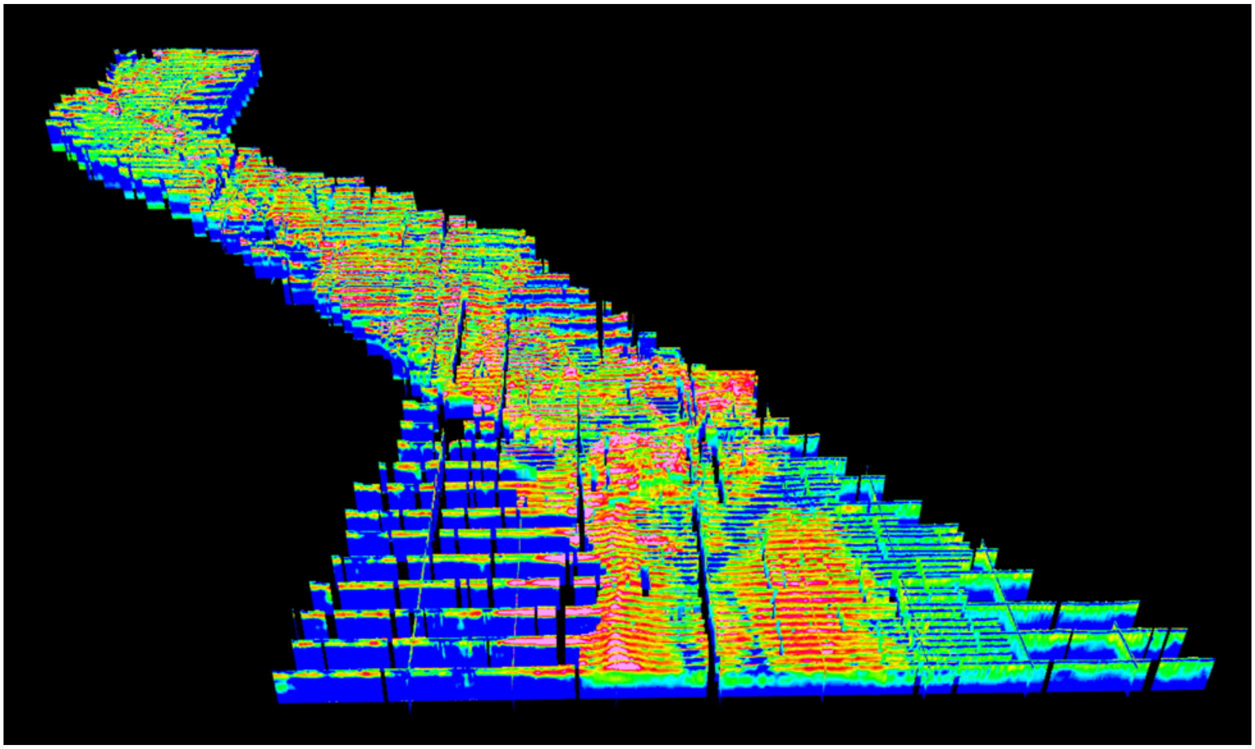
Final Spatially-Constrained Inversions Report and Data Delivery for the Airborne Electromagnetic Surveys of the Spiritwood South and Tolna Areas, North Dakota for the North Dakota State Water Commission



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

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

June 25, 2019

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 Spiritwood Aquifer South and Tolna, 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 Spiritwood Aquifer South and Tolna 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 Early-Time (VTEM-ET) systems data (Geotech, 2017). Specifically, AGF will conduct Laterally-Constrained Inversions (LCI) and Spatially-Constrained Inversions (SCI) of the VTEM-ET 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 data acquisition plan in the area of Spiritwood South is presented in Figure 1-1 and for the Tolna area in Figure 1-2. All airborne operations were carried out by Geotech utilizing their VTEM-ET system.

2. Schedule/Time Line

Geotech mobilized to the Spiritwood South area on October 15, 2018. The system was assembled October 15-19, 2018 and ground tests and airborne tests were conducted October 19-20. Production began on October 21, 2018 and continued through March 23, 2019. Preliminary processing and LCI's were performed on the data beginning on October 23, 2018 and were delivered within 48 hours of receipt of the data from Geotech.

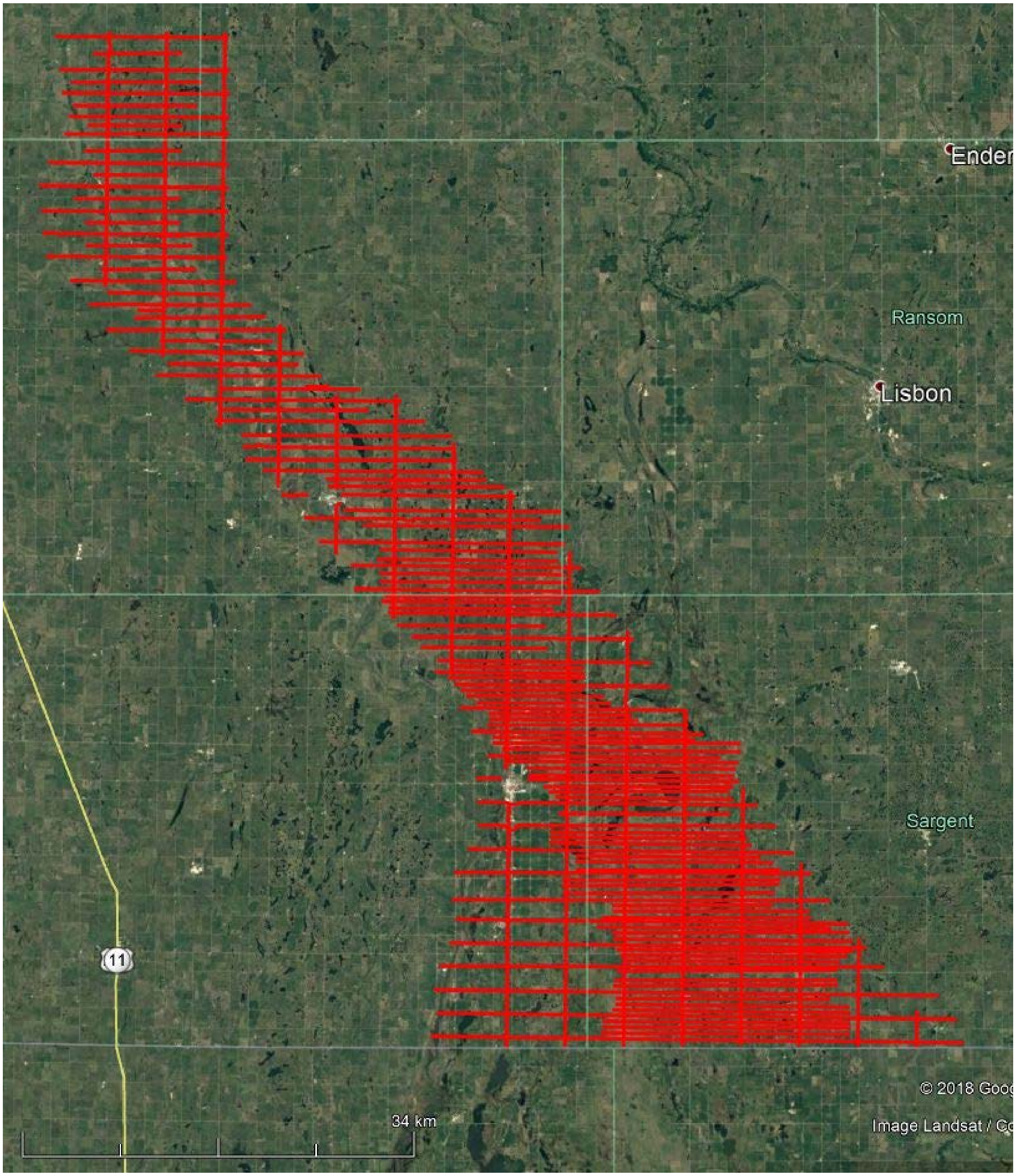


Figure 1-1. As-Flown AEM VTEM-ET data acquisition within the Spiritwood South area of North Dakota (Google Earth).

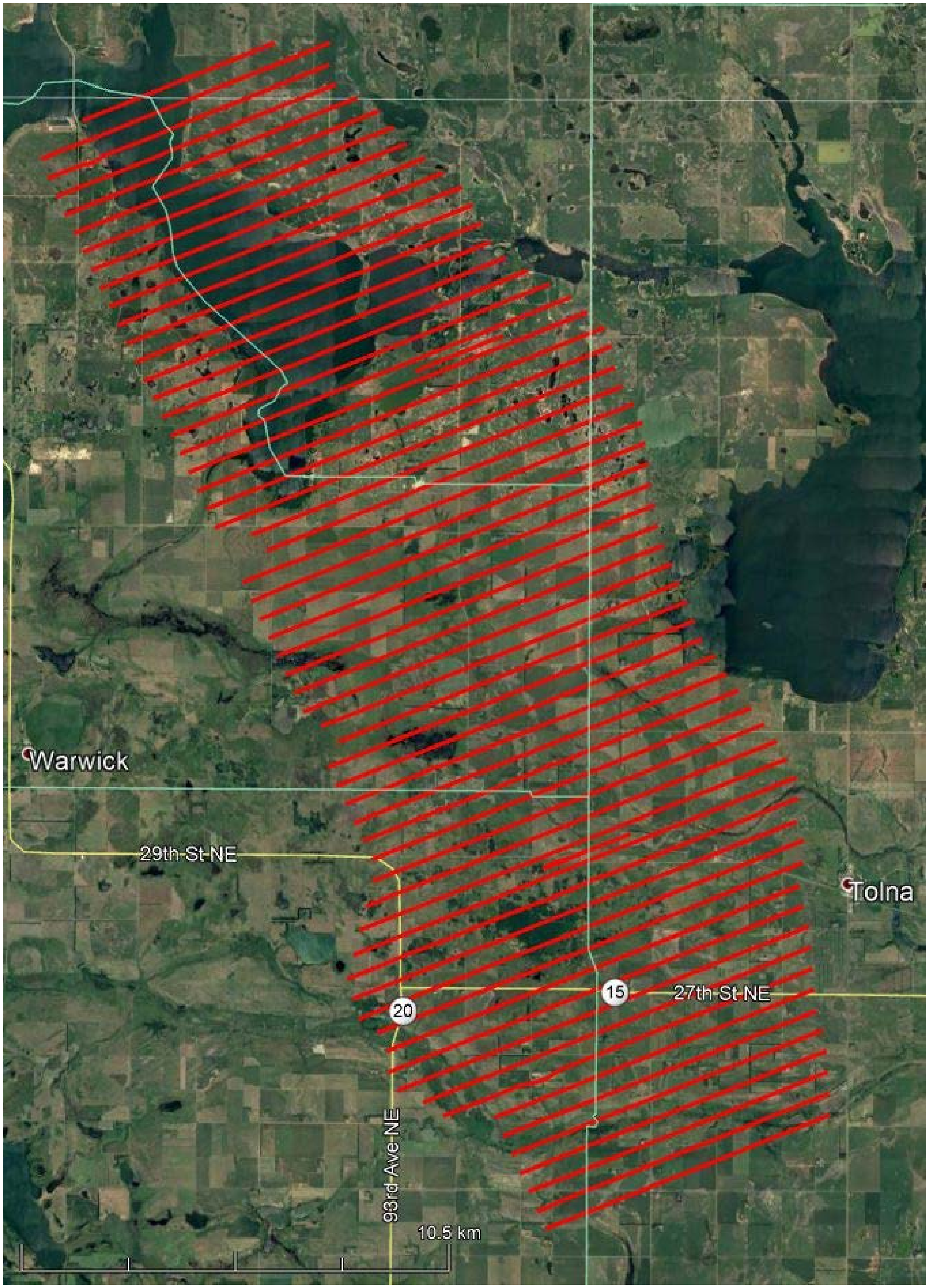


Figure 1-2. As-Flown AEM VTEM-ET data acquisition within the Tolna area of North Dakota (Google Earth).

3. System Calibration/Ground Tests

3.1 Test Line Calibration

The VTEM-ET system was flown over four known test holes locations (130775 and 130776 for the Spiritwood South area and 130791 and 130792 for the Tolna area). 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.

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

Two borehole databases were downloaded from the NDSWC MapServices (NDSWC, 2018), One was the Test Hole database and the other was the Observation Well database (NDSWC, 2018). The databases contained information on the interpreted lithology from well drilling and were examined within the area of the NDSWC. After consultation with NDSWC, only the NDSWC boreholes were used in this project (Personal Communications, Scott Parkin, Hydrologist NDSWC, November 12 2018). 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). Four modern electrical resistivity logs were also provided for the survey area holes 130775 and 130776 for the Spiritwood Southern area (Personal Communications, Scott Parkin, Hydrologist NDSWC, October 22, 2018), and 130791 and 130792 for the Tolna area (Personal Communications, David Hisz, Hydrologist NDSWC, December 12, 2018).

4. Data Acquisition

4.1 Acquisition Timing and as-flown lines

The NDSWC Spiritwood South AEM data acquisition was flown out of the Jamestown Airport and the Tolna AEM data acquisition was flown out of Devil's Lake Regional Airport. The production flights took place from October 21, 2018 off and on through March 23, 2019. After the initial reconnaissance lines were flown in the Spiritwood South area, the Tolna AEM survey was flown, and then infill lines were flown in the Spiritwood South area based on the results of the preliminary LCI's of the VTEM-ET data. Line-km totals from each flight are provided in Table 4-1. Note that the VTEM-ET data in the databases are indexed by line and flight number. Figure 4-1 is an "as flown" map view of the Spiritwood South 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. Similarly, Figure 4-2 is an as flown map view by date of the Tolna AEM data acquisition.

Table 4-1. Flight line production by flight.

Date	Flights	Location	Distance (km)	Distance (miles)
10-21-2018	1	South	15.0	9.3
12-17-2018	2, 3	South	224.3	138.4
12-18-2018	4, 5	South	237.8	146.8
12-19-2018	6, 7	South	217.3	134.2
12-20-2018	8	South	181.4	112.0
02-01-2019	9	South	50.1	31.0
02-05-2019	10	South	28.1	17.4
02-11-2019	12	South	63.3	39.1
03-10-2019	13, 14	South	292.2	180.3
03-15-2019	15	Tolna	142.6	88.0
03-16-2019	16	Tolna	166.3	102.6
03-17-2019	17, 18	Tolna	279.2	172.3
03-20-2019	19, 20	South	336.2	207.5
03-21-2019	21, 22	South	262.9	162.3
03-22-2019	23, 24	South	346.3	213.8
03-23-2019	25, 26	South	260.1	160.5
		Total	3103.1	1915.5

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 Spiritwood South data set the average height was 32.54 m with a minimum of 16.0 m and a maximum of 118.9 m and in the Tolna AEM data set the average was 30.7 m with a minimum of 22.7 m and a maximum of 49.9 m. A map of the system flight heights for the Spiritwood South and Tolna areas are presented in Figure 4-3 and Figure 4-4, respectively.

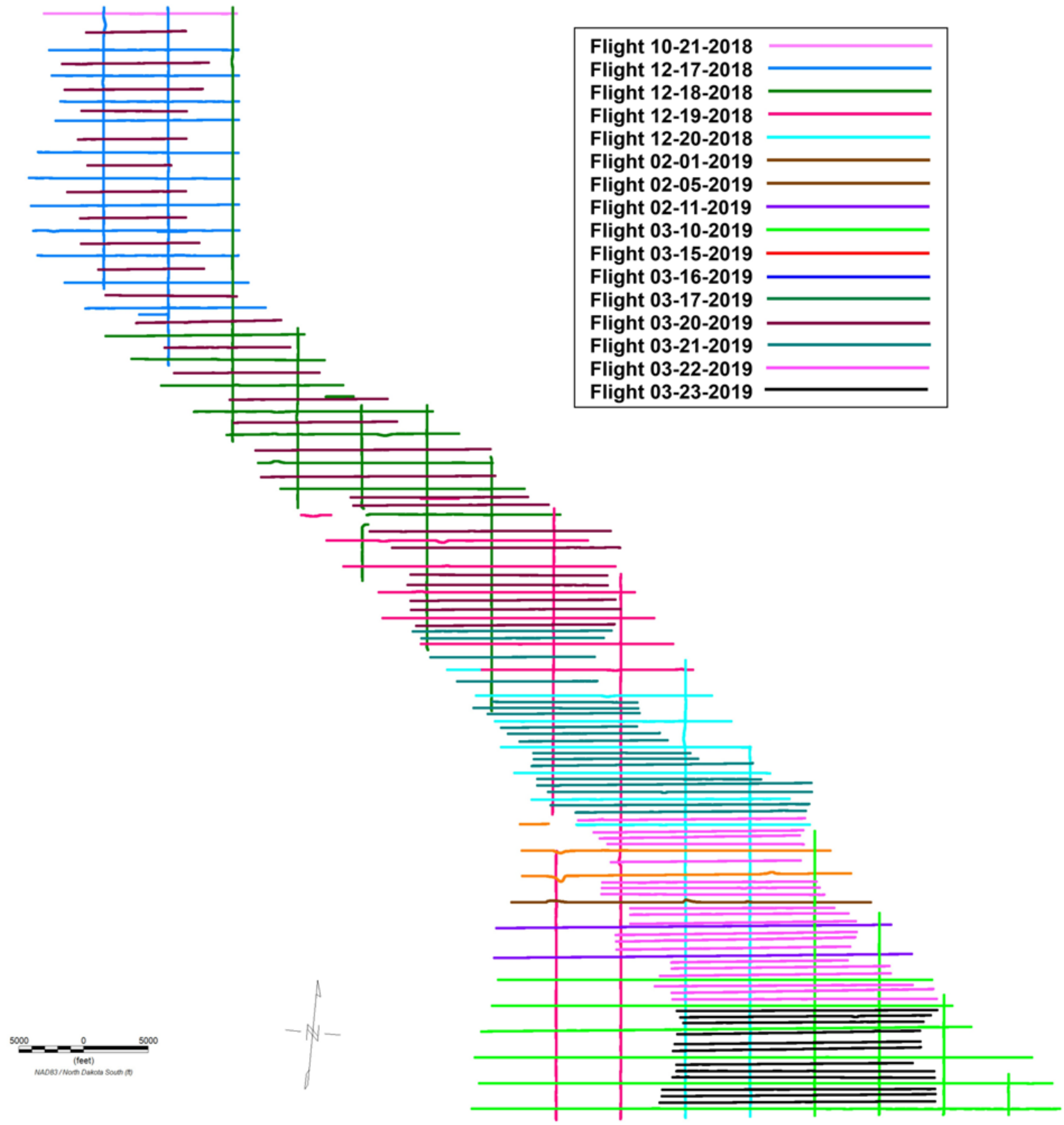


Figure 4-1. As-Flown map showing timing of the NDSWC Spiritwood South AEM survey data acquisition.

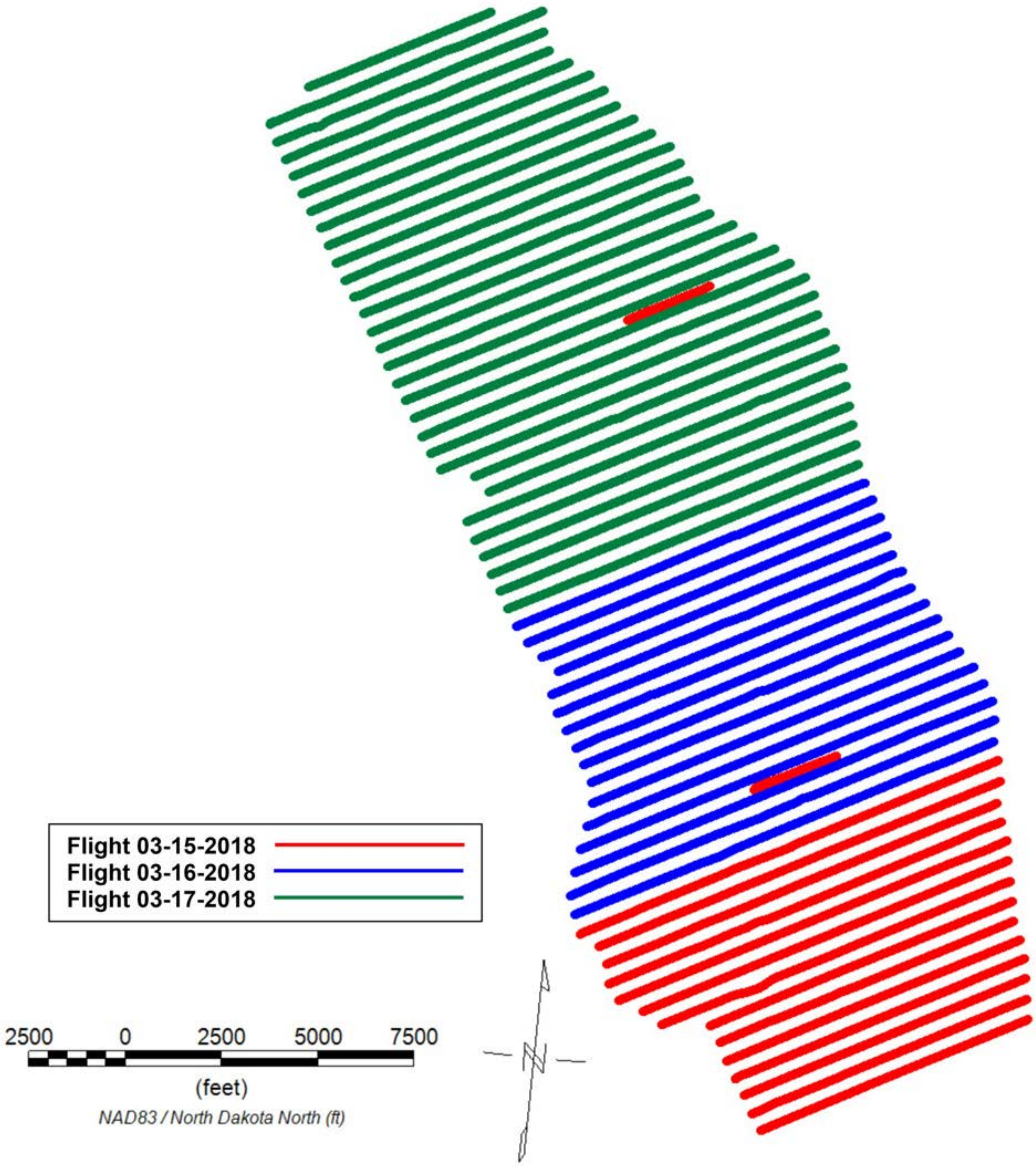


Figure 4-2. As Flown map showing timing of the NDSWC Tolna AEM survey data acquisition.

