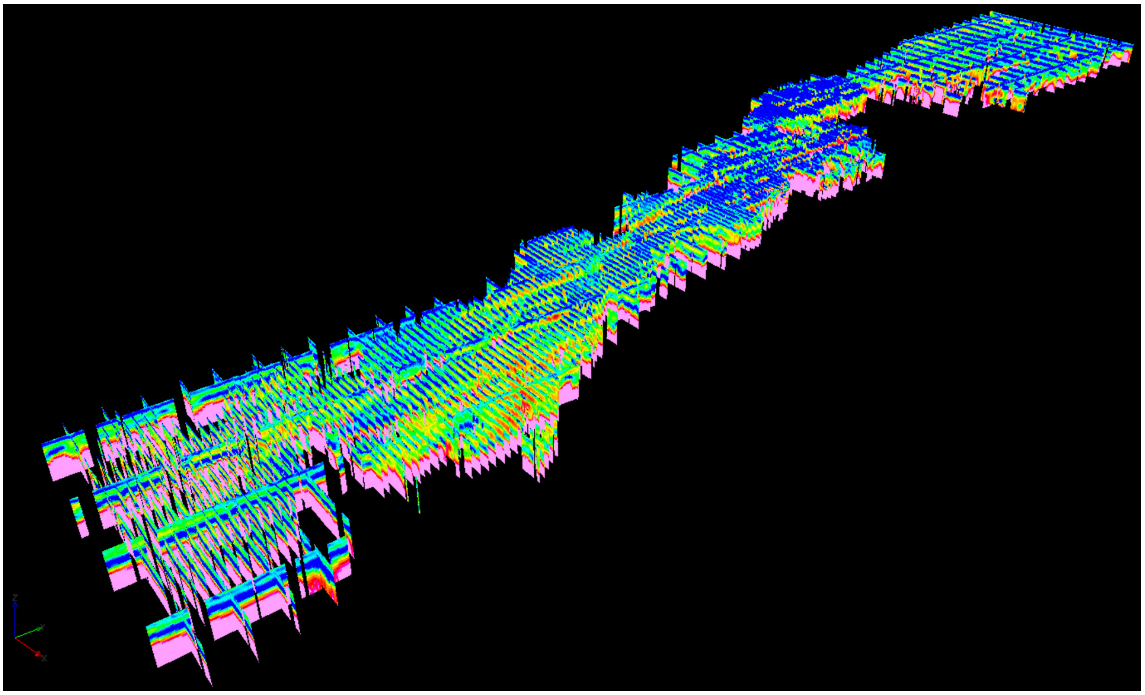
Final Spatially-Constrained Inversions Report and Data Delivery for the Airborne Electromagnetic Survey of the Wahpeton, North Dakota Area for the North Dakota State Water Commission



Jared Dale Abraham
Principle Geophysicist/Geologist
(303) 905-6240

Theodore H. Asch
Principle Geophysicist
(720) 415-7312

Aqua Geo Frameworks, LLC
130360 County Road D
Mitchell, NE 69357

Aqua Geo Frameworks

Disclaimer:
AGF conducted this project using the current standards of the geophysical industry and used in-house quality control standards to produce this geophysical survey and products. The geophysical methods and procedures described in this report are applicable to the particular project objectives, and these methods have been successfully applied by AGF to investigations and projects of similar size and nature. However, field or subsurface conditions may differ from those anticipated, and the resultant data may not achieve the project objectives. AGF's services were performed consistent with the professional skill and care ordinarily provided by professional geophysicists under the same or similar circumstances. No other warranty or representation, either expressed or implied, is made by AGF in connection with its services unless in writing and signed by an authorized representative of AGF

Table of Contents

List of Figures

List of Tables

.

1. Introduction

The North Dakota State Water Commission (NDSWC) required a detailed hydrogeological framework of the area around Wahpeton and Fargo, North Dakota in order to implement ground water management plans. NDSWC contracted Geotech Ltd. (Geotech) to implement an Airborne Electromagnetic (AEM) survey of selected areas within the Wahpeton and Fargo areas of North Dakota. Geotech contracted Aqua Geo Frameworks, LLC (AGF) to assist in the QA/QC and advanced processing and inversion of Geotech's Versatile Transient Electromagnetic (VTEM) systems data (Geotech, 2017). Specifically, AGF will conduct Laterally-Constrained Inversions (LCI) and Spatially-Constrained Inversions (SCI) of the VTEM data. These inversions will be compared to existing borehole data. NDSWC is conducting this survey as they would like to gain knowledge of the distribution of aquifer materials and their relations to drill holes in the area. The reconnaissance data acquisition plan is presented in Figure 1-1. All airborne operations were carried out by Geotech utilizing their VTEM system.

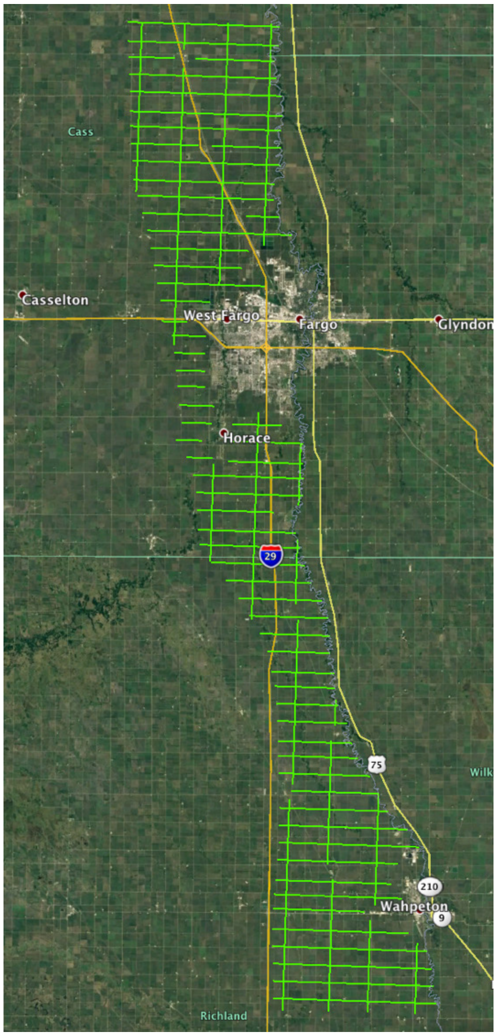


Figure 1-1. Planned Reconnaissance AEM acquisition within the Wahpeton and Fargo areas of North Dakota (Google Earth).

2. Schedule/Time Line

Geotech mobilized to the Fargo area on November 4, 2017. The system was assembled November 4-5, 2017 and ground tests and airborne tests were conducted November 6-7. Production began on November 7 and continued through November 18, 2017. Preliminary processing and LCI's were performed on the data from November 8-19.

3. System Calibration/Ground Tests

3.1 Test Line Calibration

The VTEM system was flown over two known test holes locations (130378 and 130380) with down-hole geophysical logs four times. The calibration process involves acquiring data with the system over the test hole locations. Acquired data are processed and a scale factor (time and amplitude) is determined, if necessary, so that the inversion process produces the model that approximates the known geology at test hole locations. If a calibration factor is determined, it is applied to the data before final SCI inversions. See Section 6, Forward/Inversion Modelling, for further discussion of the test line and borehole comparison analysis.

3.2 System Ground Tests

Ground tests included checking for system operation including the following sub-systems: 1) transmitter (Tx) current amplitude and stability including waveform; 2) receiver (Rx) functionality 3) altimeter operation; 4) GPS operation; 5) tilt meter/attitude sensor operation and calibration; 6) navigation and communication; 7) airborne magnetometer operation; 8) base station magnetometer stability and field strength stability; and 9) DGPS base station operation.

3.3 System Airborne Tests

Airborne tests were conducted by Geotech to verify the operation of the system and are described in the Geotech report on the data acquisition.

3.4 Boreholes

Many borehole lithology logs were downloaded from the NDSWC MapServices (NDSWC, 2017), both "TestHoles" and "Observations Wells" were downloaded for the general area of the survey. In addition to the downloaded lithology logs, NDSWC provided geophysical logs for test holes 130378 and 130380 (Personal Communications, Scott Parkin Hydrologist and Rex Honeyman Hydrologist NDSWC, November 2, 2017).

4. Data Acquisition

4.1 Acquisition Timing and as-flown lines

The NDSWC AEM data acquisition was flown out of the Fargo Airport. The production flights took place from November 7-18, 2017. After the initial reconnaissance lines were flown, infill lines were flown based on the results of the preliminary LCI's of the VTEM data. Line-km totals from each flight are provided in Table 4-1. Note that the VTEM data in the databases are indexed by line and flight number. Figure 4-1 is an "as flown" map view of the recon and infill lines and the timing of the data collection. In some locations, the as-flown lines deviate from the planned lines due to infrastructure and safety as determined by the pilot.

Table 4-1. Flight line production by flight.

Date	Flights	Distance (km)	Distance (miles)
7-Nov-17	1	199.1	123
8-Nov-17	2, 3, 4	134.6	83.1
9-Nov-17	5, 6, 7	276.2	170.5
11-Nov-17	8, 9	162.5	100.3
12-Nov-17	10, 11, 12	331.7	204.8
13-Nov-17	13, 14	269.1	166.1
17-Nov-17	15, 16, 17	356.3	219.9
18-Nov-17	18, 19, 20	284.4	175.6
	Total	2013.9	1243.3

4.2 System Flight Parameters

4.2.1 Flight Height

The system height was specified at ~30 meters; however, due to safety and other judgments by the pilot the flight heights will deviate. The goal is to maintain a height as low as possible in the window from 25 to 50 m above ground level (AGL). In the NDSWC Wahpeton data set the average height was 34.61 m with a minimum of 15.73 m and a maximum of 132.75 m. The maximum flight heights were encountered over large powerlines. Those data will be removed from the dataset before inversion due to EM coupling and will not impact the final product. A map of the flight height throughout the survey area is presented in Figure 4-2.

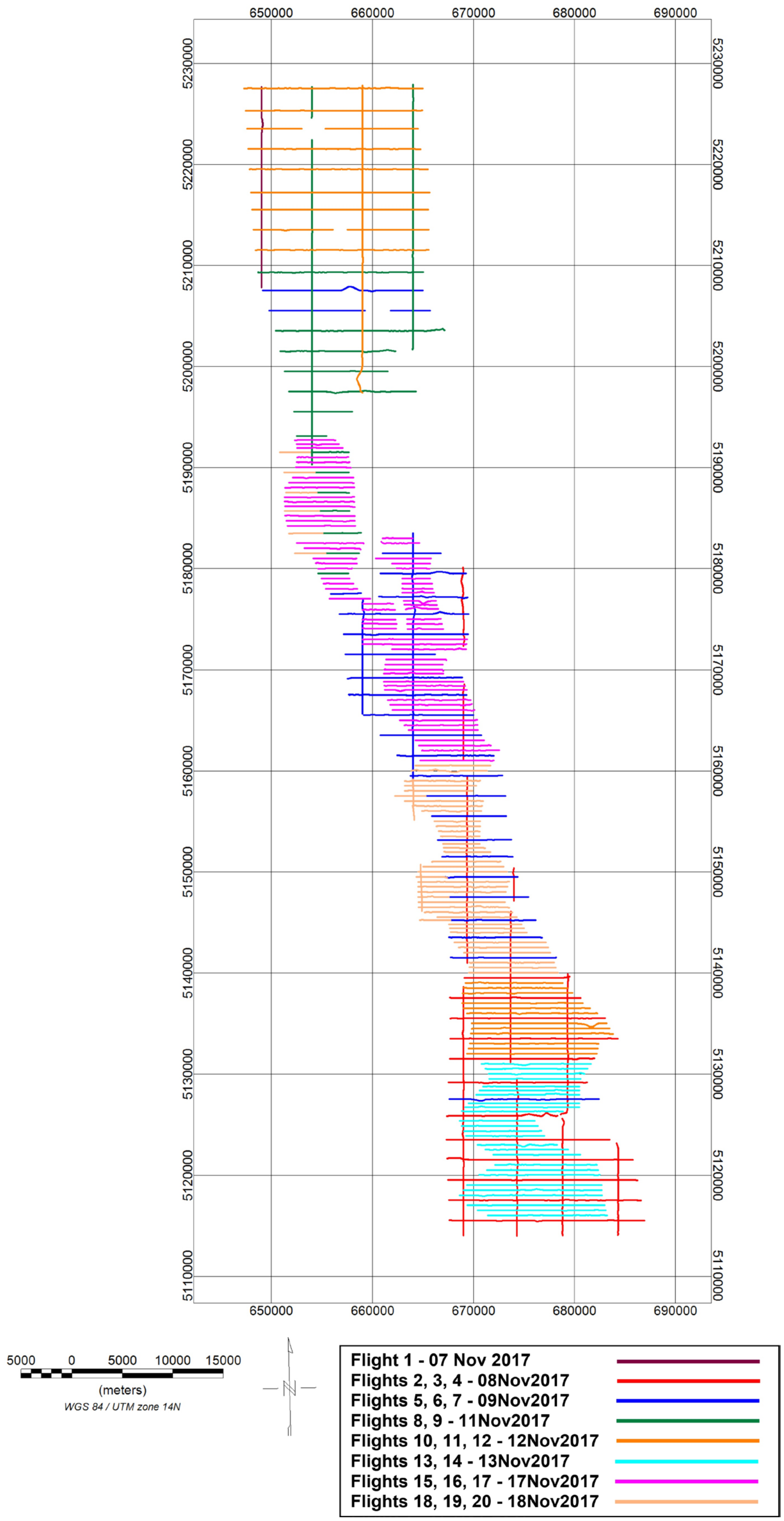


Figure 4-1. As-Flown map showing timing of the NDSWC AEM survey data acquisition.

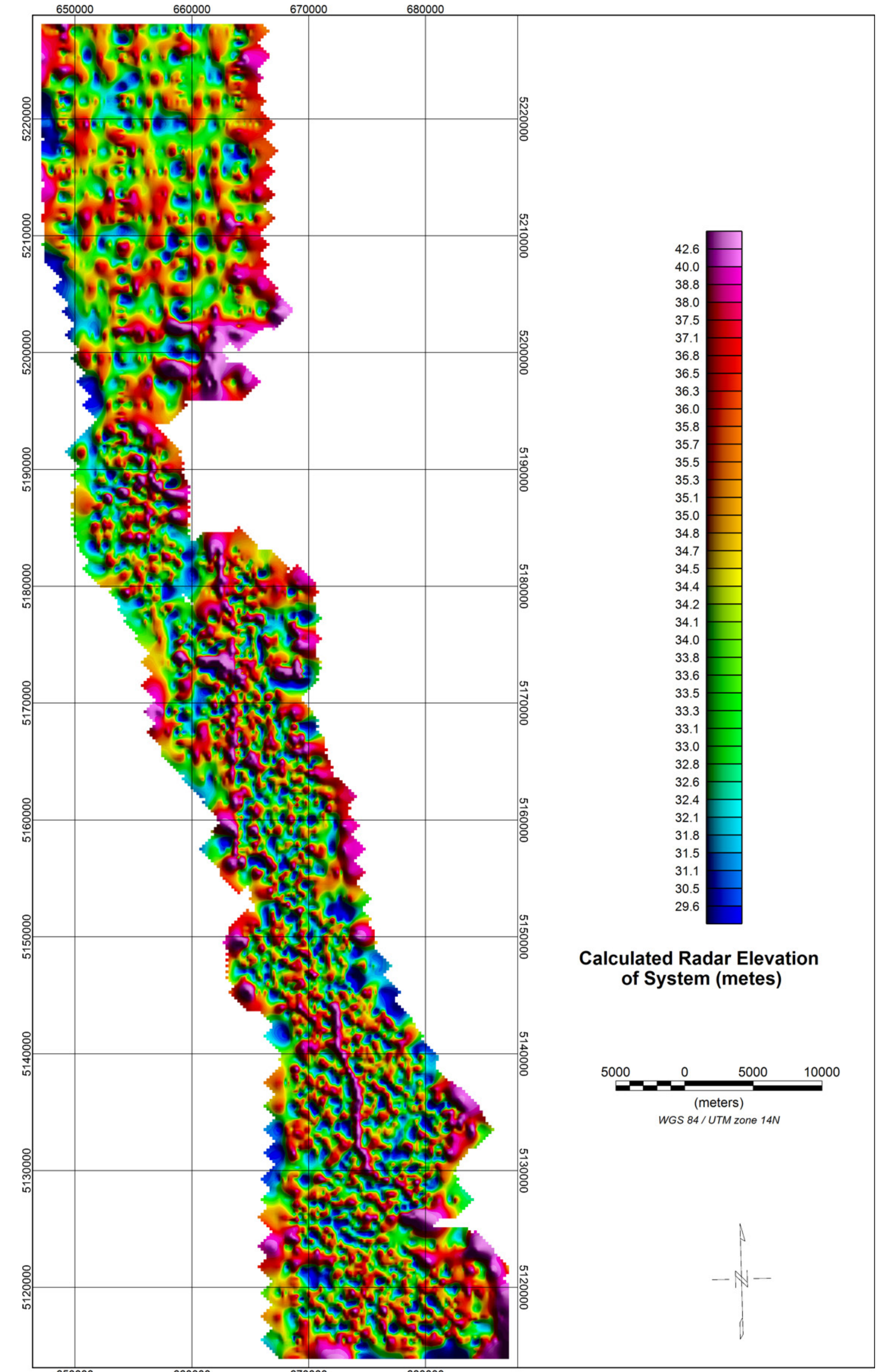


Figure 4-2. Map of the system height recorded during the NDSWC survey.

4.3 Power Line Noise Intensity

The Geotech system is configured to provide an estimate of the amplitude of the 60 Hz signals which is called the Powerline Monitor (PLM). The PLM map is useful when investigating the impacts of powerlines on the data quality. The 60 Hz powerline signals have little impact on the Rx signal due to time-gating and proper filtering. However, the conductive wires that are used to transmit the power do cause EM coupling impacts on the data and those data need to be removed prior to inversion. The PLM for the NDSWC survey is presented in Figure 4-3.

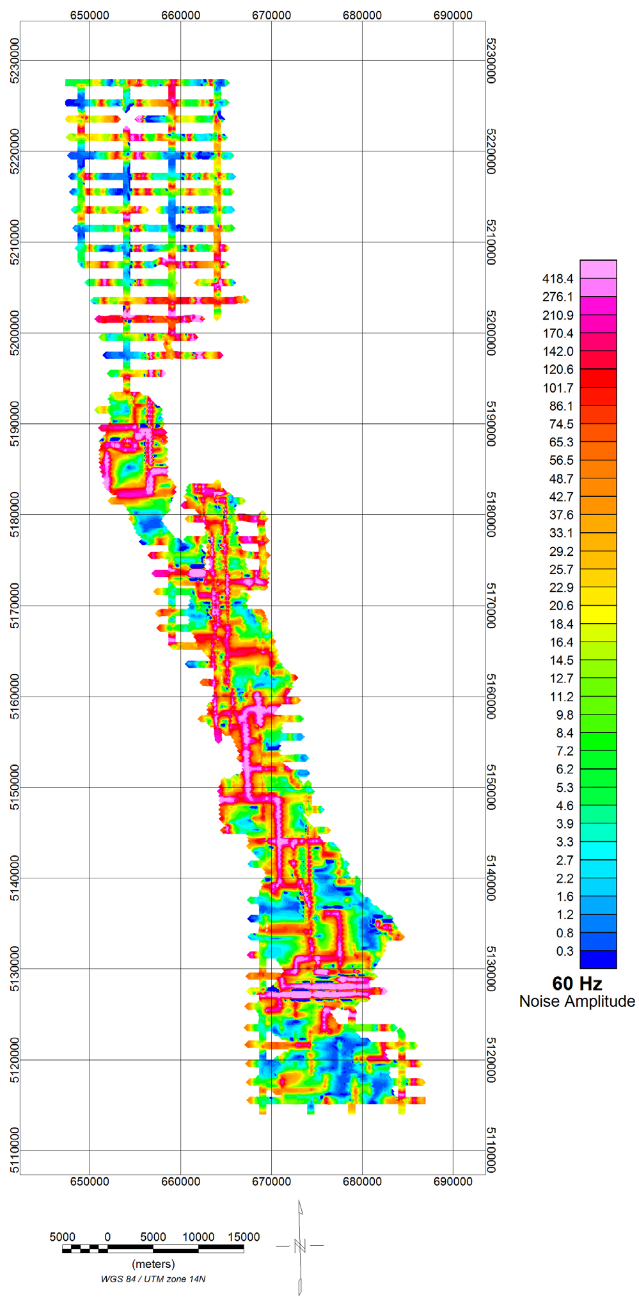


Figure 4-3. Power Line Monitor (PLM) intensity for the NDSWC AEM survey area.

