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Geophysical Survey of the Yale Landfill, Albuquerque, New Mexico

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1.0 INTRODUCTION

1.1 PROJECT DESCRIPTION

From October to December 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 Yale Landfill. A combined electromagnetic (EM) and magnetic (Mag) survey over the entire accessible landfill area, as well as five lines of two-dimensional (2D) Electrical Resistivity Tomography (ERT) were completed. This report documents results from data acquired at the Yale 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

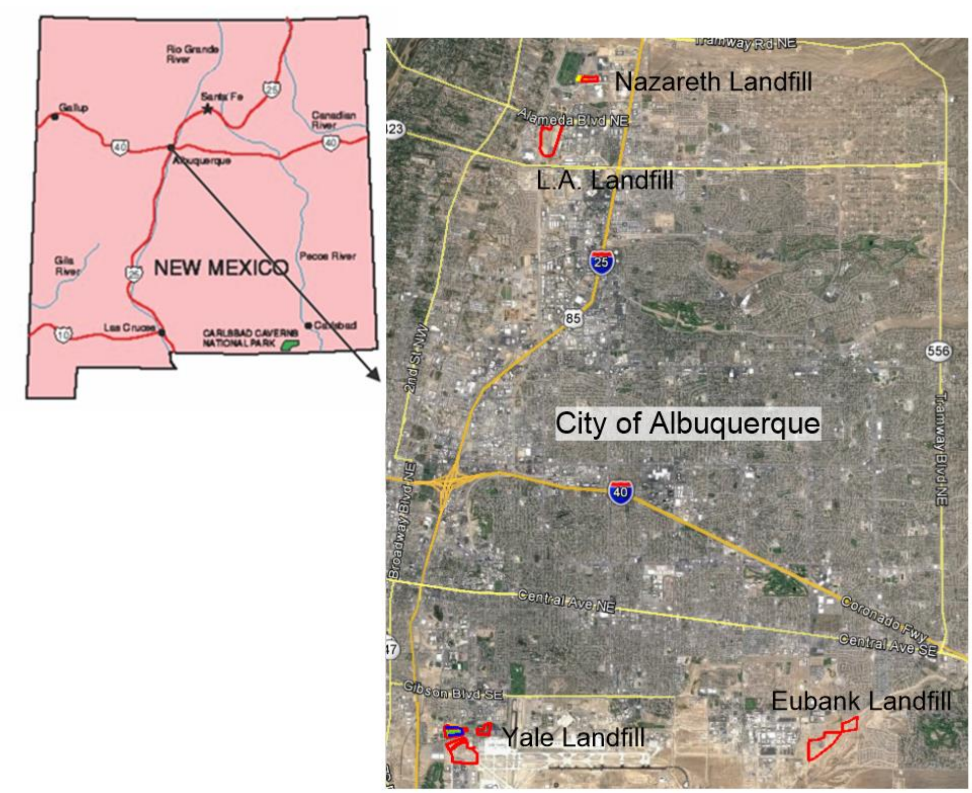
2.1 SITE LOCATION

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

The Yale Landfill is located at the northwest corner of the Albuquerque Airport. The landfill is split into several areas west of the airport, on either side of Sunset Blvd. The landfill operated during the years 1948-1965, with a total estimated waste tonnage of 1 million tons. Since 1965 Yale landfill has been open acreage. 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 Yale Landfill and cover; however, previous knowledge of the site estimates an average cover thickness of 4 feet, and average waste depth of 10 feet. These values may vary across the site. The total area covered within the assumed Yale landfill boundary is approximately 114 acres.

Figure 1. General Survey Location



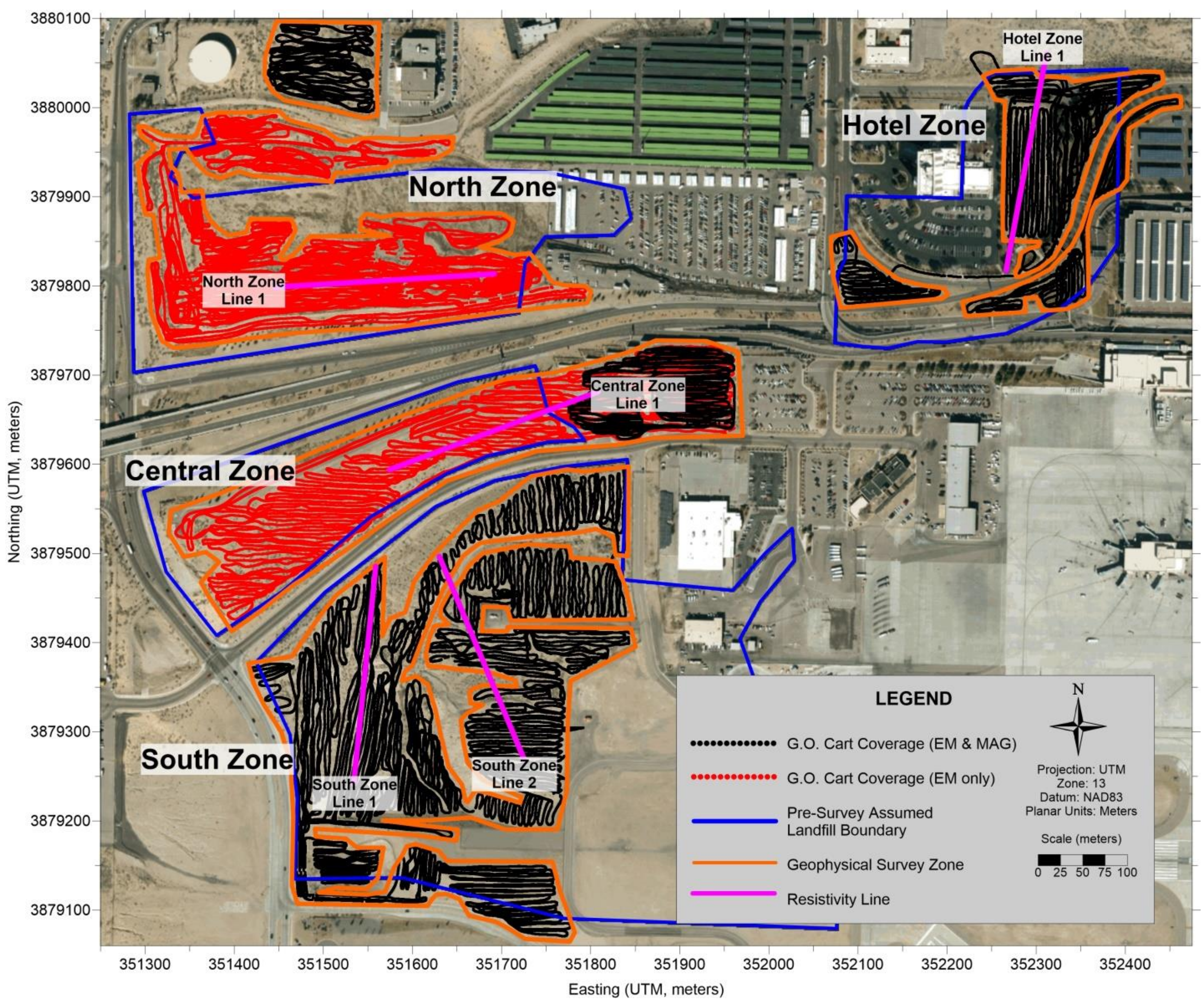
Aerial imagery © Google Earth 2016

3.0 METHODOLOGY

3.1 SURVEY AREA AND LOGISTICS

EM & Mag data were acquired between 10/20/16 and 11/7/16 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 (black lines) boundary (orange line) shown in Figure 2. The total area surveyed was approximately 80 acres; based on terrain and logistical constraints of accessing the total landfill area. The Yale landfill is divided into four general zones for the discussion of geophysical results: Hotel Zone, North Zone, Central Zone, and South Zone, as shown on Figure 2. The boundaries of these zones are largely determined by roads, fences, and the terrain, all of which resulted in a complex, segmented data coverage.

Figure 2. Detailed Survey Coverage Map of Yale Landfill.



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.

Resistivity data consisted of five lines of data, each approximately 817 feet long, with approximately 4,085 feet of total line coverage. The locations of the survey lines are shown as pink lines in Figure 2. Table 1 lists specific parameters for the resistivity survey lines.

Table 1. Resistivity Survey 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
North 1	12/10/16	10	817	S-N	352266, 3879818	352311, 3880061
Central 1	12/10/16	10	817	W-E	351574, 3879594	351808, 3879681
South 1	12/11/16	10	817	S-N	351534, 3879241	351558, 3879485
South 2	12/11/16	10	817	S-N	351725, 3879269	351630, 3879497
Hotel 1	12/12/16	10	817	W-E	351445, 3879799	351691, 3879814

The survey areas varied widely in terrain, with some areas being easier to traverse than others. There were a number of areas that could not be surveyed due to high density of surface debris and vegetation, or significant topographical relief that would have created safety issues. Some examples of the problematic vegetation and terrain are highlighted in Figure 3. In addition, parts of the site could not be surveyed due to roads (with sidewalk areas), highway overpasses, buildings, parking lots, access restrictions to areas within the Albuquerque International Airport, landscaped areas, and surface debris as follows:

- South Zone – Limited portions of this area contained paved roads, significant topography and-or high density vegetation that precluded survey coverage for safety reasons. During the time of surveying, access to the Airport property was not available and therefore, these areas were not covered as part of this survey.
- Central Zone - Challenging topography and vegetation caused significant vibration and bumping of the geophysical instrumentation, resulting in several instrument failures. As a result, areas that presented significant erosional features with undulating topography and-or vegetation could not be fully surveyed using the magnetometer. Therefore, Magnetics data was not collected over a significant portion of this zone, but the less

sensitive Electromagnetic data was completed. The northern boundary contained large trees and significant topography as it approached the highway, preventing survey coverage.

- North Zone – Survey coverage within the North Zone was limited based on access restrictions due to topography, vegetation, erosional features causing significant instrument vibration, steep side slopes and some areas contained exposed landfill waste with a large amount of broken glass and sharp metals. Magnetic data could only be collected in a small portion north of the expected landfill area, and all available coverage within the expected landfill boundary was limited to Electromagnetic data. A portion of the site, to the east, was contained within a private parking area where access was restricted.
- Hotel Zone - This area is located just north of the airport along the main airport entrance and contained several high traffic roads and highways with overpasses. Survey coverage was not completed on or surrounding roads. Many of the areas adjacent to the roads contained landscaped gardens that contained steep topography and above ground obstacles (large trees, signs, statues, etc.) that restricted survey coverage. A large hotel and its associated parking lot occupied a large portion of this survey area and could not be covered due to access restrictions and surface obstacles.

Figure 3. Photographs of Problematic Terrain at Yale Landfill.

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 4. 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 4. Geophysical Operations (G.O.) Cart.

Heads-Up Navigation System

Magnetic Sensors

GPS Antenna

Magnetic Data Acquisition System and GPS Data Acquisition System

Electromagnetic Sensor & Data Acquisition System

3.2.1.1 Magnetic Gradiometry

A G-858G dual-sensor gradiometer (Geometrics, Inc., San Jose, CA) was used to provide magnetic (Mag) 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.

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

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 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. In addition, data are corrected for diurnal changes by normalizing to a local base magnetometer. 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 10 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 5, Figure 9, and Figure 13 show the full results of the EM conductivity (sensitive to bulk conductivity changes), EM in-phase (sensitive to bulk metal), and Magnetic vertical gradient (sensitive to ferrous metal only) survey for the Hotel, North, and Central/South Zones, respectively.

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/purple and blue hues indicating anomalous areas, and yellow hues representing background values.

The data show heterogeneity throughout the survey site, generally 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 goal for the EM and Mag surveys was to provide an interpreted spatial waste boundary, delineating the landfill extent. However, as indicated earlier, the survey zones in the Yale Landfill area were heavily fragmented due to site safety and logistical constraints. Additionally, it is apparent that numerous construction projects (roads, highways, runway extension, and buildings) have occurred post landfill closure. The area appears to have been heavily altered, with potential for disturbance to the subsurface soil and waste distribution, making it difficult to provide confident delineations regarding the landfill boundary across certain areas. Within the greater pre-survey assumed landfill boundaries we observe responses that are typical of landfill waste material, however significant sections within these boundaries lack any landfill type responses. In many instances, there is not a clear basis (or insufficient data) for interpreting landfill boundaries using the EM and Mag results alone. Furthermore, in areas that do not appear to exhibit landfill waste type responses, it is unclear whether we are observing clean backfill related to construction or undisturbed background soils.

The resistivity results provide clarity in areas where the resistivity data was collected, but without additional resistivity (or other data) information these sites in most cases are too disturbed for any clear interpretations to be made regarding the landfill spatial boundaries. That said we can make some general statements of what was observed in the EM and Mag results in the following areas:

Hotel Zone:

The majority of the area surveyed in this zone was within the assumed landfill boundary, and there are a number of high amplitude responses in both the EM and Mag results that are typical of landfill waste responses. However, the majority of detected geophysical features appear indicative of non-landfill type materials such as above and below ground infrastructure. The following observations can be made:

- Above ground infrastructure features: There are several linear anomalies, appearing to border the dirt lot just east of the hotel, that are indicative of above ground infrastructure responses to walls and fences that ring the perimeter. This is most evident in the EM in-phase (dark blue feature) and the EM conductivity (light yellow with brown feature) results, with a north-south trending feature that is located to the east of the dirt lot by a large concrete wall (highlighted by the wall label in Figure 5). The remaining perimeter of the dirt lot has a metal fence that is visible in the EM and Mag data.
- Subsurface infrastructure features: There are also responses to possible subsurface infrastructure (pipelines, utilities) in several locations within the survey area, notably in the EM in-phase (dark blue feature) running in an east-west direction along the road that is directly north of the hotel (highlighted by the upper infrastructure label in Figure 5). Additional features typical of subsurface utilities are observed, such as the east-west trending feature on the lower southeast portion of the survey area, that is most prominent on the EM in-phase, and the north-south oriented feature (dark blue feature) to the far west along the airport entry road (highlighted by the lower infrastructure label in Figure 5).
- Potential waste features: Two separate "waste like" areas are evident in both EM and Mag data sets. The first is observed as the high frequency magnetic and EM in-phase responses observed in the central area of the dirt lot (east of the hotel building). The character of this feature is consistent with landfill waste, but there is no associated EM conductivity response. Therefore, it is likely that the Mag and EM in-phase responses are caused by small, distributed, and shallow metallic debris. This is supported by the resistivity results for Hotel Zone Line 1, which shows a very resistive feature in this location (350 to 450 feet along resistivity line) which is typical of clean soil. It is possible this feature is the result of construction debris from the building of the hotel. The second waste feature is only evident in the EM conductivity plot, as the yellow and brown feature located at the southwest corner of the dirt lot. This feature is consistent with increased subsurface moisture and-or landfill waste and is supported by a matching

conductive feature between 125 and 300 feet along the resistivity Hotel Zone Line 1 results.

The EM and Mag results for the Hotel Zone are shown in greater detail in Figure 6, Figure 7, and Figure 8.

Figure 5. Contoured EM and Mag Results, Yale Hotel Zone.

