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Geophysical Survey of the Eubank Landfill, Albuquerque, New Mexico

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1.0 INTRODUCTION

1.1 PROJECT DESCRIPTION

In August 2016, hydroGEOPHYSICS, Inc (HGI) performed a multi-method geophysical survey at a closed landfill in Albuquerque, New Mexico. This survey effort was completed to determine the lateral extents and thickness of buried waste and the depth of cover material over the waste at the location of the former Eubank Landfill. A combined electromagnetic (EM) and magnetic (Mag) survey over the entire accessible landfill area, as well as three lines of 2D Electrical Resistivity Tomography (ERT) were completed. This report documents results from data acquired at the Eubank Landfill - one of up to four landfill sites to be surveyed using these combined geophysical methods.

1.2 SCOPE

The scope of this project includes using EM, Mag, and ERT to characterize the subsurface at the survey site. The ground conductivity portion of the EM measurement provides a good indication of the lateral limits of covered or closed landfill, presented in a georeferenced two-dimensional (2D) plan view of the electrical properties of the subsurface. The magnetic measurements are highly sensitive to ferrous metals in the landfill, providing a high-resolution plan view map of the distribution of ferrous metallic wastes within the landfills. The electrical resistivity imaging method results in 2D cross sections of the electrical properties of the subsurface materials, allowing the depth, thickness, and lateral limits of the conductive wastes to be estimated, together with an estimate of the thickness of the cover material.

1.3 OBJECTIVE

The objective of this multi-method geophysical survey was to non-invasively determine the extent and thickness of buried waste and the depth of cover material over the waste by mapping the electrical properties of the subsurface. This is based on the theory that generally, the products of the decomposition of municipal solid waste are conductive, and as these mix with precipitation and/or groundwater flow, the resulting bulk electrical properties of the wastes are likely to be highly conductive compared to typical background bedrock geological materials. The landfill is also expected to contain metallic debris which when imaged using magnetic gradiometry should display contrast to undisturbed materials outside the landfill boundaries.

2.0 BACKGROUND

2.1 SITE LOCATION

The Eubank landfill is located in the city of Albuquerque, New Mexico, USA. Figure 1 shows the general location of the geophysical survey site.

The Eubank Landfill is located at the south end of Eubank Boulevard, northwest of Tijeras Arroyo and east of Kirtland Air Force Base. The landfill operated during the years 1963-1984, with a total estimated waste tonnage of 2 million tons. Since 1984 Eubank landfill has been open acreage. There are three landfill gas wells within the landfill, 27 perimeter wells, and four perimeter groundwater monitoring wells. The landfill has native soil, assorted fill, and natural vegetation as cover.

There are no available historical references for boundary and construction geometry for the Eubank Landfill and cover; however, tribal knowledge of the site estimates an average cover thickness of 4.6 feet, and average waste depth of 30 feet. These values may vary across the site. The total area covered by the Eubank landfill is approximately 81 acres.

Figure 1. General Survey Location

Aerial imagery © Google Earth 2016

3.0 METHODOLOGY

3.1 SURVEY AREA AND LOGISTICS

High resolution EM and Mag data were acquired between 8/18/16 and 8/26/16 using the HGI Geophysical Operations (G.O.) Cart (Section 3.2.1). Data were recorded continuously along survey lines to produce the coverage shown in Figure 2. The total area covered was approximately 112 acres. The survey area was mostly flat with isolated areas with more topography. Vegetation was present throughout the site but for the most part did not hinder the survey and could be driven over with the G.O. Cart and ATV. There were areas that could not be surveyed due to high density of debris.

Resistivity Data consisted of three lines of data approximately 817 feet long each, totaling approximately 2,450 feet total line coverage. The locations of the lines (Line 1, Line 2, and Line 3) are shown in Figure 2 (pink lines). Table 1 lists specific parameters for the resistivity survey lines.

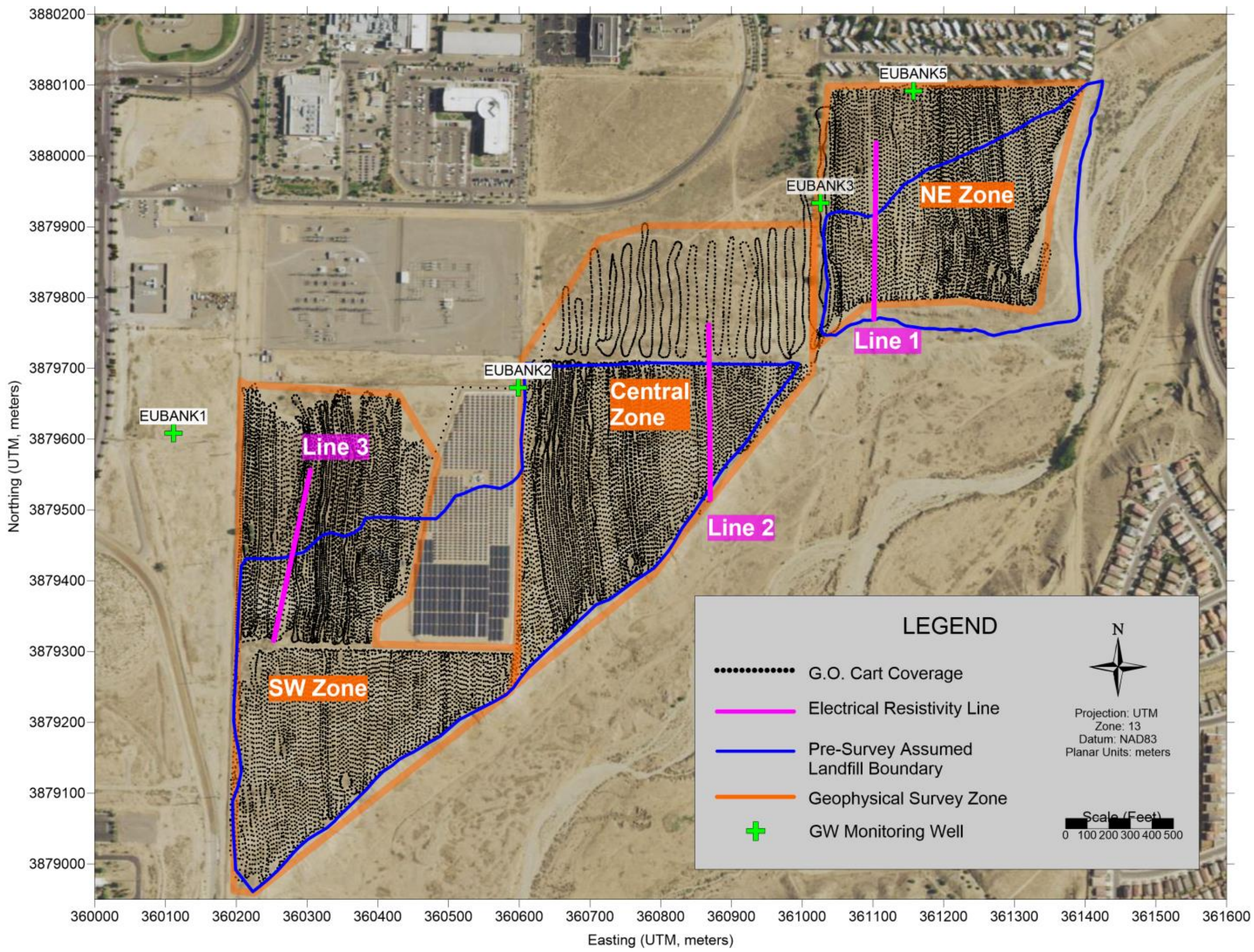
Prior to commencement of the geophysical survey, a general assumption existed on the location of the boundary of the landfill. This information is posted on Figure 2 as a blue boundary line, with extents as provided by the City of Albuquerque.

The Eubank landfill is divided into three general zones for the discussion of geophysical results: NE Zone, Central Zone, and SW Zone. These general zones are labeled on Figure 2 (orange outlines).

