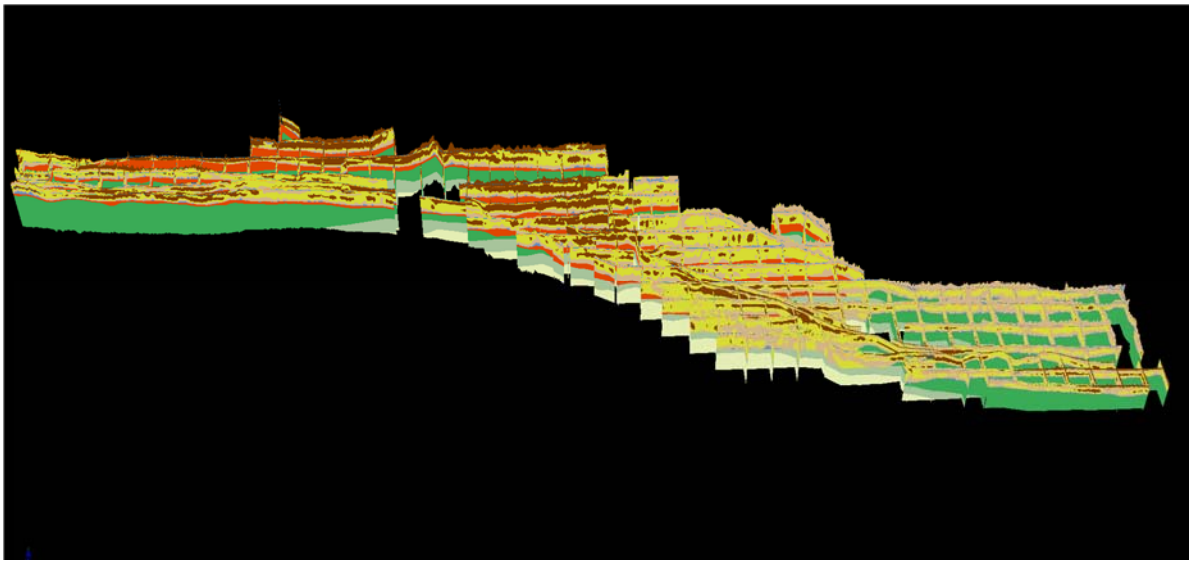
# Hydrogeologic Framework of Selected Areas in the Twin Platte and Central Platte Natural Resources Districts, Nebraska



***Prepared for*:**

**Central Platte Natural Resources District**

215 Kaufman Avenue
Grand Island, NE 68803

*and*

**Twin Platte Natural Resources District**

111 South Dewey Street,
North Platte, NE 69101

*including the*

**Platte River Recovery Implementation Program**

4111 4th Avenue, Suite 6
Kearney, NE 68845

Aqua Geo Frameworks, LLC.

December 28, 2017

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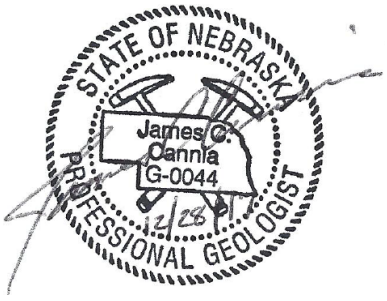
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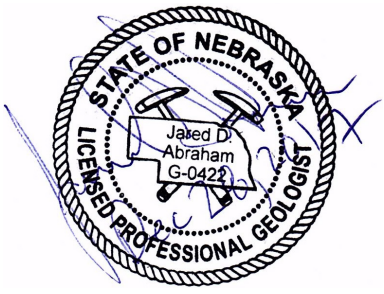
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**Disclaimer: AGF conducted this project using the current standards of the geophysical industry and used in-house quality control standards to produce this geophysical survey and products. The geophysical methods and procedures described in this report 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 geologists 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 AG**

## Executive Summary

Aqua Geo Frameworks, LLC. (AGF) is pleased to submit this report titled "*Hydrogeologic Framework of Selected Areas in the Twin Platte and Central Platte Natural Resources Districts*". The Central Platte Natural Resources District (CPNRD), the Twin Platte Natural Resources District (TPNRD), and the Platte River Recovery Implementation Program (PRRIP) commissioned a subsurface study to increase understanding of the Platte River Basin hydrogeology, particularly within the Big Bend Critical Habitat Reach and the Nebraska Cooperative Republican Platte Enhancement (N-CORPE) areas. AGF entered into an agreement with the Central Platte Natural Resources District (CPNRD) to collect, process, and interpret airborne electromagnetic (AEM) data, in conjunction with other available background information, to develop a 3D hydrogeologic framework of the TPNRD-CPNRD project areas, and to recommend future work to enhance groundwater management activities.

The scope of work for this project was as follows:

**1. SCOPE OF WORK**

**1.1** AGF began project planning upon signing of the project between the parties. This work included flight plans, database development, and review of hydrogeologic and geologic work for the area. The NRD's assisted in providing information such as power line maps, test hole databases, and related aquifer characteristic studies to AGF.

**1.2** At the conclusion of the design process, the maximum line length for the TPNRD AEM survey area was about 75 miles in length in the east-west direction and a minimum of about 5 miles in the north-south direction. For the CPNRD AEM survey area the flight lines were a maximum of about 58 miles east-west and about 15 miles north-south, including the single long PRRIP reconnaissance flight line (about 55 miles long). The N-CORPE AEM block survey consisted of eight 11.5 mile east-west flight lines separated by approximately 1 mile and twelve 8 mile long north-south flight lines, also separated by about 1 mile. In addition, in the center of the N-CORPE AEM flight block there were ten 5.5 mile long east-west flight lines separated by about 0.25 miles. The PRRIP AEM block flight area consisted of eleven 3.4 mile long east-west flight lines separated by about 0.1 miles (about 150 m)

**1.3** An AEM survey utilizing the SkyTEM304M system was flown over the TPNRD-CPNRD areas along reconnaissance-spaced flight lines and in flight blocks over the PRRIP and N-CORPE areas. These flights were provided as preliminary AEM inversions on July 8 to July 15, 2016 and the final AEM data and inversions are included as a product attached to this data report.

**1.4** Approximately 578.1 line-miles (936.5 line-kilometers) were acquired over the TPNRD AEM survey area on July 6-July 10, 2016 , approximately 727.7 line-miles (1,178.8 line-kilometers) were acquired over the CPNRD AEM survey area on July 12-13, 2016, approximately 250.7 line-miles (403.5 line-kilometers) were acquired over the N-CORPE AEM survey area on July 8-9, 2016, and approximately 95.3 line-miles (153.4 line-kilometers) were acquired over the PRRIP AEM survey area on July 10-12, 2016. Status reports of the flying were provided to the Contract Representative of CPNRD on a daily basis, including the areas flown, production rates, and flight plan for the following day.

**1.5** AGF processed and conducted quality assurance and quality control (QA/QC) procedures on all

data collected from the acquisition system. AGF delivered preliminary data and inversions on August 15, 2016.

**1.6** After final processing, 471.5 line-miles (763.8 line-km) of data were retained for the final inversions for the TPNRD AEM survey area. This amounts to a data retention of 81.6%. For the CPNRD, 586.2 line-miles (949.6 line-km) of data were retained (80.6%), for the N-CORPE area, 179.5 line-miles (290.7 line-km) of data were retained (72.1%), and for the PRRIP AEM survey area 83.6 line-miles (135.5 line-km) of data were retained (87.7%). These high rates are the result of careful flight line planning and design. The final inverted georeferenced data are delivered to the CPNRD with this report. After inversion, AGF derived 2D sections, 3D electrical models, and interpreted geologic and hydrogeologic surfaces of the surveyed area.

**1.7** AGF is providing a hydrogeologic framework report that includes maps of aquifer(s), maps of aquifer materials relationships to current test holes and production groundwater wells, estimates of water storage capacity, and maps of estimated potential recharge areas in the block flight areas. This report, as mentioned above, also includes all data (acquired, processed, developed) files. The report is delivered in PDF digital format and the data in ASCII and native formats.

## 2. KEY FINDINGS

**2.1** **Boreholes** - Information from boreholes was used to analyze the AEM inversion results. A total of 657 Conservation and Survey Division (CSD) Test Holes contained lithology information, 644 holes contained stratigraphic information, 178 holes contained geophysical log information. There were also 8,696 Nebraska Department of Natural Resources (NE-DNR) registered well lithology logs. There were 72 boreholes containing stratigraphic information from the Nebraska Oil and Gas Conservation Commission (NOGCC). The well data correlated well with the AEM and provided control to allow hydrogeological interpretations.

**2.2** **Merging 2010 and 2016 AEM Databases** - The TPNRD AEM survey area analysis did not include the flight lines collected and interpreted in the 2010 AEM survey near Keystone, NE. The 2010 inversion results were compared with the 2016 results and they were found to be in agreement. Even though the lines are not directly butted up against each other, the comparison of the AEM data collected in 2016 and the AEM data collected in 2010 show good spatial correlations. While not part of this project, there should be no issues integrating the 2010 AEM data with the 2016 AEM data.

**2.3** **Digitizing Interpreted Geological Contacts** - Characterization and interpretation of the subsurface was performed in cross-section and derived surface grid formats. Contacts between the geologic units were digitized in 2D including: Quaternary (***Q***), Tertiary Ogallala Group (***To***), Tertiary Brule Formation (***Tb***), Cretaceous Pierre Shale (***Kp***), Cretaceous Niobrara Formation (***Kn***), and the Cretaceous Carlile Shale (***Kc***). The interpretive process benefited from the use of CSD, NE-DNR, and NOGCC borehole databases. Once the AEM interpretation of the geological contacts were completed, surface grids of the interpreted geologic formations were then produced. Flight line profiles with interpretations including mapping of Quaternary and Tertiary aquifer materials are included as appendices as well as the interpretative surface grids for the geologic units identified in this report.

**2.4 Resistivity/Lithology Relationship** - Assessment of the sediment character in both the ***Q*** and the ***To*** aquifer systems was conducted to determine the overall composition of the major categories used to define the aquifer and aquitards in the project area. For the ***Q*** and ***To*** aquifer systems, a numerical assessment of the resistivity thresholds was used to characterize non-aquifer (<12 ohm-m), marginal (12-25 ohm-m), aquifer (25-40 ohm-m), and coarse sand-rich intervals (>40 ohm-m). This allowed for the characterization of the ranges of resistivities present in the aquifer units described in this report.

**2.5 Hydrogeological Framework of the TPNRD-CPNRD AEM Survey Area** - The AEM reveals considerable detail and variability within the Quaternary (***Q***) and the Tertiary Ogallala Group (***To***) aquifers. These details indicate the evolution of the structural and depositional environment of the area.

Within the survey area the ***Q*** can be characterized into three somewhat overlapping, but distinct, areas with smaller localized depositional features. These include the Quaternary alluvium (***Qa***) (mostly within the Platte River basins and tributaries), the Quaternary eolian sand (***Qes***) (associated with the sand hills), and the Quaternary Peoria loess (***Qp***) (that cover most of the uplands). The reconnaissance lines image these areas along the lines and the block flights image the spatial variability of these ***Q*** deposits. The ***Qa*** is often thin and saturated throughout the project area. Because it is in direct contact with ***To***, there is often a good hydraulic connection between the two units and with the surface water in the area. The ***Qes*** is found in the TPNRD with small areas in the CPNRD. The ***Qp*** is found on the flanks of the Platte River mostly in the CPNRD and the eastern part of the TPNRD.

Within the survey area the ***To*** can be characterized by a couple general observations. 1) the coarsest areas of the ***To*** occur mostly west of the Cambridge Arch, and 2) the ***To*** is characterized by variability throughout the vertical section. The vertical variability is characterized by zones of marginal aquifer material separating areas of aquifer materials. This is typically arranged with a marginal aquifer material zone in the upper sections of the ***To*** grading into aquifer/coarse aquifer material zone on the order of 200-300 feet thick above another marginal aquifer material zone at the lower sections of the ***To***. This pattern and its variable depth band depicts the evolution of the fluvial system within the ***To*** with the drainage from the west to the east. East of the Cambridge Arch, the ***To*** begins to be characterized by a thinner aquifer material zone on the order of 100-feet. Few instances of coarse aquifer material exist east of the Cambridge Arch within the ***To***. There are areas along the Platte River where the ***To*** aquifer/coarse aquifer materials are in direct contact with the ***Qa*** with no marginal aquifer material zone above the aquifer/coarse aquifer material zones.

**2.6 Estimation of Aquifer Volume and Water in Storage in the N-CORPE and PRRIP AEM Survey Areas –**

**N-CORPE -** Volume and storage estimations were calculated for both ***Q*** and ***To*** aquifer materials which make up the aquifer for the N-CORPE block flight area. A 3D representation of the subsurface derived from the AEM imaging provides users the ability to more accurately identify the total unsaturated and saturated aquifer volumes for the Aquifer. The saturated zones of the aquifer can be analyzed to estimate the amount of groundwater in storage and the amount of extractable water present. For all saturated aquifer materials, which are all ***To*** in N-CORPE, the amount of groundwater in storage is 3,148,190 acre feet and the amount of extractable water is

524,393 acre feet.

**PRRIP -** Volume and storage estimations were calculated for both ***Q*** and ***To*** aquifer materials which make up the aquifer for the PRRIP block flight area. A 3D representation of the subsurface derived from the AEM imaging provides users the ability to more accurately identify the total unsaturated and saturated aquifer volumes for the Aquifer. The saturated zones of the aquifer materials can be analyzed to estimate the amount of groundwater in storage and the amount of extractable water present. For all saturated aquifer material, the amount of groundwater in storage is 281,131 acre feet and the amount of extractable water is 37,072 acre feet.

**2.7 Potential Recharge Zones within the TPNRD-CPNRD AEM Survey Areas** - The greatest possibilities for recharge in the TPNRD and CPNRD reconnaissance line survey areas are the North Platte River, the South Platte River, and the Platte River alluvial valley and the tributary areas that have aquifer and coarse aquifer materials that are near the land surface. Elsewhere, the best possible location for recharge would be where there is a combination of aquifer and coarse aquifer materials at the land surface on the uplands and the Sand Hills that are made of aquifer and coarse aquifer materials with a pathway of similar materials down to the saturated aquifer at depth.

N-CORPE - 3D representations of the subsurface resulting from the N-CORPE AEM block flight investigation illustrate areas of aquifer materials from the bedrock up to the land surface. From this interpretation, a near-surface map was constructed to display the aquifer materials in the first 10 ft. These indicate that the area is nearly homogeneous and is covered by coarse aquifer material with some small areas of aquifer material. It is easy to identify that the area will collect and transmit recharge water downward into the system. However, there is a marginal aquifer layer at approximately 100 feet below ground surface that will slow recharge to lower aquifers.

PRRIP - 3D representations of the subsurface resulting from the PRRIP AEM block flight investigation illustrate areas of aquifer materials from the bedrock up to the land surface. From this interpretation, a near-surface map was constructed to display the ***Q*** aquifer materials in the first 10 ft. These indicate that the area is heterogeneous with areas covered by non-aquifer material, marginal aquifer material, aquifer material and coarse aquifer material. It is easy to conclude that the area will collect and transmit recharge water downward into the system as these are the areas covered in aquifer and coarse aquifer materials. However, there is a marginal aquifer layer at approximately 80 feet below ground surface that will slow recharge to lower aquifers.

**2.8 Value of AEM Data Analysis and Images** - One of the most important key findings from the TPNRD and CPNRD AEM investigation is the value-added products resulting from AEM data derived images. There is a step-by-step process involved from flight planning to final images. While the text of the report may not go into detail on each and every data point or every image provided in the appendices, the value to the user is in the final data analysis and associated images. These final interpretive images allow development of science-based decisions for water management by illustrating the spatial relationships of aquifers. These images can help communicate to boards and to the general public the configuration of the aquifers and how those configurations can impact water quantity and quality.

## 3. Recommendations

Recommendations provided to the TPNRD and N-CORPE - CPNRD and PRRIP in this section are based on the interpretation and understanding gained from the addition of the AEM data to existing information and from discussions with these entities about their management challenges.

3.1 **Additional AEM Mapping** - The aquifer maps provided in this report represent the framework developed for the TPNRD, CPNRD, N-CORPE, and PRRIP AEM survey areas. The detail provided in the hydrogeological interpretation of the AEM survey areas allowed for confident development of a hydrogeologic framework. The interpretations match the CSD test holes and NE-DNR registered wells. The N-CORPE and PRRIP Block areas were mapped in detail by the block flights and provide a detailed hydrogeological framework. The areas of the reconnaissance lines within the TPNRD and the CPNRD only provide detail along the lines. If additional high-resolution information is needed within the TPNRD, CPNRD, N-CORPE, and PRRIP to resolve questions of resource management, it is recommended that additional areas of closely spaced lines or "block flights" be collected to develop further detailed frameworks.

It should be noted that the ability to effectively map detailed boundary conditions and other related information of the aquifer can only happen with block flights. Thus, management needs coupled with the results of the reconnaissance flight lines can indicate the areas where flights are required for effective characterization.

For example, the detailed hydrogeologic frameworks presented in this report for the N-CORPE and PRRIP Block have provided estimates of groundwater storage capacity. This is done by using existing aquifer characteristic information and calculating groundwater in storage and effective yield for the N-CORPE and PRRIP areas. It was noted that the edges of the flight blocks often did not terminate with geological features important to understanding the amount of groundwater in storage and hydrologic connection to the surrounding area extend beyond the flight area boundary. It is recommended that additional closely spaced flight lines for collection of AEM data and interpretation be considered in critical areas like the area between the N-CORPE block flight and the South Platte and Platte Rivers to the north and the Republican River to the south, which will further understanding of the hydraulic connection between the Platte and Republican Rivers.

The PRRIP area could be expanded to collect additional block flight data in all of the areas being considered for retention cell development and managed aquifer recharge. There are many identified areas north and south of the Platte River that were discussed during flight planning for this project. A detailed block flight of all of the lands within the PRRIP interest area will provide detailed information on where best to develop facilities for groundwater storage.

Overall, this will provide the TPNRD, CPRND, and the PRRIP with necessary information to make decisions about aquifer sustainability, depletion to streams, well interference, groundwater withdrawal, and other management considerations.

3.2 **Update the Water Table map** - The groundwater data used in the analyses presented in this report use the 2013 CSD water table data. This water table map is regional in nature and is mapped at 75 foot contour intervals which makes for a low resolution map. It is recommended that a detailed groundwater mapping program be made to create a more detailed map based on at least one measurement per mile with denser measurements near the streams.

3.3 **Siting new test holes and production wells –** The AEM framework maps and profiles provided in this report provide insight in 3D on the relationship between current test holes and production groundwater wells. At the time of this report, the currently available lithology data for the TPNRD, CPNRD, N-CORPE, and PRRIP AEM survey area was used in building the framework maps and profiles. It is recommended that the results from this report be used to site new test holes and monitoring wells. Often test holes are sited based on previous work that is regional in nature. By utilizing the maps in this report, new drilling locations can be sited in optimal locations.

The location of new water supply wells for communities can also use the results in this report to guide development of new water supply wells. Planners should locate wells in areas of greatest saturated thickness with the least potential for non-point source pollution.

3.4 **Aquifer testing and borehole logging** - Additional aquifer tests are recommended to improve estimates of aquifer characteristics. No aquifer properties were available outside the larger cities in the survey area. A robust aquifer characterization program is highly recommended at the state, regional (NRD's), and smaller municipal levels. Aquifer tests can be designed based on the results of AEM surveys, and existing production wells could be used in conjunction with three or more installed water level observation wells.

Additional test holes with detailed, functional, and well calibrated geophysical logging for aquifer characteristics are highly recommended. Many of the test holes with geophysical logs in the TPNRD, CPNRD, N-CORPE, and PRRIP AEM survey area were inadequate. Only a few were calibrated and several had apparent hardware malfunctions. The borehole geophysical logs provided for this investigation demonstrate that additional calibrated and verified geophysical logs are required for future work.

Examples of additional borehole logging would be: flow meter logs and geophysical logs including gamma, neutron, electrical, and induction logs. Detailed aquifer characteristics can be accomplished with nuclear magnetic resonance logging (NMR). This is a quick and effective way to characterize porosity and water content, estimates of permeability, mobile/bound water fraction, and pore-size distributions with depth. This is very cost effective when compared to traditional aquifer tests. There has been some work done previously with NMR logging and surface NMR systems in the CPNRD and the TPNRD as research to prove the technique and calibrate the results. This technique is ready for application to aquifer characterization of the TPNRD and the CPNRD areas with the goal to select sites, collect and analyze the data, and create maps of aquifer characteristics to supplement the COHYST maps.

3.5 **Recharge Zones** - The TPNRD, CPNRD, N-CORPE, and PRRIP AEM hydrogeologic framework provides areas of recharge from the ground surface to the groundwater aquifer. The block flights of AEM data acquisition provided the most detailed information for understanding recharge in the N-CORPE and PRRIP areas. It is recommended that additional AEM data be collected and interpreted along the reconnaissance lines in promising locations utilizing closely-spaced flight lines using an AEM system that has near-surface resolution. It is further recommended that future work integrate new soils maps with the results of this study to provide details on soil permeability, slope, and water retention to provide a more complete understanding of the transport of water from the land surface to the groundwater aquifer.

3.6 **Mapping Well Production Data**- Develop maps of annual well production per year that can be used to make a comparison to the aquifer mapped using AEM. This would provide data to make an analysis of the available water supply and its use. It will also track well performance related to boundary conditions within the aquifer system. The NRDs have implemented groundwater management in the Districts and an annual report on well production would give the Boards and the public information on changes that are potentially needed for management, particularly during periods of drought. This can provide improved knowledge on groundwater management.

3.7 **Understanding Recharge and Increased Water Table Levels South of the Platte River** – Use AEM to understand recharge from the canal systems on the south side of the Platte River through the loess hills and back to the river. This is an activity that will require detailed mapping and analysis to understand the groundwater storage and flow in a difficult area complicated by groundwater level increases due to storage and canal leakage over decades.

## 4. Deliverables

In summary, the following are included as deliverables:

- Raw EM Mag data Geosoft database and ASCII *.xyz
- SCI inversion Geosoft database and ASCII *.xyz
- Borehole Geosoft databases and ASCII *.xyz
- Interpretations Geosoft database and ASCII *.xyz
- Raw Data Files - SkyTEM files *.geo, *skb, *.lin
- ESRI ArcView and Geosoft grid files – surface, topo, etc.
- 3D fence diagrams of the TPNRD/CPNRD/N-CORPE/PRRIP survey lines.
- 3D voxel models as ASCII *.xyz and *.gdb for the N-CORPE and PRRIP AEM survey areas

KMZs for the TPRND, CPNRD, N-CORPE, and PRRIP AEM survey flight lines
Profile Analyst sessions for the Profiles and 3D grids for the TPNRD-CPNRD AEM survey area analysis

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## List of Abbreviations

| | |
|---|---|
| 2D | Two-dimensional |
| 3D | Three-dimensional |
| $A*m^2$ | Ampere meter squared |

| | |
|---|---|
| AEM | Airborne Electromagnetic |
| AGF | Aqua Geo Frameworks, LLC |
| ASCII | American Standard Code for Information Interchange |
| ASR | Aquifer Storage and Recovery |
| bls | Below Land Surface |
| BOA | Base of the aquifer system |
| cm | Centimeter |
| CPNRD | Central Platte Natural Resources District |
| CSD | Conservation and Survey Division |
| Co | Company |
| COHYST | Platte River Cooperative Hydrology Study |
| dB/dt | Change in amplitude of magnetic field with time |
| D | Down |
| DEM | Digital Elevation Model |
| DOI | Depth of Investigation |
| DGPS | Differential global positioning system |
| ENWRA | Eastern Nebraska Water Resources Assessment |
| ft | Feet |
| ft/day | foot per day |
| $ft^2$/day | Square feet per day |
| ft/year | foot per year |
| Fm | Geological Formation |
| FT | Fourier Transform |
| GIS | Geographic Information System |
| GP | Geological Group |
| gpd/ft | Gallon per day per foot |
| gpm | Gallons per minute |
| HEM | Helicopter Electromagnetic |
| Hz | Hertz (cycles per second) |
| IGRF | International Geomagnetic Reference Field |
| IMP | Integrated Management Plan |
| ***Kc*** | Cretaceous Carlile Shale |
| Km/km | Kilometers |
| KMZ/kmz | Keyhole Markup language Zipped file |
| ***Kd*** | Cretaceous Dakota Group |
| ***Kgg*** | Cretaceous Greenhorn Limestone and Graneros Shale |
| ***Kn*** | Cretaceous Niobrara Formation |
| ***Kp*** | Cretaceous Pierre Shale |
| $K_r$ | Horizontal hydraulic Conductivity |
| $K_v$ | Vertical hydraulic Conductivity |
| LCI | Laterally-Constrained Inversion |
| m | Meters |
| MAG | Magnetic (data); Magnetometer (instrument) |
| MAR | Managed Aquifer Recharge |
| MCG | Minimum curvature gridding |
| mg/L | Milligrams per liter |
| µS/cm | Micro-Siemens per centimeter |
| N-CORPE | Nebraska Cooperative Republican Platte Enhancement |

| | |
|---|---|
| NAD83 | North American Datum of 1983 |
| NAVD88 | North American Vertical Datum of 1988 |
| NE | Nebraska |
| NED | National Elevation Dataset |
| NE-DNR | Nebraska Department of Natural Resources |
| NMR | Nuclear Magnetic Resonance |
| NOGCC | Nebraska Oil and Gas Conservation Commission |
| NRD | Natural Resources Districts |
| NRCS | National Resources Conservation Service |
| nT | Nano-Tesla |
| OM | Geosoft Oasis montaj |
| Ohm-m | Ohm-meter |
| PA | Profile Analyst |
| PFC | Primary Field Compensation |
| PLNI | Power Line Noise Intensity |
| PRRIP | Platte River Recovery Implementation Program |
| ***Q*** | Quaternary |
| ***Qa*** | Quaternary Alluvium |
| QA/QC | Quality Assurance/Quality Control |
| ***Qes*** | Quaternary Eolian Sands |
| ***Qp*** | Quaternary Peoria Loess |
| RA | Remaining Area |
| RMF | Residual Magnetic Field |
| Rx | Receiver |
| SCI | Spatially-Constrained Inversion |
| SNR | School of Natural Resources |
| SPCS | State Plane Coordinate System |
| STD | Standard Deviation |
| ***Sy*** | Specific yield |
| $T_2$ | Transvers components of magnetization decay of the Nuclear Magnetic Resonance |
| ***Tb*** | Tertiary Brule Formation |
| ***T*** | Tertiary |
| TBNRD | Tri-Basin Natural Resources District |
| ***Tc*** | Tertiary Chadron Formation |
| TDEM | Time-Domain Electromagnetic |
| TDS | Total dissolved solids |
| TEM | Time-Domain Electromagnetic |
| ***To*** | Tertiary Ogallala Group |
| TPNRD | Twin Platte Natural Resources District |
| ***Twr*** | Tertiary White River Group |
| Tx | Transmitter |
| U | Up |
| UNL | University of Nebraska Lincoln |
| USDA | United States Department of Agriculture |
| USGS | United States Geological Survey |
| UTM | Universal Transverse Mercator |
| XYZ | ASCII file type |
| yr | year |

# 1 Introduction

## 1.1 Purpose of Current Project

The Central Platte Natural Resources District (CPNRD), the Twin Platte Natural Resources District (TPNRD), and the Platte River Recovery Implementation Program (PRRIP) commissioned a subsurface study to increase understanding of the Platte River Basin hydrogeology, particularly within the Big Bend Critical Habitat Reach and the Nebraska Cooperative Republican Platte Enhancement (N-CORPE) areas. The aerial extent of the investigation is presented in Figure 1-1. The project includes detailed information on the subsurface geology to assist in understanding the groundwater quality, surface water/groundwater interaction, aquifer relationship to existing test holes and groundwater wells, amount of groundwater in storage (only in the block flight areas of the N-CORPE and the PRRIP), effects of groundwater pumping and potential groundwater recharge and retention cell development areas along the flight lines. An airborne electromagnetic (AEM) survey was selected to assist in the development of a 3D hydrogeologic framework of these project areas and recommend future work to enhance groundwater management activities (Figure 1-2). The main funding for this project was provided by a two year grant from the Nebraska Environmental Trust and additional funding from the PRRIP.

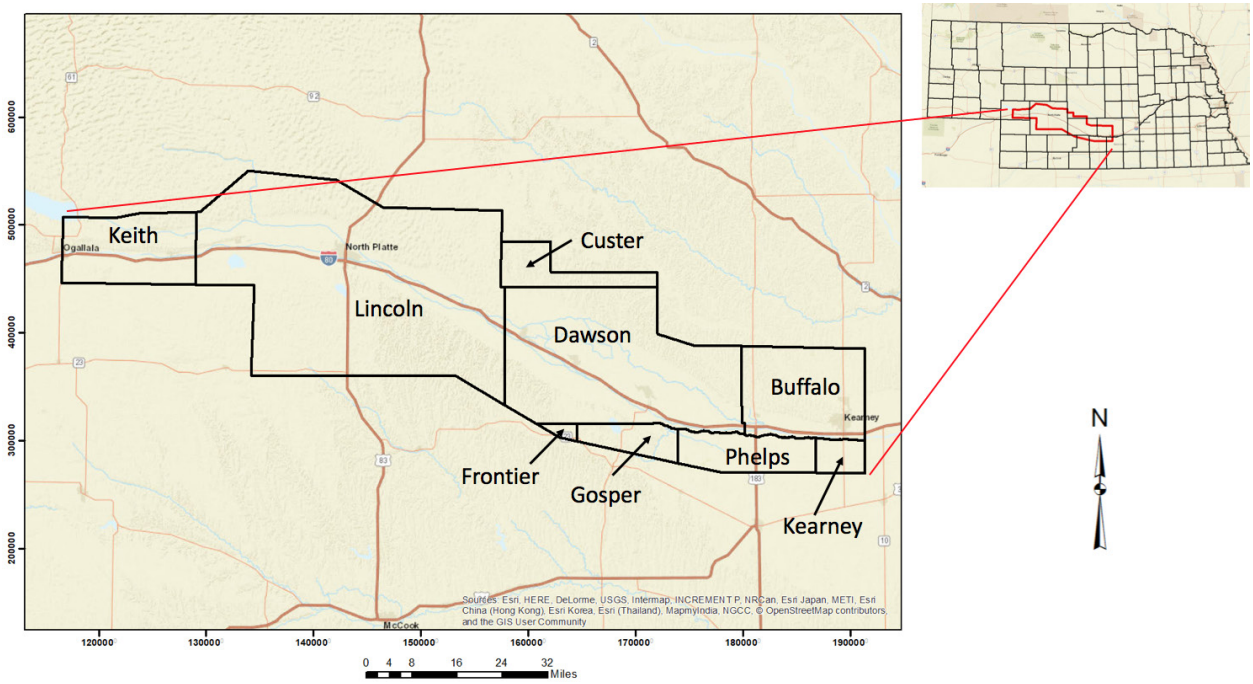



**Figure 1-1. Map of Nebraska counties, indicating the location of the Twin Platte and Central Platte Natural Resources Districts (TPNRD, CPNRD) airborne electromagnetic (AEM) surveys with an inset of the project area. The map projection is NAD 1983, Nebraska State Plane Coordinate System, code 2600, US feet.**

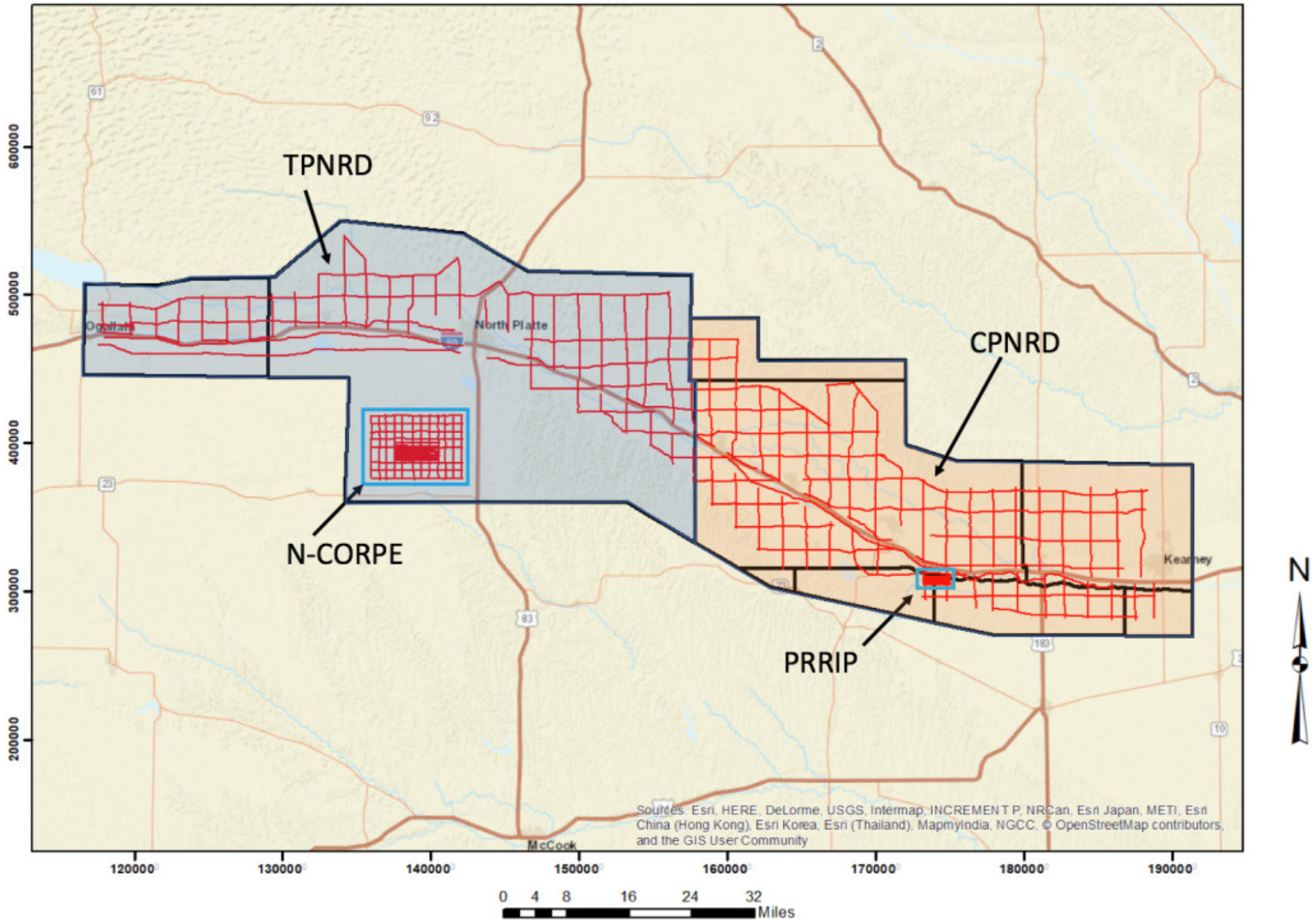



**Figure 1-2. Map of the AEM survey area including flight lines (in red) indicating the location of the Central Platte Natural Resources District (orange shading) with Platte River Recovery and Implementation Program (PRRIP) area outlined in blue, Twin Platte Natural Resources District (blue shading) including the Nebraska Cooperative Republican Platte Enhancement (N-CORPE) area outlined in blue. The map projection is NAD 1983, Nebraska State Plane Coordinate System, code 2600, US feet.**

## 1.2 Background

**Central Platte Natural Resources District**

In 1972, the State of Nebraska legislature combined over 150 special interest entities and management districts into the NRD system. NRD responsibilities include flood mitigation, erosion control, and groundwater management. NRD groundwater management includes both water quality and water quantity aspects. CPNRD adopted its groundwater quality controls in 1987, with a focus on reducing nitrate contamination. The program is having a beneficial impact on the nitrate levels in the district for groundwater over the 30 years of its implementation. Producers have participated in implementing the best management practices with efficient technologies for application of fertilizer and water. Nitrates have been lowered by 2014 to an average of 14.24 parts per million down from 19.24 when the program was initiated.

Groundwater quantity is managed in 24 groundwater supply management areas within the CPNRD. The goal of the quantity management efforts are "to assure an adequate supply of water for feasible and beneficial uses through proper management, conservation, and development and utilization of the districts water resources" (CPNRD, 2017). The CPNRD works cooperatively with the State of Nebraska Department of Natural Resources to manage groundwater and surface water where it is hydrologically connected. This is done to improve the reliability and availability of water resources. The Big Bend Critical Habitat Reach, which extends from Lexington to Chapman, NE, is an example of water management that combines multiple state, NRD, and other entities that utilize conjunctive management strategies. Involved entities work together as the PRRIP. The PRRIP and CPNRD want to understand the heterogeneity of the subsurface geologic materials and develop an estimate of groundwater in storage. The area mapped is to be evaluated for managed aquifer recharge (MAR) and surface water storage facility. The hydrogeologic framework developed in the AEM surveys for this project provides additional insight on all three areas of management for the CPNRD. Additional information on water management efforts is available at the CPNRD and PRRIP websites.

**Twin Platte Natural Resources District**.

The TPNRD administers multiple programs for a groundwater quality, quantity, and integrated management. These activities include administration of the Integrated Management Plan (IMP), offset water for the IMP, conjunctive management of groundwater & surface water, cooperative programs with Irrigation Districts within the TPNRD, cost sharing for irrigation systems, best management practices for irrigation, and water quality monitoring.

The TPNRD currently has 317,696.84 certified irrigated acres in the district. TPNRD also participates in the N-CORPE project which is the largest stream flow enhancement project of its kind in the state and provides water for the Republican and Platte river basins. N-CORPE was mapped as a subset of the AEM survey for the TPNRD. The dense flight block for N-CORPE provides a detailed representation of the hydrogeology of the flight block and provides an estimate of groundwater in storage. The hydrogeologic framework developed in the AEM surveys for this project provides insight on important areas of management for the TPNRD.

Use of AEM technology to map and evaluate groundwater resources has gained momentum over the last 20 years in the United States and abroad. The state of Nebraska has been on the forefront of implementing AEM for water resources management over the last decade with projects across the state in a variety of geologic settings. Previous work for the TPNRD included mapping the Western Canal area on the South Platte River and the Keystone area on the North Platte River (USGS-CGGSC, 2014, Hobza et al., 2014). This study provided detailed information on the elevation of the base of aquifer. The new information from the AEM survey which was gathered and interpreted for this report builds on the previous work and provides additional details of the subsurface relating to the geologic materials above the bedrock.

Additional AEM data has been collected and interpreted in the western portions of Nebraska for the North Platte and South Platte Natural Resources districts (Smith et al., 2009a; Smith et al., 2010; Abraham et al., 2010; Abraham, 2011a; Abraham et al., 2012; Cannia et al., 2012; USGS-CGGSC; 2014; and Hobza et al., 2014). The AEM technique has proven valuable in the determination of the Base of Aquifer and the configuration of the aquifers. The AEM data has also provided information directly into a groundwater model in the NPNRD (Peterson et al., 2015)

Other areas in Nebraska that have been mapped with AEM in recent years including many projects under the Eastern Nebraska Water Resources Assessment (ENWRA) which has coordinated efforts between area Natural Resources Districts (NRDs), the Nebraska Conservation and Survey Division (CSD), the U.S. Geological Survey (USGS), and Aqua Geo Frameworks, LLC (AGF) in support of several projects designed to characterize the hydrogeology across the eastern portion of the state (Smith et al., 2008; Smith et al., 2009b; Abraham et al., 2011b; Hanson et al., 2012; Korus et al., 2013a; Divine and Korus, 2013; Carney et al., 2014a; Carney et al. 2014b; Abraham et al., 2015; Carney et al., 2015a; Carney et al., 2015b).

In 2017, a study led by AGF provided information to improve the understanding of the hydrogeologic framework including areas of recharge to the aquifer and details for well head protection areas in the Bazile Creek Groundwater Management area (AGF, 2017a). Additionally, in 2017 another study led by AGF provided detailed 3D hydrogeologic framework for the western portions of Sarpy County characterized by eroded Dakota Sandstone aquifers overlain with glacial deposits (AGF, 2017b). Additional studies in the Lower Loup, Lewis and Clark, and Lower Elkhorn NRDs were completed to understand the complex glacial and non-glacial aquifers in their districts (AGF 2017c; AGF, 2017d; AGF, 2017e). The Lower Platte North NRD report was completed in August 2017 and was designed to support groundwater management efforts in the district (AGF, 2017f). The Lower Platte South NRD report, completed in November 2017, was designed to support groundwater management efforts (AGF, 2017g). Thus, AEM surveys of the glacial terrain of Nebraska have followed a progressive, long-term plan spanning nearly 10 years. This body of work shows continuing advancements in the science and application of AEM to support groundwater management.

In addition to the AEM and Magnetic Total Field data acquired during this investigation, multiple resources were used to develop the presented hydrogeologic framework and subsequent recommendations for potential recharge areas and well locations. Data and findings from previous

studies, along with geologic descriptions and geophysical data were utilized to develop the hydrogeologic framework presented herein.

## 1.3 Description of the CPNRD-TPNRD-N-CORPE-PRRIP AEM Project Area

The areas of interest in the CPNRD, TPNRD, N-CORPE, and PRRIP AEM survey area described above includes approximately 3,100 square miles and is encompassed by the reconnaissance lines spaced approximately 3 miles apart in a north-south and east-west orientation (Figure 1-2). The survey area lies within Keith and Lincoln counties in the TPNRD and Buffalo, Custer, Dawson, Frontier, Gosper, Kearney, and Phelps counties in the CPNRD survey area. The AEM survey area is part of seven distinct ground water regions: the Sand Hills, the Platte River Valley, Panhandle Tablelands, East Central Dissected Plains, Republican River Valley and Dissected Plains and South-Central Plains (Pederson et al., 1986). The geologic history of these ground water regions accounts for the great complexity and heterogeneity of the unsaturated zone, aquifer units, and bedrock in this part of central Nebraska. Figure 1-3 shows the major streams and the associated river basins. AEM is one tool which has the capacity to gather great amounts of data about such a complex geologic setting. The towns of Ogallala, North Platte, Lexington and Kearney lie within the project area.

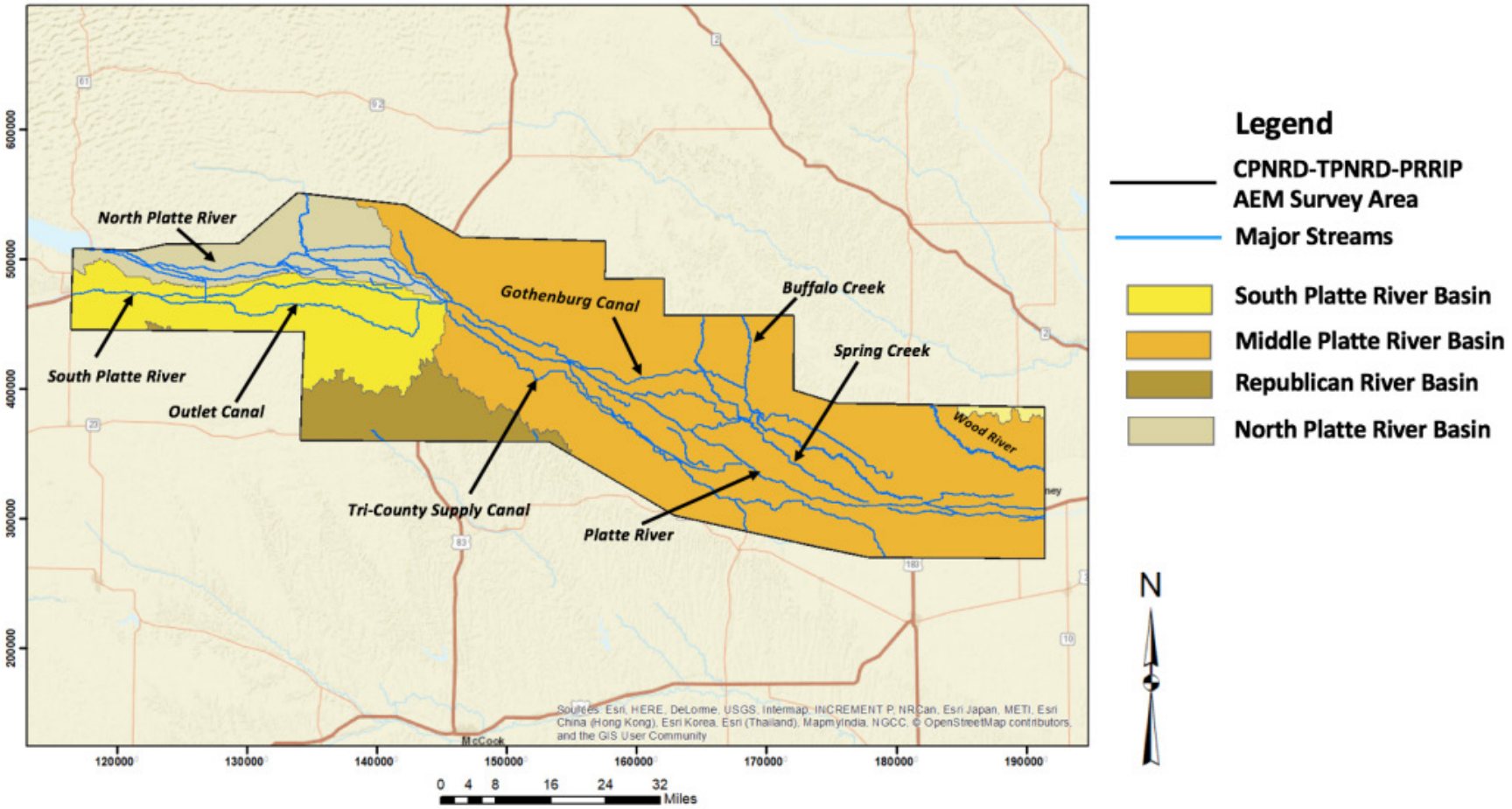



**Figure 1-3. Map of major river basins within the TPNRD- CPNRD AEM survey areas. The map projection is NAD1983, Nebraska State Plane Coordinate System (SPCS83), code 2600, feet.**

# 2 Project Area Hydrogeology

The AEM survey's objective was to map the geology and related hydrogeology of Quaternary (***Q***) and Tertiary Ogallala (***To***) deposits and the primary underlying bedrock that serves as a groundwater confining unit. Background geology and hydrogeology for the project area are discussed in more detail in Johnson (1960), Gutentag et al (1984), Peterson (2007), Carney (2008), Young et al. (2011), and additional authors found in the following text. The following narrative is based primarily on the findings from these reports. For more detailed information the reader is directed to the Cooperative Hydrology Study COHYST Hydrostratigraphic Units and Aquifer Characterization Report, 2006 (Cannia et al., 2006). This report presents a brief overview of the geology and hydrogeology of the project area pertinent to the AEM investigation and interpretation analysis.

## 2.1 Geologic Setting

The geology of the project area largely is Quaternary (***Q***) eolian sand and loess on the uplands, and Quaternary alluvium in the valleys, both of which overlie Tertiary bedrock. The valleys of the North Platte, South Platte, and Platte Rivers predominate the project area. These three valleys lie within two unique eolian deposits—high relief sand dunes and dissected loess hills of varying thickness (Young et al., 2011). The high relief dune sand of the Nebraska Sand Hills largely occupies the uplands north of the river valleys but west of about the 100° longitude, as well as an area south of the South Platte River and southwest of the city of North Platte, Nebraska. Peoria loess occupies most of the remaining areas of the uplands in the project area. Undifferentiated alluvium and colluvium deposits occupy much of the incised valleys of the uplands.

### *2.1.1 Physiography and Regional Geologic Setting*

As mentioned in the Section 1.2, AEM data were collected over the North Platte, South Platte, and Platte River valleys (unless specific to a valley, herein collectively referred to as the Platte River or Platte River valley) and also the N-CORPE. The TPNRD-CPNRD survey areas, over 3,100 $mi^2$, lie in west-central Nebraska. This survey area lies mostly within the Platte River valley between the cities of Ogallala and Kearney, Nebraska and within Groundwater Region 2—the Platte River Valley (Gosselin et al., 1996). Some flight lines of this survey extend slightly into small portions of adjacent groundwater regions—Region 8, the East-Central Dissected Plains; Region 9, the Republican River Valley and Dissected Plains; Region 10, the Sand Hills; Region 4, the South-Central Plains; Region 7, the Southern Panhandle Tablelands; and Region 5, the Southwestern Tablelands (Gosselin et al., 1996; Skipton et al, 2012). The N-CORPE area (roughly 170 $mi^2$) lies in Groundwater Region 5, the Southwestern Tablelands.

Surficial geology in the TPNRD/CPNRD AEM survey area ranges from Quaternary eolian sand (***Qes***), Peoria loess (***Qp***), and alluvium (***Qa***) to Tertiary Ogallala (***To***) bedrock. The upland areas mostly consist of the ***Qes*** and ***Qp*** deposits overlying the ***To*** bedrock (Dreeszen et al., 1973; Eversoll et al., 1988; Diffendal, 1991). Within the North Platte, South Platte, and Platte River valleys, Quaternary alluvial fan deposits along the valley walls can overlie the ***Qa***—silty alluvium and alluvial sand and gravel which makes up much of the Platte River deposits (Young et al., 2011). Underlying these Quaternary deposits, ***To***

bedrock unconformably overlies deposits of the White River Group (***Twr***)—the Chadron Formation (***Tc***) and the Brule Formation (***Tb***) —as well as the Upper Cretaceous Pierre Shale Formation (***Kp***) and Cretaceous Niobrara Formation (***Kn***) (Young et al., 2011).

Bedrock geology in the AEM survey area includes the ***To***, the ***Twr***, and the ***Kp*** (Figure 2-1). Only the sediments of the ***To*** are considered aquifer materials in the project area as the ***Twr***, ***Kp,*** and ***Kn*** are considered aquicludes. Geologic structures in the AEM survey area include the Cambridge arch (Moore and Nelson, 1974). This structure affected erosion of the Mesozoic bedrock units. Cenozoic deposition and erosional surfaces have cut into the ***Kp*** and the Cretaceous Niobrara Formation (***Kn***).

Unconsolidated sand and gravel to semi-consolidated and consolidated sandstone and siltstone deposits of the ***To*** comprise the predominant hydrogeologic bedrock in the project area. Siltstone, sandstone, and claystone of the ***Twr*** crops out at one area along the south side of the North Platte River (Diffendal, 1991; Joeckel et al., 2011). The ***Twr*** can serve as the basal confining unit to saturated ***Qa***, ***Qes***, and ***To*** deposits.

### *2.1.2 Surficial Geology*

The surficial geology of the AEM project area is a complex assortment of ***Qes***, ***Qp***, and undifferentiated ***Qa*** deposits with outcrops of ***To*** and one area of ***Twr***. The ***To*** bedrock units mostly crop out along the North and South Platte River valley walls, the south side of the Platte River Valley near North Platte, and locally on tablelands and tributaries south of the South Platte River. Where ***To*** bedrock does not outcrop, these deposits underlie undifferentiated ***Qes***, ***Qp***, and ***Qa*** deposits.

Platte River alluvial deposits (***Qal***) lie within the Platte River valley and its tributaries. These deposits comprise the largest geomorphic feature of the project area. ***Qa*** deposits consist of unconsolidated gravel in a sandy or silty matrix interbedded or underlying sandy silt to silty sand (Condon, 2005) or sand and gravel deposits with local silty sediments (Young et al., 2011, 2012, and undated). The ***Qa*** deposits range from Holocene to Plio-Pliestocene and directly overlie ***To*** in the valleys. Outside the valleys the surficial geology of the upland areas consists of mixtures of ***Qes*** and ***Qp***, also which directly overlie ***To*** deposits.

Bedrock outcrops in the project area are almost exclusively ***To***. Diffendal (1991) reported that the only ***Twr*** outcrop near the AEM survey area occurs on the south side of the North Platte River Valley, near Lake McConaughy. However, ***To*** actually outcrops along the valley walls on the north and south sides of the North Platte River Valley near Lake McConaughy. In the South Platte River valley, ***To*** crops out frequently on the north valley wall, but locally along the south valley wall. Outcrops of ***To*** also occur locally in areas south of the South Platte and Platte Rivers (Diffendal, 1991). The hydrogeological sequence of the project area is presented in Figure 2-2.

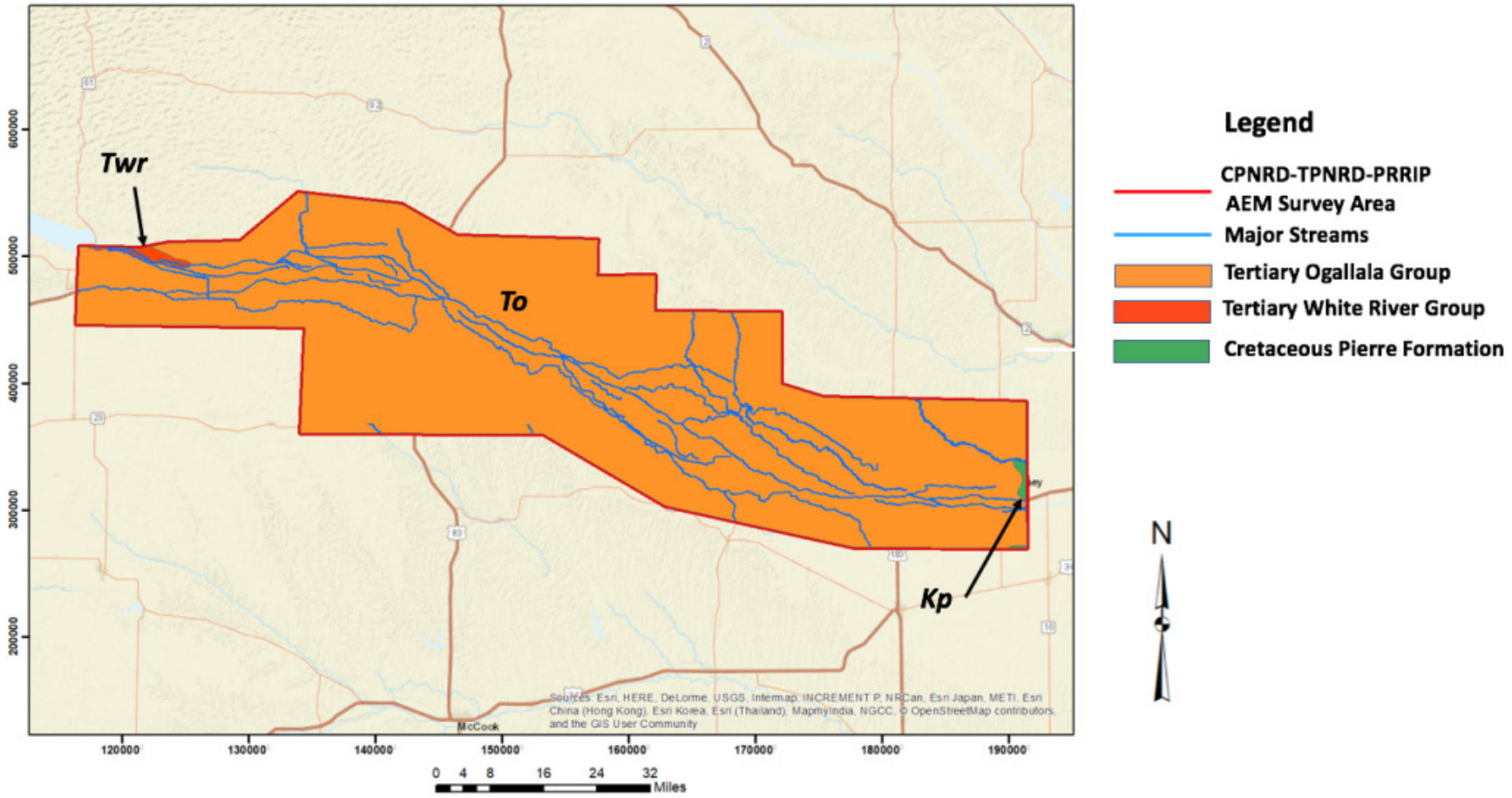



**Figure 2-1. Bedrock map of TPNRD-CPNRD AEM survey area (red polygon), modified from Burchett (1986). The Tertiary Ogallala Group (*To*) dominates the area with a small amount of Tertiary White River Group (*Twr*) along the North Platte River to the west and a small area of Cretaceous Pierre Formation (*Kp*) on the east. Projection is NAD 1983, Nebraska State Plane Coordinate System, code 2600, Feet.**

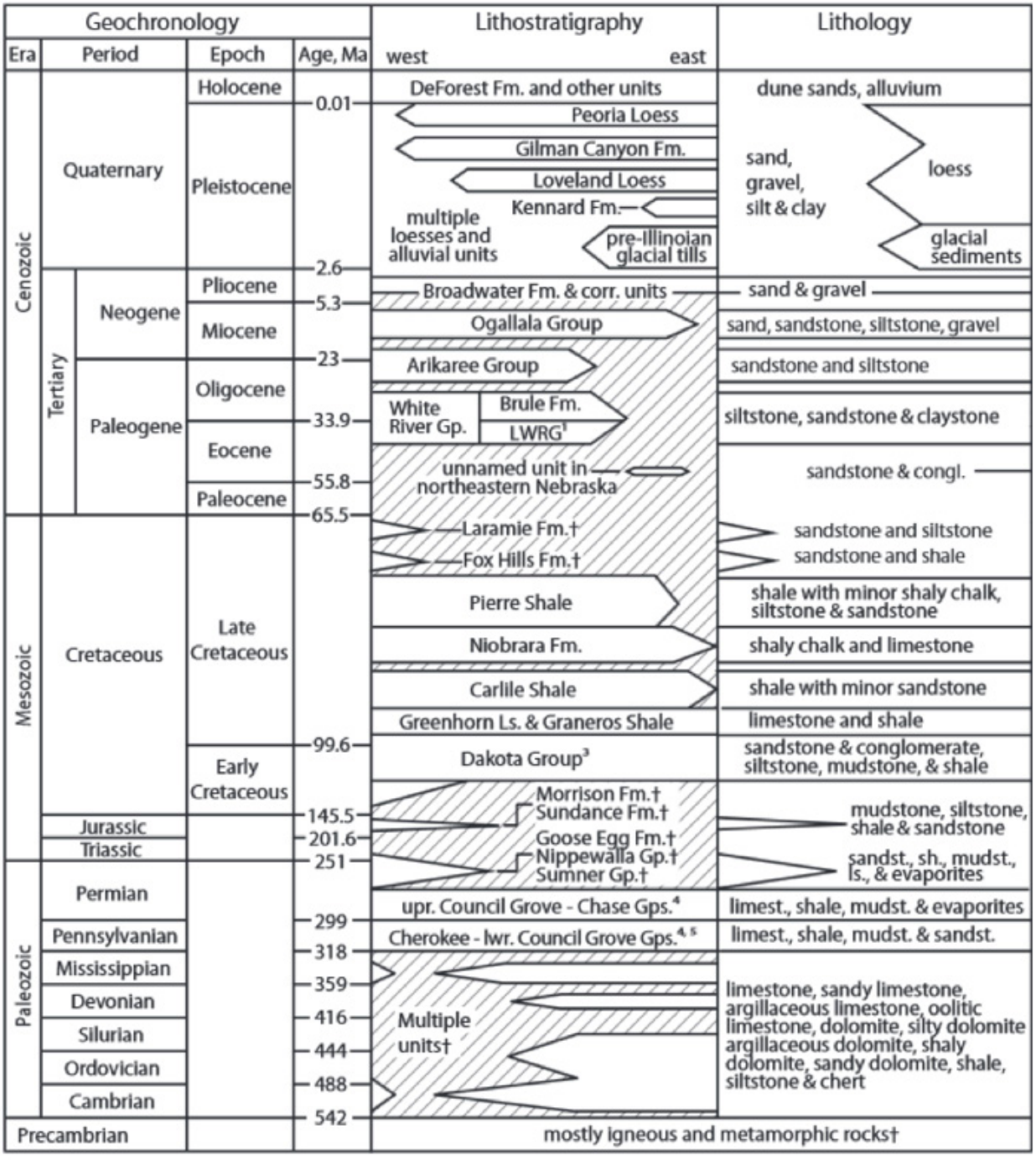



**Figure 2-2. Geologic time scale with lithostratigraphic sequence underlying Nebraska, modified from Korus and Joeckel (2011).**

### 2.1.3 Tertiary Geology

The predominant Tertiary deposit of the project area is the Miocene Ogallala Group (***To***). The ***To*** is generalized for this report but predominantly is a fluvial material comprised of a complex fining-up sequence of massive siltstones and variably cemented sandstones, pebbly sand, pebbly sandstone, gravel, and conglomerate (Diffendal, 1991; Joeckel et al., 2011). Gravel and coarse sand are poorly sorted and abundant south of the North Platte and Platte Rivers (Diffendal, 1991). In the western part, the ***To*** fines upward with conglomerates, sandstone, and siltstones toward the base. Easterly, the ***To*** contains higher amounts of silt, clay, and limestone (Condon and references therein, 2005). The ***To*** primarily consists of erosional remnants that rest unconformably on underlying Cretaceous strata (Burchett, 1986). Thicknesses of the ***To*** are variable but can exceed 300 ft in parts of the project area. Lithology of the ***To*** changes locally due to the unconformity between the ***To*** and overlying ***Q*** deposits (Condon, 2005). Where saturated, the ***To*** typically serves as a regional aquifer.

As mentioned above, a small portion of the ***Twr*** crops out on the south side of the North Platte River northwest of Ogallala (Diffendal, 1991; Joeckel et al., 2011). The ***Twr*** primarily consists of interbedded massive siltstone, sandstone, and claystone which, where fractured, can serve as an aquifer. Most of ***Twr*** is composed of the Tertiary Brule Formation (***Tb***). CSD test wells indicate that predominantly ***Tb*** is encountered at depth in the CSD test holes that encounter the ***Twr***. The Tertiary Chadron (***Tc***) occasionally was seen in well cuttings elsewhere in the project area (e.g., CSD test holes 9-H-78 and 15-H-78). Bjorklund (1957) and Barrash (1986) reported permeable zones in the ***Twr*** underlying parts of Lodgepole Creek in Cheyenne County, Nebraska (about 50 miles west of the project area). Steele et al (2014) reported (1) a miles long sand and gravel channel in the ***Twr*** and (2) a hydraulic connection between shallow fractures in the ***Twr*** and overlying ***Qa*** deposits. Similar sand and gravel channels and permeable zones in the ***Twr*** could underlie the North Platte River in the project area. However, this has not been mapped. Throughout this report the ***Tb*** is the prominent unit within the ***Twr***.

### 2.1.4 Cretaceous Geology

The Upper Cretaceous Pierre Shale (***Kp***) underlies the ***To*** and/or the ***Tb*** in much of the area, with the exception of the Cambridge Arch (Moore and Nelson, 1974) where the Cretaceous Niobrara Formation underlines the ***To*** and/or the ***Tb***. Where the ***To*** is saturated, it acts as a regional aquifer and where the ***Tb*** is absent, the ***Kp*** or ***Kn*** is the lower confining unit.

On a state-wide scale, the ***Kp*** deposits tend to dip to the west (Condon, 2005; Anna, 2012) and are predominantly a mixture of fissile clay shales with local beds of calcareous silty shale, bentonite, marl, claystone, sandy shale, and shaly sandstone (Dreeszen et al., 1973; Eversoll et al., 1988). Additional Upper Cretaceous bedrock underlies the ***Kp***, the Niobrara Formation (***Kn***), and the Carlile Shale (***Kc***). The ***Kn*** is a shalely chalk to limestone that is typically not considers an aquifer. However, some areas of eastern Nebraska, the ***Kn***, where fractured, is known to yield water for irrigation purposes (Gutentag et al., 1984; Miller and Appel, 1997). The ***Kc*** is a marine shale and is not considered an aquifer in Nebraska. Other Late and Early Cretaceous units underlie the study area including the Greenhorn Limestone and the Graneros Shale (***Kgg***) and the Dakota Group (***Kd***). These units are underlain by many

other units from Early Cretaceous to the Paleozoic. These deposits are not described in this report because these deeper units are not pertinent to most hydrogeological systems in the project area.

## 2.2 TPNRD-CPNRD AEM Project Area Hydrogeologic Characteristics

The primary hydraulic features in the project area are related to the three major streams—the North Platte, South Platte, and Platte Rivers—and several large surface-water canals/reservoirs (NE-DNR, 2017a). The Platte River is a series of gaining and losing reaches and hydraulically connected to the ***Qal***. In the project area, the Platte River mostly is a series of gaining reaches with groundwater influx toward and into the Platte River (Figure 2-3; Korus et al., 2013b). Consequently, groundwater seepage into the Platte River adds to discharge downstream.

Figure 2-3 shows a highly generalized regional groundwater flow paths around the project area (Korus et al., 2013b). Groundwater table contours are for informative purposes only and not meant to explicitly represent modern groundwater-flow regimes as the contour interval is 75 ft.

Many manmade diversions from and returns to the Platte River create myriad flow regimes in the river. The mean daily discharge for Water Year 2016 at an upstream Platte River stream gage (Maxwell, gaging station number 228500 (NE-DNR, 2017b)) was 1,391 cubic-feet/sec ($ft^3/s$). The mean daily discharge for Water Year 2016 at a downstream Platte River stream gage (Platte River at Kearney, Nebraska; USGS gage 06770200 (USGS, 2017a)) was 3,024 $ft^3/s$. These data indicate that within the AEM survey area, discharge into the Platte River generally gains in a downstream direction. However, stream flow regimes are complicated with canals (e.g. Tri-County and Thirty Mile Canals of the Nebraska Department of Natural Resources) that divert from, and empty into, the Platte River. The largest (Tri-County and Thirty Mile canals) lie atop the uplands along the south side of the Platte River valley. Smaller canals (e.g., the Gothenburg Canal) seasonally divert from either side (north or south banks) of the Platte River and generally lie within the Platte River valley.

The intricate series of irrigation canals and reservoirs mentioned above were constructed from numerous diversions along the Platte River. Most canals and their supply reservoirs lie on upland areas near the southern side of the Platte River valley. Seepage from surface-water irrigation canals in the western half of the project area, estimated at about 40 percent of the diversions (Carney, 2008), and seepage from reservoirs have created complex groundwater divide and flows within the project area (Figure 2-3; Ponte, 1995a, 1995b; Young et al, 2016a). This seepage has caused groundwater levels to rise near the reservoirs and has subsequently effected groundwater-flow direction. Groundwater flow gradients near the canals and reservoirs are steeper than those in other upland areas or within the ***Qal*** itself (Ponte, 1995a, 1995b). Therefore, groundwater gradients near the supply canals indicate that groundwater moves more directly from the canals toward the Platte River, rather than along the canals and then into the Platte River such as the northern Platte River valley where smaller canals are present or absent altogether.

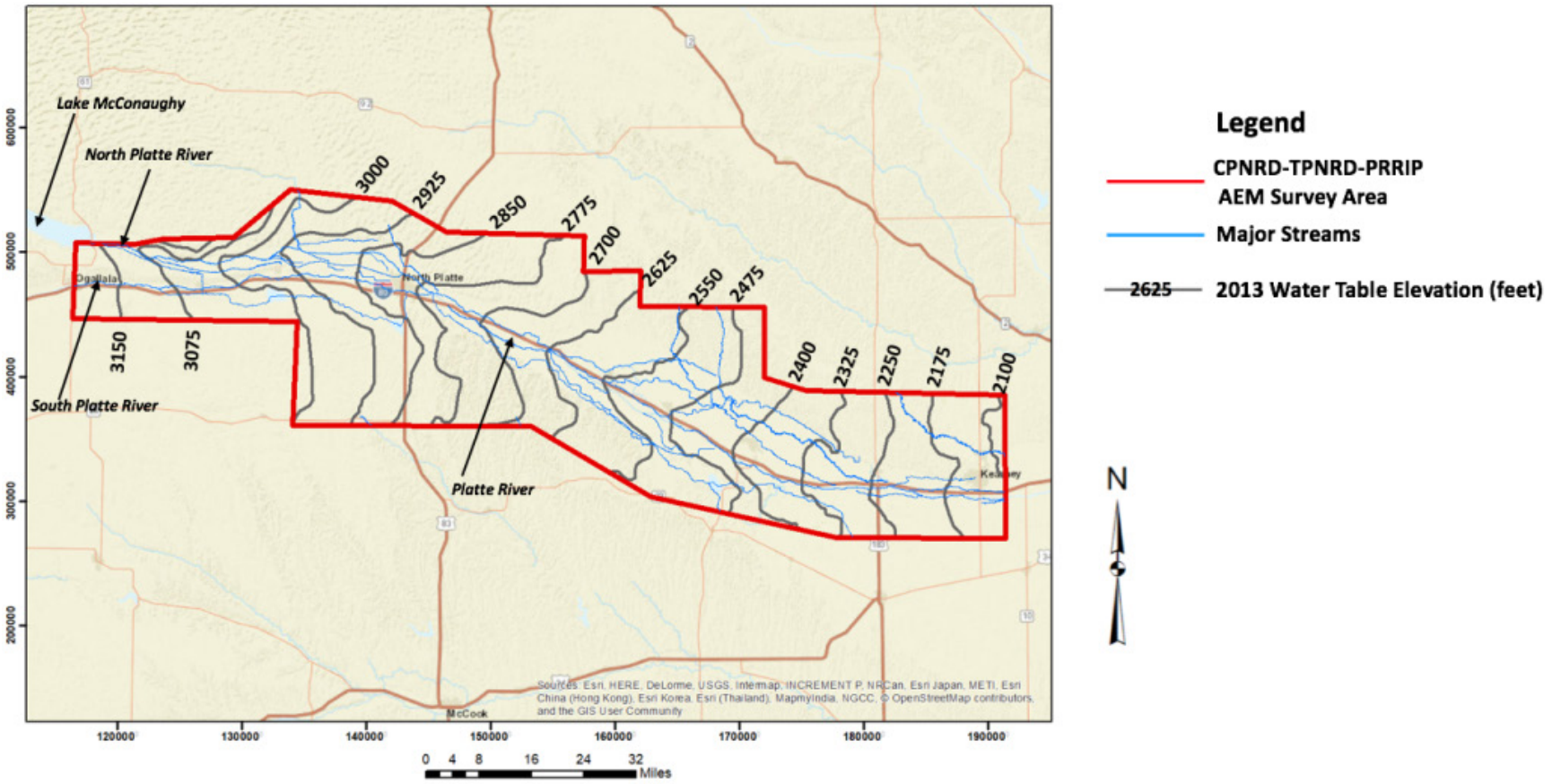



**Figure 2-3. Elevation of groundwater table surface in the TPNRD-CPNRD AEM survey area. The groundwater elevation contours show groundwater flow direction towards the North Platte, South Platte, and Platte Rivers (Korus et al., 2013b). Projection is NAD 1983, Nebraska State Plane Coordinate System, code 2600, Feet).**

Groundwater-level elevations in the form of water-table maps provide some guidance to the direction of groundwater flow. The groundwater elevation in the project area is generalized and shown in Figure 2-3. Depths to the groundwater below the land surface (bls) vary greatly with topography. Groundwater levels in the upland areas typically are (1) under unconfined to semi-confined conditions and (2) have depths to water that can exceed 200 ft bls. Groundwater levels in the ***Qal*** are under unconfined conditions and can be less than 10 ft bls. Depth to groundwater in the ***Qal*** is mostly dependent on proximity to the Platte River or the surface-water irrigation canals. Steele et al. (2014) report depths to groundwater near the major rivers are less than 3 ft; whereas near the edges of the Platte River valley bottomlands, the depths to groundwater can exceed 30 ft. Depths to water in the Platte River terraces, typically are around 50 ft. Depths to groundwater in the upland areas typically range between 65 ft and 200 ft. Moreover, larger depths to groundwater during July and August are a rule only at sites that are distant from the surface-water canals (Steele et al., 2014).

Spring 2016 water levels for Buffalo, Dawson, Keith, and Lincoln counties show median water-level elevations in shallow wells (well depth <=100 ft), medium wells (well depth <100 ft and <=200 ft), and deep wells (well depth >200 ft) were about 2,450 ft, 2,490 ft, and 2,510 ft above Sea Level, respectively. Median depths to water for the shallow, medium, and deep wells were about 9 ft, 44 ft, and 100 ft bls, respectively. Most shallow wells are open to the ***Qal***; whereas most deep wells are open to the ***To***. Medium wells generally are located in ***Qal*** but can also occur in ***To*** deposits.

Regional maps showing the configuration of the water table (Figure 2-3) indicate groundwater flow from the south and north into the Platte River valley. McMahon et al. (2007) reports hydraulic gradients in the aquifer north of the Platte River indicate a general groundwater movement from northwest to southeast. Groundwater movement south of the Platte River has a general movement of west to east. Groundwater contours presented by McMahon et al. (2007) and Ponte (1995a) and Ponte (1995b) represent regional groundwater flow paths. However, these water-table maps both suggest a general groundwater-flow direction from the upland areas toward, and into, the Platte River valley (Figure 2-3).

As with groundwater levels in the AEM survey area, groundwater flow also varies with location. Groundwater in upland areas, both north and south of the Platte River, eventually flows into the hydraulically connected ***Qal***. The magnitude and the location of this inflow into the ***Qal*** is dependent on several factors. Excluding the North Platte River valley, groundwater flow in the upland areas north of the Platte River groundwater nominally flows from west-northwest to southeasterly. In the North Platte River valley groundwater generally flows from north of Lake McConaughy west to south into the North Platte River (Figure 2-3). Upland areas along and adjacent to the southern edge of the Platte River valley contain a number of large surface-water supply canals and reservoirs (e.g., Sutherland, Lake Maloney, and Johnson Lake). In these upland areas leakage from these large reservoirs and canals on the southern uplands, that serve surface-water irrigation canals, has created steep groundwater gradients (Ponte, 1995a, 1995b; Young et al, 2016b) toward the Platte River. Furthermore, leakage from the surface-water systems has risen groundwater levels in the area more than 100 ft from predevelopment levels (Ellis and Dreeszen, 1987; Young et al., 2016b) and created a groundwater mound (approximated from contours by Ponte (1995a) and Ponte (1995b); Figure 2-3). This mound closely impacts groundwater flow into the ***Qal***. Groundwater flow north of the groundwater divide is in a southwest to northeasterly direction.

Groundwater flow south of the groundwater divide is more northwest to southeasterly (Figure 2-3). Furthermore, near these reservoirs groundwater flow within the ***Qal*** tends to be more direct into the Platte River valley. South of the supply canals and reservoirs and the groundwater divide, groundwater generally flows away from the Platte River valley.

North of the Platte River large reservoirs and their supply canals are absent. In these areas, groundwater flow generally follows the valley or flows into the ***Qal*** at a much gentler gradient than the gradient seen on the south side (Figure 2-3). Excluding a groundwater mound and the corresponding steeper gradient near Lake McConaughy (Ellis and Dreeszen, 1987; Young et al., 2016b), flow paths on the north side of the Platte River valley can be longer and follow the Platte River valley before eventually discharging into it (Figure 2-3; Ponte, 1995a, 1995b; McMahon et al., 2007).

However, smaller surface-water supply canals are locally present (e.g., Gothenburg canal) on the Platte River. These canals help influence groundwater flow toward the Platte River during the months when Platte River water is diverted into the canals for surface-water irrigation. Landon et al. (2009) reported consistently maintained surface-water levels in irrigation-supply canals on the north side of the Platte River near Gothenburg helped create groundwater gradient reversals such that during diversion months groundwater levels were highest and the gradient was directed towards the Platte River. When diversions did not occur, no groundwater gradient reversal occurred. These flow reversals are seasonal and not shown in Figure 2-3.

Temporally, groundwater levels generally reach pre-stress levels in spring (Young et al., 2016b). Pumpage from large volume production wells during irrigation season (April through September) stresses the aquifer. The magnitude of stress from pumpage and any corresponding groundwater-level decline is dependent on many factors—e.g., characteristics of the aquifer, the amount and timing of rainfall, land use, and density of high-volume wells stressing the aquifer. Consequently, pumpage of high capacity wells during drought conditions would cause groundwater levels to decline more than during times when precipitation is timely and plentiful. Recovery of groundwater levels during the non-irrigation season (October through March) is hampered during drought. The amount of recovery is dependent on the amount and source of recharge available. Copious amounts of precipitation or leakage from surface-water canals can help groundwater levels recover to, or exceed, pre-stress groundwater levels; whereas drought conditions can cause groundwater levels to barely recover.

Much of the uplands on the south side of the Platte River valley is recharged from precipitation and leakage from canals and reservoirs. Therefore, along the south side of the Platte River valley, groundwater levels in wells near the top of the valley generally do not experience large declines from pumping as those further removed from the surface-water irrigation systems. Wells within the ***Qal*** also tend to experience smaller groundwater-level declines due to greater hydraulic properties (e.g., hydraulic conductivity and specific yield) of the ***Qal***.

Table 2-1 summarizes information for Quaternary and Tertiary aquifer units within the area. Included in this table are the geologic system hosting the aquifer, generalized aquifer thickness, and a general discussion regarding the aquifer framework, groundwater flow system characteristics, and aquifer parameters.

**Table 2-1. Aquifers in Quaternary and Tertiary Age stratigraphic units.**

| System | Series | Hydrologic unit | Maximum thickness, ft. |
|---|---|---|---|
| Quaternary | Holocene to Plio-Pleistocene | Aquifer in undifferentiated alluvial deposits | Generally less than 100 ft |
| Undifferentiated sand and gravel units in stream-valley systems. Platte River stream-aquifer systems can be intermixed with paleo-Platte River sand and gravel deposits making the Holocene deposits difficult to distinguish from older Pliocene deposits. Hydraulic head is typically unconfined. Locally or regionally hydraulically connected to underlying Tertiary deposits. Recharge is principally from local precipitation and leakage from surface-water canals. Surface-water canal leakage can be rapid if the source area is primarily sand and gravel. Wells capable of yielding up to several thousand gallons per minute. Horizontal hydraulic conductivity values can exceed 100 ft/d. | | | |
| Quaternary | Holocene, Pleistocene | Aquifer in eolian deposits | Can exceed 100 ft |
| Eolian sand units in sand dune aquifers. Loess units typically do not contain aquifers. Hydraulic head generally under unconfined conditions. Thicknesses of dune aquifers vary greatly. Comprised largely of windblown sand. Mostly present in the western part of the project area; on the north side of the North Platte and Platte River valleys, and on the south side of the South Platte River valley. Regionally hydraulically connected to Quaternary and underlying Tertiary deposits. Recharge mostly from precipitation infiltration. Local recharge from surface-water systems. Well yields variable; wells capable of producing up to several thousand gallons per minute but vary greatly by location. Horizontal hydraulic conductivity values for deposits within or near the project area not determined from aquifer tests. | | | |
| Tertiary | Miocene | Aquifer in Ogallala deposits | Can exceed 400 ft |
| Generally unconfined to semi-confined aquifers comprised of poorly sorted mixture of sand, silt, clay, and gravel. Present throughout most of the project area. Locally or regionally hydraulically connected to overlying alluvial or eolian aquifer. Saturated thickness varies by location. Can exceed 400 ft and thins easterly. Recharge mostly from precipitation, canal and reservoir leakage, and inflow from hydraulically connected aquifers. Wells capable of producing over two thousand gallons per minute. Horizontal hydraulic conductivity values generally around 10 ft/d. | | | |

### *2.2.1 Soil Characteristics in the TPNRD-CPNRD AEM Survey Area*

Soils in the TPNRD/CPNRD AEM survey area were described in detail in soil survey reports by the U.S. Department of Agriculture, Natural Resources Conservation Service (NRCS) (USDA, 2017). The University of Nebraska-Lincoln School of Natural Resources (SNR) generalized soils data for the state of Nebraska and grouped them into 80 soil associations (School of Natural Resources, 2017). These 80 soil associations, are not described in this report. For detailed descriptions on soils of Nebraska, readers are encouraged to visit soil descriptions provided by NRCS (USDA, 2017).

Soils of the project area (Table 2-2) largely consist of 13 of the 80 soils groups of Nebraska (School of Natural Resources, 2017). Most soils parent materials were derived from alluvium, loess, or sand/sandstone (Elder, 1969). Soils whose parent materials were derived from alluvium or sand/sandstone have greater infiltration rates and less runoff than soils derived from loess parent material. More detailed information on parent materials, infiltration rates, and runoff for Nebraska soils data can be obtained from U.S. Department of Agriculture (2017).

Table 2-2 summarizes generalized soils information for the TPNRD/CPNRD AEM survey area based on soils groupings by the School of Natural Resources (SNR), University of Nebraska-Lincoln (UNL). Primary geomorphic feature highly generalized.

**Table 2-2. Generalized soils in the TPNRD/CPNRD AEM survey area**

| UNL SNR soil association | UNL SNR number[1] | Parent material[2] | Primary geomorphic feature |
|---|---|---|---|
| Gibbon-Gothenburg-Platte | 39 | Alluvium | River valleys—North Platte River, South Platte River, and Platte River |
| Bridget-Tripp-McCook | 41 | | |
| Lawet-Gothenburg-Platte | 49 | | |
| Coly-Uly-Holdrege | 2 | Loess | Uplands, central and eastern part of project area |
| Kuma-Keith-Colby | 7 | | |
| Holdrege-Uly-Coly | 21 | | |
| Coly-Uly | 33 | | |
| Kenesaw-Hersh | 47 | | |
| Cozad-Hord | 35 | Loess and alluvium | |
| Hord-Hall | 58 | | |
| Valentine | 1 | Sand | Uplands, western most part of study area |
| Hersh-Valentine | 15 | | |
| Kuma-Satanta-Rosebud | 32 | Sandstone | |
| Dix-Altvan-Colby | 65 | | |

[1]Number based on soil with highest number of acres present in state, not project area (e.g., "1" given to soil that covers the most acres in the state), from the School of Natural Resources (2017)
[2]From Elder (1969)

### *2.2.2 Aquifer Characteristics*

Aquifer characteristics of the AEM survey area are based on limited extent, localized, or large regional studies. Aquifer tests (constant discharge, slug, or permeameter) performed in or near (within 30 miles) of the project area help characterize the aquifer(s). However, discussion on aquifer tests are point source tests and should not be construed as representing an aquifer as a whole. Point-source tests can be qualitatively used to represent regional systems when viewed with certain caveats (e.g., difference in scale—local vs. regional, difference in sediment, and difference in aquifer thickness). Keeping the scale in mind, all discussion of aquifer tests herein are local tests used to represent a regional system. Consequently, these values are reported as regional generalities and not meant to qualitatively represent any place other than where the aquifer tests were performed.

Aquifer tests conducted in or near the AEM survey area and available to the public are limited. Constant-discharge aquifer tests conducted in or within 30 miles of the project area were McGuire and Kilpatrick (1998), Ayers et al. (1998), Chen et al. (2003), and Irons et al. (2012) (Table 2-3). Ayers et al. (1998) and McGuire and Kilpatrick (1998) conducted three aquifer tests at two locations near Shelton, Nebraska. (about 25 miles east of the project area). Ayers et al. (1998) analyzed aquifer tests from a test site between the Platte River and Shelton. McGuire and Kilpatrick (1998) analyzed two aquifer tests at the Management Systems Evaluation Area (MSEA) site south and west of Shelton. Chen et al. (2003) conducted an aquifer test in the Platte River valley west of Wood River, Nebraska. (approximately 30 miles east of the project area). In the AEM survey area, Irons et al. (2012) conducted two sets of aquifer tests (one in alluvial deposits and one on ***To*** at two sites).

Table 2-3 summarizes the generalized aquifer-test data in the Quaternary alluvium and Tertiary Ogallala deposits in or near the project area [$K_r$, horizontal hydraulic conductivity; ft/d, feet per day; *Sy*, specific yield; "—", not reported or not applicable; Tertiary Ogallala highlighted in gray)]

Permeameter tests generally conducted in the Platte River to determine stream-aquifer interaction or vertical hydraulic conductivity (***$K_v$***) values include Landon et al. (2001), Kollet and Zlotnik (2003), Chen (2007), and Song et al. (2009). Many permeameter tests from these studies were either shallow or too far from the AEM survey area so they are only noted in this report. Other aquifer tests have been completed in or near the project area (e.g., Layne Western Company, 1983, for the City of Kearney, Nebraska). However, details of municipal aquifer tests were not readily available to the public and not documented in this report. In addition, many municipal pump step-drawdown tests are designed to investigate pump efficiency as opposed to aquifer properties.

Irons et al. (2012) reported horizontal hydraulic conductivity (***$K_r$***) values in ***Qal*** alluvial sediments were about an order of magnitude greater than ***$K_r$*** values in the ***To*** deposits. Aquifer tests run by Irons et al. (2012) show ***$K_r$*** values of about 250 and 896 ft/d in the ***Qal***, and 9.9 and 16.7 ft/d in the ***To***. Reported ***$K_r$*** values from other aquifer tests in the ***Qal*** were: about 125 to 750 ft/d (Ayers et al., 1998), 340 and 390 ft/d (McGuire and Kilpatrick, 1998), about 285 to 400 ft/d (Chen et al., 2003), about 660 to 896 ft/d (Chen and Chen, 2003). Constant discharge aquifer tests, as opposed to permeameter tests, generally show the ***Qal*** deposits have ***$K_r$*** values greater than 100.

Vertical hydraulic conductivity ($K_v$) values were largely not reported. Chen et al. (2010) reported most $K_v$ values in the ***Qal*** ranged from 3.2 to 16.4 ft/d, with an average of 15.4 ft/d. Chen (2007) reports $K_v$ values ranged from about 14 to 78 ft/d with a mean of about 46 ft/d including existence of a well-connected $K_v$ dominant component of flow in the ***Qal*** system. These values indicate $K_v$ values in ***Qal*** are about an order of magnitude smaller than $K_r$ values. Readers are directed to Chen (2007) for further discussion on this $K_v$ dominant flow component.

**Table 2-3. Generalized aquifer-test data.**

| Researcher | Location | Kr (ft/d) | *Sy* |
|---|---|---|---|
| Ayers et al. (1998) | Shelton, NE | 125 to 750 | 0.001 to 0.09 |
| McGuire and Kilpatrick (1998)[1] | Shelton, NE | 340 and 390 | 0.09 |
| Landon et al. (2001) [2] | Platte River valley | 26.25 to 114 | -- |
| Chen et al. (2003) | Wood River, NE | 285 to 400 | 0.16 to 0.35 |
| Chen and Chen (2003)[3] | Platte River Island, Kearney, NE | 660 to 896 | -- |
| Chen (2007)[2] | Platte River Island, Kearney, NE | 14.4 to 78 | -- |
| Song and Chen (2010)[2] | Platte River Valley | -- | 0.01 to 0.18 |
| Chen et al. (2010) [2] | Chapman, NE | -- | 0.05 to 0.15 |
| Irons et al. (2012) [1] | Lexington, NE | 250 and 896 | 0.02 to 0.14 |
| Irons et al. (2012) [1] | Lexington, NE | 9.9 and 16.7 | -- |

[1]Two aquifer tests;
[2]Permeameter tests, sediment cores, and/or streambed hydraulic conductivity.
[3]Analyzed data from 1983 aquifer test run by Layne-Western Co. for City of Kearney, Nebraska.