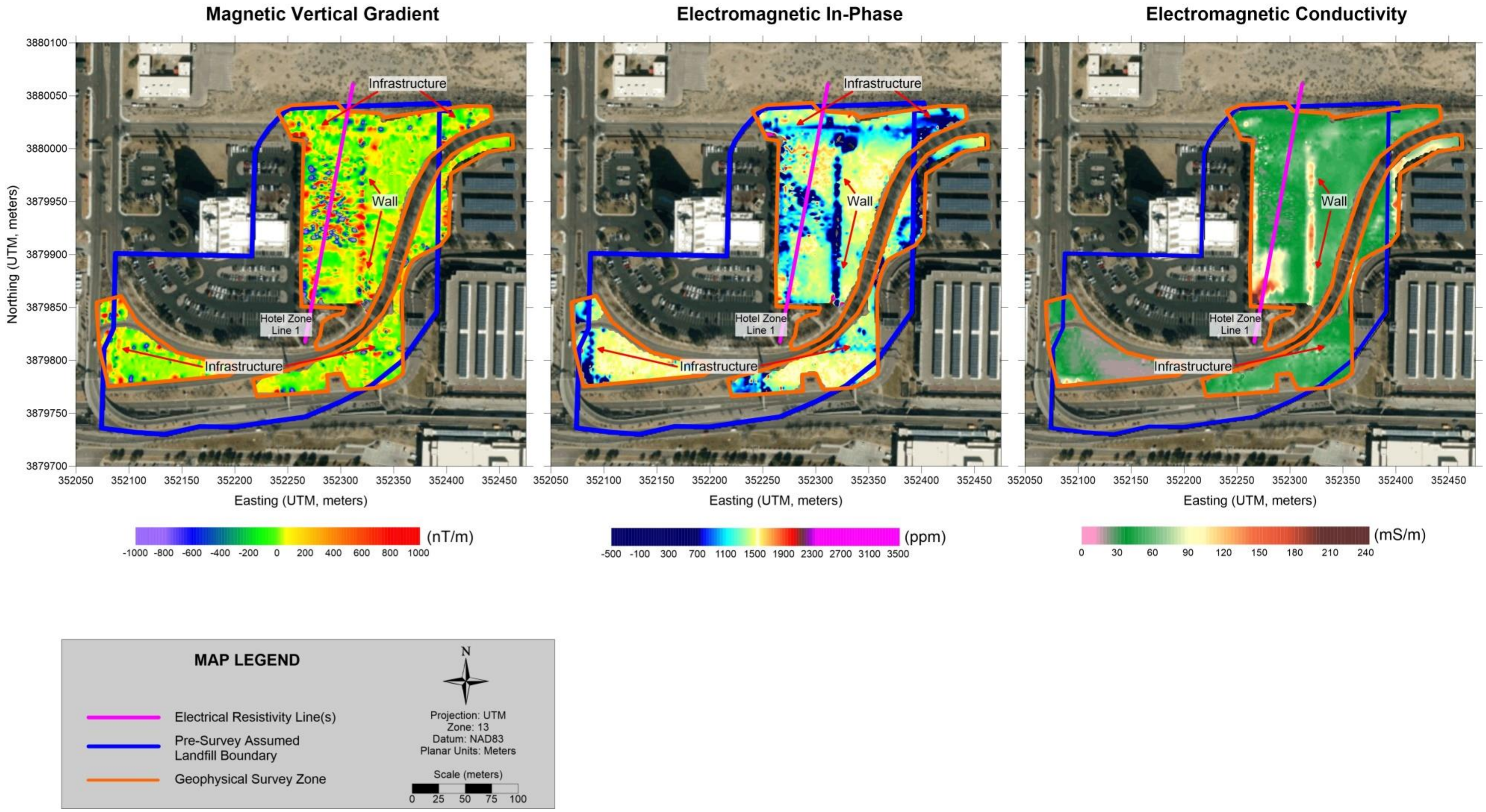


Figure 6. Contoured Magnetometry Vertical Gradient (nT/m), Yale Hotel Zone.

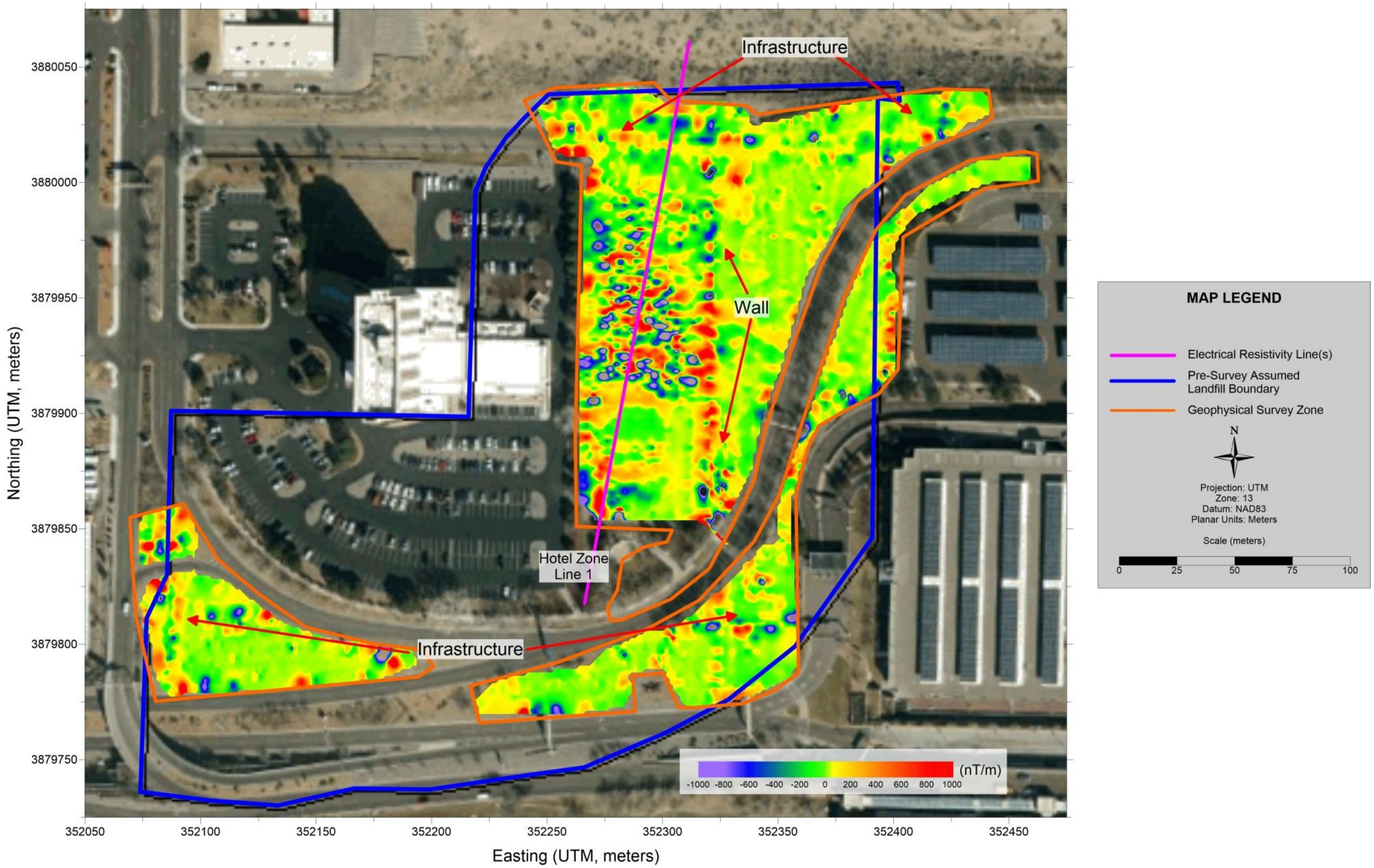


Figure 7. Contoured Electromagnetic In-Phase (ppm), Yale Hotel Zone.

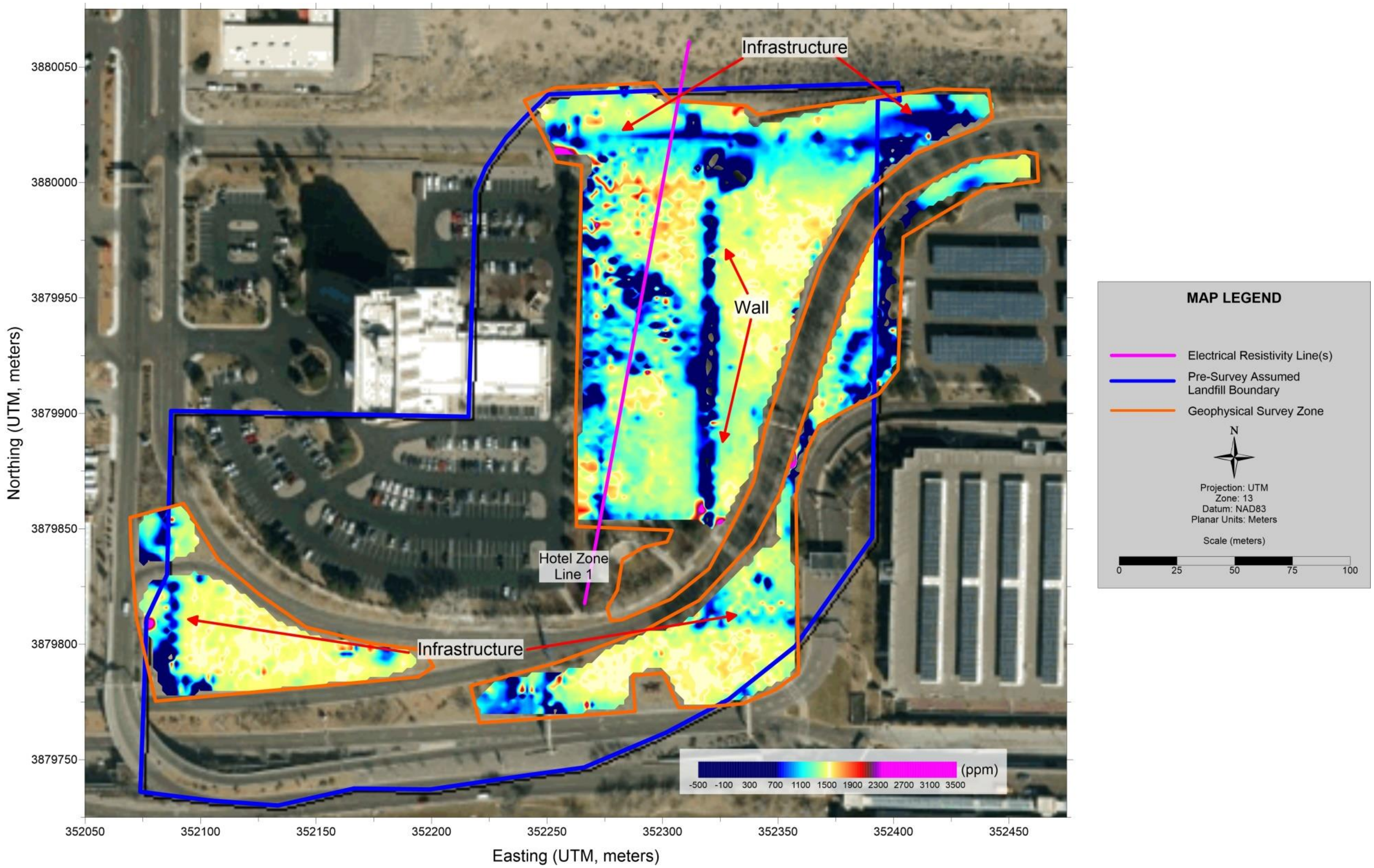


Figure 8. Contoured Electromagnetic Conductivity (mS/m), Yale Hotel Zone.

North Zone:

Survey coverage within this zone was limited and discontinuous due to site topography and safety restrictions. For the purposes of reference to help with this discussion, we have further subdivided the North Zone, and marked the three areas with an A, B, and C notation on Figure 9. In addition, Mag data could only be collected Area A of this zone due to significant site terrain that was damaging to the instrument, as previously discussed in this report. Above ground infrastructure was limited to metallic fence lines and overhead power lines:

- Fences: There is an linear EM in-phase and EM conductivity response that correlates with a metallic fence line running near the western and southern survey boundaries (highlighted by the black line in Area C of Figure 9). In some areas, it is difficult to separate the fence feature from potential landfill waste responses. An example of this can be seen along the southern boundary in the EM in-phase results where the narrow linear feature merges with broad high magnitude responses that are more typical of landfill waste response.
- Overhead power line: One overhead powerline was observed within the property and trends in an east-west direction through the area B on Figure 9 (light blue line) and turns to run due south into Area C. There is a small hint of a response to this feature in the EM in-phase data, but in general it does not appear to significantly impact the geophysical data.

Interpreting geophysical data involves identifying the relative change in response magnitude between the target (landfill waste) and background (undisturbed or clean soil) geology. Therefore, it’s important to extend the survey beyond the assumed landfill boundary in order to differentiate the waste and background responses. In this case, the assumed landfill boundary occupied almost all of the available survey area, with roads and buildings occupying the majority of the area outside of the landfill. The only area available to map expected background conditions was the northern area (Area A), between the water storage tank and the Department of Homeland Security building along Randolph Road. EM conductivity and in-phase response in this area, located outside of the assumed landfill boundary, is low magnitude and represents undisturbed soils. Our hope was to use the geophysical response magnitude in this vicinity as a control to identify areas free from landfill waste in the remaining survey area.

Survey area B, located south of the background Area A, shows similar background low-magnitude response for EM in-phase (light yellow shades) and conductivity data (green shades). The only exception being a small EM in-phase response (red orange shades), directly south of the Homeland Security building, where a paved concrete road appears to contain metal infrastructure. This survey area is located north of the assumed landfill boundary and does not appear to contain any landfill waste material based on the flat EM response.

The southernmost survey area, Area C, is located within the assumed landfill boundary and the EM results show varying responses that are typical of landfill waste, while others show low-magnitude responses that may represent background or backfilled materials. Unfortunately, the limited coverage, in particular the gap in coverage to the north of this survey area, makes it challenging to place a definitive boundary around the landfill waste. There is excellent agreement between the high-magnitude EM responses and the one available resistivity line (North Zone Line 1), where the EM responses correlate well with conductive responses on the resistivity section. However, without additional resistivity data or sampling information, it is not possible to interpret a specific landfill boundary. In general, we can say that landfill material appears to be present within the assumed landfill boundary and does not appear to be present north of the assumed boundary.

The EM and Mag results for the North Zone are shown in greater detail in Figure 10, Figure 11, and Figure 12.

Figure 9. Contoured EM and Mag Results, Yale North Zone.

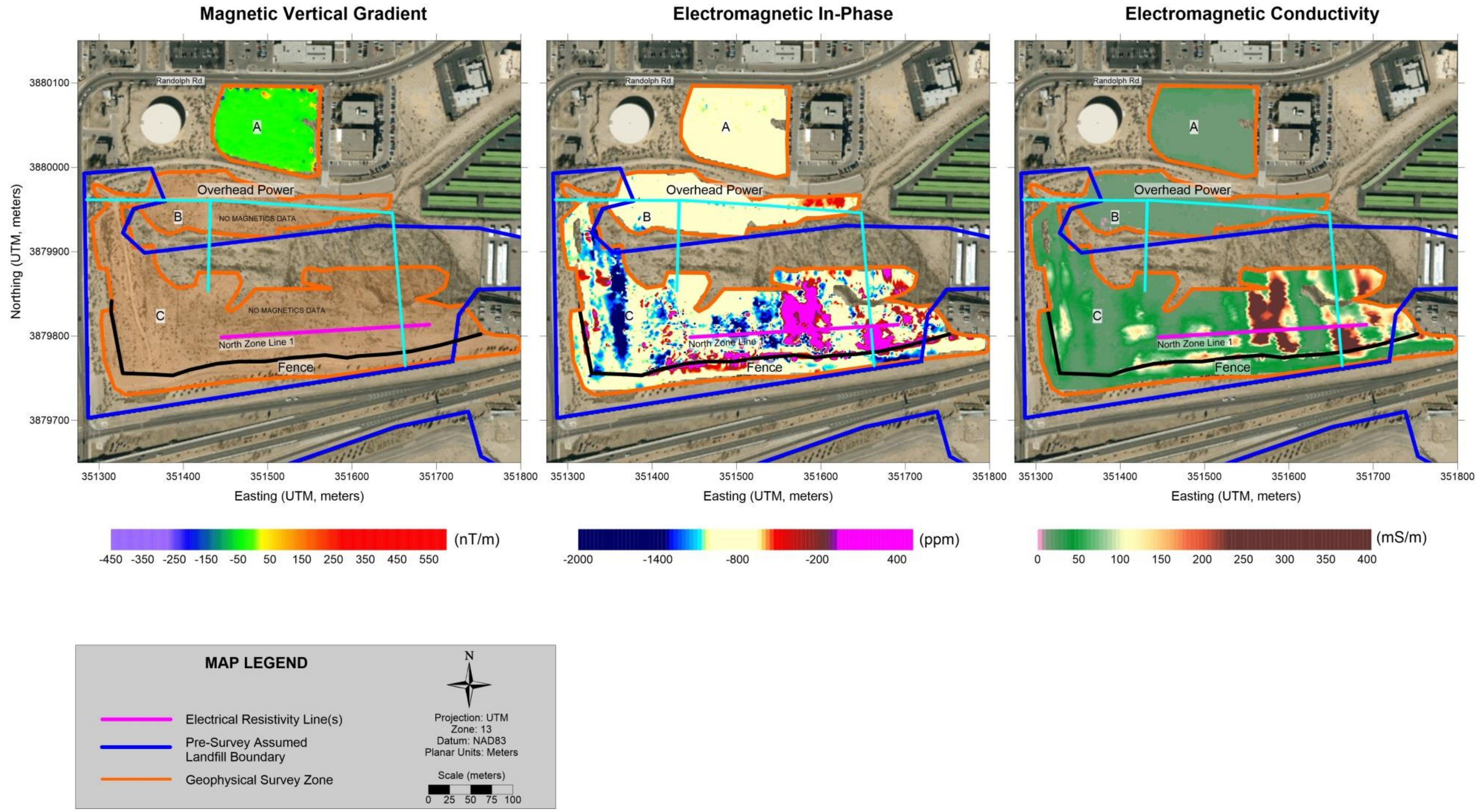


Figure 10. Contoured Magnetic Vertical Gradient (nT/m), Yale North Zone.

