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Geophysical Survey of the Nazareth Landfill, Albuquerque, New Mexico

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1.0 INTRODUCTION

1.1 PROJECT DESCRIPTION

In late 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 Nazareth Landfill. A combined electromagnetic (EM) and magnetic (Mag) survey over the entire accessible landfill area, as well as two lines of two-dimensional (2D) electrical resistivity were completed. This report documents results from data acquired at the Nazareth Landfill; one of four landfill sites 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 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

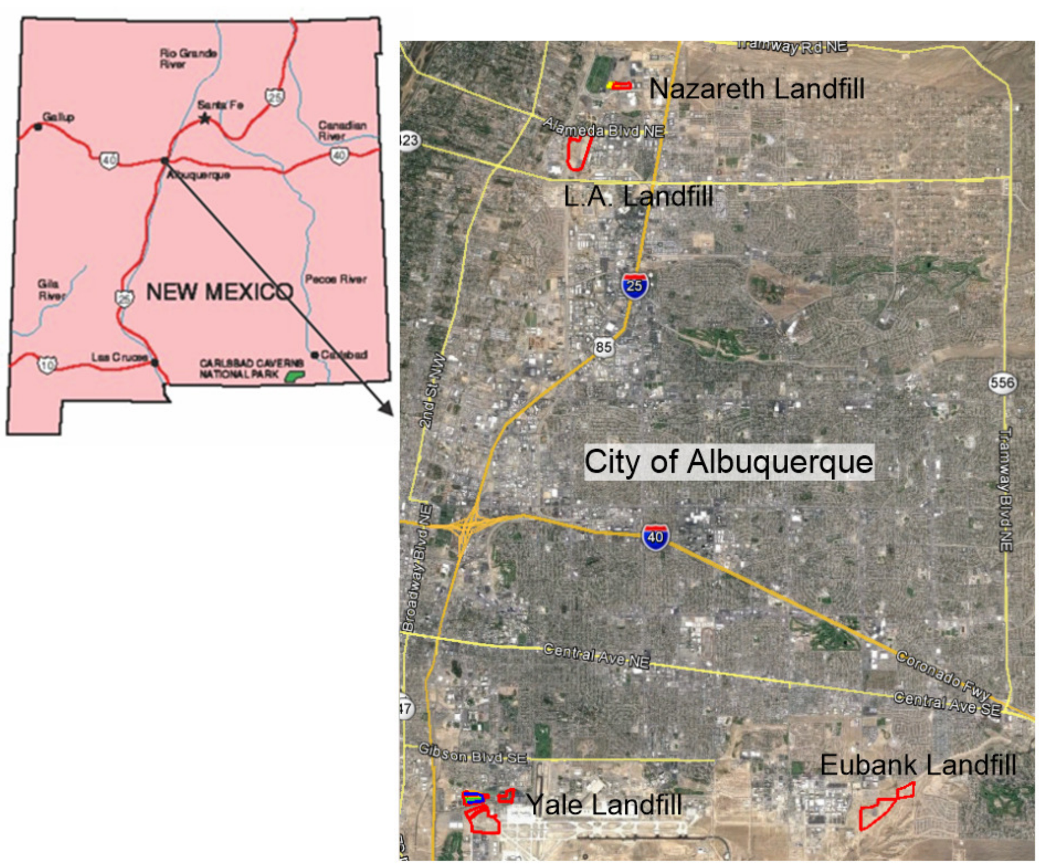
2.1 SITE LOCATION

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

The Nazareth Landfill is located at the intersection of San Diego Ave NE and Jefferson St. NE. The landfill operated during the years 1971-1972, with a total estimated waste tonnage of 172,000 tons. The landfill has a parking lot with mixed gravel and asphalt on top of it.

There are no available historical references for boundary and construction geometry for the Nazareth landfill and cover; however, previous estimates an average cover thickness of 3 feet, and average waste depth of 27 feet. These values may vary across the site. The total area covered by the Nazareth landfill is approximately 8 acres.

Figure 1. General Survey Location



Aerial imagery © Google Earth 2016

3.0 METHODOLOGY

3.1 SURVEY AREA AND LOGISTICS

EM & Mag data were acquired on 10/29/16 and 11/3/16 at high-resolution with rapid acquisition 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 10 acres. The survey area had little topography and vegetation. Most of the area had been converted to a RV parking lot for an annual Balloon Festival. The survey was split into multiple days due to a locked fence preventing surveying on the weekend. The boundaries of this survey were enclosed by a chain link fence.

Resistivity data consisted of two lines of data approximately 817 feet long each, totaling approximately 1,634 feet total line coverage. The locations of the resistivity lines 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.

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	12/9/16	10	817	W-E	355036, 3895670	355284, 3895665
2	12/9/16	10	817	NW-SE	354877, 3895816	355039, 3895635

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 (EM) 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 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

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

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 seven electrode measurements.

3.2.2.1 Handheld GPS

Positional data for the resistivity lines were acquired via a handheld Garmin GPS unit. Topographical data were incorporated into the 2D resistivity inversion modeling routines.

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 and an electrical conductivity value was calculated. The EM conductivity and EM in-phase data were selected for final processing and presentation. The EM conductivity data is more sensitive to soil conductivity (electrical properties) changes, while the EM in-phase data is more sensitive to metal in the subsurface. 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 Kriging gridding algorithm was used within the Surfer software. 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, and the EM in-phase measurements, are highly sensitive to bulk metals in the landfill, ferrous and non-ferrous. This can provide a high-resolution map of the distribution of metallic wastes within the landfills. The EM conductivity measurements would be expected to be more susceptible to moisture content and other conductive materials (clays, leachate, etc.), with the moisture in contact with waste materials of the landfill expected to be of increased conductivity.

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.

4.1.1 G.O. Cart Results

Figure 4 shows the results of the EM conductivity (sensitive to bulk conductivity changes), EM in-phase (sensitive to bulk metal), and Mag (sensitive to ferrous metal only) survey for the whole survey site. Figure 5, Figure 6, and Figure 7 provide a single larger image for each G.O. Cart geophysical parameter shown on Figure 4.

