MAGNETOTELLURICS

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I. INTRODUCTION

Magnetotellurics: magneto meaning magnetic; -telluric meaning electrical Earth currents; is a geophysical method based on time variation-measurements of both the magnetic field $B(t)$ and the induced electric field $E(t)$.Using the measurements of the Earths time-varying, naturally occurring magnetic and electric fields, magnetotellurics (MT) survey teams can derive resistivity (or conductivity) estimations of the subsurface. This geophysical method is passive, i.e. the magnetotelluric source originates from solar-winds and lightning strikes. Charged, solar storm particles interacting with the Earths magnetic field account for the solar wind, while the ionosphere acts as a waveguide for lightning strikes. The periods of these passive sources go from $0.0001Hz$ up. As the magnetic fields from these sources pass over the ground, some of the energy is directed into the subsurface generating electric fields. The instruments used in the field then measure the corresponding horizontal $E(t)$ and $B(t)$ as well as the vertical $B(t)$. It is possible to take the surficial measurements of electromagnetic currents and use the ratio of their components to estimate impedance, Z, as a function of frequency obtained through a Fourier Transform. The Z is calculated using the ratio of $E(w)$ and $B(w)$, thus combining both the electrical and magnetic components[1].

II. BACKGROUND

Prior Pagosa Springs field session MT methods (2014, 2015, and 2016) all shared the common goal of assisting in the understanding of the towns unexplained geothermal activity. Dependent upon the sampling frequencies and the time span of a survey, the MT method can successfully investigate depths from $0.30km$ to $10km$. Due to its significant depth-of-investigation (DOI) assessment, the method was again chosen for the 2017 Geophysical field camp to ascertain, confirm and support the notion of the source-location of the hot springs and the existence of other significant, sub-surficial geological features. Allowing the data to be tabulated over a significant time period, interpretation of the deep seismic line could be investigated at a depths to the Precambrian basement, beyond the capabilities of ancillary methods.

III. THEORY

To examine the physics that explicates the magnetotelluric method, the assumption must be made that charges can accumulate along discontinuities in multi-layered Earth which behaves as an Ohmic conductor and obeying the equation

$$J = \sigma E$$

where: J=electrical current density, σ = conductivity and E = electric field strength

Additionally, the assumption must be made that electromagnetic waves, produced by the aforementioned passive methods, vertically propagate into the earth in the form of plane waves. These planar waves are governed by Maxwell's equations:

Faraday's Law

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

Ampere's Law

$$\nabla \times \vec{B} = \mu_0 \vec{J} + \mu_0 \epsilon_0 \frac{\partial \vec{E}}{\partial t}$$

Gauss' Law for magnetism

$$\nabla \cdot \vec{B} = \rho_v$$

Gauss' Law

$$\nabla \cdot \vec{E} = \frac{\rho}{\epsilon_0}$$

Based on these assumptions, Maxwell's correction to Ampere's law can be utilized, denoting that a changing magnetic field creates an electric field and vice versa.

$$\nabla \times \vec{B} = \mu_0 (\vec{J} + \epsilon_0 \frac{\partial \vec{E}}{\partial t})$$

where σ, ϵ and μ represent the intrinsic, material properties subject to electromagnetic wave-field propagation . ϵ is the electric permittivity and μ is the magnetic permeability.

The ratio of these fields, in the frequency domain, demonstrated through the above equations is used to determine the apparent resistivity of the subsurface. The relationship is as follows:

$$Z(w) = \frac{\mu E_i(0)}{B_j(0)}$$

where i, j = {x, y}.