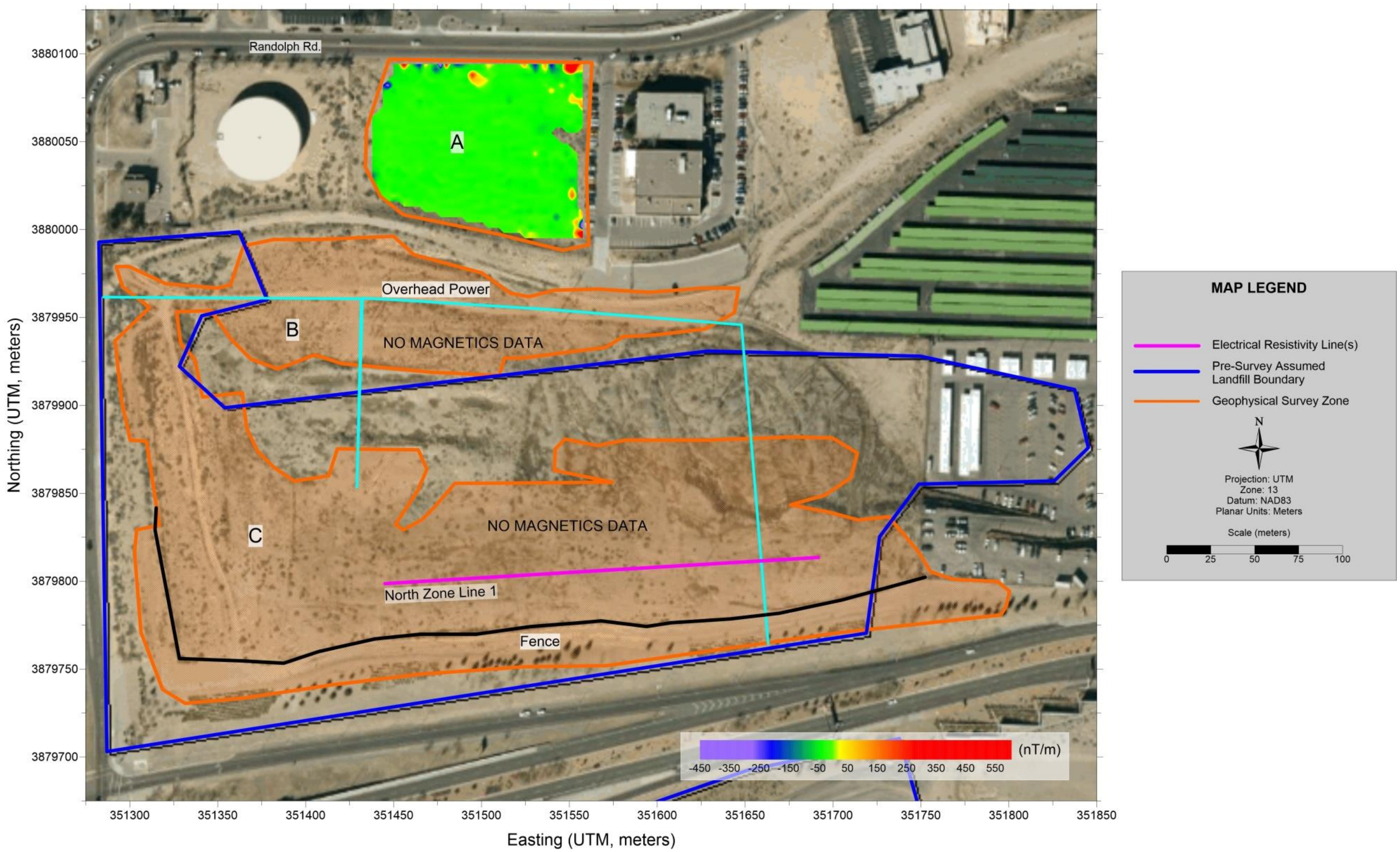


Figure 11. Contoured Electromagnetic In-Phase (ppm), Yale North Zone.

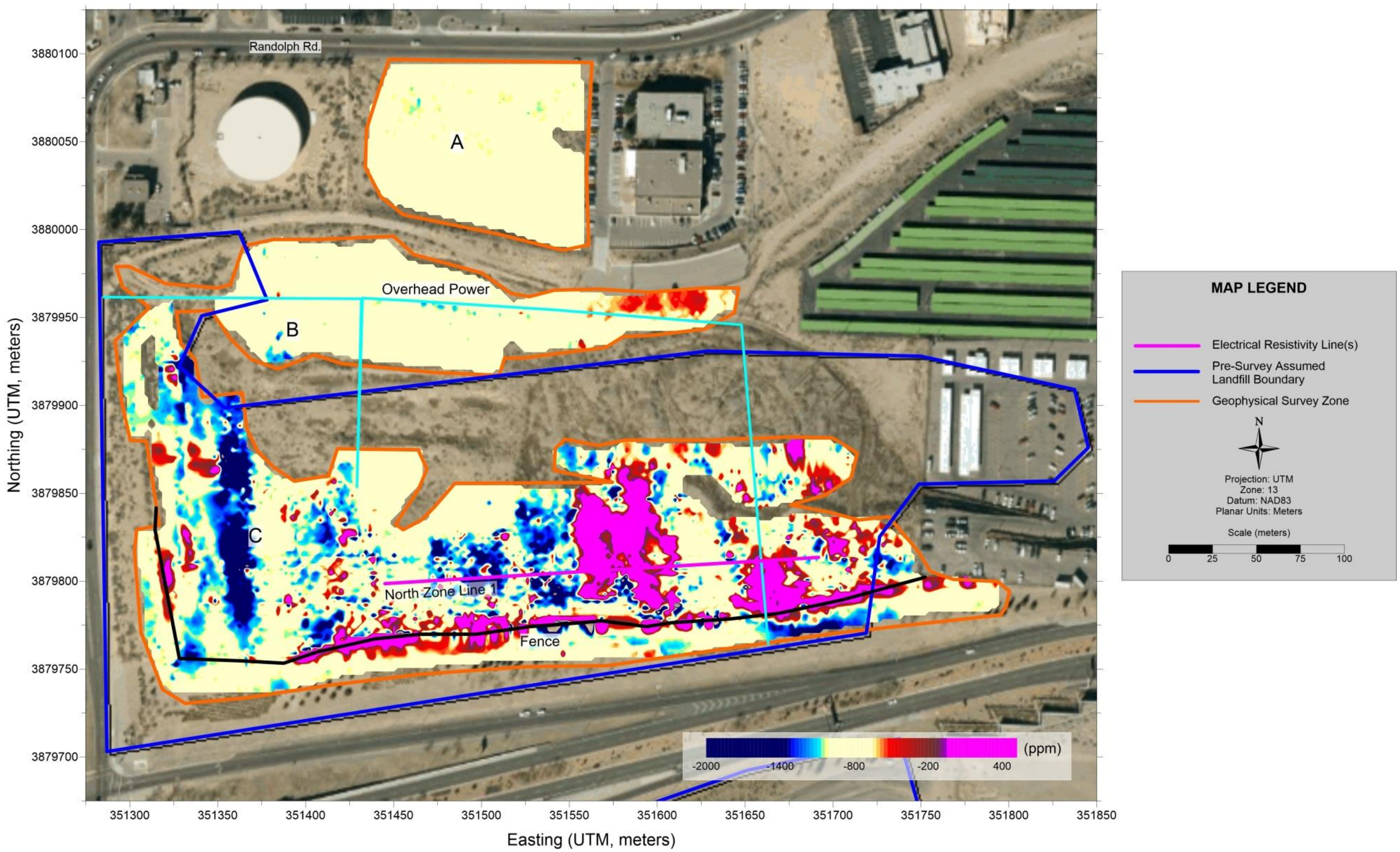
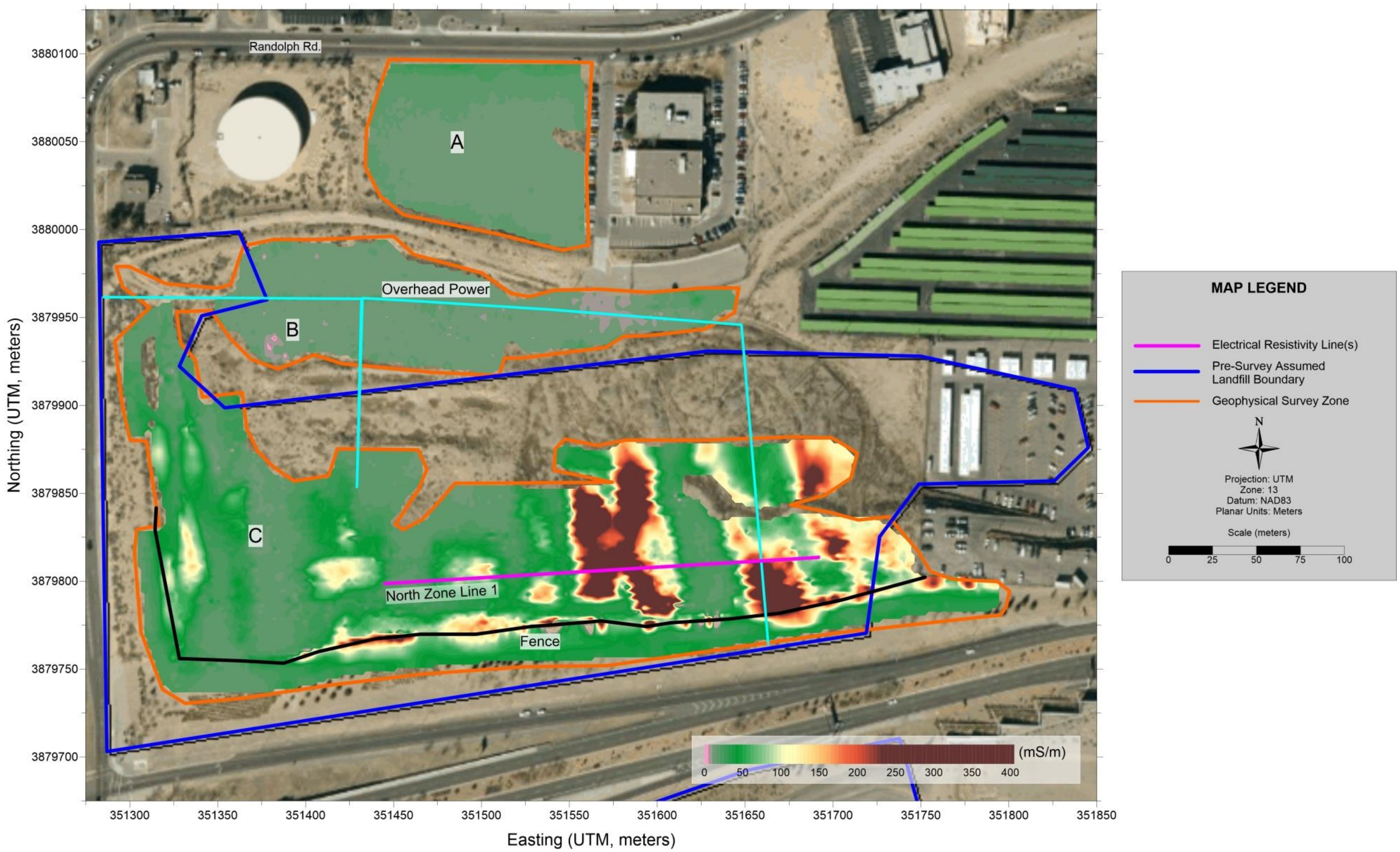


Figure 12. Contoured Electromagnetic Conductivity (mS/m), Yale North Zone.



Central Zone:

The Central Zone contained significant topography and erosional features that created significant impact to the geophysical instruments. As mentioned in prior sections, the magnetometer was unable to function under the bumpy conditions and resulted in limited data coverage for this area; however, EM data was collected continuously over the site. Data was collected to the east of the assumed landfill boundary over an area believed to be free of landfill waste, representing background conditions. In general, for Figure 13, assumed background conditions are represented with a green color in the Mag plot, light yellow in the EM in-phase plot, and a dark green color in the EM conductivity plot. Within the background area, the Mag data show a response (orange and red color) to the large highway wall on the northern edge of the area (which undoubtedly contains significant metallic reinforcement), and a response to subsurface infrastructure along the southern edge of this area.

Two linear features are evident on all geophysical parameters and likely represent responses to subsurface infrastructure. These are highlighted with a light blue line on Figure 13, and run from the east side of the survey area, through towards the highway. The Central Zone Line 1 resistivity line displays good agreement to the EM and Mag results, with two features observed in the resistivity section corresponding to the infrastructure locations.

Within the assumed landfill boundary, the EM in-phase and conductivity results both show varying zones of high amplitude responses typical of landfill waste, and also those which represent background materials. The EM conductivity data shows high magnitude responses (yellow to brown shades) over the majority of the Central Zone, with features running to the edge of the survey area on the north and west sides. In looking at Figure 13, note that the survey coverage boundary, shown with the orange line, could not extend to the assumed landfill boundary, shown with a blue line, due to topography and landscaping associated with the highway. Therefore, we cannot determine if the landfill waste extends beyond the assumed boundary along the north and western sides. Some of the waste responses extend to the southern boundary and suggest they could continue south under George Road SE towards the South Zone. This is consistent with the landfill likely predating the road; however, we can’t determine if the waste was removed prior to road construction. Landfill waste responses appear to be contained within the eastern assumed landfill boundary.

In general, there is agreement between EM in-phase (metal), EM conductivity (increased soil conductivity), and resistivity data. The resistivity profile shows a subsurface conductive feature, indicative of landfill waste, over the western half of the survey line, where EM conductivity data shows a conductive response. However, there is an area near the western survey boundary where there is a very large EM in-phase response, suggesting the presence of metal that is not accompanied by an EM conductivity response. This may represent metal waste in close proximity to the surface that may have been dumped after the main landfill which would place it at a higher elevation.

The EM and Mag results for the Central Zone are shown in greater detail in Figure 14, Figure 15, and Figure 16.

Figure 13. Contoured EM and Mag Results, Yale Central and South Zones.

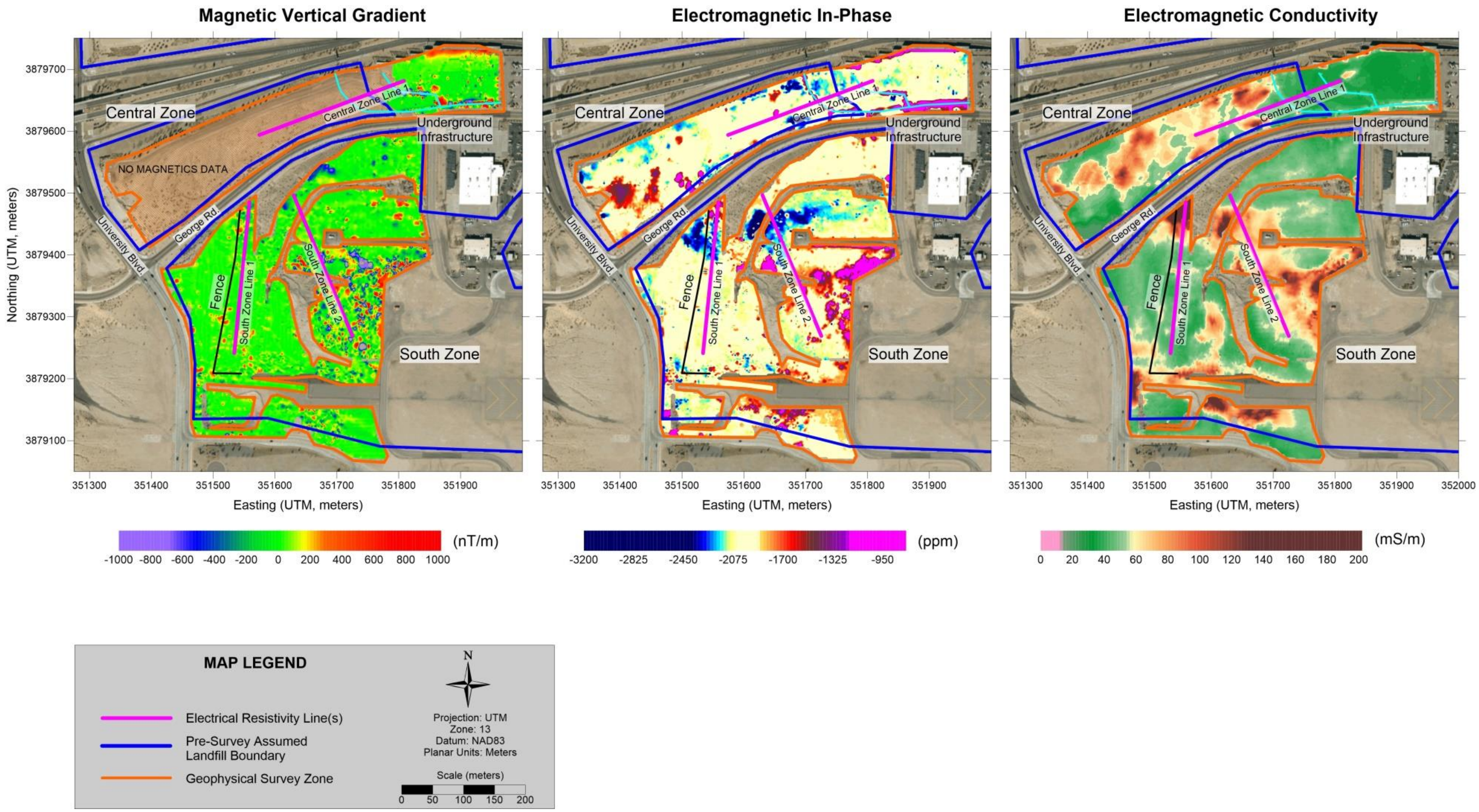


Figure 14. Contoured Magnetic Vertical Gradient (mT/m), Yale Central Zone.

