OPTIMIZATION OF TENSOR CONTROLLED-SOURCE ELECTROMAGNETIC EXPLORATION METHODS: CASE STUDY FROM TRACHYTE MESA INTRUSION, HENRY MOUNTAINS, UTAH

An Undergraduate Research Scholars Thesis

by

DAVID BECKENDORFF and SAMIR JREIJ

Submitted to the Undergraduate Research Scholars program
Texas A&M University
in partial fulfillment of the requirements for the designation as an

UNDERGRADUATE RESEARCH SCHOLAR

Approved by
Research Advisor: Dr. Mark Everett

May 2016

Major: Geology & Geophysics

TABLE OF CONTENTS

Page

ABSTRACT

Optimization of Tensor Controlled-Source Electromagnetic Exploration Methods: Case Study from Trachyte Mesa Intrusion, Henry Mountains, Utah

David Beckendorff and Samir Jreij
Department of Geology & Geophysics
Texas A&M University

Research Advisor: Dr. Mark Everett
Department of Geology & Geophysics

The Henry Mountains in Utah are home to several small igneous intrusions from the Late Oligocene to Early Miocene. One of the most critical small satellite bodies to the main intrusions of the Henry Mountains is the Trachyte Mesa intrusion. What is interesting about the Trachyte Mesa intrusion is that geologist and geophysicist are able to observe outcrops on the surface of Earth in order to characterize the mesa. An important question that is continuously being researched about this area concerns the emplacement of these intrusions. Scientist believe that by understanding the internal structure of these intrusions, answers regarding the emplacement of these intrusions will appear. There has been debate, however, regarding this internal structure. The main dispute is between two structural geologists who have competing ideas regarding Trachyte Mesa after conducting magnetic surveys in the area. Sven Morgan (2008) has concluded that the Trachyte Mesa intrusion internal structure is based on a sheet magma stacking model. Whereas Paul Wetmore (2009) believes that the mesa took the shape of the surrounding rock structures. In order to shed further light upon this dilemma, the original aim of the project was to conduct a tensor control-source electromagnetic characterization survey of the area and produce a model of the Trachyte Mesa intrusion. Due to several complications with responses from the equipment, the aim of the project was modified. The new goal is to discover the cause

of the unusual signals from the equipment, whether it be from equipment malfunctions or the resistive environment present at Trachyte Mesa. With the extensive testing of equipment, a controlled-source electromagnetic survey process that will pave the way for future projects using the same methodology will also be established.

DEDICATION

To our families, friends, colleagues,

and Texas A&M University

Gig ’em

ACKNOWLEDGMENTS

There are many people who have pushed us and helped us achieve our goals. We would first like to thank Dr. Mark Everett for his continuous support and contributions towards the accomplishment of this project. Without him, this would not have been possible. We would also like to thank our families for all the support throughout our career at this prestigious university.

We thank Dr. Mark Everett and the College of Geoscience for their financial contributions that allowed us to take the trip to collect data at the Trachyte Mesa Intrusion.

We thank Dr. Michael Heaney for sharing his geological knowledge of the area. It gave us a thorough geological background to conduct an intensive geophysical survey.

Finally, we would like to thank all the teachers who showed us and pushed us to our highest potential, especially Dr. Mark Everett, Dr. Alfonso Benavides, Dr. Juan Carlos Laya, Dr. Mike Pope, and PhD candidate Harold Johnson II.

CHAPTER I

INTRODUCTION

Geological Background of Trachyte Mesa

The Trachyte Mesa intrusion is one of several small satellite bodies to the larger intrusions of the Henry Mountains in Utah. These intrusions are dated back to the Late Oligocene to Early Miocene using Ar40/Ar39 data (Sullivan et al., 1991). The Henry Mountains contains a series of intermediate to felsic composition intrusions. The surrounding rock is the Jurassic Entrada Sandstone which is overlain by the Jurassic Summerville Formation (Morgan et. al., 2008). In 1877, Grove Gilbert interpreted that the intrusions within the Henry Mountains were emplaced onto a flat floor with the space for the intrusions being created by domal uplift of the overlying column of rocks (Wetmore et. al., 2009). Through geological mapping, it has been found that the Trachyte Mesa is 1.5 km long and 0.6 km wide, but the base structure of the mesa has been a topic of debate for several years.

Previous Studies

Sven Morgan (2008) is a structural geologist who believes that based on fabric relationships between the trachyte mesa intrusion and surrounding wall rocks, the mesa is exposed very close to its original emplacement. In one of the exposures of the Trachyte Mesa Intrusion on the surface, there are series of thin, sub-horizontal shear zones within the intrusion, which Morgan interpreted as contacts between magma sheets. Sven collected field fabric and rock magnetic data from 103 locations at the surface of the intrusion and 73 locations from cross sections exposed at a stream gorge. Using these connections, Morgan hypothesizes that the Trachyte Mesa Intrusion follows a magma sheet stacking model similar to that in Figure 1 in accordance to that of Hunt's original emplacement model for intrusions in the Henry Mountains (Hunt et. al., 1953).

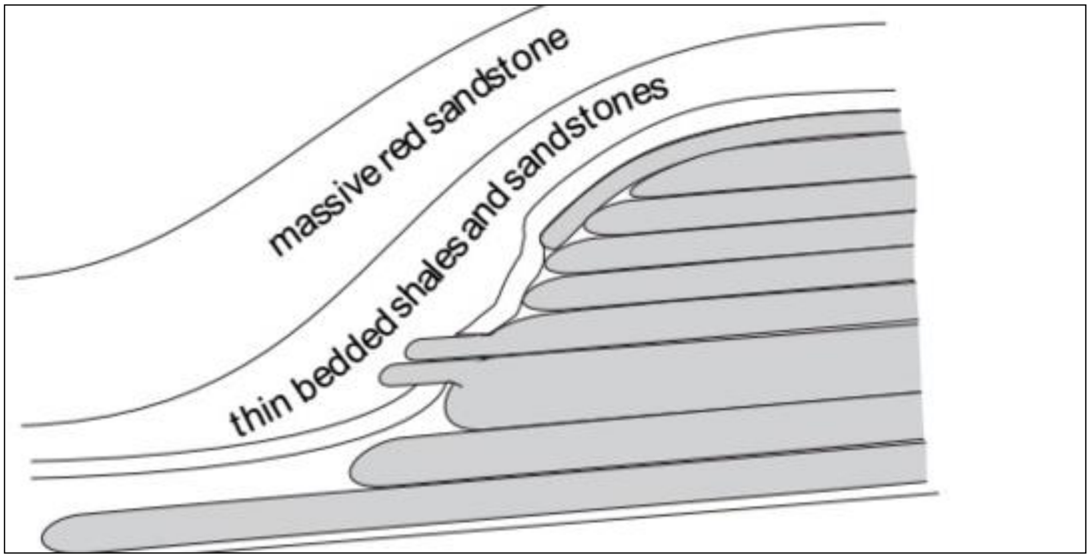

Figure 1: Magma sheet stacking model for Trachyte Mesa Intrusion (Morgan, 2008)

Paul Wetmore (2009), another structural geologist, acknowledges that the Morgan (2008) study of the Trachyte Mesa intrusion helped to understand the formation of laccoliths and the assembly of larger intrusion, but he opposes the hypothesis that the Trachyte Mesa intrusion follows a stacking magma sheet model. Instead, Wetmore hypothesizes that since the surrounding rock (Entrada Sandstone) is known to have several structures within it, the intrusion has been shaped by it. He believes that the folds within the Jurassic Entrada Sandstone constrain the geometry of the intrusion making the base of the intrusion more undulating. Wetmore supports his hypothesis using a geophysical magnetic survey over two lines shown in Figure 2. The results of Wetmore's inverse problem are shown in Figure 3.

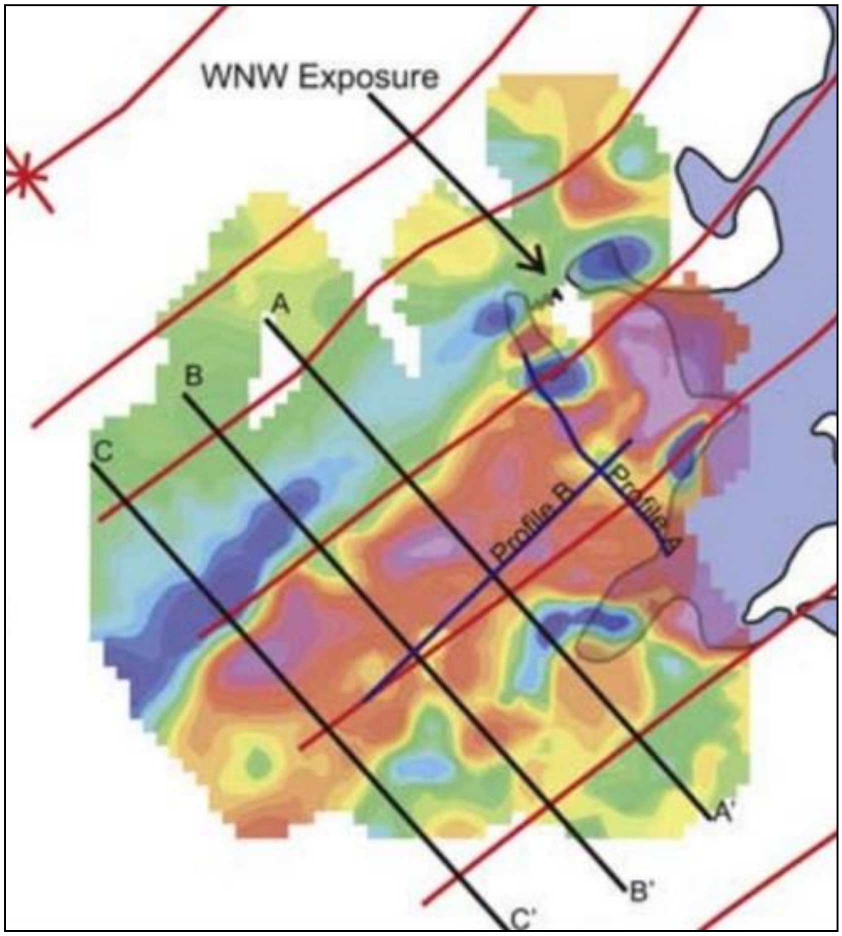

Figure 2: Paul Wetmore's survey lines includes A-A', B-B', and C-C' (Wetmore, 2009).