Assuming $E(w)$ and $B(w)$ are consistent with the following equations

$$E(w) = E_i(0)exp(-\sqrt{iw\mu\sigma z})$$

and

$$B(w) = B_j(0)exp(-\sqrt{iw\mu\sigma z})$$

and knowing Faraday's Law, one can arrive at the equation

$$Z(w) = \sqrt{\frac{iw\mu}{\sigma}} = \frac{\mu E_i(0)}{B_j(0)}$$

Using this relationship, the resistivity can be obtained by manipulating the equation into

$$\rho_a(w) = \frac{|Z(w)^2|}{w\mu}$$

The phase, angle between the imaginary and real parts of the impedance, can be found using

$$\phi = tan^{-1}(\frac{Im(Z)}{Re(Z)})$$

All of the above equations are in terms of frequency, w, meaning any apparent resistivity curve and phase will also be in terms of w. This is consistent with the idea of skin depth given by

$$\delta = \sqrt{\frac{2}{\omega\mu\sigma}}$$

As frequency increases, the DOI decreases. Similarly, as the conductivity increases, the DOI decreases. Using the apparent resistivity, phase, and skin depth equations the data obtained in the field can be transformed into apparent resistivity curves and eventually inverted into depth images.

IV. SURVEY LINE

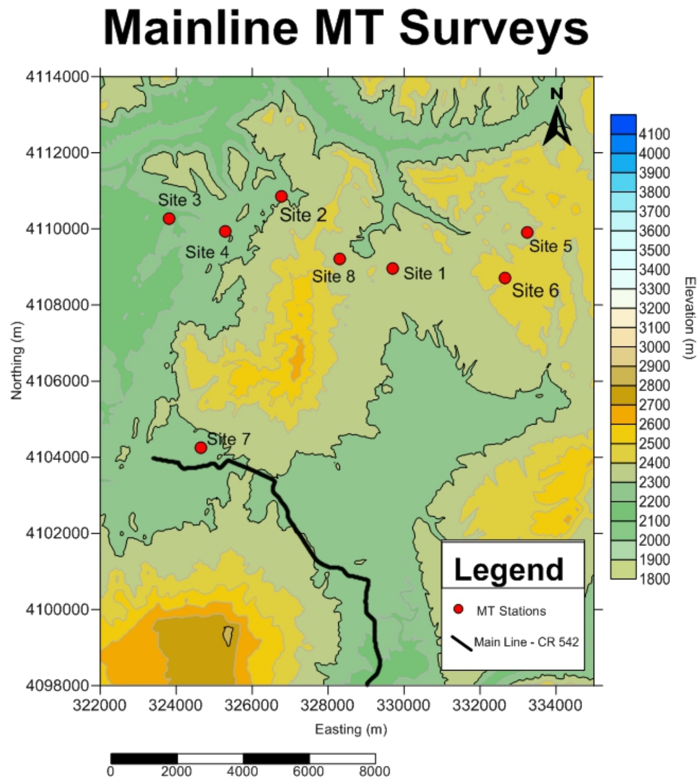

Fig. 1. All 8 sites are located in remote areas as to avoid cultural noise which will interfere with the measurements. The overall site location geometry was chosen in order to get a cross section across the dike indicated by the black line. Site 8 is located on a dike in order to obtain information about the dike itself.

A. SURVEY PARAMETERS

- 50-meter spacing from center point (True North)
- Sampling frequency: 1024 Hz (2 sites)
- Sampling frequency: 256 Hz (all sites)
- Channel gain : varied per station
- Record duration: 24 hours

V. EQUIPTMENT LIST

- Metronix^{TM}ADU-07(e) Magnetotelluric System
- Part Number: 258,286
- Field laptop
- 6 induction coil magnetometers
- 4 $Cu/CuSO_4$ non-polarizing electrodes
- 2 stainless steel- electrodes (for grounding)
- 8 Self Potential Cables (to connect electrodes to ADU)
- 4 50 meter Magnetometer Cables (to connect magnetometers to the ADU)
- 2 12 volt Car batteries with appropriate battery cables
- 2 mobile GPS units (that attach to the ADU, for time drift corrections)
- 100 meter field measuring tape

VI. DATA ACQUISITION

At each MT survey site, 2 pairs of electrodes are aligned in an orthogonal, typically North-South and East-West, arrangement in addition to ortho-normally aligned magnetometers. Electrode spacing was established at 50 meters from center, which is considered the overlay-point, adjacent to the ADU 07e. They are then attached to a grounding electrode in the center of the configuration. Magnetometers were placed in separate quadrants surrounding the grounding electrode, in the center, at least 5 meters apart.