Transmissivity values depend on $K_r$ and saturated thickness. Gosselin et al (1996) reported the base of the aquifer west of central Dawson County is generally the siltstone and claystone of the ***Twr***. The ***To*** can be as thick as 500 ft in Lincoln County. Transmissivity is used to indicate the potential of groundwater to move through an aquifer. The volume of water that moves through an aquifer would depend on the groundwater gradient at the site.

McGuire and Kilpatrick (1998) determined transmissivity values in the ***Qal*** of about 14,000 $ft^2/d$; Irons et al. (2012) reported transmissivity values in the ***Qal*** ranging from about 2,900 to 17,000 $ft^2/d$. McGuire and Kilpatrick (1998) report there was not a hydraulic connection between the ***Qal*** and ***To*** due to a thick clay unit. This thick clay unit is thinner towards or not present in the western part of the AEM survey area. Consequently, as one moves westerly in the Platte River valley, a stronger hydraulic connection between the ***Qal*** and ***To*** would exist. This can be seen from drawdown data from the ***Qal*** and ***To*** during aquifer tests (Irons et al., 2012) and a thinning of the silt and clay ***Qal*** deposits that directly overlie the ***To*** in the western part of the AEM survey area. Irons et al. (2012) reported transmissivity values for ***Qal*** versus ***To*** deposits at one site were 2,900 (***Qal***) and 3,800 $ft^2/d$ (***To***), and at a second site were 17,000

(***Qal***) and 3,300 $ft^2/d$ (***To***). Moreover, during each aquifer test (***Qal*** or ***To***), water levels in the non-stressed aquifer drew down showing a hydraulic connection between the two aquifers at Lexington, Nebraska. Also, the smaller transmissivity at the first site was due to a small 15 ft thickness of the alluvial aquifer. Otherwise, these tests show a magnitude difference in $\mathbf{K_r}$ values between the ***Qal*** and ***To*** deposits, and transmissivity values in Platte River alluvium are higher generally higher than transmissivity values in ***To*** deposits.

Specific yield (***Sy***) can be related closely to, but is less than, an aquifer's total porosity (Bear, 1979). Specific Yield is an estimate of the percentage of water in an aquifer that will drain under gravity (Heath, 1983). Specific Yield values in ***Qal*** deposits were reported by Ayers et al. (1998), ranging from 0.001 to 0.09; McGuire and Kilpatrick (1998) 0.09; Chen et al. (2003), ranging from 0.16 to 0.35; Song and Chen (2010) 0.01 to 0.18 with a mean of 0.08, and Irons et al. (2012), 0.017 to 0.14. Chen et al. (2010) reported the most common ***Sy*** values were 0.05 to 0.15. Therefore, ***Sy*** values in the ***Qal*** likely range between 0.01 and 0.35. These values lie on the lower end of the range with a higher percentage of silt and clay in the aquifer, whereas they lie on the higher end of the range with a higher percentage of sand and gravel in the aquifer.

Recharge rates vary with location, soil type, depth to water, and irrigated vs. dryland (Landon et al., 2009; Steele et al., 2014). McMahon et al. (2007) reports regional recharge rates in upland areas ranged from 0.02 to 0.05 ft/yr. Recharge rates in the Sand Hills were about 8 times larger on average than in areas without the sandy soils and colder recharge temperatures—such as the central High Plains aquifer in the eastern upland areas of the AEM survey area. Steele et al. (2014) reported irrigation is an important control on water movement through the unsaturated zone and can create recharge values that are more than an order of magnitude greater than dryland sites. Steele et al. (2014) reported an estimated minimum flux of about 1.89 inches/yr and a mean recharge of 2.6 inches/yr (from potassium bromide tests) at a groundwater irrigated agricultural site in the Platte River valley northeast of Gothenburg, Nebraska, and an estimated recharge rate of 0.39 to 2.0 inches/yr and a mean recharge of 0.5 inches/yr (from potassium bromide tests) at an uplands rangeland site north of Lexington, Nebraska In addition, greater recharge was evident west to east due to a greater mean annual precipitation.

### *2.2.3 Connectivity to Surface Water and Other Aquifers*

Groundwater connectivity to surface-water systems in the project area is complex due to the numerous surface-water features that recharge the groundwater system. Ponte (1995a and 1995b), Stanton (2000), and McMahon et al. (2007) report the Platte River as a regional discharge system in the project area. Chen (2007) reports almost simultaneous fluctuation in groundwater levels with stream stage. These reports suggest a strong relation between the Platte River system and the underlying ***Qal***.

Landon et al. (2009) reported consistently maintained surface-water levels in irrigation-supply canals on the north side of the Platte River near Gothenburg helped create a groundwater flow direction toward the Platte River. Data collected from groundwater wells installed near a Platte River gaging station (e.g., USGS groundwater well 403954099152101 (U.S. Geological Survey, 2017b) and NDNR surface water site 06770000 near Odessa, Nebraska (NE-DNR, 2017c)) correlate groundwater fluctuation with Platte River

stage. Figure 2-4 shows a definitive groundwater-surface water correlation as groundwater concordantly fluctuates with changing stage in the Platte River. Therefore, together with data collected from Chen (2007) and groundwater wells adjacent to a stream gage such as USGS 403954099152101 and DNR 06770000, a strong hydraulic connection between the Platte River and the underlying ***Qal*** deposits exists.

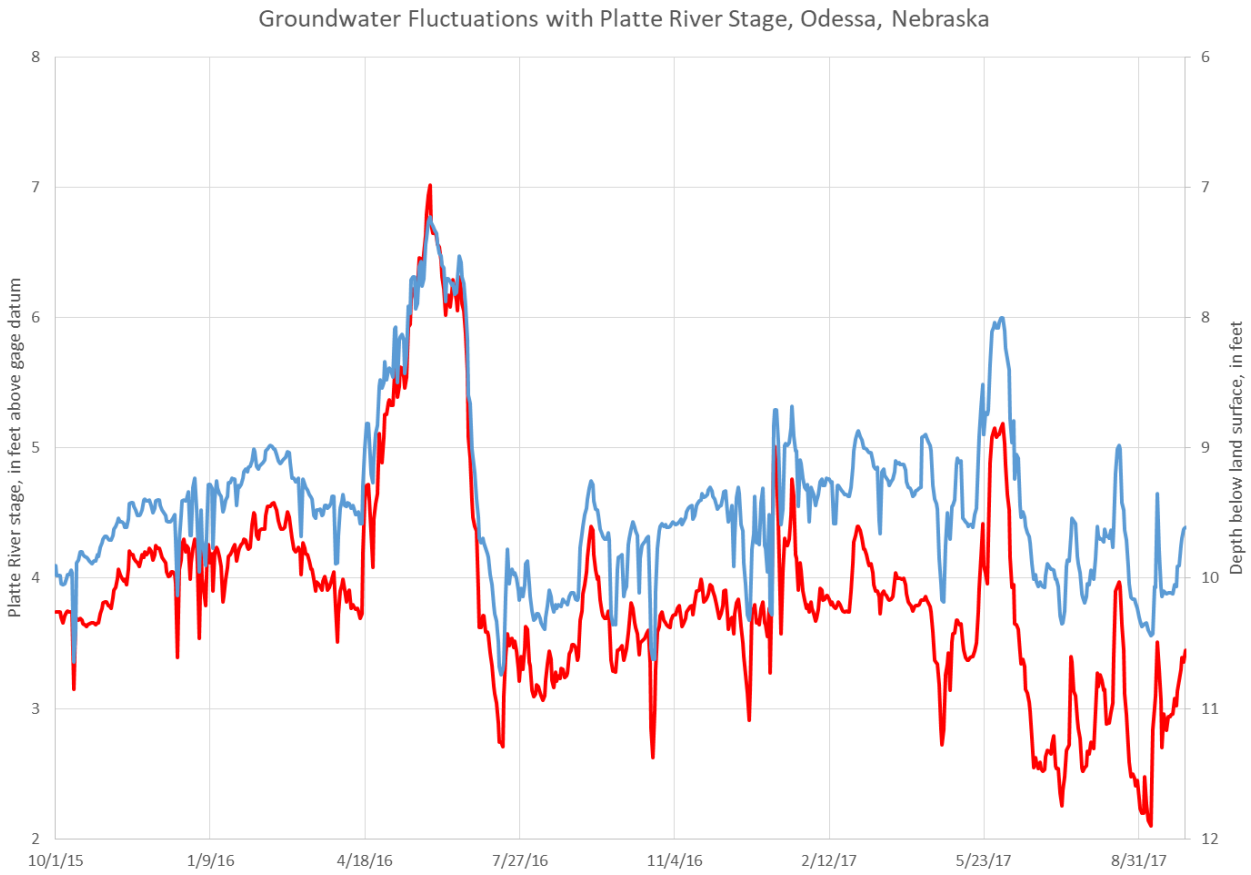



**Figure 2-4. Graph showing groundwater fluctuations (blue line) with Platte River stage (red line), Platte River near Odessa, Nebraska, October 1, 2015 to September 30, 2017. [Data from: USGS Odessa Groundwater Well (403954099152101) and NDNR Platte River near Odessa (06770000)].**

### *2.2.4 Water Quality*

Concentrations of total dissolved solids (TDS) above 1,500 milligrams per liter (mg/L) can affect the bulk resistivity values impacting the interpretations of the geological materials. Engberg (1984) provides an historic overview of water quality in the state of Nebraska. Of interest is the map of TDS for the state which shows that the overall groundwater quality for TDS in the TPNRD-CPNRD AEM survey area ranges widely from about 250 to more than 2,250 mg/l. This is important to the AEM survey results because Enberg (1984) reports most of the highest TDS values were in the Platte River valley in Dawson and Buffalo Counties and in the South Platte River valley in Keith County.

To follow up on these TDS concentrations on a more local scale, water-quality data from the same wells used to determine water-level statistics (Section 2.2 above) were downloaded from the U.S. Geological

Survey (2017c) National Water Information System and the National Water Quality Monitoring Council's (2017) Water Quality Portal. Forty-six wells in Buffalo, Dawson, Keith, and Lincoln counties contained data with TDS concentrations. Most TDS concentrations were less than the 1,500 mg/L threshold given above. However, 8 of the 46 sites showed TDS concentrations above 1,500 mg/L (Figure 2-5).

All TDS concentrations exceeding 1,500 mg/L were located in the Platte River and South Platte River valleys. Two of the eight highest TDS concentrations were collected from wells in the South Platte River valley outside the AEM survey area and would not have affected the AEM survey. Six wells containing TDS concentrations exceeding 1,500 mg/L were located in the project area. Three of the six samples with TDS concentrations in the AEM survey area exceeding 1,500 mg/L were collected from three wells in a single clustered well site northwest of Lexington. The remaining three samples had TDS concentrations between 1,500 and 2,160 mg/L. The well containing the sample with the highest TDS concentration, 2,160 mg/L, was located in Overton, Nebraska (Figure 2-5). A point other than a regional source could cause a high TDS value in a community setting. Two samples with TDS concentrations exceeding 1,500 mg/L were collected from two other wells—one well near Lexington and another well in the South Platte River valley near Ogallala. Besides these samples, all but one water sample collected from the wells in the project area were less than 1,000 mg/L (one sample was between 1,000 and 1,500 mg/L). All samples collected from wells on the upland were less than 500 mg/L. As a result, groundwater samples collected from wells throughout the AEM survey area show most TDS concentrations were less than the 1,500 mg/L threshold. Therefore, water quality in the project area likely did not affect interpretation of bulk resistivity values.

Nitrate as nitrogen concentrations in water samples in Buffalo, Dawson, Lincoln, and Keith Counties were downloaded from the Nebraska ground water quality clearing house (University of Nebraska-Lincoln, 2000). Data indicate 1,088 samples from January 2006 to September 2017 ranged from less than 10 to greater than 35 mg/L (Figure 2-6). About three-fourths of the concentrations (71%, 772 of 1,088 samples) were less than the U.S. Environmental Protection Area (EPA) Maximum Contaminant Level (MCL) of 10 mg/L. Moreover, samples exceeding 10 mg/L generally were located in the Platte River valley around Lexington, Nebraska.

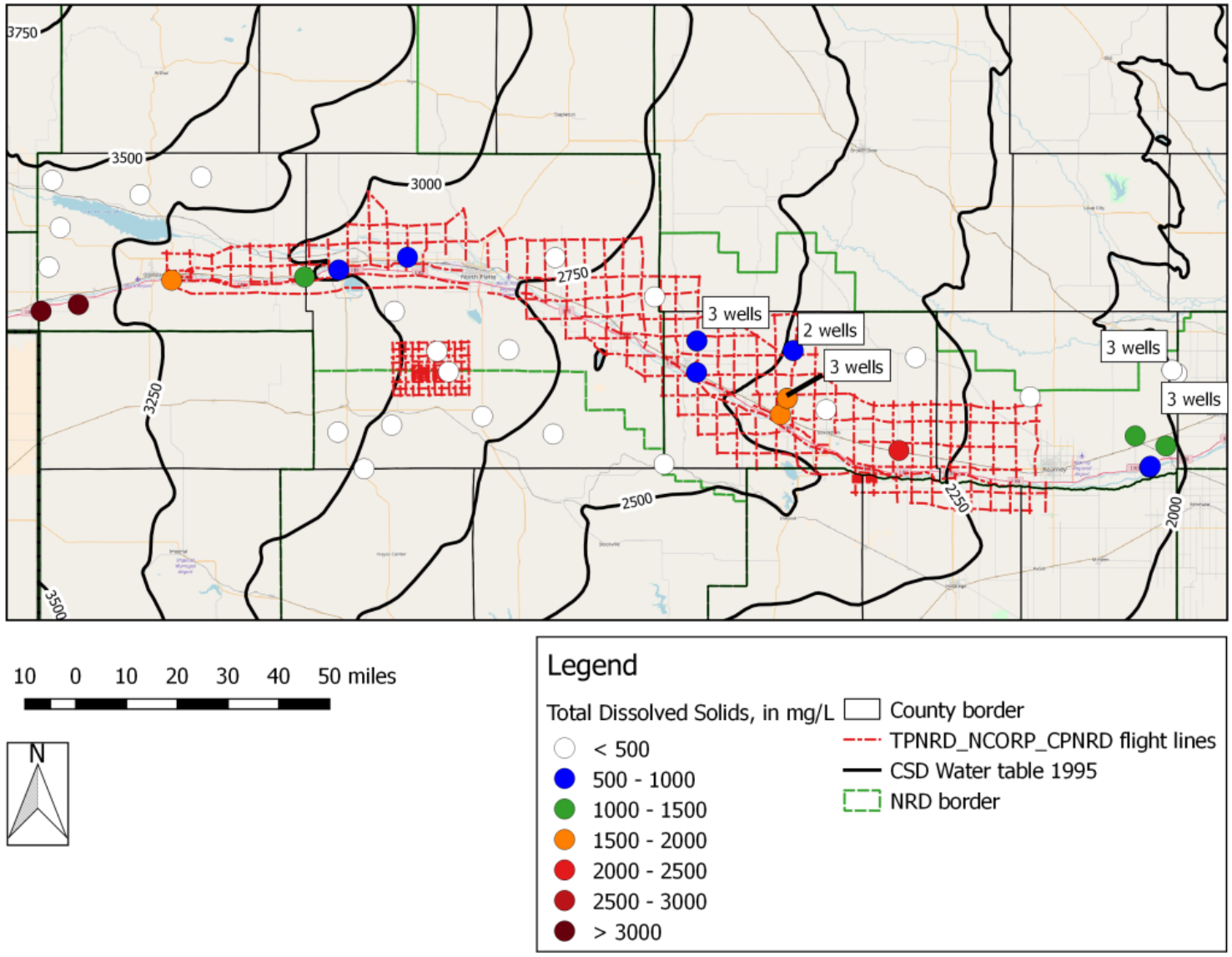



**Figure 2-5. Map showing concentrations of total dissolved solids in groundwater samples in Buffalo, Dawson, Lincoln, and Keith Counties, Nebraska. [Data from USGS National Water Information System, 2017].**

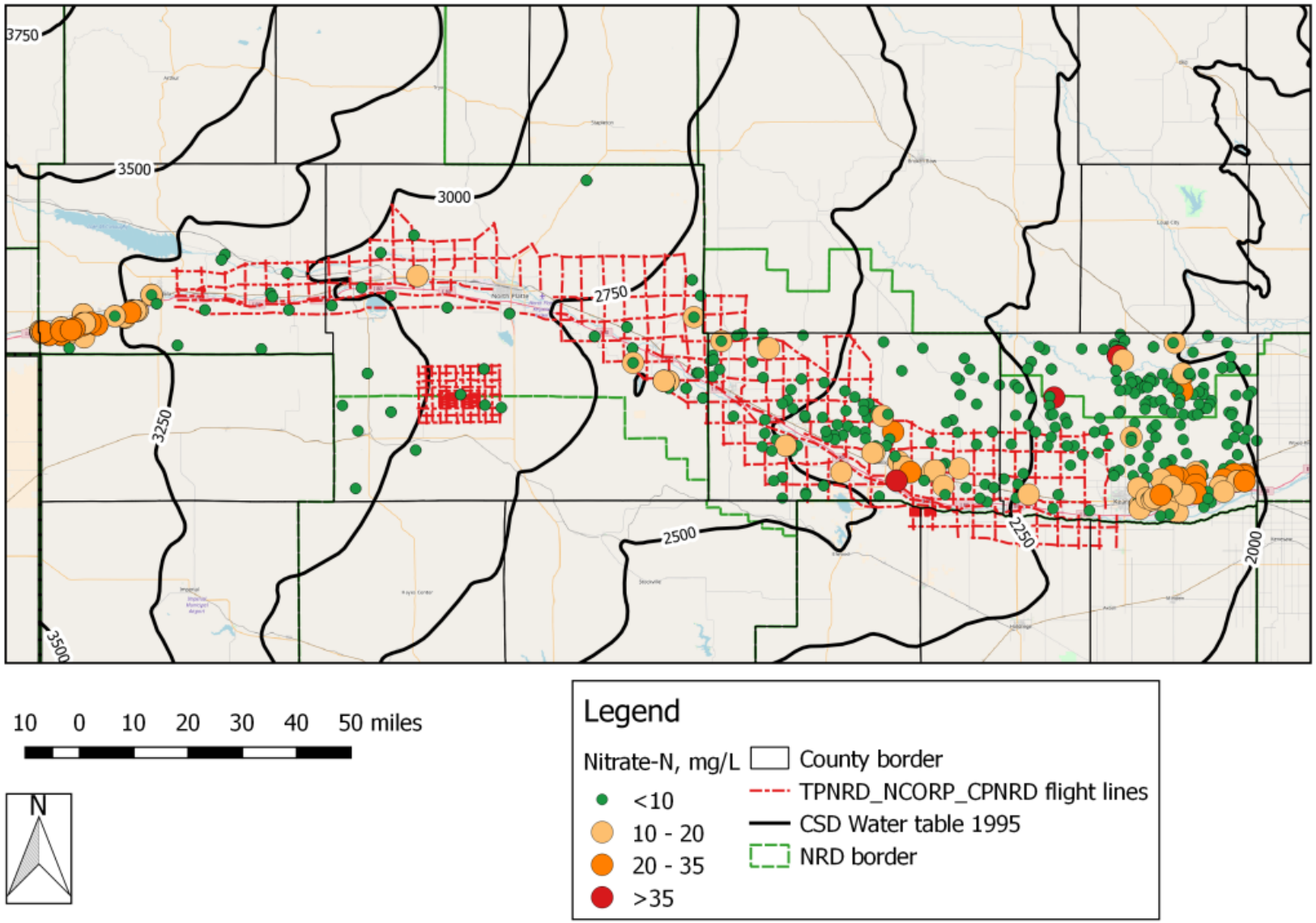



**Figure 2-6. Map showing concentrations of nitrate as N in groundwater samples in Buffalo, Dawson, Lincoln, and Keith Counties, Nebraska. [Data from University of Nebraska-Lincoln, 2000].**

# 3 Additional Background Information

Various sources of background information were used to interpret the AEM data, which is discussed in Section 5.

## 3.1 Borehole Data

Borehole data for this project consisted of a combination of lithologic, stratigraphic, and downhole geophysical logs. The borehole information was gathered from three sources: 1) CSD Nebraska Statewide Test Hole Database (UNL, 2016), which contains information from boreholes drilled between 1930 and 2016 by the CSD and other cooperating agencies; and 2) NE-DNR (NE-DNR, 2017d); and 3) Nebraska Oil and Gas Conservation Commission (NOGCC, 2017).

The locations of all of the boreholes with geophysical logs (178) utilized in the TPNRD-CPNRD AEM survey are indicated in Figure 3-1. In the TPNRD, a total of 115 CSD holes contained geophysical logs. In the CPNRD, a total of 41 CSD holes contained geophysical logs. In the N-CORPE area, 3 CSD holes contained geophysical logs and in the TBNRD, there were 19 boreholes with geophysical logs.

CSD boreholes (657) in the TPNRD-CPNRD AEM survey area containing lithology information are presented in Figure 3-2. In the TPNRD, a total of 271 CSD holes contained lithologic logs. In the CPNRD, a total of 287 CSD holes contained lithology logs. In the N-CORPE area, 3 CSD holes contained lithology logs and in the TBNRD, there were 96 boreholes with lithology logs.

CSD boreholes (644) in the TPNRD-CPNRD AEM survey area containing stratigraphy information are presented in Figure 3-3. In the TPNRD, a total of 267 CSD holes contained stratigraphic logs. In the CPNRD, a total of 282 CSD holes contained stratigraphy logs. In the N-CORPE area, 3 CSD holes contained stratigraphic logs and in the TBNRD, there were 92 boreholes with stratigraphic logs.

DNR boreholes (8,696) in the TPNRD-CPNRD AEM survey area containing lithology information are presented in Figure 3-4. In the TPNRD, a total of 2,628 DNR holes contained lithologic logs. In the CPNRD, a total of 3,796 DNR holes contained lithology logs. In the N-CORPE area, 287 DNR holes contained lithology logs and in the TBNRD, there were 1,985 boreholes with lithology logs.

Nebraska Oil and Gas Conservation Commission (NOGCC) boreholes (72) containing stratigraphic information in the vicinity of the TPNRD-CPNRD AEM survey are presented in Figure 3-5.

The borehole utilized in this study are included in Appendix_3_Deliverables/Boreholes as Geosoft Oasis montaj gdb databases.

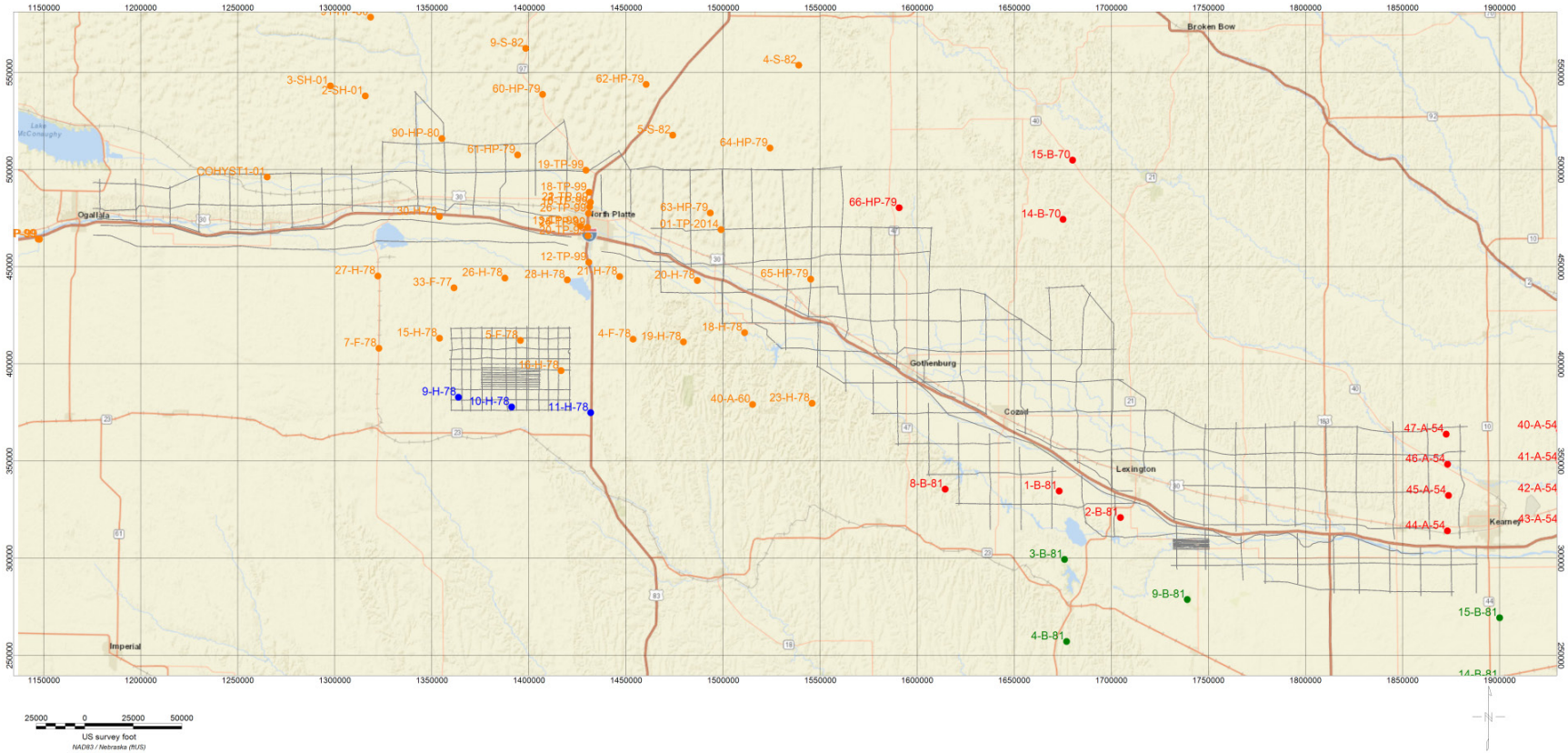



**Figure 3-1. Locations of the Nebraska Conservation Survey Division (CSD) boreholes with geophysical logs used in this study of the TPNRD-CPNRD AEM survey area. Orange dots – TPNRD boreholes, red dots – CPNRD boreholes, blue dots – N-CORPE boreholes, green dots – TBNRD boreholes. The grey lines are the AEM flight lines. Projection is NAD83, Nebraska SPCS83, code 2600, feet.**

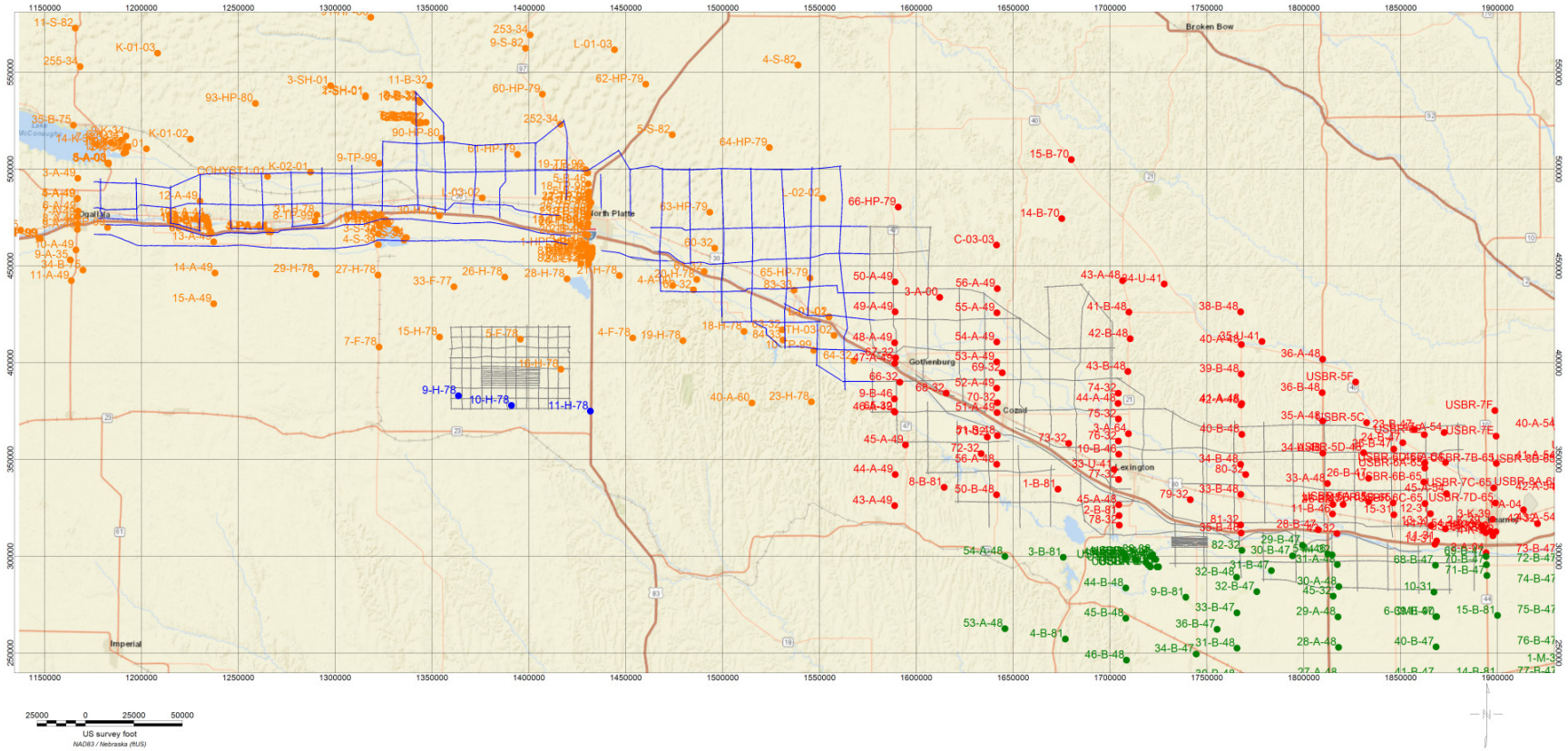



**Figure 3-2. Locations of the Nebraska Conservation Survey Division (CSD) boreholes with lithological logs used in this study of the TPNRD-CPNRD AEM survey area. Orange dots – TPNRD boreholes, red dots – CPNRD boreholes, blue dots – N-CORPE boreholes, green dots – TBNRD boreholes. The grey lines are the AEM flight lines. Projection is NAD83, Nebraska SPCS83, code 2600, feet.**

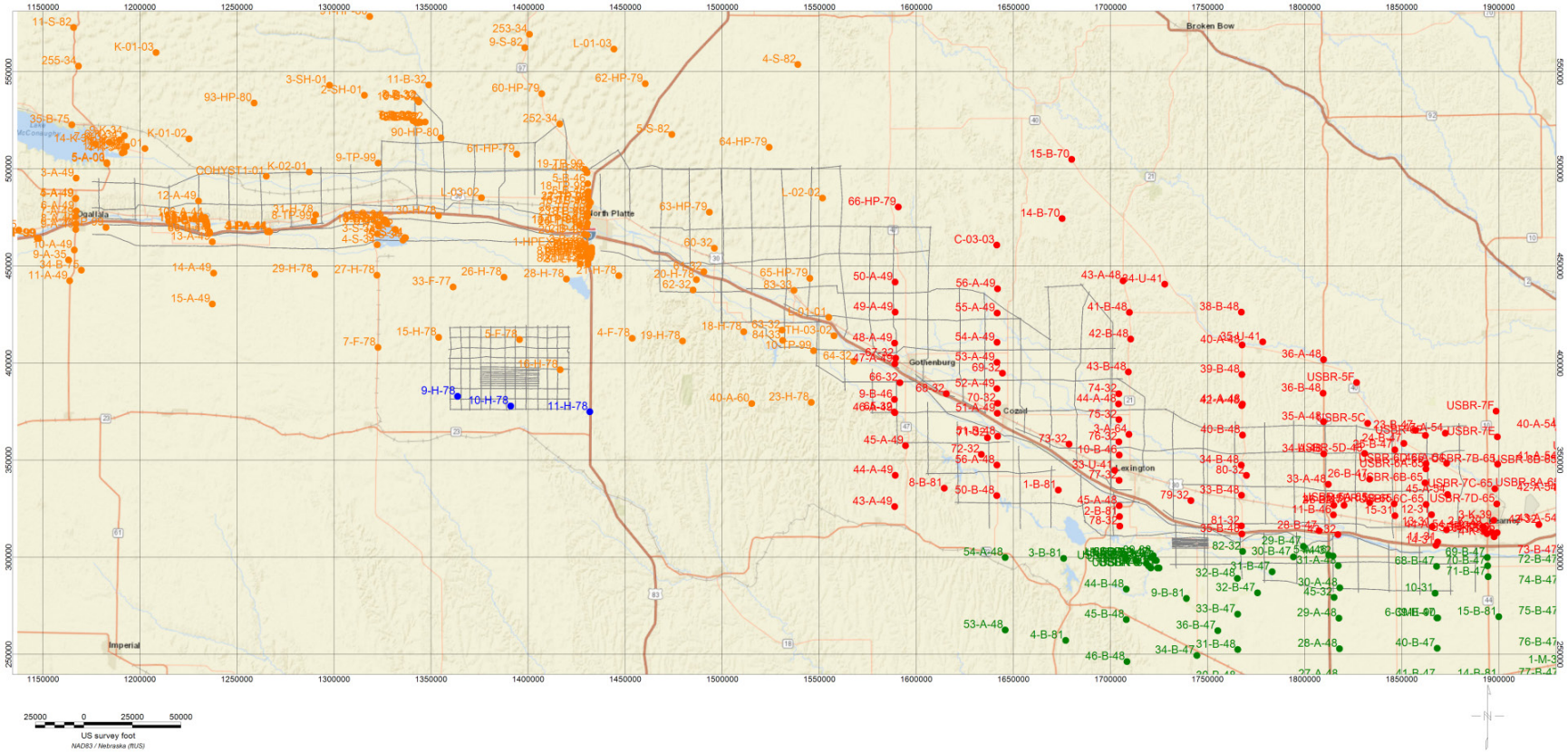



**Figure 3-3. Locations of the Nebraska Conservation Survey Division (CSD) boreholes with stratigraphic logs used in this study of the TPNRD-CPNRD AEM survey area. Orange dots – TPNRD boreholes, red dots – CPNRD boreholes, blue dots – N-CORPE boreholes, green dots – TBNRD boreholes. The grey lines are the AEM flight lines. Projection is NAD83, Nebraska SPCS83, code 2600, feet.**

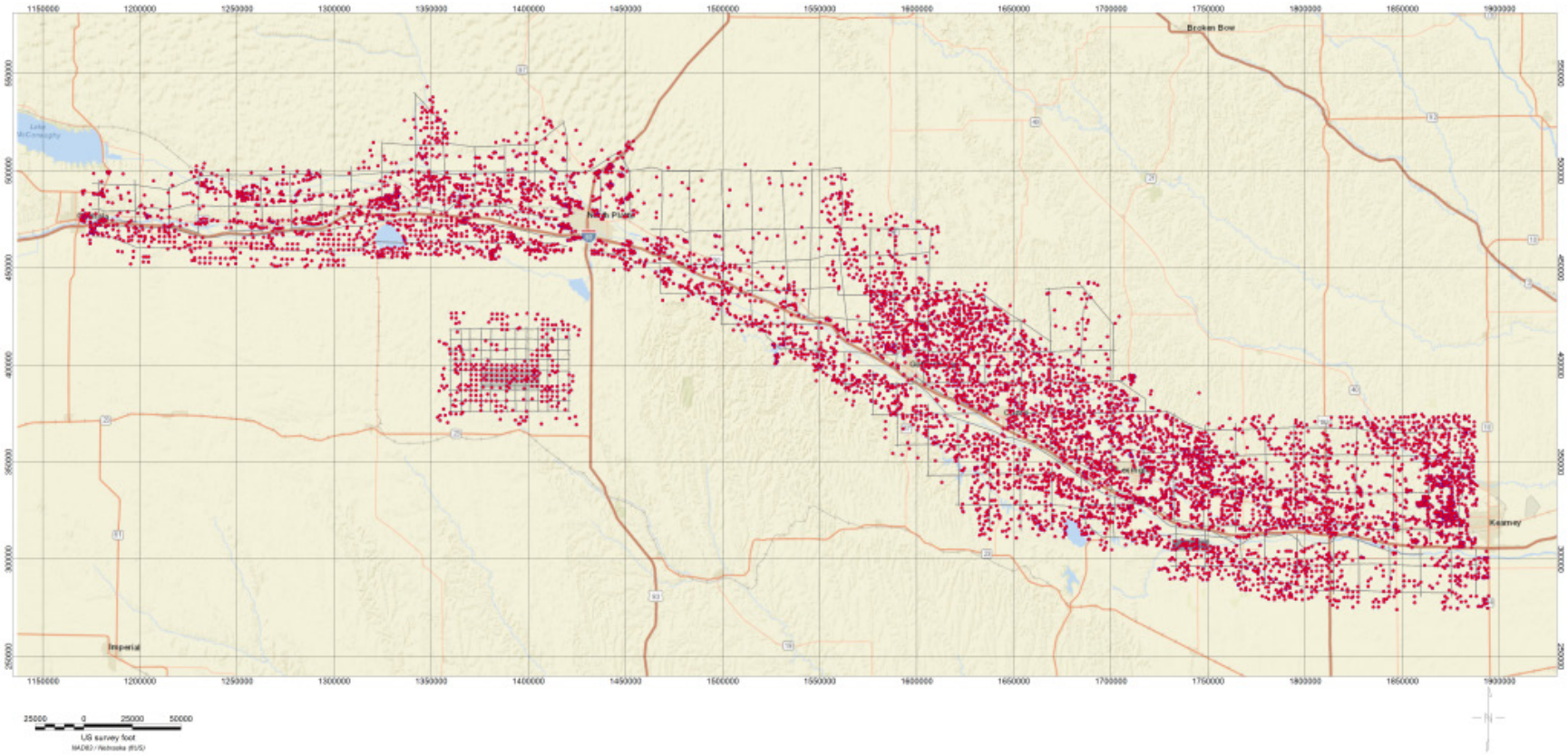



**Figure 3-4. Locations of the Nebraska Department of Natural Resources (DNR) boreholes (red dots) with lithological logs used in this study of the TPNRD-CPNRD AEM survey area. The grey lines are the AEM flight lines. Projection is NAD83, Nebraska SPCS83, code 2600, feet.**

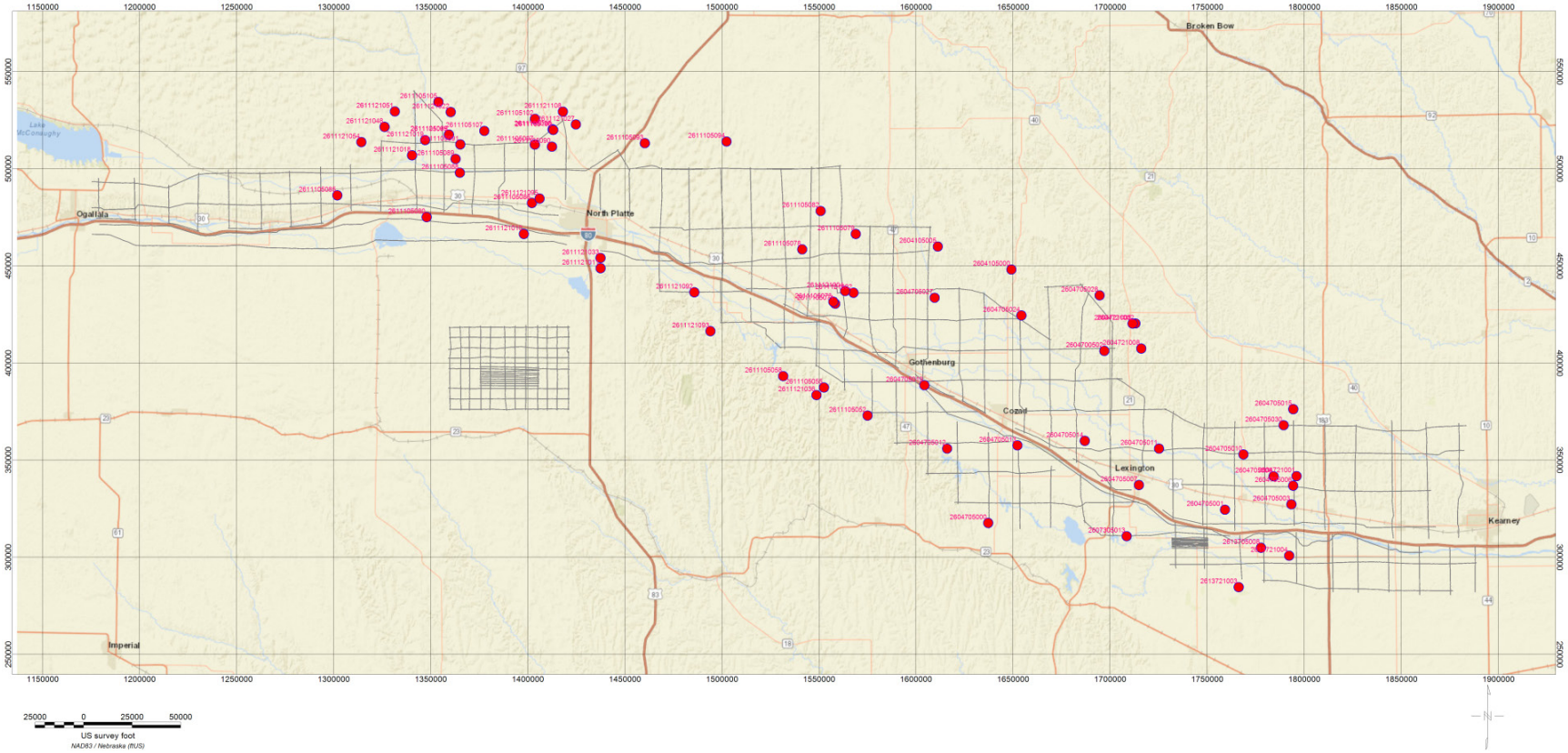



**Figure 3-5. Locations of the Nebraska Oil and Gas Conservation Commission (NOGCC) boreholes (red dots) with stratigraphic logs used in this study of the TPNRD-CPNRD AEM survey area. The grey lines are the AEM flight lines. Projection is NAD83, Nebraska SPCS83, code 2600, feet.**

# 4 Geophysical Methodology, Acquisition and Processing

## 4.1 Geophysical Methodology

Airborne Transient Electromagnetic (TEM) or airborne Time-Domain Electromagnetic (TDEM), or generally AEM, investigations provide characterization of electrical properties of earth materials from the land surface downward using electromagnetic induction. Figure 4-1 gives a conceptual illustration of the airborne TEM method.

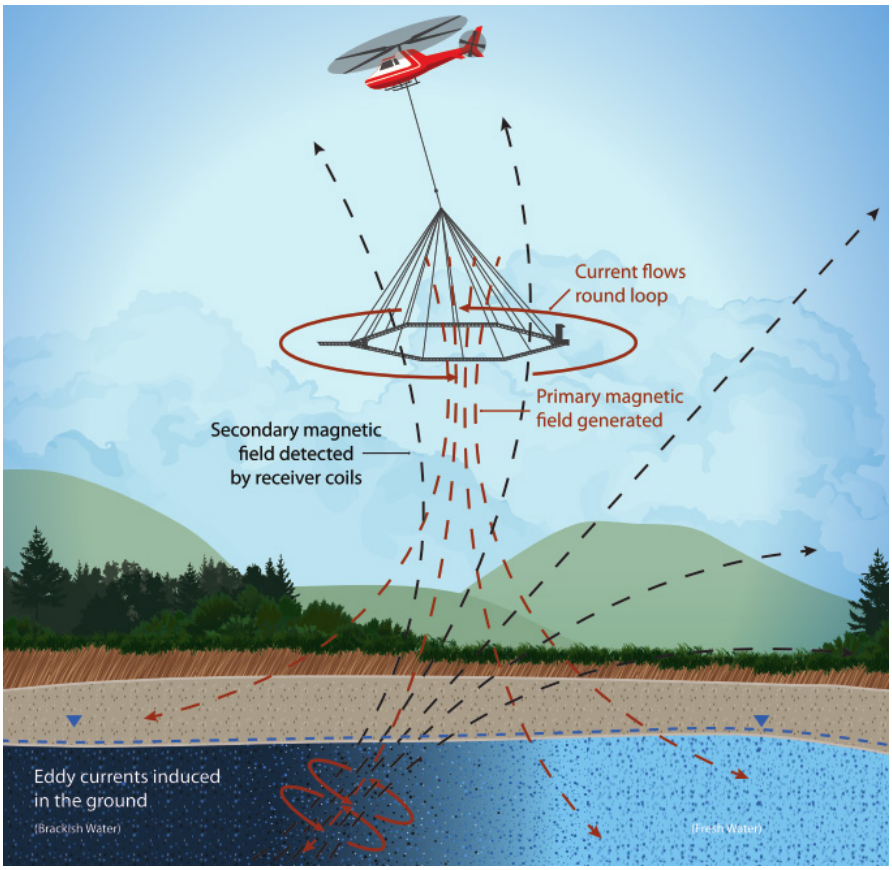



**Figure 4-1. Schematic of an airborne electromagnetic survey, modified from Carney et al. (2015a).**

To collect TEM data, an electrical current is sent through a large loop of wire consisting of multiple turns which generates an electromagnetic (EM) field. This is called the transmitter (Tx) coil. After the EM field produced by the Tx coil is stable, it is switched off as abruptly as possible. The EM field dissipates and decays with time, traveling deeper and spreading wider into the subsurface. The rate of dissipation is dependent on the electrical properties of the subsurface (controlled by the material composition of the geology including the amount of mineralogical clay, the water content, the presence of dissolved solids, the metallic mineralization, and the percentage of void space). At the moment of turnoff, a secondary time-varying EM field, which also begins to decay, is generated within the subsurface. The decaying secondary EM field generates a current in a receiver (Rx) coil, per Ampere's Law. This current is measured at several different moments in time (each moment being within a time band called a "gate"). From the induced current, the time rate of decay of the magnetic field, B, is determined (dB/dt). When

compiled in time, these measurements constitute a “sounding” at that location. Each TEM measurement produces an EM sounding at one point on the surface.

The sounding curves are numerically inverted to produce a model of subsurface resistivity as a function of depth. Inversion relates the measured geophysical data to probable physical earth properties. Figure 4-2 shows an example of a dual-moment TEM dB/dt sounding curve and the corresponding inverted electrical resistivity model.

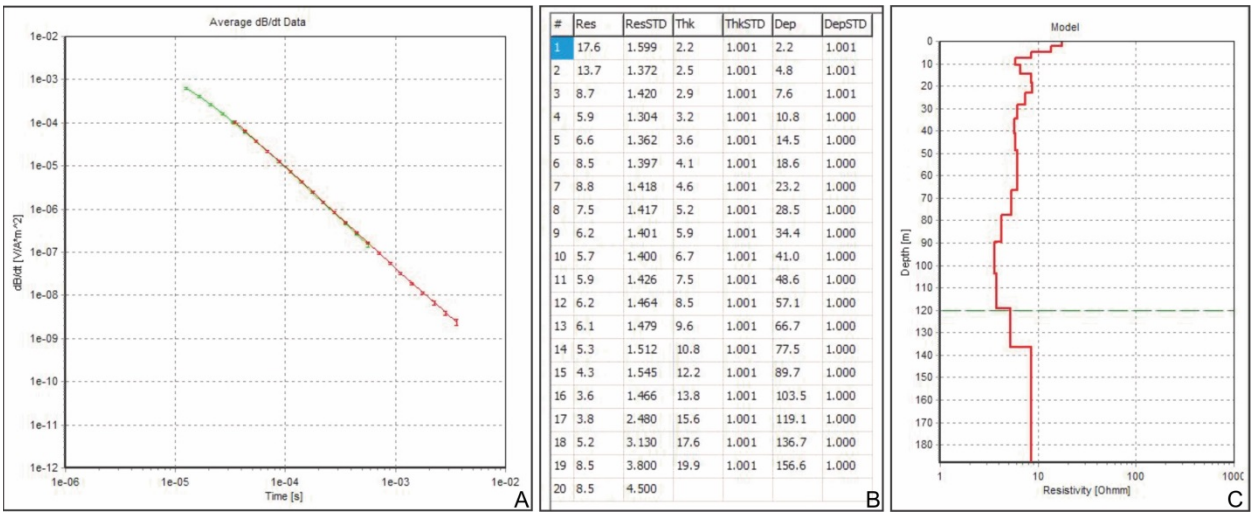



**Figure 4-2. A) Example of a dB/dt sounding curve. B) Corresponding inverted model values. C) Corresponding resistivity earth model.**

## 4.2 Flight Planning/Utility Mapping

The primary source of noise in geophysical electromagnetic surveys are other electromagnetic devices that are part of typical municipal utility infrastructure. These include, for example, power lines, railroads, pipelines, and water pumps. Prior to AEM data acquisition in the TPNRD and CPNRD, three types of utilities (pipelines, railroads, and power lines) were located. Various public power districts in central Nebraska provided power line locations in Google Earth “kmz” format that were then converted to a Geographic Information Systems (GIS) Arc shapefile format. Some areas did not have coverage available for power line locations and were mapped by inspection from Google Earth imagery.

A GIS Arc shapefile of railroads in Nebraska was downloaded from the United States Department of Agriculture’s Natural Resource Conservation Service (US Dept Agriculture, 2014) and a shapefile of the pipelines in Nebraska was obtained. Maps of the utilities were exported in GeoTIFF and Google Earth kmz formats and were used during data processing and interpretation.

The locations of the flight lines were converted from a regularly spaced grid to one with flight lines optimized in order to avoid electromagnetic coupling with the previously mentioned utilities. This was done by moving along each flight line in Google Earth to inspect the path for visible power lines, radio towers, railroads, highways and roads, confined feeding operations and buildings, and any other obstructions that needed to be avoided during flight.

At the conclusion of the design process (Figure 1-2), the maximum line length for the TPNRD AEM survey area was about 75 miles in length in the east-west direction and a minimum of about 5 miles in the north-south direction. For the CPNRD AEM survey area the flight lines were a maximum of about 58 miles east-west and about 15 miles north-south, including the single long PRRIP reconnaissance flight line (about 55 miles long). The N-CORPE AEM block survey consisted of eight 11.5 mile east-west flight lines separated by approximately 1 mile and twelve 8 mile long north-south flight lines, also separated by about 1 mile. In addition, in the center of the N-CORPE AEM flight block there were ten 5.5 mile long east-west flight lines separated by about 0.25 miles. The PRRIP AEM block flight area consisted of eleven 3.4 mile long east-west flight lines separated by about 0.1 miles (about 150 m).

## 4.3 AEM Survey Instrumentation

AEM data were acquired using the SkyTEM304M (304M) airborne electromagnetic system (SkyTem Airborne Surveys Worldwide, 2016). The 304M is a rigid frame, dual-magnetic moment (Low and High) TEM system. The area of the 304M Tx coil is 337 $m^2$ and the coil contains four (4) turns of wire. A peak current of nine (9) amps is passed through one turn of wire in the Tx for Low Moment measurements and a peak current of 120 amps is passed through the four turns of wire for High Moment measurements. This results in peak Tx Low and High magnetic moments of ~3,000 Ampere-meter-squared ($A*m^2$) and ~160,000 $A*m^2$, respectively.

The SkyTEM304M system utilizes an offset Rx positioned slightly behind the Tx resulting in a 'null' position which is a location where the intensity of the primary field from the system transmitter is minimized. This is desirable as to minimize the amplitude of the primary field at the Rx to maximize the sensitivity of the Rx to the secondary fields. The SkyTEM304M multi-turn Rx coil has an effective area of 105 $m^2$. In addition to the Tx and Rx that constitute the TEM instrument, the SkyTEM304M is also equipped with a Total Field magnetometer (MAG) and data acquisition systems for both instruments. The SkyTEM304M also includes two each of laser altimeters, inclinometers/tilt meters, and differential global positioning system (DGPS) receivers. Positional data from the frame mounted DGPS receivers are recorded by the AEM data acquisition system. The magnetometer includes a third DGPS receiver whose positional data is recorded by the magnetometer data acquisition system. Figure 4-3 gives a simple illustration of the SkyTEM304M frame and instrument locations. The image is viewed along the +z axis looking at the horizontal x-y plane. The axes for the image are labeled with distance in meters. The magnetometer is located on a boom off the front of the frame (right side of image). The Tx coil is located around the octagonal frame and the Rx Coil is located at the back of the frame (left side of image).

The coordinate system used by the 304M defines the +x direction as the direction of flight, the +y direction is defined 90 degrees to the right and the +z direction is downward. The center of the transmitter loop, mounted to the octagonal SkyTEM frame is used as the origin in reference to instrumentation positions. Table 4-1 lists the positions of the instruments (in feet) and Table 4-2 lists the corners of the transmitter loop in feet (whereas units of meters are presented in Figure 4-3).

The DGPS and magnetometer mounted on the frame of the SkyTEM304M require the use of base stations, which are located on the ground and are positioned in an area with low cultural noise. Data

from the magnetometer and DGPS base stations were downloaded each day after the end of the day's AEM flights. The DGPS and magnetometer base stations were placed at the Universal Transverse Mercator (UTM) coordinate system location listed in Table 4-3. The horizontal geodetic reference used is North American Datum of 1983 (NAD83 in feet). All elevations are from USGS's National Elevation Dataset, referenced to the North American Vertical Datum of 1988; with feet as the unit of measurement.

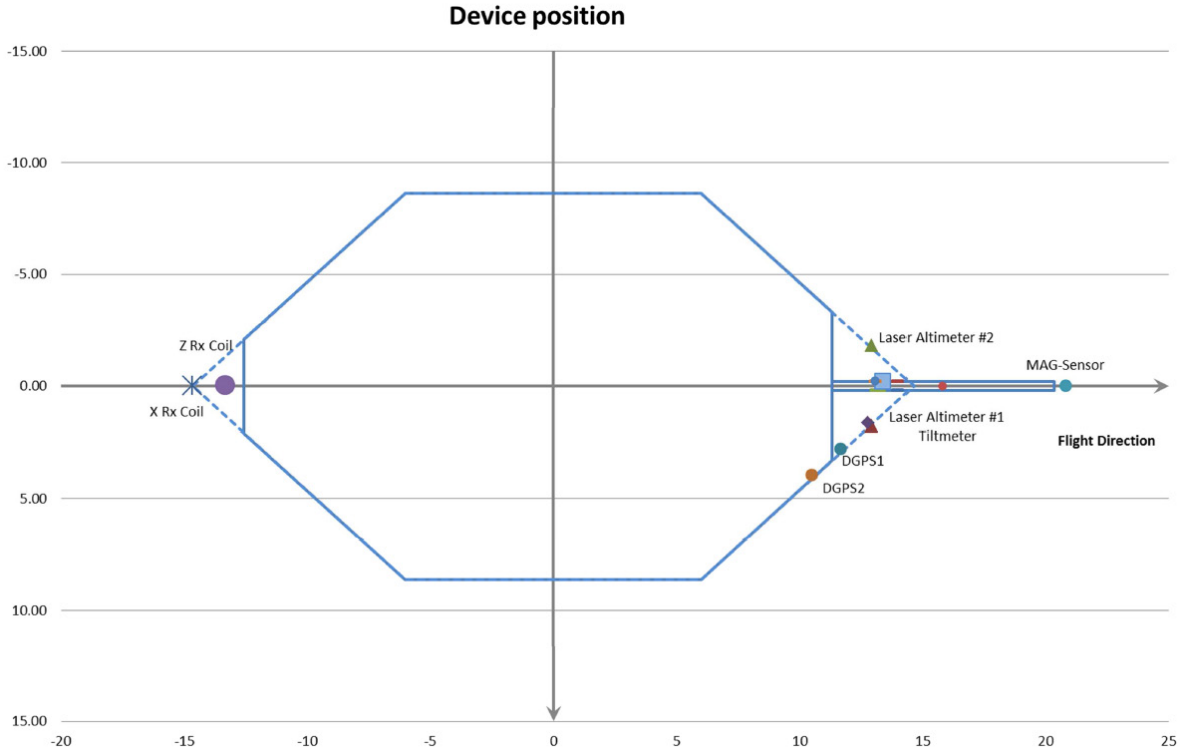



**Figure 4-3. SkyTEM304M frame, including instrumentation locations and X and Y axes. Distances are in meters. Instrumentation locations listed in Table 4-1.**



**Figure 4-4. Photos of the SkyTEM304M system in suspension beneath the helicopter.**

For this project, the 304M was flown at an average speed of 62 mi/hr (100.5 kilometers/hr) at an average flight height of 36.4 m above land surface, using the sling-load cargo system of a Eurocopter

AS350BA FX2 helicopter. Figure 4-4 displays a couple of images of the 304M in operation.

**Table 4-1: Positions of instruments on the SkyTEM304M frame, using the center of the frame as the origin, in feet.**

| | DGPS 1 | DGPS 2 | Inclinometer 1 | Inclinometer 2 | Altimeter 1 | Altimeter 2 | Magnetic Sensor | Rx Coil |
|---|---|---|---|---|---|---|---|---|
| **X** | 38.31 | 34.47 | 41.95 | 41.95 | 42.44 | 42.44 | 67.24 | -43.46 |
| **Y** | 9.15 | 12.96 | 5.38 | -5.38 | 5.87 | -5.87 | 0.00 | 0.00 |
| **Z** | -0.52 | -0.52 | -0.39 | -0.39 | -0.39 | -0.39 | -1.71 | -6.56 |

**Table 4-2: Positions of corners of the SkyTEM304M transmitter coil, using the center of the frame as the origin in feet.**

| Tx Corners | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| **X** | -41.46 | -20.17 | 18.83 | 36.51 | 36.51 | 18.83 | -20.17 | -41.46 |
| **Y** | -6.99 | -28.18 | -28.18 | -10.46 | 10.46 | 28.18 | 28.18 | 6.99 |

**Table 4-3: Locations of DGPS and magnetic field base station instruments.**

| Instrument | Easting (ft) | Northing (ft) | Zone |
|---|---|---|---|
| DGPS Base Station (NEHO) – Ogallala Airport | 1817978 | 221032 | SPCS83 Feet |
| Magnetometer Base Station – Ogallala Airport | 1153257 | 475906 | SPCS83 Feet |
| Magnetometer Base Station – N-CORPE | 1401051 | 389850 | SPCS83 Feet |
| Magnetometer Base Station – Gothenburg Airport | 1599097 | 398456 | SPCS83 Feet |
| Magnetometer Base Station – Lexington Airport | 1704324 | 348674 | SPCS83 Feet |

## 4.4 Data Acquisition

All SkyTEM systems are calibrated to a ground test site in Lyngby, Denmark prior to being used for production work (HydroGeophysics Group Aarhus University, 2010; HydroGeophysics Group Aarhus University, 2011; Foged et al., 2013). The calibration process involves acquiring data with the system hovering at different altitudes, from 16 ft to 164 ft, over the Lyngby site. Acquired data are processed and a scale factor (time and amplitude) is applied so that the inversion process produces the model that approximates the known geology at Lyngby.

For these surveys, installation of the navigational instruments in the helicopter and assembly of the SkyTEM304M system commenced at the beginning in Ogallala, Nebraska. Calibration test flights were flown to ensure that the equipment was operating within technical specifications. Survey set-up procedures included measurement of the transmitter waveforms, verification that the receiver was properly located in a null position, and verification that all positioning instruments were functioning properly. A high altitude test, used to verify system performance, was flown prior to the beginning of the survey's production flights. In the field, quality control of the operational parameters for the EM and magnetic field sensors including current levels, positioning sensor dropouts, acquisition speed, and system orientation were conducted with proprietary SkyTEM software following each flight.

Approximately 578.1 line-miles (936.5 line-kilometers) were acquired over the TPNRD AEM survey area on July 6-July 10, 2016 (Figure 4-5), approximately 727.7 line-miles (1,178.8 line-kilometers) were acquired over the CPNRD AEM survey area on July 12-13, 2016 (Figure 4-6), approximately 250.7 line-miles (403.5 line-kilometers) were acquired over the N-CORPE AEM survey area on July 8-9, 2016 (Figure

4-7), and approximately 95.3 line-miles (153.4 line-kilometers) were acquired over the PRRIP AEM survey area on July 10-12, 2016 (Figure 4-8). Several airports including the Ogallala Airport, the North Platte Airport, the Gothenburg Airport, the Lexington Airport, and the Kearney Airport as well as the landing strip at N-CORPE were used during these flights for refueling and landings including overnight storage.

### *4.4.1 Primary Field Compensation*

A standard SkyTEM data acquisition procedure involves review of acquired raw data by SkyTEM in Denmark for Primary Field Compensation (PFC) prior to continued data processing by AGF (Schamper et al., 2014). The primary field of the transmitter affects the recorded early time gates, which in the case of the Low Moment, are helpful in resolving the near surface resistivity structure of the ground. The Low Moment uses a saw tooth waveform which is calculated and then used in the PFC correction to correct the early time gates.

### *4.4.2 Automatic Processing*

The AEM data collected by the 304M were processed using Aarhus Workbench version 5.2.0.0 (at Aarhus Geosoftware (http://www.aarhusgeosoftware.dk/aarhus-workbench-ib3ao) described in HydroGeophysics Group, Aarhus University (2011).

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 AEM data are corrected for tilt deviations from level and so filters were also applied to both of the tilt meter readings with a median filter of three seconds and an average filter of two seconds. 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 Low Moment were $1.0x10^{-5}$ sec, $1.0x10^{-4}$ sec, and $1.0x10^{-3}$ sec with widths of 5, 8, and 12 seconds. The times used to define the trapezoid for the High Moment were $1.0x10^{-4}$ sec, $1.0x10^{-3}$ sec, and $1.0x10^{-2}$ sec with widths of 10, 12, and 20 seconds. The trapezoid sounding distance was set to 2.5 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 were both set to 25 percent for both soundings. Lastly, the locations of the averaged soundings were synchronized between the two moments.

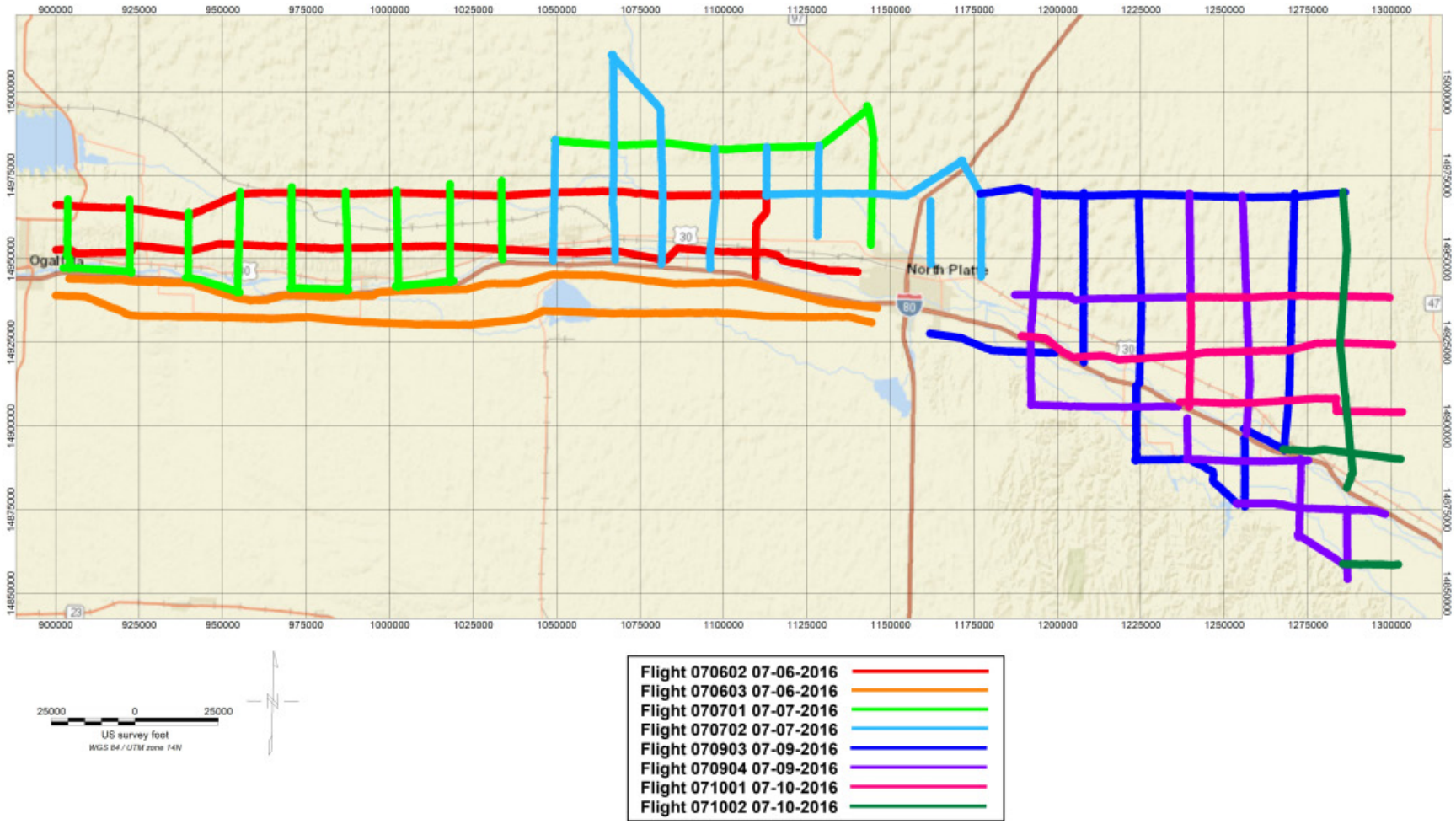



**Figure 4-5. TPNRD AEM flight lines grouped by acquisition date.**

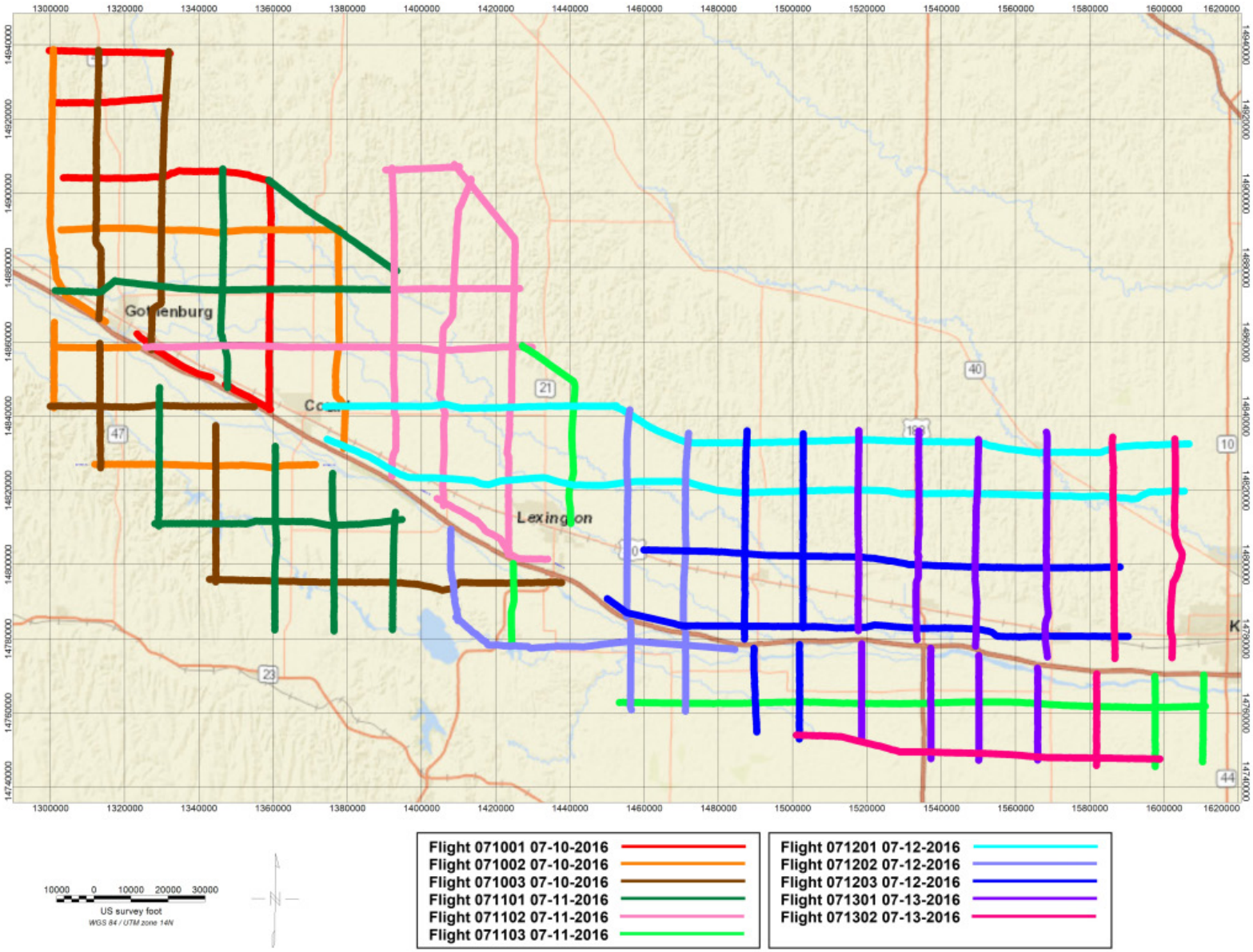



**Figure 4-6. CPNRD AEM flight lines grouped by acquisition date.**

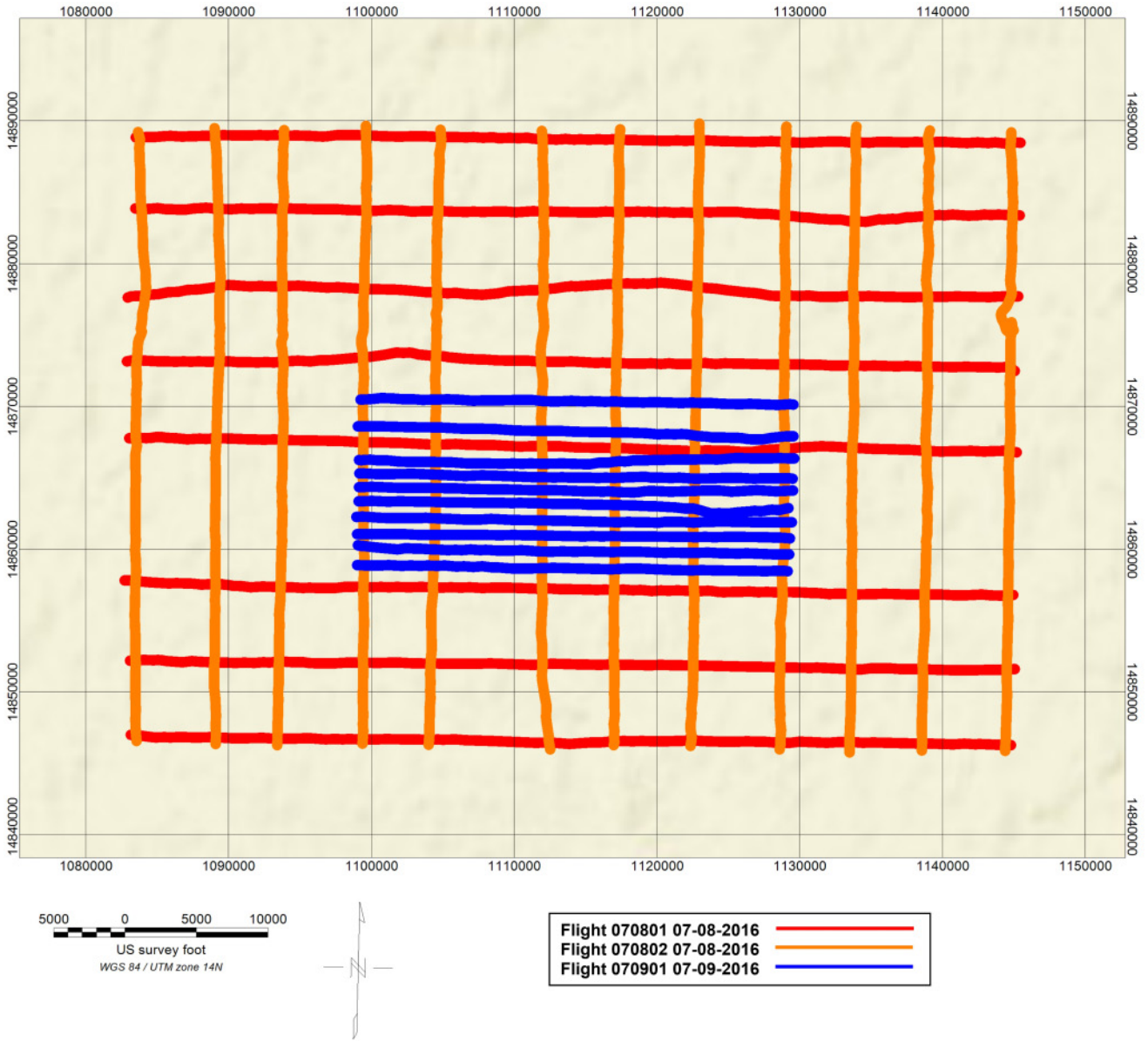



**Figure 4-7. N-CORPE AEM flight lines grouped by acquisition date.**

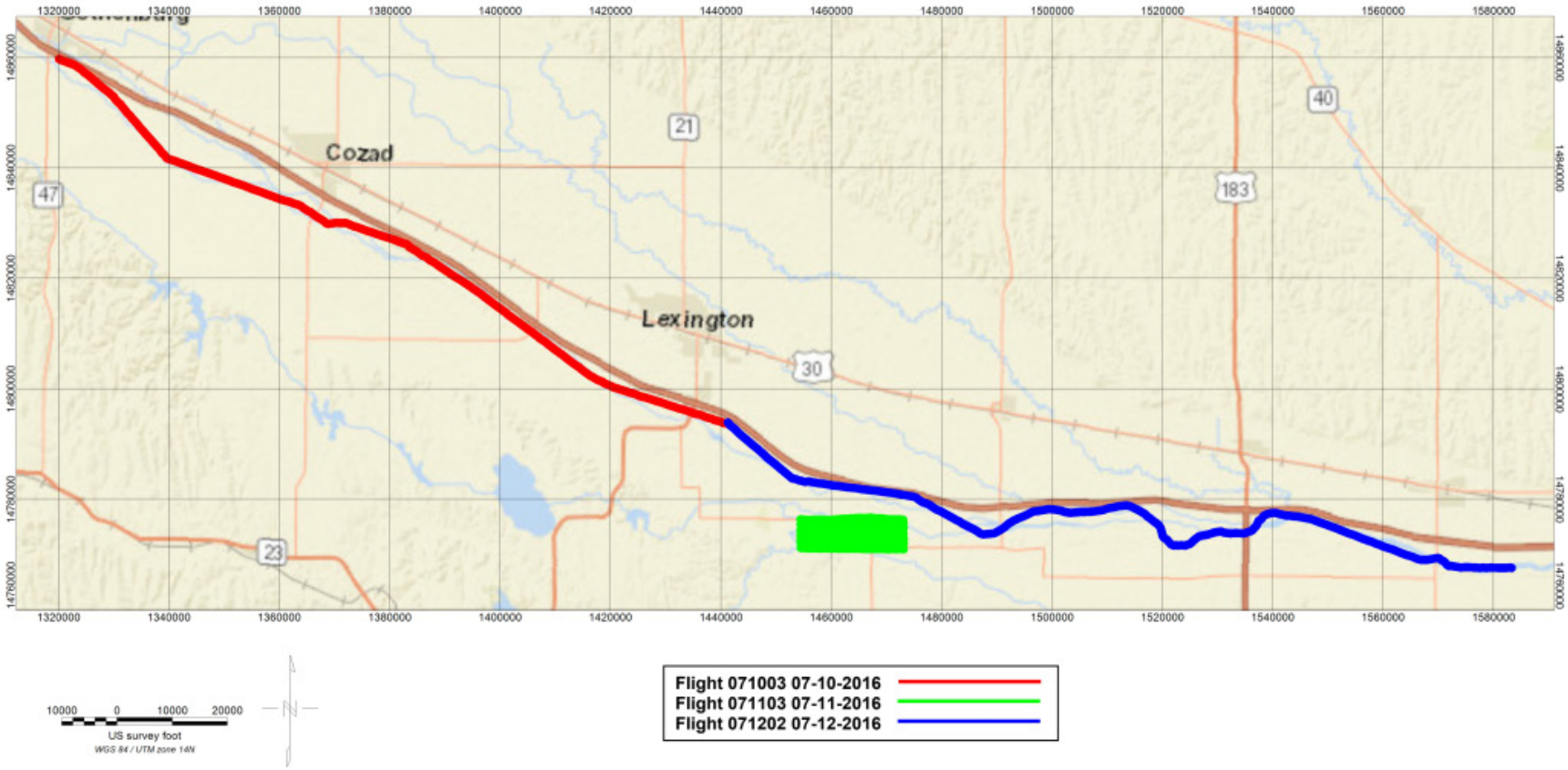



**Figure 4-8. PRRIP AEM flight lines grouped by acquisition date.**

### *4.4.3 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. Examples of locating areas of EM coupling with pipelines or power lines and recognizing and removing coupled AEM data in Aarhus Workbench are shown in Figure 4-9 and Figure 4-10, respectively. Examples of two inversions, one without EM coupling and the other with EM coupling, are shown in Figure 4-11. Areas were also cut out where the system height was flown greater than 200 feet above the ground surface which caused a decrease in the signal level. This problem was encountered at several locations along the Loup River due to the tall cottonwood trees.

The AEM data were then inverted using a Laterally-Constrained Inversion (LCI) algorithm (Christensen et al., 2009; HydroGeophysics Group Aarhus University, 2011). The profile and depth slices were examined, and any remaining electromagnetic couplings were masked out of the data set.

After final processing, 471.5 line-miles (763.8 line-km) of data were retained for the final inversions for the TPNRD AEM survey area. This amounts to a data retention of 81.6%. For the CPNRD, after final processing, 586.2 line-miles (949.6 line-km) of data were retained for the final inversions (80.6%), for the N-CORPE area, after final processing 179.5 line-miles (290.7 line-km) of data were retained for final inversions (72.1%), and for the PRRIP AEM survey area 83.6 line-miles (135.5 line-km) of data were retained for final inversions (87.7%). These high rates are the result of careful flight line planning and design.

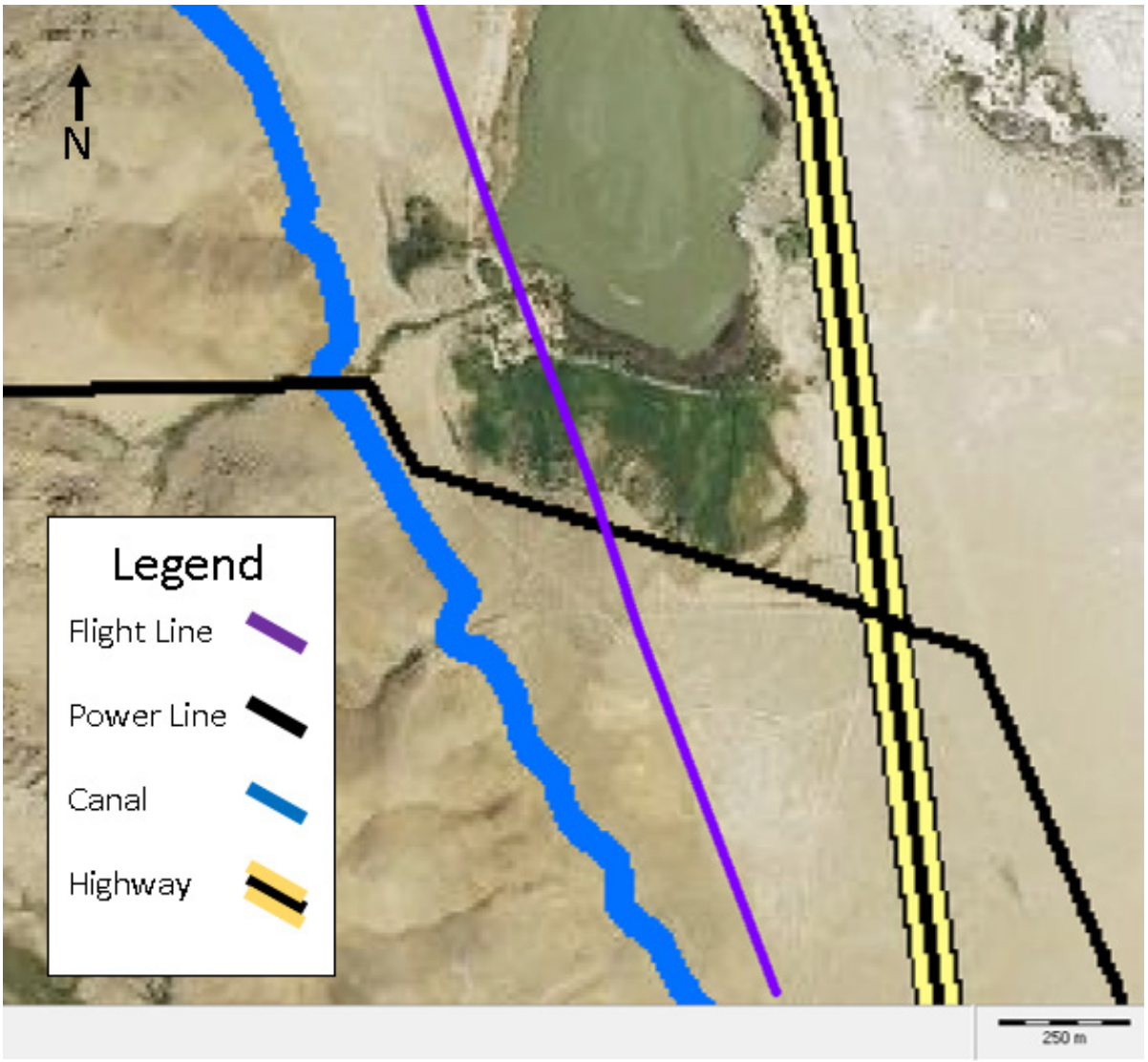



**Figure 4-9. Example locations of electromagnetic coupling with pipelines or power lines.**

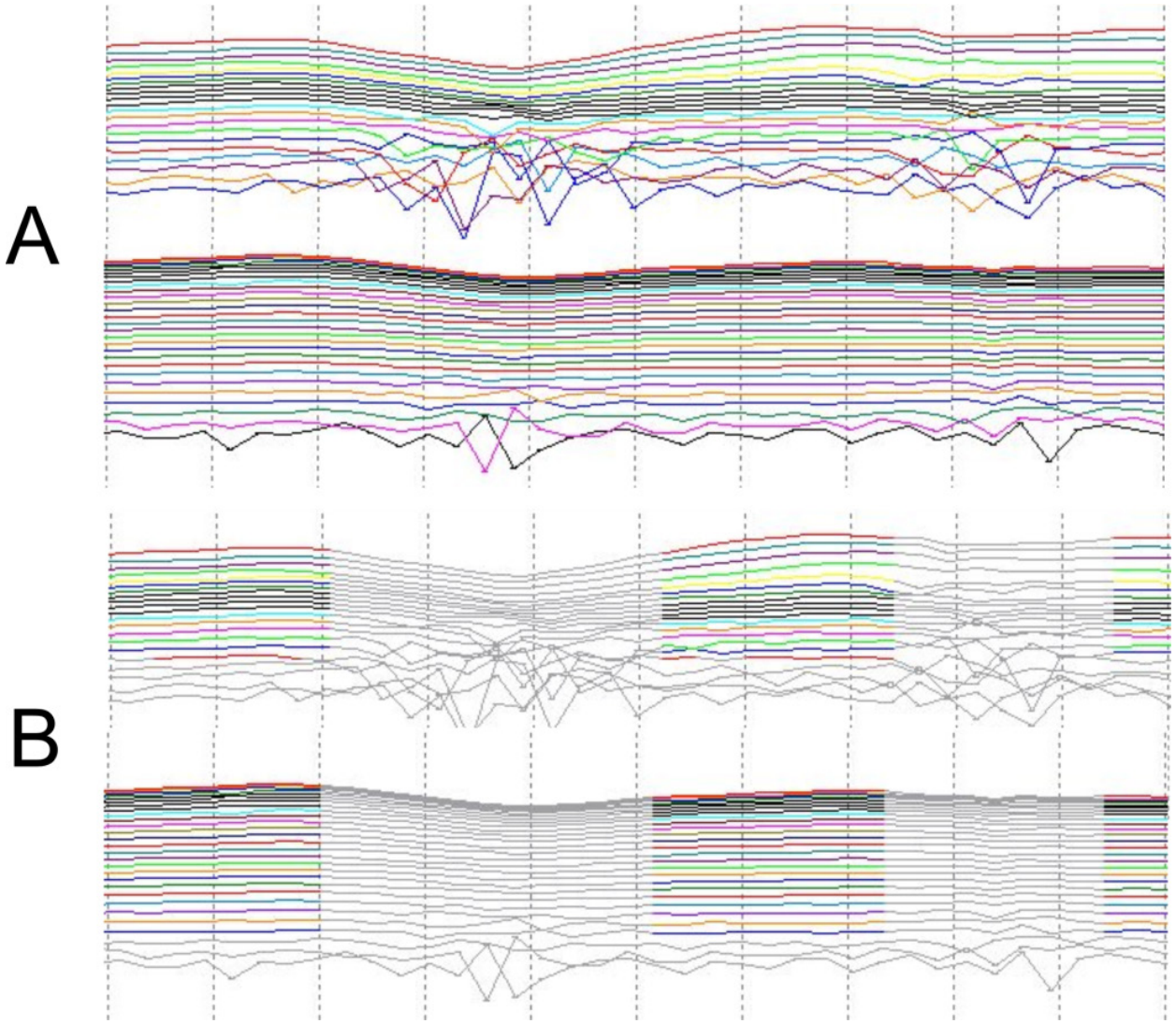



**Figure 4-10. Example of AEM data affected by electromagnetic coupling in the Aarhus Workbench editor. The top group of lines is the unedited data with the Low Moment on top and the High Moment on the bottom. The bottom group shows the same data after editing.**

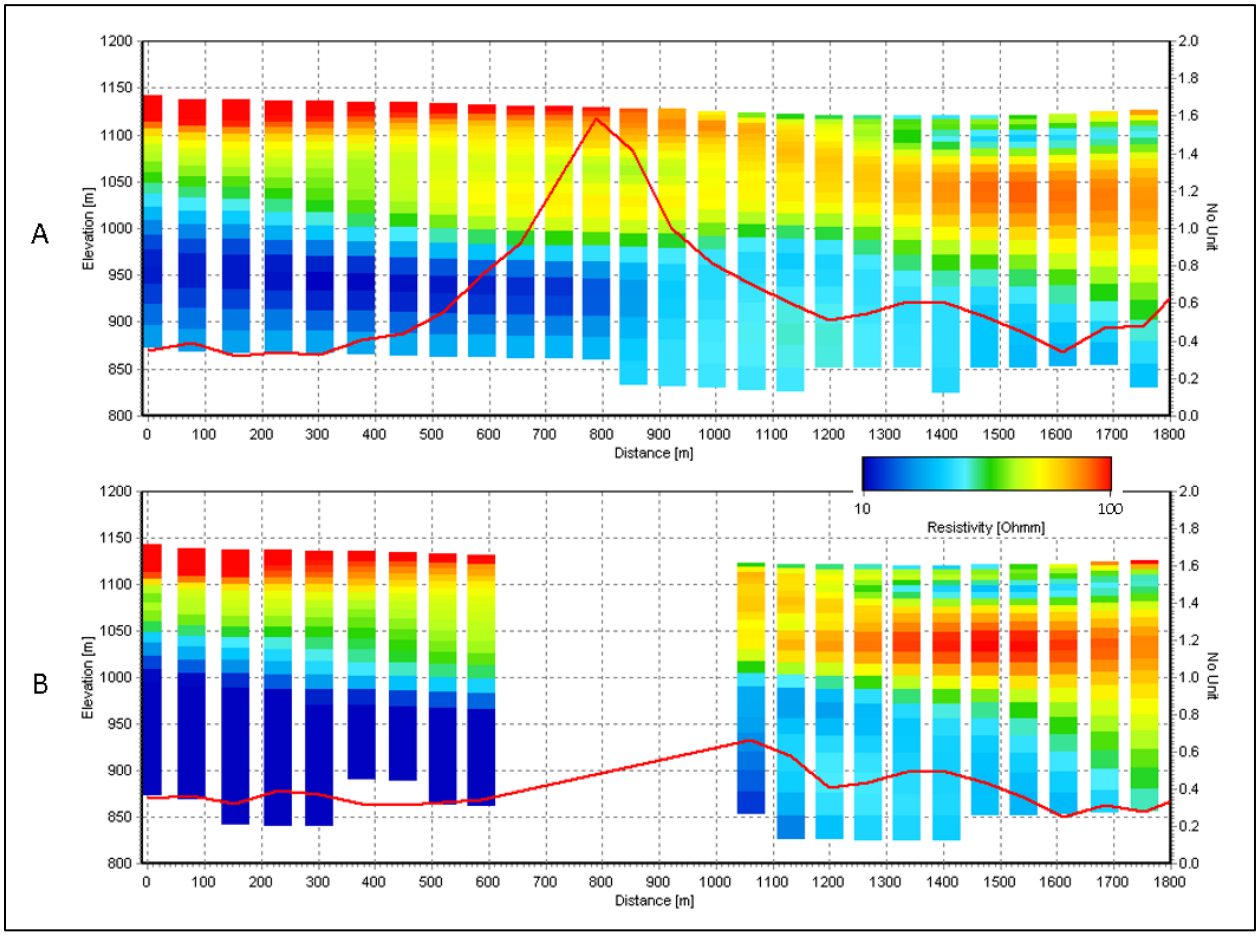



**Figure 4-11. A) Example of Laterally-Constrained inversion results where AEM data affected by coupling with pipelines and power lines were not removed. B) Inversion results where AEM data affected by coupling were removed.**

### *4.4.4 Power Line Noise Intensity (PLNI)*

The Power Line Noise Intensity (PLNI) channel assists in identifying possible sources of noise from power lines. Pipelines, unless they are cathodically-protected, are not mapped by the PLNI. The PLNI is produced by performing a spectral frequency content analysis on the raw received Z-component SkyTEM data. For every Low Moment data block, a Fourier Transform (FT) is performed on the latest usable time gate data. The FT is evaluated at the local power line transmission frequency (60 Hz) yielding the amplitude spectral density of the local power line noise. The PLNI data for the TPNRD AEM survey area are presented in Figure 4-12, for the CPNRD, in Figure 4-13, for the N-CORPE AEM survey area, in Figure 4-14, and for the PRRIP AEM survey area, in Figure 4-15.

