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Geophysical Survey of the Los Angeles Landfill, Albuquerque NM

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1.0 INTRODUCTION

1.1 PROJECT DESCRIPTION

In November and 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 Los Angeles Landfill. A combined electromagnetic (EM) and magnetic (Mag) survey over the entire accessible landfill area, as well as seven lines of two-dimensional (2D) Electrical Resistivity Tomography (ERT) were completed. This report documents results from data acquired at the Los Angeles Landfill (LA 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

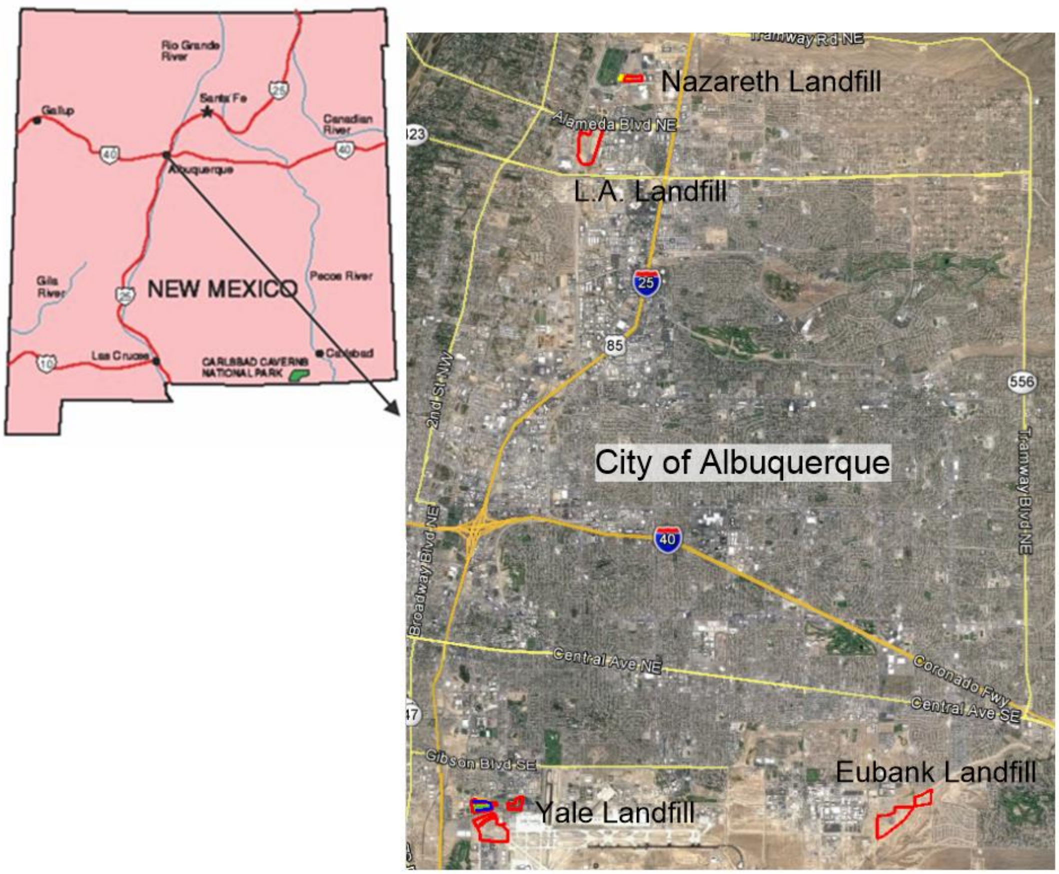
2.1 SITE LOCATION

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

The Los Angeles Landfill is located at 4300 Alameda Blvd. NE. The landfill operated during the years 1978-1983, with a total estimated waste tonnage of 2 million tons. The landfill has a gravel parking lot, as well as some natural vegetation as cover. The site is known to contain subsurface/surface utilities and some amount of infrastructure.

There are no available historical references for boundary and construction geometry for the Los Angeles landfill and cover; however, tribal knowledge of the site estimates an average cover thickness of 3 feet, and average waste depth of 35 feet. These values may vary across the site. The total area covered by the Los Angeles landfill is approximately 77 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 10/31/16 and 11/3/16 at high-resolution sampling 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 77 acres. The survey area had little topography and vegetation as most of the area had been converted to a RV parking lot for the Balloon Festival. Some of the RV parking areas contained surface and subsurface utilities and infrastructure that were likely contributed to geophysical responses in their vicinity. The vegetation that was present on the site was sparse could be driven over with the G.O. Cart and ATV. The only area that was unable to be surveyed was a runoff ditch that was fenced off. The boundaries of this survey were enclosed by a chain link fence, so we were unable to survey much beyond the landfill fenced area.

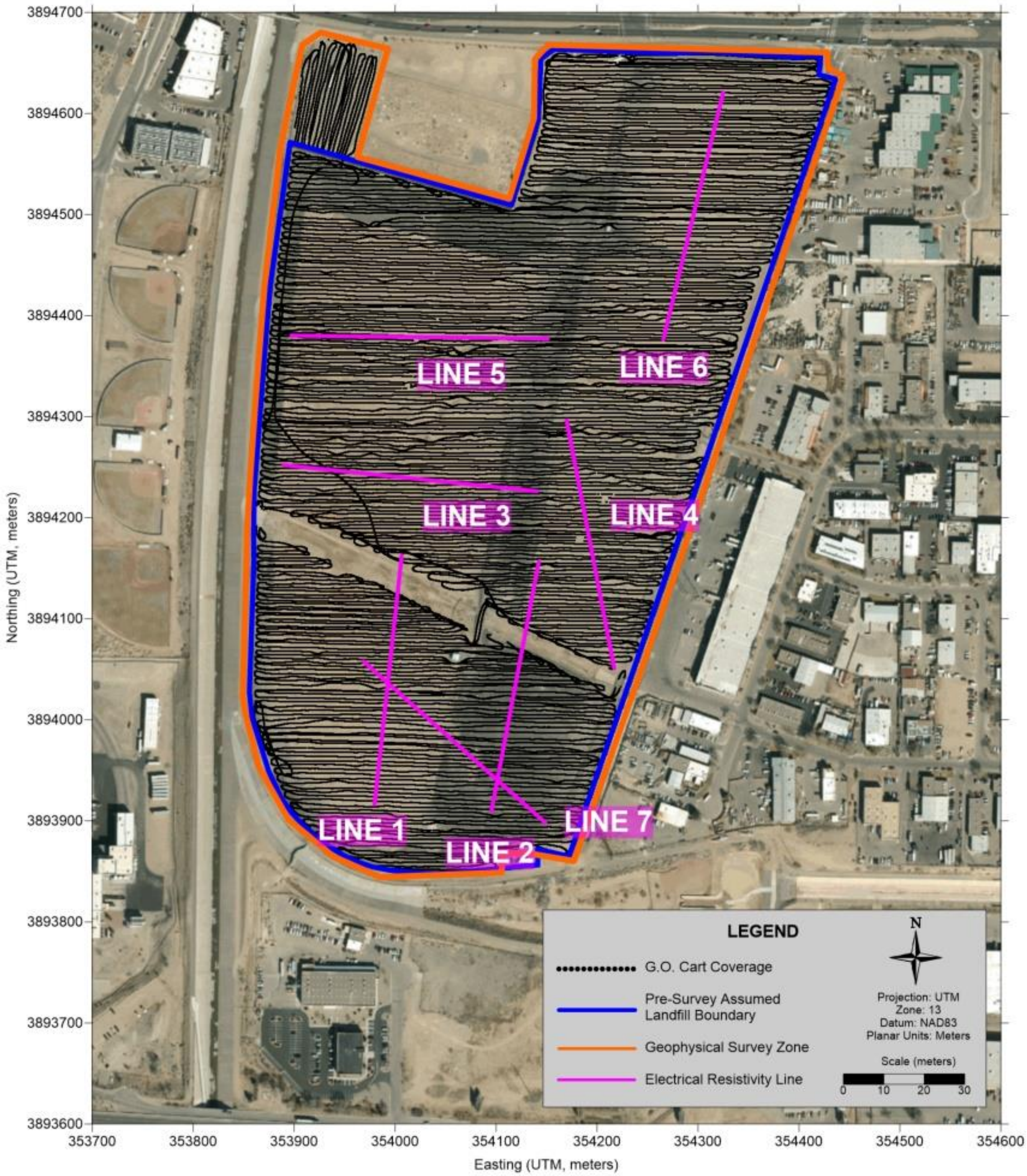
Resistivity data consisted of seven lines of data approximately 817 feet long each, totaling approximately 5,719 feet of total line coverage. The locations of the survey lines are shown in Figure 2 (pink lines). Table 1 lists specific parameters for the resistivity survey lines.

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	12/5/16	10	817	S-N	353979, 3893916	354006, 3894162
2	12/7/16	10	817	S-N	354095, 3893910	354142, 3894156
3	12/6/16	10	817	W-E	353889, 3894245	354141, 3894226
4	12/7/16	10	817	S-N	354217, 3894051	354170, 3894296
5	12/6/16	10	817	W-E	353902, 3894381	354151, 3894377
6	12/8/16	10	817	S-N	354266, 3894377	354325, 3894621
7	12/8/16	10	817	NW-SE	353969, 3894058	354149, 3893898

Figure 2. Detailed Survey Coverage Map.

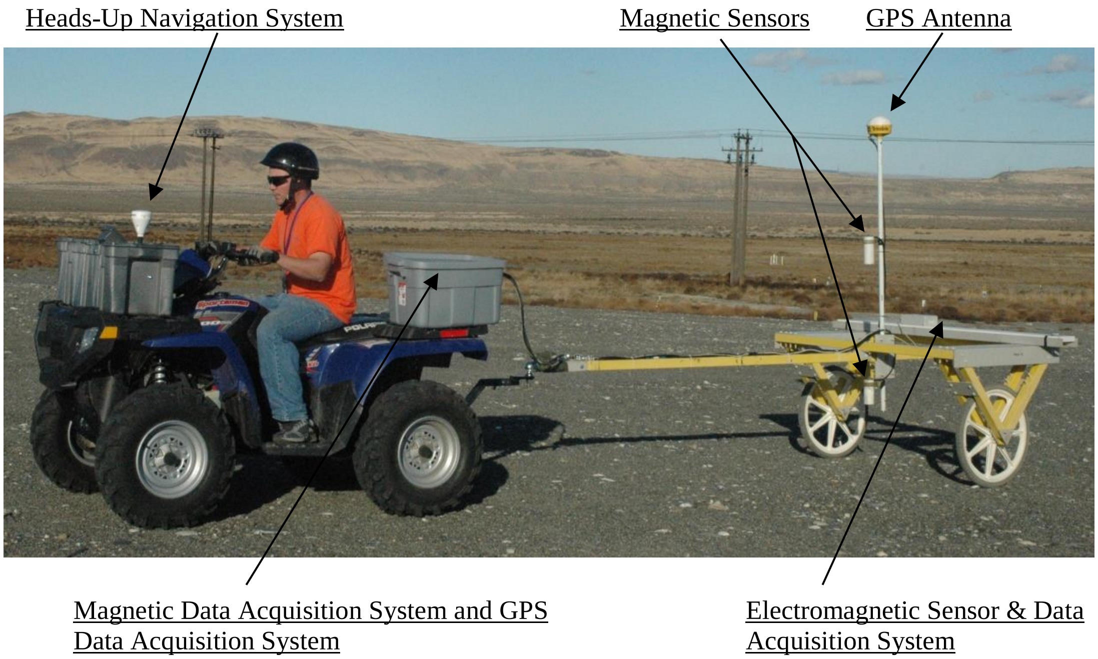


3.2 EQUIPMENT

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 (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, for example 55-gallon steel drums that can often contain hazardous wastes. 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.