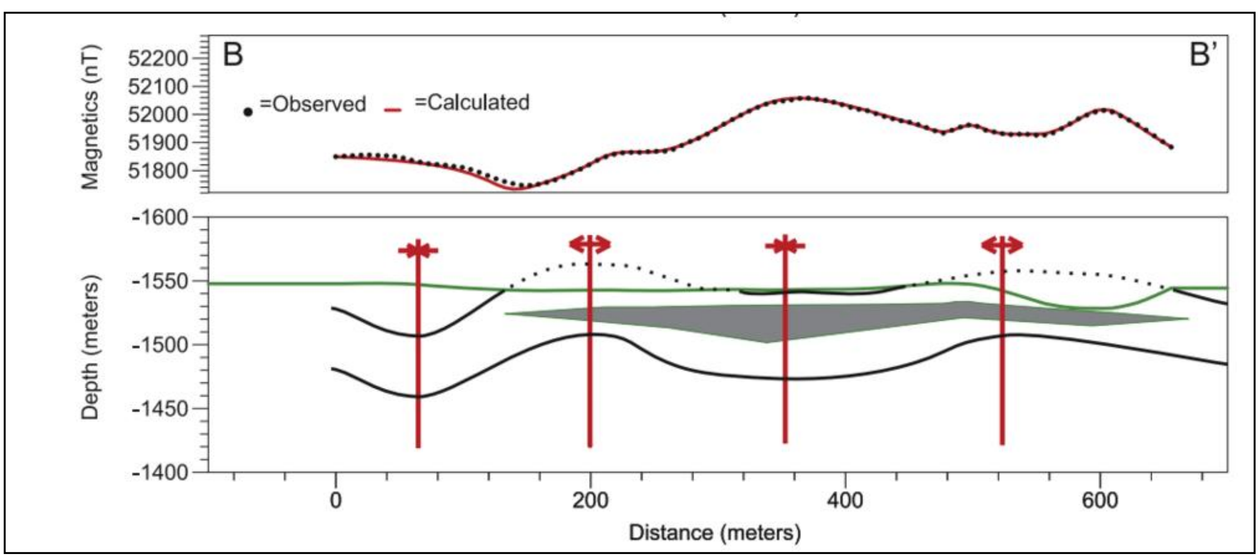

Figure 3: Results from Paul Wetmore's forward modeling of magnetic data on Trachyte Mesa Intrusion on profile B-B' (Wetmore, 2009).

Survey Description

Although very different conclusions were obtained by the two authors stated above, both of these hypotheses were created using data from magnetic surveys. Considering the same surveys were conducted for the area, the validity of the surveys must be questioned and the results from these papers must be verified. Many possible geophysical surveys could be conducted in order to verify the data that is presented. The one that our group intends to utilize is tensor controlled-source electromagnetic characterization. Due to the sharp contrast in conductivity between the Entrada Sandstone (a conductive body) and the Trachyte Mesa intrusion (a resistive body), the non-invasive nature of the survey, and the ease at which the survey may be conducted, an electromagnetic characterization seemed like the most viable option. Two electromagnetic surveys were conducted throughout this project. The first survey was conducted by our advisor, Dr. Mark Everett, during the summer of 2015. The survey lines that were used correspond to those within Sven Morgan's (2008) survey lines. Figure 4 shows the exact survey lines and where they intersect.

The results from this survey appeared noisier than usual, so the original goal of inverting and modeling the data was thought to not succeed. For this reason, the validity of the survey that was conducted by our advisor became suspect. This gave rise to two questions regarding the survey. First, is the noisy data that was collected previously at Trachyte Mesa because of the resistive environment that was present or because of the electromagnetic equipment malfunctioning? In order to test the environment that is present in the Henry Mountains, Utah, another survey was conducted by our team in 2016. This survey that was conducted by our team is shown in Figure 5. In order to analyze the electromagnetic equipment, extensive tests were conducted at Texas

A&M Riverside campus on various parts of the system. Second, how can one insure high quality electromagnetic responses are acquired at Texas A&M Riverside campus and can these responses be applied to future electromagnetic surveys?

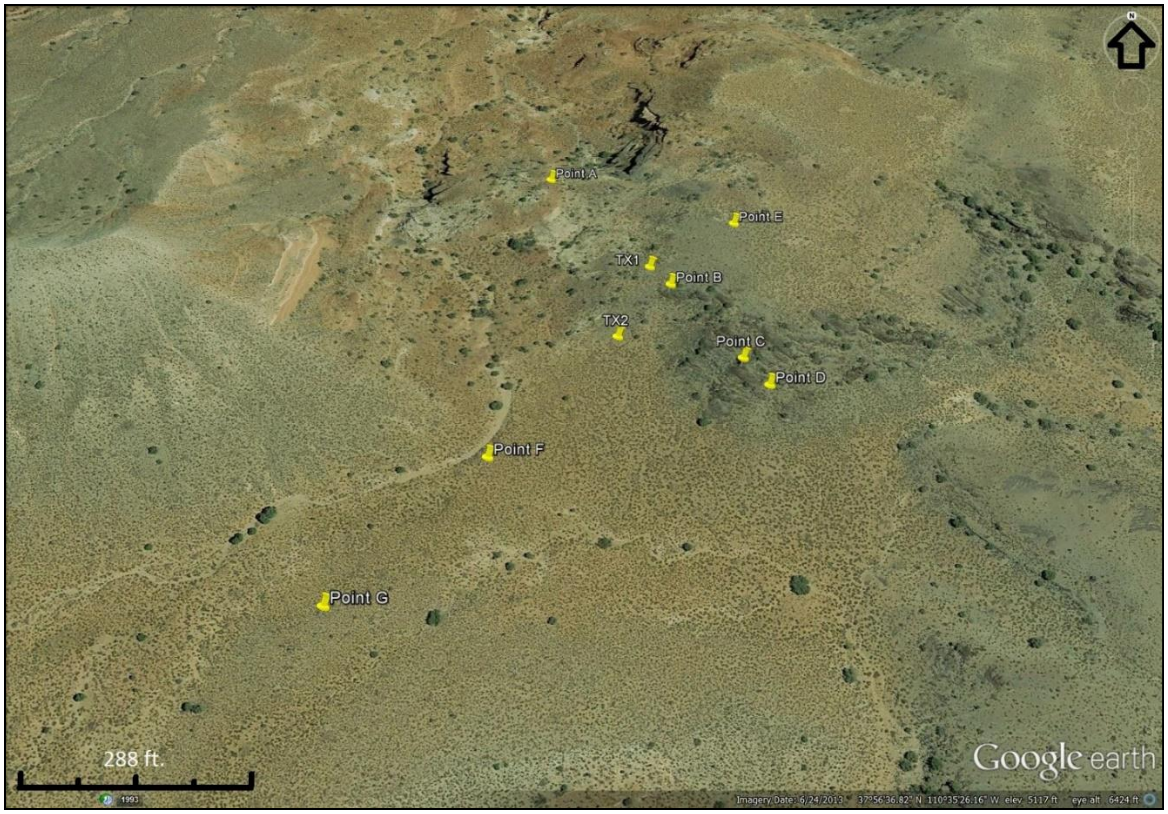

Figure 4: Survey area for the tensor control-source experiment conducted by Dr. Mark Everett. Point A to Point D comprise 'profile A' and point E to point G comprise 'profile B'.

