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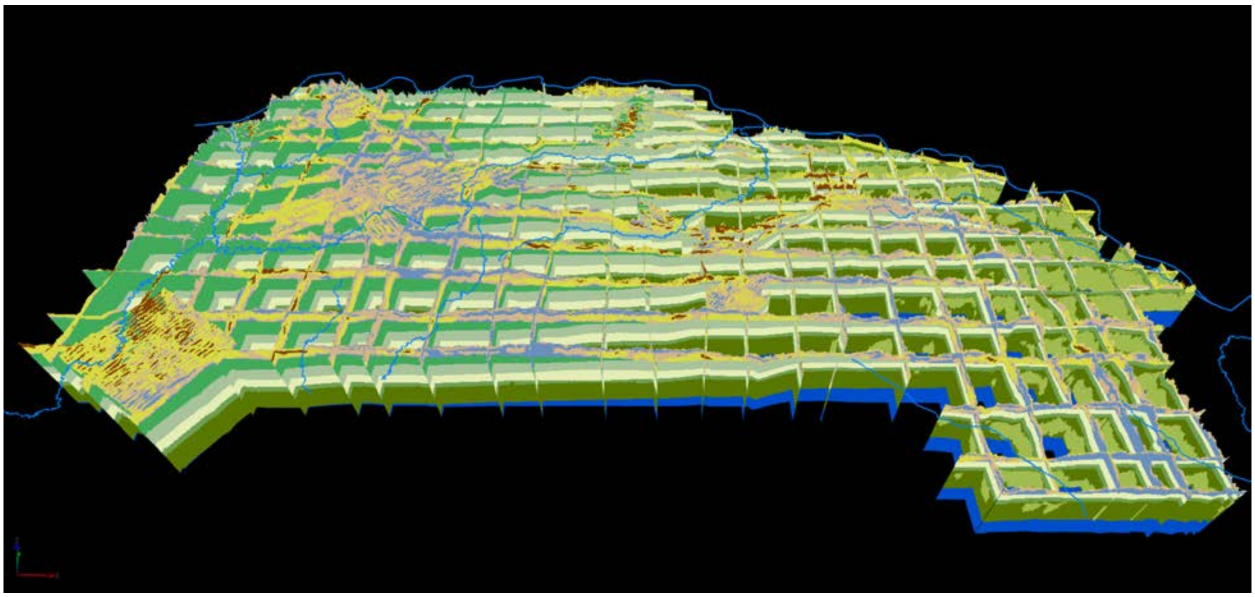
"Airborne Electromagnetic Mapping and Hydrogeologic Framework of Selected Regions of the Eastern Nebraska Water Resources Assessment Area" Chapter on the Lewis & Clark Natural Resources District



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Executive Summary

Aqua Geo Frameworks, LLC. (AGF) is pleased to submit this report titled *"Airborne Electromagnetic Mapping and Hydrogeologic Framework of Selected Regions of the Eastern Nebraska Water Resources Assessment Area" Chapter on the Lewis & Clark Natural Resources District*.

An understanding of the hydrogeological framework in the survey area is desired to assist in resource management. AGF entered into an agreement with the Eastern Nebraska Water Resources Assessment (ENWRA) and the Lewis & Clark Natural Resources District (LCNRD) to collect, process, and interpret airborne electromagnetic (AEM) data, in conjunction with other available background information, to develop a 3D hydrogeologic framework of the LCNRD project area 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 An AEM survey utilizing the SkyTEM304M and SkyTEM312 systems was flown over the LCNRD project area. These flights have been provided as preliminary AEM inversions and the final AEM data and inversions are included as a product attached to this data report.

1.2 AGF began project planning upon signing of the project between AGF, ENWRA, and the LCNRD. This work included flight plans, database development, and review of hydrogeologic and geologic work for the area. The LCNRD assisted in providing information such as power line maps, test hole databases, and related aquifer characteristic studies, if available. LCNRD and the Conservation Survey Division (CSD) provided the flight planning for the survey.

1.3 Upon conclusion of the design process, the LCNRD AEM investigation consisted of Reconnaissance flight lines utilizing the SkyTEM312 system and seven (7) AEM Block flight areas including the Aten, Bloomfield, Hartington, Lindy, Menominee, Obert, and Lindy survey areas utilizing the SkyTEM304M system. The SkyTEM312 Reconnaissance flight lines had a maximum length of approximately 58 miles (94 km) in length in the east-west direction and about 23 miles (37 km) at their longest in the north-south direction and were separated by approximately 2.5 to 3 miles (about 4-5 km) in both east-west and north-south directions. The AEM Block flights with the SkyTEM304 had variable flight line lengths and separations, from approximately 10 miles (16 km) to approximately 3 miles (5 km) and were separated by about 1,500 feet to 4,900 ft (0.9 miles) (or 450 m to 1.5 km).

1.4 AGF acquired AEM data over the LCNRD, commencing 18 July 2018 and finishing on 26 July 2018, to support development of the hydrogeological framework. During this time frame data were collected in other adjacent NRD's near the LCNRD. Approximately 1,210.5 line-miles (1,901 line-kilometers) were acquired over the LCNRD AEM survey area (SkyTEM 312 - 822 miles/1331 km and SkyTEM 304 – 389 miles/630 km). Status reports of the flying were provided to the Contract Representative of ENWRA and LCNRD daily, 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 July 21 – July 27, 2018. Approximately 1,034-line-miles (1,675-line kilometers) were retained for inversion amounting to a retention rate of 85.4% (SkyTEM 312 – 713 miles/1,155 km, SkyTEM

304 – 321 miles/520 km). This high rate is the result of careful flight line planning and design given the infrastructure that was encountered during the acquisition.

1.6 AGF inverted the AEM data. These final inverted georeferenced data are delivered to the LCNRD with this report. After inversion, AGF derived 2D sections, 3D electrical models, and interpreted geologic and hydrogeologic surfaces of the surveyed area.

1.7 An amendment was made to the contract for AGF to merge all the AEM data collected within the LCNRD as well as the area around Creighton, Nebraska. This included data collected in 2014 and 2016. This total, merged, AEM dataset was used in the development of the hydrogeologic framework.

1.8 AGF is providing a hydrogeologic framework report that includes maps of aquifer materials and their relationships to current test holes and production groundwater wells, and maps of estimated potential recharge 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 and was important for all areas in the LCNRD. The CSD stratigraphic control was utilized to distinguish the ***Kp***, ***Kn***, ***Kc***, ***Kgg,*** and ***Kd***. Contacts between the Quaternary (***Q***) Tertiary Ogallala (***To***)***,*** and Cretaceous Dakota Group (***Kd***) can have limited or no contrast in the electrical resistivity between the different geologic formations. Use of CSD stratigraphy calls and the presence of sandstone and shale in the NE- DNR (Nebraska Department of Natural Resources) registered wells were used to pick the contact when no resistivity contrast was present. The dependence on just boreholes for geologic interpretation also has its limitations because sometimes the borehole logs are wrong, improperly located, have improper stratigraphic/lithology picks, and/or other errors. These errors in the boreholes are usually encountered in the NE-DNR registered wells. Rare inconsistencies are encountered in the oldest of the NE- CSD wells. The limited errors in the CSD wells may very well be due to poor positioning from a time before GPS and modern survey methods. As a guide in the interpretation of the AEM***,*** a bedrock surface was prepared using the of CSD and NE-DNR borehole logs and surface maps of the geologic outcrops. As in all surveys of this nature the use of boreholes with AEM needs to be approached in a thoughtful and considered manner as to the value of information from an individual borehole.

2.2 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***), Cretaceous Pierre Shale (***Kp***), Cretaceous Niobrara Formation (***Kn***), Cretaceous Carlile Shale (***Kc***), Cretaceous Greenhorn Limestone and Graneros Shale (***Kgg***), Cretaceous Dakota Group (***Kd***), and undifferentiated Pennsylvanian (***IP***). The interpretive process benefited from the use of CSD, Nebraska Oil and Gas Conservation Commission (NEOGCC), and NE-DNR borehole logs. Geologic maps of surface outcrops and geologic maps contributed to the understanding of geologic interpretation. Surface grids of the interpreted geologic formations were then produced. Each flight line profile with interpretation including the Quaternary (***Q***)aquifer material mapping is included in the appendices as well as interpretative surface grids.

2.3 Resistivity/Lithology Relationship - Assessment of the sediment character in the Quaternary aquifer system and the bedrock strata was conducted to determine the overall composition of the major categories used to define the aquifer and aquitards in eastern Nebraska. A statistical assessment of the resistivity thresholds was used to characterize non-aquifer (<12 ohm-m), marginal (12-20 ohm-m), and aquifer (20-50 ohm-m), including coarse sand-rich intervals (>50 ohm-m) was determined in 2015 (Carney et al., 2015a). This allowed for the characterization of the ranges of resistivities present in the major geologic units described in this report.

2.4 Hydrogeological Framework of the LCNRD - The 2018 LCNRD AEM survey reveals variability in the Quaternary (***Q***), Tertiary Ogallala (***To***) and Cretaceous Dakota Group (***Kd***) deposits across the LCNRD AEM survey area that make up the aquifer materials. The ***Q*** and ***To*** make up the aquifer materials overlying the Cretaceous bedrock units of which the ***Kd*** Sandstone/Sand Dominant material is the aquifer material. In the north and south parts of the AEM survey area, the aquifer material and coarse aquifer material exist in paleovalleys and glacial outwash deposits that are separated by ***Q*** deposits which consist of predominantly marginal to non-aquifer materials that are glacial till and loess and that can be more than 400 ft thick. ***Q*** aquifer and coarse aquifer materials are thick in the paleovalleys located in Aten, Menominee, and Obert 2018 survey areas.

Estimates of the groundwater in storage within the ***Q***-portion of the Aten AEM Block of aquifer material below the 1995 CSD water table elevation is 211,513 acre-ft. The amount of extractable groundwater from aquifer material is 8,831 acre-ft and coarse aquifer material is 386 acre-ft. The amount of extractable groundwater from ***Kd*** Sandstone/Sand Dominant material is 111,988 acre-ft.

Estimates of the groundwater in storage within the ***Q***-portion of the Bloomfield AEM Block of aquifer material below the 1995 CSD water table elevation is 1,650,569 acre-ft. The amount of extractable groundwater from aquifer material is 38,998 acre-ft and coarse aquifer material is 25 acre-ft.

Estimates of the groundwater in storage within the ***Q***-portion of the Hartington AEM Block of aquifer material below the 1995 CSD water table elevation is 184,310 acre-ft. The amount of extractable groundwater from aquifer material is 6,385 acre-ft and coarse aquifer material is 56. While these materials will produce water, the yields and specific capacity will be reduced.

Estimates of the groundwater in storage within the ***Q***-portion of the Menominee AEM Block of aquifer material below the 1995 CSD water table elevation is 28,947 acre-ft. The amount of extractable groundwater from aquifer material is 1,069 acre-ft and coarse aquifer material is 4.

Estimates of the groundwater in storage within the ***Q***-portion of the Santee AEM Block of aquifer material below the 1995 CSD water table elevation is 2,602 acre-ft. The amount of extractable groundwater from aquifer material is 52 acre-ft and coarse aquifer material is 0.

2.5 Potential Recharge Zones within the LCNRD AEM Survey Area - Within the LCNRD Reconnaissance AEM flight area the highest rate of recharge can be expected along the river and stream valleys due to the presence of aquifer and coarse aquifer materials from the land surface down to the water table and beyond. Areas with aquifer and coarse aquifer materials at the surface can also become conduits for infiltration of nitrates into the groundwater system. These areas exist in the river and stream areas of the survey area where the reconnaissance lines are the basis for this determination. It should be noted that in these areas the results shown in the recharge maps are based on actual AEM data. A potential solution for any nonpoint source water quality contamination is adding additional fresh surface water as recharge to select areas of rangeland that can dilute any potential nitrate contaminant problem occurring from cropland. Additional work can be done to identify where the best locations are for these type of management efforts. The current recharge analysis allows for more accurate representation of the aquifer materials in the first 10 feet from the land surface downward.

The use of Block flights for Aten, Bloomfield, Hartington, Lindy, Menominee, Obert, and Santee 2018 AEM survey areas as well as the 2016 AEM Block survey areas Coleridge and Creighton illustrate the preferred method of using AEM to identify areas where the potential for recharge to the aquifer can be high and low. Locations where the flight lines are closely spaced showing either aquifer or coarse aquifer material at the land surface should be considered as locations for higher likelihood for recharge because of the 2D and 3D spatial nature of the aquifer material distribution. The opposite is also true where AEM data analysis shows non-aquifer or marginal aquifer material. Those areas will likely not be optimal recharge locations. The areas throughout the Aten, Creighton, Hartington, Menominee, and Obert AEM survey areas have potential recharge that is good across most of the area due to the ***Q*** aquifer and coarse aquifer materials at the land surface. The areas throughout the Bloomfield, Coleridge, Lindy, and Santee AEM survey areas have potential recharge that is limited in extent due to the ***Q*** marginal and non-aquifer aquifer materials at the land surface.

2.6 Hydrologic Connection Between Groundwater and Surface Water in the LCNRD AEM Survey Area - The AEM data and interpretation provides detailed empirical data for determining earth materials at depth that are related to aquifer characteristics. The ***Q*** aquifer materials are a guide with coarse aquifer and aquifer materials being the most able to recharge, store, and provide groundwater flow. The marginal aquifer material provides limited groundwater flow with poor recharge and the non-aquifer material provides virtually no groundwater flow. The areas mapped and presented in this report show areas that contain large amounts of marginal and non-aquifer deposits. These areas can be boundary conditions between different parts of the groundwater system and the surface water of the area. Any planning or detailed analysis related to groundwater and surface water relationships should take this information into account.

3. RECOMMENDATIONS

Recommendations provided to the LCNRD 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 the LCNRD about their management challenges.

3.1 **Preparing the Results from AEM Hydrogeological Investigations for Groundwater Modeling** - The LCNRD has acquired AEM data for groundwater management purposes. With the completion of this current AEM study there needs to be additional work done to integrate any additional data and geologic modeling to create optimal datasets for input into groundwater models and water quality studies.

3.2 **Additional AEM Mapping** - No additional reconnaissance-level AEM mapping is needed for the LCNRD at this time. Future additional Block data acquisition should be considered as needed depending on future projects by the LCNRD.

3.3 **Update the Water Table map** - The groundwater data used in the analyses presented in this report utilized the 1995 CSD water table map which is now 24 years old. Additional water level measurement locations would improve the water table map where groundwater conditions are unconfined. The areas of glacial till and loess covering the parts of the district will need great care in developing a water level map of potentiometric heads due to the confined to semiconfined nature of the area. Use of the data collected in this survey and future surveys will provide the best possible water table and conditions map for the district.

3.4 **Siting new test holes and production wells** – The AEM hydrogeological framework profiles, maps, and surfaces provided in this report provide great 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 LCNRD area was used in building the framework maps and profiles. Additional information from previous groundwater reports were helpful in this work. 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 more 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. A good example of this would be confined aquifers with large volumes of coarse aquifer and aquifer material with minimal aquiclude boundary conditions. The previous AEM studies have already found use by CSD and local well drillers to locate test wells and production wells within the LCNRD.

3.5 **Aquifer testing and borehole logging** - Aquifer tests are recommended to improve estimates of aquifer characteristics. Limited aquifer properties from previous reports 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. Examples of additional logging would be flow meter logs and geophysical logs including gamma, neutron, electrical, and induction logs. Detailing aquifer characteristics can be accomplished with nuclear magnetic resonance logging (NMR) at a reduced cost when compared to traditional aquifer tests. 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.

3.6 **Recharge Zones** - The LCNRD hydrogeologic framework in this report provides areas of recharge from the ground surface to the groundwater aquifer. Reconnaissance-level AEM investigations provide limited detailed information between the lines for understanding recharge throughout the survey area. It is recommended that future work integrate new soils and land use 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. A potential solution to water quality, quantity, and stream depletions is adding additional fresh surface water as recharge to select areas of rangeland or other areas. Additional work can be done to identify where the best locations are for these type of management efforts. This information can and has been used in Nebraska to improve Well Head Protection Areas by refining the estimated travel time estimates and the boundary areas.