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. 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 data show heterogeneity throughout the survey site, generally within the assumed landfill boundaries.

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, 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 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 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.

An additional objective at the LA Landfill site was to investigate any potential correlation between the geophysical survey results and methane fluxes across the site. A number of the electrical resistivity survey lines were located to target the area of elevated methane flux associated with the southern portion of the landfill (Figure 8).

Figure 4. Contoured Electromagnetics and Magnetics Map

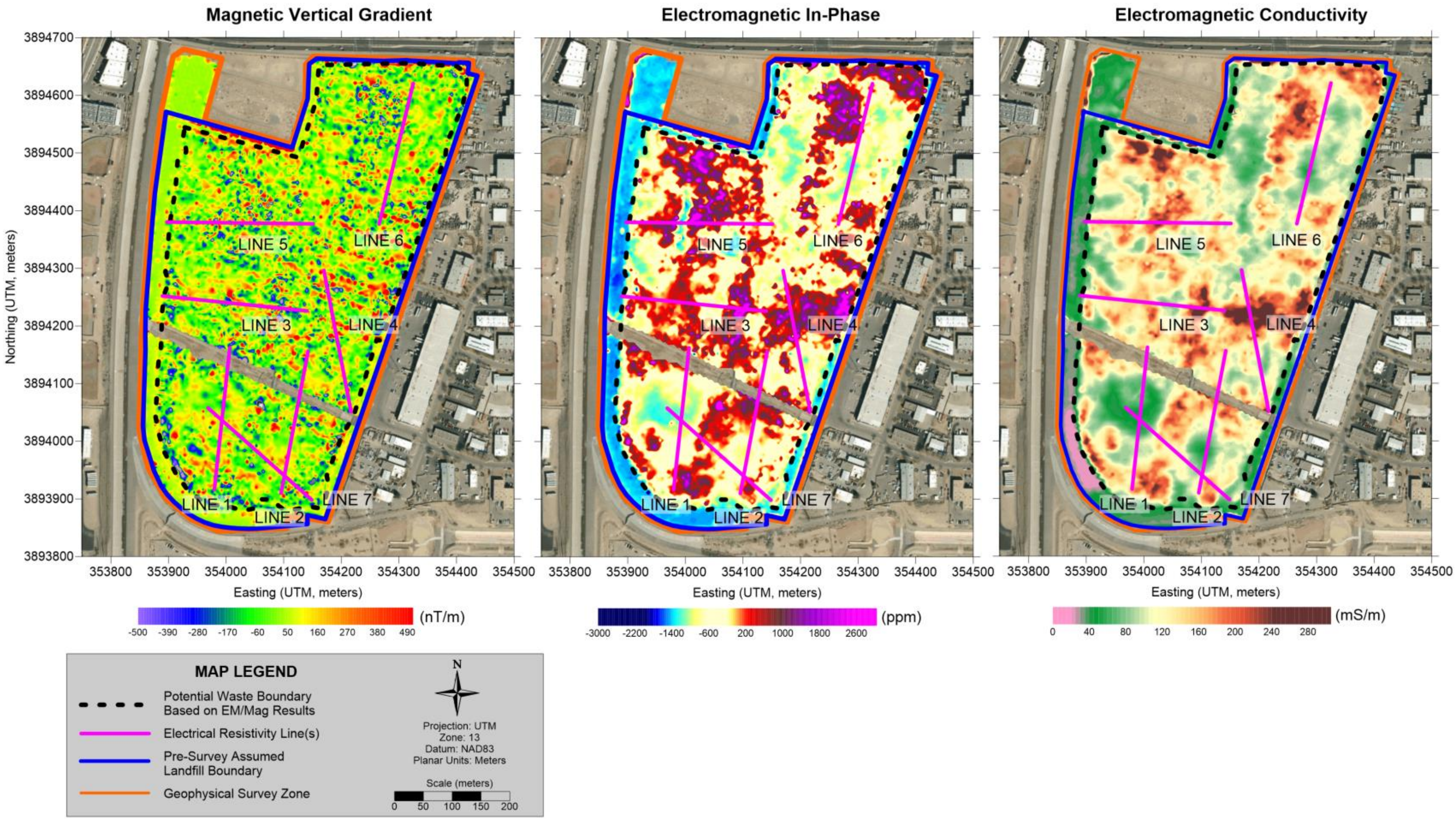


Figure 5. Magnetic Vertical Gradient Contour Map

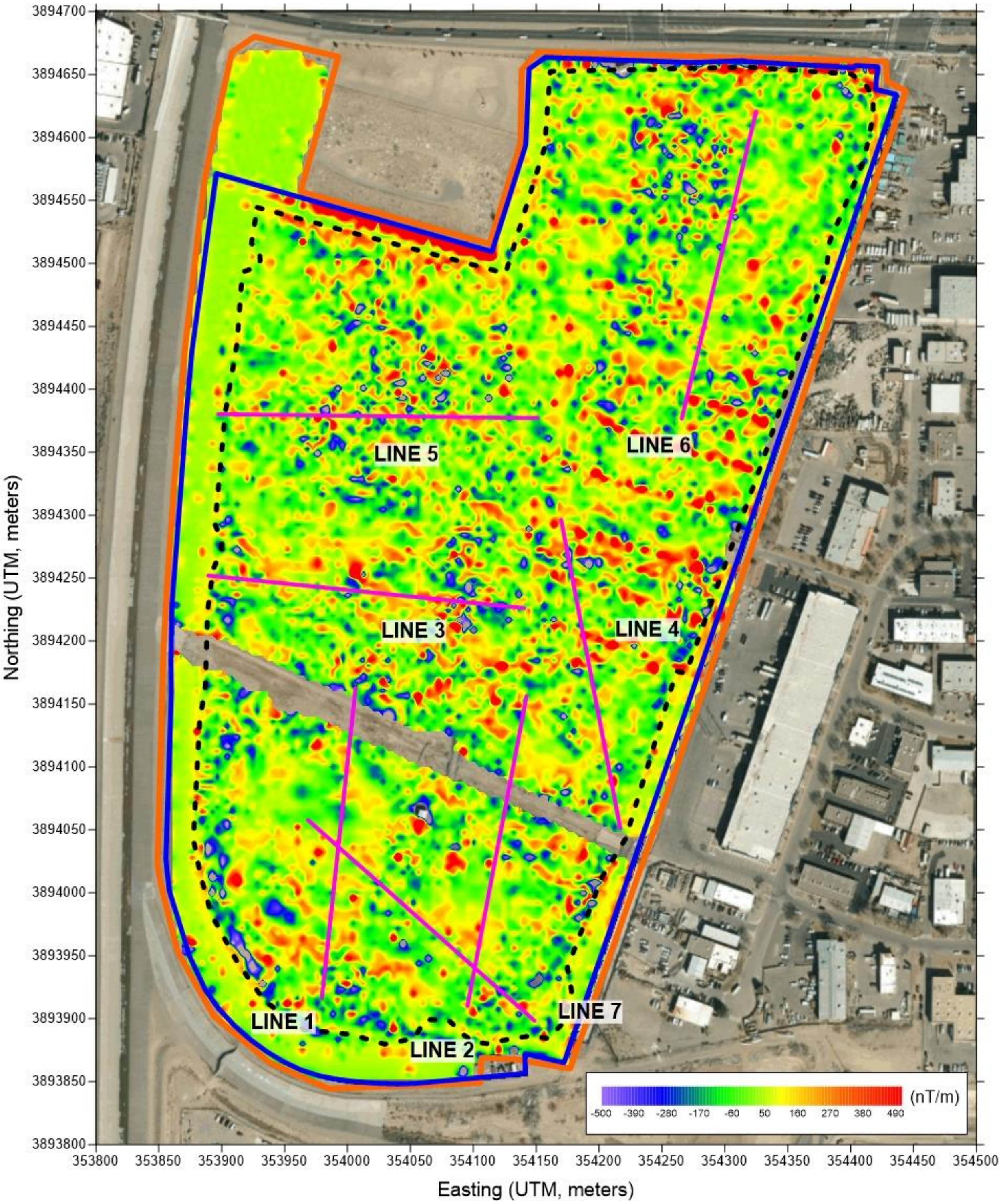


Figure 6. Electromagnetic Conductivity Contour Map

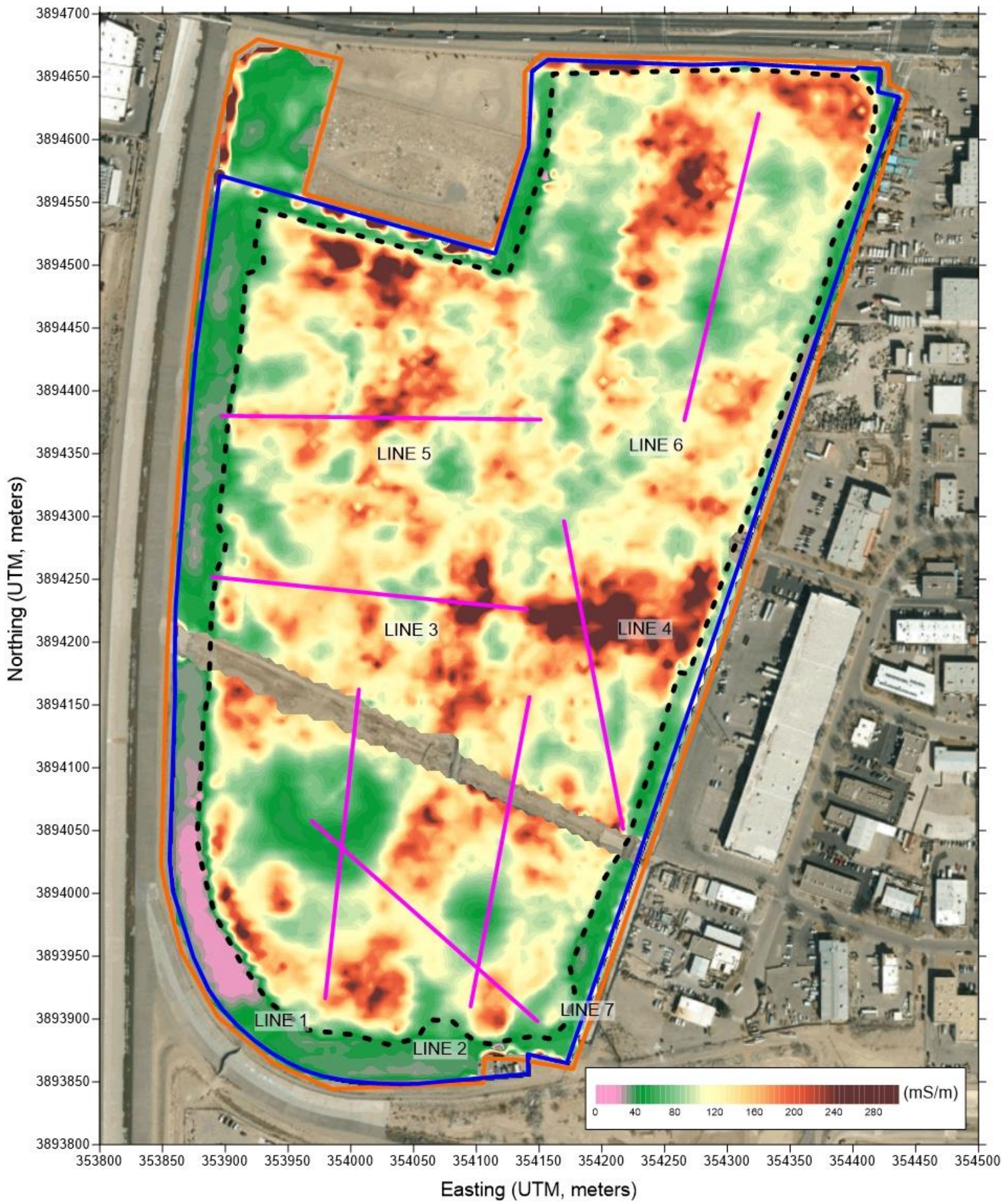
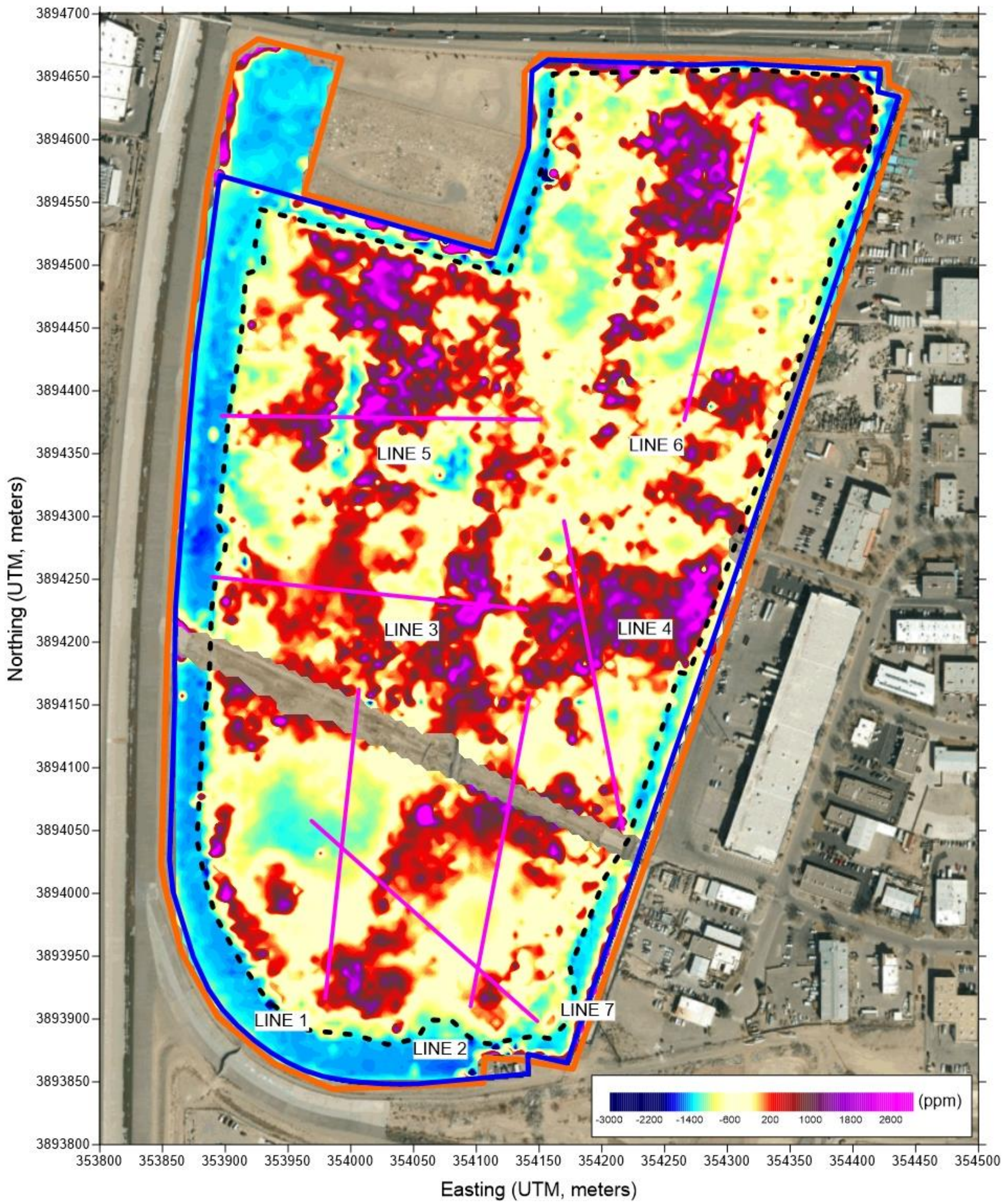


Figure 7. Electromagnetic In-phase Contour Map

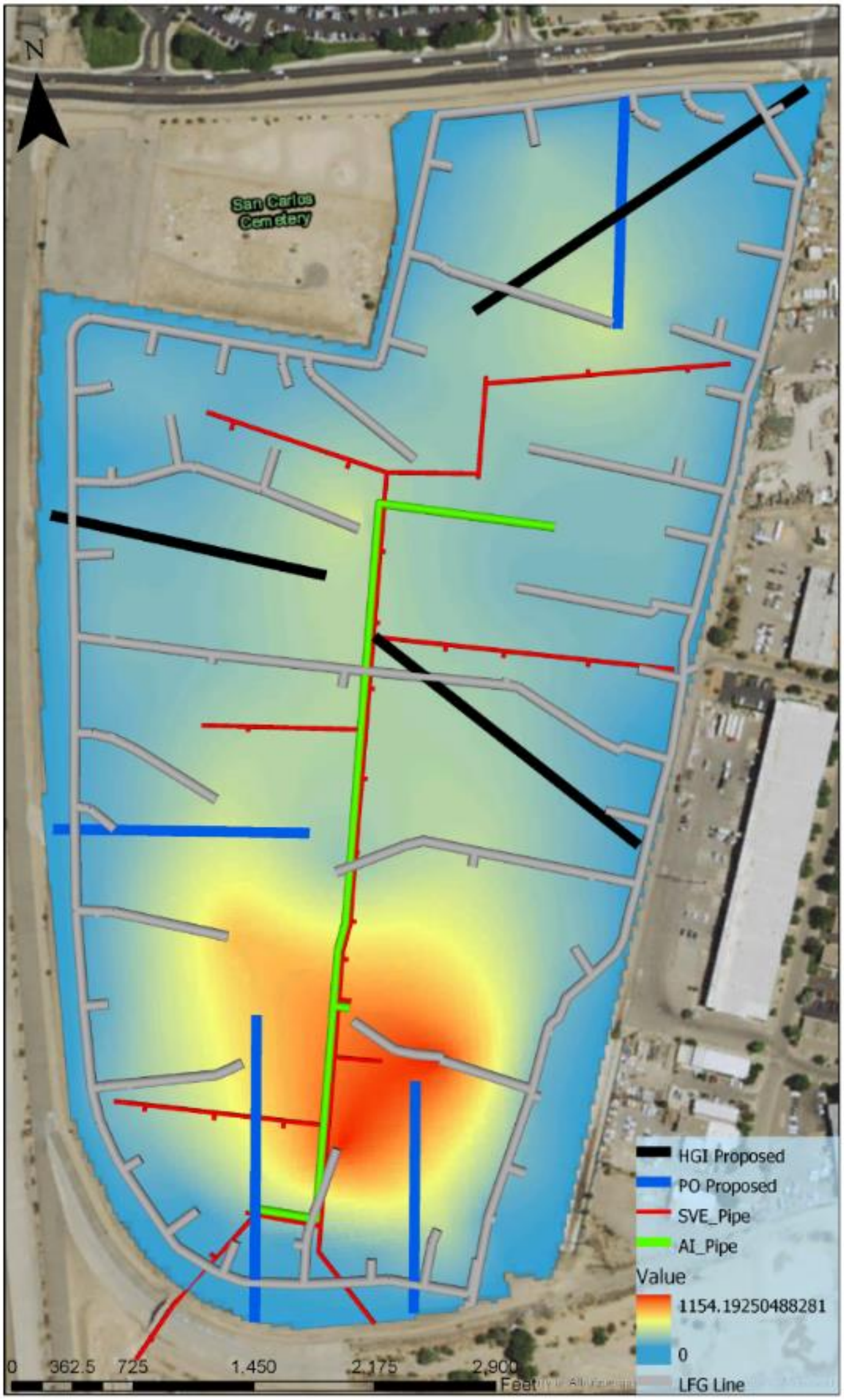


The results of the EM and Mag surveys have been interpreted to provide a potential waste boundary to delineate the spatial extent of the landfill, shown with a black dashed perimeter line in Figure 4, and in greater detail in Figure 5, Figure 6, and Figure 7. This would move the western landfill boundary to the east by approximately 82 and 131 feet (25 and 40 meters), at the south and north ends of the landfill respectively. The southern landfill boundary would move on average approximately 98 feet (30 meters) to the north. The eastern landfill boundary displays an average shift of 49 feet (15 meters) to the west for the southern section of the landfill. The northern section of the eastern landfill boundary appears to extend to pre-survey assumed landfill boundary, which correlates to the boundary fence around the landfill property. Similarly, the top section of the northern landfill boundary extends to the pre-survey assumed landfill boundary, which correlates to the boundary fence around the landfill property. The section of the northern boundary which borders the cemetery property would suggest the landfill boundary is shifted approximately 49 feet (15 meters) to the east and 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 along the eastern edge of the landfill, trending roughly in an east-west orientation, which are potentially a response to the landfill gas line infrastructure and RV connecting infrastructure or utilities (Figure 5 and Figure 8).