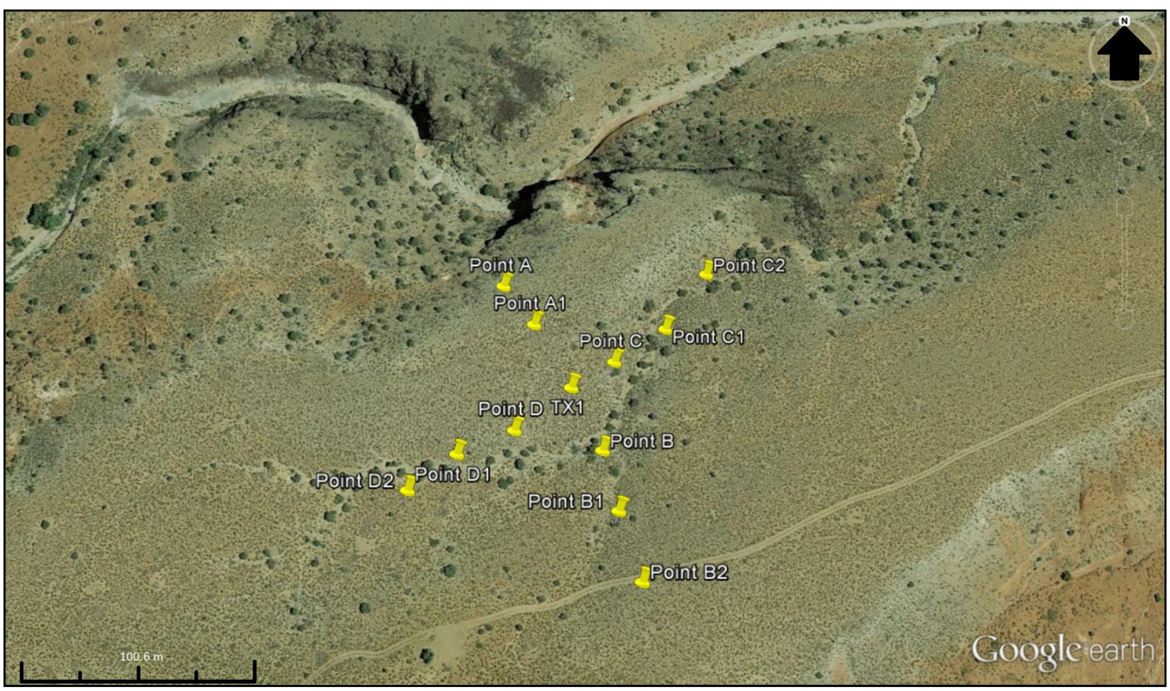

Figure 5: Second survey area for the tensor controlled-source experiment conducted by our team. This survey area is just south of the survey conducted in Figure 4.

Electromagnetic Theory

All electromagnetic methods use the concept of eddy-current induction. When a conductive body is exposed to a time-varying magnetic field (referred to as a primary field), it will generate an electric field described by Faraday's law. This electric field will cause electric currents to flow in the conductive body. This effect is described by Ohm's law. These new electric currents will produce a magnetic field of their own (referred to as a secondary field). The primary and secondary field can be recorded using a receiver coil, which allows for the analysis of subsurface electrical conductivity using remote methods.

The method utilized in this paper is described as time-domain electromagnetics (TDEM). This method depends on a source that generates an abruptly changing primary field and a receiver that measures the time rate of decay of the secondary 'transient' field. The unique transmitter generates a series of pulses or currents that vary with time. These currents induce eddy currents into the ground that decay when the transmitter is suddenly switched off. As the eddy currents decay, the secondary magnetic field also decays and is sampled by measuring the output voltage within the receiver-coil. Information regarding the subsurface conductors is given by the measurements of the secondary decaying magnetic field.

CHAPTER II

METHODS

Trachyte Mesa Surveys

The transmitter that was used for this study, further referred to as the PROTEM47, was manufactured by Geonics Ltd. In addition to the transmitter, the PROTEM receiver, also manufactured by Geonics Ltd., was used to recover information from the subsurface. The PROTEM system is most often used for shallow resistivity sounding of groundwater contamination, saline intrusions, and geologic units.

The PROTEM47 is a battery operated transmitter with a quick turn off time. Since the transmitter is able to output currents of 3 Amps into a 100m x 100m loop to give resolutions to depths of 150m, it will be possible to conduct a survey of the Trachyte Mesa Intrusion considering that the mesa is thought to be 40m thick at maximum (Wetmore et. al., 2009). The transmitter creates a current within the loop of wire that is connected to it. The eddy currents that are produced take the shape of the loop of wire connected to the PROTEM47 (i.e. a circular loop of wire will produce circular eddy currents). In the first survey conducted by Dr. Mark Everett, a 1 meter, 1-turn loop of wire was used as a transmitter loop. In the second survey that was conducted by our team, a 1 meter, 3-turn loop of wire that is threaded through PVC pipe was used as a transmitter loop. By adding more loops of wire, the electromagnetic signal would be amplified. This, in turn, would allow the effects of the transient field to be observed a higher resolution.

The original aim of this project was to verify the results of either Morgan or Wetmore; in order to do this, Dr. Everett conducted the electromagnetic survey approximately on the same profiles that Morgan and Wetmore took magnetic measurements.

As discussed earlier, the current that the PROTEM47 transmitter creates within the loop of wire will create a temporary electromagnetic field in the area. This electromagnetic field will then impose an induced transient electromagnetic field on the rocks in the area. Induced currents within rocks are not sustainable if a field is temporary. When the transmitter is turned off, the electromagnetic field that is produced decays exponentially. By measuring the time-derivative of this transient magnetic field as a function of position on the earth's surface, information can be derived about a survey target.

In order to actually record measurements of rate of decay of the induced magnetic field, the PROTEM receiver will be used. The unique thing about the PROTEM receiver that was used by Dr. Mark Everett is that it was able to measure the induced magnetic field along 3 axes.

The transmitter was set on the 'less than 5 turn' setting for this study. At the start of each stack of shots, the current was set to 3 amperes. Due to the current being unstable and dropping after being set at 3 amps, it was recorded after each shot. The transmitter was rotated on the X, Y, and Z axis. The trigger wire, which communicates current shut offs, was run from the transmitter to the receiver.

On the receiver side, there were 30 time gates recorded for every shot. The repetition rate was set to 30. The 3D receiver coil was able to record X, Y, and Z measurements simultaneously on every shot. These receiver and transmitter configurations gave a full tensor of data shown in Figure 6 (i.e. all variations of receiver-transmitter directions were recorded). A gain of 4 and turn-off time of 2 microseconds was used. The integration time was set to 120 seconds with a calibration time of 3 seconds. A series of calibration checks was conducted at the beginning of each day to ensure the equipment was working properly. As discussed previously, two lines were taken during Dr. Everett's Survey, Profile A and B from Wetmore (2009). These lines are shown in Figure 4. The line from point A to point B (Profile A) consisted of a 200 meters long line that was sampled every 20 meters. The transmitter was set at point TX1 (shown in Figure 4) for Profile A. The second line was measured N75°E of the first line and consists of the distance from point G to point E. The line was approximately 280 meters long and was sampled every 20 meters as well. This survey was conducted without the stacking of data.

$$\begin{pmatrix} xx & xy & xz \\ yx & yy & yz \\ zx & zy & zz \end{pmatrix}$$

Figure 6: Example of full tensor data from different receiver-transmitter configurations. The first letter represents the direction of the receiver and the second letter represents the direction of the transmitter.

When the data was downloaded and displayed, an unusually noisy signal was observed. For this reason, our research team went out on another trip to collect data at Trachyte Mesa, but now in another portion of the intrusion. This time, however, there was a strong emphasis on making sure the signal-to-noise ratio was maximized. The 3-D receiver coil was exchanged for a 1-D receiver coil to ensure that the coil was not the source of noise. The only difference between the coils is that instead of simultaneously measuring the 3 axis (X, Y, and Z), the 1-D coil must be rotated manually to measure different axes. Due to time constraints, this survey only measured the z-axis of the transmitter loop. It was found that the previous gain of 4 and a turn-off time of 2 microseconds was producing the same signal-to-noise ratio even with a different receiver coil, so a decision was made to try stacking the data to attenuate the coherent noise.

During an initial test of 10 shots, it was determined that the signal-to-noise ratio was no longer improving after a stack of 7 shots. Therefore, 7 shots were taken for each receiver axis at each station. In the second survey, two lines of data were recorded at Trachyte Mesa. One line was recorded at increments of 30 meters and was 180 meters long with the transmitter loop stationed in the center. The second line was 147 meters long due to half of the line butting up to a cliff which caused the maximum distance to be 57 meters long. The other portion of the line was recorded in increments of 30 meters all the way up to 90 meters. In total, this survey produced 231 shots of data which corresponds to 33 stacks of 7 shots. The two lines that were measured are displayed in Figure 5.

After the data was recorded, it was downloaded and an interpretation was attempted. Unfortunately, the data produced similar signals as the first survey, which raised a lot of suspicion regarding the quality of data that was being recorded by the instrument. These results motivated the idea to go out to Texas A&M's Riverside campus and conduct extensive testing on every component of the electromagnetic equipment.

Riverside Campus Testing

The unique thing about the Texas A&M Riverside campus is that there are certain portions that are isolated from metal, which can amplify electromagnetic waves. The work was performed in the geophysical testing sight at the entrance to the Riverside campus from Texas Highway 47. The results from the testing are shown below in the 'Results' section. For all tests, 30-time gate measurements were used.

The first component that was tested was the receiver gain and turn-off time settings. A 3-turn transmitter loop was used with a current of 3 amps in the z-direction for this test. The receiver was set 40 meters away from the transmitter. The receiver coil was set to record the Z-axis (a ZZ response was recorded with this transmitter-receiver combination). First, gains of 3, 4, and 5 were tested with a constant turn-off time of 2-microseconds. Second, the several turn-off time, gain, and separation combinations were tested.