Magnetic data are plotted as magnetic field vertical gradient, measured in nanoteslas per meter (nT/m). Red and purple hues indicate highest anomalous areas, while green hues are more representative of background values. The results of the EM survey are plotted as 10 kHz in-phase data in parts per million (ppm) and 10 kHz conductivity data in millisiemens per meter (mS/m). In the EM conductivity results, 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 EM in-phase results display red to purple hues indicating anomalous areas, and blue hues representing background values.

The data show heterogeneity throughout the survey site, largely within the assumed landfill boundaries. Generally speaking, the magnetic response patterns are in congruence with the EM results. It is important to note that the vertical gradient magnetic method is more sensitive to near surface ferrous metal while the EM in-phase method is sensitive to bulk metal (ferrous and non-ferrous) across a greater depth of investigation. As a result, EM in-phase data tend to group individual metal objects into larger and more diffuse bodies, whereas vertical gradient responses tend to image smaller more individual metal objects. The two methods therefore, provide a crude means of differentiating waste constituents. Data for the complete survey site, as well as the results of the resistivity transects, are discussed in detail in the following sections.

The results of the EM and Mag surveys have been interpreted to provide a potential waste boundary to delineate the spatial extent of the landfill, shown with a black dashed perimeter lines in Figure 4 through Figure 7**Error! Reference source not found.**. For most of the landfill area, the "Pre-Survey Assumed Landfill Boundary" (shown as a solid blue line) match the EM and Mag results; however, there are a few regions of difference:

- Southeast Corner: The southeast corner contains a region approximately 150 feet by 100 feet (45 meters by 30 meters) in size where the EM and Mag results show no evidence of subsurface landfill material. Therefore, we have moved the eastern landfill boundary to the west by approximately 150 feet (~514 meters).
- Southern Boundary: The interpreted landfill boundary based on EM and Mag results appear to extend beyond the pre-survey assumed landfill boundary along must of the southern boundary. The southern landfill boundary would move on average approximately 30 feet (~10 meters) to the south. A resistivity profile, Line 1, was placed over this boundary area to investigate further and is discussed below in Section 4.1.2.
- Western Boundary: The western landfill boundary was more difficult to interpret due to above ground infrastructure that makes it more challenging to separate landfill from infrastructure response. However, we believe that the landfill material extends further west by approximately 50 to 65 feet (~16 to 20 meters) than shown in the pre-survey

assumed boundary. The additional area of landfill material has an uneven shape as shown by the black dashed line on Figure 4. There are some gaps in the data near the northwestern boundary due to proximity to surface infrastructure, presenting some difficulty in designating a clear landfill boundary based on the EM and Mag data alone. A resistivity profile, Line 2, was placed over this area to investigate further and is discussed below in Section 4.1.3.

- Northwest Corner: Differences between pre- and post-survey landfill boundaries are the most dramatic for the northwestern boundary. In contrast to the pre-survey assumed boundary, the northwest corner showed significantly less landfill material, shifting the geophysically interpreted boundary approximately 50 to 100 feet (~15 to 30 meters) to the south in this area.

As stated, the EM results are in general congruence with the Mag results, with high amplitude anomalies in the EM conductivity correlating with high amplitude anomalies in the EM in-phase results. These high amplitude anomalies tend to correlate to regions in the Mag results that display greater heterogeneity; with a higher density of high amplitude positive and negative anomalies. The Mag results display a number of linear high amplitude positive anomalies, notably in the center of the coverage area oriented in a roughly north-south direction, and also west of the western boundary, also trending in a roughly north-south direction. The central feature is a response to an above ground fence, and the western feature is likely a response to above ground RV connecting infrastructure or utilities.

Figure 4. Contoured Electromagnetic and Magnetic Survey Results.