In Figure 4-16 (for the TPNRD), Figure 4-17 (for the CPRND), Figure 4-18 (for the N-CORPE), and Figure 4-19 (for the PRRIP) are flight lines with blue colors representing data retained for inversion and red lines representing data removed due to infrastructure and late time noise.

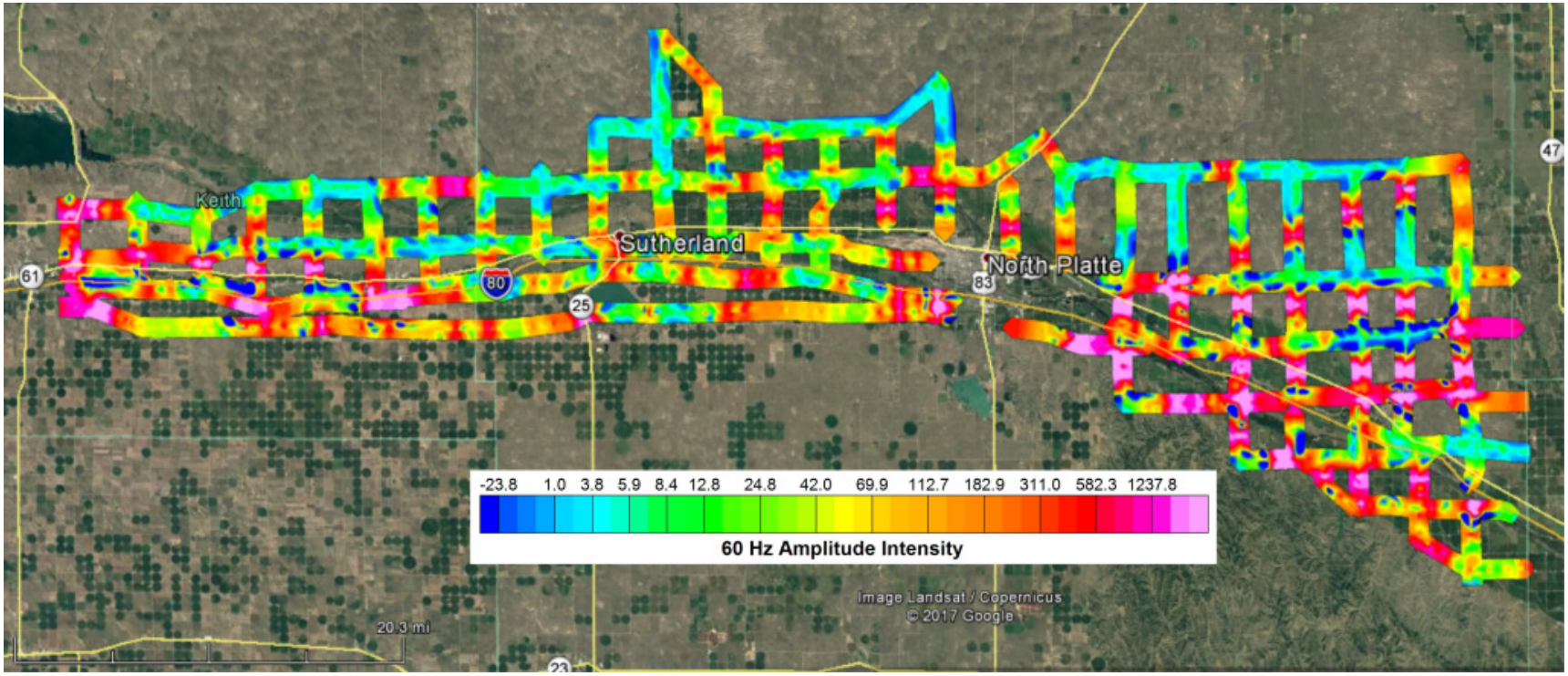



**Figure 4-12. Power Line Noise Intensity (PLNI) map of the TPNRD AEM survey area.**

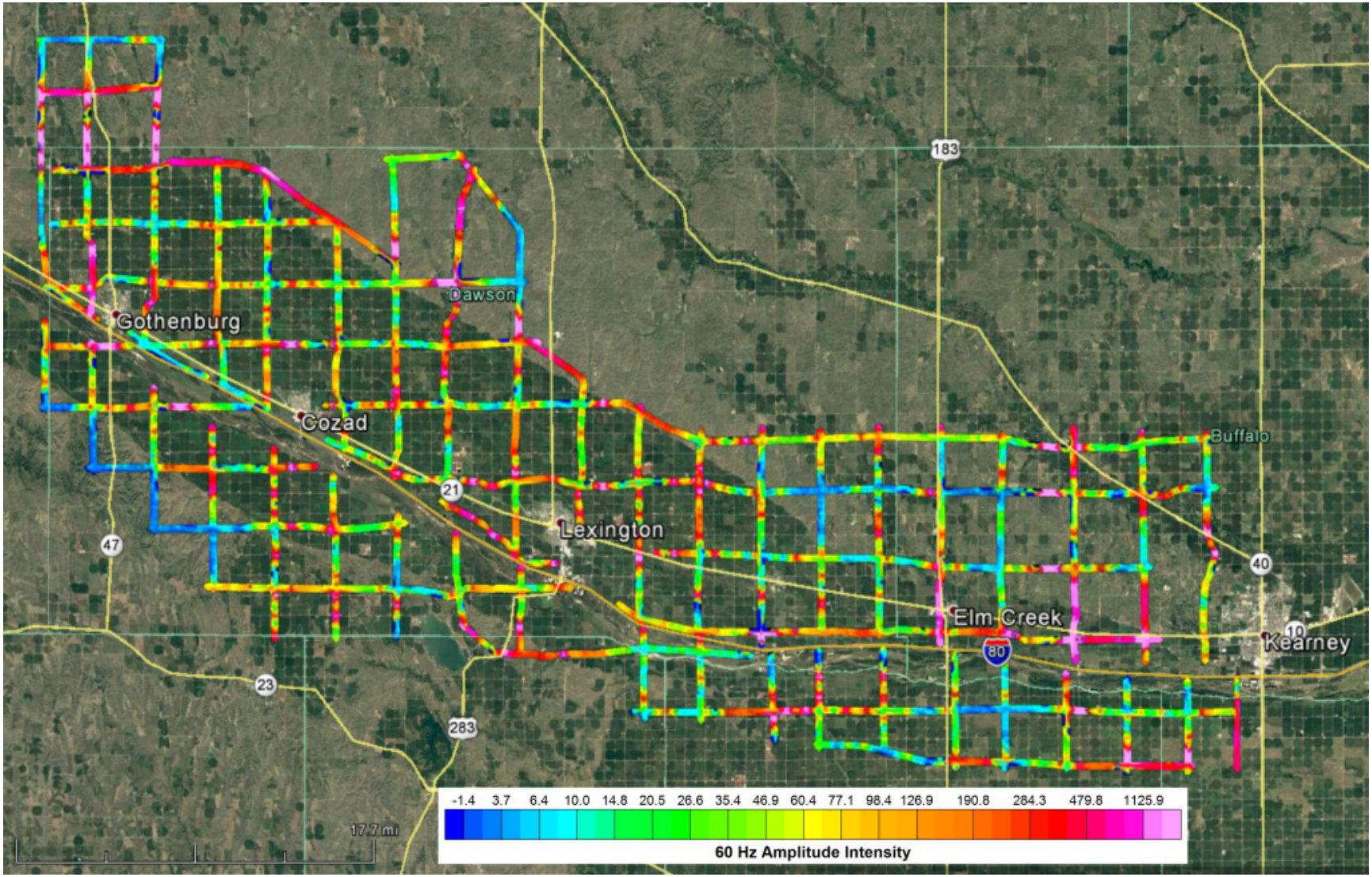



**Figure 4-13. Power Line Noise Intensity (PLNI) map of the CPNRD AEM survey area.**

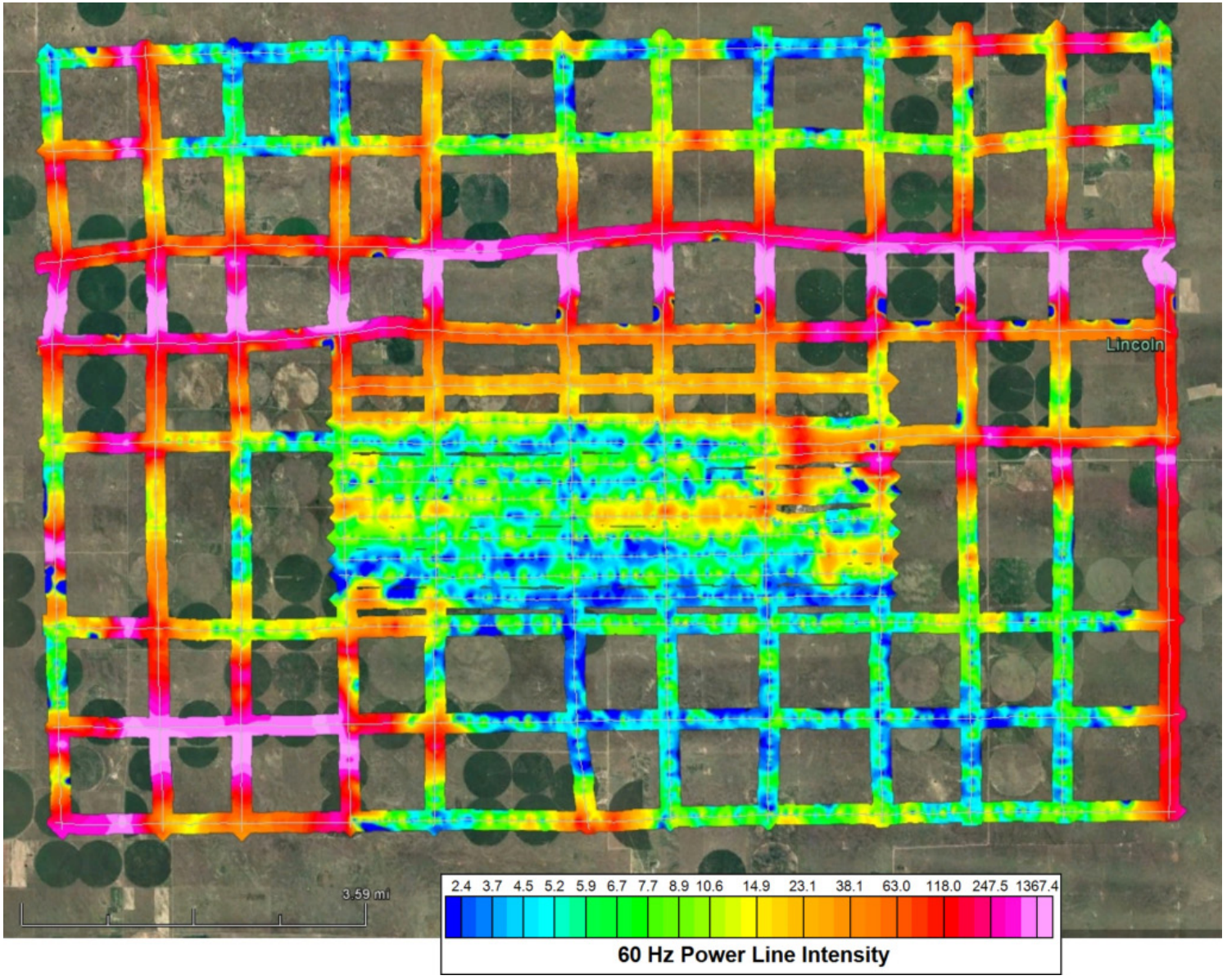



**Figure 4-14. Power Line Noise Intensity (PLNI) map of the N-CORPE AEM block survey area.**

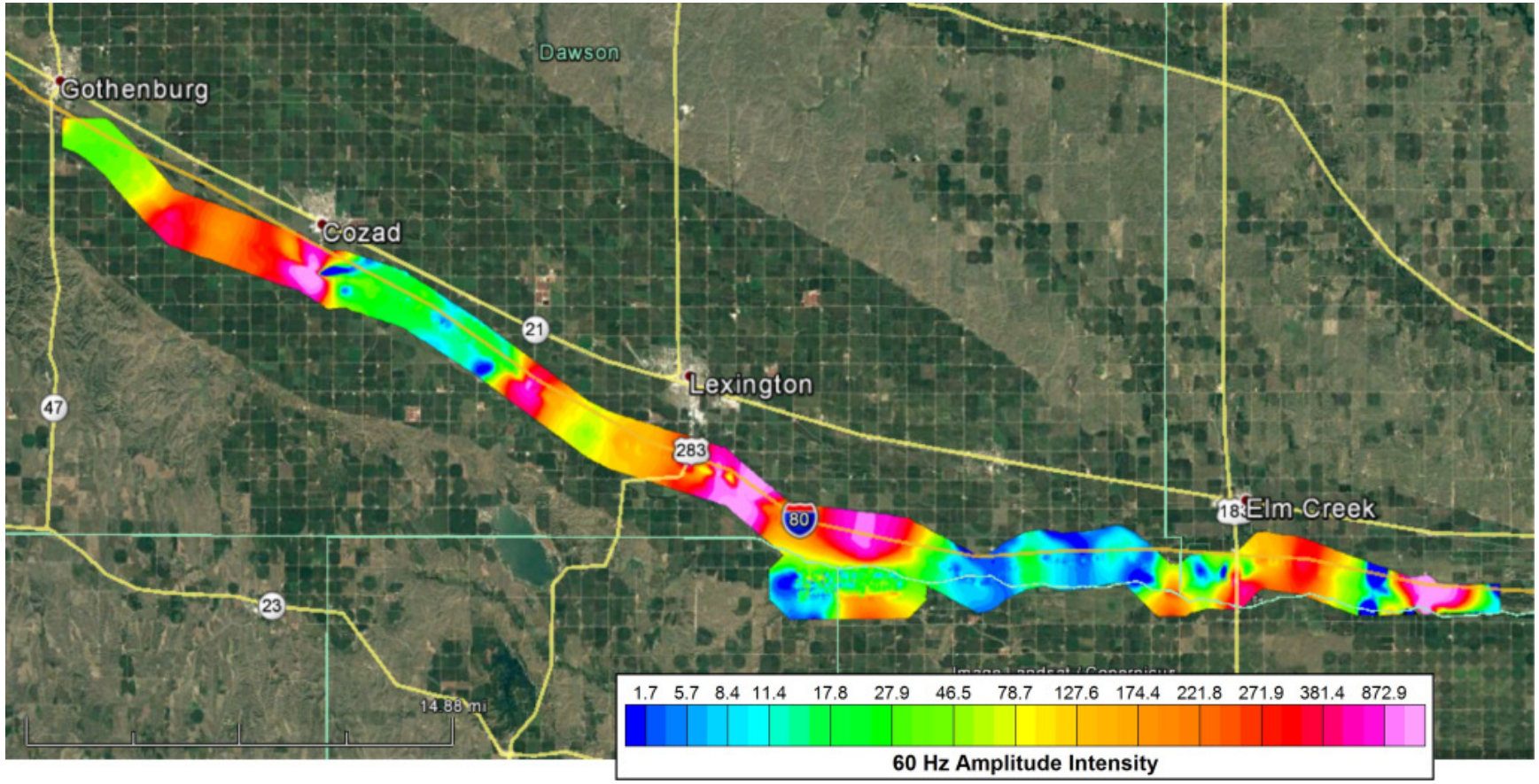



**Figure 4-15. Power Line Noise Intensity (PLNI) map of the PRRIP AEM survey area.**

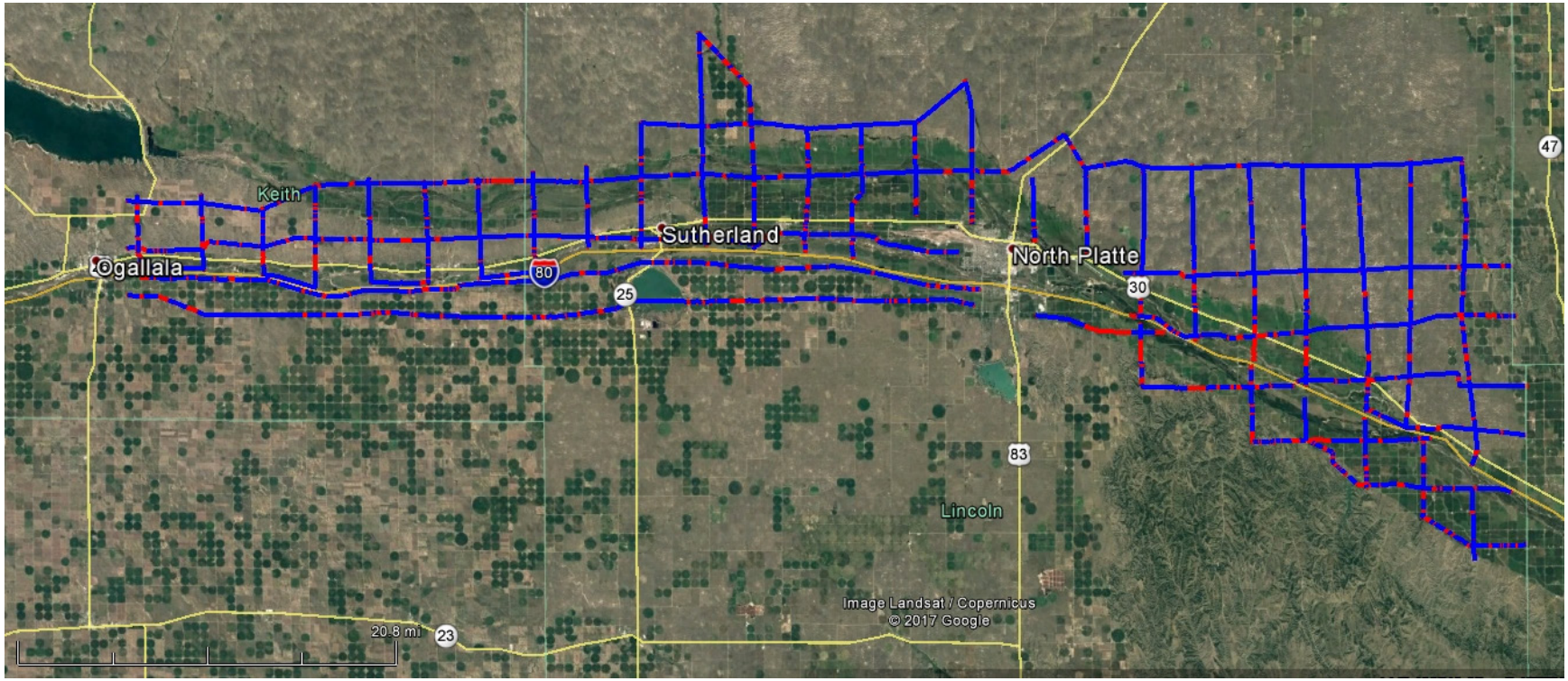



**Figure 4-16. Locations of inverted data (blue lines) along the AEM flight lines (red lines) in the TPNRD AEM survey area. Where blue lines are not present indicates decoupled (removed) data. Google Earth kmz's of the inverted data locations as well as the flight lines are included in Appendix_3_Deliverables\KMZ.**

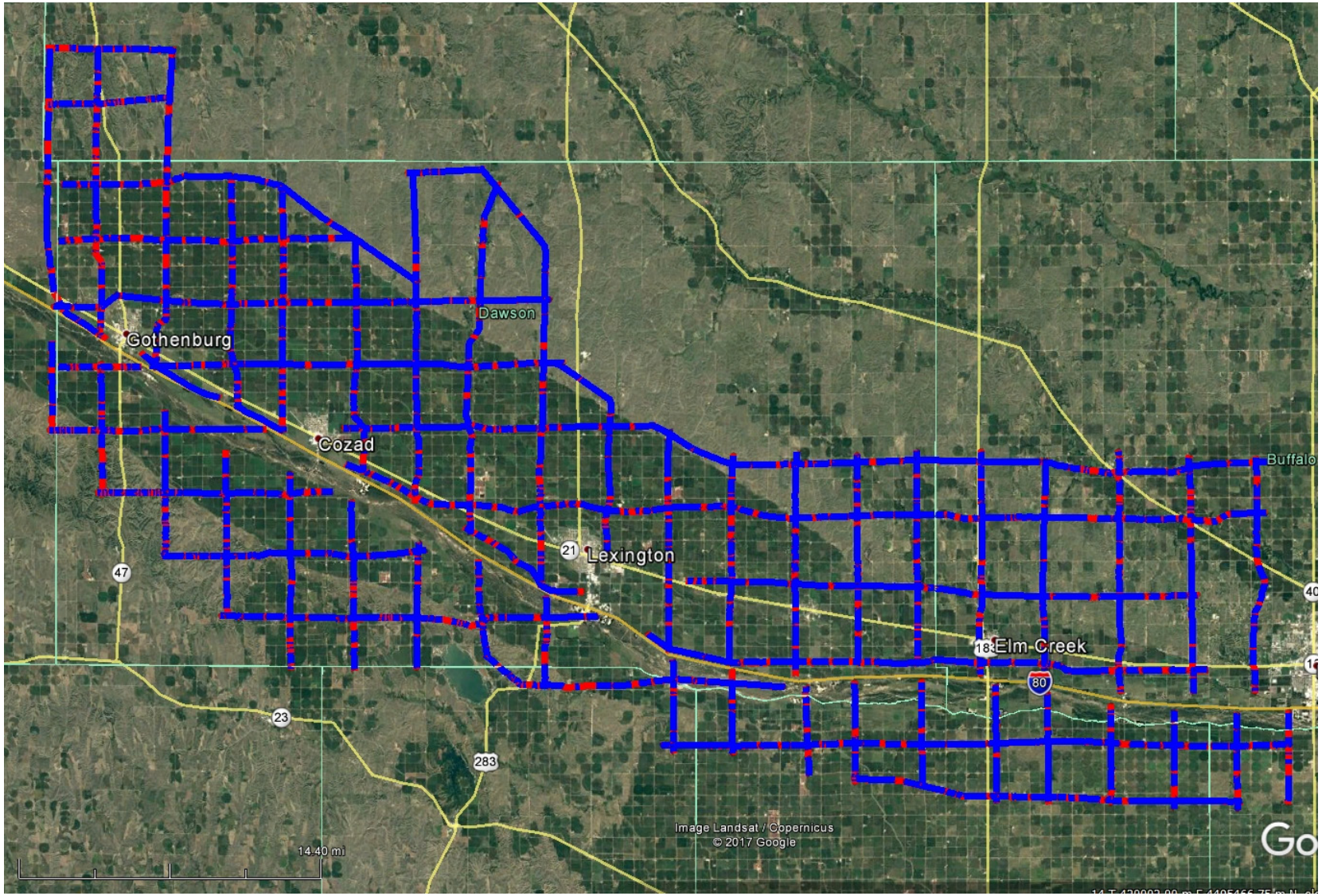



**Figure 4-17. Locations of inverted data (blue lines) along the AEM flight lines (red lines) in the CPNRD AEM survey area. Where blue lines are not present indicates decoupled (removed) data. Google Earth kmz's of the inverted data locations as well as the flight lines are included in Appendix_3_Deliverables\KMZ.**

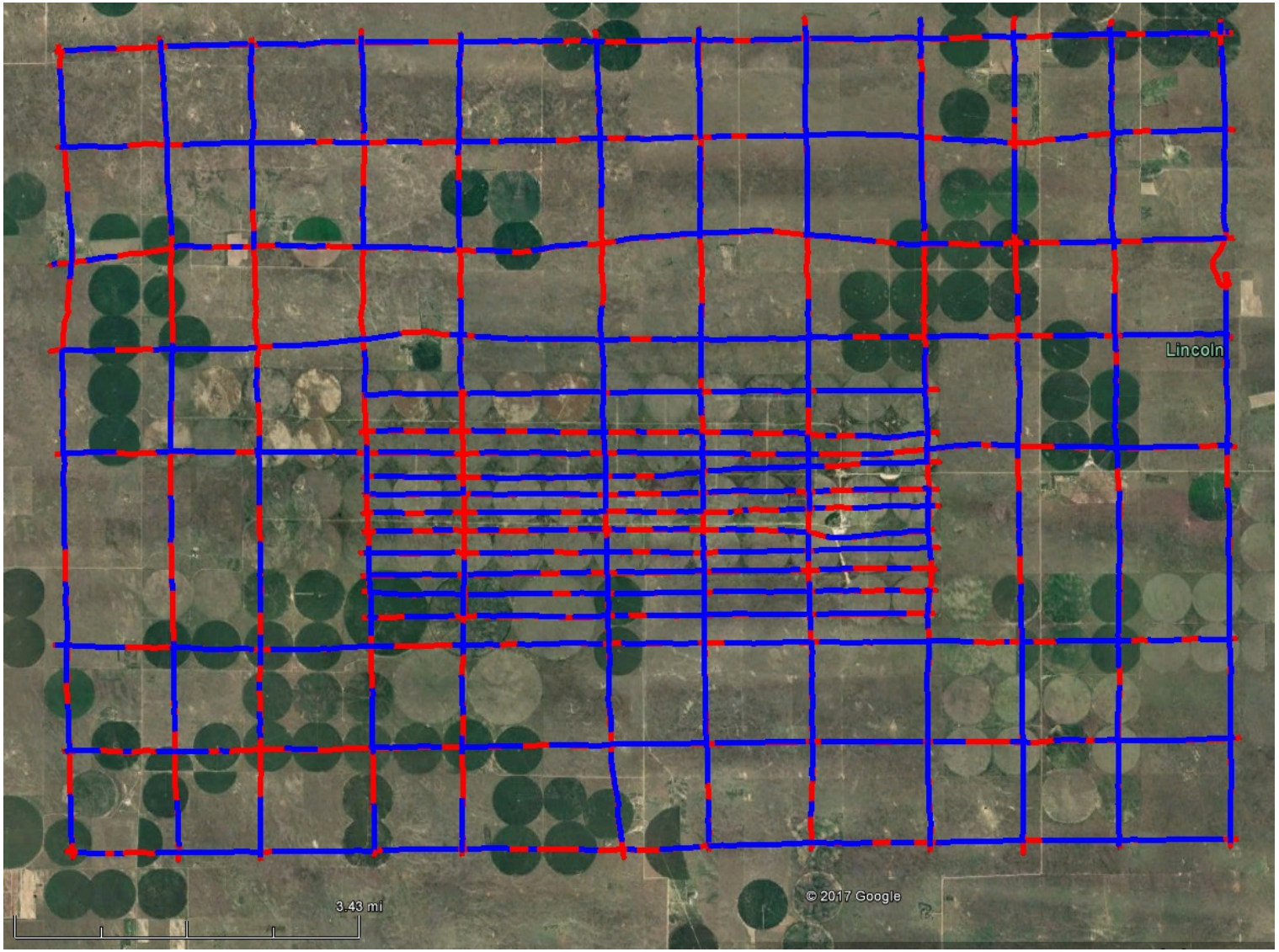



**Figure 4-18. Locations of inverted data (blue lines) along the AEM flight lines (red lines) in the N-CORPE AEM block survey area. Where blue lines are not present indicates decoupled (removed) data. Google Earth kmz's of the inverted data locations as well as the flight lines are included in Appendix_3_Deliverables\KMZ.**

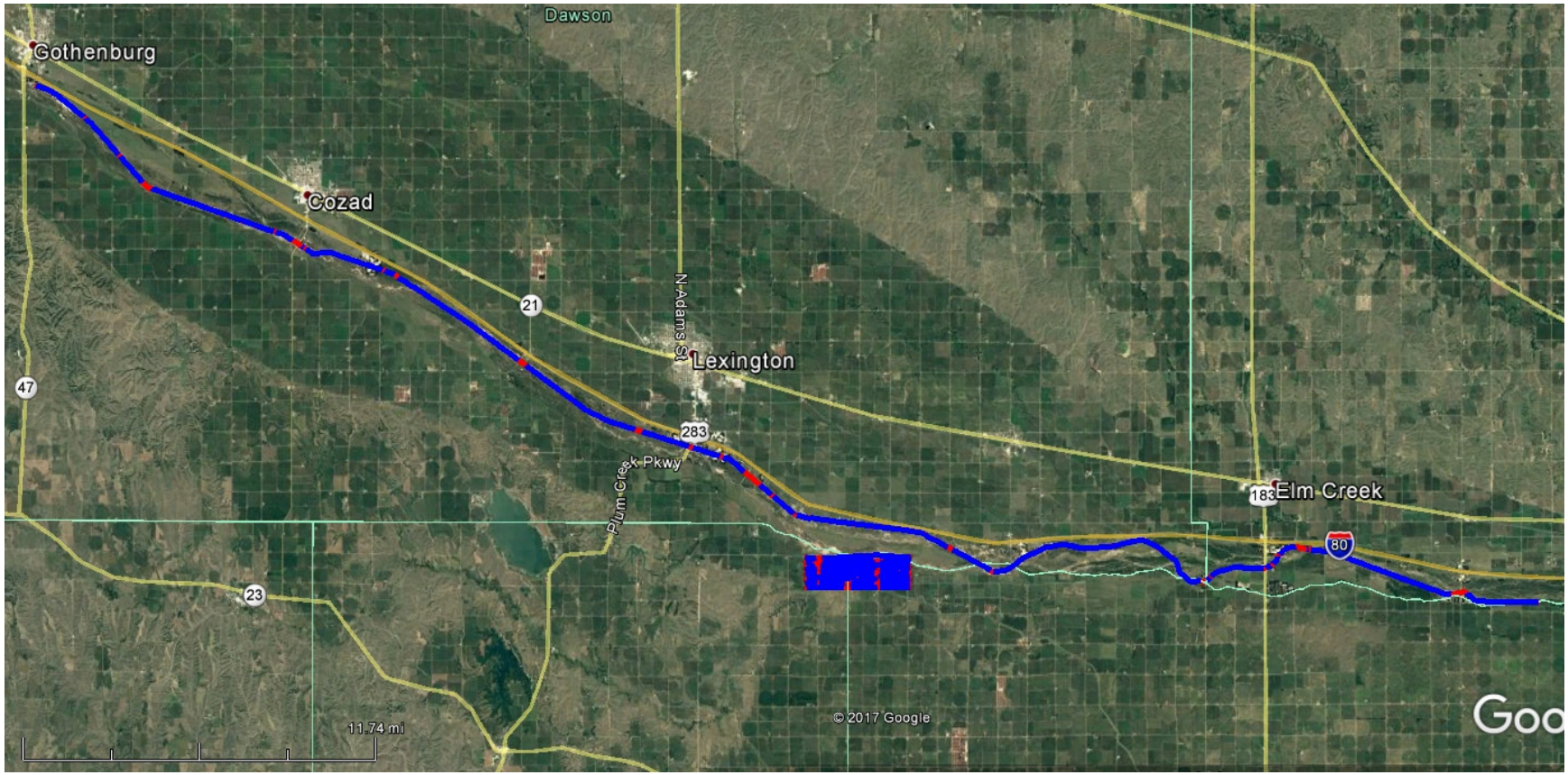



**Figure 4-19. Locations of inverted data (blue lines) along the AEM flight lines (red lines) in the PRRIP AEM survey area. Where blue lines are not present indicates decoupled (removed) data. Google Earth kmz's of the inverted data locations as well as the flight lines are included in Appendix_3_Deliverables\KMZ.**

### 4.4.5 *Magnetic Field Data*

As discussed above, the SkyTEM 304M includes a Total Field magnetometer. The magnetic Total Field data can yield information about infrastructure as well as geology. Figure 4-20 shows the magnetic Total Field intensity data for the TPNRD AEM survey area after correcting for diurnal drift and removing the International Geomagnetic Reference Field (IGRF) creating the Residual Magnetic Field (RMF). These data are used in decoupling efforts.

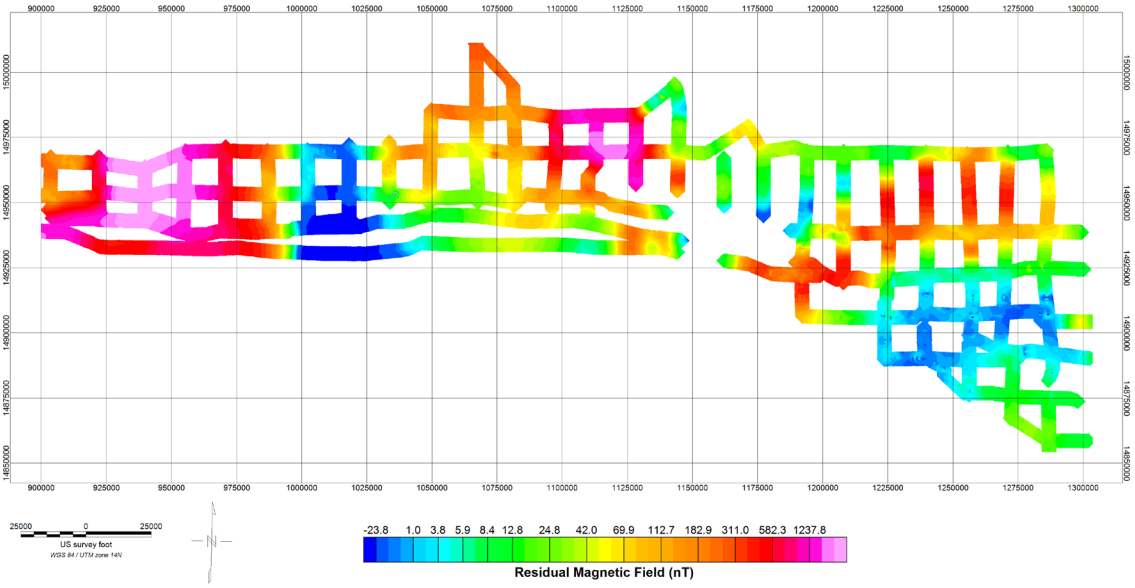



**Figure 4-20. Magnetic Total Field intensity data for the TPNRD AEM survey area corrected for diurnal drift, with the International Geomagnetic Reference Field (IGRF) removed.**

For comparison purposes, images of magnetic Total Field data collected by the USGS (Sweeney and Hill, 2005) are presented in Figure 4-21 for the TPNRD AEM survey area. The USGS data were collected over a much larger reconnaissance grid spacing (5 mile line separation) than were collected in the present survey over the TPNRD and then the USGS data were "upward continued" to a 1000 ft elevation. Even so the comparison between the two data sets are quite good – especially the large high amplitude anomalies in similar positions in each set of images.

Similar figures for the CPNRD are presented in Figure 4-22 (CPNRD AEM RMF) and Figure 4-23 (USGS RMF), in Figure 4-24 (AEM RMF) and Figure 4-25 (USGS RMF) for the N-CORPE AEM block fight area, and in Figure 4-26 (AEM RMF) and Figure 4-27 (USGS RMF) for the PRRIP AEM survey area.

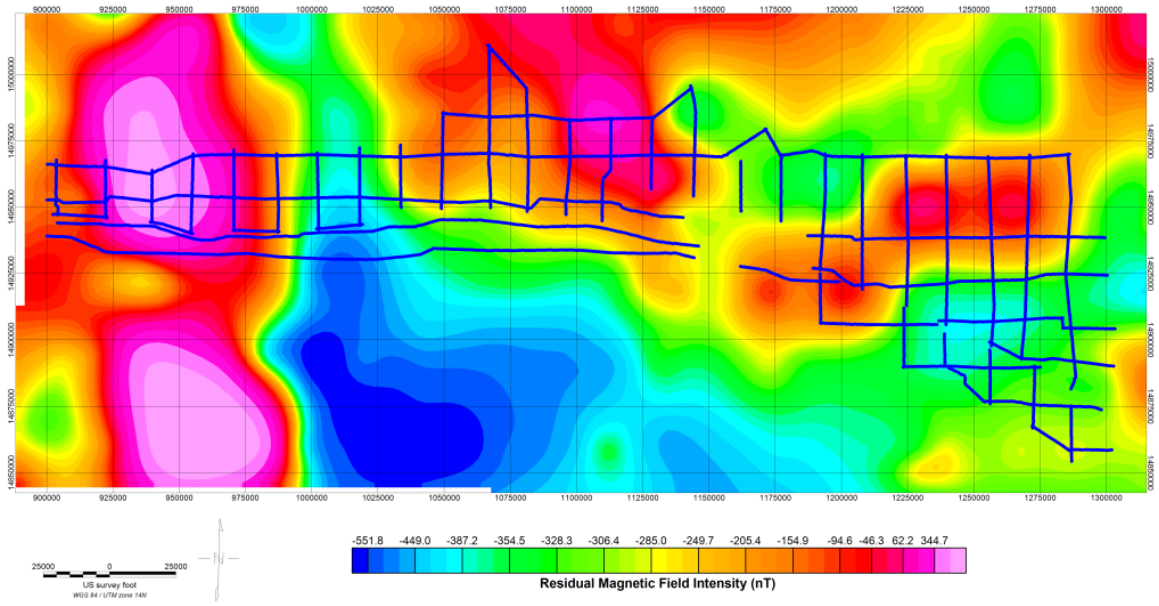



**Figure 4-21. USGS magnetic Total Field intensity data for the TPNRD AEM survey area corrected for diurnal drift, with IGRF removed (Sweeney and Hill, 2005). The data was collected on an approximately 5-mile line spacing and upward continued to a reference elevation of 1000 ft. The AEM survey lines are marked in blue.**

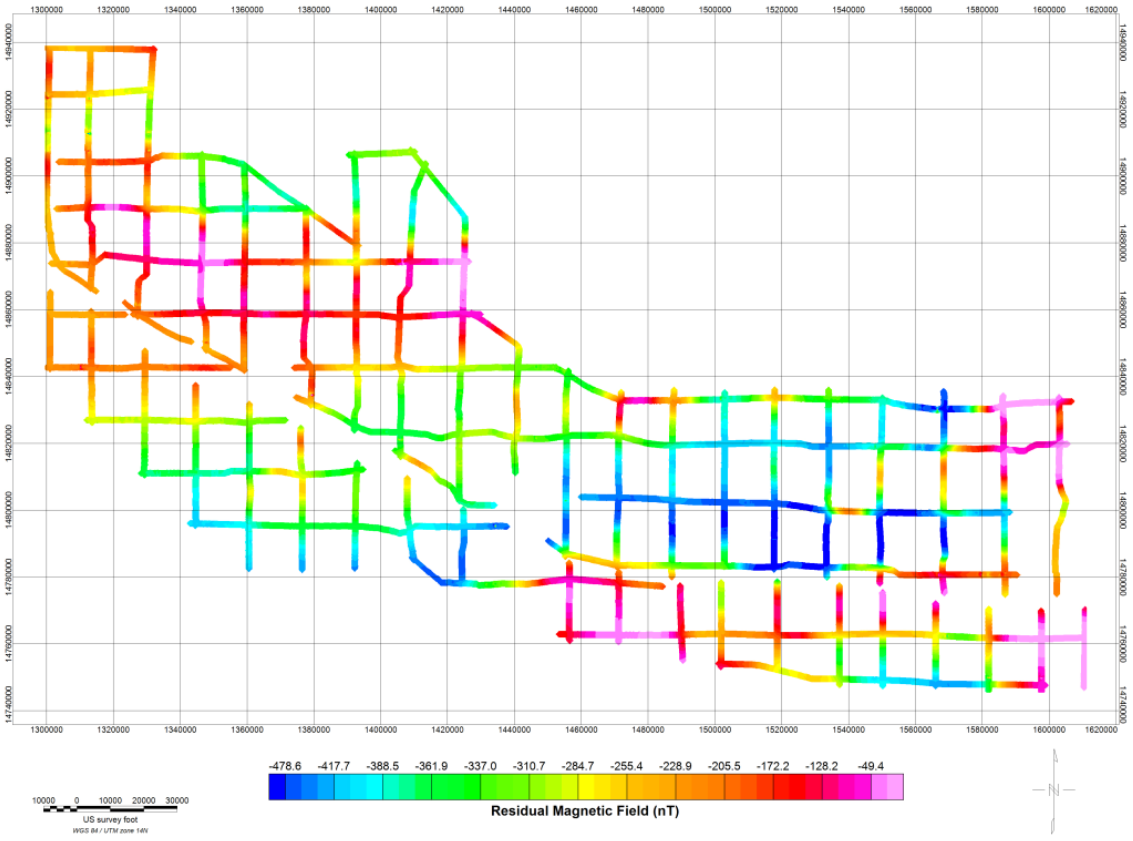



**Figure 4-22. Magnetic Total Field intensity data for the CPNRD AEM survey area corrected for diurnal drift, with the International Geomagnetic Reference Field (IGRF) removed.**

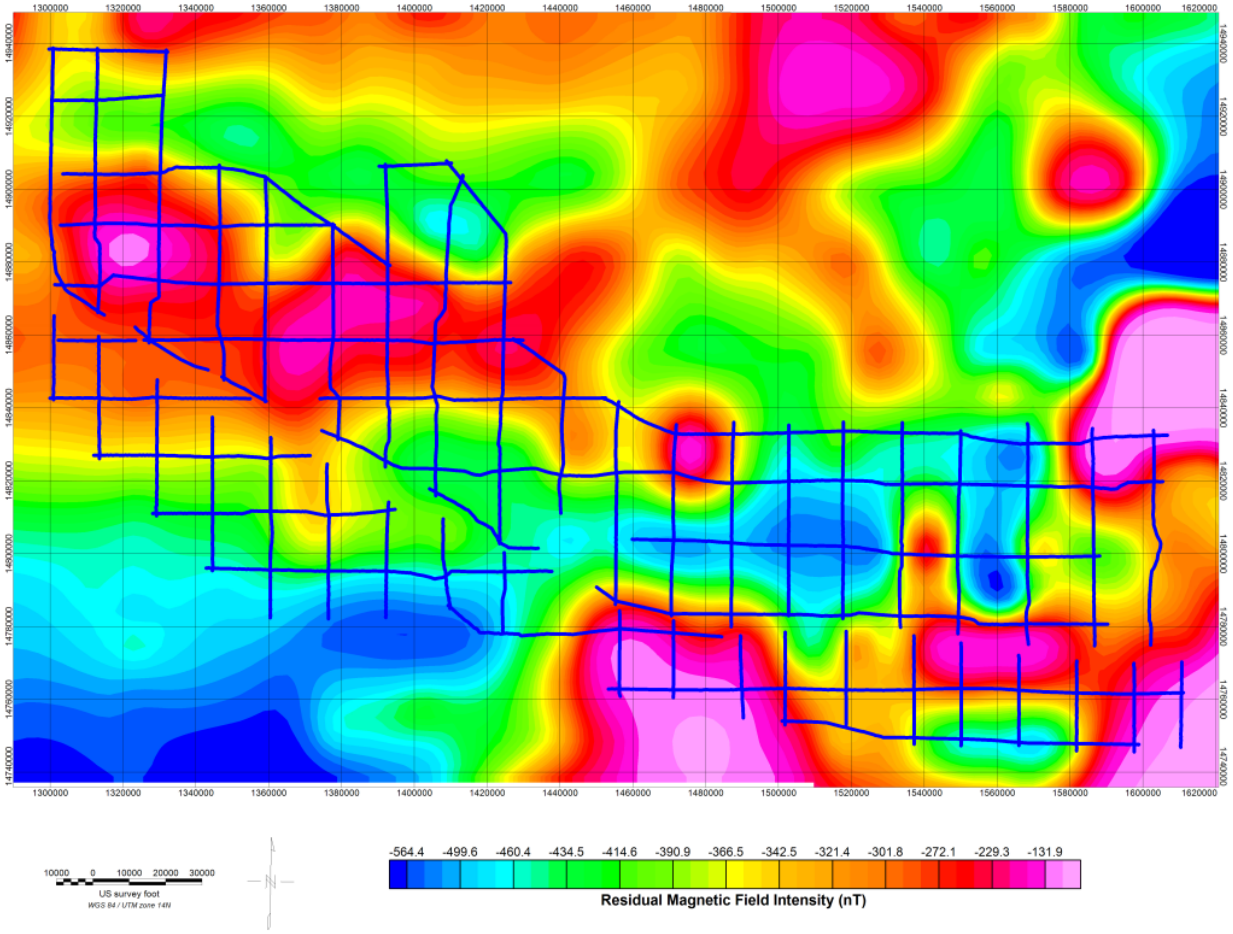



**Figure 4-23. USGS magnetic Total Field intensity data for the CPNRD AEM survey area corrected for diurnal drift, with IGRF removed (Sweeney and Hill, 2005). The data was collected on an approximately 5-mile line spacing and upward continued to a reference elevation of 1000 ft. The AEM survey lines are marked in blue.**

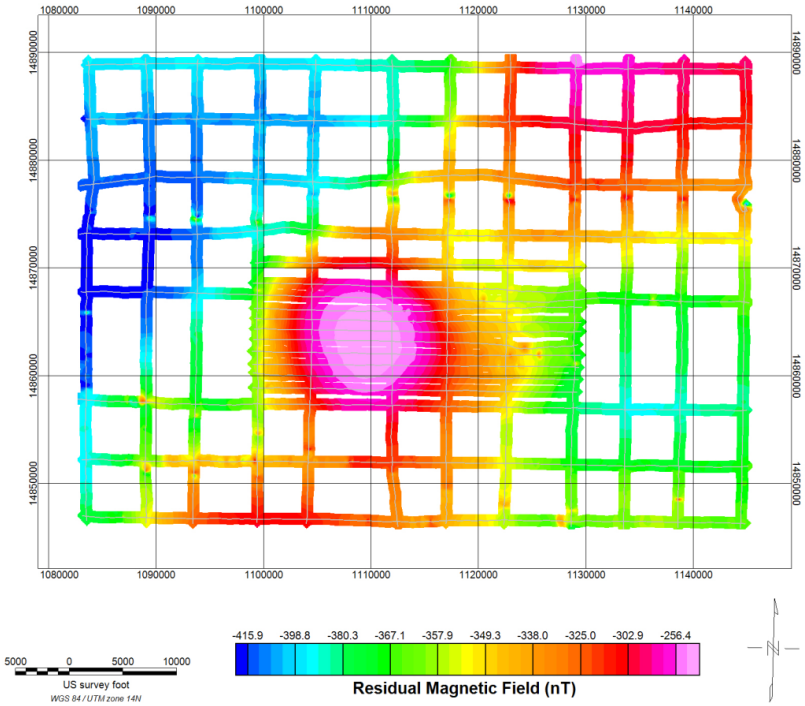



**Figure 4-24. Magnetic Total Field intensity data for the N-CORPE AEM block survey area corrected for diurnal drift, with the International Geomagnetic Reference Field (IGRF) removed.**

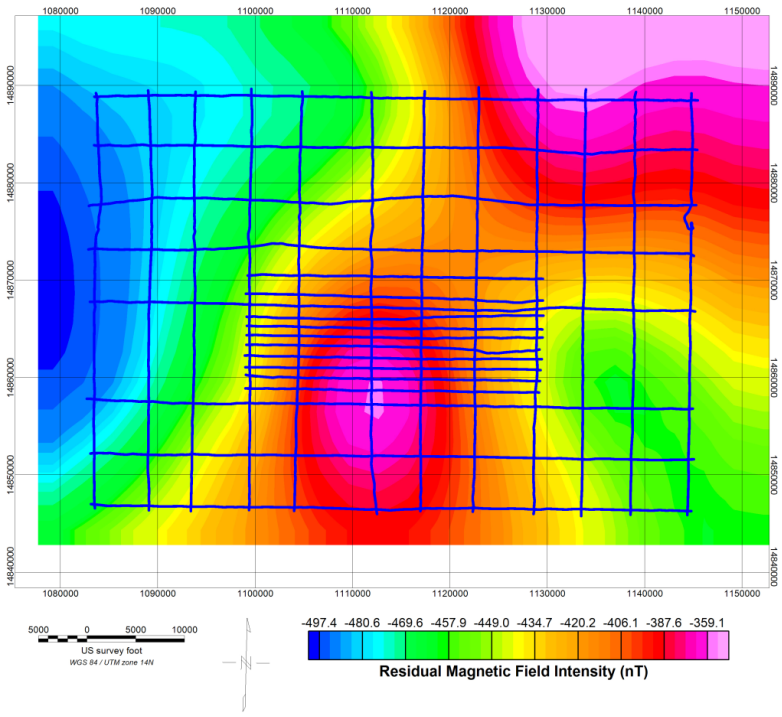



**Figure 4-25. USGS magnetic Total Field intensity data for the N-CORPE AEM block survey area corrected for diurnal drift, with IGRF removed (Sweeney and Hill, 2005). The data was collected on an approximately 5-mile line spacing and upward continued to a reference elevation of 1000 ft. The AEM survey lines are marked in blue.**

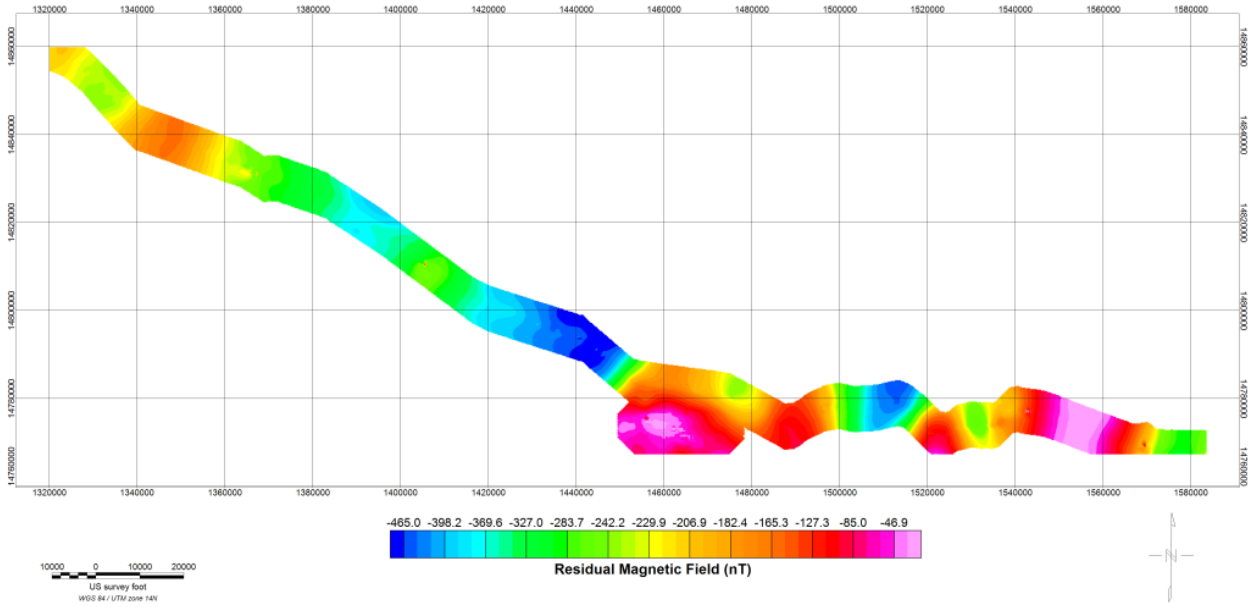



**Figure 4-26. Magnetic Total Field intensity data for the PRRIP AEM survey area corrected for diurnal drift, with the International Geomagnetic Reference Field (IGRF) removed.**

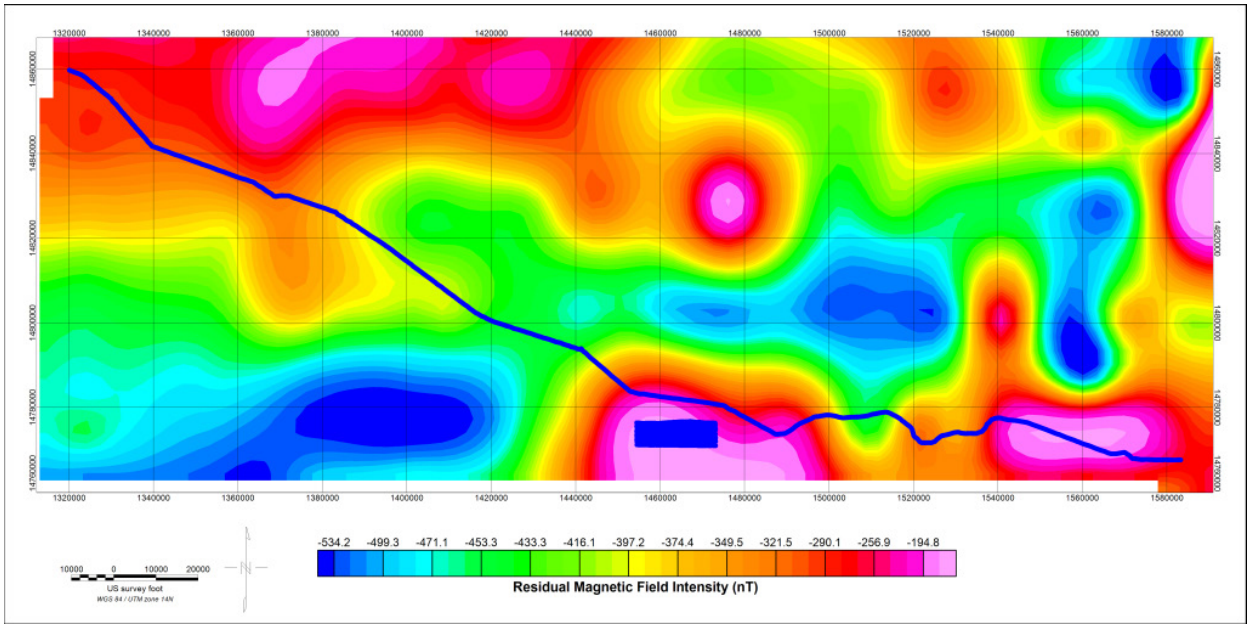



**Figure 4-27. USGS magnetic Total Field intensity data for the PRRIP AEM survey area corrected for diurnal drift, with IGRF removed (Sweeney and Hill, 2005). The data was collected on an approximately 5-mile line spacing and upward continued to a reference elevation of 1000 ft. The AEM survey lines are marked in blue.**

## 4.5 Spatially-Constrained Inversion

Following the initial decoupling and LCI analysis, Spatially-Constrained Inversions (SCI) were performed. SCIs use EM data along, and across, flight lines within user-specified distance criteria (Viezzoli et al., 2008).

The TPNRD, CPNRD, N-CORPE, and PRRIP AEM data were inverted using SCI smooth models with 29 layers, each with a starting resistivity of 10 Ohm-m (equivalent to a 10 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. The depths to the bottoms of the 28$^{th}$ layers were set to 1,023 ft, with thicknesses up to about 85 ft. The thicknesses of the layers increase with depth (Table 4-4 and Figure 4-28) as the resolution of the technique decreases. The spatial reference distance, ***s***, for the constraints were set to 98 ft with power laws of 0.5. The vertical and lateral constraints, ***ResVerSTD*** and ***ResLatStD***, were set to 2.7 and 1.6, respectively, for all layers.

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; SkyTEM Airborne Surveys Worldwide, 2012). 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).

**Table 4-4: Thickness and depth to bottom for each layer in the 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 | 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 | 1023.0 | 84.9 |
| 15 | 267.2 | 28.9 | | | |

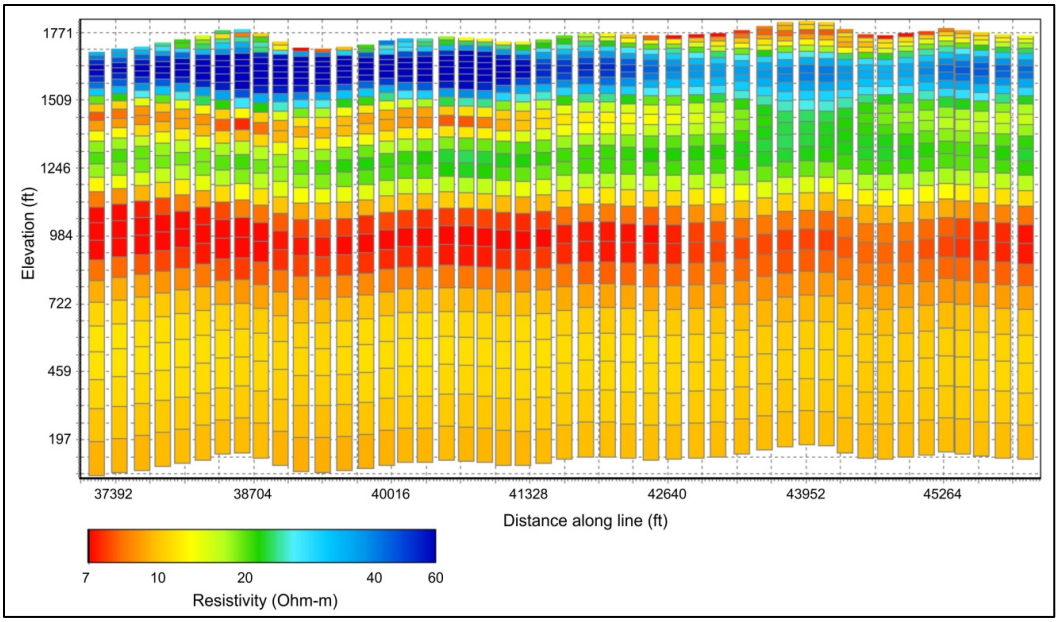



**Figure 4-28. An example of an AEM profile illustrating increasing model layer thicknesses with depth.**

Figure 4-29 presents a histogram of the TPNRD, CPNRD, and-PRRIP SCI inversion data/model residuals. A similar histogram for the N-CORPE SCI inversion data/model residuals is presented in Figure 4-30. Maps of data residuals for the TPNRD AEM study area are presented in Figure 4-31, in Figure 4-32 for the CPNRD, in Figure 4-33 for the N-CORPE, and in Figure 4-34 for the PRRIP.

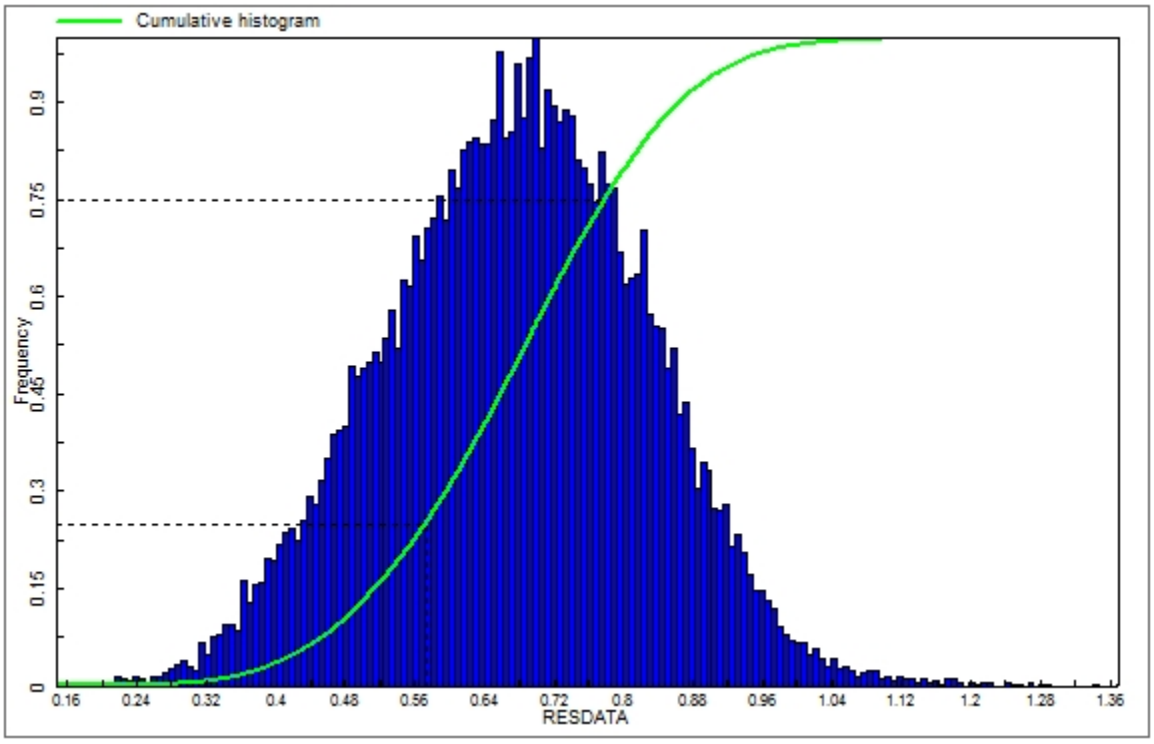



**Figure 4-29. Data/model residual histogram for the TPNRD, CPNRD, and PRRIP SCI inversion results.**

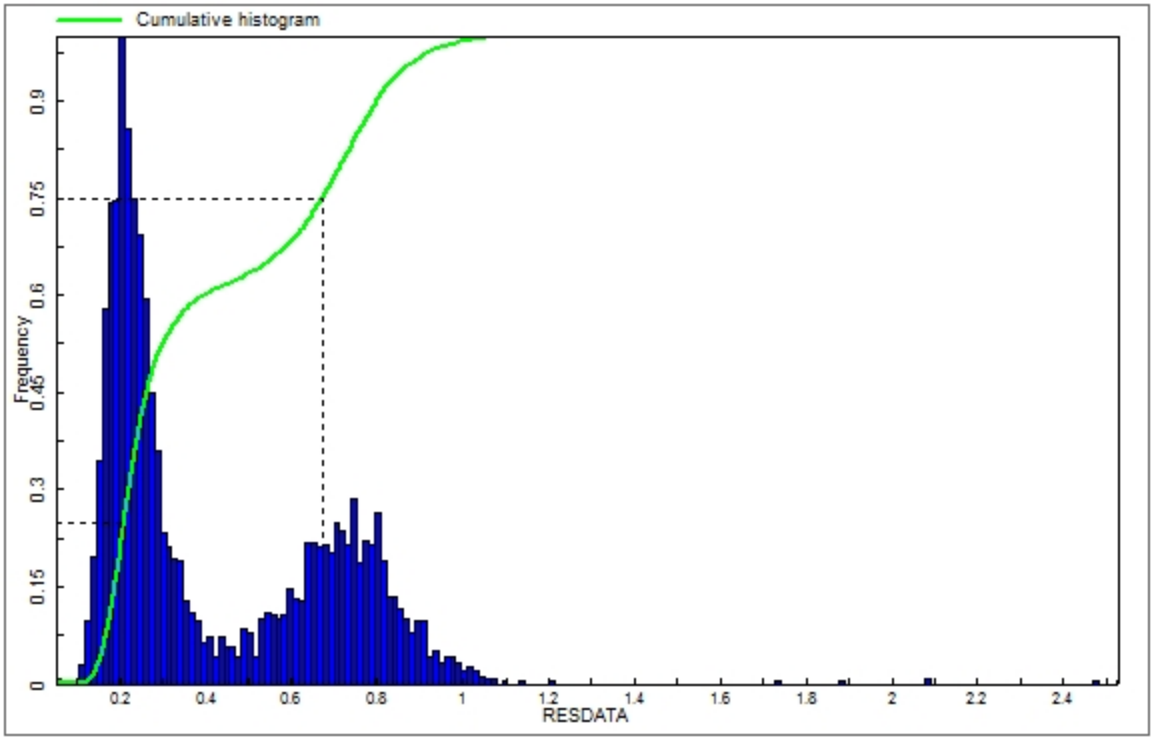



**Figure 4-30. Data/model residual histogram for the N-CORPE SCI inversion results.**

The N-CORPE SCI histogram in Figure 4-30 indicates a bi-modal residual error distribution. Examination of Figure 4-33, a map of the residual data/model errors for the N-CORPE SCI results, shows that the errors on the east-west reconnaissance flight lines were much higher than either the north-south reconnaissance flight lines or the east-west block flight lines. As indicated in Figure 4-7, the N-CORPE AEM data were acquired over a two day period on July 8th-9th, 2016 with the first flight on July 8 being the east-west reconnaissance flight and the second flight on July 8th being the north-south reconnaissance flight. Examination of the raw and processed data indicates that the altitude control was much more irregular for the east-west flight on July 8 than the north-south flight, most likely due to strong winds in the east-west direction. The recorded altitude data for Flight 1 on July 8 (the east west flight) shows a high frequency variation in altitude (i.e. choppy flying conditions with the helicopter moving rapidly up and down as it tried to maintain a fixed 30 m altitude but was having trouble) and a much smoother flight with a steadier altitude for the second flight (in the north-south direction.

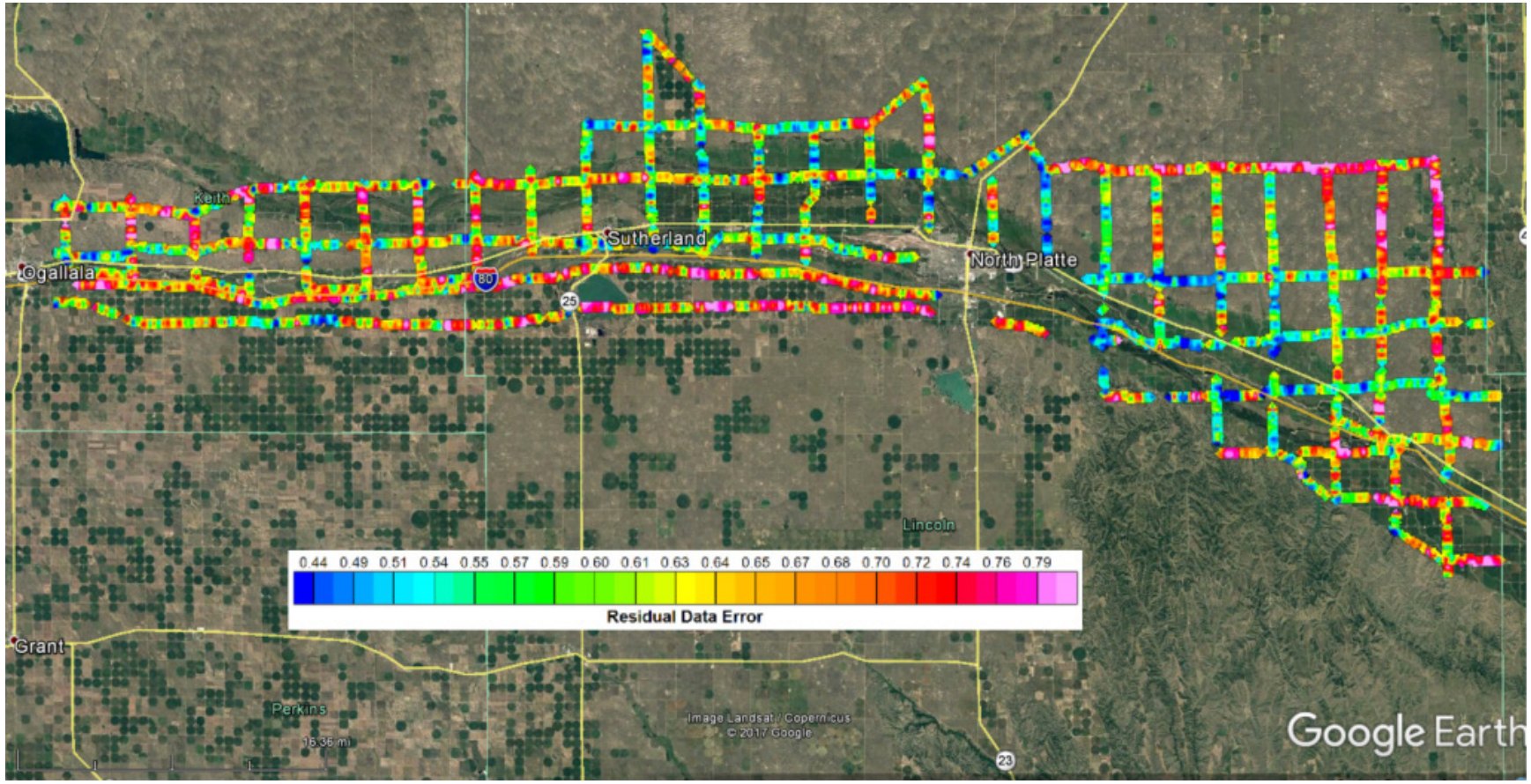



**Figure 4-31. Map of data residuals for the TPNRD SCI inversion results.**

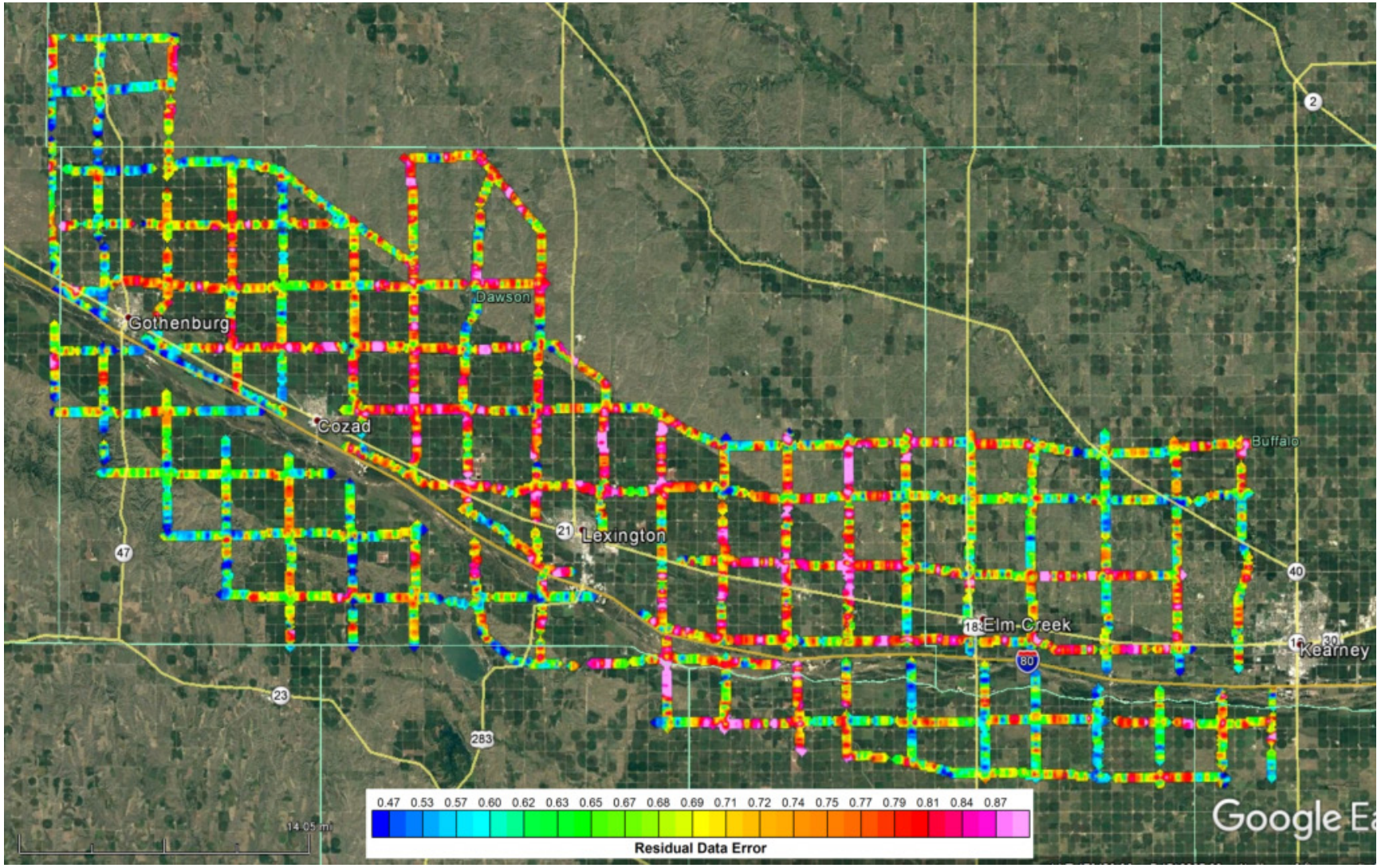



**Figure 4-32. Map of data residuals for the CPNRD SCI inversion results.**

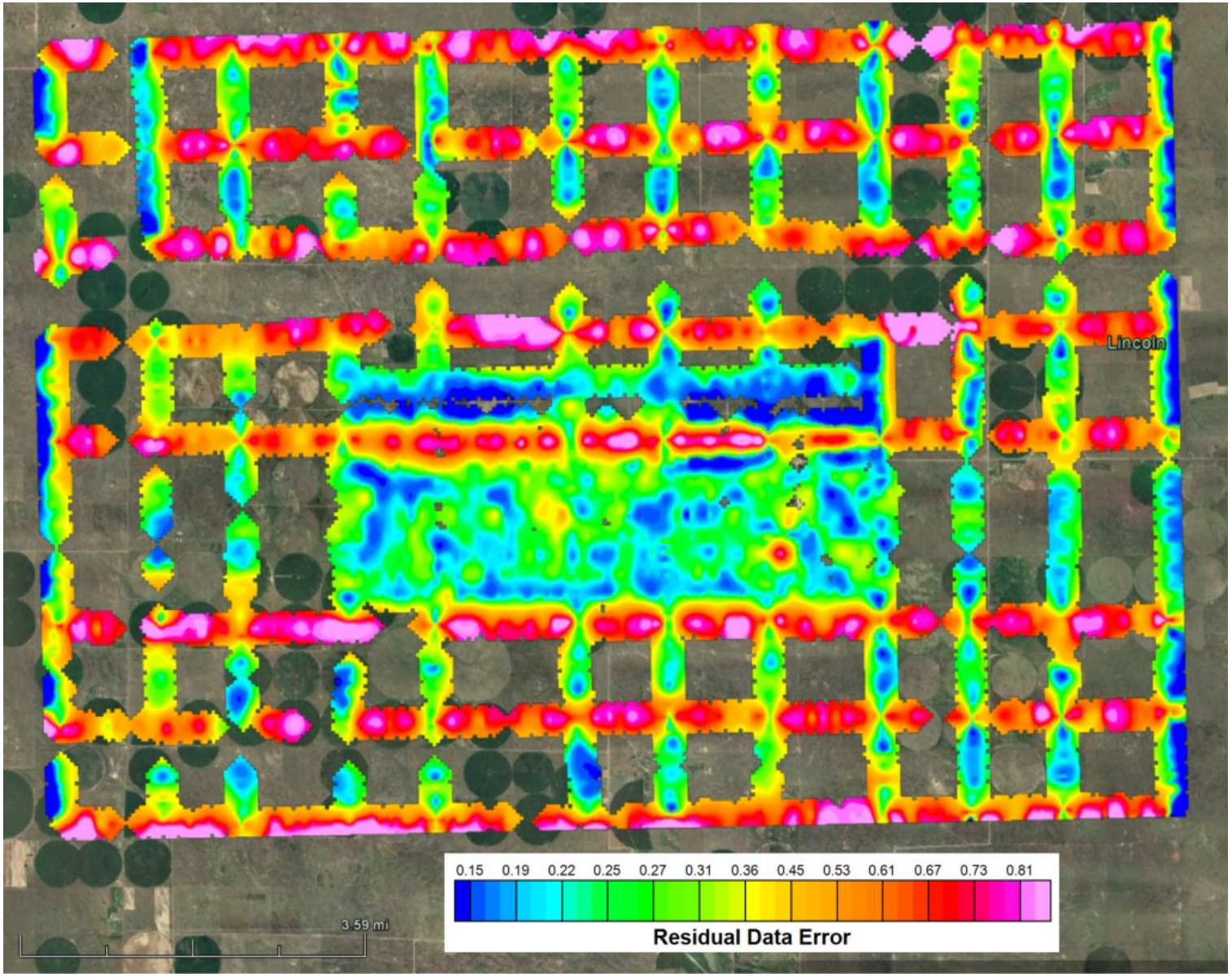



**Figure 4-33. Map of data residuals for the N-CORPE SCI inversion results.**

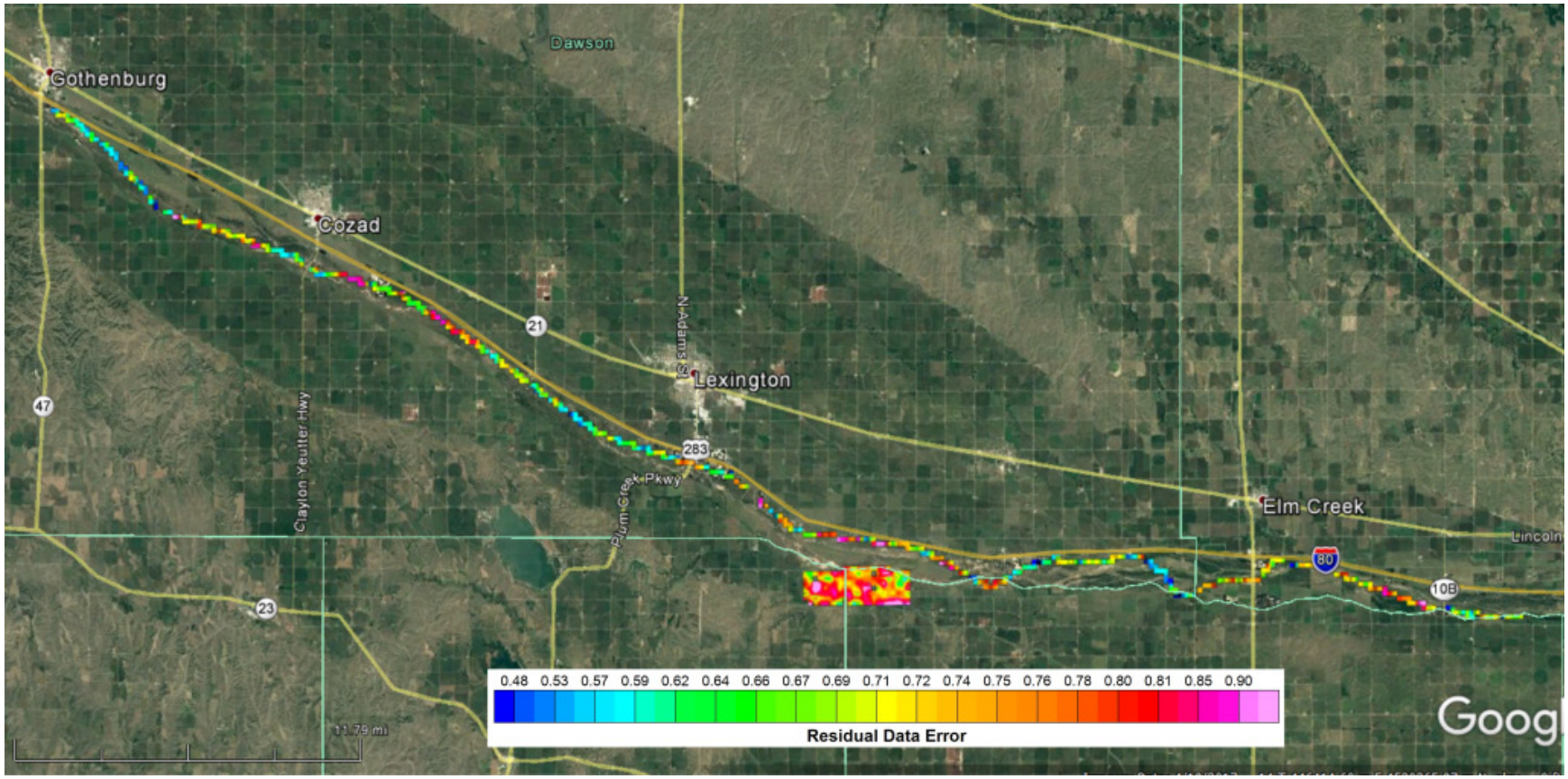



**Figure 4-34. Map of data residuals for the PRRIP SCI inversion results.**

# 5 AEM Results and Interpretation

This section provides the details on the process involved in the interpretation of the TPNRD, CPNRD, N-CORPE and PRRIP AEM data and inversion results.

## 5.1 Interpretive Process

### *5.1.1 Merging and Splitting AEM Flight Lines*

After the inversion process, several long lines and lines with turns were split into shorter segments. Short lines and line segments were combined to form continuous lines within the TPNRD and CPNRD AEM survey area. These split and merged lines allow for improved viewing and interpretation of the AEM inversions results. Table 5-1 lists the original flown lines and the splits that were implemented. Table 5-2 lists the original lines and the new combined lines.

**Table 5-1. Flight lines Split within TPNRD and CPNRD AEM Survey Area**

| NRD | Original Source Lines | Direction | New Lines |
|---|---|---|---|
| TPNRD | L100501 | East-West | L100501, and L100501b |
| TPNRD | L102401 | North-South and Southeast-Northwest | L102401, and L102401b |
| TPNRD | L200101 | East-West | L200101, and L200101b |
| TPNRD | L200301 | East-West | L200301, and L200301b |
| TPNRD | L200603 | East-West | L200603, and L200602b |
| CPNRD | L103901 | East-West and Southeast-Northwest | L103901, and L103901b |
| CPNRD | L106801 | North-South and Southeast-Northwest | L106801, and L106801b |
| CPNRD | L107001 | North-South and Southeast-Northwest | L107001, and L107001b |

An AEM survey was flown in 2010 in the western portion of the TPNRD along the North Platte River in the Keystone area (Abraham et al., 2012; Cannia et al., 2012; Hobza et al., 2014; USGS-CGGSC, 2014). This 2010 AEM data acquisition just overlaps on the north-western end of 2016 AEM data coverage (Figure 5-1). A comparison of the data collected in 2010 (with the SkyTEM 304) and 2016 (with the SkyTEM 304M) can indicate the stability of the system and the ability of the data to be integrated together. When examining the combination of the two separate data sets that were collected by different systems at different times and inverted separately, it is important to note that both data sets were calibrated and all system bias was removed prior to inversion. Inspection of the profiles created from the combined lines displaying inverted resistivity at the same color scale can indicate an issue with calibration and incomplete bias removal. Figure 5-2 is a 3D resistivity fence diagram of the overlapping lines of the 2010 AEM (SkyTEM 304) and 2016 (SkyTEM 304M) looking from the north towards the south. In Figure 5-2 the resistivity values for both surveys continue along the same trend. The combination of the two datasets indicates that there is no observable bias that was not removed from the data prior to inversion. Even though the lines are not directly butted up against each other, the

comparison of the AEM data collected in 2016 and the AEM data collected in 2010 show good spatial correlations.