3.7 **Managed Aquifer Recharge** – The areas which may have potential for managed aquifer recharge (MAR) can be approximately located by the interpreted results from AEM reconnaissance line interpretations. Detailed analysis for this purpose would need to be done to determine where viable opportunities for the LCNRD exist and what additional information would be required for final selections of MAR sites. Additional AEM mapping in new block flight locations and along the streams in the LCNRD would also be beneficial in locating potential MAR locations. A detailed plan for locating and developing MAR sites would be beneficial to the LCNRD for storage and release of water for stream flow and other uses.

3.8 **Updating previous groundwater reports and Groundwater Management Plans** - The groundwater reports and management plans should be updated with the AEM information. The addition of estimates of groundwater in storage, recharge areas, hydrologic connection to streams and consideration of managed aquifer recharge sites will greatly improve and groundwater management plan.

3.9 **Assist the LCNRD staff with additional interpretation and data analysis for groundwater management needs** – The AEM reports provided to the district are complete, but there is always a need to extract and analyze the AEM data in conjunction with a particular management need or area. Examples include using the AEM data to define areas for management practices related to water quality problems, use the AEM data to site water well development, assist groundwater modelers with input data sets for groundwater modeling, and define hydrologic connections between groundwater and surface water to name a few.

4. DELIVERABLES

In summary, the following are included as deliverables:

- Raw EM Mag data as ASCII *.xyz
- SCI inversion as ASCII *.xyz
- Interpretations as ASCII *.xyz
- Raw Data Files - SkyTEM files *.gex, *skb, *.lin
- ESRI ArcView grid files – surface, topo, *.flt, *.grd, etc
- Voxel Grids of the Aten, Bloomfield, Hartington, Menominee, and Santee Blocks *.csv
- 2D Profiles and 3D fence diagrams of the AEM survey lines

Google Earth KMZs for LCNRD AEM flight lines, interpretation, and recharge.

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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
ASR	Aquifer Storage and Recovery
dB/dt	Change in amplitude of magnetic field with time
BMP	Best management plan
CSD	Conservation and Survey Division
DEM	Digital Elevation Model
DEQ	Nebraska Department of Environmental Quality
DOI	Depth of Investigation
DGPS	Differential global positioning system
DNR	Nebraska Department of Natural Resources
em, EM	Electromagnetic
ENWRA	Eastern Nebraska Water Resources Assessment
FT	Fourier Transform
FT, ft	Feet
ft^3	cubic feet
Fm	Formation
GIS	Geographic Information System
Hr, hr	hours
Hz	Hertz (cycles per second)
IGRF	International Geomagnetic Reference Field
IP	undifferentiated Pennsylvanian units
Km, km	Kilometers
KMZ, kmz	Keyhole Markup language Zipped file
Kc	Cretaceous Carlile Shale Formation
Kd	Cretaceous Dakota Group
Kgg	Cretaceous Greenhorn Limestone and Graneros Shale
Kn	Cretaceous Niobrara Shale Formation
Kp	Cretaceous Pierre Shale Formation
LCI	Laterally-constrained Inversions
LCNRD	Lewis and Clarke Natural Resources District
LENRD	Lower Elkhorn Natural Resources District
MAG	Magnetic (data); Magnetometer (instrument)
MCG	Minimum curvature gridding
M, m	Meters
mi^2	Miles squared
NAD83	North American Datum of 1983
MAR	Managed Aquifer Recharge
NAVD88	North American Vertical Datum of 1988
NE	Nebraska
NED	National Elevation Dataset
NE-DEQ	Nebraska Department of Environmental Quality
NE-DNR	Nebraska Department of Natural Resources

NMR	Nuclear Magnetic Resonance
NOGCC	Nebraska Oil and Gas Conservation Commission
NRD	Natural Resources Districts
OM	Geosoft Oasis montaj
PFC	Primary Field Compensation
PLNI	Power Line Noise Intensity
P-MRNRD	Papio-Missouri River Natural Resources District
Q	Quaternary
Rx	Receiver
recon	Reconnaissance
sec	second
SCI	Spatially-Constrained Inversion
STD	Standard Deviation
TEM	Transient Electromagnetic
TDEM	Time-Domain Electromagnetic
To	Tertiary Ogallala Formation
Tx	Transmitter
UNL	University of Nebraska Lincoln
USGS	United States Geological Survey
UTM	Universal Transverse Mercator
V.E.	Vertical Exaggeration
V/m^2	Volts per meter squared
X, x	The x-direction in a cartesian coordinate system
XRI	Exploration Resources International
Y, y	The y-direction in a cartesian coordinate system
Z, z	The z-direction (positive is up) in a cartesian coordinate system

1 Introduction

1.1 Purpose of Current Project

Sound management of groundwater and surface water in eastern Nebraska has become increasingly important in recent years. There are expanding pressures placed on the resource by the ever growing and dynamic demands for: water supply for rural water districts, agricultural production, population growth and urbanization, potential contamination from natural and anthropogenic sources, industrial and commercial needs; along with ever present changing climate.

The combination of these stresses on water resources has increased the need for detailed hydrogeologic frameworks of the subsurface. Of particular concern for the LCNRD is providing adequate water supply for the rural water districts that they operate or that they support. Being able to supply safe high-quality water to the districts, towns and private citizens is a priority for the LCNRD. Groundwater management strategies and policies implemented to address water quality concerns is another effort that can be improved with better understanding of groundwater recharge, and its relationship with the underlying aquifers. The mapping of the subsurface related to groundwater flow and hydrologic connection between different aquifers and streams is also important in understanding water quality and quantity. Geographic regions that are identified as major contributors to recharge could be areas targeted for enhanced promotion of best management practices (BMP) to reduce or eliminate future contamination events. The Bazile Groundwater Management Area (BMGA) is a good example of current LCNRD activity to improve water quality. Additional uses of these AEM surveys will be to determine potential areas of Managed Aquifer Recharge (MAR) for additions to current supplies of groundwater in areas if there is a need to replace depletions from development or supply future development. This data can be used to enhance the hydrogeologic framework for groundwater modeling for testing management scenarios at a regional level where boreholes are not sufficient or are of limited use. Where AEM Block flights exist, this dense flight line data would be excellent for local groundwater models by having a high-resolution framework to build the model.

This report describes the general hydrogeologic conditions using data collected from three AEM surveys conducted in 2014, 2016, and 2018. In addition to the AEM data, reports from previous studies, analysis of historic groundwater levels, and geologic descriptions from University of Nebraska-Lincoln Conservation and Survey Division (CSD) test holes, Nebraska Oil and Gas Conservation Commission (NOGCC), and drillers logs obtained from registered wells at the Nebraska Department of Natural Resources (NE-DNR) were used. The AEM survey data were collected along reconnaissance (recon) lines spaced approximately 2.5 miles apart and block flight lines separated by about 1,500 ft to 2,000 ft (450 m – 600 m). The AEM Block flight areas are Aten, Bloomfield, Hartington, Lindy, Menominee, Obert, and Santee. This AEM survey was planned and selected by LCNRD and AGF with assistance from scientists from CSD to assist in the development of a 3D hydrogeologic framework of this project area and recommend future work to enhance groundwater management activities. This work was supported by the Natural Resources Commission Water Sustainability Fund, the LCNRD, and in-kind service from CSD.

A location map showing the LCNRD is presented in Figure 1-1. A location map showing the Block AEM survey areas is presented in Figure 1-2. A Google Earth image of the "As-Flown" flight lines are presented in Figure 1-3 and also included as a kmz in Appendix 3-Deliverables \KMZ\Flight Lines. These are discussed in detail in Section 2. The main AEM flight area was between Yankton, NE in the north and Wakefield, NE in the south and between Springfield, NE in the west and Elk Point, NE in the east.

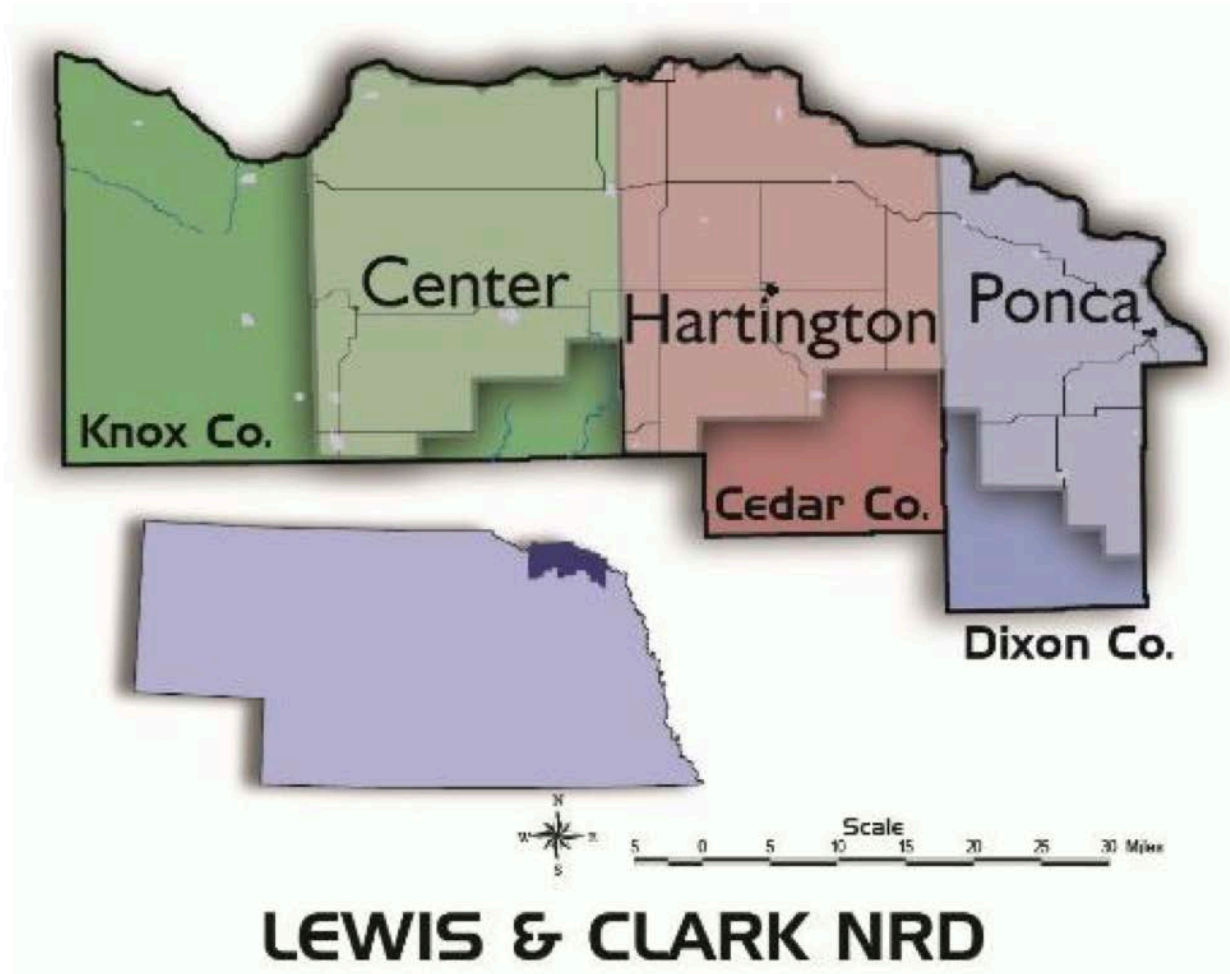


Figure 1-1. Map of the LCNRD in eastern Nebraska (modified from https://www.nrdnet.org/sites/default/files/groundwater_management_summary_2018.pdf)

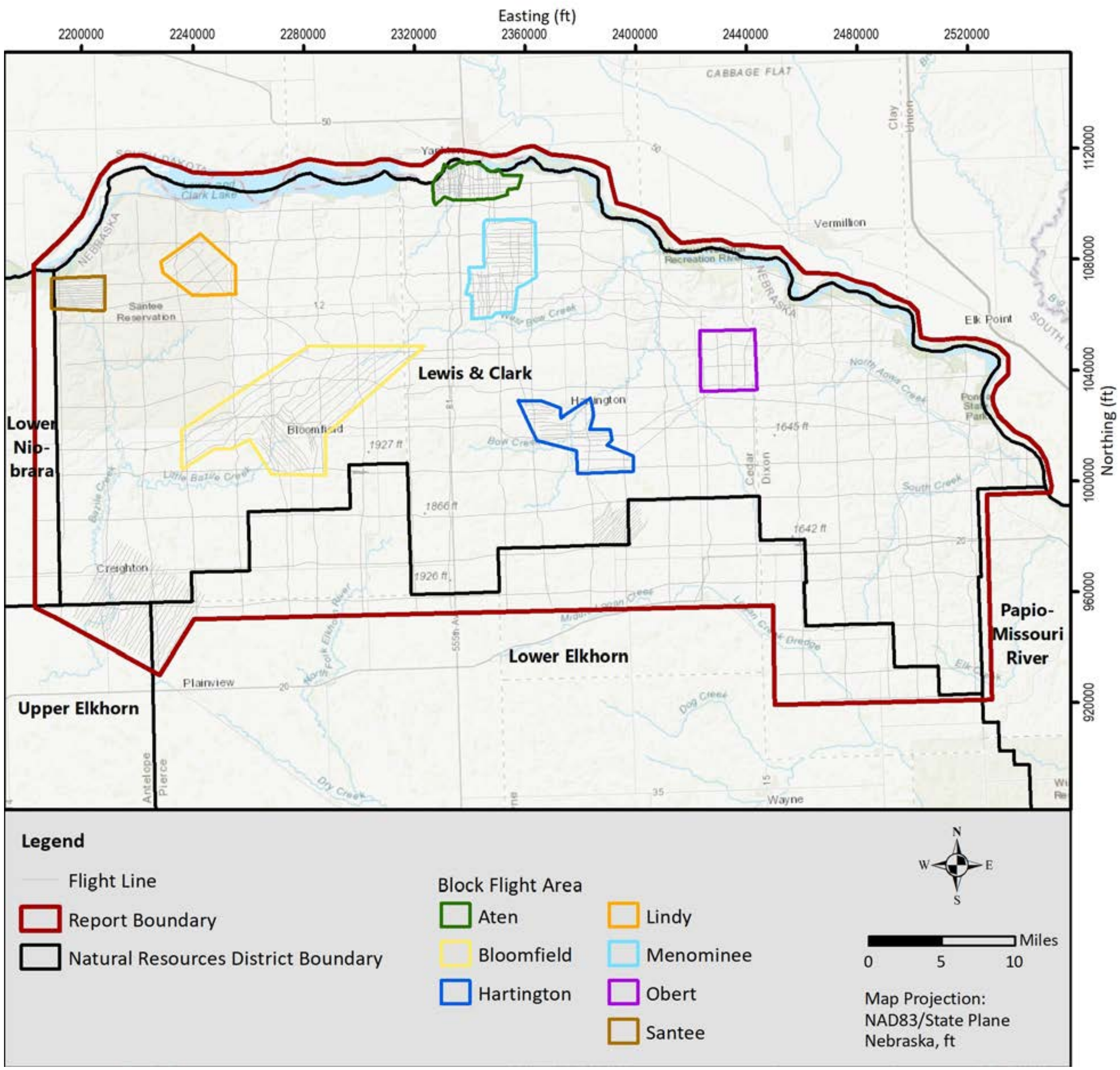


Figure 1-2. Location map of the LCNRD Reconnaissance and Block AEM survey flight areas.