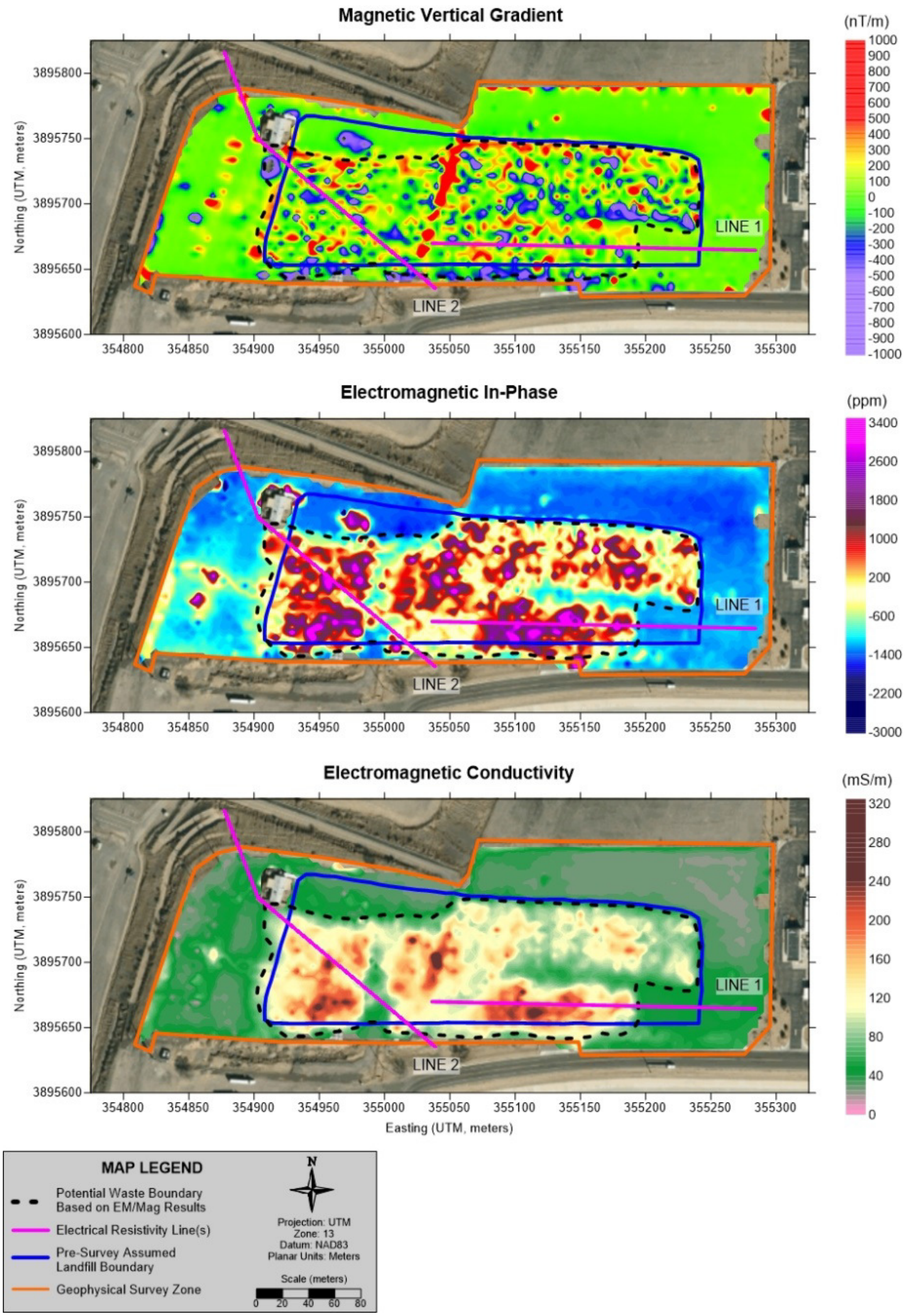


Figure 5. Contoured Magnetometry Results, Vertical Gradient (nT/m).

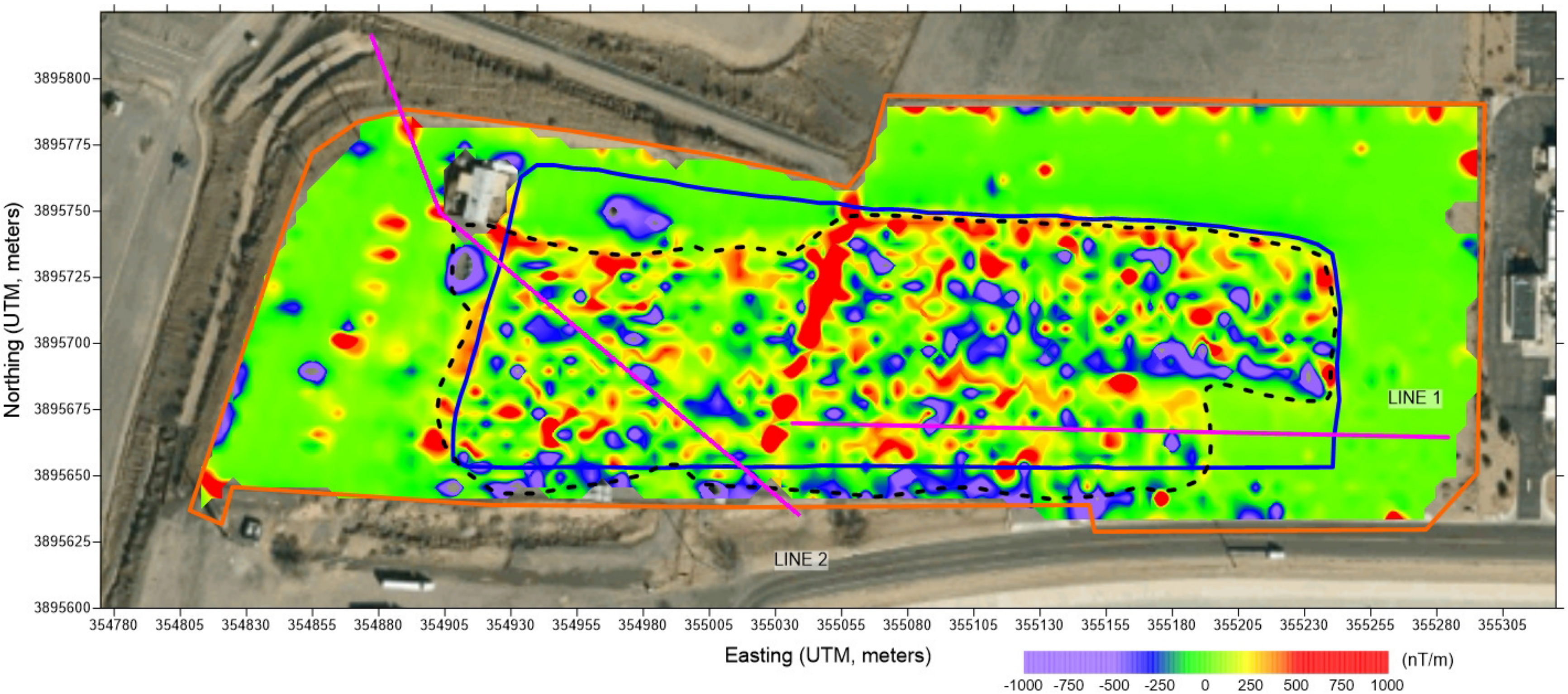


Figure 6. Contoured Electromagnetic Results, In-Phase (ppm).