**Table 5-2. Combination of flight lines within TPNRD and CPNRD AEM Survey Area**

| NRD | Original Source Lines | Direction | New Line |
|---|---|---|---|
| TPNRD | L100301, and L100302 | East-West | L200603 |
| TPNRD | L100701, and L100702 | East-West | L201403 |
| TPNRD | L101101, and L200101 | East-West | L301802 |
| TPNRD | L200901, and L200902 | East-West | L401803 |
| TPNRD | L101301, and L101302 | Southeast-Northwest | L202603 |
| TPNRD | L201101, and L201101 | Southeast-Northwest | L402203 |
| TPNRD | L102801, and L102802 | North-South | L205603 |
| TPNRD | L103801, and L200201 | North-South | L304002 |
| TPNRD | L104201, and 200401 | North-South | L304602 |
| TPNRD | L104401, L104402, and L200601 | North-South | L409404 |
| TPNRD | L170801, and L171001 | North-South | L341803 |
| TPNRD | L104601, and L104801 | North-South | L305402 |
| TPNRD | L105001, and L201201 | North-South | L306202 |
| CPNRD | L103301, L103302, and L103301 | East-West | L309906 |
| CPNRD | L103501, and L201501 | East-West | L305002 |
| CPNRD | L103701, L103702, and L201701 | East-West | L409104 |
| CPNRD | L103901, and L201901 | East-West | L304802 |
| CPNRD | L103901b, L104501, L104701, L104901, and L105101 | Southeast-Northwest | L523105 |
| CPNRD | L102702, and L107001b | Southeast-Northwest | L209703 |
| CPNRD | L105201, and L201401 | North-South | L306602 |
| CPNRD | L105401, and L201601 | North-South | L307002 |
| CPNRD | L106001, and L202201 | North-South | L308202 |
| CPNRD | L106401, and L202601 | North-South | L309002 |
| CPNRD | L106601, L202801, and L202802 | North-South | L512204 |
| CPNRD | L106801b, and L203001 | North-South | L309802 |
| CPNRD | L107201, and L203201 | North-South | L310402 |
| CPNRD | L107401, and L203401 | North-South | L310802 |
| CPNRD | L107801, and L203801 | North-South | L311602 |
| CPNRD | L108001, and L204001 | North-South | L312002 |
| CPNRD | L108401, and L204401 | North-South | L312802 |




**Figure 5-1. Google earth image of the location of the 2010 AEM survey (orange lines) in relation to the 2016 AEM survey (white lines).**

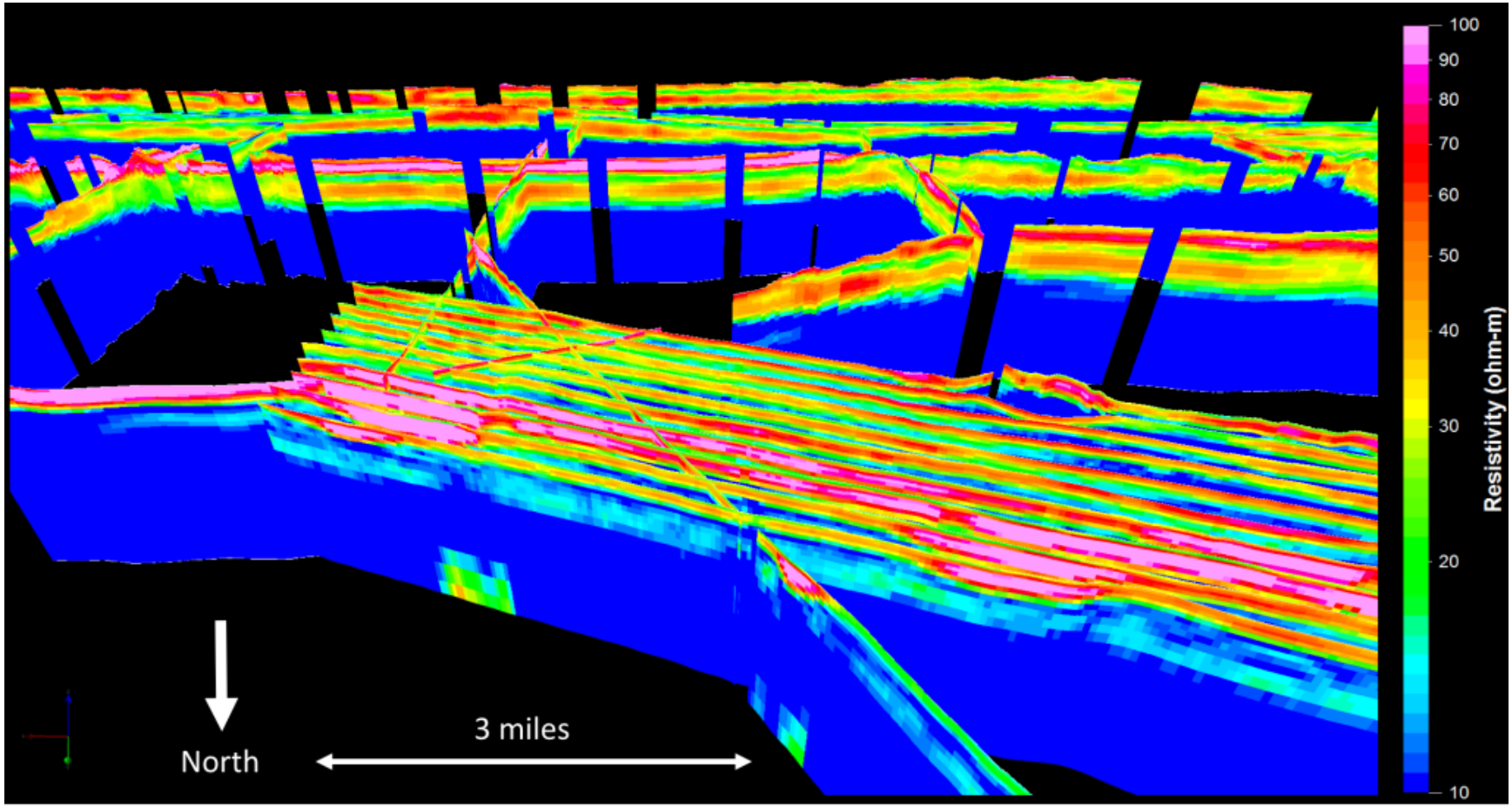



**Figure 5-2. 3D resistivity fence diagram of the overlapping lines of the 2010 AEM (SkyTEM 304) and 2016 (SkyTEM 304M), looking from the north towards the south. Vertical exaggeration is 10X.**

### *5.1.2 Construction of 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 TPNRD-CPNRD 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 Nebraska (US 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 5-3 is a map of the DEM of the TPNRD and CPNRD 2016 AEM survey area showing a vertical relief of 1,462 ft with a minimum elevation of 2,124 ft and a maximum elevation of 3,586 ft. This DEM was used to reference all elevations within the TPNRD and CPNRD AEM survey area. A subset DEM was constructed for each of the four survey areas (CPNRD, N-CORPE, PRRIP, and TPNRD) (Section 1.3) and can be found in Appendix 2.

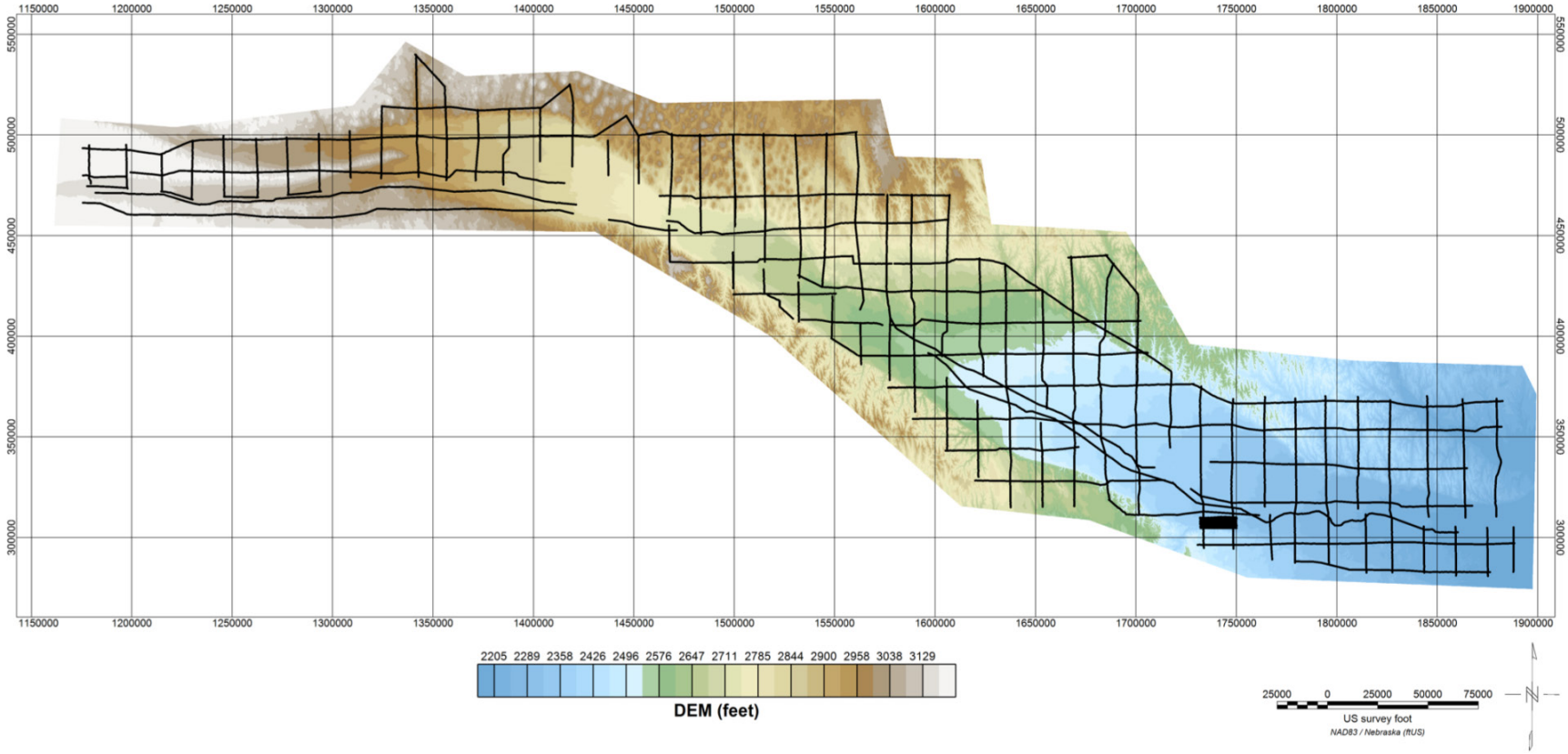



**Figure 5-3. Map of the Digital Elevation Model for the 2016 TPNRD and CPNRD AEM Survey Area. Data source is the one (1) arc-second National Elevation Dataset (U.S. Geological Survey, 2016). North American Datum of 1983 (NAD 83) State Plane Nebraska (US foot) and the elevation values are referenced to the North American Vertical Datum of 1988 (NAVD 88) (feet).**

### 5.1.3 *Interpretation of the 2D Profiles*

After final AEM database preparations, characterization of the subsurface was performed in cross-section format using Encom PA (Datamine Discover, 2017). During interpretation, the horizontal and vertical scales of the profiles were adjusted to facilitate viewing. The color scale of the resistivity data was also adjusted to illuminate subtle differences in the resistivity structure within the inverted AEM resistivity data relative to the area being interpreted. The first step in the interpretation process is digitizing the contacts between the geological units including: the Quaternary (***Q***); Tertiary Ogallala Group (***To***); Tertiary Brule Formation (***Tb***) (part of the Tertiary White River Group (***Twr***)); Cretaceous Pierre Shale (***Kp***); Cretaceous Niobrara Formation (***Kn***); and the Cretaceous Carlile Shale (***Kc***). The interpretive process benefited from the use of CSD, NE-DNR, and NOGCC borehole logs, which provided lithologic, stratigraphic, and geophysical information. The interpretations were simultaneously checked against the CSD's Nebraska bedrock geology map (Burchett, 1986) as well as the COHYST Hydrostratigraphic Units Report (Cannia et al., 2006).

The interpretation began with picking the ***Tb***, ***Kp***, and ***Kc*** contacts. The process was iterative around the eroded segments of the ***Tb*** and ***Kp***. These units were interpreted first due to their low electrically resistive nature (containing low electrically resistive clay minerals). The ***Tb*** has a much lower resistivity than the ***To*** in most of the survey area. The ***Kp*** has a much lower resistivity than the ***To***, ***Tb***, and ***Kn***. And finally, the ***Kc*** has a much lower resistivity than the ***Kn***. Along the eastern margin of the ***Tb*** that is in contact with the ***Kn*** within the Cambridge Arch, the ***Tb*** displayed a much more resistive nature than in other areas within western NE (Abraham, et al., 2011a). In the areas of the resistive ***Tb***, sitting on top of the ***Kn***, the interpretation was much more challenging and the use of boreholes was necessary to estimate the ***Tb***/***Kn*** contact.

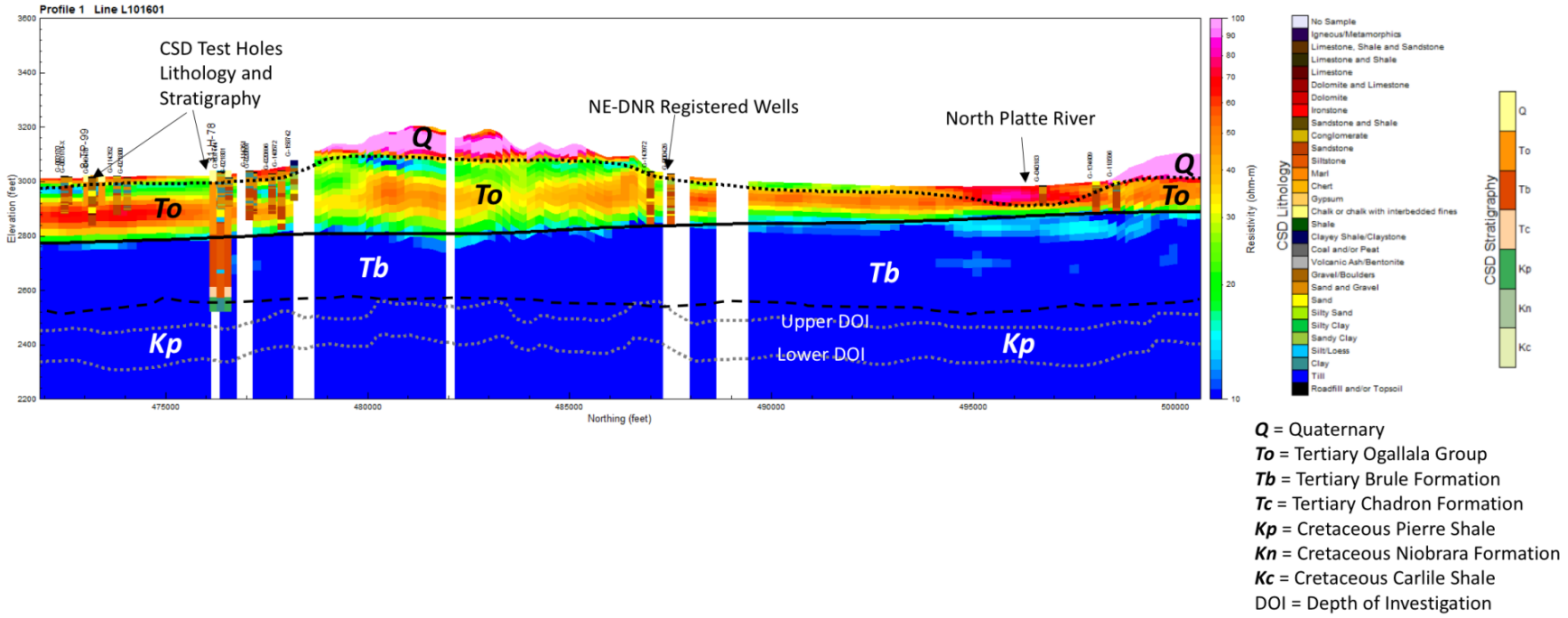
The interpretation of the top of the ***Kn*** and ***Kc*** within the TPNRD and CPNRD AEM survey area was limited to the areas of the Cambridge Arch where the ***Kn*** and ***Kc*** are close to the surface due to the uplift and within the resolution window (the DOI) of the AEM. Many of the CSD test holes as well as the NE-DNR borehole logs stop at the Cretaceous formations due to those stratigraphic units not being aquifers, due to their being composed predominantly of limestone and shale. Many of the CSD boreholes have stratigraphic calls that assist in the location of the stratigraphic contacts, but seldom penetrate very deep into the Cretaceous. NOGCC stratigraphic logs were used to augment the CSD logs. For the profiles, the clipping distance from the flight lines was set independently for the CSD boreholes and for the NE-DNR boreholes. Typically, the CSD clipping distance was set to one mile or 5,280 ft, and the NE-DNR boreholes were set to between a quarter mile and half mile or 1,340-2,640 ft, but in areas of limited boreholes these numbers were expanded. The clipping distance for the NOGCC wells was typically set to three-miles or 15,840 ft.

The interpretation of the ***To*** included examination of the CSD and NE-DNR boreholes and comparison with the AEM resistivities. Unlike the ***To***/***Tb*** and ***To***/***Kp*** surfaces, there is not a strong resistivity contrast between the ***Q***/***To*** and the ***To***/***Kn***. Borehole information is critical in the determination of an estimated top of the ***To*** and a bottom of ***To*** when overlying ***Kn***. The following criteria were used to locate the top of the ***To***: 1) ***To*** indicated on the CSD borehole stratigraphic logs; 2) indication of sandstone in the CSD

borehole lithology logs; 3) indication of sandstone in the NE-DNR lithology logs; and 4) a generally lower electrical resistivity than the overlying ***Q*** alluvial and eolian deposits. Spatial patterns in the resistivity were also used to map the ***Q*** and the ***To***. The use of the boreholes was critical for the interpretation of the area of the ***To*** in contact with the ***Kn*** within the area of the Cambridge Arch.

Figure 5-4 is an approximately 5.4-mile-long north-south line (L101601) that is approximately five miles east of Paxton, Nebraska. The line crosses from the South Platte River valley into the North Platte River valley and crosses the North Platte River. There are two CSD test holes within one mile (5,280 feet) and several NE-DNR registered wells within a quarter mile (1,320 feet) of the flight line. The base of the aquifer (BOA) system is the low electrically resistive ***Tb***. Below the ***Tb*** there is an indication of the ***Tc*** and the ***Kp*** from the CSD test hole *11-H-78*; However, the low resistivity sediments and the proximity of the DOI obscures the positon of the ***Kp*** in this portion of the AEM survey area. The ***Q***/***To*** contact is interpreted as a dashed line and is verified by the CSD test holes and the NE-DNR registered wells. Generally, the ***Q*** materials are more resistive then the ***To*** in this section. In this area, it may be more appropriate to look at the ***Tb*** and ***Tc*** as the Tertiary White River Group (***Twr***).

Figure 5-5 is an approximately 7.8-mile-long east-west segment of line L200301 that extends over Sutherland Reservoir. There are three CSD test holes within one-mile (5,280 feet) and several NE-DNR registered wells within a quarter mile (1,320 feet) of the flight line. The BOA is the low electrically resistive ***Tb***. Below the ***Tb*** there is interpreted ***Kp.***, The low electrically resistive sediments and the proximity of the DOI obscures the positon of the ***Kp*** in this portion of the AEM survey area. The ***Q***/***To*** contact is interpreted as a dashed line and is verified by the CSD test holes and the NE-DNR registered wells. In this area, there is not a clear higher or lower resistivity contrast between the ***Q*** and the ***To***. In the area of the Sutherland Reservoir there is a moderately low resistivity feature related to the water and the fine-grained sediments in the reservoir. The top of the ***To*** is estimated from the CSD test holes and the NE-DNR registered wells.




***Q*** = Quaternary
***To*** = Tertiary Ogallala Group
***Tb*** = Tertiary Brule Formation
***Tc*** = Tertiary Chadron Formation
***Kp*** = Cretaceous Pierre Shale
***Kn*** = Cretaceous Niobrara Formation
***Kc*** = Cretaceous Carlile Shale
DOI = Depth of Investigation

**Figure 5-4. 2D resistivity profile of a north-south line approximately 5.4-mile-long (L101601) within the TPNRD AEM flight area. There are two CSD Test Holes within one-mile (5,280 feet) and several NE-DNR registered wells within a quarter mile (1,320 feet) of the flight line indicated by the vertical boreholes. The boreholes are colored with the lithology (inside) and stratigraphy, when available, (outside) as indicated by the legends. Interpretations are indicated by black dashed and solid lines and are labeled with stratigraphic names. The upper and lower depths of investigation are indicated by dashed gray lines.**

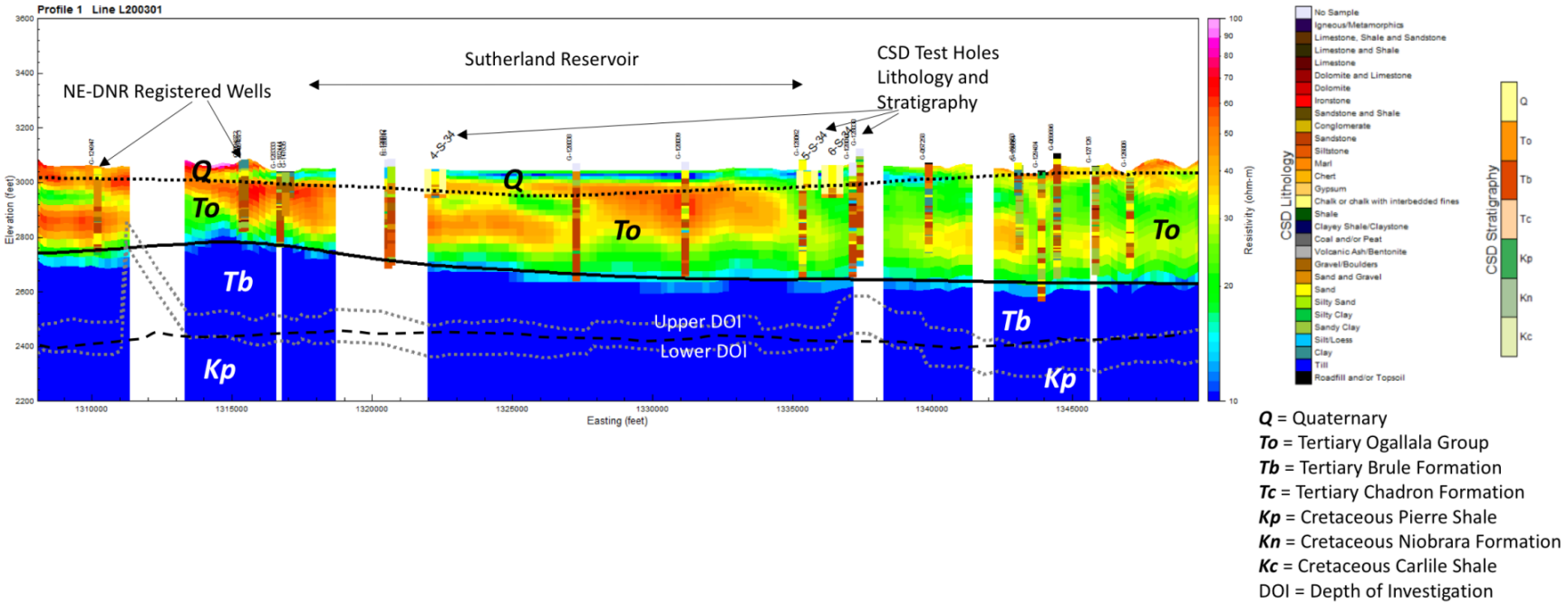



**Figure 5-5. 2D resistivity profile of an east-west approximately 7.8-miles-long line segment (L200301) within the TPNRD AEM flight area. There is one CSD Test Holes within one-mile (5,280 feet) and several NE-DNR registered wells within a quarter mile (1,320 feet) of the flight line indicated by the vertical boreholes. The boreholes are colored with the lithology (inside) and stratigraphy, when available, (outside) as indicated by the legends. Interpretations are indicated by black dashed and solid lines and are labeled with stratigraphic names. The upper and lower depths of investigation are indicated by dashed gray lines.**

An approximately 11.5-mile-long east-west line (L206701) is presented in Figure 5-6 that extends over the center of the N-CORPE AEM flight area. There is one CSD Test Holes within 1-mile (5,280 feet) and several NE-DNR registered wells within ¼-mile (1,320 feet) of the flight line. The BOA in this area is a combination of the ***Tb*** and ***Tc*** and can be looked at as the ***Twr***. The ***Twr*** overlies the ***Kp*** and is indicated in CSD Test Hole 16-H-78. The interpretation of the BOA in this area is slightly more challenging using resistivity only, but with the combination of the CSD Test Holes and the NE-DNR registered wells the bottom can be confidently interpreted. The top of the ***To*** is estimated using the CSD Test Hole and the indication of sandstone in the NE-DNR registered wells. The top of the ***Q*** is clearly more resistive with unsaturated sands dominating the lithology, but transitions into a silty/loess zone that is directly deposited on the ***To***.

Figure 5-7 is an approximately 19.6-mile-long segment of east-west line L304802. The line segment is approximately 3-miles north of the city of Lexington, Nebraska and is also over the crest of the Cambridge Arch. There are two CSD test holes within one mile (5,280 feet) and several NE-DNR registered wells within a quarter mile (1,320 feet) of the flight line. The obvious feature in this line segment is the change in the elevation of the low electrically resistive materials at the base of the profile. This difference in elevation is due to a fault on the eastern side of the Cambridge Arch. The western side of the BOA is the ***Tb*** and ***Kn*** and the eastern side is the ***Kp***. It is important to note that the interpretations were not conducted exclusively on this survey line and many other flight lines were examined as well as many NOGCC wells in the area. The ***Q/To*** contact is also challenging in this area but with the use of the CSD test holes and the NE-DNR registered wells, an estimate can be made. A feature that is easily observed in the ***Q*** is the thicker loess hills that can be seen on the eastern end of the line segment. Of special interest in this line segment is CSD Test Hole *10-B-46* which is approximately 3,700 feet south of the AEM line and indicates ***Kp*** at the bottom and a much thicker ***Q*** segment. The ***Kp*** pick at this hole is suspect as no other holes in the CSD and NOGCC database in this area indicated the ***Kp*** at the top of the Cambridge Arch. Moore and Nelson (1974) also indicate that the ***Kp*** is eroded off in this location. CSD test hole *10-B-46* may be a hole with a suspect location(?).

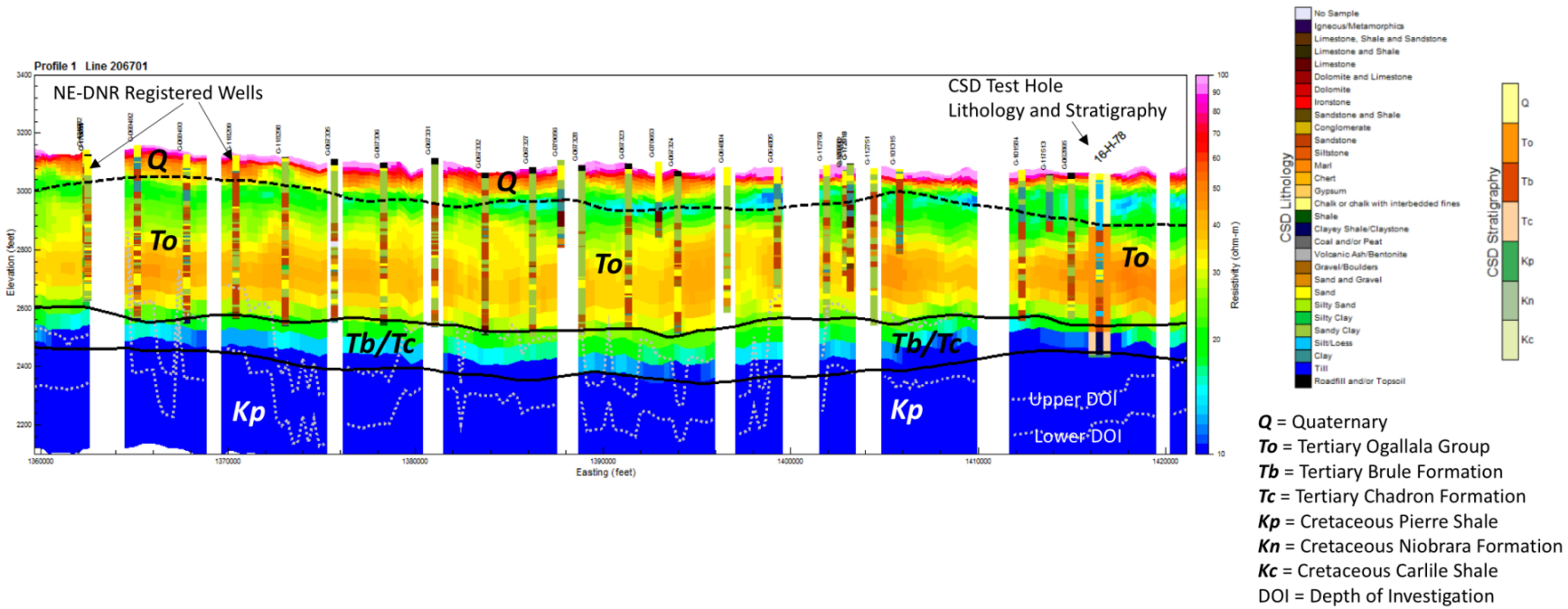



**Figure 5-6. 2D resistivity east-west profile approximately 11.5 miles-long (L206701) within the N-CORPE AEM flight area. There is one CSD test hole within one-mile (5,280 feet) and several NE-DNR registered wells within a quarter mile (1,320 feet) of the flight line which are indicated by the vertical boreholes. The boreholes are colored with the lithology (inside) and stratigraphy, when available, (outside) as indicated by the legends. Interpretations are indicated by black dashed and solid lines and are labeled with stratigraphic names. The upper and lower depths of investigation are indicated by dashed gray lines.**

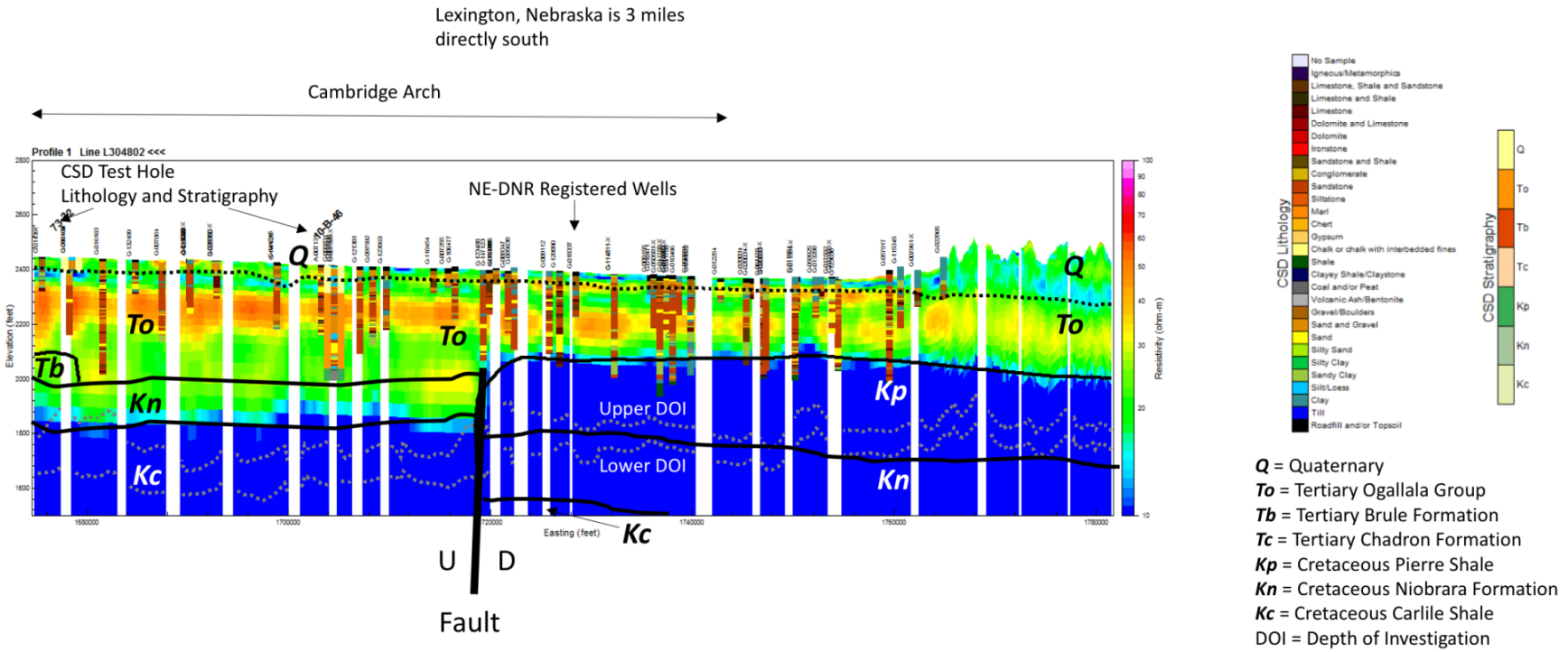
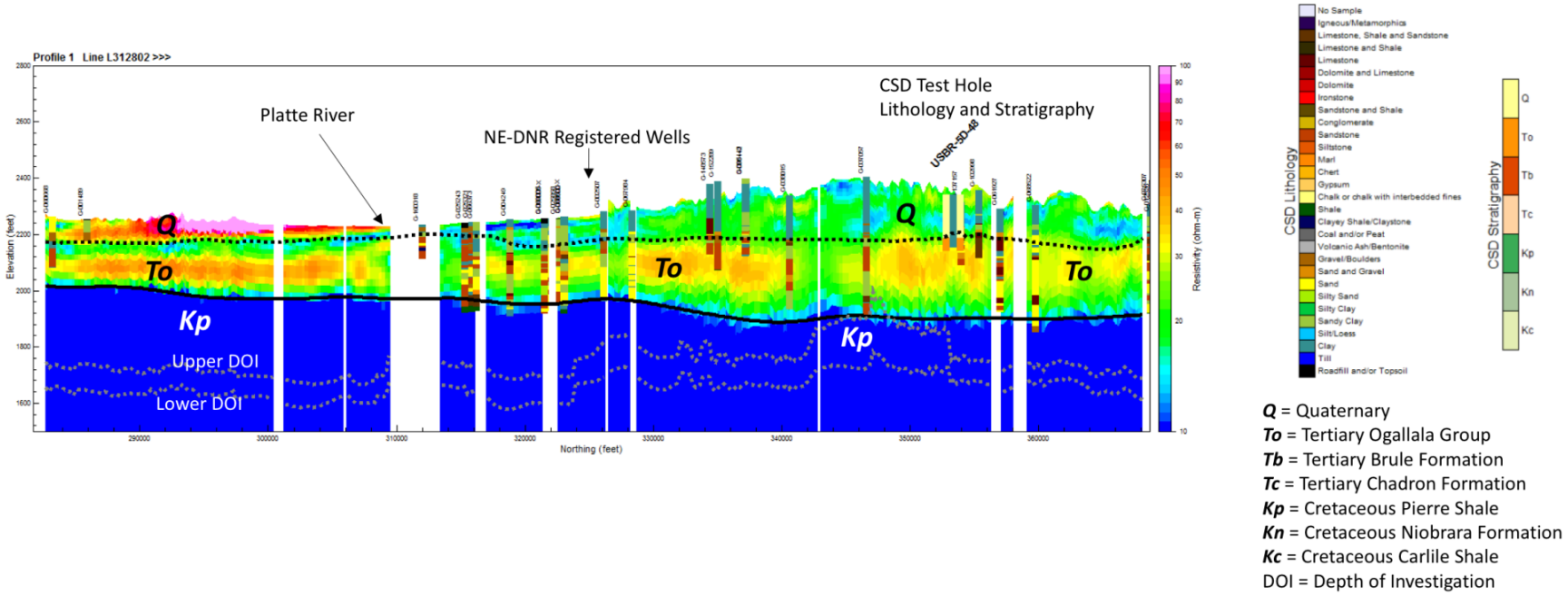



**Figure 5-7. 2D resistivity east-west profile approximately 19.6-miles long (L304802) within the CPNRD AEM flight area. There are two CSD test holes within one mile (5,280 feet) and several NE-DNR registered wells within a quarter mile (1,320 feet) of the flight line as indicated by the vertical boreholes. The boreholes are colored with the lithology (inside) and stratigraphy, when available, (outside) as indicated by the legends. Interpretations are indicated by black dashed and solid lines and are labeled with stratigraphic names. The upper and lower depths of investigation are indicated by dashed gray lines.**

Figure 5-8 is an approximately 14.9-mile-long north-south line (L312802). The line is approximately 3-miles east of the Elm Creek, Nebraska and crosses the Platte River. There is one CSD test hole within one mile (5,280 feet) and several NE-DNR registered wells within a quarter mile (1,320 feet) of the flight line. The BOA in the area is the ***Kp*** and is easily detected by the low resistivity. The nature of the ***Q/To*** contact changes from south of the river to north of the river with the ***Q*** being more resistive than the ***To*** south of the river, changing to the ***Q*** having a lower electrical resistivity north of the river than the ***To*** due to an increase of clay content in the ***Q***.

Figure 5-9 is an approximately 3.4-mile-long east-west line (L204301). The line is in the center of the PRRIP AEM flight block. There are several NE-DNR registered wells within a quarter mile (1,320 feet) of the flight line. The BOA in the area is the ***Kp*** and is easily detected by its low resistivity. The ***Kn*** and ***Kc*** can also be interpreted on the western end of the line but are not detectable under the ***Kp*** due to the low electrical resistive nature and the high DOI in this area. The ***Q***/***To*** contact is interpreted as a dashed line and is verified by NE-DNR registered wells. In this area, there is not a clear higher or lower resistivity contrast between the ***Q*** and the ***To***. However, there is a detectable lower resistivity zone toward the top of the ***To*** that is also indicated in some of the NE-DNR registered wells.

The above examples illustrate the interpretive process that was used on the profiles provided within this report. Each flight line with an interpretation including the Quaternary and Tertiary Ogallala Group Aquifer material-type mapping (Section 5.2.1) are included in Appendix_1_2D_Profiles. The profiles in Appendix 1 are organized by AEM survey area (CPNRD, N-CORPE, PRRIP, and TPNRD).




***Q*** = Quaternary
***To*** = Tertiary Ogallala Group
***Tb*** = Tertiary Brule Formation
***Tc*** = Tertiary Chadron Formation
***Kp*** = Cretaceous Pierre Shale
***Kn*** = Cretaceous Niobrara Formation
***Kc*** = Cretaceous Carlile Shale
DOI = Depth of Investigation

**Figure 5-8. 2D north-south resistivity profile approximately 14.9 miles-long (L312802) in the CPNRD AEM survey area. There is one CSD test hole within one-mile (5,280 feet) and several NE-DNR registered wells within a quarter mile (1,320 feet) of the flight line as indicated by the vertical boreholes. The boreholes are colored with the lithology (inside) and stratigraphy, when available, (outside) as indicated by the legends. Interpretations are indicated by black dashed and solid lines and are labeled with stratigraphic names. The upper and lower depths of investigation are indicated by dashed gray lines.**

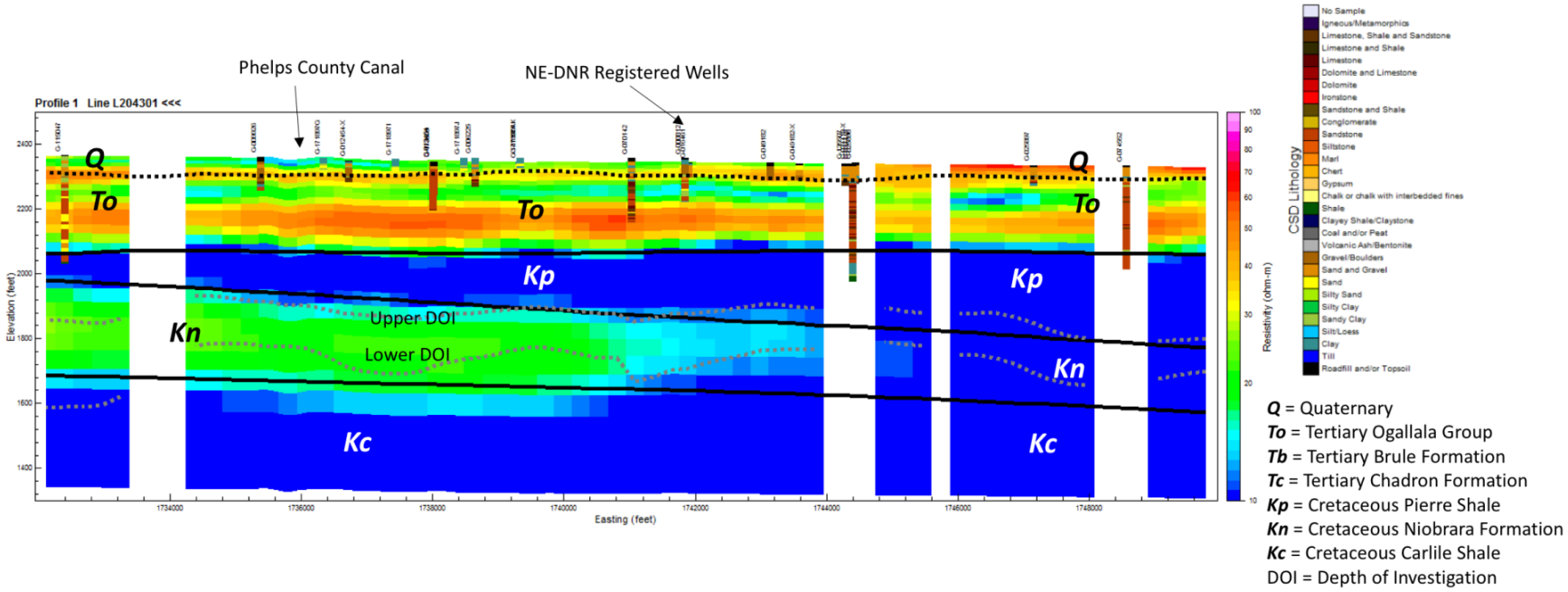



**Figure 5-9. 2D east-west resistivity profile approximately 3.4 miles-long (L204301) in the PRRIP AEM survey block. There are several NE-DNR registered wells within a quarter mile (1,320 feet) as indicated by the vertical boreholes. The boreholes are colored with the lithology indicated by the legend. Interpretations are indicated by black dashed and solid lines and are labeled with stratigraphic names. The upper and lower depths of investigation are indicated by dashed gray lines.**

### *5.1.4 Create Interpretative Surface Grids*

Within the TPNRD and CPNRD AEM survey area surface grids of geologic formations were produced for the five survey areas including the CPNRD combined with the TPNRD, the CPNRD, the N-CORPE, the PRRIP Block, and the TPNRD. To create these grids, the elevations of the AEM-interpreted top of the formations were imported to a Geosoft Oasis montaj (OM) database. The interpreted elevation data were then gridded for each formation independently using the OM minimum curvature gridding (MCG) algorithm. CSD test hole and selected NOGCC stratigraphic top picks were used to augment the AEM data.

For the ***To*** top surface, 3,531 AEM picks and 159 CSD test hole picks were used in the grid with a cell size of 250 feet and the "cells to extend beyond" set to 10. All other parameters were either left as the default or blank. The grid was then clipped to the individual AEM survey areas. Figure 5-10 is a map of the elevation of the top of the ***To*** for the combined TPNRD and CPNRD AEM reconnaissance areas. The ***To*** surface grids for the CPNRD, N-CORPE, PRRIP Block, and TPNRD AEM flight areas can be found Appendix 2.

For the top of the Tertiary Brule Formation (***Tb***), or the top of the Tertiary White River Group (***Twr***) surface, 2,144 AEM picks, 40 CSD test hole, and one NOGCC stratigraphic top picks were used in the grid with a cell size of 1,000 feet and the "cells to extend beyond" set to 10. All other parameters were either left as the default or blank. The grid was then clipped to the individual AEM survey areas. Figure 5-11 is a map of the elevation of the top of the ***Tb*** for the combined TPNRD and CPNRD AEM reconnaissance areas. For the N-CORPE area, a 250-foot grid cell size was made specifically for the higher resolution survey area. The ***Tb*** doesn't extend throughout the TPNRD and CPNRD survey area, but is eroded off, effectually east of the Cambridge Arch. The ***Tb*** surface grids for the CPNRD, N-CORPE, PRRIP Block, and TPNRD AEM flight areas can be found in Appendix 2.

For the top of the Cretaceous Pierre Shale (***Kp***), 1,812 AEM picks, 28 CSD Test Hole, and 12 NOGCC stratigraphic top picks were used in the grid with a cell size of 1,000 feet and the "cells to extend beyond" set to 10. All other parameters were either left as the default or blank. The grid was then clipped to the individual AEM survey areas. Two CSD test holes (*10-B-46* and *54-A-49*) were omitted from the database as the top of the ***Kp*** had a major discrepancy as indicated in the CSD logs versus the interpretations of the AEM and other borehole information. For the N-CORPE and PRRIP-block areas a 250-foot grid cell size was used specifically for those higher resolution survey areas. Note that the ***Kp*** doesn't extend over the complete survey area. The area associated with the Cambridge Arch has the ***Kp*** eroded off due to the uplift during the Tertiary (Moore and Nelson 1974). More information on the bedrock configuration can be found below. Figure 5-12 is a map of the elevation of the top of the ***Kp*** for the combined TPNRD and CPNRD AEM reconnaissance areas. The ***Kp*** surface grids for the CPNRD, N-CORPE, PRRIP Block, and TPNRD AEM flight areas can be found in Appendix 2.

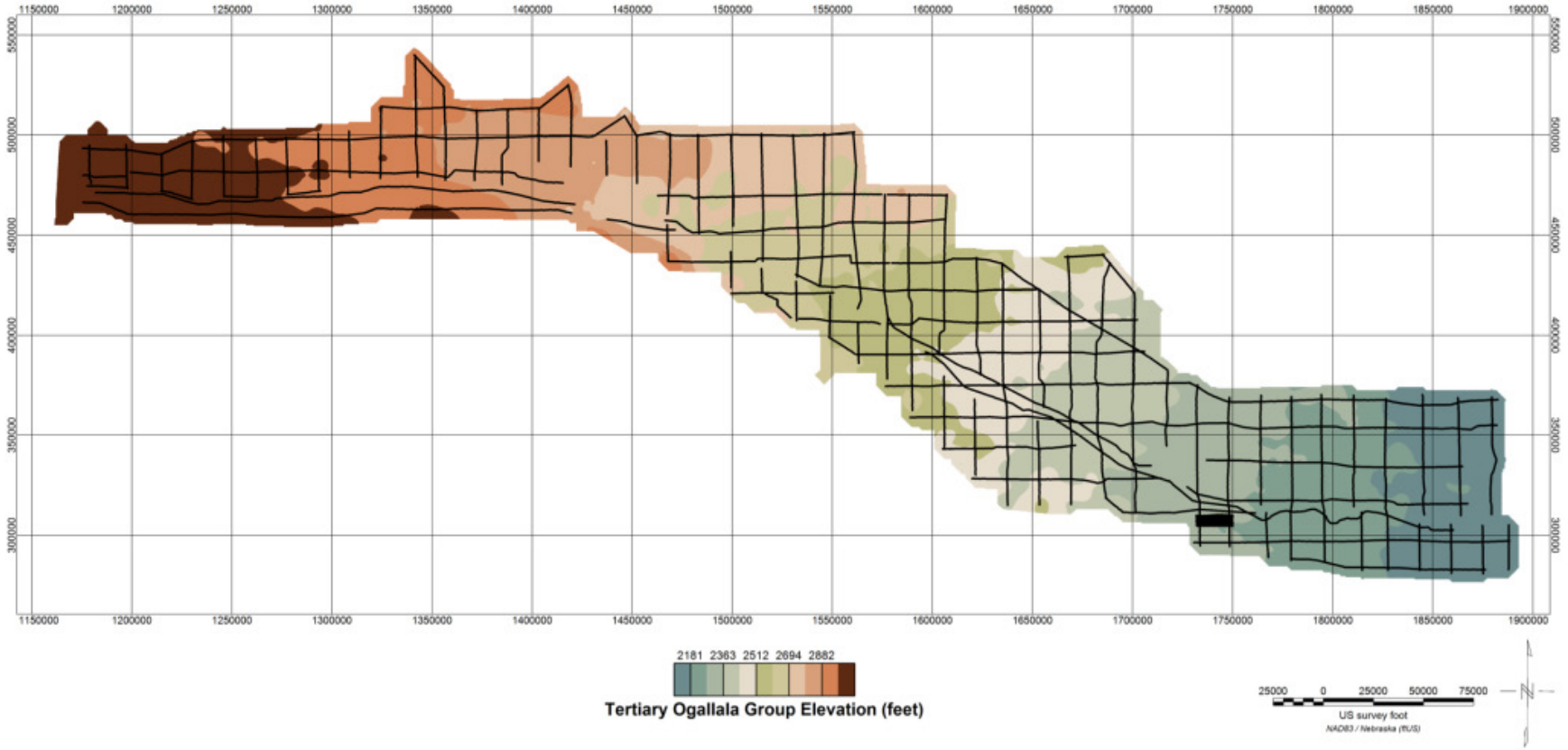



**Figure 5-10. Map of the elevation of the top of the Tertiary Ogallala Group (*To*) for the combined TPNRD and CPNRD AEM reconnaissance flight area. Flight lines are indicated by black lines. The projection is NAD83, State Plane (US foot), and the elevation values are referenced to NAVD 88 (feet).**

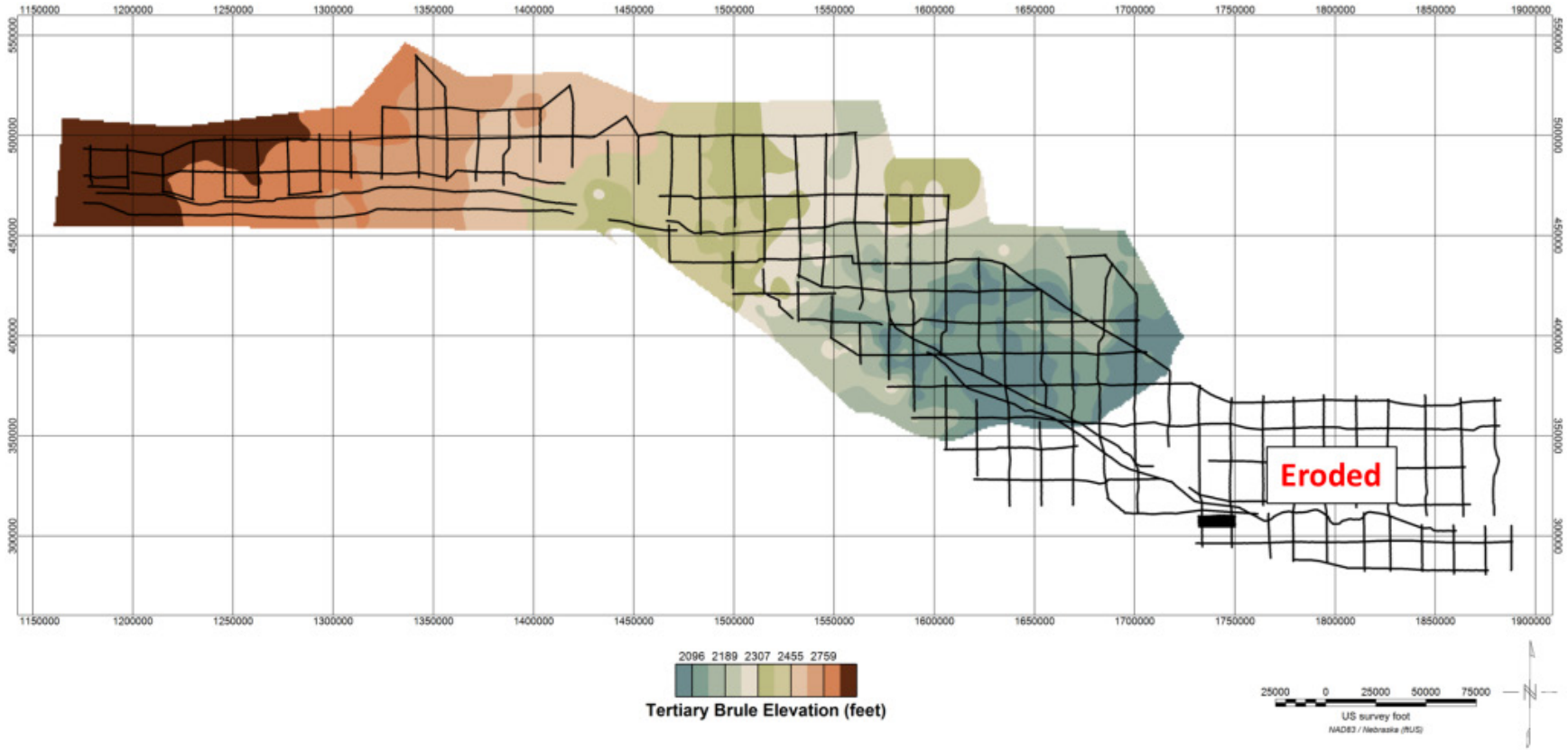



**Figure 5-11. Map of the elevation of the top of the Tertiary Brule Formation (*Tb*) for the combined TPNRD and CPNRD AEM reconnaissance flight area. Flight lines are indicated by black lines. The projection is NAD83, State Plane (US foot), and the elevation values are referenced to NAVD 88 (feet).**

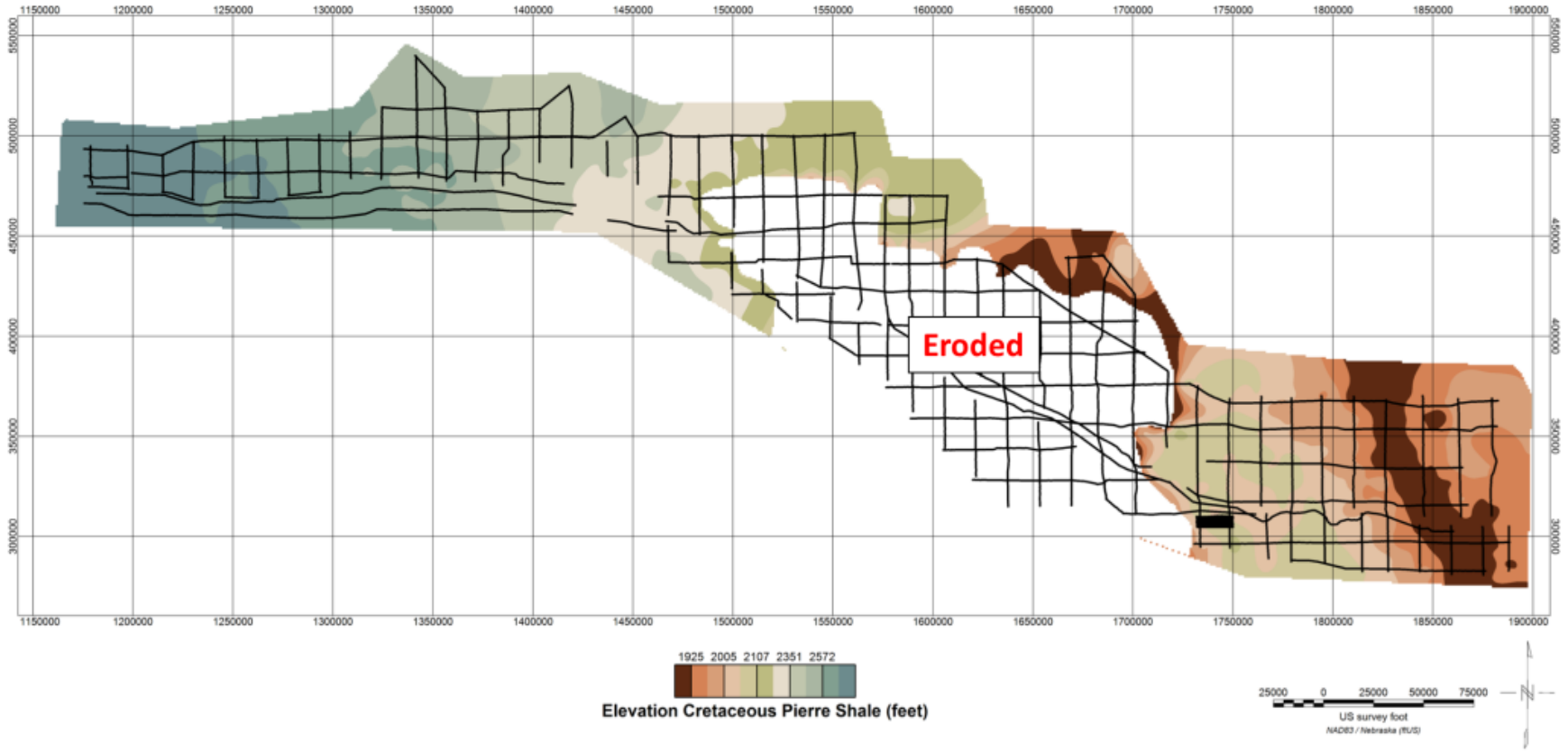



**Figure 5-12. Map of the elevation of the top of the Cretaceous Pierre Shale (*Kp*) for the combined TPNRD and CPNRD AEM reconnaissance flight area. Flight lines are indicated by black lines. The projection is NAD83, State Plane (US foot), and the elevation values are referenced to NAVD 88 (feet).**

For the top of the Cretaceous Niobrara Formation (***Kn***), 931 AEM picks, 13 CSD test holes, and 53 NOGCC stratigraphic top picks were used in the grid with a cell size of 1,000 feet and the "cells to extend beyond" set to 10. All other parameters were either left as the default or blank. The grid was then clipped to the individual AEM survey areas. For the PRRIP-Block area a 250-foot grid cell size was made specifically for that higher resolution survey area. The ***Kn*** grid doesn't extend over the complete survey area due to the lack of resolution of the AEM at the depths that the ***Kn*** is found on the far eastern and western ends of the AEM survey area. There were no picks of the ***Kn*** in the N-CORPE area. The area associated with the Cambridge Arch has been interpreted with the ***Kn*** continuous over the area. The ***Kn*** is considerably thinned by erosion at the peak of the arch but was interpreted as still being present. Moore and Nelson (1974) indicated that the ***Kn*** had zero thickness over portions of the arch based on their examination of the Oil and Gas Wells at the time of their study. With the addition of the AEM data and the use of the NE-DNR registered wells (using limestone as a flag for the top of the ***Kn***), the current interpretation in this report is that the ***Kn***, while thinned, is continuous over the Cambridge Arch within the AEM survey area. More information on the bedrock configuration can be found below. Figure 5-13 is a map of the elevation of the top of the ***Kn*** for the combined TPNRD and CPNRD AEM reconnaissance areas. The ***Kn*** surface grids for the CPNRD, PRRIP Block, and TPNRD AEM flight areas can be found in Appendix 2.

For the top of the Cretaceous Carlile Shale (***Kc***), 605 AEM picks and 69 NOGCC stratigraphic top picks were used in the grid with a cell size of 1,000 feet and the "cells to extend beyond" set to 10. All other parameters were either left as the default or blank. The grid was then clipped to the individual AEM survey areas. The ***Kc*** grid doesn't extend over the complete survey area due to the lack of resolution of the AEM at the depths that the ***Kc*** is found on the far eastern and western ends of the AEM survey area. There were no picks of the ***Kc*** in the N-CORPE area and no individual grid was calculated for the PRRIP-Block. Figure 5-14 is a map of the elevation of the top of the ***Kc*** for the combined TPNRD and CPNRD AEM reconnaissance flight areas. The ***Kc*** surface grids for the CPNRD and TPNRD AEM flight areas can be found in Appendix 2.

The base of aquifer (BOA) in the TPNRD and CPNRD AEM flight area is composed the Tertiary Brule Formation (***Tb***) or Tertiary White River Group (***Twr***) the Cretaceous Pierre Shale (***Kp***); and the Cretaceous Niobrara Formation (***Kn***). The Quaternary (***Q***) and Tertiary Ogallala Group (***To***) aquifers overlie the BOA. A BOA surface was calculated by adding the grids of the ***Tb***, ***Kp***, and ***Kn*** together. The grid cell size of 1,000 feet was used for the TPNRD and CPNRD reconnaissance areas. The BOA for the N-CORPE area is equal to the ***Tb*** surface and the BOA for the PRRIP Block is equal to the ***Kp*** surface, both of which are at the 250-foot cell size. Figure 5-15 is the grid of the elevation of the BOA for the combined TPNRD and CPNRD AEM reconnaissance areas. Previous work by Cannia et al. (2006) also provided a BOA and a geological separation of the "Tertiary Brule" and undifferentiated "Cretaceous". Comparing the two BOA maps provides insights into the addition of the AEM data. The overall configuration is not different, but the inclusion of the AEM has provided a much more detailed BOA (Figure 5-16). Using the interpreted surface for the ***Kp*** and ***Kn*** units, a Cretaceous bedrock map can be constructed. Figure 5-17 illustrates the Cretaceous units that make up the Cretaceous bedrock.

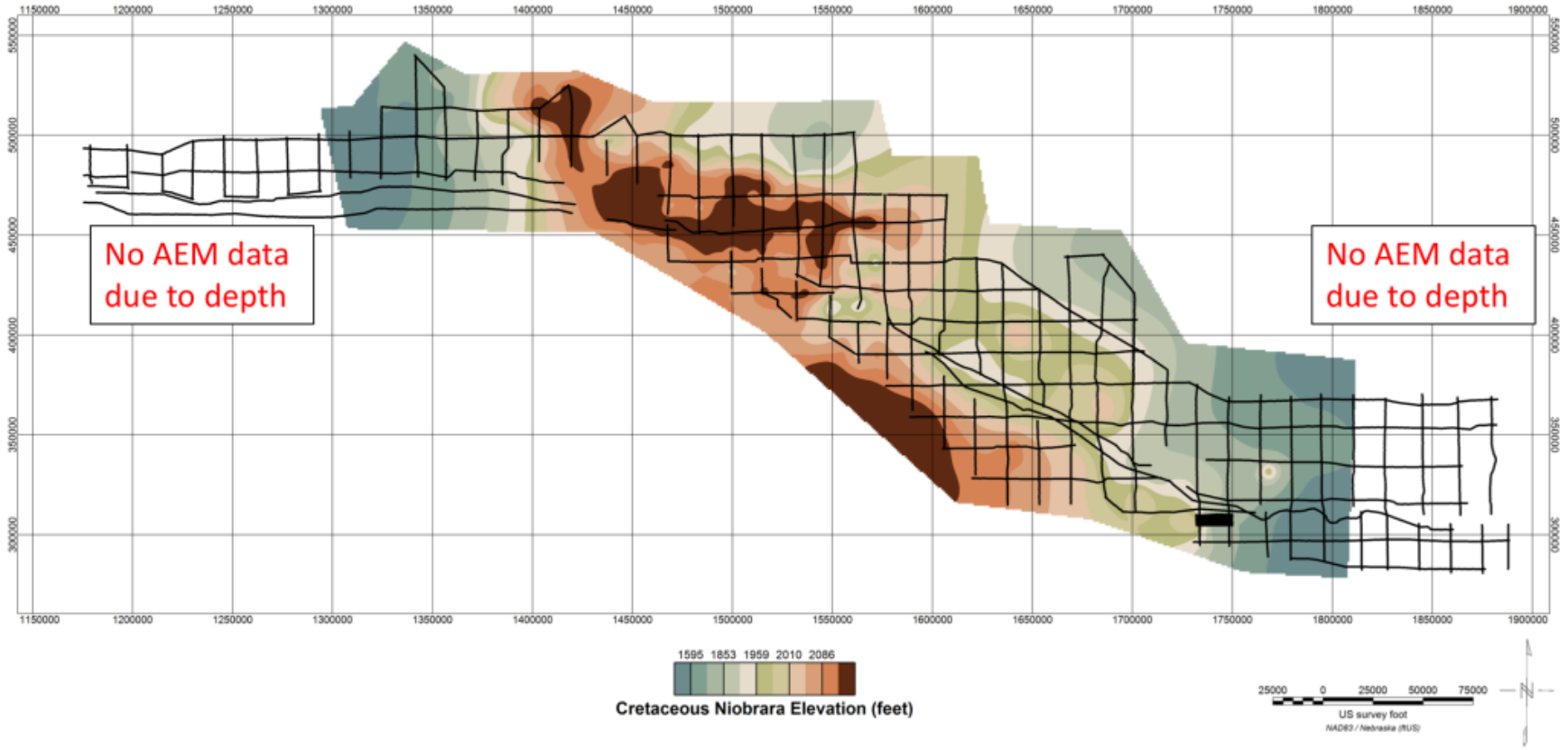



**Figure 5-13. Map of the elevation of the top of the Cretaceous Niobrara (*Kn*) for the combined TPNRD and CPNRD AEM reconnaissance flight area. Flight lines are indicated by black lines. The projection is NAD83, State Plane (US foot) and the elevation values are referenced to NAVD 88 (feet).**

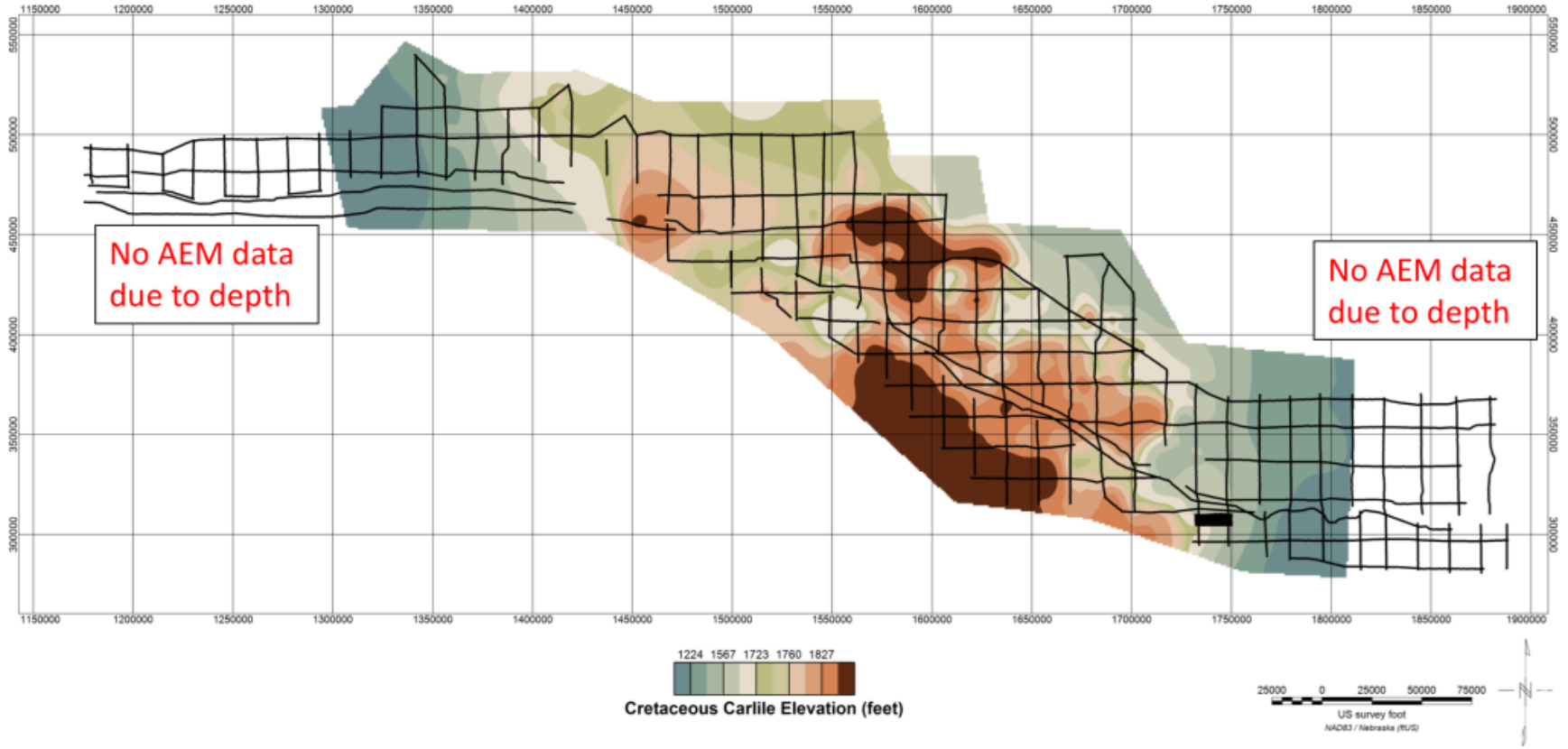



**Figure 5-14. Map of the elevation of the top of the Cretaceous Carlile Shale (*Kc*) for the combined TPNRD and CPNRD AEM reconnaissance flight area. Flight lines are indicated by black lines. The projection is NAD83, State Plane (US foot) and the elevation values are referenced to NAVD 88 (feet).**

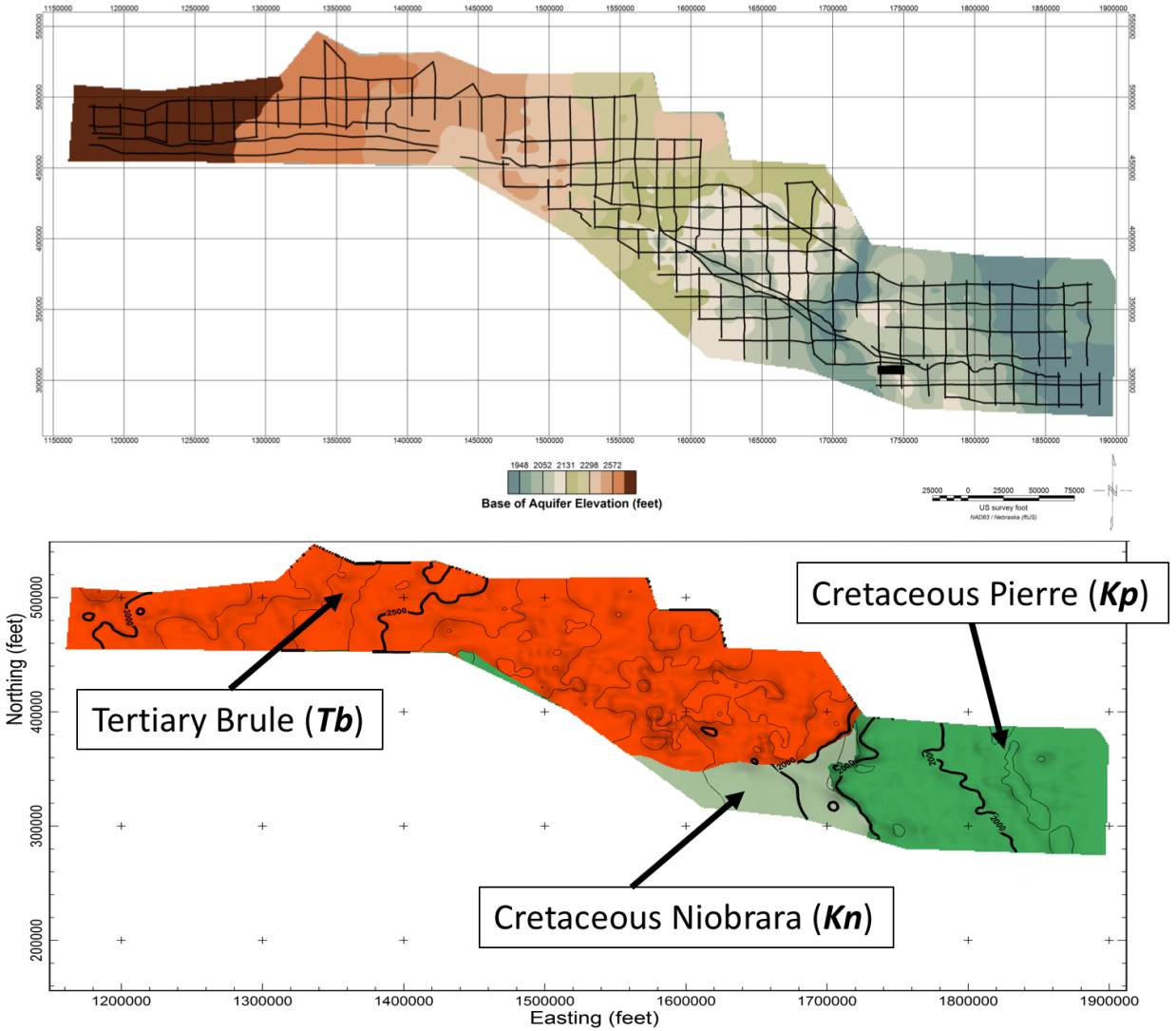



**Figure 5-15. Map of the elevation of the top of the Base of Aquifer (BOA) for the combined TPNRD and CPNRD AEM reconnaissance flight areas (top map). Flight lines are indicated by black lines; The BOA is composed of the Tertiary Brule Formation (*Tb*), the Cretaceous Pierre Shale (*Kp*), and the Cretaceous Niobrara (*Kn*) (bottom map). The projection is NAD83, State Plane (US foot) and the elevation values are referenced to NAVD 88 (feet).**

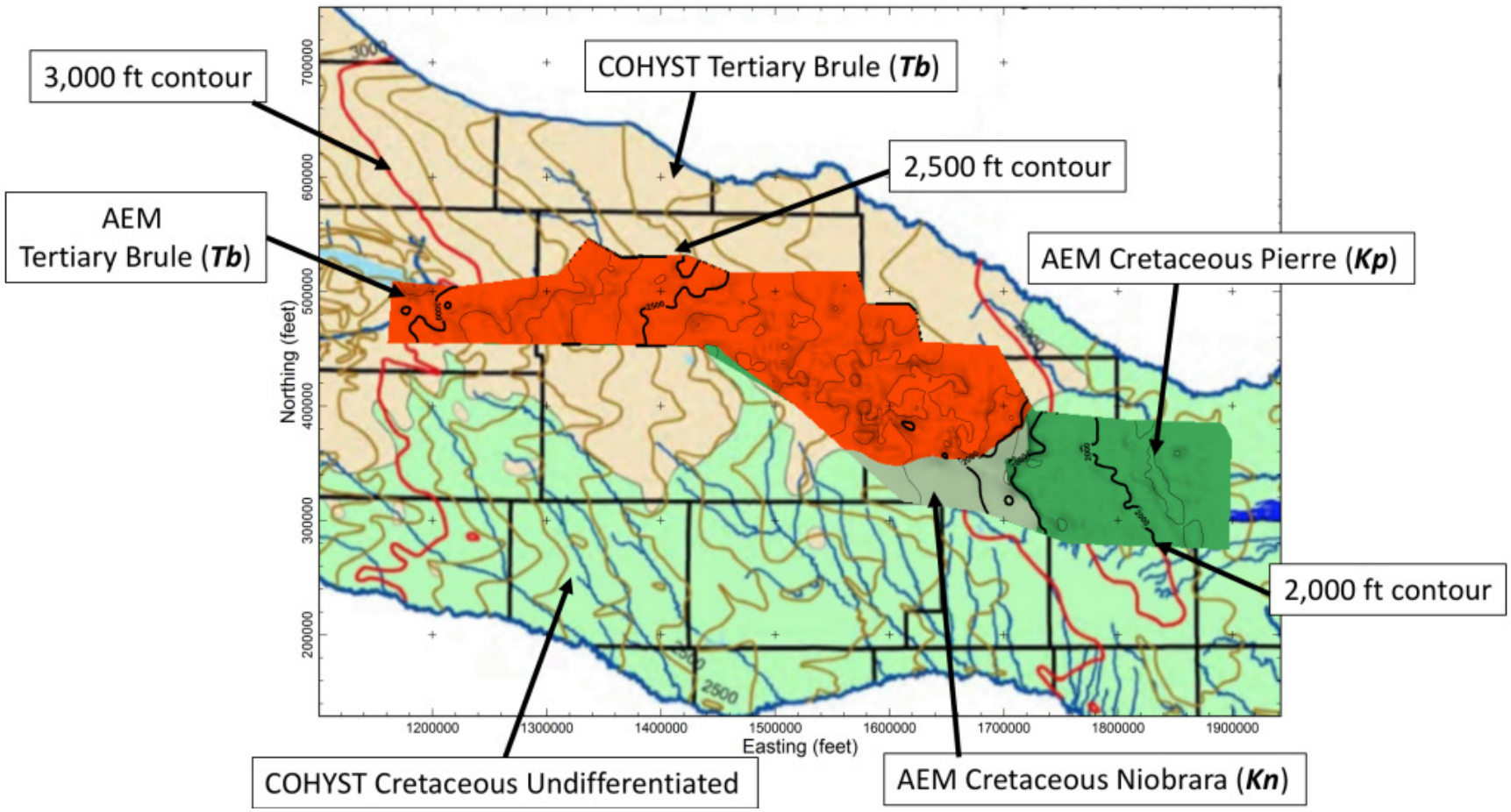



**Figure 5-16. Contour map of the elevation of the top of the Base of Aquifer for a segment of the COHYST model area and geological units (modified from Cannia et al., 2006) corresponding to the combined TPNRD and CPNRD AEM reconnaissance flight areas with the new AEM interpreted contour map of the Base of Aquifer composed of the Tertiary Brule Formation (*Tb*), Cretaceous Pierre Shale (*Kp*), and the Cretaceous Niobrara (*Kn*). Contour lines on the COHYST map are red and brown and the contour lines on the AEM map are black. The projection is NAD83, State Plane (US foot) and the elevation values are referenced to NAVD 88 (feet).**

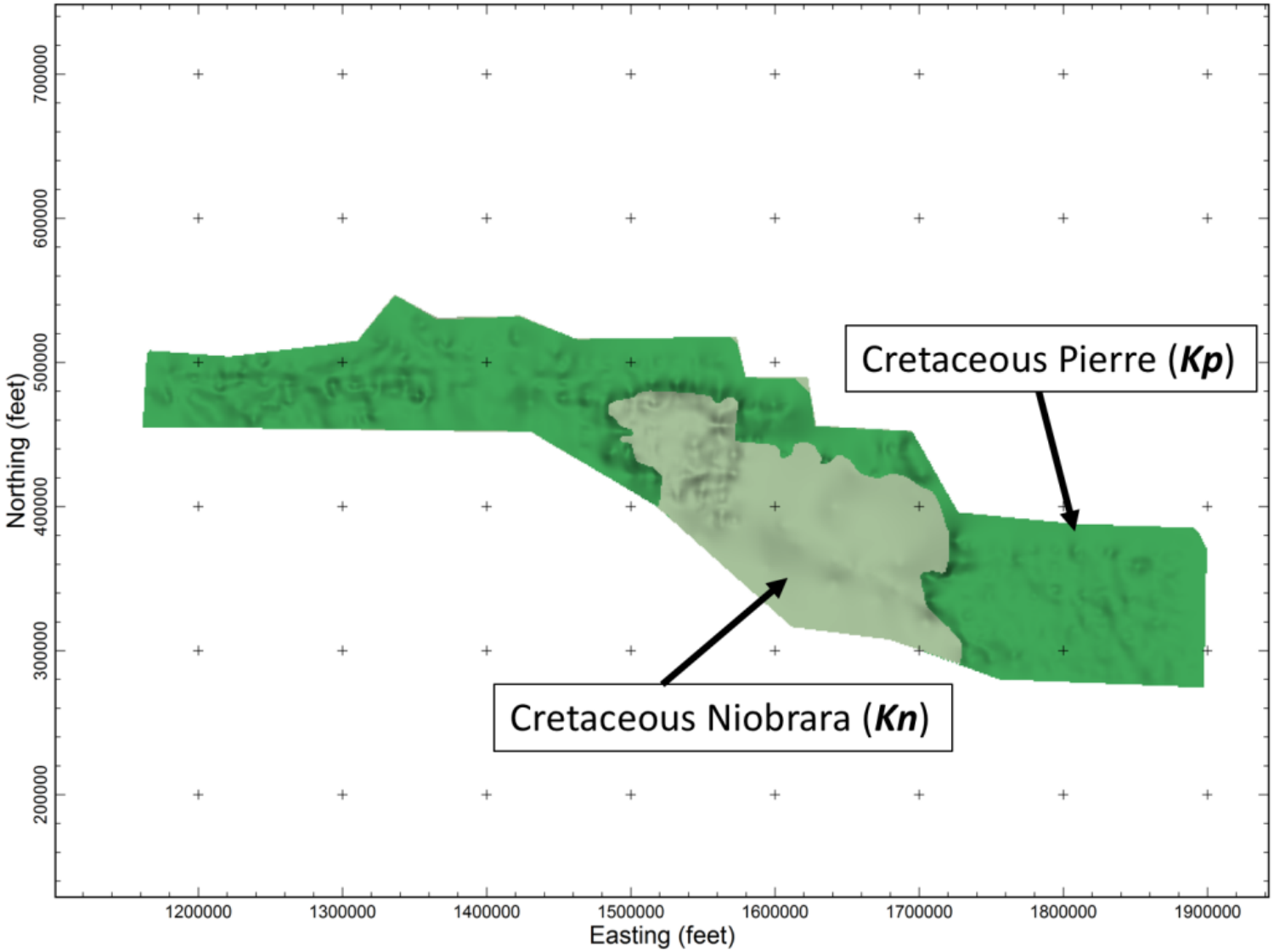



**Figure 5-17. Map of Cretaceous bedrock units for the combined TPNRD and CPNRD AEM reconnaissance flight areas. The map is composed of the Cretaceous Pierre Shale (*Kp*) and the Cretaceous Niobrara (*Kn*). The projection is NAD83, State Plane (US foot) and the elevation values are referenced to NAVD 88 (feet).**

The materials in the Quaternary (***Q***) and the Tertiary Ogallala Group (***To***) system were separated by four major resistivity thresholds. These ranges include less than 12 ohm-m, representing non-aquifer materials ("aquitard"- primarily clay, loess), 12-25 ohm-m, representing marginal aquifer deposits with the potential for interlayered silt, sand, and clay, 25-40 ohm-m of aquifer material containing mostly sand, and an interval of 40 ohm-m or greater, indicating the coarsest, sand and gravel intervals within the aquifer (further discussion regarding the selection of these threshold ranges is provided in Section 5.2. Results of these interpretations can be found in Appendix 1 and in Appendix 2. The color scheme presented in Figure 5-18 will be used when discussing interpreted aquifer materials.

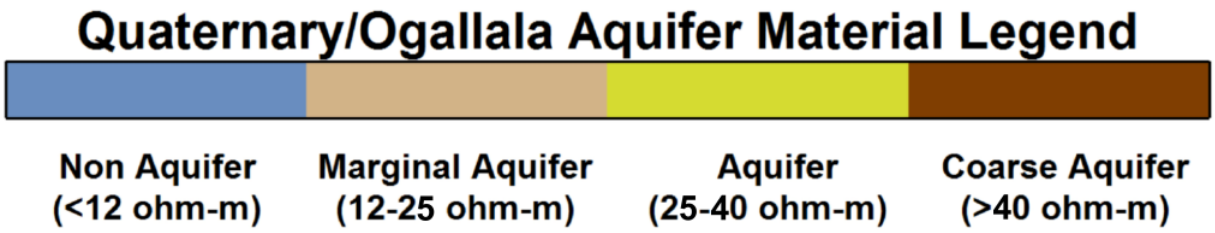



**Figure 5-18. Major resistivity thresholds for aquifer materials.**

Following construction of the geological surfaces, the ***Q*** deposits were isolated within the AEM data. Figure 5-19 is a ***Q*** thickness map for the combined TPNRD and CPNRD AEM reconnaissance survey areas. Similarly, the ***To*** deposits can be isolated from the ***Q*** and Cretaceous materials and a thickness map can be developed (Figure 5-20).

To assist in the approximation of the saturated materials along the surveyed AEM flight lines, the 2013 CSD statewide water table (Korus et al., 2013b) was mapped into the cross-sections. It should be noted that this inclusion provides only a generalized characterization of the saturated thickness of the aquifer as the CSD's dataset is based on a 75-foot contour level with limited data, and local conditions likely deviate in areas with variable topography. The water table in the TPNRD and CPNRD AEM survey area is close to the surface in some of the areas. To this end a topographic correction was required to adjust the water table height to be below the surface topography. The original water table contour lines were gridded at a 1,000 ft cell size using the OM MCG and a blanking distance of 5,000 ft. The cells were set "to extend beyond" to 50. The resulting grid was then re-gridded at a 100 ft cell size and compared with the DEM of the TPNRD and CPNRD AEM survey area. In areas where the water table was greater than the topography the water table was set to an elevation of the topography minus three feet. The grid was then clipped to the individual AEM acquisition areas within the TPNRD and CPNRD survey area (Figure 5-21).

Using the water table, estimates of the saturated thickness of the Quaternary (***Q***) and Tertiary Ogallala Group (***To***) can also be calculated using the BOA surface. Figure 5-22 is an example of the saturated thickness of the Quaternary and Tertiary Ogallala Group for the combined TPNRD and CPNRD Reconnaissance areas.

All the interpretive surface plots of the surfaces can be found in Appendix 2. Arc and Geosoft format girds of the interpretive surface can be found in Appendix 3 Deliverables-Grids.