The next component that was tested was the of number turns within the transmitter loop. The receiver was set 60 meters away from the transmitter in the z-direction. The gain was set at 4 and the turn-off time was set at 2-microseconds. Only the ZZ response was recorded for this study. Three types of loops were tested: 1-turn loop, 3-turn loop, and 8-turn loop.

At this point, results were analyzed and the quality of data could still not be determined. For this reason, an old analog receiver was taken out of storage in order to compare to our current digital receiver. This receiver was used in a previous study by a master of science program graduate of Dr. Everett in 1998, Khamla Sananikone. The results from Sananikone's tests had the signal-to-noise ratio that this study is trying to achieve (Sananikone, 1998). The tests regarding the number of turns within the transmitter loop were conducted again with the analog receiver using the same settings (gain of 4, turn-off time of 2-microseconds, and transmitter-receiver separation of 60 meters). Three types of loops were tested again: 1-turn loop, 3-turn loop, and 8-turn loop.

One of the final physical components of the electromagnetic system that had to be analyzed was the transmitter. A hypothesis arose regarding the quality of the transmitter turn-off curve. Ideally, the transmitter turn-off is similar to that of a box car function. The immediate turn-off as opposed to a slow decay allows for better sampling of the transient electromagnetic field. If the transmitter is malfunctioning and producing a slow decay of the current in the transmitter loop, it could cause the data to appear noisy. A transmitter that is known to work was borrowed in order to conduct a comparison with the Texas A&M transmitter. A transmitter-receiver separation of 50 meters was used along with a gain of 4 and a turn-off time of 2 microseconds.

The last thing that needed to be analyzed was the transmitter loop radius. Sananikone (1998) used a 5-meter radius transmitter loop. In both the first and second Trachyte Mesa trips, a 1-meter radius transmitter loop was used. 1-meter, 3-meter, and 5-meter radii loops were tested at the Riverside campus to analyze what would happen as loop radii increased.

CHAPTER III

RESULTS

3-Axes Receiver Coil vs. 1-Axis Receiver Coil

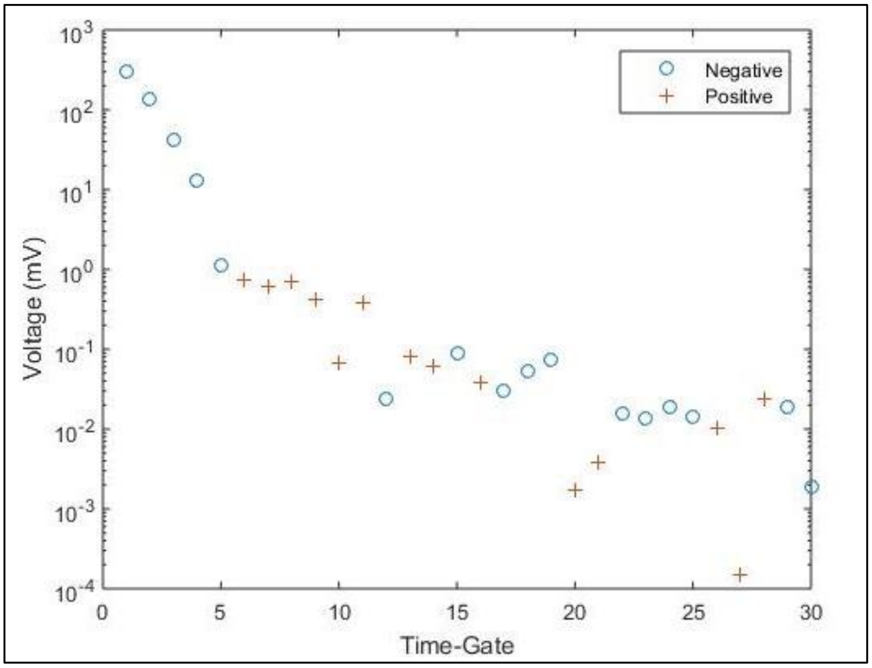

Figure 7: Plot of ZZ electromagnetic response of a 3-axes receiver coil with 60 meter separation. Results from Trachyte Mesa trip 1.

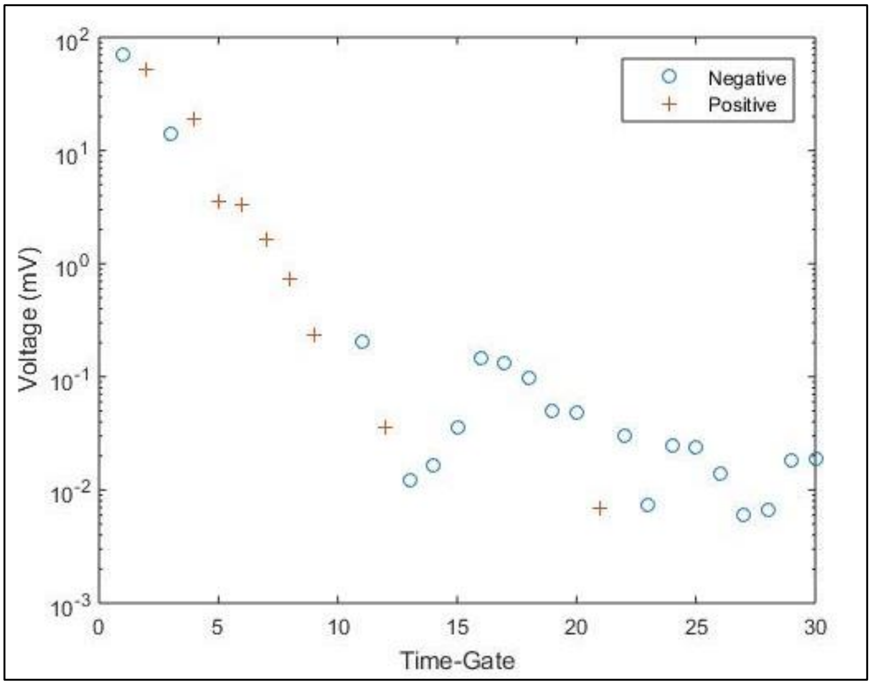

Figure 8: Plot of ZZ electromagnetic response of a 1-axis receiver coil with 60 meter separation. Results from Trachyte Mesa trip 2.

Gain and Turn-Off Time Settings

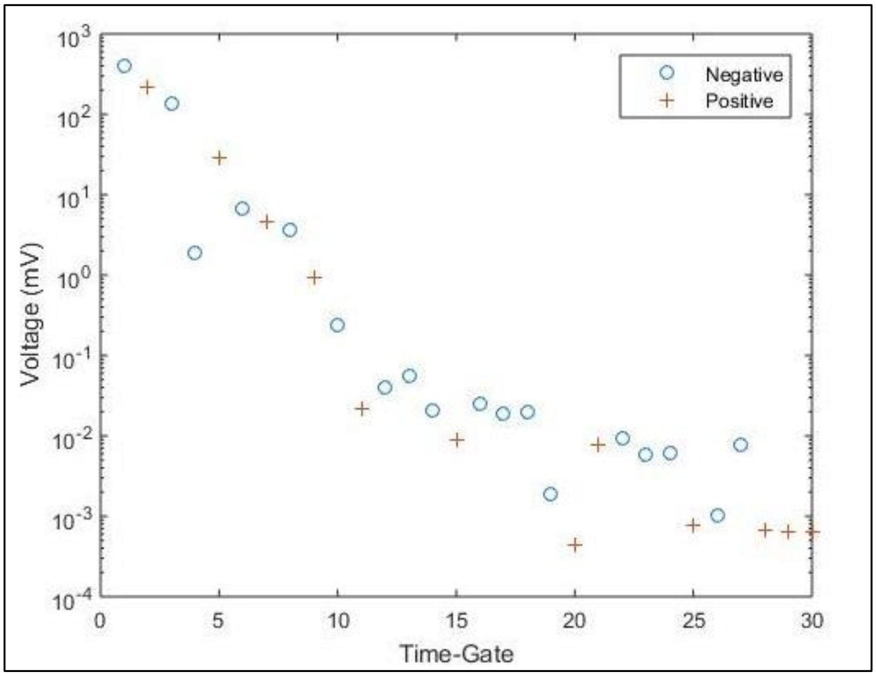

Figure 9: Plot of ZZ electromagnetic response of a 1-axis receiver coil with 40-meter separation, gain of 3, and turn-off time of 2 microseconds.

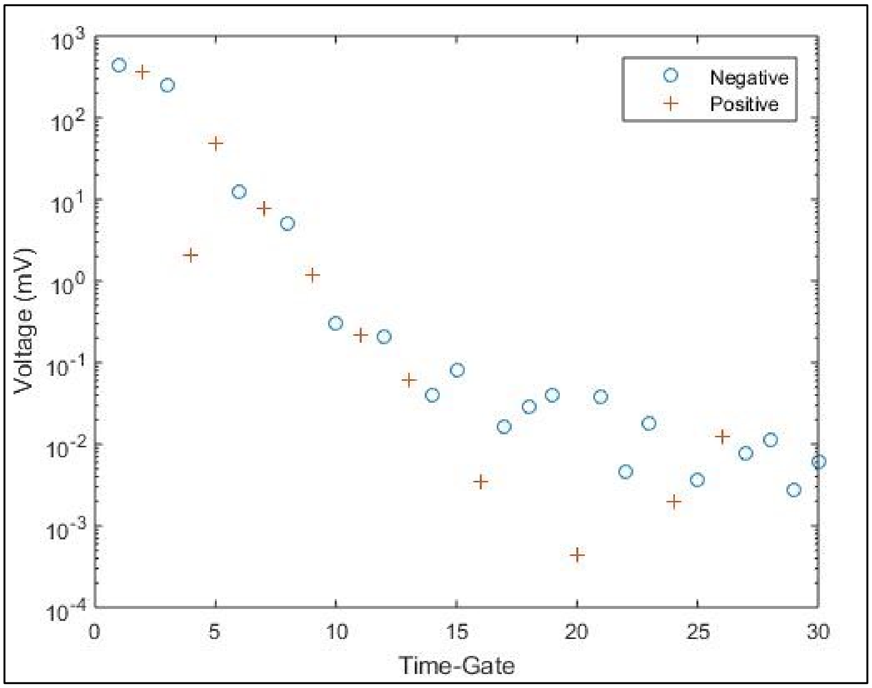

Figure 10: Plot of ZZ electromagnetic response of a 1-axis receiver coil with 40-meter separation, gain of 4, and turn-off time of 2 microseconds.

