours every 200 nT. b.) RTP magnetics with interpreted and inferred fissures and fractures based on Moore & Trundell (1991). Both figures have been color shaded to enhance structure.

There are areas in the dataset that may have a positive correlation with topographic relief. In some regions, a positive magnetic anomaly is observed near or over an area with elevated topography. Two strong, spherical magnetic low anomalies are imaged to the southwest of PGV and appear to correlate with the Pu‘ulena and Pawai craters. These magnetic low anomalies may be due to terrain effects, as flying an accurate flight drape over such steep gradients would be challenging. These anomalies may also be the result of alteration occurring in an area of increased permeability or may be areas of lowered magnetic intensity derived from complicated depositional processes.

The 1978 USGS survey and the 2024 Ormat survey show good agreement when sampled over a profile. To facilitate this comparison, the 2024 RTP data were upward continued to a height of 300 m and plotted against the more regional survey. The magnetic intensity profiles are in good agreement, showing the two datasets are generally consistent with each other.

6. Discussion

A key objective of this survey was to capture images of buried structures perpendicular to the LERZ. The apparent offset in the magnetic signature suggests that we may have effectively imaged such rift-perpendicular structures. It is also plausible that magnetic discontinuities in the datasets may be imaging subsurface heterogeneity, variations in dike structure and deposition. Alternatively, we may be measuring highly magnetic intrusive dike complexes that have formed along the rift trend, flanked by relatively lower magnetic intensity material. This juxtaposition in intensity may be creating lineaments that closely correlate with mapped fractures and fissures.

Intermediate to low magnetic lineaments align with mapped fissures and fractures. These geologic features may project into the deep reservoir and are interpreted as potential influencing structures within the geothermal system. However, it is unlikely that the magnetic lows observed in this data set can be directly attributed to hydrothermal alteration from the geothermal system. The geothermal reservoir is overlain by a clay cap, ~1000 m of subaerial basalt and hyaloclastite sequences and a pervasive cold-water aquifer. These are all factors likely to limit hydrothermal alteration near the surface. Given the uncertainty in the depth of investigation, it is highly unlikely that airborne magnetics can image the deep hydrothermal alteration occurring within the reservoir at depths of 1000 m and below. The anomalous magnetic lineaments imaged by this survey correspond with mapped geologic features (Hoversten et al., 2022). Apparent offset in rift-parallel magnetic highs may indicate a NW/SE trending structural fabric, manifesting as a localized left-step structure near PGV (Figure 6). NW/SE-trending structures likely intersect the main N63°E fissures and fractures, potentially acting as additional geothermal fluid pathways and enhancing reservoir connectivity at PGV (Kenedi, 2010).

