

Preliminary Results of a Magnetotelluric (MT) Survey across and Core-Hole Drilling into East Maui Volcano (Hawai‘i, USA)

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ABSTRACT

The Ghyben-Herzberg relation is considered the standard model for groundwater hydrology in ocean-island environments. This model is based on simplified assumptions but is still used to provide a basic level of groundwater storage in Hawai‘i. Over the last 25 years, each and every scientific drilling project on Hawai‘i Island has revealed complex hydrology, which the standard model does not explain. Scientists encountered surprisingly deep freshwater, warm water, and perched freshwater under a variety of groundwater regimes and hydrostatic pressures. It is hypothesized that Hawai‘i’s groundwater and geothermal systems are complex, and that more surveying is required to understand the storage of freshwater and prospective geothermal resources across all islands as they age.

This study aims to investigate the unique hydrology and prospective resources on the southwest rift zone of East Maui Volcano, more commonly known as Haleakalā. Our survey is located along the southwest rift zone of East Maui Volcano, which is a critically understudied leeward region of East Maui. A large portion of this rift zone is privately owned and classified for agricultural use. East Maui Volcano’s current volcanic state provides an opportunity to examine the distribution and transport of groundwater and residual magmatic heat from more permeable shield-stage aquifers to post shield-stage structures.

We conducted a magnetotelluric (MT) survey of 59 stations on and around the rift zone. The resistivity data is inverted to 1D and 3D models to confirm the elevation of the water table and understand the system that is driving groundwater storage. We also have commenced drilling of a cored borehole to confirm and compare the findings from the electromagnetic survey. Drilling to date has been challenging. The goal of this project is to provide an accurate depiction of the extent, source, and temperature of groundwater along an understudied region of Maui. This paper introduces and provides a project status update.

1. INTRODUCTION

Outside of the Puna area, only a handful of deep slim-holes have been drilled across the State of Hawai‘i—four on Hawai‘i Island and one on Lāna‘i. Early 2025, the Hawai‘i State Energy Office provided \$5M to the University of Hawai‘i to drill a ~2 km deep subsurface characterization slim-hole. The project decided to drill into the SW rift zone of East Maui Volcano at an elevation ~800m above sea level. To better characterize the subsurface prior to drilling an ~60 station magnetotelluric survey was conducted.

2. METHODS

The magnetotelluric (MT) method is a geophysical survey technique that utilizes temporal variations in Earth’s magnetic field to study the subsurface resistivity structure of the Earth. These fluctuations induce electrical eddy currents in the subsurface, which allows us to study depths into the upper mantle. Simultaneous time series recordings of electric and magnetic field vectors at the surface allow us to compute a frequency-dependent transfer function that are influenced by the electrical resistivity structure of the Earth in the spatial vicinity of the measurement station. The lower the frequency the deeper the penetration of the electromagnetic field. Thus, measuring the electromagnetic vectors at the surface, and transforming the data to an array of frequency-dependent transfer values, allows for the interpretation of the subsurface electrical resistivity as a function of position and depth (Chave and Jones, 2012). Numerous characteristics affect Earth’s resistivity. The most common being mineral composition, water saturation, and temperature. Aquifers significantly lower resistivity as groundwater becomes an electrolyte, dissolving and absorbing ions from the surrounding rock. Increased temperatures in geothermal or volcanic systems also lower resistivity by increasing the mobility of ions in subsurface fluid. As a result, the focus of this study encompasses the low resistivity anomalies detected and interpreted from the MT survey, shown in 1D and 3D models.

2.1 Data collection

Measuring magnetotelluric data is a passive electromagnetic process requiring multi-day data acquisition intervals. MT sites are composed of data loggers, three magnetometers, and two electric dipole antennas (**Fig. 1**). The magnetometers record all three components (B_x , B_y , B_z) of the magnetic flux density field, whereas the electrodes record two components (E_x , E_y) of the electric field. The third, vertical

component of the electric field is nonexistent due to the atmosphere being electrically insulating (Chave and Jones, 2012). These data are collected as time series, with the duration of the acquisition tailored to the specific needs of the survey.

Our survey consisted of 59 MT sites, forming an array of measurements almost covering the entire southwest rift zone (Fig. 1). Each station acquired data for approximately three days, with the total fieldwork spanning two months. We generally equipped each station with two horizontal Phoenix MTC-150 magnetometer coils, and one vertical MTC-185 coil, Borin Stealth 1 electrodes, and Phoenix MTU-5c data loggers. To ensure electrical signal, each electrode was contained in saturated bentonite (industrial clay) and watered in place.