Table 1. Resistivity Line Parameters

Line #	Date of Acquisition	Electrode Spacing (feet)	Length (feet)	Line Orientation	Start Position (Easting, Northing) UTM - meters	End Position (Easting, Northing) UTM - meters
1	8/28/16	10	817	S-N	361103,3879770	361103,3880019
2	8/28/16	10	817	S-N	360870,3879515	360870,3879764
3	8/28/16	10	817	S-N	360252,3879316	360306,3879559

Figure 2. Detailed Survey Coverage Map



3.2 EQUIPMENT

3.2.1 G.O. Cart

hydroGEOPHYSICS, Inc. (HGI) Geophysical Operations Cart or G.O. Cart is a custom designed and fabricated non-magnetic, non-metallic, all-terrain vehicle towed, platform that can house a variety of geophysical sensors that are synchronized via a Global Positioning System (GPS) and a heads-up navigation system. The G.O. Cart is equipped with both electromagnetic and magnetic sensors as shown in Figure 3. To acquire data for the magnetic and electromagnetic surveys, the G.O. Cart was towed behind an All-Terrain Vehicle (ATV). The G.O. Cart is constructed of fiberglass, nylon, and plastic materials so that no metallic noise or interference occurs with the geophysical equipment. An extended tongue of 15 feet is used to separate the ATV from the G.O. Cart in order to reduce metallic interference caused by the ATV. The G.O. Cart was equipped with two cesium-vapor magnetic sensors spaced one meter apart in a vertical orientation, a broadband electromagnetic conductivity meter, a differential GPS for geo-referencing of geophysical data, and a heads-up GPS display for navigation along the survey lines. All data were stored within a data logger unique to each instrument. The data loggers also allowed parameter control of each instrument during data acquisition.

Figure 3. Geophysical Operations (G.O.) Cart.

3.2.1.1 Magnetic Gradiometry

A G-858G dual-sensor gradiometer (Geometrics, Inc., San Jose, CA) was used to provide magnetic data for the project. The instrument is commercially available and was designed to provide detection of subsurface ferrous metals by mapping distortions to the measured localized magnetic field. The gradiometer is easily adapted for use on the non-magnetic G.O Cart. Dual-sensor magnetometers are called gradiometers and measure gradient of the magnetic field; single-sensor magnetometers measure total field. The use of the two sensors on the gradiometer allows for nulling of the earth's magnetic field making the system highly sensitive to subsurface ferrous metals. The gradient measurement, in this case a vertical gradient, is the resulting difference between the top sensor and bottom sensor measurements.

The separation between the two sensors and the data acquisition and storage console is increased using standard extension cables to cover the span between the cart and the ATV or operator. The gradiometer console contains a serial input and necessary firmware that is used to interface with and store GPS data. Interchangeable low voltage 12V dc gel cell batteries are used to power the gradiometer console that is located on the ATV just behind the operator.

A daily inspection is completed by the qualified operator to ensure all components are in satisfactory working condition. Quality assurance tests including a visual inspection, a function test, a static response test, a vibration test, and a dynamic response test were performed daily.

3.2.1.2 Electromagnetic Induction

The GEM-2® electromagnetic instrument (Geophex Ltd, Raleigh, NC) was used to provide electromagnetic data. The electromagnetic system is used to detect variations in subsurface soil moisture, soil conductivity, and the presence of subsurface infrastructure (utilities, pipes, tanks, etc.). The GEM-2 consists of a sensor housing (the "ski"), and the electronics console. The console includes the data acquisition, rechargeable battery, and data storage hardware. Accessories include a battery charger, carrying straps, a download cable, a brief field guide, and manual. The console contains one DB9 serial connector for downloading data to a PC using the manufacturer-supplied WinGEM software, and another DB9 serial connector that accepts and records a GPS data stream. The GPS time and location are appended to each electromagnetic data point. The instrument is commercially available and is widely used within the geophysical arena.

The instrument was easily adapted for use on the non-magnetic G.O Cart. The instrument, which contains a data acquisition console and an antenna ski, is lightweight and could be mounted as a single unit on the back of the G.O. Cart. The large battery and memory capacity provided increased field time.

A daily inspection is completed by the qualified operator to ensure all components are in satisfactory working condition. Quality assurance tests including a visual inspection, a function test, a static response test, a vibration test, and a dynamic response test were performed daily.

3.2.1.3 G.O. Cart GPS

The Novatel Smart V1 GPS is used on the G.O. Cart for acquiring Global Positioning System (GPS) data which are used to geo-reference (spatially locate) specific data points for the G.O. Cart data. The exact location of the individual data points is important in order to correlate the physical location of any interpreted anomalies that might need further investigation. The GPS equipment used to interface with the G.O. Cart instruments provides a lateral accuracy of less than 3.3 feet (1.0 meter) and a vertical accuracy less than approximately 6.6 feet (2.0 meters). The geophysical instruments both require a real time GPS data stream that is stored directly within the respective geophysical instruments. This process allows a common spatial reference for multiple geophysical data sets. The G.O. Cart includes a GEM-2 electromagnetic instrument and a G-858G dual-sensor gradiometer instrument. Both instruments are capable of interfacing with a GPS instrument that provides an NMEA-compatible data stream. The G.O Cart travels at

® GEM-2 is a registered trademark of Geophex, Ltd.

approximately 3 to 4 miles per hour, which requires a GPS sampling and output rate of 1 Hz (1 second). The line spacing varied between 7 and 10 feet and was influenced by site conditions at the time of the survey such as vegetation, extreme topography or debris fields. Elevation data are not currently used for processing electromagnetics or magnetics data; therefore, no accuracy requirements exist. The magnetic instrument is sensitive to ferrous and/or magnetic material. Therefore, a GPS that has the smallest magnetic footprint is advantageous as it reduces environment noise. Geometrics, Inc., the manufacturer of the selected gradiometer, performed rigorous testing with the Novatel Smart V1 GPS. The system provides the smallest magnetic footprint as tested by Geometrics. The Smart V1 GPS provides the necessary accuracy without any post processing or the need for a base-station GPS. A GPS positional check is completed at the beginning of each day to ensure the GPS unit has no or minimal drift of data and is within 5 feet of the original calibration.

3.2.2 Resistivity

Data were collected using a Supersting™ R8 multichannel electrical resistivity system (Advanced Geosciences, Inc. (AGI), Austin, TX) and associated cables, electrodes, and battery power supply. The Supersting™ R8 meter is commonly used in surface geophysical projects and has proven itself to be reliable for long-term, continuous acquisition. The stainless steel electrodes were laid out along lines with a constant electrode spacing of approximately 10 feet (3 meters). Multi-electrode systems allow for automatic switching through preprogrammed combinations of four electrode measurements.

3.2.2.1 Handheld GPS

Positional data for the resistivity lines were acquired via a handheld Garmin GPS unit. Minimal topography existed at the site and elevation data were not necessary for the 2D resistivity inversion modeling.

3.3 DATA CONTROL AND PROCESSING

3.3.1 Quality Control

All data were given a preliminary assessment for quality control (QC) in the field to assure quality of data before progressing the survey. Following onsite QC, all data were transferred to the HGI server for storage and detailed data processing and analysis. Each line or sequence of acquisition was recorded with a separate file name. Data quality was inspected and data files were saved to designated folders on the server. Raw data files were retained in an unaltered format as data editing and processing was initiated. Daily notes on survey configuration, location, equipment used, environmental conditions, proximal infrastructure or other obstacles, and any other useful information were recorded during data acquisition and were saved to the

HGI Tucson server. The server was backed up nightly and backup tapes were stored at an offsite location on a weekly and monthly basis.

3.3.2 G.O Cart Data Processing

Appropriately sized grids were established within the area of concern in accordance with maps of the area. At the end of each day, data were downloaded and processed to a preliminary level in order to assure data quality.

3.3.2.1 Magnetic Gradiometry

Time, date, and magnetic data were stored within a data logger and downloaded to a laptop PC for processing. Magnetic data were processed using MAGMAPPER software. The raw data are downloaded to a computer and then the GPS data are integrated with the magnetic data to provide sub-meter accuracy. There are several options that are employed to remove any spikes in the data set from anomalous data points. Data are reviewed on a daily basis with emphasis on making sure the data quality is good. As the survey progressed, each new day was added into the existing data base to ensure coherency among the whole dataset. There are typical offsets from one day to the next and to ensure that the whole dataset was on the same datum we collected calibration lines at several times during the day; in the morning, and at about every 3 hours when there was a battery change. Each dataset collected was corrected to the first day's calibration line using a calculated correction factor.

3.3.2.2 Electromagnetic Induction

Multiple frequencies were acquired for the electromagnetic data and each were processed and analyzed. Both in-phase and quadrature data were acquired at 3 frequencies ranging from 5 kHz to 20 kHz. These electromagnetic data were processed using the WinGEM Software as provided by the manufacturer. The quadrature data were selected for final processing and presentation as this part of the EM dataset is more sensitive to soil conductivity (electrical properties) changes relative to the in-phase component of the data. For the purposes of this survey, all frequencies were reviewed and there was virtually no difference in the interpretation of the datasets, so only the 18.5 kHz data are presented. A similar process to the mag dataset is used to integrate the GPS and correct each dataset against the calibration line.