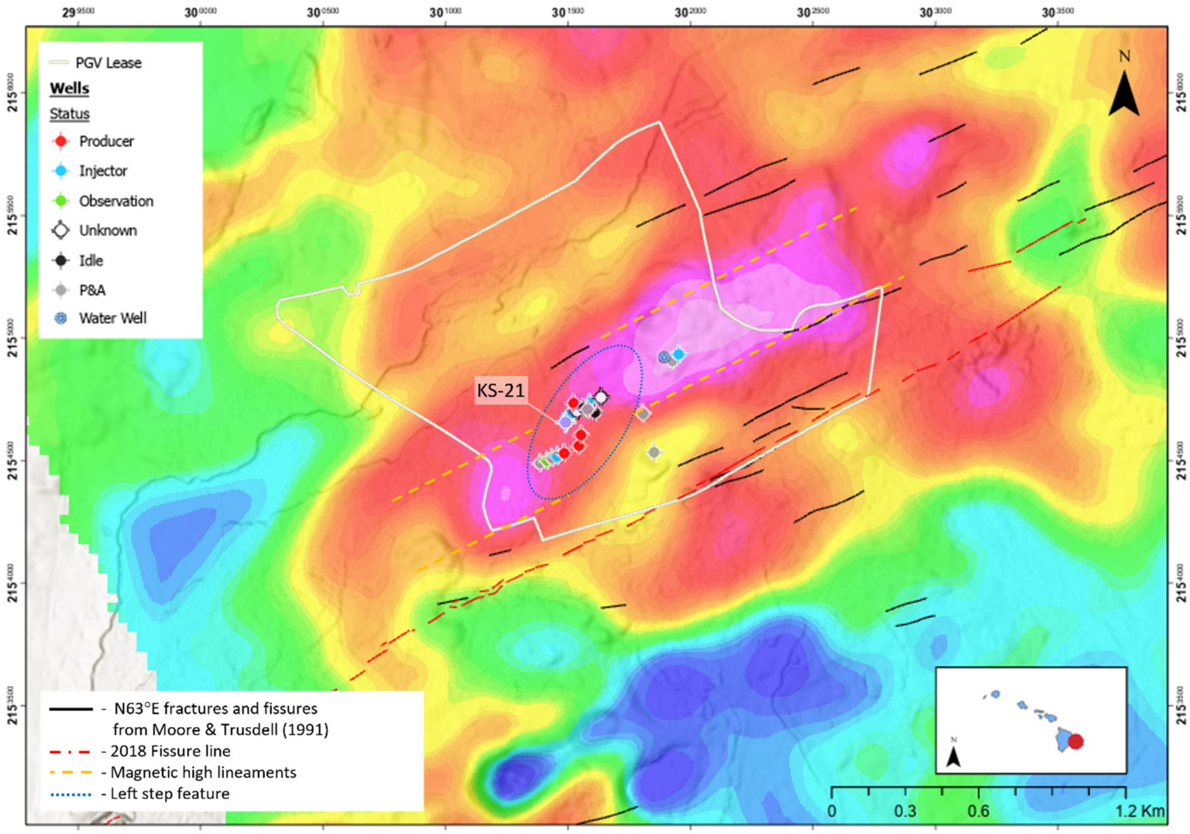

Figure 6: RTP magnetic map highlighting the left-step feature along with interpreted and inferred fractures and fissures.

Strong magnetic high anomalies have been interpreted to result from slower cooling, often associated with in-situ deposition. Intrusive dike complexes and inflated sheet flows share similar mechanisms of emplacement where lava has more time to cool, allowing ferromagnetic minerals to align more effectively with the ambient magnetic field (Audunsson et al., 1992). In contrast, broad intermediate to low magnetic anomalies may be caused by terrestrial flows like ‘a’ā or by weathering alteration processes. The rapid cooling and varying orientation of clasts in ‘a’ā flows do not allow magnetic crystals to align as consistently with the magnetic field, yielding an intermediate to anomalously low response (Harris et al., 2016; Bücker et al., 1999).

The likelihood of encountering reversely magnetized rocks on the Island of Hawai’i is low, and the probability is even lower in the Lower East Rift Zone (LERZ). The oldest rocks on the island have been dated to approximately 0.70 ma, which is younger than the last geomagnetic field reversal that occurred around 0.78 ma. All radiometric ages for rocks in the LERZ are significantly younger than the last geomagnetic reversal, and no reversely magnetized rocks have been documented on the Big Island (Langenheim and Clague, 1987; Doell and Cox, 1965).

Paleomagnetic data collected by Rosenbaum et al. (2009) from boreholes SOH1 and SOH4 (Figure 2) help us understand the magnetic properties of the geology in the LERZ and PGV. Measurements show that shallow dikes have the highest total magnetization compared to other rock types encountered (Table 1). This suggests that shallow dikes are significant sources of short-wavelength magnetic high anomalies associated with the LERZ, while deep dikes likely present as longer wavelength, intermediate magnetic values. These results are consistent with the finding of this study, that high-amplitude magnetic anomalies are often flanked by broader magnetic low anomalies, likely representing mixed domain terrestrial flows or rock may have been altered in the LERZ (Rosenbuam et al., 2009). Over time, weathering or other forms of alteration may reduce the magnetization of these rocks, explaining the lack of magnetic high anomalies in older areas of the rift zone and in exposed terrestrial flows (Garnier et al., 1996).

Rock Type	Total Magnetization (Am^{-1})
Terrestrial flow	5.4 ± 0.6
Hyaloclastites	3.7 ± 2.1
Pillow basalt	9.4 ± 2.8
Shallow dikes (<800 m)	12.6 ± 2.5
Deep dikes	8.4 ± 1.4

Table 1: Total Magnetization values measured by Rosenbaum et al. (2009)

An acoustic borehole image log and Pressure/Temperature/Spinner (PTS) data were collected and analyzed from well KS-21. Despite overall low image log quality, 248 fractures were picked over the 3,266 ft log interval. Most fractures identified are sub-vertically dipping and NE-SW striking, consistent with the trend of the LERZ (Figure 7), and combined analysis of image and PTS surveys supports rift-parallel fractures controlling permeability over imaged feedzones. In addition to the NE-SW striking fractures, there is a minor, but significant, population of WNW- to NNW-trending features distributed throughout the image log. These features are broadly consistent with the attitude of rift-cutting fractures expected from interpretation of magnetic lineaments, however, they do not appear to be major contributors to permeability in the imaged interval and evidence for large, throughgoing NW-trending fractures has so far not been encountered.