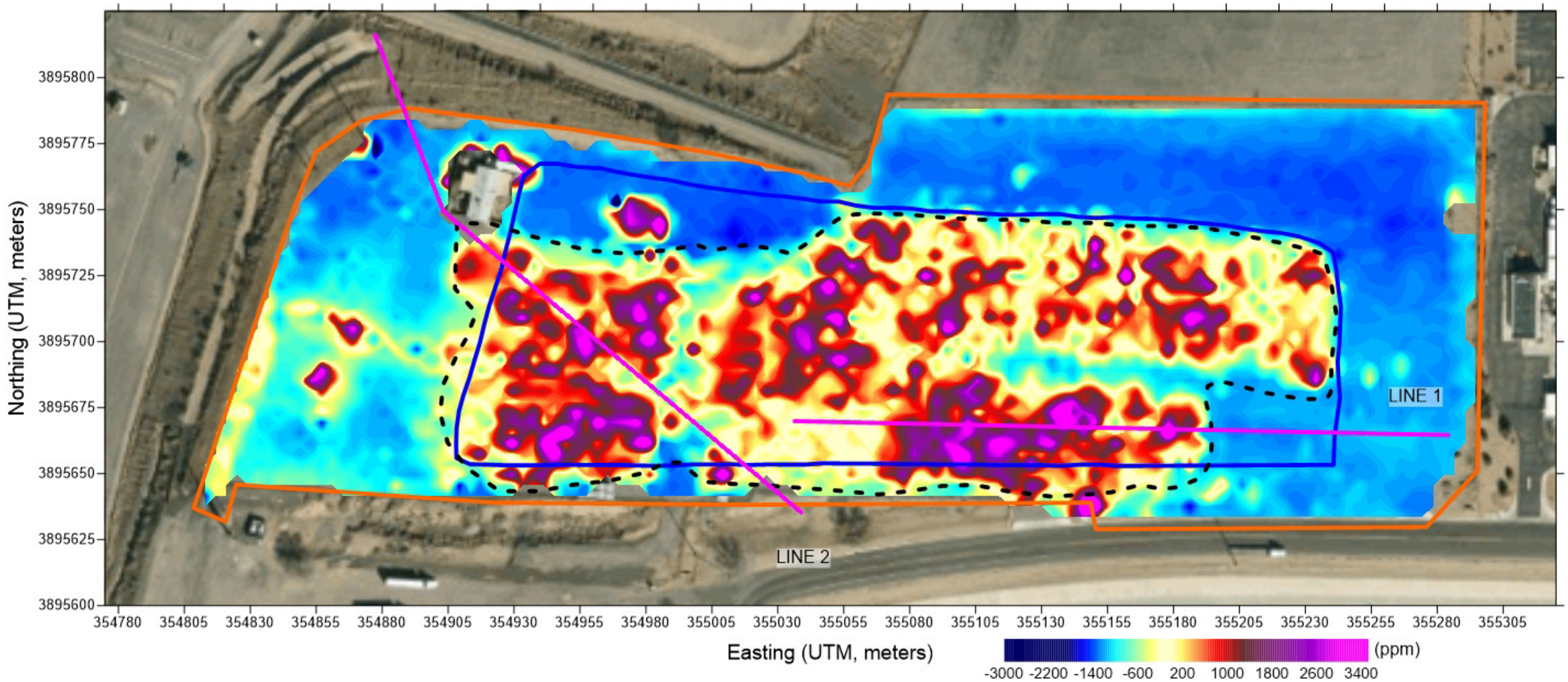
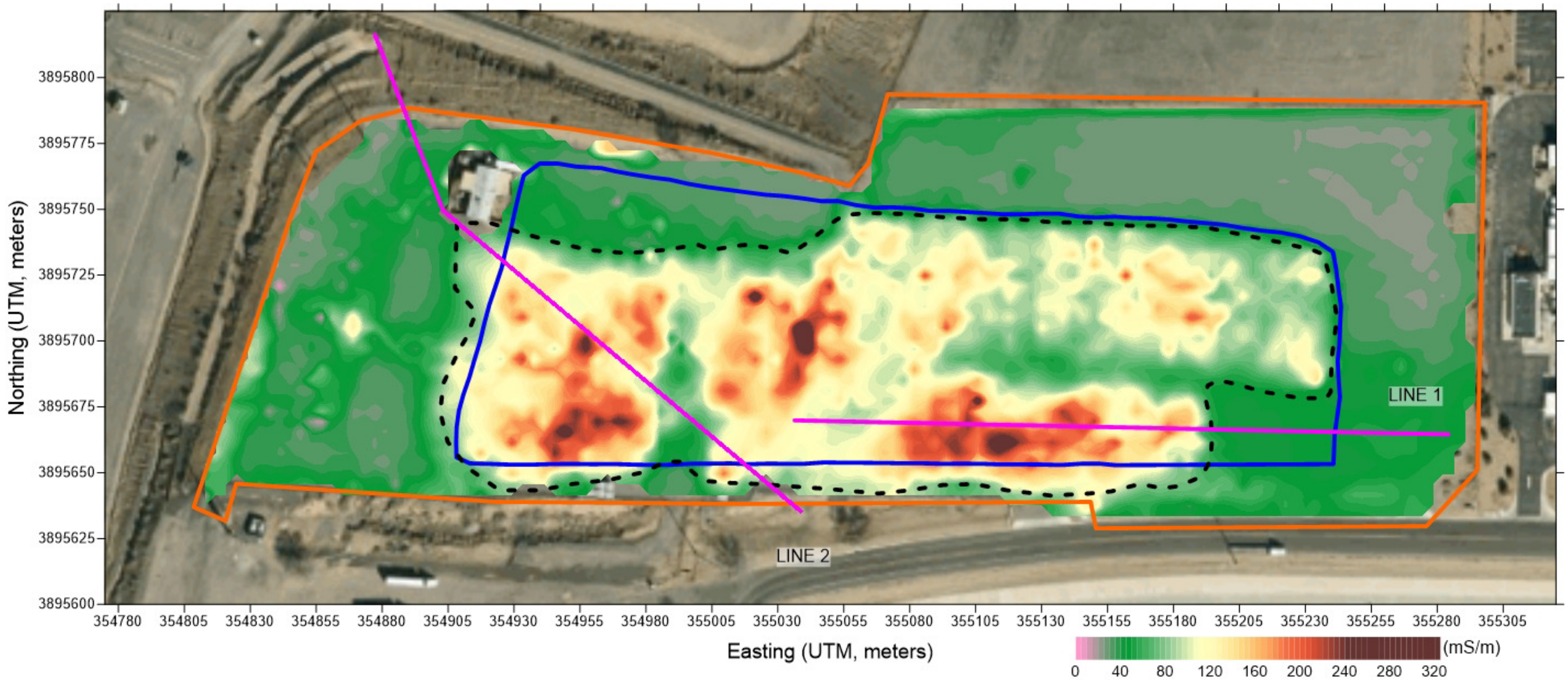


Figure 7. Contoured Electromagnetic Results, Conductivity (mS/m).