3.3.2.3 EM & Mag Plotting

The EM and Mag data were gridded and color contoured in Surfer (Golden Software, Inc.). The combined EM and Mag datasets, after being compensated for the calibration set, were combined into one master file with approximately 1 million data points in each file. The minimum curvature gridding algorithm was used within the Surfer software at 3-foot spacing. This algorithm is good for large datasets and honors the actual raw data very well without adding in artificial character to the datasets.

3.3.3 Resistivity Data Processing

The geophysical data for the resistivity survey, including measured voltage, current, measurement (repeat) error, and electrode position, were recorded digitally with the AGI SuperSting R8 resistivity meter. Quality control both in-field and in-office was performed throughout the survey to ensure acceptable data quality. Data were assessed and data removal was performed based on quality standards and degree of noise/other erroneous data. Edited data were inverted and the results plotted for final presentation and analysis.

The raw data were evaluated for measurement noise. Those data that appeared to be extremely noisy and fell outside the normal range of accepted conditions were manually removed within an initial Excel spreadsheet analysis. Examples of conditions that would cause data to be removed include, negative or very low voltages, high-calculated apparent resistivity, extremely low current, and high repeat measurement error. Secondary data removal occurred for some of the lines via the RMS error filter built in to the RES2DINVx64 software. RMS error filter runs were performed removing no greater than 5% of the data, and were initiated to bring the final RMS value down to 5% or below based on model convergence standards (see section 3.3.3.1 for more details).

3.3.3.1 2D Resistivity Inversion

RES2DINVx64 software (Geotomo, Inc.) was used for inverting individual lines in two dimensions. RES2DINV is a commercial resistivity inversion software package available to the public from www.geoelectrical.com. An input file was created from the initial edited resistivity data and inversion parameters were chosen to maximize the likelihood of convergence. It is important to note that up to this point, no resistivity data values had been manipulated or changed, such as smoothing routines or box filters. Noisy data had only been removed from the general population.

The inversion process followed a set of stages that utilized consistent inversion parameters to maintain consistency between each model. Inversion parameter choices included the starting model, the inversion routine (robust or smooth), the constraint defining the value of smoothing and various routine halting criteria that automatically determined when an inversion was complete. Convergence of the inversion was judged whether the model achieved an RMS of less than 5% within three to five iterations.

Additional data editing was performed for some of the lines using the RMS error filter with RES2DINVx64. This option provides a secondary means of removing bad data points from the data set; the RES2D program displays the distribution of the percentage difference between the logarithms of the observed and calculated apparent resistivity values in the form of a bar chart. It is expected the "bad" data points will have relatively large "errors", for example above 100 percent. Points with large errors can be removed and a new input file is created omitting these points based on the cut-off error limit selected. The data are then re-run through the inversion routine, and named with the naming convention (_i, _ii) to denote the filter trial number.

3.3.3.2 2D Resistivity Plotting

The inverted data were output from RES2DINV into a .XYZ data file and were gridded and color contoured in Surfer (Golden Software, Inc.). Where relevant, intersecting features were plotted on the resistivity section to assist in data analysis. Qualified in-house inversion experts subjected each profile to a final review.

4.0 RESULTS

4.1 GENERAL DISCUSSION

The analysis of the EM & Mag results is based on the anticipated contrast in electrical properties between the conductive (low resistivity) landfill materials and the more resistive natural background materials. Generally, the products of the decomposition of waste are conductive, and as these mix with precipitation and/or groundwater flow, the resulting bulk electrical properties of the wastes are likely to be highly conductive compared to typical natural background materials. Metal waste within the landfill will also be electrically conductive. The electromagnetic and magnetic survey methods via the G.O. Cart result in high-resolution 2D plan view maps of the electrical properties of the subsurface materials, allowing the lateral limits of the landfill to be estimated.

The magnetic measurements are highly sensitive to ferrous metals in the landfill. This can provide a high-resolution map of the distribution of ferrous metallic wastes within the landfills, for example 55-gallon steel drums that can often contain hazardous wastes. The electromagnetic measurements would be expected to be more susceptible to moisture content, with the moisture in contact with waste materials of the landfill expected to be of increased conductivity.

Figure 4 shows the results of the Mag survey for the whole survey site, as magnetic field vertical gradient, measured in nanoteslas (nT). Red and purple hues indicate highest anomalous areas, green hues represent background values. The data show heterogeneity throughout the survey site, with the highest contrasts occurring in the NE zone, and generally within the assumed landfill boundaries.

Figure 5 shows the results of the EM survey, as 18 kHz quadrature data in parts per million (ppm). Tan to orange hues indicate anomalous areas, green hues represent background values, and pink hues represent lowest values that are least likely to contain high moisture. The data show heterogeneity throughout the survey site, with the highest contrasts occurring in the NE zone, and generally within the assumed landfill boundaries.

Generally speaking, the magnetic response patterns are in congruence with the EM results. Data for each survey zone (NE, Central, and SW), as well as the results of the resistivity transects, are discussed in detail in the following sections.

The inverse model results for the electrical resistivity survey lines are presented as two-dimensional (2D) profiles. Common color contouring scales are used for all of the lines to provide the ability to compare anomalies from line to line. Electrically conductive (low resistivity) subsurface regions are represented by cool hues (purple to blue) and electrically resistive regions are represented by warm hues (orange to brown). The locations of the assumed landfill boundary, as provided to HGI by City of Albuquerque, and any potential modified boundary based on the geophysical data results are annotated on the tops of the profiles for spatial reference.

The objective of the survey is to geophysically characterize heterogeneities in the subsurface that can indicate contrasts in electrical conductivity or metallic content. As such, within the resistivity profiles, the zones of lower resistivity (higher conductivity) would be assumed to be within the landfill, while contrasting higher resistivity would be expected to persist in the outer undisturbed materials.

Figure 4. Contoured Magnetometry Results, Vertical Gradient in nanoteslas (nT).