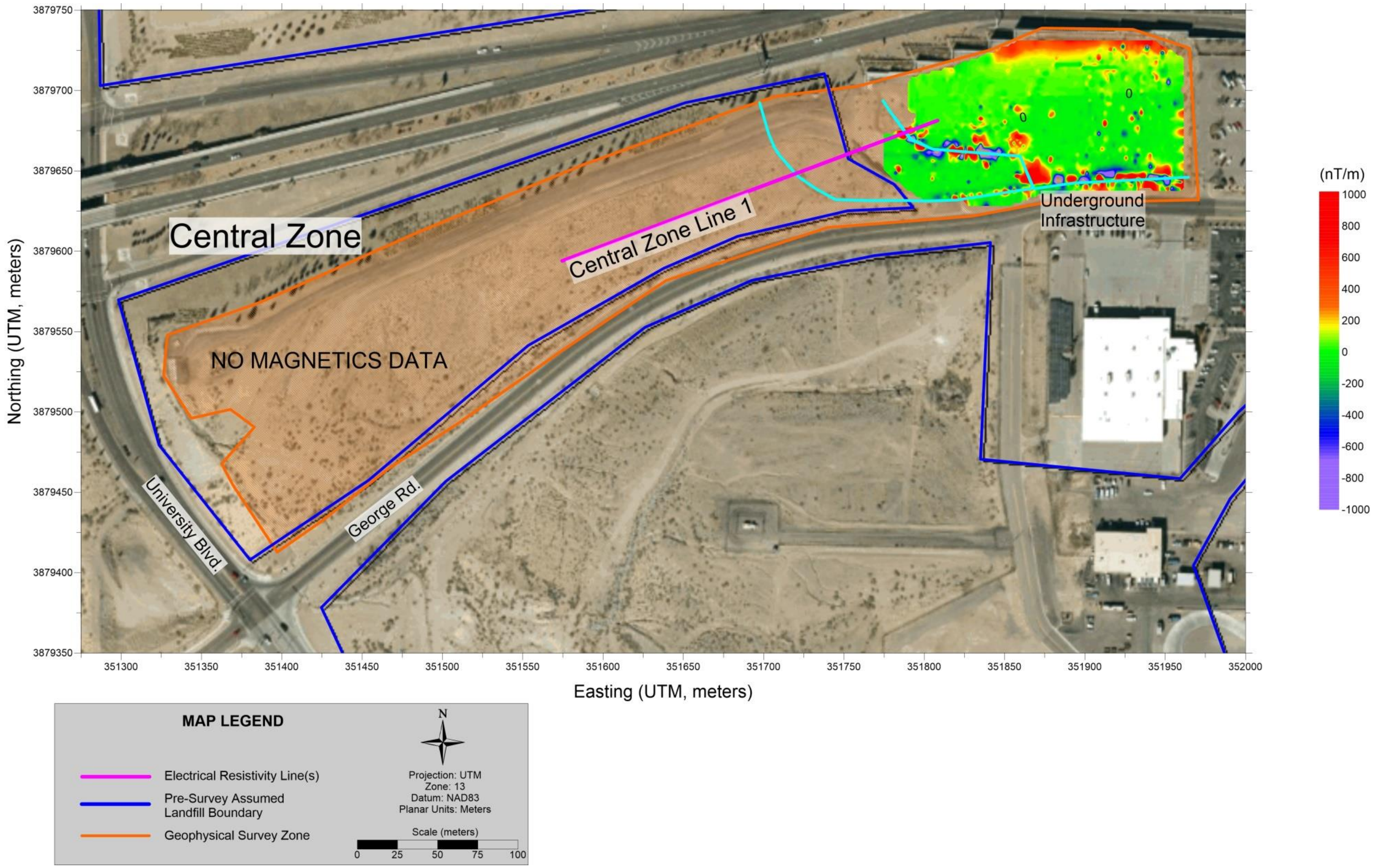


Figure 15. Contoured Electromagnetic In-Phase (ppm), Yale Central Zone.

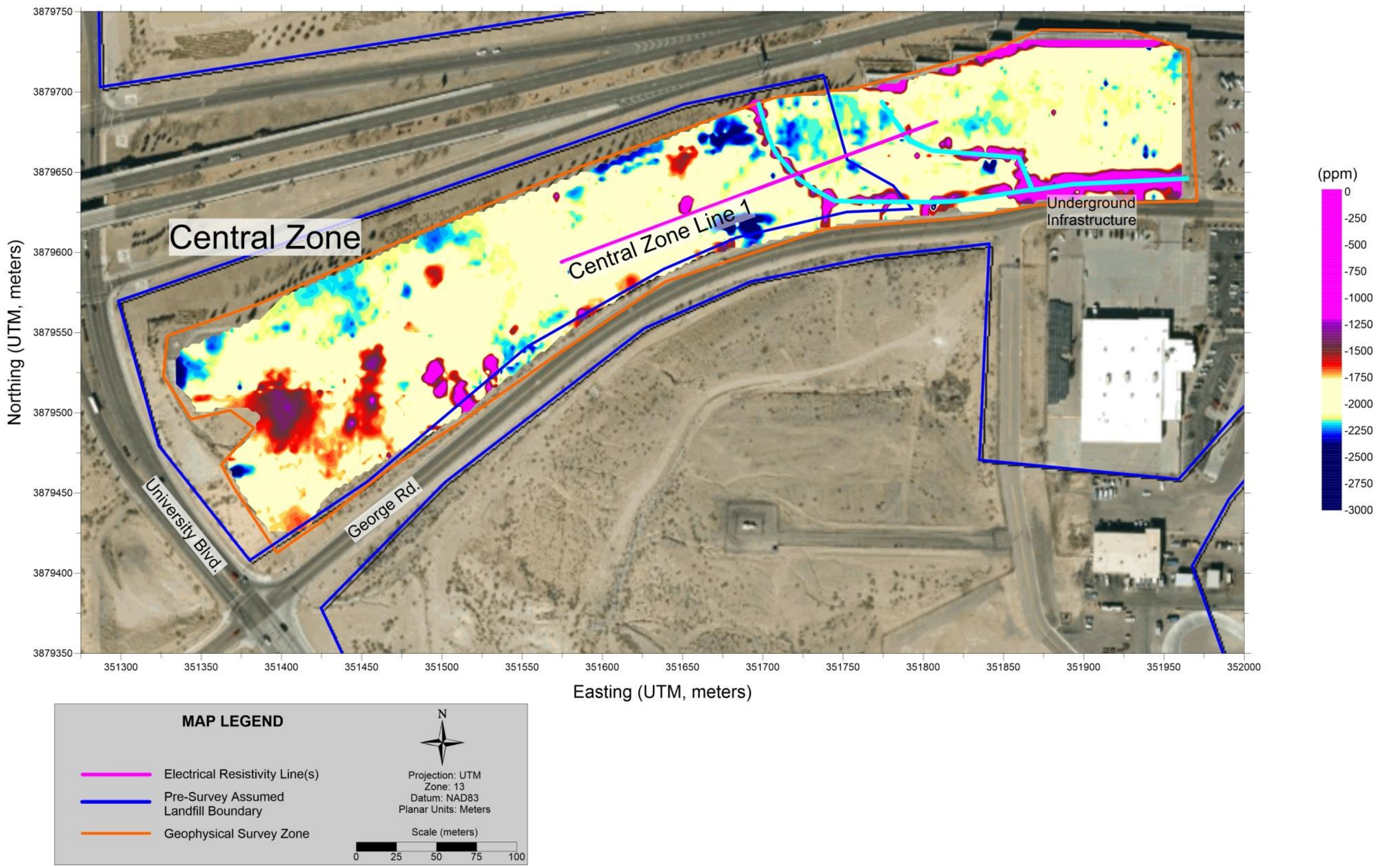
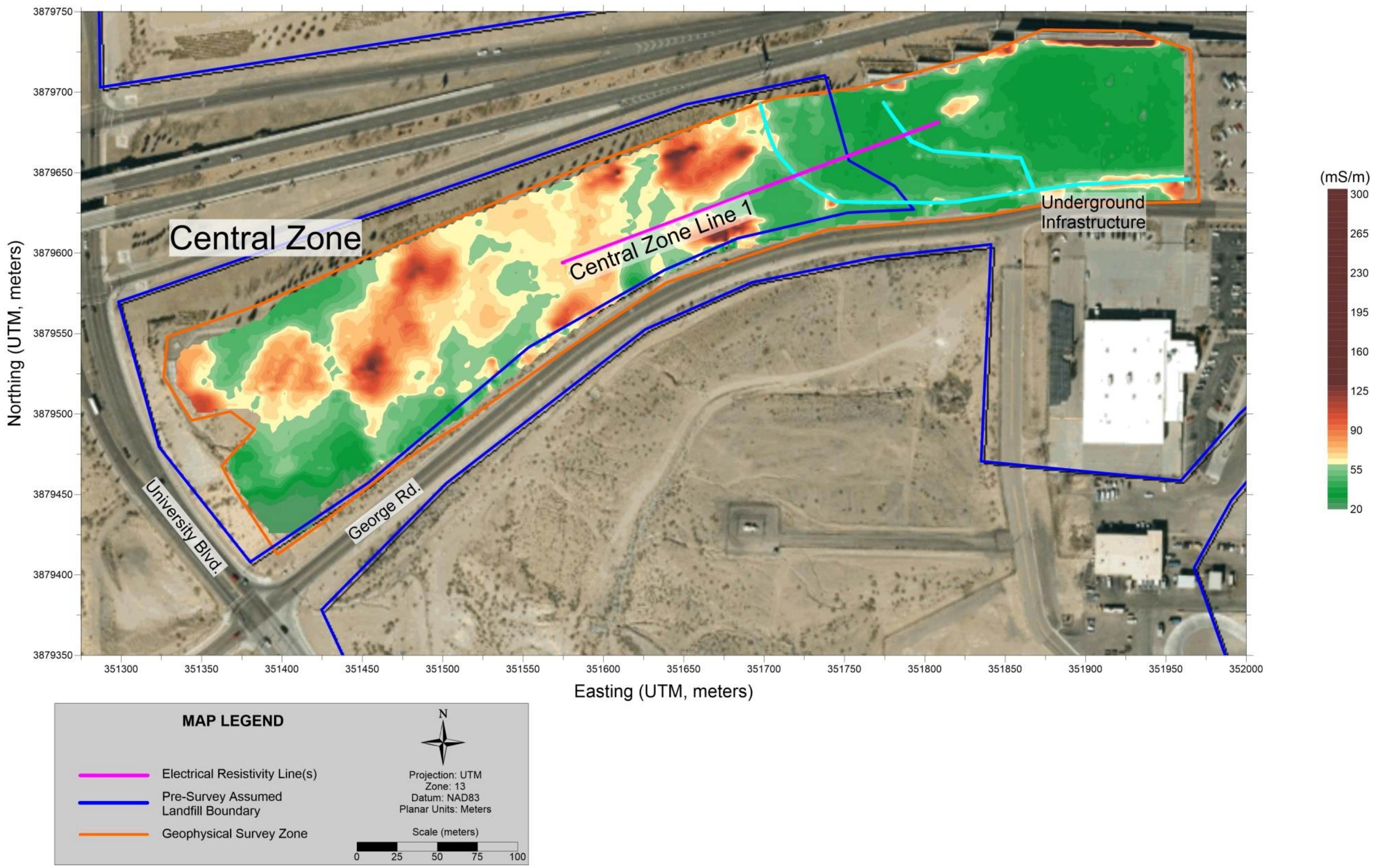


Figure 16. Contoured Electromagnetic Conductivity (mS/m), Yale Central Zone.



South Zone:

The South Zone was by far the most technically challenging area from a data collection standpoint, because it involved significant topography due to the uneven landfill surface, airport construction soil rework, large erosional areas, fences, excavation areas, and above ground infrastructure. In addition, the EM and Mag data was collected almost entirely within the assumed landfill boundary with little ability to collect background data in areas believed to be free of landfill waste. The survey area is fragmented where data collection was not possible due to site topography and logistical difficulties. There is good agreement between the three geophysical parameters with landfill waste-like responses being evident in the same location for all methods. There is little response to subsurface or above ground infrastructure, other than in very close proximity to the airport perimeter fence.

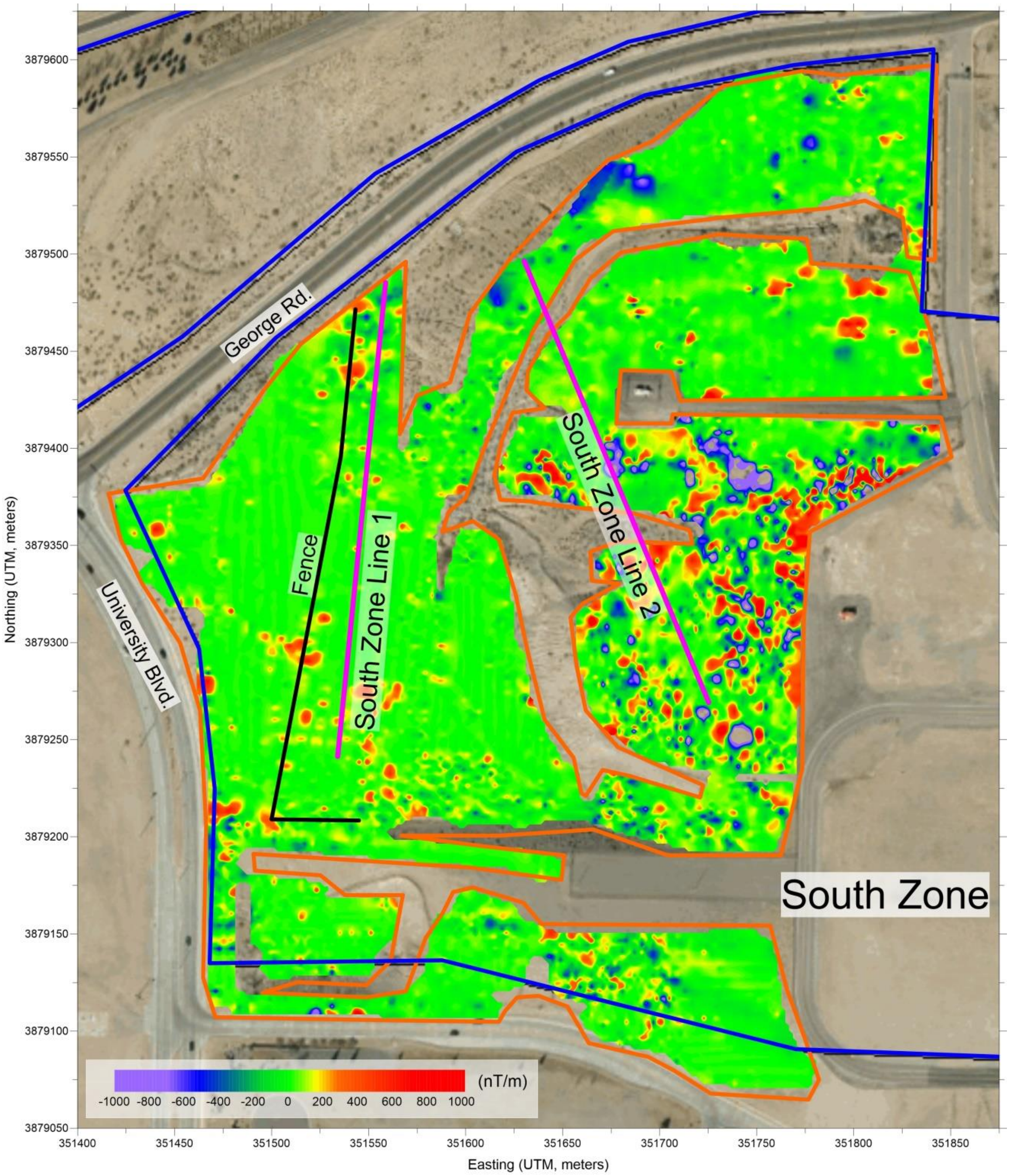
There are two main areas of high amplitude responses, indicative of landfill waste, shown in Figure 13. The first is a broad area, starting from the eastern survey boundary, along the airport fence line, extending northwest towards the Central Zone, and likely continuing under George Road SE. The response appears to extend beyond the eastern survey boundary into the airport property, which is consistent with the location of assumed landfill waste. Unfortunately, access to the airport area was restricted at the time of surveying so we can’t confirm the extent of the landfill material in this area.