4.4 Magnetics

As part of the Geotech system multiple Total Field magnetometers are included in the data acquisition package. The magnetic field signal is useful for determining deep seated geological contacts and is also extremely valuable for locating intrusive bodies. Neither of those was the target of the survey within NDSWC Wahpeton survey Area. However, the magnetic field is also sensitive to anthropogenic features that contain ferrous metal and is also used in the electromagnetic decoupling process. A plot of the residual magnetic signal in the area of the NDSWC Wahpeton survey area is presented in Figure 4-4. Both geological structure and cultural features can be identified within the survey area, but the signal is dominated by the complex basement features.

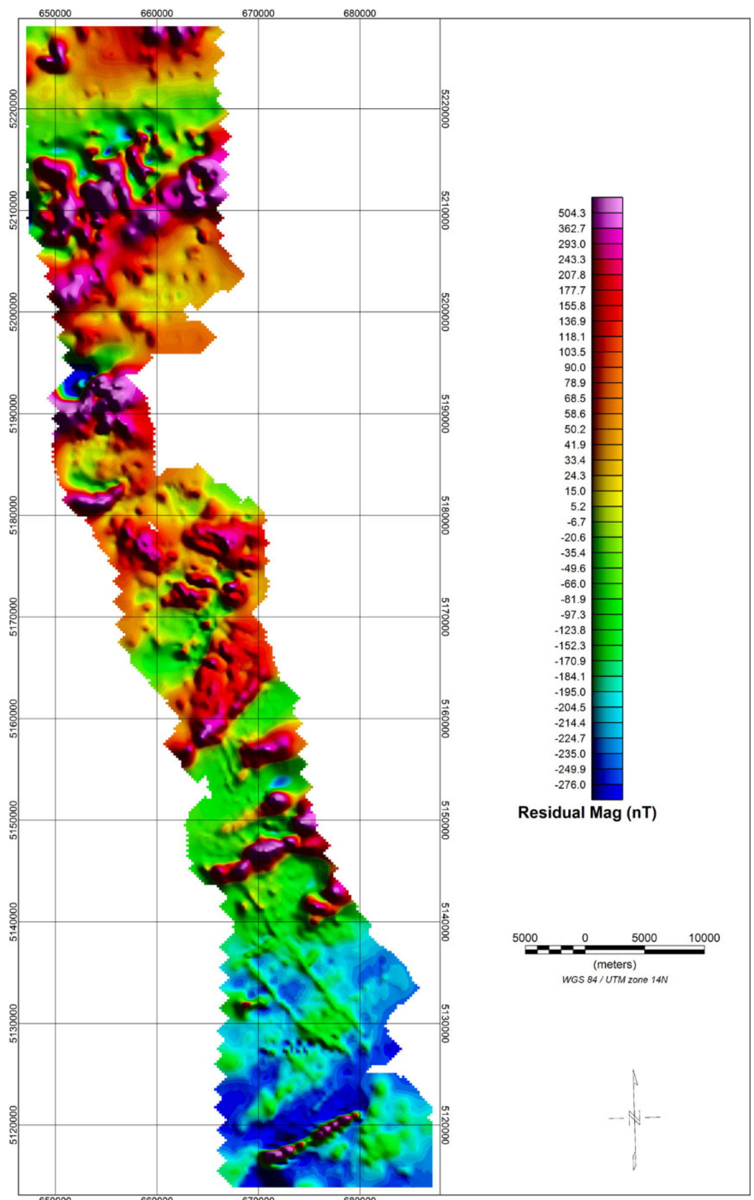


Figure 4-4. Residual magnetic total field for the NDSWC survey area.

5. Processing and Laterally Constrained Inversions

5.1 Primary Field Processing

A standard Geotech data acquisition procedure involves review and processing of acquired raw data by Geotech in Canada. Details of that processing are provided in the Geotech acquisition report.

5.2 Automatic Processing

The AEM data were processed using Aarhus Workbench version 5.5.0.0 (Aarhus Geosoftware, 2017)

Automatic processing algorithms provided within the Workbench program are initially applied to the AEM data. DGPS locations were filtered using a stepwise, second-order polynomial filter of nine seconds with a beat time of 0.5 seconds, based on flight acquisition parameters. The altitude data were corrected using a series of two polynomial filters. The lengths of both eighth-order polynomial filters were set to 30 seconds with shift lengths of six (6) seconds. The lower and upper thresholds were 1 and 100 meters, respectively.

Trapezoidal spatial averaging filters were next applied to the AEM data. The times used to define the trapezoidal filters for the VTEM data were 1.0×10^{-5} sec, 1.0×10^{-4} sec, and 1.0×10^{-3} sec with widths of 1, 3, and 5 seconds. The trapezoid sounding distance was set to 1.0 seconds and the left/right setting, which requires the trapezoid to be complete on both sides, was turned on. The spike factor and minimum number of gates (as a percent (%)) were both set to 25 percent.

5.3 Manual Processing and Laterally-Constrained Inversions

After the implementation of the automatic filtering, the AEM data were manually examined using a sliding two-minute time window. The data were examined for possible electromagnetic coupling with surface and buried utilities and metal, as well as for late time-gate noise. Data affected by these were removed. Areas were also cut out where the system height was flown greater than approximately 50 m (164 ft) above the ground surface which caused a decrease in the signal level.

The AEM data were then inverted using a Laterally-Constrained Inversion (LCI) algorithm (Aarhus Geosoftware, 2017). The LCI uses nearby soundings along the flight lines as constraints. The profile and depth slices were examined, and any remaining electromagnetic couplings were masked out of the data set. Vertical constraints on the resistivity were set at 2.7 and at 1.6 for the horizontal resistivity constraints with a reference distance of 100 m (328 ft). The data were processed, edited, and inverted as they became available with the goal of having the analysis of each day's acquired data completed before the next data became available.

The smooth model 30-layer structure used in the LCI inversions is presented in Table 5-1.

Table 5-1. Thickness and depth to bottom for each layer in the Laterally Constrained Inversion (LCI) AEM earth models. The thickness of the model layers increase with depth as the resolution of the AEM technique decreases.

Layer	Depth to Bottom (ft)	Thickness (ft)	Layer	Depth to Bottom (ft)	Thickness (ft)
1	9.8	9.8	16	298.4	31.2
2	20.5	10.6	17	332.1	33.7
3	31.9	11.5	18	368.5	36.4
4	44.3	12.4	19	407.8	39.3
5	57.7	13.4	20	450.3	42.5
6	72.2	14.5	21	496.2	45.9
7	87.8	15.6	22	545.7	49.5
8	104.7	16.9	23	599.2	53.5
9	122.9	18.2	24	657	57.8
10	142.5	19.7	25	719.4	62.4
11	163.8	21.2	26	786.8	67.4
12	186.7	22.9	27	859.5	72.8
13	211.5	24.8	28	938.1	78.6
14	238.3	26.8	29	1023	84.9
15	267.2	28.9	30	Infinite	Infinite

Figure 5-1 presents a comparison of the acquired data (the “as-flown”) and the data retained for the LCI inversions. The as-flown data are displayed by red lines and are overlain by blue retained data. So where red is visible, the data have been edited out. A quick comparison between the PLM data in Figure 4-3 and the gaps in the retained data in Figure 5-1 shows where they were decoupled.

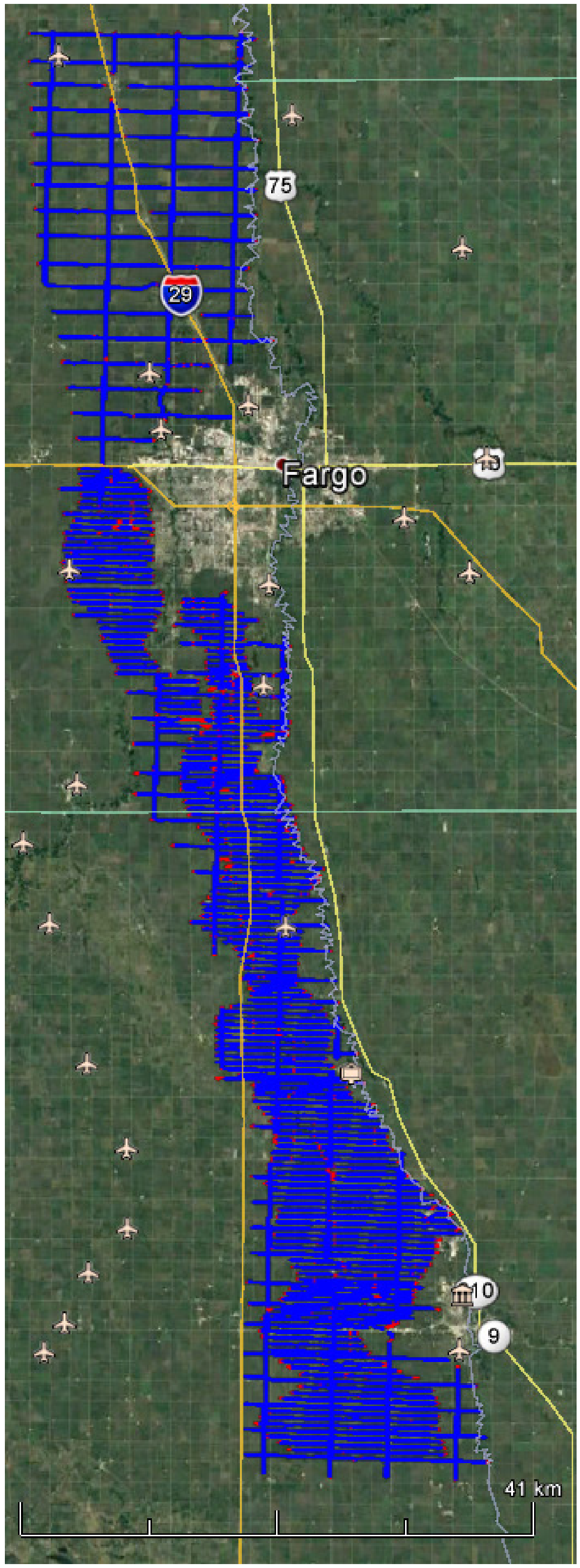


Figure 5-1. Comparison of the acquired data (red) versus the retained data (blue) for the NDSWC Wahpeton AEM survey area preliminary LCI inversions.

6. Forward/Inversion Modeling

6.1 Modeling of Borehole Geophysical Logs 130378 and 138380 and Comparisons with VTEM31 Test Line Data

This section describes the analysis and comparison of Wahpeton Test Line data with borehole logs provided by NDSWC. The concept is to obtain ground truth borehole data, calculate the response to the ground truth data of the VTEM system used in the Wahpeton AEM survey (forward dB/dt and inverted resistivities), and then compare that calculated VTEM response to the measured response acquired over the borehole locations as part of the project and then determine if time or amplitude calibration shifts are necessary.

6.1,1 Methodology

In order to do the analysis, the program AarhusInv64, developed at Aarhus University in Aarhus, Denmark (http://hgg.au.dk/software/aarhusinv/) was utilized to calculate both forward model responses to the geology described by the logs and then inversions of those responses. VTEM31 system parameters, provided by Geotech Airborne, including the transmitter waveforms were compiled into a system description file utilized by AarhusInv64. Information from two boreholes (130378 and 130380), whose locations are indicated in Figure 6-1, included geophysical logs in the form of LAS files and images. Minimum-layered models were developed from examination of the LAS files. Minimum layered meaning that the geophysical logs were examined and a minimum number of layers were compiled that generally describe what the logs presented. As it turned out, for each of the two holes, seven (7) layer models were developed into forward models. This isn't too surprising since the boreholes are not that far apart. The forward models list the resistivities, the thicknesses of each layer, and the depths to the bottom of each layer, with the last resistivity being a lower halfspace for the model. The inversions used the same 30-layered model structure, Table 5-1, as was used in the Aarhus Workbench to invert the Test Line data (as well as the rest of the Wahpeton AEM data). The results of those inversions were then compared to Wahpeton VTEM test line data (Figure 6-1) that were acquired as part of the Wahpeton AEM survey and which were specifically flown over the locations of the boreholes provided by NDSWC.

Now both the short-normal (16-inch) and long-normal (64-inch) resistivity logs were examined and, initially, the short-normal logs, labeled N16 in the LAS files, were used to develop the layered models. This is usually the typical procedure. However, preliminary results of the analysis suggested that the long-normal logs, labeled N64 in the LAS files, would provide more representative descriptions of the geology as compared to the imaging provided by airborne geophysics.

On the following pages are resistivity versus depth plots and dB/dt amplitude versus time plots showing comparisons between the original long-normal logs, the forward/inverse modeling results based on the logs, and the inverted test line responses over the lines (and soundings) closest to the locations of the two boreholes analyzed. The borehole logs are presented as continuous curves and the inverted responses are presented in step-wise manner so that the effects (if any) of the layered structure can be examined.

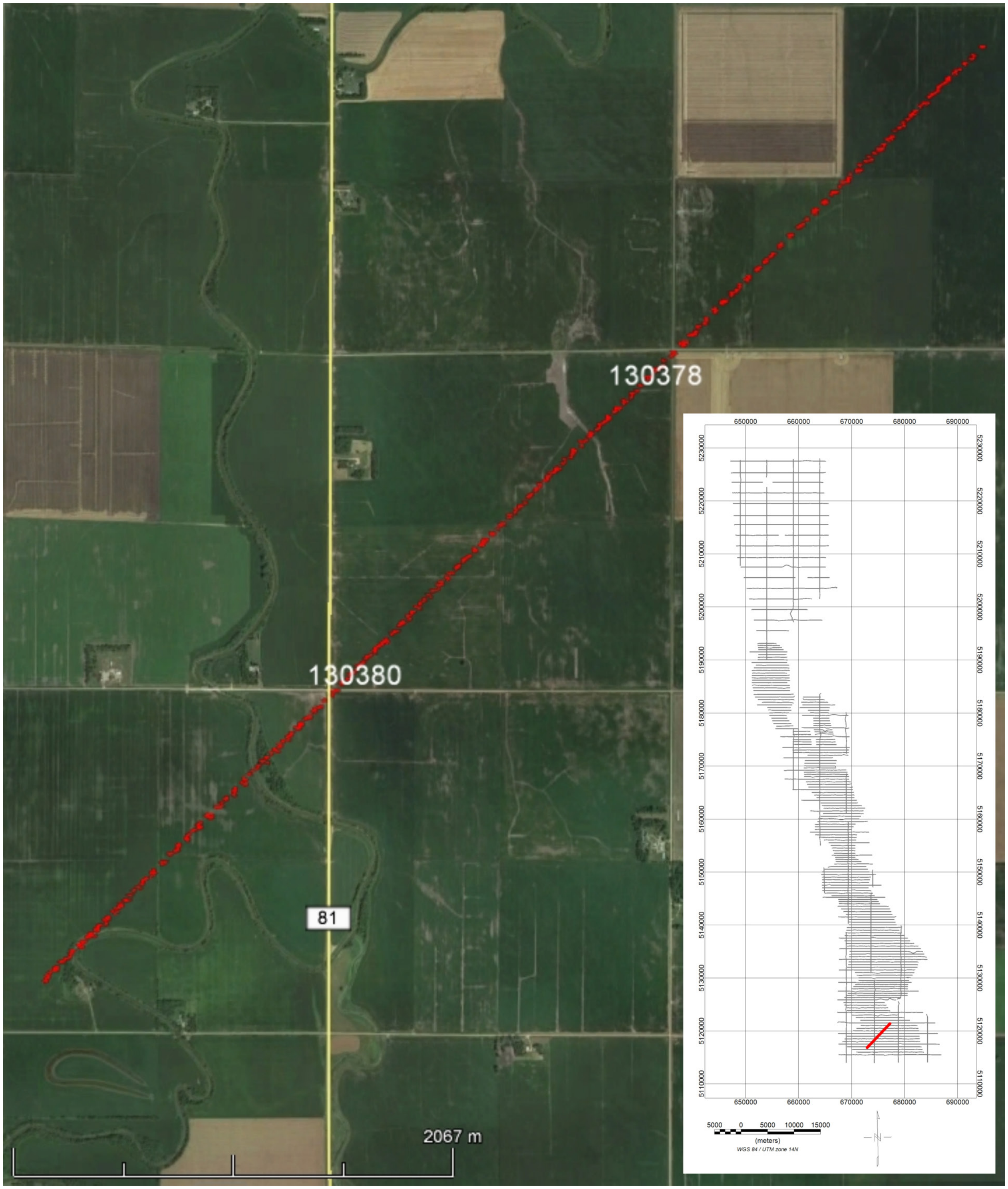


Figure 6-1. Location of the Wahpeton AEM Test Line and the boreholes used in the comparison analysis. The Test Line is indicated by the red line in the inset map.

However, since the borehole logs only went to approximately 60 m depth, only a little over half of the layers used in the forward modeling and inversion are presented in the resistivity plots. Also note that because the VTEM is imaging to several hundred meters depth, an additional layer was added to the forward model that was not indicated in the borehole log in order to grossly approximate the resistivities at depth below the log that are influencing the measured VTEM system response.

6.1.2 Forward/Inversion Modeling Discussion

Figure 6-2 presents the resistivity inversion results for the location along Test Line 9000 (purple line) close to borehole 130378 and the forward/inverse model results (blue line), along with the borehole log (red line). The corresponding dB/dt amplitudes for these data are provided in Figure 6-3. The inversion results generally match the log, where there is data to be matched. The surface down to about 13 m depth is not recorded in the log (this is due to the air filled annulus and the galvanic resistivity tool that needs to be run in a fluid-filled borehole), nor anything below 60 m depth (this is due to the bottom of the hole). Note that the inverted smooth model (the blue line), that was developed from examination of the log, matches the Test Line 9000 inversion result quite well, except at the resistor at -30 m and at depths below -40 m. A lack of ground truth at depth below where the log stopped is contributing to the poor fit at depth in Figure 6-2 and at late times in Figure 6-3.

It is a similar result for borehole 130380 (Figure 6-4 and Figure 6-5). The match with the borehole log is generally ok and there is a good fit (except at depth) between the smooth model based on the long-normal N64 log and the Test Line 9003 sounding closest to the borehole location.

There is a long-standing issue with using geophysical logs of various vintage as ground truth when comparing to AEM inversions that are well calibrated using modern techniques (Ley-Copper and Davis, 2010). It is important to remember that the geophysical logs are calculations of apparent resistivity and not inverted values.

Thus, the borehole information provided by the NDSWC and acquired VTEM data (after the forward modeling and inversion analysis required to make them comparable) match as well as can be expected given the limitations of the borehole logs. The VTEM system response and calibration and leveling procedures applied by Geotech are functioning as designed. No additional calibration procedures or shift factors in time and amplitude are indicated.