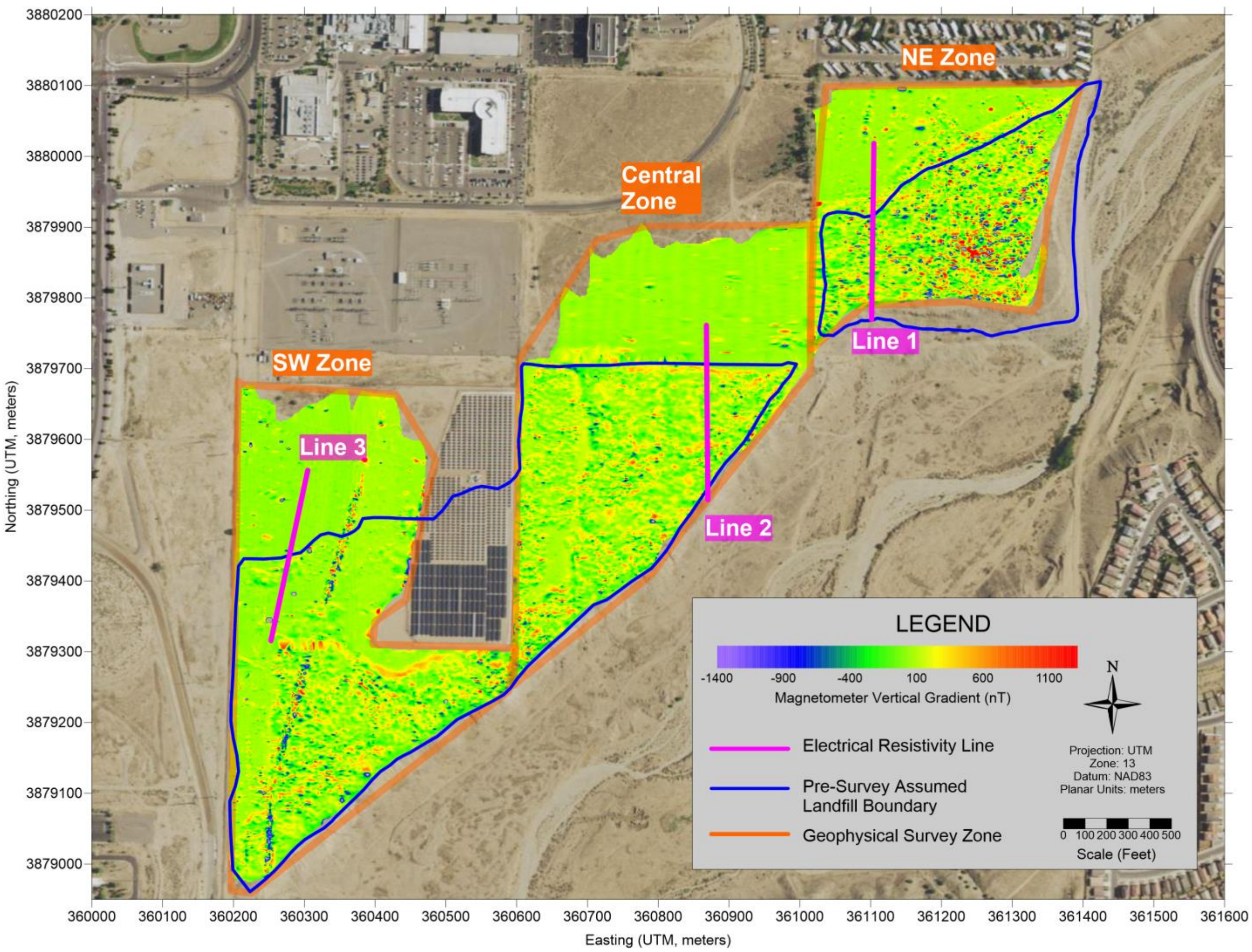
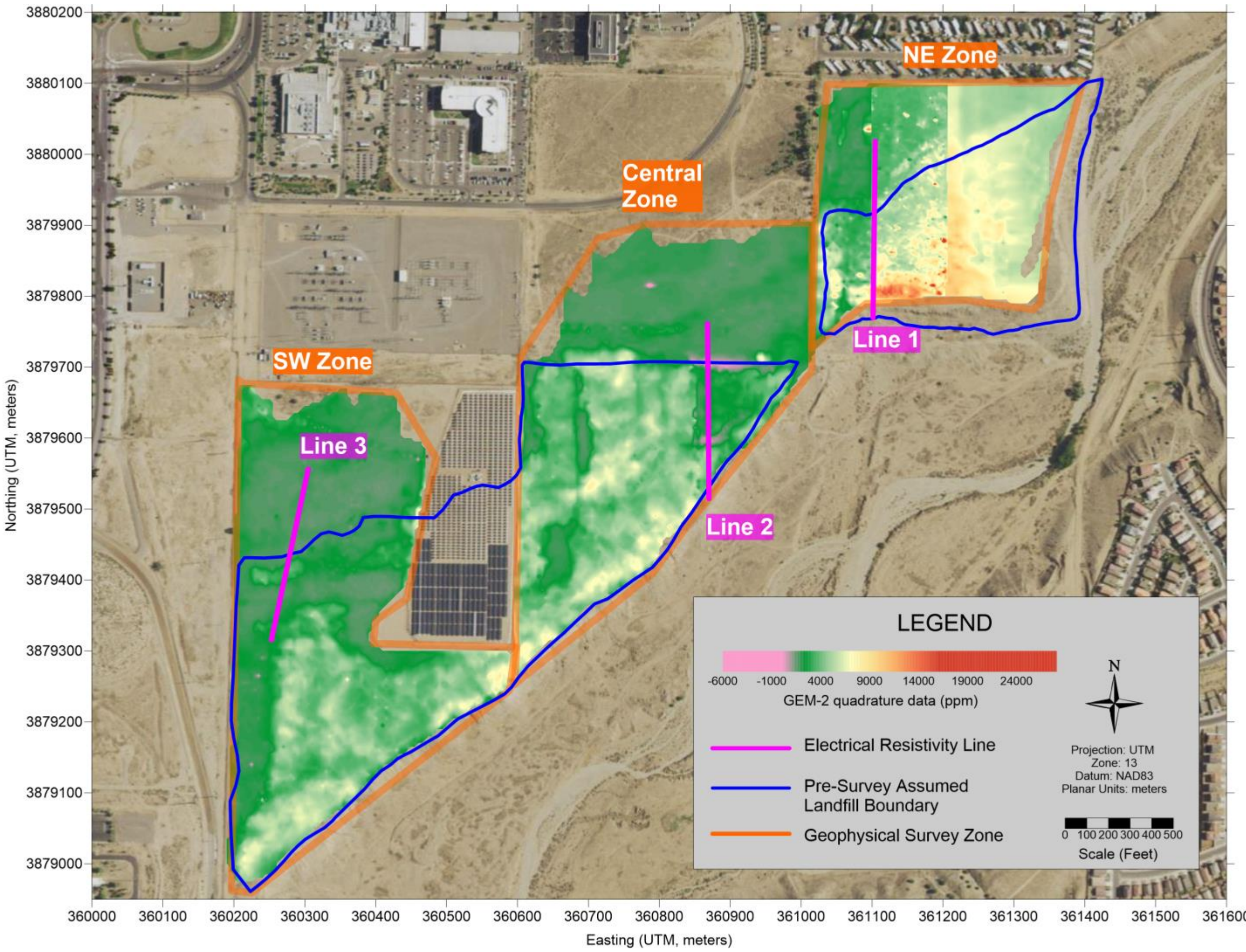


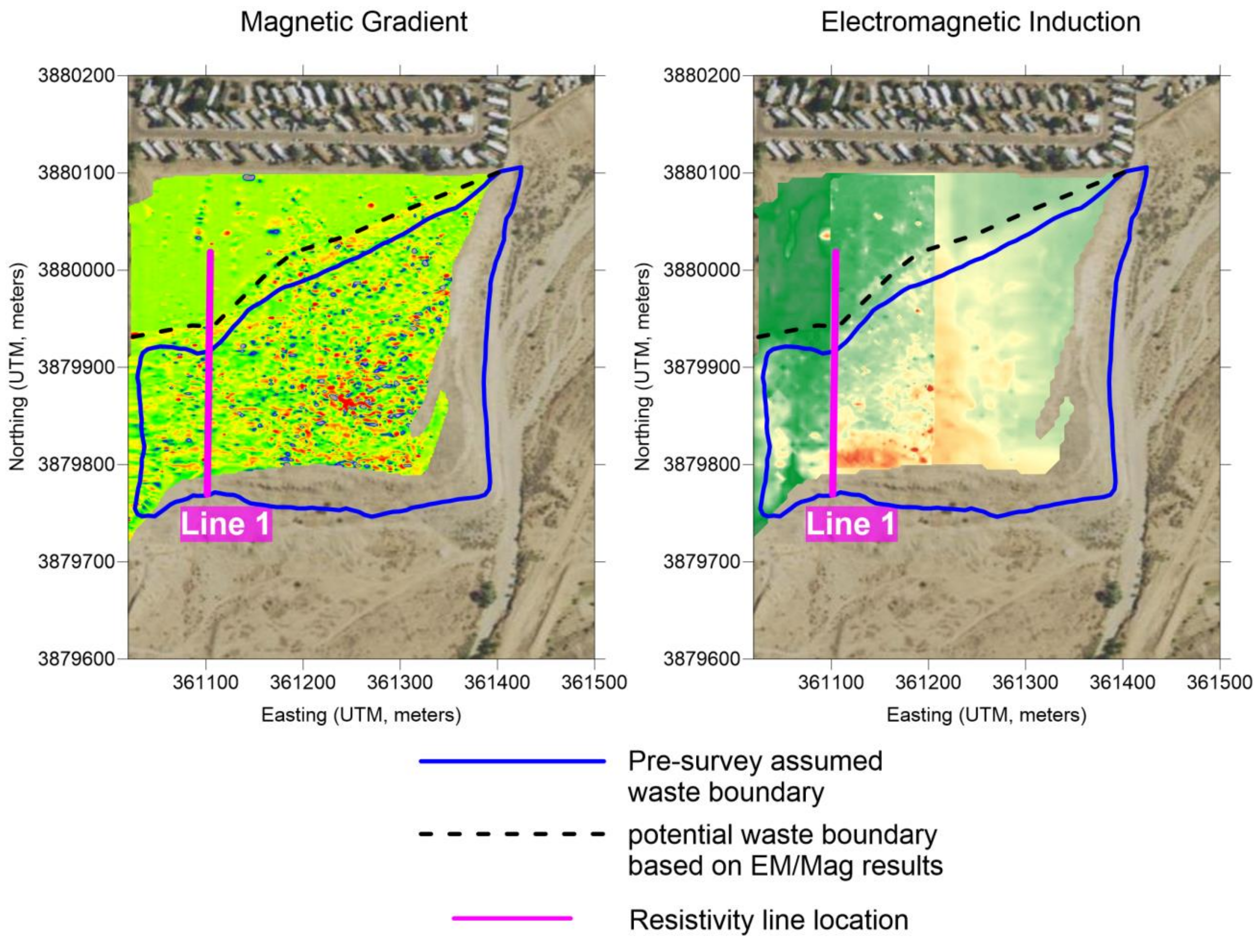
Figure 5. Contoured Electromagnetic Induction Results, Quadrature in ppm.