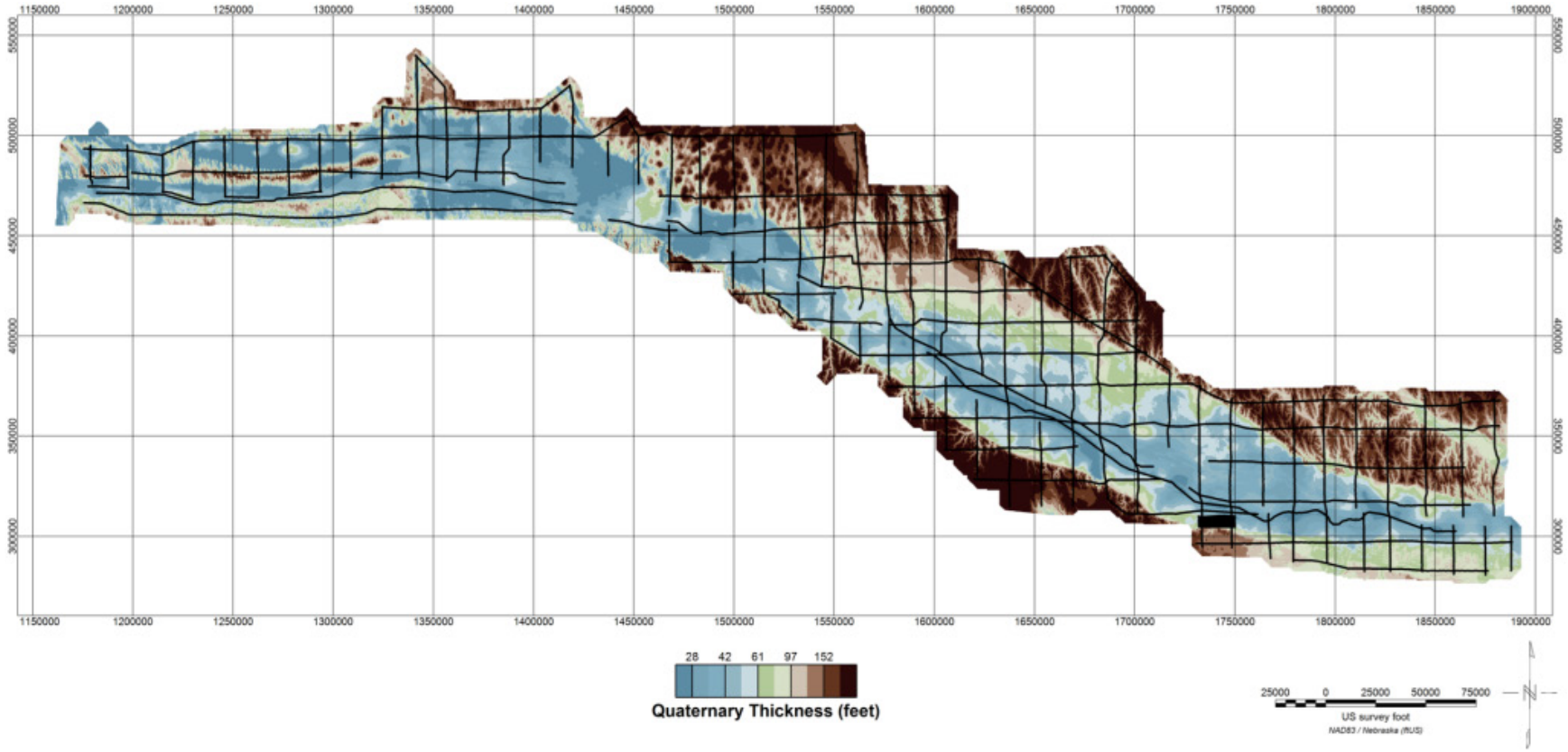



**Figure 5-19. Map of the Quaternary (*Q*) thickness for the combined TPNRD and CPNRD AEM reconnaissance flight area. Flight lines are indicated by black lines. The projection is NAD83, State Plane (US foot) and the elevation values are referenced to NAVD 88 (feet).**

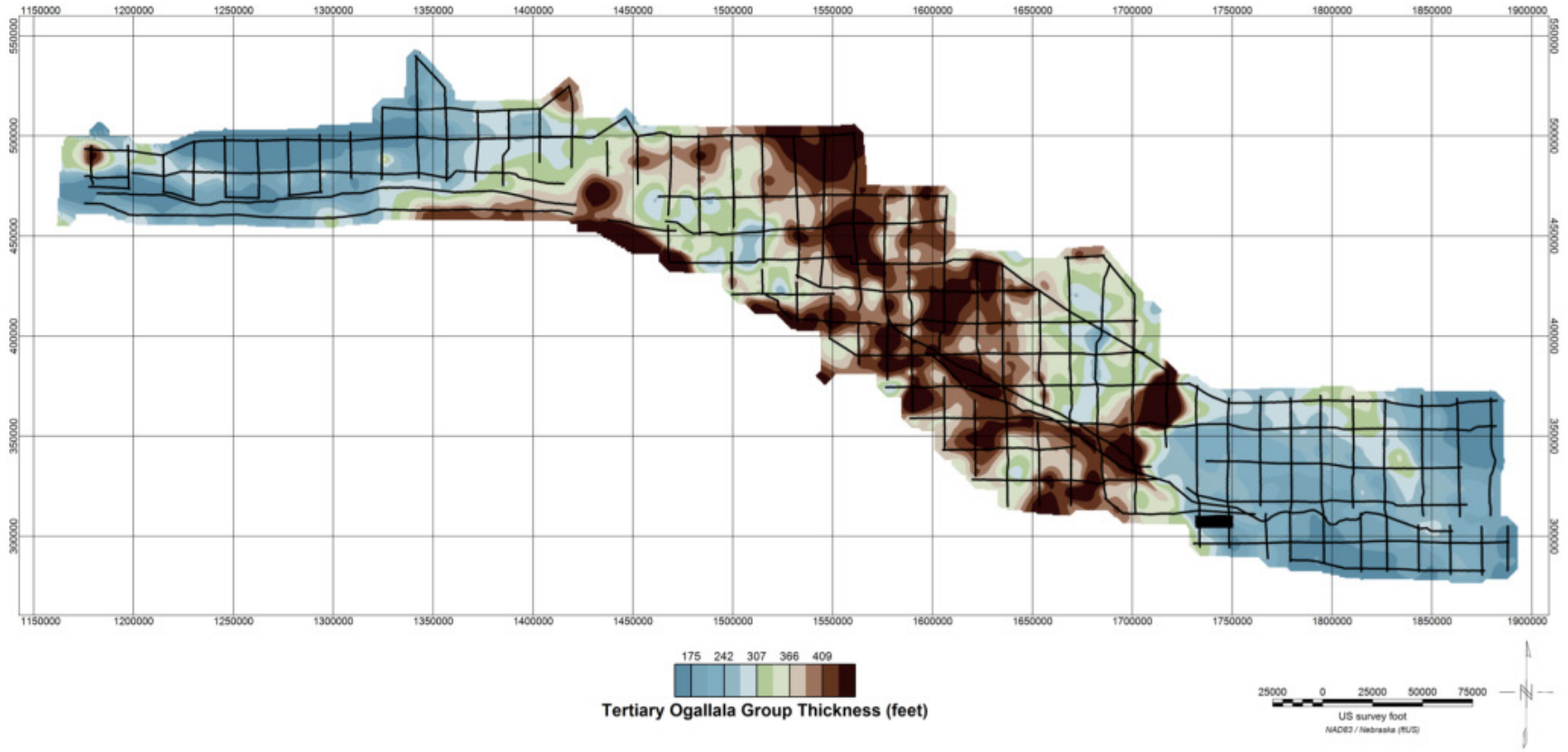



**Figure 5-20. Map of the Tertiary Ogallala (*To*) thickness for the combined TPNRD and CPNRD AEM reconnaissance flight area. Flight lines are indicated by black lines. The projection is NAD83, State Plane (US foot) and the elevation values are referenced to NAVD 88 (feet).**

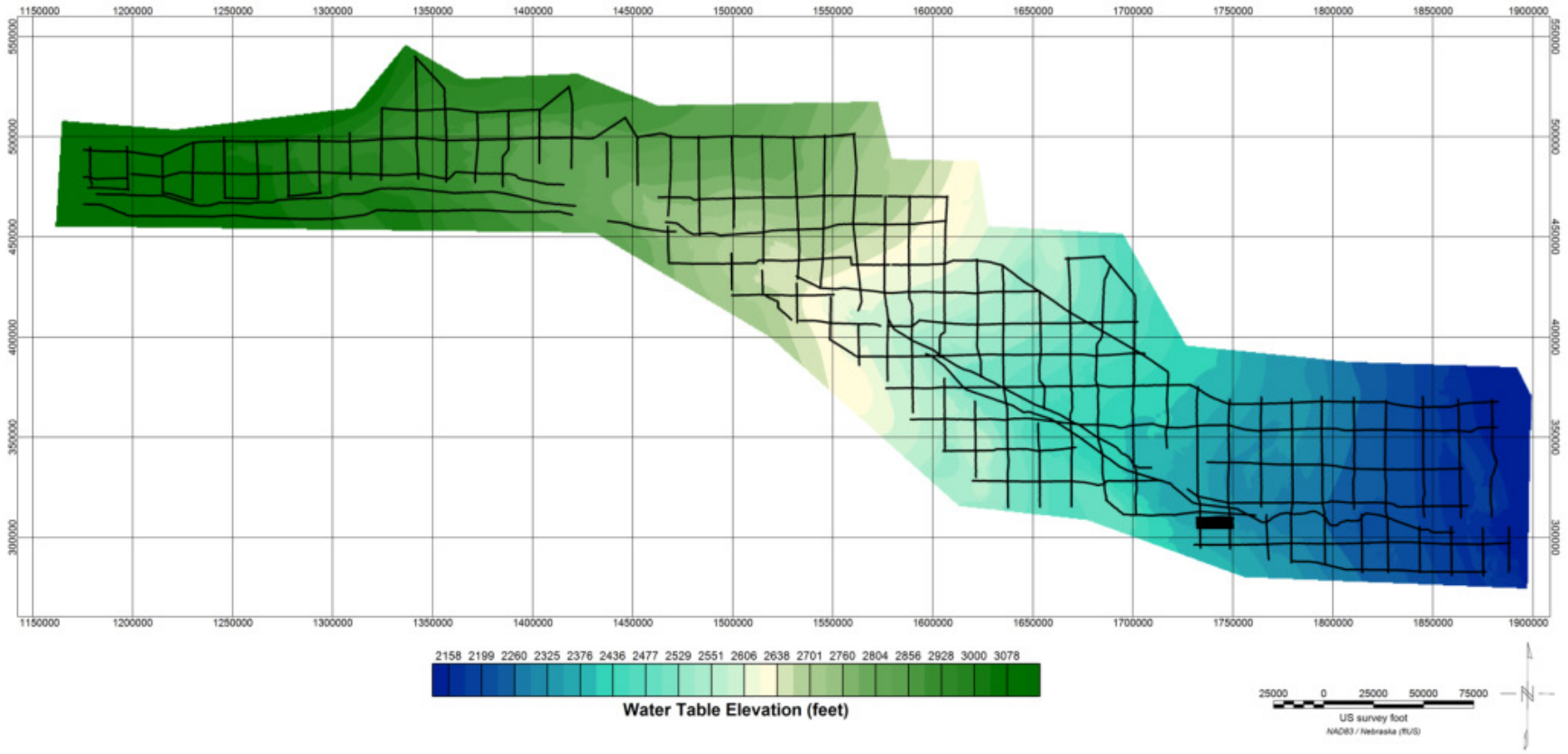



**Figure 5-21. Map of the elevation of the 2013 CSD water table (Korus et al., 2013b) for the combined TPNRD and CPNRD AEM reconnaissance flight area. Flight lines are indicated by black lines. The projection is NAD83, State Plane (US foot) and the elevation values are referenced to NAVD 88 (feet).**

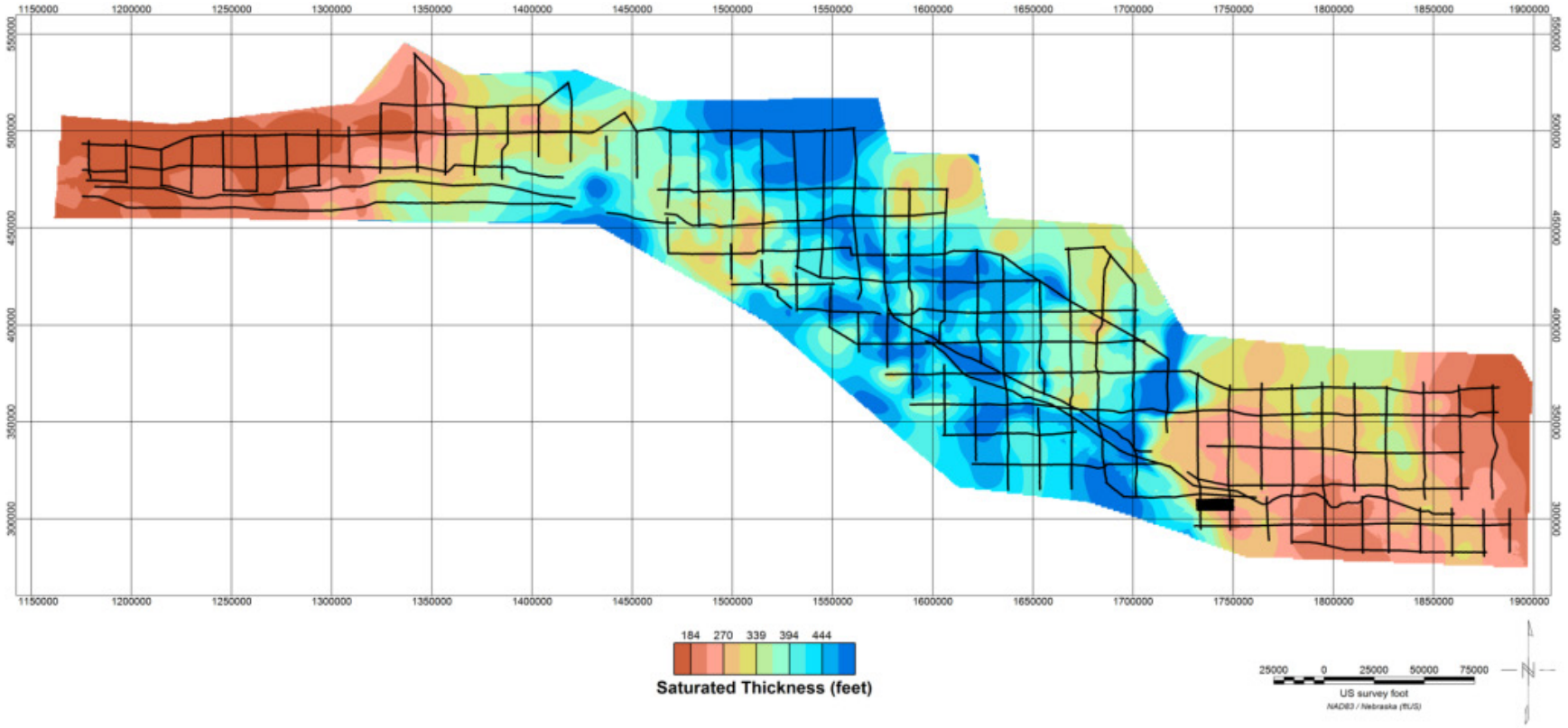



**Figure 5-22. Map of the saturated thickness of the Quaternary (*Q*) and Tertiary Ogallala Group (*To*) for the combined TPNRD and CPNRD AEM reconnaissance flight areas. The projection is NAD83, State Plane (US foot) and the elevation values are referenced to NAVD 88 (feet).**

### *5.1.5 Create 3D Interpretative Voxel Grids*

A voxel grid was completed for the N-CORPE and PRRIP Blocks within the TPNRD and CPNRD AEM survey area. A voxel grid was not created for reconnaissance lines due to the large distance between lines and the reconnaissance nature of the survey line layout. The voxel grids were made using a 250 ft grid cell size and the model layer thickness (Table 4-4 in the previous section). A minimum curvature method was used within Datamine Discover PA (Datamine Discover, 2017). All layers were referenced to their depth from the surface. After the grid was calculated, the base of aquifer (BOA) was then truncated/clipped from the voxel grid using the BOA elevation grids discussed above in Section 5.1.4. The voxels were further sliced at the water table elevation.

The resulting grids are from the surface down to the water table, the surface down to the BOA, and from the water table down to the BOA. These grids can be used to explore the distribution of the aquifer materials within the areas in 3D. Specifically, these grids can allow for the calculation of the volume of materials above the bedrock as well as be used to illustrate the surface materials. The grids can be found in *Appendix 3_Deliverables\Voxel*.

Thickness grids are calculated for the thickness of the saturated aquifer materials (>25 ohm-m) in the saturated section. When these grids are displayed the materials that are below the thresholds are transparent only showing the thickness of the materials above the specified thresholds for the ***Q*** and ***To***. Specifically, these grids can allow for the calculation of the volume of materials above the BOA as well as be used to illustrate the surface materials. The grids can be found in *Appendix 3_Deliverables\Grids*. An example of the saturated ***To*** aquifer materials (>25 ohm-m) from the N-CORPE block is shown in Figure 5-23. An example of the unsaturated aquifer materials ***Q*** and ***To*** (>25 ohm-m) from the PRRIP block is presented in Figure 5-24. Appendix 2 contains the thickness grids for the aquifer materials.

Estimates of the recharge of an area can be made by looking at the surface layer of the voxel grids which is 9.8 ft thick and represents the average resistivity of that zone. Grids of the surface layer were constructed for the N-CORPE and PRRIP blocks. Appendix 2 contains the surface layer grids for the survey blocks. Figure 5-25 is the surface layer from the N-CORPE block and Figure 5-26 is the surface layer from the PRRIP block. The N-CORPE grid doesn't show much change as the surface materials are composed of dry sands.

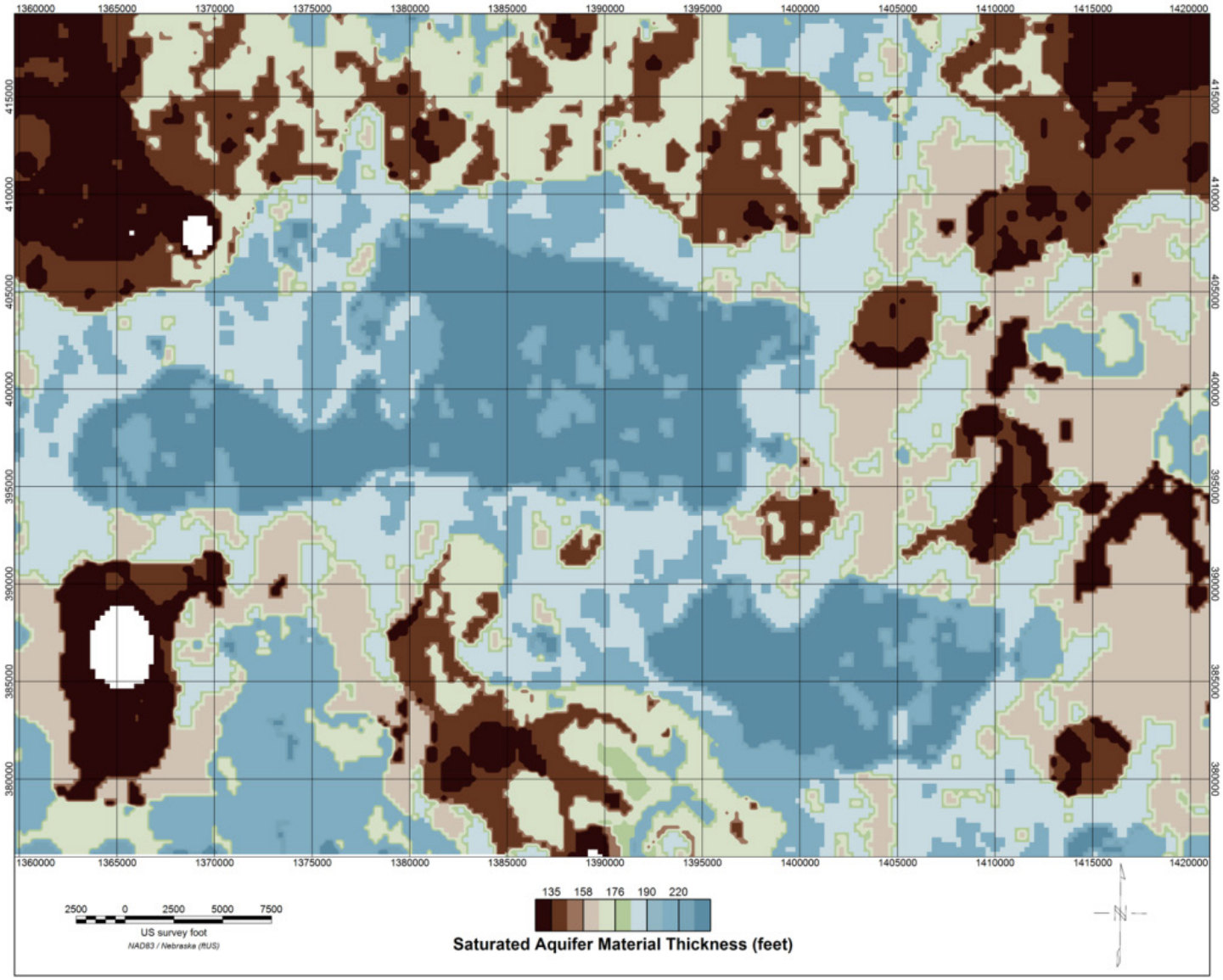



**Figure 5-23. Map of the saturated Tertiary Ogallala Group aquifer materials (>25 ohm-m) for the N-CORPE block. The projection is NAD83, State Plane (US foot) and the elevation values are referenced to NAVD 88 (feet).**

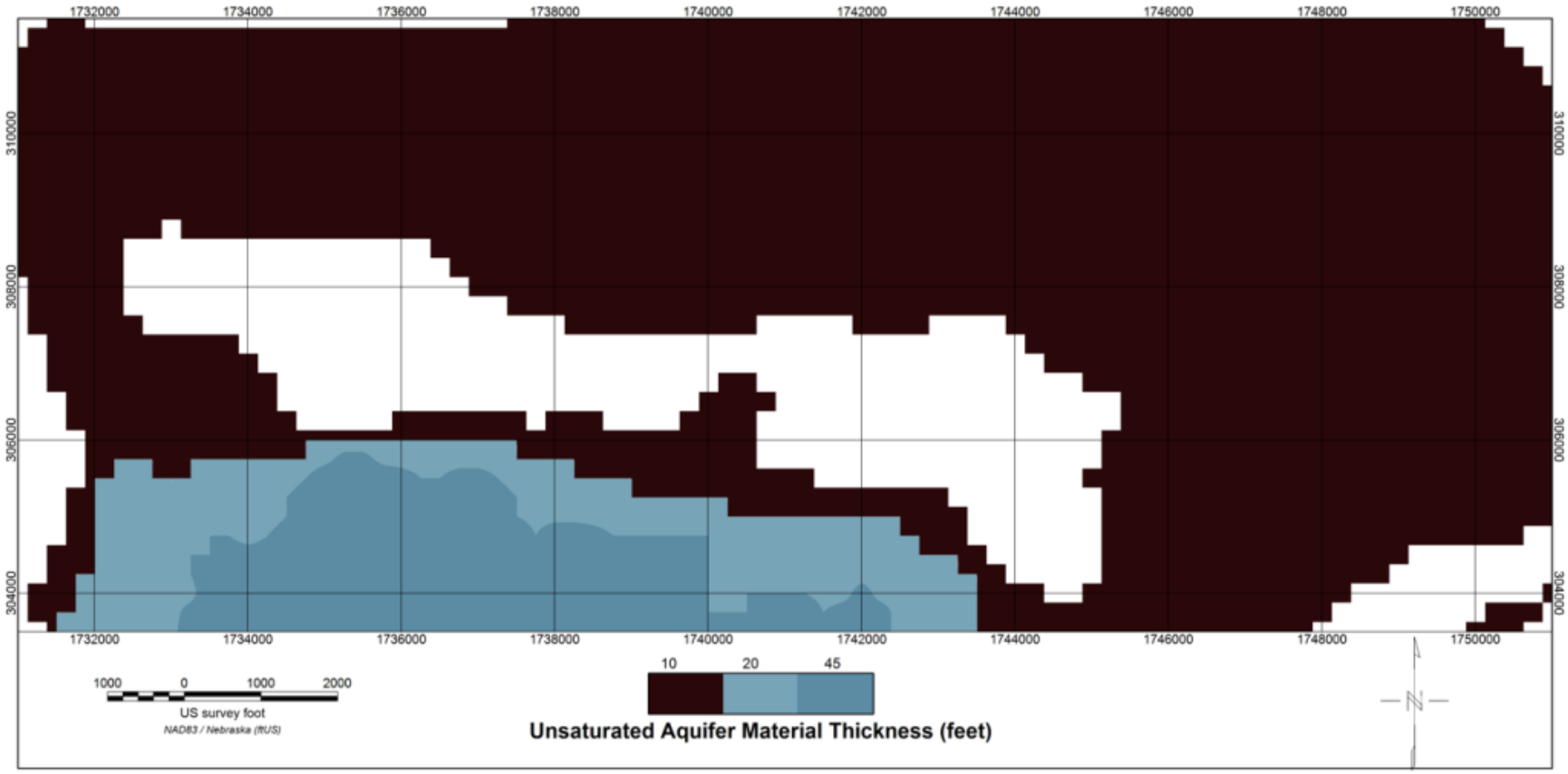



**Figure 5-24. Map of the unsaturated Quaternary and Tertiary Ogallala Group aquifer materials (>25 ohm-m) for the PRRIP block. The projection is NAD83, State Plane (US foot) and the elevation values are referenced to NAVD 88 (feet).**

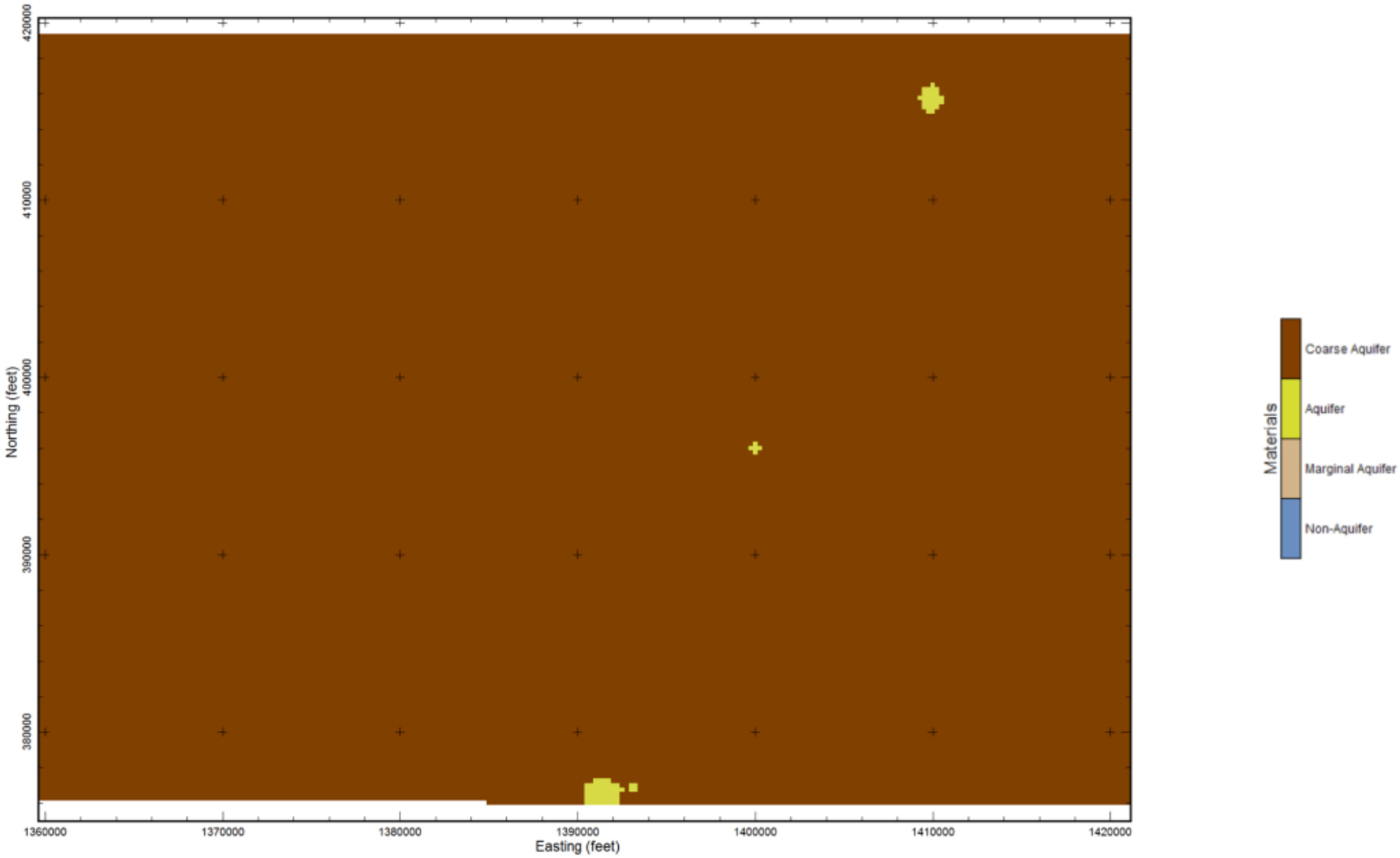



**Figure 5-25. Map of the first layer aquifer material for the N-CORPE block. The projection is NAD83, State Plane (US foot) and the elevation values are referenced to NAVD 88 (feet).**

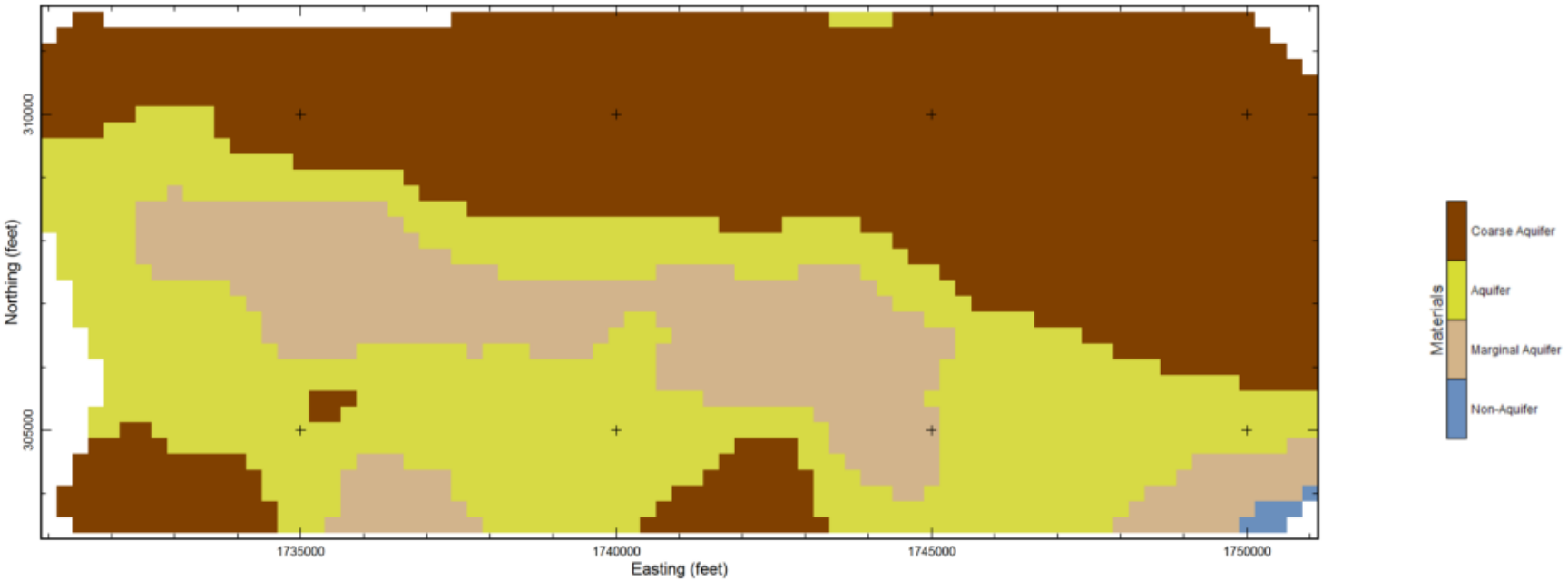



**Figure 5-26. Map of the first layer aquifer material for the PRRIP block. The projection is NAD83, State Plane (US foot) and the elevation values are referenced to NAVD 88 (feet).**

## 5.2 Resistivity-Lithology Relationship

### *5.2.1 Quaternary and Ogallala Aquifer System*

A critical aspect of a geophysical survey is assessing the nature of the material detected by the geophysical method applied in the investigation. Regarding the TPNRD and CPNRD AEM survey area, assessment of the sediment character in the Quaternary (***Q***) and Tertiary Ogallala (***To***) aquifer system was conducted to determine the overall composition of the major categories used to define the aquifer and aquitards in western Nebraska. An assessment of the resistivity thresholds used to characterize non-aquifer, marginal, aquifer, and coarse aquifer was conducted. This allows for the characterization of the ranges of resistivities present in the ***Q*** and ***To*** units described in this report. This analysis has been used in the current report for the categorization of the Quaternary and Ogallala aquifer system over the survey area.

First, all the available CSD borehole lithology log locations from the TPNRD, CPNRD, TBNRD, and MRNRD in the general vicinity of the AEM survey area were compiled into one database in Geosoft Oasis montaj and then the borehole name and easting, northing, and relative elevation were exported as an ASCII XYZ file out of Oasis, with the easting and northing in NAD83, Nebraska State Plane Coordinates System (US foot).

Next, the SCI inversion results for the TPNRD, CPNRD, PRRIP, and N-CORPE were compiled into one database in Oasis montaj. From this database, the easting, northing, DEM, and inverted resistivity earth-model array (29 elements from 29 SCI model layers Table 4.4) were exported as an ASCII XYZ.

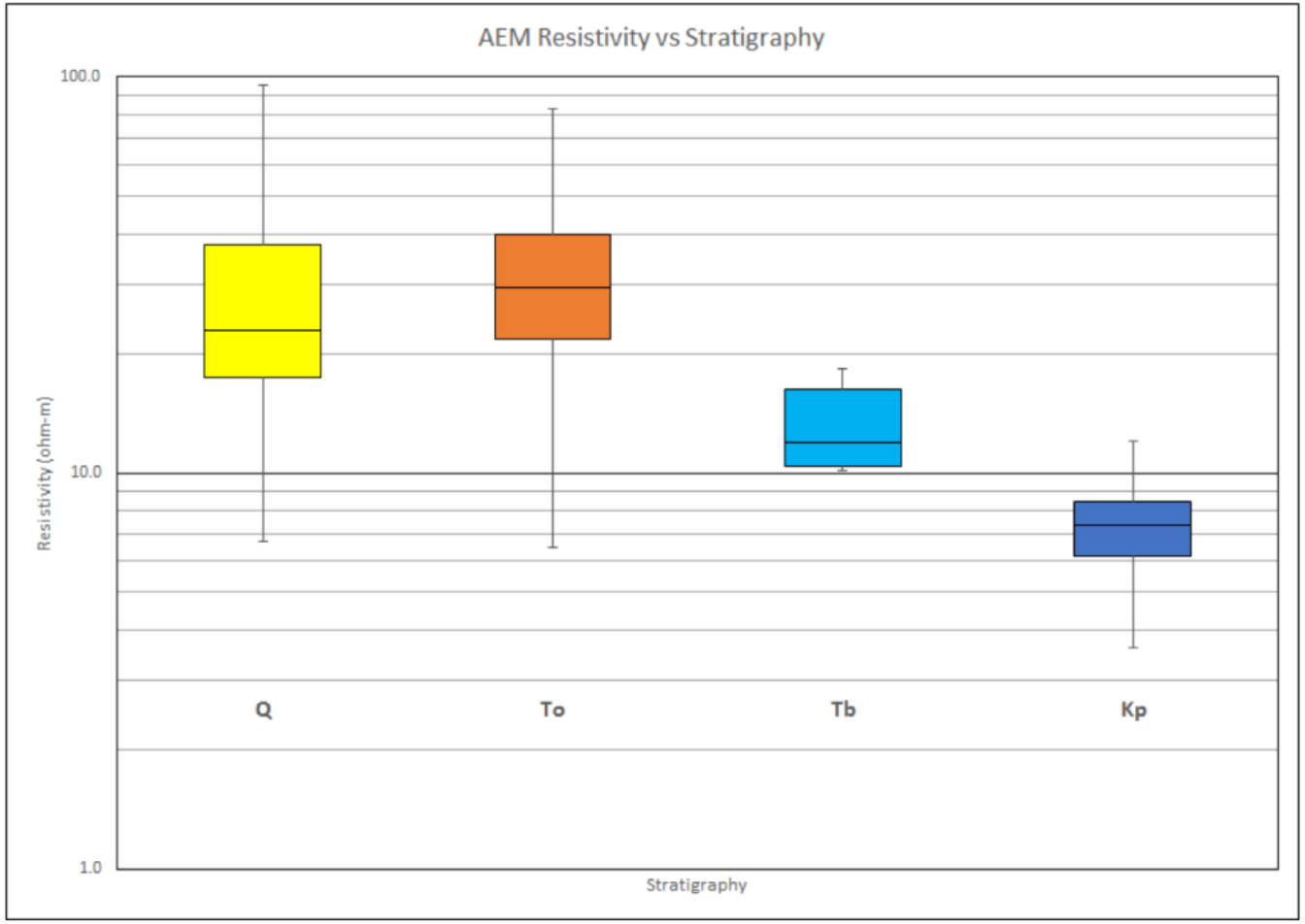
A program was then developed to determine the distance between the locations of the CSD boreholes with lithology and the AEM inverted resistivity sounding locations. Once the lithology borehole locations and the AEM inverted sounding locations were entered and the distance calculated, the program user would set a cut-off search radius (in feet) that would limit the number of boreholes to those within the cut-off distance of an AEM sounding.

For this project, the cut-off distance was set to 1,000 feet which resulted in 44 CSD boreholes with lithology being selected for comparison with the nearby AEM soundings. The AEM resistivity earth-models associated with a given lithology borehole were then averaged into one AEM resistivity model for each lithology borehole. The averaged AEM resistivities were then mapped by layer thickness and depth into the lithology borehole depth discretization. This means that if several AEM model resistivities mapped into only one lithology over a given thickness, those AEM resistivities were averaged over the lithology thickness.

Finally, the resistivities and lithologies were grouped based on lithology and stratigraphy. A “box and whiskers” chart, developed for stratigraphy (***Q, To, Tb,*** and ***Kp***) versus resistivity, is presented in Figure 5-27 which clearly demonstrates the resistivity change from the aquifers of the ***Q*** and ***To*** versus the aquicludes of the ***Tb*** and ***Kp***. The ***Tb*** also includes the ***Tc*** in this analysis and could also be looked at as the ***Twr***. Unfortunately, no CSD boreholes were within the 1,000 feet demarcation for looking at the ***Kn***. The ***Kn*** is typically a moderately resistive unit (Carney et al., 2015a). Also, no CSD test holes within the

TPNRD and CPNRD AEM survey area were drilled into the ***Kc***. However, Carney et al. (2015a) indicated that the ***Kc*** is a low resistivity unit composed of shale. Figure 5-28 is a box and whisker chart of the lithology versus resistivity for all the stratigraphic units. This plot shows much overlap in the resistivity distributions, but also shows that the Clay, Clayey Shale/Claystone, and Shale are over a much lower resistivity range. The next step is to look at the different material within the two aquifers of the ***Q*** and the ***To***. Pie charts of the lithology for the two stratigraphic breaks are presented in Figure 5-29 (***Q***) and Figure 5-30 (***To***). The pie chart in Figure 5-30 indicates that the ***To*** has the consolidated lithologies of sandstone, siltstone and marl, but also contains the unconsolidated lithologies of clay, silt/loess, sand, and sand and gravel. Going back and looking at Figure 5-27 shows that the ranges of the ***Q*** and ***To*** are very similar and do not warrant a splitting of the two units by resistivity alone. This is a similar conclusion to that reached in eastern Nebraska in Carney et al. (2015a).

The ***Q*** and ***To*** aquifers were broken down by resistivity for aquifer materials (less than 12 ohm-m – non-aquifer material, 12-25 ohm-m – marginal aquifer material, 25-40 ohm-m for aquifer material, and greater than 40 ohm-m for coarse aquifer material). Figure 5-31 is a histogram of the resistivities of the ***Q*** and ***To*** materials with the aquifer material categories indicated by colors. This histogram shows that the aquifer material breaks/categories lie in natural breaks within the histogram. For verification of these breaks in resistivity, the lithologies should show an increase in the coarse material with increasing resistivity. Pie charts have been created mapping the lithologies into the aquifer materials categories (Figure 5-32 – non-aquifer, Figure 5-33 - marginal, Figure 5-34 – aquifer materials, and Figure 5-35 – coarse aquifer materials). The non-aquifer materials (Figure 5-32) have approximately 68% of the materials as silt/loess and clay, with only approximately 23 % composed of sand, sand and gravel, and sandstone. For the marginal aquifer material (Figure 5-33) approximately 52% of the material is silt/loess, clay, silty clay, and silty sand; while approximately 40% is sand, sand and gravel, and sandstone; with the remaining being non-aquifer materials like siltstone, limestone and marl. The aquifer material category (Figure 5-34) contains approximately 61% sand, sand and gravel, and sandstone with the remaining being non-aquifer materials. The coarse aquifer material category (Figure 5-35) contains approximately 63% sand, sand and gravel, and sandstone. The coarse aquifer material category also contains approximately 25% silt/loess which may represent the unsaturated loess within the Quaternary section. To that end it is important to note the location of the water table in the examination of the profiles, especially in the Sand Hill and Loess Hill areas of the survey.




***Q*** = Quaternary
***To*** = Tertiary Ogallala Group
***Tb*** = Tertiary Brule Formation
***Kp*** = Cretaceous Pierre Shale

**Figure 5-27. For the TPNRD-CPNRD AEM survey area, a comparison of AEM model resistivities versus borehole stratigraphy from 44 CSD boreholes.**

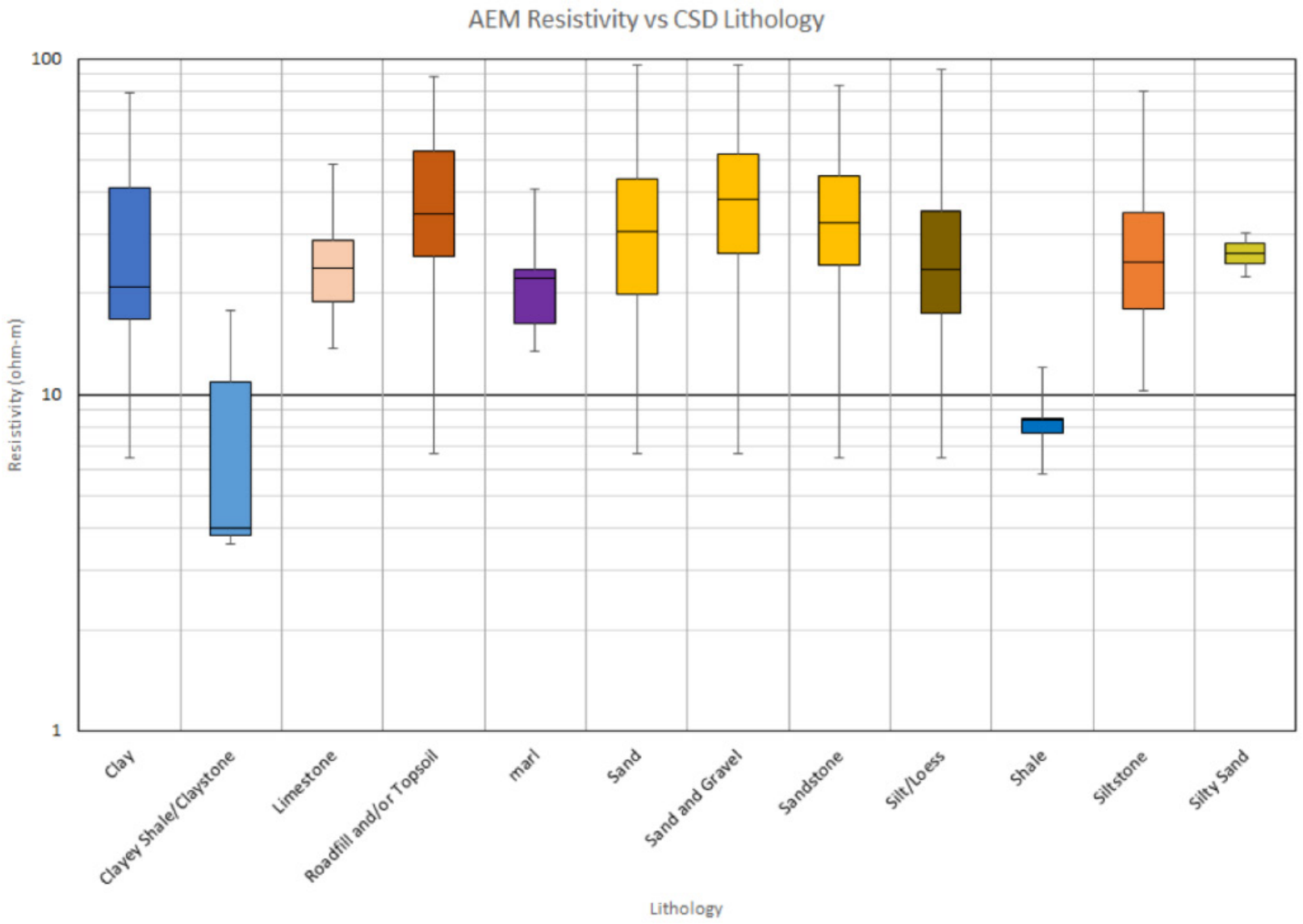



**Figure 5-28. For the TPNRD-CPNRD AEM survey area, a comparison of AEM model resistivities versus borehole lithology from 44 CSD boreholes.**

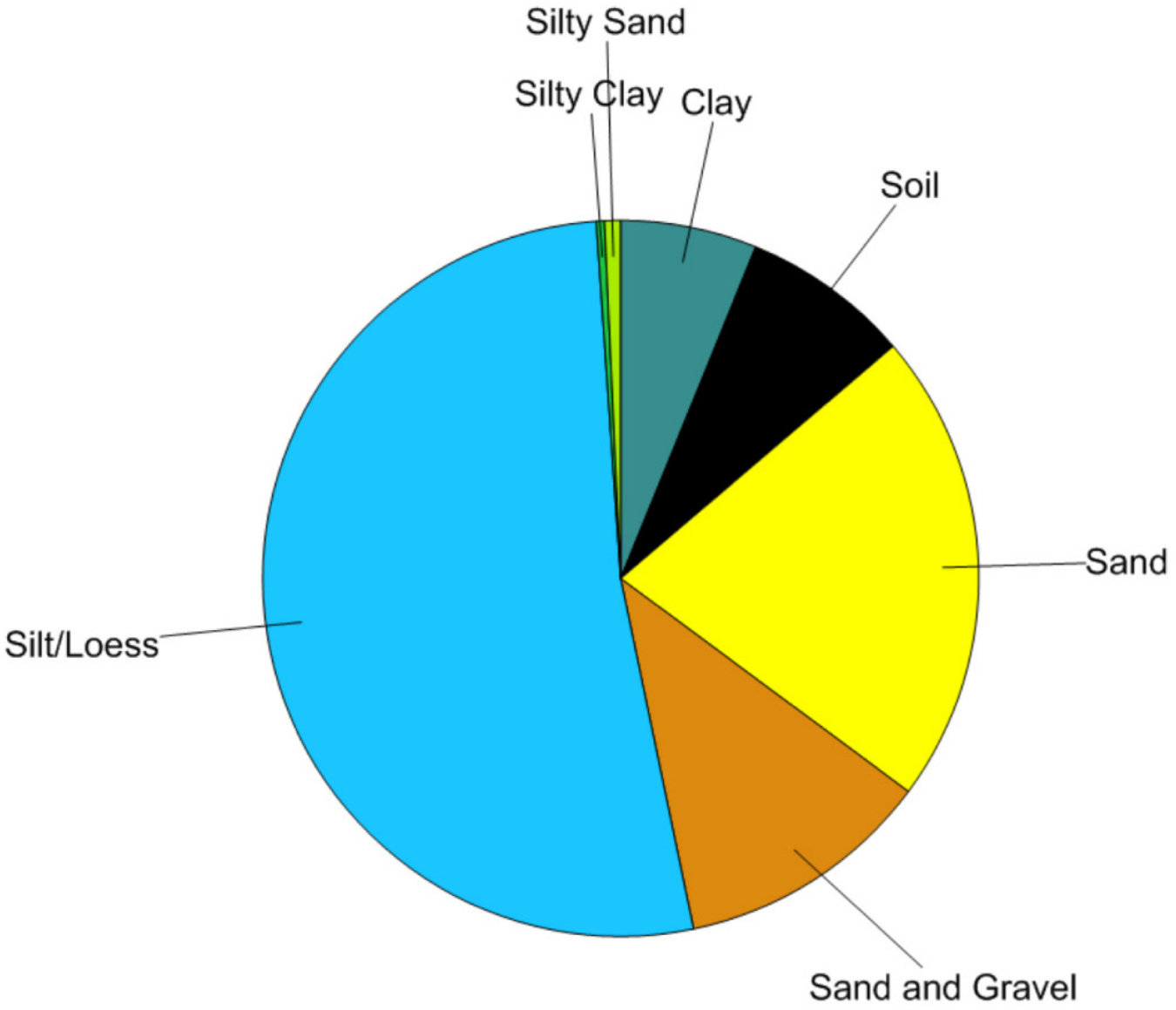



**Figure 5-29. Pie chart of the lithologies in the Quaternary (*Q*).**

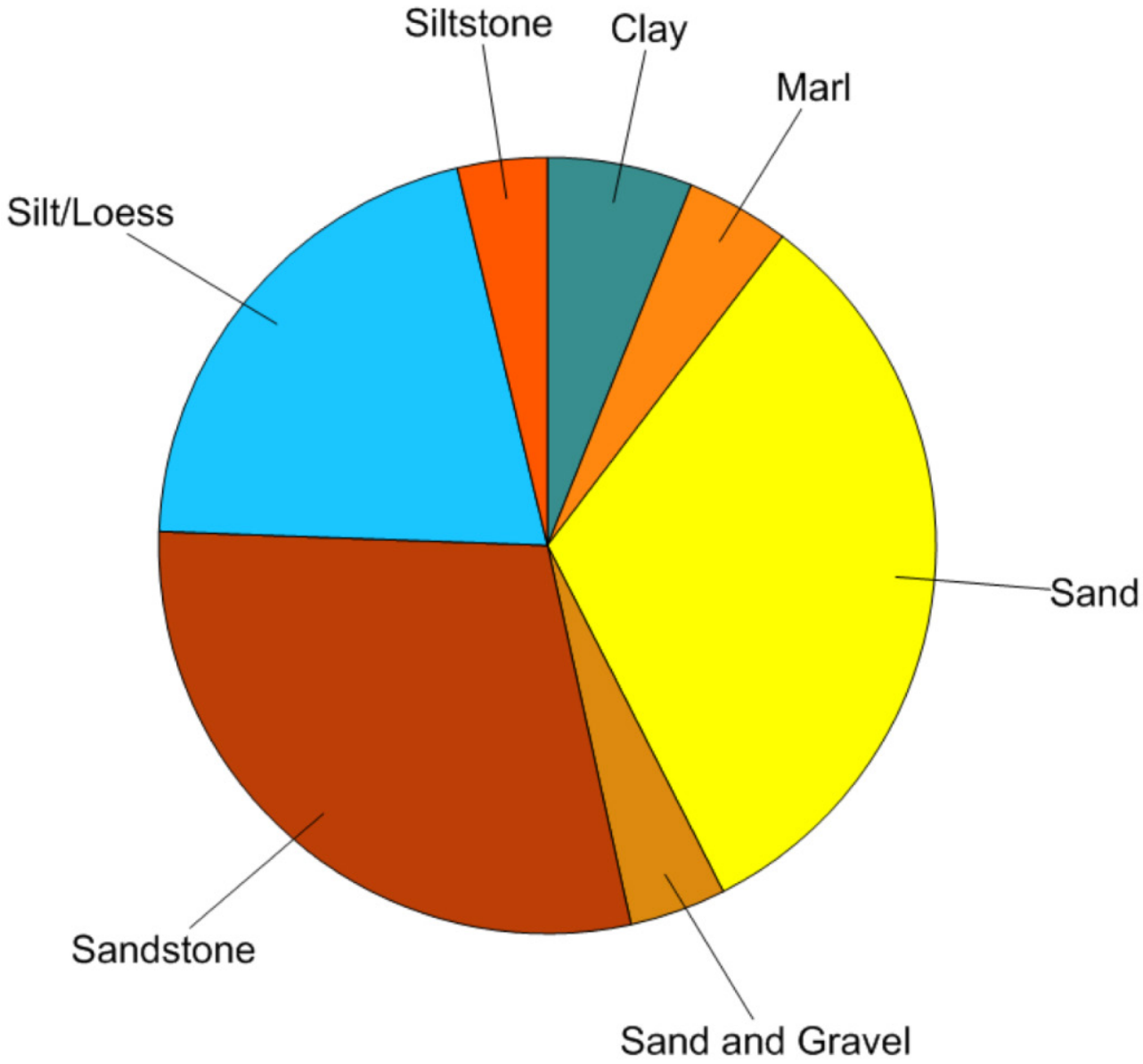



**Figure 5-30. Pie chart of the lithologies in the Tertiary Ogallala (*To*).**

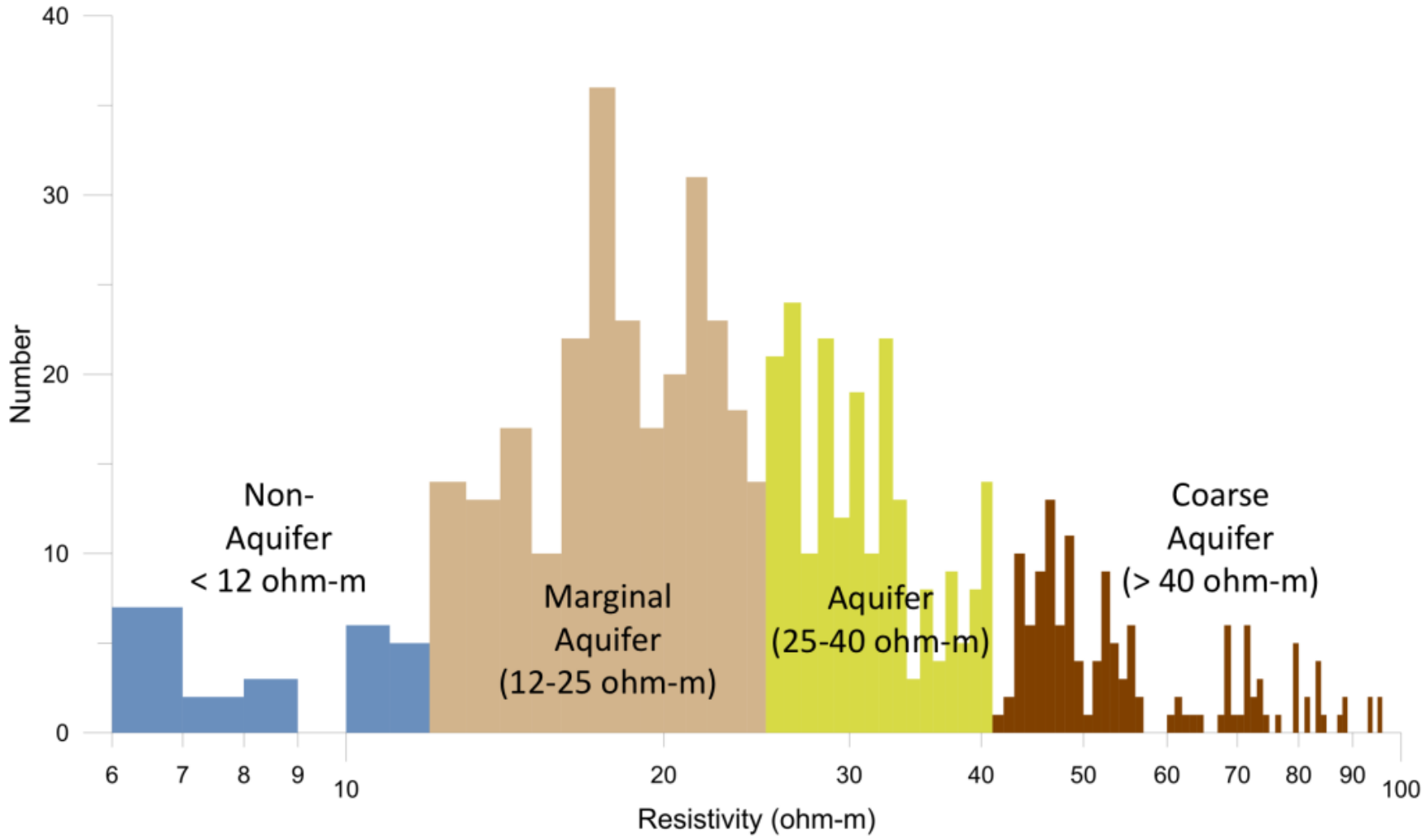



**Figure 5-31. Histogram of the resistivities within the Quaternary (*Q*) and Tertiary Ogallala (*To*). Colors represent the aquifer material ranges.**

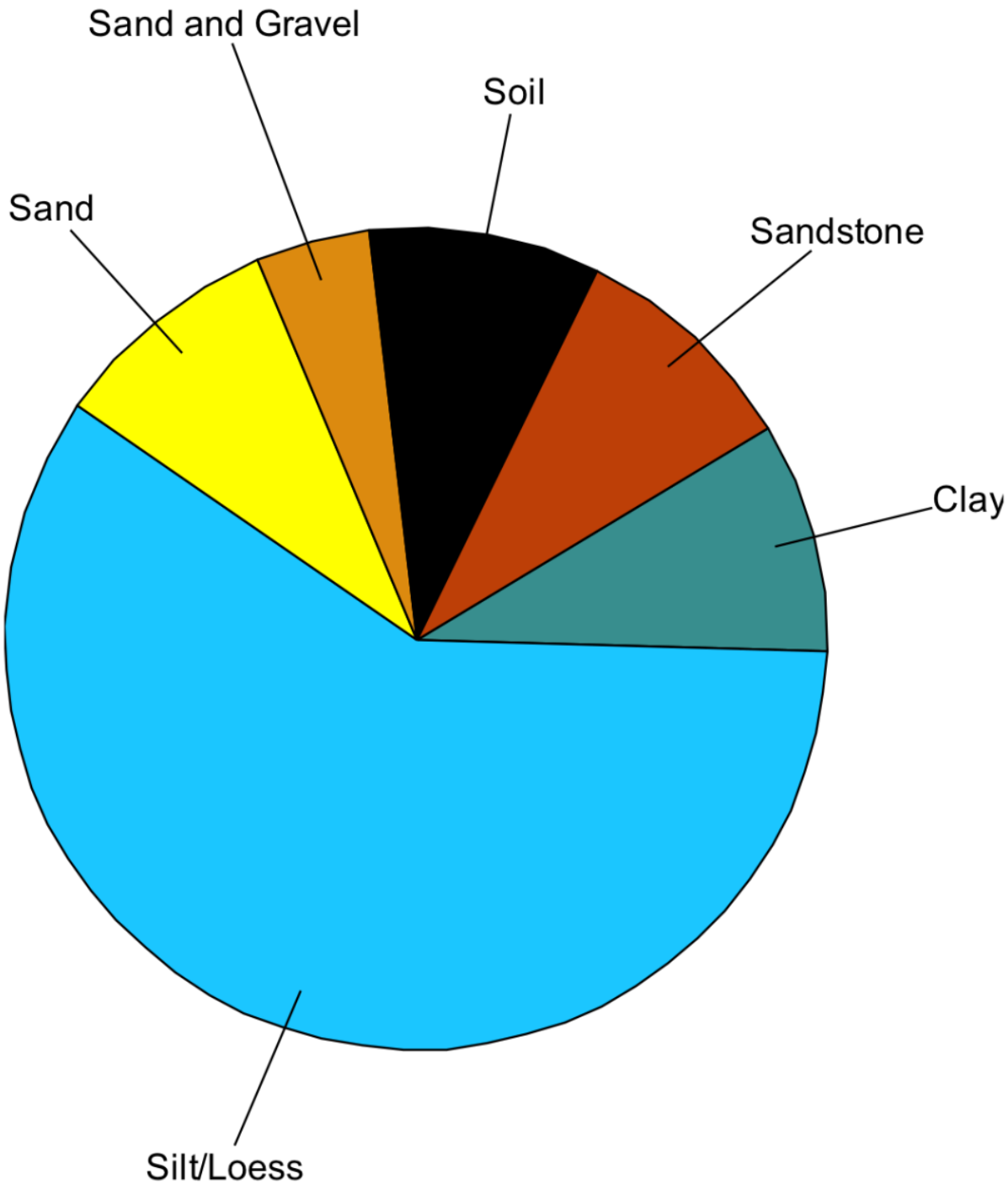



**Figure 5-32. Pie chart of the lithologies in the non-aquifer materials category (less than 12 ohm-m).**

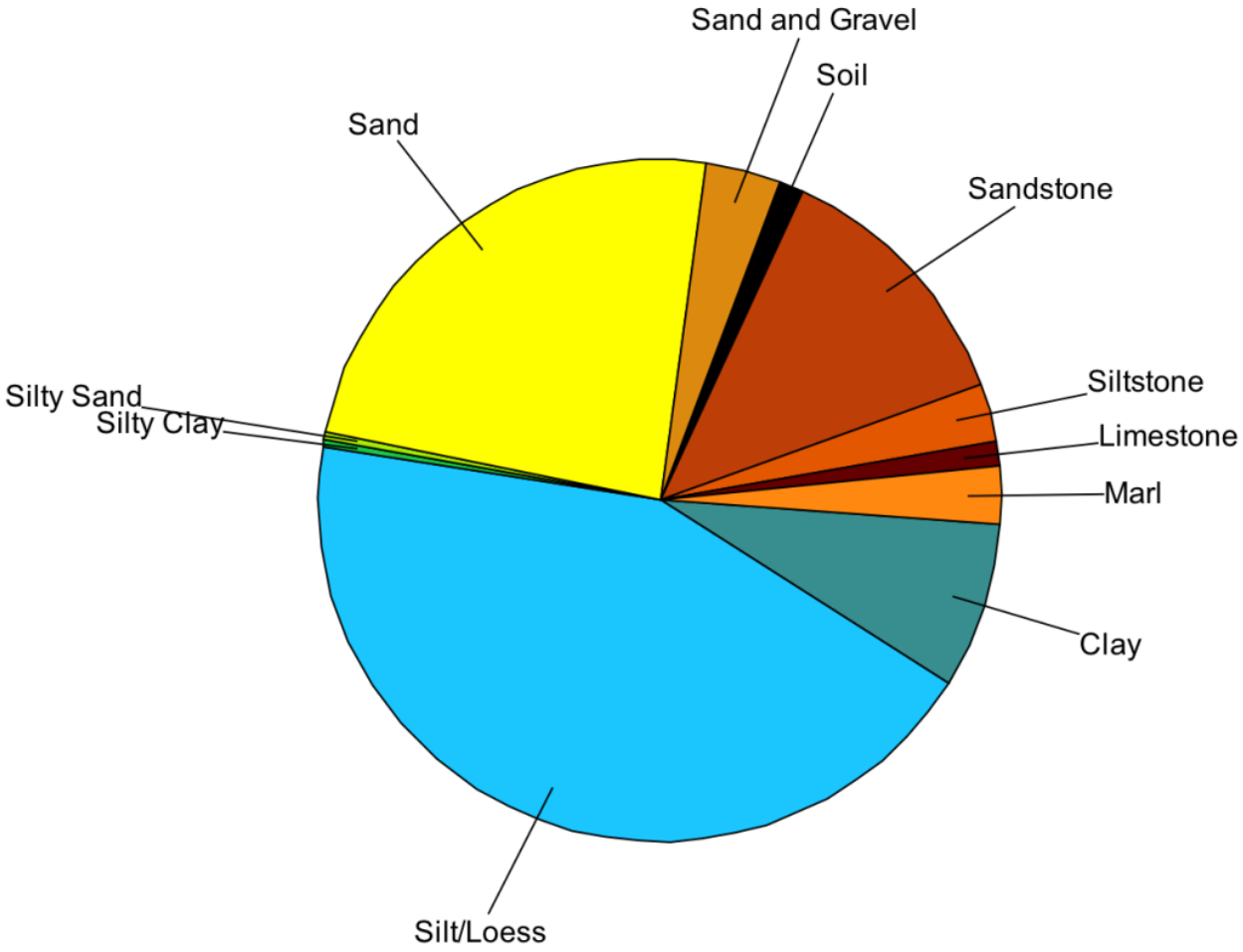



**Figure 5-33. Pie chart of the lithologies mapping into marginal aquifer materials category (between 12 ohm-m and 25 ohm-m).**

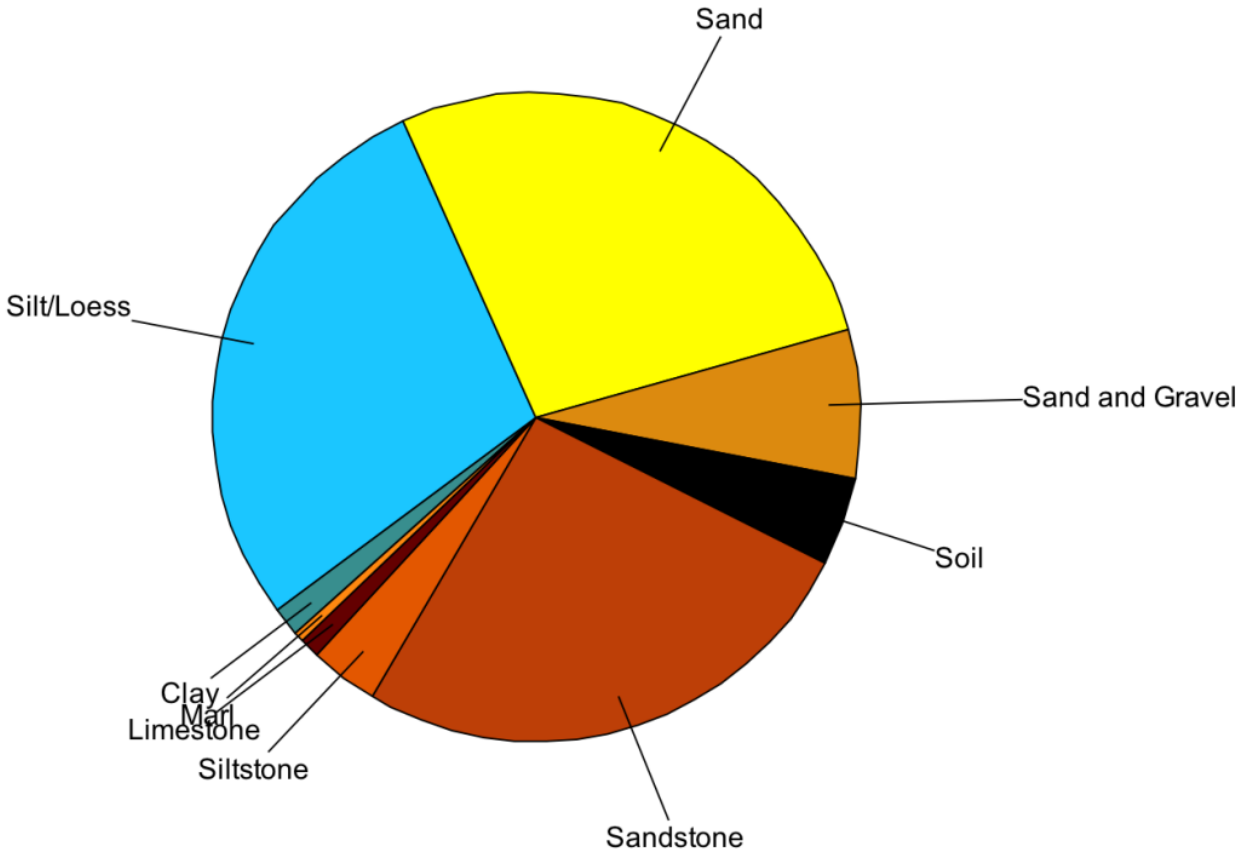



**Figure 5-34. Pie chart of the lithologies mapping into aquifer materials category (between 25 ohm-m and 40 ohm-m).**

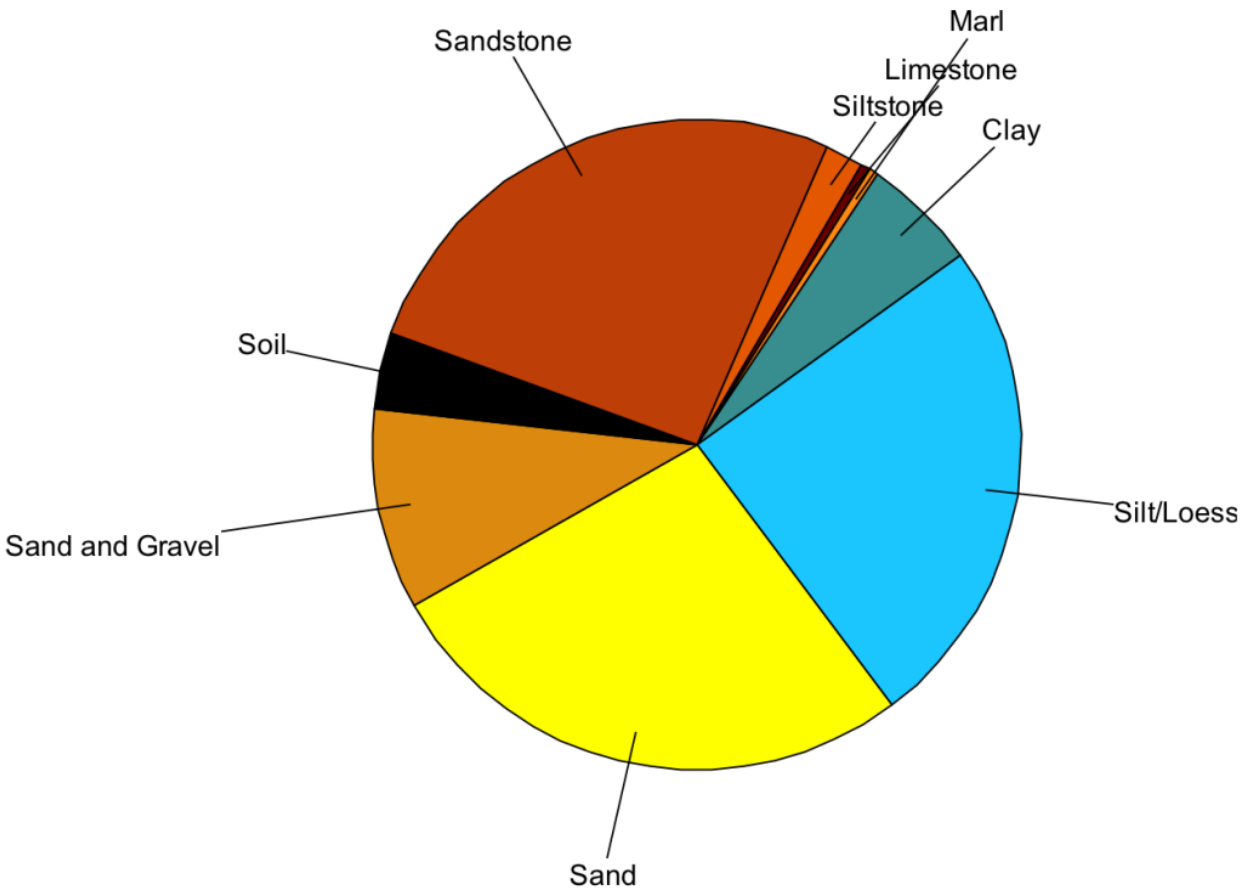



**Figure 5-35. Pie chart of the lithologies mapping into coarse aquifer materials category (greater than 40 ohm-m).**

### *5.2.2 Comparison of AEM Inversion Resistivity to Borehole Geophysical Resistivity Logs*

Of the 30 geophysical logs that were within the TPNRD and CPNRD AEM survey area, only two logs showed semi-calibrated and reliable values and were close enough to the flight lines to be useful. These included *COHYST1-01* and *90-HP-80*. The remaining logs showed either log malfunctions, calibration errors, or were too far from the flight lines. Since the resistivity logs within the CSD database are of various vintages and conducted by various staff with differing equipment, a critical examination of the absolute values of the resistivity needs to include an awareness of errors in calibration and in the proper operation of the equipment. There is a long-standing issue with using geophysical logs as ground truth when comparing to AEM inversions or other techniques that are well calibrated using modern methods. Throughout much of the geophysical logging at the time it was acquired, the relative deflections of the resistivity measurements were all that was required or expected from a geophysical log. Operators were seldom trained in the proper operation of a calibrated sonde or in the ability to recognize high contact resistance of a cable head. This has led to many geophysical logs that are uncalibrated within the CSD database. Note that these logs still have scientific merit in their ability to qualitatively indicate an increase or a decrease in the formation resistivity. The logs used herein are for qualitative comparison to the AEM because detailed calibration and corrections would need to be carried out for the resistivity values in the logs to be directly used as numerical constraints in the inversion of the AEM data (Ley-Copper and Davis, 2010).

Figure 5-36 is a plot of the *COHYST1-01* 16-inch short normal resistivity log plotted with the inverted AEM resistivity for line L200603. *COHYST1-01* is located 1,437 feet from line L200603 and the AEM sounding is selected from the closest point to the borehole geophysical log. The agreement in the shape of the resistivity is reasonable with the AEM indicating a higher overall resistivity compared to the geophysical log. The shape of the curves shows a good agreement. The key is that the AEM clearly indicates the ***Q*** and ***To*** aquifer materials (sand, sand and gravel, and sandstone) over the ***Tb*** siltstone. The AEM also indicates that the upper section of the ***Q*** is composed of resistive coarse aquifer materials.

Figure 5-37 is a plot of the *90-HP-80* 16-inch short normal resistivity log plotted with the inverted AEM resistivity for line L102401. *90-HP-80* is located 1,086 feet from line L102401 and the AEM sounding is selected from the closest point to the borehole geophysical log. The agreement in the shape of the resistivity is good with the AEM indicating a higher overall resistivity at the top and a lower resistivity at the bottom compared to the geophysical log. The key is that the AEM clearly indicates the ***Q*** and ***To*** aquifer materials (sand, sand and gravel, and sandstone) over the ***Tb*** siltstone. The AEM also indicates that the upper section of the ***Q*** is composed of resistive coarse aquifer materials. The AEM doesn't detect the thin clay layer at approximately 70 feet. This may be due to the distance between the AEM sounding and the well log or that the log indicates a low/high/low pattern and the AEM cannot resolve that small-scale feature when the clay layer is that thin.

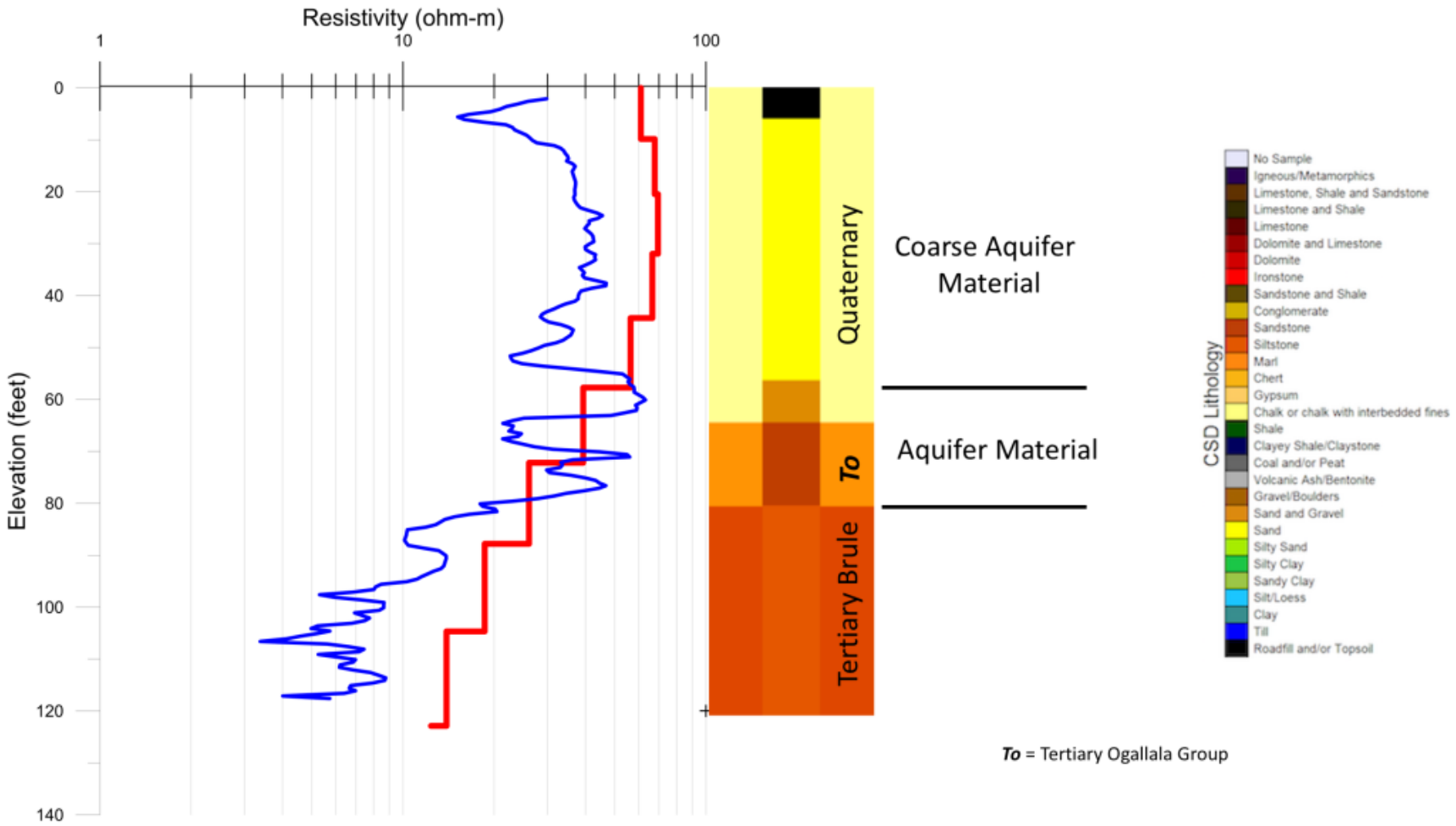



**Figure 5-36. Graph of the *COHYST1-01* 16-inch normal resistivity log values (blue line) and the inverted airborne electromagnetic resistivity values (red line). Also indicated is the lithology and stratigraphy log from *COHYST1-01* as well as the Quaternary/Tertiary Ogallala aquifer material properties from the AEM inversion.**

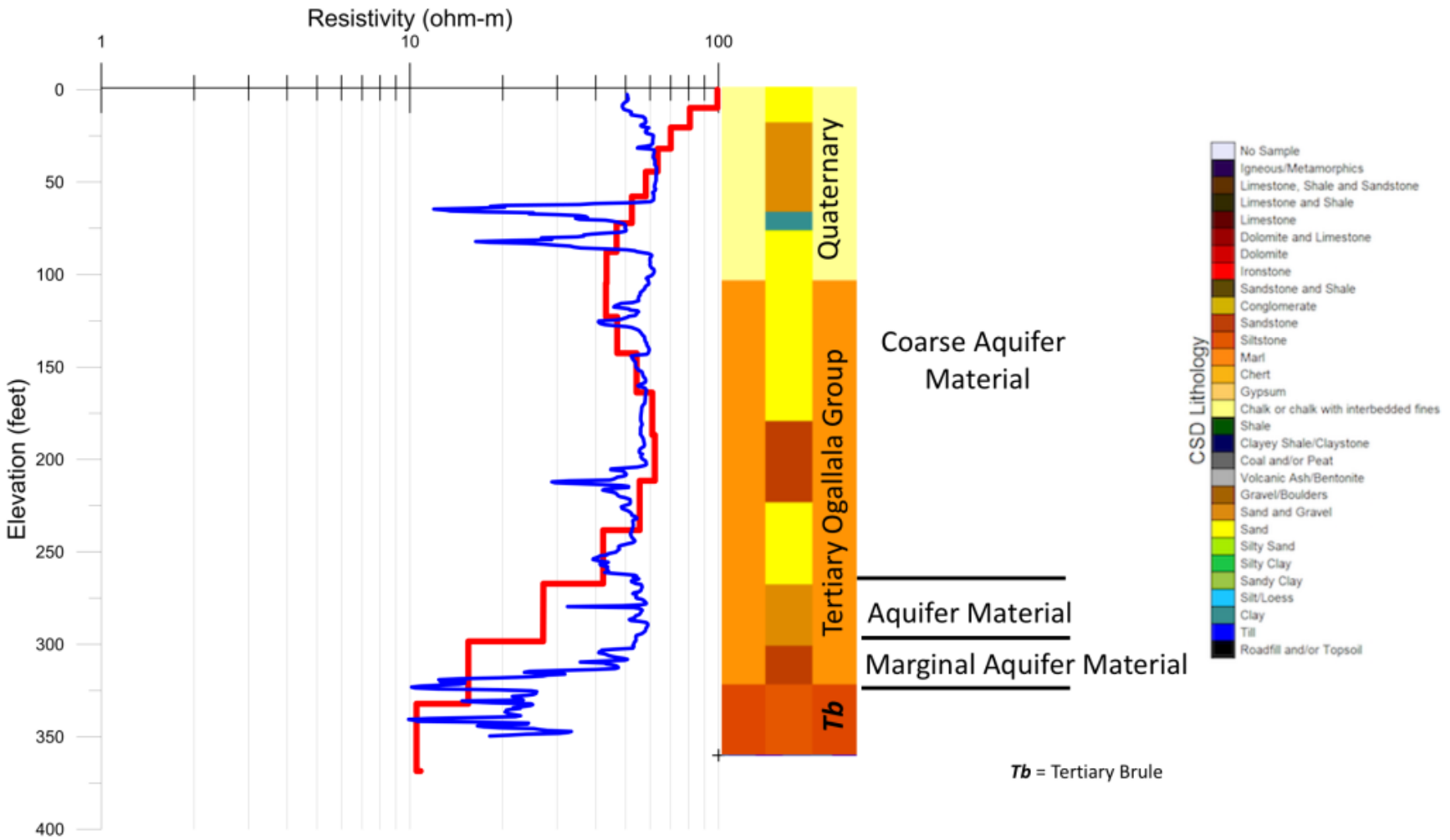



**Figure 5-37. Graph of the *90-HP-80* 16-inch normal resistivity log values (blue line) and the inverted airborne electromagnetic resistivity values (red line). Also indicated is the lithology and stratigraphy log from *90-HP-80* as well as the Quaternary/Tertiary Ogallala aquifer material properties from the AEM inversion.**

## 5.3 Hydrogeological Framework of the TPNRD and CPNRD AEM Survey Areas

This AEM survey has revealed the variability in the Quaternary (***Q***) and Tertiary (***T***) deposits which make up the aquifer system across the survey area. Quaternary (***Q***) and Tertiary Ogallala Group (***To***) are terms used in the interpretative section of this report to describe all unconsolidated, semi-consolidated, and consolidated materials considered as the "aquifer." The aquifer overlies the Tertiary Brule Formation (***Tb***), the Cretaceous Pierre Shale (***Kp***), and the Cretaceous Niobrara Formation ***(Kn***) which is considered the base of the aquifer (BOA). The 3D fence diagram displayed in Figure 5-38 presents interpreted profiles showing the overall distribution of ***Q***, ***To***, ***Tb***, ***Kp***, ***Kn***, and Cretaceous Carlile Shale (***Kc***) along the reconnaissance flight lines and block flight areas within the TPNRD and CPNRD survey area (The ***Q*** and ***To*** are broken down into aquifer material types as described in Section 5.2). Due to the large geographic area of the reconnaissance lines and the two individual block flights (N-CORPE, PRRIP), it is difficult to describe and display all the data on one figure. Additional fence diagrams and interpretation for the individual NRD and block flight areas will be described separately later in this section. The appendices of this report contain all interpreted profiles, 2D surface maps, 3D fence diagrams, and 3D voxels. Along the reconnaissance lines the subsurface distribution of aquifers can generally be characterized into four somewhat overlapping, but distinct, areas with smaller localized depositional features described within the block flight areas. These include the Quaternary alluvium (***Qa***) mostly within the Platte River basin and tributaries within the AEM survey area, Quaternary eolian sand (***Qe***s), and Quaternary Peoria loess (***Qp***) deposits that cover most uplands of the project area, and the ***To*** which occurs throughout the area. The bedrock units are the ***Tb***, ***Kp***, ***Kn***, and ***Kc***. The following discussion is in two parts, the TPNRD with N-CORPE subsection and the CPNRD with discussion on the PRRIP subsection.

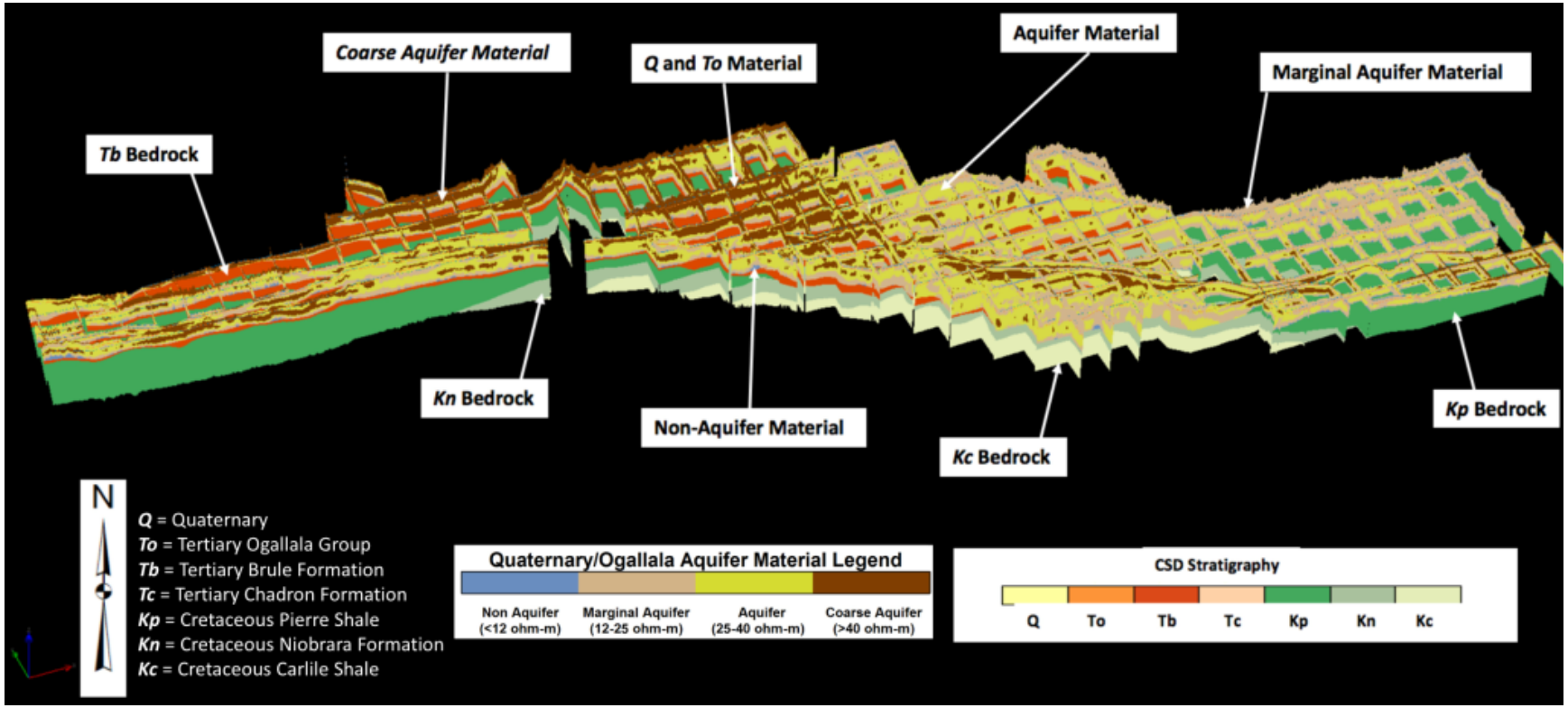



**Figure 5-38. 3D fence diagram showing the reconnaissance flight lines, looking to the north of the interpreted distributions of aquifer material within the TPNRD and CPNRD AEM Reconnaissance survey areas. Geologic units include Quaternary deposits (*Q*), Tertiary Ogallala (*To*), and the Tertiary Brule Formation (*Tb*), Cretaceous Pierre Shale (*Kp*), Cretaceous Niobrara Formation, and Cretaceous Carlile Shale (*Kc*) which are aquicludes for the area. Vertical exaggeration is 30x. Projection is NAD83, Nebraska State Plane Coordinate System, code 2600, feet.**

## *5.3.1 Hydrogeology of the TPNRD AEM Survey Area*

### *5.3.1.1 Quaternary Deposits*

The ***Qa*** areas of the TPNRD AEM survey are predominantly composed of unconsolidated aquifer and coarse aquifer materials with areas of marginal aquifer and non-aquifer materials composed of alluvial sediments. The alluvial sediments are thin and mostly saturated in the flood plain from the near surface down to the base of the aquifer (BOA). Most alluvial materials lie in the North Platte, South Platte, and Platte River valleys and their tributaries. The ***Q***a overlies the ***To*** and ***Tb*** (only in the far western areas of the AEM data collection) along the North Platte River and the ***To*** in the South Platte River as seen along Profile L101001 which lies east of the town of Ogallala, NE (Figure 5-39). Note the elevation difference between the South Platte River and the North Platte River, the South Platte River is higher than the North Platte River in Figure 5-39. The estimated water table slopes from west to east but also slopes from the South Platte River towards the North Platte River. The ***Qa*** fills channels incised directly into the ***Tb*** within the North Platte River basin near Lake McConaughy. Towards the east, the ***To*** is present as a thin layer under the ***Qa*** within the North Platte River canal and extends east towards profile L101201 near Paxton, NE (Figure 5-40). The South Platte River contains more marginal and non-aquifer materials than the North Platte River alluvium which is mostly coarse aquifer material. Profile L102201 (Figure 5-41) is oriented south to north and crosses the South Platte and North Platte rivers near Sutherland, NE. Along this profile the South Platte and North Platte rivers are within the same valley with a thin mix of shallow saturated aquifer material and coarse aquifer material connecting the rivers with a good groundwater-surface water connection. Just east of the confluence of the South Platte and North Platte rivers, Profile L104001 (Figure 5-42) extends from the Platte River north into the Sand Hills which are made up of Quaternary eolian sand (***Qes***). Aquifer materials consist of aquifer and coarse aquifer materials with basal marginal and non-aquifer materials. There is a shallow water table that is a near match to the ***To*** contact in the river valley with a deeper ***To*** and water table elevation below the Sand Hills. Again, there is a good groundwater-surface water connection along the entire profile. Figure 5-43 shows profile L306202, which is oriented south to north parallel to the eastern TPNRD boarder starting at the Platte River and extending into the Sand Hills. There is a thin layer of marginal aquifer material below the surface of the Platte River that extends from the south bank most of the way across the valley, which can act as a boundary condition and create localized semi-confined conditions. As along Profile L104001, there is a shallow water table that is a near match to the ***To*** contact in the river valley with a deeper ***To*** and water table elevation below the Sand Hills. The relationships between the ***Q*** and the ***To*** sediments are complex along every profile and it is best if the reader uses the appropriate profiles in the *Appendix 1* when looking for information on a specific area in the TPNRD.