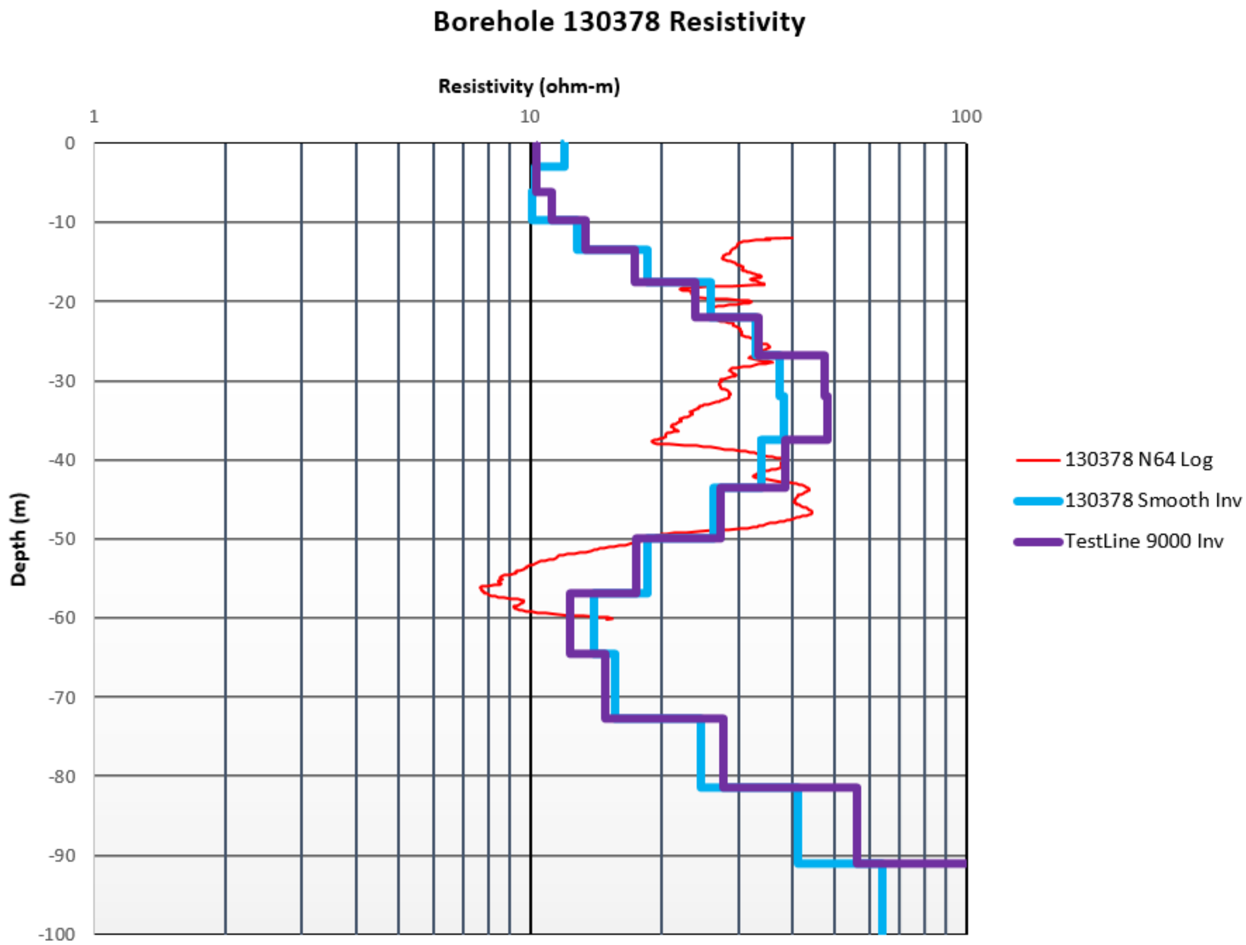


Figure 6-2. Comparison of borehole 130378 long-normal resistivity log (N64) (red line) and the forward/inversion modeling result (blue line) based on the N64 log to the Wahpeton Test Line 9000 (purple line) sounding closest to the borehole location.

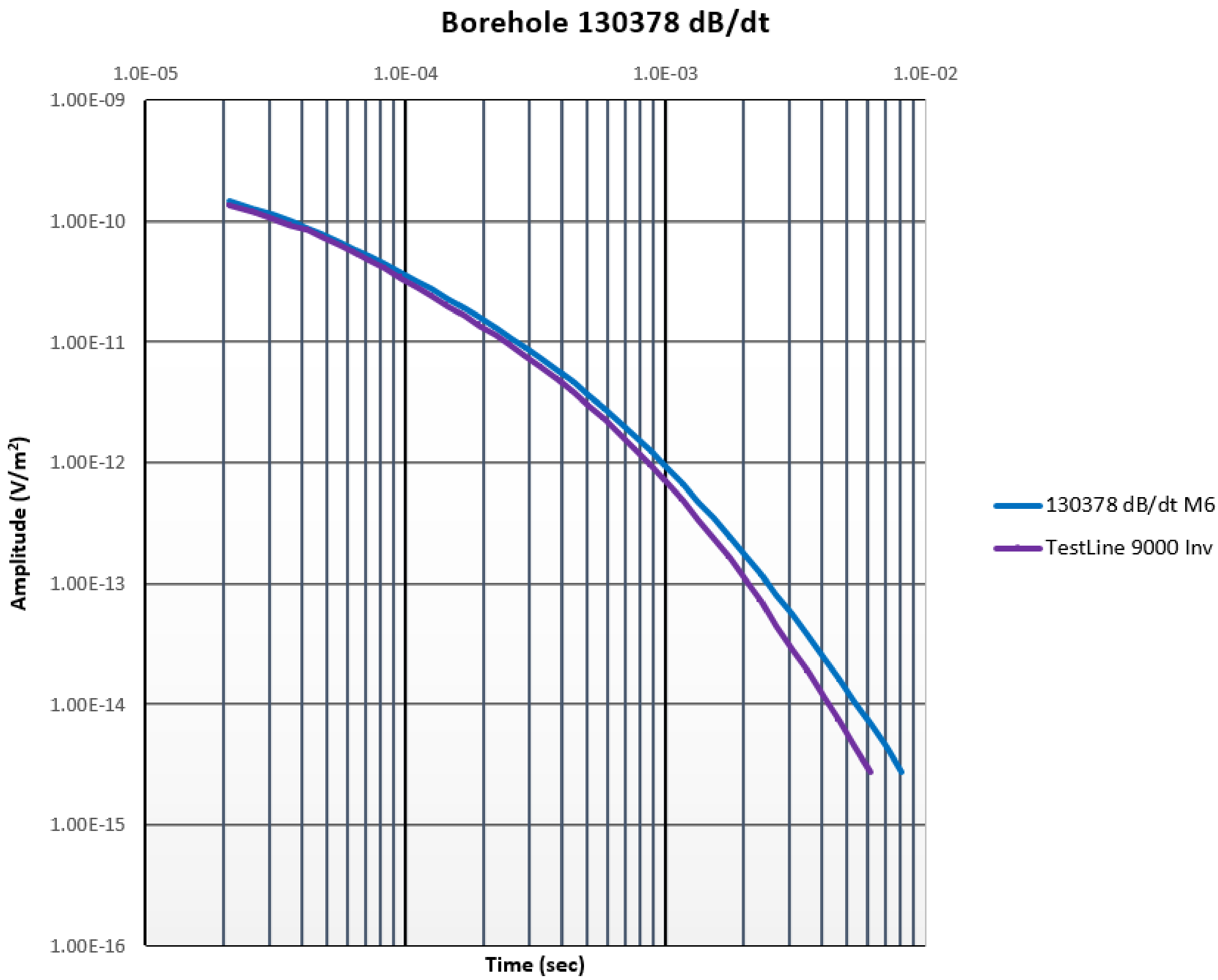


Figure 6-3. Comparison of dB/dt data for Wahpeton AEM Test Line 9000 (purple line) to the dB/dt data from the forward model (blue line) based on the 130378 N64 log.

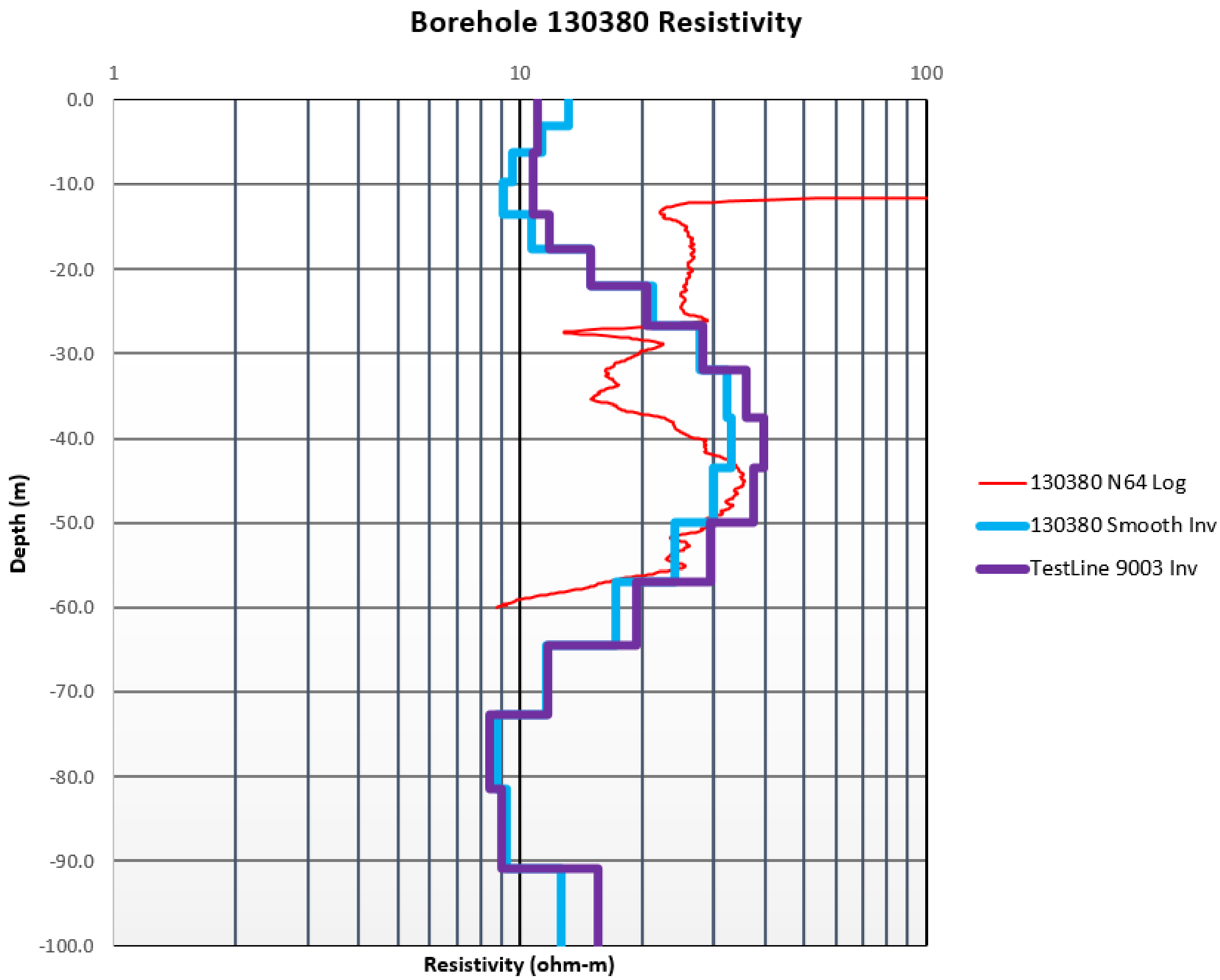


Figure 6-4. Comparison of borehole 130380 long-normal resistivity log (N64) and the forward/inversion modeling result based on the N64 log to the Wahpeton Test Line 9003.

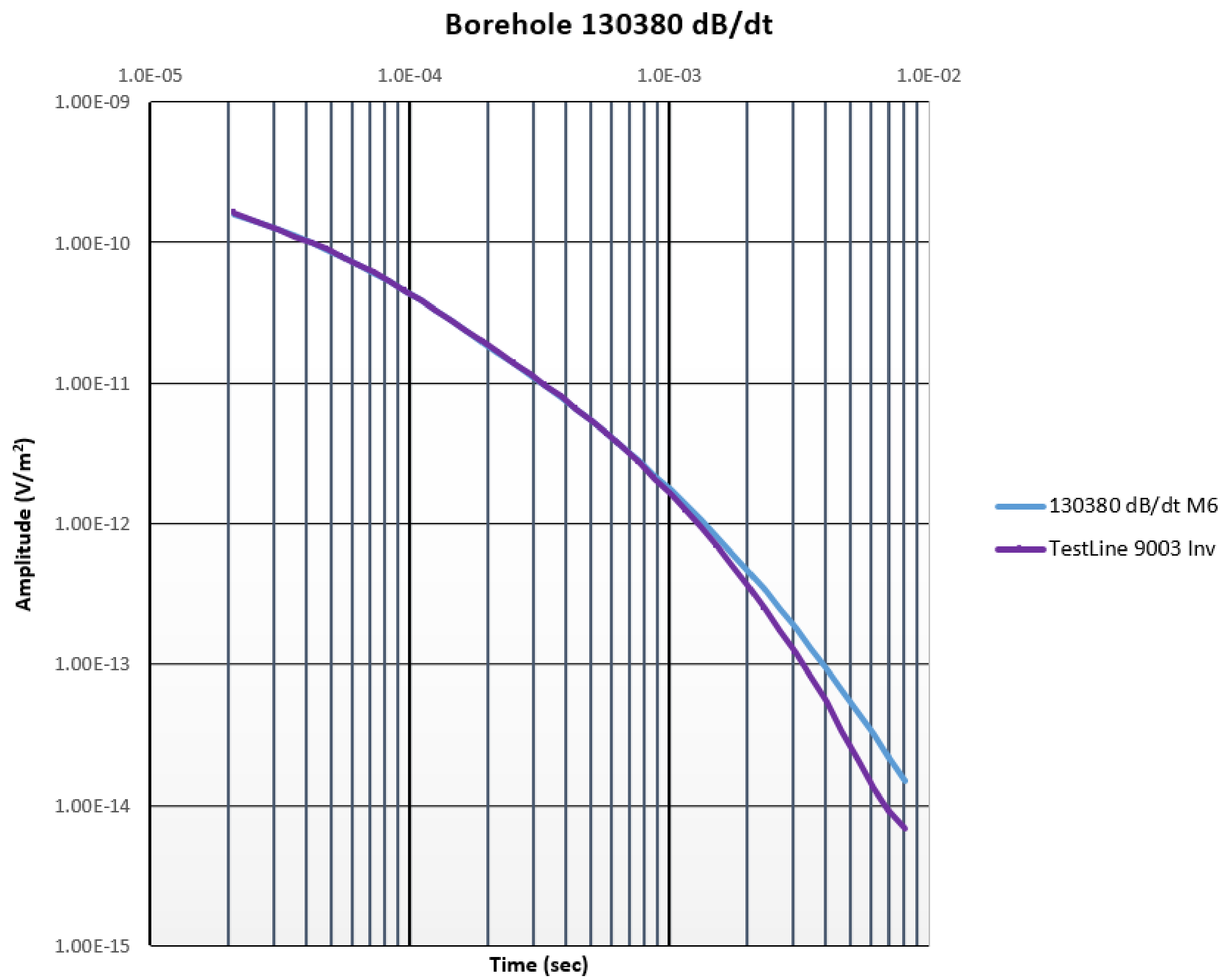


Figure 6-5. Comparison of dB/dt data for Wahpeton AEM Test Line 9003 to the dB/dt data from the forward model based on the 130380 N64 log.

6.2 Forward/Inverse Modelling of a 3-Layer Geologic Structure

In addition to the borehole comparison analysis discussed above, an additional model study was performed in order to examine the nature of the sensitivity of the AEM technique as a layer of interest with a fixed thickness gets deeper in the earth. In this particular case a three (3) layer model was constructed of 10 ohm-m material overlying a 30 m thick zone of 50 ohm-m material which is overlying a 10 ohm-m halfspace. Two models are presented in Figure 6-6: 1) Depth of top of the 50 ohm-m material is -10 m (orange line); 2) Depth of top of the 50 ohm-m material is -60 m (turquoise line). The inverted resistivity earth models are the red (-10 m to top) and the blue (-60 m to top) lines in Figure 6-6. Note the difference in amplitude of the inverted responses. The maximum inverted resistivity for model 1 is about 40 ohm-m; For model two it is about 20 ohm-m.

It is normal for the sensitivity of the electromagnetic geophysical exploration technique to fall off with depth. This is a function of the physics of the electromagnetic signal passing through the earth. Besides needing a reasonable resistivity contrast, the depth to sensitivity ratio of the technique, i.e. resolution, is about 10:1, meaning that a layer must have a thickness that is at least 10% of the depth to the bottom of that layer to be resolved. For example, a 10 m layer with a bottom at 100 m. This is not to say that if the layer is thinner than 10% it is not detected. It likely is detected, but not accurately resolved, and the resistivities in that "too thin" layer are averaged into the bulk resistivity of the full inverted layer that it is part of. More discussion on depth of resolution versus of depth of detection can be found in Asch (2015).

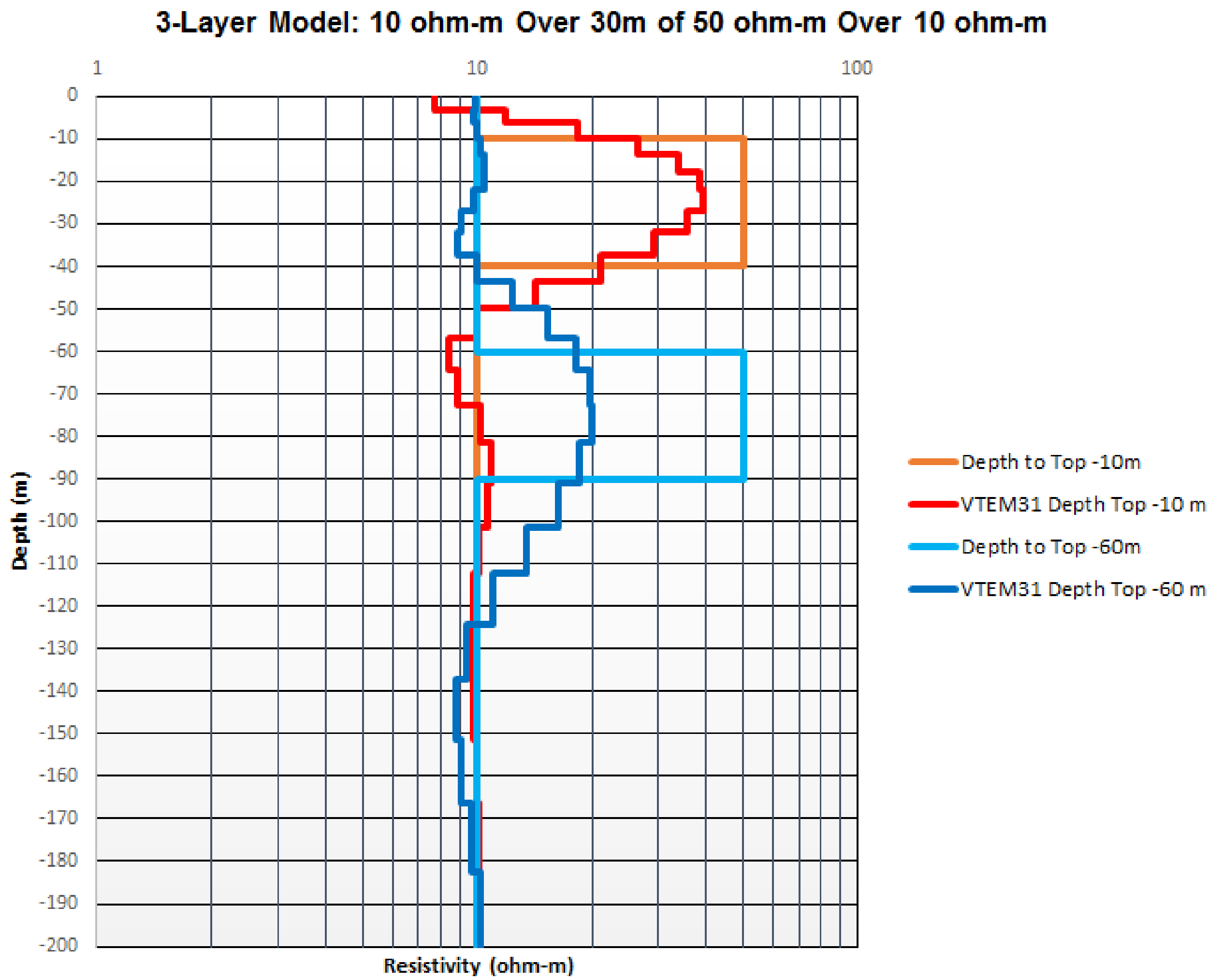


Figure 6-6. 3-layer model study consisting of a 10 ohm-m zone overlying a 30 m zone of 50 ohm-m material that overlies 10 ohm-m material. The purpose is to indicate the nature of the sensitivity of the AEM technique with depth.