The second response area is located towards the southern portion of the survey area, running in a generally east-west orientation. A portion of this response was not mapped as it appears to run beneath the runway light fenced-off extension, located west of the main airport runway. There appears to be a response on both sides (south and north) of this fenced-off area which suggests the possibility of landfill waste beneath the runway light area. This response area extends to the western edge of the survey area, University Blvd., which is coincident with the assumed landfill boundary. The abundance of high-magnitude response along this boundary suggests it is possible that landfill wastes extend beyond the assumed boundary in this vicinity, continuing under University Blvd.

The remaining area appears to be free of typical high-magnitude landfill responses, as indicated by the respective background colors for each geophysical method. One example of this is in the vicinity of the South Zone Line 1 resistivity line, which appears to only encounter landfill type responses on the northern portion of the resistivity line. In contrast, review of the South Zone Line 1 resistivity cross-section shows the presence of a thin conductive layer, indicative of landfill waste (or at least increased soil moisture), over the majority of the survey line. This may be an example where the physical property contrast between the waste and the surrounding soil is insufficient for the EM method to detect, and-or in some locations the waste depth may be greater than the depth of investigation limits for the EM and Mag detection.

The EM and Mag results for the South Zone are shown in greater detail in Figure 17, Figure 18, and Figure 19.

Figure 17. Contoured Magnetic Vertical Gradient (mT/m), Yale South Zone.



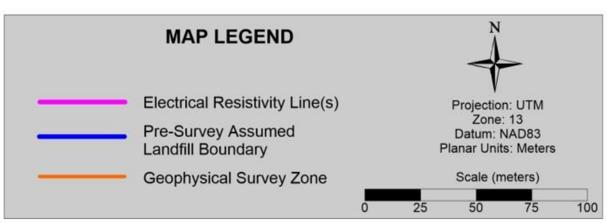


Figure 18. Contoured Electromagnetic In-Phase (ppm), Yale South Zone.

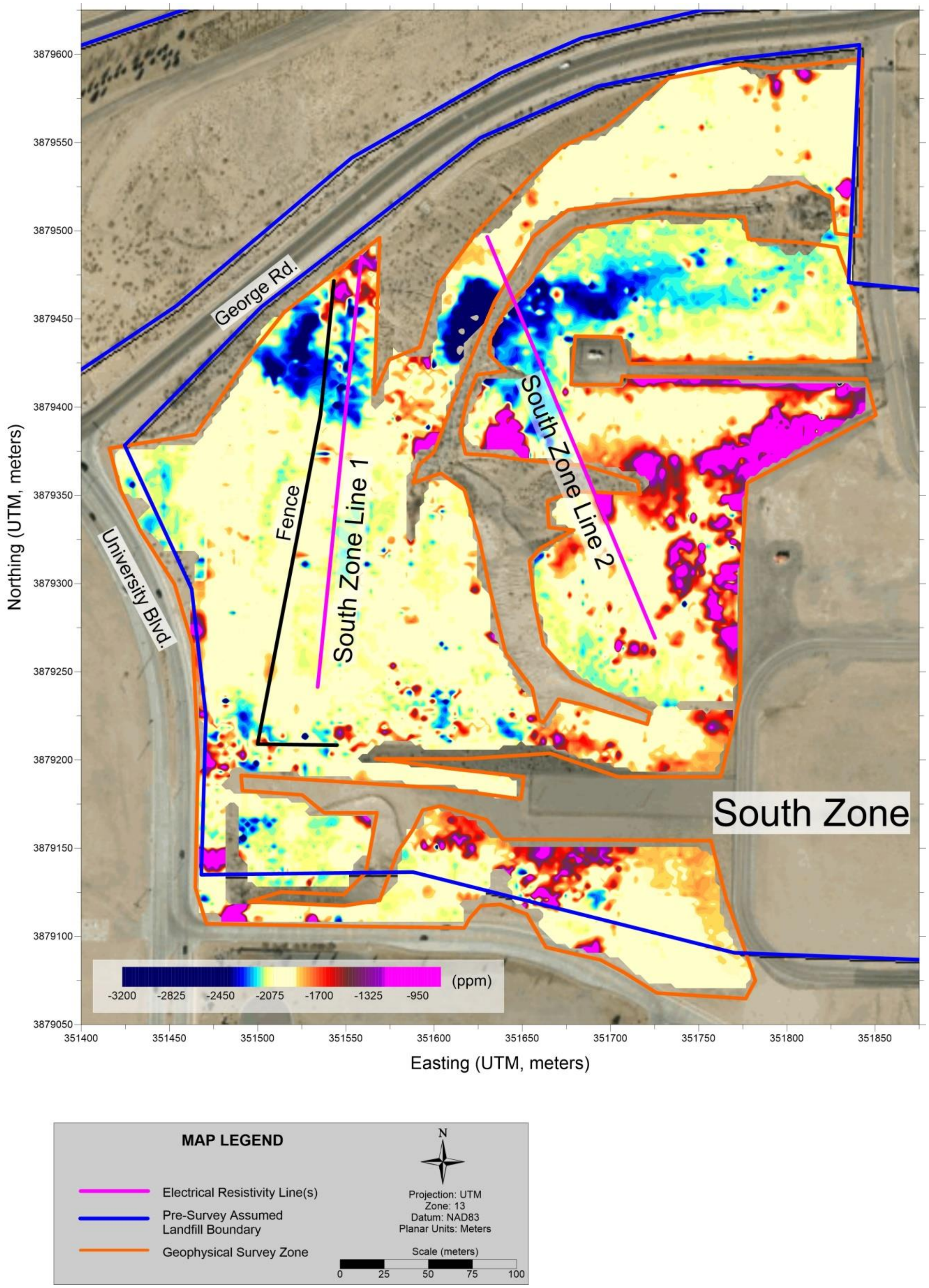
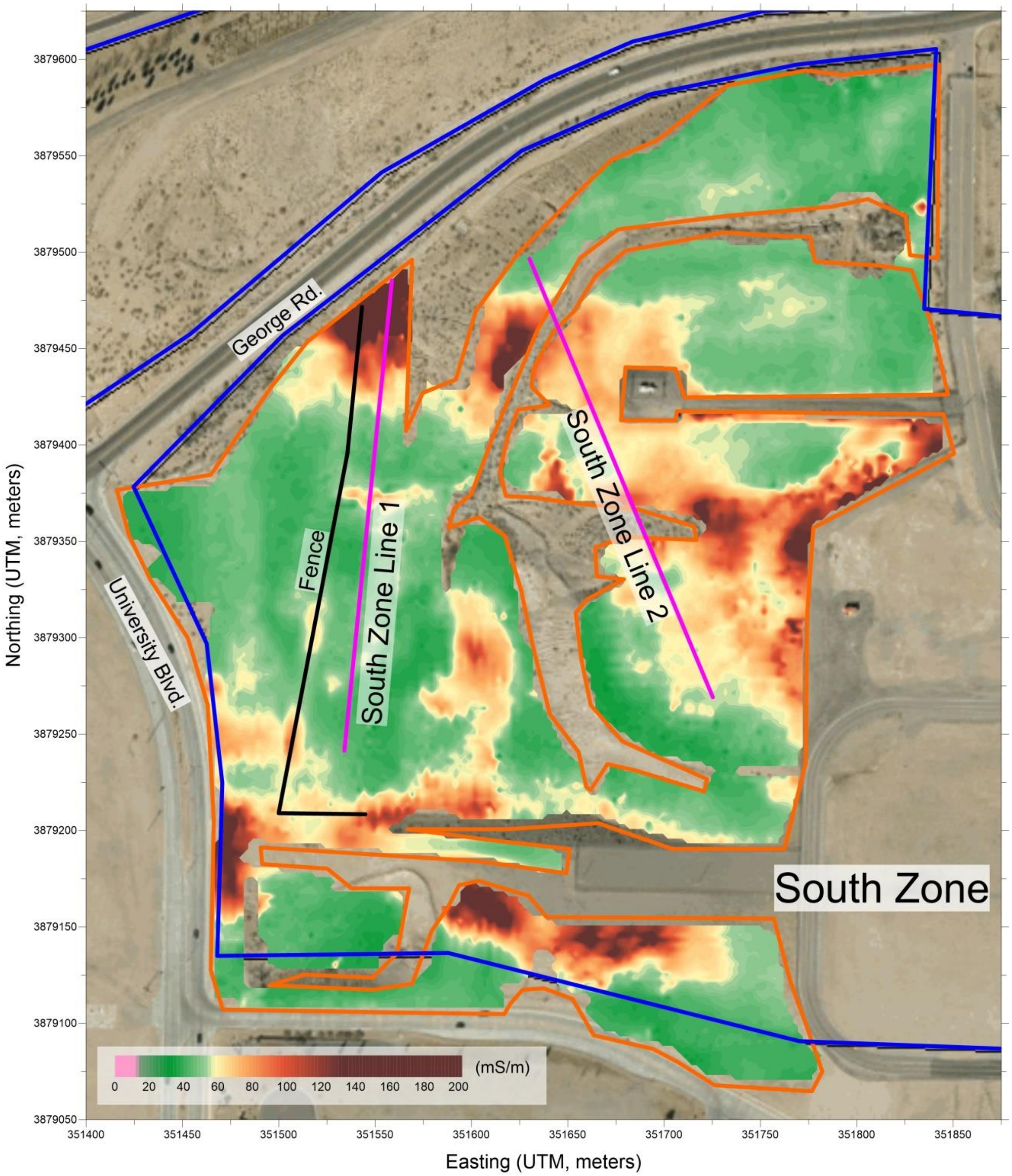
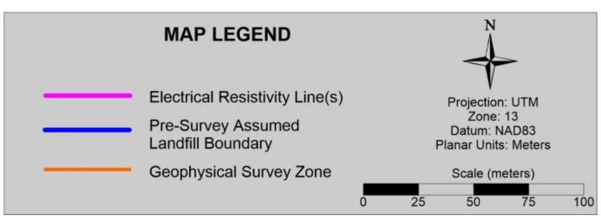


Figure 19. Contoured Electromagnetic Conductivity (mS/m), Yale South Zone.





4.1.2 Hotel Zone Combined Method Results

Figure 20 shows the resistivity profile for Hotel Zone Line 1, which ran approximately south to north across the central portion of the Hotel Zone of the landfill, alongside EM and Mag data extracted at the location of the resistivity line. The resistivity profile is shown in greater detail in Figure 21. Hotel Zone Line 1 was collected within the landfill boundary and also extends to the north beyond the northern landfill boundary in this zone. The line location was selected by evaluating the EM and Mag results, placed in an area where we observe significant differentiation in the EM and Mag readings.

The landfill wastes typically present as a conductive target (purple and blue colors), therefore between approximately 0 to 300 feet along the line the depth of the waste is estimated to be on average approximately 25 feet (~ 7.5 meters) (the interpreted base of the waste material is highlighted by the black dashed line in Figure 20). The thickness of the cover material is estimated to be around 5 to 9 feet (~ 1.5 to 2 meters), based on the more resistive near-surface layer (brown and red colors). The extracted EM conductivity results correlate well to this conductive feature. A proportion of this conductive waste feature, extending to a depth of 45 feet (~ 14 meters) between approximately 160 and 200 feet along the line, may be a response to a conductive "plume" from the waste material which has migrated deeper within the survey zone. The model results then transition to a highly resistive region, noted between approximately 300 to 500 feet along the line, where a number of anomalous responses are also observed in the Mag and EM In-phase results. It is possible that this is an area where waste material was extracted and replaced with a backfill containing crushed pavement or other construction materials associated with the neighboring hotel, whose magnetic properties would differ from the typical natural soils and sediments.

Secondary conductive targets are noted between approximately 500 to 600 feet and 650 to 750 feet along the line. Although these secondary features are markedly less conductive than the feature observed along the initial section of the line, they do appear to extend to the same depth, indicating that these areas may also be part of the original landfill area. However, the EM and Mag results along this portion of the line seem to be influenced by subsurface infrastructure running along the road, which may prevent detection of the landfill material responses. This infrastructure response is also noted on the resistivity section at approximately 650 feet along the line, with a vertical conductive region that extends down to the depth limits of the model. This type of feature is not typical to landfill waste responses and more typical of a metallic and/or conductive pipeline.

The resistivity model results seem to support the location of the pre-survey assumed landfill boundary. However without EM and Mag results to back this up, and the appearance of excavation and backfill in these areas, it is difficult to make a clear judgment on the true boundary.

Figure 20. Hotel Zone Line 1 Electrical Resistivity Comparison with EM & Mag Slices.