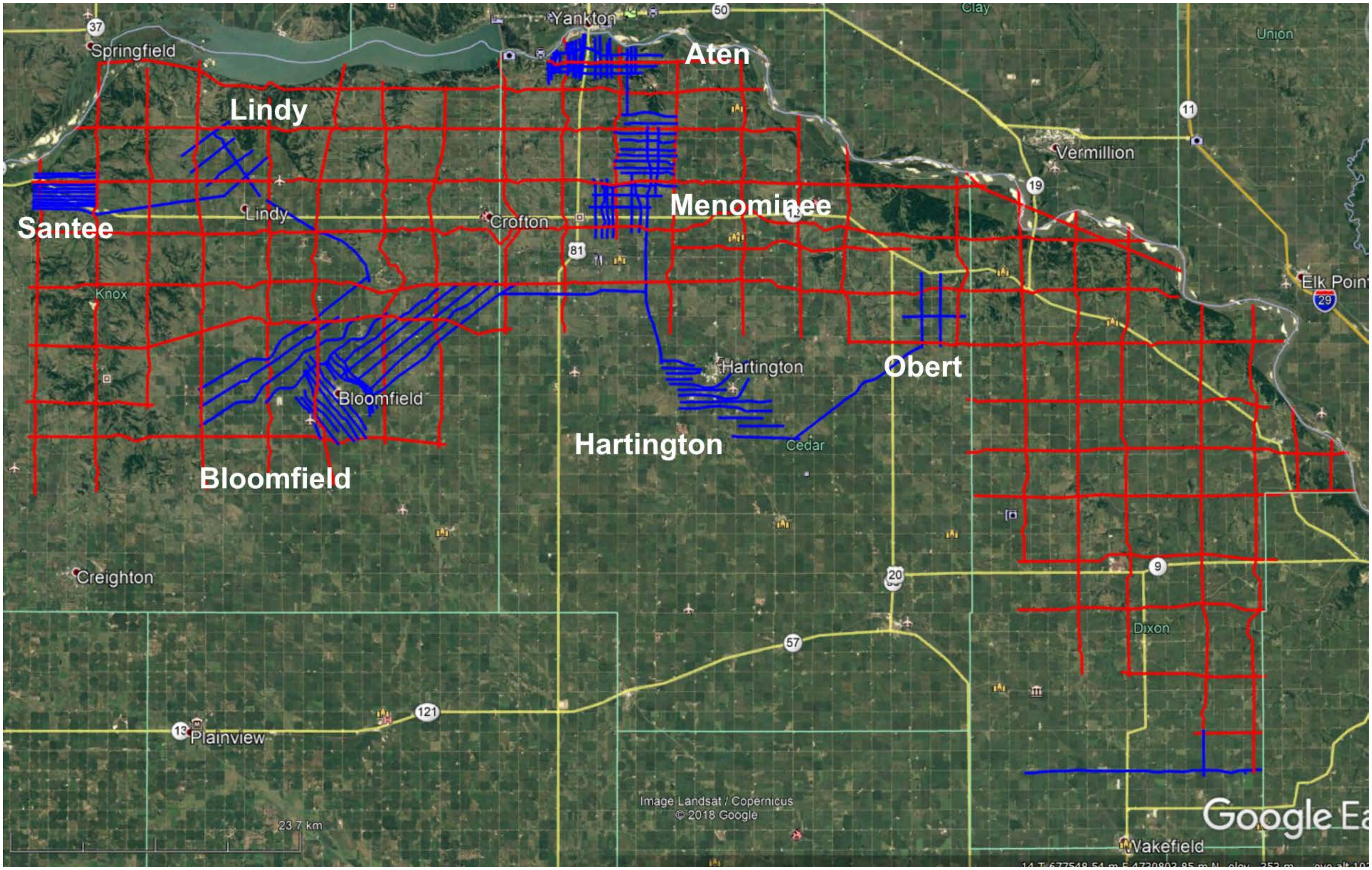


Figure 1-3. Google Earth image of the LCNRD 2018 AEM survey flight lines (Red – SkyTEM 312, Blue – SkyTEM 304) with detailed block areas indicated along with county lines and major roads.

1.2 Background

In 2014-2015 the ENWRA funded Exploration Resources International (XRI) for a large-scale reconnaissance AEM survey over the glaciated portion of Nebraska, approximately 2,200 line-km of approximately 32 km spaced lines (Abraham et al., 2015; Carney et al., 2015a; Carney et al., 2015b). In 2016 AGF conducted AEM studies of LCNRD including reconnaissance lines, the Coleridge Block (AGF, 2017a) as well as the Bazile Groundwater Management Area (BGMA) AEM Survey (AGF, 2017b), as well as adjacent areas of the Lower Elkhorn Natural Resources District (LENRD) (AGF, 2017c). Figure 1-4 shows the overlap area for the BGMA with the LCNRD. Adjacent areas to the LCNRD also flown in 2018 including the LENRD (AGF, 2018) as well as the Papio-Missouri River Natural Resources District (P-MRNRD) (AGF 2019) were included in this study. The 2015 reconnaissance study, the 2016 LCNRD flight lines, the BGMA flights adjacent to the LCNRD, and the 2018 flights discussed in this report provided information to improve the understanding of the hydrogeologic framework within the LCNRD

On February 1, 2015, the LCNRD declared the entire District a Level I Groundwater Quantity Management Area. This includes the Niobrara Chalk Bedrock Reservoir, Dakota Sandstone Bedrock Reservoir, Area of Limited Aquifer Development Potential, Remaining Areas, Missouri River Groundwater Reservoir, and the Community Water System Protection Areas (AGF, 2017a). There are three possible phases of management in the plan based on water use, changes in water supply, and aquifer characteristics. In addition, the LCNRD has a water quality management area for nitrogen management in portions of the BGMA. This determination was based on studies by the LCNRD and the Nebraska Department of Environmental Quality (NE-DEQ) and others. The conclusions from these studies indicated that the aquifers appeared to be contaminated due to varying degrees with nitrate/nitrogen and the causes were likely related to fertilizer application and irrigation practices. The report also concluded that the most affected region, with some of the highest nitrate/nitrogen concentrations in the groundwater, occur in the Creighton area of the district. Based on this information, BGMA was declared a Phase III water quality area.

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. In recent years, the Eastern Nebraska Water Resources Assessment (ENWRA) has coordinated efforts between area Natural Resources Districts (NRDs), 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 state. For purposes of this project, LCNRD, ENWRA, and CSD are cooperating with AGF because of the shared borders and common groundwater management efforts between these NRDs.

The ENWRA project was formed in 2006 with sponsors from six NRDs (Lewis and Clark, Lower Elkhorn, Papio-Missouri River, Lower Platte North, Lower Platte South, and Nemaha) and cooperating agencies including the CSD and the USGS. The long-term goal of the project is to develop a geologic framework and water budget for the glaciated portion of eastern Nebraska.

1.3 Description of the LCNRD AEM Project Area

The LCNRD spans approximately 1,607 square miles (mi^2) in eastern Nebraska. It contains all or part of Cedar, Dixon, and Knox counties. The elevation of the area ranges from 1,079 ft to 1,906 ft above sea level**.** It is underlain by parts of two of Nebraska's eight topographic regions—Valleys, Dissected Plains, Plains, and Rolling Hills (Elder et al., 1951).

The LCNRD has a population of approximately 15,018 (https://www.nrdnet.org/nrds/lewis-clark-nrd) Principal cities within the project area, based on 2010 population estimates, include (alphabetically) with population in parenthesis, Bloomfield (1,028), Coleridge (473), Creighton (1,154), Hartington (1,554), Ponca (933), and Santee (346) (U.S. Census Bureau, 2013).

A CSD-derived (Burchett, 1986) map of the bedrock geology extents within the LCRND AEM survey area is presented in Figure 1-5.

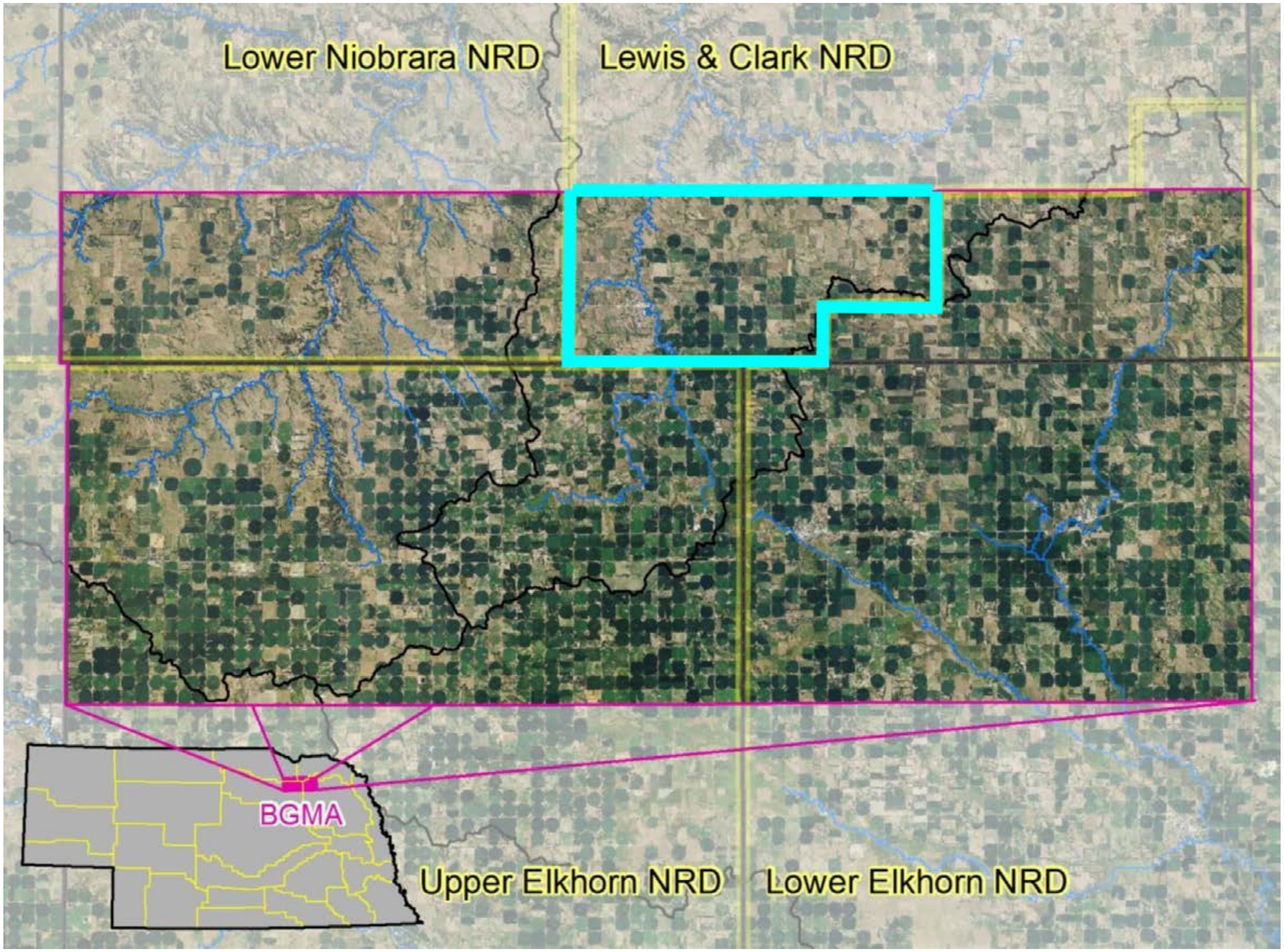


Figure 1-4. Map of the Bazile Creek Groundwater Management Area. The portion in the blue polygon is the area that LCNRD has responsibility to manage for water quality. Map is from the Bazile Creek Groundwater Management Area Plan (http://uenrd.org/_storage/pagefiles/2016bgma319approvedplan(1).pdf).

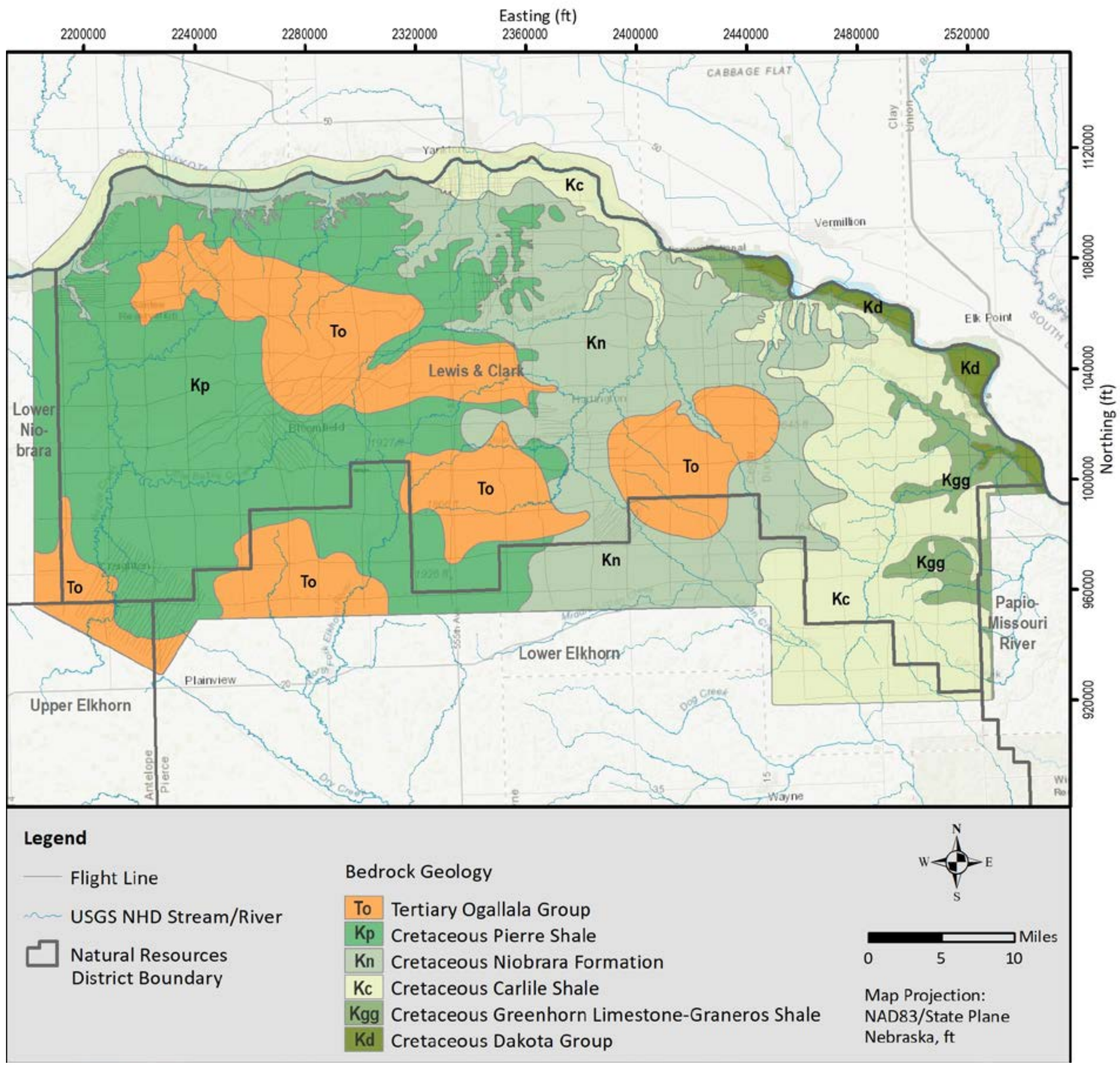


Figure 1-5. Map of the bedrock geology extents within the LCRND AEM survey area. The projection is NAD83 State Plane Nebraska (feet), modified from (Burchett, 1986).

2 Geophysical Methodology, Acquisition and Processing

2.1 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 2-1 gives a conceptual illustration of the airborne TEM method.