7. Spatially-Constrained Inversions

Following the initial EM decoupling and LCI analysis and then the releveling analysis performed by Geotech, the Wahpeton AEM data were again processed and edited to remove power line effects, resulting in about 1,525.4 line-km (941 line-miles) of data retained for inversion. This amounts to a retention rate of about 75.7%. A visual image of a comparison of the as flown data to the data retained for the SCI inversions is presented in Figure 7-1. A comparison with Figure 5-1 indicates that more decoupling was performed for the SCI than for the preliminary LCI inversions. Note also that very little averaging was performed on the data during processing for the SCI as compared to the LCI processing.

After processing and editing of the data, Spatially-Constrained Inversions (SCI) were performed. Note that SCI's use AEM data along, and across, flight lines within a user-specified distance criteria (Viezzoli et al., 2008) versus the LCI where only data along a given flight line are used as constraints. The NDSWC AEM data were inverted using smooth models with 30 layers, each with a starting resistivity of 20 Ohm-m (equivalent to a 20 ohm-m halfspace). The thicknesses of the first layers of the models were about 10 ft with the thicknesses of the consecutive layers increasing by a factor of 1.08 (Table 5-1). The depths to the bottoms of the 29th layers were set to 1,023 ft (312 m), with thicknesses up to about 85 ft (26 m). The thicknesses of the layers are set to increase with depth as the resolution of the technique decreases. The spatial reference distance for 100% constraint was set to 246 ft (75 m) with a power law fall-off of 0.75. The vertical and lateral constraints, ***ResVerSTD*** and ***ResLatStD***, were set to 2.4 and 1.3, respectively, for all layers. These parameters provided both a reasonable and constrained, yet smooth, result.

In addition to the recovered resistivity models the SCIs also produce data residual error values (single sounding error residuals) and Depth of Investigation (DOI) estimates. The data residuals compare the measured data with the response of the individual inverted models (Christensen et al., 2009). The DOI provides a general estimate of the depth to which the AEM data are sensitive to changes in the resistivity distribution at depth (Christiansen and Auken, 2012). Two DOI's are calculated: a "Conservative" DOI at a cumulative sensitivity of 1.2 and a "Standard" DOI set at a cumulative sensitivity of 0.6. A more detailed discussion on the DOI can be found in Asch et al. (2015).

Figure 7-2 presents a histogram of the Wahpeton AEM SCI inversion data/model residuals. A Google Earth map of the SCI data residuals for the Wahpeton AEM study area is presented in Figure 7-3.

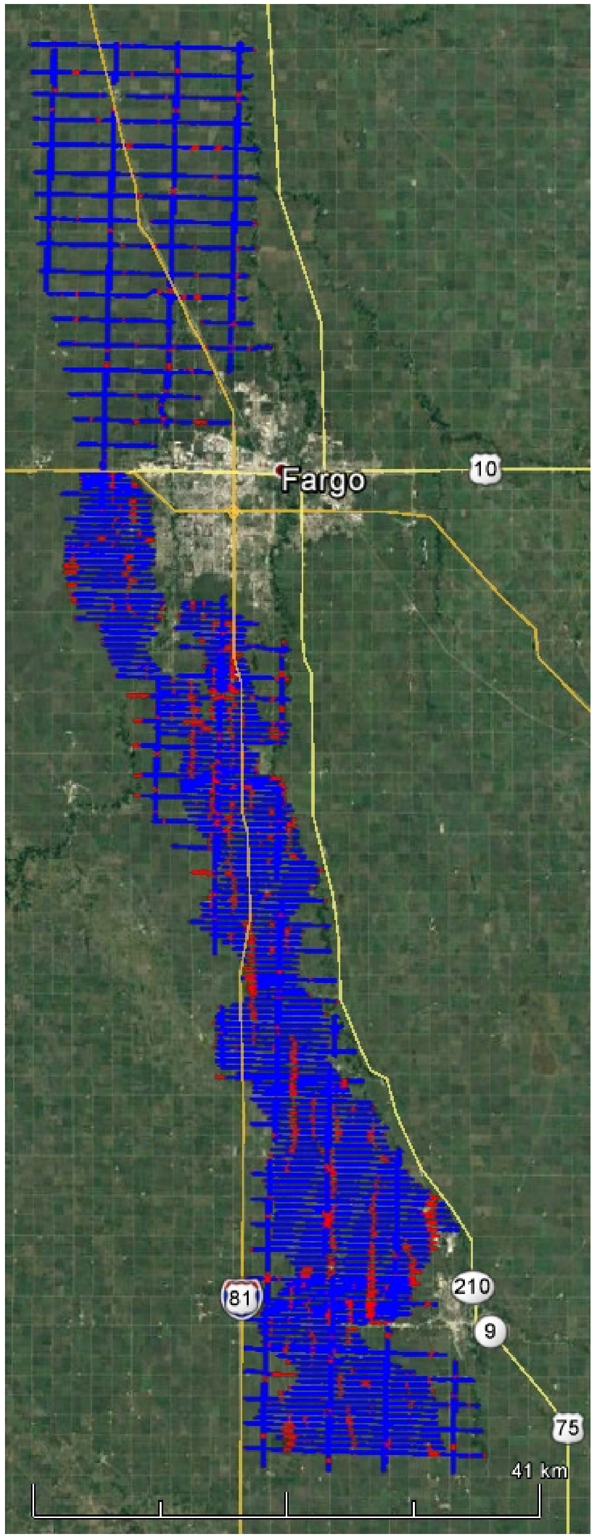


Figure 7-1. Comparison of the acquired data (red) versus the final retained data (blue) for the NDSWC Wahpeton AEM survey area Final SCI inversion. A comparison with Figure 5-1 indicates that more decoupling was performed for the SCI than for the preliminary LCI inversions. This kmz is included in Appendix 3 Deliverables\KMZ.

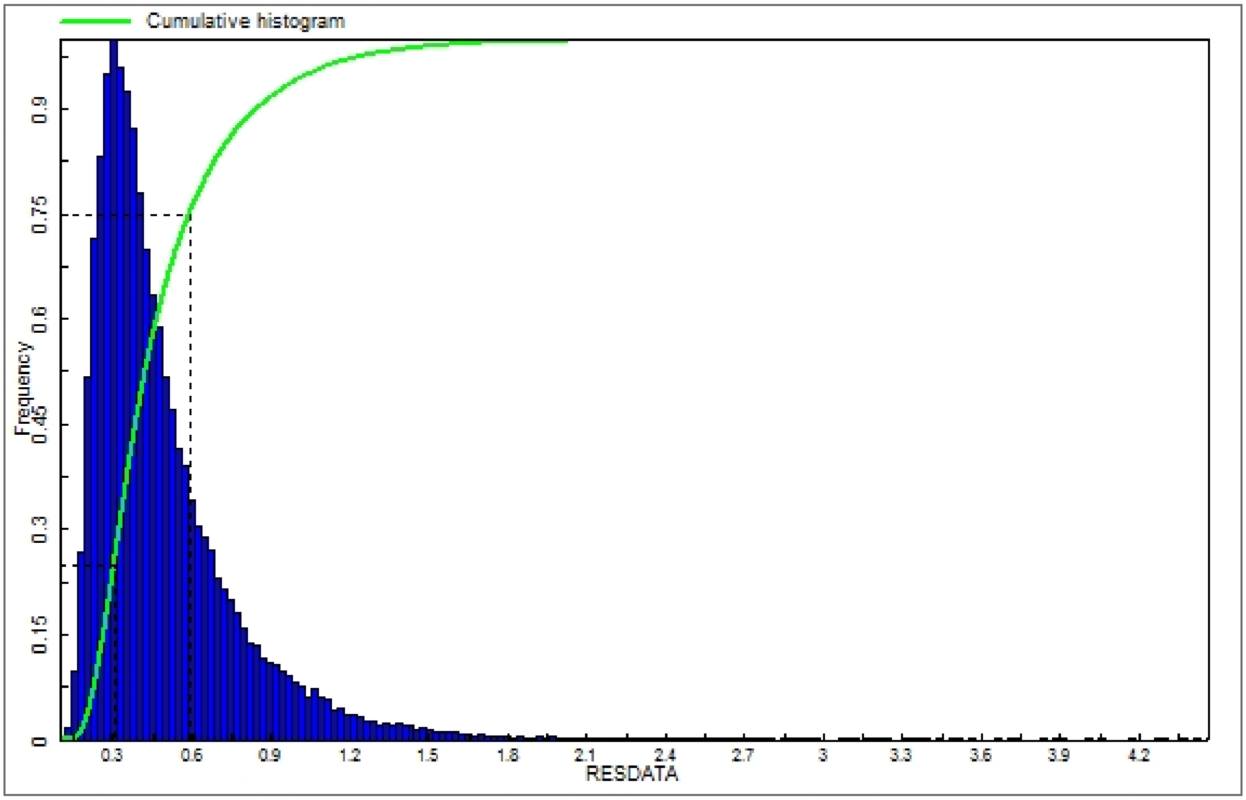


Figure 7-2. Data/model residual histogram for the MCWD SCI inversion results.

In Figure 7-2 note that the maximum data/model residuals are over 4.2. These are considered to be high residual errors. They primarily occur along the east end of AEM flight line 1300. The data along this section of line, presented on the left side of Figure 7-4, were examined and found to have late time noise which had been edited out prior to the inversion. The right side of Figure 7-4 shows the inverted section with the residual data error (red line on lower right). The thick red line in the upper right part of the image is line 1300 overlain on the power line monitor grid (red colors are high noise, blue are low noise). This section of line 1300 is in a lower power line noise area as indicated by the blue colors surrounding that end of the line.

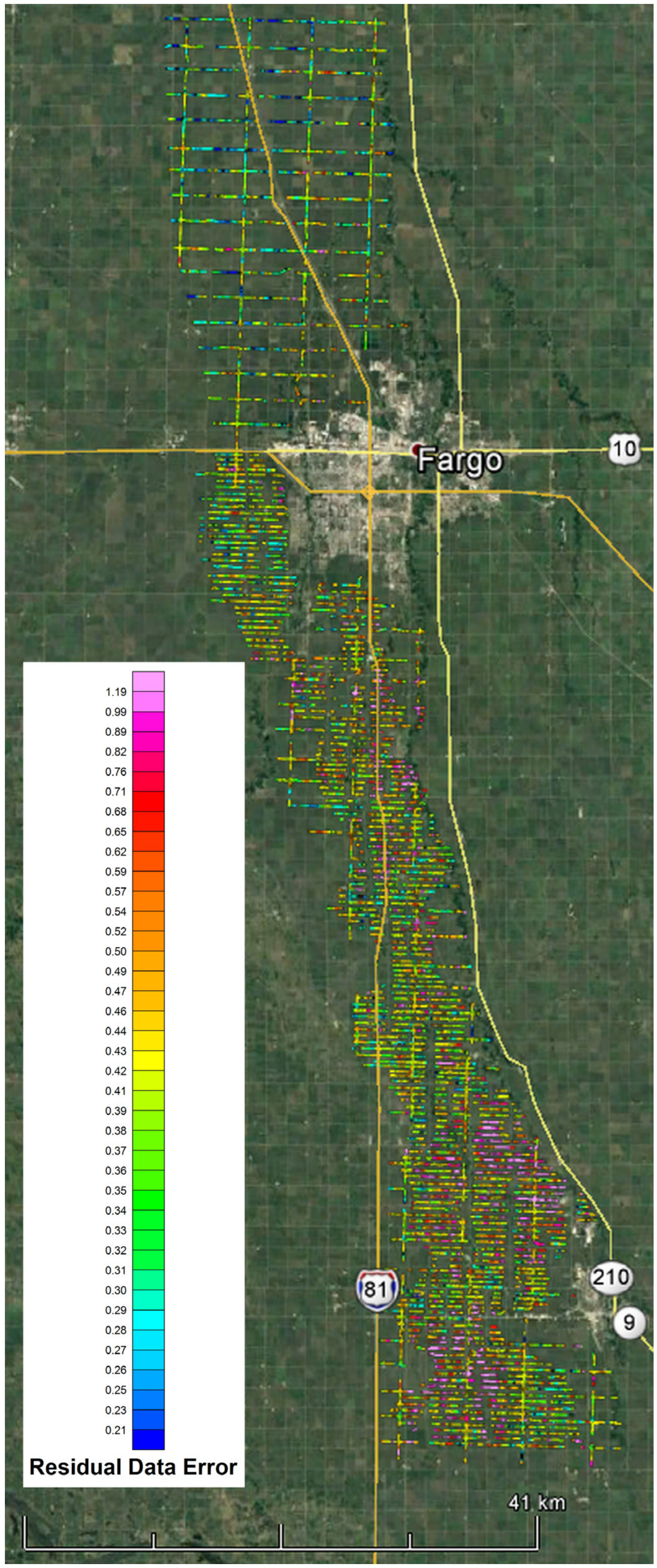


Figure 7-3. Map of data residuals for the Wahpeton AEM SCI inversion results plotted in Google Earth. These data are included as a Google Earth KMZ file in Appendix 3.

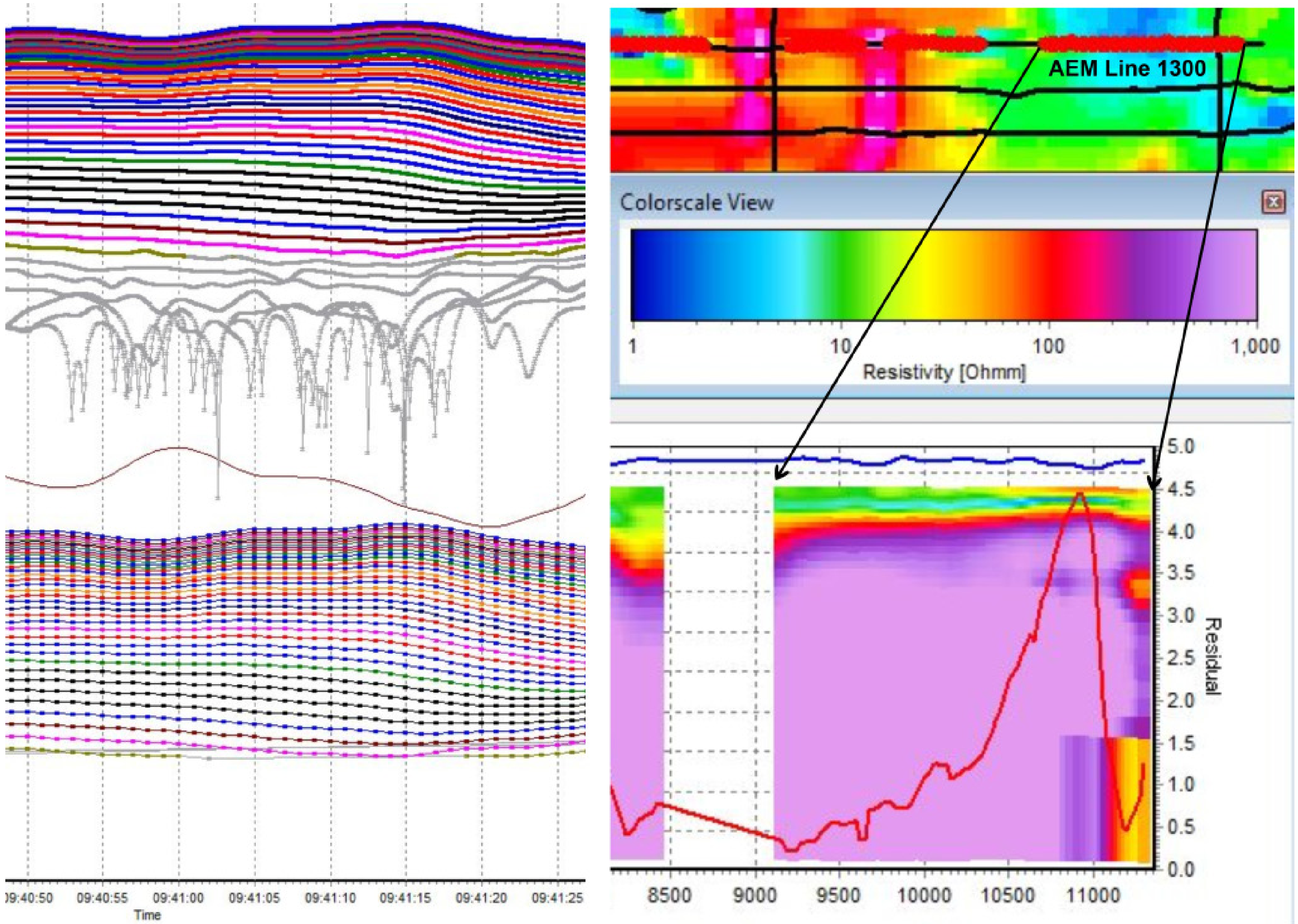


Figure 7-4. East end of AEM flight line 1300. Left side is the time series in the vicinity of the high residual data error (red line) shown on the inverted section on the bottom right. The color scale for the inverted section is on the mid-right. The thick red line in the upper right part of the image is line 1300 overlain on the power line monitor grid (red colors are high noise, blue are low noise). This section of line 1300 is in a lower power line noise area.

8. Comparison of AEM Inversion Results to Boreholes

8.1 Merging Lines

After the inversion process several short lines and line segments were combined to form continuous lines within the Wahpeton AEM survey area. These merged lines allow for improved viewing and interpretation of the AEM inversions results. Table 8-1 lists the original lines and the new combined lines. For lines that have overlapping data (examples are the line extensions on the west), the overlapping regions of the flight lines were sorted in the dominant line direction (east-west or north-south) and combined. This has no impact on the SCI as the actual X, Y, and Z locations of the survey data are used in the inversions. For display purposes, this allows for consecutive soundings in the dominant direction.

Table 8-1. Combination of flight lines within the Wahpeton AEM Survey Area.

Original Source Lines	Direction	New Line
L1020, and L1021	East-West	L2041
L1070, and L1071	East-West	L2141
L1110, and L1112	East-West	L2222
L1230, and L1231	East-West	L2461
L1232, and L1233	East-West	L2465
L1234, and L1235	East-West	L2469
L1236, and L1237	East-West	L2473
L1240, and L1241	East-West	L2481
L1242, and L1243	East-West	L2485
L1244, and L1245	East-West	L2489
L1246, and L1247	East-West	L2493
L1249, and L1250	East-West	L2499
L1251, and L1252	East-West	L2503
L1255, and L1256	East-West	L2511
L1257, and L1258	East-West	L2515
L1262, and L1263	East-West	L2525
L1264, and L1265	East-West	L2529
L1266, and L1267	East-West	L2533
L1272, and L1273	East-West	L2545
L1274, and L1275	East-West	L2549
L3060, and L3061	North-South	L3062

8.2 Construct the Project Digital Elevation Model

To ensure that the elevation used in the project is constant for all the data sources (i.e. boreholes and AEM) a Digital Elevation Model (DEM) was constructed for the NDSWC Wahpeton AEM survey area. The data was downloaded from the National Elevation Dataset (NED) located at the National Map Website (U.S. Geological Survey, 2016) at a resolution of 1 arc-second or approximately 100 ft. The geographic coordinates are in North American Datum of 1983 (NAD83), State Plane North Dakota South (International foot), and the elevation values are referenced to the North American Vertical Datum of 1988 (NAVD 88) (in feet). The 100 ft grid cell size was used throughout the project and resulting products. Figure 8-1 is a map of the DEM of the NDSWC Wahpeton AEM survey area showing a vertical relief of 202 ft with a minimum elevation of 845 ft and a maximum elevation of 1,047 ft. This DEM was used to reference all elevations within the NDSWC Wahpeton survey area. The ArcView Binary Raster Grid (*.flt) and can be found in Appendix 3 Deliverables\SCI\Grids.