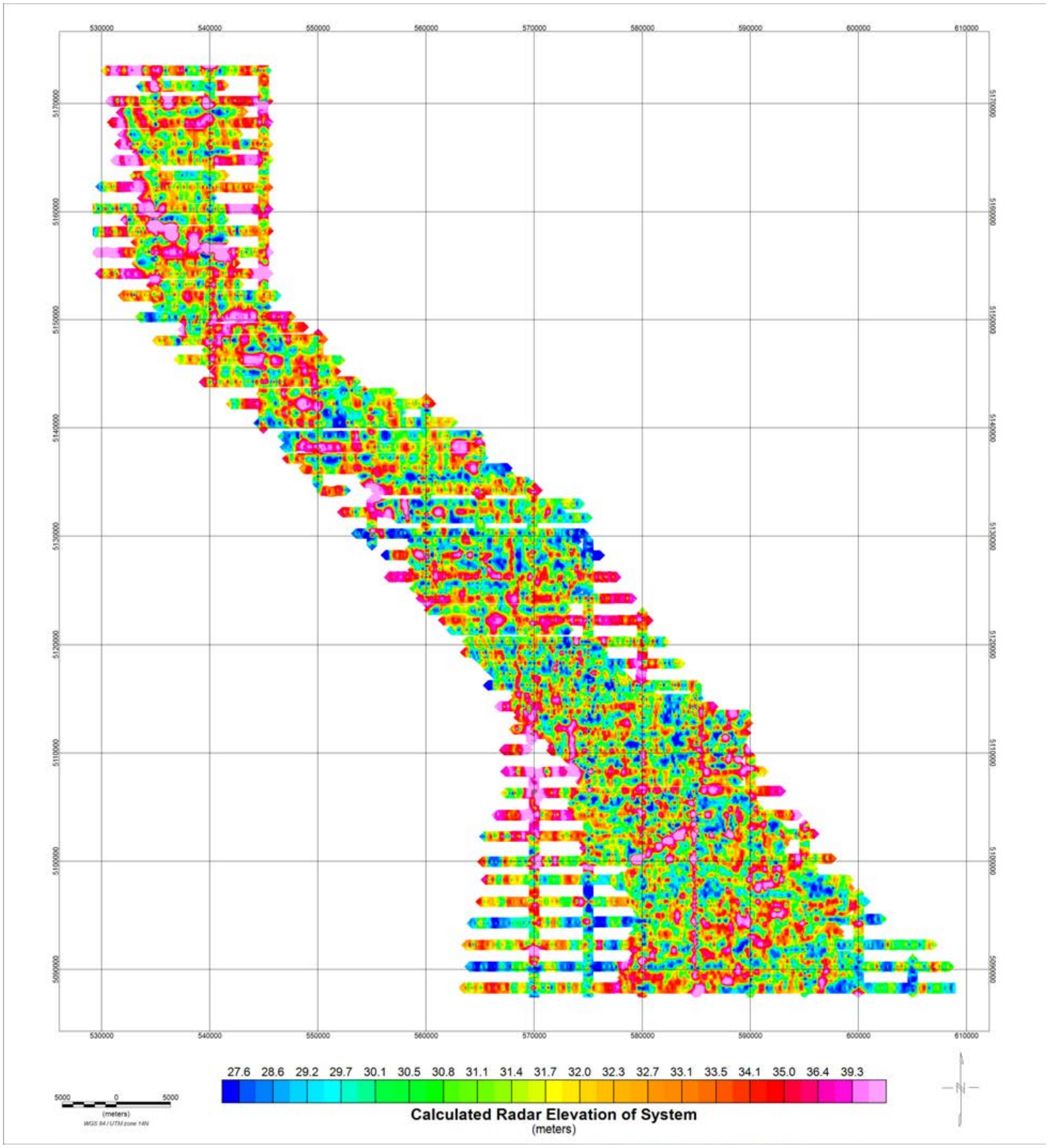


Figure 4-3. Map of the system height recorded during the NDSWC Spiritwood South AEM survey.

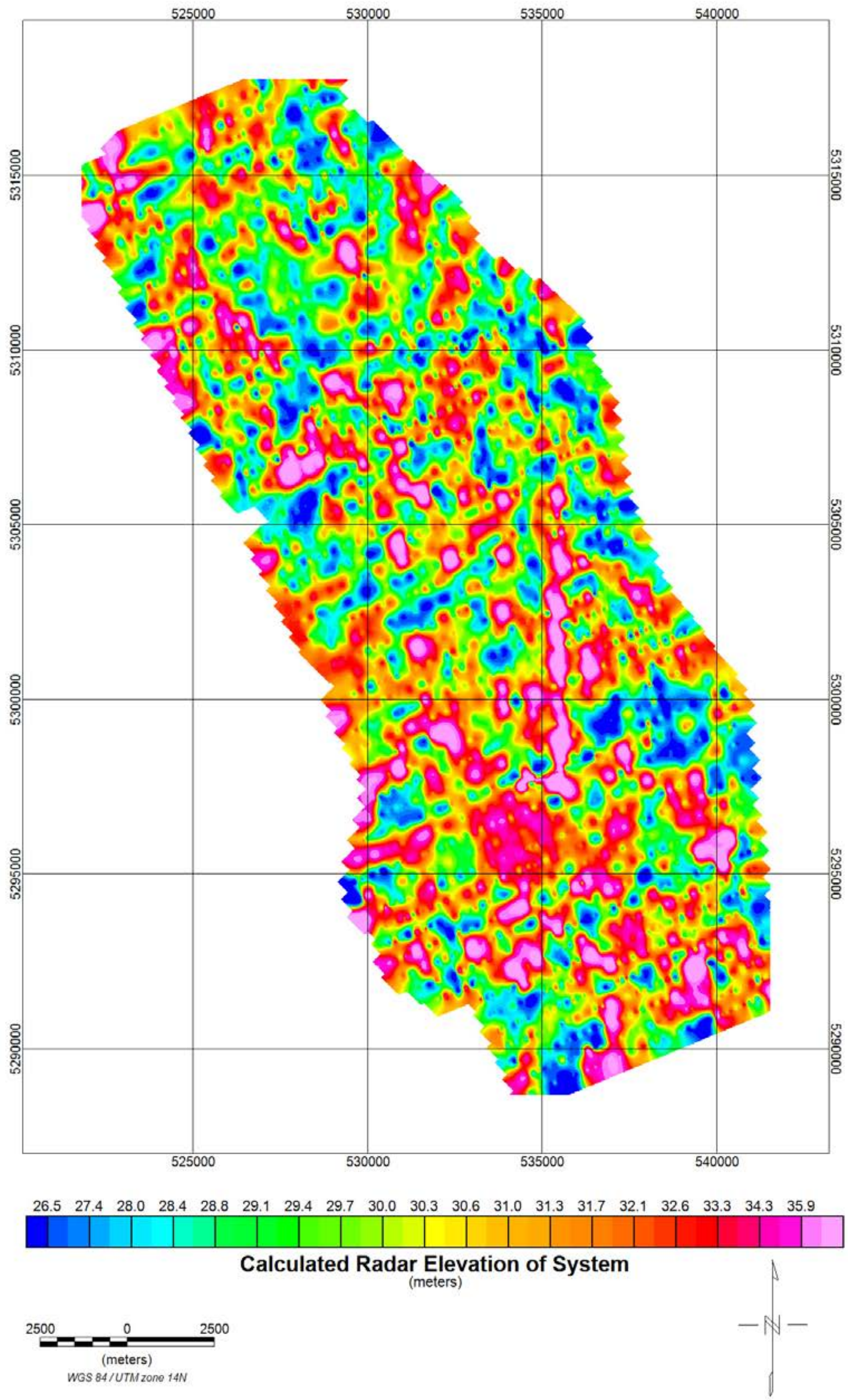


Figure 4-4. Map of the system height recorded during the NDSWC Tolna AEM survey.

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 Spiritwood South AEM survey is presented in Figure 4-5 and for the Tolna area in Figure 4-6.

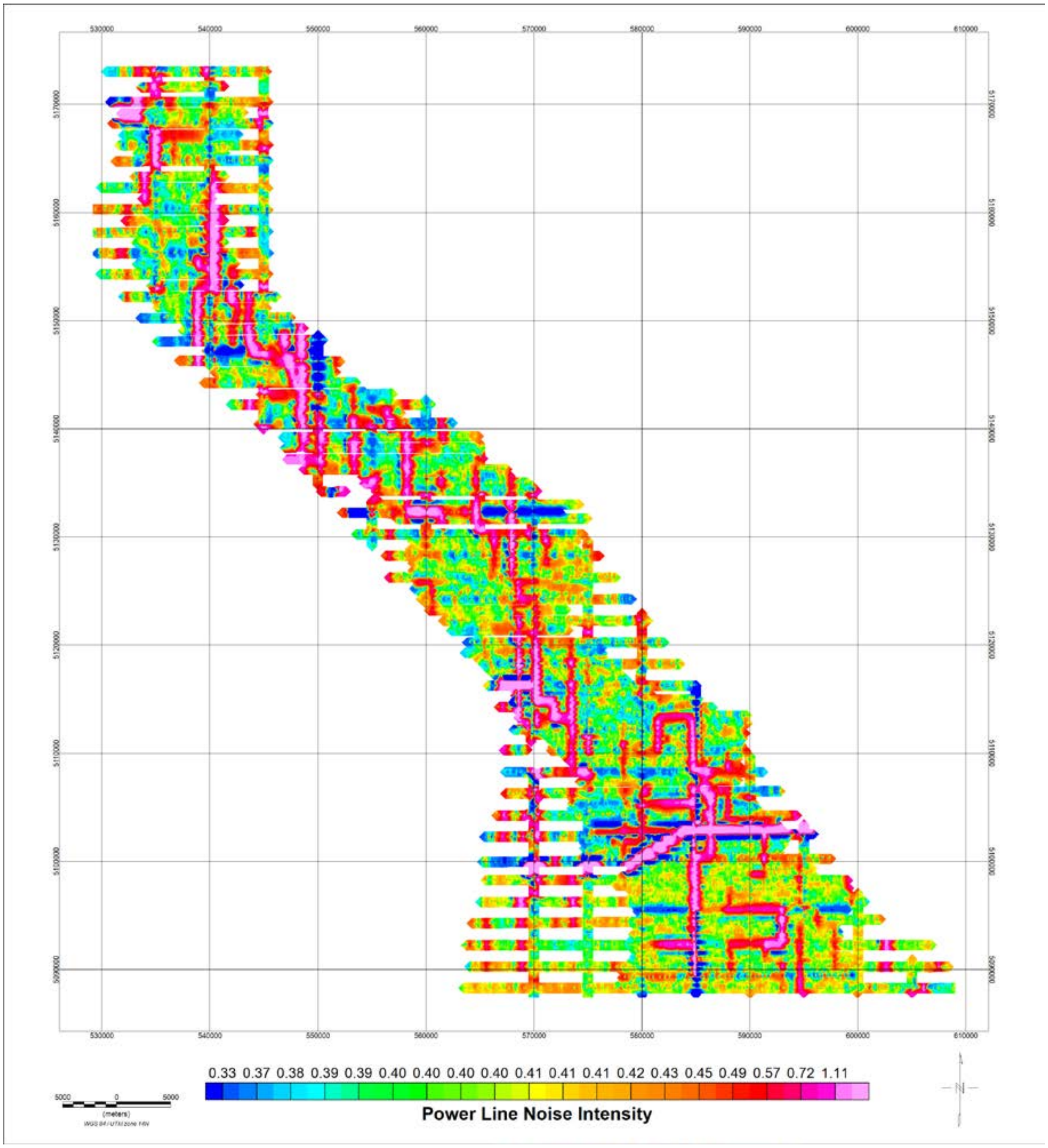


Figure 4-5. Power Line Monitor (PLM) intensity for the NDSWC Spiritwood South AEM survey area.

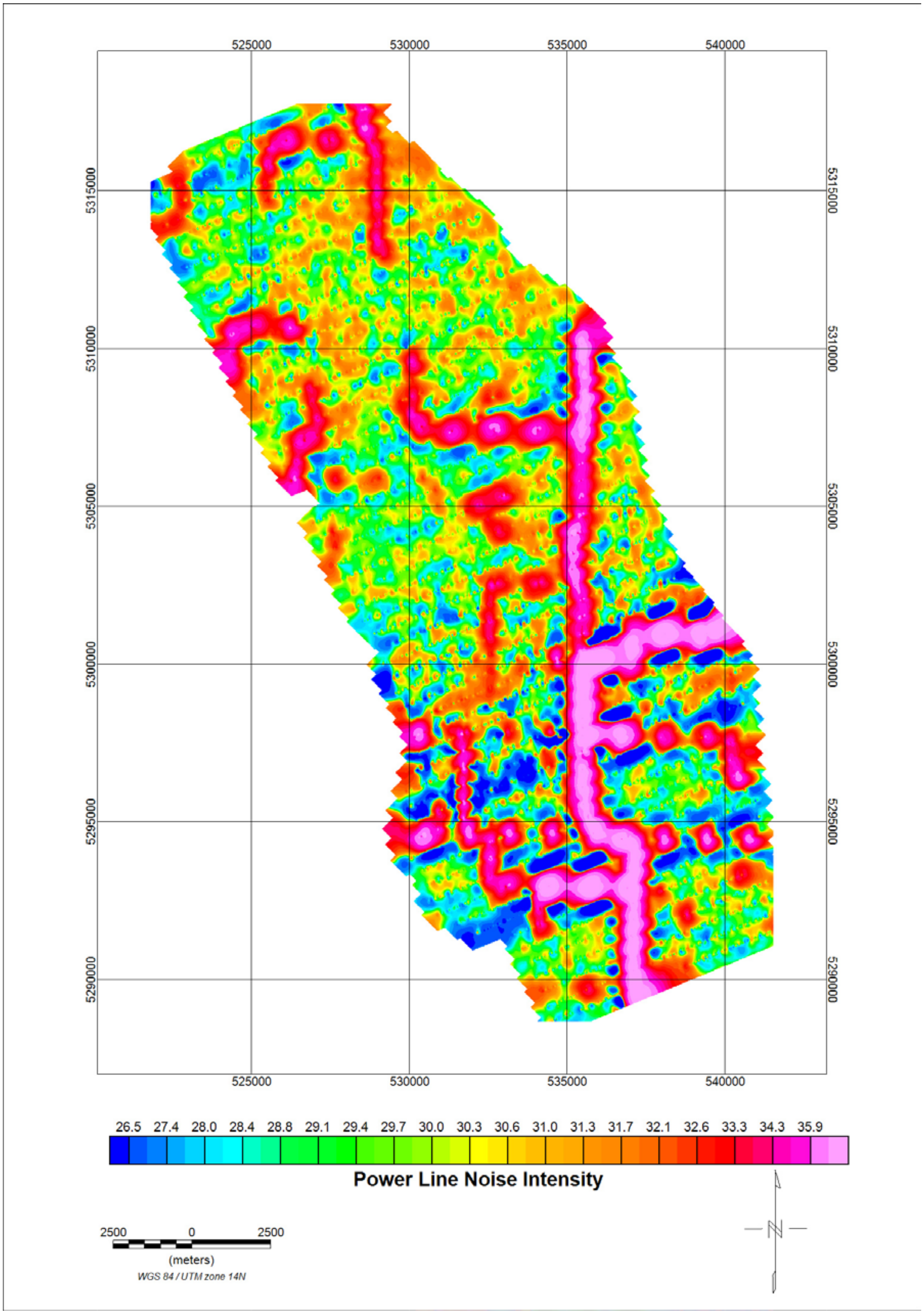


Figure 4-6. Power Line Monitor (PLM) intensity for the NDSWC Tolna AEM survey area.

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 Spiritwood South or Tolna AEM survey areas. 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 magnetic Total Field signal in the area of the NDSWC Spiritwood South survey area is presented in Figure 4-7. And for the Tolna AEM survey area in Figure 4-8. Both geological structure and cultural features can be identified within the survey area, but the signal is dominated by the complex basement features.

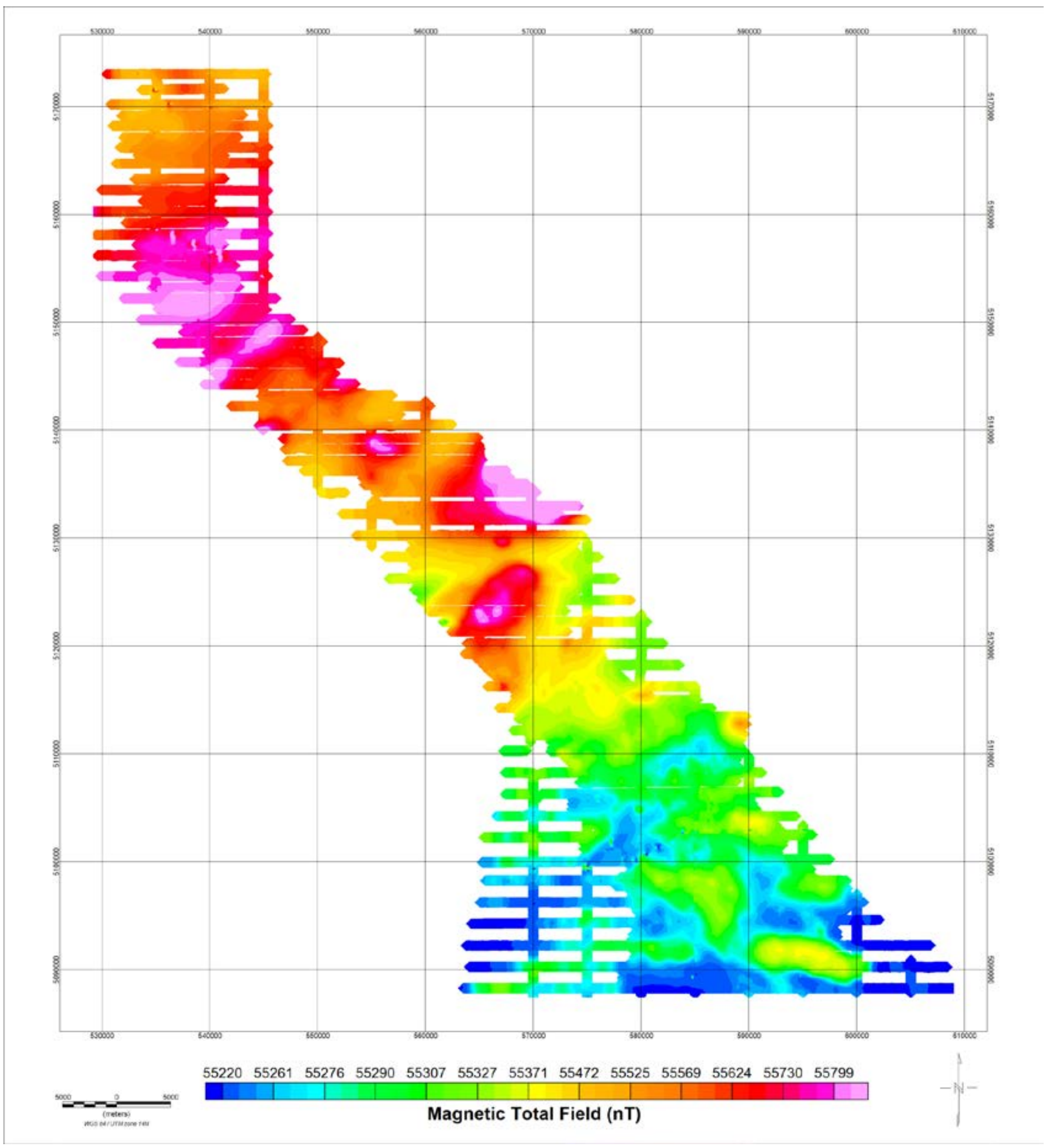


Figure 4-7. Magnetic Total Field for the NDSWC Spiritwood South AEM survey area.

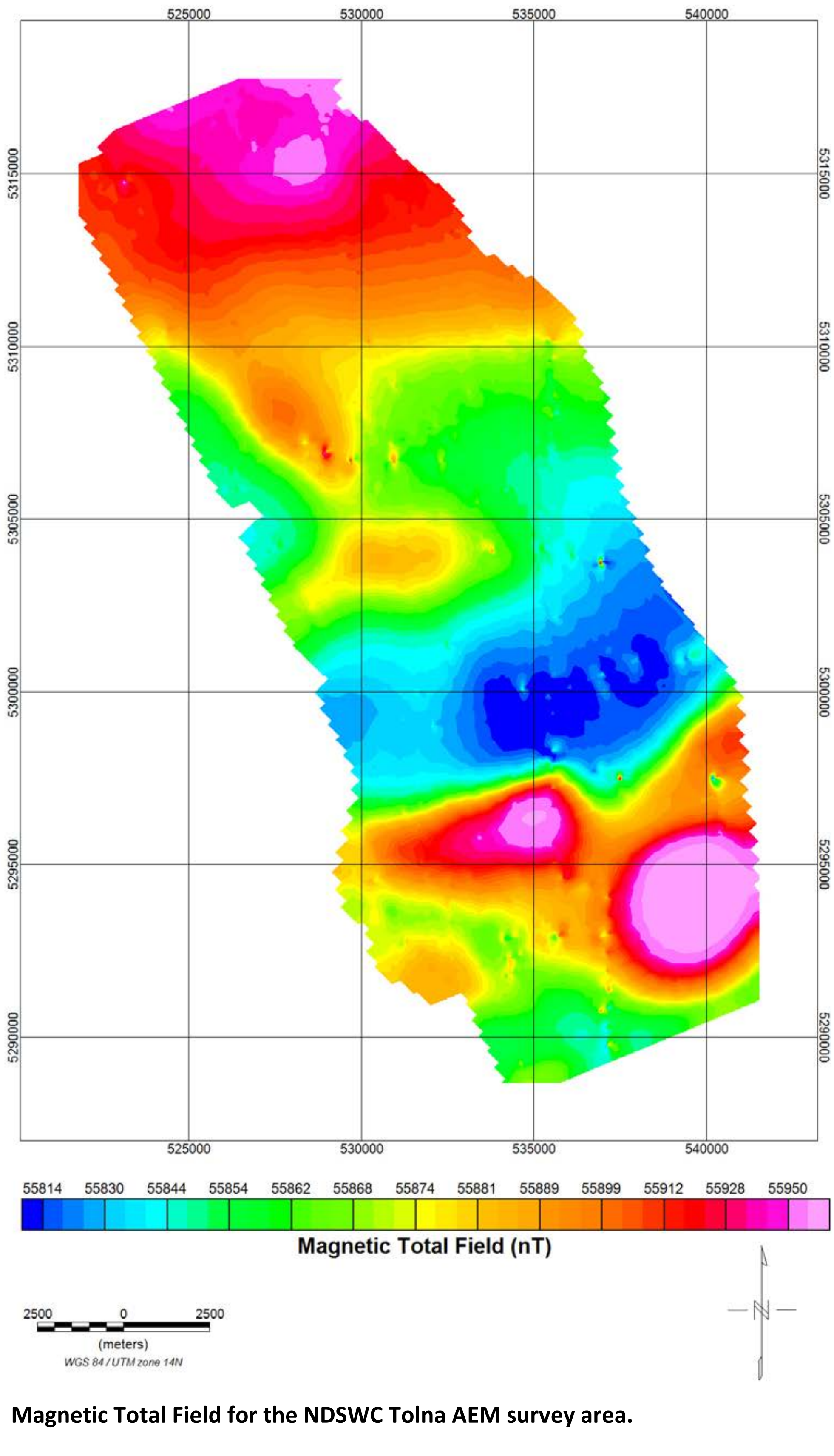


Figure 4-8. Magnetic Total Field for the NDSWC Tolna AEM survey area.

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 5.8.3 (Aarhus Geosoftware, 2019)

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-ET 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 20 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 55 m (180 ft) above the ground surface which caused a decrease in the signal level. These high areas usually only occurred around infrastructure that would cause coupling and had little impact on the overall survey.

The AEM data were then inverted using a Laterally-Constrained Inversion (LCI) algorithm (Aarhus Geosoftware, 2019). 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	657.0	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

6. Spatially-Constrained Inversions

Following the initial EM decoupling and LCI analysis and then the releveling analysis performed by Geotech, the Spiritwood South and Tolna AEM data were again processed and edited to remove power line effects. This resulted in about 2,276 line-km (1,405 line-miles) of data retained for inversion for the Spiritwood South AEM area and 533 line-km (328 line-miles) of data retained for inversion for the Tolna AEM area. This amounts to a retention rate of about 90.9% for the Spiritwood South AEM area and a 91.1% retention rate for the Tolna AEM survey area. A visual image of a comparison of the as flown data for the Spiritwood South area to the data retained for the SCI inversions is presented in Figure 6-1. A similar image of the data retained for inversion is presented in Figure 6-2 for the Tolna AEM survey area.

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 40 layers, each with a starting resistivity of 5 ohm-m (equivalent to a 5 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 about 1.08 (Table 5-1). The depths to the bottoms of the 39^{th} layers were set to 1,024 ft (312 m), with thicknesses up to about 55 ft (17 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 328 ft (100 m) with a power law fall-off of 0.75. The vertical and lateral constraints, ***ResVerSTD*** and ***ResLatStD***, were set to 2.4 and 1.4, 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 6-3 presents a histogram of the Spiritwood South AEM SCI inversion data/model residuals and Figure 6-4 presents a histogram of the Tolna AEM SCI inversion data/model residuals. A Google Earth map of the SCI data residuals for the Spiritwood South AEM study area is presented in Figure 6-5 and a similar image of the data/model residuals for the Tolna AEM study area is presented in Figure 6-6.