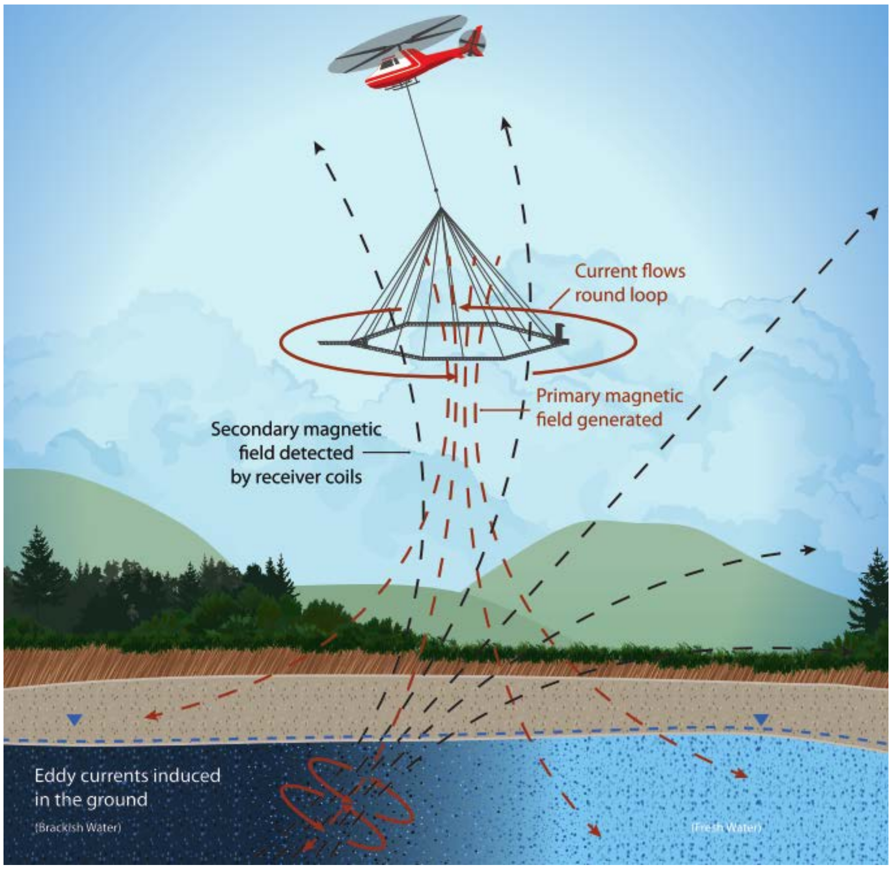
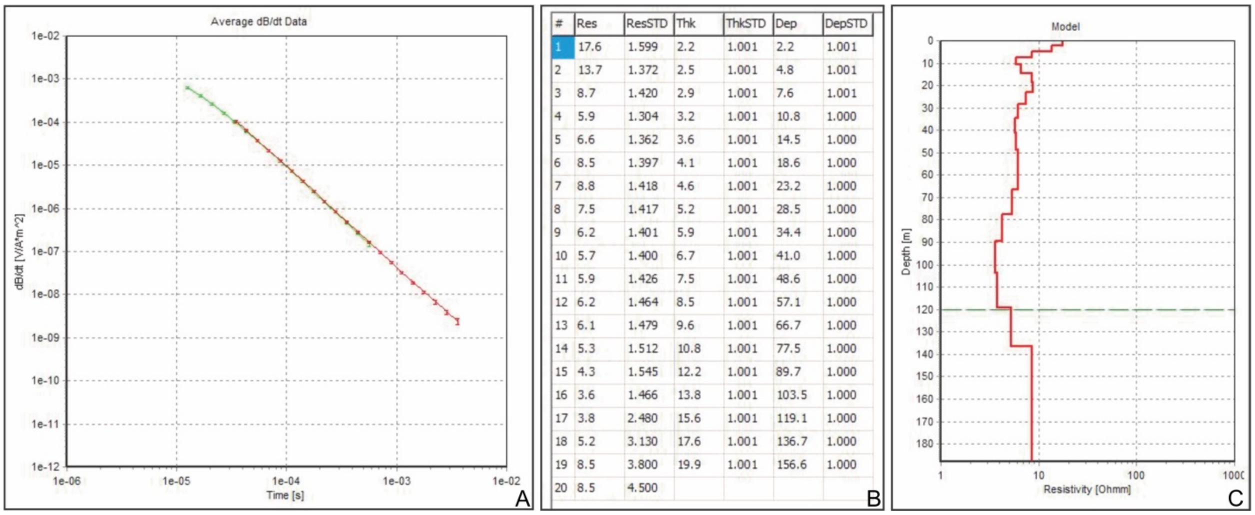


Figure 2-1: Schematic of an airborne electromagnetic survey, modified from Carney et al. (2015a).

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 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 2-2 shows an example of a dual-moment TEM dB/dt sounding curve and the corresponding inverted electrical resistivity model.



#	Res	ResSTD	Thk	ThkSTD	Dep	DepSTD
1	17.6	1.599	2.2	1.001	2.2	1.001
2	13.7	1.372	2.5	1.001	4.8	1.001
3	8.7	1.420	2.9	1.001	7.6	1.001
4	5.9	1.304	3.2	1.001	10.8	1.000
5	6.6	1.362	3.6	1.001	14.5	1.000
6	8.5	1.397	4.1	1.001	18.6	1.000
7	8.8	1.418	4.6	1.001	23.2	1.000
8	7.5	1.417	5.2	1.001	28.5	1.000
9	6.2	1.401	5.9	1.001	34.4	1.000
10	5.7	1.400	6.7	1.001	41.0	1.000
11	5.9	1.426	7.5	1.001	48.6	1.000
12	6.2	1.464	8.5	1.001	57.1	1.000
13	6.1	1.479	9.6	1.001	66.7	1.000
14	5.3	1.512	10.8	1.001	77.5	1.000
15	4.3	1.545	12.2	1.001	89.7	1.000
16	3.6	1.466	13.8	1.001	103.5	1.000
17	3.8	2.480	15.6	1.001	119.1	1.000
18	5.2	3.130	17.6	1.001	136.7	1.000
19	8.5	3.800	19.9	1.001	156.6	1.000
20	8.5	4.500				

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

2.2 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 LCNRD, three types of utilities (pipelines, railroads, and power lines) were located. Various public power districts in Eastern 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 provided by the ENWRA group. Maps of the three 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 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.

Upon conclusion of the design process, the LCNRD AEM investigation consisted of Reconnaissance flight lines utilizing the SkyTEM312 system and seven (7) AEM Block flight areas including the Aten, Bloomfield, Hartington, Lindy, Menominee, Obert, and Lindy survey areas utilizing the SkyTEM304M system. The SkyTEM312 Reconnaissance flight lines had a maximum length of approximately 58 miles (94 km) in length in the east-west direction and about 23 miles (37 km) at their longest in the north-south direction and were separated by approximately 2.5 to 3 miles (about 4-5 km) in both east-west and north-south directions. The AEM Block flights with the SkyTEM304 had variable flight line lengths and separations, from approximately 10 miles (16 km) to approximately 3 miles (5 km) and were separated by about 1,500 feet to 4,900 ft (0.9 miles) (or 450 m to 1.5 km).

2.3 AEM Survey Instrumentation

AEM data were acquired using both the SkyTEM304M (304M) and the SkyTEM312 (312) airborne electromagnetic systems (SkyTem Airborne Surveys Worldwide, 2018). The 304M is a rigid frame, dual-magnetic moment (Low and High) TEM system. The area of the 304M Tx coil is 342 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 110 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 ~150,000 $A*m^2$, respectively.

The SkyTEM312 uses the same frame as the 304M but different electronics and transmitter wiring. A peak current of six (6) amps is passed through two (2) turns of wire in the Tx for Low Moment measurements and a peak current of 110 amps is passed through the twelve (12) turns of wire for High Moment measurements. This results in peak Tx Low and High magnetic moments of ~4,100 Ampere-meter-squared ($A*m^2$) and ~450,000 $A*m^2$, respectively.

The SkyTEM304M and 312 systems utilize 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 304M and 312 multi-turn Rx vertical (Z) coil has an effective area of 105 m^2. In addition to the Tx and Rx that constitute the TEM instrument, the 304M and 312 are also equipped with a Total Field magnetometer (MAG) and data acquisition systems for both instruments. The 304M and 312 also include 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 2-3 gives a simple illustration of the 304M and 312 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 and 312 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 2-1 lists the positions of the instruments and Table 2-2 lists the corners of the transmitter loop.

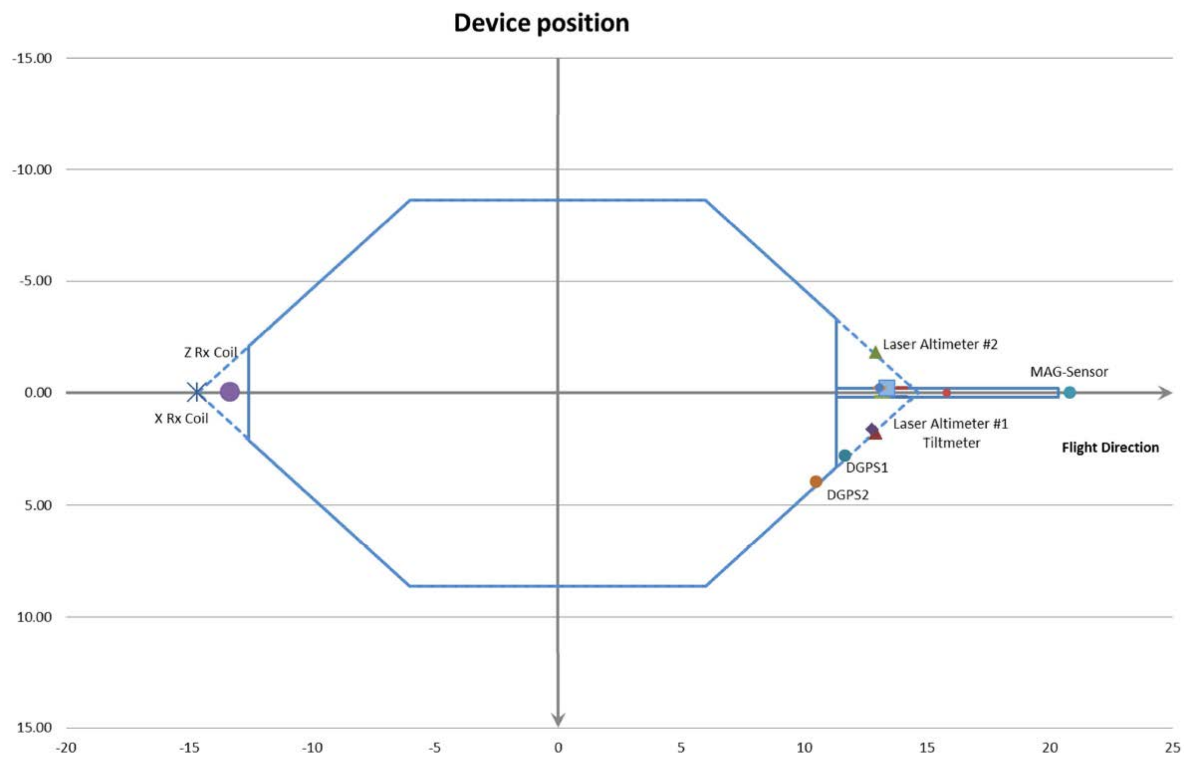


Figure 2-3: SkyTEM304M/312 frame, including instrumentation locations and X and Y axes. Distances are in meters. Instrumentation locations listed in Table 2-1.

Figure 2-4: Photos of the SkyTEM304M/312 system in suspension beneath the helicopter.

For this project, the 312 was flown at an average speed of 52 mi/hr (84.1 kilometers/hr) at an average flight height of 114.5 ft (41.4 m) above land surface and the 304M was flown at an average speed of 53 mi/hr (85.0 kilometers/hr) at an average flight height of 109.3 ft (33.3 m) above land surface, using the sling-load cargo system of a Eurocopter AS350 helicopter. Figure 2-4 displays a couple of images of the 304M/312 in operation.

Table 2-1: Positions of instruments on the SkyTEM304M/312 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 2-2: Positions of corners of the SkyTEM304M/312 transmitter coil, using the center of the frame as the origin in feet.

Tx Corners	1	2	3	4	5	6	7	8
X	-41.16	-19.78	18.83	37.19	39.19	18.83	-19.78	-41.16
Y	-6.89	-27.98	-28.18	-10.85	10.85	28.18	27.98	6.89

2.4 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 of the ENWRA project. The helicopter and the SkyTEM304M system were initially located at the Nebraska City, Nebraska airport. 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.

AGF acquired AEM data over the LCNRD, commencing 18 July 2018 and finishing on 26 July 2018, to support development of the hydrogeological framework. During this time frame data were collected in other adjacent NRD's near the LCNRD. Approximately 1,210.5 line-miles (1,901 line-kilometers) were acquired over the LCNRD AEM survey area (SkyTEM 312 - 822 miles/1331 km and SkyTEM 304 – 389 miles/630 km). A data acquisition map is presented in Figure 2-5 with the flight lines grouped by acquisition date.

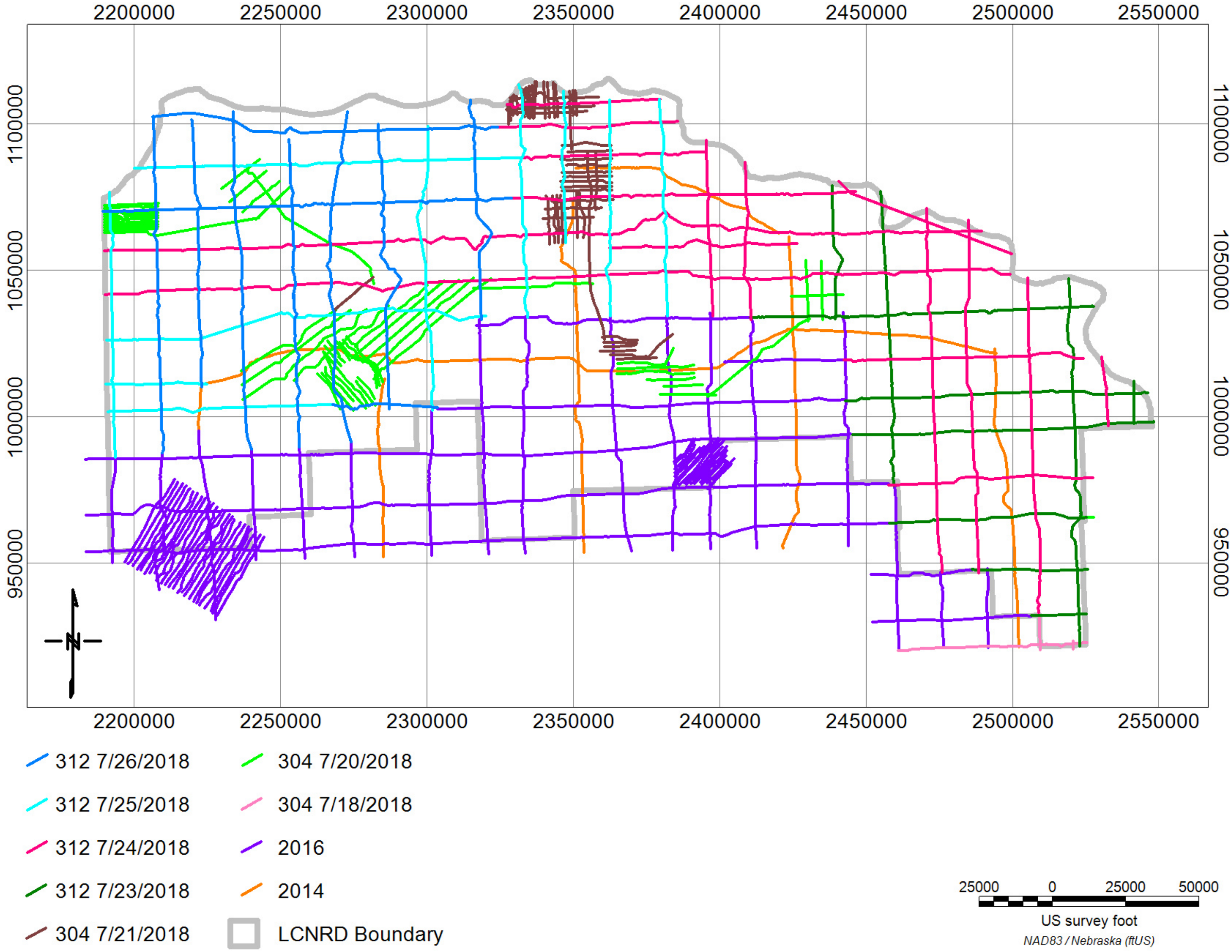


Figure 2-5: LCNRD 2018 AEM flight lines grouped by acquisition date. Projection is Nebraska State Plane NAD83, feet.

2.4.1 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.

2.4.2 Automatic Processing

The AEM data collected by the 304M were processed using Aarhus Workbench version 5.8.3.0 (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 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 15 seconds with shift lengths of twelve (12) 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 1.0×10^{-5} sec, 1.0×10^{-4} sec, and 1.0×10^{-3} sec with widths of 4, 7, and 18 seconds. The times used to define the trapezoid for the High Moment were 1.0×10^{-4} sec, 1.0×10^{-3} sec, and 1.0×10^{-2} sec with widths of 10, 20, and 36 seconds. The trapezoid sounding distance was set to 1.0 seconds and the left/right setting, which requires the trapezoid to be complete on both sides, was turned on. The spike factor and minimum number of gates were both set to 20 percent for both soundings. Lastly, the locations of the averaged soundings were synchronized between the two moments.