4.1.2 Line 1 Combined Method Results

Figure 8 shows the resistivity profile for Line 1 which ran across the eastern edge of the survey site. EM and Mag data was extracted along the resistivity survey line at this location and the geophysical parameters are plotted in relation to the resistivity cross section for comparison. The Line 1 resistivity profile is shown alone in greater detail in Figure 9. Line 1 was collected within the landfill boundary and extends to the east beyond the landfill boundary. Its location was selected by evaluating the EM and Mag results which showed a large discrepancy between the pre- and post-survey landfill boundary in this area. We observe a significant level of variability in the extracted EM and Mag readings over resistivity Line 1.

The landfill wastes typically present as a conductive target (purple and blue colors), while background undisturbed soils/rock tend to be more resistive (browns and red colors). A fairly continuous conductive near surface (surface to approximately 20 feet below ground surface [bgs]), extends for the majority of the resistivity profile with highly conductive zones limited to areas between 100 and 550 feet along the profile.

The depth of the waste is estimated at approximately 20 feet (~ 6 meters), based on the portion of the resistivity profile from 100 to 300 feet, and the thickness of the cover is around 5 to 7 feet (1.5 to 2 meters). A black dashed line has been placed along the resistivity profile to highlight the lower interpreted waste vertical boundary. A thin, more resistive layer (tan color) can be seen above the conductive waste material, indicating a surface soil cover that is likely free of landfill waste and relatively dry. Within the post-survey landfill boundary, the resistivity data show a strong correlation with the lateral boundaries as seen in the EM and Mag results, with high and low amplitude responses matching the areas of increased conductivity in the resistivity profile

From 300 to 450 feet, the conductive target appears to reach deeper into the subsurface to a depth of approximately 40 feet bgs (~ 12 meters), as indicated by the magenta dashed line in Figure 8. The thin resistive surface layer, evident from 0 to 300 feet along the profile, is almost absent in this region. The absence of this layer could be the result of a different material used for surface cover that may be more conductive or increased soil moisture. The increased depth for the conductive feature could indicate a conductive “plume” resulting from the waste material, which has migrated deeper within the survey zone.

There is a sharp change at approximately 425 feet along the profile, where the waste thickness returns to depths similar to the west end of the survey line. At the proposed landfill boundary, there is a noted transition (520 feet to 550 feet along profile) from highly (dark blue) to moderately conductive (light blue) waste material. In addition, there is good agreement between the resistivity and EM/Mag results within this area, and this transition zone supports the refinement of the proposed landfill boundary. The moderately conductive (light blue) material appears to continue to the east, well beyond both the pre- and post-survey landfill boundaries. This could be the result of an increase in conductive waste water, or a "plume", that is migrating away from the original landfill. It is also possible that the moderately conductive layer is natural and represents a natural change in soil properties; however, we cannot determine the specific reason without some amount of sampling.

The lower section (below elevation 5100 feet) of the model is dominated by a highly resistive (red color) layer that extends for entire profile. This layer likely represents a response to native materials, for example sediments or potentially bedrock based on the resistivity values and proximity to foothills to the north.

Figure 8. Line 1 Electrical Resistivity Comparison with EM & Mag Slices.