4.1.1 NE ZONE COMBINED METHOD RESULTS

The results of the EM and Mag surveys move the landfill boundary by about 20 meters to the north for the northern boundary in this survey zone (Figure 6). The remainder of the data within the assumed boundary show EM and Mag responses as expected of landfill material with the majority of the EM and Mag anomalous data occurring south of the assumed boundary. North of the landfill boundary, the Mag and EM results show less debris and anomalous data, implying a return to background conditions. Some metallic debris, however, may be present in this area, as the magnetic and EM data show a few isolated anomalies outside of both the assumed and proposed landfill boundary.

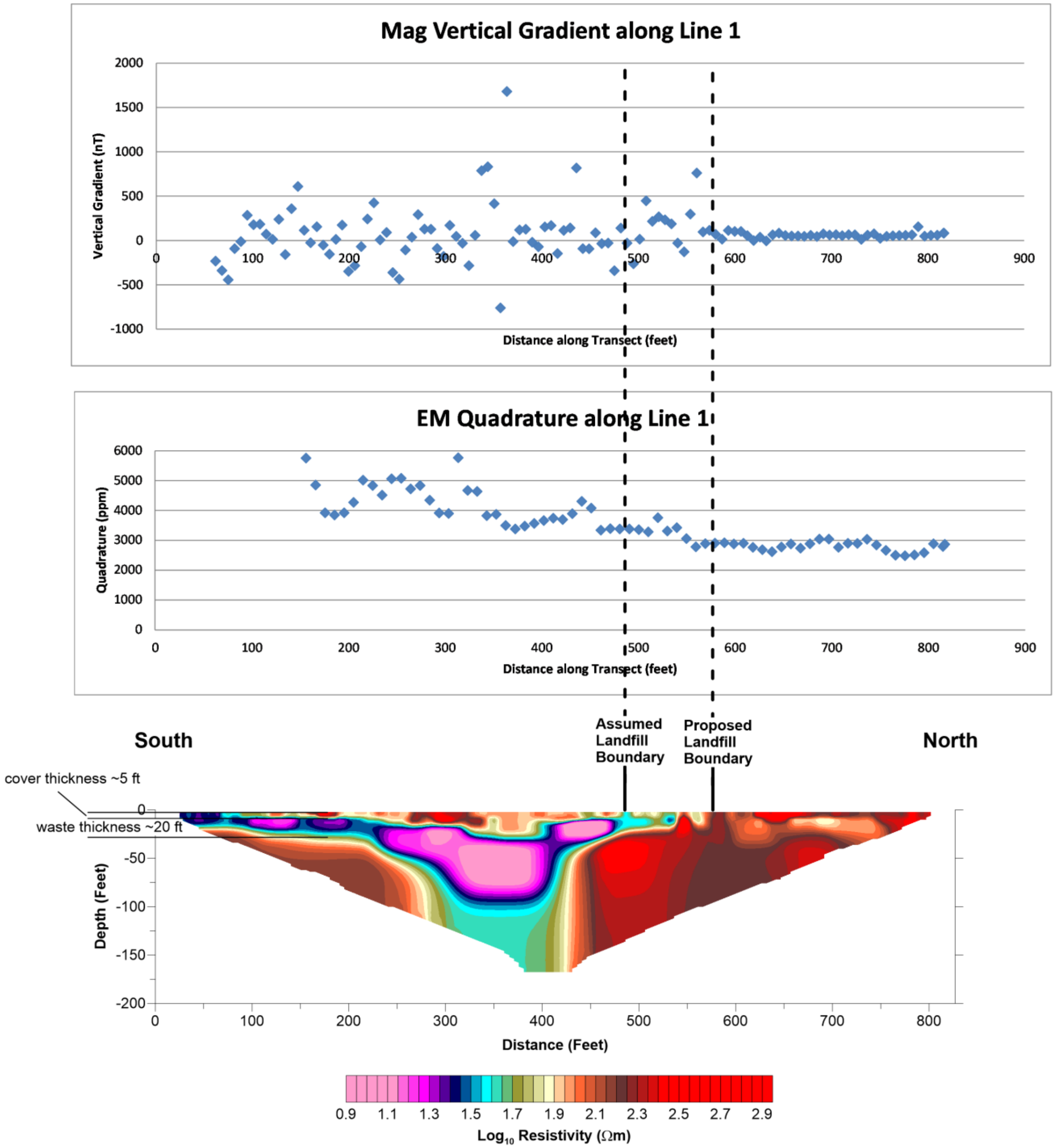
Figure 6. Mag and EM Results (NE Zone), with Potential Modified Waste Boundary.



The resistivity data correlate well with the assumed and proposed boundaries as seen in Figure 6. Figure 7 shows the resistivity profile for Line 1 which ran across the NE zone of the survey site, alongside Mag and EM data extracted at the location of the resistivity line. The depth of the waste is estimated at approximately 20 feet, based on the portion of the resistivity profile from 0 to 200 feet, and the thickness of the cover is around 5-7 feet.

From 250 to 425 m, the conductive target appears to thicken and reach deeper into the subsurface. This could indicate a conductive "plume" resulting from the waste material, which has migrated deeper within the NE survey zone. After approximately 450 m, the waste thickness returns to depths as seen at the south end of the line, and at approximately 550 m along the line, the resistivity values transition to resistive from the surface to the depth limits of the model, coinciding with the proposed boundary of the landfill. At the assumed landfill boundary, at the transition to the zone south of the proposed landfill boundary, there is a noted transition from highly to moderately conductive waste material, suggesting this may be a secondary boundary for major versus minor landfill content.

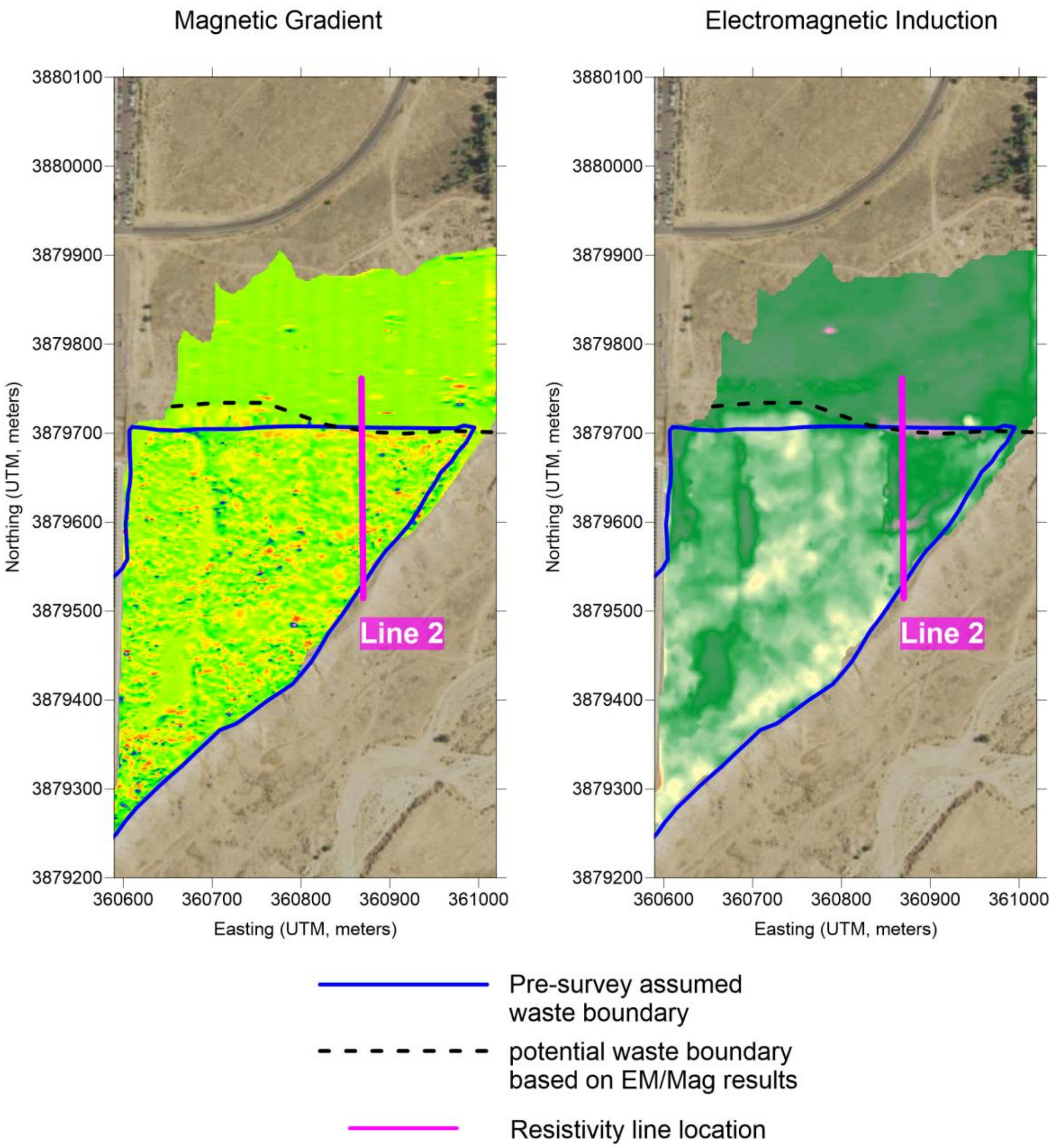
Figure 7. Line 1 Electrical Resistivity Comparison with EM & Mag Slices.