The ***Qa*** is eroded into the surface of the ***To*** and is observed along the South Platte, North Platte, and Platte rivers with the exception of the areas along the North Platter River discussed above. There is a good groundwater-surface water connection between the ***Q*** sediments and the streams. The ***Tb*** bedrock is an aquiclude as the base of aquifer for the TPNRD area and the eroded surface is the result of the ***To*** eroding into the surface and being deposited upon it. The maps of the elevation of the top of the ***Tb*** is considered the base of ***Q*** and ***To*** aquifer throughout the TPNRD AEM survey area (Figure 5-44). .

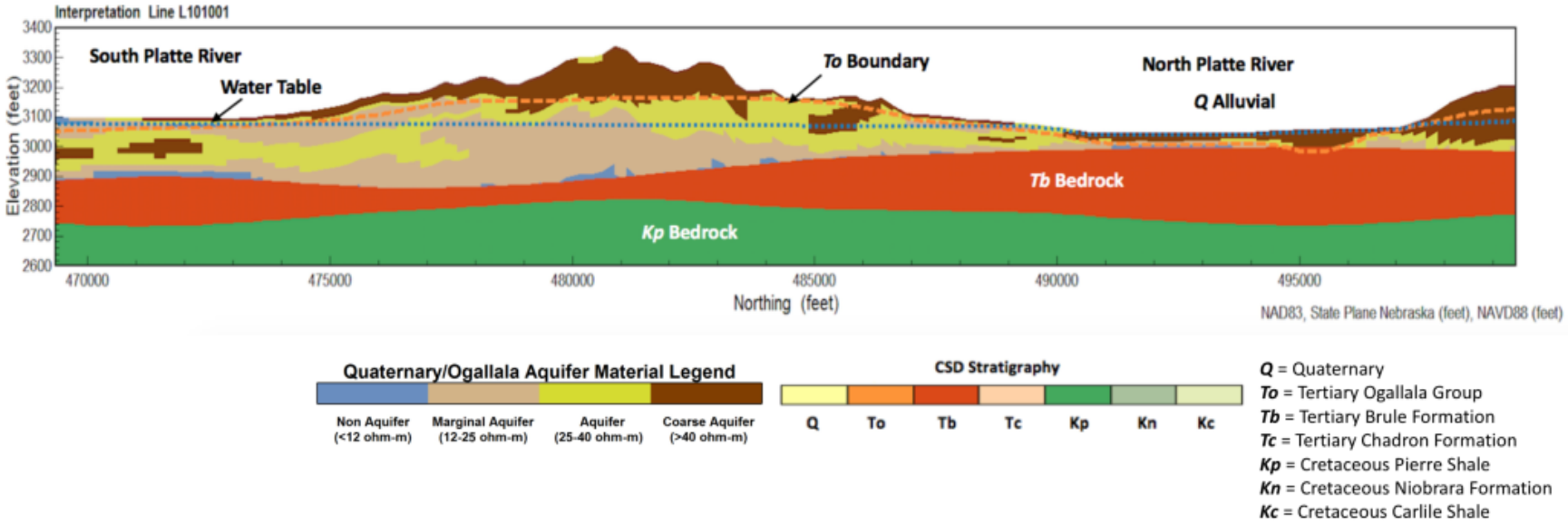



**Figure 5-39. Profile L101001 is a north-south flight line east of Ogallala, NE that shows thin Quaternary alluvium (*Qa*) in the South Platte River and thicker Qa in the North Platte River. This profile also shows coarse aquifer, aquifer, marginal aquifer, and non-aquifer materials that are deposited above and within the Tertiary Ogallala Group (*To*), much of which is saturated within the river valleys with a good groundwater-surface water connection. Note that the North Platte River has mostly coarse aquifer and aquifer materials that are incised nearly into the Tertiary Brule Formation (*Tb*). Projection is NAD83, Nebraska State Plane Coordinate System, code 2600, feet.**

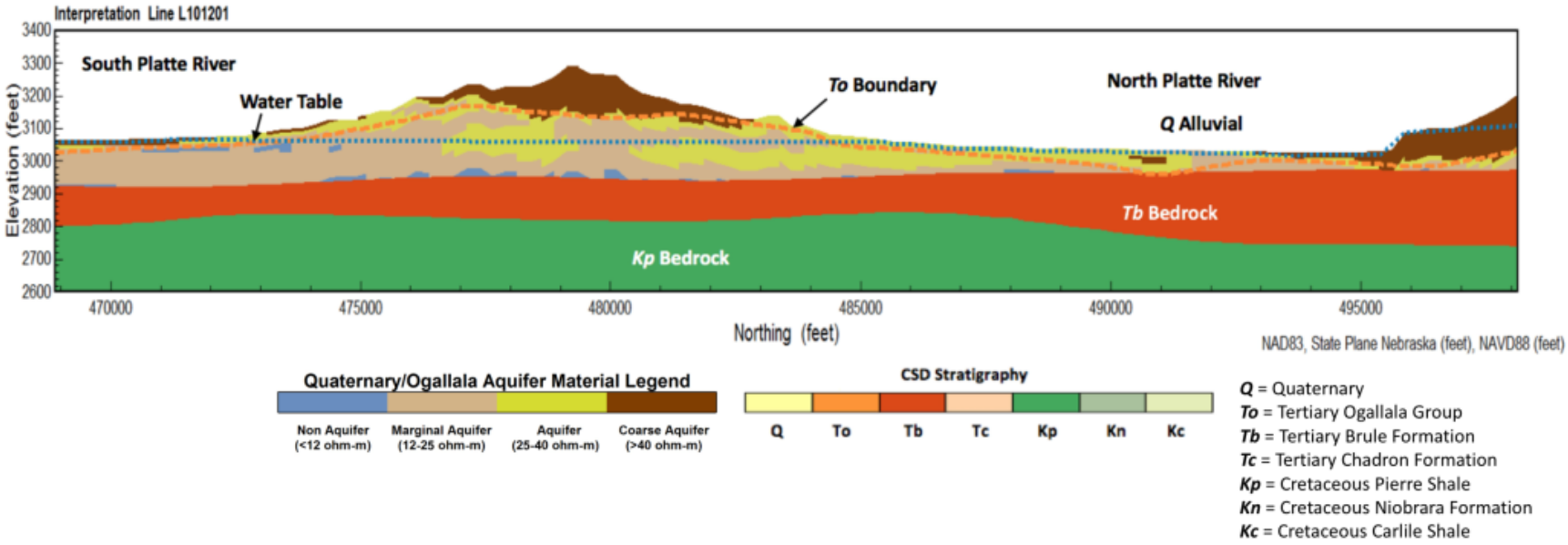



**Figure 5-40. Profile L101201 is a north-south flight line near Paxton, NE that shows thin Quaternary alluvium (*Qa*) in the South Platte River and thicker *Qa* in the North Platte River. This profile also shows coarse aquifer, aquifer, marginal aquifer, and non-aquifer materials deposited above and within the Tertiary Ogallala Group (*To*), much of which is saturated within the river valleys with a good groundwater-surface water connection. Note that the North Platte River is a mix of marginal aquifer, aquifer, and coarse aquifer materials that are lying on the Tertiary Ogallala Group (*To*) and are no longer incised close to the Tertiary Brule formation (*Tb*). Projection is NAD83, Nebraska State Plane Coordinate System, code 2600, feet.**

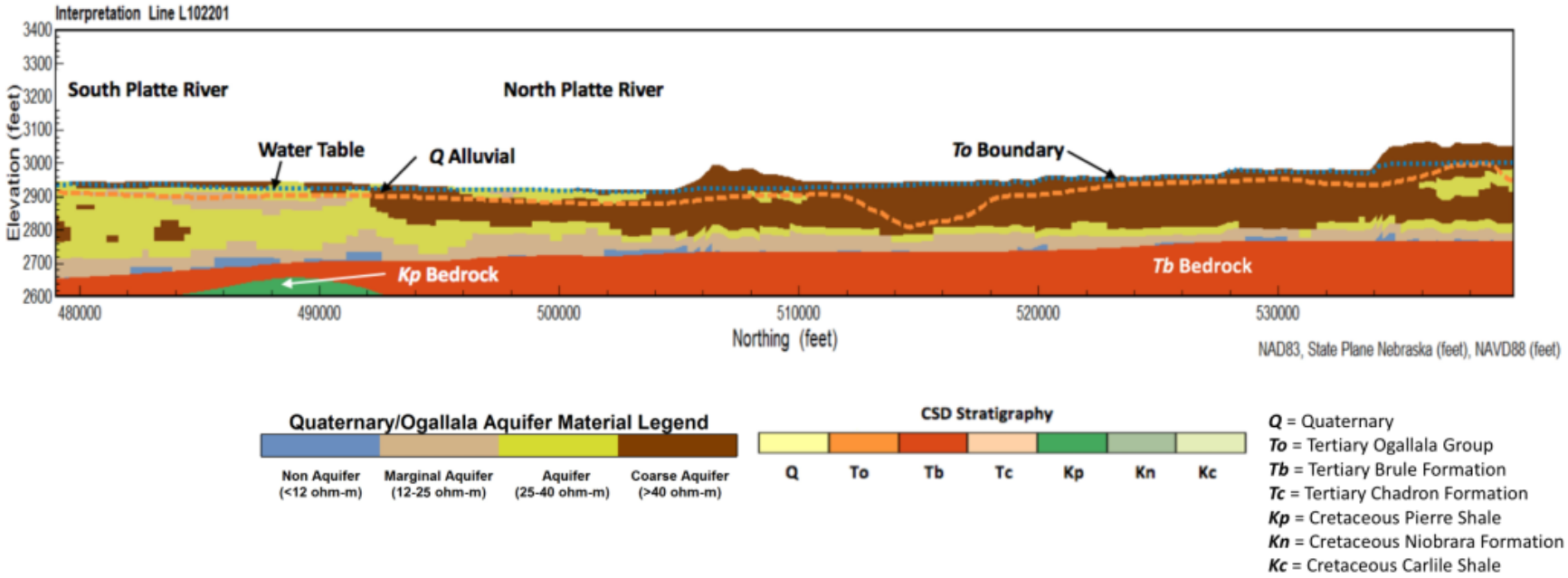



**Figure 5-41. Profile L102201 is a north-south flight line near Sutherland, NE that shows Quaternary alluvium (*Qa*) in the South Platte and North Platte rivers. This interpretive profile shows coarse aquifer, aquifer, marginal aquifer, and non-aquifer materials deposited above and within the Tertiary Ogallala Group (*To*), much of which is saturated within the river valleys with a good groundwater-surface water connection. Note that the North Platte River and South Platte River are now in the same valley. Projection is NAD83, Nebraska State Plane Coordinate System, code 2600, feet.**

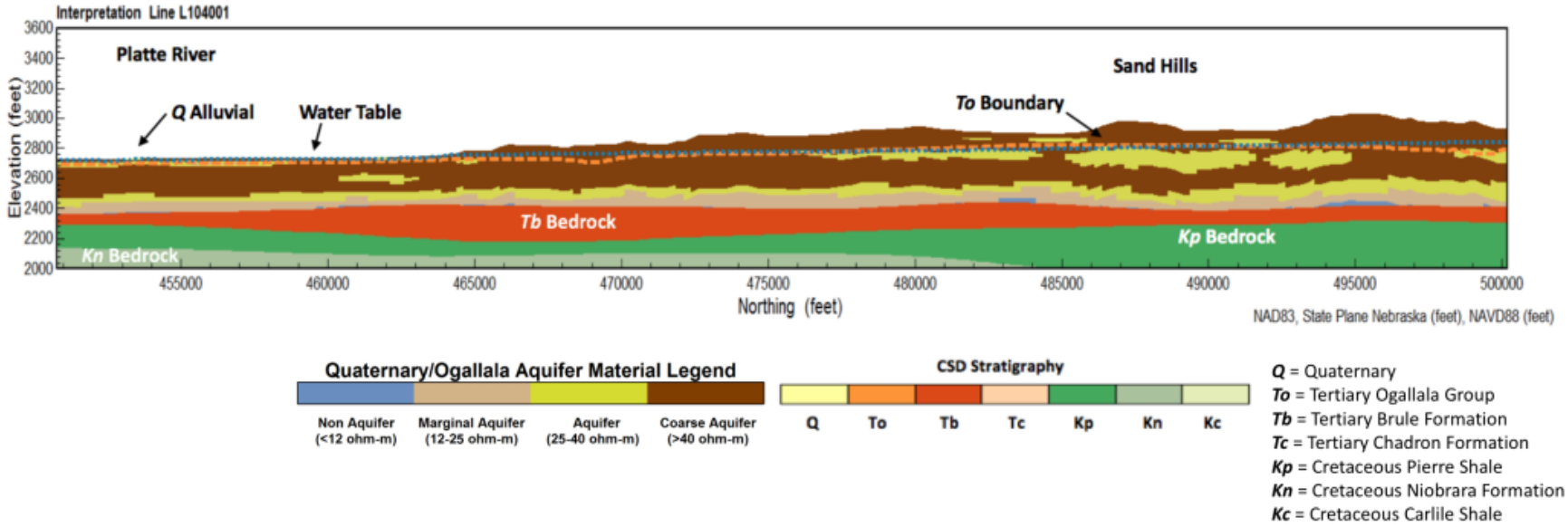



**Figure 5-42. Profile L104001 is a north-south flight line west of Maxwell, NE that shows thin Quaternary alluvium (*Qa*) in the Platte River. This profile also shows coarse aquifer, aquifer, marginal aquifer, and non-aquifer materials deposited above and within the Tertiary Ogallala Group (*To*), much of which is saturated within the river valleys with a good groundwater-surface water connection. Projection is NAD83, Nebraska State Plane Coordinate System, code 2600, feet.**

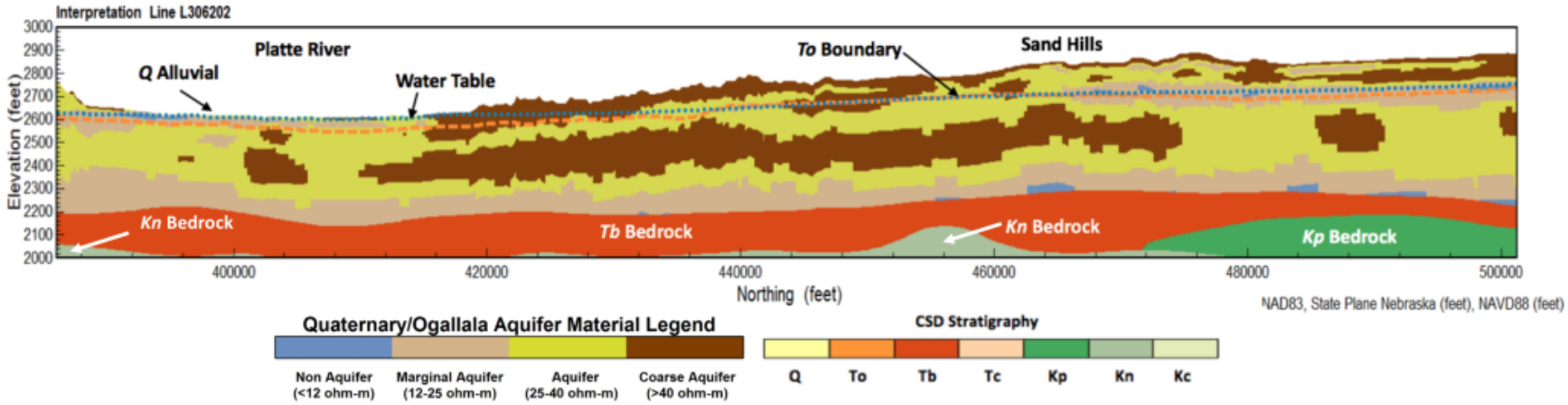



**Figure 5-43. Profile L306262 is a north-south flight line near the eastern border of the TPNRD that shows the thin Quaternary alluvium (*Qa*) in the South Platte and North Platte rivers. The section also shows a thin near-surface, marginal aquifer deposit extending from under the south bank out into the flood plain. Aquifer and coarse aquifer materials are deposited near the north side of the flood plain. Within the Tertiary Ogallala Group (*To*) there are a mix of non-aquifer, marginal aquifer, aquifer, and coarse aquifer materials, much of which is saturated, with a good groundwater-surface water connection. Also present are Tertiary Brule Formation (*Tb*), Cretaceous Pierre Shale (*Kp*), Cretaceous Niobrara Formation (*Kn*). Projection is NAD83, Nebraska State Plane Coordinate System, code 2600, feet.**

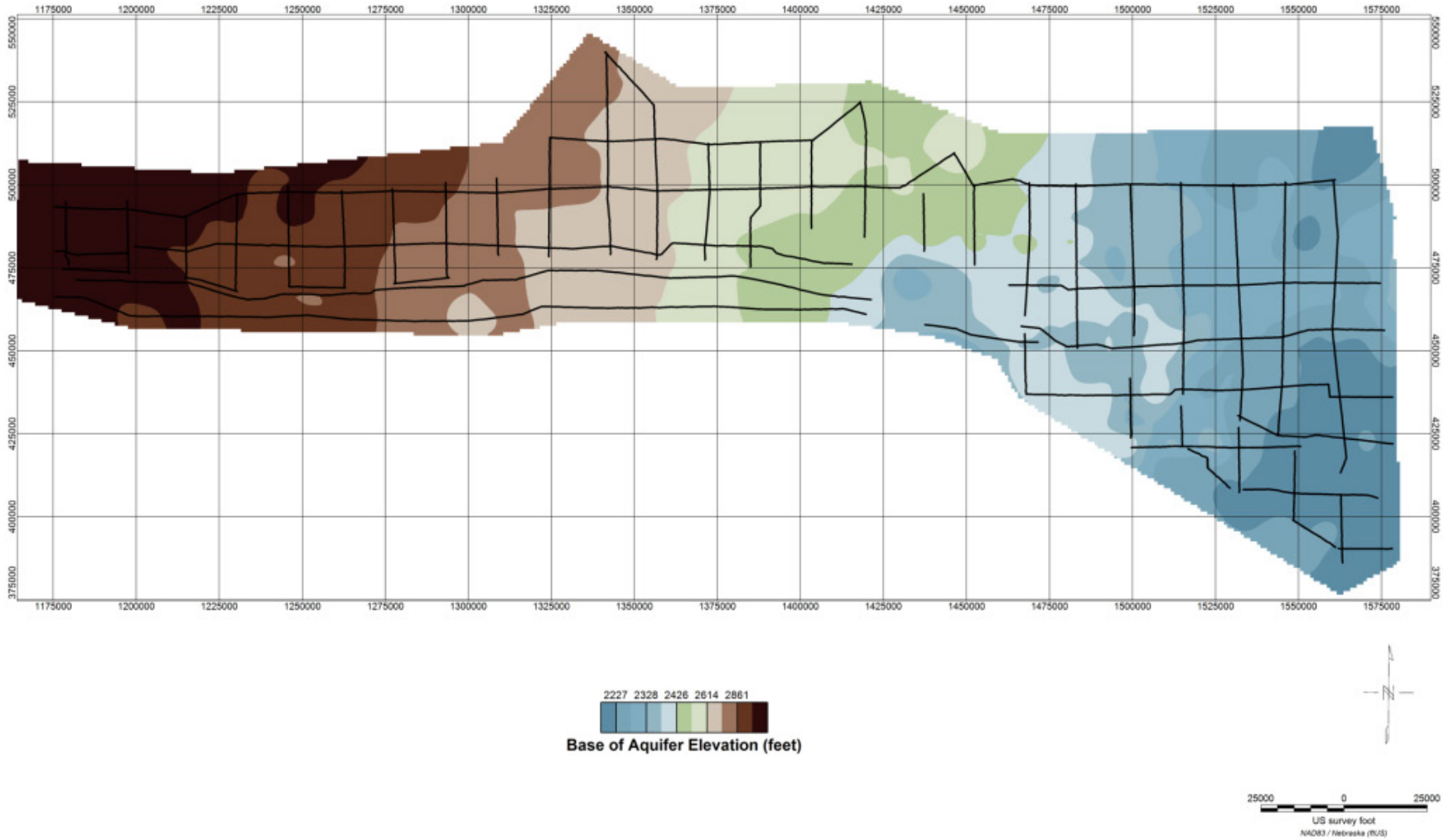



**Figure 5-44. This is a 2D surface map of the elevation of the Tertiary Brule Formation (*Tb*) which is the base of aquifer. Note that the surface slopes from west to east. The irregular surface is a result of the Brule Formation being eroded during deposition of the Tertiary Ogallala (*To*). Projection is NAD83, Nebraska State Plane Coordinate System, code 2600, feet.**

Within the alluvial aquifer system there are areas of non-aquifer and marginal aquifer materials. These areas are typically confined to near surface deposits and basal silts and clays. These layers are localized and can act as an aquiclude and prevent recharge or serve as local confining units. Due to the nature of the reconnaissance flight lines being widely spaced (approximately three miles), if greater detail of the aquifer materials distribution is required, block-flight surveys could be implemented.

A disadvantage of the reconnaissance lines and widely spaced block flight lines is that they have only identified ***Q*** deposits along the AEM flight lines and the complete extent of these deposits cannot be determined expediently without further AEM acquisition or exhaustive interpretation from added boreholes or additional ground-based geophysical surveys. However; the AEM reconnaissance survey has provided a much clearer view of the distribution of the geological units and aquifers within the area at the three-mile spacing. The reconnaissance survey should not be used for well head protection nor well field development, but does provide a useful hydrogeological framework for making management decisions at a NRD-wide scale.

#### *5.3.1.2 The Tertiary Ogallala Group*

The ***To*** is located throughout the AEM survey area except for small areas where it is eroded off in the western end of the North Platte Valley. The ***To*** is characterized by a combination of non-aquifer, marginal aquifer, aquifer, and coarse aquifer materials. The formation is heterogeneous and the ***To*** is an important aquifer where saturated and the aquifer materials yield water in sufficient quantities. The ***To*** can also be hydrologically connected to the ***Qa*** materials and streams. The ***To*** non-aquifer and marginal aquifer materials are considered boundaries to groundwater flow both vertically and horizontally making the AEM derived maps valuable for groundwater modeling projects, particularly for stream depletion calculations and recharge area assessments. There are some ***To*** outcrops along the streams of the survey area. The ***To*** varies in thickness from approximately 100 feet to over 425 feet, which is shown in Figure 5-45. The thickest sections of the ***To*** are in the eastern part of the TPNRD AEM survey area. Many of the profiles show the ***To*** in hydrologic connection to the stream. The patterns that define the shape of present day ***To*** are related to erosion over many episodes of fluvial processes in addition to recent erosion by the South Platte, North Platte, and the Platte River and their tributaries**.** Selection of drilling sites based on the greatest saturated ***To*** thickness containing aquifer and coarse aquifer materials improves the chances of a successful water supply. Thickness of the aquifer does not include the effect of partial cementation or inclusion of fine grained material that can clog the pore spaces of the ***To***, which would lead to lower yield and transmissivity.

Caution needs to be used in application of the aquifer thickness maps. An area of good hydrologic connection is where the ***Q*** and ***To*** contain both aquifer and coarse aquifer materials that are in contact. Due to the nature of the reconnaissance flight lines, greater detail of the ***Q*** and ***To*** materials distribution can only be achieved in this area with increased numbers of flight lines similar to the N-CORPE block flight area.

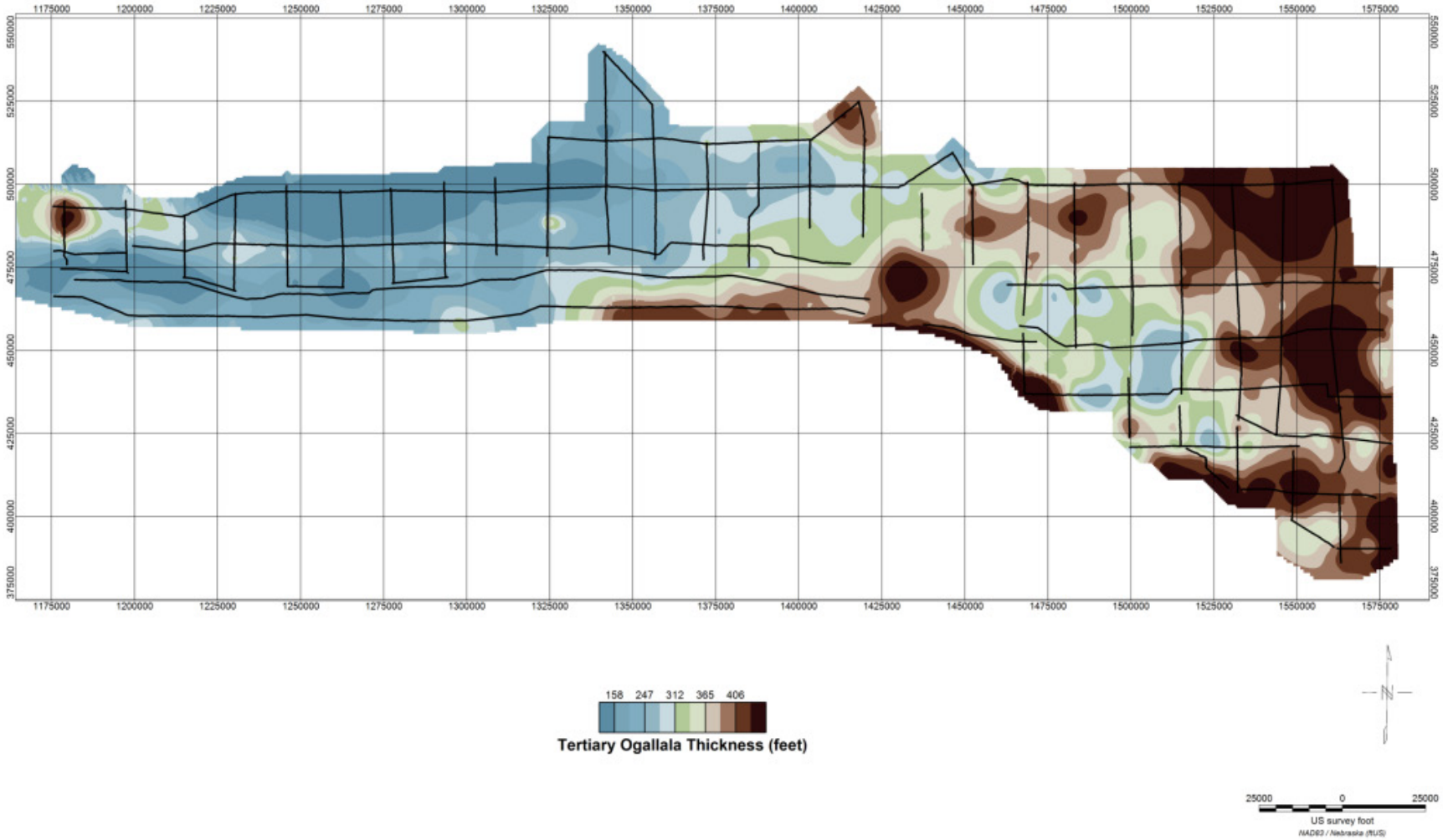



**Figure 5-45. Tertiary Ogallala Group (*To*) 2D thickness surface map in (feet). Note that the thickest areas of *To* are in the eastern part of the TPNRD AEM survey area. The irregular surface is a result of previous erosion and deposition and then more recent erosion by rivers and streams in the South Platte, North Platte, and Platte rivers and their tributaries. Projection is NAD83, Nebraska State Plane Coordinate System, code 2600, feet.**

#### *5.3.1.3 The Tertiary Brule Formation, Cretaceous Pierre Shale, Niobrara Formation, and Carlile Shale*

The ***Kp***, ***Kn***, and ***Kc*** underlie the ***Tb*** throughout the TPNRD AEM survey area. These units dip to the west as a result of the uplift of the Cambridge arch as seen on the right side of the 3D fence diagram in Figure 5-46. As such, the highest elevations of the ***Kp***, ***Kn***, and ***Kc*** within the TPNRD are near the eastern end of the TPNRD (outlined on the right in Figure 5-46). Because of the westward dip of these units, they were eroded during the deposition of the ***Tb*** which lies unconformably upon them. The ***Tb*** dip is nearly parallel to the ***To*** and the base of the ***Q*** sediments. Thus, as you move downstream along the Platte River, the ***Kp*** and ***Kn*** are eroded off with a thin veneer of ***Kn*** above the ***Kc*** as you approach the eastern TPNRD border. There are 2D surfaces for each of the ***Kp***, ***Kn*** and ***Kc*** in the TPNRD AEM survey area in *Appendix 2\2D Surfaces*.

### *5.3.2 Hydrogeology of the N-CORPE AEM Block Flight Area*

The hydrogeology of the N-CORPE block flight area is dominated by ***Qes*** deposits in some areas greater than 100 feet thick covering a loess layer that can be up to 40 feet thick lying above the ***To,*** all lying on the ***Tb*** which is present throughout the area (described in Section 5.3.1). The ***Qes*** material is made up of sand and some silt. Figure 5-47 shows a 3D fence diagram showing the ***Qes*** deposits resting on the ***To*** which is a heterogeneous mix of marginal aquifer, aquifer, and coarse aquifer materials with the ***Tb*** underlying the entire area. This figure provides insight into the aquifer of this area that is made up of the ***To*** which is saturated approximately 200 feet below ground level. Figure 5-48 shows profile L206601, oriented south to north, which shows the nature of the hydrogeology and the extent of the aquifer made up of the ***To*** materials that are capped by marginal aquifer materials (loess) near the ***To-Qes*** contact. Figure 5-49 shows profile L206701, oriented west to east, which shows the relatively flat lying nature of the ***To*** materials which are capped by a thin layer of marginal aquifer materials (loess) near the ***To-Qes*** contact and are underlain by the ***Tb***. The water table has approximately 130 feet of elevation change across the block flight area from a high in the northwest corner to a low in the southeast corner of the area (Figure 5-50). The saturated thickness of the ***To*** aquifer material (>25 ohm-m) is shown in Figure 5-51 and varies from approximately 135 to 230 feet. Estimates of saturated thickness would benefit from a more detailed water table map. The ***Tb*** bedrock exists throughout the area and is the base of aquifer in this area (Figure 5-52). The ***Tb*** surface slopes from the northwest to the southeast and has an elevation change of approximately 250 feet.

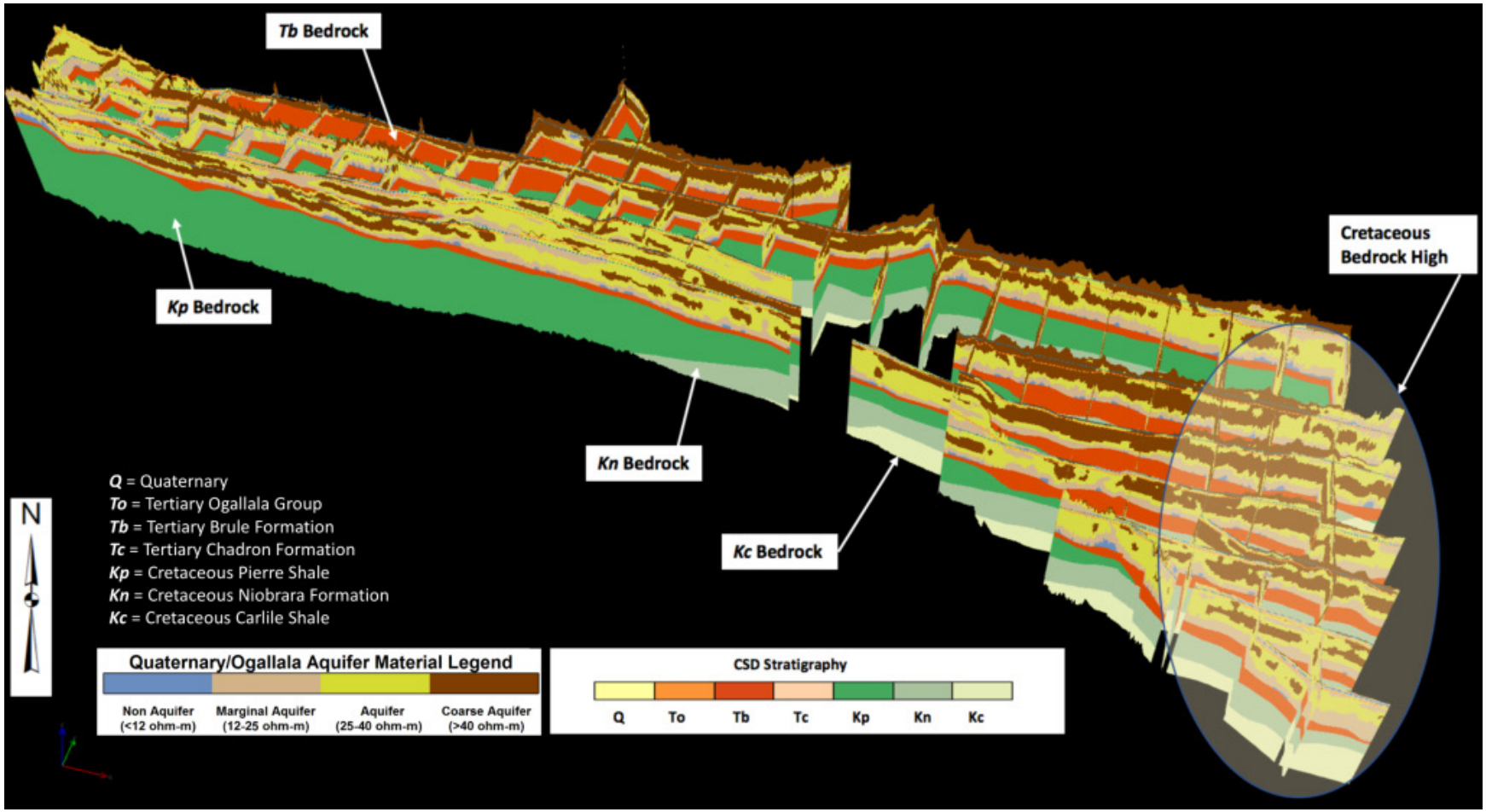



**Figure 5-46. The 3D fence diagram looking north shows the Cretaceous formations (Pierre Shale (*Kp*), Niobrara Formation (*Kn*), and Carlile Shale (*Kc*)) are dipping form the east end of the TPNRD to the west due to the influence of the Cambridge Arch. The highest elevation of the *Kp*, *Kn*, and *Kc* is highlighted by the light-colored oval on the map. These formations have been eroded off by the Tertiary Brule Formation (*Tb*) which is identified by the red-orange layer. The Tertiary Ogallala Group (*To*) and the Quaternary (*Q*) sediments are deposited on top of the *Tb*. Vertical exaggeration is 30x. Projection is NAD83, Nebraska State Plane Coordinate System, code 2600, feet.**

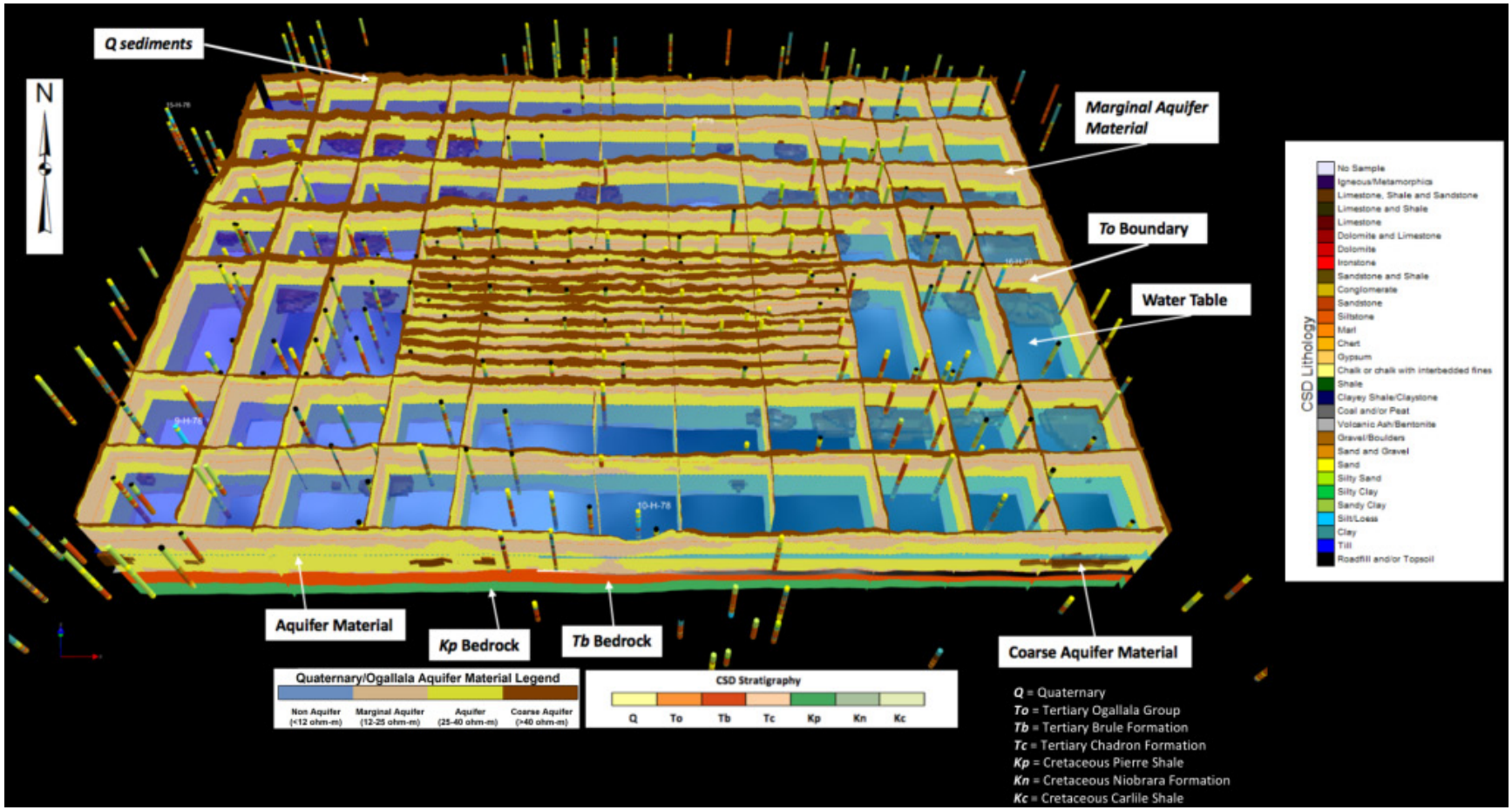



**Figure 5-47. 3D fence diagram showing the N-CORPE block flight lines looking to the north showing distribution and thickness of Quaternary eolian sand (*Qes*) materials and Tertiary Ogallala Group (*To*) materials lying on the Tertiary Brule Formation (*Tb*). The area has *Qes* material that is greater than 100 feet thick in some areas with a layer of loess near the *Q*-*To* contact. Saturated *To* is the aquifer for the area. The top of the 2013 water table is indicated by the blue surface. The coarse aquifer material (> 40 ohm-m) within the *To* is shown as a voxel above and below the water table surface. CSD test holes and NE-DNR registered wells are indicated by vertical tubes with the coloring indicated by the CSD lithology legend. Vertical exaggeration is 10x. Projection is NAD83, Nebraska State Plane Coordinate System, code 2600, feet.**

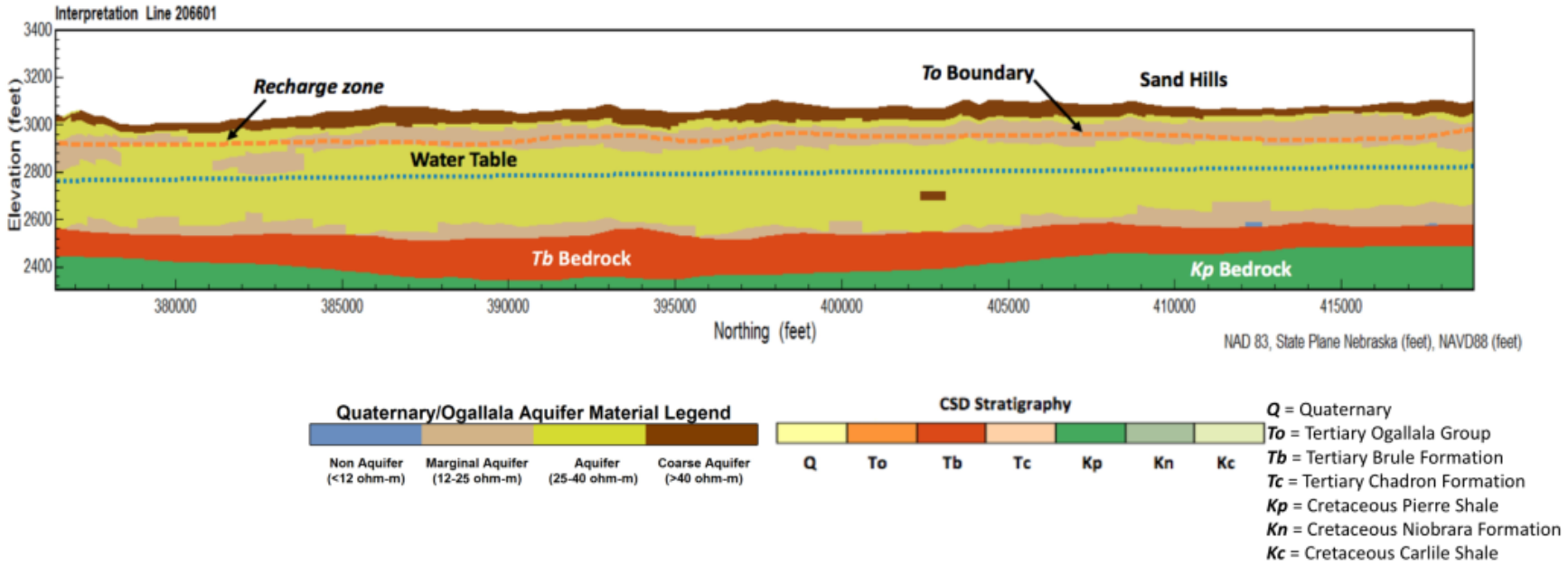



**Figure 5-48. Profile L206601 is a south to north profile centered in the N-CORPE block and shows the thickness of the Quaternary eolian sand (*Qes*) with a layer of loess near the Tertiary Ogallala Group (*To*) contact. This section shows coarse aquifer, aquifer, marginal aquifer, and non-aquifer materials that are deposited in the *Qes* above and within the *To*. Note the opening in the marginal aquifer material layer (loess) near the *To* contact on the south end of the profile where aquifer material is present (indicated by "Recharge Zone") that can allow recharge to easily enter the lower aquifer. The *To* is saturated approximately 200 feet below ground surface and rests upon the Tertiary Brule Formation (*Tb*) which is present throughout the area. Projection is NAD83, Nebraska State Plane Coordinate System, code 2600, feet.**

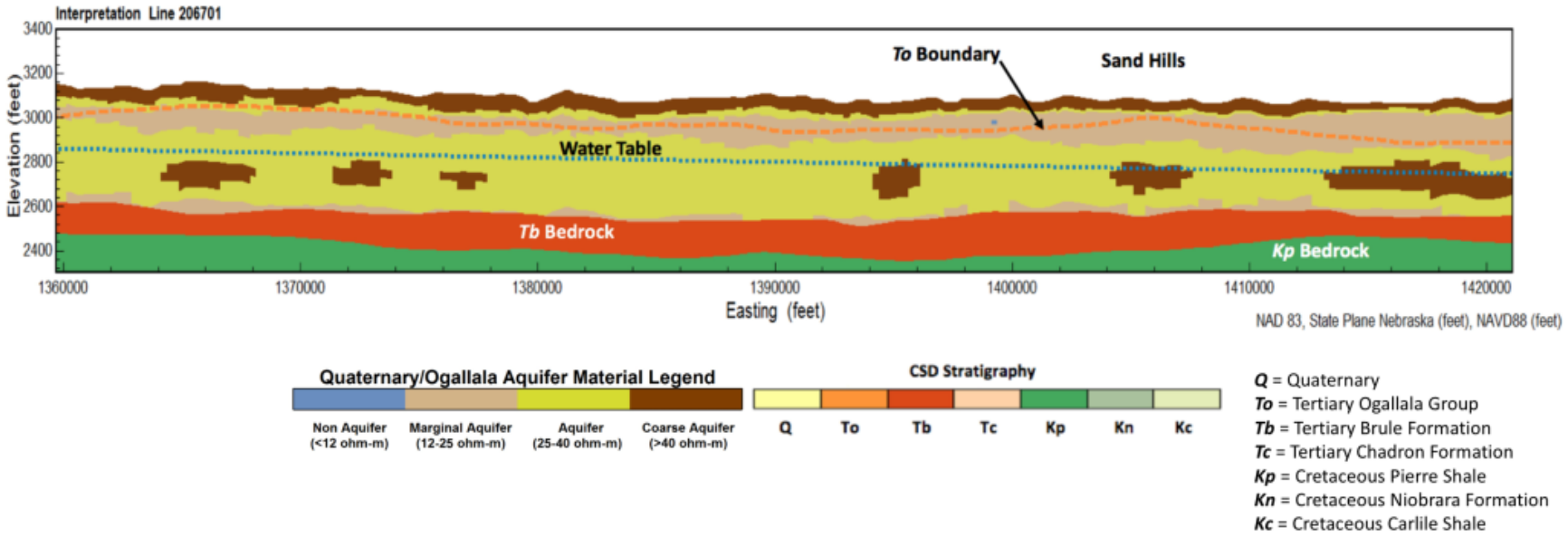



**Figure 5-49. Profile L206701 is a west to east section centered in the N-CORPE block and shows the Quaternary eolian sand (*Qes*) with a layer of loess near the *Q*-Tertiary Ogallala Group (*To*) contact. This profile has coarse aquifer, aquifer, marginal aquifer, and non-aquifer materials that are deposited above and within the *To*. The *To* is saturated approximately 200 feet below ground surface and rests upon the Tertiary Brule Formation (*Tb*) which is present throughout the area. Projection is NAD83, Nebraska State Plane Coordinate System, code 2600, feet.**

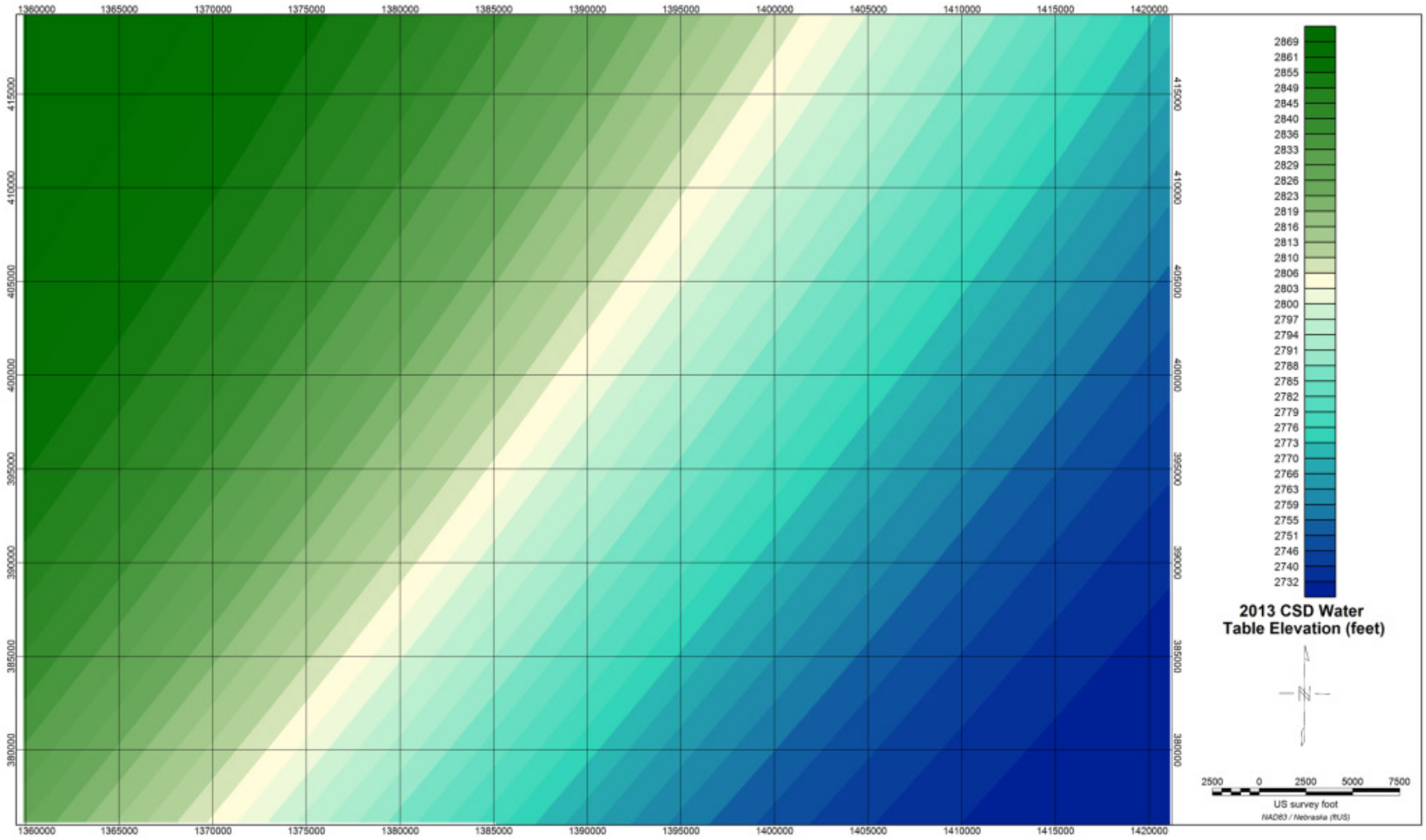



**Figure 5-50. This is a 2D surface elevation map of the water table (Korus et al., 2013b). Note that the surface slopes from northwest to southeast and has approximately 130 feet of relief. Projection is NAD83, Nebraska State Plane Coordinate System, code 2600, feet.**

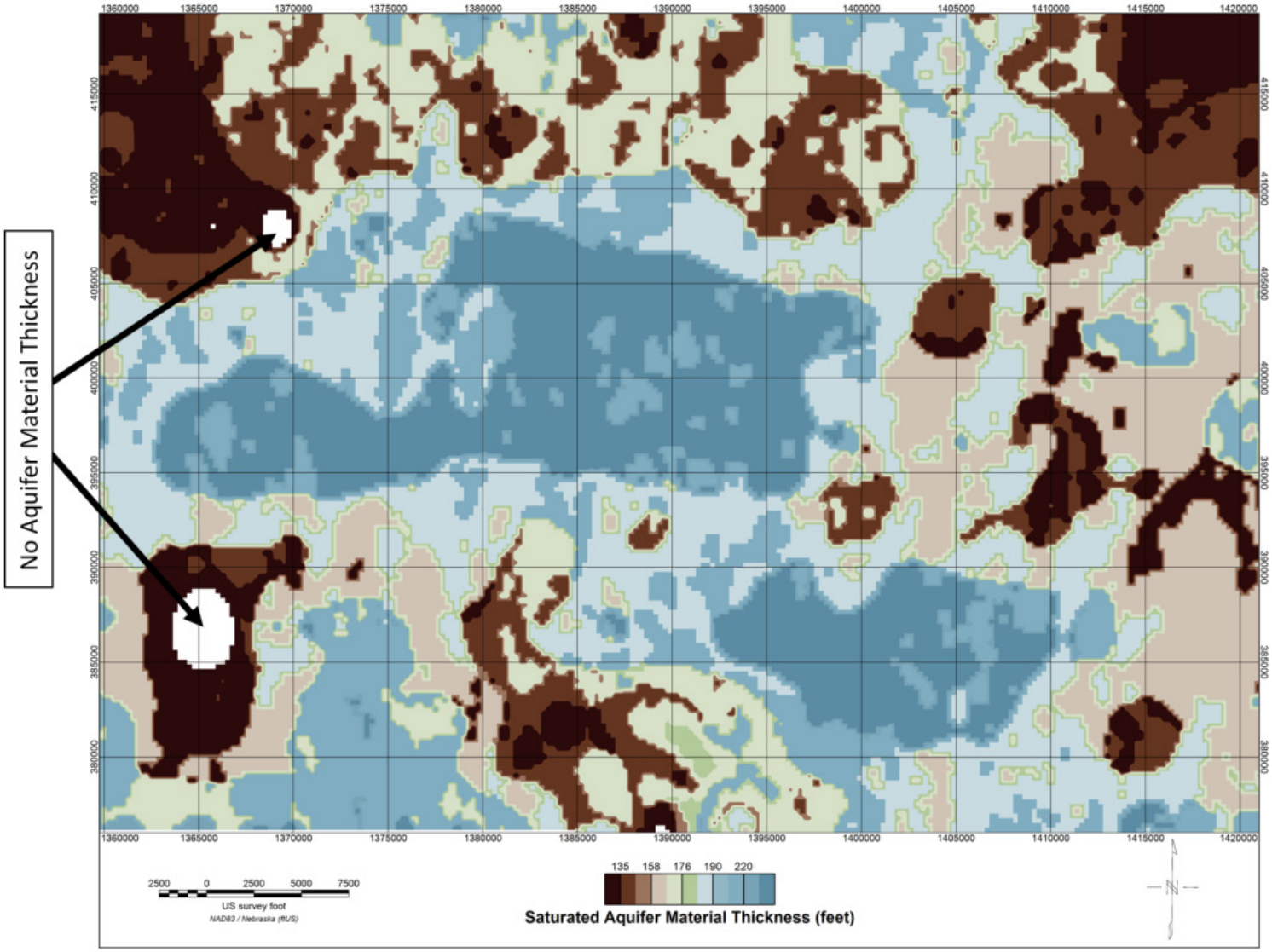



**Figure 5-51. This is a 2D surface map of the saturated aquifer material (>25 ohm-m) thickness (feet) which is composed of the Tertiary Ogallala Group (*To*). The thickness varies from 135 to 230 feet thick. Projection is NAD83, Nebraska State Plane Coordinate System, code 2600, feet.**

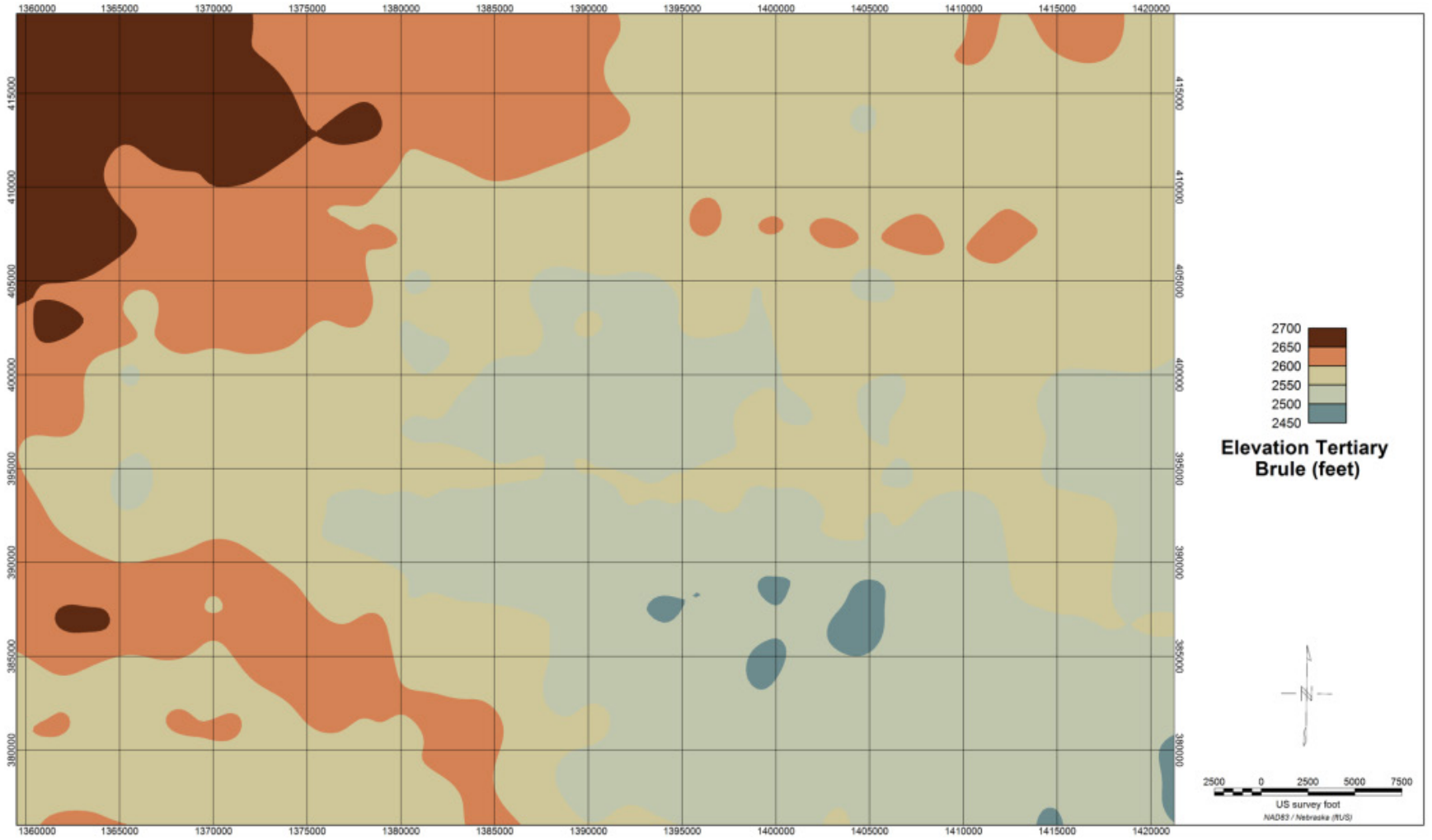



**Figure 5-52. This is a 2D surface map of the top of the Brule formation (*Tb*) which slopes approximately 250 feet from the northwest to the southeast. The top of the *Tb* is considered the base of aquifer in this area. Projection is NAD83, Nebraska State Plane Coordinate System, code 2600, feet.**

### *5.3.3 Hydrogeology of the CPNRD AEM Survey Area*

#### *5.3.3.1 The Quaternary Deposits*

The Quaternary deposits in the CPNRD consist of Quaternary alluvium (***Qa***) (mostly within the Platte River basin and tributaries within the AEM survey area), Quaternary eolian sand (**Qes**), and Quaternary Peoria loess (***Qp***) deposits. The ***Qa*** aquifer area of the CPNRD AEM survey area is predominantly composed of unconsolidated aquifer and coarse aquifer materials with areas of marginal aquifer and non-aquifer materials in the Platte River valley and along the tributaries. The alluvial sediments are thin, approximately 30 to 80 feet thick, and mostly saturated in the flood plain from the near surface down to top of the Tertiary Ogallala Group (***To***) (Figure 5-53). Most alluvial materials lie in the Platte River valley. The ***Qa*** overlies the ***To*** along the Platte River with the 2013 water table being shallow in this area. Figure 5-54 is a 3D fence diagram showing the distribution of the aquifer materials including non-aquifer, marginal aquifer, aquifer, and coarse aquifer materials which shows the heterogeneity of the ***Q*** and ***To*** deposits across the CPNRD AEM survey area. The bedrock units are also shown in the fence diagram. Note that the ***Tb*** bedrock exists only in the northwest part of the district (Figure 5-55) having been eroded off in the south and eastern part. The estimated water table (Korus et al., 2013b) generally slopes from west to east losing approximately 500 feet in elevation across the CPNRD AEM survey area with local direction of flow towards the Platte River (Figure 5-56). The ***Q*** thickness map (Figure 5-53) shows the nearly flat Platte River valley with thin ***Q*** thickness flanked north and south by the dissected nature of the thick ***Qp*** deposits.

The following is a discussion of selected profiles in the CPNRD AEM survey area featuring the ***Q*** system and its relationship to the ***To*** and the bedrock units. Profile L306602 is located west of Gothenburg, NE, where the ***Qa*** and ***Qp*** sediments lie upon the ***To*** (Figure 5-57). The ***Qa*** lies within the Platte River valley with the ***Qp*** flanking the valleys to the north and south. There are marginal aquifer materials in the near surface on the south side of the Platte valley which can restrict groundwater flow. There are also thick basal deposits above the ***Tb*** which limits the amount of water available to wells. Profile L512204 (Figure 5-58), west of Lexington, NE, where the ***Qa*** and ***Qp*** sediments lie upon the ***To***. There are marginal aquifer materials in the near surface on the south side of the Platte valley which can restrict groundwater flow. There are also thick basal deposits above the ***Tb*** which limits the amount of water available to wells. The ***Qa*** and ***Qp*** contains coarse aquifer, aquifer, marginal aquifer, and non-aquifer materials that are deposited above and within the Tertiary Ogallala Group (***To***), much of which is saturated and has a good groundwater-surface water connection except where near surface marginal aquifer materials are present. Profile L312802 (Figure 5-59), west of Kearney, NE, where the ***Qa***, a small area of ***Qes*** south of the Platte river, and ***Qp*** sediments lie upon the ***To***. The ***Q*** materials contain coarse aquifer, aquifer, marginal aquifer, and non-aquifer materials that are deposited above and within the Tertiary Ogallala Group (***To***), much of which is also saturated and has a good groundwater-surface water connection except where near surface marginal aquifer materials are present. Profile L409104 (Figure 5-60), is a west to east profile through the center of the CPNRD where the ***Qa*** and ***Qp*** sediments lie upon the ***To***. The relationships between the ***Q*** sediments and the ***To*** sediments are complex along every profile and it is best if the reader uses the appropriate profiles in the *Appendix 1- 2D Profiles* when looking for specific information on select areas in the CPNRD.

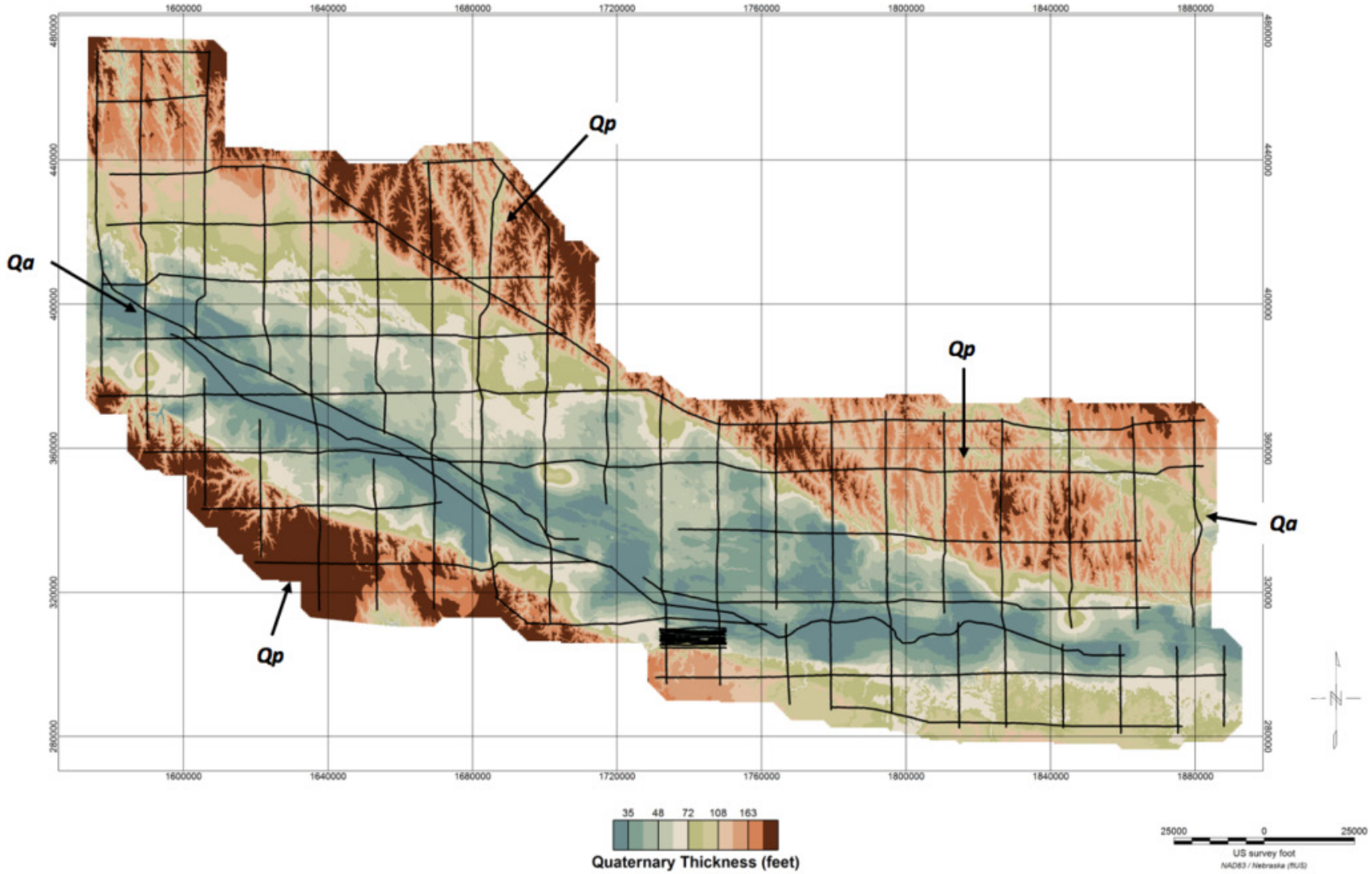



**Figure 5-53. This is a 2-D surface map of the thickness of the Quaternary in the CPNRD AEM survey area including Quaternary alluvium (*Qa*) and Quaternary Peoria loess (*Qp*) in feet. The *Q* materials (*Qa*) are thin in the Platte River valley and thicker on the flanks of the valley where there is *Qp*. There are also small areas of *Qes* in some areas of the CPNRD. Projection is NAD83, Nebraska State Plane Coordinate System, code 2600, feet.**

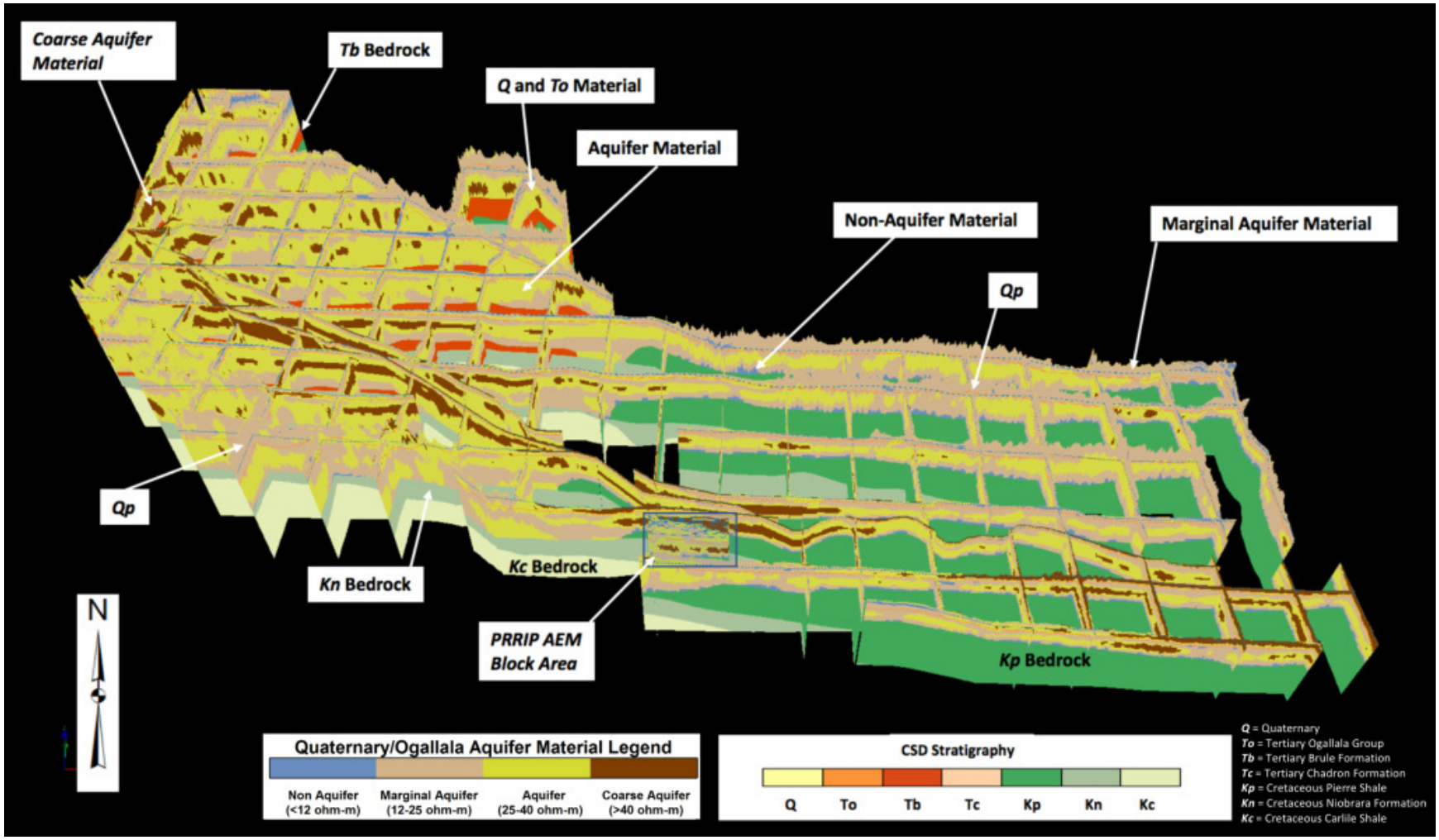



**Figure 5-54. 3D fence diagram looking to the north showing the CPNRD reconnaissance flight lines and interpreted distributions of aquifer material within the CPNRD AEM survey area. Geologic units include Quaternary (*Q*) deposits and the Tertiary Ogallala Group (*To*). The Tertiary Brule Formation (*Tb*), Cretaceous Pierre Shale Formation (*Kp*), Cretaceous Niobrara Formation (*Kn*), and the Cretaceous Carlile Shale (*Kc*) are aquicludes for the area. Vertical exaggeration is 30x. Projection is NAD83, Nebraska State Plane Coordinate System, code 2600, feet.**

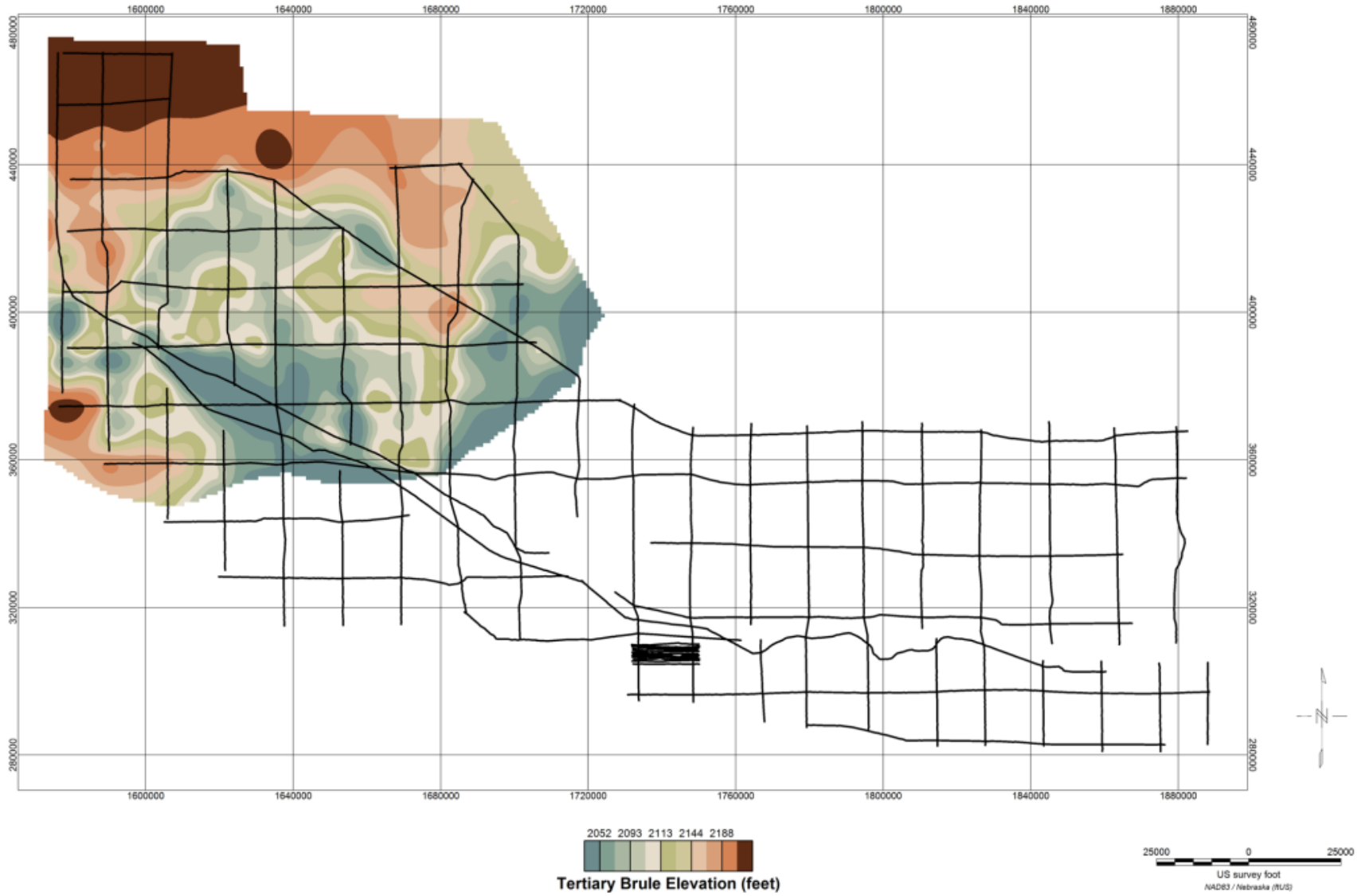



**Figure 5-55. This is a 2D surface map of the elevation of the top of the Tertiary Brule Formation (*Tb*) which only partially covers the CPNRD AEM survey area in the northwest corner. The top of the *Tb* is considered a base of aquifer for this area where it exists. Projection is NAD83, Nebraska State Plane Coordinate System, code 2600, feet.**

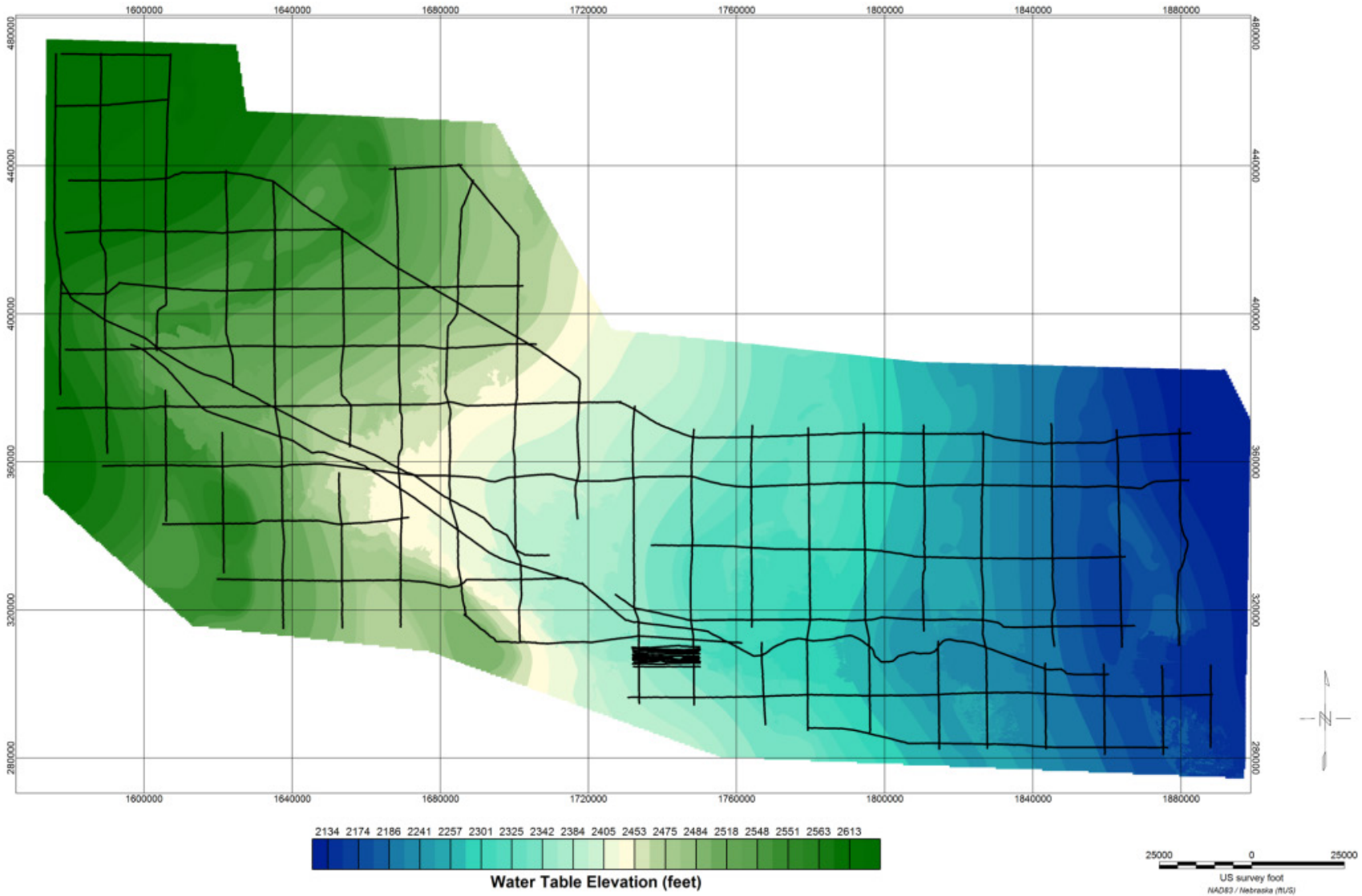



**Figure 5-56. This is a 2D surface map of the elevation of the water table (Korus et al., 2013b). Note that the surface slopes from northwest to southeast with localized flow direction towards the Platte River. There is approximately 500 feet of change across the area. Projection is NAD83, Nebraska State Plane Coordinate System, code 2600, feet.**

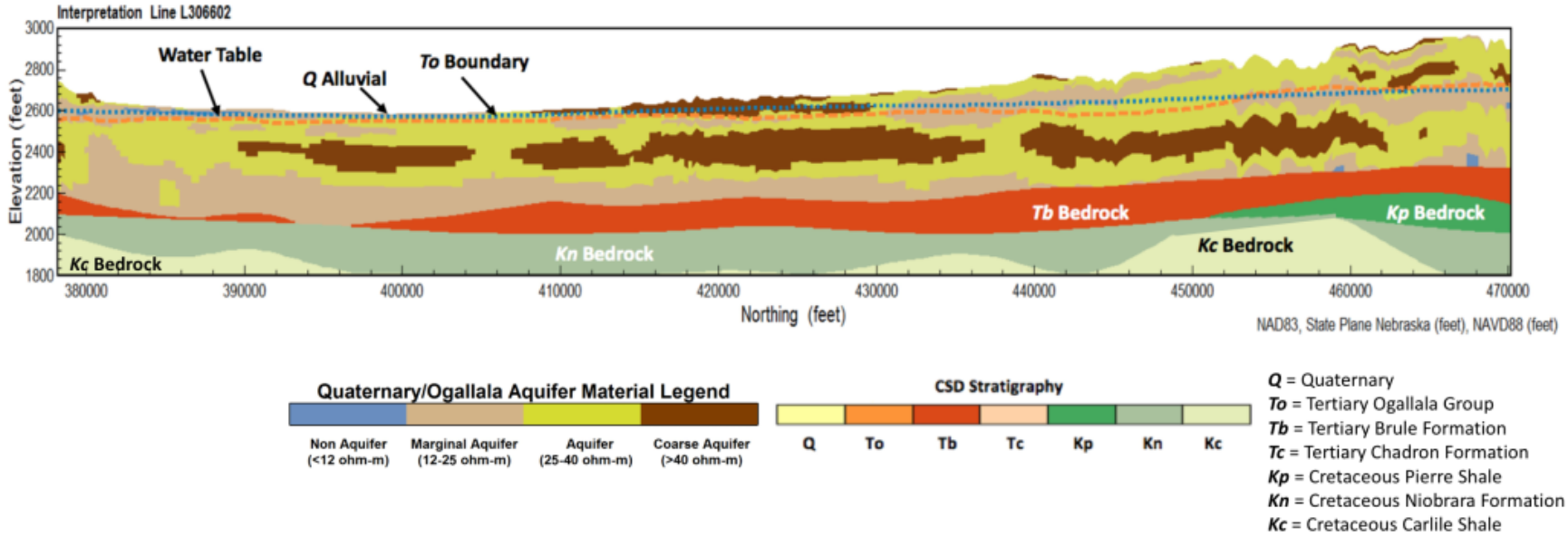



**Figure 5-57. Profile 306602 is a north-south flight line west of Gothenburg, NE and shows thin Quaternary alluvium (*Qa*) in the Platte River valley and thick Quaternary Peoria loess (*Qp*) deposits along the flanks of the river. The *Qa* and *Qp* contains coarse aquifer, aquifer, marginal aquifer, and non-aquifer materials that are deposited above and within the Tertiary Ogallala Group (*To*) much of which is saturated and has a good groundwater-surface water connection except where near surface marginal aquifer materials are present. The blue dashed line is the top of the water table and the orange dashed line is the top of the *To*. Projection is NAD83, Nebraska State Plane Coordinate System, code 2600, feet.**

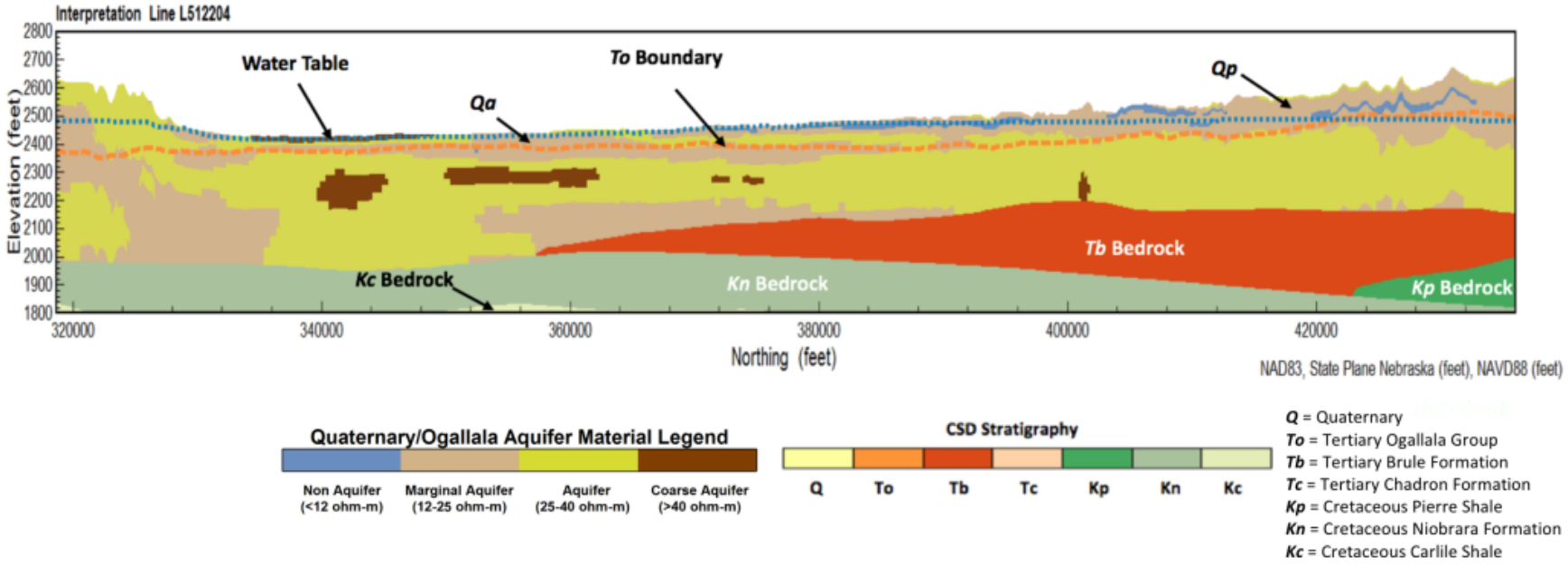



**Figure 5-58. Profile 512204 is a north-south flight line west of Lexington, NE and shows thin Quaternary alluvium (*Qa*) in the Platte River valley and thick Quaternary Peoria loess (*Qp*) deposits along the flanks of the river. The *Qa* and *Qp* contain coarse aquifer, aquifer, marginal aquifer, and non-aquifer materials that are deposited above and within the Tertiary Ogallala Group (*To*) much of which is saturated and has a good groundwater-surface water connection except where near surface marginal aquifer materials are present. The blue dashed line is the top of the water table and the orange dashed line is the top of the *To*. Projection is NAD83, Nebraska State Plane Coordinate System, code 2600, feet.**

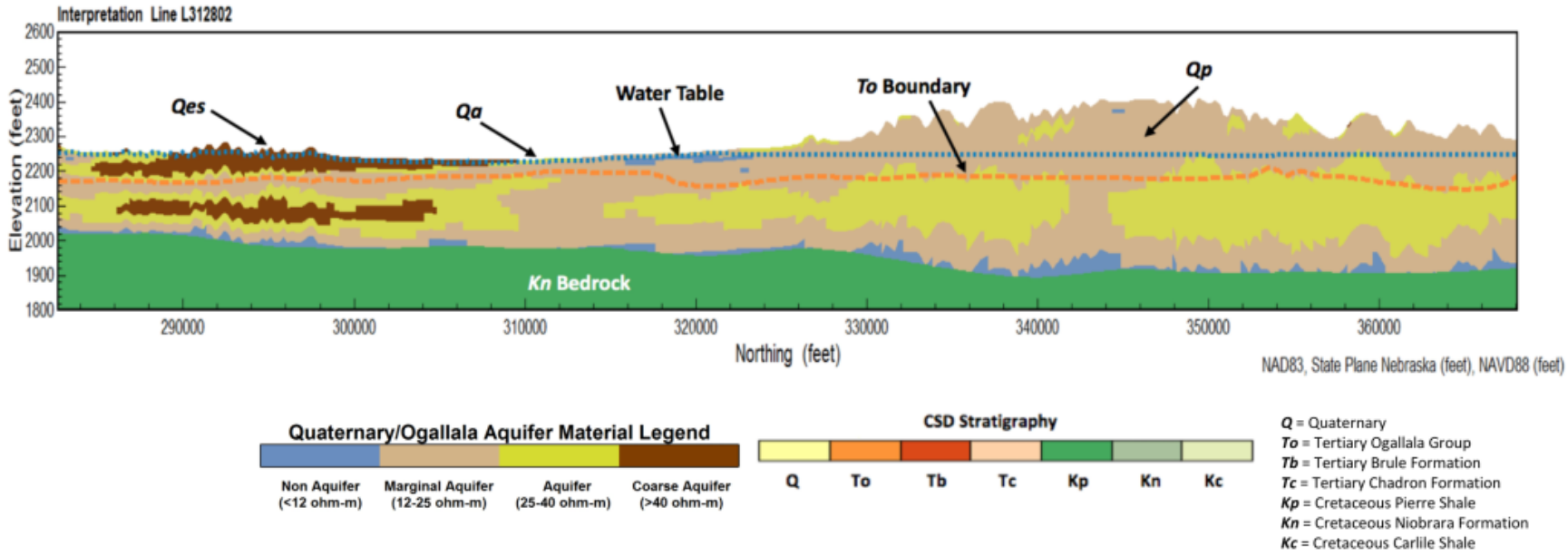



**Figure 5-59. Profile 312802 is a north-south flight line west of Kearney, NE and shows thin Quaternary alluvium (*Qa*) in the Platte River valley and thick Quaternary Peoria loess (*Qp*) deposits along the flanks of the river. The *Qa* and *Qp* contains coarse aquifer, aquifer, marginal aquifer, and non-aquifer materials that are deposited above and within the Tertiary Ogallala Group (*To*) much of which is saturated and has a good groundwater-surface water connection except where near surface marginal aquifer materials are present. The blue dashed line is the top of the water table and the orange dashed line is the top of the *To*. Projection is NAD83, Nebraska State Plane Coordinate System, code 2600, feet.**

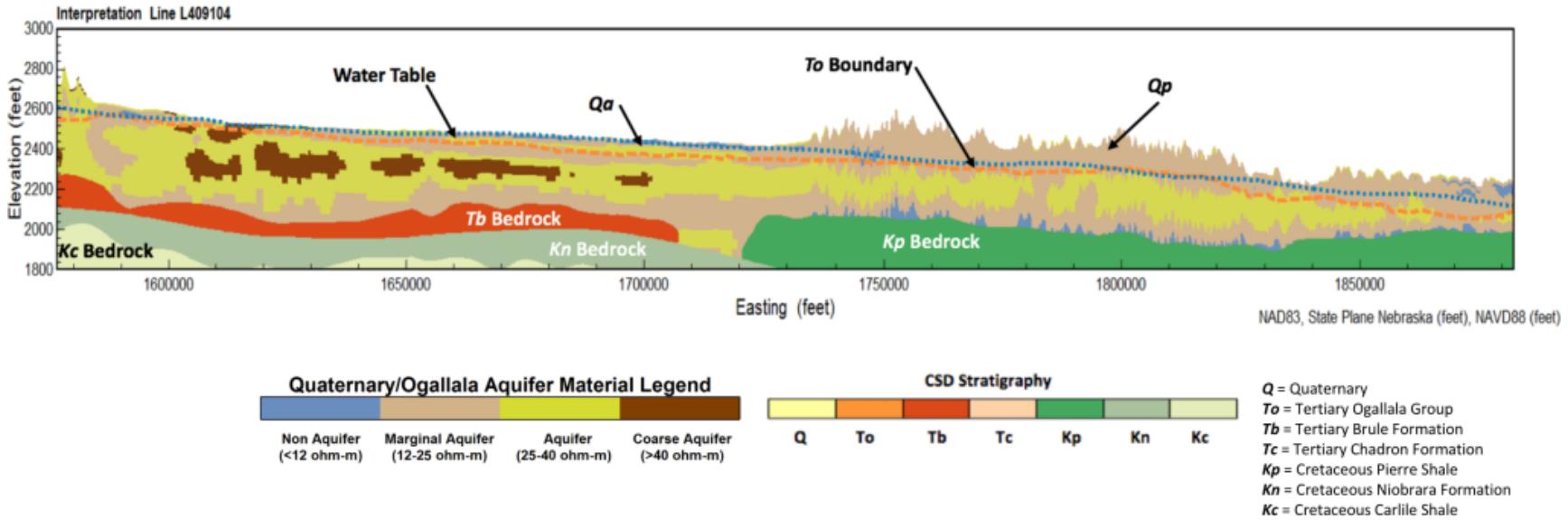



**Figure 5-60. Profile 409104 is a north-south flight line west of Kearney, NE and shows thin Quaternary alluvium (*Qa*) in the Platte River valley and thick Quaternary Peoria loess (*Qp*) deposits along the flanks of the river. The *Qa* and *Qp* contains coarse aquifer, aquifer, marginal aquifer, and non-aquifer materials that are deposited above and within the Tertiary Ogallala Group (*To*) much of which is saturated and has a good groundwater-surface water connection except where near surface marginal aquifer materials are present. The blue dashed line is the top of the water table and the orange dashed line is the top of the *To*. Projection is NAD83, Nebraska State Plane Coordinate System, code 2600, feet.**

The ***Qa*** is eroded into the surface of the ***To*** (Figure 5-61). There is a good groundwater-surface water connection between ***Q*** aquifer materials and the streams.