A secondary objective of the LA Landfill geophysical mapping was related to landfill gas production and flux across the site. There is significant infrastructure at LA Landfill related to the capture and extraction of landfill gas and further understanding of the potential for gas production and flux would benefit operations at the landfills. Several authors have published research regarding a link between the electrical properties of municipal waste sites and landfill gas concentrations and flux (Rosqvist et al, 2011; Dahlin et al, 2009). These studies tended to indicate the landfill gas was associated with resistive regions of the surveyed areas or correlations were observed between variations in resistivity during time-lapse monitoring and landfill gas fluxes. It was acknowledge that there are additional factors controlling the resistivity within the landfills and monitoring the landfills over time was likely to lead to the highest correlations to gas flux. The EM conductivity and in-phase results do not appear to display any correlation to the elevated landfill gas flux observed in Figure 8. This is likely based on the large sampling volume of the EM instrument, which has the effect of averaging the electrical response of the subsurface.

Figure 8. LA Landfill Gas Flux Contour Map (Provided by City of Albuquerque).



4.1.1 Line 1 Combined Method Results

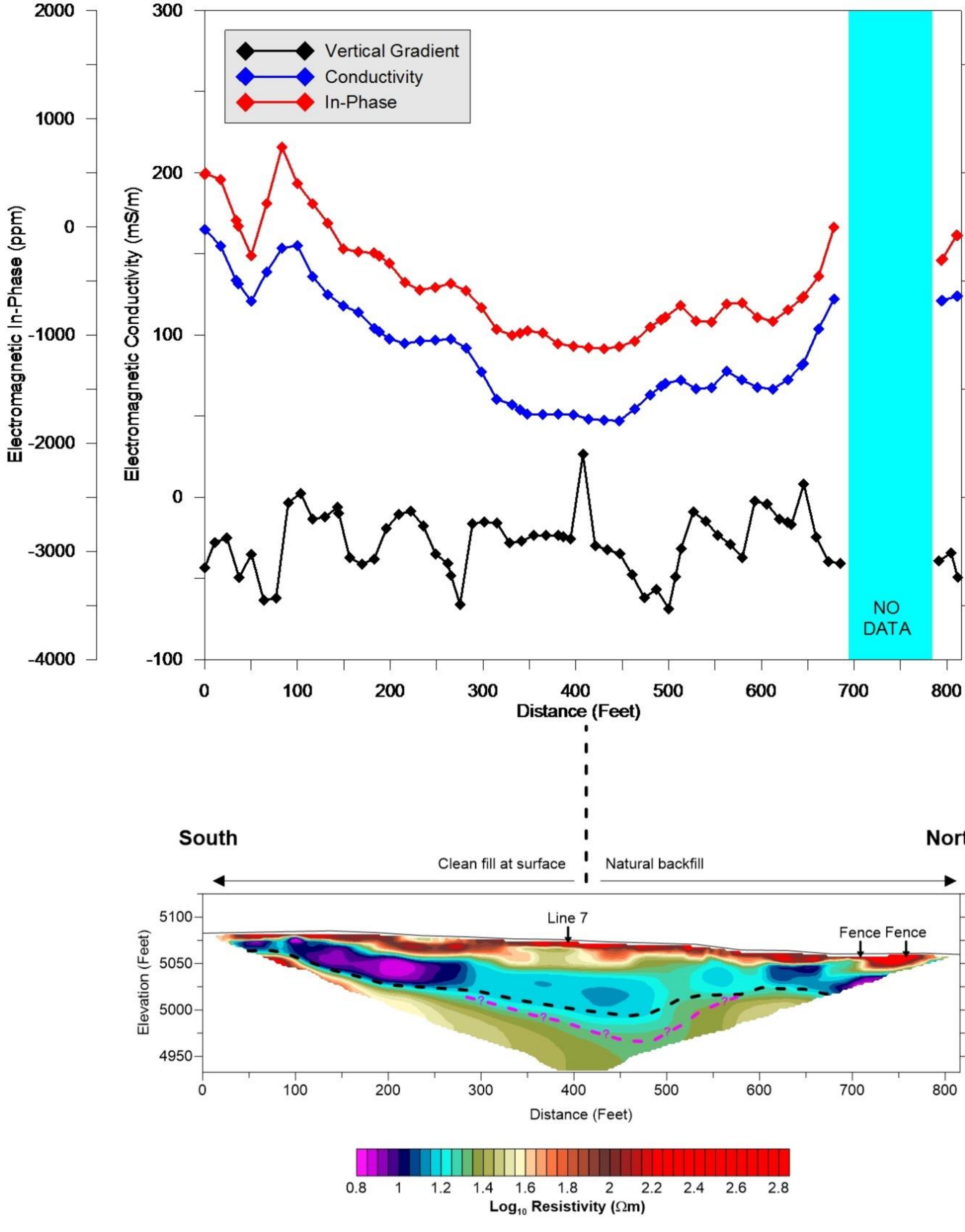
Figure 9 shows the resistivity profile for Line 1, which ran approximately south to north across the southwest portion of the landfill, alongside Mag and EM data extracted at the location of the resistivity line. Line 1 was collected entirely within the landfill boundary and its location was selected by evaluating the EM and Mag results. 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), therefore between approximately 0 to 100 feet along the line the depth of the waste is estimated to be on average approximately 24 feet (the base of the waste material is highlighted by the black dashed line in Figure 9), and the thickness of the cover is around 6 to 7 feet based on the more resistive near-surface layer (brown and red colors). Between approximately 100 to 550 feet along the line the depth of the conductive waste feature appears to increases to approximately 88 feet, with the cover thickness also increasing to what appears to be approximately 30 feet based on the resistivity values. However, it is likely that a proportion of the conductive waste feature between depths of 30 to 88 feet below ground surface (bgs) is a response to a conductive "plume" from the waste material, which has migrated deeper within the NE survey zone (highlighted by the magenta dashed line in Figure 9). The increase in cover material correlates well with information communicated to HGI by the City of Albuquerque staff; which indicates that this area has been subject to a degree of subsidence related to waste material decomposition. This has resulted in the area being backfilled with additional cover material over the intervening years, likely leading to the bowl shaped nature of the near-surface resistive layer. There is what appears to be a thin more conductive layer (tan color) embedded within this increase in cover material, between approximately 350 to 400 feet along the line and at a depth of approximately 10 feet. This may represent a perched water layer within the cover material or possibly different fill material containing higher clay content, based on the conductive nature of the feature.

Alternatively, based on the location of this section of the survey line within the high landfill gas flux region of the landfill, some of the apparent thickening of the cover layer is potentially a response to the high landfill gas content of the near-surface layer. As mentioned in the previous section a number of researchers have observed that landfill gas accumulations often appear as resistive regions within the subsurface of solid waste sites. Therefore, a number of the more resistive zones, located just below the near-surface highly resistive layer, along this section of the survey line, notably 225, 270, 340, and 440 feet along the line, could be related to accumulations or elevated flux of landfill gas. It is difficult to assign one particular interpretation to the apparent thickening of the cover layer, either an actual thickening of the cover material based on the subsidence and backfill or if the upper portion of the waste layer appears more resistive due to the presence of landfill gas in this region. Indeed, this could also be a response to a combination of the above reasons, with thicker cover layer and an elevated landfill gas concentration and/or flux in the wastes.

Beyond approximately 550 feet along the survey line, the depth of the conductive waste feature decreases to approximately 40 feet, with the thickness of the cover also decreases to around 8 to 10 feet. This trend continues to the end of the coverage for this survey line, which ends just to the north of the drainage ditch trending east-west across the landfill.

Figure 9. Line 1 Electrical Resistivity Comparison with EM & Mag Slices.



4.1.2 Line 2 Combined Method Results

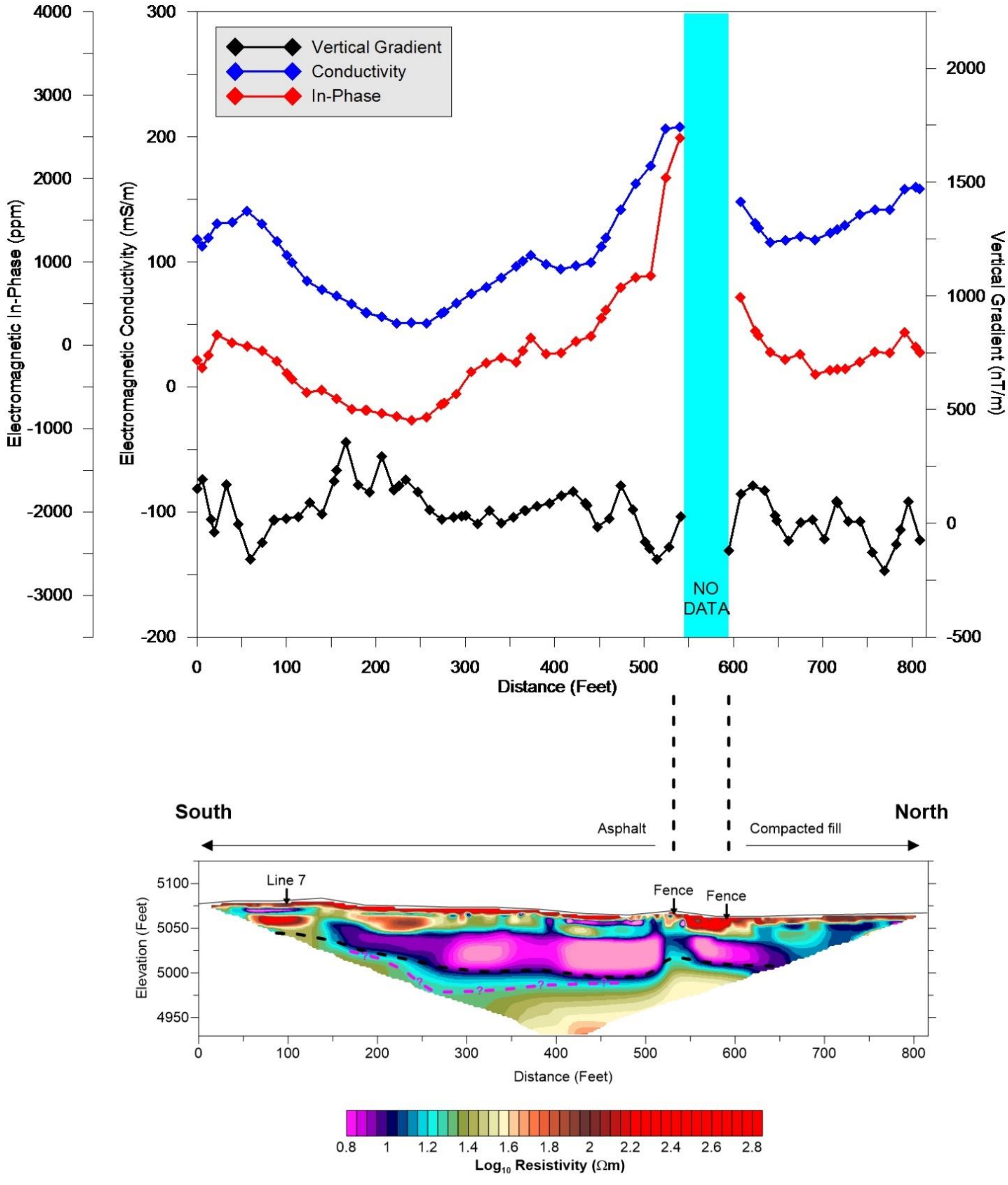
Figure 10 shows the resistivity profile for Line 2, which ran approximately south to north across the southeast portion of the landfill, alongside Mag and EM data extracted at the location of the resistivity line. Line 2 was collected entirely within the landfill boundary, with the location determined through evaluation of the EM and Mag results. We observe significant variability in the extracted EM and Mag readings as expected for variable waste constituents.