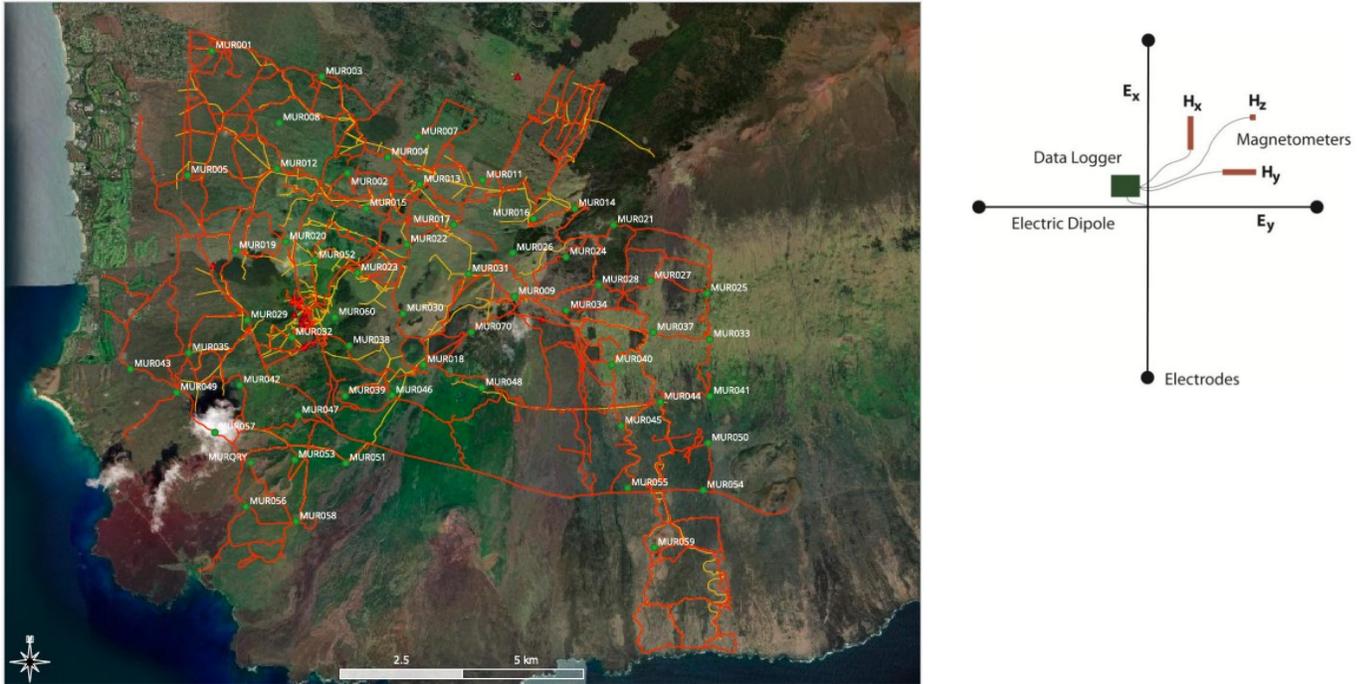


Figure 1: Left: Our survey involved 59 magnetotelluric sites, covering almost the entire southwest rift zone of Maui. Each station collected data for about three days, and the total fieldwork spanned two months. Each station features these equipment: Phoenix MTC-150 magnetometer coils with MTC-185 sensors, Borin Stealth 1 electrodes, and Phoenix MTU-5c data loggers. To ensure electrical signal, each electrode was contained in saturated bentonite (industrial clay) and watered in place. Right: A schematic showing the basic setup for an MT station (Comeau, 2015).

2.2 Data processing

From data acquisition to interpretation, the processing procedures are the following. The electromagnetic signals are recorded as time series. These signals follow the governing principles of Maxwell’s equations, which correspondingly derive into the time-dependent wave equation. Although, solving this requires a complex partial differential equation, whereas a modified frequency-dependent wave equation is much simpler. For this reason, it is routine to convert the time series data into the frequency domain using a Fast-Fourier Transform (FFT). Using Robust processing software can estimate the transfer function between the electrical and magnetic field components generally referred to as impedance (Z)(Eq. 1), along with uncertainty, for the recorded time series measurements (Chave and Jones, 2012). The processing software used for this study is FFMT (Castro et al., 2025)., which functions as a MATLAB app.

$$Z_{xy} = \frac{\mu_0 E_x}{B_y} \quad (\text{Eq. 1})$$

$$\begin{pmatrix} E_x \\ E_y \end{pmatrix} = \begin{pmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{pmatrix} \begin{pmatrix} B_x \\ B_y \end{pmatrix} \quad (\text{Eq. 2})$$

We enhance the data quality with the co-processing of an additional remote MT station, typically located a ‘reasonable’ distance from the area of study. The ideal location for a remote station is a region with less urbanization and electromagnetic noise, such as powerlines and road traffic. However, this station must be close enough to the survey area that the Earth’s magnetic field measurements coincide. Including a magnetic field component from a remote site reduces the impedance biases produced by noise (Gamble et al., 1979). In this survey, we remote-reference each MT dataset with a time-matching dataset from a permanent MT station located on the Big Island (station K1). The impedance results are stored as electronic data interchange files (.edi) and inversion is now possible.