Due to the nature of the reconnaissance flight lines being widely spaced, greater detail of the distribution of the aquifer materials distribution can be achieved in this area with block flight-type surveys. A disadvantage of the reconnaissance lines and widely spaced block flight lines is that they have only identified deposits along the AEM flight line and the complete character of these deposits between the widely separated lines cannot be determined expediently without further AEM acquisition or exhaustive interpretation from added boreholes or other ground-based geophysical surveys.

#### *5.3.3.2 The Tertiary Ogallala Group*

The Tertiary Ogallala Group (***To***) is located throughout the survey area and is characterized by a combination of non-aquifer, marginal aquifer, aquifer, and coarse aquifer materials and together with the Quaternary (***Q***) materials is considered part of the aquifer of the area. The ***To*** Group is heterogeneous and is an important aquifer where saturated and the sediments are made up of aquifer and coarse aquifer material, that yield water to a well in quantity. It can also be hydrologically connected to the Quaternary aquifer and streams. The ***To*** non-aquifer and marginal aquifer materials are considered boundaries to groundwater flow both vertically and horizontally making the AEM derived maps valuable for groundwater modeling, particularly for stream depletion calculations and recharge area assessments. The ***To*** varies in thickness from 100 feet to over approximately 425 feet, which is shown in Figure 5-62. The thickest sections of the ***To*** are in the central west part of the CPNRD. Many of the profiles show the ***To*** in hydrologic connection to streams. There is a paleochannel developed in the ***Kp*** on the eastern part of the CPNRD area that is filled with ***To*** (Figure 5-63). The patterns that define the shape of present day ***To*** are related to erosion over many episodes of fluvial processes, structural control from the Chadron and Cambridge arches, and to recent erosion by the Platte River and its tributaries***.*** In Figure 5-62 the estimated location of a fault is indicated near Lexington and it is also indicated in profile L304802 (Figure 5-63). This fault displaces the ***Kp*** in relation to the ***Kn*** and ***Kc***, making ***Kn*** the bedrock on the west side of the fault and ***Kp*** the bedrock on the east side of the fault, This displacement also caused a thickening of the ***To*** on the west side of the fault with an increase in the amount of aquifer and coarse aquifer material. Further detailed work on the orientation, location, and offset of the fault will need to be done using detailed AEM survey blocks, seismic surveys, and drilling and logging.

Selection of drilling sites based on the greatest saturated ***To*** thickness improves the chances of a successful water supply. Thickness of the aquifer does not include the effect of partial cementation of the pore spaces of the ***To***, which would lead to lower yield and transmissivity. Where the ***Q*** and ***To*** aquifer and coarse aquifer materials are in contact is an area of good hydrologic connection. Due to the nature of the reconnaissance flight lines greater detail of the ***To*** materials distribution can be achieved in this area with increased numbers of flight lines similar to the block flight areas elsewhere in this project.

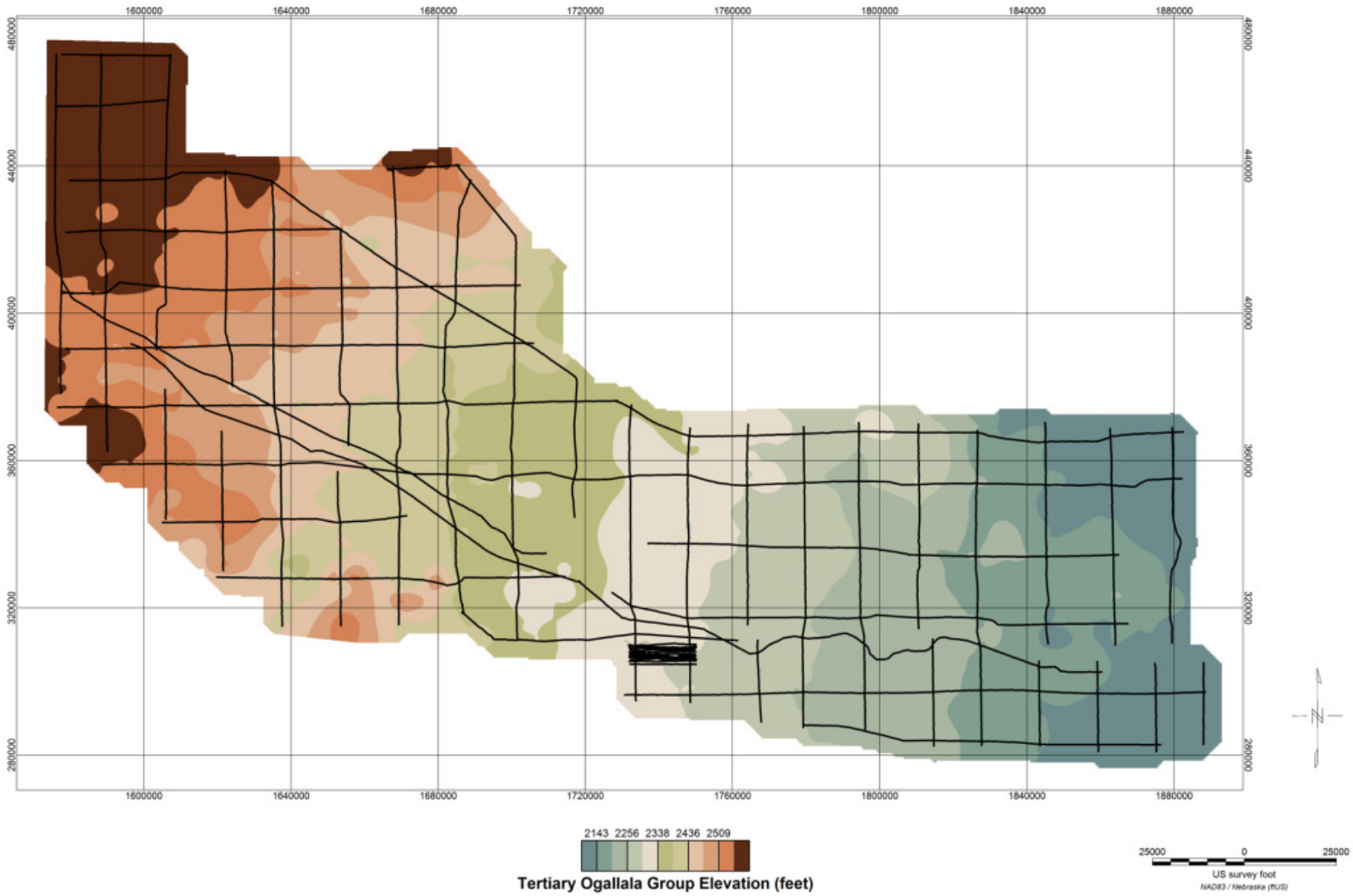



**Figure 5-61. This is a 2D surface map of the elevation (feet) of top of the Tertiary Ogallala Group (*To*). Note that the eroded surface of the top of the *To* is similar to the west to east trend of the Quaternary (*Qa*) deposits. Projection is NAD83, Nebraska State Plane Coordinate System, code 2600, feet.**

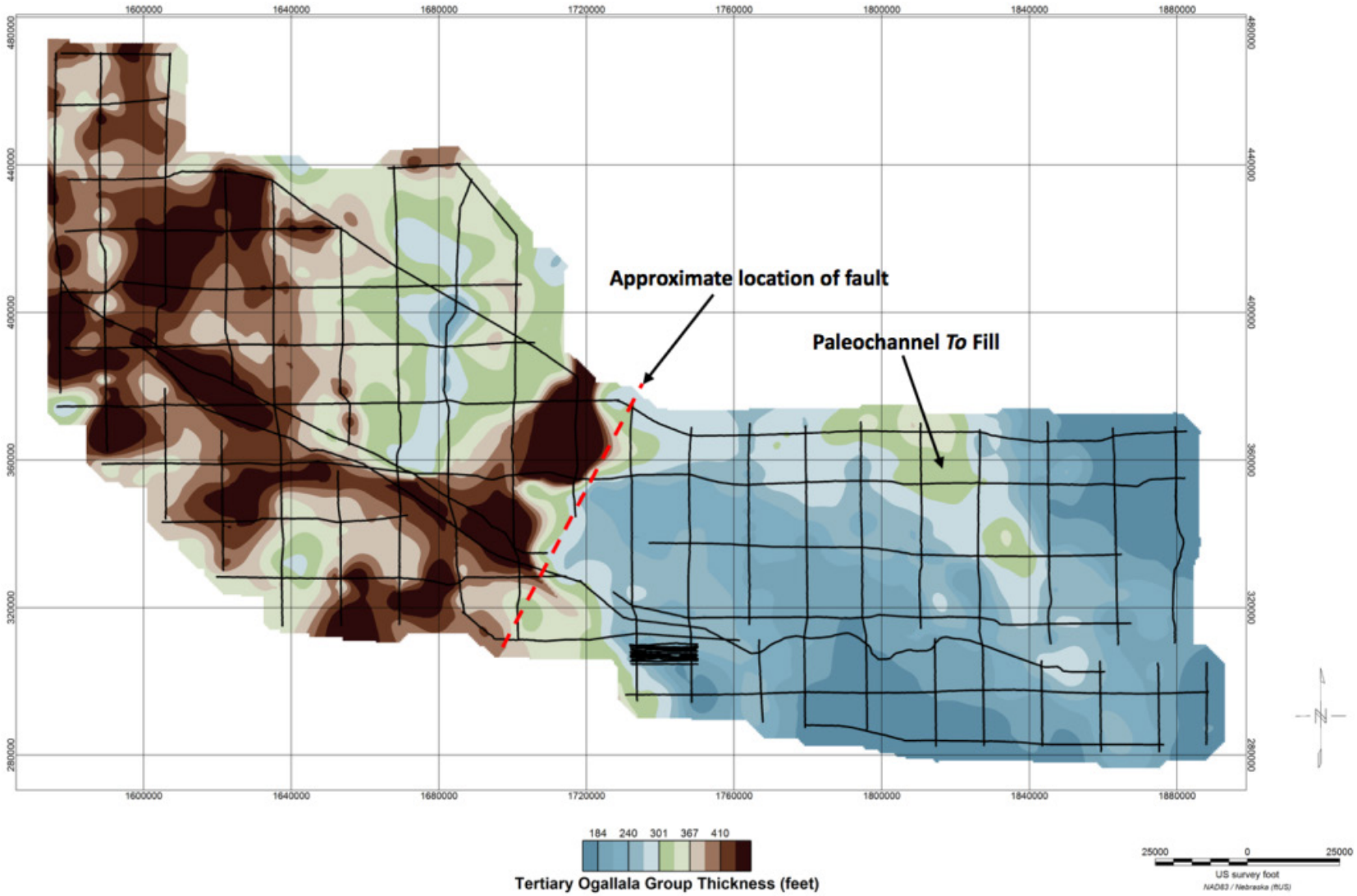



**Figure 5-62. 2D thickness map (in feet) of the Tertiary Ogallala Group (*To*). Note that the thickest areas of *To* are in the central west part of the CPNRD. Note the location of the interpreted fault which is a dashed red line. There is a paleochannel on the east side of the CPNRD AEM survey area that is filled with *To*. The irregular pattern is a result of the erosion and deposition of past and present fluvial systems. Projection is NAD83, Nebraska State Plane Coordinate System, code 2600, feet.**

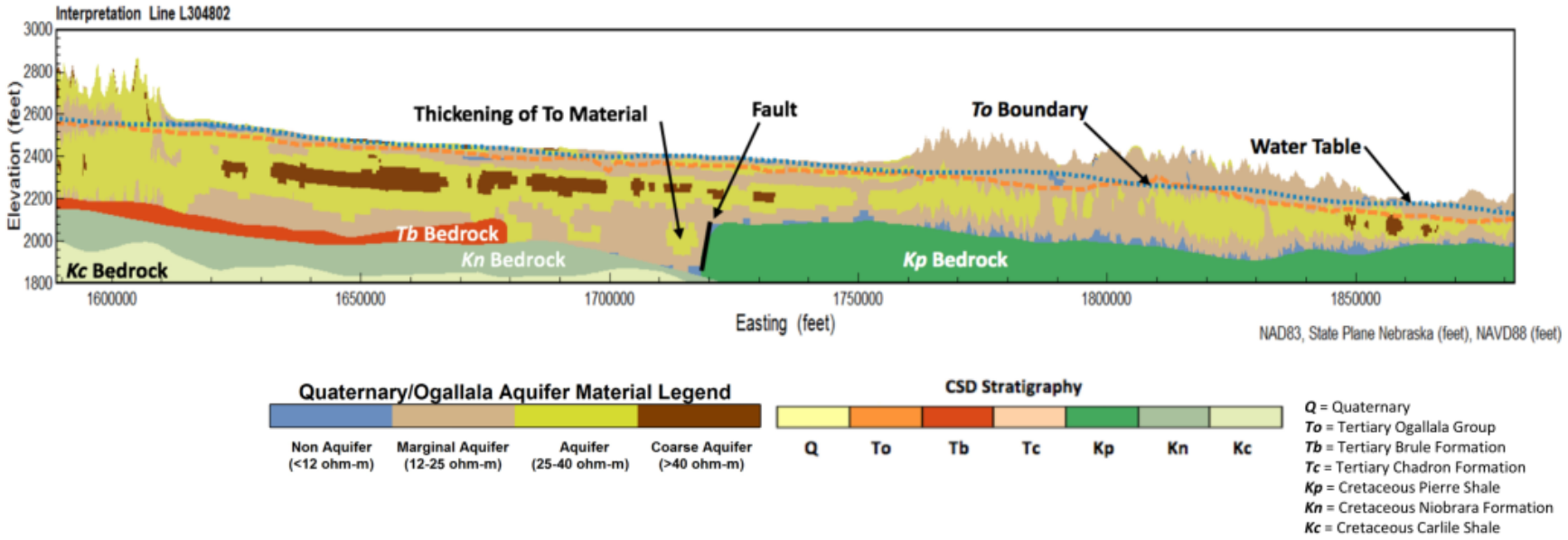



**Figure 5-63. Profile 304802 is a west to east flight line west of Kearney, NE that shows thin Quaternary alluvium (*Qa*) in the Platte River valley and thick Quaternary Peoria loess (*Qp*) deposits along the flanks of the river. The *Qa* and *Qp* contains coarse aquifer, aquifer, marginal aquifer, and non-aquifer materials that are deposited above and within the Tertiary Ogallala Group (*To*), much of which is saturated and has a good groundwater-surface water connection except where near surface marginal aquifer materials are present. Note the presence of an interpreted fault that offsets the Cretaceous Pierre Shale (*Kp*), the Cretaceous Niobrara (*Kn*), and the Cretaceous Carlile Shale (*Kc*). This fault results in thicker *To* on the west side than on the east side. Projection is NAD83, Nebraska State Plane Coordinate System, code 2600, feet.**

#### *5.3.3.3 The Tertiary Brule Formation and Cretaceous Pierre Shale, Niobrara Formation, and Carlile Shale*

The Tertiary Brule Formation (***Tb***) lies unconformably upon the Cretaceous Pierre Shale (***Kp***) and Cretaceous Niobrara Formation (***Kn***) in the CPNRD AEM area. The ***Tb*** dips nearly parallel to the Tertiary Ogallala Group (***To***) and the base of the Quaternary (***Q***) sediments and exists only in the northwest corner of the CPNRD AEM survey area. As mentioned earlier, the ***Tb*** bedrock is an aquiclude within the base of aquifer units for the CPNRD AEM survey area and the ***Tb*** surface is the result of the ***To*** eroding into the surface and being deposited upon it. The ***Kp***, ***Kn***, and ***Kc*** underlie the ***Tb*** in parts of the CPNRD AEM survey area. These units dip to the east on the east flank of the Cambridge Arch which is further discussed in Moore and Nelson (1974) (Figure 5-64). The highest elevations of the Cretaceous units are near the western end of the CPNRD, around the crest of the Cambridge Arch, and are outlined on the fence diagram in Figure 5-64. The Cretaceous units were eroded during the deposition of the ***Tb*** and ***To***. The surfaces of the ***Tb***, ***Kp***, ***Kn***, and ***Kc*** can be found in *Appendix 2\2D Surfaces*. The ***Kp*** is eroded off the crest of the Cambridge Arch and the ***Tb*** is eroded off to the east of the crest of the Cambridge Arch. The ***Kn*** is the BOA on the west side of the Arch with the ***To*** directly overlying the eroded ***Kn***.

### *5.3.4 Hydrogeology of the PRRIP AEM Survey Area*

The hydrogeology of the PRRIP block flight is shown in the 3D fence diagram in Figure 5-65. The area is covered by ***Qa*** deposits with some small areas of ***Qes*** along the south end of the block area. These deposits range from approximately 30 feet to over 100 feet thick (Figure 5-66). These deposits are important to understanding the near surface recharge to the aquifer which is made up of the ***Qa***, ***Qes***, and ***To***. The ***Qa*** and ***Qes*** lie unconformably upon the ***To*** which is present throughout the area. Figure 5-67 shows the saturated thickness of the aquifer in the block flight area which varies in thickness between 260 and 310 feet and contains all saturated materials. The PRRIP is interested the ***Qa***, ***Qes***, and ***To*** for installing a retention facility that is separated by a slurry wall that can store water separate from the groundwater surrounding the facility. In order to identify the best area in the PRRIP block flight area, inspection of the flight line profiles for the marginal and non-aquifer materials in the aquifer that will be a boundary condition for groundwater flow is necessary. Figure 5-68 presents profile L204501, oriented west to east, which shows the complex nature of the hydrogeology and the extent of the aquifer made up of the ***Qa*** and ***To*** materials that are bounded by thick marginal aquifer material. This would be a good area for the slurry wall as the depth to the marginal aquifer material boundary is near the ***To-Qes*** contact at approximately 80 feet below ground surface. Along the same profile, the near surface, approximately 10 feet below ground surface, has areas of aquifer and coarse aquifer material allowing good hydrologic connection to the aquifer. Figure 5-69 shows a 3D fence diagram with a blue-shaded polygon that outlines a layer of continuous marginal material down to a depth of approximately 80 feet that exists on each profile in the diagram. This is the area that should be explored for the location of the retention cell. Bedrock for this area is ***Kp*** which is an aquitard and a boundary to groundwater flow. Because of its greater depth below land surface it would not be a good base for construction of a slurry wall. Information on the amount of groundwater in storage and volume of potential unsaturated material is found in Section 5-4 for the PRRIP block flight area. A reconnaissance flight line down the Platte River from Gothenburg to just east of Odessa was flown to assess the ***Qa*** and ***To*** aquifer near the Platte River.

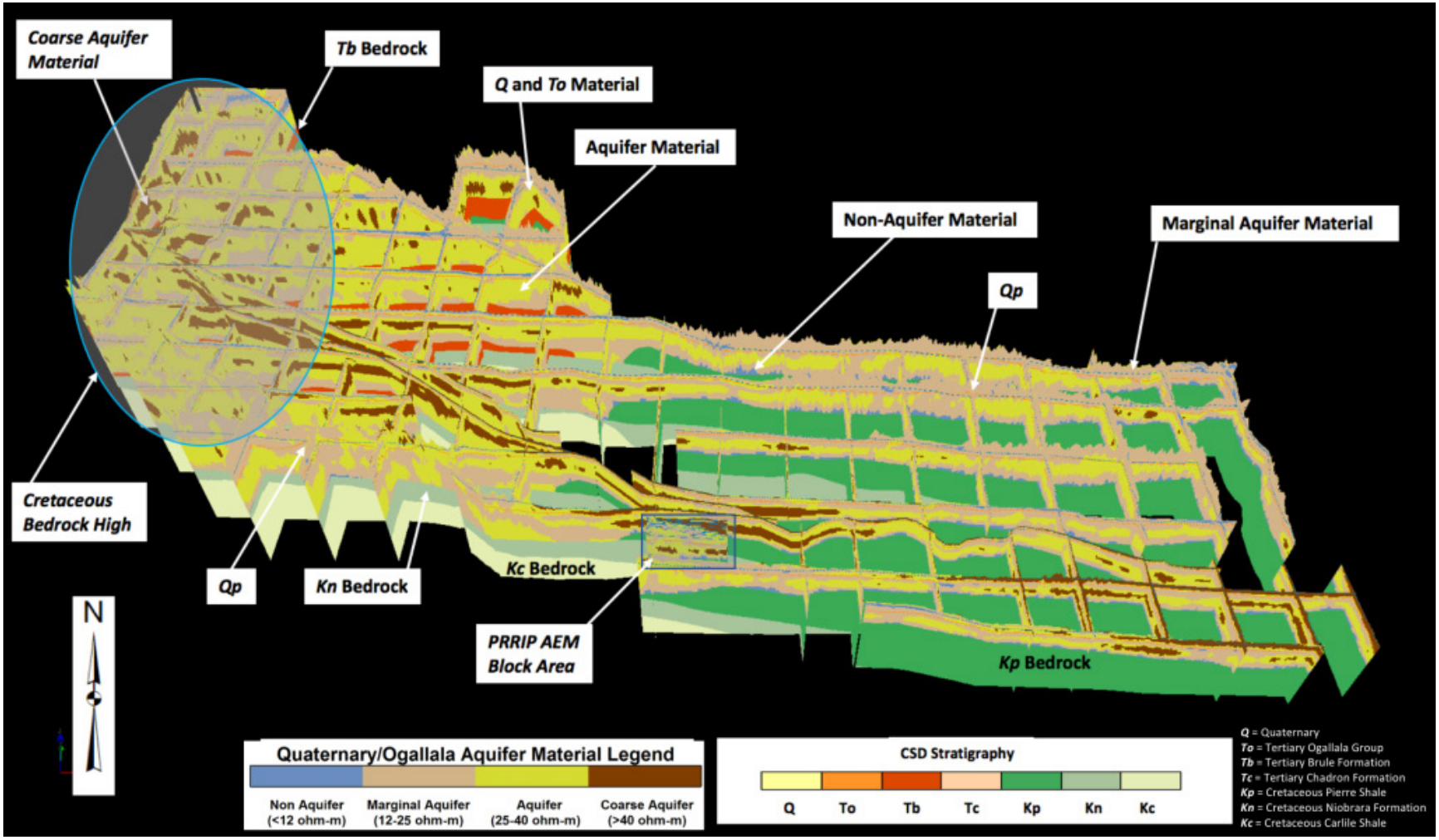



**Figure 5-64. 3D fence diagram looking north shows the Cretaceous Pierre Shale (*Kp*), Cretaceous Niobrara Formation (*Kn*), and Cretaceous Carlile Shale (*Kc*) dipping from the west end of CPNRD to the east due to the influence of the Cambridge Arch. The highest elevation of the Cretaceous units are highlighted by the light-colored oval on the map. These formations have been eroded by the Tertiary Brule Formation (*Tb*) which is identified by the red-orange layer and the Tertiary Ogallala Group (*To*) which is divided into aquifer materials on the 3D fence diagram and separated by an orange dashed line from the Quaternary (*Q*). Projection is NAD83, Nebraska State Plane Coordinate System, code 2600, feet.**

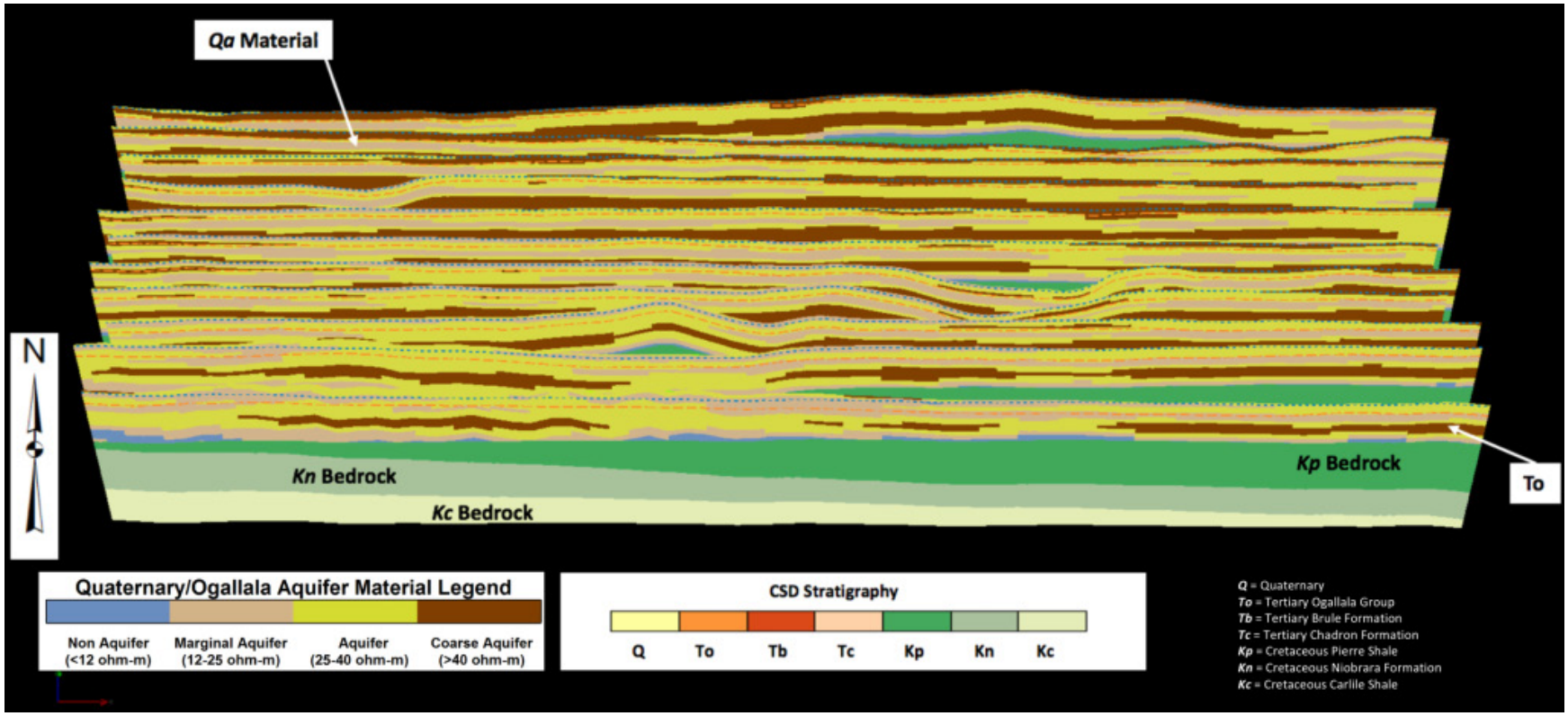



**Figure 5-65. 3D fence diagram showing the PRRIP block flight lines, looking to the north, showing distribution and thickness of Quaternary alluvium (*Qa*), Quaternary eolian sand (*Qes*) materials, and Tertiary Ogallala Group (*To*) materials lying on the Tertiary Brule Formation (*Tb*). The area has *Qes* material that is greater than 100 feet thick in some areas. The saturated *Qa*, *Qes*, and *To* material is the aquifer for the area. Vertical exaggeration is 3x. Projection is NAD83, Nebraska State Plane Coordinate System, code 2600, feet.**

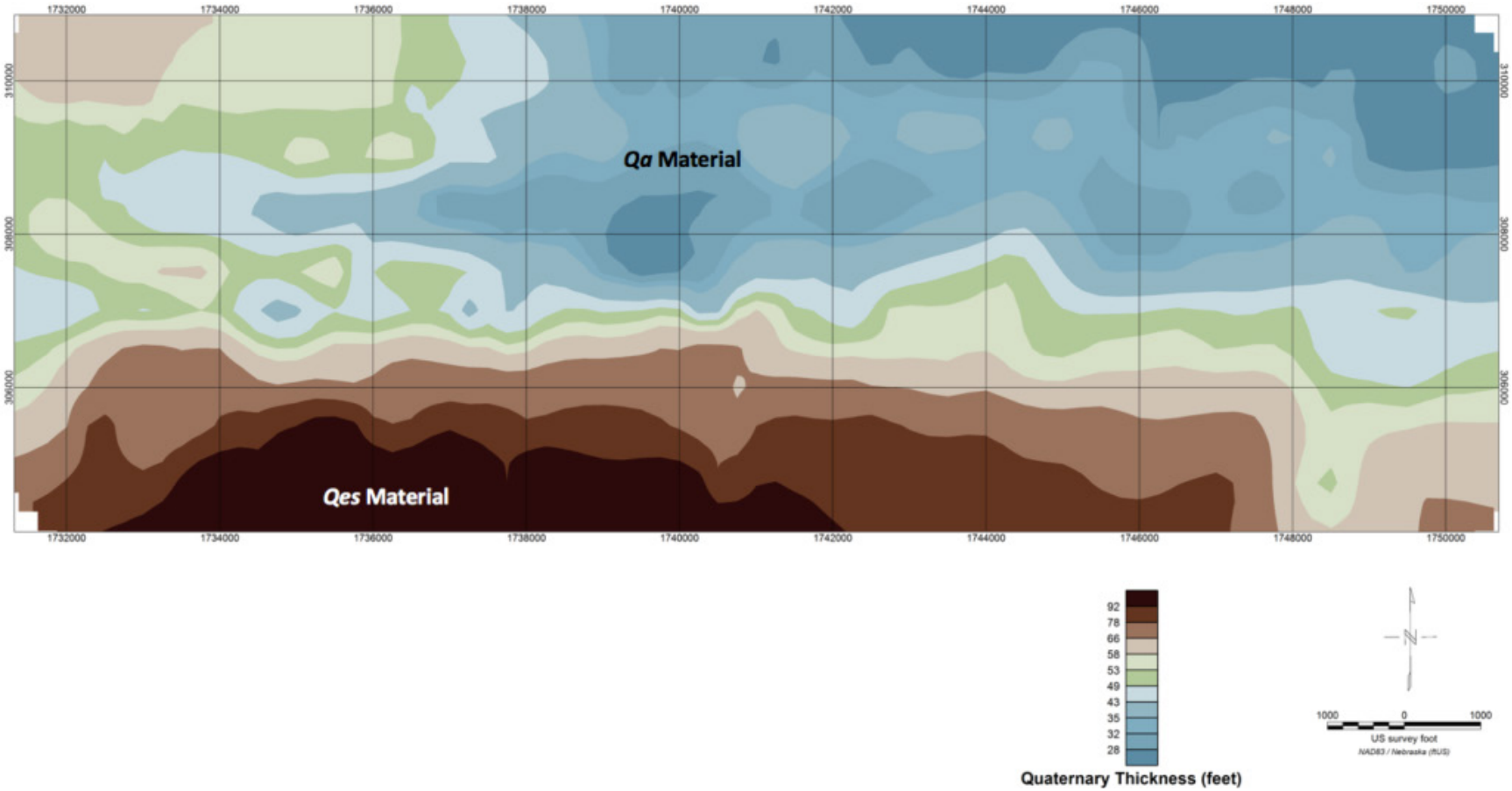



**Figure 5-66. This is a 2-D surface map of the thickness (feet) of the Quaternary (*Qa*). Note the thickest material is along the south end of the block where there is a deposit of Quaternary eolian sand (*Qes*). Projection is NAD83, Nebraska State Plane Coordinate System, code 2600, feet.**

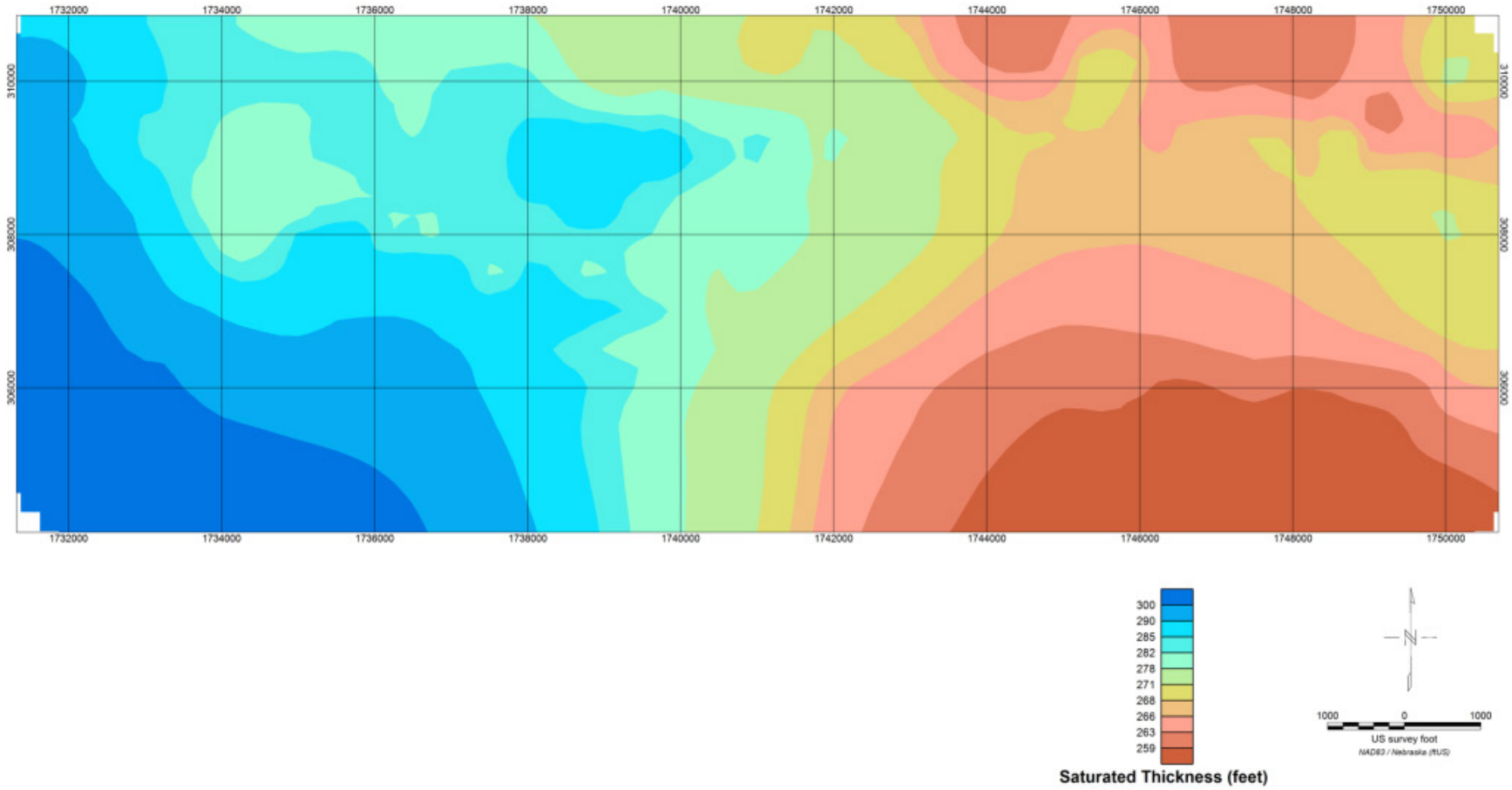



**Figure 5-67. This is a 2-D surface map of the saturated thickness of the aquifer in feet, including Quaternary alluvium (*Qa*), Quaternary eolian sand (*Qes*), and Tertiary Ogallala Group (*To*). The thickness varies from approximately 255 to 305 feet thick. Note that the thickest material is along the southwest end of the block flight area. Projection is NAD83, Nebraska State Plane Coordinate System, code 2600, feet.**

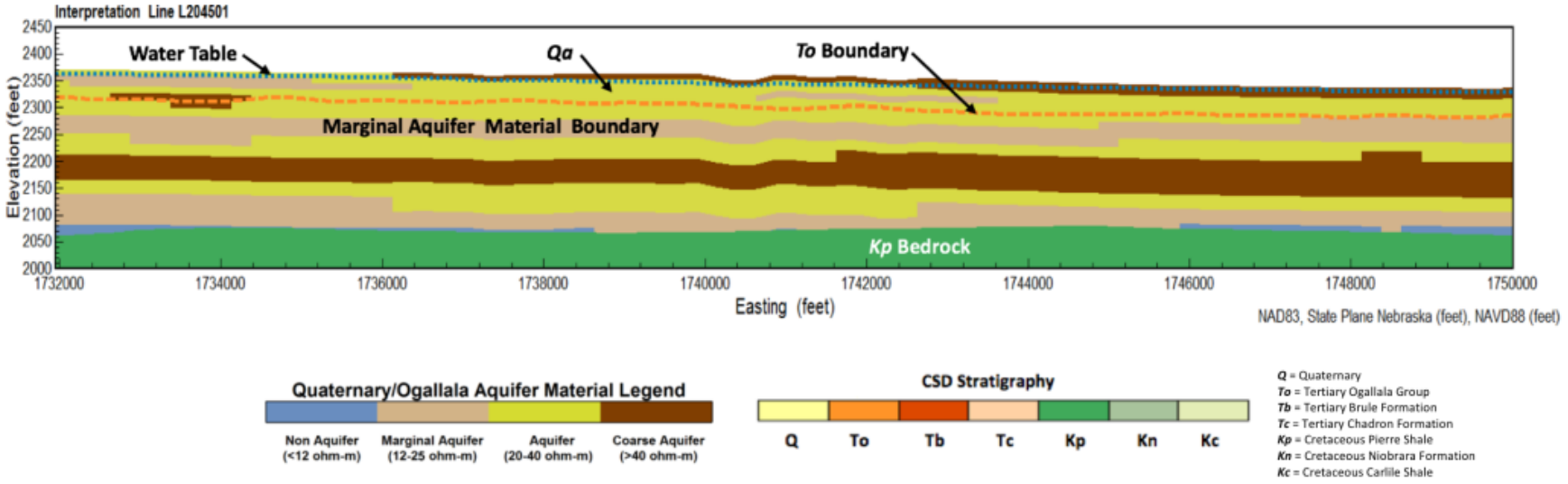



**Figure 5-68. Profile L204501 is a west to east profile in the PRRIP block and shows the thickness of the Quaternary alluvium (*Qa*) and Tertiary Ogallala Group (*To*) aquifer. This aquifer contains a mix of coarse aquifer, aquifer, marginal aquifer, and non-aquifer materials. Projection is NAD83, Nebraska State Plane Coordinate System, code 2600, feet.**

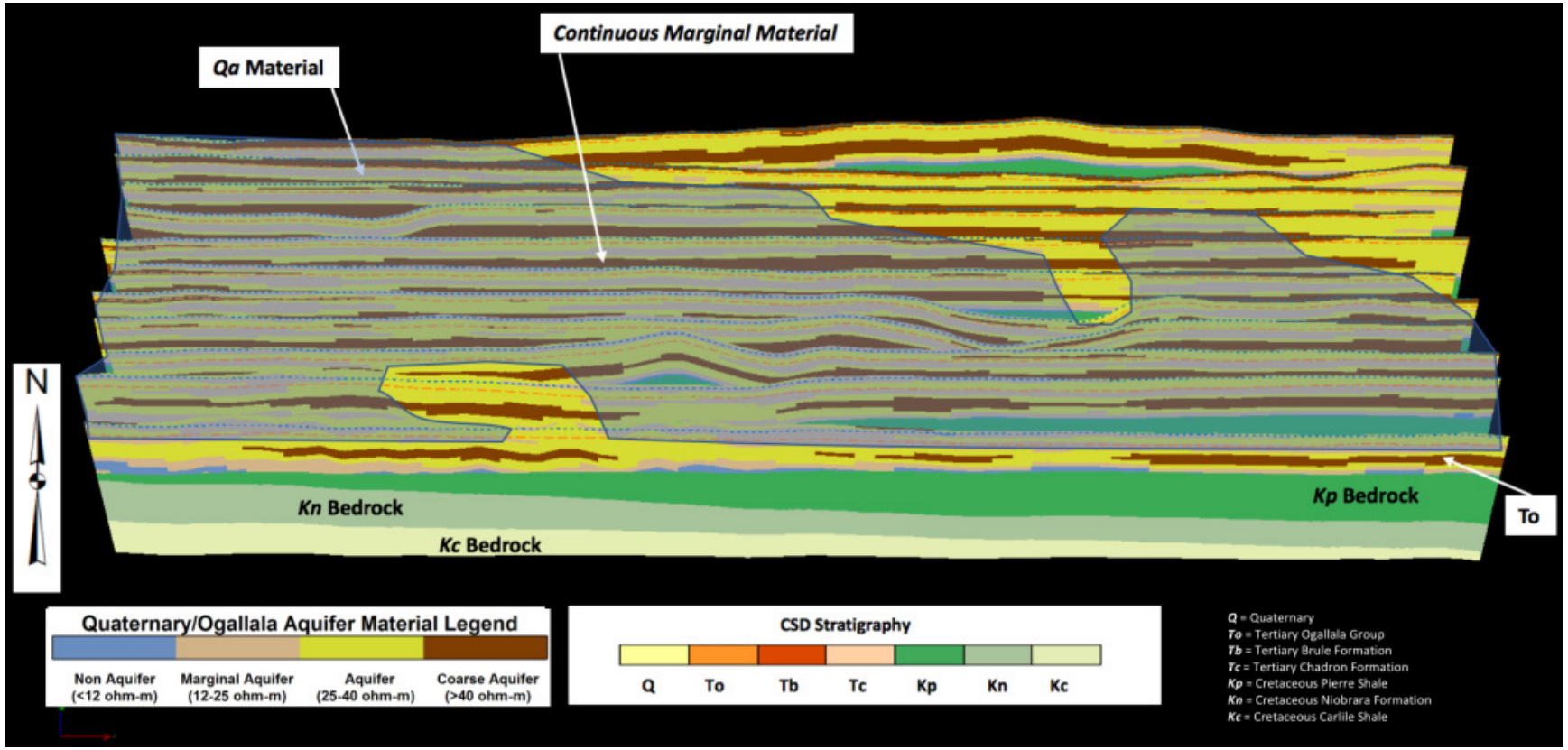



**Figure 5-69. 3D fence diagram of the PRRIP block flight lines, looking to the north, showing the distribution and thickness of the Quaternary alluvium (*Qa*), Quaternary eolian sand (*Qes*) materials, and Tertiary Ogallala Group (*To*) materials lying on the Tertiary Brule Formation (*Tb*). The blue-shaded polygon is drawn around a nearly continuous layer of marginal aquifer material that exists in each flight line at nearly the same elevation. Vertical exaggeration is 3x. Projection is NAD83, Nebraska State Plane Coordinate System, code 2600, feet.**

Figure 5-70, profile L203101, is the western side of this flight line and Figure 5-71, profile L203102, is the eastern side of this flight line. The upper surface of the ***To*** is very near the land surface as is the water table. Therefore the ***Qa*** is thin and saturated along the entire length of both profiles. There is a marginal aquifer material layer that is nearly continuous along both profiles near the upper surface of the ***To*** making this a barrier to groundwater flow. The rest of the ***To*** is a mix of non-aquifer, marginal aquifer, aquifer, and coarse aquifer material. There is a large amount of aquifer and coarse aquifer material in the ***To*** that is continuous and would make good locations for groundwater wells. There is likely a good hydrologic connection from the stream to the ***To*** in this area of the river. However, since this is but a single reconnaissance line, there are but a few openings identified of aquifer material that is continuous from the surface to the ***To***.

#### *5.3.4.1 Results of the Rapid Scanning Surface Nuclear Magnetic Resonance (NMR) Measurements at the Cook-Dyer Property*

Vista Clara, in partnership with Aqua Geo Frameworks, completed a pilot survey of shallow groundwater in central Nebraska using newly developed "Rapid Scanning Surface-NMR" (RS SNMR) technology. The surveys were conducted from July 24-28, 2017 on the Cook-Dyer property. The RS SNMR technology is based on the established geophysical method of surface-NMR, which has previously been applied in studies of the Central Platte groundwater system (Irons et al., 2012). The surface-NMR method allows direct detection of groundwater and aquifer properties from the surface using large wire loops.

Two perpendicular survey lines were completed over the course of approximately three-days at an average production rate of 200-250 ft/hr (Figure 5-72). Data quality was generally very good, however, some periodic gaps occurred in the data due to electromagnetic noise radiating from electric fences. The two primary perpendicular datasets were inverted to estimate water content and scaled hydraulic conductivity. The inverted results provide good imaging of the upper sand unit and the top of the underlying clay unit along the profile lengths. Overall, variability across the site was found to be minimal, though there was an indication that the sand unit thins to the south of the survey area and thickens to the north. Figure 5-73 show the inversion results for a sounding that shows a variable water content as a percent of volume (personal communication Elliot Grunewald, Chief Geophysicist, Vista Clara, Inc., December 1, 2017). The Cook-Dyer property contained several boreholes (personal communication, Kevin Werbylo, Water Resources Engineer, Headwaters Corporation, October 14, 2016) and had one of the 2016 AEM reconnaissance flight lines along the river. Figure 5-74 shows the 3D fence of the AEM and the boreholes in the area of the Cook-Dyer property.

The integration of the AEM survey results with SNMR soundings will be a valuable tool in the future. Figure 5-75 shows a voxel model coarse aquifer material only with the NE-DNR registered wells displayed and the fence diagram of the profiles showing all aquifer materials. Acquiring soundings at appropriate locations in the block aquifer, characteristics can be determined for the volumes of materials. Thus, the AEM results which are separated into non-aquifer, marginal aquifer, aquifer and coarse aquifer materials can be displayed as individual materials in a voxel similar to Figure 5-75 and the aquifer characteristics allied to that volume. The SNMR soundings provide a low cost non-invasive, repeatable way to capture aquifer properties in situ. The SNMR and Borehole NMR methods are proven technology that were partially developed in the CPNRD (Irons et al., 2012; Dlubac et al., 2013).

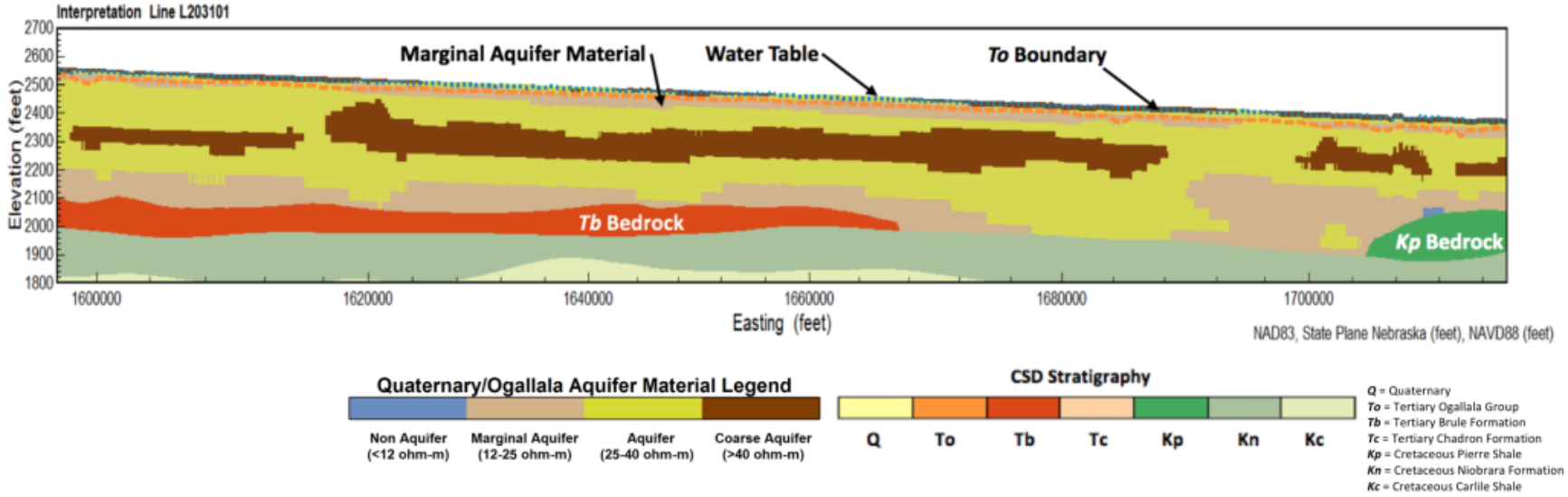



**Figure 5-70. Profile L203101 is the western side of the long reconnaissance line flown along the Platte River. The profile shows the thickness of the Quaternary alluvium (*Qa*) and Tertiary Ogallala Group (*To*) aquifer. This aquifer contains a mix of coarse aquifer, aquifer, marginal aquifer, and non-aquifer materials. Note the close to continuous layer of marginal aquifer material near the shallow *To* boundary that restricts recharge to the lower aquifer. Projection is NAD83, Nebraska State Plane Coordinate System, code 2600, feet.**

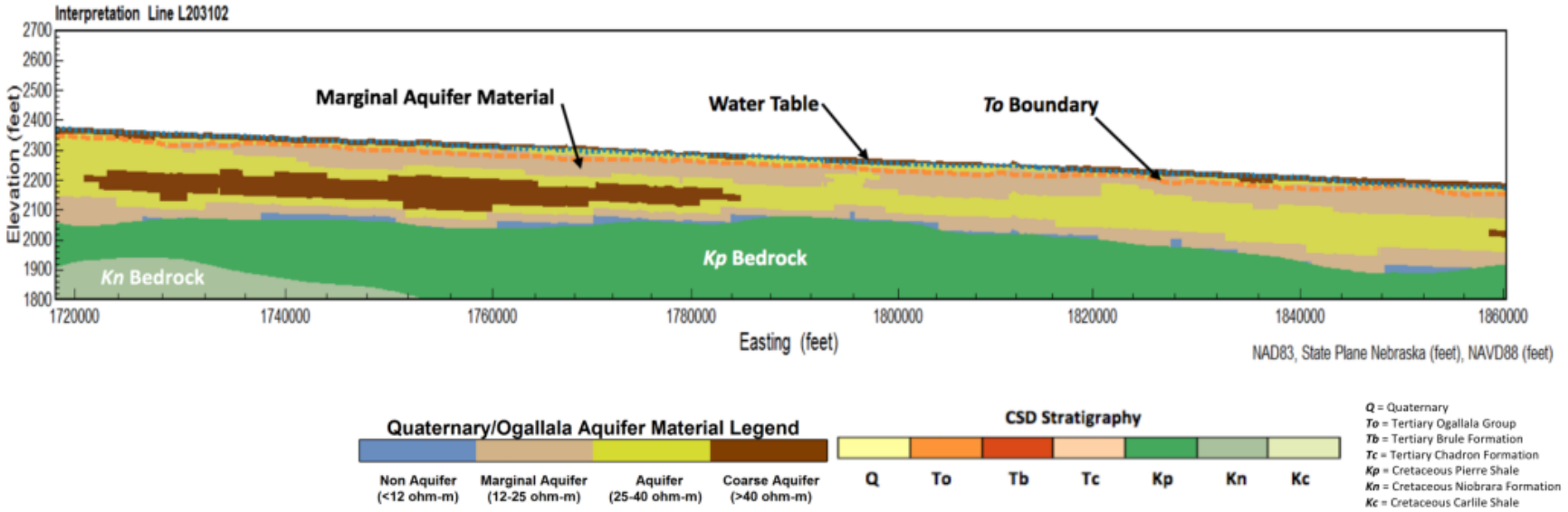



**Figure 5-71. Profile L203102 is the eastern side of the long reconnaissance line flown along the Platte River and shows the thickness of the Quaternary alluvium (*Qa*) and Tertiary Ogallala Group (*To*) aquifer. This aquifer contains a mix of coarse aquifer, aquifer, marginal aquifer, and non-aquifer materials. Note the almost continuous layer of marginal aquifer material near the shallow *To* boundary that restricts recharge to the lower aquifer. Projection is NAD83, Nebraska State Plane Coordinate System, code 2600, feet.**




**Figure 5-72. Location of the Rapid Scanning Surface-NMR" (RS SNMR) survey at the Cook-Dyer Property. Google Map of surface-NMR loop locations of lines for the north-south survey (16 stations – 800ft total distance) and east-west survey (25 stations – 1200 ft total distance).**

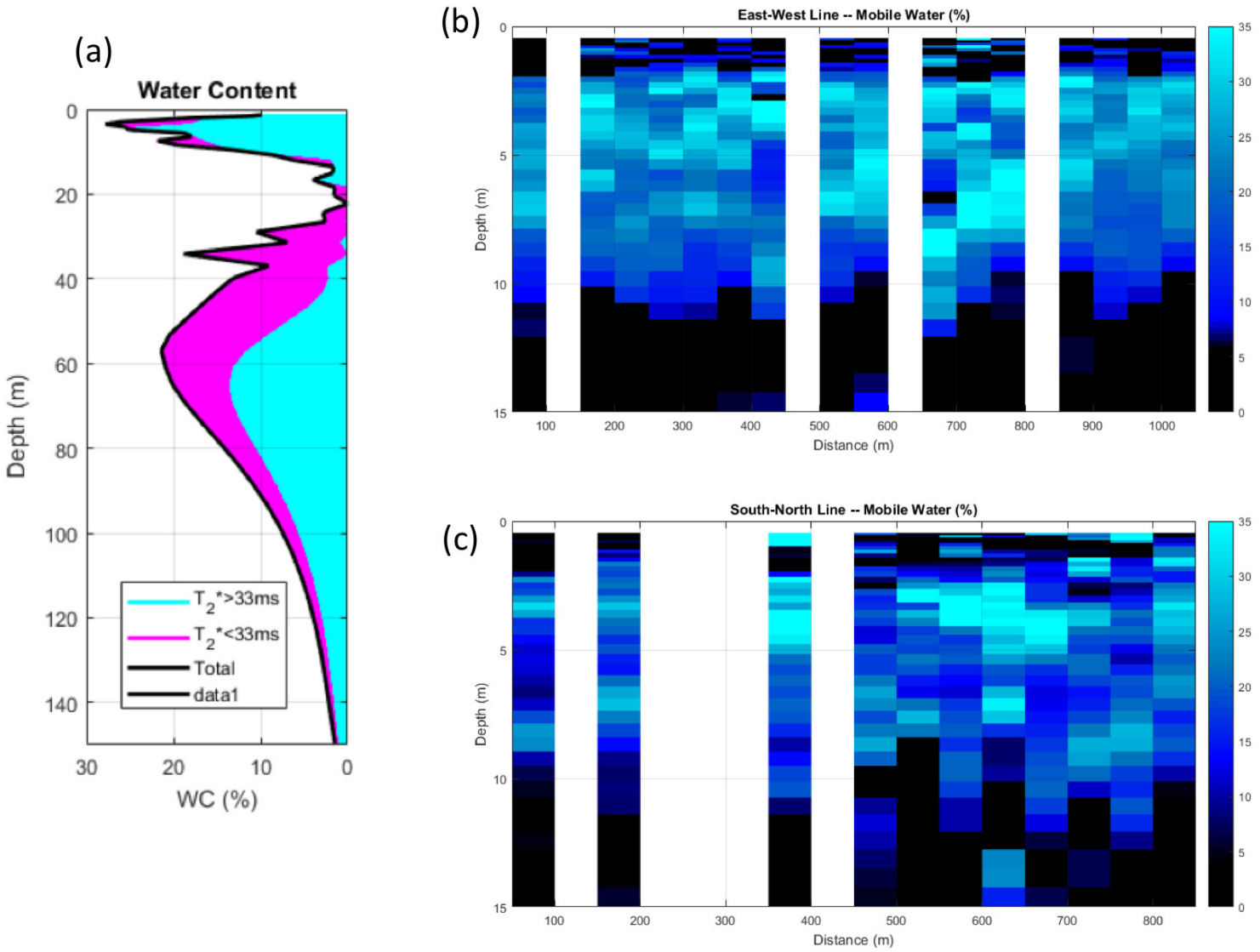



**Figure 5-73. RS SNMR inversion: (a) Inversion results for the deep stationary survey with water content; (b) east-west line mobile percent (%) water; (c) north-south line mobile percent (%) water (personal communication Elliot Grunewald, Chief Geophysicist, Vista Clara, Inc., December 1, 2017).**

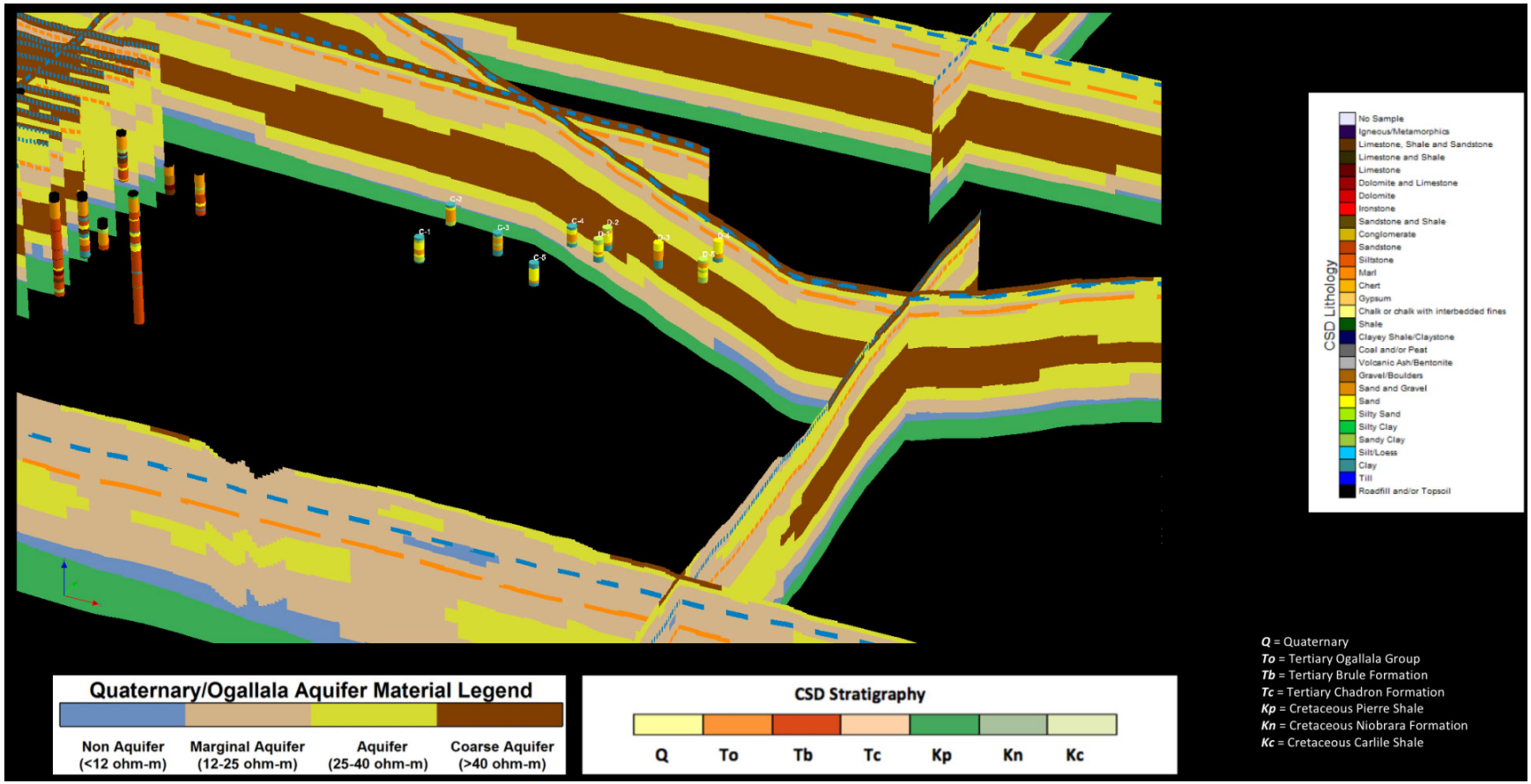



**Figure 5-74. 3D fence of the AEM and the boreholes in the area of the Cook-Dyer property. Boreholes are indicated by vertical tubes and the colors are indicated by the CSD lithology legend. The PRRIP Block can be seen immediately to the west (left side of figure) with the NE-DNR registered wells. Vertical exaggeration is 10x.**

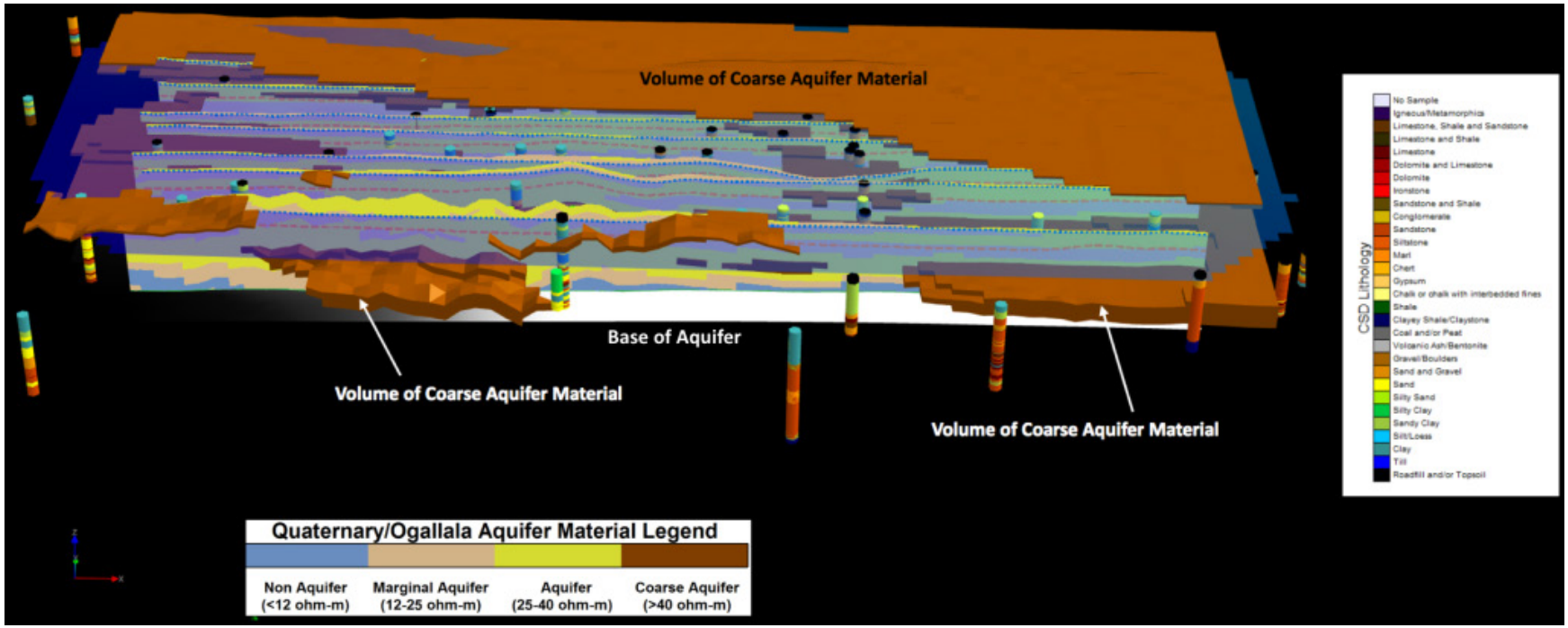



**Figure 5-75. 3D voxel model of the coarse aquifer material (>40 ohm-m) with NE-DNR registered wells (colors indicated by the CSD lithology legend) and a 3D fence diagram of the profiles showing all aquifer materials. The blue surface is the 2013 water table. Vertical exaggeration is 3x.**

## 5.4 Estimation of Aquifer Volume and Water in Storage for the TPNRD - CPNRD AEM Survey Areas

### *5.4.1 TPNRD AEM Survey Area (N-CORPE Block)*

A 3D representation of the subsurface derived from the AEM voxels provides users with the ability to more accurately identify the unsaturated and saturated aquifer volumes for the ***Q*** and ***To***. A block flight was flown for the N-CORPE area which is approximately 24 miles southwest of North Platte, Nebraska. (Figure 1-2). The saturated zones of the ***To*** materials can be analyzed to estimate the amount of groundwater in storage and the amount of extractable water present. The saturated ***To*** aquifer material volumes were calculated along with the amount of extractable water estimate; there were no saturated ***Q*** sediments. Analysis of the unsaturated ***Q*** and ***To*** aquifer materials can be used to determine the availability of the potential volume of material that can be used for storage via future managed aquifer recharge (MAR) or aquifer storage and recovery (ASR) activities.

The criteria for determining the basis for the range of resistivity values used in calculating the volumes of interpreted aquifer material are provided in Section 5.2. The resistivity ranges for interpreted ***Q*** and ***To*** non-aquifer (<12 ohm-m), marginal aquifer (12-25 ohm-m), aquifer (25-40 ohm-m), and coarse aquifer materials (>40 ohm-m) are presented in Figure 5-18. Individual fence diagrams that show the ***Q*** and the saturated ***To*** aquifer and coarse aquifer materials were presented in Section 5.3. These figures illustrate the complex nature and interconnections between the saturated ***Q*** and ***To*** materials of the area. They show how these aquifers can change in extent, both vertically and horizontally. Note that the profiles in the figures were created in Datamine Discover PA, version 2015, Release Build 15.0.13 (DatamineDiscover, 2017). They can be examined in greater detail by opening the PA sessions provided in Appendix 3-Deliverables\PA Sessions.

All aquifer materials within the ***To*** sediments, including non-aquifer material, marginal aquifer material, aquifer material, and coarse aquifer material are used for calculating the groundwater in storage volume and the extractable water volumes for the survey area. Reported values of the average porosity for sand making up the aquifer material and sand and gravel making up coarse aquifer material are based on values from Freeze and Cherry (1979). Clay ranges from 40%-70%, silt ranges from 35%-50%, sand ranges from 25%-50%, and gravel is from 25%-40%. Conservative estimates for the porosity values used in these calculations within the survey area are 40% for non-aquifer material, 35% for marginal aquifer material, 20% for the aquifer material, and 25% for the coarse aquifer material.

Understanding this complexity in the AEM survey area and within the sedimentary deposits shows that estimated average values for porosity and specific yield are the best values to use in making volume and groundwater storage calculations. While nuclear magnetic resonance (NMR) surveys and aquifer tests were completed in the AEM survey area (Irons et al, 2012), they are point sources in nature. So, it is best to use published results for porosity and specific yield. Section 2 of this report presented a list of aquifer tests completed in the TPNRD and CPNRD project area. Specific yield values for all ***Q*** and ***To*** aquifer materials were selected by estimating the values from these aquifer test results. Specific yield for non-aquifer materials was selected to be 0.02 (Heath, 1983) and for marginal aquifer materials a value of

0.05 was selected (Heath, 1983). The specific yield for the aquifer material which makes up the bulk of the saturated aquifer materials present is 0.22 (Heath, 1983). While coarse aquifer materials exist as localized deposits in the survey area, estimates of specific yield for the coarse aquifer material is 0.19 (Heath, 1983). Specific yield maps of the area would be improved if new maps were produced using this new AEM survey information plus the addition of aquifer tests or other methods of gaining new data including NMR surveys to capture aquifer characteristics.

Maps of saturated and unsaturated aquifer material thickness (>25 ohm-m) in the N-CORPE AEM survey area have been developed. Figure 5-76 presents the saturated aquifer thickness of ***To*** in the N-CORPE AEM block survey area. The saturated ***To*** is thickest in the northwest and northeast corners of the N-CORPE survey area.

From the data used to develop this map, volumetric tables have been developed for the N-CORPE AEM block flight area for saturated ***To*** aquifer materials and the unsaturated ***Q*** and ***To***. Table 5-3 presents the results of the analysis for groundwater in storage calculated by multiplying the volume of all aquifer materials below and above the water table by the estimated porosity. For the saturated ***To***, the non-aquifer material has an estimated aquifer volume of **8,881** acre-ft and contains **3,502** acre-ft of groundwater in storage. Marginal aquifer material has an estimated aquifer volume of **2,717,596** acre-ft and contains **951,158** acre-ft groundwater in storage and aquifer material has an estimated aquifer volume of **10,000,775** acre-ft and contains an estimated volume of **2,000,155** acre-ft of groundwater in storage. Coarse aquifer material has an estimated aquifer volume of **773,302** acre-ft and contains an estimated volume of **193,325** acre-ft of groundwater in storage. The amount of groundwater in storage for all material groups is **3,148,190** acre-ft.

The estimate of extractable volume of water is calculated by taking the amount of groundwater in storage times the specific yield. Non-aquifer materials in the N-CORPE AEM block flight area will yield approximately **71** acre-ft, marginal aquifer materials will yield approximately **47,557** acre-ft, aquifer materials will yield **440,034** acre-ft, and coarse aquifer materials will yield approximately **36,731** acre-ft. A total of **524,393** acre-ft is available from the combined aquifer materials.

These estimates and the estimates that follow are based on “The Groundwater Atlas of Nebraska, third revised edition” (Korus et al, 2013b) water table map. This map is very general in nature with a 75-foot contour interval, making assumptions of the actual water level in any location less accurate. Also, these volumetric estimates consider only the volume of water assumed to be in the pore spaces of the aquifer material defined by the resistivity threshold levels and do not account for possible “confined or semi-confined” water under pressure (head above the aquifer). This volume of water would add to the values reported in Table 5-3. However, too much uncertainty exists in developing an average level of head above the top of the aquifer across the entire project area, as well as defining a representative storativity term for the confined or semi-confined aquifers. Thus, the volumes listed in Table 5-3 are conservative estimates and the amounts released from the decline in pressure are not considered.

It should be noted that all values are very conservative in nature and are estimates based on published values for porosity and specific yield. The actual amount of extractable water will vary due to many

things such as sediment grain size, sorting, cementation and other considerations. Actual values determined from additional field measurements and analysis of the various sediment packages in the ***To*** would greatly help the estimates of groundwater in storage and extractable water volume.

A map of unsaturated ***Q*** aquifer material (>25 ohm-m) in the N-CORPE AEM survey area is presented in Figure 5-77. Figure 5-78 presents the unsaturated ***To*** aquifer material (>25 ohm-m) in the N-CORPE survey area. The values for the unsaturated (volume of material above the water table) ***Q*** and ***To*** are listed in Table 5-4. These calculations for the unsaturated materials can be used for estimating potential MAR for the N-CORPE block area. They show the non-aquifer material has an estimated aquifer volume of **141** acre-ft and could contain **56** acre-ft of groundwater in storage and the marginal aquifer material has an estimated aquifer volume of **6,055,444** acre-ft and could contain **2,119,405** acre-ft groundwater in storage. Aquifer material has an estimated aquifer volume of **6,276,522** acre-ft and could contain an estimated volume of **1,255,304** acre-ft of groundwater in storage and the coarse aquifer material has an estimated aquifer volume of **169,302** acre-ft and could contain an estimated volume of **42,325** acre-ft of groundwater in storage. The amount of potential groundwater storage for all material groups if they become saturated is **3,417,090** acre-ft.

The estimate of extractable volume of water, if saturated, is calculated by taking the amount of potential groundwater in storage times the specific yield. Non-aquifer materials in the N-CORPE block flight area could yield approximately **1** acre-ft, marginal aquifer materials could yield approximately **105,970** acre-ft, and aquifer materials could yield **276,166** acre-ft. Coarse aquifer materials could yield **8,041** acre-ft. A total of **390,178** acre-ft is available from the combined aquifer materials for potential withdrawal if they become saturated.

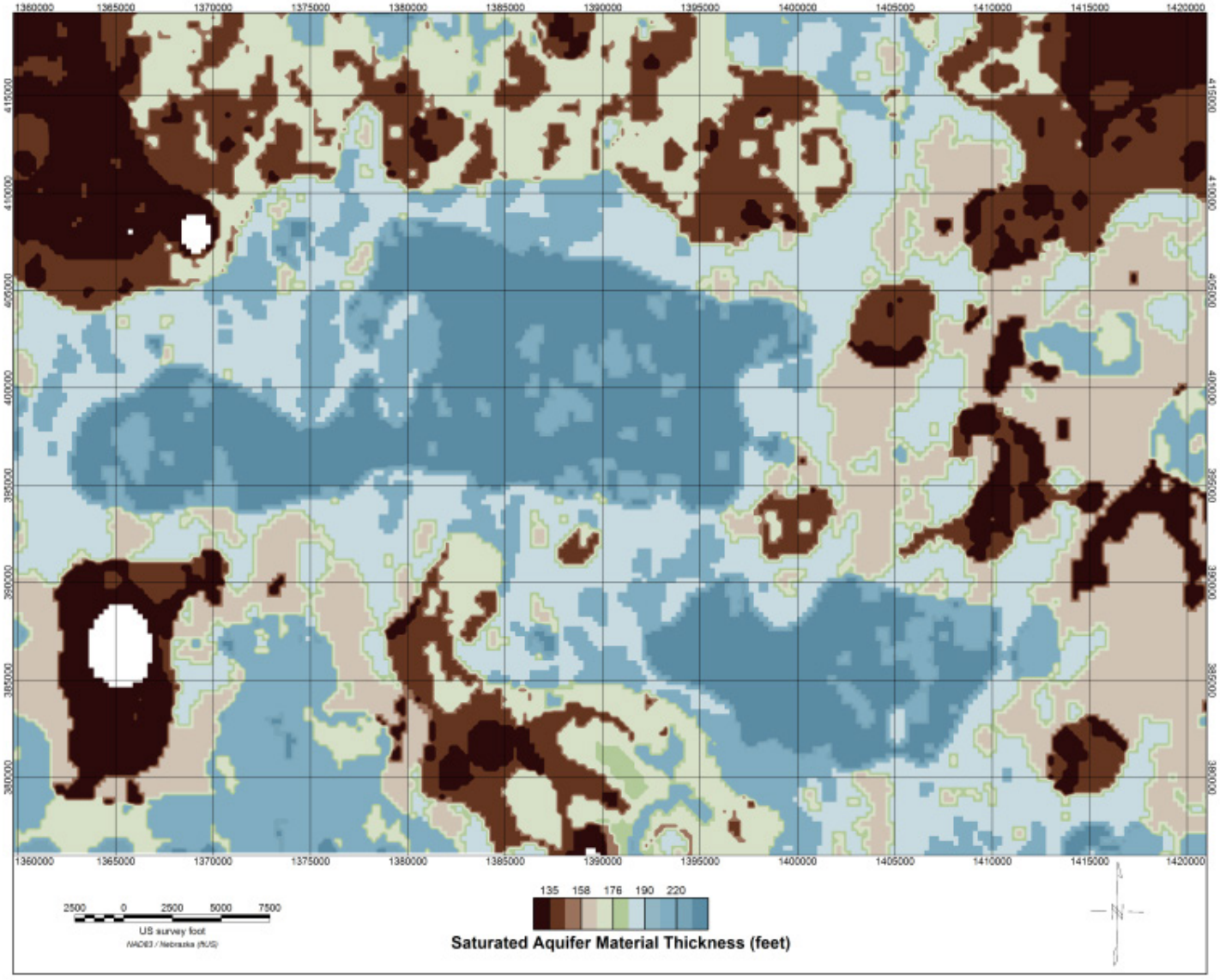



**Figure 5-76. Saturated Tertiary Ogallala (*To*) aquifer material (>25 ohm-m) thickness (in feet) in the N-CORPE AEM Block survey area. Map projection is NAD83, Nebraska SPCS83, code 2600, in feet.**

**Table 5-3. Saturated *To* aquifer materials underlying the N-CORPE AEM block flight survey area.**

| Aquifer Material Type | Aquifer Volume ($ft^3$) | Aquifer Volume (acre-ft) | Average Porosity | Groundwater in Storage Volume (acre-ft) | Average Specific Yield | Extractable Water Volume (acre-ft) |
|---|---|---|---|---|---|---|
| Non-Aquifer | 386,865,750 | 8,881 | 0.40 | 3,552 | 0.02 | 71 |
| Marginal | 118,378,490,250 | 2,717,596 | 0.35 | 951,158 | 0.05 | 47,557 |
| Aquifer | 435,633,774,000 | 10,000,775 | 0.20 | 2,000,155 | 0.22 | 440,034 |
| Coarse | 33,685,046,500 | 773,302 | 0.25 | 193,325 | 0.19 | 36,731 |
| TOTAL | 588,084,176,500 | 13,500,545 | | 3,148,190 | | 524,393 |

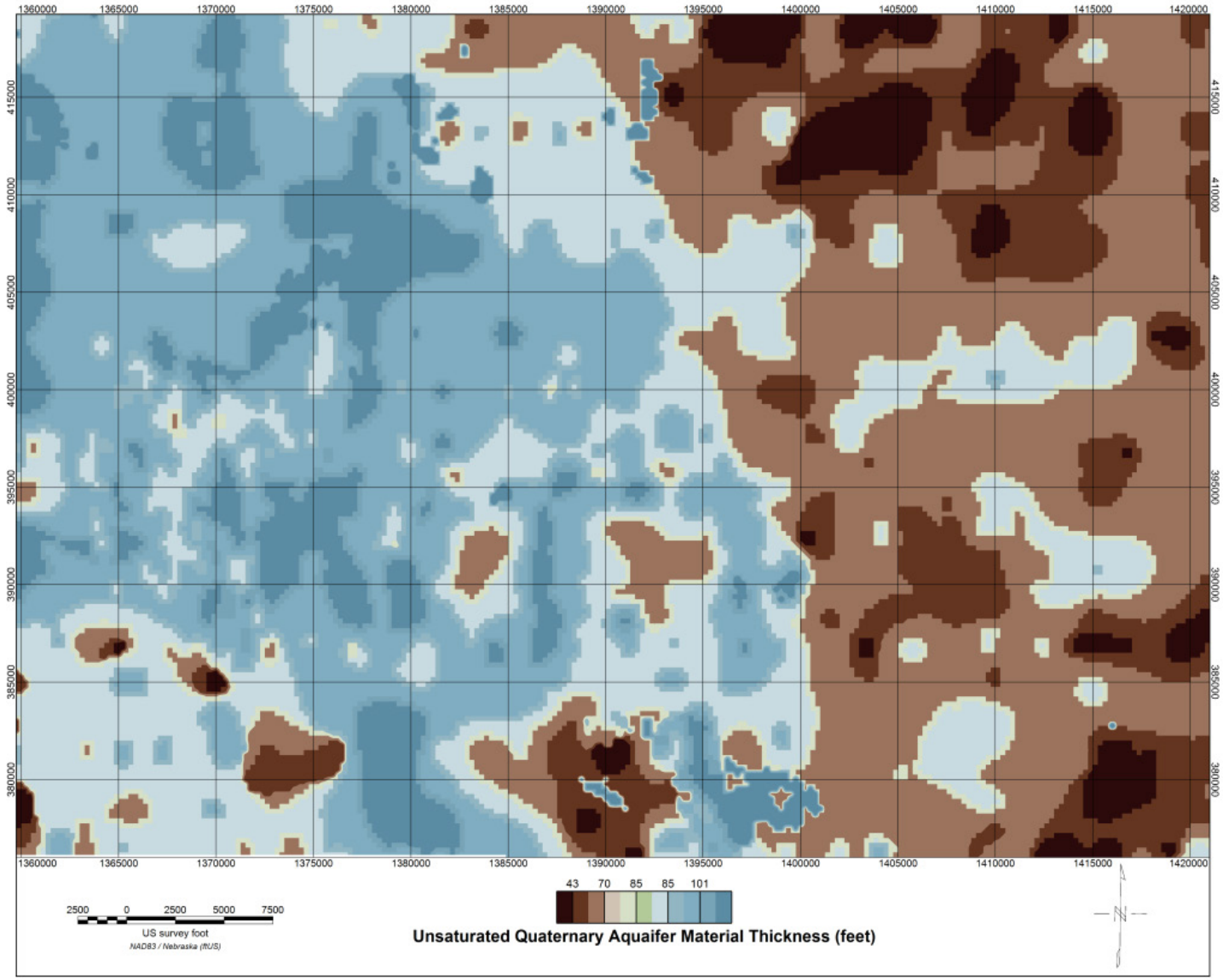



**Figure 5-77. Unsaturated Quaternary (*Q*) aquifer material (>25 ohm-m) thickness (in feet) in the N-CORPE AEM Block survey area. Map projection is NAD83, Nebraska SPCS83, code 2600, in feet.**

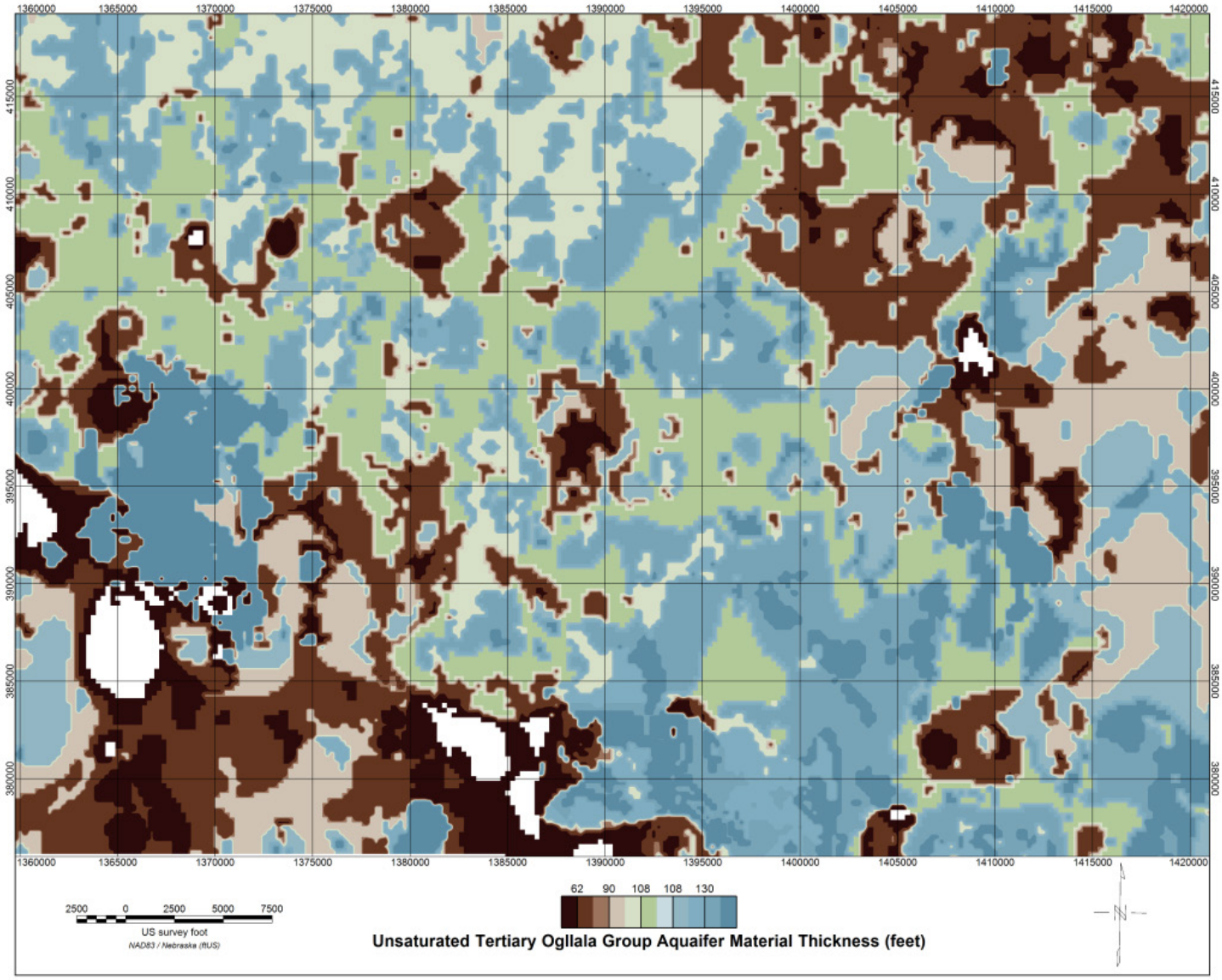



**Figure 5-78. Unsaturated Tertiary Ogallala (*To*) aquifer material (>25 ohm-m) thickness (in feet) in the N-CORPE AEM survey area. Map projection is NAD83, Nebraska SPCS83, code 2600, in feet.**

**Table 5-4. Unsaturated *Q* and *To* aquifer materials underlying the N-CORPE AEM Block Flight survey area.**

| Aquifer Material Type | Aquifer Volume ($ft^3$) | Aquifer Volume (acre-ft) | Average Porosity | Groundwater in Storage Volume (acre-ft) | Average Specific Yield | Extractable Water Volume (acre-ft) |
|---|---|---|---|---|---|---|
| Non-Aquifer | 6,170,500 | 141 | 0.40 | 56 | 0.02 | 1 |
| Marginal | 263,775,181,000 | 6,055,444 | 0.35 | 2,119,405 | 0.05 | 105,970 |
| Aquifer | 273,405,312,250 | 6,276,522 | 0.20 | 1,255,304 | 0.22 | 276,166 |
| Coarse | 7,374,813,500 | 169,302 | 0.25 | 42,325 | 0.19 | 8,041 |
| TOTAL | 544,561,477,250 | 12,501,409 | | 3,417,090 | | 390,178 |

### 5.4.2 CPNRD AEM Survey Area (PRRIP Block)

A 3D representation of the subsurface derived from the AEM voxels provides users the ability to more accurately identify the unsaturated and saturated aquifer volumes for the ***Q*** and ***To***. A block flight was flown in the CPNRD PRRIP area which is approximately 6 miles southwest of Overton, Nebraska. (Figure 1-2). The saturated zones of the ***Q*** and ***To*** materials can be analyzed to estimate the amount of groundwater in storage and the amount of extractable water present based on estimates of the material volumes. Analysis of the unsaturated ***Q*** and ***To*** aquifer materials can be used to determine the availability of potential volume of material that can be used for storage via future managed aquifer recharge (MAR) or aquifer storage and recovery (ASR) activities.