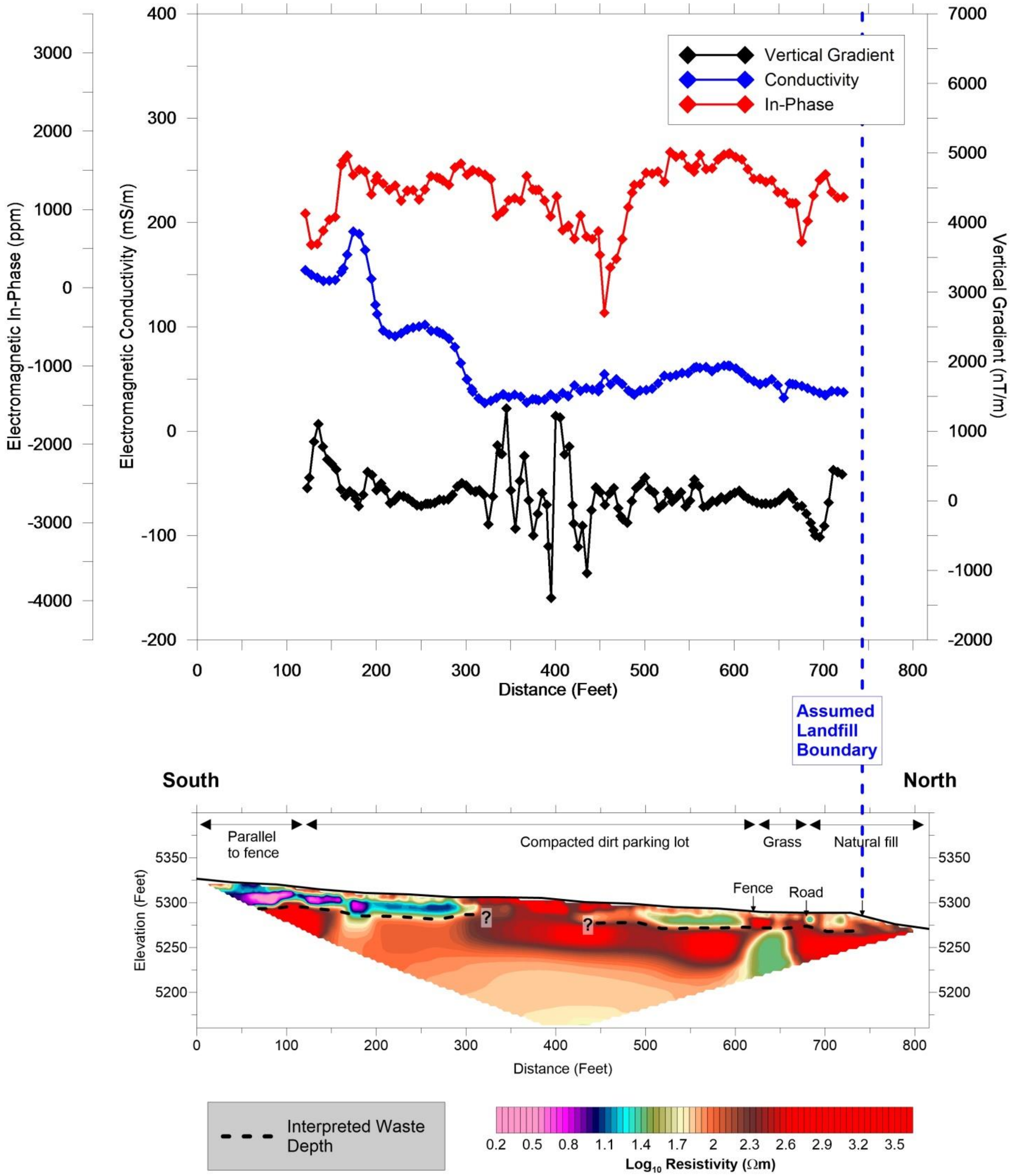
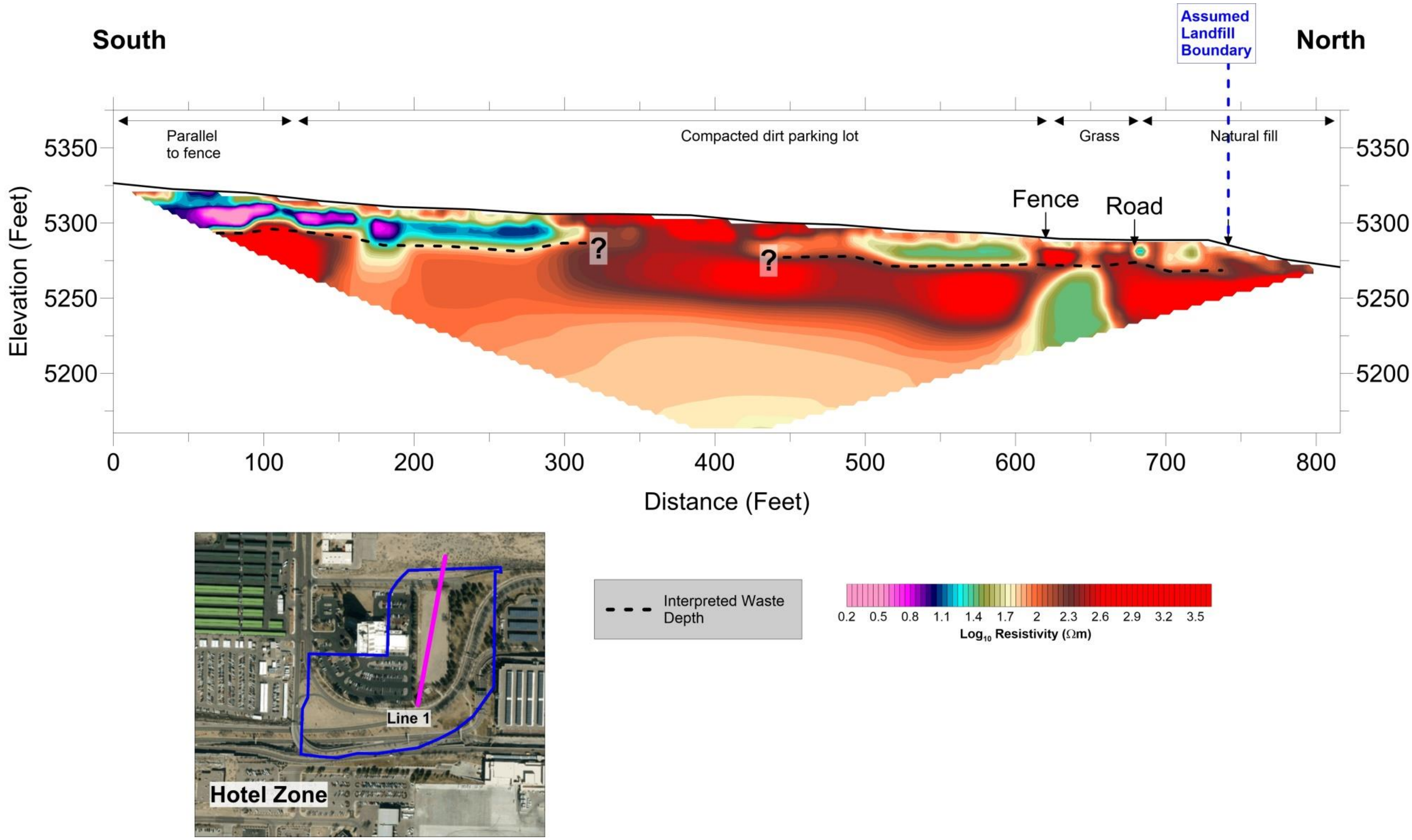


Figure 21. Hotel Zone Line 1 Electrical Resistivity Profile.



4.1.3 North Zone Combined Method Results

Figure 22 shows the resistivity profile for North Zone Line 1, which ran approximately west to east across the North Zone of the landfill, alongside EM data extracted at the location of the resistivity line. The resistivity profile is shown in greater detail in Figure 23. North Zone Line 1 was collected entirely within the assumed landfill boundary, and we observe a significant level of variability in the extracted EM readings reflecting this. Difficulties due to site topography and vegetation resulted in no magnetics data collection in this area.

Again the landfill wastes are represented by the highly conductive target observed along the length of most of the survey line (the interpreted base of the waste material is highlighted by the black dashed line in Figure 22). The first 75 feet along the line are modeled as resistive, though it is unlikely this represents the end of the landfill waste. EM and Mag results west of the survey line encounter additional landfill waste responses and it is therefore more likely that this resistive zone is only a break in the landfill waste or that the waste is beneath the investigation depth in this vicinity. From approximately 75 to 250 feet along the line a conductive layer reaches to a depth of about 21 feet (~ 6.5 meters). A more resistive cover material layer is present that varies between approximately 5 to 12 feet (~ 1.5 to 3.5 meters) in thickness. The model then transitions to a more resistive region between approximately 250 and 300 feet along the line. Directly below this however, is a more conductive body that extends down to the limits of the model. This feature may be extending down as a “plume” from another near surface highly conductive target, observed between approximately 300 and 600 feet along the line, with an average depth of about 30 feet (~ 9 meters). Interestingly, a resistive anomaly is noted in roughly the center of this feature, at 450 feet along the line. As discussed in the Los Angeles Landfill report, this type of a feature could be related to methane gas production in the waste material, though additional information would be needed to make such a correlation. The model again transitions to a more resistive region between 600 and 650 feet along the line, and then again to a highly conductive region from 650 feet to the end of the line. This conductive feature extends to about 22 feet (~ 6.5 meters) in depth, and has a more resistive cover layer that is approximately 8 feet in thickness (~ 2.5 meters). The extracted EM in-phase and conductivity results correlate well with the noted features along the line, with higher amplitude responses matching the more conductive areas along the line. The resistive regions observed along the line (from 0-75 feet, 250-300 feet, and 600-650 feet) could represent a border within the landfill composed of more resistive material, such as clean soil, that separated differing waste cells for example. Alternatively, this could be a response to more resistive waste materials in this region of the landfill. Without additional information it is difficult to make any conclusions regarding these regions.

The combined results of the EM and Mag and electrical resistivity data do not appear to indicate a clear landfill boundary along this survey line.

Figure 22. North Zone Line 1 Electrical Resistivity Comparison with EM & Mag Slices.

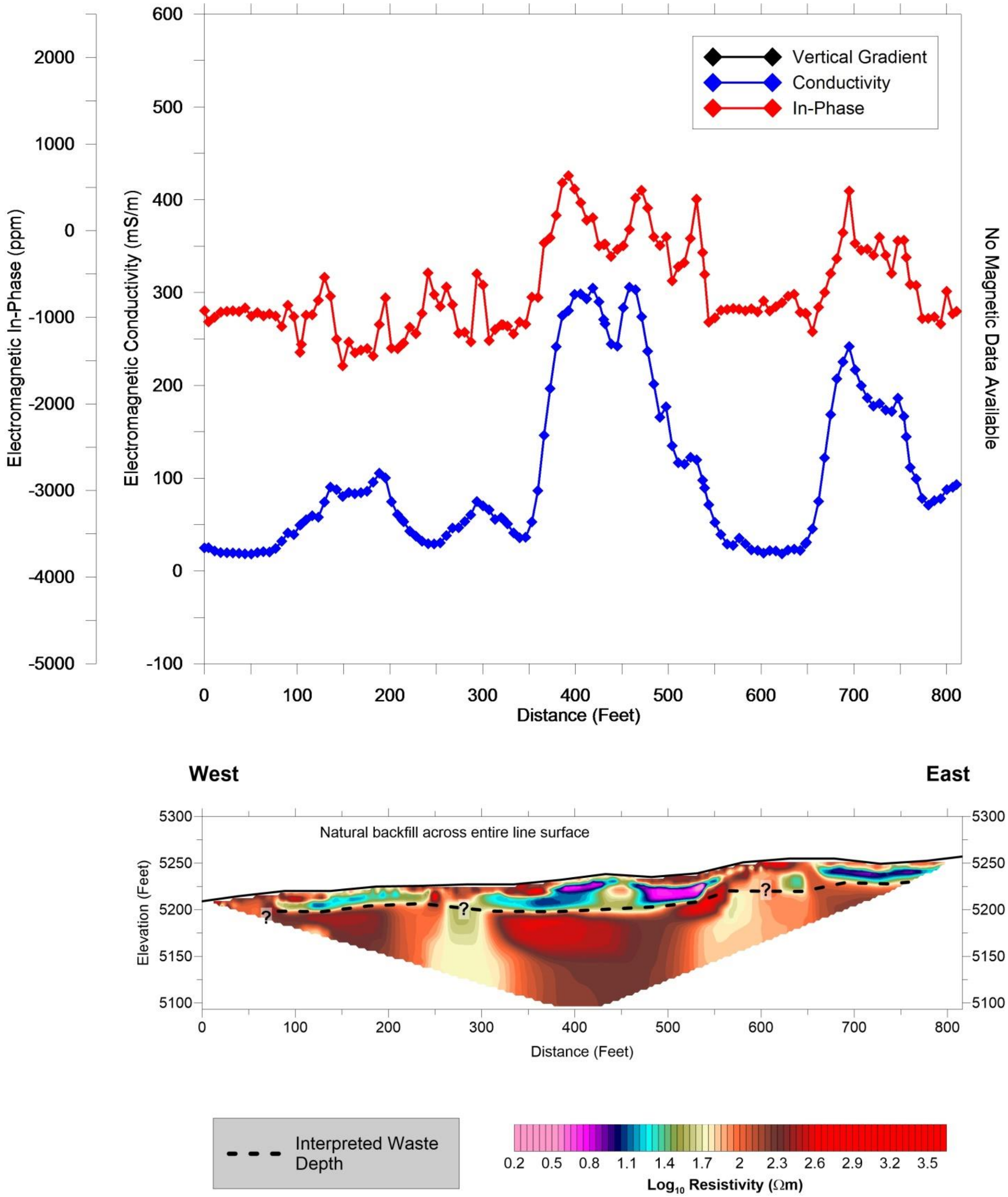
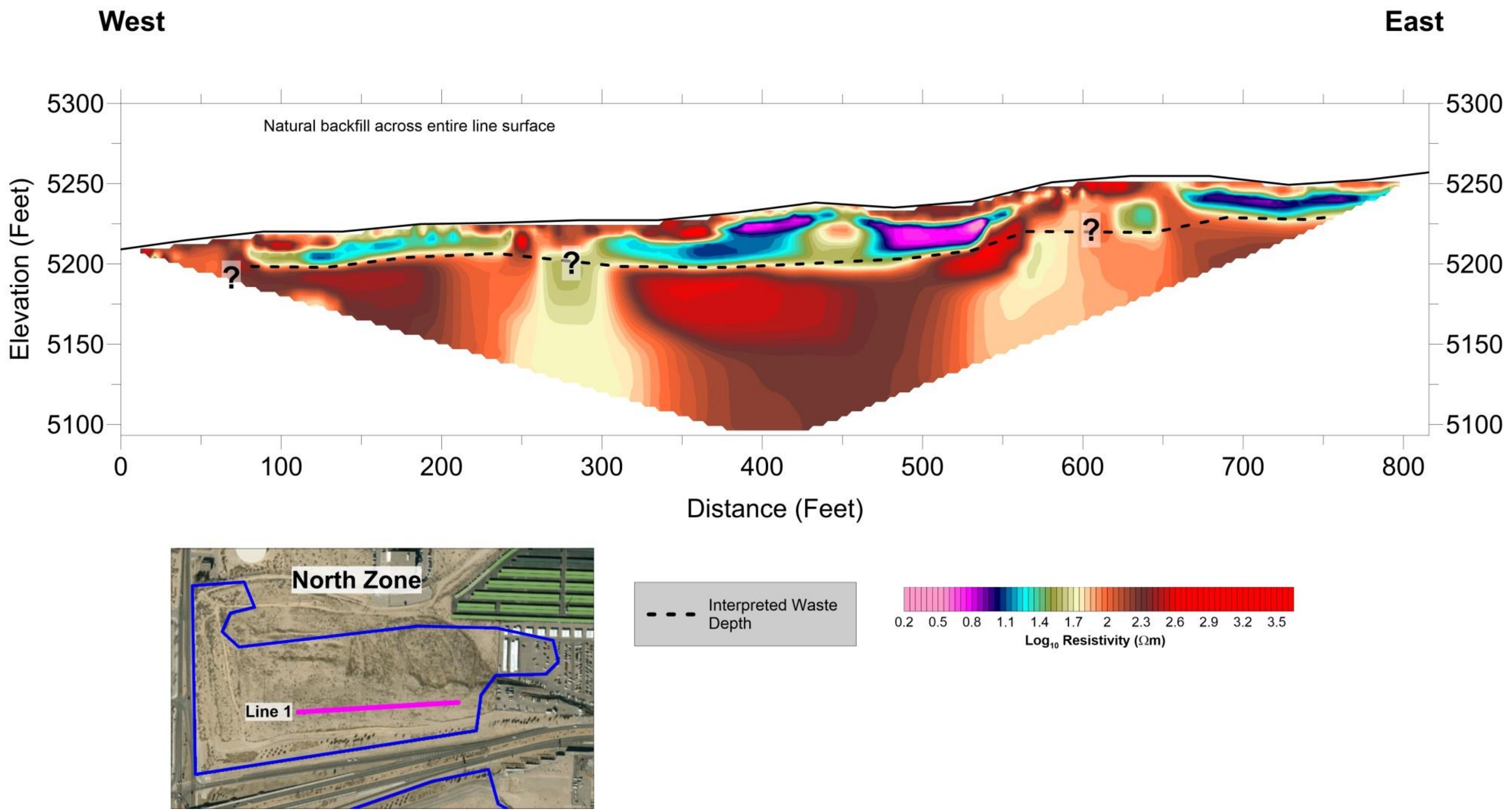


Figure 23. North Zone Line 1 Electrical Resistivity Profile.



4.1.4 Central and South Zone Combined Method Results

Figure 24 shows the resistivity profile for Central Zone Line 1, which ran approximately southwest to northeast across the Central Zone of the landfill, alongside EM and Mag data extracted at the location of the resistivity line. The resistivity profile is shown in greater detail in Figure 25. Central Zone Line 1 was collected predominantly within the assumed landfill boundary, with a small section extending beyond the eastern border. Again, difficulties due to site topography and vegetation restricted magnetics data collection to the far eastern edge of this zone.

Landfill wastes are represented by the conductive target observed along the western portion of the survey line (the interpreted base of the waste material is highlighted by the black dashed line in Figure 24). A highly conductive target is noted from 0 to 120 feet along the line, which extends to a depth of approximately 25 feet (~ 7.5 meters). This region then transitions to moderately conductive between 120 and about 360 feet along the line. This conductive region is covered by a resistive surface layer, a response to the cover material, which varies in thickness between approximately 9 to 15 feet (~ 2.5 to 4.5 meters).

The remainder of the profile shows a transition to a highly resistive layer that reaches from the surface to a depth of approximately 22 feet (~ 6.5 meters). This layer is more resistive than the deeper, likely natural background soils, and has the appearance of potentially being an area of excavation and backfill. Furthermore, given the similarities in this layer's thickness in relation to nearby landfill waste layers, it is unclear whether the pre-survey assumed landfill boundary is correctly located in this area. It is possible that the true eastern landfill boundary could be moved approximately 100 feet to the west.

A more conductive, anomalous feature is noted at approximately 500 feet along the line. This anomaly extends from the near surface down through the more 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 metallic and/or conductive pipeline, correlating to a high amplitude response noted in the EM In-phase data, sensitive to bulk metal content, at the same location. Another such response is noted in the EM In-phase and Mag data at approximately 750 feet along the line. However, there does not appear to be any significant response in the resistivity model at this location; this is a region of limited imaging depth and resolution being close to the end of the resistivity line.

Electromagnetic results along this line show a minimal degree of variability when viewing the extracted EM data (blue and red lines in upper plot in Figure 24), however, when viewing the broader EM data presented in Figure 13, one can see good agreement to the conductive resistivity response as indicated by the EM conductivity moderate response (yellow shades). It is possible that the conductive layer, noted along the first 360 feet of the line, is not conductive enough, or too deep to result in a high magnitude EM response, which typically image only the uppermost 20 to 25 feet of earth. The highly resistive near surface layer noted in the resistivity profile is likely dominating the EM readings.

Figure 24. Central Zone Line 1 Electrical Resistivity Comparison with EM & Mag Slices.