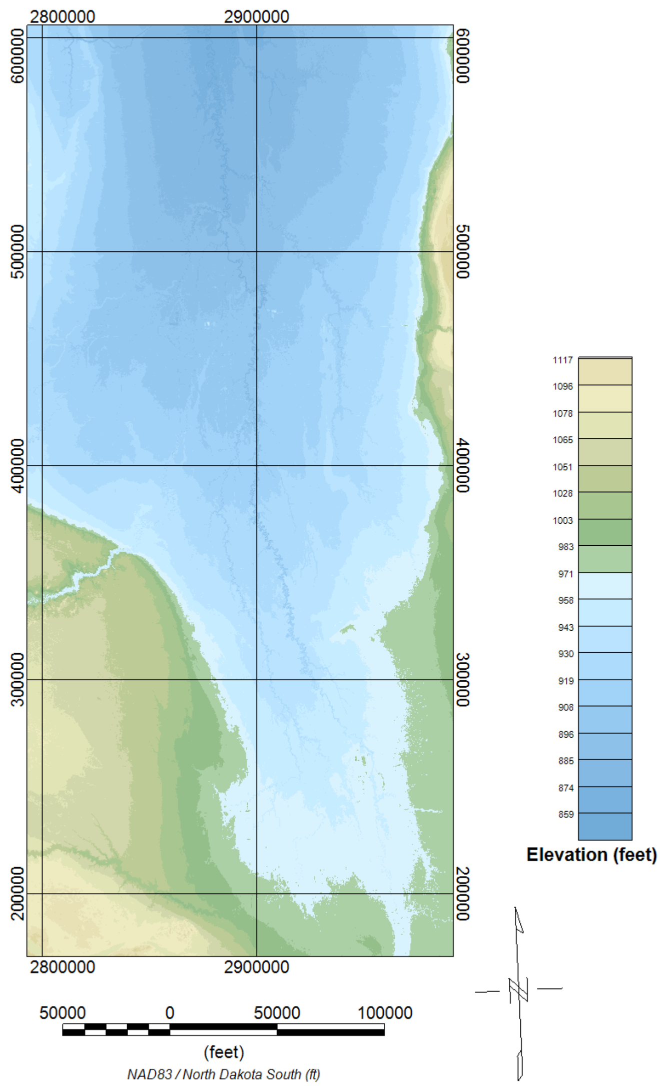


Figure 8-1. Digital elevation model (DEM) of the NDSWC Wahpeton AEM survey area.

8.3 Display of the AEM Inversions in 2D and 3D

Two-dimensional (2D) and three-dimensional (3D) images of the SCI inversion results have been developed using Datamine Discover PA (DatamineDiscover, 2017). An example 2D-profile for line L1424 is presented in Figure 8-2. Each profile has a unique length and the profiles are fitted to the size of the profile page. Each profile has a small index map on the lower right showing the location of the survey flight lines with the red line indicating the current profile being displayed. Also displayed on the small index map is the locations of the NDSWC Test Holes (orange dots) and NDSWC Observation Wells (blue dots). On the upper left is a flight path 2D map of the displayed profile on a background topography map. The horizontal scale of the Flight Path Map is exactly the same as the profile. The lower profile is the AEM inversion (SCI) resistivity profile along with the lithology of the test holes if the test hole is within 1/4 mile or 1,320 feet of the flight line. The color scale is in log-space and stretches from 10 to 150 ohm-m.

The gray dashed lines are the upper and lower depth of investigation (DOI). The DOI provides a general estimate of the depth to which the AEM data are sensitive to changes in the resistivity distribution at depth (Christiansen and Auken, 2012). Two DOI's are calculated: an "Upper" DOI at a cumulative sensitivity of 1.2 and a "Lower" DOI set at a cumulative sensitivity of 0.6. A more detailed discussion on the DOI can be found in Asch et al. (2015). Figure 8-3 is a map view of the upper DOI and Figure 8-4 is a map view of the lower DOI for the Wahpeton AEM survey area. The vertical exaggeration is set high to allow inspection of the details of the inversions. It is important to note that the vertical exaggeration will change with the changing profile length. Appendix 1 contains all the flight line 2D profiles.

3D fence diagrams were constructed using a vertical exaggeration of 1:10 of the geolocated profiles using a 10-140 ohm-m log color scale very similar to those used in the 2D Profiles. Figure 8-5 is an 3D fence diagram example of the complete NDSWC Wahpeton AEM survey looking toward the northeast. It is important to note that the resistivity correlates between lines and that there are no sharp breaks in the resistivities over the area of the survey. A series of images of the 3D fence diagrams can be found in Appendix 2.

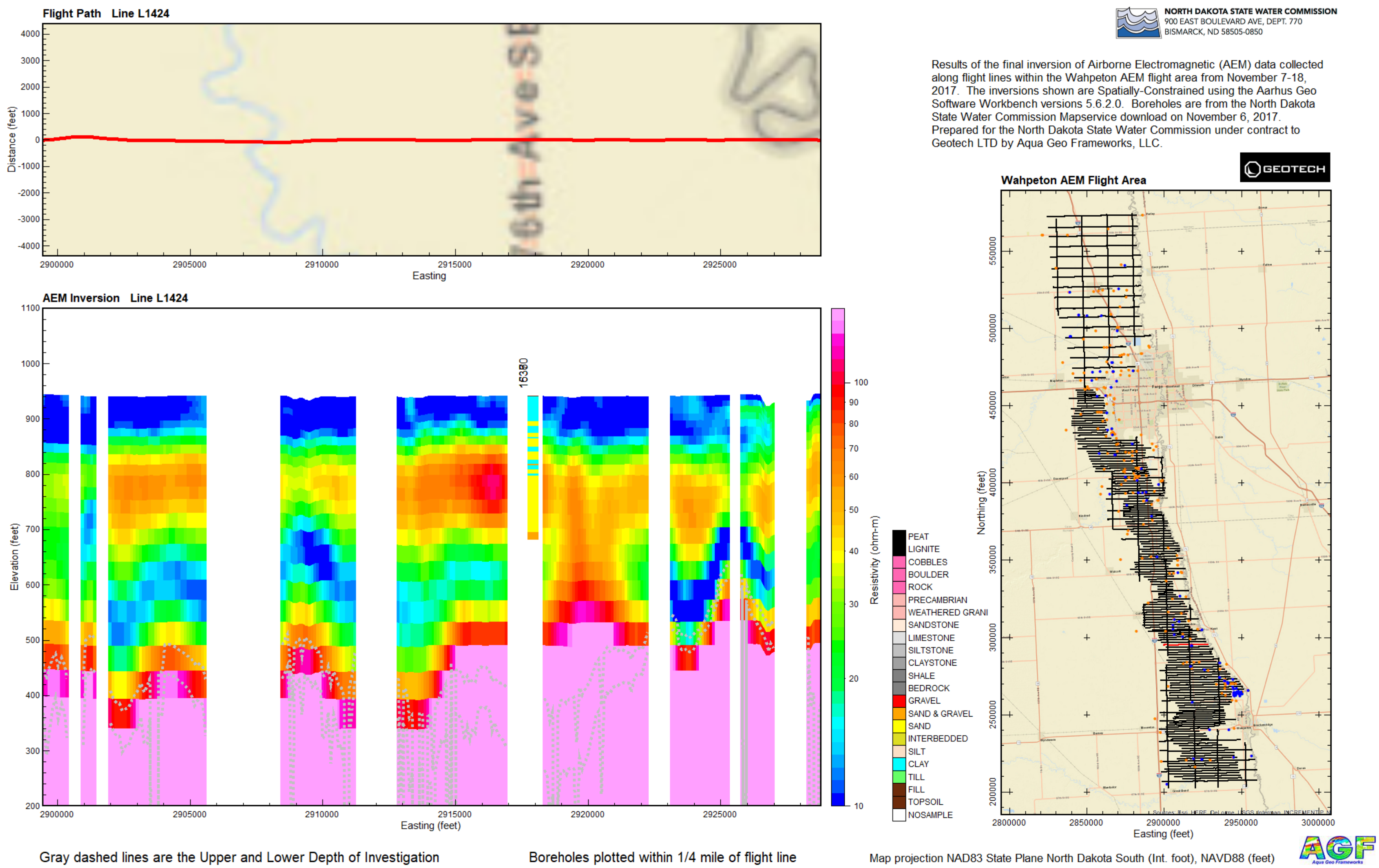


Figure 8-2. Example 2D profile displaying the results of the SCI inversion of NDSWC Wahpeton AEM survey flight line L1424 including local borehole lithologies within ¼ mile of the flight line. The resistivity color scale is on the right side of the profile.

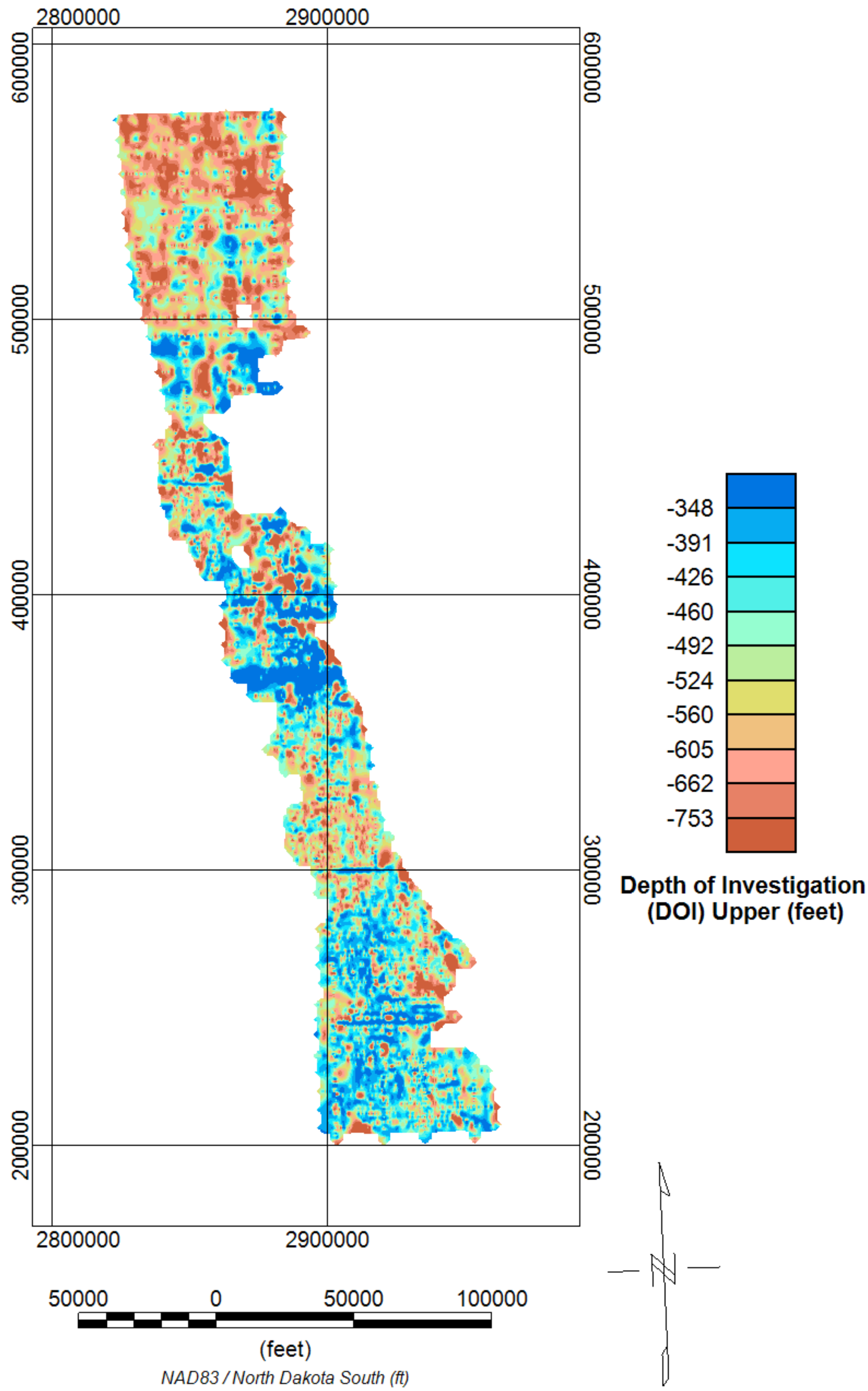


Figure 8-3. The Upper Depth of Investigation (DOI) of the NDSWC Wahpeton AEM Spatially-Constrained Inversion (SCI).

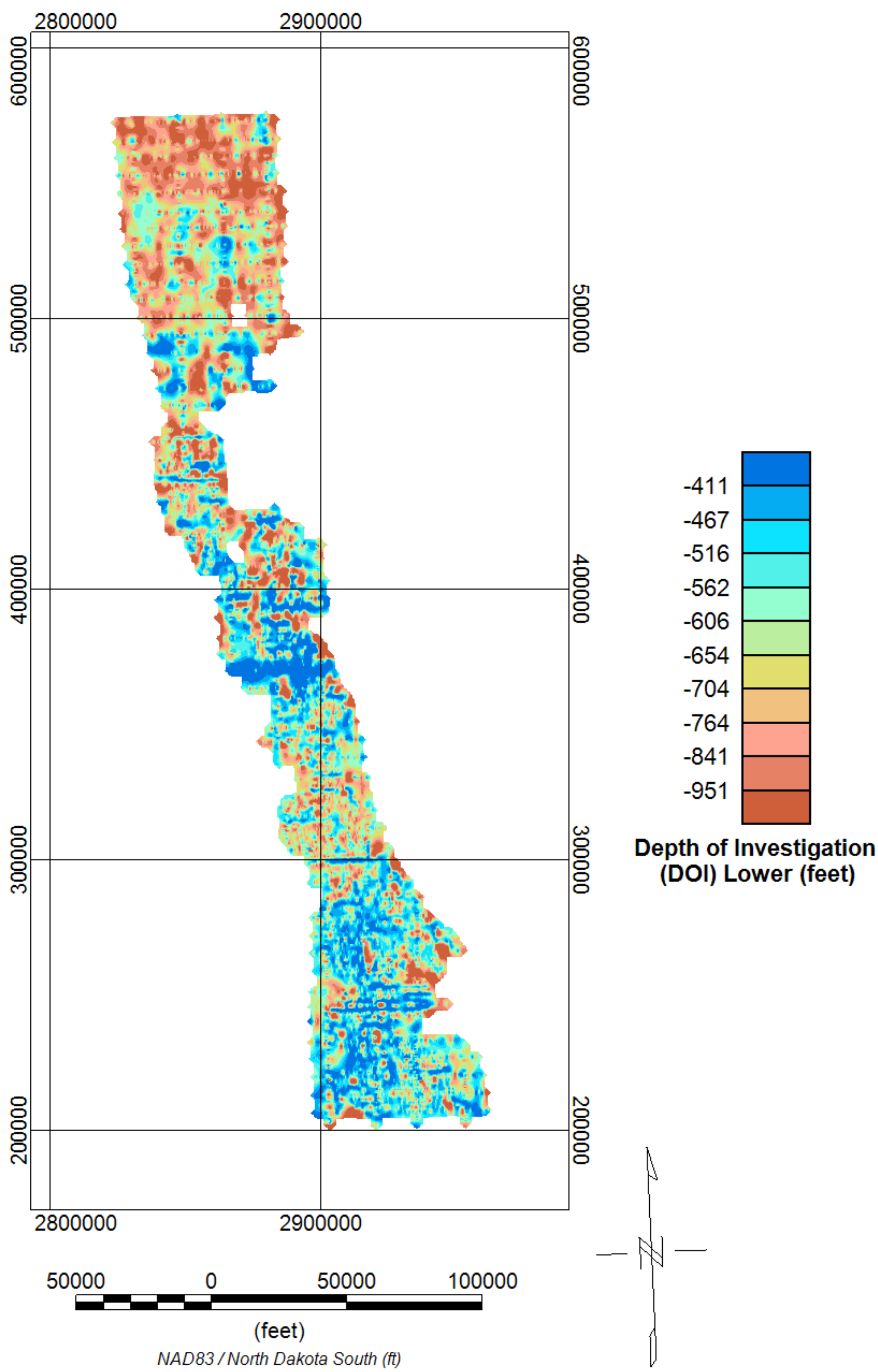


Figure 8-4. The Lower Depth of Investigation (DOI) of the NDSWC Wahpeton AEM Spatially-Constrained Inversion (SCI).

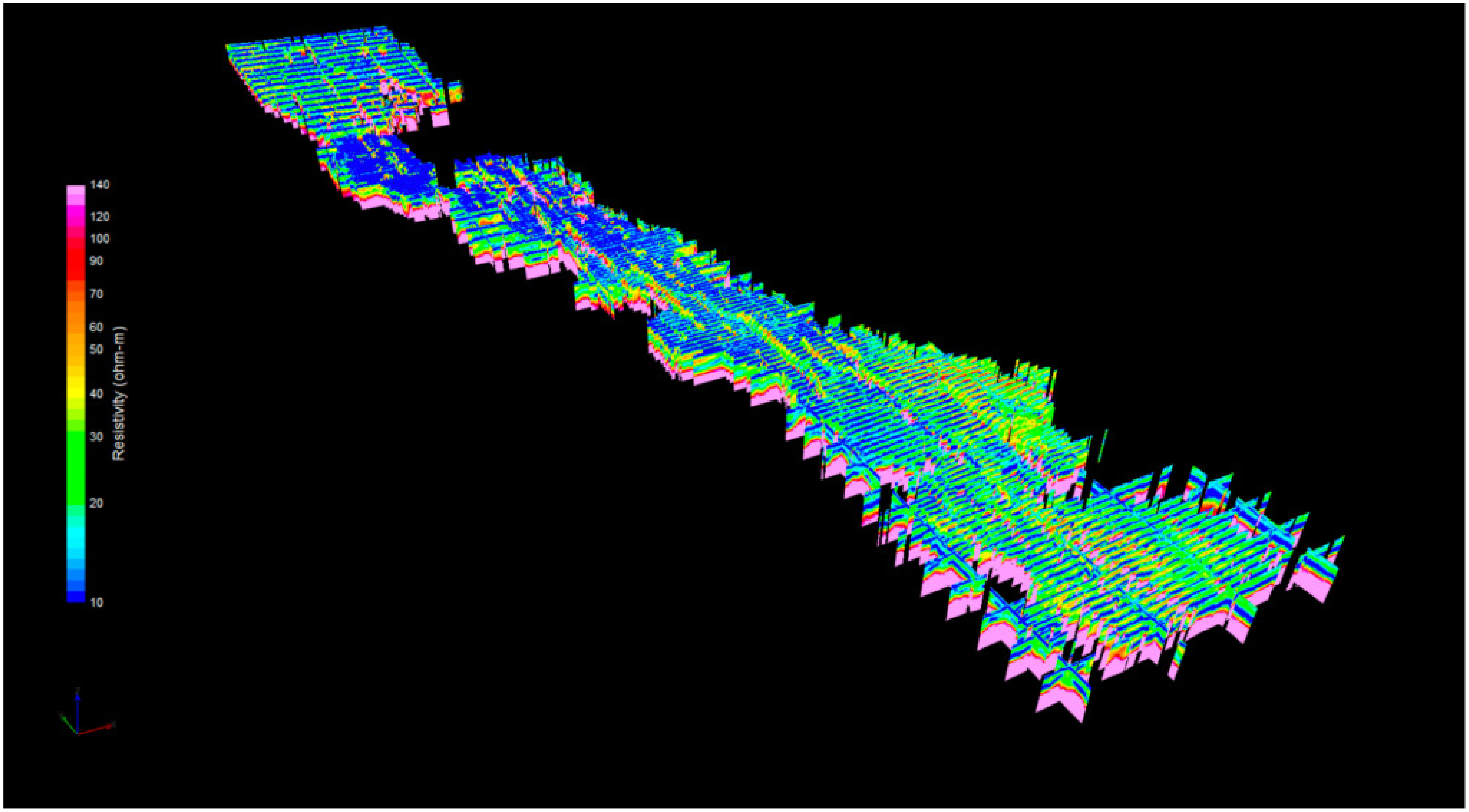


Figure 8-5. A 3D fence diagram displaying the results of the NDSWC AEM survey. The color scale is from 10-140 ohm-m, log-based. The view is to the northeast. Vertical Exaggeration = 1:10.