Again the landfill wastes are represented by the highly conductive target along the length of the survey line (the base of the waste material is highlighted by the black dashed line in Figure 10). Between approximately 0 to 140 feet along the line there appears to be a thin approximately 5 feet thick cover material layer, overlying and a thin highly conductive layer approximately 5 feet in thickness. The thin highly conductive layer may again be a response to a perched water layer similar to that observed in Line 1. The model results then transitions to a highly resistive region between approximately 16 to 30 feet depth (bgs). Due to the limited imaging depth and resolution at the ends of the survey line the large contrasts of these two features may be biasing the background resistivity of the surrounding regions. Therefore, the waste material may extend below the resistive region but the bias from the resistive region is obscuring the return to more conductive values. The resistive region could again be a response to elevated concentrations of landfill gas within the wastes and cover material in the near-surface. Beyond 140 feet along the line we observe a much better defined conductive layer, that extends to the end of the survey line. The depth to the top of this layer remains fairly consistent, varying between 20 to 27 feet (bgs), but the thickness of the layer increases from approximately 30 feet at 150 feet along the line, to approximately 50 feet between 270 to 515 feet along the line. At approximately 520 feet along the line it decreases to approximately 33 feet in thickness, and then remains fairly constant until the end of the survey line. It is difficult to determine what portion of the response is landfill waste and what portion is conductive leachate fluid (plume – one interpretation is highlighted by the magenta dashed line in Figure 10).

Above the conductive layer, the upper 20 to 27 feet display a significant amount of heterogeneity. The near-surface displays a thin resistive layer, approximately 5 feet in thickness, which appears continuous across the length of the survey line. Between approximately 150 to 505 feet along the line we observe a similar bowl shaped, overall more resistive region to that observe in Line 1. This could again be related to the subsidence and backfill operations within the southern area of the landfill. Alternatively, a number of the more resistive zones, located just below the near-surface highly resistive layer, along this section of the survey line, notably 195-245, 295, 325, 350, 425, and 475 feet along the line, could be related to accumulations or elevated flux of landfill gas. As mentioned in the previous section a number of researchers have observed that landfill gas accumulations often appear as resistive regions within the subsurface of solid waste sites. Therefore the elevated landfill gas concentrations may be increasing the resistivity of the typically conductive wastes in these regions, explaining the heterogeneity of this layer. This is potentially supported by the more conductive upper layer between approximately 620 feet and the end of the survey line, where the landfill gas flux is much lower (Figure 8) and the conductive wastes are dominating the resistivity value.

Another thin highly conductive layer, approximately 5 feet in thickness, is observed between approximately 410 to 495 feet along the line. This layer, at a depth of approximately 10 feet (bgs), may again be a response to a perched water layer similar to that observed at the beginning of Line 2 and in Line 1. We also observe a highly resistive feature between approximately 545 to 595 feet along the line, extending from the ground surface to a depth of approximately 15 feet (bgs). This corresponds to the location of the drainage ditch trending east-west across the landfill and may be a response to the construction or materials used for this structure.

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



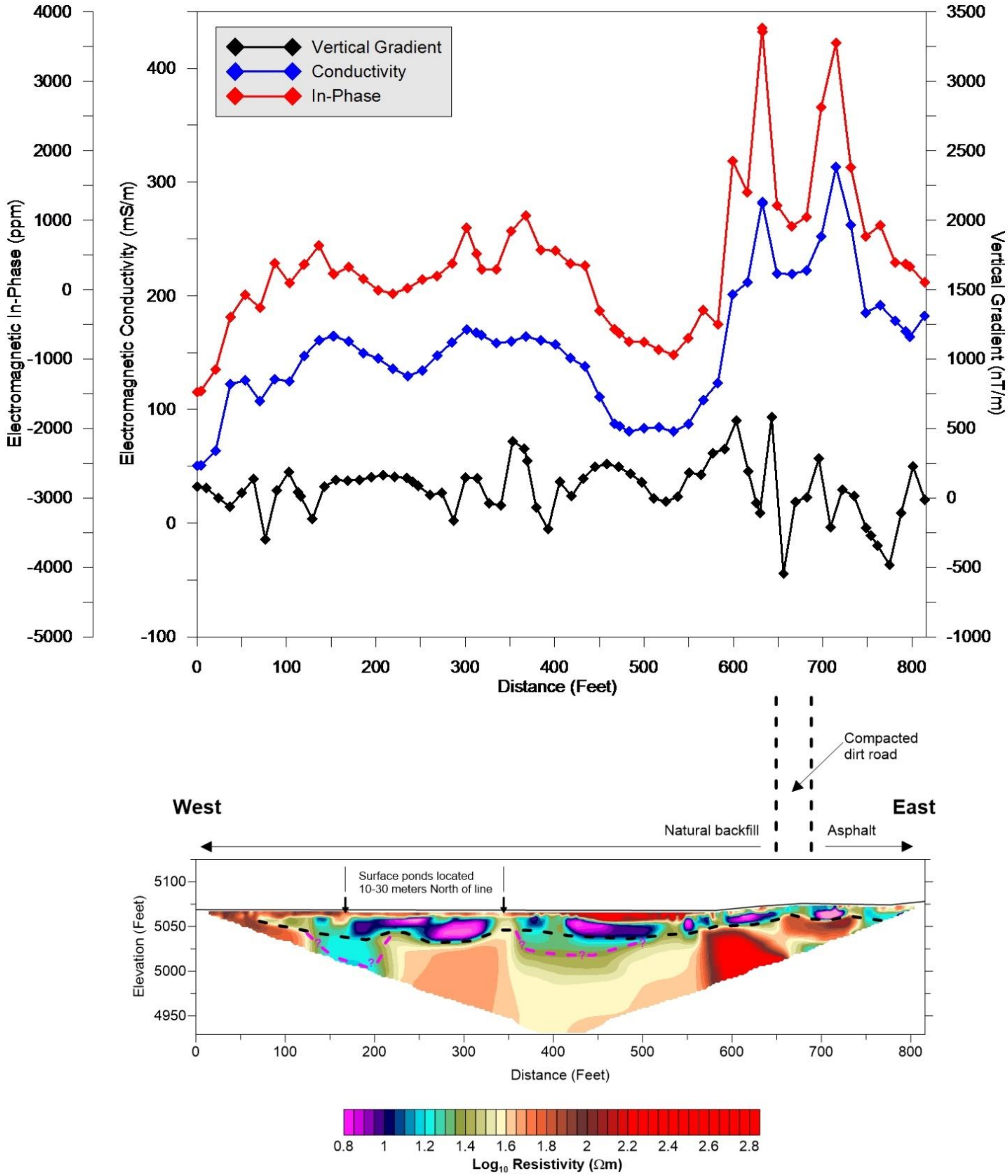
4.1.3 Line 3 Combined Method Results

Figure 11 shows the resistivity profile for Line 3, which ran approximately west to east across the central portion of the landfill beginning on the western edge of the landfill wastes, alongside Mag and EM data extracted at the location of the resistivity line. Again, Line 3 was collected entirely within the landfill boundary proposed by the EM and Mag results, and we observe a significant level of variability in the extracted EM and Mag readings reflecting this.

Again the landfill wastes are represented by the highly conductive target along the length of the survey line (the base of the waste material is highlighted by the black dashed line in Figure 11). Between approximately 0 to 70 feet along the line the model results appear resistive, potentially suggesting that landfill wastes are not present. The resistivity survey line does start approximately 25 feet to the west of the proposed landfill boundary identified from the EM and Mag results, however, the resistivity results would tend to suggest this boundary should potentially shift a further 45 feet to the east. A thin resistive layer, likely representing the cover material, extends across the survey line; this is approximately 10 feet thick up to 170 feet along the line where it decreases to approximately 5 feet. The section between approximately 445 to 550 feet along the line thickens to 10 feet and appears highly resistive. The conductive layer representing the landfill wastes begins at approximately 70 feet along the line, appearing to increase in thickness with distance to approximately 36 feet at approximately 150 feet along the line. It remains fairly similar in thickness until approximately 500 feet along the line, where it decreases in thickness to approximately 16 feet for the remainder of the survey line.

There are a number of deviations from this trend, including between approximately 130 to 210 feet along the line where the conductive layer appears to extend down to the imaging depth limit of the model results, approximately 60 feet in this location. Since the landfills are unlined this could be a response to a conductive “plume” from the waste material, which has migrated deeper into the subsurface in this zone (highlighted by the magenta dashed line in Figure 11). Around 345 feet along the line a more resistive region appears to cut through the conductive layer, extending almost to the ground surface. This may 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. Another highly resistive feature is observed between approximately 575 to 650 feet along the line, extending from a depth of 26 feet (bgs) to the imaging depth limit of the model results, approximately 68 feet (bgs) in this location. This could be a response to more consolidated material in the subsurface at this location, possibly bedrock or cemented sediments.