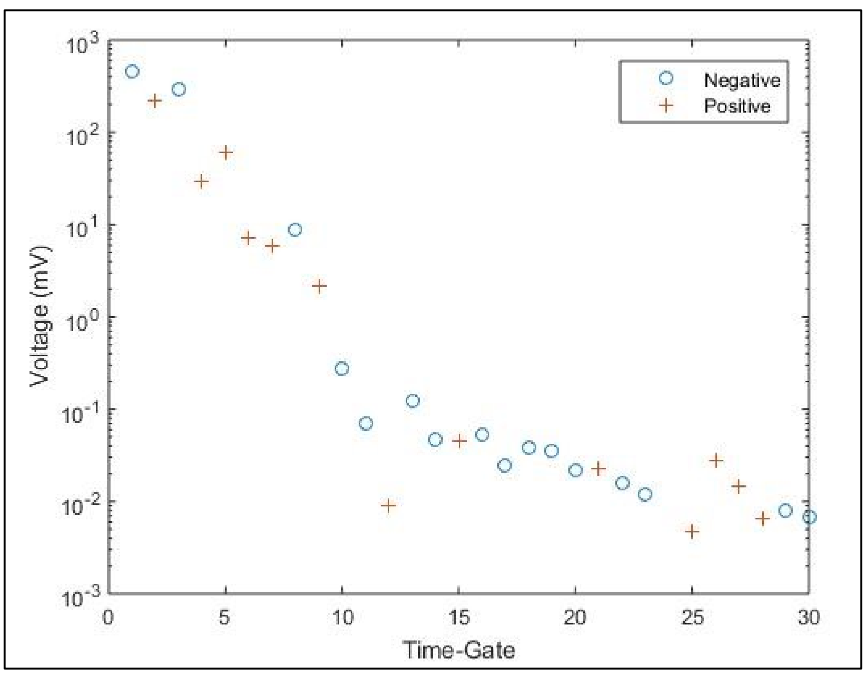

Figure 11: Plot of ZZ electromagnetic response of a 1-axis receiver coil with 40-meter separation, gain of 4, and turn-off time of 1.5 microseconds.

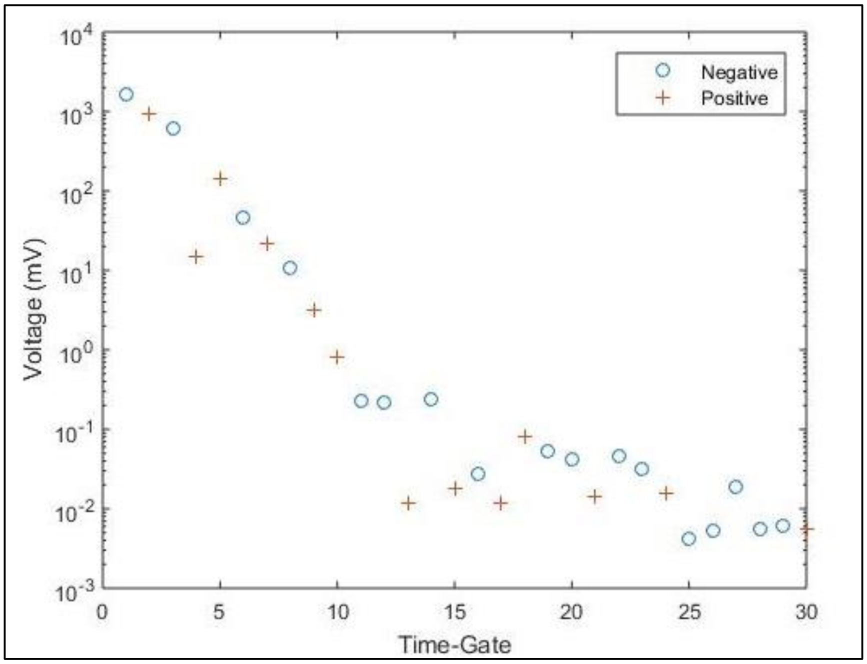

Figure 12: Plot of ZZ electromagnetic response of a 1-axis receiver coil with 40-meter separation, gain of 5, and turn-off time of 2 microseconds.

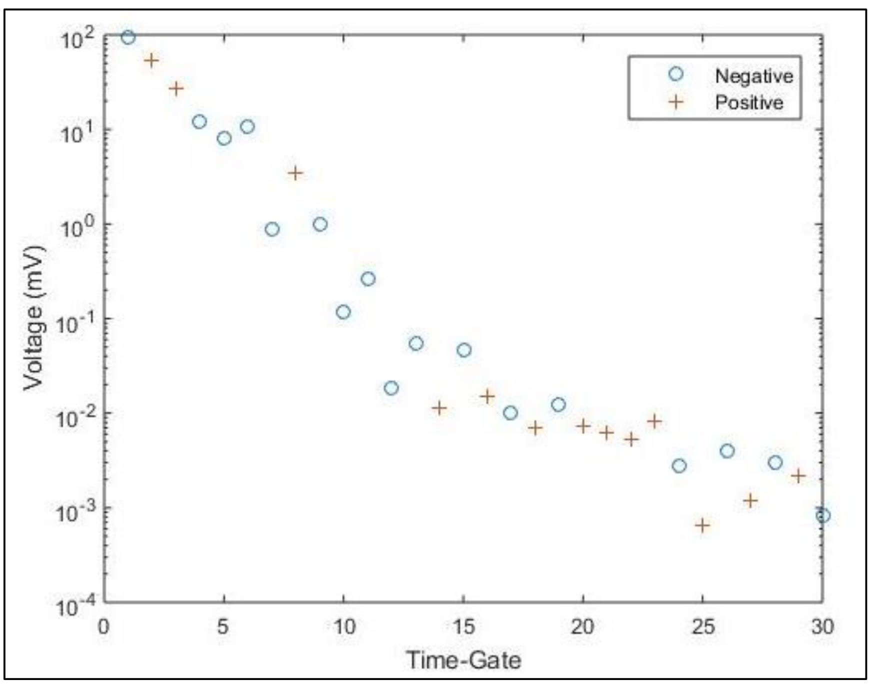

Figure 13: Plot of ZZ electromagnetic response of a 1-axis receiver coil with 20-meter separation, gain of 2, and turn-off time of 3 microseconds.

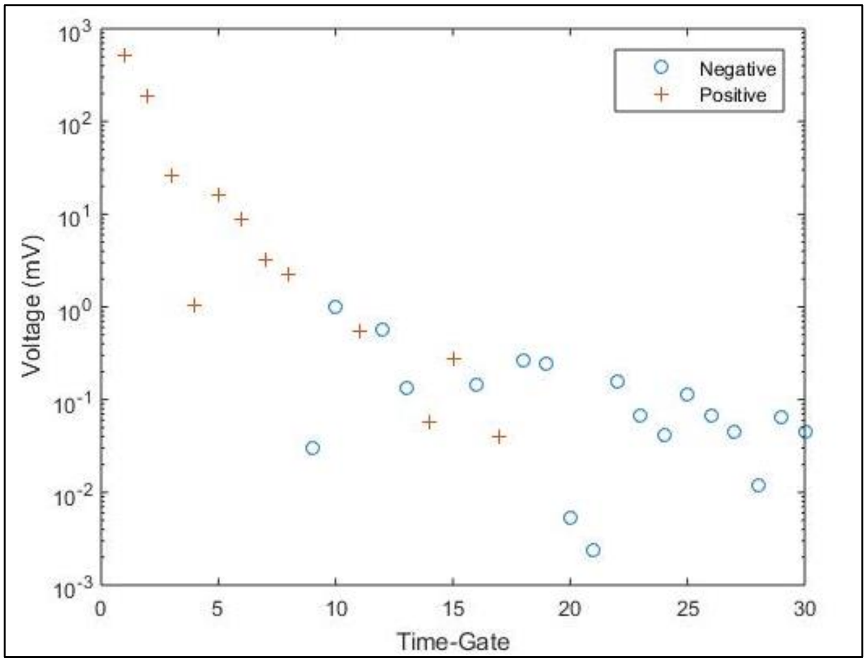

Figure 14: Plot of ZZ electromagnetic response of a 1-axis receiver coil with 100-meter separation, gain of 6, and turn-off time of 2.5 microseconds.