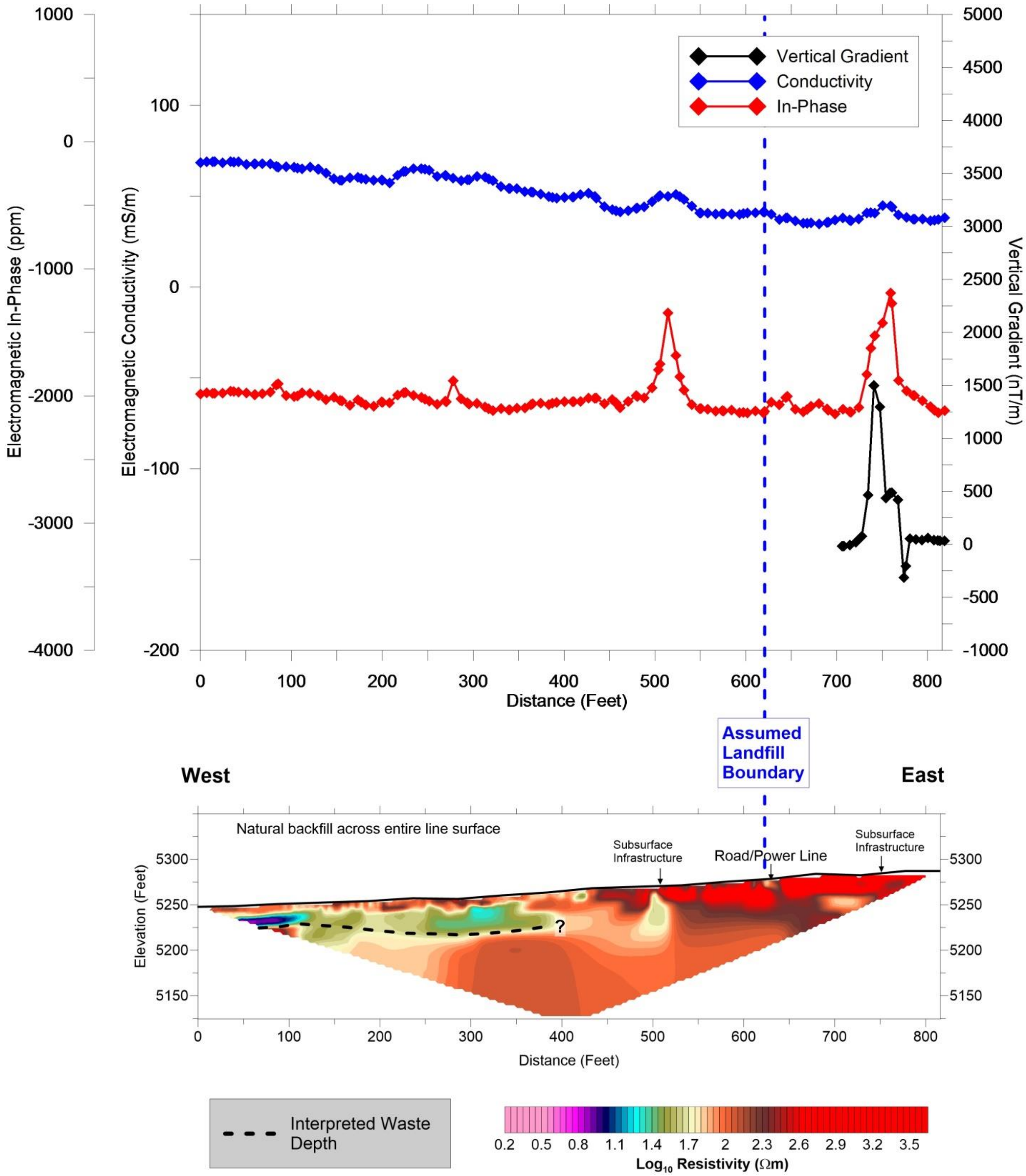


Figure 25. Central Zone Line 1 Electrical Resistivity Profile.

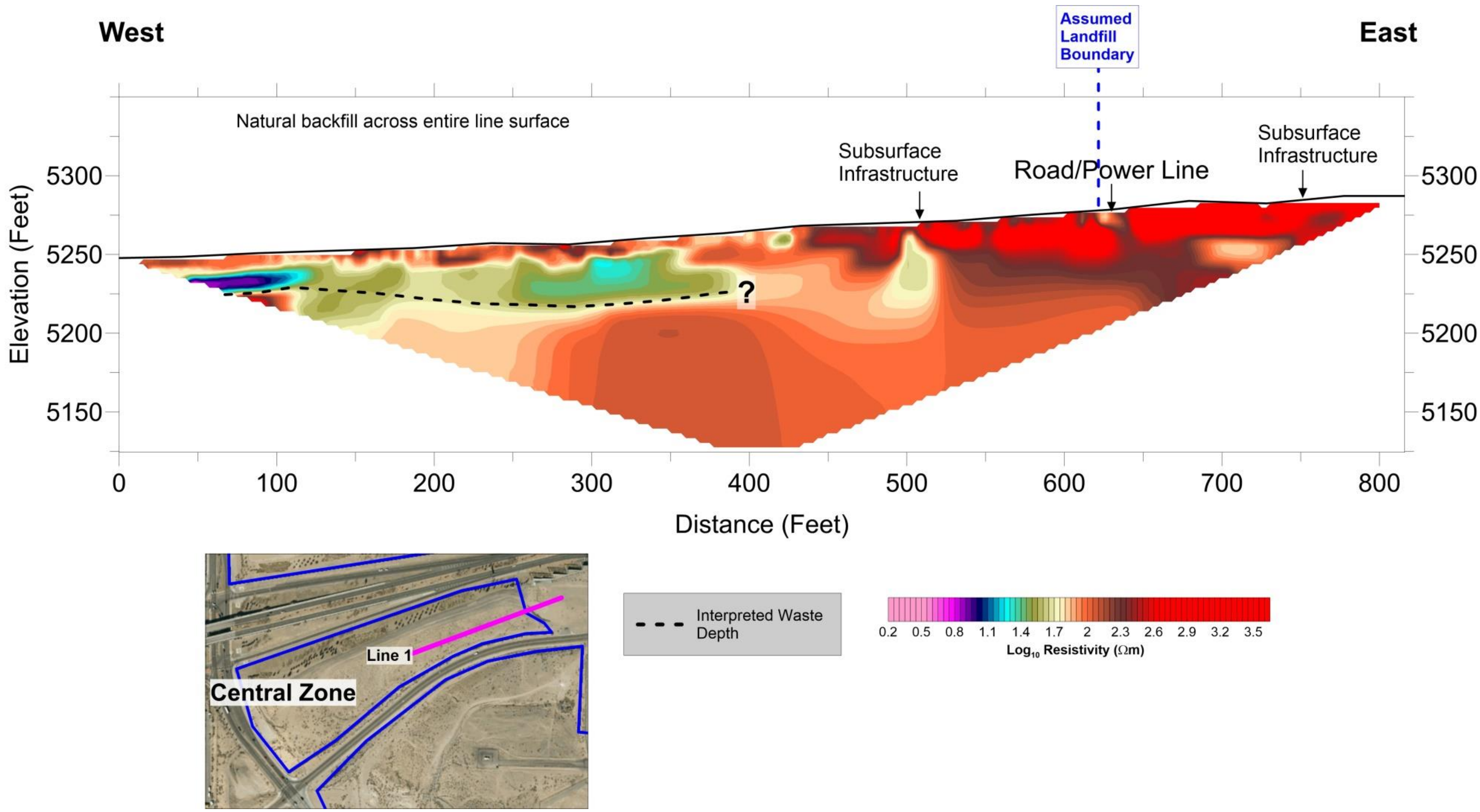


Figure 26 shows the resistivity profile for South Zone Line 1, which ran approximately south to north across the South Zone of the landfill, alongside EM and Mag data extracted at the location of the resistivity line. The resistivity profile is shown in greater detail in Figure 27. South Zone Line 1 was collected entirely within the assumed landfill boundary, and we observe a level of variability in the extracted EM and Mag readings reflecting this.

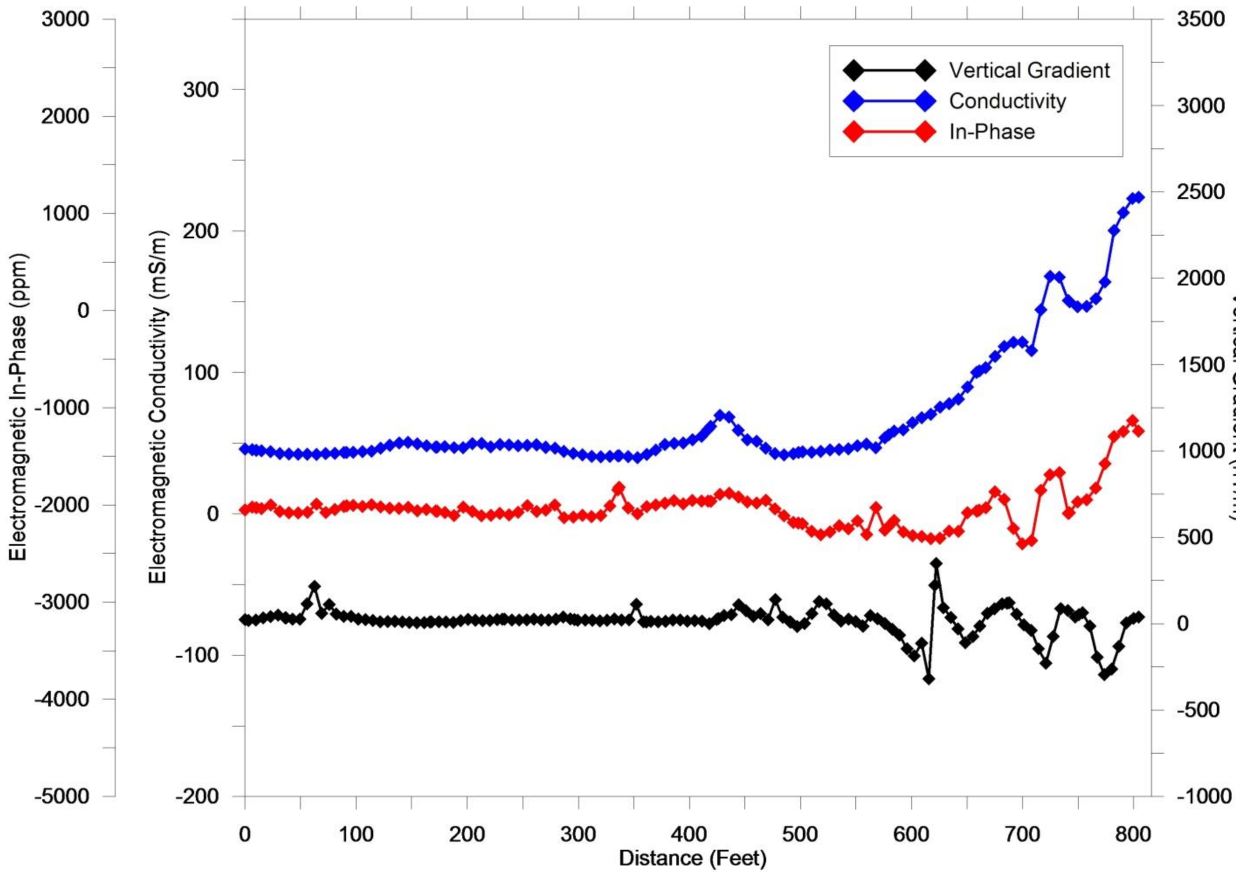
Landfill wastes are represented by the moderately conductive target observed along the length of most of the survey line (the interpreted base of the waste material is highlighted by the black dashed line in Figure 26). The resistivity model profile shows a highly resistive zone on the southern end of the line, which then transitions to a layer containing several zones of low to moderate conductivity. This layer is noted from 100 to 500 feet along the line and reaches to a depth of approximately 35 feet (~ 10 meters). Within this layer, the region of highest conductivity is observed between 350 and 500 feet along the line. A highly resistive layer covers this feature, with an average thickness of about 15 feet (~ 4.5 meters), likely representing the cover material. Although these features do have an appearance that is similar to interpreted landfill waste features in other profiles, without agreement from the EM and Mag results or additional information such as soil sampling, it is not clear whether this is an area containing landfill waste materials or simply an area of increased soil moisture.

The model then transitions to a zone of high resistivity until approximately 650 feet along the line, where a conductive target is observed that extends to the end of the model profile. A resistive layer covering this target appears to thin towards the northern end of the line, where the conductive target nearly reaches the surface. The conductive feature reaches to a depth of approximately 35 feet (~ 10 meters).

The EM and Mag results show a low level of variability along the extracted readings until approximately 600 feet along the line, after which high and low amplitude responses are noted that are indicative of landfill wastes. One exception is a slightly higher amplitude response observed in the EM conductivity results at about 425 feet along the line, which correlates to the most conductive region seen in the low to moderately conductive layer extending from 100 to 500 feet along the line. Again, in this case it may be that these low to moderate conductive features are either too deep or not conductive to register a response in the EM and Mag readings. Additionally, the highly resistive cover layer could be dominating the readings, which again, represent an average bulk reading for a volume of earth.

The combined results of the EM and Mag and electrical resistivity data do not appear to indicate a clear landfill boundary along this survey line.

Figure 26. South Zone Line 1 Electrical Resistivity Comparison with EM & Mag Slices.



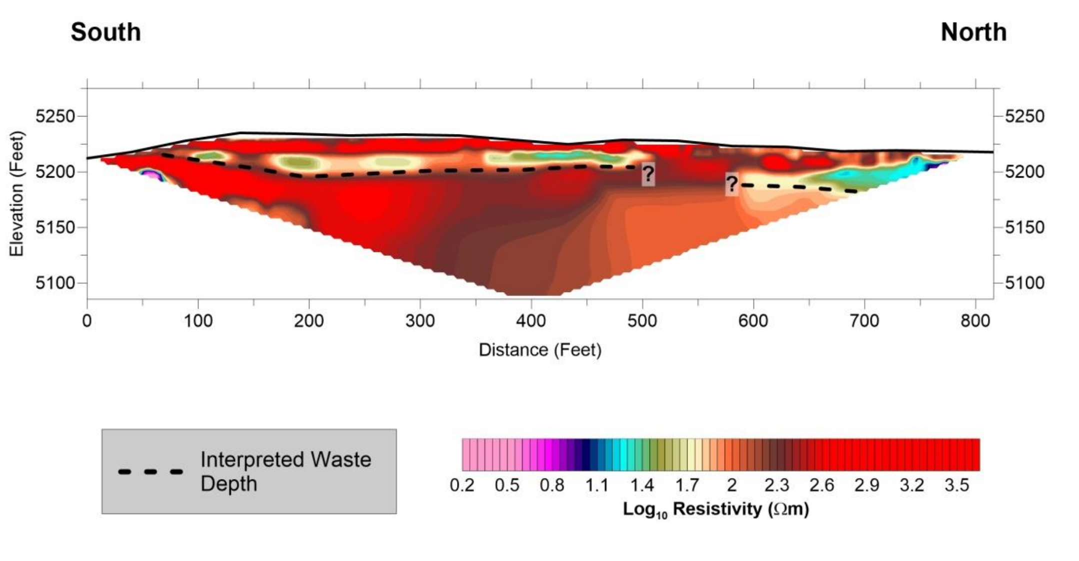


Figure 27. South Zone Line 1 Electrical Resistivity Profile.