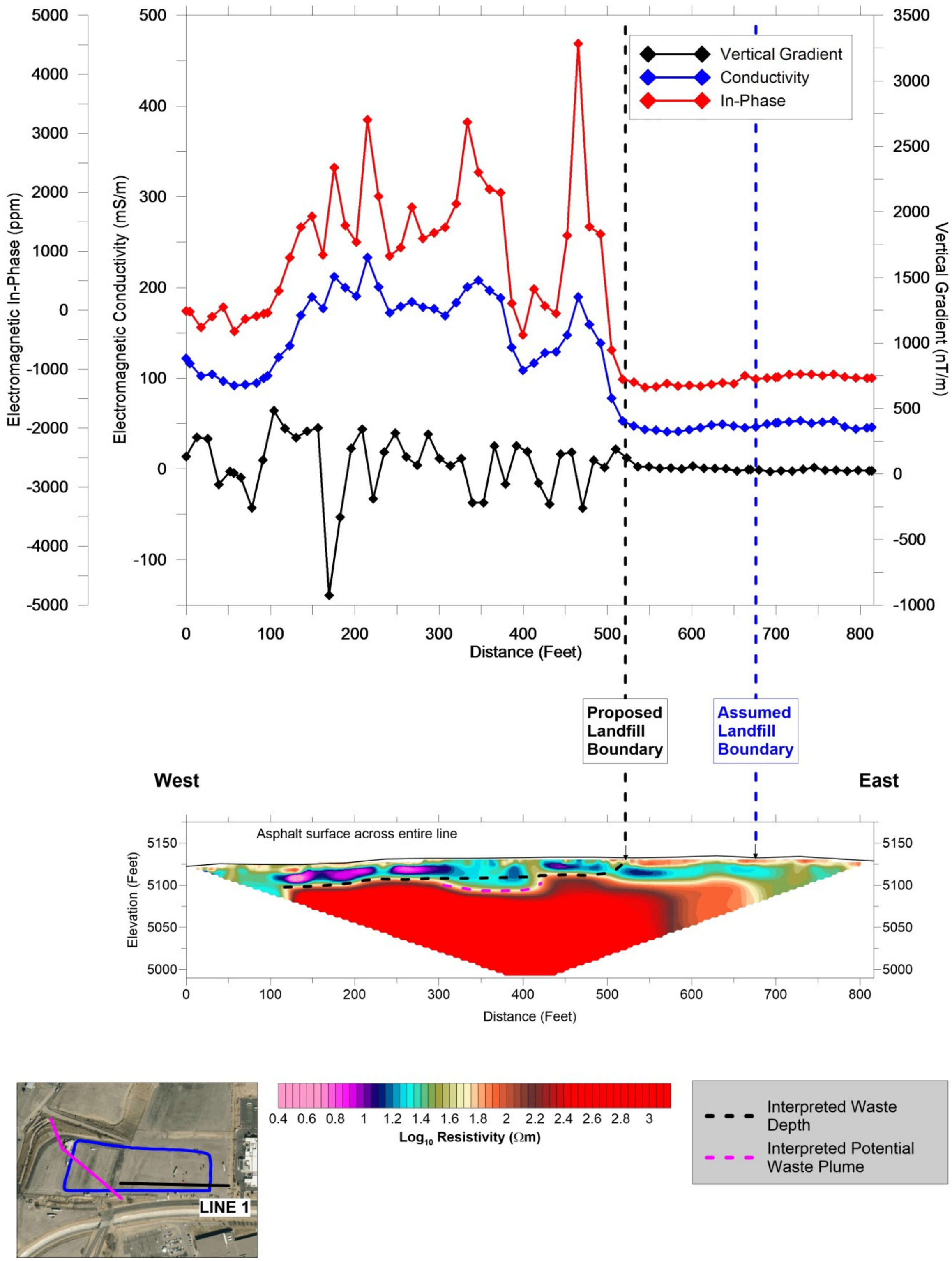
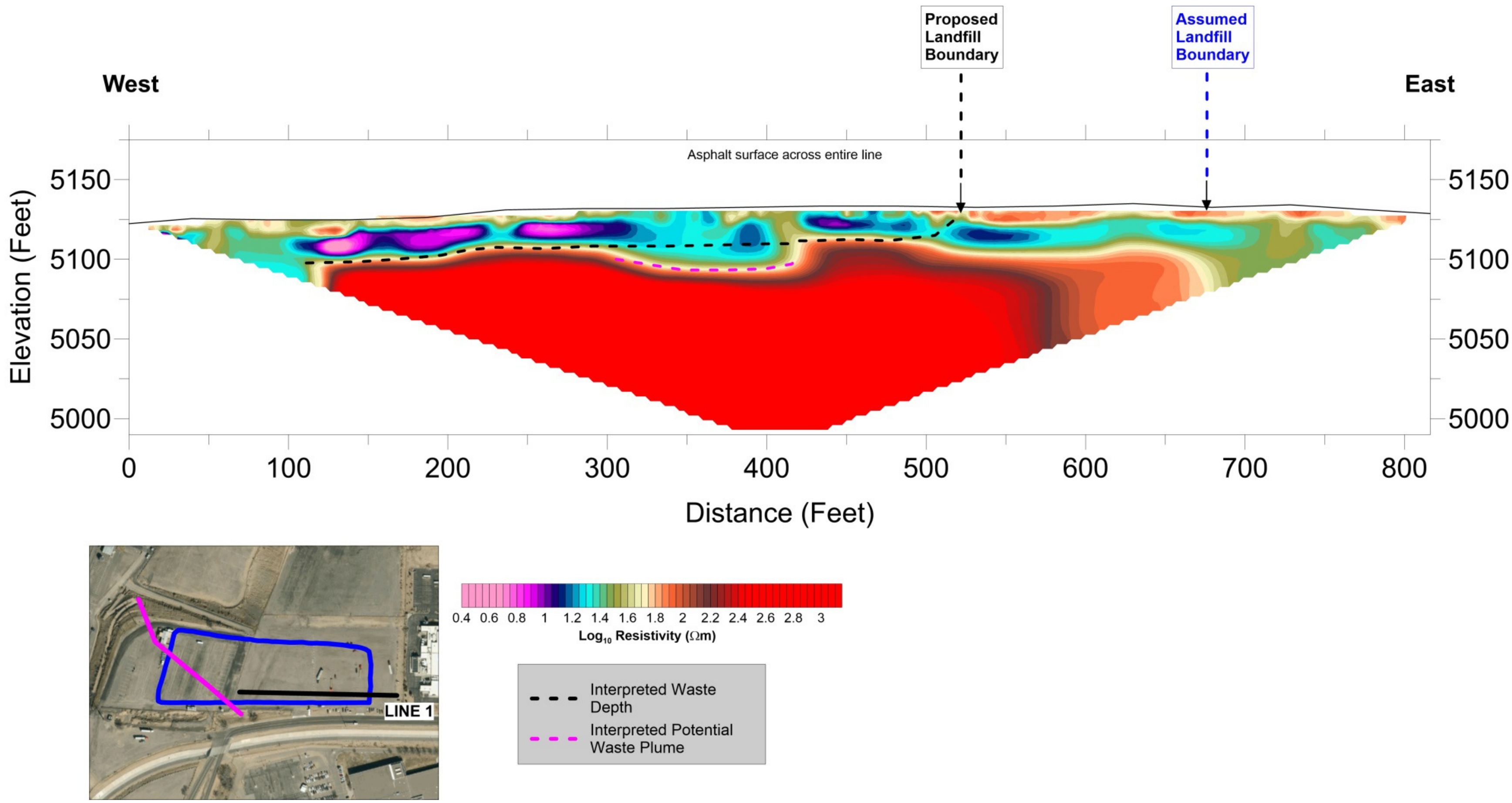


Figure 9. Line 1 Electrical Resistivity Profile.



4.1.3 Line 2 Combined Method Results

Figure 10 shows the resistivity profile for Line 2, which ran across the western zone of the survey site, alongside EM and Mag data extracted at the location of the resistivity line. The Line 2 resistivity profile is shown alone in greater detail in Figure 11. A moderate to highly conductive layer extends across the section from approximately 250 feet 750 feet along the profile as shown by the light blue, purple and pink colors and is attributed to landfill waste material. In the case of the western boundary, where EM and Mag results were complicated by above ground infrastructure, the resistivity data proved essential in selecting the final placement of the proposed lateral boundary. The depth of the waste is estimated at approximately 20 to 25 feet (6 to 7.5 meters), based on the portion of the resistivity profile from 250 to 600 feet. A black dashed line has been placed along the interpreted lower vertical landfill boundary. A thin resistive layer (tan to red colors), approximately 5 to7 feet (1.5 to 2 meters) in thickness, extends over the conductive waste in this region, showing good agreement with the surface cover for survey Line 1. The resistivity data correlate well with the proposed EM and Mag western and southern boundaries, further confirming extension of the landfill boundaries from pre-survey assumed boundaries.

As with the Line 1 results, the lower section (below elevation 5100 feet) of the model is dominated by a highly resistive (red color) layer that extends over the entire profile. This model layer, likely representing a response to native soil or bedrock, is disrupted by a conductive feature observed at approximately 615 feet along the profile. The conductive anomaly extends from the near surface down through the resistive lower layer, presenting an unusually sharp contrast and exaggerated depth that is not typical of landfill responses. This suggests interference from near surface infrastructure, such as a conductive metallic pipeline. In addition, this appears to correlate with a north-south trending feature observed in the electromagnetic data, located in the west section of the survey zone. Unlike Line 1 results, the lower resistive layer is not uniform and appears to change fairly substantially in magnitude from the start to end of the profile. However, it is likely that this layer would show continuous and uniform data throughout if it were not for the possible infrastructure feature.