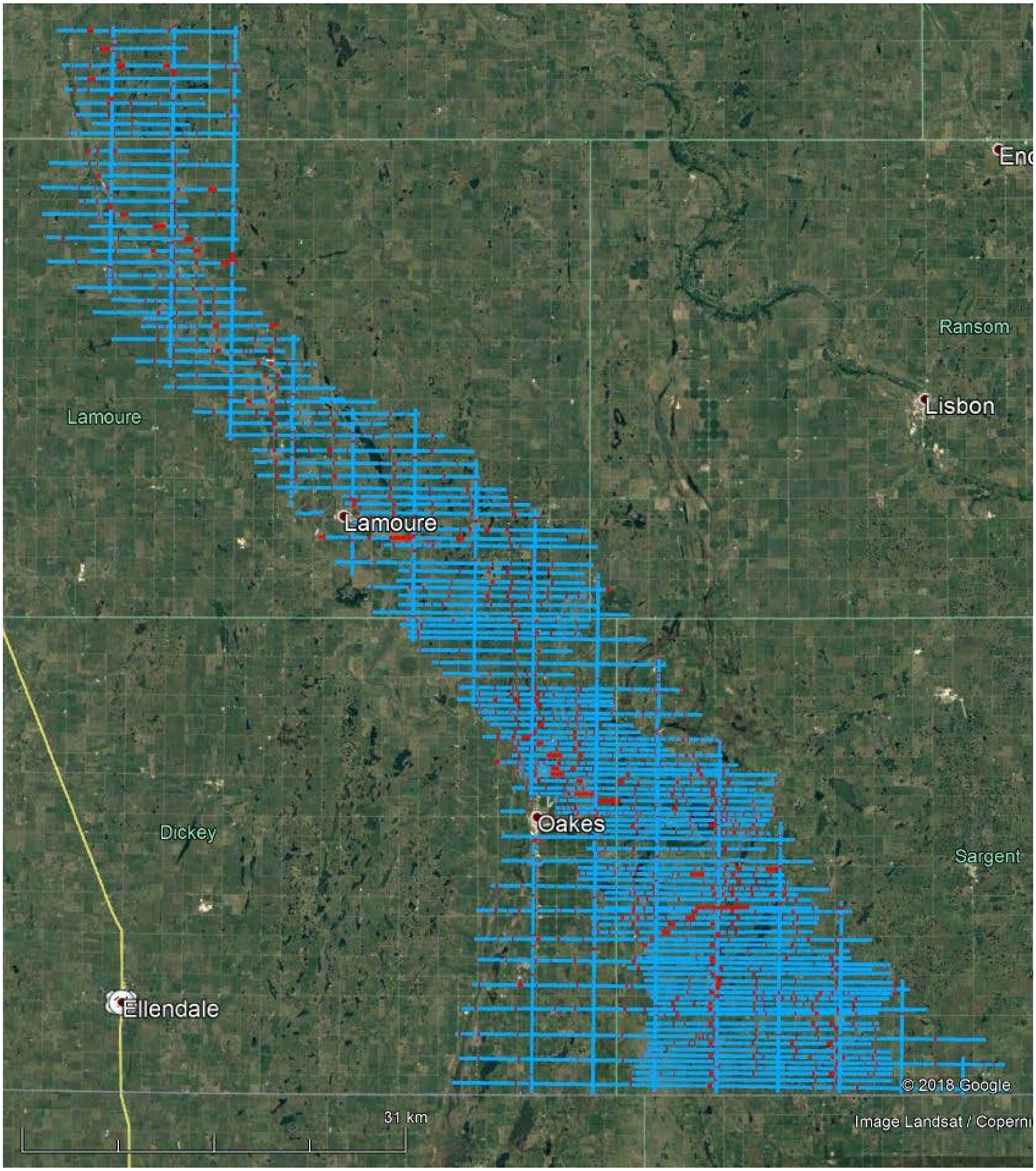


Figure 6-1. Comparison of the acquired data (red) versus the final retained data (blue) for the NDSWC Spiritwood South AEM survey area Final SCI inversion. This kmz is included in Appendix 3 Deliverables\KMZ.

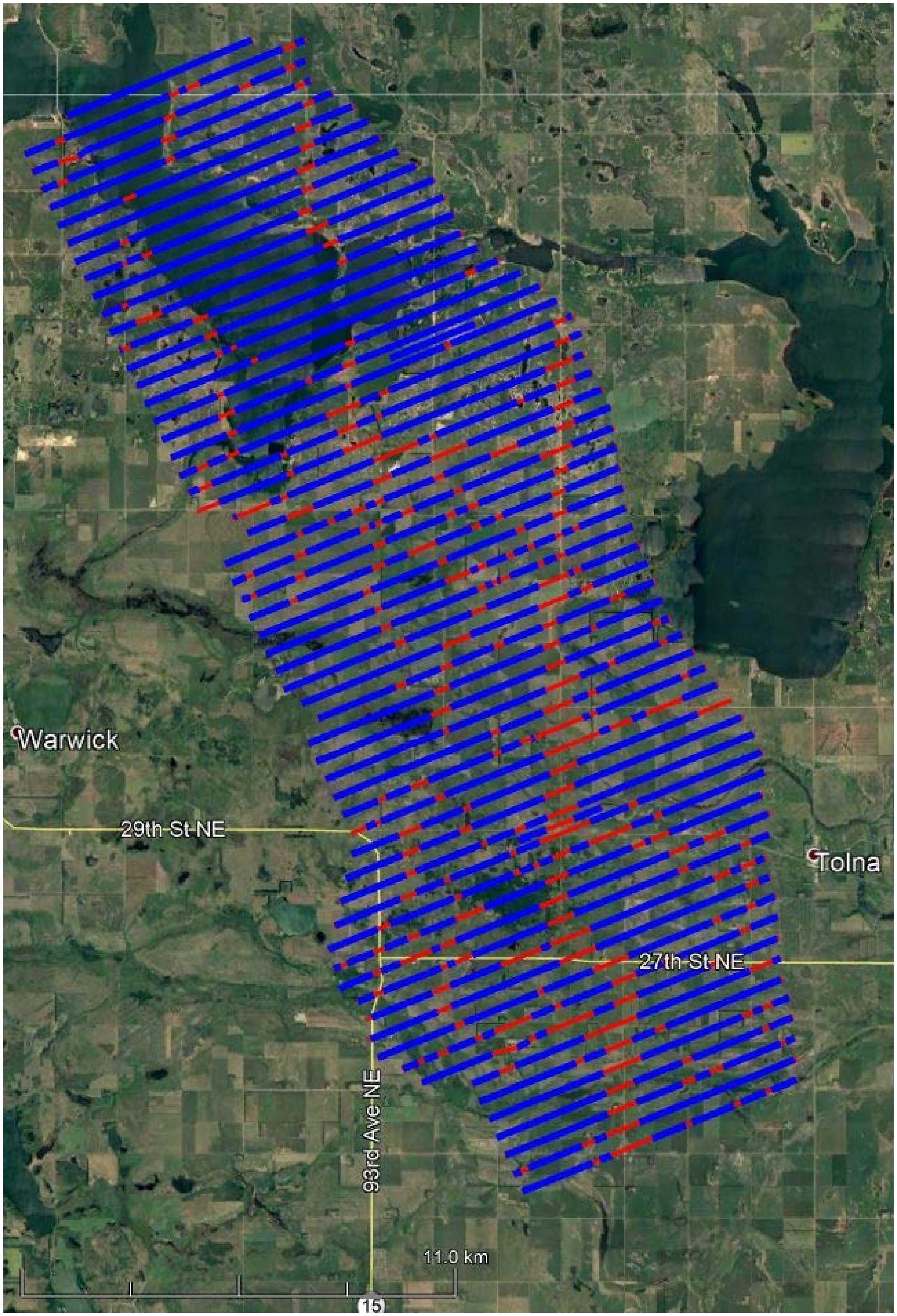


Figure 6-2. Comparison of the acquired data (red) versus the final retained data (blue) for the NDSWC Tolna AEM survey area Final SCI inversion. This kmz is included in Appendix 3 Deliverables\KMZ.

Table 6-1. Thickness and depth to bottom for each layer in the 40-layer Spatially-Constrained Inversion (SCI) 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	21	336.3	24.3
2	20.0	10.2	22	361.6	25.3
3	30.8	10.8	23	388.1	26.6
4	42.0	11.2	24	416.0	27.9
5	53.8	11.8	25	444.9	28.9
6	66.3	12.5	26	475.1	30.2
7	79.1	12.8	27	506.9	31.8
8	92.5	13.5	28	540.1	33.1
9	106.6	14.1	29	574.8	34.8
10	121.4	14.8	30	611.3	36.4
11	136.8	15.4	31	649.3	38.1
12	152.9	16.1	32	689.0	39.7
13	169.6	16.7	33	730.7	41.7
14	187.3	17.7	34	774.3	43.6
15	205.7	18.4	35	819.9	45.6
16	225.1	19.4	36	867.5	47.6
17	245.4	20.3	37	917.4	49.9
18	266.7	21.3	38	969.5	52.2
19	288.7	22.0	39	1024.0	54.5
20	312.0	23.3	40	Infinite	Infinite

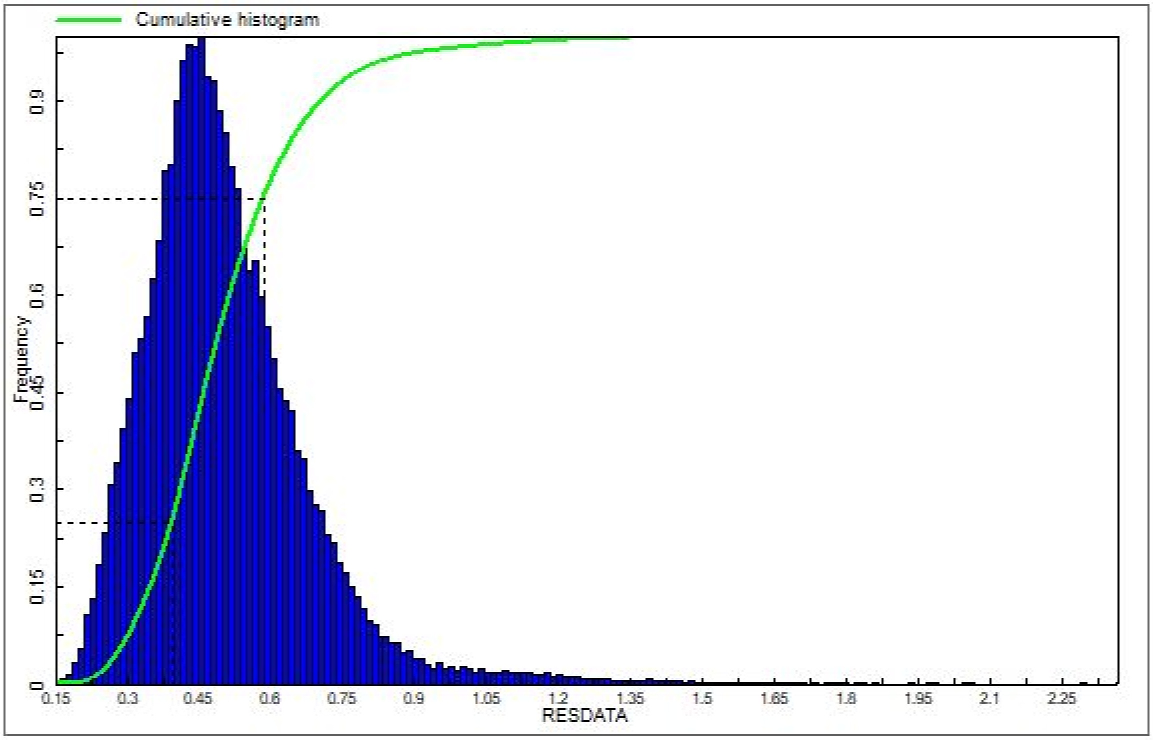


Figure 6-3. Data/model residual histogram for the NDSWC Spiritwood South SCI inversion results.

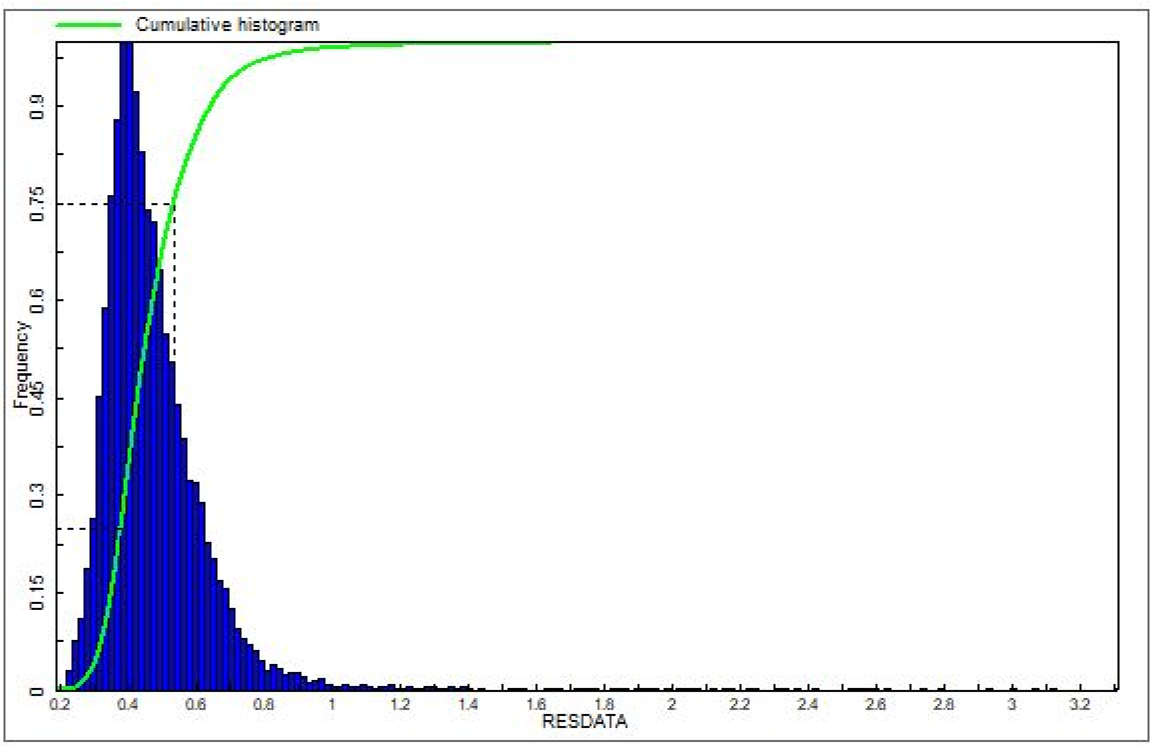


Figure 6-4. Data/model residual histogram for the NDSWC Tolna SCI inversion results.

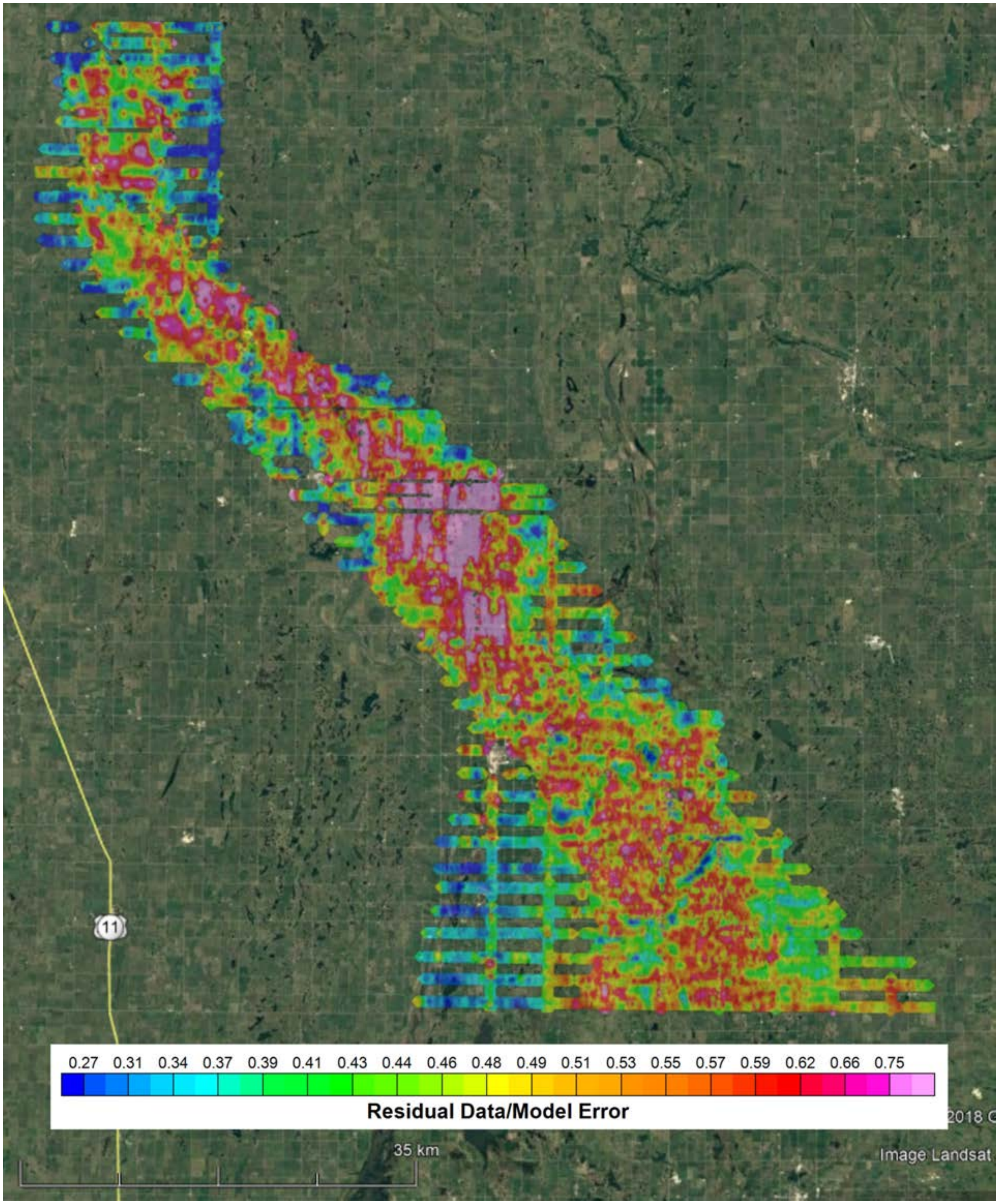


Figure 6-5. Map of data residuals for the Spiritwood South AEM SCI inversion results plotted in Google Earth. These data are included as a Google Earth KMZ file in Appendix 3.

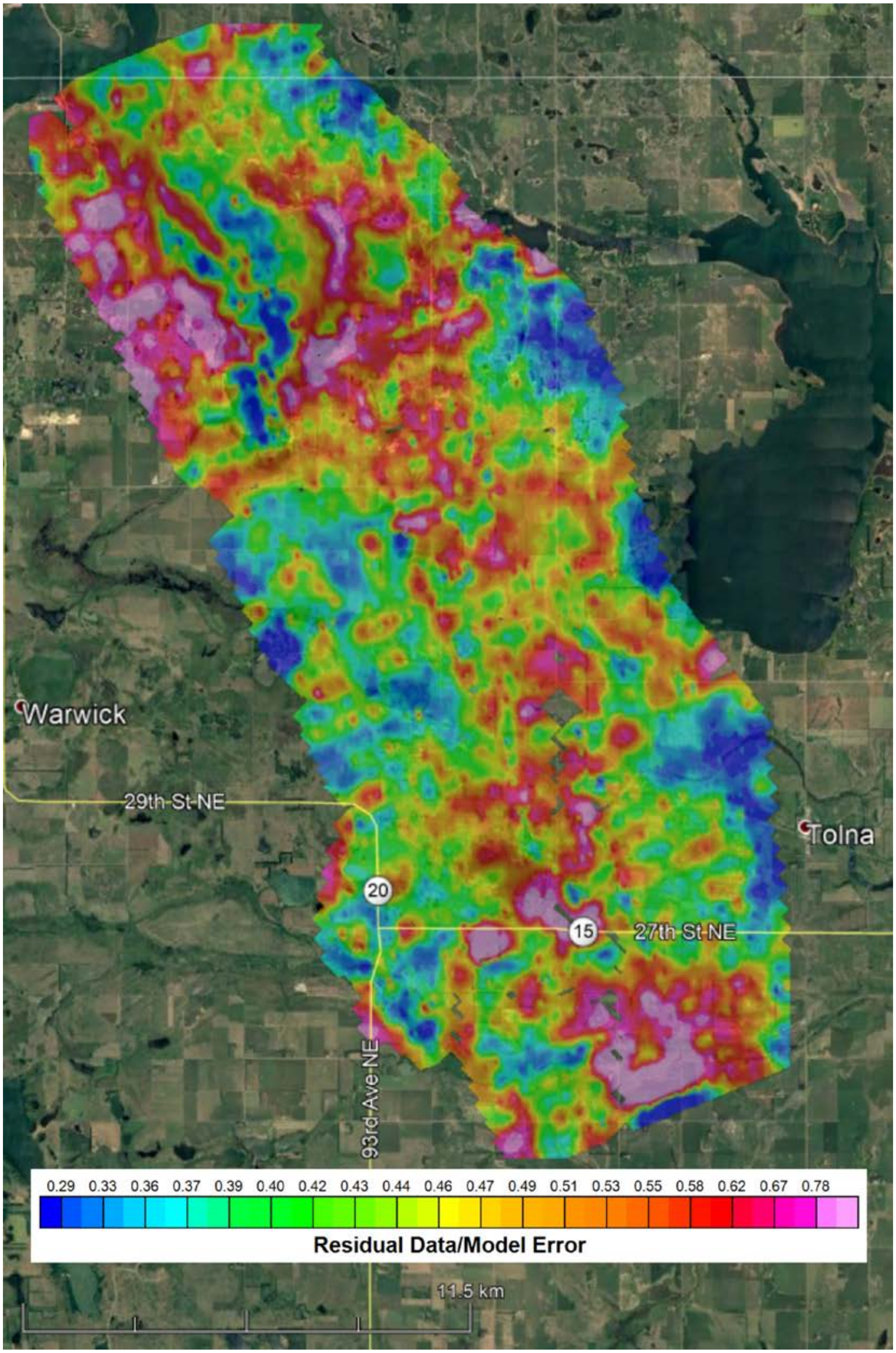


Figure 6-6. Map of data residuals for the Tolna AEM SCI inversion results plotted in Google Earth. These data are included as a Google Earth KMZ file in Appendix 3.

7. Comparison of AEM Inversion Results to Boreholes

7.1 Merging Lines

After the inversion process several short lines and line segments were combined to form continuous lines within the Spiritwood South and Tolna AEM survey area. These merged lines allow for improved viewing and interpretation of the AEM inversions results. Table 7-1 lists the original lines and the new combined lines for the Spiritwood South survey area. Table 7-2 lists the original lines and the new combined lines for the Tolna survey area. For lines that have overlapping data (examples are the line extensions or the test lines), the overlapping regions of the flight lines were sorted in the dominant (east-west or north-south) line direction 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.

Table 7-1. Combination of flight lines within the Spiritwood South AEM Survey Area.

Original Source Lines	Direction	New Line
L1080, L20000, and L20001	East-West	L1085
L1191, and L1200	East-West	L1195
L1260, and L1261	East-West	L1265
L1320, and L1330	East-West	L1325
L5070, L5071, and L5080	North-South	L5075
L5110, and L5120	North-South	L5115
L6180, L20006, and L20007	East-West	L6185
L6740, and L6741	East-West	L6745
L20002, and L20003	(Test Line) East-West	L20010
L20004, and L20005	(Test Line) East-West	L20011

Table 7-2. Combination of flight lines within the Tolna AEM Survey Area.

Original Source Lines	Direction	New Line
L1000, and L1001	(Test Line) Northeast-Southwest	L1004
L1002, and L1003	(Test Line) Northeast-Southwest	L1005

7.2 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 Spiritwood South AEM survey area and for the Tolna AEM survey area. The data was downloaded from the National Elevation Dataset (NED) located at the National Map Website (U.S. Geological Survey, 2018) at a resolution of 1 arc-second or approximately 100 ft. The geographic coordinates for the Spiritwood South survey area 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 geographic coordinates for the Tolna survey area are in North American Datum of 1983 (NAD83), State Plane North Dakota North (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 DEM products. Figure 7-1 is a map of the DEM of the NDSWC Spiritwood South AEM survey area showing a vertical relief of 253 ft with a minimum elevation of 1,259 ft and a maximum elevation of 1,512 ft. Figure 7-2 is a map of the DEM of the NDSWC Tolna AEM survey area showing a vertical relief of 135 ft with a minimum elevation of 1374 ft and a maximum elevation of 1,616 ft. These respective DEM's were used to reference all elevations within the survey areas. The Geosoft Binary Raster Grids (*.grd) and can be found in Appendix 3 Deliverables\Grids\ DEM - Geosoft_ND-SPS_Feet.