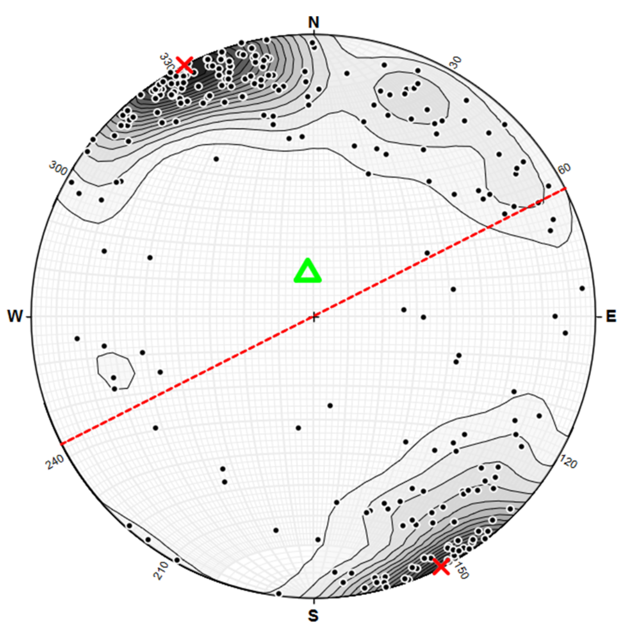

Figure 7: Lower hemisphere stereonet with all fractures identified in the image log (n=248) plotted as black dots representing poles to planes. The trend of the LERZ (063°/243°) is represented by the dashed red great circle, with poles to that vertically dipping plane indicated by red X's. The average attitude of the borehole through the logged interval is plotted as a bold green triangle.

Several tracer studies both pre- and post-eruption have been conducted within the PGV resource to gain a better understanding of potential fluid pathways and the connectivity between production and injection wells. Most notably, tracer studies show a high degree of connectivity within the N63°E-trending rift parallel structures which are well characterized by downhole data including fluid losses during drilling, image logs, and pressure and temperature (PT) surveys.

However, results from multiple tracer studies have also suggested that injection into the northern rift-parallel fractures return to production wells in the southern portion of the reservoir. A cross-cutting structure may explain the connected pathway to allow for the tracer returns. With more recent drilling, additional tracer studies are required to further investigate these potential pathways.

6. Conclusion

The 2024 airborne magnetic survey of the Puna Geothermal Venture within the LERZ has provided a new perspective into the area's magnetic characteristics and structural complexities and has provided a solid foundation for future geophysical interpretation. This survey has identified high magnetic anomalies interpreted as intrusive dikes and thick inflated sheet pāhoehoe flows. In contrast, intermediate and low magnetic anomalies in some areas may be the result of alteration or weathering along mapped fissures and fractures.

Utilizing a multi-disciplinary approach to incorporate the interpretations from this airborne magnetic survey has proven valuable to understanding the geologic structure at PGV. Pairing interpretations from paleointensity data, image logs, and reservoir tracer tests bolsters the interpretation that there are rift-perpendicular structures may exist in the geothermal reservoir and could be conduits for fluid flow. Further integration of these data with existing datasets will improve the geologic conceptual model and inform future resource management decisions.

Further investigation may include additional geophysical investigations, additional injection testing through tracer studies and production data, and geologic mapping. Ground-based electromagnetic geophysics, particularly magnetotellurics (MT), may be helpful in mapping subsurface alteration and understanding the structural controls of the geothermal system, including the geometry clay cap overlying the geothermal reservoir.

Acknowledgement

The authors would like to express our gratitude to our colleagues at Ormat Technologies for their support and encouragement throughout this project. We would like to thank the MWH team for executing this survey in a safe, efficient manner while collecting excellent data. Special thanks to the PGV on-site operational team for their assistance and commitment to safety throughout the duration of the survey. We are very appreciative of our fellow scientists Robin Zuza and Simon Webbison for their insightful feedback and valuable contributions to this study. I would like to express my heartfelt gratitude to my father, John Reynolds, whose passion for geophysics and support have inspired my career path.

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