4.1.2 CENTRAL ZONE COMBINED METHOD RESULTS

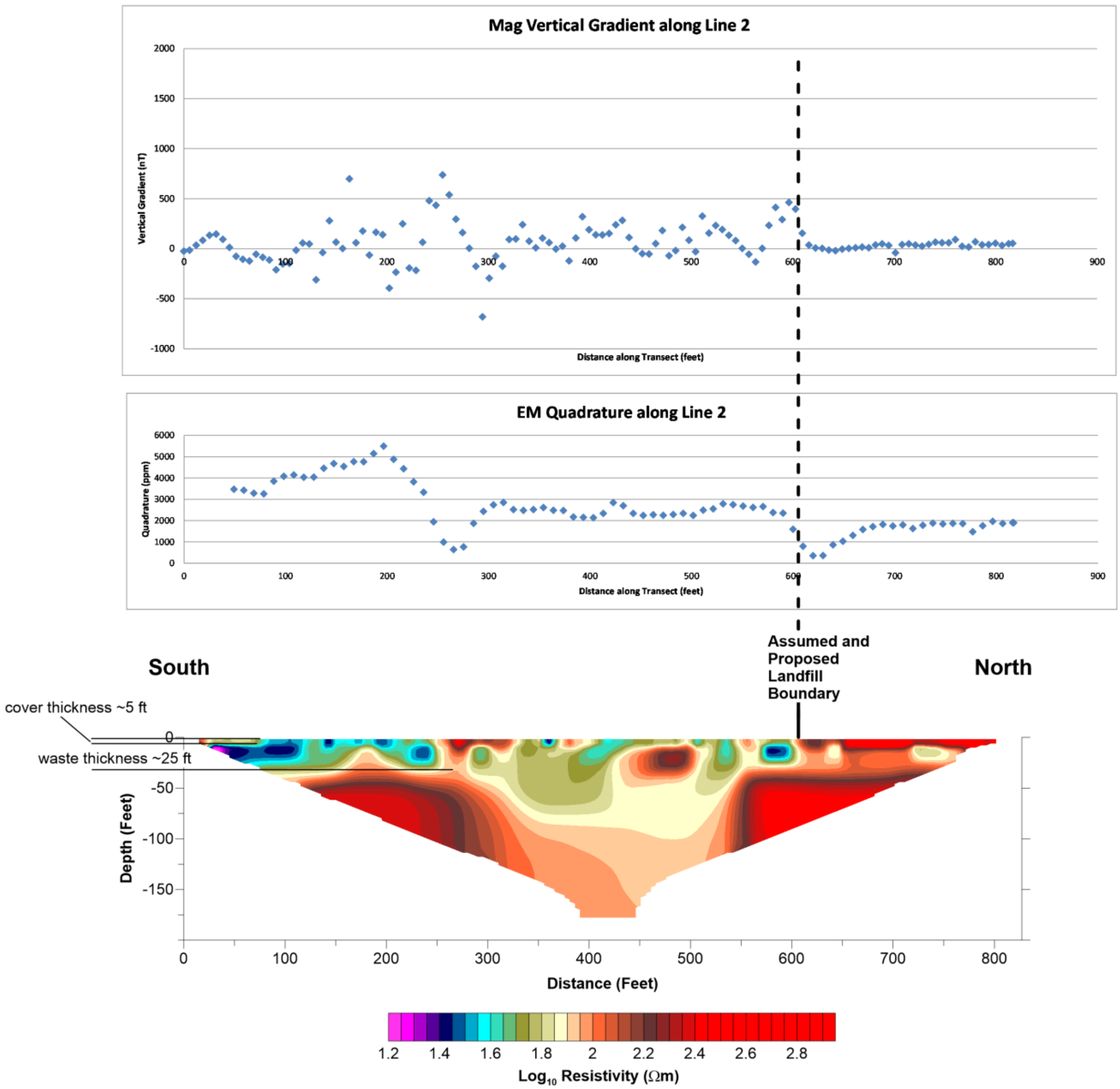
The results of the EM and Mag surveys move the landfill boundary by about 30 meters to the north for a portion of the northern boundary in this survey zone (Figure 8). The remainder of the data show good correlation to the assumed boundary with the majority of the EM and Mag anomalous data occurring south of the pre-survey assumed boundary.

Figure 8. Mag and EM Results (Central Zone), with Potential Modified Waste Boundary.



The resistivity data correlate well with the assumed and proposed boundary (same location for this zone) as seen in Figure 8. Figure 9 shows the resistivity profile for Line 2 which ran across the Central zone of the survey site, alongside Mag and EM data extracted at the location of the resistivity line. The depth of the waste is estimated at approximately 25 feet, based on the portion of the resistivity profile from 0 to 250 feet, and the thickness of the cover is around 5-7 feet.

Figure 9. Line 2 Electrical Resistivity Comparison with EM & Mag Slices.



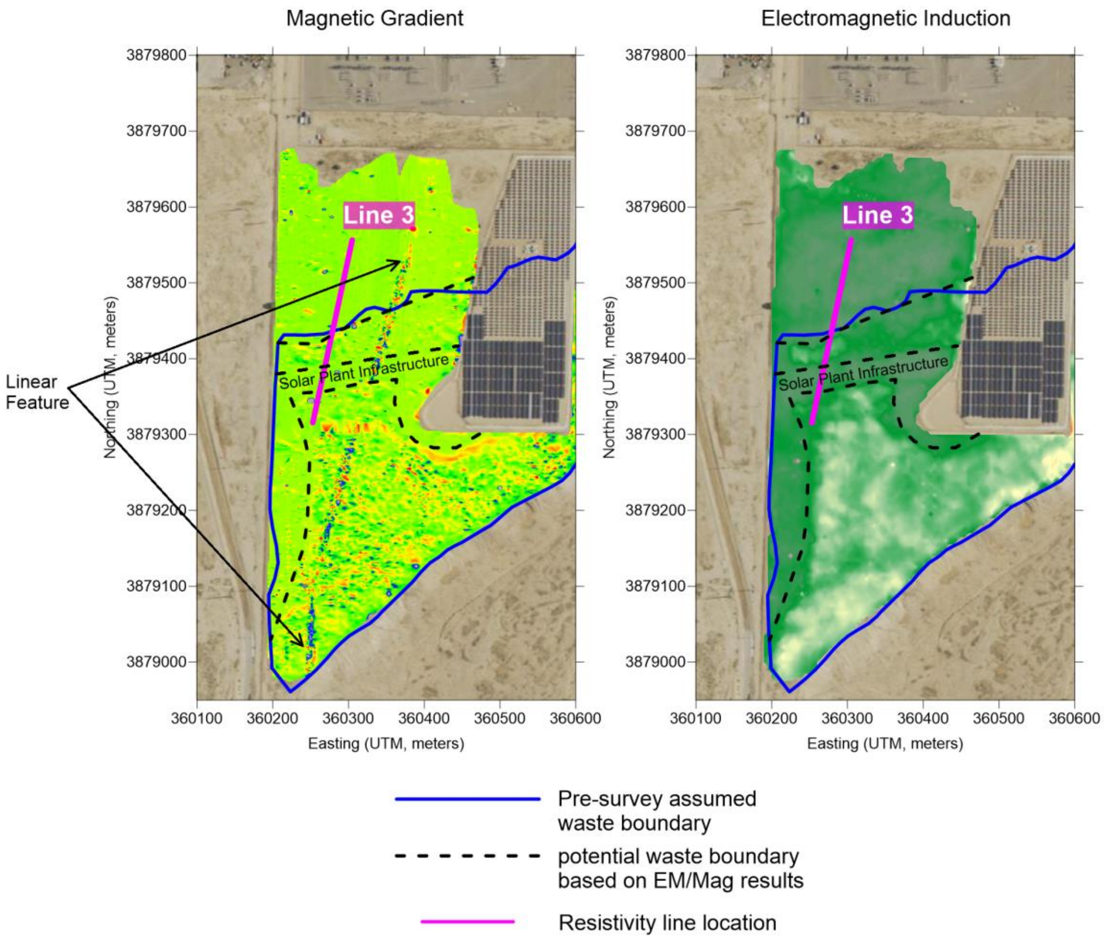
The data for all methods show higher amplitude responses, or higher conductivity, across the first 250 or so feet along the line; this could indicate higher level of waste or moisture in this region of the landfill.