Type of Transmitter Loop (Digital Receiver)

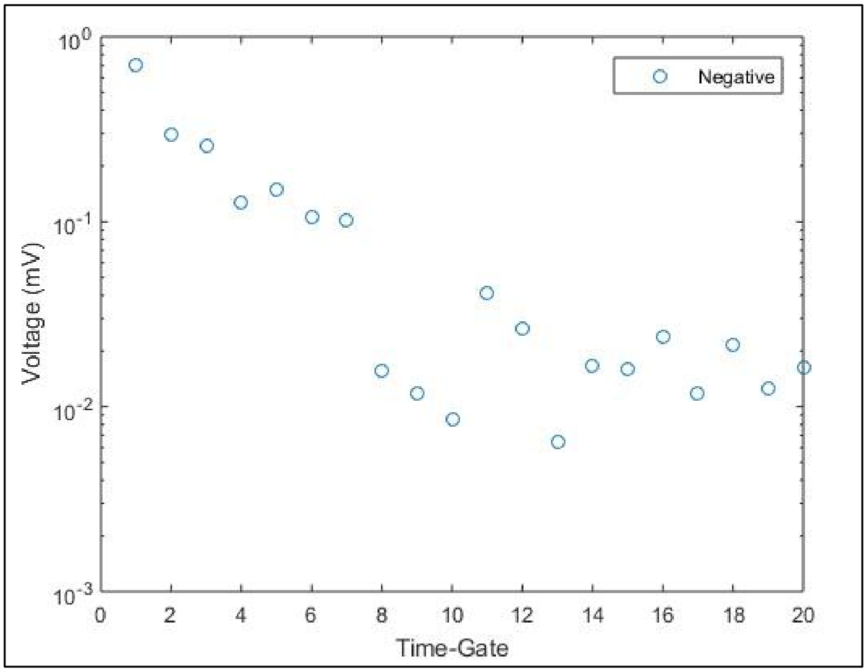

Figure 15: Plot of ZZ electromagnetic response of a 1-axis receiver coil and 1-turn transmitter loop with a separation of 60-meters. The gain was set to 4 and the turn-off time was set to 2 microseconds. This result was from a digital receiver.

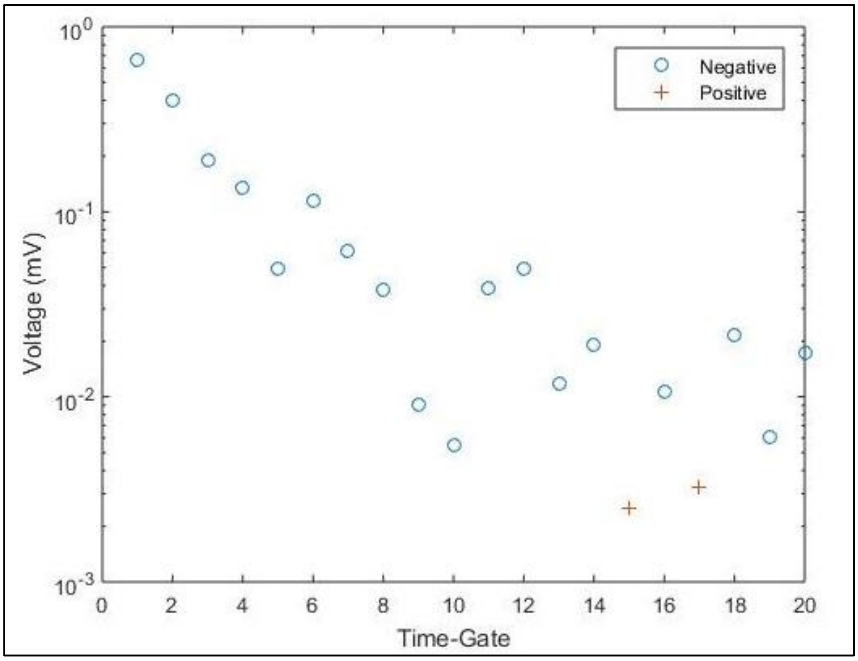

Figure 16: Plot of ZZ electromagnetic response of a 1-axis receiver coil and 3-turn transmitter loop with a separation of 60-meters. The gain was set to 4 and the turn-off time was set to 2 microseconds. This result was from a digital receiver.

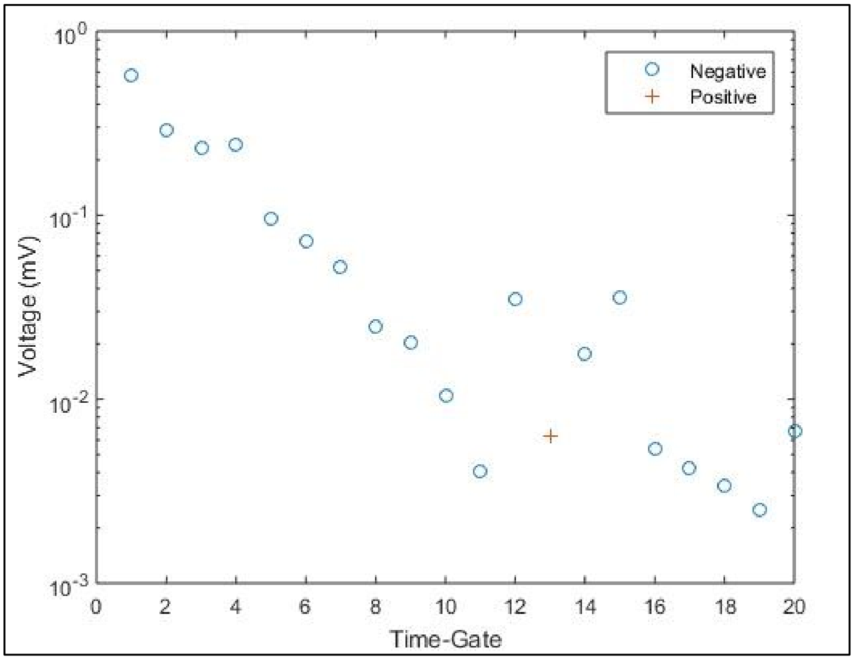

Figure 17: Plot of ZZ electromagnetic response of a 1-axis receiver coil and 3-turn transmitter loop with a separation of 60-meters. The gain was set to 4 and the turn-off time was set to 2 microseconds. This result was from a digital receiver.

Type of Transmitter Loop (Analog Receiver)

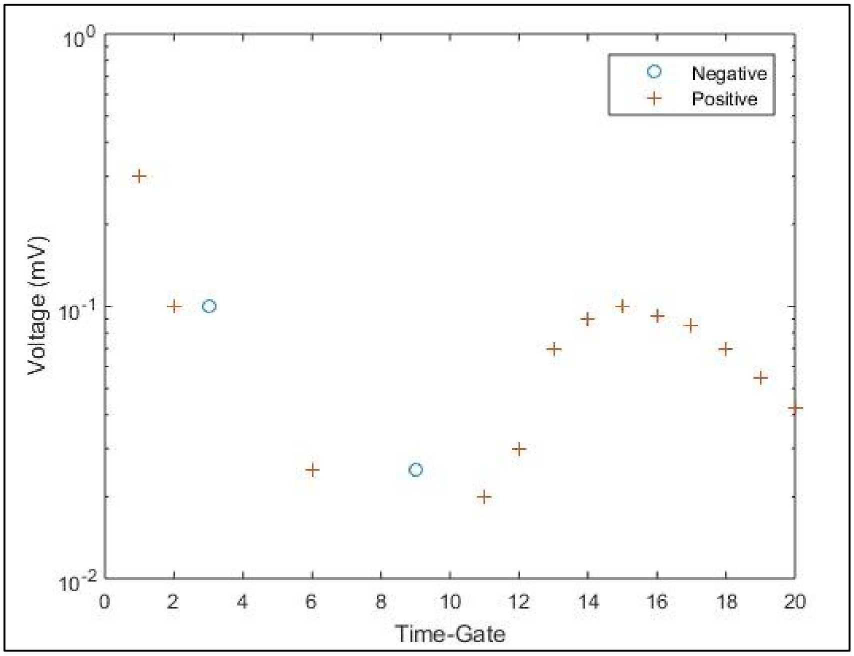

Figure 18: Plot of ZZ electromagnetic response of a 1-axis receiver coil and 1-turn transmitter loop with a separation of 60-meters. The gain was set to 4 and the turn-off time was set to 2 microseconds. This result was from an analog receiver.