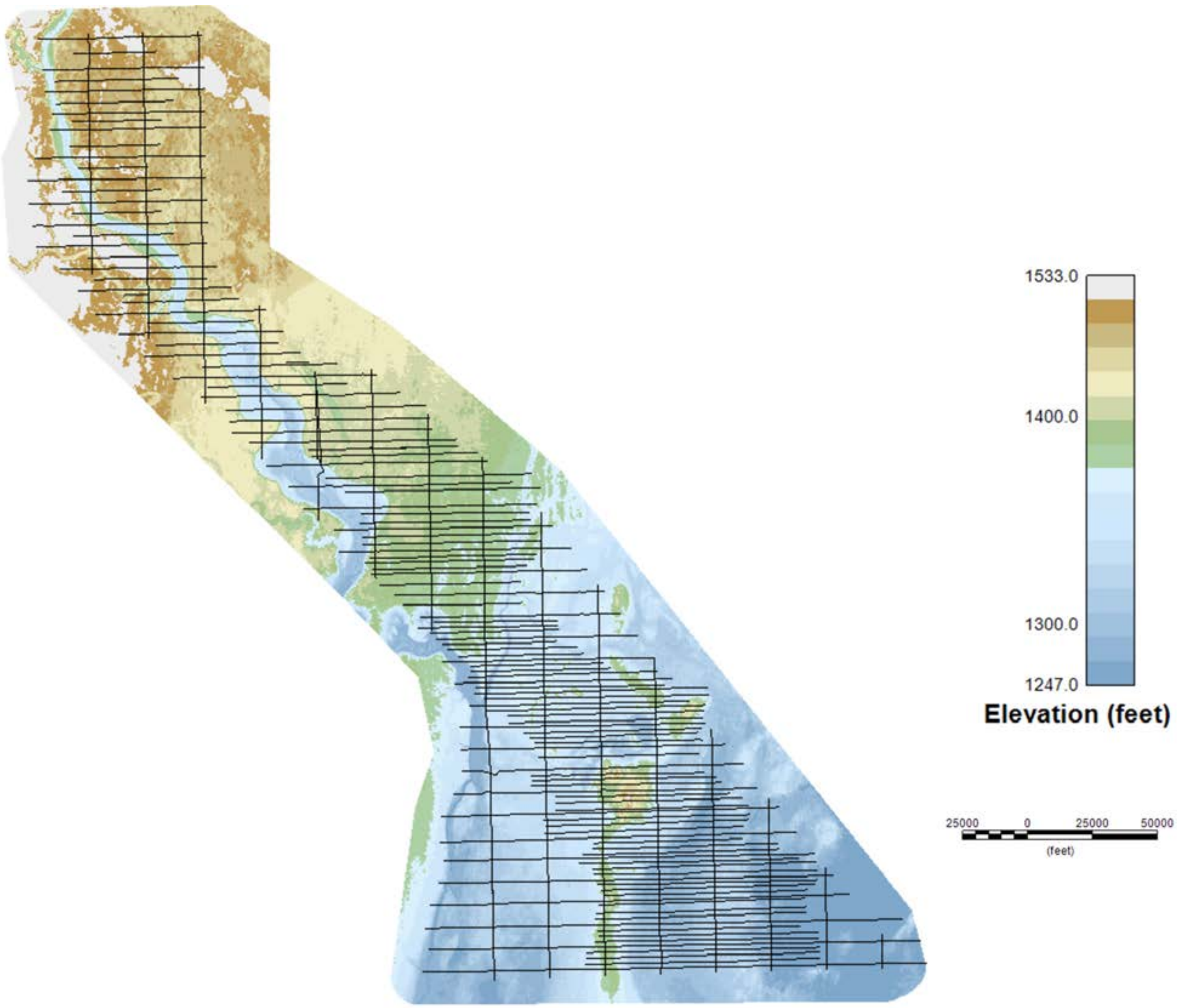


Figure 7-1. Digital elevation model (DEM) of the NDSWC Spiritwood South AEM survey area. Flight Lines are indicated by black lines.

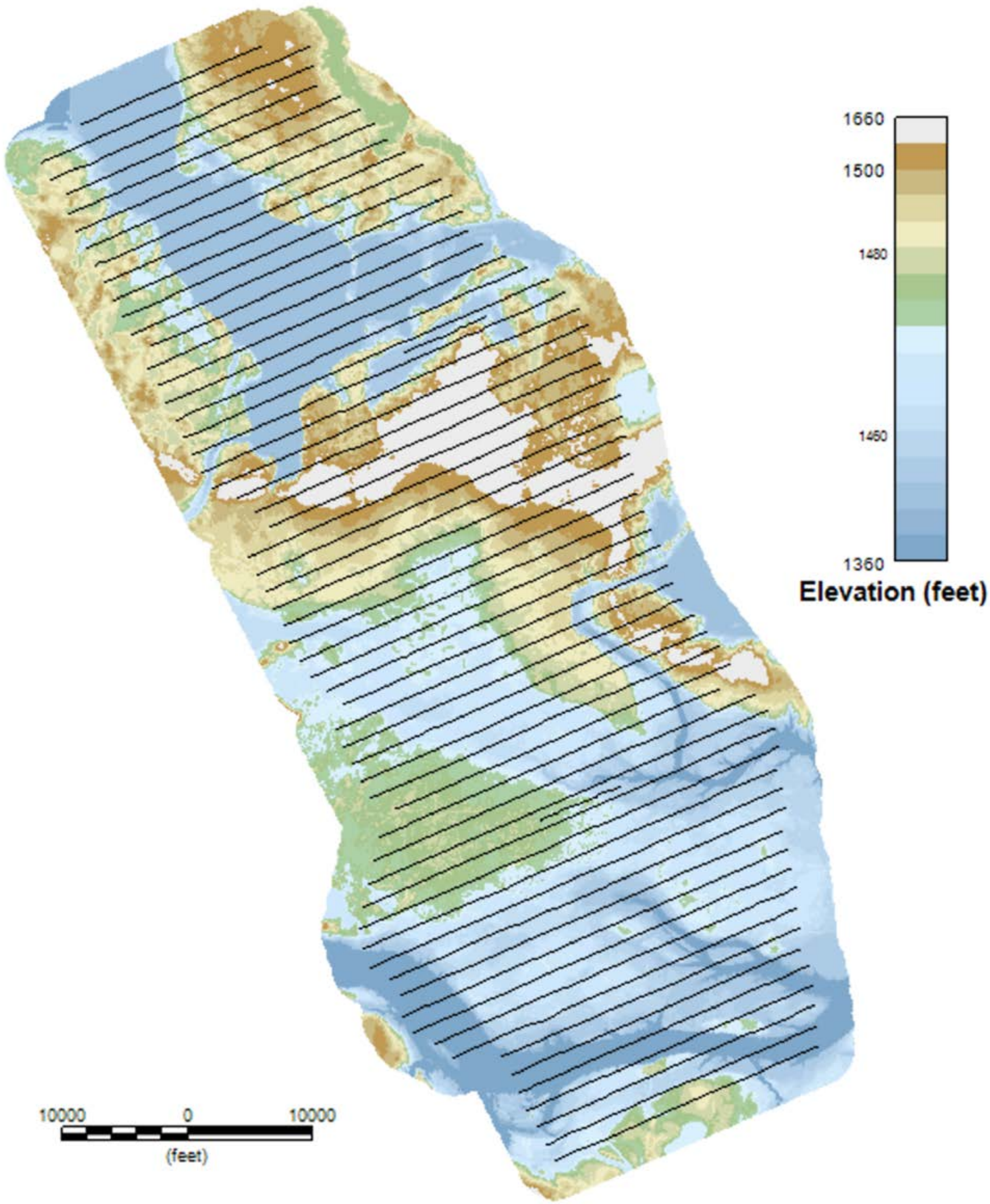


Figure 7-2. Digital elevation model (DEM) of the NDSWC Tolna AEM survey area. Flight Lines are indicated by black lines.

7.3 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, 2018). An example 2D-profile for line L1030 is presented in Figure 7-3. 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 upper right showing the location of the survey flight lines with the red line indicating the current profile being displayed. On the upper left is a flight path 2D map of the displayed profile on a background map with the land survey system indicated. The horizontal scale of the flight path map is exactly the same as the profile. The lower profile is the AEM SCI inverted resistivity (ohm-m) profile along with the lithology of the borehole if the borehole 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 50 ohm-m. 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.

The gray dashed lines, when visible, 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 7-4 is a map view of the lower DOI and upper DOI for the Spiritwood South AEM survey area. and Figure 7-5 is a map view of the lower DOI and upper DOI for the Tolna AEM survey area. The DOI reflects the bandwidth of the system, resistivity of the area, the system/ambient noise, and altitude of the sensor. Typically, in areas of more resistive materials the depth is greater.

3D fence diagrams were constructed using a vertical exaggeration of 1:15 of the geolocated profiles using a 10-50 ohm-m log color scale very similar to those used in the 2D Profiles. Figure 7-6 is a 3D fence diagram example of the NDSWC Spiritwood South AEM survey looking toward the north. Figure 7-7 is an 3D fence diagram example of the NDSWC Tolna AEM survey looking slightly toward the northwest. 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 are contained within Appendix 2 – 2D and 3D Images.

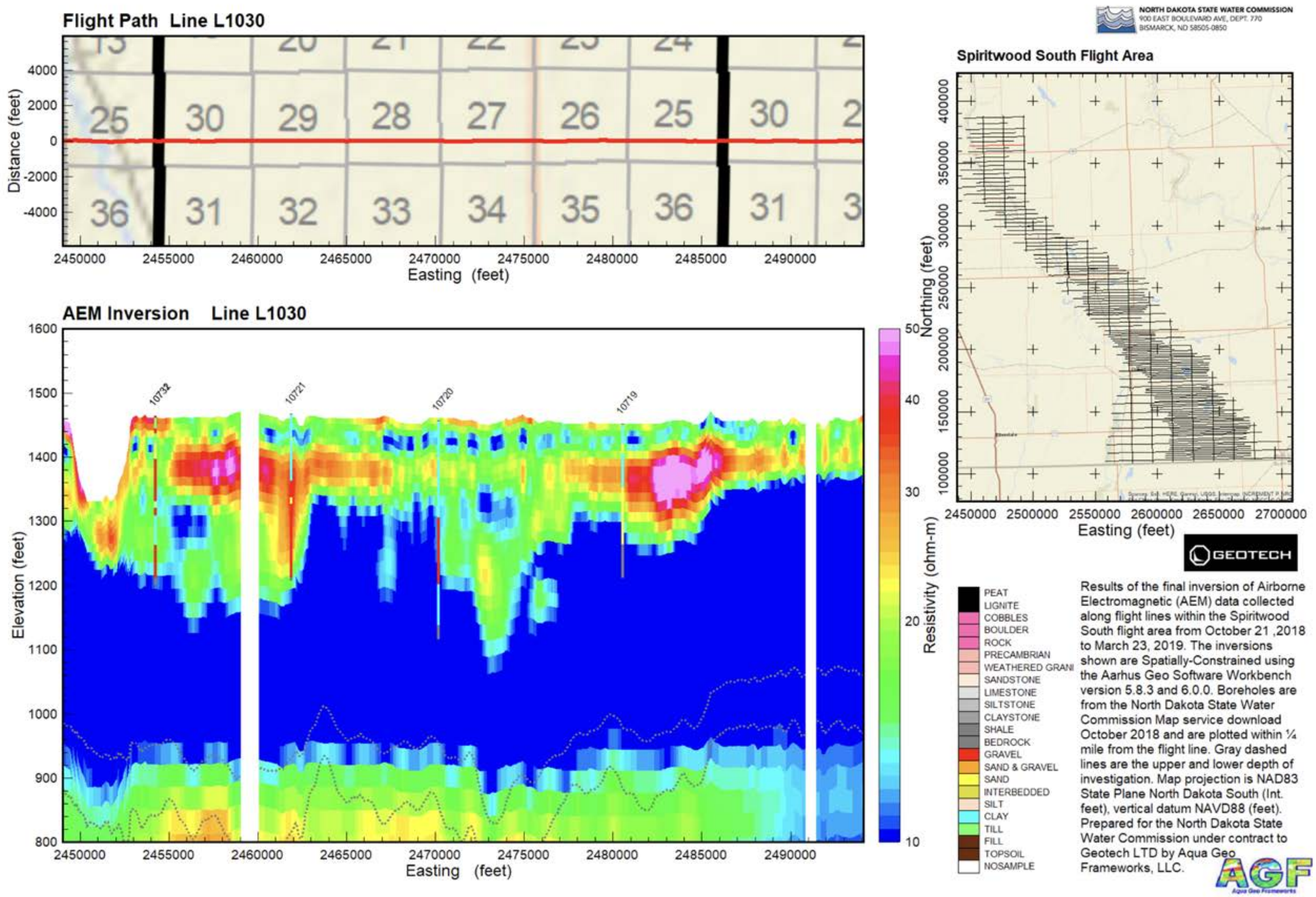


Figure 7-3. Example 2D profile displaying the results of the SCI inversion of NDSWC Spiritwood South AEM survey flight line L1030 including NDSWC borehole lithologies within ¼ mile of the flight line. The resistivity color scale is on the right side of the profile.

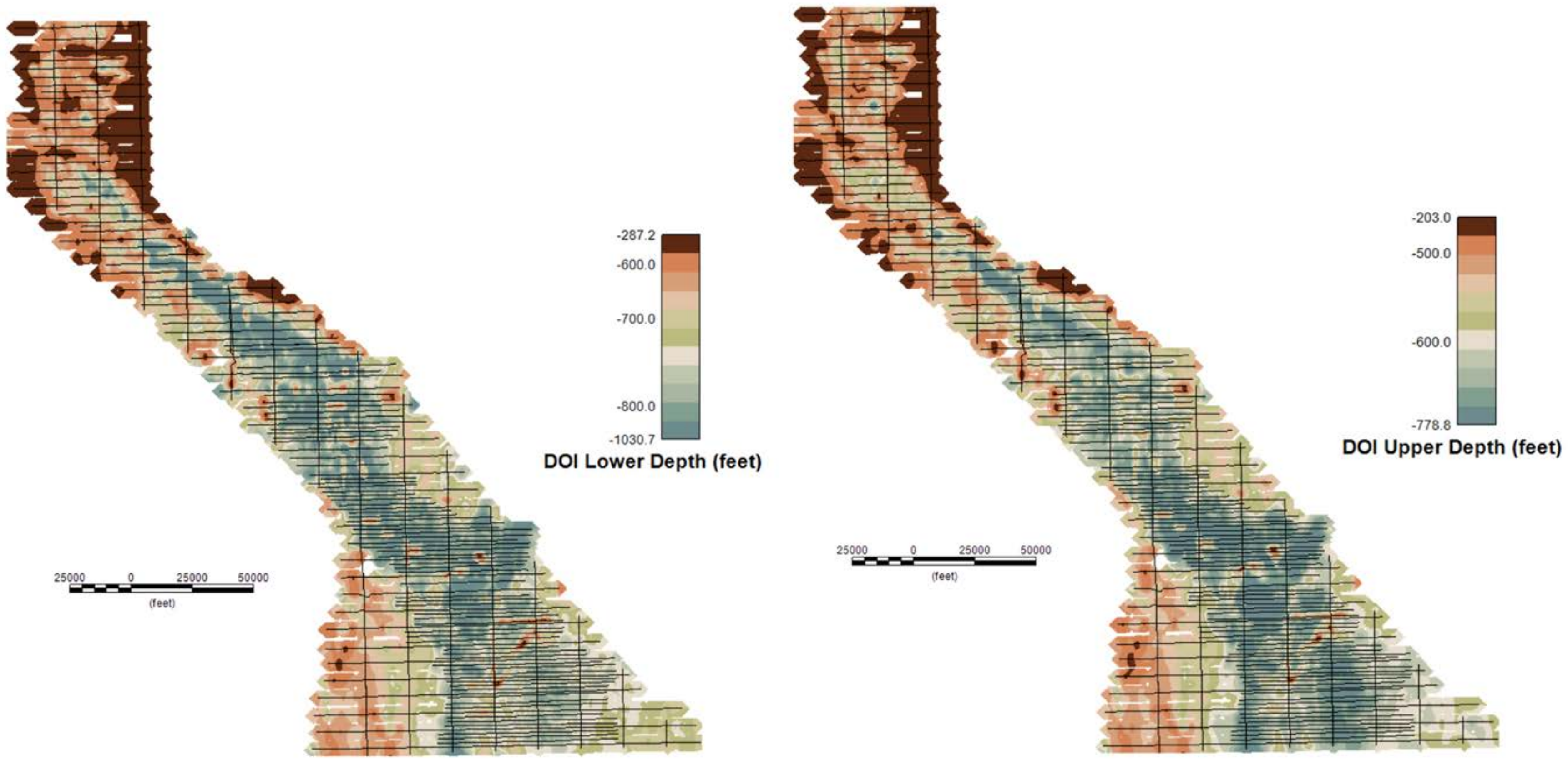


Figure 7-4. The Upper and Lower Depth of Investigation (DOI) of the NDSWC Spiritwood South AEM Spatially-Constrained Inversion (SCI). Flight Lines are indicated by black lines. Note that each image has its own color scale which is different from the other.

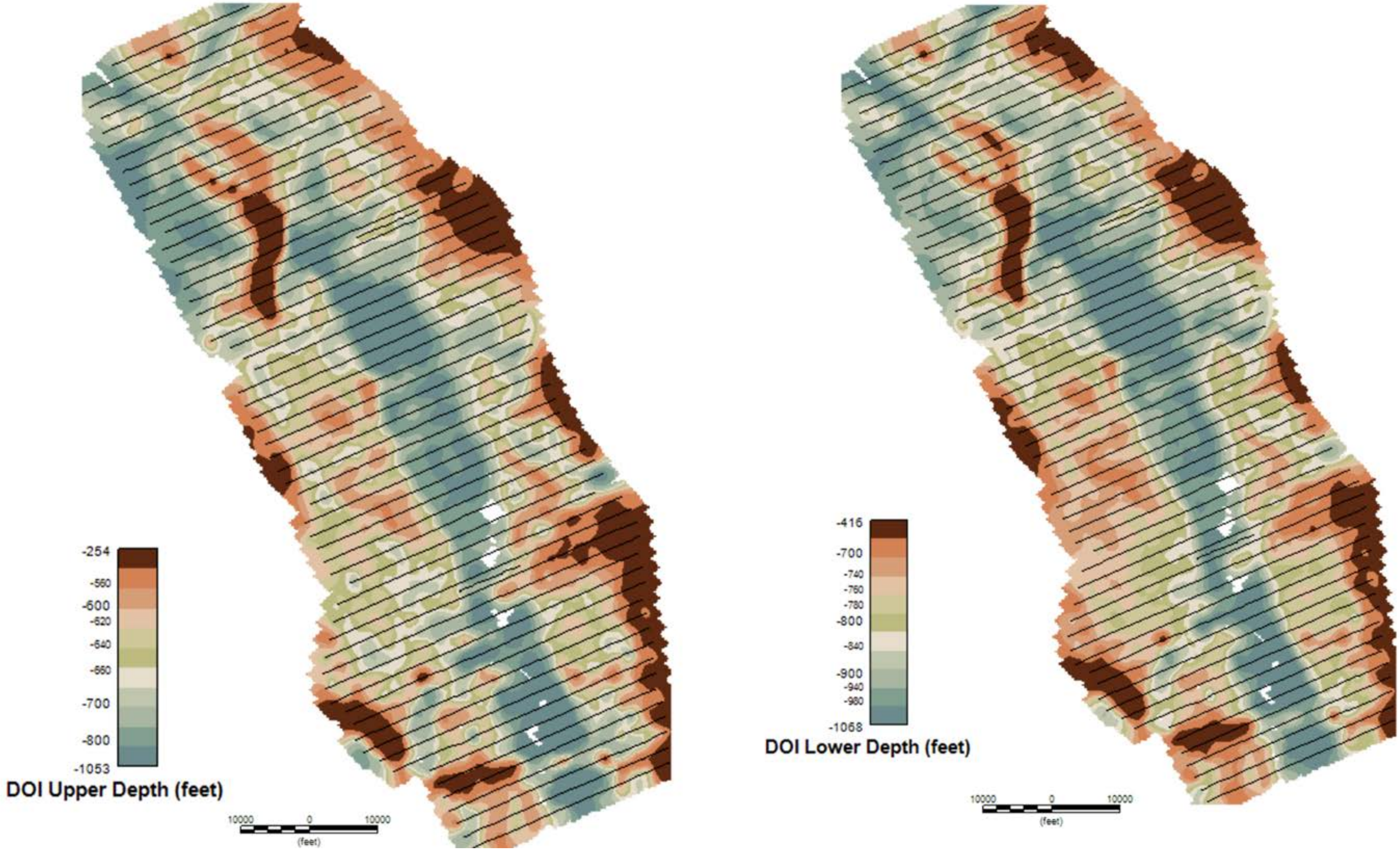


Figure 7-5. The Upper and Lower Depth of Investigation (DOI) of the NDSWC Tolna AEM Spatially-Constrained Inversion (SCI). Flight Lines are indicated by black lines. Note that each image has its own color scale which is different from the other.

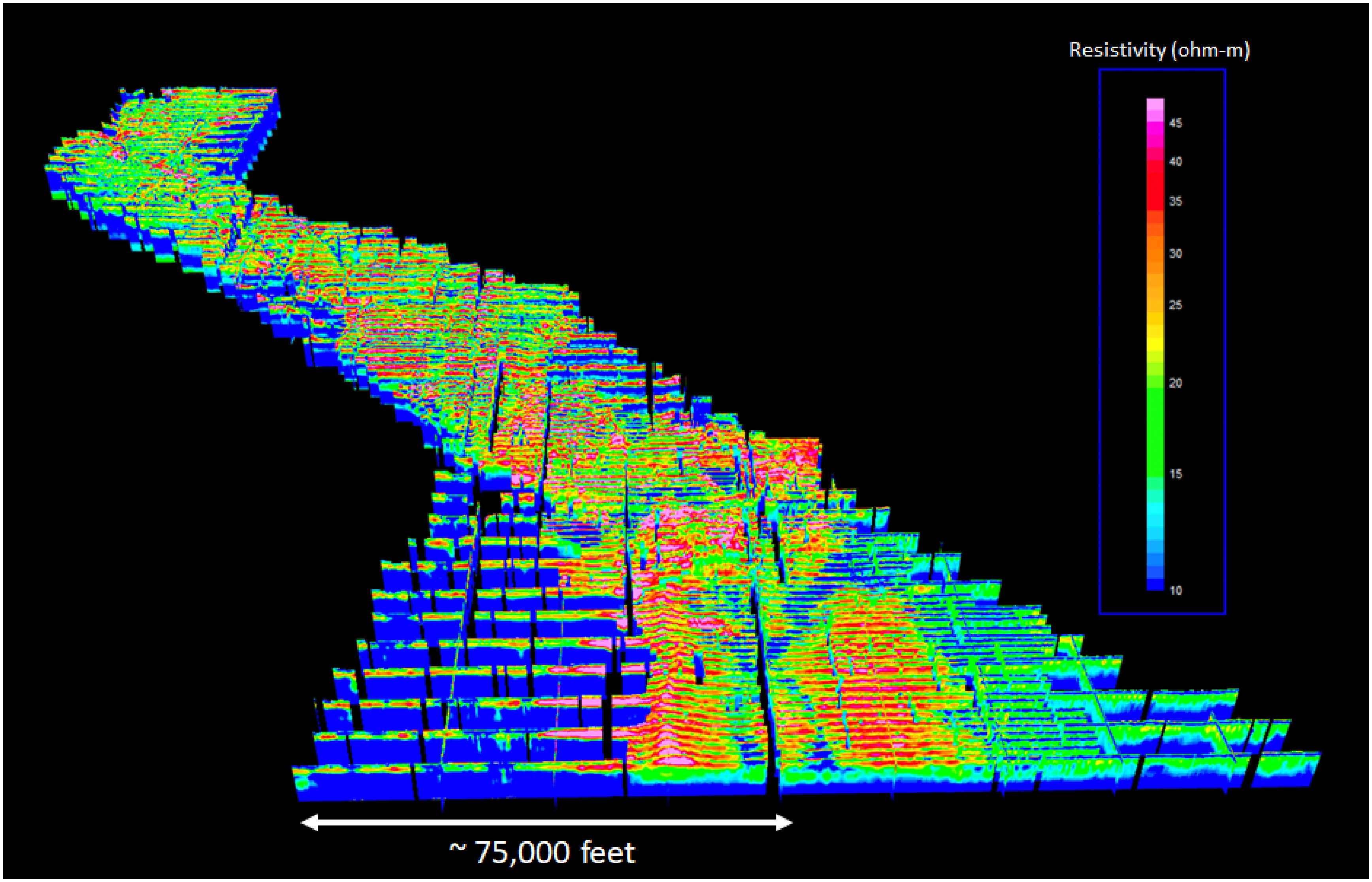


Figure 7-6 Example 3D fence diagram displaying the results of the NDSWC Spiritwood South AEM survey. The color scale is from 10-50 ohm-m, log-based. The view is to the north.