The western side of the profile, from 0 to 250 feet, shows areas beyond the landfill boundary that still contain some interesting features. There is a decrease in the usual thin resistive surface layer between 150 and 250 feet along the profile. This lower resistivity zone appears to increase in depth as it progresses towards the western side of the profile. This may indicate a zone of increased moisture that is migrating away from the landfill.

A highly resistive surface layer (red color), approximately 12 to 15 feet (~ 3.5 to 4.5 meters) in thickness, extends from the start of the survey line to approximately 145 feet along the line.

This region was collected over a sloped topographic surface as the landfill hillside drops approximately 25 feet in elevation to the surrounding neighborhood. The resistive zone is likely an area of fill with lower moisture content as one would expect for a hill side slope.

Figure 10. Line 2 Electrical Resistivity Comparison with EM & Mag Slices.

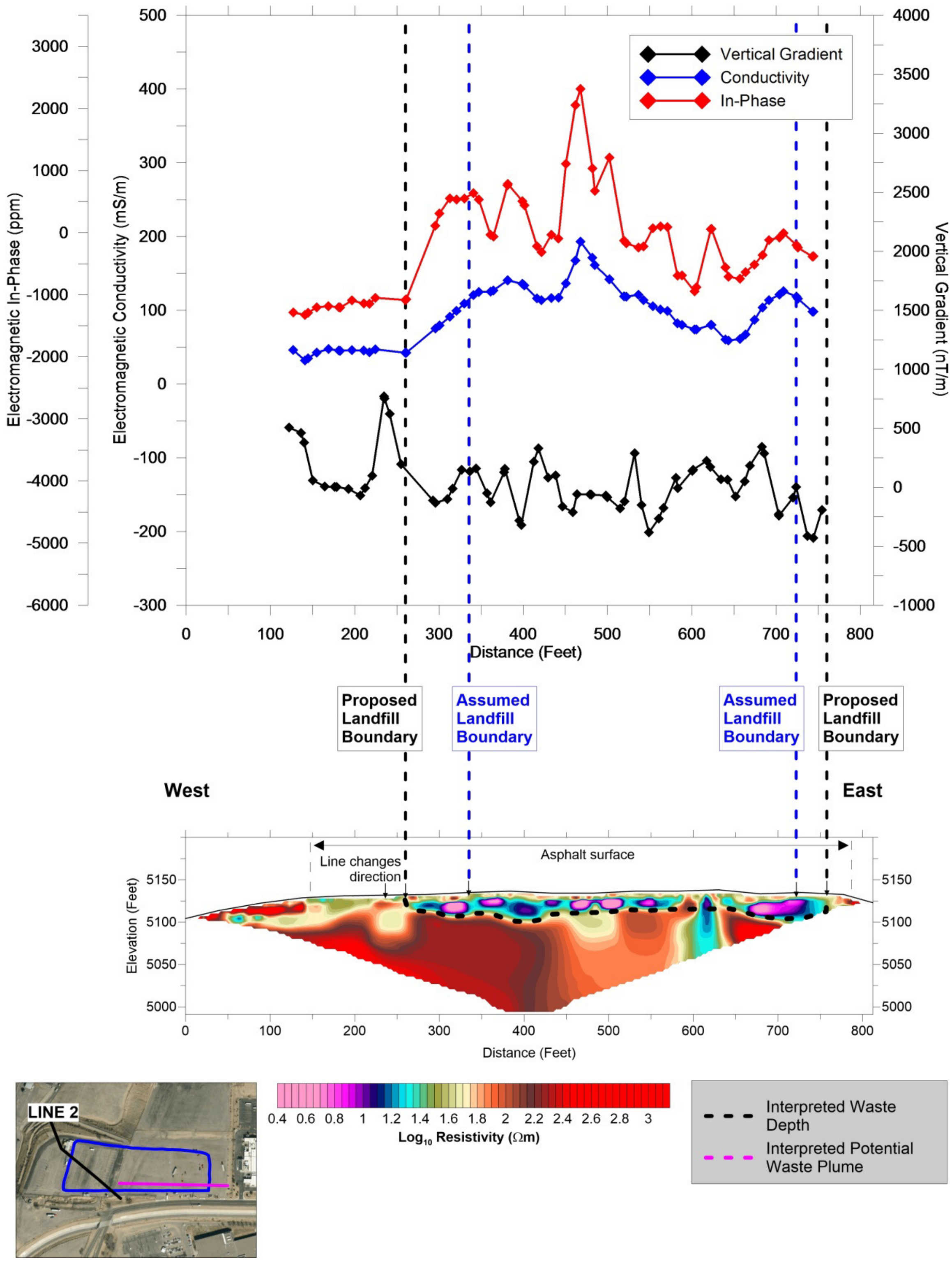
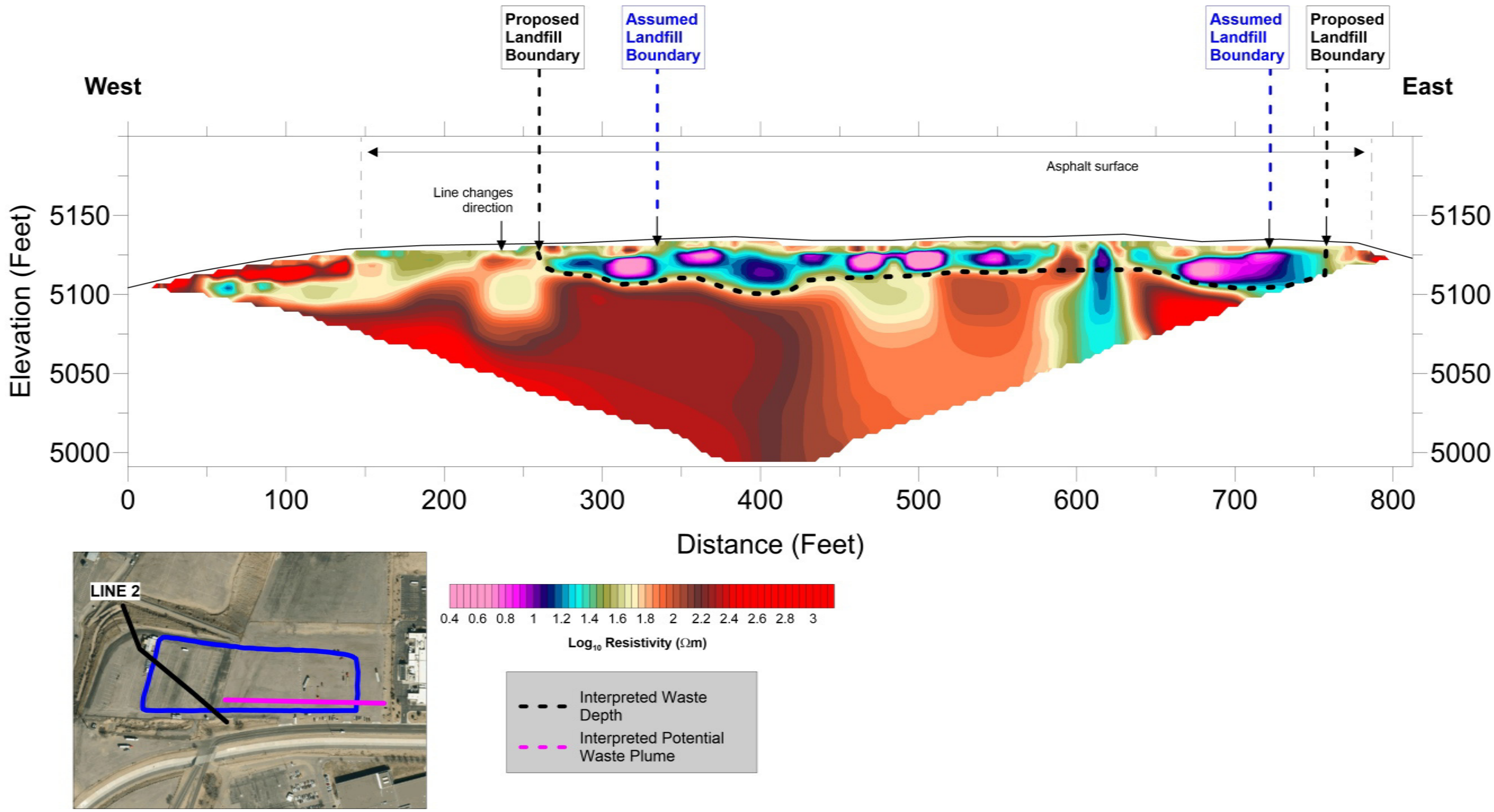