Inferring the resistivity model that best suits the impedance values requires a type of geophysical inversion. A preferred method for 1D inversion applies a linearized, least-squares optimization problem to constrain the smoothest acceptable model, known as Occam’s inversion (Constable et al., 1987). The forward model (F) describes Earth as horizontal layers of uniform thickness, each assigned a resistivity value, which operates on the model vector (m) defined as the log resistivity of each layer. The misfit between the observed data (d) and the forward model operator ($F(m)$) of the best-fit model ideally falls within the error bounds assigned to the impedance to be representative. Creating the smoothest model in this case simply means finding the model with the smallest roughness within the acceptable fit range. Occam’s Inversion (Constable et al., 1987) formulates these parameters into a solvable minimization problem that iterates until the misfit matches the target value (Eq. 3). The first term includes a diagonal matrix (W) of reciprocals of the data standard deviation. The second term contains the Lagrange multiplier (μ) and the first difference operator (D) acting on the model. These conjoined terms simultaneously minimize the misfit and the roughness of the model. For this study, we create the 1D inversion models with a pre-existing Occam’s Inversion MATLAB code (University of Alberta).

$$\min_m \|W(d - F(m))\|^2 + \mu \|Dm\|^2 \quad (\text{Eq. 3})$$

3. MAGNETOTELLURIC SURVEY: PRELIMINARY RESULTS

Measured impedance values in MT are commonly displayed as phase tensor ellipses for a specific frequency in map views (Bibby, Caldwell, Brown, 2004). In general, a phase tensor captures the relationship between horizontal electric and magnetic field vectors with the advantage that these representations are not galvanically distorted. The tensor values at specific frequencies are displayed as ellipses that can be interpreted with visual aids to understand current flow within the subsurface. The illustrated phase tensor values displayed for a frequency of 11.5 Hz show a largely consistent image across the survey area. Variable azimuths indicate that the subsurface at this depth is predominantly 3D, which is an expected result for the complex rift zone in direct vicinity to the electrically conductive ocean. All stations indicate conductivity with depth as phases are consistently greater than 45° . It appears that data complexity increases towards the coastline, which motivates the application of 3D inversion in future work to obtain a plausible subsurface resistivity structure.

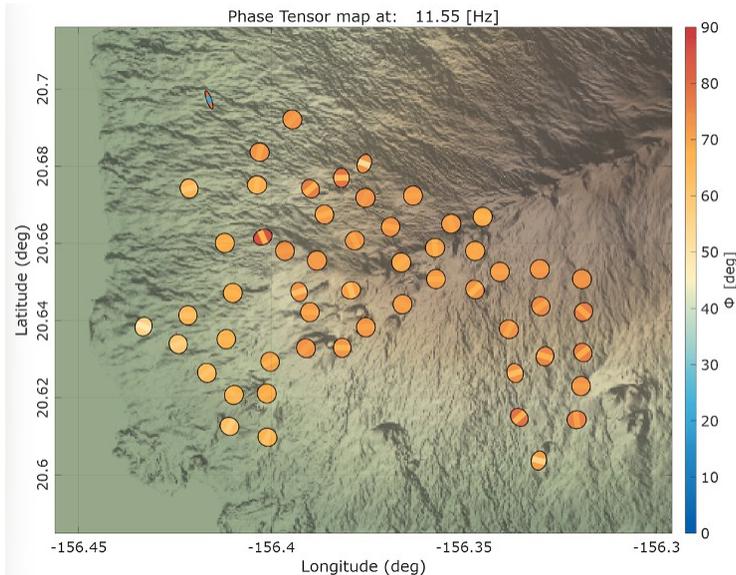


Figure 2: The illustrated phase tensor values displayed for a frequency of 11.5 Hz show a largely consistent image across the survey area. Variable azimuths indicate that the subsurface at this depth is predominantly 3D, which is an expected result for the complex rift zone in direct vicinity to the electrically conductive ocean. It appears that data complexity increases towards the coastline

4. DRILLING: STATUS UPDATE

From surface, the project is drilling into the piled up dense vent-rock of a post-shield scoria cone along the SW Rift Zone of East Maui Volcano (**Fig. 6**). Progress has been slow and challenging. An initial hole encountered a ~15 foot thick void 4 feet below surface that made it difficult to secure surface casing. Still, this hole was cored to slightly over 1500 feet below surface before caving caused immobilization. Interestingly, the water table was encountered below sea level. A second hole was initiated, surface (PWT) casing was better set deeper and into hard rock. This hole is approaching 1000 feet below surface, still with many challenges encountered.