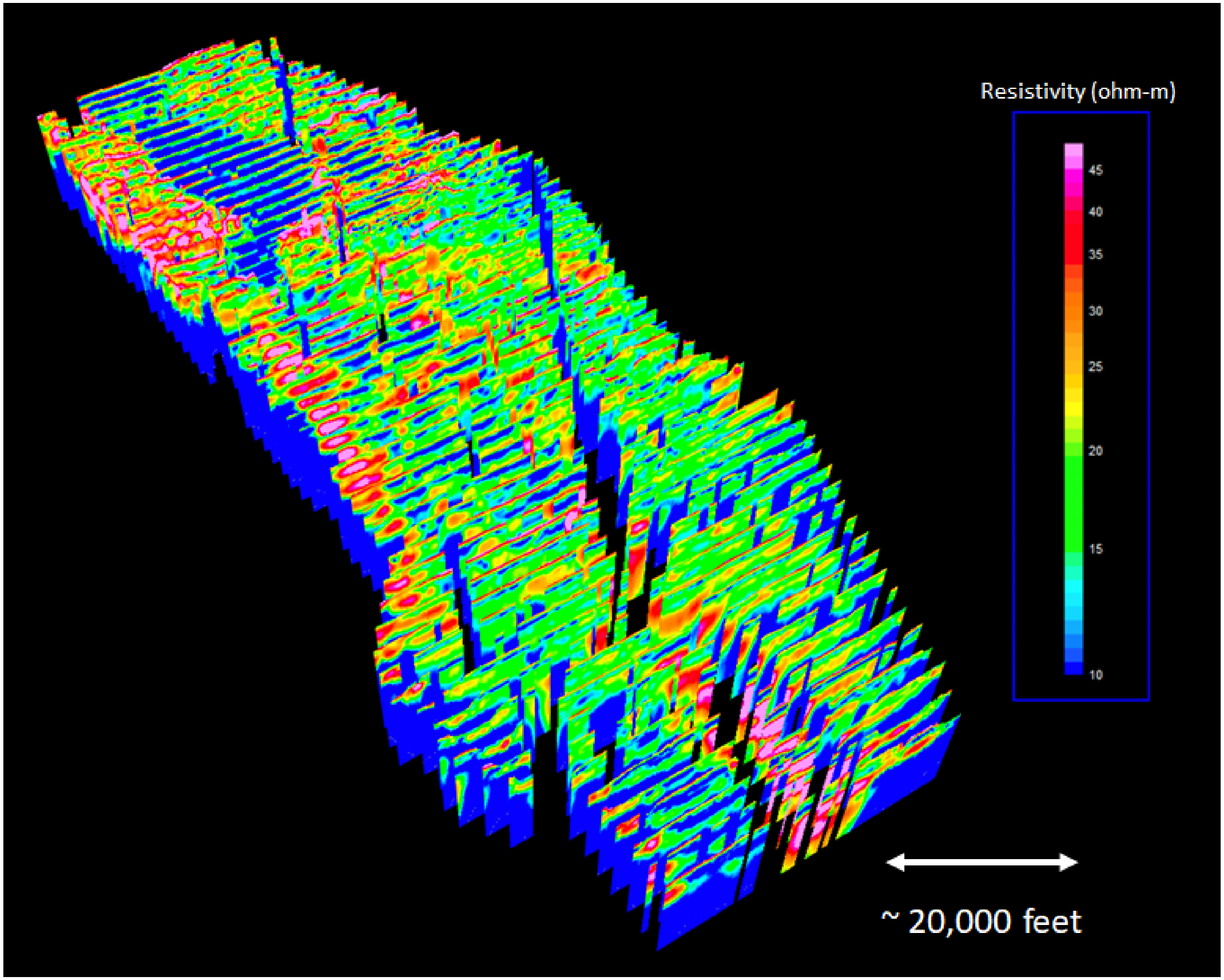


Figure 7-7. Example 3D fence diagram displaying the results of the NDSWC Tolna AEM survey. The color scale is from 10-50 ohm-m, log-based. The view is to the northeast.

7.4 Resistivity Depth Layers

Resistivity depth layers were created based on the SCI model cell spacing (Table 6-1) and were used to produce resistivity layer plots of the both AEM survey areas. 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 250 feet, a blanking distance of 500 feet was applied, and the "cells to extend beyond" set to 7 or 1,750 feet. All other parameters were either left as the default or blank. These layers are useful for inspecting the vertical changes in the resistivity. The color scale that was used for these maps was selected to illuminate the sands and gravels within the Quaternary section. Figure 7-8 is an example of a model depth layer 9, from -92.5ft to -106.6 ft from the Spiritwood South area. At this depth the basic fabric of the Quaternary sands and gravels are indicated by the high resistivities. Figure 7-9 is an example of a model depth layer 18, from –245.4 to -266.7 ft from the Tolna area. 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. The pdf files are located in Appendix 2 – 2D Surfaces. The grids of these layers can be found in Appendix 3 - Deliverables/Grids as well as layered pdf's in Appendix 2 – 2D Surfaces.

7.5 Voxel Grid

Voxel grids were developed for the NDSWC Spiritwood South and the Tolna AEM survey areas. The voxel grids were made using a 250ft grid cell size and the model layer thicknesses (Table 6-1). A minimum curvature method was used within Datamine Discover PA (Datamine Discover, 2018). The grid was allowed to interpolate to the extents of the survey with some areas of no data coverage due to EM coupling clipped from the grids. 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 Spiritwood South AEM survey there are three areas of resistive materials that are of interest. One is the resistive Quaternary sands and gravels in the northern area showing the discreet channelized deposits. The second area is the middle section that is dominated by a large resistive area. The third is a set of thinner resistive deposits in the southern area. Figure 7-10 is a 3D plot of the voxel for the NDSWC Spiritwood South AEM survey area with magnification of the three areas showing clipped grids to highlight the 25-50 ohm-m deposits. Figure 7-11 presents two 3D plots of the NDSWC Tolna AEM survey area voxel: (a) resistive material > 23 ohm-m on a fence diagram showing every second flight line; and a second image, (b), a 3D voxel looking northwest of the Tolna area showing the material > 23ohm-m excluding the first 10 feet with the low resistivity basement (< 10 ohm-m) set as transparent.

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. Layered PDF's of resistivities of model layers can also be found in Appendix 2 – 2D surfaces. ArcView Binary Raster Grids and the voxel as an ASCII xyz file are found in Appendix 3 - Deliverables in the \Grids and \Voxels folders, respectively.

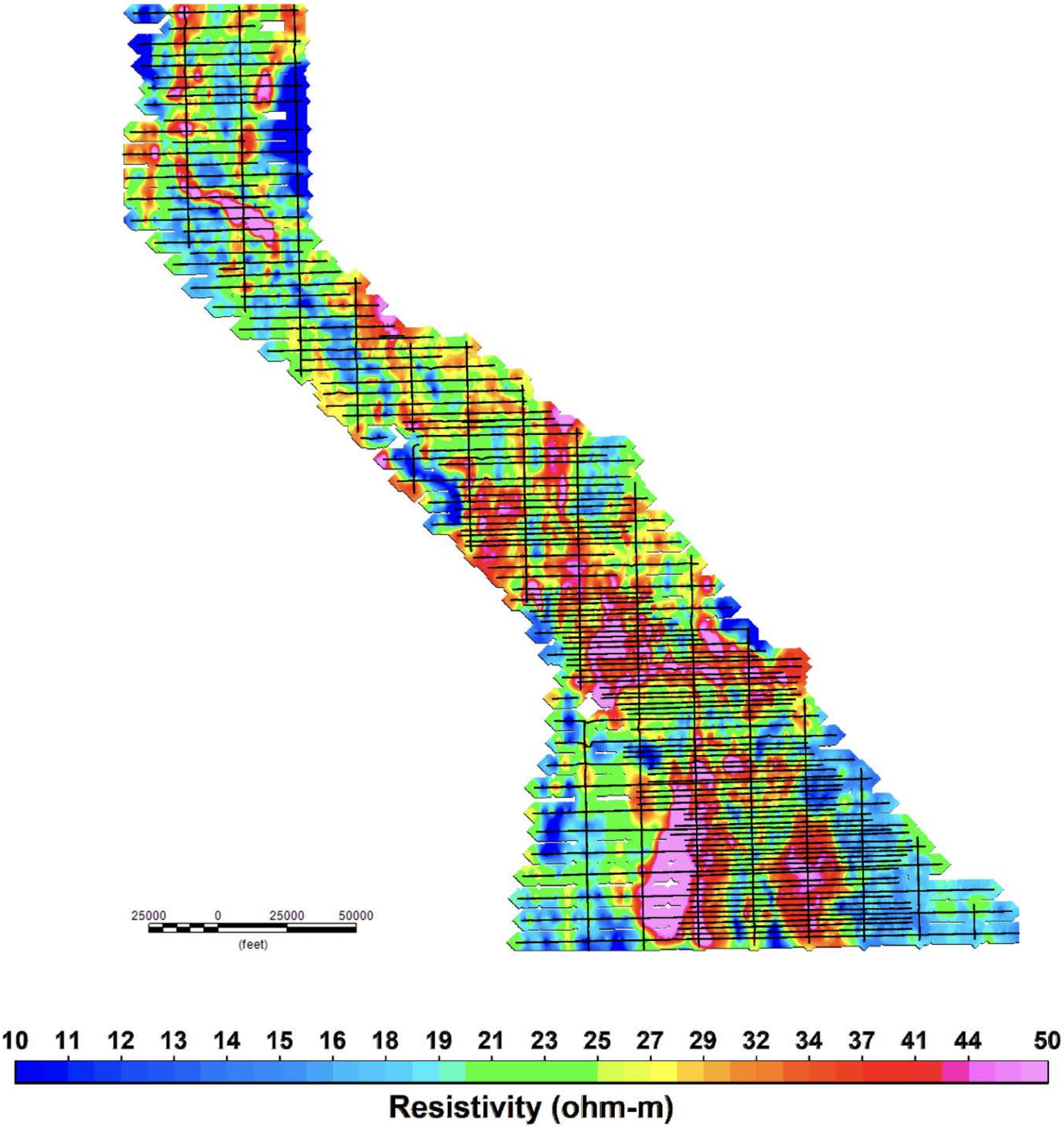


Figure 7-8. Map view of the inverted resistivity for the 9th SCI model layer from -92.5 to -106.6 feet for the NDSWC Spiritwood South AEM survey area. Flight Lines are indicated by black lines.

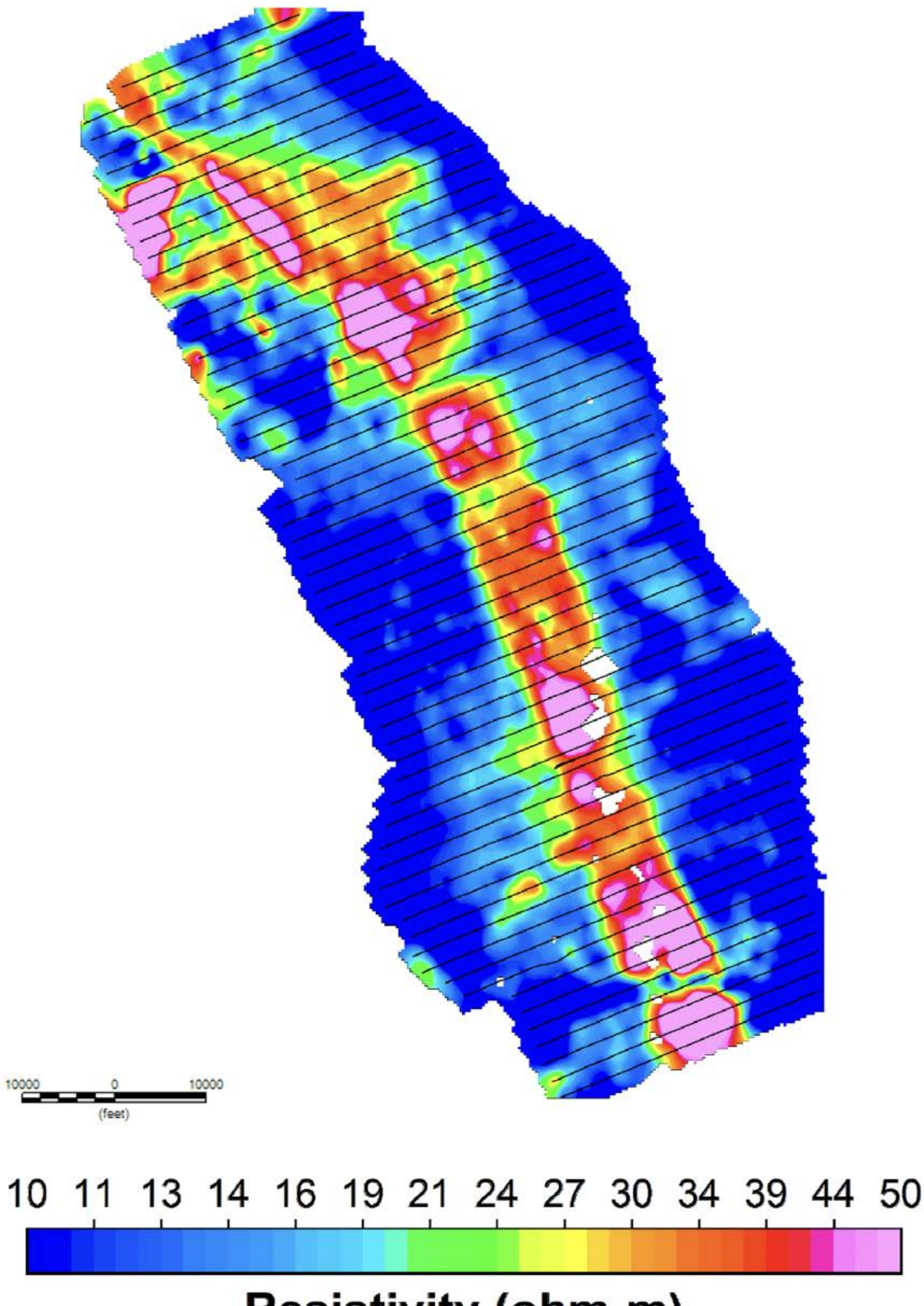


Figure 7-9. Map view of the inverted resistivity for the –245.4 to -266.7 ft SCI model layer 18 for the NDSWC Tolna AEM survey area. Flight Lines are indicated by black lines.

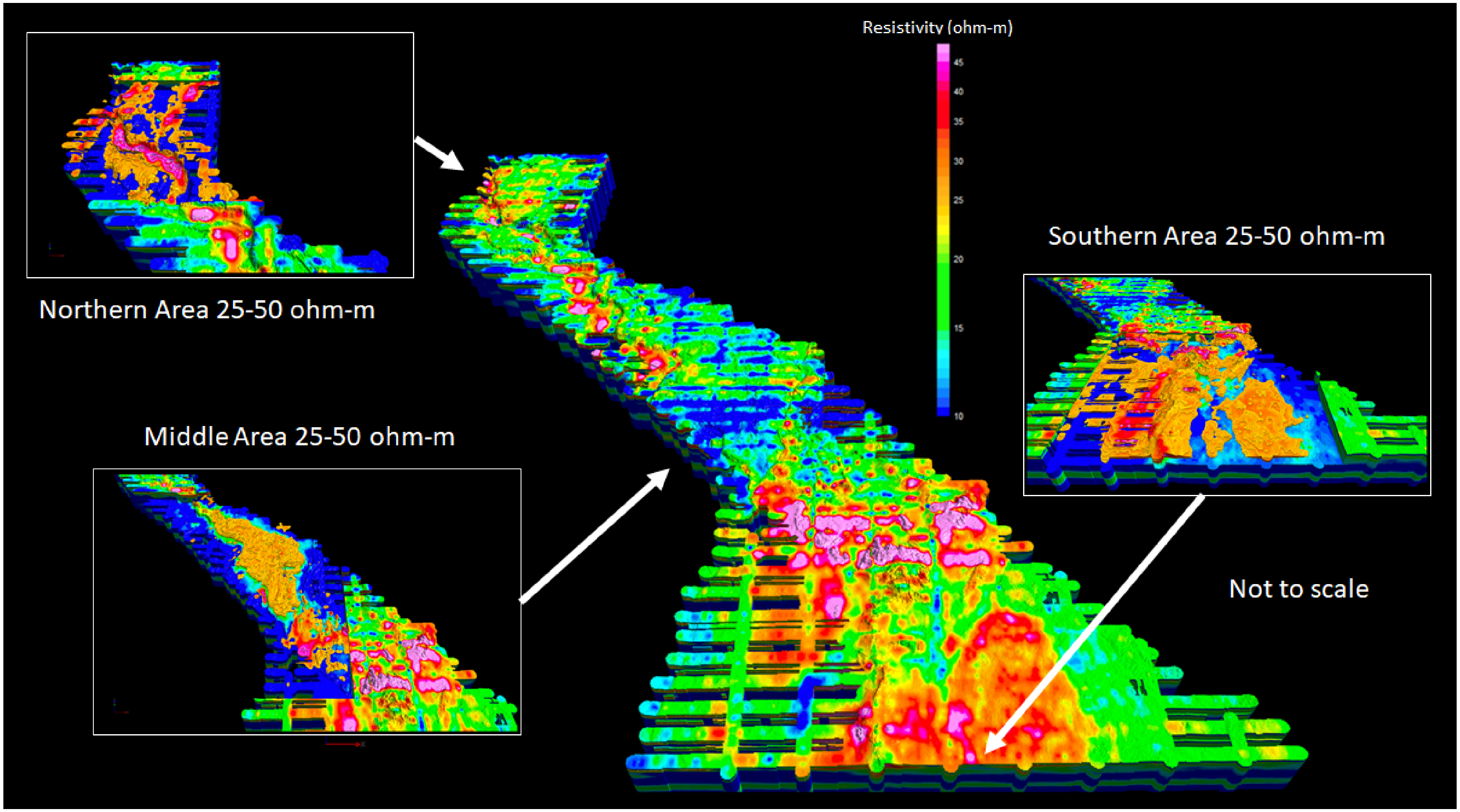


Figure 7-10. 3D voxel looking north of the Spiritwood South area. Three 'chair'-clipped zooms of areas within the survey highlighting the 25 to 50 ohm-m deposits. Vertical Exaggeration 15x.

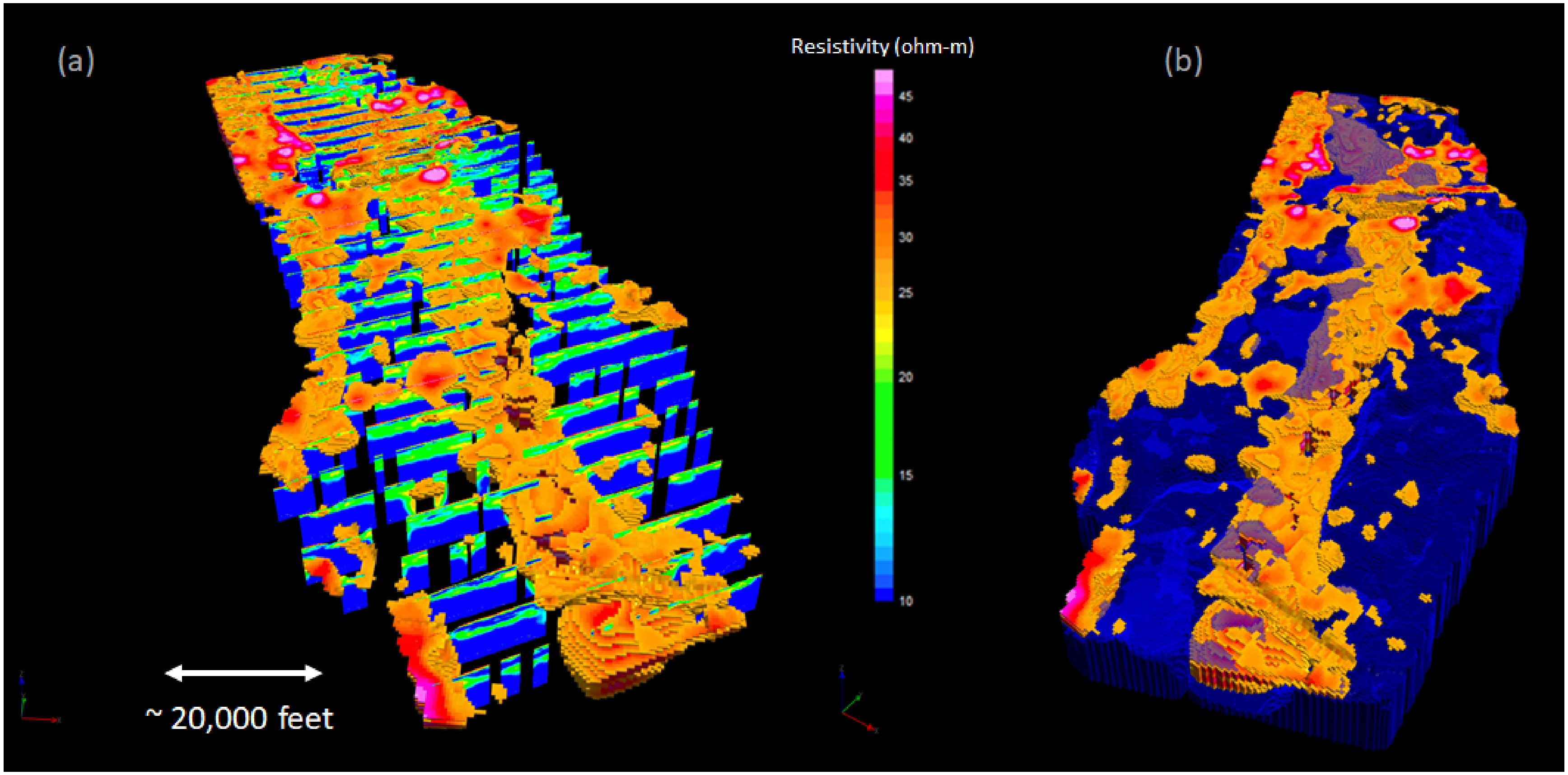


Figure 7-11. (a) 3D voxel looking north of the Tolna area showing the material > 23ohm-m excluding the first 10 feet on a fence diagram showing every second flight line. (b) 3D voxel looking northwest of the Tolna area showing the material > 23ohm-m excluding the first 10 feet with the low resistivity basement < 10 ohm-m set as transparent. Vertical Exaggeration 15x.

7.6 Resistivity Elevation Layers

Resistivity elevation layers were created based on the voxel model in order to assist in the visualization of the variations of the elevations of the deposits. To create these grids, the voxel model was sampled at discrete elevation ranges and the resulting resistivities were gridded at a 250 ft cell size. Figure 7-12 is an example of two elevation layers, 1,300 ft and 1,100 ft, from the Spiritwood South area. At this elevation the basic fabric of the Quaternary sands and gravels are indicated by the high resistivities and have a strong depth component as the large resistor in the middle of the survey area is not seen in the higher elevations. Figure 7-13 presents two examples of resistivities at elevations 1,400 ft and 1,200 ft of the Tolna AEM survey area. These two layers show the changes in the deposits with elevation.

All the elevation layers for both the Spiritwood South and the Tolna were combined into two different 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. These files are located in Appendix 2. The grids of these layers can be found in Appendix 3 Deliverables/Grids.