2.4.3 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 2-6 and Figure 2-7, respectively. The time series data in Figure 2-7 is from the Menominee Block along one line that passes across the paleochannel. Examples of two inversions, one without EM coupling and the other with EM coupling, are shown in Figure 2-8. Areas were also cut out where the system height was flown greater than 213 feet (65 m) above the ground surface which caused a decrease in the signal level. This problem was encountered at several locations along the major rivers and streams due to the tall cottonwood trees.

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

Approximately 1,034-line-miles (1,675-line kilometers) were retained for inversion amounting to a retention rate of 85.4% (SkyTEM 312 – 713 miles/1,155 km, SkyTEM 304 – 321 miles/520 km). This high rate is the result of careful flight line planning and design given the infrastructure that was encountered during the acquisition.

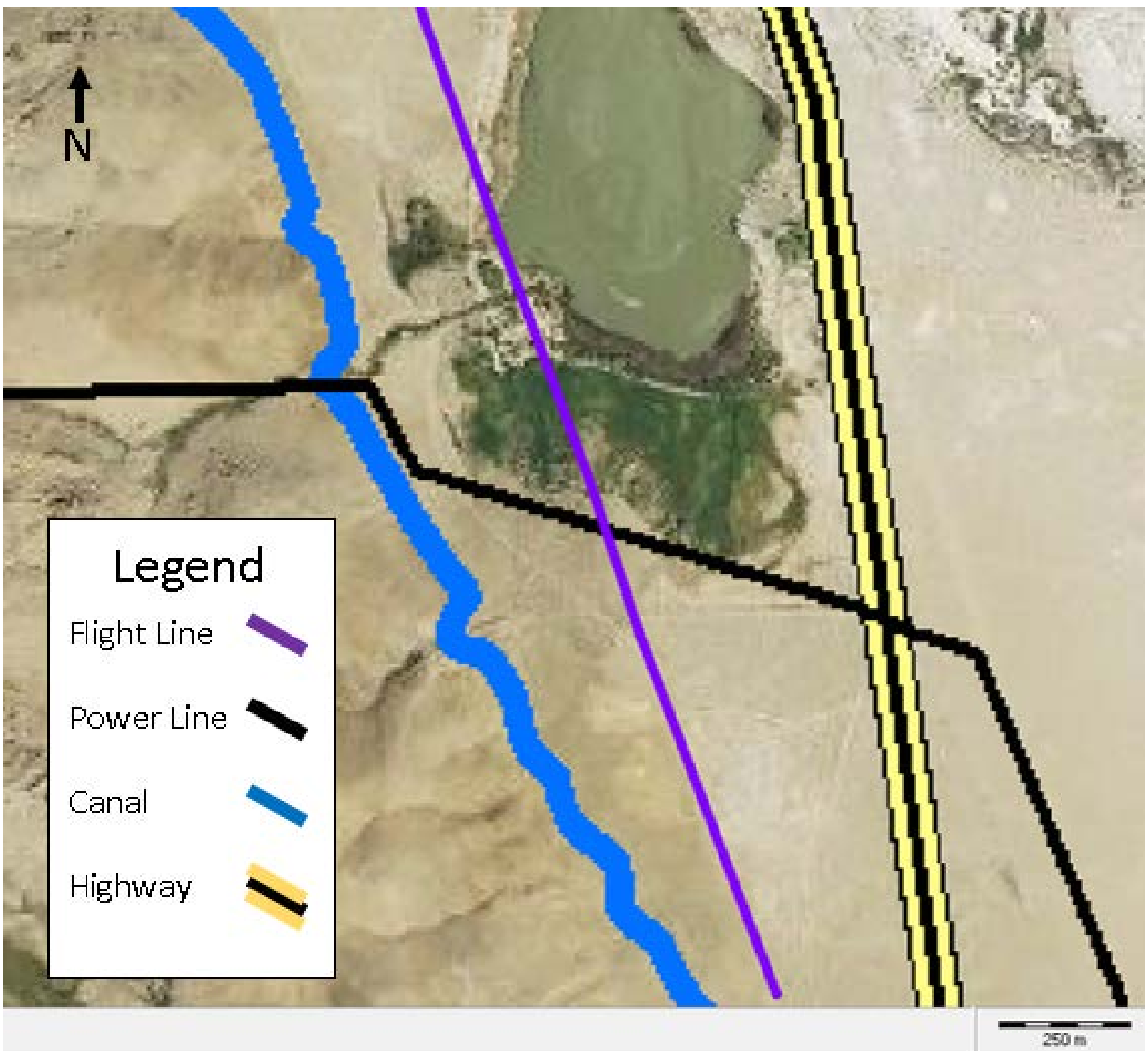


Figure 2-6: Example locations of electromagnetic coupling with pipelines or power lines.

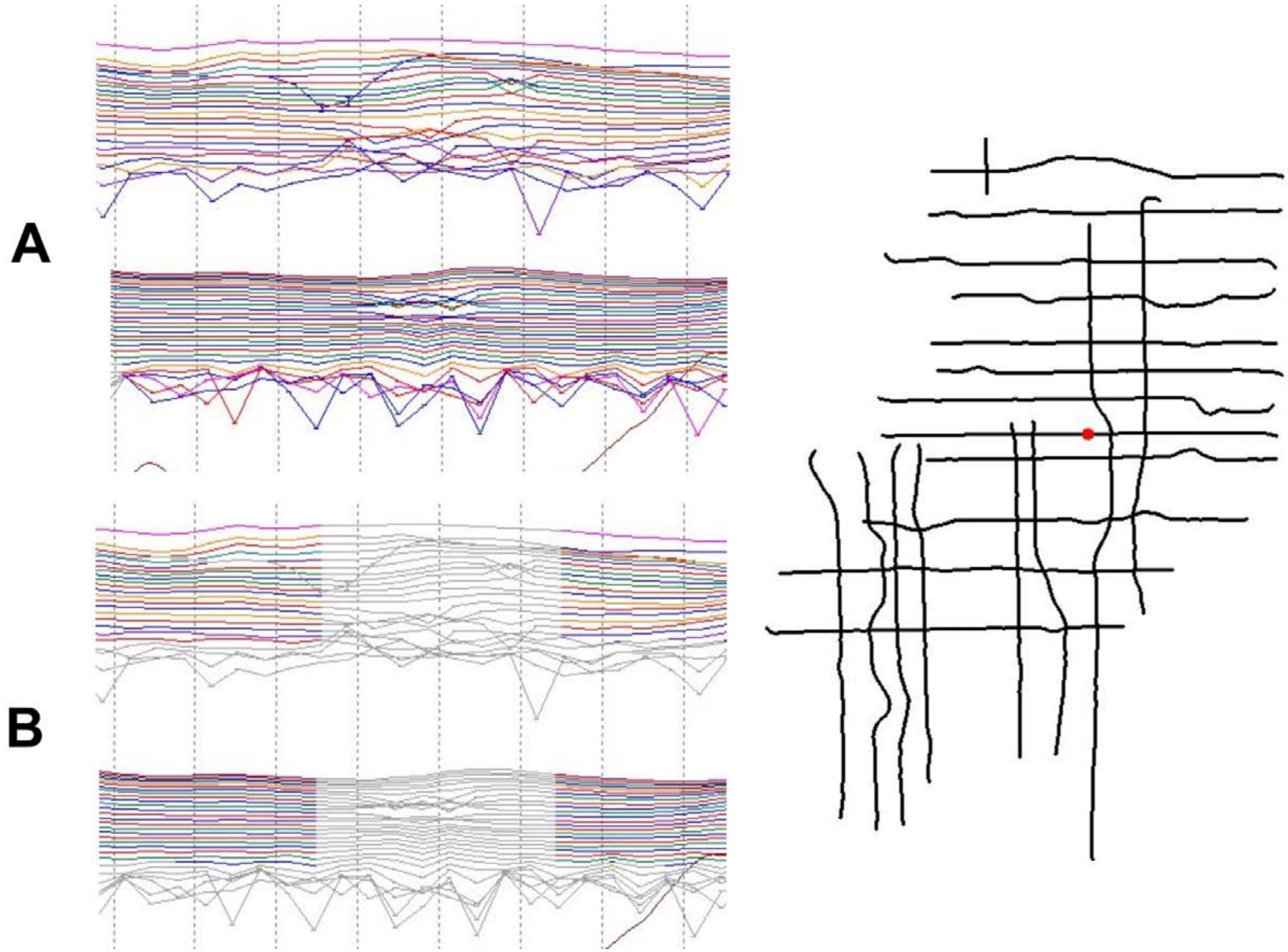


Figure 2-7: Example of AEM data from the Menominee Block across the paleochannel affected by electromagnetic coupling as presented in the Aarhus Workbench editor. The top group of lines (A) is the unedited data with the Low Moment on top and the High Moment on the bottom. The bottom group (B) shows the same data after editing out the coupling and late time noise.

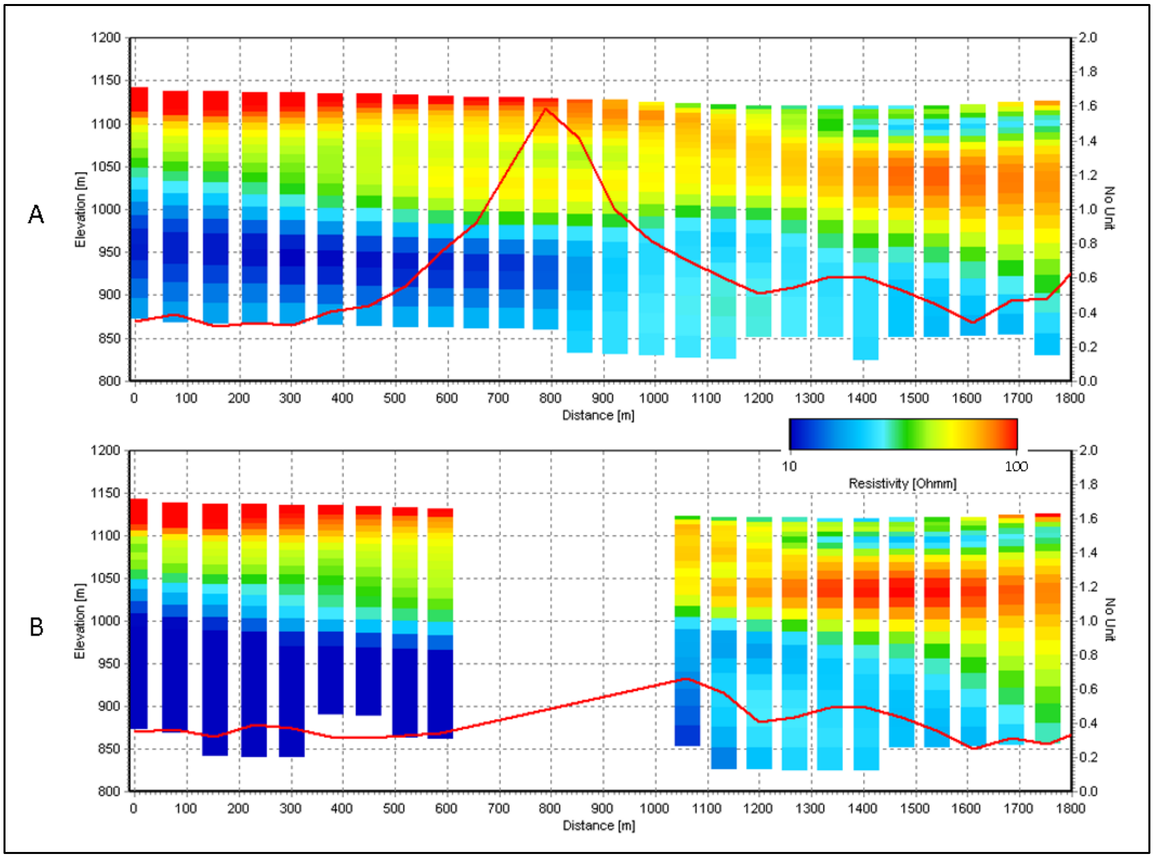


Figure 2-8: A) Example of Laterally-Constrained inversion results where AEM data affected by coupling with pipelines and power lines were not removed. B) Inversion results where AEM data affected by coupling were removed.

2.4.4 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 LCNRD 2018 AEM survey are presented in Figure 2-9. The LCNRD-flight lines with blue colors representing the 85.4% of data retained for inversion and red lines representing data removed due to infrastructure and late time noise are presented in Figure 2-10.

2.4.5 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 2-11 shows the residual magnetic Total Field intensity data for the LCNRD AEM survey area after correcting for diurnal drift and removing the International Geomagnetic Reference Field (IGRF). This data is used in decoupling efforts.

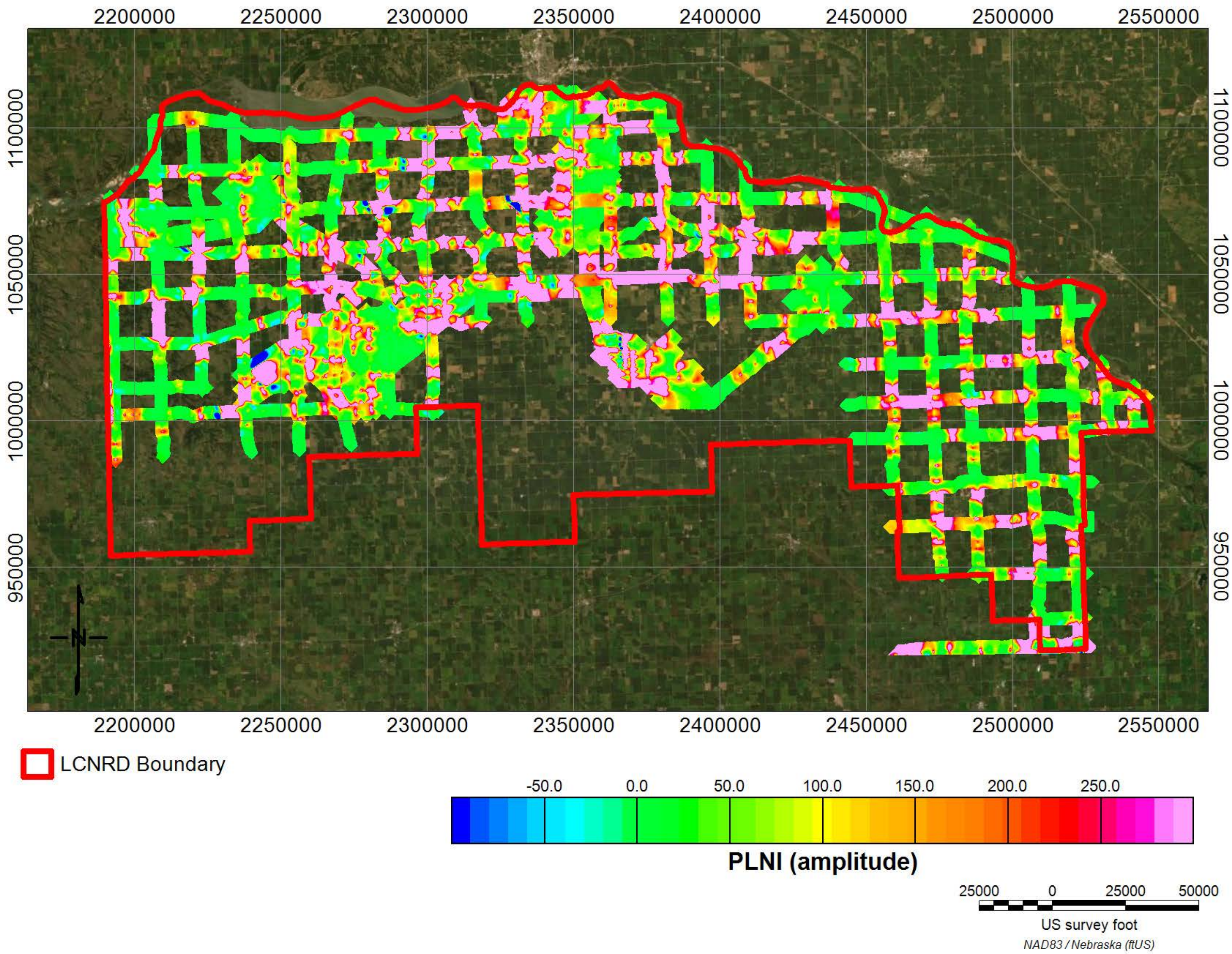


Figure 2-9: Power Line Noise Intensity (PLNI) map of the LCNRD 2018 project area.