For the E-field measurements, the electrodes will provide low-noise, low-resistive coupling with the Earth. In contrast to 1-Dimensional MT, where σ is solely dependent on $\vec{z}$ orientation, its noted that in 2-Dimensional MT where $\sigma = \sigma(x, y)$, conductivity changes horizontally as a function of depth; The subsidiary horizontal component is commonly known as strike. This is significant when examining the anisotropic/isotropic nature of the subsurface, since at each point σ is possibly dependent on vectors of current flow, meaning, if σ is dependent on direction an anisotropic subsurface has been encountered.

Based on the attenuated nature of the EM plane wave propagation into the subsurface, lower frequencies penetrate more deeply, whereby apparent resistivity, ρ_a varies with frequency if conductivity changes with depth. Apparent resistivity can be tabulated (by approximation) for any combination of these horizontal layering, whether anisotropic or isotropic, as long as E and B- field alignment is perpendicular.

Since the induction coils of the magnetometers are motion-sensitive to wind and other vibrational sources, the coils relating to the x-axis and y-axis were buried in 12 to 18 -inch trenches and leveled within 1°

In order to run the survey, all electrodes and magnetometers are attached to the ADU 07e unit as well as a computer. In the computer, Firefox needs to be opened and the IP address typed into the address bar. The correct ADU number must be selected. The gain must be set to auto. A test must be run under "Self Test Configuration" to determine the appropriate gain. Once the tests are finished, the survey can begin.

VII. EXPECTATIONS

The MT sites were placed in an orientation such that a cross section over the dike could be obtained from the data. It was expected that Sites 2-4 on the West side of the dike will have similar resistivity values and depths. Likewise, the sites to the East of the dike (Sites 1, 5-6, and 8) were expected to be have the same characteristics. From the geological interpretation provided, the depth to basement is around 1,600 meters. Knowing this, it is expected that the 16 and 4 Hz bands in the data would show the basement (calculated using the skin depth equation). Through noise removal and inversion, these expectations can be met.

VIII. PROCESSING

In order to meet the expectations previously mentioned, the data needed to be turned into a format suitable for inversion. This was done through the use of the *Mapros* Software. Data sets for each location were imported into the program. The first task was to remove the noise. The time series was filtered into 256, 64, 16, 4, and 1 Hz frequency bands. Then, the time series for each band was looked over by a member of the MT processing crew. Any noise seen in the time series was marked. The team identified noise as any irregularities in the data. The irregularities generally consisted of spikes, extremely choppy data (the measurements would instantly increase by over 200 mV then move back down), changes in general sinusoidal trends.

Once this was done, the data was processed using the setting "Remove all Marked Sections". The result was an amplitude spectrum and phase spectrum. If the amplitude spectrum was generally smooth for all bands, the data was exported as an ASCII file. If the data was not smooth enough, the parzen radius and sampling length were adjusted or the processor revisited the time series to mark more data.

A. *ipi2win.MT*

The exported ASCII file was in the format as shown in the table below, the file was then convert to an appropriate format for the *ipi2win.MT* program to read. This was done by taking the frequency, the apparent resistivity, the apparent resistivity variance, the phase, and the phase variance and putting them into an Excel spreadsheet in that order. The first column was then turned in the square root of the period (square root of the inverse) and the third was turned into percent error. The file was then saved as a .mt file so it could be opened by *ipi2win.MT*. Once opened in *ipi2win.MT* the percent error had to be added by hand to the file for the apparent resistivity. Afterwards, the suspected number of layers were added and a line of best fit and a corresponding model were found for the graphs.

TABLE I

DESCRIPTION OF COLUMNS IN EXPORTED ASCII FILES FROM *ipi2win.MT*

Column	Information
A	MT Site
B	Band
C	Frequency (Hz)
D	$Z_{xx,real}$
E	$Z_{xx,imaginary}$
F	Z_{xx} variance
G	$Z_{xy,real}$
H	$Z_{xy,imaginary}$
I	Z_{xx} variance
J	$Z_{yx,real}$
K	$Z_{yx,imaginary}$
L	Z_{yx} variance
M	$Z_{yy,real}$
N	$Z_{yy,imaginary}$
O	Z_{yy} variance
P	$T_{x,real}$
Q	$T_{x,imaginary}$
R	$T_{y,real}$
S	$T_{y,imaginary}$
T	ρ_{xy}
U	ϕ_{xy}
V	ρ_{xy} variance
w	ϕ_{xy} variance
x	ρ_{yx}
Y	ϕ_{yx}
Z	ρ_{yx} variance
AA	ϕ_{yx} variance