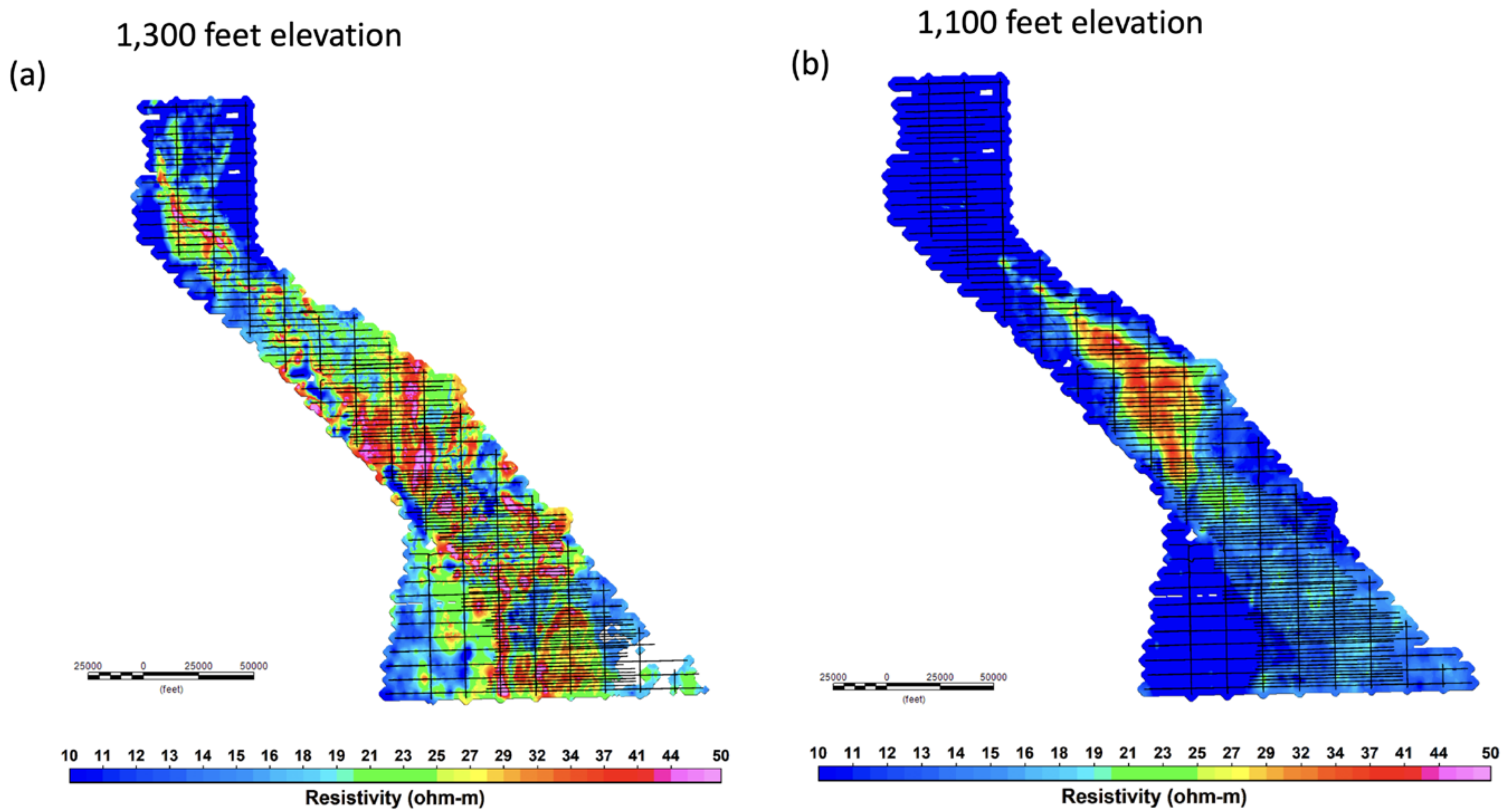


Figure 7-12. (a) Resistivity layer at an elevation of 1,300 ft of the Spiritwood South AEM survey area (b) Resistivity layer at an elevation of 1,100 ft of the Spiritwood South AEM survey area. Flight Lines are indicated by black lines.

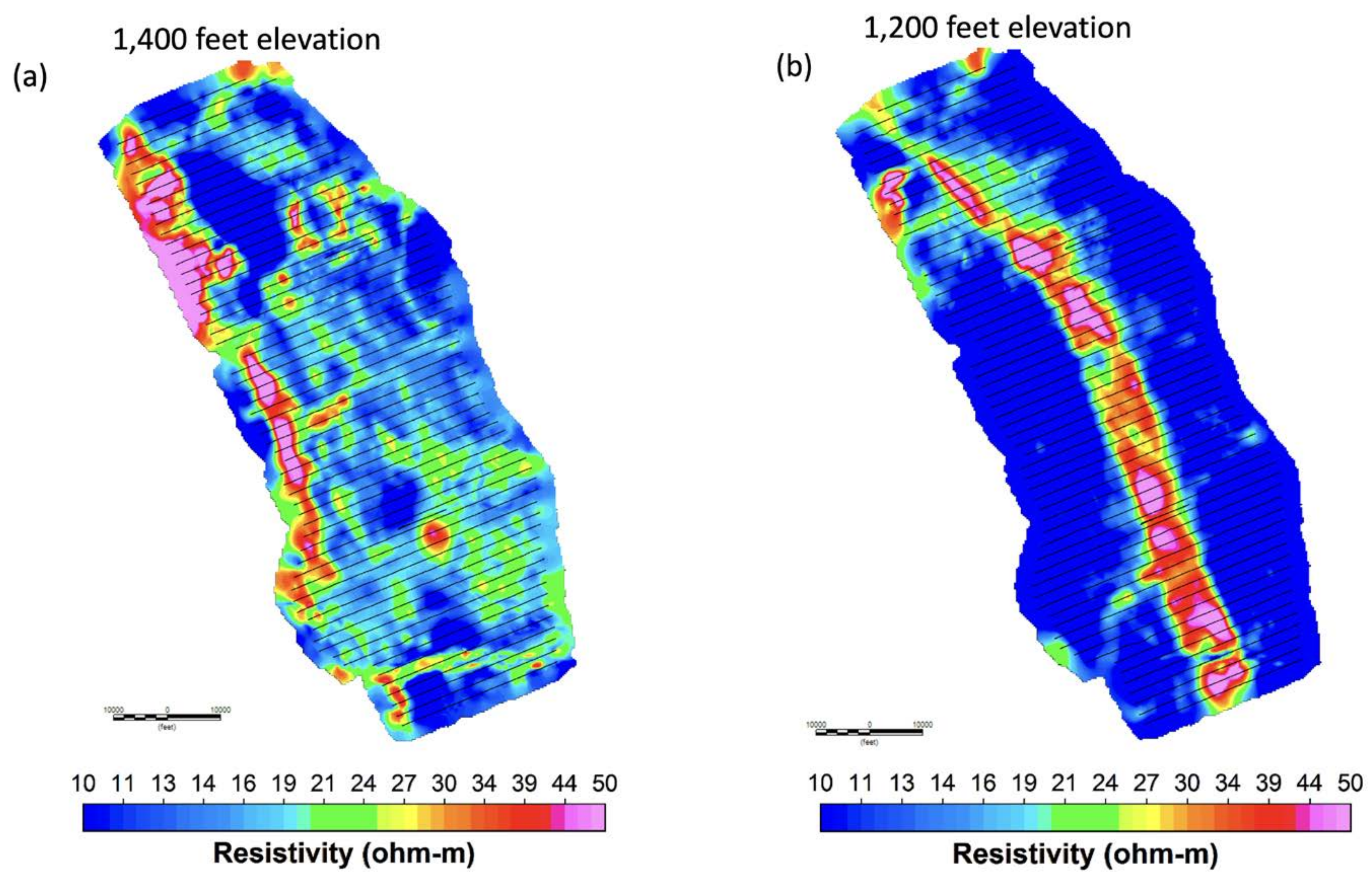


Figure 7-13. (a) Resistivity layer at an elevation of 1,400 ft of the Tolna AEM survey area (b) Resistivity layer at an elevation of 1,200 ft of the Tolna AEM survey area. Flight Lines are indicated by black lines.

7.7 Examples of Boreholes Electrical Resistivity and 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, 2018). The databases contained information on the interpreted lithology from well drilling and were examined within the area of the NDSWC. After consultation with NDSWC only the NDSWC boreholes were used in this project (Personal Communications, Scott Parkin, Hydrologist NDSWC, November 12 2018). 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). Four modern electrical resistivity logs were also provided for the survey area holes 130775 and 130776 for the Spiritwood South area (Personal Communications, Scott Parkin, Hydrologist NDSWC, October 22, 2018), and 130791 and 130792 for the Tolna area (Personal Communications, David Hisz, Hydrologist NDSWC, December 12, 2018). As indicated in Section 7.3, 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 resistivities 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.

On the side of the AEM technique, the 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 amplitude of the signals returned that are detectable decreases. This has the impact of decreasing the resolution of the EM signals with increasing depth. The AEM inversion models also increase layer thickness with depth that also expresses the decreased resolution with depth (Table 6-1).

Lithology logs are also 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 with the AEM inverted resistivities. Appendix 1 – 2D Profiles includes these examples and others for comparison of selected flight lines with the borehole lithology logs.

7.7.1 E-Log Comparisons to AEM

The 16-inch normal and the 64-inch normal resistivity logs were used by Geotech LTD to calibrate the AEM data. Several test lines were flown over the test holes to be used in the calibration. Two lines per test hole were combined into a single profile and will be compared with the borehole resistivities (Table 7-3).

Table 7-3. Test lines with E-log test holes.

Flight Lines	Combined Line	Test hole	Area
L20002 **L20003**	**L20010**	**130775**	**Spiritwood South**
L20004 **L20005**	**L20011**	**130776**	**Spiritwood South**
L1000 **L1001**	**L1004**	**130792**	**Tolna**
L1002 **L1003**	**L1005**	**130791**	**Tolna**

Figure 7-14 is a comparison of the SCI inversions of the two test lines combined as line L20010 flown over test hole 130775 for both the 16-inch and 64-inch normal for the Spiritwood South area. The 16-inch normal and the 64-inch normal logs are quite similar resistivity indicating that there is limited lateral variation on the order of the 64 inches around the borehole. The AEM and the E-logs corelate well at the top of the resistive materials at ~ 1,360 feet as the resistivities match well. The AEM also indicates the bottom of the resistive materials ending at a low resistivity unit at ~1,140 feet. The AEM inversion however doesn't indicate resistive material from the 1,140 ft elevation to the 1,360 elevation as the E-logs do. The AEM has a higher resistivity unit from ~ 1,260 to 1,360 feet. While the boundaries of the top of the low resistivity unit and the top of the high resistivity unit are well imaged, the potential non unique solution of the resistivity may be unable to image the precise distribution of the resistivity unit between those two boundaries.

Figure 7-15 is a comparison of the SCI inversions of the two test lines combined as line L20011 flown over test hole 130776 for both the 16-inch and 64-inch normal for the Spiritwood South area. The 16-inch normal and the 64-inch normal logs are similar but not exactly the same in resistivity indicating that there is lateral variation on the order of the 64 inches around the borehole. The AEM and the E-logs corelate well at the top of the resistive materials, at ~ 1,400 feet the resistivities match well. The AEM also indicates the bottom of the resistive materials ending at a low resistivity unit at ~1,260 feet. The AEM inversion matches the vertical boundaries well with the 16-inch normal, but misses the 20-foot thick ~ 20 ohm-m layer in the middle of the resistive unit. The 64-inch normal also does not indicate the 20 ohm-m layer, indicating that it is possibly local to the borehole and doesn't extend far beyond. but does indicate a ~ 30 ohm-m layer over the same region. This is most likely an issue of resolution and potentially non-unique solution of the resolved resistivity which may be unable to image the precise distribution of the resistivity unit between those two boundaries, but indicates the boundaries well.

Figure 7-16 is a comparison of the SCI inversions of the two test lines combined as line L1004 flown over test hole 130792 for both the 16-inch short- and 64-inch long-normal logs for the Tolna area. The 16-inch and the 64-inch logs are similar but not exactly the same in resistivity indicating that there is lateral variation on the order of the 64 inches around the borehole. The AEM and the 16-inch short normal E-logs corelate well at the bottom of the surface resistive materials at ~ 1,440 feet and corelate well down to the bottom of the low resistivity materials at ~1,360. The AEM also indicates that the low resistivity unit is at ~1,160 feet where the E-log indicates a unit at ~1,240. This is a major discrepancy and is odd as the upper units are delineated well.

Figure 7-17 is a comparison of the SCI inversions of the two test lines combined as line L1005 flown over test hole 130791 for both the 16-inch and 64-inch normal for the Tolna area. The 16-inch short-normal and the 64-inch long-normal logs are similar but not exactly the same in resistivity, indicating that there is a lateral variation on the order of the 64 inches around the borehole. The biggest difference is the indication of a resistive unit from ~ 1,380 to 1,420 feet on the 64-inch long-normal log. The AEM has a large coupling in the area of the borehole. Some general conclusions can be made across the coupling area. The AEM and the 16-inch and 64-inch normal E-logs all indicate a resistive layer at around 1,310 feet. The AEM do differ at the bottom of the resistive unit with the logs indicating a bottom around ~1,140 ft and the AEM indicating a bottom of ~1,120 ft.

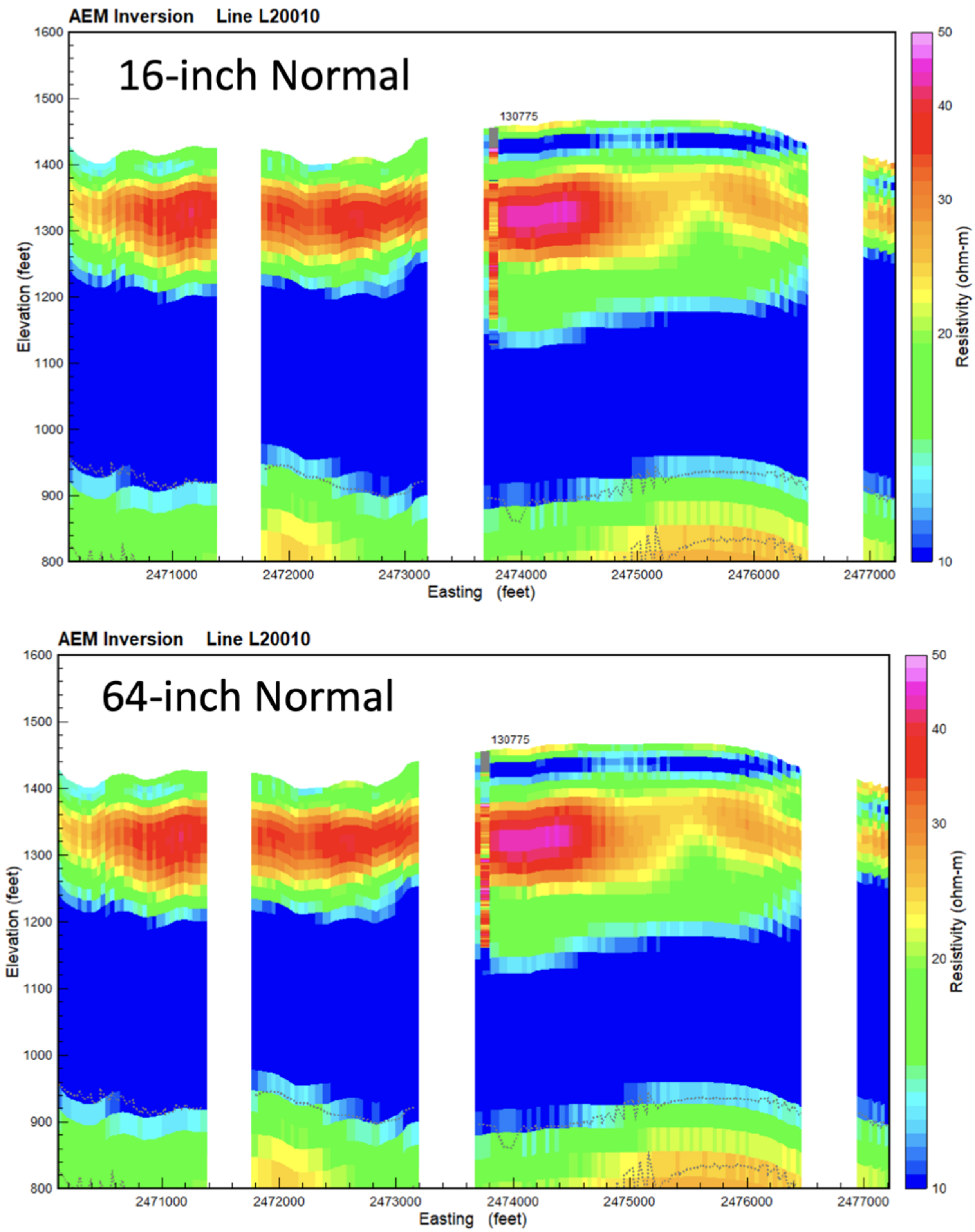


Figure 7-14. A comparison of the SCI inversions of the two test lines combined as line L20010 flown over test hole 130775 for both the 16-inch and 64-inch normal within the Spiritwood Southern area.

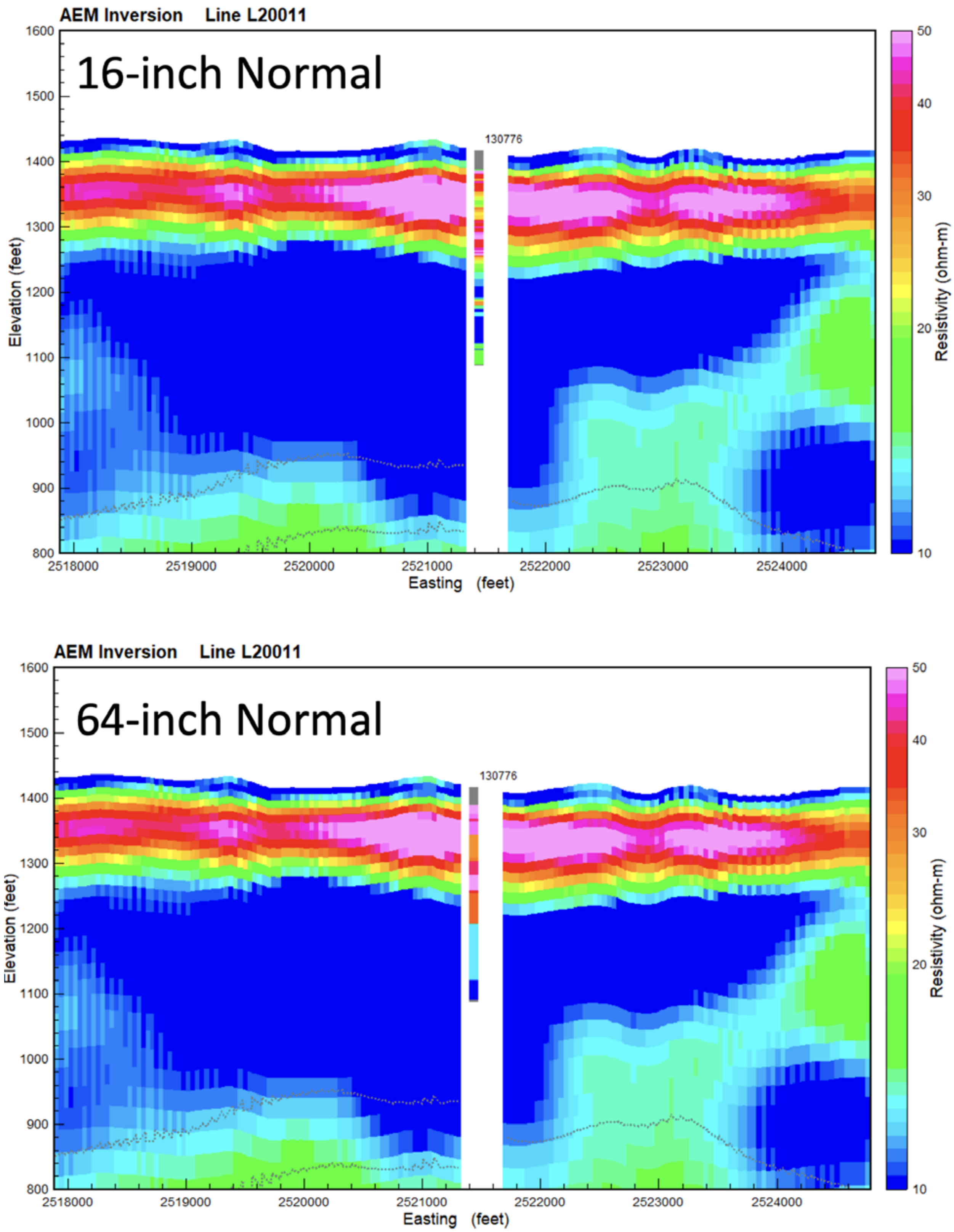
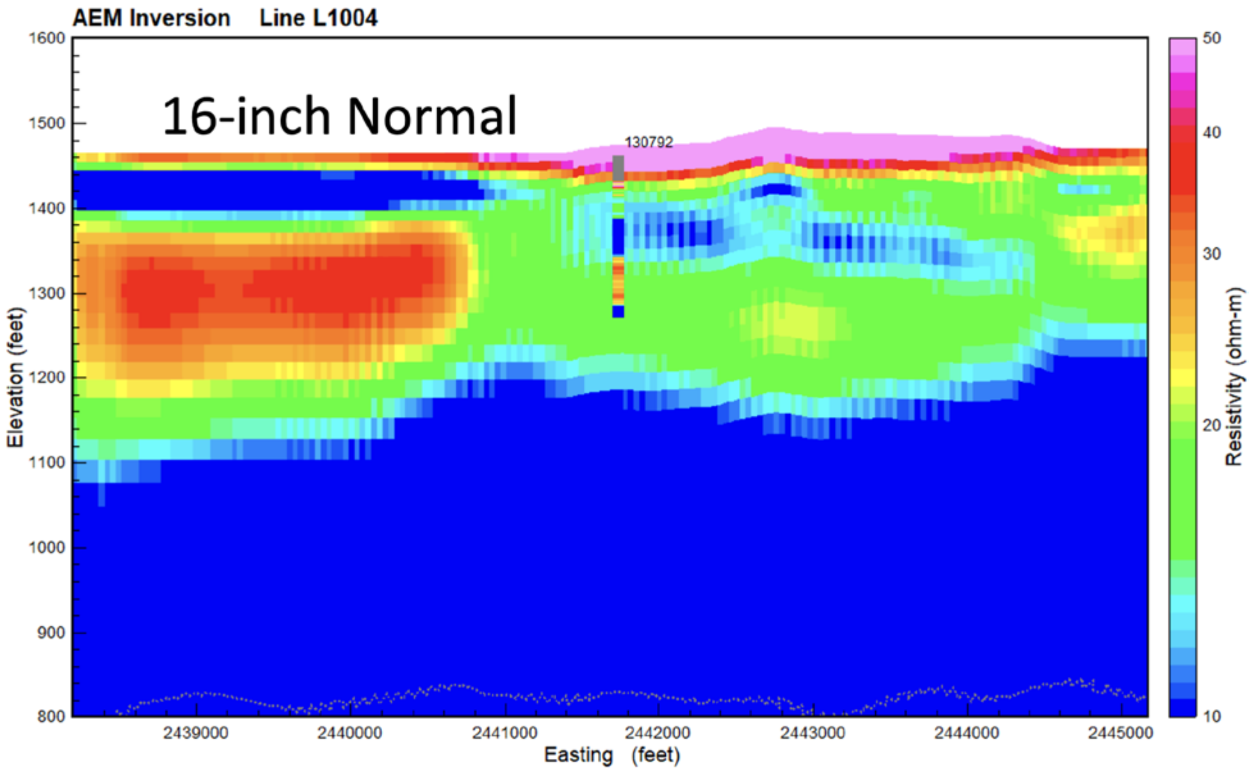


Figure 7-15. A comparison of the SCI inversions of the two test lines combined as line L20011 flown over test hole 130776 for both the 16-inch and 64-inch normal within the Spiritwood Southern area.