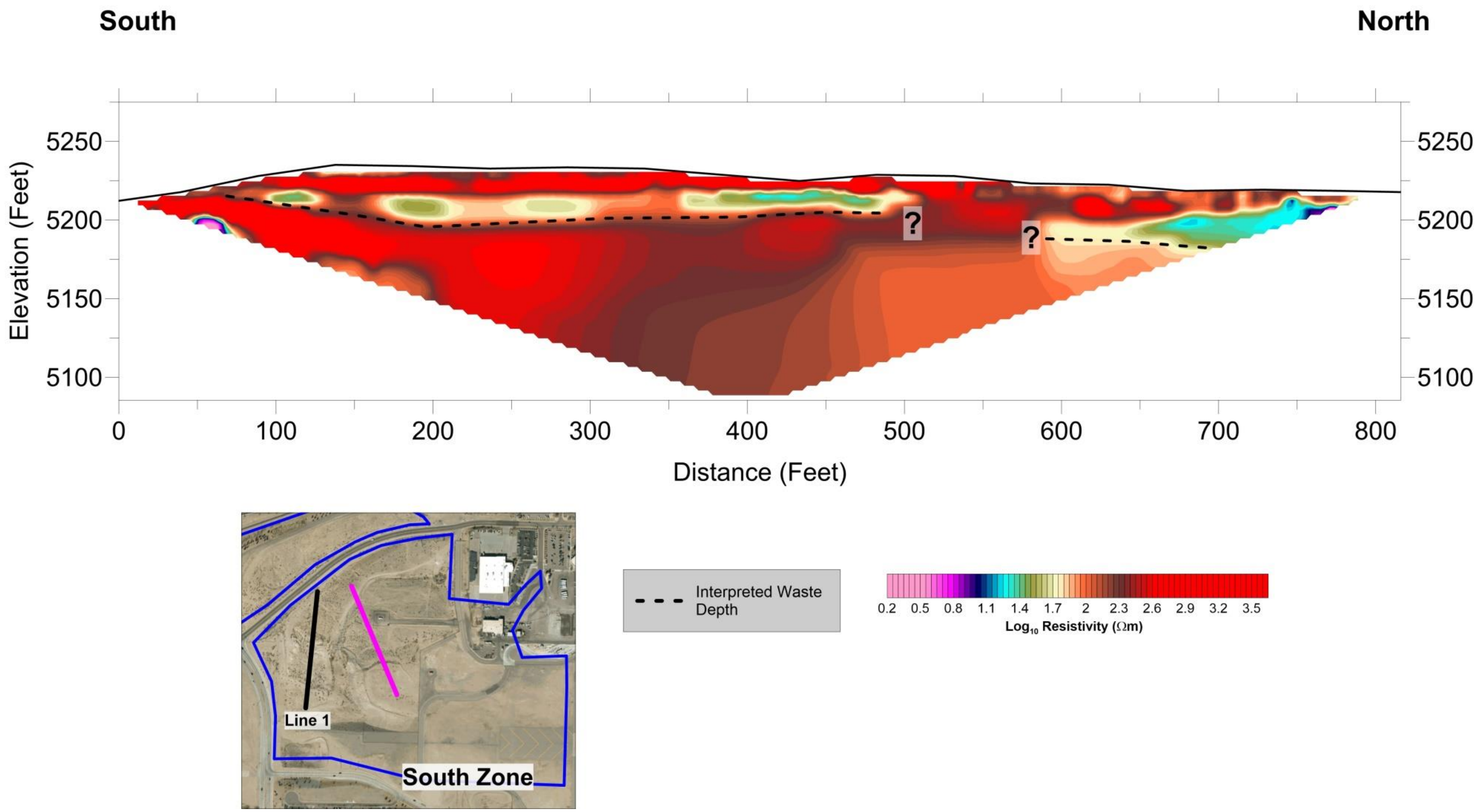


Figure 28 shows the resistivity profile for South Zone Line 2, which ran approximately south to north across the South Zone of the landfill, alongside EM and Mag data extracted at the location of the resistivity line. The resistivity profile is shown in greater detail in Figure 29. South Zone Line 2 was collected entirely within the assumed landfill boundary, and we observe a significant level of variability in the extracted EM and Mag readings reflecting this.

Landfill wastes are represented by the highly conductive target along the length of most of the survey line (the interpreted base of the waste material is highlighted by the black dashed line in Figure 28). A highly conductive layer is observed starting from the south end of the line to approximately 500 feet along the model profile. The depth of this layer reaches to an average of approximately 40 feet (~ 12 meters) below ground surface. The level of conductivity does vary along this layer with the highest conductivity noted at about 200 feet along the line. At roughly this same point we see high amplitude responses in the EM in-phase and conductivity results; additionally there is a very high resistivity layer directly above the feature coinciding with a topographical rise along the surface. There is a gap in the EM and Mag data in this area that is likely due to the difficulties related to the noted topographical rise. The remainder of the conductive layer, in fact the entire model profile, is also covered by a highly resistive layer ranging in thickness from approximately 10 to 25 feet (~ 3 to 7.5 meters).

The model then transitions to a moderately conductive region over the remainder of the profile. The area of transition does also coincide with a surface area where the resistivity line was noted to be running near and parallel to a fenced area enclosing an electrical transformer station. It is possible that infrastructure related to this area influenced the resistivity readings and model results. There are two small features of slightly higher conductivity at approximately 625 to 650 feet along the line. The first is located directly beneath the highly resistive near surface layer, and the second is located deeper and slightly further along the line, and extending to the limits of the model profile. Again, it is unclear whether the readings in this area have been influenced by near surface infrastructure or changes in soil or landfill waste composition. High and low amplitude responses are noted in the EM conductivity and in-phase results in these areas.

The combined results of the EM and Mag and electrical resistivity data do not appear to indicate a clear landfill boundary along this survey line.

Figure 28. South Zone Line 2 Electrical Resistivity Comparison with EM & Mag Slices.

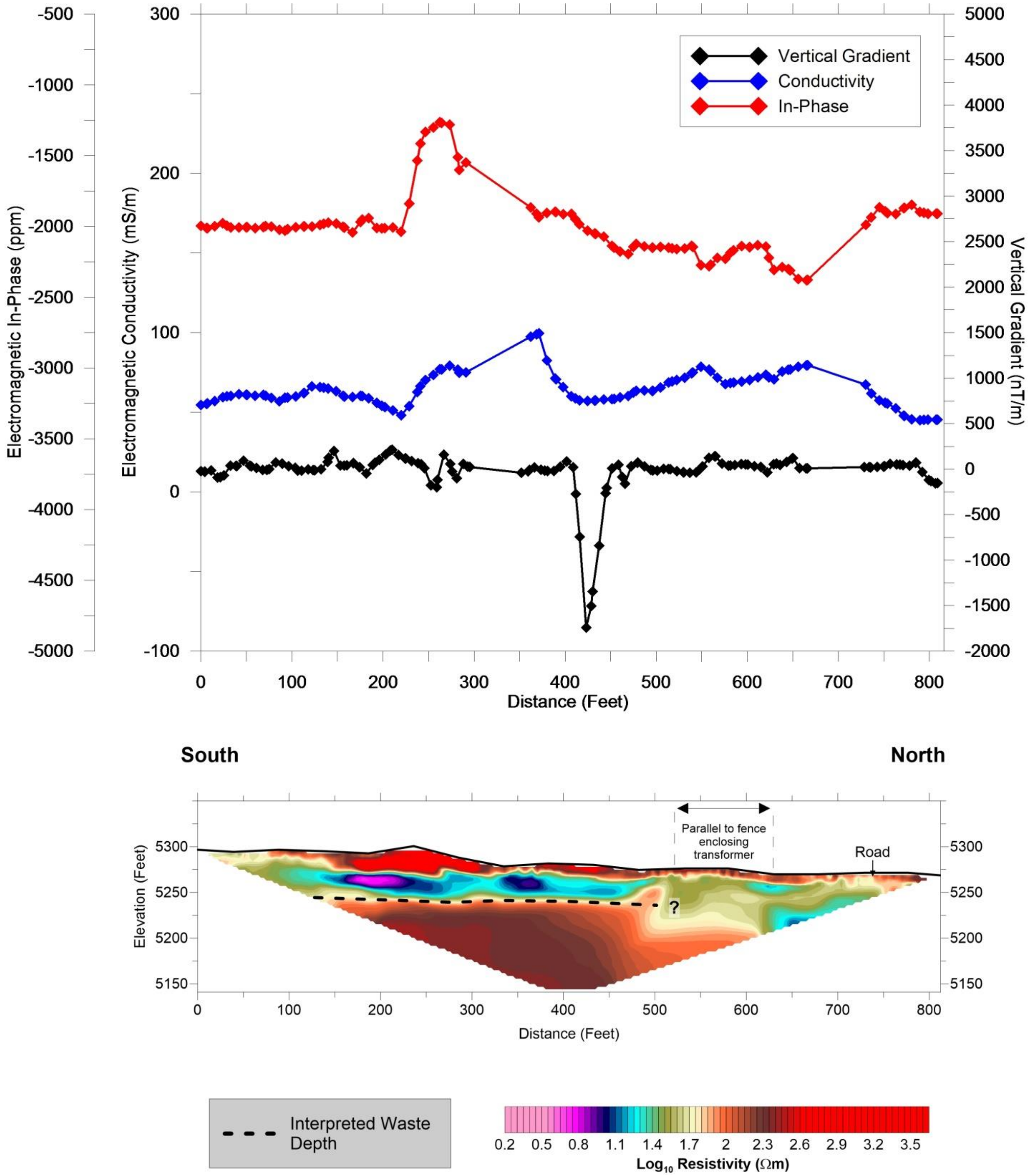
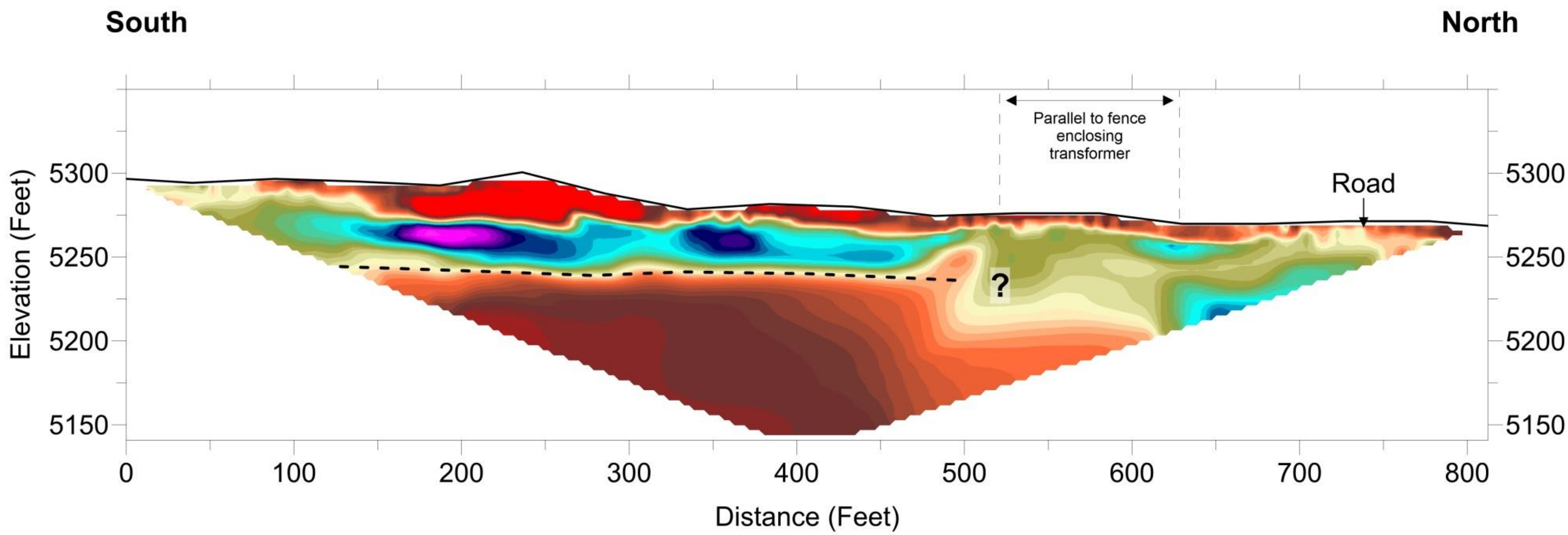
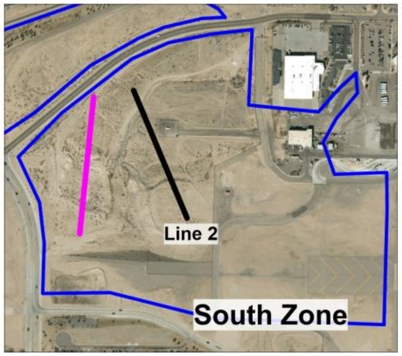
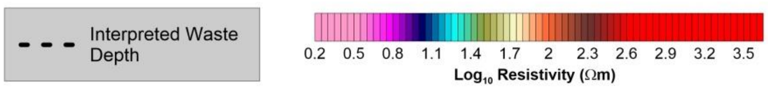


Figure 29. South Zone Line 2 Electrical Resistivity Profile.







5.0 CONCLUSIONS

A multi-method geophysical survey was performed at the Yale Landfill in Albuquerque, New Mexico, between October and December 2016. The survey was performed to determine the lateral extents and thickness of landfill wastes and the thickness of the cover material. Combined electromagnetic and magnetic (EM and Mag) surveys over the entire accessible landfill area, as well as five lines of two-dimensional (2D) electrical resistivity were completed. The EM and Mag measurements provided some indication of the lateral limits of covered landfill, and the electrical resistivity imaging method contributed greatly 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 an 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 responses that would indicate the presence of landfill waste material. The responses 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 predominantly display low amplitude, homogeneous response, indicating background conditions have been mapped effectively. However, definitive interpretation of the landfill boundary was problematic due to the fragmented nature of this landfill, due to the road and property construction and airport property that have occurred following the landfill closure. There are some areas where high-magnitude responses, indicative of landfill waste, extended to the edge of the data collection area and the pre-survey assumed landfill boundary. These are areas where it is possible that landfill waste extends beyond the pre-survey landfill boundary, but can't be confirmed without additional survey coverage or other sampling techniques. One example of this can be viewed on Figure 19, where the conductive feature (in brown) towards the southwest corner, extends westward to University Blvd. The presence of significant site topography and other obstructions created gaps in coverage, and also that much of this site appears to have been disturbed by construction activities, such as hotel and office building construction. A large proportion of the site also had a highly resistive near surface layer, whether from natural soils or backfill material, which may have limited the instrumentation from sensing deeper conductive layers associated with waste materials.

- The 2D resistivity data provided, in our view, an essential additional imaging method to correlate interpretations of the landfill lateral extents determined using the EM and Mag data. In many cases at this site, resistivity data showed evidence of landfill waste that was not detected by EM and Mag results. Further sampling would be required to confirm these results. The resistivity profile results estimated the thickness of the waste to be variable, ranging from approximately 20 to 40 feet (~ 6 to 12 meters) at the locations of the resistivity survey lines, often depending on the thickness of the cover layer which was estimated to vary between 5 to 25 feet (~ 1.5 to 7.5 meters). This varies significantly from the previous assumed average of 10 and 4 feet for the waste and cover material respectively, and may reflect the fragmented and disturbed history of this landfill.

6.0 REFERENCES

Constable, S. C., Parker, R. L., and Constable, C. G., 1987, Occam's inversion: A practical algorithm for generating smooth models from electromagnetic sounding data: Geophysics,**52**, No. 3, 289-300.

Dey, A., and H.F. Morrison, 1979, Resistivity modeling for arbitrarily shaped three-dimensional structures: Geophysics, 44, 753-780.

Ellis, R.G., and D.W. Oldenburg, 1994, Applied geophysical inversion: Geophysical Journal International, 116, 5-11.

Loke, M.H., I. Acworth, and T. Dahlin, 2003, A comparison of smooth and blocky inversion methods in 2D electrical imaging surveys: Exploration Geophysics, 34, 182-187.

Rucker, D.F., Levitt, M.T., Greenwood, W.J., 2009. Three-dimensional electrical resistivity model of a nuclear waste disposal site. Journal of Applied Geophysics 69, 150-164.

Rucker, D.F., G.E. Noonan, and W.J. Greenwood, 2011. Electrical resistivity in support of geologic mapping along the Panama Canal. Engineering Geology 117(1-2):121-133.

Sasaki, Y., 1989, Two-dimensional joint inversion of magnetotelluric and dipole-dipole resistivity data: Geophysics, 54, 254-262.

Telford, W. M., Geldart, L. P., and Sherriff, R. E., 1990, Applied Geophysics (2^{nd} Edition), Cambridge University Press.

APPENDIX A

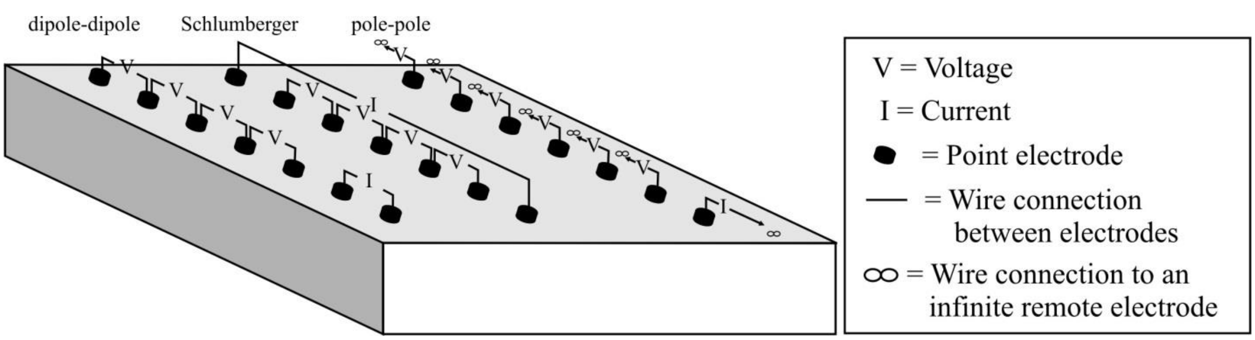
Description of Electrical Resistivity

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 30 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 30. 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):

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

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):

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

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

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

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 may be 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 spacing 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.