B. IX1Dv3

The same columns were used in the *IX1Dv3* software. The frequency column could remain in terms of frequency and the resistivity variance was changed to percent error (resistivity variance divided by resistivity). The best points were chosen to ensure only one point was given per frequency as was done in the *ipi2win.MT* input file. In the *IX1Dv3* software, a new "MT Sounding" was created and all values were input into the program. The inversion model was created by adjusting the layer lines so the apparent resistivity line matches the data. Once the inversion models were correct, the model was exported as an ASCII file and imported into Excel where the corresponding model was created.

IX. ERRORS AND UNCERTAINTIY

A. Field

In the field most of the sites were placed along the forest road with the focus being along the dike. An issue with this is that there are people who drive on these roads and there cars and movement create serious issues with the quality of data acquisition. In the survey setup the magnetometers must be perfectly aligned with North-South, and East-West, these can easily be knocked off of alignment causing issues within the data. The magnetometer must be level, this is difficult to do with a hole as dirt is placed back in to bury the magnetometer the instrument may be moved and knocked off of alignment, thus giving rise to issues within data acquisition. Issues with acquisition of data results in issues that make processing more difficult, and will leave more room for uncertainty in the results and later analysis.

B. Processing

The processing portion of of field camp the way of cleaning out the noise from the data was done manually, in which the team had found anomalies throughout the data at various frequencies. The errors were expunged in the software *Mapros*, these were highlighted and then ignored when processing. These cleansing happened at the frequencies of 256, 64, 16, 4, and 1 Hz, in this data sets were choppy and anomalies were taken out at the best judgment of the team, the issue is that these files are so extensive that there was a fine line between noise and data, thus not all of the noise could be filtered from the survey. The noise reduced data sets were exported from *Mapros* in the form of an ASCII file and reduced in Microsoft Excel to only the data required for an inversion. The data then had to be smoothed and points were chosen by hand to best showcase the inversion. This was a judgment call made by the processing team and again was subject to human error, therefore the best point was not chosen in every case which leads to another uncertainty within the final product. From this the file was then saved as a .mt file and then inverted in *ipi2win.MT*. The percent error of these files had to be adjusted by hand and the resulting inversion of the MT data shows the various processing errors with the large error bars found within the majority of the phase graphs along with the peaks and valleys found within the apparent resistivity curves.

X. RECOMMENDATIONS

A. Field

In observation of data from this year and previous years the largest recommendation for each MT survey would be to take a moment to observe and consider each survey site before charging into the set-up. MT is extremely sensitive to the topography and surrounding environment, a little bit of exploitative quality control in the field could provide a much cleaner data set. This quality control could include taking extra time to ensure Ex/Ey electrodes and Hx/Hy coils are aligned with proper directions, making sure survey location is generally flat, checking that there are no power lines within a 1km radius, and even looking to make sure there are no nearby roads. Another recommendation for next years MT acquisition crew would be that everyday in the field *Mapros* should be used to try and remove noise from the acquired data. If the in field noise removal was well documented and efficiently executed, then the processing portion of MT back in Golden would be finished much faster and the actual interpretation and inversion could be more meticulously done. This would allow for more time to really understand the method and programs that encompass the MT method and give more freedom to make a more in depth investigation into the data acquired.

B. Processing

In order to smooth the processing portion, another noise removal program *ProcMT* could be utilized. It might be useful to understand how the program works and it could eventually make the noise removal process easier. One recommendation for inversion would be to choose a single inversion program. *ipi2win.MT* seemed to work better with the actual inversion. *IX1Dv3* made it easy to export the inverted model into a format that is easy to work with in excel. Choosing the right inversion and processing programs will lead to faster inversion and more time for integration.

XI. INTERPRETATION/CONCLUSIONS

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