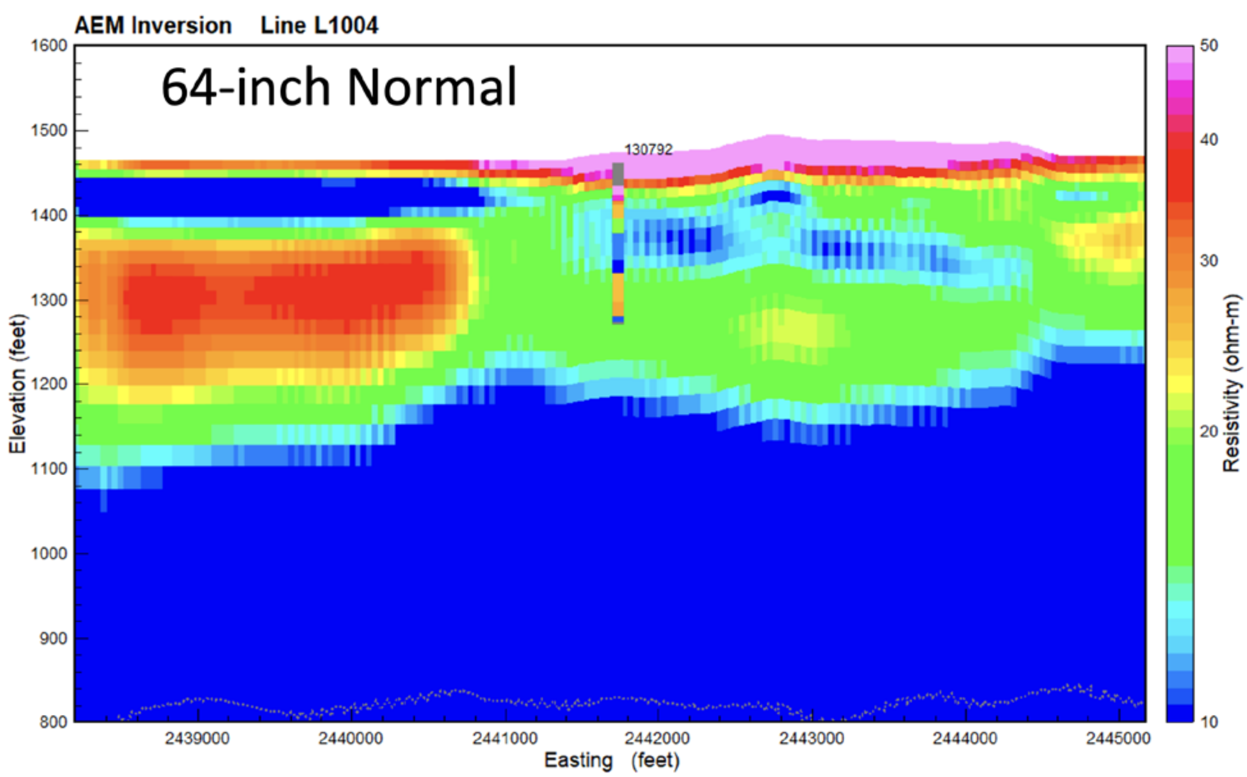


Figure 7-16. A comparison of the SCI inversions of the two test lines combined as line L1004 flown over test hole 130792 for both the 16-inch and 64-inch normal within the Tolna area.

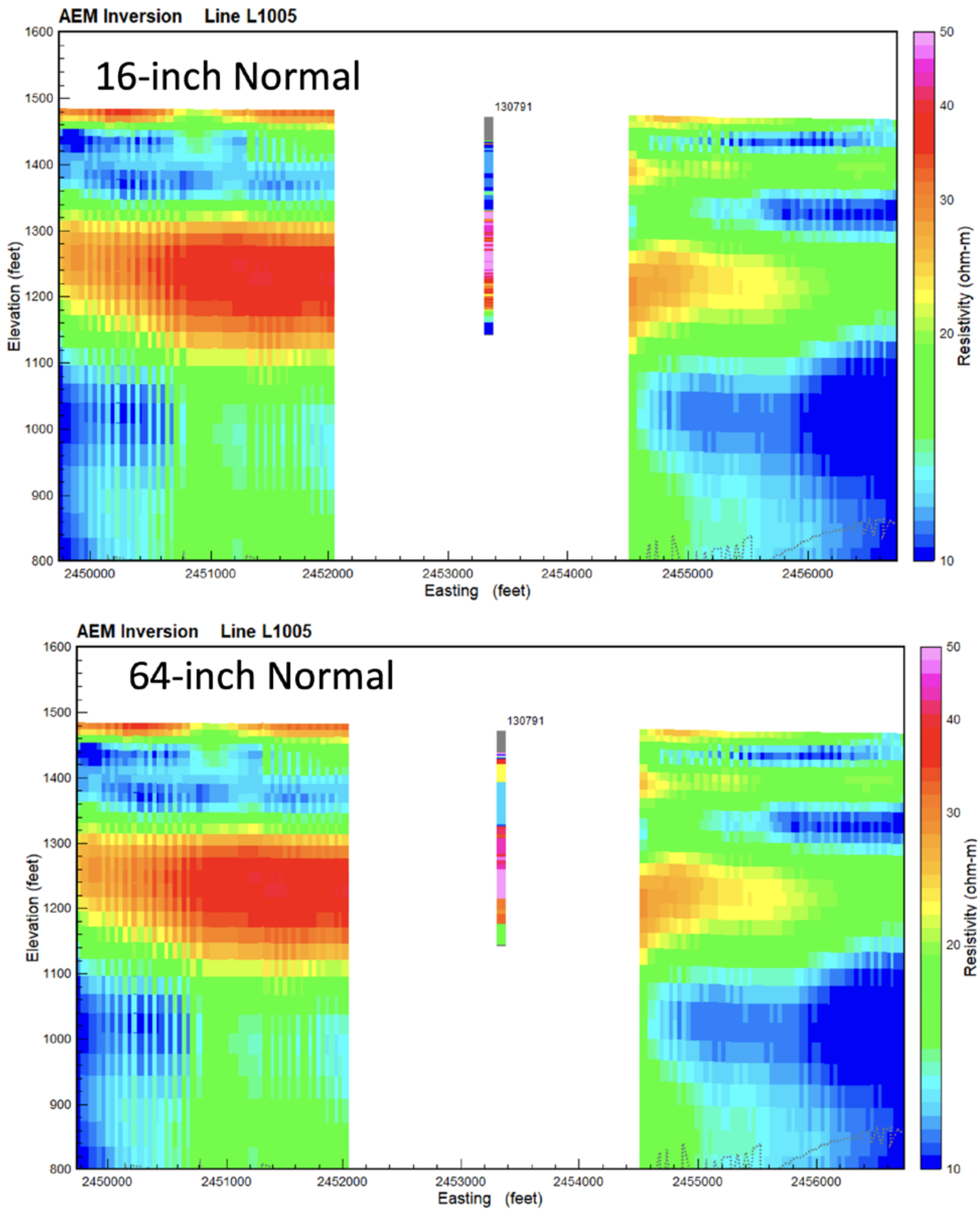


Figure 7-17. A comparison of the SCI inversions of the two test lines combined as line L1005 flown over test hole 130791 for both the 16-inch and 64-inch normal within the Tolna area.

7.7.2 Spiritwood South Area

As noted above there are three areas of differing resistivity structure within the Spiritwood South area. One is the resistive Quaternary sands and gravels in the northern area showing the discreet channelized deposits. The second area in the middle section is dominated by a large resistive area. The third is a set of thinner resistive deposits in the southern part of the survey area. A selected profile from each of the areas will be examined with the borehole lithology.

Figure 7-18 is a profile view of east-west Line L1050 located in the northern portion of the Spiritwood South area which is dominated by discreet channelized deposits. There are three boreholes within a ¼ mile of the flight line and they show good matches to the conductive bedrock indicated by the AEM. They also show good correlation with the sediments along the line. Additionally, there is a resistive paleochannel that is imaged within the section at approximately easting 2470500 (feet) at an elevation of ~ 1,300-1,100 feet. Below the DOI there is an indication of more resistive materials within the basement, which is possibly Cretaceous Niobrara formation?

Figure 7-19 is a profile view of east-west Line L1220, located in the central portion of the Spiritwood South AEM survey area, which is dominated by a large resistive area. There are many boreholes within a ¼ mile of the flight line and the show good matches to the AEM bedrock with the exception of the area of the large resistor. One hole "1927" does show a sand deposit throughout that resistor. Many of the holes only show sand and gravel at the top of the resistor. The large resistor is a dominant feature in the area of the survey and may provide clues to the genesis of the deposits in the area. Below the DOI there is also an indication of more resistive materials within the basement, which is possibly Cretaceous Niobrara formation?

Figure 7-20 is profile view of east-west infill Line L6680 located in the southern portion of the Spiritwood South AEM survey area. This area is dominated by thinner resistive deposits. There seven boreholes within a ¼ mile of the flight line and they show good matches to the AEM bedrock. Four holes show good correlation of sand with the AEM resistor. There is also a clay rich zone that is seen on the eastern end of the line near the surface. The DOI is below the 800-foot elevation of the image.

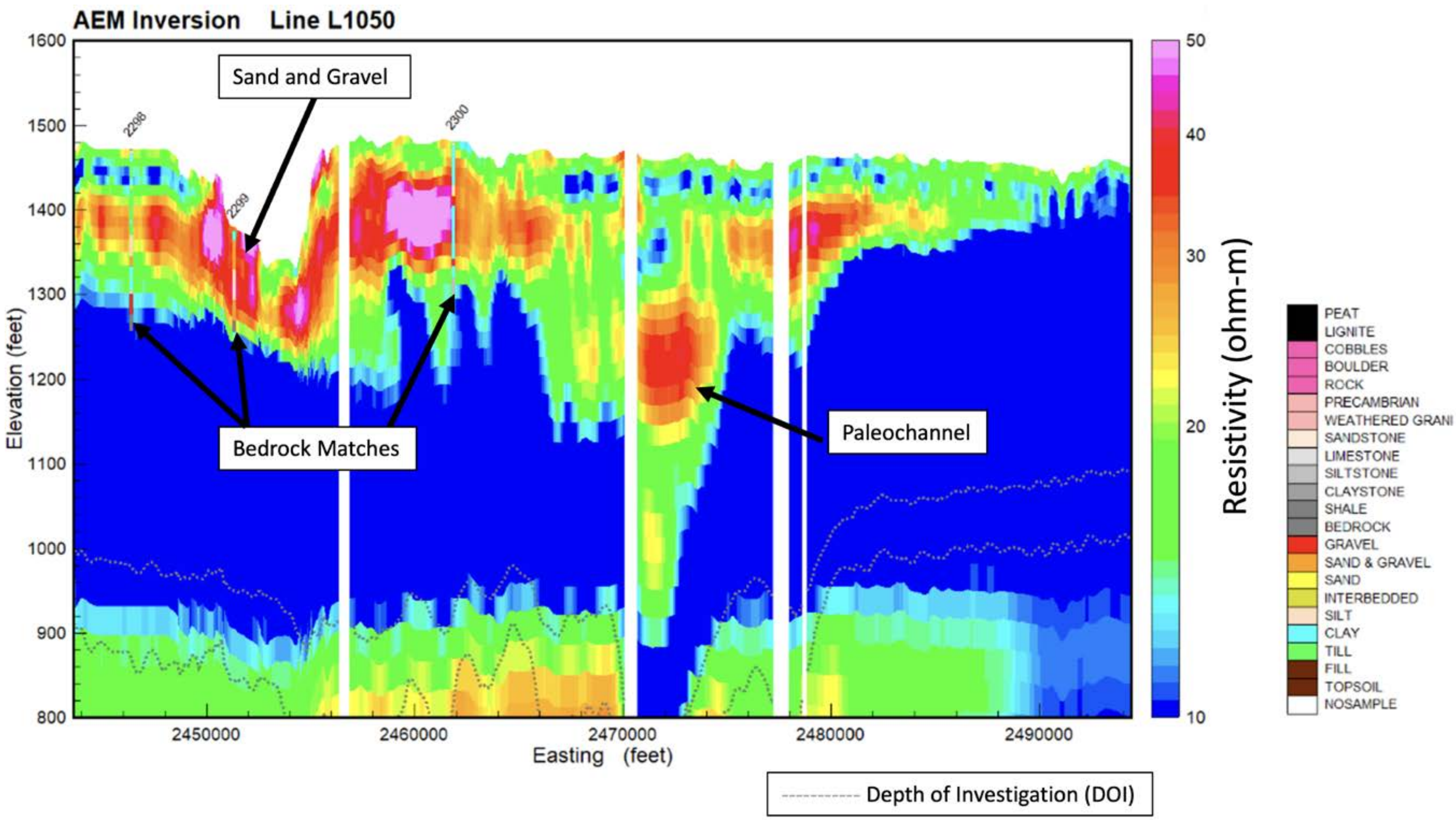


Figure 7-18. East-west flight line L1050 within the northern portion of the Spiritwood South survey area.

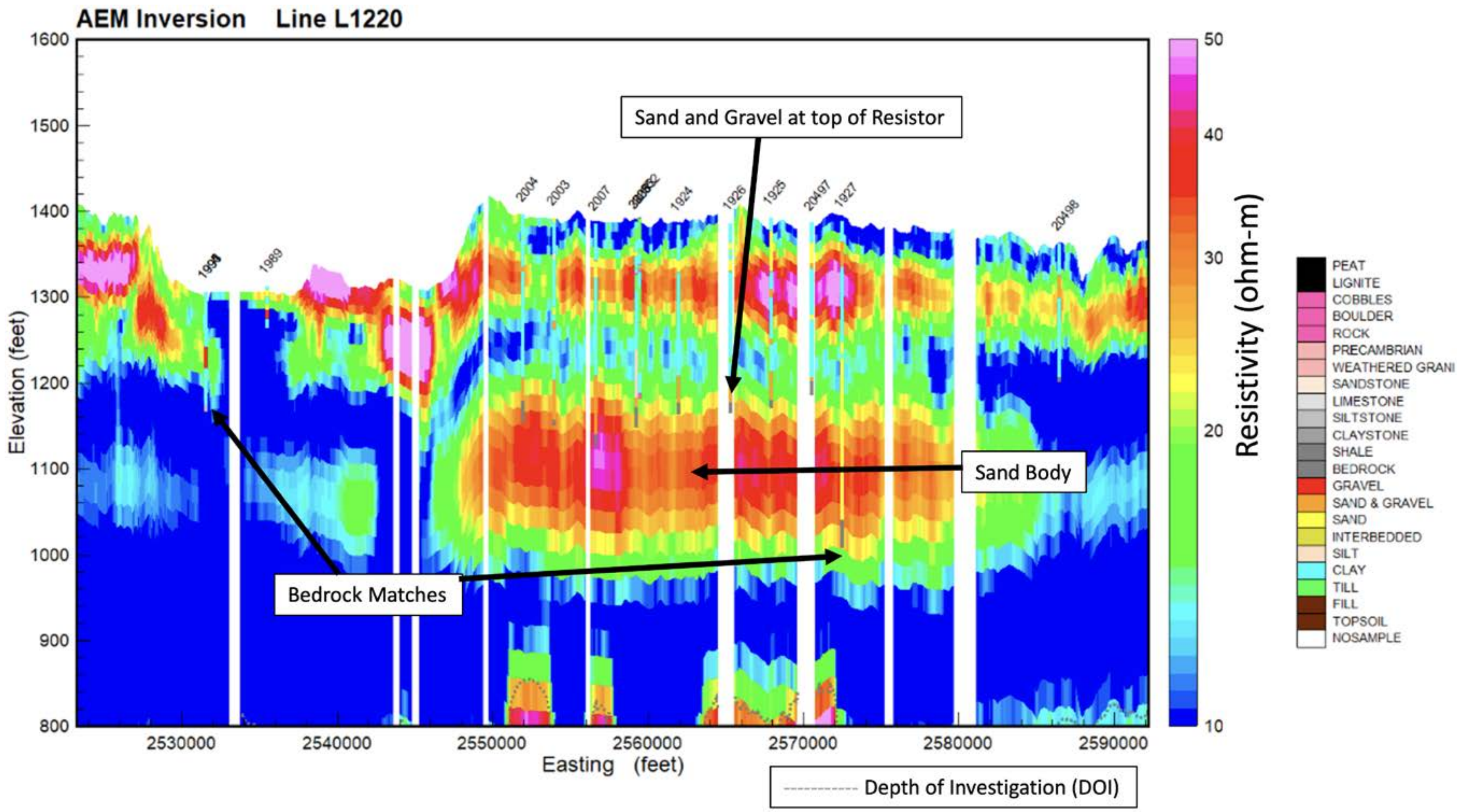


Figure 7-19. East-west flight line L1220 within the middle portion of the Spiritwood South survey area.

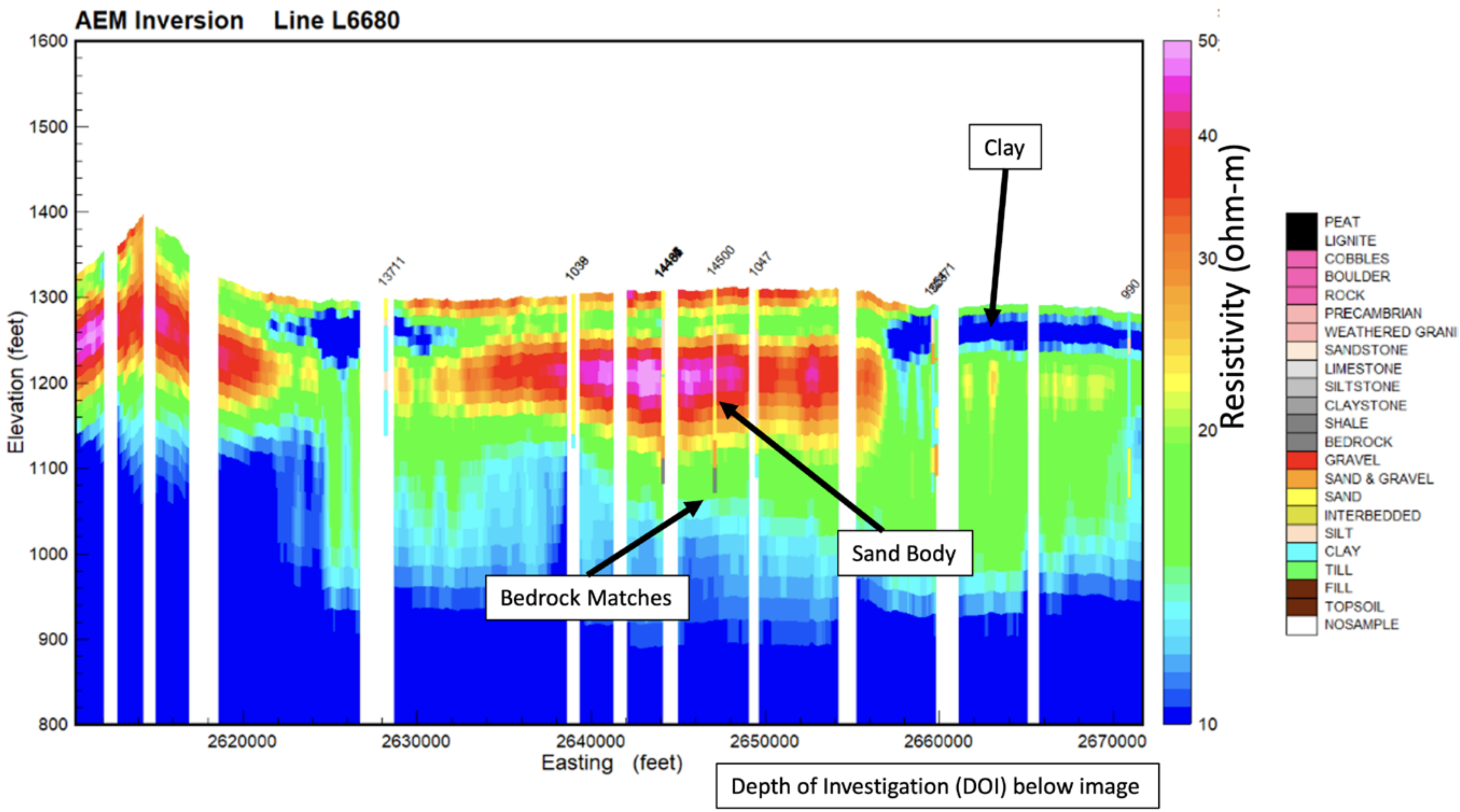


Figure 7-20. East-west infill flight line L6680 within the southern portion of the Spiritwood South survey area.

7.7.3 Tolna area

The dominant feature as discussed above within the Tolna survey area is the large resistive paleochannel deposit. There are several cross-cutting resistors within the section at different elevations, but the dominant feature is the large paleochannel cut into the low resistivity cretaceous basement.

Figure 7-21 is a profile view of the AEM resistivity inversion along Line L10400 in the central area of the Tolna AEM survey. There are several boreholes that penetrate into the sand and gravels of the paleochannel and also indicate the bedrock. There is a thick clay unit that is indicated by the low resistivity areas toward the top of the section. In the area of the large resistor, there are also areas of coupling that have been removed from the section. In the deepest part of the section the bedrock is potentially masked by the resistor. This may be caused by several reasons within the smooth model including low signal to noise in the late times in the area of the resistor and proximity to the areas of coupling. Line L10590 (Figure 7-22) also displays a similar condition in the deepest parts of the section below the large resistor that has many zones of coupling throughout the anomaly. However, when using the boreholes in concert with the resistivity image, an accurate estimation of the depth of the paleochannel can be achieved.

Figure 7-23 is a profile view of Line L10140 in the northern portion of the Tolna survey area. In this area the flight line goes over Devils Lake (which was frozen at the time of the acquisition, March 15-17). This profile indicates a resistor on the southwest end of the line at the surface and another resistor deeper that has two boreholes that fully penetrate the deposit. Both boreholes indicate the bedrock as well as the deposits composed of gravel and sand. The boreholes also indicate clay that corelates with low resistivity areas of the profile above the resistor and under areas of Devils Lake. Examining a profile view of line L10000 (Figure 7-24), which is also over Devils Lake, shows the very near surface resistive layer associated with the ice on the lake. It is important to note that there is not sufficient bandwidth to image a precise thickness of the ice and the smooth model that is very well suited for glacial deposits causes a smoothing of the thin resistive zone pulling the surface resistance down in the section. It is worth noting the sensitivity of the system and the inversion to the near surface and the seasonality of the interpretation of this data set.

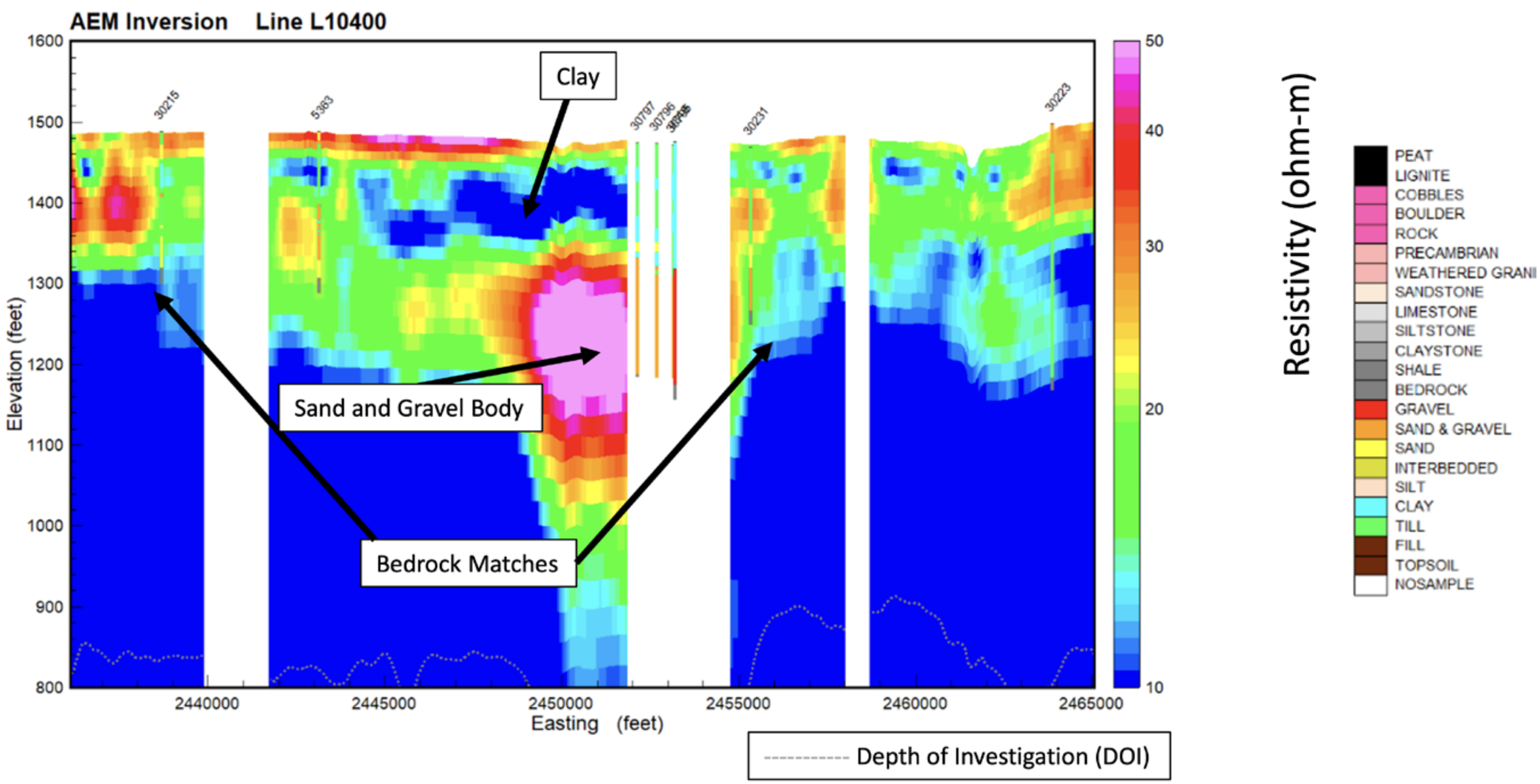


Figure 7-21. Tolna flight line L10400 within the middle of the Tolna AEM survey area.