The criteria for determining the basis for the range of resistivity values used in calculating the volumes of interpreted aquifer material are provided in Section 5.2. The resistivity ranges for the interpreted non-aquifer (<12 ohm-m), marginal aquifer (12-25 ohm-m), aquifer (25-40 ohm-m), and coarse aquifer materials (>40 ohm-m) are presented in Figure 5-18. Individual fence diagrams presenting the saturated ***Q*** and ***To*** aquifer and coarse aquifer materials are shown in Section 5.3. These figures illustrate the complex nature and interconnections between the saturated ***Q*** and ***To*** materials of the area. They show how these aquifers can change in extent, both vertically and horizontally. Thus, in the discussion below no distinction is made between the ***Q*** and ***To*** in terms of the saturated and unsaturated aquifer materials. That is, the ***Q*** and ***To*** are treated as one aquifer unit, partially saturated and partially unsaturated.

All aquifer materials within the ***Q*** and ***To*** sediments, including non-aquifer material, marginal aquifer material, aquifer material, and coarse aquifer material are used for calculating the groundwater in storage volume and the extractable water volumes for the survey area. Reported values of the average porosity for sand making up the aquifer material and sand and gravel making up coarse aquifer material are based on values from Freeze and Cherry (1979). Clay ranges from 40%-70%, silt ranges from 35%-50%, sand ranges from 25%-50%, and gravel is from 25%-40%. Conservative estimates for the porosity values used in these calculations within the survey area are 40% for non-aquifer material, 35% for marginal aquifer material, 20% for the aquifer material, and 25% for the coarse aquifer material.

Understanding this complexity in the area and within the sedimentary deposits shows that estimated average values for porosity and specific yield are the best values to use in making volume and groundwater storage calculations. While NMR surveys and aquifer tests were completed in the area (Irons et al., 2012), they are point source in nature. It is best to use published results for porosity and specific yield. Section 2 of this report has a list of aquifer tests completed in the TPNRD-CPNRD AEM project area. Specific yield values for all ***Q*** and ***To*** aquifer materials were selected by estimating values. Specific yield for non-aquifer materials was chosen at 0.02 (Heath, 1983) and for marginal aquifer materials a value of 0.05 was selected (Heath, 1983). The specific yield for the aquifer material is 0.22 (Heath, 1983). While coarse aquifer materials exist as localized deposits in the survey area, estimates of specific yield for the coarse aquifer material is 0.19 (Heath, 1983). Specific yield maps of the area would be improved if new maps were produced using this new information plus the addition of aquifer tests or other methods of gaining new data including NMR on aquifer characteristics.

Maps of saturated and unsaturated aquifer thickness in the PRRIP AEM block survey area have been developed. Figure 5-79 presents the saturated aquifer (>25 ohm-m) thickness in the PRRIP AEM block survey area. The saturated ***To*** is thickest in the southwest and south-central areas of the PRRIP AEM block survey area.

From the data used to develop this map, volumetric tables have been developed for the PRRIP AEM block flight area for saturated ***Q*** and ***To*** aquifer materials. Table 5-5 presents the results of the analysis for groundwater in storage calculated by multiplying the volume of all aquifer materials below and above the water table by the estimated porosity. The non-aquifer material has an estimated aquifer volume of **59,928** acre-ft and contains **23,971** acre-ft of groundwater in storage. The marginal aquifer material has an estimated aquifer volume of **303,416** acre-ft and contains approximately **106,195** acre-ft groundwater in storage. The aquifer material has an estimated aquifer volume of **433,727** acre-ft and contains an estimated volume of **86,745** acre-ft of groundwater in storage. The coarse aquifer material has an estimated aquifer volume of **256,881** acre-ft and contains an estimated volume of **64,220** acre-ft of groundwater in storage. The amount of groundwater in storage for all material groups is **281,131** acre-ft.

The estimate of extractable volume of water is calculated by taking the amount of groundwater in storage times the specific yield. Non-aquifer materials in the PRRIP AEM block flight area will yield approximately **479** acre-ft, marginal aquifer materials will yield approximately **5,309** acre-ft, aquifer materials will yield **19,083** acre-ft, and coarse aquifer materials will yield **12,201** acre-ft. A total of **37,072** acre-ft is available from the combined aquifer materials.

These estimates and the estimates that follow are based on "The Groundwater Atlas of Nebraska, third revised edition" (Korus et al, 2013b) water table map. This map is very general in nature with a 75-foot contour interval making assumptions of the actual water level less accurate. Also, these volumetric estimates only consider the volume of water assumed to be in the pore spaces of the aquifer material defined by the resistivity threshold levels and do not account for the possible "confined or semi-confined" water under pressure (head above the aquifer). This volume of water would add to the values reported in Table 5-5. However, too much uncertainty exists in developing an average level of head above the top of the aquifer across the entire project area, as well as defining a representative storativity term for the confined or semi-confined aquifers. Thus, the volumes listed in Table 5-5 are conservative estimates and the amounts released from the decline in pressure are not considered.

As just discussed, it should be noted that all values are very conservative in nature and are estimates based on published values for porosity and specific yield. The actual amount of extractable water will vary due to many things such as sediment grain size, sorting, cementation and other considerations. Actual values determined from additional field measurements and analysis of the various sediment packages in the ***Q*** and ***To*** would greatly help the estimates of groundwater in storage and extractable water volume.

A map of unsaturated aquifer materials (>25 ohm-m) in the PRRIP AEM block survey area is presented in Figure 5-80. The values for the unsaturated (volume of material above the water table) are listed in

Table 5-6. These calculations for the unsaturated materials can be used for estimating potential MAR for the PRRIP AEM block area. They show the non-aquifer material has an estimated aquifer volume of **871** acre-ft and could contain **348** acre-ft of groundwater in storage, marginal aquifer material has an estimated aquifer volume of **17,705** acre-ft and could contain **6,196** acre-ft groundwater in storage, aquifer material has an estimated aquifer volume of **25,978** acre-ft and could contain an estimated volume of **5,195** acre-ft of groundwater in storage, and coarse aquifer material has an estimated aquifer volume of **17,835** acre-ft and could contain an estimated volume of **4,458** acre-ft of groundwater in storage. The amount of potential groundwater storage for all material groups if they become saturated is **16,197** acre-ft.

The estimate of extractable volume of water, if it was saturated, is calculated by taking the amount of potential groundwater in storage times the specific yield. Non-aquifer materials in the PRRIP block flight area could yield approximately **7** acre-ft, marginal aquifer materials could yield approximately **310** acre-ft, aquifer materials could yield **1,142** acre-ft, and coarse aquifer materials could yield **847** acre-ft. A total of **2,306** acre-ft is available from the combined aquifer materials for potential withdrawal if they become saturated.

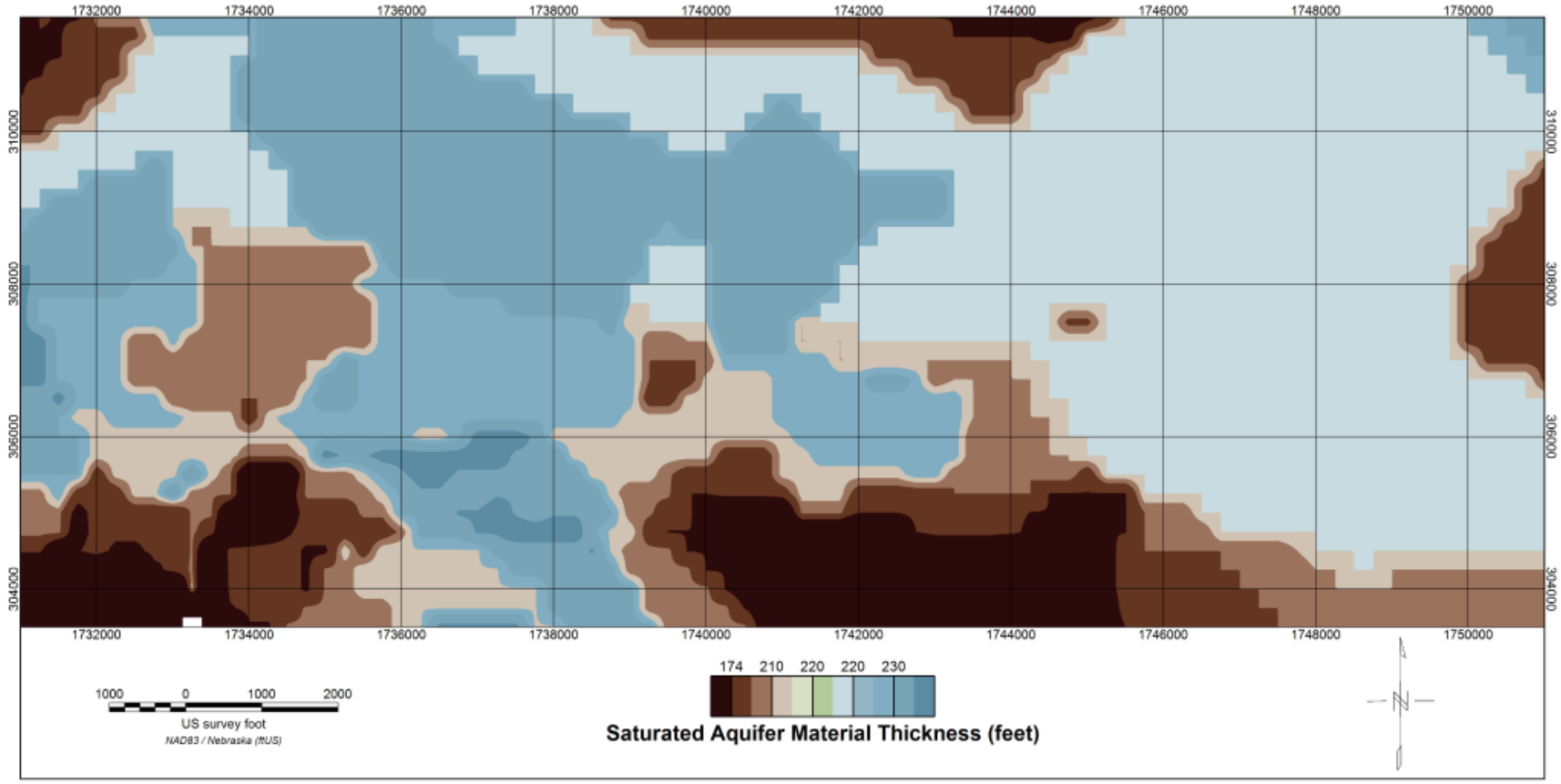



**Figure 5-79. Saturated aquifer material (>25 ohm-m) thickness (in feet) in the PRRIP AEM block survey area. Map projection is NAD83, Nebraska SPCS83, code 2600, in feet.**

**Table 5-5. Saturated *Q* and *To* aquifer materials underlying the PRRIP AEM block flight survey area.**

| Aquifer Material Type | Aquifer Volume ($ft^3$) | Aquifer Volume (acre-ft) | Average Porosity | Groundwater in Storage Volume (acre-ft) | Average Specific Yield | Extractable Water Volume (acre-ft) |
|---|---|---|---|---|---|---|
| Non-Aquifer | 2,610,470,000 | 59,928 | 0.40 | 23,971 | 0.02 | 479 |
| Marginal | 13,216,821,500 | 303,416 | 0.35 | 106,195 | 0.05 | 5,309 |
| Aquifer | 18,893,189,500 | 433,727 | 0.20 | 86,745 | 0.22 | 19,083 |
| Coarse | 11,189,771,250 | 256,881 | 0.25 | 64,220 | 0.19 | 12,201 |
| TOTAL | 45,910,252,250 | 1,053,954 | | 281,131 | | 37,072 |

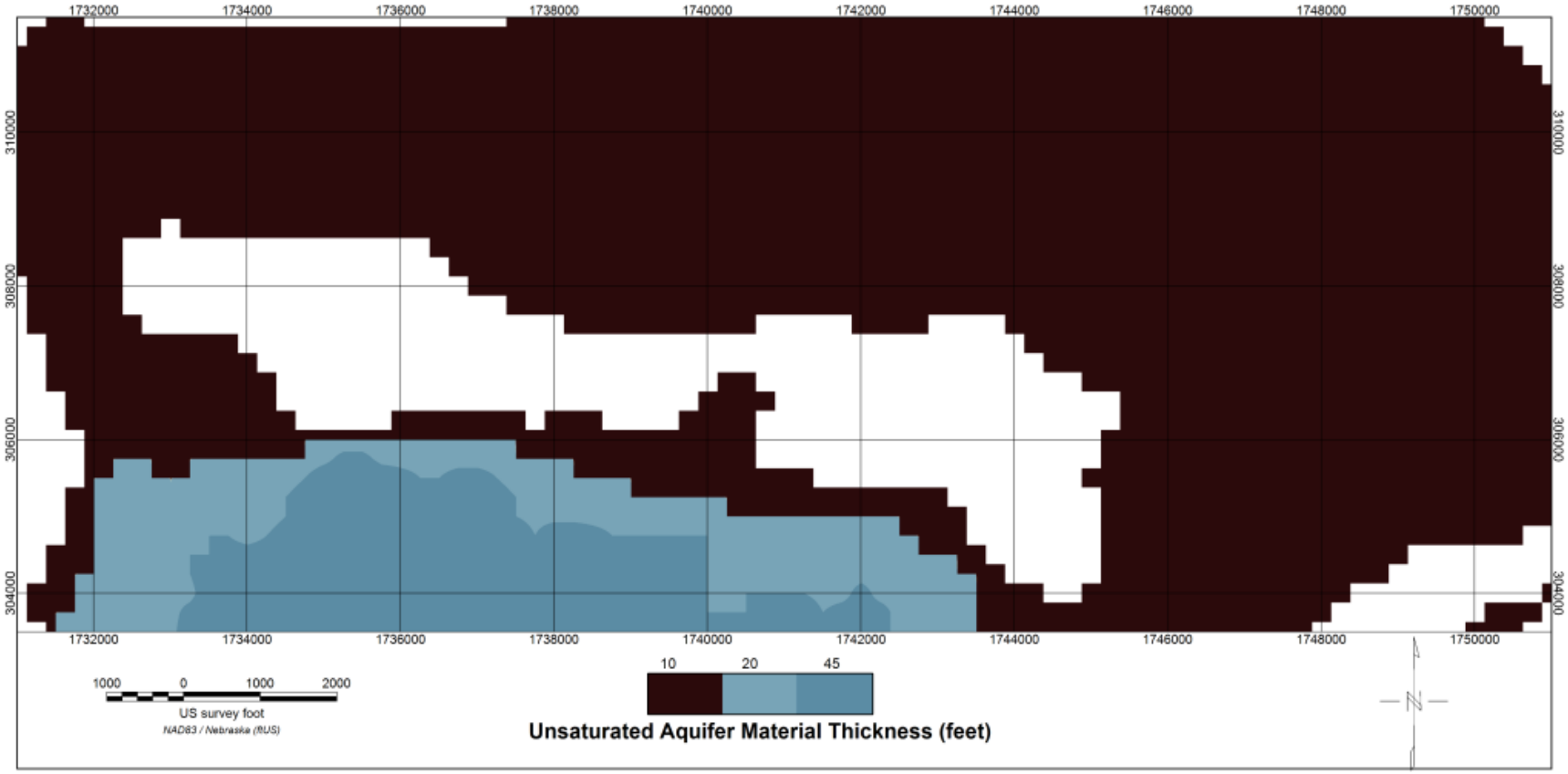



**Figure 5-80. Unsaturated aquifer material (>25 ohm-m) thickness (in feet) in the PRRIP AEM block survey area. Map projection is NAD83, Nebraska SPCS83, code 2600, in feet.**

**Table 5-6. Unsaturated *Q* and *To* aquifer materials underlying the PRRIP AEM block flight survey area.**

| Aquifer Material Type | Aquifer Volume ($ft^3$) | Aquifer Volume (acre-ft) | Average Porosity | Groundwater in Storage Volume (acre-ft) | Average Specific Yield | Extractable Water Volume (acre-ft) |
|---|---|---|---|---|---|---|
| Non-Aquifer | 37,966,000 | 871 | 0.40 | 348 | 0.02 | 7 |
| Marginal | 771,271,500 | 17,705 | 0.35 | 6,196 | 0.05 | 310 |
| Aquifer | 1,131,641,000 | 25,978 | 0.20 | 5,195 | 0.22 | 1,142 |
| Coarse | 776,929,500 | 17,835 | 0.25 | 4,458 | 0.19 | 847 |
| TOTAL | 2,717,808,000 | 62,392 | | 16,197 | | 2,306 |

## 5.5 Recharge within the TPNRD-CPNRD AEM Survey Area

3D representations of the subsurface resulting from AEM investigations illustrate areas of aquifer materials from the bedrock up to the land surface. From these interpretations, a new series of near-surface maps were constructed that include the interval from 0 to10 feet (about 3 m). The interval of 0-10 feet is noteworthy because this is the first layer of the inverted AEM earth model. Remember from the discussion around Table 4-4 that each model layer represents an average of the earth's resistivities within those depths, based on the physics of the electromagnetic exploration technique. These first layer maps show all aquifer materials including non-aquifer material, marginal aquifer material, aquifer material, and coarse aquifer material and indicate the areas at the land surface that can potentially transmit water to the groundwater aquifers in the area. The coarse aquifer material can transmit the largest volume of water and the non-aquifer material being the least able to transmit water.

The results of the interpretation of the aquifer materials of the TPNRD-CPNRD AEM survey area are explained in detail in Section 5.2 and Section 5.3. The interpreted aquifer materials for the first model layer (0 – 10 ft) are presented below for the AEM block survey areas (N-CORPE and PRRIP) as a color from the ***Q-To*** material legend (Figure 5-18). Areas of coarse aquifer material (brown colored material) will have the highest potential to transmit the largest amount of water to the groundwater system with the aquifer material (yellow colored material) potentially transmitting slightly less precipitation downward as both units are permeable and transmissive. The marginal aquifer material (tan colored material) has a low potential to transmit some water downward and the non-aquifer material (blue colored material) will transmit minimal to no water to the groundwater aquifer.

However, since the amount of slope of the land surface plays a large role in the amount of residence time that water will spend in an area, the greater the length of time spent at a location, the greater the amount of infiltration potential. The greatest possibility for recharge in the TPNRD-CPNRD AEM survey area is the North Platte, South Platte, and Platte rivers within the alluvial valley floor and the creek beds that have aquifer and coarse aquifer materials near the land surface. On the table lands, the best possible location for recharge would be where there is a combination of aquifer and coarse aquifer materials at the land surface on the uplands with little relief in elevation with a pathway of similar materials down to the saturated aquifer at depth. The most likely place for recharge would be the Sand Hills areas. Figure 5-41, line L10201 in Section 5-3, provides an example of excellent recharge areas across the entire profile which is near Sutherland, NE. Shown on this profile is a wide expanse of the South Platte River which continues north through the North Platte River and on into the Sand Hills which are excellent areas for recharge and have strong hydrologic connection to the rivers and streams. Conversely, line L312802 (Figure 5-59 in Section 5-3) provides limited recharge areas along the profile, which is west of Elm Creek, NE. There is a small area of Sand Hills on the south end of the profile which is a good place for recharge. However, it is bounded by marginal aquifer material on all sides vertically and horizontally. As you continue north along the profile the presence of thick loess deposits that contain marginal and non-aquifer materials restricts any recharge from the surface. These examples of recharge along the reconnaissance lines show where the general areas for good to poor recharge areas

can potentially be found and expanded on. Future AEM surveys can characterize recharge areas in block flight areas similar to what was performed in the TPNRD-CPNRD AEM survey.

### *5.5.1 N-CORPE Block*

A block flight was flown over the N-CORPE area and was interpreted in the near-surface for recharge. Due to the thick ***Qes*** deposits on the surface, recharge is very good in the near-surface (Figure 5-81) and down to greater than 100 feet at which point there is a nearly continuous marginal aquifer layer made of silt/loess (Figure 5-48 in Section 5-3). Note the small opening in the loess layer at the south end of profile 206601 in Figure 5-48. This is where recharge from the surface can travel down to the water table. Figure 5-82 is a Google Earth image of resistivity across the N-CORPE block area of the coarse aquifer material. The higher resistivity correlates with higher recharge rates in the near-surface. This kmz is included in Appendix 3 Deliverables\KMZ\Recharge.

### *5.5.2 PRRIP Block*

A block flight was flown for the PRRIP area and was interpreted in the near-surface for recharge. Due to the heterogeneous nature of the ***Q*** deposits on the surface, recharge is very good to very poor in the near surface (Figure 5-83). The area to north near the Platte River has a thick recharge area of aquifer and coarse aquifer material. To the south there are smaller, discontinuous zones of aquifer and coarse aquifer material. The central portion of the PRRIP area has a band of shallow marginal material at the surface which is extremely thin (10 feet or less) and is not easily identified on the interpretative 2D profiles along the flight lines. There is marginal to non-aquifer material along the southern and southeastern border. This can be seen in Figure 32 in Section 5-3. Note the area of marginal material at the west end of profile 204501 in Figure 32. This is where recharge from the surface can travel down to the water table. Figure 5-84 is a Google Earth image of recharge materials in the PRRIP near surface. This kmz is included in Appendix 3 Deliverables\KMZ\Recharge.

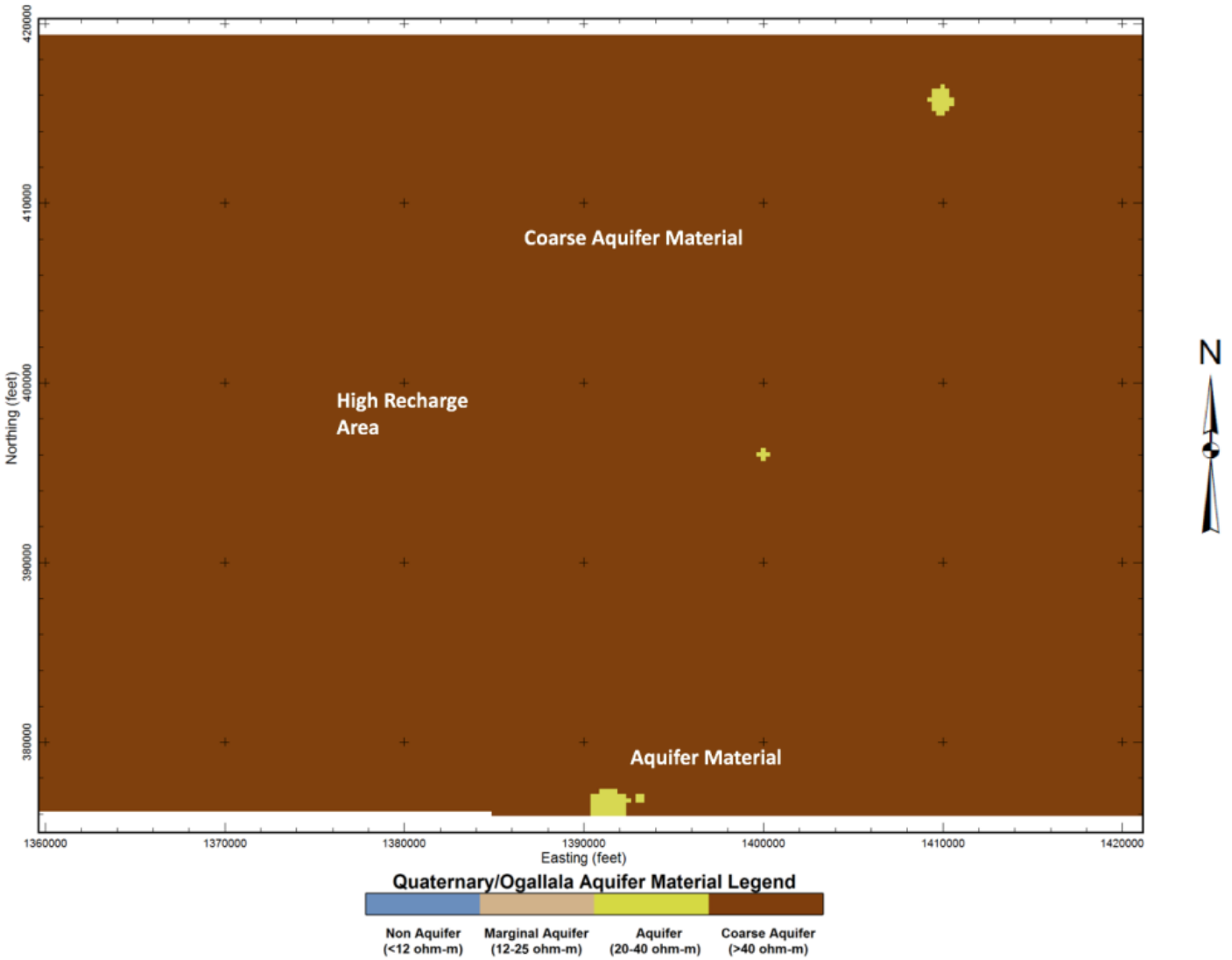



**Figure 5-81. Map of all aquifer materials for the first 0 to 10 feet displayed over the N-CORPE AEM block survey area. The material color legend indicates that different colors relate to different aquifer material types. This area is almost completely made of coarse aquifer material and some aquifer material. Projection is NAD83, Nebraska State Plane Coordinate System, code 2600, Feet.**

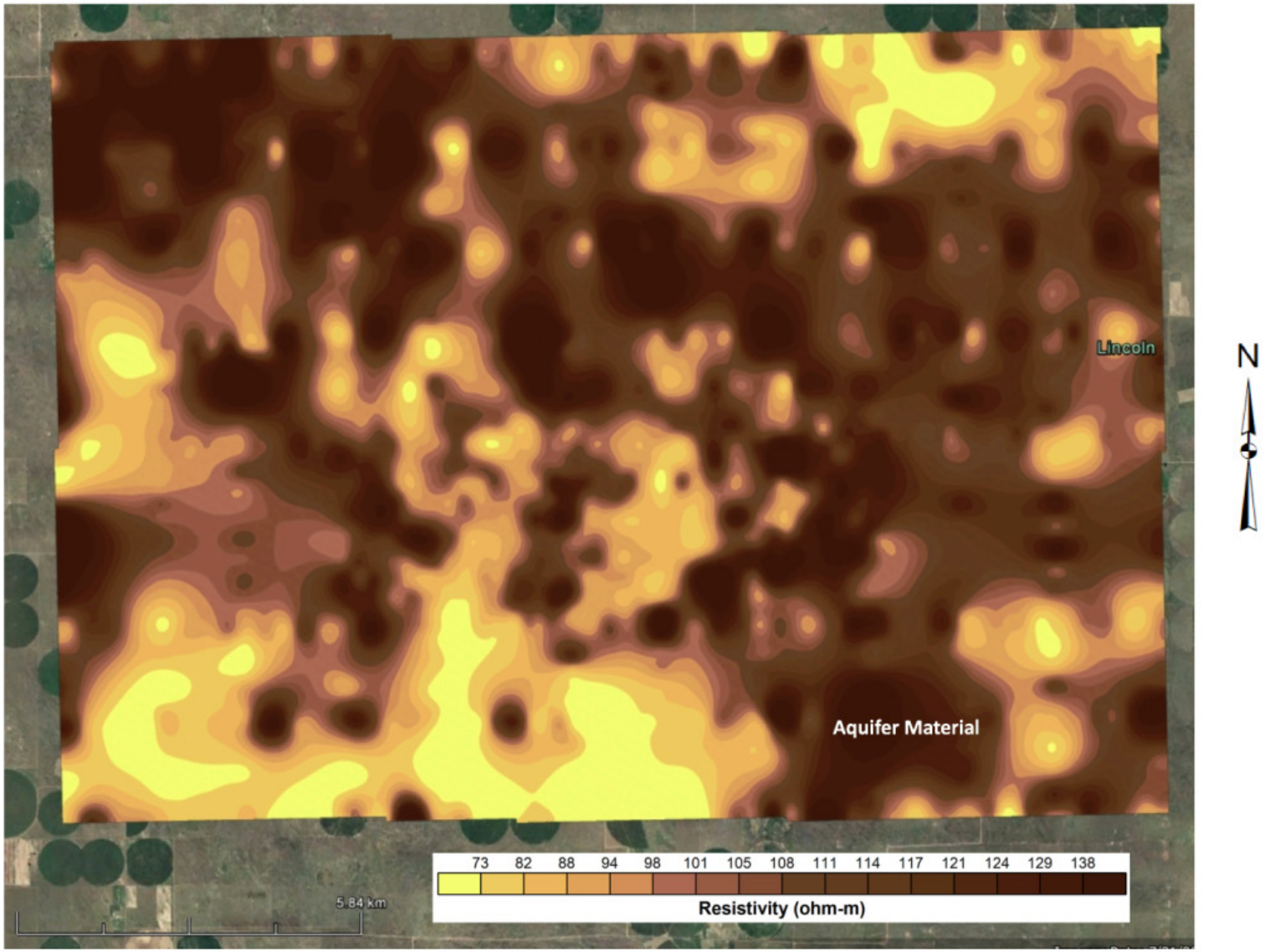



**Figure 5-82. Google Earth recharge kmz of coarse aquifer material displayed over the N-CORPE block flight survey area. Displayed values of resistivity (ohm/m) with higher resistivity correlating to higher recharge rates.**

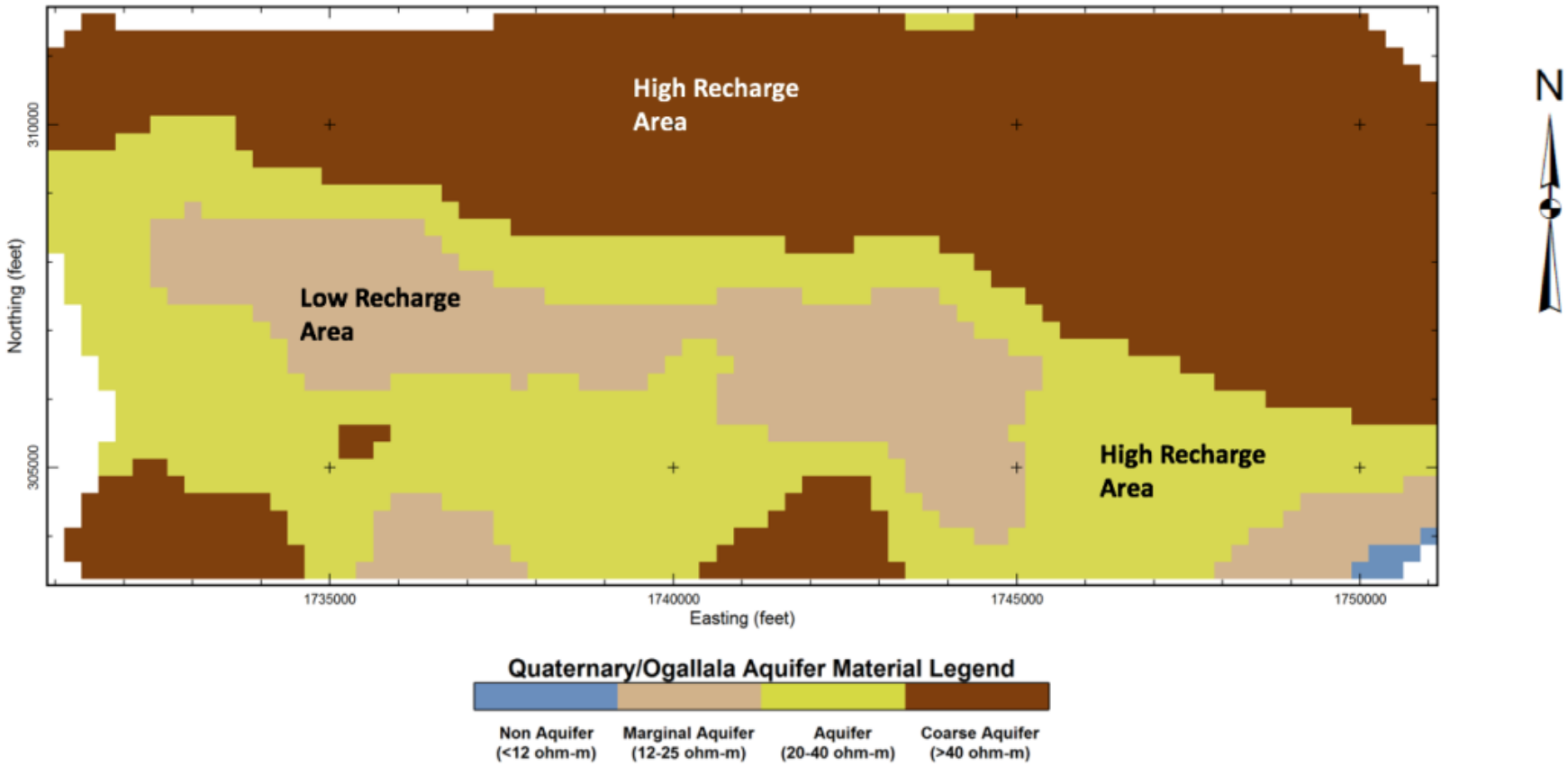



**Figure 5-83. Map of all aquifer materials for the first 0 to 10 feet displayed over the PRRIP block flight AEM survey area. The material color legend indicates that different colors relate to different aquifer material types. This area is heterogeneous mix of non-aquifer, marginal aquifer, aquifer, and coarse aquifer material. The marginal aquifer material in center of the area is very thin 10 feet or less. Projection is Projection is NAD83, Nebraska State Plane Coordinate System, code 2600, Feet.**

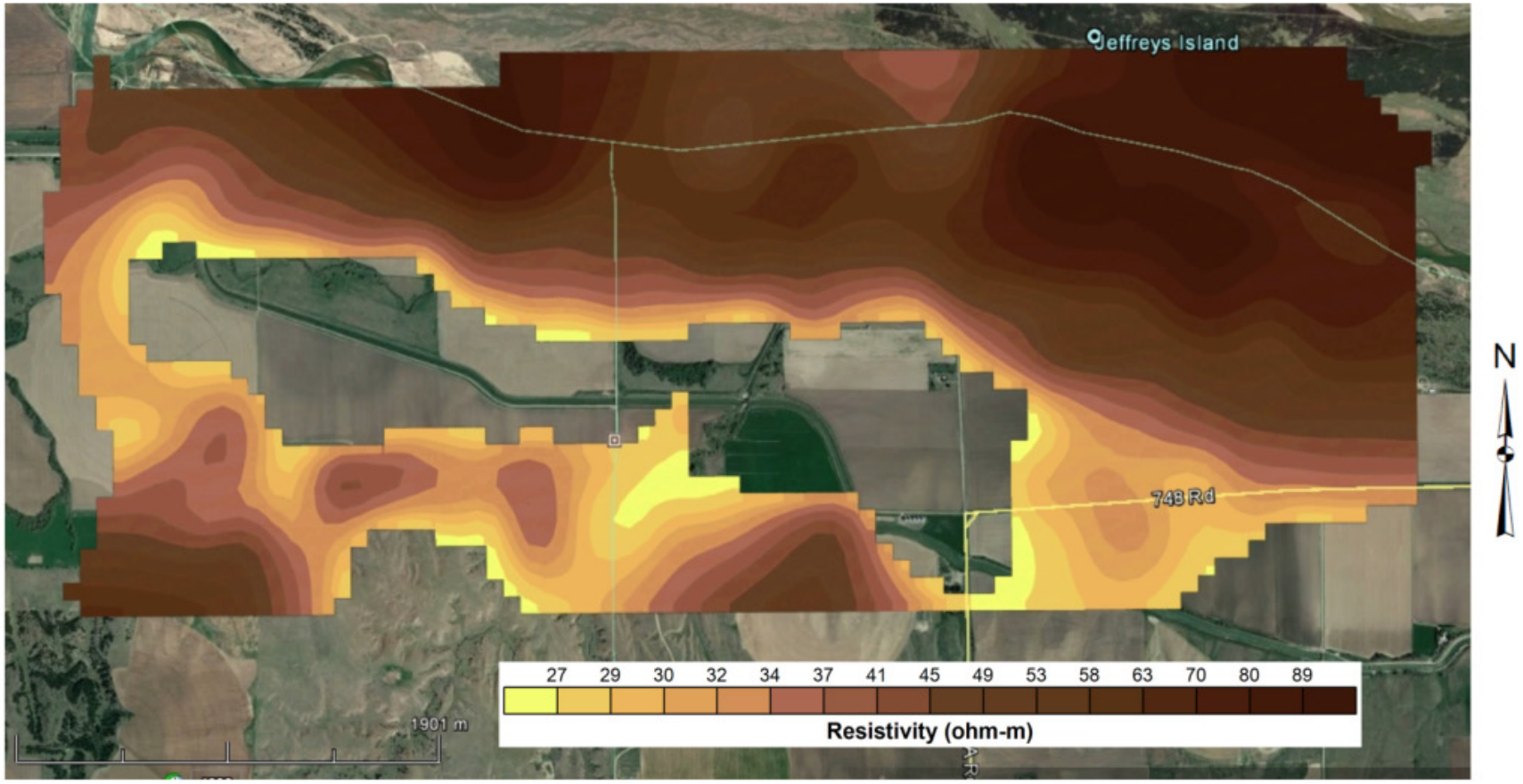



**Figure 5-84. Google Earth recharge kmz of aquifer material and coarse aquifer material displayed over the PRRIP AEM block flight survey area. Displayed values of resistivity (ohm/m) with higher resistivity correlating to higher recharge rates.**

## 5.6 Key AEM Findings

### *5.6.1 Boreholes*

Information from boreholes was used to analyze the AEM inversion results. A total of 657 CSD holes contained lithology information, 644 holes contained stratigraphic information, 178 holes contained geophysical log information. There were also 8,696 NE-DNR lithology logs. There were 72 boreholes containing stratigraphic information from the NOGCC. The well data correlated well with the AEM and provided control to allow hydrogeological interpretations. Section 5-3 of this report has further detail.

### *5.6.2 Merging 2010 and 2016 AEM Databases*

The TPNRD AEM survey area analysis did not include the flight lines collected and interpreted in the 2010 AEM survey near Keystone, NE. The 2010 inversion results were compared with the 2016 results and they were found to be in agreement. Even though the lines are not directly butted up against each other, the comparison of the AEM data collected in 2016 and the AEM data collected in 2010 show good spatial correlations. While not part of this project, there should be no issues integrating the 2010 AEM data with the 2016 AEM data.

### *5.6.3 Digitizing Interpreted Geological Contacts*

Characterization and interpretation of the subsurface was performed in cross-section and derived surface grid formats. Contacts between the geologic units were digitized in 2D including: Quaternary (***Q***), Tertiary Ogallala Group (***To***), Tertiary Brule Formation (***Tb***), Cretaceous Pierre Shale (***Kp***), Cretaceous Niobrara Formation (***Kn***), and the Cretaceous Carlile Shale (***Kc***). The interpretive process benefited from the use of CSD, NE-DNR, and NOGCC borehole databases. Once the AEM interpretation of the geological contacts were completed, surface grids of the interpreted geologic formations were then produced. Flight line profiles with interpretations including mapping of Quaternary and Tertiary aquifer materials are included as appendices as well as the interpretative surface grids for the geologic units identified in this report.

### *5.6.4 Resistivity/Lithology Relationship*

Assessment of the sediment character in both the ***Q*** and the ***To*** aquifer systems was conducted to determine the overall composition of the major categories used to define the aquifer and aquitards in the project area. For the ***Q*** and ***To*** aquifer systems, a numerical assessment of the resistivity thresholds was used to characterize non-aquifer (<12 ohm-m), marginal (12-25 ohm-m), aquifer (25-40 ohm-m), and coarse sand-rich intervals (>40 ohm-m). This allowed for the characterization of the ranges of resistivities present in the aquifer units described in this report.

### 5.6.5 Hydrogeological Framework of the TPNRD-CPNRD AEM Survey Area

The AEM reveals considerable detail and variability within the Quaternary (***Q***) and the Tertiary Ogallala Group (***To***) aquifers. These details indicate the evolution of the structural and depositional environment of the area.

Within the survey area the ***Q*** can be characterized into three somewhat overlapping, but distinct, areas with smaller localized depositional features. These include the Quaternary alluvium (***Qa***) (mostly within the Platte River basins and tributaries), the Quaternary eolian sand (***Qes***) (associated with the sand hills), and the Quaternary Peoria loess (***Qp***) (that cover most of the uplands). The reconnaissance lines image these areas along the lines and the block flights image the spatial variability of these ***Q*** deposits. The ***Qa*** is often thin and saturated throughout the project area. Because it is in direct contact with ***To***, there is often a good hydraulic connection between the two units and with the surface water in the area. The ***Qes*** is found in the TPNRD with small areas in the CPNRD. The ***Qp*** is found on the flanks of the Platte River mostly in the CPNRD and the eastern part of the TPNRD.

Within the survey area the ***To*** can be characterized by a couple general observations. 1) the coarsest areas of the ***To*** occur mostly west of the Cambridge Arch, and 2) the ***To*** is characterized by variability throughout the vertical section. The vertical variability is characterized by zones of marginal aquifer material separating areas of aquifer materials. This is typically arranged with a marginal aquifer material zone in the upper sections of the ***To*** grading into aquifer/coarse aquifer material zone on the order of 200-300 feet thick above another marginal aquifer material zone at the lower sections of the ***To***. This pattern and its variable depth band depicts the evolution of the fluvial system within the ***To*** with the drainage from the west to the east. East of the Cambridge Arch, the ***To*** begins to be characterized by a thinner aquifer material zone on the order of 100-feet. Few instances of coarse aquifer material exist east of the Cambridge Arch within the ***To***. There are areas along the Platte River where the ***To*** aquifer/coarse aquifer materials are in direct contact with the ***Qa*** with no marginal aquifer material zone above the aquifer/coarse aquifer material zones.

### 5.6.6 Estimation of Aquifer Volume and Water in Storage in the N-CORPE and PRRIP AEM Survey Areas

#### 5.6.6.1 N-CORPE

Volume and storage estimations were calculated for both ***Q*** and ***To*** aquifer materials which make up the aquifer for the N-CORPE block flight area. A 3D representation of the subsurface derived from the AEM imaging provides users the ability to more accurately identify the total unsaturated and saturated aquifer volumes for the Aquifer. The saturated zones of the aquifer can be analyzed to estimate the amount of groundwater in storage and the amount of extractable water present. For all saturated aquifer materials, which are all ***To*** in N-CORPE, the amount of groundwater in storage is 3,148,190 acre feet and the amount of extractable water is 524,393 acre feet.

#### 5.6.6.2 PRRIP

Volume and storage estimations were calculated for both ***Q*** and ***To*** aquifer materials which make up the aquifer for the PRRIP block flight area. A 3D representation of the subsurface derived from the AEM imaging provides users the ability to more accurately identify the total unsaturated and saturated aquifer volumes for the Aquifer. The saturated zones of the aquifer

materials can be analyzed to estimate the amount of groundwater in storage and the amount of extractable water present. For all saturated aquifer material, the amount of groundwater in storage is 281,131 acre feet and the amount of extractable water is 37,072 acre feet.

### *5.6.7 Potential Recharge Zones within the TPNRD-CPNRD AEM Survey Areas*

The greatest possibilities for recharge in the TPNRD and CPNRD reconnaissance line survey areas are the North Platte River, the South Platte River, and the Platte River alluvial valley and the tributary areas that have aquifer and coarse aquifer materials that are near the land surface. Elsewhere, the best possible location for recharge would be where there is a combination of aquifer and coarse aquifer materials at the land surface on the uplands and the Sand Hills that are made of aquifer and coarse aquifer materials with a pathway of similar materials down to the saturated aquifer at depth.

N-CORPE

3D representations of the subsurface resulting from the N-CORPE AEM block flight investigation illustrate areas of aquifer materials from the bedrock up to the land surface. From this interpretation, a near-surface map was constructed to display the aquifer materials in the first 10 ft. These indicate that the area is nearly homogeneous and is covered by coarse aquifer material with some small areas of aquifer material. It is easy to identify that the area will collect and transmit recharge water downward into the system. However, there is a marginal aquifer layer at approximately 100 feet below ground surface that will slow recharge to lower aquifers.

PRRIP

3D representations of the subsurface resulting from the PRRIP AEM block flight investigation illustrate areas of aquifer materials from the bedrock up to the land surface. From this interpretation, a near-surface map was constructed to display the ***Q*** aquifer materials in the first 10 ft. These indicate that the area is heterogeneous with areas covered by non-aquifer material, marginal aquifer material, aquifer material and coarse aquifer material. It is easy to conclude that the area will collect and transmit recharge water downward into the system as these are the areas covered in aquifer and coarse aquifer materials. However, there is a marginal aquifer layer at approximately 80 feet below ground surface that will slow recharge to lower aquifers.

### *5.6.8 Value of AEM Data Analysis and Images*

One of the most important key findings from the TPNRD and CPNRD AEM investigation is the value-added products resulting from AEM data derived images. There is a step-by-step process involved from flight planning to final images. While the text of the report may not go into detail on each and every data point or every image provided in the appendices, the value to the user is in the final data analysis and associated images. These final interpretive images allow development of science-based decisions for water management by illustrating the spatial relationships of aquifers. These images can help communicate to boards and to the general public the configuration of the aquifers and that those configurations can impact water quantity and quality.

## 5.7 Recommendations

Recommendations provided to the TPNRD and N-CORPE - CPNRD and PRRIP in this section are based on the interpretation and understanding gained from the addition of the AEM data to existing information and from discussions with these entities about their management challenges.

### *5.7.1 Additional AEM Mapping*

The aquifer maps provided in this report represent the framework developed for the TPNRD, CPNRD, N-CORPE, and PRRIP AEM survey areas. The detail provided in the hydrogeological interpretation of the AEM survey areas allowed for confident development of a hydrogeologic framework. The interpretations match well the CSD test holes and NE-DNR registered wells. The N-CORPE and PRRIP Block areas were mapped in detail by the block flights and provide a detailed hydrogeological framework. The areas of the reconnaissance lines within the TPNRD and the CPNRD only provide detail along the lines. If additional high-resolution information is needed within the TPNRD, CPNRD, N-CORPE, and PRRIP to resolve questions of resource management, it is recommended that additional areas of closely spaced lines or “block flights” be collected to develop further detailed frameworks.

It should be noted that the ability to effectively map detailed boundary conditions and other related information of the aquifer can only happen with block flights. Thus, management needs coupled with the results of the reconnaissance flight lines can indicate the areas where flights are required for effective characterization.

For example, the detailed hydrogeologic frameworks presented in this report for the N-CORPE and PRRIP Block have provided estimates of groundwater storage capacity. This is done by using existing aquifer characteristic information and calculating groundwater in storage and effective yield for the N-CORPE and PRRIP areas. It was noted that the edges of the flight blocks often did not terminate with geological features important to understanding the amount of groundwater in storage and hydrologic connection to the surrounding area extend beyond the flight area boundary. It is recommended that additional closely spaced flight lines for collection of AEM data and interpretation be considered in critical areas like the area between the N-CORPE block flight and the South Platte and Platte Rivers to the north and the Republican River to the south which will further understanding of the hydraulic connection between the Platte and Republican Rivers.

The PRRIP area could be expanded to collect additional block flight data in all of the areas being considered for retention cell development and managed aquifer recharge. There are many identified areas north and south of the Platte River that were discussed during flight planning for this project. A detailed block flight of all of the lands within the PRRIP interest area will provide detailed information on where best to develop facilities for groundwater storage.

Overall, this will provide the TPNRD, CPRND, and the PRRIP with necessary information to make decisions about aquifer sustainability, depletion to streams, well interference, groundwater withdrawal, and other management considerations.

### 5.7.2 Update the Water Table map

The groundwater data used in the analyses presented in this report use the 2013 CSD water table data (Korus et al., 2013b). This water table map is regional in nature and is mapped at 75 foot contour intervals which makes for a low resolution map. It is recommended that a detailed groundwater mapping program be made to create a more detailed map based on at least one measurement per mile with denser measurements near the streams.

### 5.7.3 Siting new test holes and production wells

The AEM framework maps and profiles provided in this report provide insight in 3D on the relationship between current test holes and production groundwater wells. At the time of this report, the currently available lithology data for the TPNRD, CPNRD, N-CORPE, and PRRIP AEM survey area was used in building the framework maps and profiles. It is recommended that the results from this report be used to site new test holes and monitoring wells. Often test holes are sited based on previous work that is regional in nature. By utilizing the maps in this report, new drilling locations can be sited in optimal locations.

The location of new water supply wells for communities can also use the results in this report to guide development of new water supply wells. Planners should locate wells in areas of greatest saturated thickness with the least potential for non-point source pollution.

### 5.7.4 Aquifer testing and borehole logging

Additional aquifer tests are recommended to improve estimates of aquifer characteristics. No aquifer properties were available outside the larger cities in the survey area. A robust aquifer characterization program is highly recommended at the state, regional (NRD's), and smaller municipal levels. Aquifer tests can be designed based on the results of AEM surveys and existing production wells could be used in conjunction with three or more installed water level observation wells.

Additional test holes with detailed, functional, and well calibrated geophysical logging for aquifer characteristics are highly recommended. Many of the test holes with geophysical logs in the TPNRD, CPNRD, N-CORPE, and PRRIP AEM survey area were inadequate. Only a few were calibrated and several had apparent hardware malfunctions. The borehole geophysical logs provided for this investigation demonstrate that additional calibrated and verified geophysical logs are required for future work.

Examples of additional borehole logging would be flow meter logs and geophysical logs including gamma, neutron, electrical, and induction logs. Detailed aquifer characteristics can be accomplished with nuclear magnetic resonance logging (NMR). This is a quick and effective way to characterize porosity and water content, estimates of permeability, mobile/bound water fraction, and pore-size distributions with depth. This is very cost effective when compared to traditional aquifer tests. There has been some work done on NMR logging and surface NMR systems in the CPNRD (Dlubac et al., 2013; Irons et al., 2012) and the TPNRD (Kass et al., 2014) as research to prove the technique and calibrate the results. This technique is ready for application to aquifer characterization of the TPNRD and the CPNRD

areas with the goal to select sites, collect and analyze the data, and create maps of aquifer characteristics to supplement the COHYST maps.

### *5.7.5 Recharge Zones*

The TPNRD, CPNRD, N-CORPE, and PRRIP AEM hydrogeologic framework provides areas of recharge from the ground surface to the groundwater aquifer. The block flights of AEM data acquisition provided the most detailed information for understanding recharge in the N-CORPE and PRRIP areas. It is recommended that additional AEM data be collected and interpreted along the reconnaissance lines in promising locations utilizing closely-spaced flight lines using an AEM system that has near-surface resolution. It is further recommended that future work integrate new soils maps with the results of this study to provide details on soil permeability, slope, and water retention to provide a more complete understanding of the transport of water from the land surface to the groundwater aquifer.

### *5.7.6 Mapping Well Production Data*

Develop maps of annual well production per year that can be used to make a comparison to the aquifer mapped using AEM. This would provide data to make an analysis of the available water supply and its use. It will also track well performance related to boundary conditions within the aquifer system. The NRDs have implemented groundwater management in the Districts and an annual report on well production would give the Boards and the public information on changes that are potentially needed for management particularly during periods of drought. This can provide improved knowledge on groundwater management.

### *5.7.7 Understanding Recharge and Increased Water Table Levels South of the Platte River*

Use AEM to understand recharge from the canal systems on the south side of the Platte River through the loess hills and back to the river. This is an activity that will require detailed mapping and analysis to understand the groundwater storage and flow in a difficult area complicated by groundwater level increases due to storage and canal leakage over decades.

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# 6 Description of Data Delivered

## 6.1 Tables Describing Included Data Files

Table 6-1 describes the data columns in the ASCII EM_MAG *.xyz files for the TPNRD-CPNRD AEM survey areas as well as the Geosoft database files *_EM_MAG.gdb. These files contain the electromagnetic raw data, plus the magnetic and navigational data, as supplied directly from SkyTEM.

The results of the SCI are included in TPCP_NCORPE_AEM_SCI_inv_v1.gdb and .xyz and the data columns of these files are described in Table 6-2.

The borehole data used to constrain the SCI inversion and to assist in the interpretation of the inversion results for the TPNRD-CPNRD AEM survey are included in the files listed in Table 6-3. Each type of borehole information has both a collar file containing the location of each of the wells, and a second file containing the borehole data for the individual wells. The data column descriptions for the collar files are listed in Table 6-4. Table 6-5 describes the channels in all the borehole data files as well as indicates which type of data contains each channel.

Table 6-6 describes the raw data files included in Appendix 3_Deliverables \Raw_Data. As discussed above, twenty (20) flights were required to acquire the TPNRD-CPRND AEM data (Figure 4-5, Figure 4-6, Figure 4-7, and Figure 4-8). Grouped by flight date, there are four (4) data flies included in Appendix_3_Deliverables\Raw_Data for each flight. These files have extensions of "*.sps" and "*.skb". The "*.sps" files include navigation and DGPS location data and the "*.skb" files include the raw AEM data that have been PFC-corrections (discussed in Section 4.4.1). Two additional files are used for all the flights. These are the system description and specifications file (with the extension "*.gex") in the GEO subdirectory and the 'mask' file (with the extension "*.lin"), in the MASK subdirectory, which correlates the flight dates, flight numbers, and assigned line numbers.

The various interpretation results are included in data files TPNRD/CPNRD/N-CORPE/PRRIP_InterpSurfaces_v1 in gdb and ASCII xyz formats. Table 6-7 describes the data columns of those files. Note that the N-CORPE interpretation database and xyz does not have any ***Kn*** or ***Kc*** interpretations due to the depth of those units.

ESRI Arc View Binary Grids and equivalent Geosoft grids of the surfaces that were used in the interpretation (DEM, water table) and derived from the interpretation (top of geological units) of the AEM and borehole are listed in Table 6-8. And stored in Appendix 3_Deliverables\Grids.

Voxel grids were completed for each of the N-CORPE and PRRIP AEM block survey areas of the ***Q*** and ***To*** units combined. The voxel grids were made using a 250 ft grid cell size and the model layer thickness (Table 4-4). The voxel grid was clipped below the bedrock surf ace interpreted from the AEM and the boreholes as detailed in Section 5.2.3. Table 6-9 is a list of the channel names in both ASCII *.xyz and Geosoft *.gdb format for the voxel files.

In summary, the following are included as deliverables:

- Raw EM Mag data Geosoft database and ASCII *.xyz
- SCI inversion Geosoft database and ASCII *.xyz
- Borehole Geosoft databases and ASCII *.xyz
- Interpretations Geosoft database and ASCII *.xyz
- Raw Data Files - SkyTEM files *.geo, *skb, *.lin
- ESRI ArcView and Geosoft grid files – surface, topo, etc
- 3D fence diagrams of the TPNRD/CPNRD/N-CORPE/PRRIP survey lines.
- 3D voxel models as ASCII *.xyz and *.gdb for the TPNRD-CPNRD AEM survey areas

KMZs for the TPRND, CPNRD, N-CORPE, and PRRIP AEM survey flight lines (Discussed in Section 6.2)

Profile Analyst sessions for the Profiles and 3D grids for the TPNRD-CPNRD AEM survey area analysis. (Discussed in Section 6.3)

**Table 6-1: Channel name, description, and units for TPNRD, CPNRD, PRRIP, N-CORPE EM_MAG Geosoft *.gdb and *.xyz with EM, magnetic, DGPS, Inclinometer, altitude, and associated data.**

| Parameter | Description | Unit |
|---|---|---|
| Fid | Unique Fiducial Number | |
| Line | Line Number | |
| Flight | Name of Flight | yyyymmdd.ff |
| DateTime | DateTime Format | Decimal days |
| Date | DateTime Format | yyyymmdd |
| Time | Time UTC | hhmmss.sss |
| AngleX | Angle (in flight direction) | Degrees |
| AngleY | Angle (perpendicular to flight direction) | Degrees |
| Height | Filtered Height Measurement | Meters [m] |
| Lon | Longitude, WGS84 | Decimal Degrees |
| Lat | Latitude, WGS84 | Decimal Degrees |
| E_UTM14N_M | Easting, NAD83 UTM Zone 14N | Meters [m] |
| N_UTM14N_M | Northing, NAD83 UTM Zone 14N | Meters [m] |
| DEM_M | Digital Elevation | Meters [m] |
| Alt | DGPS Altitude above sea level | Meters [m] |
| GDSpeed | Ground Speed | Kilometers/hour [km/h] |
| Curr_LM | Current, Low Moment | Amps [A] |
| Curr_HM | Current, High Moment | Amps [A] |
| LMZ_G01 [Gates 0-27] | Normalized (PFC-Corrected) Low Moment Z-RxCoil value | $pV/(m^4*A)$ |
| HMZ_G01 [Gates 0-36] | Normalized (PFC-Corrected) High Moment Z-RxCoil value | $pV/(m^4*A)$ |
| LMX_G01 [Gates 0-27] | Normalized (PFC-Corrected) Low Moment X-RxCoil value | $pV/(m^4*A)$ |
| HMX_G01 [Gates 0-36] | Normalized (PFC-Corrected) High Moment X-RxCoil value | $pV/(m^4*A)$ |
| _60Hz_IntenSity | Power Line Noise Intensity monitor | |
| bmag_f | Raw Base Station Mag Data filtered | nanoTesla [nT] |
| Diurnal | Diurnal Mag Data | nanoTesla [nT] |
| MA1_orig | Raw Mag Data | nanoTesla [nT] |
| Mag_fil | Mag filtered | nanoTesla [nT] |
| Mag_CD | Mag Data Corrected for Diurnal Drift | nanoTesla [nT] |
| RMF | Residual Magnetic Field | nanoTesla [nT] |
| IGRF | International Geomagnetic Reference Field | nanoTesla [nT] |
| East_ft | Easting, NAD83 Nebraska SPCS83 | Feet [ft] |
| North_ft | Northing, NAD83 Nebraska SPCS83 | Feet [ft] |
| Elevation_ft | Elevation, 100 ft grid of NED DEM NAVD88 | Feet [ft] |

**Table 6-2: Channel name, description, and units for TPCP_SCI_Inv_v3 Geosoft gdb and xyz files with EM inversion results.**

| Parameter | Description | Unit |
|---|---|---|
| LINE | Line Number | Feet [ft] |
| X_FT | Easting NAD83, UTM Zone 14 | Feet [ft] |
| Y_FT | Northing NAD83, UTM Zone 14 | 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] |
| DELTAALT | Change in Altitude 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 6-3: Files containing borehole information for the TPNRD-CPNRD AEM survey.**

| Database (*.xyz, *.gdb) | Description |
|---|---|
| CPNRDElogs_Collar | Geophysical ELogs from CSD registered wells within the CPNRD |
| CPNRDElogs_Data | |
| CPNRDLith_Collar | Lithology logs from CSD registered wells within the CPNRD |
| CPNRDLith_Lith | |
| CPNRDStrat_Collar | Stratigraphy logs from CSD registered wells within the CPNRD |
| CPNRDStrat_Strat | |
| CPNRDDNRLith_Collar | Lithology logs from DNR registered wells within the CPNRD AEM Survey; Range 16-22 West |
| CPNRDDNRLith_Lith | |
| NCORPDNRLith_Collar | Lithology logs from DNR registered wells within the N-CORPE AEM survey area |
| NCORPDNRLith_Lith | |
| NCORPMRNRDElog_Collar | Geophysical ELogs from CSD registered wells within the MRNRD for the N-CORPE AEM survey area |
| NCORPMRNRDElog_Data | |
| NCORPMRNRDLith_Collar | Lithology logs from CSD registered wells within the MRNRD for the N-CORPE AEM survey area |
| NCORPMRNRDLith_Lith | |
| NCORPMRNRDStrat_Collar | Stratigraphy logs from CSD registered wells within the MRNRD for the N-CORPE AEM survey area |
| NCORPMRNRDStrat_Strat | |
| TBNRDELog_Collar | Geophysical ELogs from CSD registered wells within the TBNRD |
| TBNRDELog_Data | |
| TBNRDLith_Collar | Lithology logs from CSD registered wells within the TBNRD |
| TBNRDLith_Lith | |
| TBNRDStrat_Collar | Stratigraphy logs from CSD registered wells within the TBNRD |
| TBNRDStrat_Strat | |
| TPCPNRDDNRLith_Collar | Lithology logs from DNR registered wells within the TPNRD and CPNRD AEM survey areas; Range 23-29 West |
| TPCPNRDDNRLith_Lith | |
| TPNRDDNRWestLith_Collar | Lithology logs from DNR registered wells within the west side of the TPNRD AEM survey areas; Range 30-38 West |
| TPNRDDNRWestLith_Lith | |
| TPNRDElog_Collar | Geophysical ELogs from CSD registered wells within the TPNRD |
| TPNRDElog_Data | |
| TPNRDLith_Collar | Lithology logs from CSD registered wells within the TPNRD |
| TPNRDLith_Lith | |
| TPNRDStrat_Collar | Stratigraphy logs from CSD registered wells within the TPNRD |
| TPNRDStrat_Strat | |
| O&GStrat_Collar | Stratigraphy logs from NOGCC registered wells |
| O&GStrat_Strat | |

**Table 6-4: Channel name, description, and units for collar files.**

| Parameter | Description | Unit |
|---|---|---|
| DH_Hole | Name of individual boreholes | |
| DH_East | Easting of boreholes, NAD83, UTM Zone 14 | Feet [ft] |
| DH_North | Northing of boreholes, NAD83, UTM Zone 14 | Feet [ft] |
| DH_RL | Elevation of top of borehole | Feet [ft] |
| DH_Dip | Dip of borehole | Degrees |
| DH_Azimuth | Azimuth of borehole | Degrees |
| DH_Top | Depth to top of borehole | Feet [ft] |
| DH_Bottom | Depth to bottom of borehole | Feet [ft] |
| DH_ZMin | Minimum elevation in borehole | Feet [ft] |
| DH_ZMax | Maximum elevation in borehole | Feet [ft] |

**Table 6-5: Channel name description and units for borehole data.**

| Parameter | Description | Unit | Type of Log |
|---|---|---|---|
| DH_East | Easting of boreholes, NAD83, UTM Zone 14 | Feet [ft] | All |
| DH_North | Northing of boreholes, NAD83, UTM Zone 14 | Feet [ft] | All |
| DH_RL | Elevation of top of borehole | Feet [ft] | All |
| DH_From | End of interval | Feet[ft] | Strat, Lith |
| DH_To | Start of interval | Feet [ft] | Strat, Lith |
| DH_Strat_Code | Code used to indicate type of stratigraphy | | Strat |
| DH_Soil_Code | Code used to indicate type of lithology | | Lith |
| DH_Lith_Number | 1 of 30 numbers assigned to reference lithology | | |
| Lithcode | Lithology description associated with 30 categories | | |
| StratCode | Formation designation (e.g. "***Q***", "***Kd***") | | |
| DH_Description/DH_Des | Description of stratigraphy or lithology | | Strat, Lith |
| DH_Depth | Depth | Feet [ft] | GP |
| DH_SP | Self Potential | milliVolt [mV] | GP, E, Geo |
| DH_SN | Short Normal Resistivity | Ohm-m | GP |
| DH_SFL | Spherically Focus Log | Ohm-m] | GP |
| DH_ILD | Induction Log Deep | Siemens/m [S/m] | GP |
| DH_ILM | Induction Log Medium | Siemens/m [S/m] | GP |
| DH_LAT | Laterolog | Ohm-m | GP |
| DH_Res | Resistivity | Ohm-m | Constrain, E |
| DH_Nat_Gam | Natural Gamma | Counts | Geo |
| DH_Res_SnglPt | Resistivity Single Point | Ohm-m | Geo |
| DH_Res_16 | Resistivity 16in | Ohm-m | Geo |
| DH_Res_64 | Resistivity 64in | Ohm-m | Geo |
| DH_Res_Lat | Res Laterolog | Ohm-m | Geo |
| DH_SP_Cond | Self Potential Induction | milliVolt [mV] | Geo |
| DH_Res_FL | Resistivity of the fluid | Ohm-m | Geo |
| DH_Tmp_FL | Temperature of the fluid | Degrees F | Geo |
| DH_Del_Tmp | Change in temperature of the fluid | Degrees F | Geo |

**Table 6-6: Raw SkyTEM data files**

| Folder | File Name | Description |
|---|---|---|
| Data | ..NavSys.sps, …PaPc.sps, ...RawData_PFC.skb, …DPGS.sps | Raw data files included for each flight used in importing to Aarhus Workbench |
| Geo | 20160815_337m2_Cal_DualWaveform_60Hz.gex | 304M System Description |
| Mask | TPNRD_CPNRD_NCORPE_PRRIP_Linefile.lin | Production file listing dates, flights, and assigned line numbers |

**Table 6-7: Channel name description and units for the interpretation results files TPNRD/CPNRD/N-CORPE/PRRIP_InterpSurfaces_v1 "gdb" and "xyz" files.**

| Parameter | Description | Unit |
|---|---|---|
| Line | Flight Line Number | |
| East_ft | Easting NAD83, Nebraska State Plane CS, code 2600 | Feet [ft] |
| North_ft | Northing NAD83, Nebraska State Plane CS, code 2600 | Feet [ft] |
| DEM_ft | Topography at 100ft sampling (NAVD 1988) | Feet [ft] |
| RHO[0] through RHO[28] | Array of Inverted model resistivities of each later | Ohm-m |
| RHO_STD[0] through RHO_STD[28] | Array of standard deviations of inverted model resistivities of each layer | |
| RESDATA | Inversion model residuals of each individual sounding | |
| RESTOTAL | Average of all model inversion residuals | |
| DEP_TOP_ft[0] through DEP_TOP_ft[28] | Depth to the top of individual layers | Feet [ft] |
| DEP_BOT_ft[0] through DEP_BOT_ft[28] | Depth to the bottom of individual layers | Feet [ft] |
| DOI_UPPER_FT | More conservative estimate of DOI from Workbench | Feet [ft] |
| DOI_LOWER_FT | Less conservative estimate of DOI from Workbench | Feet [ft] |
| WaterTable_2013 | Elevation of the top of the water table from the Nebraska School of Natural Resources Configuration Report, 2013. | Feet [ft] |
| AquiferMaterialType[0] through AquiferMaterialType[28] | Array of Aquifer Material types: 0 - Bedrock; 1 - Non-Aquifer Material; 2 - Marginal Aquifer Material; 3 - Aquifer Material; 4 - Coarse Aquifer Material | Integer Array |
| ***To*** | Elevation of the top of the Tertiary Ogallala Formation | Feet (ft) |
| Top_Upper_AqMat | Elevation of top of upper Aquifer Material (25 - 40 ohm-m) | Feet [ft] |
| Bot_ Upper_AqMat | Elevation of bottom of upper Aquifer Material (25 - 40 ohm-m) | Feet [ft] |
| Top_Lower_AqMat | Elevation of top of lower Aquifer Material (25 - 40 ohm-m) | Feet [ft] |
| Bot_ Lower_AqMat | Elevation of bottom of lower Aquifer Material (25 - 40 ohm-m) | Feet [ft] |
| Top_CoarseAqMat | Elevation of top of Coarse Aquifer Material (>40 ohm-m) | Feet [ft] |
| Bot_CoarseAqMat | Elevation of bottom of Coarse Aquifer Material (>40 ohm-m) | Feet [ft] |
| Base_of_Aquifer | Elevation of interpreted base of aquifer surface | Feet [ft] |
| ***Tb*** | Elevation of the top of the Tertiary Brule Formation. | Feet [ft] |
| ***Kp*** | Elevation of the top of the Cretaceous Pierre Formation | Feet [ft] |
| ***Kn*** | Elevation of the top of the Cretaceous Niobrara Formation | Feet [ft] |
| ***Kc*** | Elevation of the top of the Cretaceous Carlile Formation | Feet [ft] |
| * | No data or unit not detected | |

**Table 6-8. Files containing ESRI ArcView Binary Grids *.flt and Geosoft Grids *.grd (NAD 83 State Plane Nebraska (US foot)**

| Grid File Name | Description | Grid Cell Size (feet) |
|---|---|---|
| CPNRD_WT_Elevation<br>NCORPE_WT_Elevation<br>PRRIP_Block_WT_Elevation<br>TPCP_WT_Elevation<br>TPNRD_WT_Elevation | Grids of the 2013 CSD water table elevation; NAVD88 (feet) | 100 |
| CPNRD_BOA_Elevation<br>NCORPE_Tb_Elevation<br>PRRIP_Kp_Elevation<br>TPCP_BOA_Elevation<br>TPNRD_BOA_Elevation | Grids of the top of the Base of Aquifer. For the CPNRD and TPNRD composed of Tertiary Brule Formation (***Tb***), Cretaceous Pierre Shale (***Kp***), Cretaceous Niobrara Formation (***Kn***) at 1,000 feet cell size. For the N-CORPE composed of Tertiary Brule Formation (***Tb***) at 250 feet cell size. For the PRRIP Block composed of Cretaceous Pierre Shale (***Kp***) at 250 feet cell size; NAVD88 (feet) | 1,000,<br>250 |
| CPNRD_DEM<br>NCORPE_DEM<br>PRRIP_DEM<br>TPCP_DEM<br>TPNRD_DEM | Grids of the Digital Elevation Models (DEM) downloaded from the National Elevation Dataset (NED) August 2016; NAVD88 (feet) | 100 |
| CPNRD_To_Elevation<br>NCORPE_To_Elevation<br>PRRIP_ To_Elevation<br>TPCP_To_Elevation<br>TPNRD_To_Elevation | Grid of the top of the Tertiary Ogallala Group (***To***); NAVD88 (feet) | 250 |
| CPNRD_Tb_Elevation<br>NCORPE_Tb_Elevation<br>TPCP_Tb_Elevation<br>TPNRD_Tb_Elevation | Grid of the top of the Tertiary Brule Formation (***Tb***) or the top of the Tertiary White River Group (***Twr***) elevation. For the N-CORPE area a 250 feet cell size; NAVD88 (feet) | 1,000,<br>250 |
| CPNRD_Kp_Elevation<br>NCORPE_ Kp _Elevation<br>PRRIP_ Kp _Elevation<br>TPCP_ Kp _Elevation<br>TPNRD_ Kp _Elevation | Grid of the top of the Cretaceous Pierre Shale (***Kp***) elevation. For the N-CORPE and PRRIP Block area a 250 feet cell size; NAVD88 (feet) | 1,000,<br>250 |
| CPNRD_Kn_Elevation<br>PRRIP_ Kn _Elevation<br>TPCP_ Kn _Elevation<br>TPNRD_ Kn _Elevation | Grid of the top of the Cretaceous Niobrara Formation (***Kn***) elevation. For the PRRIP Block area a 250 feet cell size. Areas to the west and east are truncated due to depth of investigation of the AEM; NAVD88 (feet) | 1,000,<br>250 |
| CPNRD_Kc_Elevation<br>TPCP_ Kc _Elevation<br>TPNRD_ Kc _Elevation | Grid of the top of the Cretaceous Carlile Shale (***Kc***) elevation. Areas to the west and east are truncated due to depth of investigation of the AEM; NAVD88 (feet) | 1,000 |
| CPNRD_Saturated_thickness<br>NCORPE_ Saturated_thickness<br>PRRIP_ Saturated_thickness<br>TPCP_ Saturated_thickness | Grids of the thickness of the saturated Quaternary (***Q***) Tertiary Ogallala Group (***To***). For the N-CORPE and PRRIP Block area a 250 feet cell size; (feet) | 1,000,<br>250 |

| | | |
|---|---|---|
| TPNRD_ Saturated_thickness | | |
| CPNRD_Q_thickness<br>NCORPE_ Q_thickness<br>PRRIP_ Q_thickness<br>TPCP_ Q_thickness<br>TPNRD_ Q_thickness | Grids of the thickness of the Quaternary (***Q***); (feet) | 250 |
| CPNRD_To_thickness<br>NCORPE_ To _thickness<br>PRRIP_ To _thickness<br>TPCP_ To _thickness<br>TPNRD_ To _thickness | Grids of the thickness of the Tertiary Ogallala Group (***To***); (feet) | 250 |
| NCORPE_To_Saturated_AquMat_thickness<br>PRRIP_Saturated_AquMat_thickness | Grids of the thickness of the saturated Aquifer Material (>25 ohm-m). For the N-CORPE it is only the Tertiary Ogallala Group (***To***). For the PRRIP Block it is the Quaternary (***Q***) and the Tertiary Ogallala Group (***To***); (feet) | 250 |
| NCORPE_Q_Unsaturated_AquMat_thickness<br>NCORPE_To_Unsaturated_AquMat_thickness<br>PRRIP_Unsaturated_AquMat_thickness | Grids of the thickness of the unsaturated Aquifer Material (>25 ohm-m). For the N-CORPE it is separately the Quaternary (***Q***) and the Tertiary Ogallala Group (***To***). For the PRRIP Block it is the Quaternary (***Q***) and the Tertiary Ogallala Group (***To***); (feet) | 250 |

**Table 6-9. Channel name, description, and units for NCORP_Q_To_voxel and PRRIP_Q_To_Voxel as*.xyz and *.gdb.**

| Parameter | Description | Unit |
|---|---|---|
| X | Easting NAD83, State Plane Nebraska | US Foot [ft] |
| Y | Northing NAD83, State Plane Nebraska | US Foot [ft] |
| Z | Elevation of Voxel Node | NAVD88 [ft] |
| Resistivity | Voxel cell resistivity value of the Quaternary (***Q***) and the Tertiary Ogallala Group (***To***) | Ohm-m |
| Elevation | Ground Surface Elevation NAVD 88 100 ft grid | Feet [ft] |

## 6.2 Description of Included Google Earth KMZ Data and Profiles

In addition to the data delivered in .xyz format, Google Earth .KMZ files were generated to view the geophysical AEM flight line locations and interpreted geologic data. KMZ files for all "*As-Flown*" flight lines and data "*Retained*" for inversion after editing are included in the folder "*Appendix_3_Deliverables**KMZs**FlightLines*".

KMZ files of the potential recharge zones for the N-CORPE and PRRIP flight block survey areas are included in the folder "*Appendix_3_Deliverables**KMZs**Recharge*".

Unique KMZ files were created for each individual flight line in approximately 10-mile segments (some shorter, some longer). Within these specialized KMZ files, the AEM flight line is shown as well as place marks at each location where there are interpreted geologic results. The attribute data for each unique place mark contains location information plus the elevations of tops and bottoms of aquifer material and coarse aquifer material as well as bedrock, the water table (2013), and the elevations of the tops of the Tertiary Ogallala Group (***To***) and the Brule Formation (***Tb***) and Cretaceous Pierre Shale (***Kp***), Niobrara Formation (***Kn***), and the Carlile Shale (***Kc***). These KMZ files are located within the "*Appendix_3_Deliverables**KMZs**Interpretation* folder. There are separate interpretation profile folders for the CPNRD, TPNRD, N-CORPE, and the PRRIP survey areas. Also in each of the profile folders is a "*GoogleE_Readme.pdf*" file that provides instructions in regards to the "*Settings*" changes that need to be made in Google Earth, and how to use the KMZ files in Google Earth including a legend of what attributes are displayed when an AEM sounding location is clicked. The file for the CPNRD is repeated below as a convenience. An example of the CPNRD KMZ is presented in Figure 6-1.

### *6.2.1 Included README for the CPNRD Interpretation KMZ's*

README for:

**CPNRD_Interpretation_v1.kmz**

Data Files – Within the folder "*CPNRD_Interpretation_Profiles*" is the folder "*CPNRD_Profiles*". Please copy the folder *CPNRD_Profiles* to your C:\ drive. Do not rename any of the files or directories within the folder.

Google Earth Instructions:

STEP 1: In Google Earth, click "*Tools*", then "*Options*".

STEP 2: In the Google Earth Options box, click the "*General*" tab.

STEP 3: Under "*Placemark balloons*", make sure the box is checked to allow access to local files (the profiles).

STEP 4: Under "*Display*", make sure the box is checked to show web results in external browser.

STEP 5: The *CPNRD_Interpretation_v1.kmz* file within the folder named *CPNRD_Interpretation_Profiles* can now be opened and viewed in Google Earth.

Data:

***East (m)*** – Easting coordinate in NAD83, UTM 14N, in meters

***North (m)*** – Northing coordinate in NAD83, UTM 14N, in meters

***East (ft)*** – Easting coordinate in NAD83, Nebraska SPCS83, code 2600, in feet

***North (ft)*** – Northing coordinate in NAD83, Nebraska SPCS83, code 2600, in feet

***Elevation (ft)*** – DEM elevation in feet

***WaterTable2013 Elev (ft)*** – 2013 Water Table elevation, in feet.

***Elevation To (ft)*** – Elevation of the Top of the Tertiary Ogallala Group, in feet

***Top Upper AqMat (ft)*** – Elevation of the Top of the Upper Aquifer Material zone, in feet

***Bottom Upper AqMat (ft)*** – Elevation of the Bottom of the Upper Aquifer Material zone, in feet

***Top Lower AqMat (ft)*** – Elevation of the Top of the Lower Aquifer Material zone, in feet

***Bottom Lower Quaternary AqMat (ft)*** – Elevation of the Bottom of the Lower Aquifer Material zone, in feet

***Top Coarse AqMat (ft)*** – Elevation of the Top of the Coarse Aquifer Material zone, in feet

***Bottom Coarse AqMat (ft)*** – Elevation of the Bottom of the Coarse Aquifer Material zone, in feet

***Elevation Base of Aquifer (ft)*** – Elevation of the Base of Aquifer, in feet

***Elevation Tb (ft)*** – Elevation of the Top of the Tertiary Brule Formation, in feet

***Elevation Kp (ft)*** – Elevation of the Top of the Cretaceous Pierre Shale Formation, in feet

***Elevation Kn (ft)*** – Elevation of the Top of the Cretaceous Niobrara Formation, in feet

***Elevation Kc (ft)*** – Elevation of the Top of the Cretaceous Carlile Shale Formation, in feet

***Profile*** – Link to Interpreted AEM profile images

***Legend*** – Link to this write-up describing data channels listed here

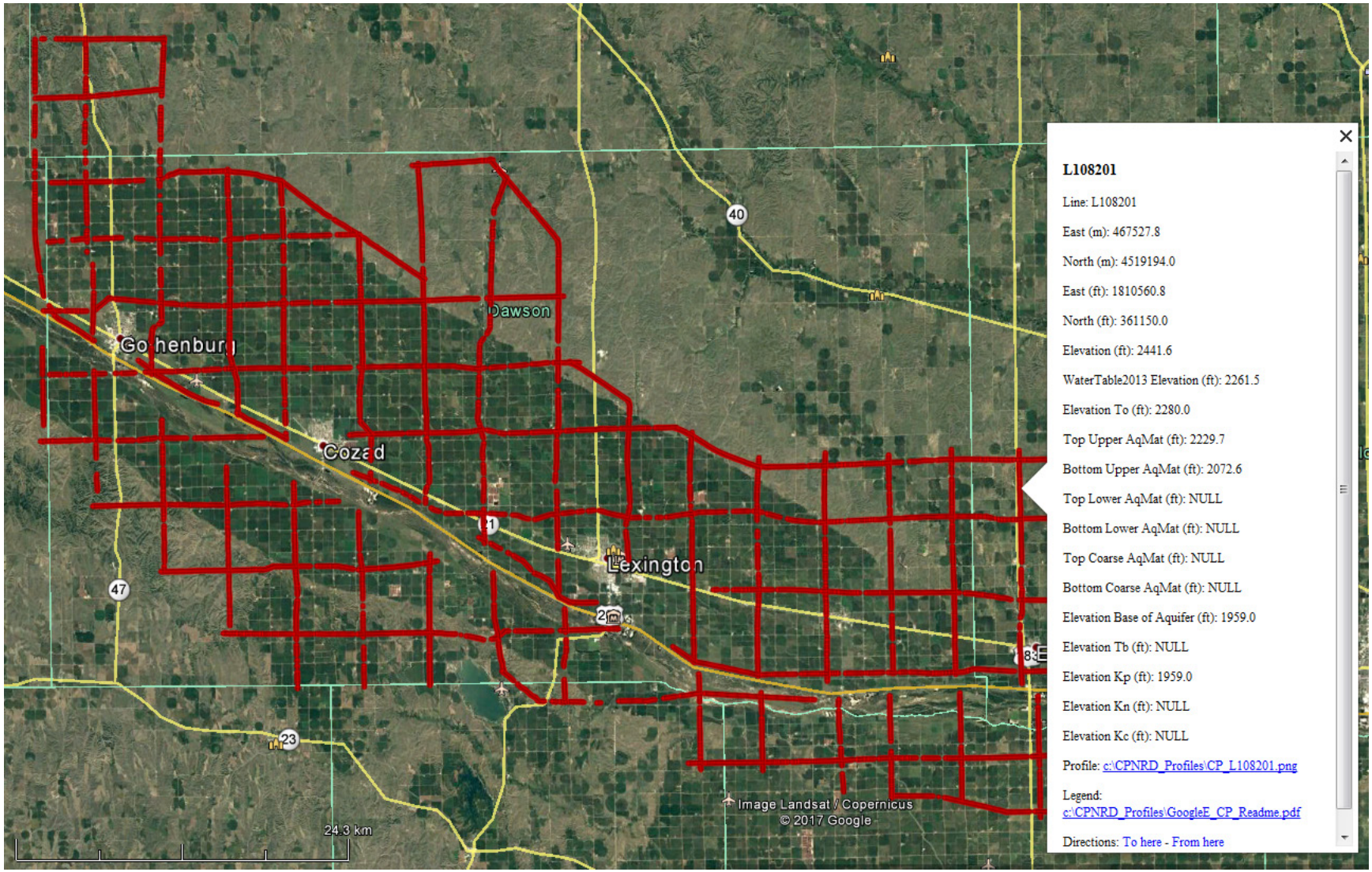



**Figure 6-1. Example Google Earth image for the CPNRD Interpretation kmz.**

## 6.3 Description of Included Profile Analyst (PA) Session Material

As discussed above Datamine Discover PA Version 2015 Release Build 15.0.13 (dataminediscover, 2017) was used to create the 3D volumes and the profiles used in the interpretation within this report. In order to allow the future use of the information imported into the PA platform, PA Session Package files were created and are included within this report. A free viewer is available from the Datamine Discover PA website: http://support.dataminesoftware.com/software-downloads/

The files located in the Appendix_3_Deliverables\PA_Sessions need to be unzipped and copied to a directory and then the Session file needs to be opened within Discover PA. Details on the function of Discover PA can be accessed from the pbEncom website and the help functions within Discover PA. The session files that are included with the project deliverables are summarized in Table 6-10.

**Table 6-10. Datamine Discover (formerly pbEncom Discover) PA Session Files**

| Area Covered | View Format | File name (*.zip) |
|---|---|---|
| **Reconnaissance 2D Profiles for the CPNRD** | **2D** | **CPNRD_Profiles_package** |
| **2D Profiles for the N-CORPE Area** | **2D** | **NCORPE_Profiles_package** |
| **Reconnaissance 2D Profiles for the PRRIP and the PRRIP Block** | **2D** | **PRRIP_Profiles_package** |
| **Reconnaissance 2D Profiles for the TPNRD** | **2D** | **TPNRD_Profiles_package** |
| **3D Fence diagrams and Voxel for the N-CORPE Area** | **3D** | **NCORPE_3DVoxel_Package** |
| **3D Fence diagrams and Voxel for the PRRIP Block** | **3D** | **PRRIP_3DVoxel_Package** |

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