8.4 Resistivity Depth Layers

Resistivity depth layers were created based on the LCI and SCI model cells spacing (Table 5-1) and were used to produce resistivity layer plots of the AEM survey area. To create these grids, the resistivities of the individual model layers were imported to a Geosoft Oasis montaj (OM) database. The individual model layers were then gridded independently using the OM minimum curvature gridding (MCG) algorithm. The cell size was set to 300 feet and the "cells to extend beyond" set to 7 or 2,100 feet. All other parameters were either left as the default or blank. These layers are useful for inspecting the vertical changes in the resistivity. It should be noted as the depth increases the Precambrian basement is the predominate formation that is imaged. The color scale that was used for these maps was selected to illuminate the sands and gravels within the Quaternary section. The high resistivities of the Precambrian saturate the color scale on the high end. Figure 8-6 is an example of a model depth layer, from -105 ft to -123 ft. At this depth the basic fabric of the Quaternary sands and gravels are indicated by the high resistivities. These layers were combined into both a PDF file and Google Earth KMZ that allows the user to inspect the individual layers by selecting a specific layer under the Data tab in the pdf file down to the 600 feet in depth. These files are located in Appendix 2. The grids of all the depth layers can be found in Appendix 3 Deliverables/SCI/Grids.

8.5 Voxel Grid

A voxel grid was completed for the NDSWC Wahpeton AEM survey. The voxel grids were made using a 300 ft grid cell size and the model layer thicknesses (Table 5-1). A minimum curvature method was used within Datamine Discover PA (Datamine Discover, 2017). The grid was allowed to interpolate to the extents of the survey. Later the grids were clipped to the outline of the survey area data coverage. All layers were referenced to their depth from the surface. After the grid was calculated, the DEM was added as an offset.

The voxels allow for another view with which inspection of the 3D distribution of the inverted model resistivities can be made. Specifically, for the inspection of the NDSWC Wahpeton AEM survey there are two resistive materials that are of interest in the area. One is the resistive Precambrian basement and the other is the resistive Quaternary sands and gravels. Figure 8-7 is a 3D plot of the Voxel for the NDSWC Wahpeton AEM survey with two thresholds applied and looking toward the north-east with a vertical exaggeration of 1:15. First the voxel threshold is set to greater than 110 ohm-m (pink area), and second the voxel threshold from 0-300 feet in depth is set for greater than 36 ohm-m (the shallower yellow-orange area). A series of images of the 3D Voxel can be found in Appendix 2.

8.6 Image Products

The complete collection of the 2D profiles are contained in Appendix 1 and the 3D fence diagrams, resistivity depth layers, and voxels, are contained in Appendix 2. The layered PDF of resistivities of model layers can also be found in Appendix 2. ArcView Binary Raster Grids and the voxel as an ASCII xyz file are found in Appendix 3 Deliverables\SCI in the \Grids and \Voxels folders, respectively.

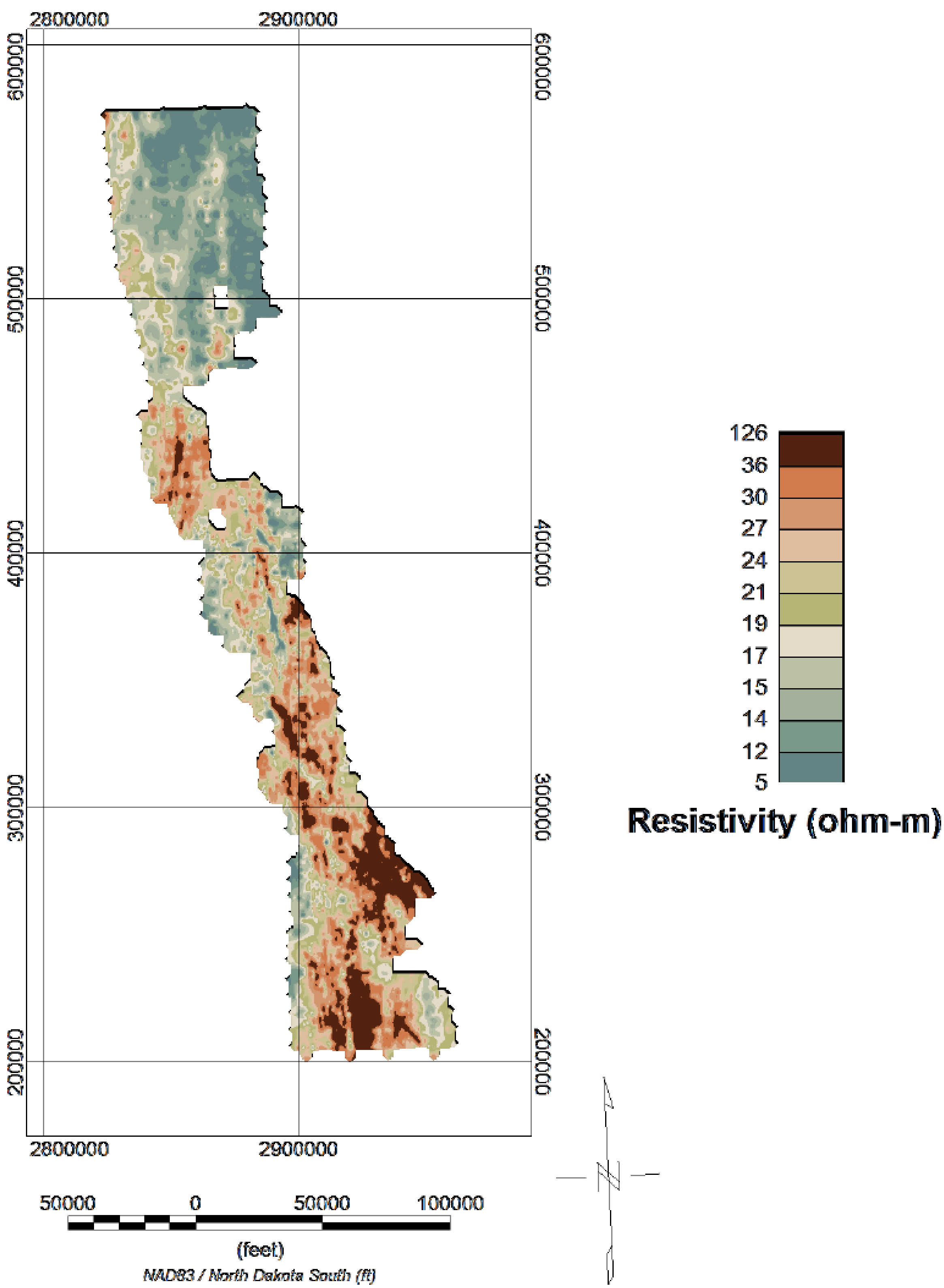


Figure 8-6. Map view of the inverted resistivity for the 105 to 123 feet SCI model layer for the NDSWC Wahpeton AEM survey area.

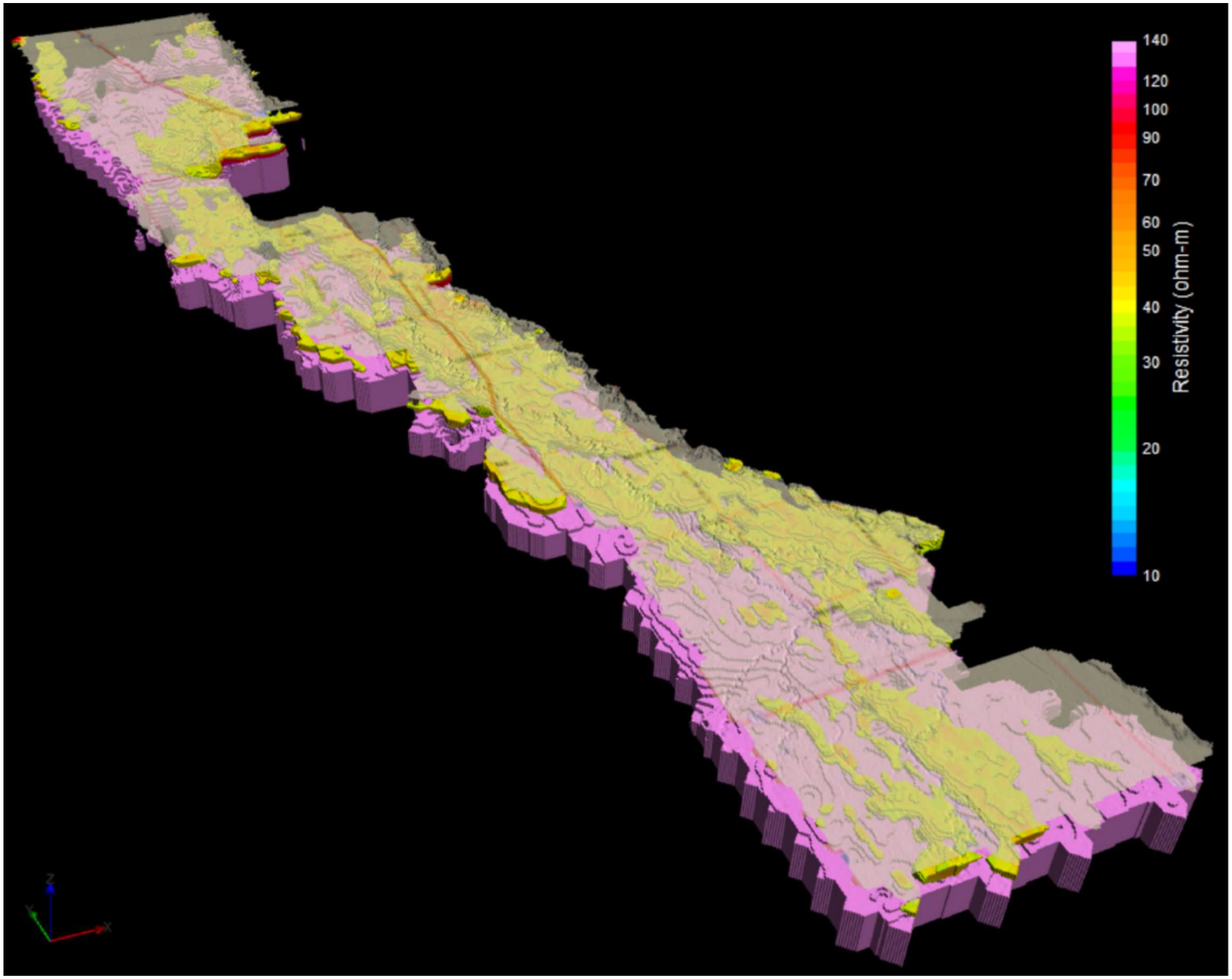


Figure 8-7. 3D voxel looking toward the north-east. Two thresholds are set: a) > 110 ohm-m (pink); b) From 0-300 feet depth and > 36 ohm-m (yellow-orange). The DEM is overlain as a general map of the area with some transparency for aid in location. Vertical Exaggeration of 1:15.

8.7 Examples of Boreholes Lithology Compared to AEM Inversion

Two borehole databases were downloaded from the NDSWC website. One was the Test Hole database and the other was the Observation Well database (NDSWC, 2017). The databases contained information on the interpreted lithology from well drilling and were examined within the area of the NDSWC. Wahpeton AEM survey area. Edits were conducted on the database to correct typo's or inconsistencies in the lithology descriptions. The lithologies were examined and the color scale for the display of the lithologies was provided by the NDSWC (Personal Communications, Scott Parkin, Hydrologist and Rex Honeyman, Hydrologist NDSWC, November 2, 2017). As indicated in Section 8.3, 2D profiles, boreholes that were within ¼ of a mile or 1,320 feet of the flight line were projected onto the AEM inverted resistivity profiles. Several observations have been noted that will hopefully assist the NDSWC in the interpretation of the AEM inverted resistivity including pointing out some areas of good correlation with the borehole lithology as well as areas of poor correlation of the borehole lithology to the inverted AEM resistivity. It is of paramount importance that the interpreter understands the limitation of the lithology descriptions as compared to the resistivity as well as understand the limitations of the AEM.

Lithology logs quality are limited to the following: drilling method, drilling mud, drilling speed, and skill and experience of the geologist performing the descriptions. The lithology log is an interpretation by the geologist of the material that is brought to the surface. Different vintages of lithology logs catalogued at differing times by different geologists may have varying accuracies in specific picks of similar lithologies. Cores are an improvement in the interpretation of the lithology over other methods but are also plagued with difficult recovery in unconsolidated materials. With all the limitations of the lithology logging of well cuttings, the fact remains that they are still a window into the subsurface and provide important clues to the geology. Below are several examples of comparisons of boreholes and the AEM inverted resistivities. Appendix 1 includes these examples and others for comparison of selected flight lines with the borehole lithology logs.

The AEM system is responding to changes in the electrical resistivity of the subsurface while flying at approximately 50 mph at approximately 100 ft AGL with a finite EM bandwidth. This means that the AEM could provide a fuzzy or unfocused view of the subsurface as compared to borehole lithology or borehole geophysics. As the EM signal diffuses down into the earth, the frequency of the signals that are detectable decreases. This has the impact of decreasing the resolution of the EM signals with increasing depth. Figure 6-6 shows a modeling example of a resistive layer at two depths in a more conductive medium. The AEM inversions have an increasing layer thickness with depth that also expresses the decreased resolution with depth (Table 5-1). If the layers of the geology are thinner than the model layer thickness, they are effectively averaged.

8.7.1 Precambrian Basement

Within the survey area the Precambrian igneous and metamorphic rocks make up the basement as detected by the AEM (NDSWC, 2017 and Bluemle, 2003). These rocks are characterized as being electrically resistive. This is not the most ideal situation for electromagnetic techniques such as AEM. The AEM is more sensitive to conductive materials and the response to resistive materials at depth are low. However, the system did have the resolution and the depth of investigation to clearly indicate the presence of resistive materials throughout the survey area. Figure 8-8 presents east-west line L1450. In the center of the section borehole 27730 indicates Precambrian weathered granite at the same depth that the AEM resistivity is indicating a resistive contact. The borehole is along a gap in the AEM from decoupling the EM interference. However, it is easy to interpret across the gap.

Also, along line L1450 on the right center of the section, borehole 16628 indicates bedrock at a resistive contact. The borehole lithology in those two holes as well as 569 and 16598 correlates well with the AEM inverted resistivity.

Figure 8-9 is east-west line L1140 along which two boreholes (13350 and 13352), on the right-hand side of the section, bottom in Precambrian material. The basement is also much higher in elevation than that presented in Figure 8-8. Borehole 13352 also indicates gravel at the bottom of the borehole.

Figure 8-10 is east-west line L1300. This line indicates a decrease in the depth of the resistive unit toward the east by 300 feet. Borehole 15737 does not indicate Precambrian material but does indicate the depth of the units that are less resistive with a general correlation to the resistivity and lithology.

During the processing and inversion of the AEM data, areas of EM coupling did adversely impact the determination of the basement resistivity. Most of the EM couplings were removed. However, in some areas the near-surface did not indicate the impacts of the EM couplings because they were only affecting the later time gates. In those cases, the AEM soundings were not cut out of the section. This did, in some cases, cause anomalies in the basement resistor that are not geologically-based.

Figure 8-11 is east-west line L1090 that crosses over **I-29**. The area circled by the dashed black line should not be interpreted as anything but EM coupling, and the interpretation of the resistive basement should be continued through that zone. Borehole 14043 also indicates a good correlation between the lithology and the AEM inverted resistivity.

Figure 8-12 is east-west line L1481. This line shows impacts of EM-coupling which is reflected as a depression in the depth of the resistive basement. No boreholes exist in this location and careful interpretations would need to be conducted looking at the lines to the north and south of this line to verify the depression in the basement in this area.

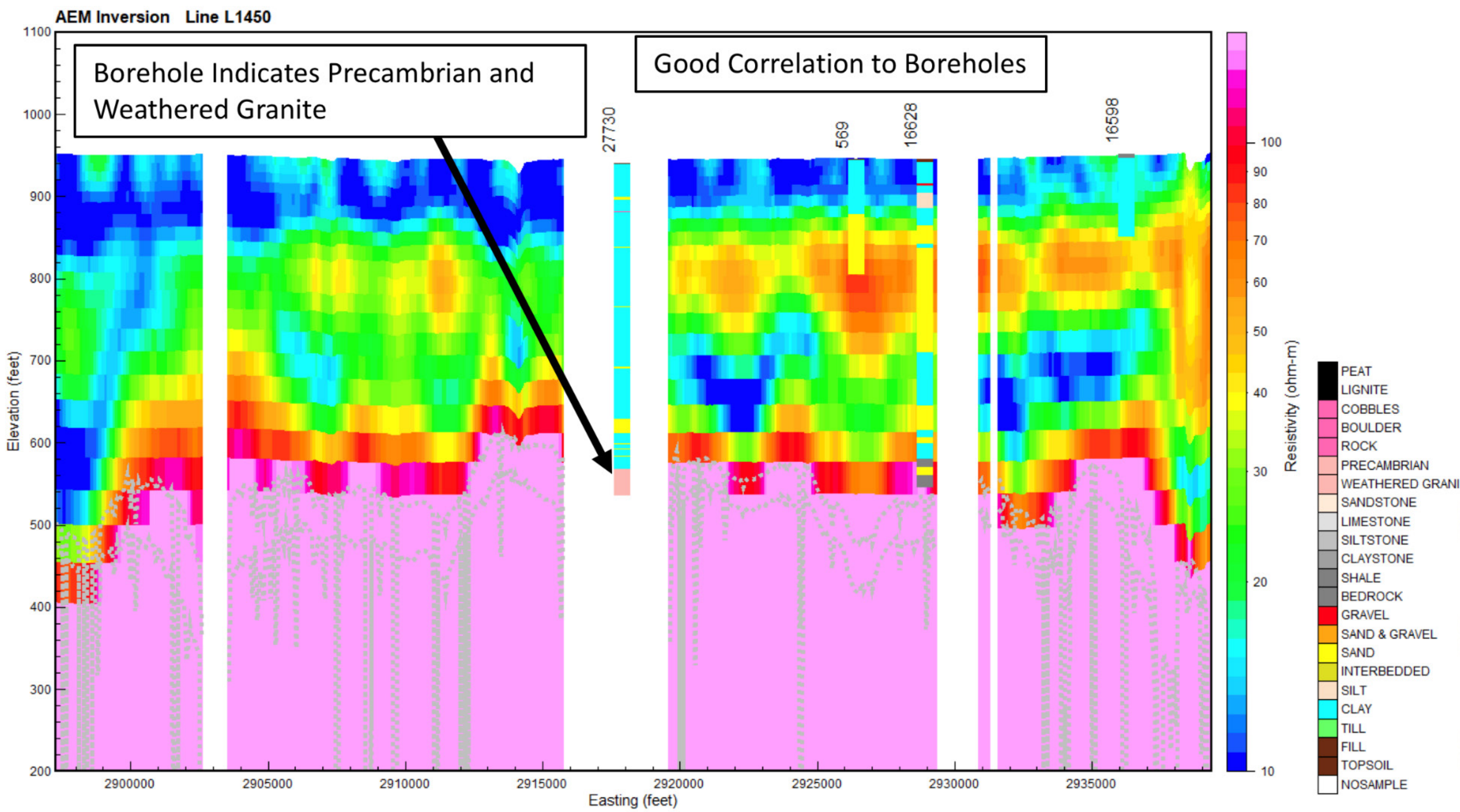


Figure 8-8. Inverted AEM resistivity along line L1450 with boreholes within ¼ of a mile of the flight path. Showing borehole indications of Precambrian bedrock.