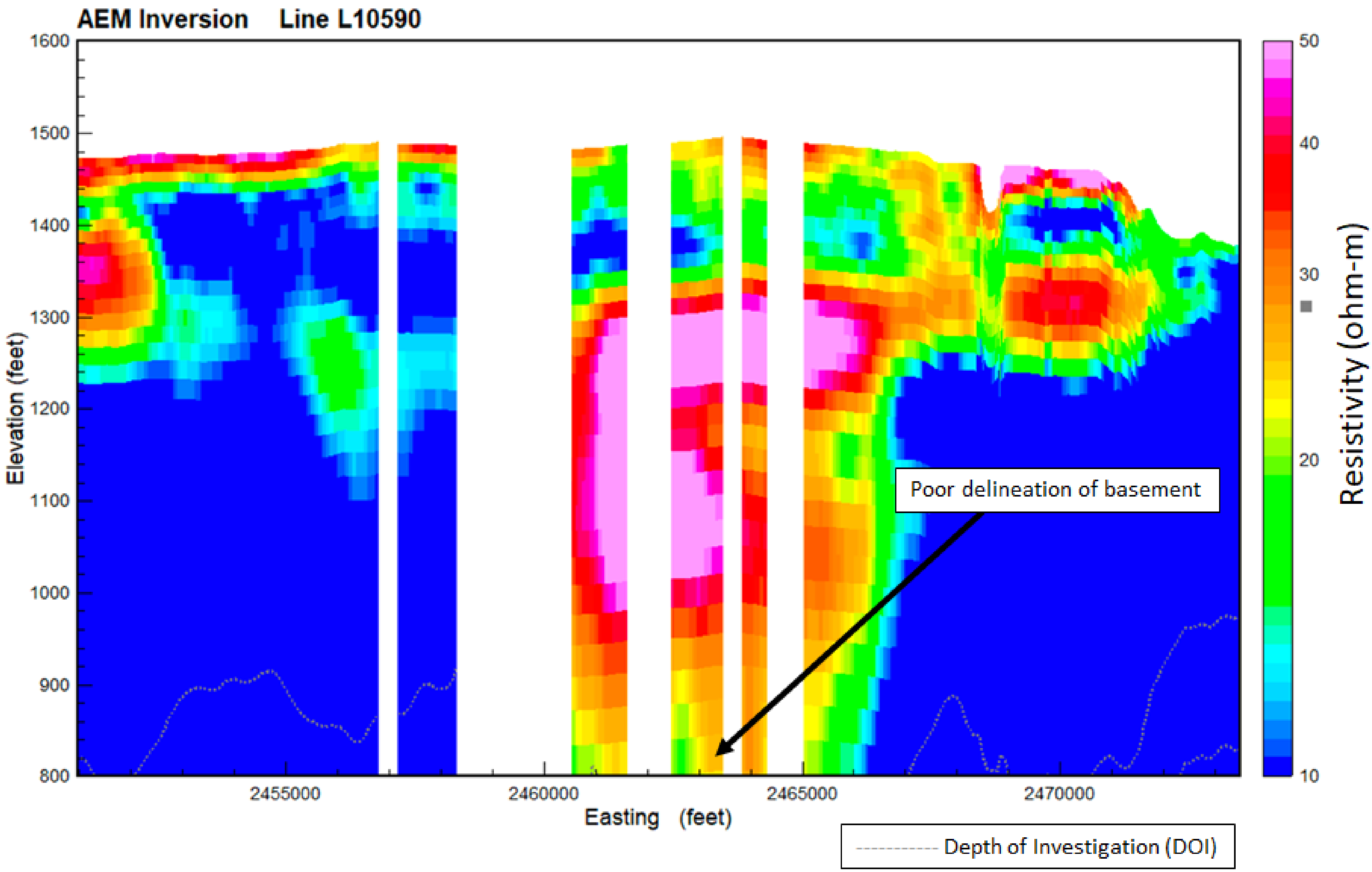


Figure 7-22. Tolna flight line L10590 within the southern portion of the Tolna AEM survey area.

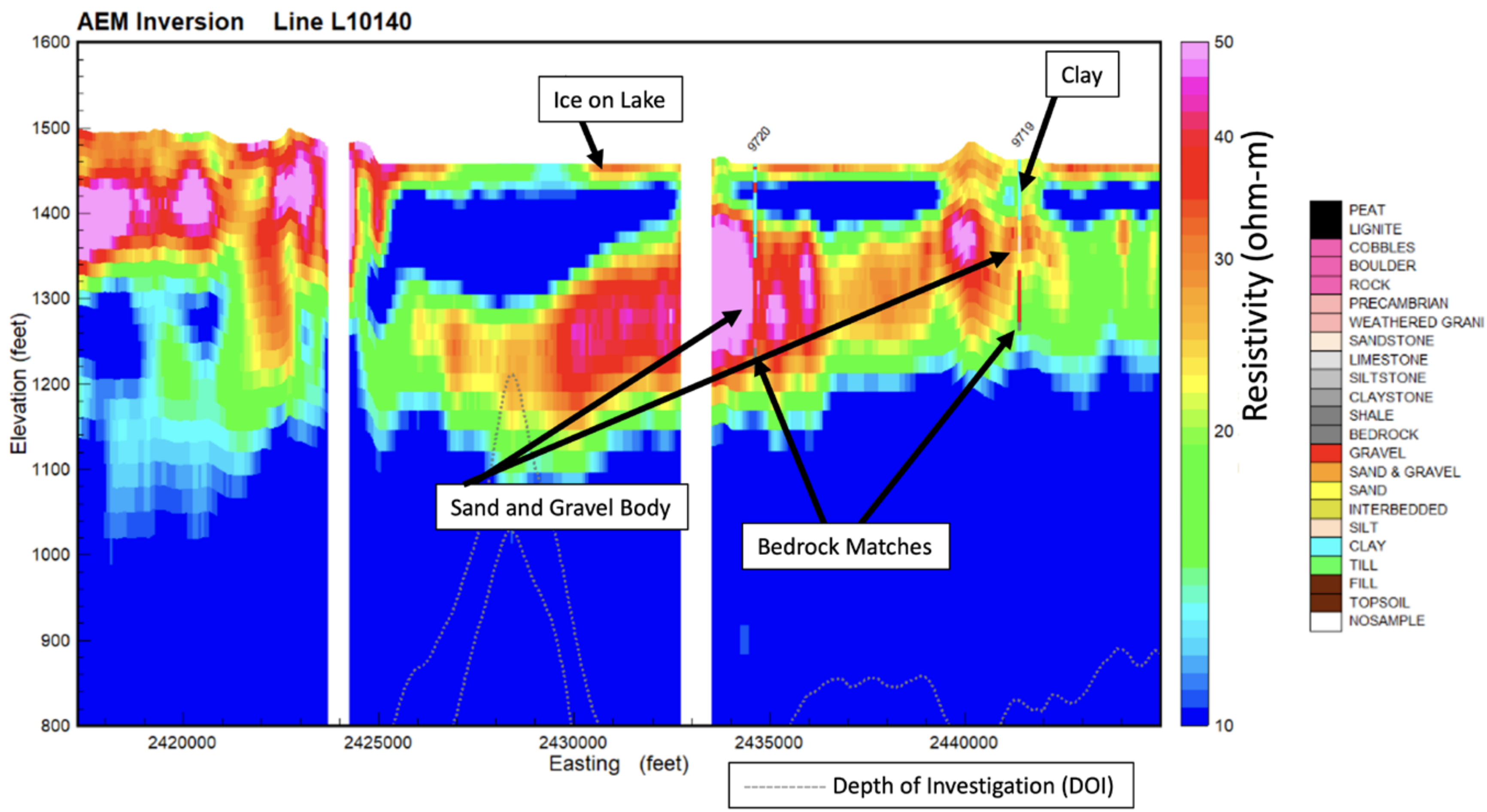


Figure 7-23. Tolna flight line L10140 within the northern portion of the Tolna AEM survey area.

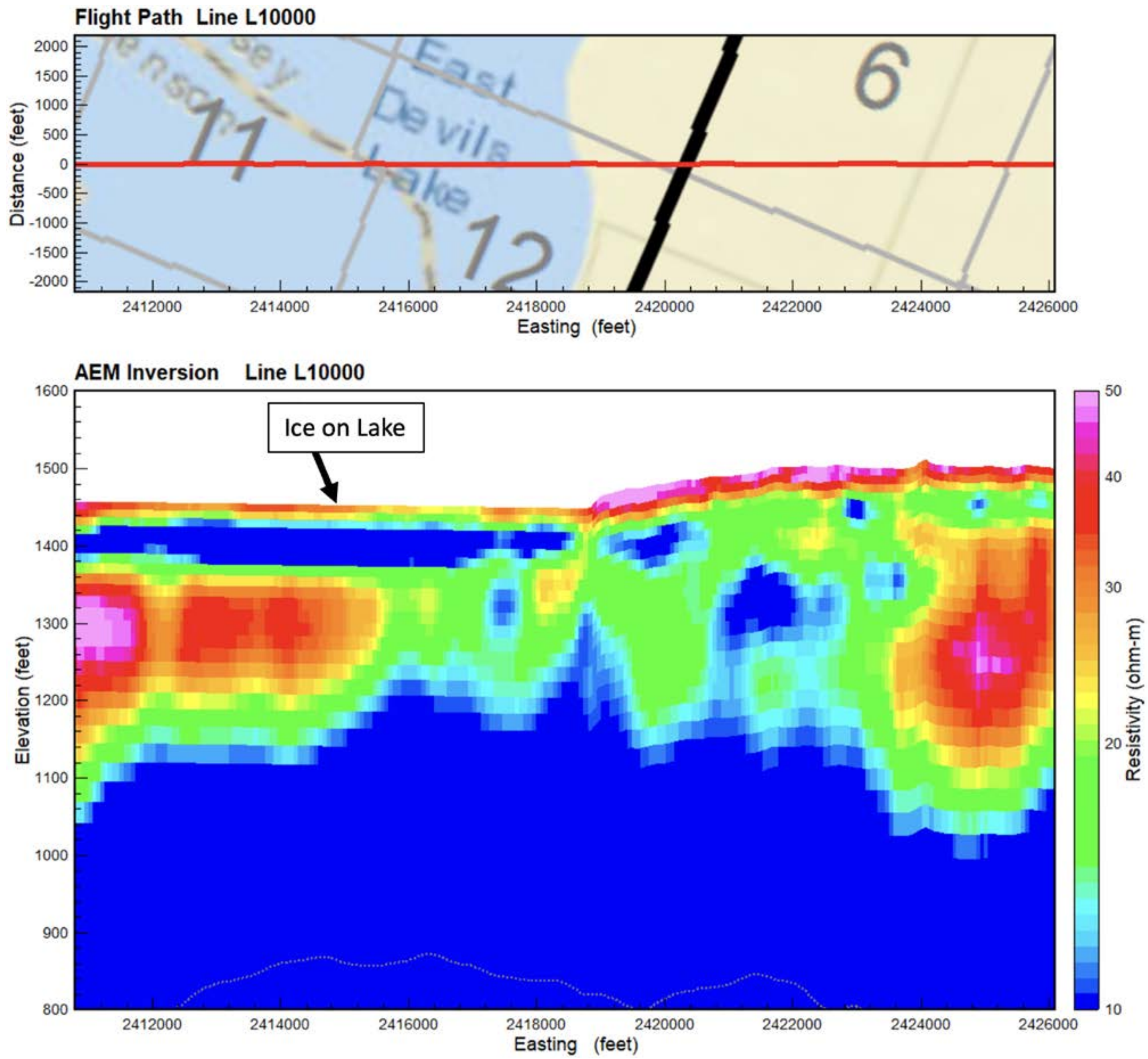


Figure 7-24. Tolna flight line L10000 within the northern portion of the Tolna AEM survey area over Devils Lake.

7.8 Suggestions on Interpretation

The NDSWC Spiritwood South and Tolna AEM survey is a data set rich in providing details of the geology from the surface down to the Cretaceous basement. Even so, note that 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. Within the Tolna area the ice on Devils Lake has caused a resistive layer to occur on the lake that can be seen in the section. It is not a precise layer as the smooth model will pull the resistivity down in the section. There is also an observed feature of the large resistive materials within the Tolna block where the model is not able to resolve the low resistivity basement in the thick resistive zones especially in areas of lateral coupling interference.

The first suggestion in interpreting this dataset is to delineate 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 Cretaceous low resistivity units.

8. 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 Spiritwood South and Tolna area, the preliminary LCI analysis, and the final 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, depth slices, and elevation layers. 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 Spiritwood and Tolna AEM acquisition survey area, these results provide a good, solid starting point for development of a hydrogeologic framework of the NDSWC Spiritwood and Tolna AEM survey areas.

Dropbox Link:

https://www.dropbox.com/sh/d2hmsuf6a53ybj4/AAC2G0PuOdLgV0R0IkqE1oHaa?dl=0

9. Deliverables

In the Appendix 3 - Deliverables folder are five subfolders entitled Grids, KMZs, Processed Data, Raw Data, and Voxel.

Table 9-1 lists the channels in calibrated raw data files (Geosoft gdb's) provided by Geotech for both the Spiritwood South and Tolna AEM survey areas. Table 9-2 lists the channels in the final measured waveforms (also as Geosoft gdb's) provided by Geotech. The combination of these two were input as raw data into the analysis software. These data are included in the *Raw Data* folder with the Final Waveforms in a separate sub-folder.

Table 9-3 presents the channels in the Spiritwood South AEM survey SCI inversion results and Table 9-4 lists the channels for the Tolna AEM survey area SCI inversion results. These are provided as both Geosoft gdb and ASCII xyz data files. These data are included in the *Processed Data* folder.

Table 9-5 lists the delivered grids. in ArcView *.FLT format. These data are included in the *Grids* folder. In the *Grids* folder are four subfolders: *DOI*, *DEM - Geosoft_ND-SPS_Feet*, *Grids_Resistivity_Elevation_Layers*, and *Grids-Resistivity_Depth_Layers*. The *DOI* folder contains grids of the upper and lower DOI's for both the Spiritwood South and Tolna AEM survey areas. The *DEM* folder contains the Digital Elevation Model grids for both the Spiritwood South and Tolna areas. The other two *Grids* sub-folders contain their own subfolders for both the Spiritwood South and Tolna areas that display the SCI inversion results in two ways: 1) Depth slice grids with each depth being a SCI model layer as per Table 6-1 and 2) Depth slice grids with each depth being an elevation above sea level.

The Resistivity Depth Slice and Elevation Slice data are provided as grids as described and also as Google Earth KMZ's and as multi-layer PDF files. In addition, the KMZ and PDF data are provided with two different color schemes; While both are LOG-space 10 ohm-m to 50 ohm-m, the colors run from blue to red and also from red to blue.

Table 9-6 and Table 9-7 list the channels in the delivered voxel data files for both the Spiritwood South AEM survey area and the Tolna AEM survey area, respectively. The files are provided as both ASCII xyz and Geosoft gdb files in the *Voxel* folder.

The *KMZ* folder contains the resistivity depth and elevation slices as described above and also the As-Flown-Retained data for both the Spiritwood South and the Tolna AEM survey areas.

Table 9-1: Calibrated raw data: Channel name, description, and units for GL1703498_Spiritwood_Final.gdb and GL1703498_Tolna_Final.gdb.

Parameter	Description	Unit
X	Easting WGS84/UTM 14 North	Meters (m)
Y	Northing WGS84/UTM 14 North	Meters (m)]
Z	Aircraft elevation (Above Geoid)	Meters (m)]
Longitude	GPS Longitude	Degrees
Latitude	GPS Latitude	Degrees
DEM	Estimated elevation above Geoid	Meters [m]
RADAR	Helicopter terrain clearance	Meters [m]
RADARB	EM bird terrain clearance	Meters (m)
LASER	Laser altimeter	Meters (m)
LASERB	Laser altimeter	Meters [m]
GTIME	Seconds of GPS time	Seconds (s)
BASEMAG	Magnetic field diurnal variation data	Nanoteslas (nT)
MAG1, MAG2, MAG3	Magnetic field data	Nanoteslas (nT)
CVG	Calculated Vertical Gradient of the Magnetic Field	nT/m
SFZ[0] – SFZ[63]	dB/dt data for gates 1 to 64 (1-4,59-64 blank)	picoVolts/A*m^4
PLM	60 Hz Power Line Monitor	
TAUSF	Time constant	
NCHANSF	Number of Channels for SF	

Table 9-2. Raw Data: Transmitter waveforms by flight (1 to 26 except for 11 (no flight)). Flights 15-18 were acquired over the Tolna AEM survey area.

Parameter	Description	Unit
Time	Transmitter waveform time	milliseconds (ms)
Tx-Current	Measured Tx waveform voltage	Volts (v)]

Table 9-3. Channel name, description, and units for SpiritwoodSouth_SCI.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]
ELEVATION_M	Elevation of Inversion Surface	Meters [m]
DEM_FT	DEM from 100 ft grid NED NAVD88	Feet [ft]
DISTANCE_FT	Distance down line	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]
DISTANCE_M	Distance down line	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_38	Inverted resistivity of each later	Ohm-m
RHO_STD_0 THROUGH RHO_STD_38	Inverted resistivity standard deviation	
SIGMA_I_0 THROUGH SIGMA_I_38	Conductivity	S/m
DEP_TOP_0_FT THROUGH DEP_TOP_38_FT	Depth to the top of individual layers	Feet [ft]
DEP_BOT_0_FT THROUGH DEP_BOT_38_FT	Depth to the bottom of individual layers	Feet [ft]
THK_0_FT THROUGH THK_38_FT	Thickness of individual layers	Feet [ft]
DEP_TOP_0_M THROUGH DEP_TOP_38_M	Depth to the top of individual layers	Meters [m]
DEP_BOT_0_M THROUGH DEP_BOT_38_M	Depth to the bottom of individual layers	Meters [m]
THK_0_M THROUGH THK_38_M	Thickness of individual layers	Meters [m]

Table 9-4. Channel name, description, and units for Tolna_SCI.gdb and *.xyz files with AEM inversion results.

Parameter	Description	Unit
LINE	Line Number	Feet [ft]
X_FT	Easting NAD83, State Plane North Dakota, North	Int. Feet [ft]
Y_FT	Northing NAD83, State Plane North Dakota, North	Int. Feet [ft]
ELEVATION_M	Elevation of Inversion Surface	Meters [m]
DEM_FT	DEM from 100 ft grid NED NAVD88	Feet [ft]
DISTANCE_FT	Distance down line	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]
DISTANCE_M	Distance down line	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_38	Inverted resistivity of each later	Ohm-m
RHO_STD_0 THROUGH RHO_STD_38	Inverted resistivity standard deviation	
SIGMA_I_0 THROUGH SIGMA_I_38	Conductivity	S/m
DEP_TOP_0_FT THROUGH DEP_TOP_38_FT	Depth to the top of individual layers	Feet [ft]
DEP_BOT_0_FT THROUGH DEP_BOT_38_FT	Depth to the bottom of individual layers	Feet [ft]
THK_0_FT THROUGH THK_38_FT	Thickness of individual layers	Feet [ft]
DEP_TOP_0_M THROUGH DEP_TOP_38_M	Depth to the top of individual layers	Meters [m]
DEP_BOT_0_M THROUGH DEP_BOT_38_M	Depth to the bottom of individual layers	Meters [m]
THK_0_M THROUGH THK_38_M	Thickness of individual layers	Meters [m]

Table 9-5. Files containing ESRI ArcView Binary Grids *.flt.

Grid File Name	Description	Grid Cell Size (feet)
SpiritwoodSouth_DOI_Lower_ft	**Grid of the lower depth of investigation (DOI) (feet) NAD83, State Plane North Dakota, South (Int. ft)**	**250**
SpiritwoodSouth_DOI_Upper_ft	**Grid of the upper depth of investigation (DOI) (feet) NAD83, State Plane North Dakota, South (Int. ft)**	**250**
Tolna_DOI_Lower_ft	**Grid of the lower depth of investigation (DOI) (feet) NAD83, State Plane North Dakota, North (Int. ft)**	**250**
Tolna_DOI_Upper_ft	**Grid of the upper depth of investigation (DOI) (feet) NAD83, State Plane North Dakota, North (Int. ft)**	**250**
SP2_RHO_LayXX	**Spiritwood South Resistivity grids of the 39 inverted model depth layers (ohm-m), NAD83, State Plane North Dakota, South (Int. ft)**	**250**
Tolna_RHO_LayXX	**Tolna Resistivity grids of the 39 inverted model depth layers (ohm-m), NAD83, State Plane North Dakota, South (Int. ft)**	**250**
Spirtwood_South_ElevXXXX	**Spiritwood South Elevation Resistivity (ohm-m) grids, from 300 to 1,500 feet NAVD88, NAD83, State Plane North Dakota, South (Int. ft)**	**250**
Tolna_ElevXXXX	**Spiritwood South Elevation Resistivity (ohm-m) grids, from 450 to 1,625 feet NAVD88, NAD83, State Plane North Dakota, North (Int. ft)**	**250**
SpiritwoodSouthDEM_ft	**Grid of the USGS National Elevation Dataset (NED) digital elevation model (DEM) NAVD88 (feet), NAD83, State Plane North Dakota, South (Int. ft)**	**100**
TolnaDEM_ft	**Grid of the USGS National Elevation Dataset (NED) digital elevation model (DEM) NAVD88 (feet), NAD83, State Plane North Dakota, North (Int. ft)**	**100**

Table 9-6. Channel name, description, and units for SpiritwoodSouth_Res_voxel *.xyz and Geosoft Database *.gdb

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]

Table 9-7. Channel name, description, and units for Tolna_Res_Voxel *.xyz and Geosoft Database *.gdb.

Parameter	Description	Unit
X	Easting NAD83, State Plane North Dakota North	Int. Foot [ft]
Y	Northing NAD83, State Plane North Dakota North	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]

10. References

Aarhus Geosoftware, 2019 Aarhus Workbench, available on the world-wide web at: https://www.aarhusgeosoftware.dk/aarhus-workbench (accessed June 18, 2019)

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.

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, 2018, Datamine Discover Profile Analyst, available on the world-wide web at: https://www.dataminediscover.com/discover. (accessed on December 31, 2018).

Geotech LTD., 2019,VTEM-ET (Versatile Time Domain Electromagnetic) System, available on the world-wide web at: http://geotech.ca/wp-content/uploads/2019/01/VTEM-ET-Brochure.pdf (accessed on June 24, 2019).

North Dakota State Water Commission, 2018, Map Services, available on the world-wide web at: http://mapservice.swc.nd.gov (accessed November 6, 2018).

U.S. Geological Survey (USGS), 2018, The National Map, 2018, 3DEP products and services: The National Map, 3D Elevation Program Web page, http://nationalmap.gov/3DEP/3dep_prodserv.html (accessed October 7, 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