4.1.3 SW ZONE COMBINED METHOD RESULTS

A high correlation between EM and Mag responses is observed in the southern region of the SW Zone. Whereas the Central and NE zones look to correspond fairly closely with the assumed landfill boundary, the SW Zone is less clearly aligned. Figure 10 shows the EM and mag results for the SW Zone, shown side by side, with the potential shifted boundary noted as a dotted black line. Multiple dotted lines have been added to represent the assumed landfill extents in this region. A break is observed in the EM and Mag results in the middle of the surveyed area, where there appears to be a diminished response to landfill material. It was relayed to HGI that this zone (labeled “Solar Plant Infrastructure”) is likely an area that was excavated or disturbed for installation of infrastructure associated with the solar plant to the east, such as a storm drain or similar. The magnetic data do not show a response in this area, indicating that any drain materials, if present, are not ferrous. The EM data show a lowered response that is in contrast to the regions both south and north of the infrastructure zone, which would be expected for changes in soil material or conditions. It is assume that the landfill continues north of the excavated region, as marked.

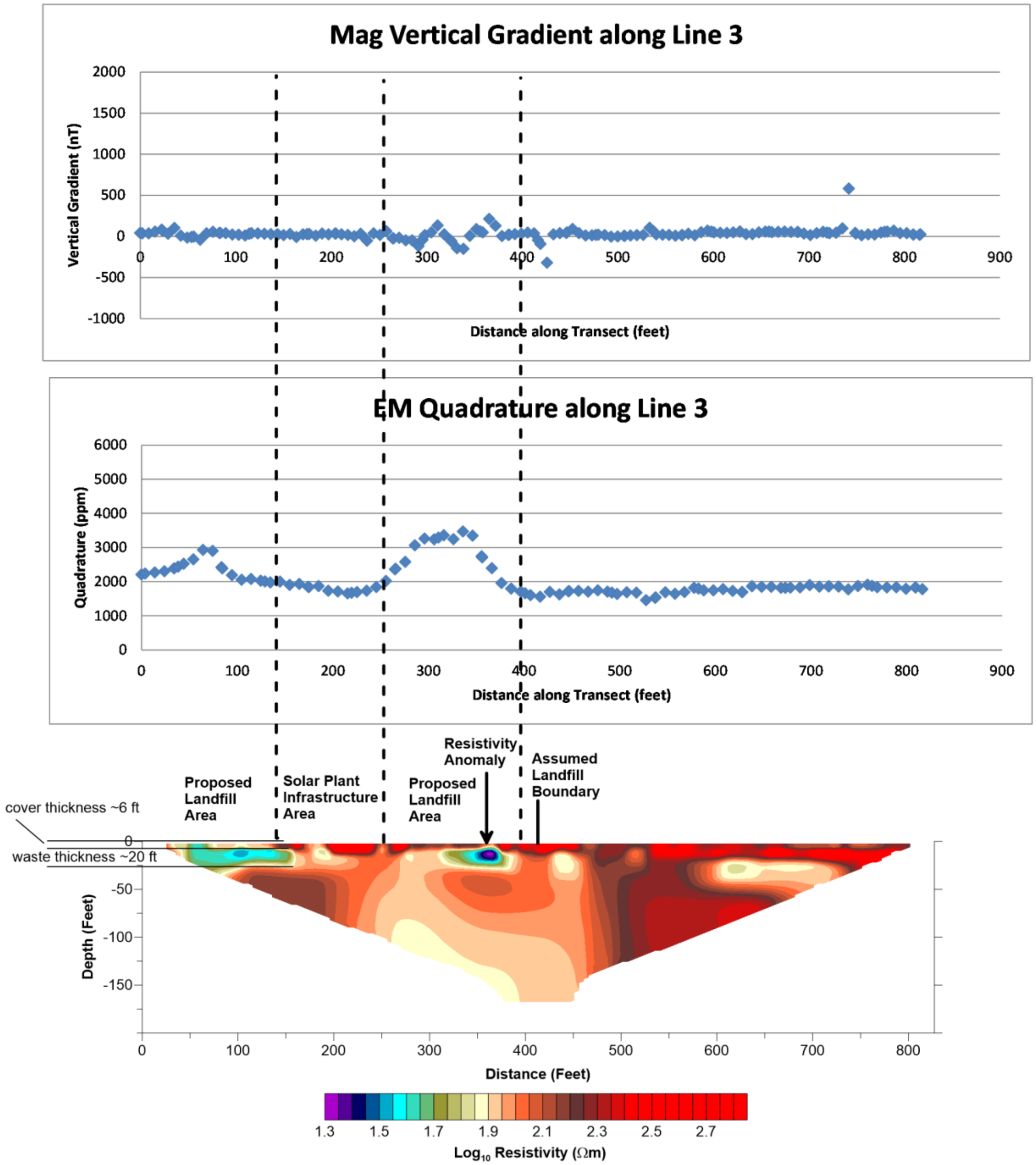
A long linear feature is observed within the SW Zone, running approximately southwest to northeast across the section, which has a large magnitude response in the magnetic data. This feature is indicated with black lines and arrows as “Linear Feature” in Figure 10. This feature correlates well to the location of the high voltage power lines running across this zone from the transformer yard to the north and is likely interference from these lines.

Figure 10. Mag and EM Results (SW Zone), with Potential Modified Waste Boundary.



The resistivity data correlate well with the assumed and proposed boundaries as seen in Figure 10. Figure 11 shows the resistivity profile for Line 1 which ran across the NE zone of the survey site, alongside Mag and EM data extracted at the location of the resistivity line. The depth of the waste is estimated at approximately 20 feet, based on the portion of the resistivity profile from 0 to 150 feet, and the thickness of the cover is around 6 feet.

Figure 11. Line 3 Electrical Resistivity Comparison with EM & Mag Slices.



5.0 CONCLUSIONS

A multi-method geophysical survey was performed at the Eubank landfill in Albuquerque, New Mexico, in August, 2016. The survey was performed to determine the lateral extents and thickness of landfill waste and the thickness of the cover material. Combined electromagnetic and magnetic surveys over the entire accessible landfill area, as well as three lines of 2D electrical resistivity were completed. The EM and Mag measurements provided an indication of the lateral limits of covered landfill. The electrical resistivity imaging method confirmed these boundary results and allowed the depth and thickness of the conductive wastes and the thickness of the cover material to be estimated.

Based on the theory that the products of the decomposition of municipal solid waste will be conductive compared to background geological materials, and that areas with metallic debris will display increased magnetic gradient contrast to undisturbed materials outside the landfill boundaries, the following observations have been made using the acquired geophysical data:

- The EM and Mag data were acquired at high spatial resolution throughout the survey site, and showed good agreement for distribution of anomalous data that would indicate the presence of landfill waste material. The anomalous data for both methods mainly occur within the boundary of the landfill that was assumed prior to geophysical surveying. The data outside of this assumed boundary mostly show little anomalous data, indicating background conditions have been mapped effectively. In some areas, the pre-survey assumed northern landfill boundary was shifted based on combined analysis of the EM, Mag, and Resistivity results. The boundary was extended by approximately 60-90 feet at certain locations in the northeast and central portions of the landfill, and potentially receded within the southwest zone.
- The resistivity data provided additional imaging to support the lateral extents determined using the EM and Mag data, and the results aligned well with the proposed landfill boundaries. The resistivity profile results estimated the thickness of the waste to be approximately 20-25 feet at the locations of the resistivity survey lines, with cover thickness estimated at approximately 5-7 feet. This is close to pre-survey assumed values averaging 30 feet for waste thickness and 4.6 feet for cover thickness. In resistivity Line 1, thickness for a highly conductive anomaly increased near the center of the survey line; this could indicate a "plume" of waste that has migrated deeper at locations within the subsurface of the NE portion of the landfill.