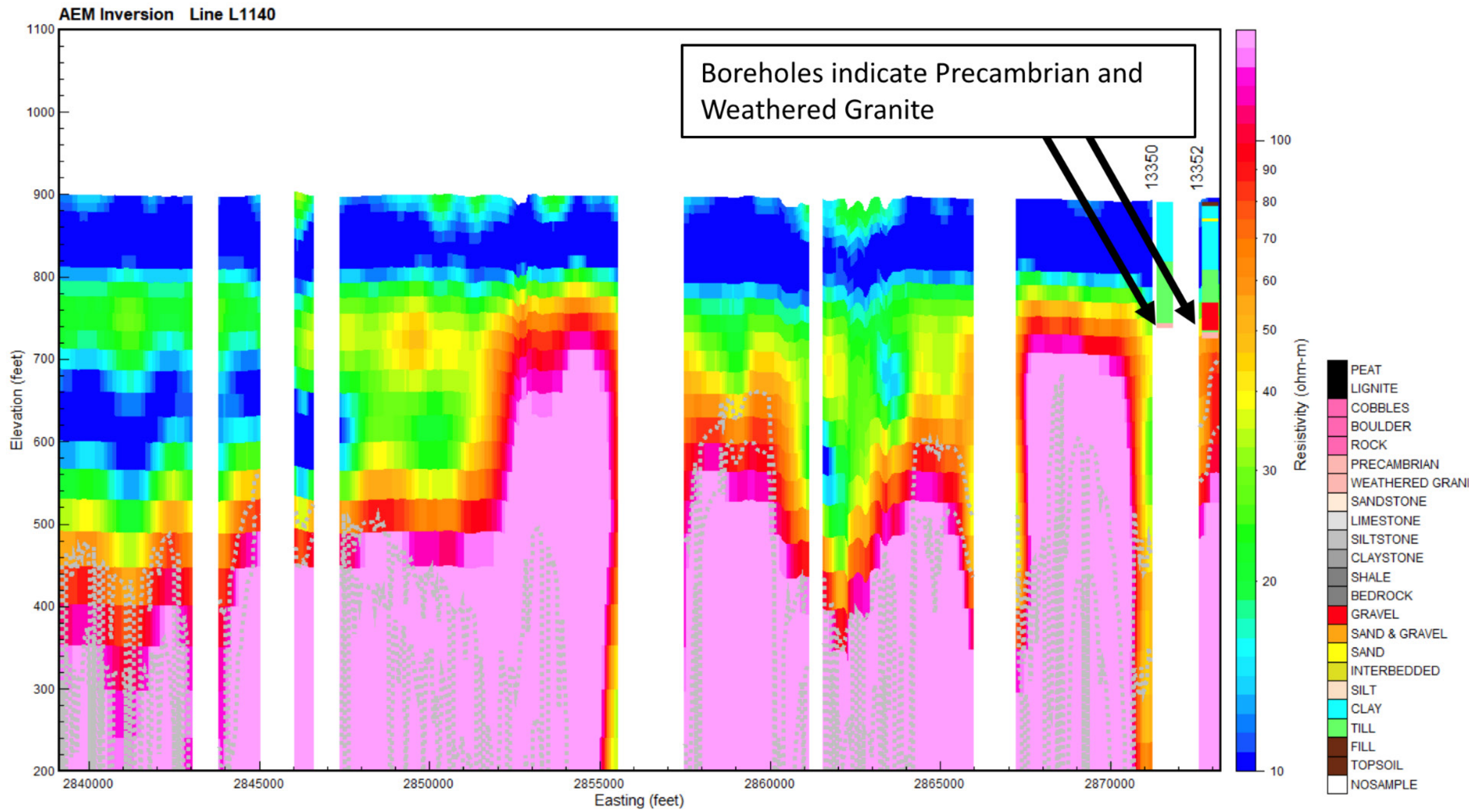


Figure 8-9. Inverted AEM resistivity along line L1140 with boreholes within ¼ of a mile of the flight path. Showing borehole indications of Precambrian.

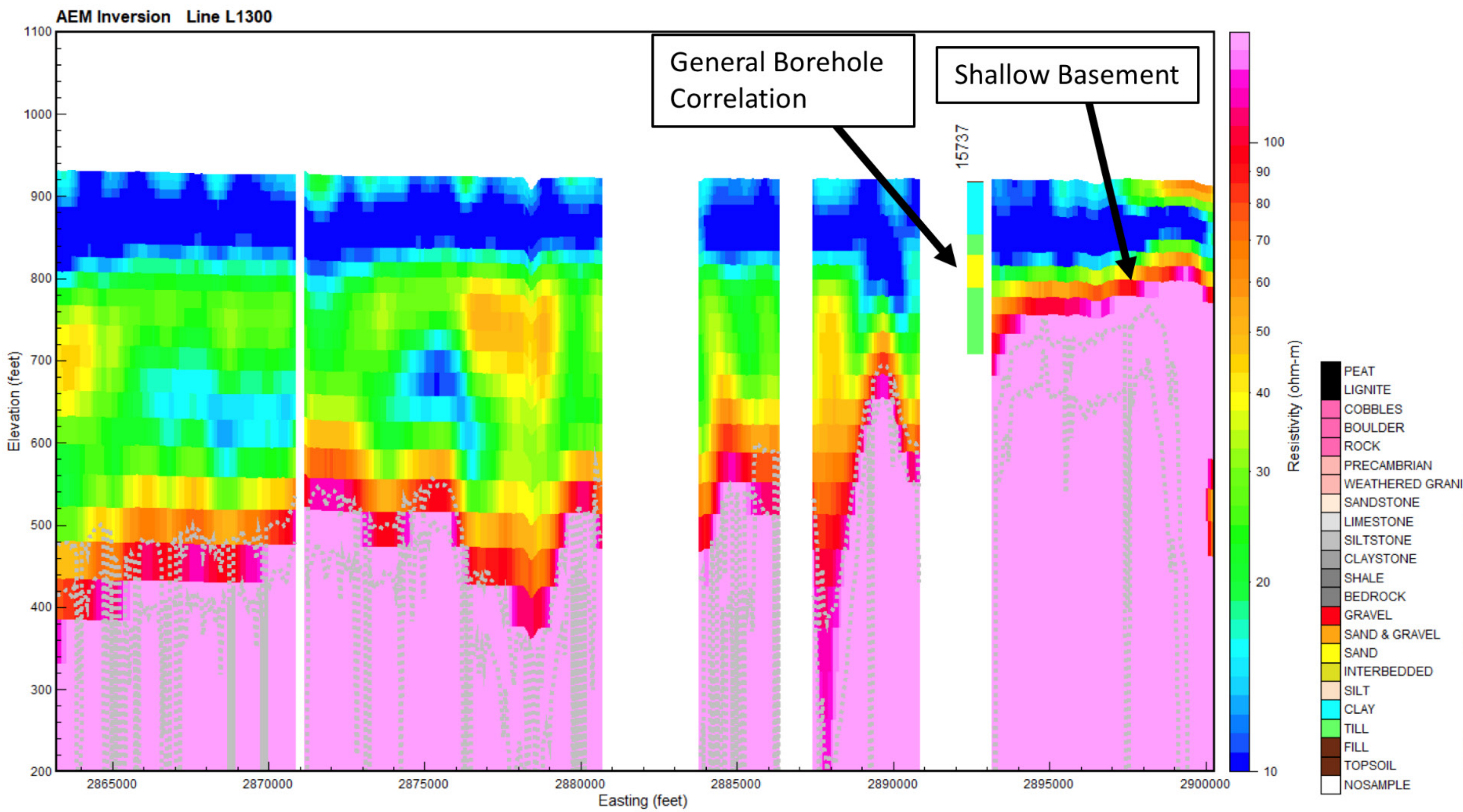


Figure 8-10. Inverted AEM resistivity along line L1300 with boreholes within ¼ of a mile of the flight path. Showing the resistive basement depth decreasing to the east.

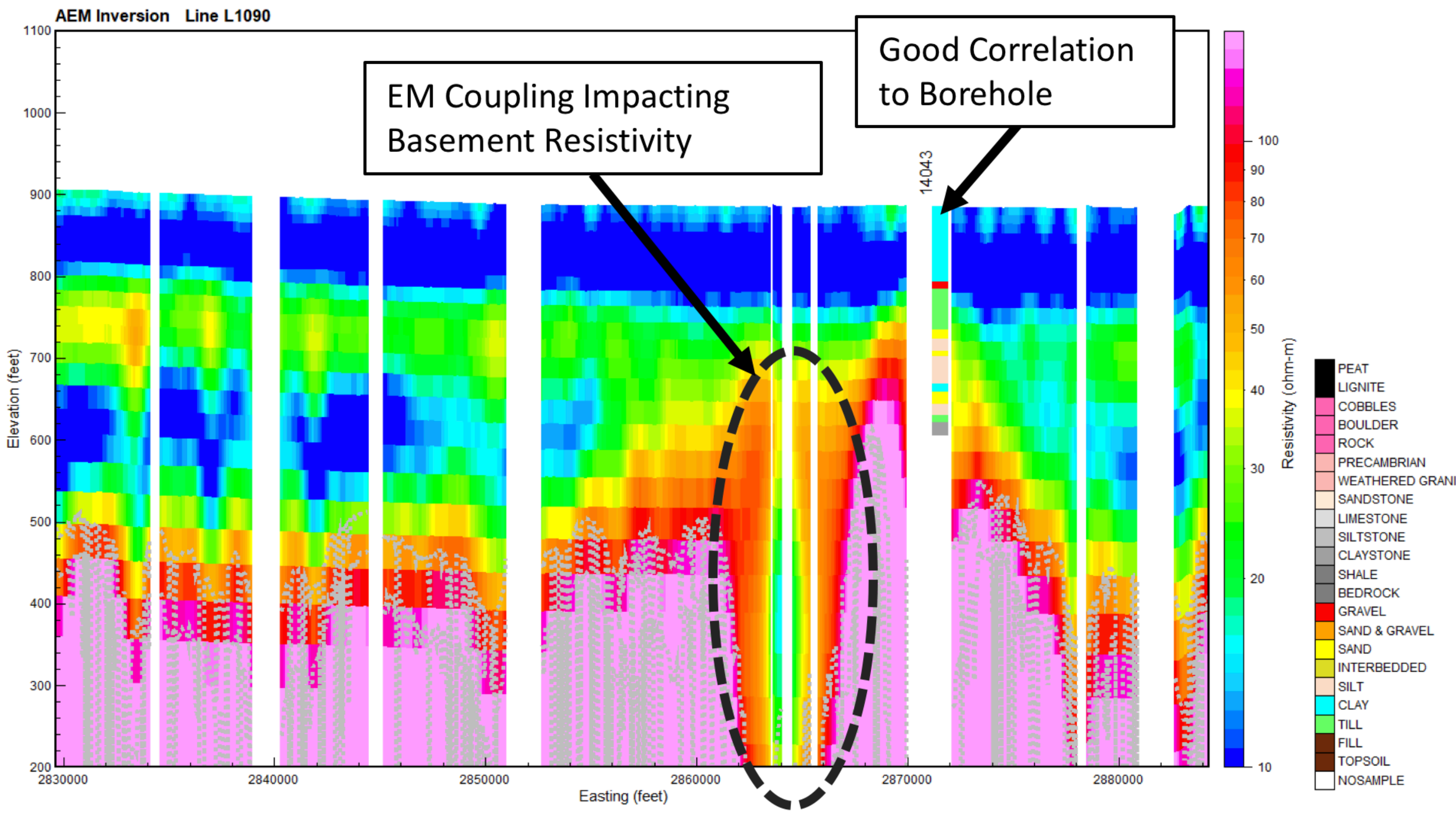


Figure 8-11. Inverted AEM resistivity along line L1090 with boreholes within ¼ of a mile of the flight path. Showing the resistive basement at depth interrupted by an EM coupling in the vicinity of interstate I-29.

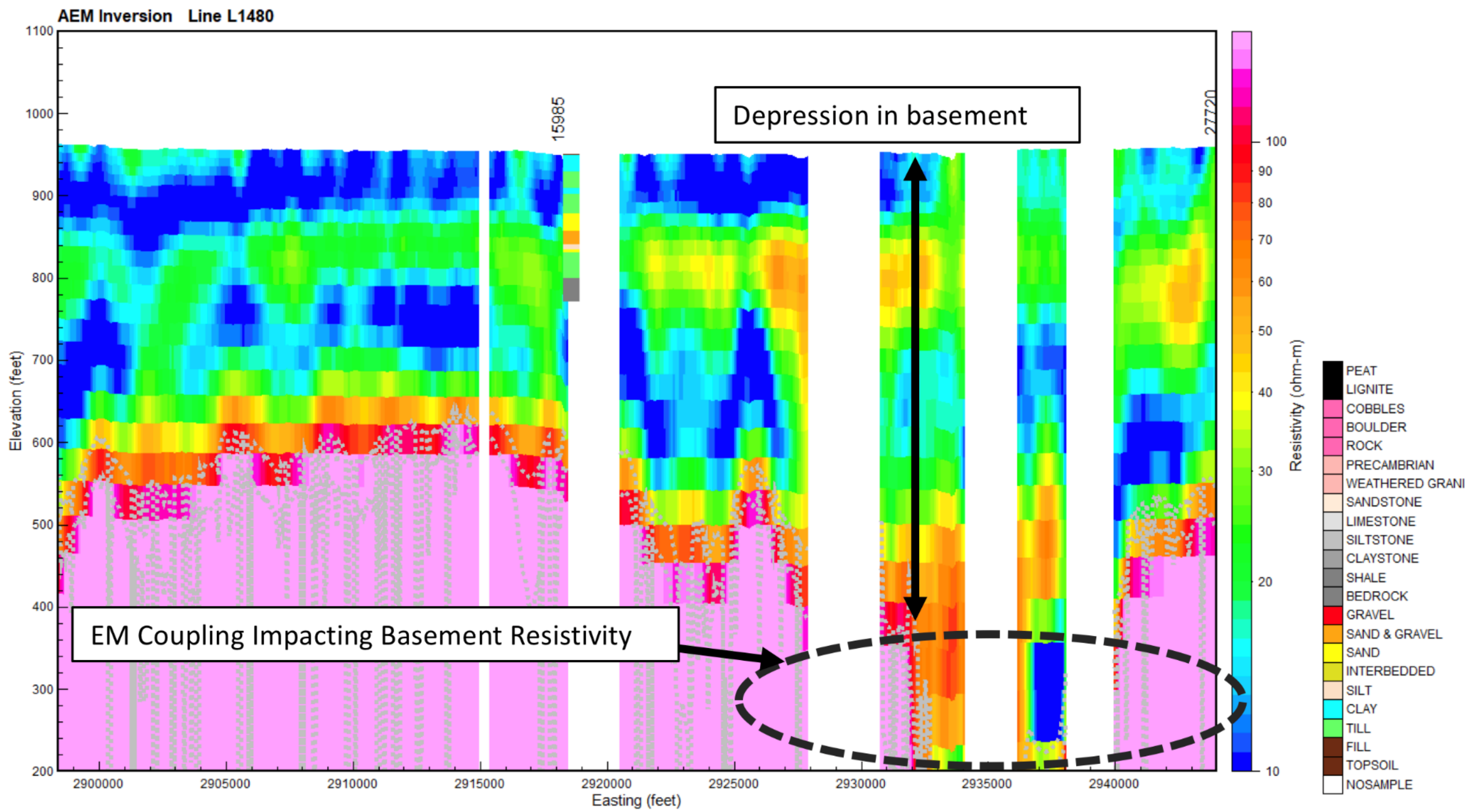


Figure 8-12. Inverted AEM resistivity along line L1480 with boreholes within ¼ of a mile of the flight path. Showing the resistive basement at depth interrupted by an EM coupling. The AEM resistivity also shows a depression in the basement.

8.7.2 Cretaceous bedrock units

Geological bedrock maps and boreholes (NDSWC, 2017 and Bluemle, 2003) in the survey area indicate the presence of Cretaceous units including the Cretaceous Belle Fourche Shale, Mowry Shale, Newcastle Sandstone, and Skull Creek Shale Formation (***Kb***). East-west line L1464 (Figure 8-13) has several boreholes that indicate shale at depth. Borehole 19734 indicates weathered granite at depth, but this is most likely weathered material that was deposited upon the Cretaceous bedrock in the area.

8.7.3 Quaternary

The main objective of the AEM survey was to map the extent and vertical location of the Quaternary sands and gravels that form the aquifers in the area. These deposits are typically overlain by clays and tills. These deposits may lie directly on the Cretaceous units and on the Precambrian basement but are typically underlain by other fine grained Quaternary deposits. Line L1464 (Figure 8-13) indicates good correlations of the borehole lithology and the resistivity in the boreholes along the eastern end of the line, but also shows a disagreement in borehole 16650 that indicates all clay in an area of a relative resistor.

Figure 8-14 is east-west line L1224 with borehole 25607 indicating a sand zone directly on the Precambrian basement that correlates well with the resistivity. Boreholes 27072 and 13668 indicate clay and tills with very thin sands and gravels within an EM coupling gap.

Figure 8-15 shows two boreholes along east-west line L1408. The AEM resistivity indicates a resistive body within the Quaternary section immediately below a conductive layer and above a conductive unit (likely Cretaceous) upon the resistive basement (Precambrian). Borehole 24271 indicates a sand and gravel layer that correlates with the resistive body within the Quaternary. Borehole 17703 indicates the Cretaceous bedrock but only displays a thin gravel and sand layer within a till. There would seem to be a disagreement between the two boreholes with borehole 24271 agreeing more with the AEM resistivity.