5. ROCK CORE: PRELIMINARY FINDINGS

The first ~1500 ft (~460 m) of rock core recovered is overwhelmingly 'a'ā, which represents probably well over 95% of the recovered rock by volume. While the number of lava flow units and their contacts have not been rigorously identified yet, initial examination of the core has revealed few thin pāhoehoe and transitional units so far.

The 'a'ā flows are composed of top and bottom clinker intervals of variable thickness, with much more dense, massive interiors in between. The thickest unit encountered so far is well over 100 ft (>30 m), and most of that unit is composed of a massive, only weakly fractured interior. Drilling through these 'a'ā flow interiors is no problem at all, but the unconsolidated nature of the clinker is causing drilling issues; it both shortens bit life and leads to unstable sidewall intervals in the borehole. As a result, our core recovery rate has been only ~78%, rather than the 90+% we've achieved in previous core drilling projects in Hawai'i (García et al, 2007).

The dominance of 'a'ā flows of the Hāna and Kula Volcanics was noted by Stearns and Macdonald (1942) and refined via more recent mapping work by Sherrod et al. (2003). These flows materialized most recently between 1449 and 1633 CE (Sherrod et al., 2006), and began ~900,000 years ago (Chen et al., 1991). Our drilling has or will intersect both of these alkali-rich post-shield phases of the volcano's late lifespan, and will eventually reach the more alkali-poor shield stage known as the Honomanū Basalt, whose exposures have been dated ~1 Ma (Chen et al., 1991). Drilling should additionally reach older Honomanū Basalt than can be found anywhere on the eroded surface of the volcano. Exposures of the Honomanū Basalt indicate it is composed of much more pāhoehoe lava. Therefore, a greatly increased frequency of that lava flow type may be a good visual indicator of reaching the shield lavas when we drill down into them.

Rocks range from aphyric (no phenocrysts) to porphyritic (easily visible phenocrysts), with the main large minerals being olivine (1-3 mm) and clinopyroxene, the latter of which can be even larger than olivine in the more porphyritic rocks. Additionally, the drilled core commonly shows plagioclase, but mostly as large xenocrysts averaging ~1 cm long. Xenoliths are also present but more rare, only seen in a few flows so far and only a bit larger in size and more equant in shape than the xenocrysts. The xenoliths appear to be mainly composed of plagioclase and clinopyroxene.

The location of the borehole on the southwest rift zone of the volcano leads us to two expectations: 1) The presence of intrusive dike units (and associated heat), at least once we get down into the Honomanū Basalt if not before, and 2) The steeper slope of the rift zone vs. the other flanks of the volcano promotes more 'a'ā flow formation. However, near-vent flows typically look like pāhoehoe in drill core so we still expect to see much more of this flow type once we reach the Honomanū Basalt.

While many of the 'a'ā interiors are largely unaltered, there is some alteration that can easily be seen on fracture surfaces and in vesicles. Presumably, the fractures have long been pathways for rainwater and groundwater to pass through and interact with the rock. A common family of minerals created by even low-temperature interaction of Hawai'i basalts with water are zeolites (Tschernich, 1992); indeed, the zeolite mineral phillipsite has been identified in our Maui core and typically is found partially to wholly filling vesicles and in some fractures. Additional secondary material in the core has been observed, but not yet identified beyond minor amounts of clay within the smectite family. As for the 'a'ā clinker, the top clinker of a given unit commonly tends to show significant alteration due to both weathering and baking/oxidation from the overlying flow. A bright, rusty-orange flow top consisting of clinker clasts mixed with finer soil or ash is fairly common (**Fig. 3**).



Figure 3 (Left): Baked float top—A bright, rusty-orange flow top consisting of clinker clasts mixed with finer soil or ash is fairly common

Figure 4 (Right): A plagioclase xenocryst-bearing ‘a‘ā unit creating a bright baked contact at the top of an olivine-rich pahoehoe flow



Figure 5: Photo of alternation in the drill core.



Figure 6: Photos of Maui project drill site and geology

5. CONCLUSION

The goal of this paper is to inform of an exciting project of considerable relevance to the State of Hawai‘i’s understanding of its groundwater and geothermal resources. Although the results we present herein are preliminary, we hope to both solicit input and pique interest in this project.

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