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APPENDIX A

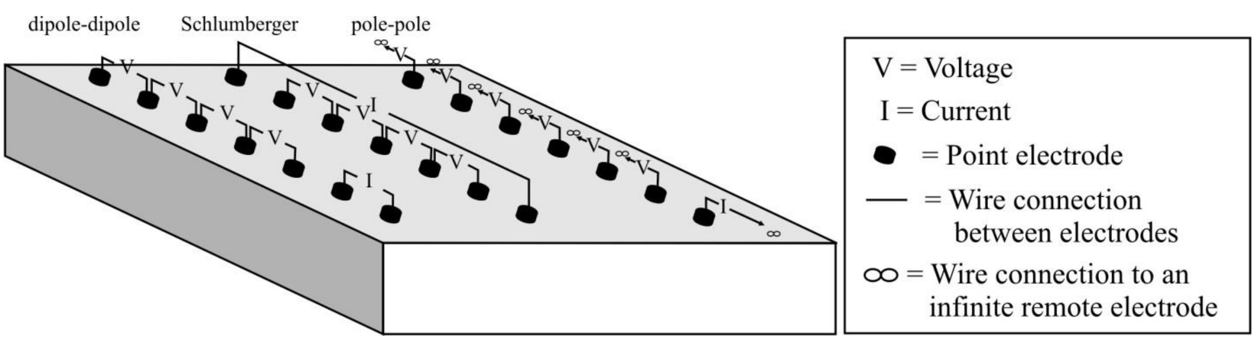
Description of Electrical Resistivity

7.0 DESCRIPTION OF ELECTRICAL RESISTIVITY

Electrical resistivity is a volumetric property that describes the resistance of electrical current flow within a medium (Rucker et al., 2011; Telford et al., 1990). Direct electrical current is propagated in rocks and minerals by electronic or electrolytic means. Electronic conduction occurs in minerals where free electrons are available, such as the electrical current flow through metal. Electrolytic conduction, on the other hand, relies on the dissociation of ionic species within a pore space. With electrolytic conduction, the movement of electrons varies with the mobility, concentration, and the degree of dissociation of the ions.

Mechanistically, the resistivity method uses electric current (I) that is transmitted into the earth through one pair of electrodes (transmitting dipole) that are in contact with the soil. The resultant voltage potential (V) is then measured across another pair of electrodes (receiving dipole). Numerous electrodes can be deployed along a transect (which may be anywhere from feet to miles in length), or within a grid. Figure 12 shows examples of electrode layouts for surveying. The figure shows transects with a variety of array types (dipole-dipole, Schlumberger, pole-pole). A complete set of measurements occurs when each electrode (or adjacent electrode pair) passes current, while all other adjacent electrode pairs are utilized for voltage measurements. Modern equipment automatically switches the transmitting and receiving electrode pairs through a single multi-core cable connection. Rucker et al. (2009) describe in more detail the methodology for efficiently conducting an electrical resistivity survey.

Figure 12. Possible Arrays for Use in Electrical Resistivity Characterization



The modern application of the resistivity method uses numerical modeling and inversion theory to estimate the electrical resistivity distribution of the subsurface given the known quantities of electrical current, measured voltage, and electrode positions. A common resistivity inverse method incorporated in commercially available codes is the regularized least squares optimization method (Sasaki, 1989; Loke, et al., 2003). The objective function within the optimization aims to minimize the difference between measured and modeled potentials (subject to certain constraints, such as the type and degree of spatial smoothing or regularization) and the optimization is conducted iteratively due to the nonlinear nature of the model that describes the potential distribution. The relationship between the subsurface resistivity (ρ) and the measured voltage is given by the following equation (from Dey and Morrison, 1979):

$$-\nabla \cdot \left[\frac{1}{\rho(x,y,z)} \nabla V(x,y,z) \right] = \left(\frac{I}{U} \right) \delta(x-x_s)\delta(y-y_s)\delta(z-z_s) \quad (1)$$

where I is the current applied over an elemental volume U specified at a point (x_s, y_s, z_s) by the Dirac delta function.

Equation (1) is solved many times over the volume of the earth by iteratively updating the resistivity model values using either the L_2-norm smoothness-constrained least squares method, which aims to minimize the square of the misfit between the measured and modeled data (de Groot-Hedlin & Constable, 1990; Ellis & Oldenburg, 1994):

$$\left(J_i^T J_i + \lambda_i W^T W \right) \Delta r_i = J_i^T g_i - \lambda_i W^T W r_{i-1} \quad (2)$$

or the L_1-norm that minimizes the sum of the absolute value of the misfit:

$$\left(J_i^T R_d J_i + \lambda_i W^T R_m W \right) \Delta r_i = J_i^T R_d g_i - \lambda_i W^T R_m W r_{i-1} \quad (3)$$

where g is the data misfit vector containing the difference between the measured and modeled data, J is the Jacobian matrix of partial derivatives, W is a roughness filter, R_d and R_m are the weighting matrices to equate model misfit and model roughness, Δr_i is the change in model parameters for the i^{th} iteration, r_i is the model parameters for the previous iteration, and λ_i = the damping factor.

APPENDIX B

Description of Electromagnetic Induction and Magnetic Gradiometry

8.0 DESCRIPTION OF EM & MAG

8.1 MAGNETOMETRY

Magnetometry is the study of the Earth's magnetic field and is the oldest branch of geophysics. The Earth's field is composed of three main parts:

1. Main field is internal (i.e., from a source within the Earth that varies slowly in time and space)

2. Secondary field is external to the Earth and varies rapidly in time

3. Small internal fields constant in time and space are caused by local magnetic anomalies in the near-surface crust.

Of interest to the geophysicist are the localized anomalies. These anomalies are either caused by magnetic minerals, mainly magnetite or pyrrhotite, or buried steel and are the result of contrasts in the magnetic susceptibility (k) with respect to the background sediments. The average values for k are typically less than 1 for sedimentary formations and upwards to 20,000 for magnetite minerals.

The magnetic field is measured with a magnetometer. Magnetometers permit rapid, non-contact surveys to locate buried metallic objects and features. A one person portable field unit can be used virtually anywhere a person can walk; although, they maybe sensitive to local interferences, such as fences and overhead wires. Airborne magnetometers are towed by aircraft and are used to measure regional anomalies. Field-portable magnetometers maybe single- or dual-sensor. Single-sensor magnetometers measure total field. Dual-sensor magnetometers are called gradiometers and measure gradient of the magnetic field.

Magnetic surveys are typically conducted with two separate magnetometers. The first magnetometer is used as a base station to record the Earth's primary field and the diurnally changing secondary field. The second magnetometer is used as a rover to measure the spatial variation of the Earth's field and may include various components (e.g., inclination, declination, and total intensity). By removing the temporal variation and perhaps the static value of the base station from that of the rover, one is left with a residual magnetic field that is the result of local spatial variations only. The rover magnetometer is moved along a predetermined linear grid laid out at the site. Readings are virtually continuous and results can be monitored in the field as the survey proceeds.

The shortcoming with most magnetometers is that they only record the total magnetic field (**F**) and not the separate components of the vector field. This shortcoming can make the interpretation of magnetic anomalies difficult, especially since the strength of the field between the magnetometer and target is reduced as a function of the inverse of distance between the magnetometer and target, cubed. Additional complications can include the inclination and declination of the Earth's field, the presence of any remnant magnetization associated with the target, and the shape of the target.

8.2 ELECTROMAGNETIC INDUCTION

EM data is typically collected using portable ground conductivity instrumentation. Basically, a transmitting coil induces an electromagnetic field and a receiving coil at a fixed separation usually measures the amplitudes of the in-phase and quadrature components of the magnetic field. Various instruments have different coil spacings and operating frequencies. Spacing and frequency effect depth of signal penetration. Both single frequency and multi-frequency instruments have been developed for commercial use.

Earth materials have the capacity to transmit electrical currents over a wide range. Earth conductivity is a function of soil type, porosity, permeability, and dissolved salts. Terrain conductivity methods seek to identify various Earth materials by measuring their electrical characteristics and interpreting results in terms of those characteristics. EM techniques are used to measure Earth conductivities of various soil, rock, and water components at individual survey areas employing portable, rapid, non-invasive equipment operating at various frequencies depending on range and depth desired.

The recorded electromagnetic field is separated into two sub-components: in-phase and conductivity (also referred to as quadrature). The in-phase component is the most sensitive to metallic objects and is measured in parts per million (ppm). The conductivity component is sensitive to soil condition variations and is measured in log Siemens per meter (log S/m) using the GEM-2 instrument.

The EM method was chosen due to the capability of mapping changes in soil conductivity that are caused by changes in soil moisture, disruption, other conductivity changes caused by physical property contrasts, the ability to detect metallic objects (i.e., ferrous and non-ferrous), and the relatively rapid rate of data acquisition.