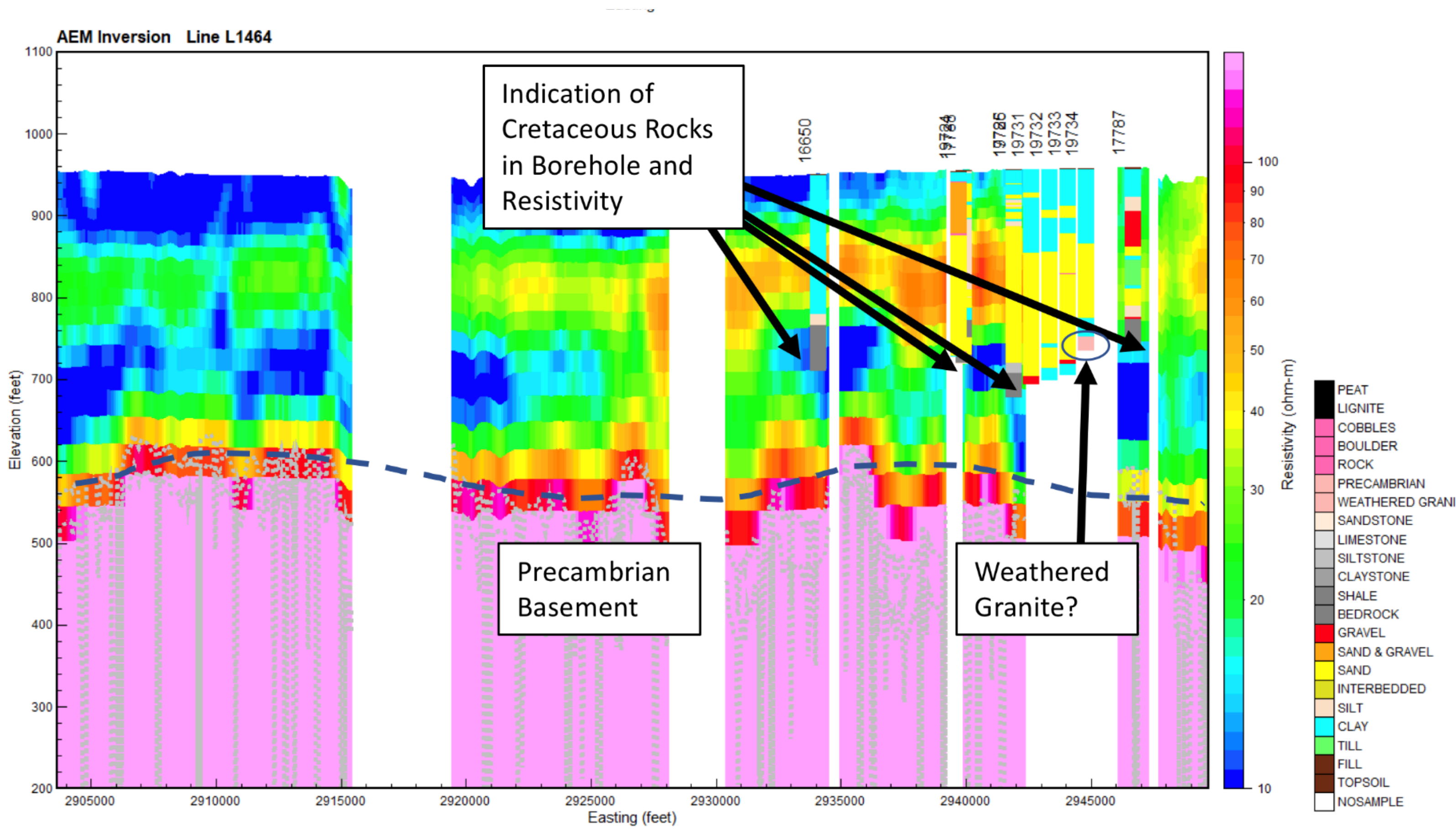


Figure 8-13. Inverted AEM resistivity along line L1464 with boreholes within ¼ of a mile of the flight path. Showing the conductive Cretaceous Belle Fourche Shale (*Kb*) above the resistive Precambrian basement. Borehole 19734 indicates an anomalous weathered granite above the shale.

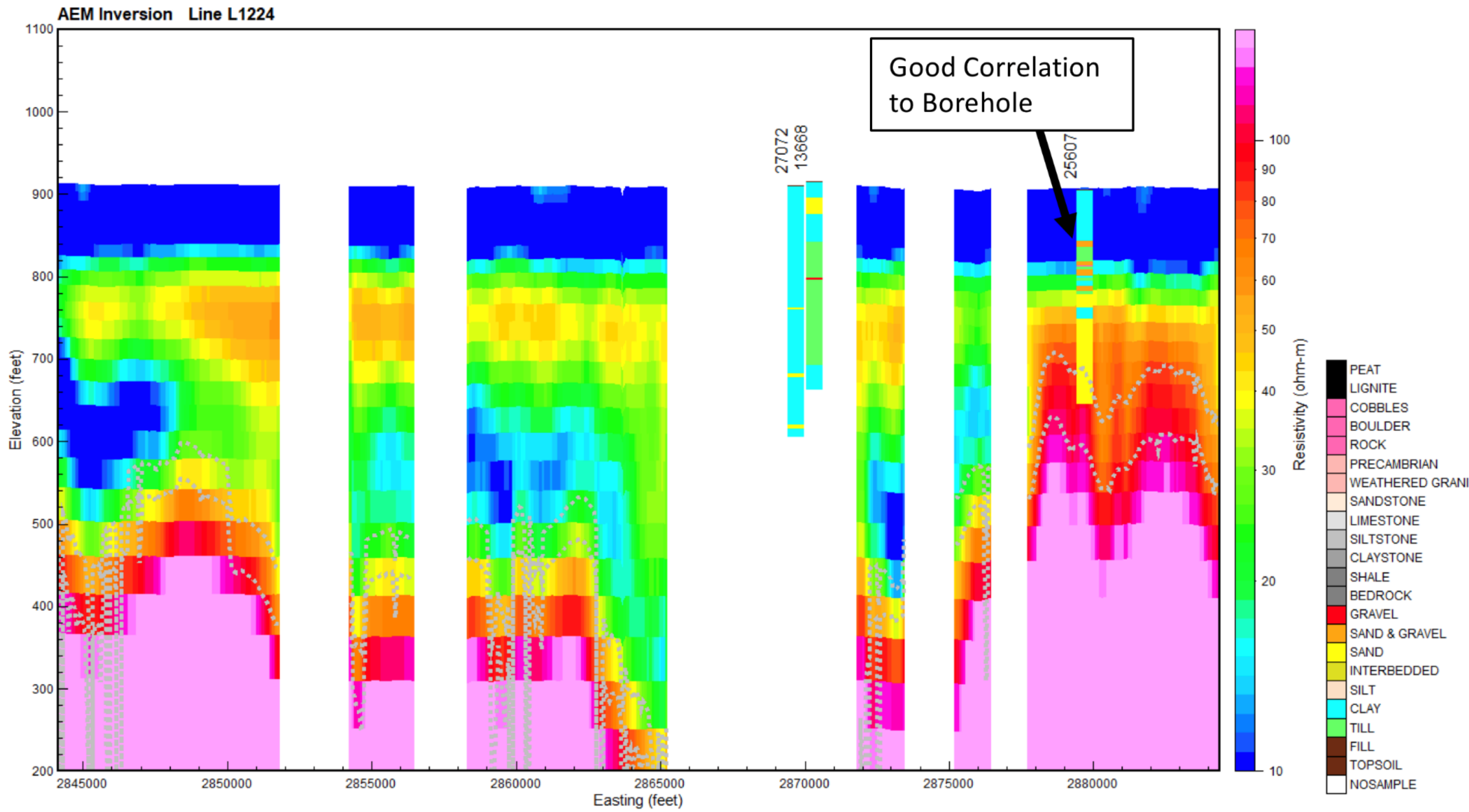


Figure 8-14. Inverted AEM resistivity along line L1224 with boreholes within ¼ of a mile of the flight path. Borehole 25607 lithology is in good correlation to the resistivity.

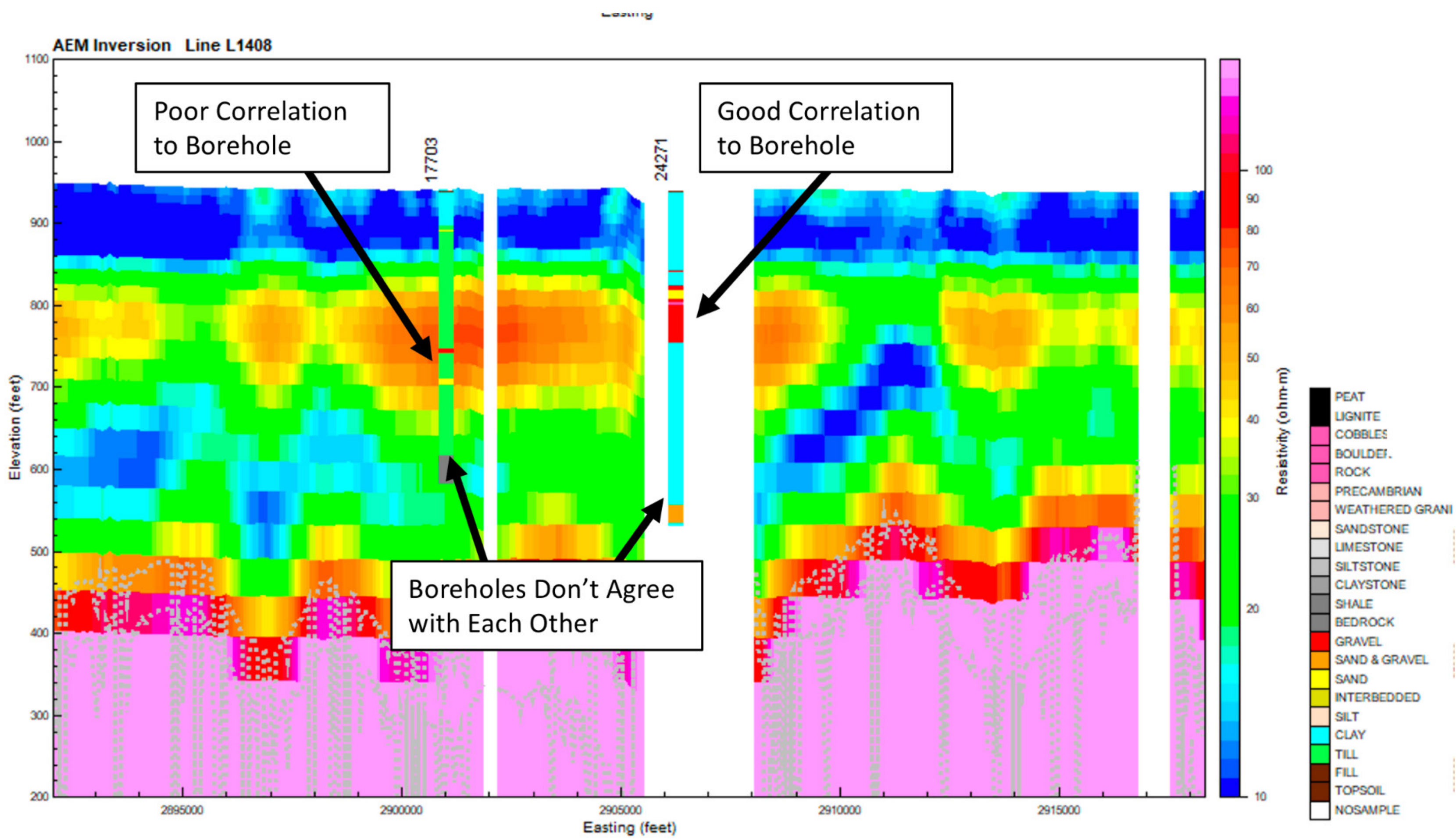


Figure 8-15. Inverted AEM resistivity along line L1408 with boreholes within ¼ of a mile of the flight path. Two boreholes are within the same resistive body but indicate different lithology.

8.8 Suggestions on Interpretation

The NDSWC Wahpeton AEM survey is a data set rich in details of the geology from the surface down to the Precambrian basement. Even so, care needs to be exercised in the interpretation of the resistivity, keeping in mind the limitations of the AEM resolution and quality of the borehole lithologies.

The first suggestion in interpreting this dataset is to delineate the Precambrian resistive basement and then the Cretaceous bedrock units. The next step would be to utilize resistivity thresholds on the Quaternary to identify the sand and gravel aquifers within the area. Another powerful technique is to adjust the resistivity color ramp to bring the details of the resistivity changes out of the Quaternary units without the need to display the Precambrian resistors. A profile by profile approach is the best way to ensure consistent interpretation.

9. Summary

This final report presents the Quality Assurance and Quality Control procedures, and the results of that analysis, that were applied to the setup and data acquisition of the airborne electromagnetic survey of NDSWC Wahpeton area, the preliminary LCI analysis, a forward and inverse modeling analysis comparing the AEM with borehole geophysical logs, and finally, SCI inversion results.

The QA/QC analysis included airborne testing of the system, the as-flown flight lines, and the flight altitude as the data was acquired. In addition, the power line noise monitor and magnetic field data were also examined and found to present no indications of any system or data acquisition issues.

The final spatially-constrained results are presented as 2D resistivity profiles, 3D fence diagrams, 3D voxels, and as combined depth slices. Google Earth KMZ files including the as flown-retained, the location of the AEM test line, the residual errors in the inversion, and the resistivity depth slices. A link to the DropBox location of these files is presented below.

We believe that given the challenge of the infrastructure in the NDSWC Wahpeton AEM acquisition survey area, these results provide a good, solid starting point for development of a hydrogeologic framework of the NDSWC Wahpeton AEM survey area.

Dropbox Link:

https://www.dropbox.com/sh/63x7lxs509t7s1p/AACOTAg6oW_dchCxoHQh_AJOa?dl=0

10. Deliverables

In the Appendix 3 Deliverables folder are two subfolders entitled KMZ and SCI. The KMZ folder contains Google Earth KMZ's of the calibration Test line, the data/model residual error, the as flown and retained AEM flight data, and the combined resistivity depth slices (including a color bar).

The SCI folder contains four sets of data. The \Grids folder contains the grids of the upper and lower DOI surfaces, a grid of the DEM, and the resistivity depth slices, all in ArcView GIS FLT format. The SCI dBdt folder contains the dB/dt data (in ASCII xyz and Geosoft Oasis montaj database)) that were used to create the inverted models resulting from the SCI analysis, the results of which are in the SCI Inv folder (again in ASCII xyz and Geosoft database). The last folder, Voxels, contains the data presented in the voxel images (Figure 8-7).

Table 9-1: Channel name, description, and units for Wahpeton_SCI_dBdt_dat Geosoft gdb and xyz files.

Parameter	Description	Unit
LINE	Line Number	
X_FT	Easting NAD83, State Plane North Dakota South	Int. Feet [ft]
Y_FT	Northing NAD83, State Plane North Dakota South	Int. Feet [ft]
DEM_FT	DEM from 100 ft grid NED NAVD88	Feet [ft]
X_M	Easting NAD83, UTM Zone 14	Meters [m]
Y_M	Northing NAD83, UTM Zone 14	Meters [m]
DEM_M	DEM from survey	Meters [m]
FID	Unique Fiducial Number	
TIME	Date Time Format	Decimal days
ALT_M	Altitude of system above ground	Meters [m]
INVALT	Inverted Altitude of system above ground	Meters [m]
INVALTSTD	Inverted Altitude Standard Deviation of system above ground	Meters [m]
RESDATA	Residual of individual sounding	
RESTOTAL	Total residual for inverted section	
DATA_0 THROUGH DATA_41	dB/dt data for gates 4 to 45	picoVolts/A*m^4
DATASTD_0 THROUGH DATASTD_41	Standard Deviation of dB/dt data	

Table 9-2: Channel name, description, and units for Wahpeton_SCI_Inv Geosoft gdb and xyz files with AEM inversion results.

Parameter	Description	Unit
LINE	Line Number	Feet [ft]
X_FT	Easting NAD83, State Plane North Dakota South	Int. Feet [ft]
Y_FT	Northing NAD83, State Plane North Dakota South	Int. Feet [ft]
DEM_FT	DEM from 100 ft grid NED NAVD88	Feet [ft]
X_M	Easting NAD83, UTM Zone 14	Meters [m]
Y_M	Northing NAD83, UTM Zone 14	Meters [m]
DEM_M	DEM from survey	Meters [m]
FID	Unique Fiducial Number	
TIME	Date Time Format	Decimal days
ALT_M	Altitude of system above ground	Meters [m]
INVALT	Inverted Altitude of system above ground	Meters [m]
INVALTSTD	Inverted Altitude Standard Deviation of system above ground	Meters [m]
RESDATA	Residual of individual sounding	
RESTOTAL	Total residual for inverted section	
DOI_UPPER_FT	More conservative estimate of DOI	Feet [ft]
DOI_LOWER_FT	Less conservative estimate of DOI	Feet [ft]
DOI_UPPER_M	More conservative estimate of DOI	Meters [m]
DOI_LOWER_M	Less conservative estimate of DOI	Meters [m]
RHO_I_0 THROUGH RHO_I_28	Inverted resistivity of each later	Ohm-m
RHO_STD_0 THROUGH RHO_STD_28	Inverted resistivity standard deviation	
SIGMA_I_0 THROUGH SIGMA_I_28	Conductivity	S/m
DEP_TOP_0_FT THROUGH DEP_TOP_28_FT	Depth to the top of individual layers	Feet [ft]
DEP_BOT_0_FT THROUGH DEP_BOT_28_FT	Depth to the bottom of individual layers	Feet [ft]
THK_0_FT THROUGH THK_28_FT	Thickness of individual layers	Feet [ft]
DEP_TOP_0_M THROUGH DEP_TOP_28_M	Depth to the top of individual layers	Meters [m]
DEP_BOT_0_M THROUGH DEP_BOT_28_M	Depth to the bottom of individual layers	Meters [m]
THK_0_M THROUGH THK_28_M	Thickness of individual layers	Meters [m]

Table 9-3. Files containing ESRI ArcView Binary Grids *.flt (NAD 83 State Plane North Dakota South (international foot).

Grid File Name	Description	Grid Cell Size (feet)
DOI_Lower_Depth	Grid of the lower depth of investigation (DOI) (feet)	300
DOI_Upper_Depth	Grid of the upper depth of investigation (DOI) (feet)	300
Res_Depth_XXX_XXXXft	Resistivity grids of the 29 inverted model depths (ohm-m)	300
Wahpeton_AEM_SurveyArea_DEM	Grid of the USGS National Elevation Dataset (NED) digital elevation model (DEM) NAVD88 (feet)	100

Table 9-4. Channel name, description, and units for Wahpeton_Voxel_Res.csv.

Parameter	Description	Unit
X	Easting NAD83, State Plane North Dakota South	Int. Foot [ft]
Y	Northing NAD83, State Plane North Dakota South	Int. Foot [ft]
Z	Elevation of Voxel Node	NAVD88 [ft]
Resistivity	Voxel cell resistivity value of the Inverted AEM Model	Ohm-m
Elevation	Ground Surface Elevation NAVD 88 100 ft grid	Feet [ft]

11. References

Aarhus Geosoftware, 2017 Aarhus Workbench, available on the world-wide web at: https://www.aarhusgeosoftware.dk/aarhus-workbench (accessed January 24, 2018)

Asch, T.H., Abraham, J.D., and Irons, T., 2015, "A discussion on depth of investigation in geophysics and AEM inversion results", Presented at the Society of Exploration Geophysicists Annual Meeting, New Orleans.

Bluemle, J.P., 2003, Generalized Bedrock Map of North Dakota, North Dakota Geological Survey, North Dakota Miscellaneous Maps, MM-36 https://www.dmr.nd.gov/ndgs/Publication_List/ndmisc.asp (accessed Jan 22, 2018).

Christensen, N. B., Reid, J. E., and Halkjaer, M., 2009, "Fast, laterally smooth inversion of airborne time-domain elecromagnetic data." *Near Surface Geophysics* 599-612.

Christiansen, A. V., and E. Auken, 2012, "A global measure for depth of investigation." *Geophysics,Vol. 77, No. 4* WB171-177.

DatamineDiscover, 2017, Datamine Discover Profile Analyst, available on the world-wide web at: https://www.dataminediscover.com/discover. (accessed on January 24, 2018).

Geotech LTD., 2017,VTEM (Versatile Time Domain Electromagnetic) System, available on the world-wide web at: http://geotech.ca/services/electromagnetic/vtem-versatile-time-domain-electromagnetic-system/ (accessed on January 24, 2018).

Ley-Cooper, Y. and Davis, A., 2010, Can a borehole conductivity log discredit a whole AEM survey?: *in* Extended abstracts of the Australian Society of Exploration Geophysicists Annual meeting Aug 20-24, Sydney, Australia.

North Dakota State Water Commission, 2017, Map Services, available on the world-wide web at: http://mapservice.swc.nd.gov (accessed November 6, 2017).

U.S. Geological Survey (USGS), 2016, The National Map, 2016, 3DEP products and services: The National Map, 3D Elevation Program Web page, http://nationalmap.gov/3DEP/3dep_prodserv.html (accessed January 24, 2018).

Viezzoli, A., Christiansen, A. V. , Auken, E., and Sorensen, K., 2008, "Quasi-3D modeling of airborne TEM data by spatially constrainted inversion." *Geophysics Vol. 73 No. 3* F105-F11