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

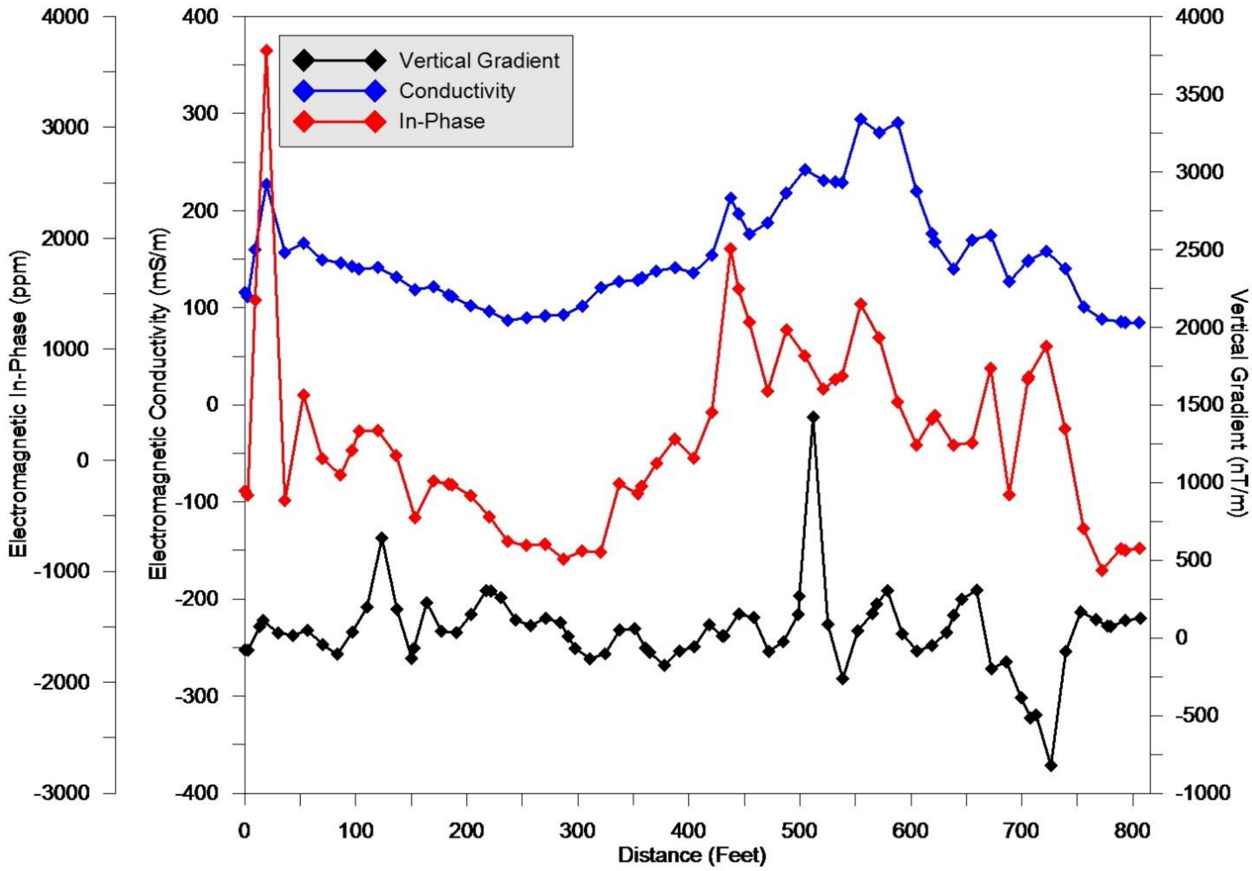


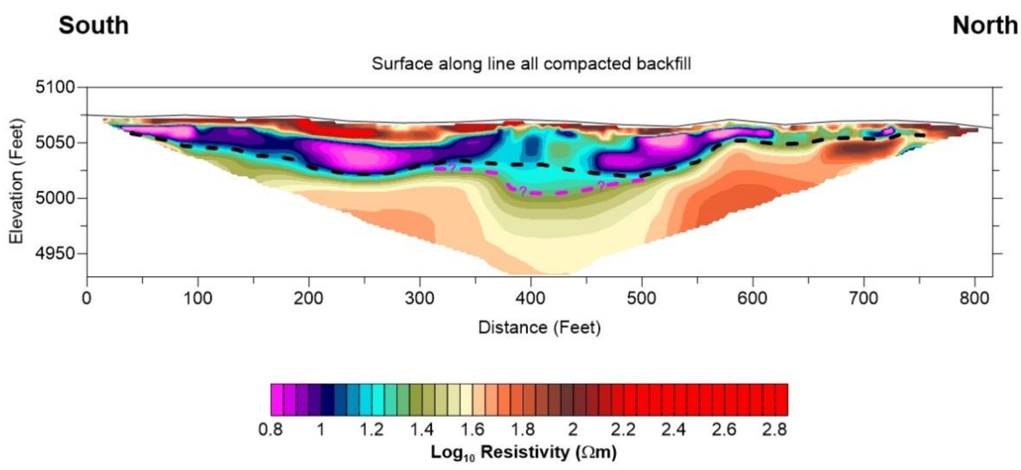
4.1.4 Line 4 Combined Method Results

Figure 12 shows the resistivity profile for Line 4, which ran approximately south to north across the central portion of the landfill beginning on the eastern edge of the landfill wastes, alongside Mag and EM data extracted at the location of the resistivity line. Again, Line 4 was collected entirely within the landfill boundary proposed by the EM and Mag results, and we observe a significant level of variability in the extracted EM and Mag readings reflecting this.

Again the landfill wastes are represented by the highly conductive target along the length of the survey line (the base of the waste material is highlighted by the black dashed line in Figure 12). A thin resistive layer, likely representing the cover material, extends across the survey line; this is approximately 7 feet thick up to 165 feet along the line. Between 165 to 370 feet along the line the cover material appears to increase to maximum of 17 feet thick, before decreasing back to a thickness of approximately 7 feet for the remainder of the survey line. The conductive layer representing the landfill wastes appears to increase in thickness between approximately 0 to 150 feet along the line, from approximately 10 to 22 feet thick. Between approximately 200 to 550 feet along the line the waste material thickness remains fairly similar, at approximately 30 feet. There is a suggestion of a conductive plume from the waste material between approximately 370 to 490 feet along the line, appearing to extend down an additional 40 feet in depth (highlighted by the magenta dashed line in Figure 12). After 550 feet along the line the thickness of the waste material layer appears to decrease significantly, to approximately 12 feet by around 595 feet along the line. It remains of a similar thickness until 755 feet along the line, where the subsurface becomes more resistive potentially indicating no waste materials are present, or that the materials change to more resistive types of waste.

Figure 12. Line 4 Electrical Resistivity Comparison with EM & Mag Slices.





4.1.5 Line 5 Combined Method Results

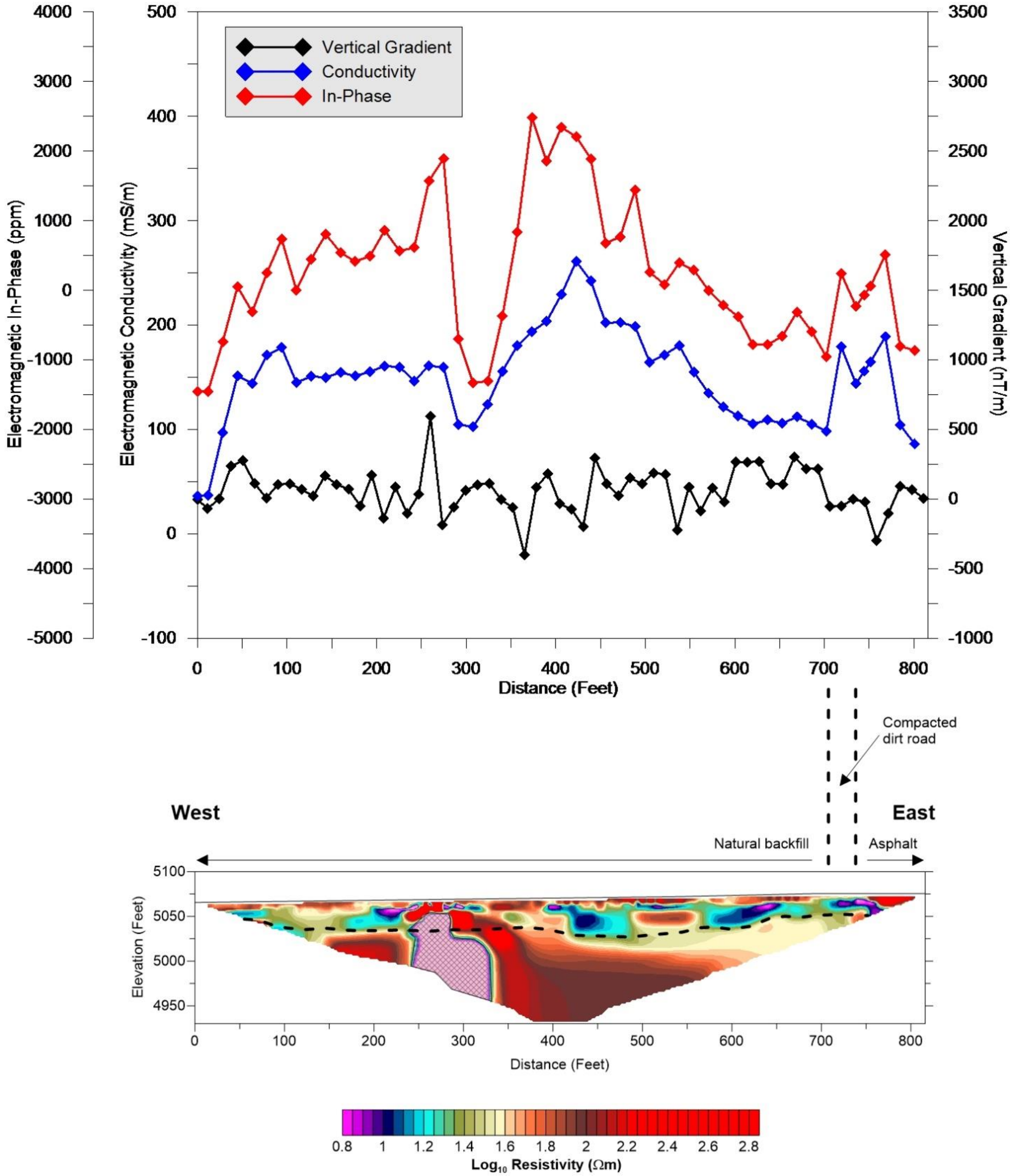
Figure 13 shows the resistivity profile for Line 5, which ran approximately west to east across the northwest portion of the landfill, beginning on the western edge of the landfill wastes, alongside Mag and EM data extracted at the location of the resistivity line. Again, Line 5 was collected entirely within the landfill boundary proposed by the EM and Mag results, and we observe a significant level of variability in the extracted EM and Mag readings reflecting this.