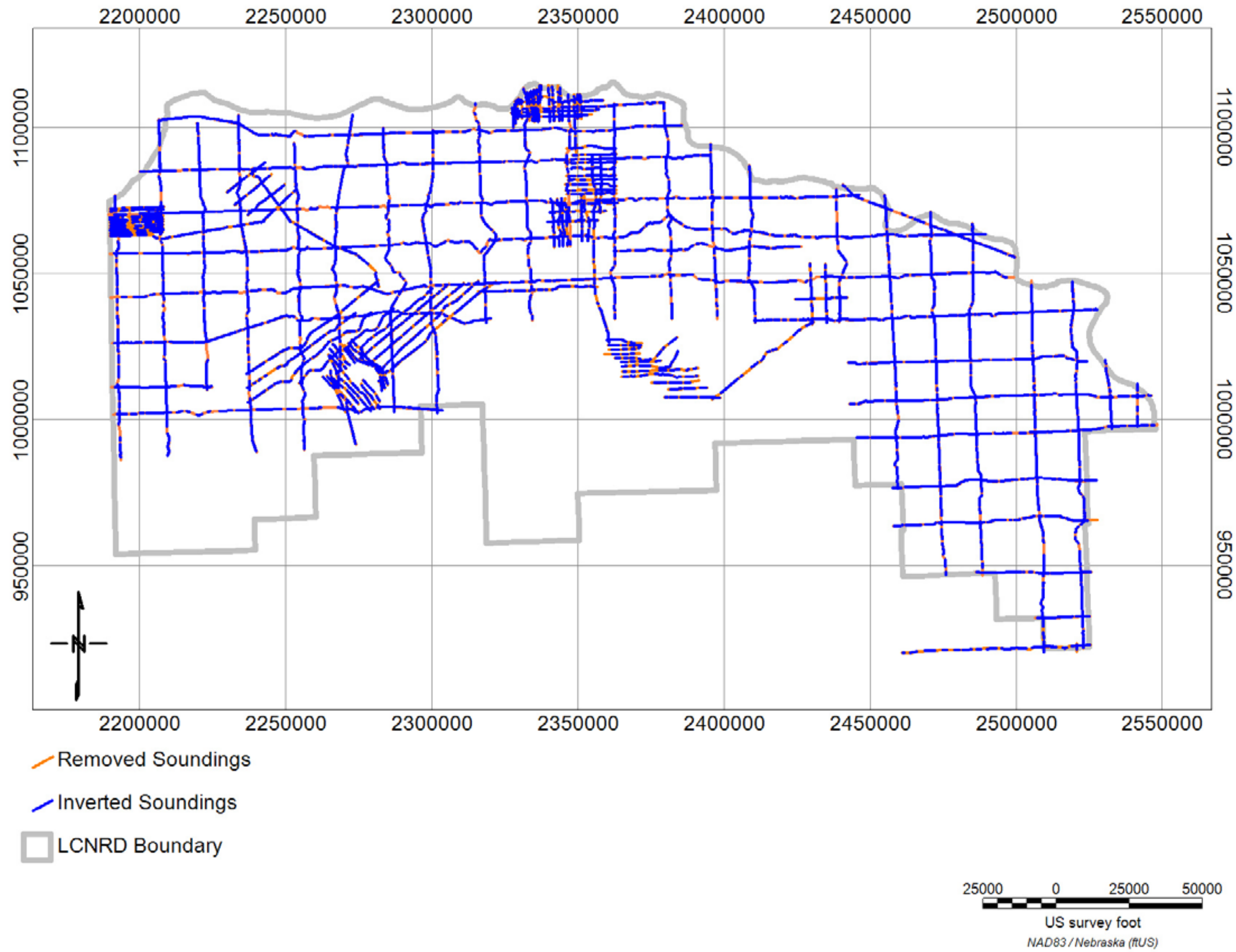


Figure 2-10: Locations of inverted data (blue lines) along the AEM flight lines (red lines) in the LCNRD 2018 AEM survey area. Where blue lines are not present indicates decoupled (removed) data. 85.4% of the acquired data were retained for inversion and interpretation. Google Earth kmz's of the inverted data locations as well as the "as-flown" flight lines are included in Appendix 3\KMZ.

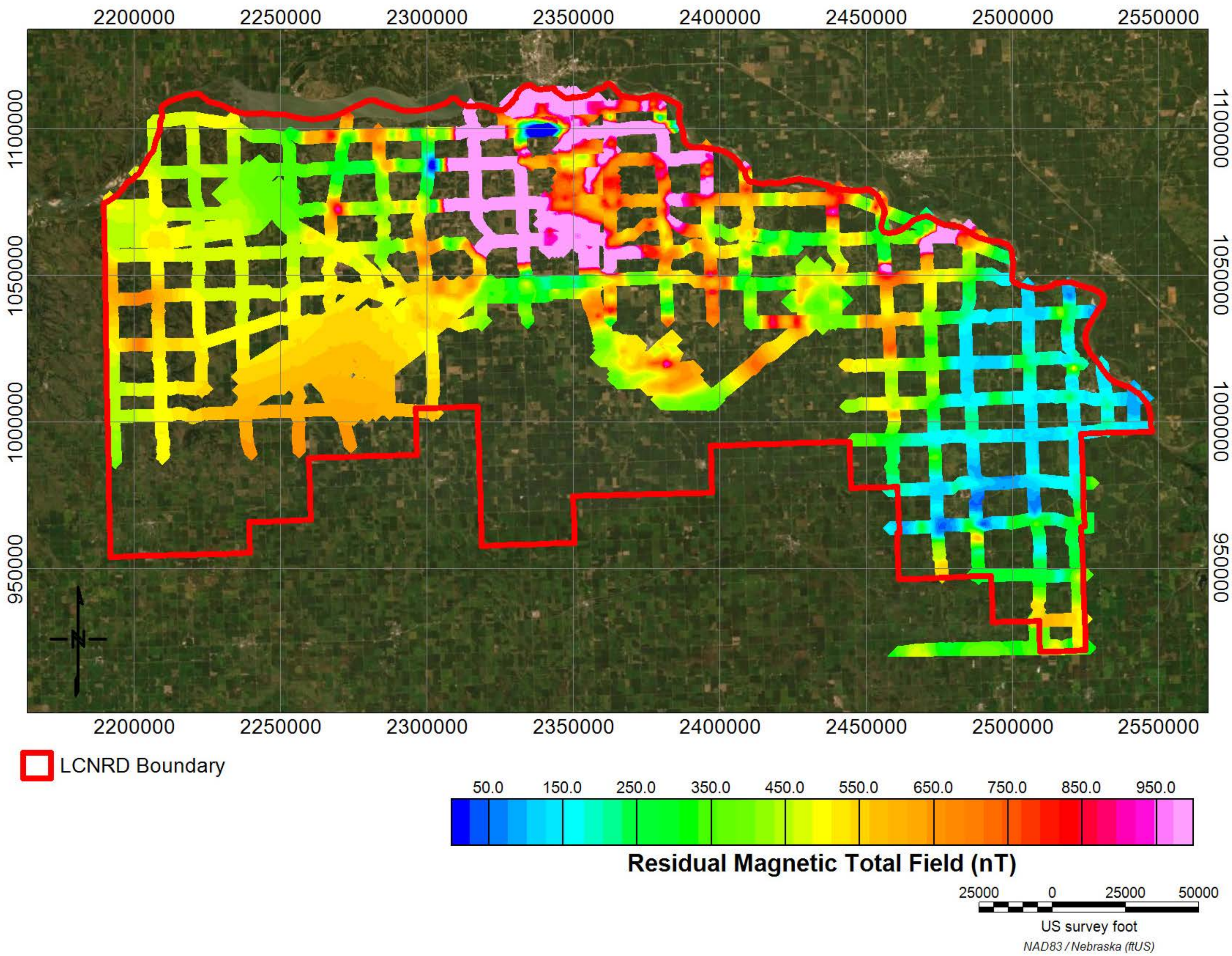


Figure 2-11: Residual magnetic Total Field intensity data for the LCNRD 2018 survey area corrected for diurnal drift, with the International Geomagnetic Reference Field (IGRF) removed.

2.5 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 LCNRD AEM data were inverted using SCI smooth models with 40 layers, each with a starting resistivity of 10 Ohm-m (equivalent to a 10 ohm-m halfspace). The thicknesses of the inversion models for the 304M and the 312 were different because of the different sensing character of the two systems. While the 312 images deeper than the 304 (and needs deeper and thicker layers), the 304M is more sensitive to the near-surface (and so needs finer layering at the surface). Also, the thicknesses of the layers increase with depth as the resolution of the technique decreases (an example of a 30-layer model is presented in Figure 2-12). The thicknesses of the first layer of the 304M models were about 3 ft (1 m) (Table 2-3) with the thicknesses of the consecutive layers increasing by a factor of about 1.1. The thicknesses of the first layer of the 312 models (Table 2-4) were about 10 ft (3 m) with the thicknesses of the consecutive layers increasing by a factor of about 1.07. The depths to the bottoms of the 39th layers for the 304M were set to 1,066 ft, with maximum thicknesses up to about 93 ft. The depths to the bottoms of the 39th layers for the 312 were set to 1,801 ft, with maximum thicknesses up to about 126 ft. The spatial reference distance, ***s***, for the constraints were set to 328 ft (100 m) with a power law fall-off of 0.75. The vertical and lateral constraints, ***ResVerSTD*** and ***ResLatStD***, were set to 2.4 and 1.4, respectively, for all layers.

It is important to note that the SCI's for the 304M used much earlier LM vertical (Z) receiver time gates than for the 312. The 304M used LM-Z-time gates 3-26 and the 312 used LM-Z time gates of 9-26. The 304M LM used the system response analysis for the five earliest time gates (3, 4, 5, 6 and 7).

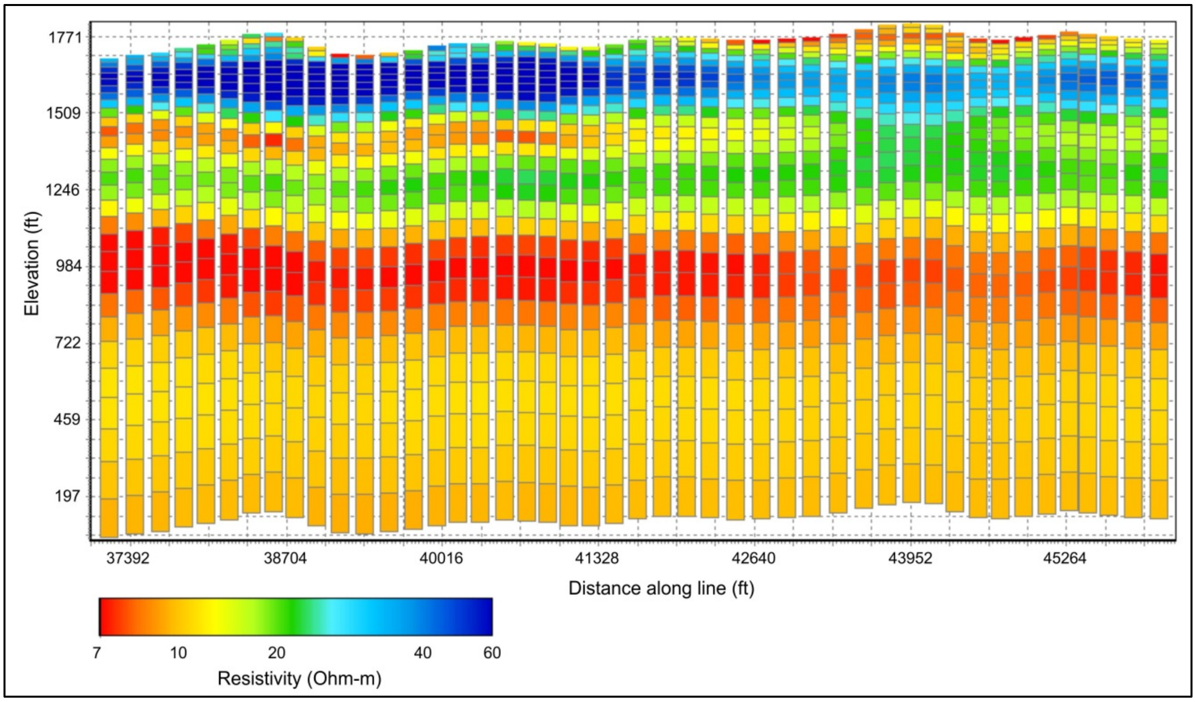


Figure 2-12: An example of an AEM profile illustrating increasing model layer thicknesses with depth.

In addition to the recovered resistivity models the SCIs also produce data residual error values (single sounding error residuals) and Depth of Investigation (DOI) estimates. The data residuals compare the measured data with the response of the individual inverted models (Christensen et al., 2009). The DOI provides a general estimate of the depth to which the AEM data are sensitive to changes in the resistivity distribution at depth (Christiansen and Auken, 2012). Two DOI's are calculated: 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 2-3: Thickness and depth to bottom for each layer in the Spatially Constrained Inversion (SCI) AEM earth models for the SkyTEM 304M data. The thickness of the model layers increase with depth as the resolution of the AEM technique decreases.

Layer	Depth to Bottom (ft)	Thickness (ft)	Depth to Bottom (m)	Thickness (m)	Layer	Depth to Bottom (ft)	Thickness (ft)	Depth to Bottom (m)	Thickness (m)
1	3.3	3.3	1.0	1.0	21	190.6	19.0	58.1	5.8
2	6.9	3.6	2.1	1.1	22	211.3	20.7	64.4	6.3
3	10.8	3.9	3.3	1.2	23	234.0	22.6	71.3	6.9
4	15.1	4.3	4.6	1.3	24	258.9	24.9	78.9	7.6
5	19.7	4.6	6.0	1.4	25	286.1	27.2	87.2	8.3
6	25.0	5.2	7.6	1.6	26	315.7	29.5	96.2	9.0
7	30.5	5.6	9.3	1.7	27	347.8	32.2	106	9.8
8	36.8	6.2	11.2	1.9	28	382.9	35.1	116.7	10.7
9	43.3	6.6	13.2	2.0	29	421.3	38.4	128.4	11.7
10	50.5	7.2	15.4	2.2	30	463.3	42.0	141.2	12.8
11	58.4	7.9	17.8	2.4	31	509.2	45.9	155.2	14.0
12	67.0	8.5	20.4	2.6	32	559.4	50.2	170.5	15.3
13	76.5	9.5	23.3	2.9	33	614.2	54.8	187.2	16.7
14	86.6	10.2	26.4	3.1	34	673.9	59.7	205.4	18.2
15	97.8	11.2	29.8	3.4	35	739.2	65.3	225.3	19.9
16	109.9	12.1	33.5	3.7	36	810.4	71.2	247	21.7
17	123.4	13.5	37.6	4.1	37	888.2	77.8	270.7	23.7
18	138.1	14.8	42.1	4.5	38	973.2	85.0	296.6	25.9
19	154.2	16.1	47.0	4.9	39	1066.0	92.9	324.9	28.3
20	171.6	17.4	52.3	5.3					

Table 2-4: Thickness and depth to bottom for each layer in the Spatially Constrained Inversion (SCI) AEM earth models for the SkyTEM 312 data. The thickness of the model layers increase with depth as the resolution of the AEM technique decreases.