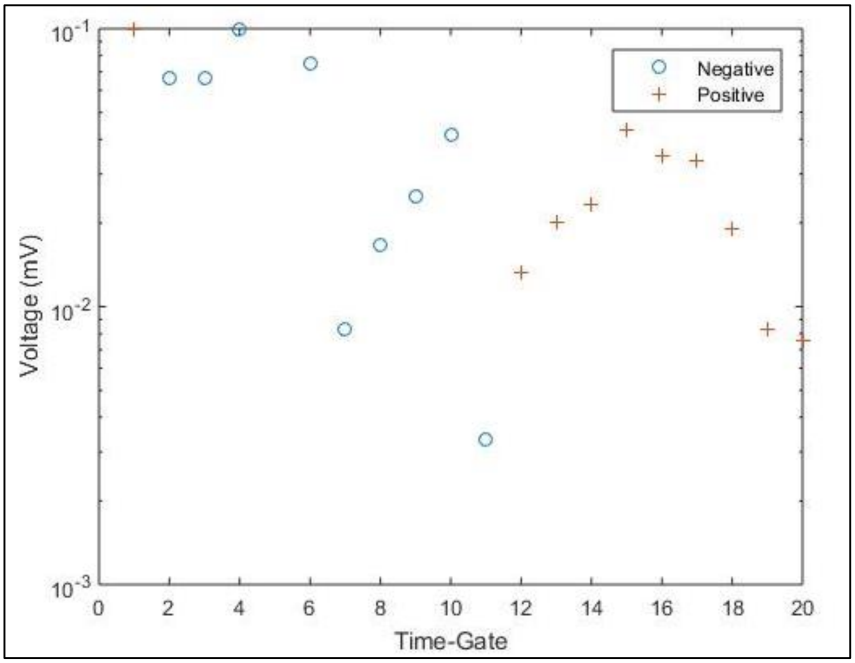

Figure 19: Plot of ZZ electromagnetic response of a 1-axis receiver coil and 3-turn transmitter loop with a separation of 60-meters. The gain was set to 4 and the turn-off time was set to 2 microseconds. This result was from an analog receiver.

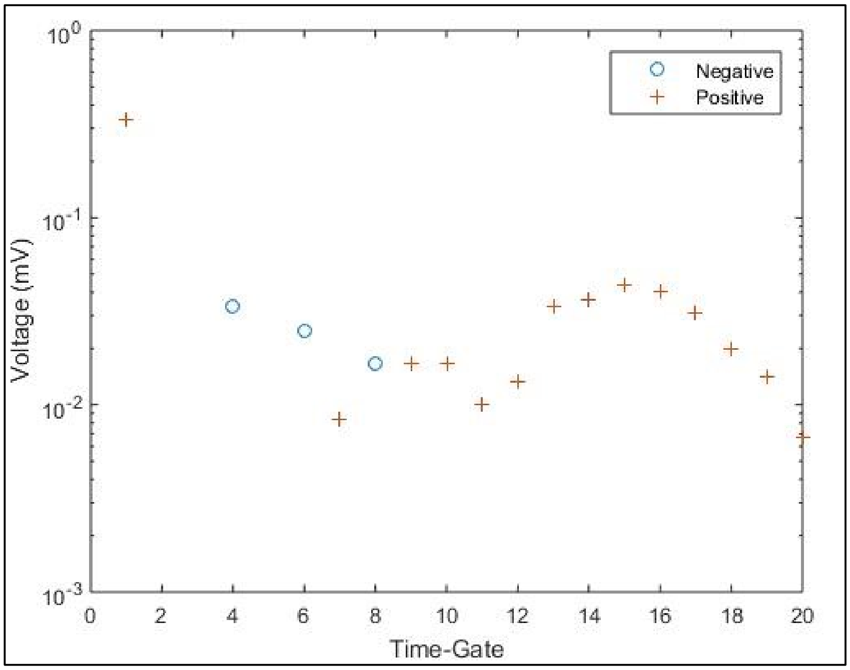

Figure 20: Plot of ZZ electromagnetic response of a 1-axis receiver coil and 8-turn transmitter loop with a separation of 60-meters. The gain was set to 4 and the turn-off time was set to 2 microseconds. This result was from an analog receiver.

Transmitter Turn-Off Curve Analysis

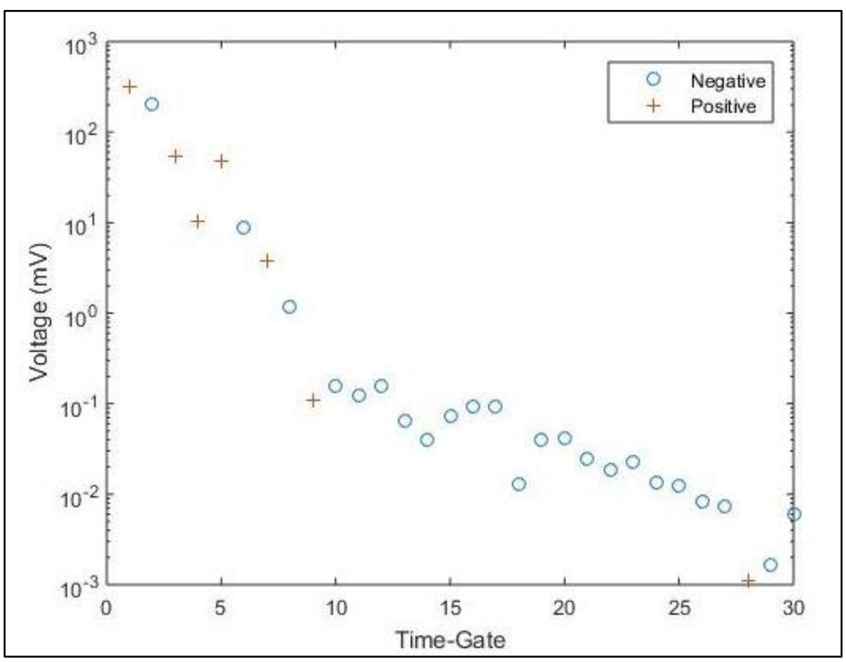

Figure 21: Receiver response using transmitter that was thought to have an issue with turn-off signal. The gain was set to 4 and the turn-off time to 2 microseconds.

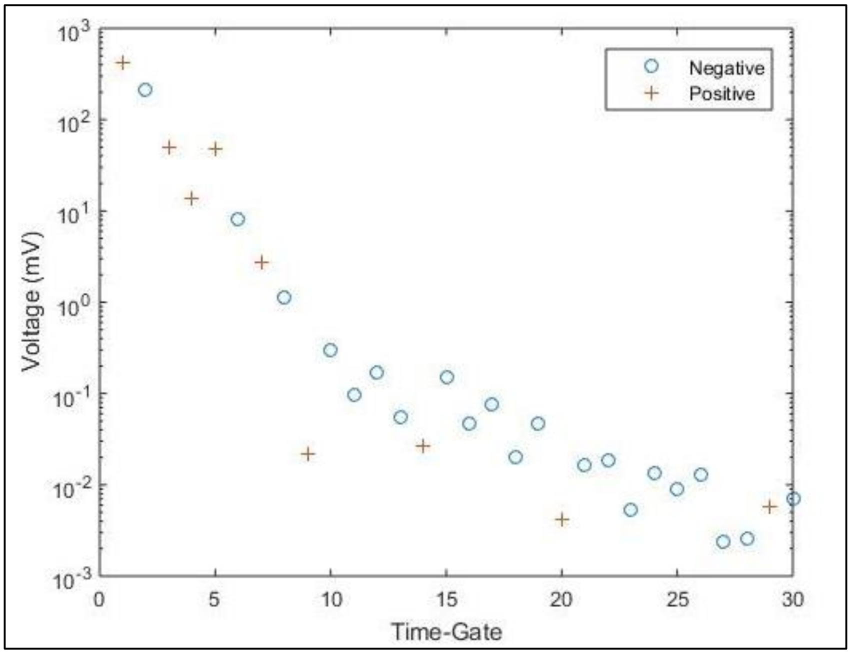

Figure 22: Receiver response using new rental transmitter. The gain was set to 4 and the turn-off time to 2 microseconds.

Transmitter Radius Analysis

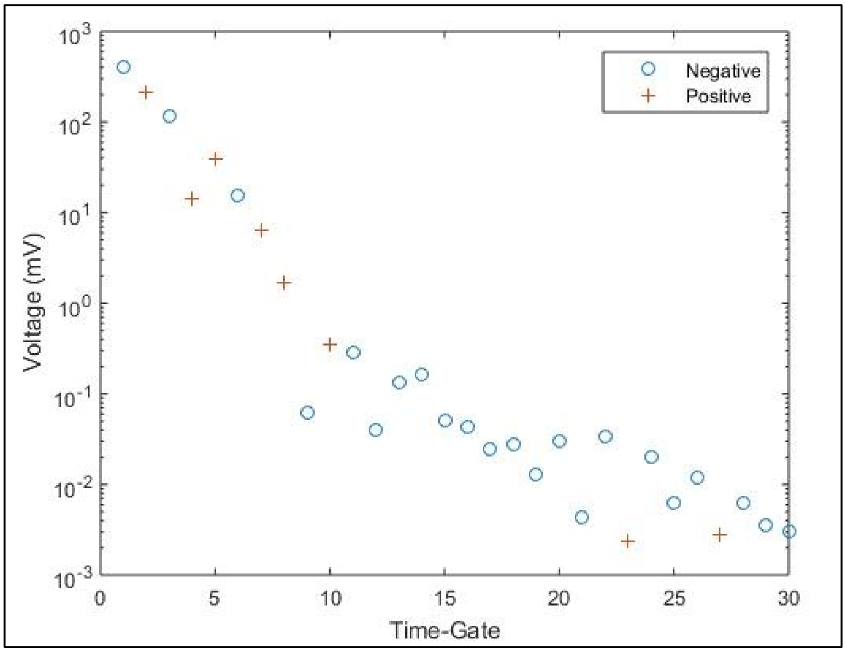

Figure 23: Plot of ZZ electromagnetic response of a 1-axis receiver coil using a 1-turn, 1-meter radius transmitter loop and transmitter-receiver separation of 30-meters. The gain was set to 4 and turn-off time to 2 microseconds.