Again the landfill wastes are represented by the conductive target along the length of the survey line. A thin resistive layer, likely representing the cover material, extends across the survey line; this is approximately 8 feet thick across the length of the survey line. An obvious highly conductive feature is observed between approximately 240 to 320 feet along the line (highlighted by the gray cross-hatch region in Figure 13), extending from a depth of approximately 13 feet (bgs) to the depth limit of the model (approximately 90 feet in this location). The location of this feature also corresponds to significant responses in the EM-conductivity and EM-in-phase profiles, both reflected as decreases in values. This is likely a response to metallic infrastructure in the subsurface, possible a conductive pipeline or drain for example, that the resistivity survey line crosses over. The EM-conductivity and EM-in-phase results presented in Figure 6 and Figure 7 appear to indicate the significant decrease in values extends in a linear nature to the north and south of the resistivity survey line, lending weight to the pipeline response. We observe a number of highly resistive responses around this highly conductive feature in the resistivity model results, which are likely to be artifacts of the inversion process (where the model tries to accommodate the highly conductive response to the potential pipeline) making interpretation problematic in this region.

The conductive layer representing the landfill wastes can be traced across the length of the survey line (the base of the waste material is highlighted by the black dashed line in Figure 13), though it is broken by a few smaller resistive bodies along the length. It appears to increase in thickness between approximately 0 to 80 feet along the line, from approximately 10 to 20 feet thick. Between approximately 80 to 615 feet along the line the waste material thickness remains fairly similar, at approximately 25 feet. There is a suggestion of a conductive plume from the waste material between approximately 425 to 585 feet along the line, appearing to extend down an additional 20 feet in depth. After 615 feet along the line the thickness of the waste material layer appears to decrease, to approximately 16 feet by around 650 feet along the line. It remains of a similar thickness until the end of the survey line. Overall, the landfill wastes appear to be less conductive, when compared to the previous resistivity survey lines, potentially suggesting a difference in the wastes and/or their decomposition potential and/or decrease in overall moisture content.

Outside of the region potentially affected by the highly conductive feature, there are a number of resistive regions that deviate from the general conductive waste layer trend. This includes what appears to be a resistive break between approximately 380 to 415 feet along the line, and a resistive region between approximately 500 to 550 feet along the line. The former may represent a border within the landfill composed of more resistive material, such as clean soil, that separated differing waste cells for example. Alternatively, this and the latter resistive region could be a response to more resistive waste materials which were placed in this area of the landfill that are more resistant to breaking down and forming conductive decomposition products.

Figure 13. Line 5 Electrical Resistivity Comparison with EM & Mag Slices.



4.1.6 Line 6 Combined Method Results

Figure 14 shows the resistivity profile for Line 6, which ran approximately south to north across the northeast portion of the landfill, alongside Mag and EM data extracted at the location of the resistivity line. Again, Line 6 was collected entirely within the landfill boundary proposed by the EM and Mag results, and we observe a significant level of variability in the extracted EM and Mag readings reflecting this.

Again the landfill wastes are represented by the conductive target, which appears to extend along the length of the survey line (the base of the waste material is highlighted by the black dashed line in Figure 14). A resistive near-surface layer, likely representing the cover material, is observed along the length of the survey line. This layer displays some variation in thickness, being approximately 8 feet thick between approximately 0 to 140 feet along the line. It then increases in thickness to approximately 20 feet between approximately 150 to 270 feet along the line, and again to approximately 30 feet between approximately 270 to 250 feet along the line. The cover material layer then decreases gradually in thickness to approximately 7 feet at around 460 feet along the line; remaining fairly consistent from that location to the end of the survey line. It is uncertain whether the increase in thickness of the resistive near-surface layer is a response to a thicker layer of cover material or if so of the variability is related to changes in waste materials in this area. The underlying waste material is moderately conductive and could indicate potential for decomposition and related subsidence, that would require backfilling with additional cover material in this area. In addition, the EM-conductivity and EM–in-phase profile results display a general dip in the amplitude of the readings associated with the thicker resistive layer possibly suggesting a higher degree of non-waste material, and so thicker cover material.

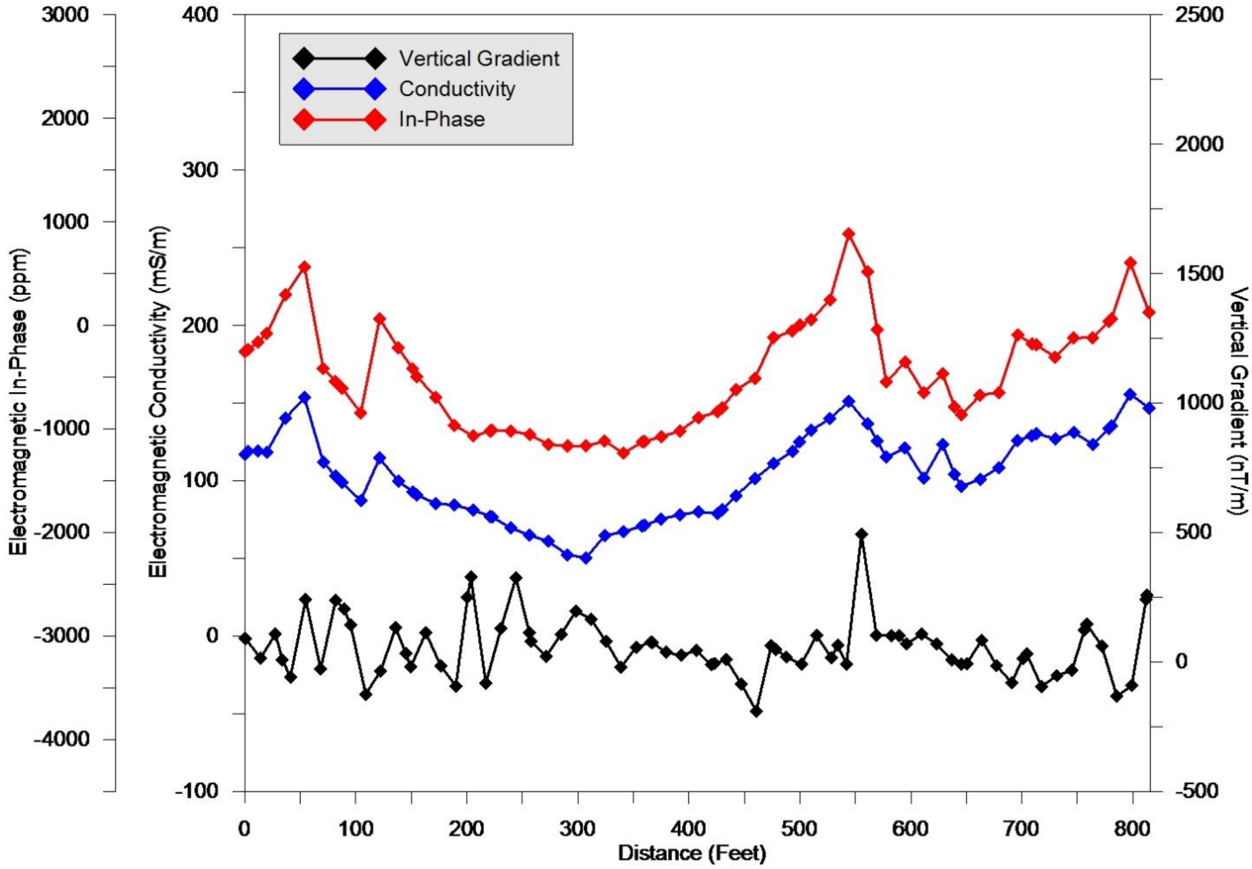
The conductive layer representing the landfill wastes can be traced across the length of the survey line. The beginning of this layer, between approximately 80 to 105 feet along the line where it is approximately 12 feet in thickness, appears to be almost separated from the remainder of this layer by a more resistive, almost vertical, region between approximately 120 to 130 feet along the line. We have observed similar features before in other resistivity lines, and another such region is observed between approximately 460 to 490 feet along this line, and a number of interpretations are possible:

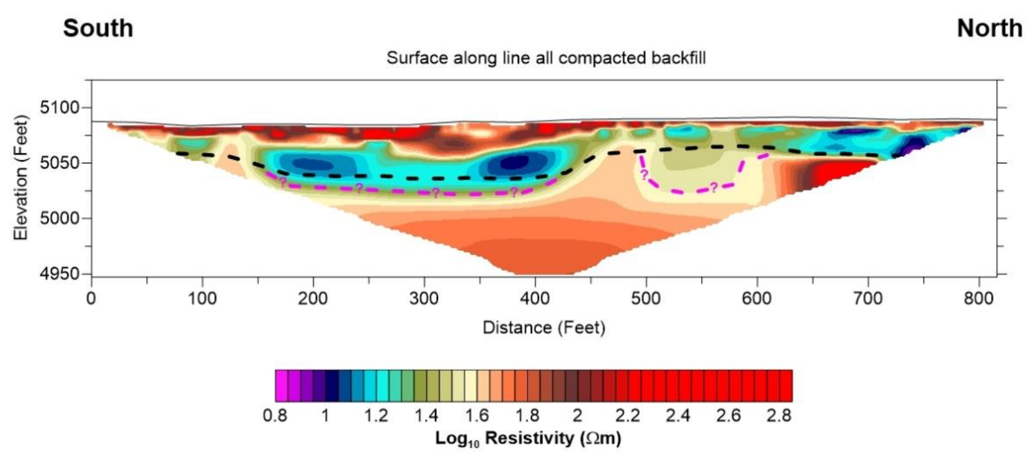
- These resistive regions could represent more competent or less permeable underlying geology where the waste decomposition products are not infiltrating to create a waste 'plume',
- They may represent borders within the landfill composed of more resistive material, such as clean soil, that separated differing waste cells for example,

- Alternatively, they could be a response to more resistive waste materials which were placed in this area of the landfill that are more resistant to breaking down and forming conductive decomposition products.

Without additional groundtruthing information from drilling and sampling, etc. it is difficult to determine which interpretation is correct. For example, the conductive layer between approximately 150 to 430 feet along the line is approximately 37 feet in thickness, but extends almost 60 feet (bgs) due to the thick over material layer in this location. However, it may be that the waste material is concentrated in the upper 20 feet of this layer, where we observe the highly conductive values, with the lower remaining portion related to a conductive plume from the decomposition products (highlighted by the magenta dashed line in Figure 14). In a similar manner, the section of the conductive layer between approximately 450 feet along the line and the end of the survey line is on average 20 feet in thickness, with the apparent thickening of this layer between approximately 510 to 590 feet associated with a conductive plume.

Figure 14. Line 6 Electrical Resistivity Comparison with EM & Mag Slices.