Layer	Depth to Bottom (ft)	Thickness (ft)	Depth to Bottom (m)	Thickness (m)	Layer	Depth to Bottom (ft)	Thickness (ft)	Depth to Bottom (m)	Thickness (m)
1	3.3	9.8	3.00	3.0	21	435.4	37.7	133.90	11.5
2	13.8	10.5	6.20	3.2	22	475.8	40.4	146.20	12.3
3	25.0	11.2	9.60	3.4	23	519.1	43.3	159.40	13.2
4	37.1	12.1	13.30	3.7	24	565.3	46.3	173.50	14.1
5	49.9	12.8	17.20	3.9	25	614.6	49.2	188.50	15.0
6	63.7	13.8	21.40	4.2	26	667.4	52.8	204.60	16.1
7	78.4	14.8	25.90	4.5	27	723.8	56.4	221.80	17.2
8	94.2	15.7	30.70	4.8	28	784.2	60.4	240.20	18.4
9	110.9	16.7	35.80	5.1	29	848.8	64.6	259.90	19.7
10	129.0	18.0	41.30	5.5	30	918.0	69.2	281.00	21.1
11	148.3	19.4	47.20	5.9	31	991.9	73.8	303.50	22.5
12	169.0	20.7	53.50	6.3	32	1070.9	79.1	327.60	24.1
13	191.0	22.0	60.20	6.7	33	1155.6	84.6	353.40	25.8
14	214.6	23.6	67.40	7.2	34	1245.8	90.2	380.90	27.5
15	239.9	25.3	75.10	7.7	35	1342.6	96.8	410.40	29.5
16	266.8	26.9	83.30	8.2	36	1446.0	103.4	441.90	31.5
17	295.6	28.9	92.10	8.8	37	1556.5	110.6	475.60	33.7
18	326.5	30.8	101.50	9.4	38	1674.6	118.1	511.60	36.0
19	359.6	33.1	111.60	10.1	39	1801.0	126.3	550.10	38.5
20	395.1	35.4	122.40	10.8					

Figure 2-13 presents a histogram of the LCNRD SkyTEM 304M SCI inversion data/model residuals. Figure 2-14 presents a histogram of the LCNRD SkyTEM 312 SCI inversion data/model residuals. Figure 2-15 presents a map of data to model error residuals for the SkyTEM 304 inversion results and Figure 2-16 present the data to model error residuals for the SkyTEM 312 inversion results.

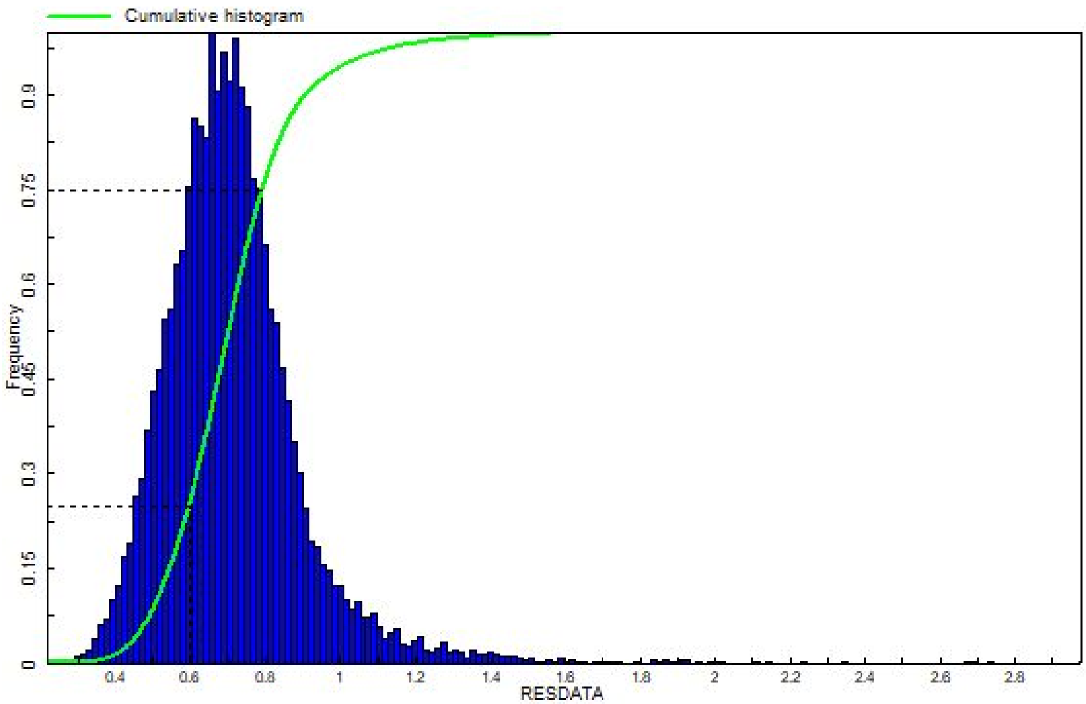


Figure 2-13. Data/model residual histogram for the LCNRD 2018 SkyTEM304M SCI inversion results.

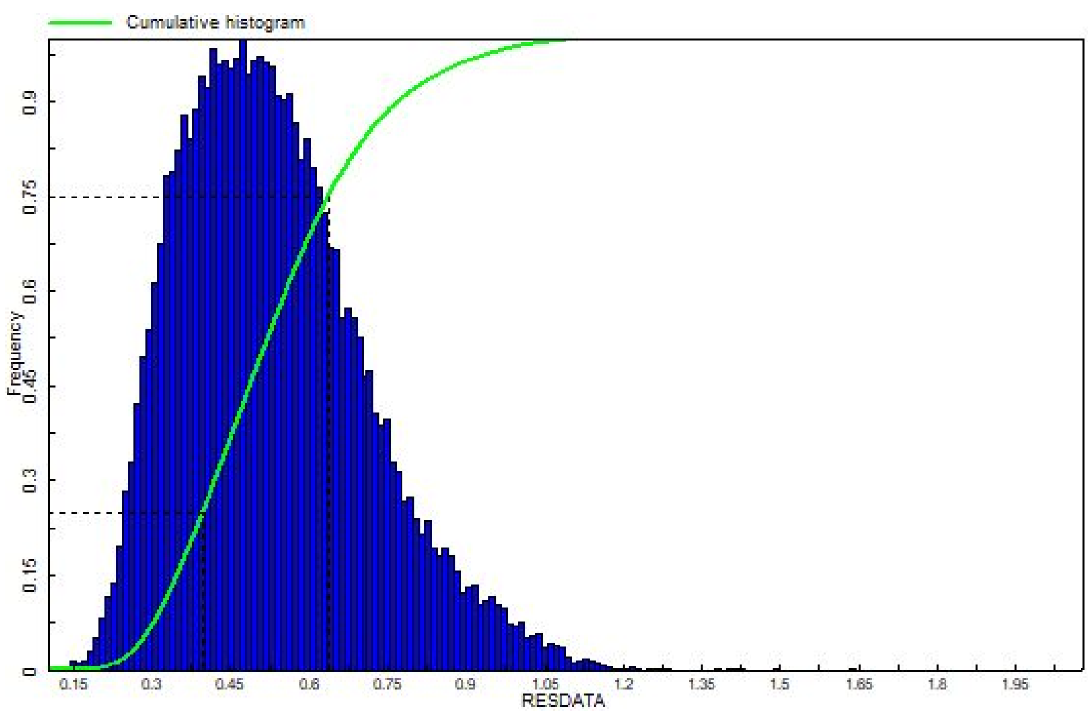


Figure 2-14. Data/model residual histogram for the LCNRD 2018 SkyTEM312 SCI inversion results.

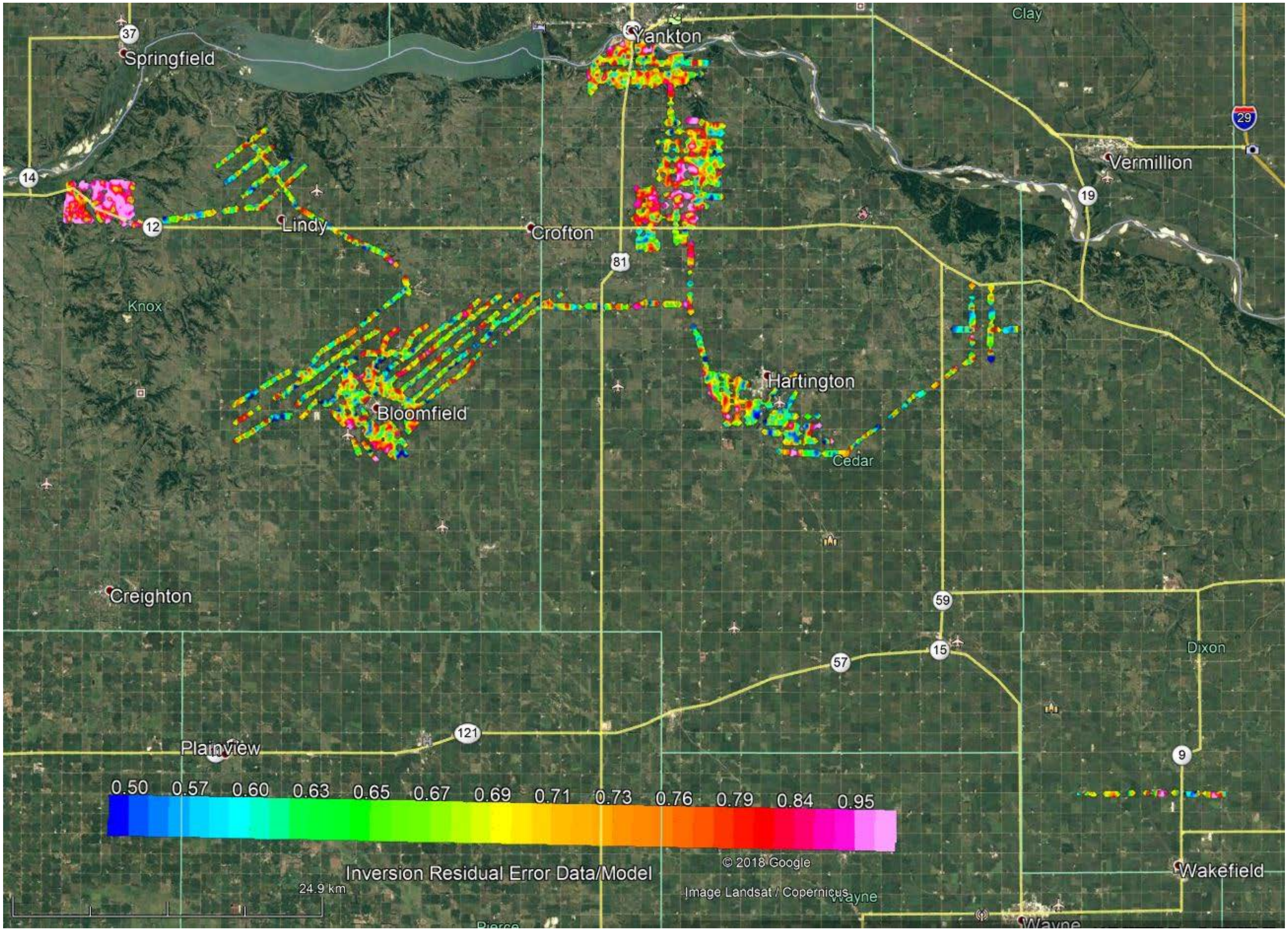


Figure 2-15. Map of data-inversion model residuals for the LCNRD 2018 SkyTEM 304 SCI inversion results.

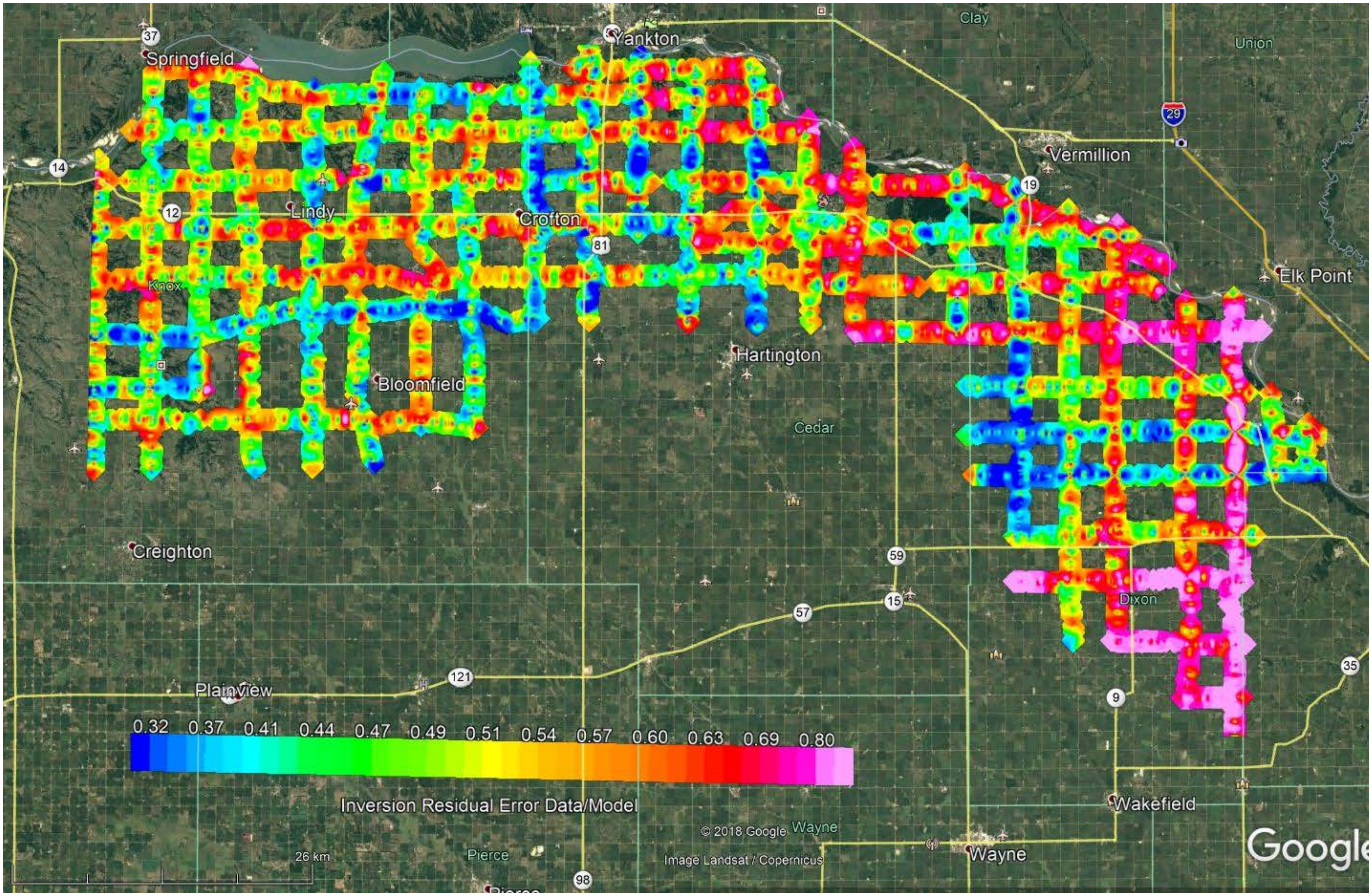


Figure 2-16. Map of data-inversion model residuals for the LCNRD 2018 SkyTEM 312 SCI inversion results.

3 AEM Results and Interpretation

This section provides the details on the process involved in the interpretation of the LCNRD AEM data and inversion results.

3.1 Interpretive Process

3.1.1 Merge AEM Databases from Different Flights

A substantial portion of the LCNRD has had AEM data collection before. This is summarized in Carney et al. (2015a) and AGF (2017a). Since data acquired in 2014 and 2016 exists within the boundaries of the 2018 block, the 2014 and 2016 lines were added to the 2018 AEM data set to provide the best possible data coverage for interpretation. Adjacent areas within the LENRD as well as the P-MNRD were also added. Several short lines were combined to form continuous lines within the survey area. These continuous lines allow for improved viewing and interpretation of the AEM inversions results. Prior to combining the multi-year flight lines, a set of AEM data acquired just in 2016 were first combined (Table 3-1). Then the 2014, 2016, and 2018 flight lines were combined. These are listed in Table 3-2 as the year acquired, the original line names, and the new combined lines.

In Table 3-1 and Table 3-2, flight lines from 2016 are in a purple font. Flight lines from 2014 are listed in a green font. Flight lines from 2018 that used the SkyTEM 312 system are in a red font and flight lines from 2018 that used the SkyTEM 304 system are in a light blue font.

Table 3-1. Combination of flight lines within the LCNRD from just the 2016 AEM survey.