Figure 11. Line 2 Electrical Resistivity Profile.



5.0 CONCLUSIONS

A multi-method geophysical survey was performed at the Nazareth landfill in Albuquerque, New Mexico, in October to December, 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 were completed over the entire accessible landfill area, as well as two lines of 2D electrical resistivity. The EM and Mag measurements provided an indication of the lateral limits of covered landfill. The electrical resistivity imaging method added additional detail to 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 by this survey. In some areas, the pre-survey assumed landfill boundary was shifted based on combined analysis of the EM, Mag, and Resistivity results. The boundary was extended by approximately 30 feet (~ 10 meters) along much of the southern boundary and approximately 50 to 65 feet (~ 16 to 20 meters) west of the western boundary. The boundary receded by as much as 150 feet (~ 45 meters) within the northwest and southeast corners.

- 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 to 25 feet beneath the resistivity survey lines, with cover thickness estimated at approximately 5 to 7 feet. This is close to pre-survey assumed values averaging 30 feet for waste thickness and 4.6 feet for cover thickness.

6.0 REFERENCES

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APPENDIX A

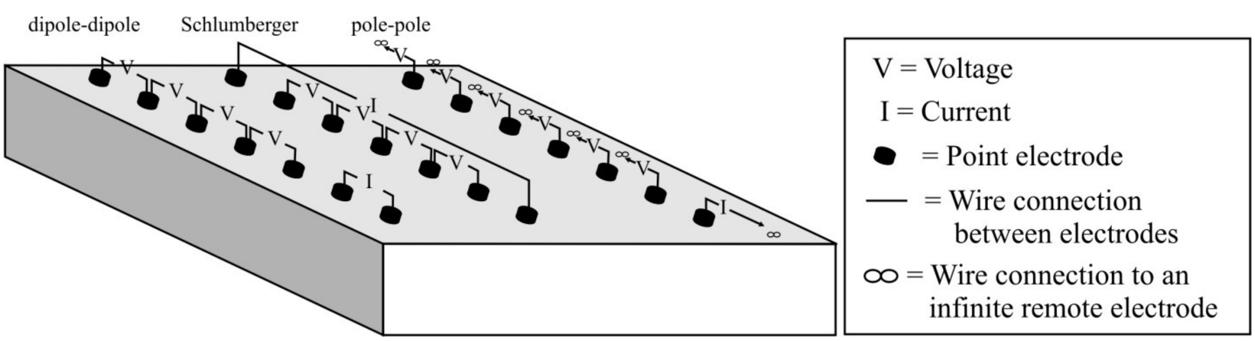
Description of Electrical Resistivity

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):

$$-\nabla \cdot \left[\frac{1}{\rho(x,y,z)} \nabla V(x,y,z) \right] = \left(\frac{I}{U} \right) \delta(x-x_s)\,\delta(y-y_s)\,\delta(z-z_s) \qquad (0)$$

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 (0) 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):

$$\left(J_i^T J_i + \lambda_i W^T W \right) \Delta r_i = J_i^T g_i - \lambda_i W^T W r_{i-1} \qquad (0)$$

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

$$\left(J_i^T R_d J_i + \lambda_i W^T R_m W \right) \Delta r_i = J_i^T R_d g_i - \lambda_i W^T R_m W r_{i-1} \qquad (0)$$

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 may be 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.