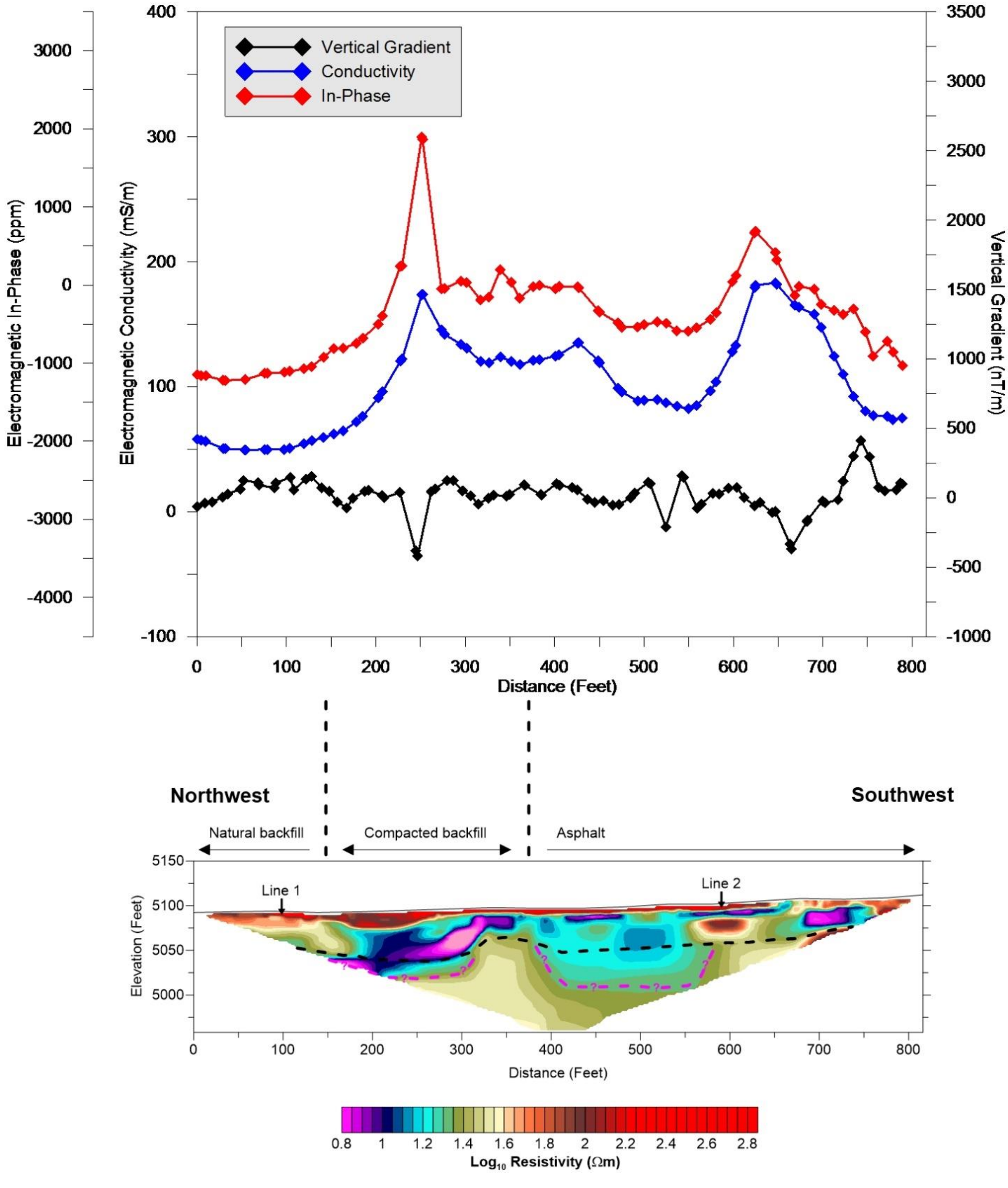
4.1.7 Line 7 Combined Method Results

Figure 15 shows the resistivity profile for Line 7, which ran approximately northwest to southeast across the southern portion of the landfill, alongside Mag and EM data extracted at the location of the resistivity line. Again, Line 7 was collected entirely within the landfill boundary proposed by the EM and Mag results, and we observe a significant level of variability in the extracted EM and Mag readings reflecting this. This line was positioned to further investigate the area of elevated landfill gas flux and the possible perched water observed in Line 2.

Line 7 crosses Line 1 around 100 feet along the line, and we observe a good agreement between the two model results. Both display a near-surface resistive layer, approximately 30 feet in thickness, likely representing the cover material, overlying the more conductive waste material. We have a limited imaging depth at this location in Line 7 and so the model results only display a small section of the conductive layer from the waste materials. However, as we progress further along the line to the southwest, and the imaging depth increases, we observe the conductive layer resolved much better (the base of the waste material is highlighted by the black dashed line in Figure 15). We observe significant variation in the thickness of this layer; approximately 46 feet thick between approximately 175 to 310 feet along the line, decreasing to approximately 25 feet between approximately 315 to 375 feet along the line. Increasing significantly to approximately 65 feet thick between approximately 385 to 545 feet along the line, before decreasing to an average of 25 feet for the remainder of the line. Once again, these significant increases are likely related to a conductive plume related to the decomposition products extending into the underlying native strata, as is potentially reflected in the model results of Lines 1 and 2 as well (highlighted by the magenta dashed line in Figure 15). The southern portion of the landfill has been subjected to subsidence as the landfill wastes break down, indicating the potential for decomposition products to be migrating in the subsurface.

Where Line 7 crosses Line 2, around 590 feet along the line, we again observe a good agreement between the two model results. Line 7 also displays a thin highly conductive layer, just below the resistive near-surface cover material layer, which may represent a perched water layer in this location. A similar feature is also observed between approximately 420 to 480 feet along the line, at the same depth, which could indicate another perched water layer. In addition, beneath the highly conductive layer we also observed the resistive region, which again could be a response to elevated concentrations of landfill gas within the wastes and cover material in the near-surface. A number of additional resistive regions within the conductive layer are observed, notably around 145 and 450 feet along the line, which possibly indicate areas where the landfill gas is accumulating in this high flux area of the landfill.

Figure 15. Line 7 Electrical Resistivity Comparison with EM & Mag Slices.



5.0 CONCLUSIONS

A multi-method geophysical survey was performed at the LA Landfill in Albuquerque, New Mexico, during November and 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 over the entire accessible landfill area, as well as seven lines of 2D electrical resistivity were completed. The EM and Mag measurements provided an indication of the lateral limits of covered landfill. The electrical resistivity imaging method confirmed these boundary results and allowed the depth and thickness of the conductive wastes and the thickness of the cover material to be estimated. A secondary objective at the LA Landfill was to determine if the geophysical results displayed any correlation to landfill gas production and flux across the site.

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. Combined analysis of the EM, Mag, and Resistivity results would tend to suggest the western assumed landfill boundary would recede by approximately 82 and 131 feet (25-40 meters), with the southern assumed landfill boundary receding by approximately 98 feet (30 meters). The EM, Mag, and Resistivity results agreed with the majority of the eastern and northern assumed boundaries, although these were bounded by the property fence line in most cases. It did indicate that the southern half of the eastern assumed boundary would recede by approximately 49 feet (15 meters).
- The resistivity data provided additional imaging to support the lateral extents determined using the EM and Mag data; with the resistivity results displaying a good alignment where they crossed or approached the proposed landfill boundaries. The resistivity profile results estimated the thickness of the waste to be approximately 20-25 feet (6-8 meters) at the locations of the resistivity survey lines, with cover thickness estimated on average to be 8-10 feet (2.5-3 meters). This differs somewhat from the pre-survey assumed values averaging 25 feet (8 meters) for waste thickness and 3 feet (1 meter) for cover thickness. We observe some significant deviations from these averages, for example portions of the southern area of the landfill indicated an increase in the cover

thickness to 30 feet (9 meters) in places. This area has been subject to subsidence and associated backfilling with additional cover material, which may explain this increase in thickness. In addition, the conductive layer, which has been interpreted as representing the waste materials, displays a number of increases in thickness above this average across the majority of the survey lines. Since these landfills are not lined this could indicate a "plume" of decomposition products that has migrated into the underlying strata as the waste breaks down and interacts with moisture, etc.

- We have identified a number of resistive regions that are generally located just below the cover material layer within the conductive waste material. These could be related to elevated landfill gas accumulations or flux within the waste materials, based on relationships observed between electrical properties of these sites and landfill gas in the literature. As the landfill gas is produce and migrates up through the waste materials, it is assumed that it would accumulate in more porous parts of the waste or displace fluid in the pore space, producing these more resistive regions. It is difficult to be certain without more detailed information on these fluxes or concentrations of landfill gas in the subsurface. One recommendation would be to repeat the resistivity measurements over time in the areas of identified elevated landfill gas flux (like those observed in the location of Lines 1 and 2). In this way the changes in landfill gas flux could be correlated to changes seen in resistivity, since it is assumed other conditions controlling the resistivity value would remain constant over time.

6.0 REFERENCES

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APPENDIX A

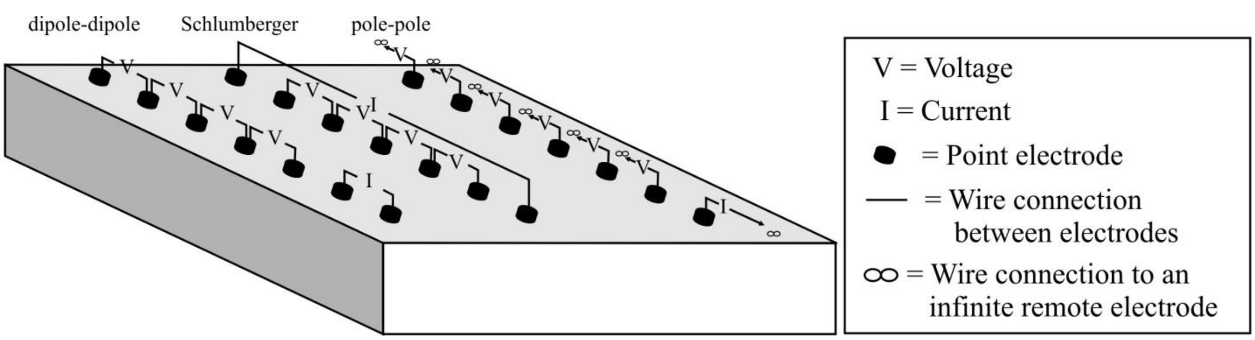
Description of Electrical Resistivity

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 16 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 16. 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):

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

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

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

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

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

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

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

APPENDIX B

Description of Electromagnetic Induction and Magnetic Gradiometry

8.0 DESCRIPTION OF EM & MAG

8.1 MAGNETOMETRY

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

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

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

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

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

The magnetic field is measured with a magnetometer. Magnetometers permit rapid, non-contact surveys to locate buried metallic objects and features. A one person portable field unit can be used virtually anywhere a person can walk; although, they 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.