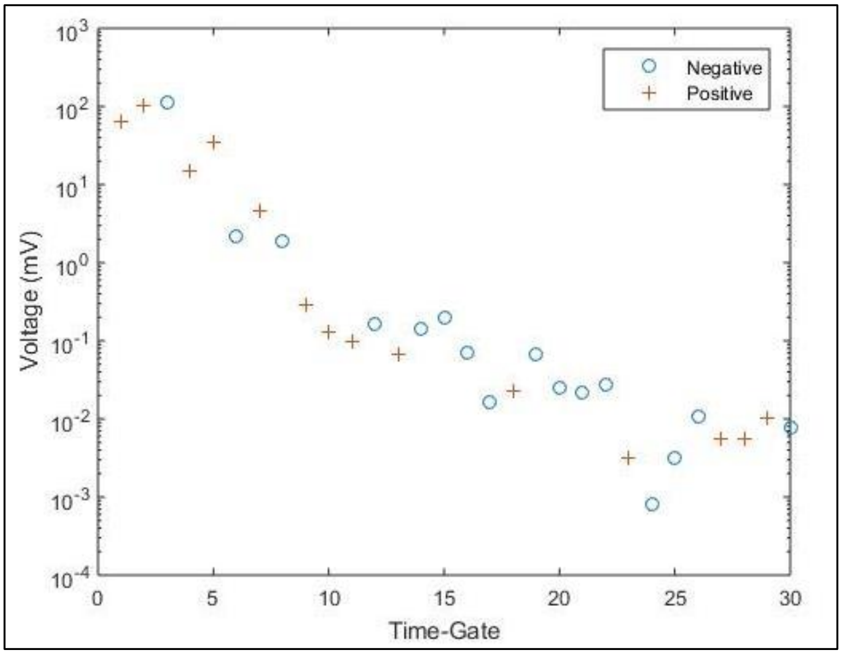

Figure 24: Plot of ZZ electromagnetic response of a 1-axis receiver coil using a 1-turn, 3-meter radius transmitter loop and transmitter-receiver separation of 30-meters. The gain was set to 4 and turn-off time to 2 microseconds.

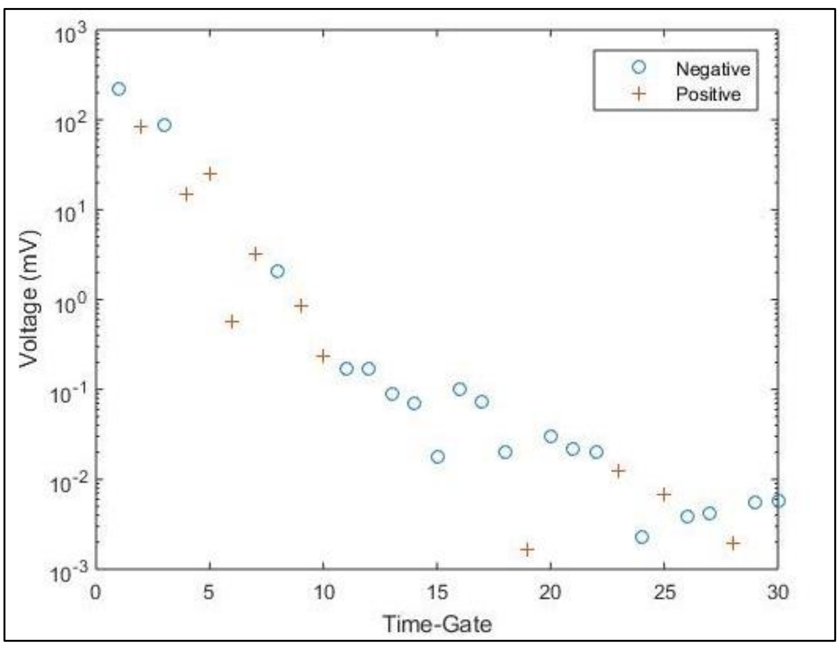

Figure 25: Plot of ZZ electromagnetic response of a 1-axis receiver coil using a 1-turn, 8-meter radius transmitter loop and transmitter-receiver separation of 30-meters. The gain was set to 4 and turn-off time to 2 microseconds.

CHAPTER IV

DISCUSSION & CONCLUSION

When comparing the 3-axes receiver coil to the 1-axis receiver coil, there was no significant difference in response. Although not in the exact same location, the receivers still produced results (Figure 7 and 8) that were similar enough to say that they were both working properly.

After the extensive tests at the Texas A&M Riverside campus, it was discovered that a gain of 4 appears to be the ideal setting for an electromagnetic survey response. It gave the smoothest decay curve (Figure 10) out of the three gain settings that were tested (gain of 3, 4, and 5). A transmitter turn-off time of 2 microseconds (Figure 10) was found to produce the best results. Other turn-off times (Figure 11) produced a noisy curve that is not able to be modelled.

When comparing different types of transmitter loops (i.e. 1-turn, 3-turn, or 8-turn), the differences in curve shape results were minimal. The magnitude of the voltage increased at later time gates as more loops were added. By choosing a 3-turn transmitter loop, a valuable amount of data may allowed to be collected without sacrificing too much battery within the transmitter. Also, the 8-turn loop was missing the ideal upward trend towards the later time gates that the 3-turn loop was showing.

Unlike the digital receiver, the analog receiver was not producing ideal responses to the lithology that was observed at the Riverside Campus. In an ordinary 1-D layered Earth model, the expected electromagnetic voltage response consists of a downward trend followed by a short upward trend concluding with a low-slope downward trend. Instead, the analog receiver was recording a more scattered, random response when using the same configuration as the digital receiver (Figure 19 vs. Figure 16).

The transmitter loop shut off curve was thought to be malfunctioning as this was one of the last things that was not tested. After measuring the response of a rental transmitter that was known to function properly and comparing it to the response of the transmitter that was used at Trachyte Mesa, it was found the hypothesis regarding the malfunction was false. The transmitters gave similar results using the same exact receiver system meaning that they were functioning properly.

The last thing that was analyzed was the transmitter loop radius. Sananikone had used a 5-meter, 1-turn radius loop. It was attempted to recreate Sananikone's study, but the responses with a 5-meter radius loop were not very clean. 1-meter and 3-meter radii loop responses were also analyzed. As the radius of the transmitter loop was increased, the magnitude of the voltage response was also increased. This is expected since the voltage response is proportional to the square of the transmitter loop radius. The signal-to-noise ratio, however, was not improved by increasing the transmitter loop radius.

The original aim of the project was to produce a model and interpret the data that was collected by Dr. Everett. Due to a hypothesis that the data was too noisy to model, another survey was conducted slightly south of the original site with a 1-axis receiver coil as opposed to the original 3-axes receiver coil that was used by Dr. Everett. Very similar responses were observed. This gave rise to the opinion that the electromagnetic equipment that was being used might have been malfunctioning. To settle this, extensive tests on all the components were conducted at the Texas A&M Riverside Campus. After compiling the data and comparing it component by component, a conclusion was made that the equipment was in fact functioning properly. With this conclusion, the hypothesis that must be proven is that the unusual electromagnetic response observed at Trachyte Mesa is due to the highly resistive environment of the area.

The next logical flow of work in this project is to model and interpret the Trachyte Mesa intrusion. The structure of the Trachyte Mesa intrusion can be determined through a forward modeling study of the data that was collected throughout this project. Dr. Everett has developed a program which allows for forward modeling of a vertical magnetic field for a horizontal loop over a multi-layered Earth using modified electromagnetic expressions from Jisoo Ryu et. al. (1970). There also exists code that will allow for a 3-dimensional model and inversion of the data. The response of several Earth structures (i.e. undulating resistive body and flat resistive body) can be investigated using the forward code.

REFERENCES

Hunt, C. B., et. al. (1953). Geology and geography of the Henry Mountains region, Utah, *Geological Survey Professional Paper*, 228, pg. 1-230. Web.

Morgan, S., et. al. (2008). Emplacement of multiple magma sheets and wall rock deformation: Trachyte Mesa intrusion, Henry Mountains, Utah. *Journal of Structural Geology*, doi: 10.1016, pg. 491-512. Web.

Ryu, J., Morrison, H. F., and Ward, S.H., (1970). Electromagnetic fields about a loop source of current: *Geophysics*, 35, pg. 862-896. Web.

Sananikone, K. (1998). Subsurface characterization using time-domain electromagnetics at the Texas A&M University Brazos River Hydrological Field Site, Burleson County, Texas (Masters Thesis, Office of Graduate Studies of Texas A&M University in partial fulfillment of the requirements for the degree of Master of Science in Geophysics, Texas A&M University).

Sullivan, K.R., Kowallis, B.J., and Mehnert, H.H., (1991). Isotopic ages of igneous intrusions in southeastern Utah: evidence for a mid-Cenozoic Reno–San Juan magmatic zone: *Brigham Young University Geology Studies*, v. 37, p. 139–144. Web.

Wetmore, P. H., et. al. (2009). Geometry of the Trachyte Mesa intrusion, Henry Mountains, Utah: Implications for the emplacement of small melt volumes into the upper crust. *G^3: An Electronic Journal of the Earth Sciences*, vol. 10.8, pg. 1-13. Web.