Year Acquired	Original Lines	New Line
2016	L127501	L127500
2016	L132301	
2016	L127701	L127700
2016	L132501	
2016	L127901	L127900
2016	L132701	
2016	L128101	L128100
2016	L132901	
2016	L134101	L134100
2016	L134102	
2016	L134301	L134300
2016	L134302	

Year Acquired	Original Lines	New Line
2016	L135101	L135100
2016	L135301	
2016	L135501	L135500
2016	L135701	
2016	L135901	L135900
2016	L136101	
2016	L136301	L136300
2016	L136501	
2016	L145801	L145800
2016	L150801	

Table 3-2. Combination of flight lines within the LCNRD from 2014, 2016, and the 2018 AEM survey.

Year Acquired	Original Lines	New Line		Year Acquired	Original Lines	New Line
2018 312	L1100800	L1100809		2018 312	L1200101	L1200100
2016	L133101			2016	L148201	
2018 312	L1101001	L1101000		2018 312	L1200201	L1200200
2014	L100201			2016	L148401	
2018 312	L1101100	L1101109		2018 312	L1200301	L1200300
2018 312	L1101701			2014	L200101	
2016	L117701			2018 312	L1200401	L1200400
2016	L133501			2016	L148602	
2016	L133502			2018 312	L1200500	L1200509
2018 312	L1101601	L1101600		2016	L148801	
2016	L133301			2018 312	L1200601	L1200600
2018 312	L1101801	L1101800		2016	L149001	
2016	L117901			2018 312	L1200801	L1200800
2016	L117902			2016	L144601	
2016	L124701			2016	L149201	
2016	L124702			2018 312	L1200900	L1200909
2016	L124703			2016	L149401	
2016	L133701			2016	L149601	
2018 312	L1101900	L1101909		2018 312	L1201001	L1201000
2016	L118101			2016	L144801	
2016	L118102			2016	L149801	
2016	L133901			2018 312	L1201201	L1201200
2016	L124901			2016	L145001	
2016	L124902			2016	L150001	
2016	L124903			2018 312	L1201301	L1201300
2016	L124904			2016	L145201	
2018 312	L1102001	L1102000		2016	L150201	
2016	L125101			2018 312	L1201401	L1201400
2016	L125102			2016	L145401	
2016	L125103			2016	L150401	
2016	L118301			2018 312	L1201501	L1201500
2016	L118302			2016	L145601	
2018 312	L1102101	L1102100		2016	L150601	
2016	L118502			2018 312	L1201701	L1201700
2018 312	L1102201	L1102200		2016	L146001	
2016	L118701			2018 312	L1201801	L1201800
2018 312	L1200101	L1200100		2016	L146201	
2016	L148201			2018 312	L1202001	L1202000
				2018 304	L1004700	

3.1.2 Construct the Project Digital Elevation Model

To ensure that the elevation used in the project is constant for all the data sources (i.e. boreholes and AEM), a Digital Elevation Model (DEM) was constructed for the ENWRA area. The data was downloaded from the National Elevation dataset (NED) located at the National Map Website (U.S. Geological Survey, 2018) at a resolution of 1 arc-second or approximately 100 ft. The geographic coordinates are North American Datum of 1983 (NAD 83) and the elevation values are referenced to the North American Vertical Datum of 1988 (NAVD 88). The 100 ft grid cell size was used throughout the project and resulting products. Figure 3-1 presents a map of the DEM for the LCNRD Reconnaissance AEM survey area. The LCNRD Reconnaissance project area has a vertical relief of 935 ft with a minimum elevation of 1.080 ft and a maximum elevation of 2,015 ft. This DEM was used to reference all elevations within the AEM and borehole datasets.

The DEM used for each of the AEM Block survey areas are presented in Figure 3-2 (Aten), Figure 3-3 (Bloomfield), Figure 3-4 (Hartington), Figure 3-5 (Lindy), Figure 3-6 (Menominee), Figure 3-7 (Obert), and Figure 3-8 (Santee).

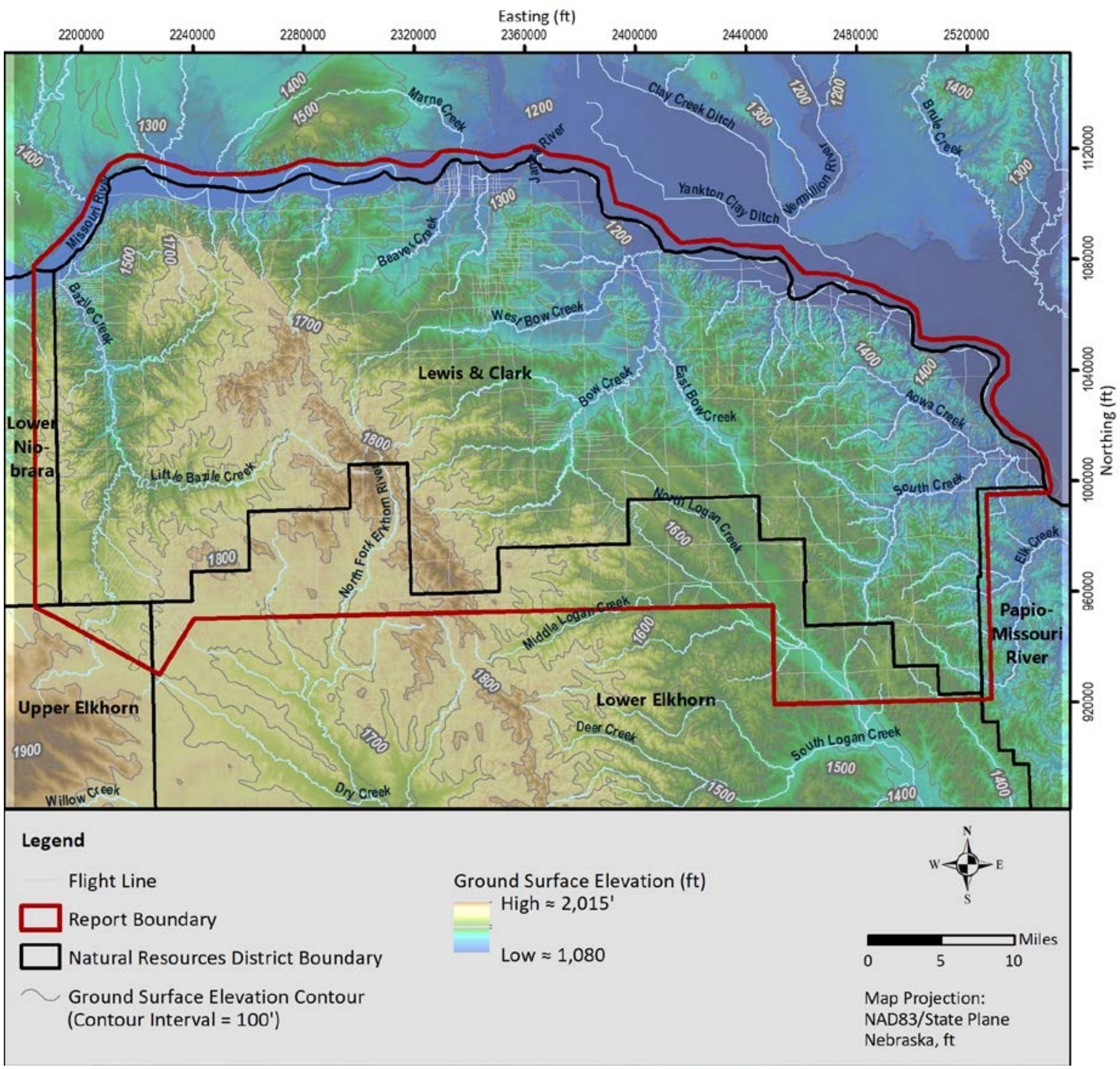


Figure 3-1. Map of the Digital Elevation Model (DEM) for the LCNRD study area. Flight lines are indicated with white lines. Data source is the one (1) arc-second National Elevation Dataset (U.S. Geological Survey, 2018). The projection is NAD 83 State Plane Nebraska (feet) and the elevation values are referenced to the North American Vertical Datum of 1988 (NAVD 88).

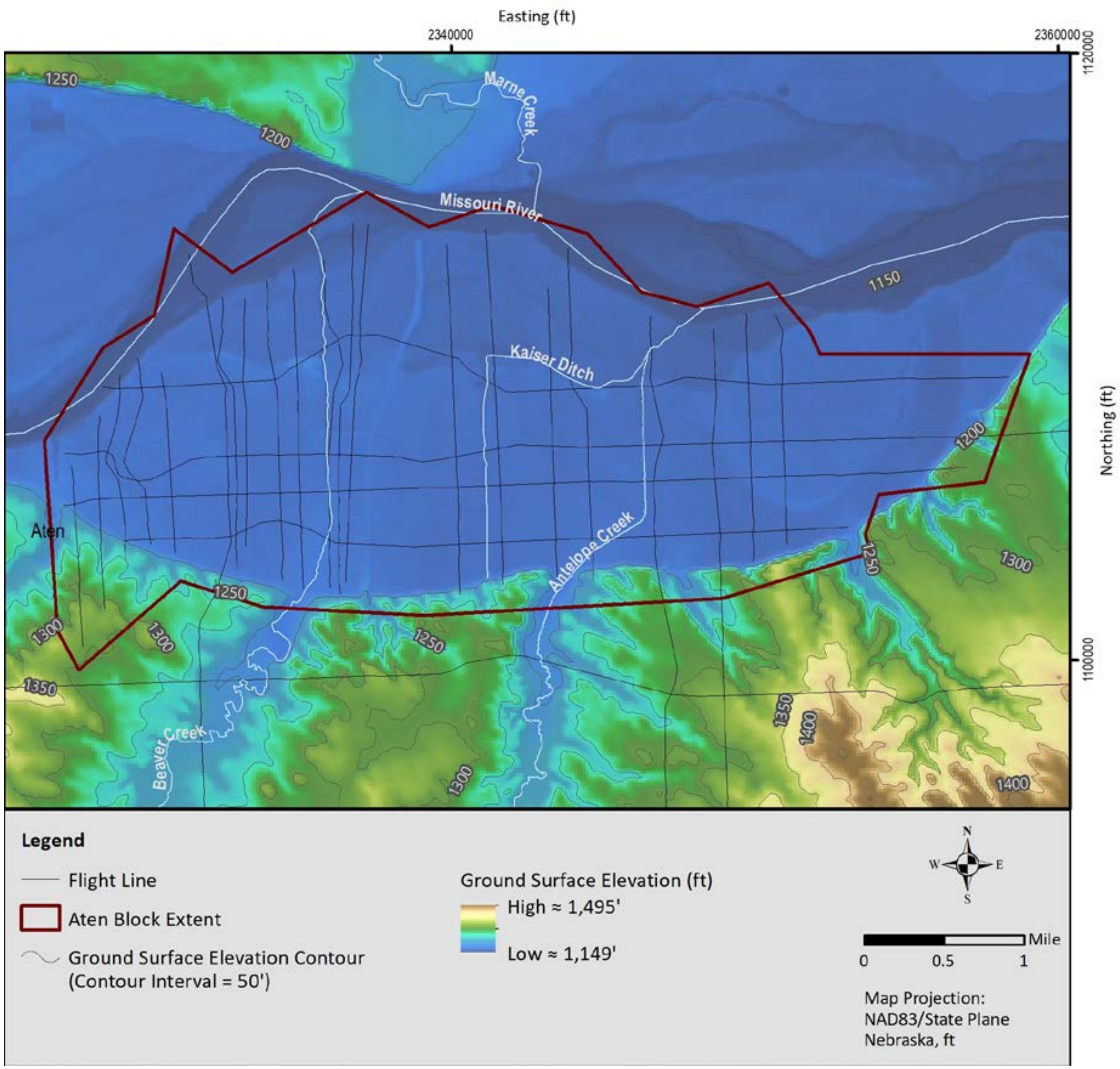


Figure 3-2. Map of the Digital Elevation Model for the Aten Block AEM survey area. Flight lines are indicated with gray lines. Data source is the one (1) arc-second National Elevation Dataset (U.S. Geological Survey, 2018). North American Datum of 1983 (NAD 83) State Plane Nebraska (feet) and the elevation values are referenced to the North American Vertical Datum of 1988 (NAVD 88).

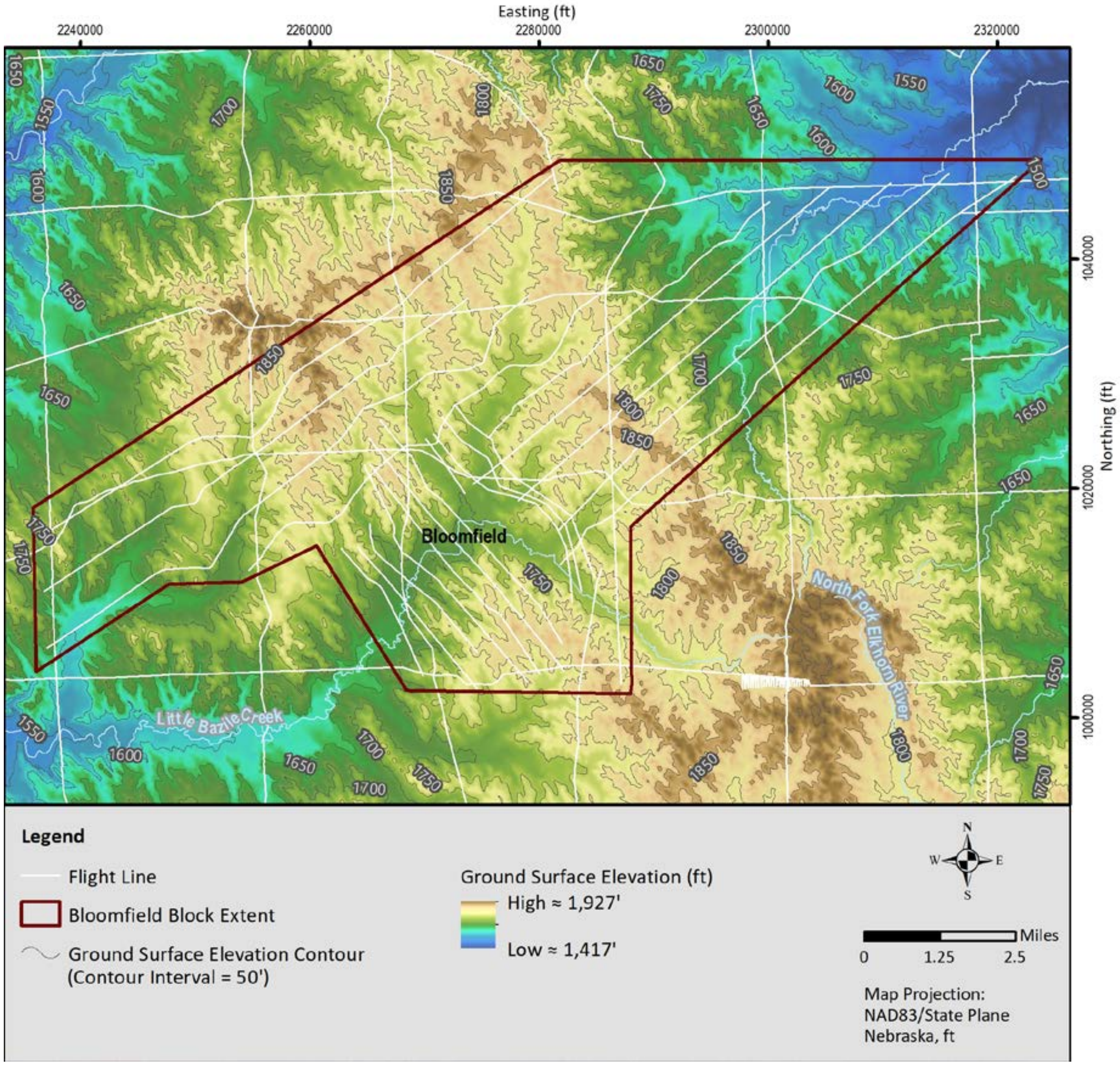


Figure 3-3. Map of the Digital Elevation Model for the Bloomfield Block AEM survey area. Flight lines are indicated with gray lines. Data source is the one (1) arc-second National Elevation Dataset (U.S. Geological Survey, 2018). North American Datum of 1983 (NAD 83) State Plane Nebraska (feet) and the elevation values are referenced to the North American Vertical Datum of 1988 (NAVD 88).

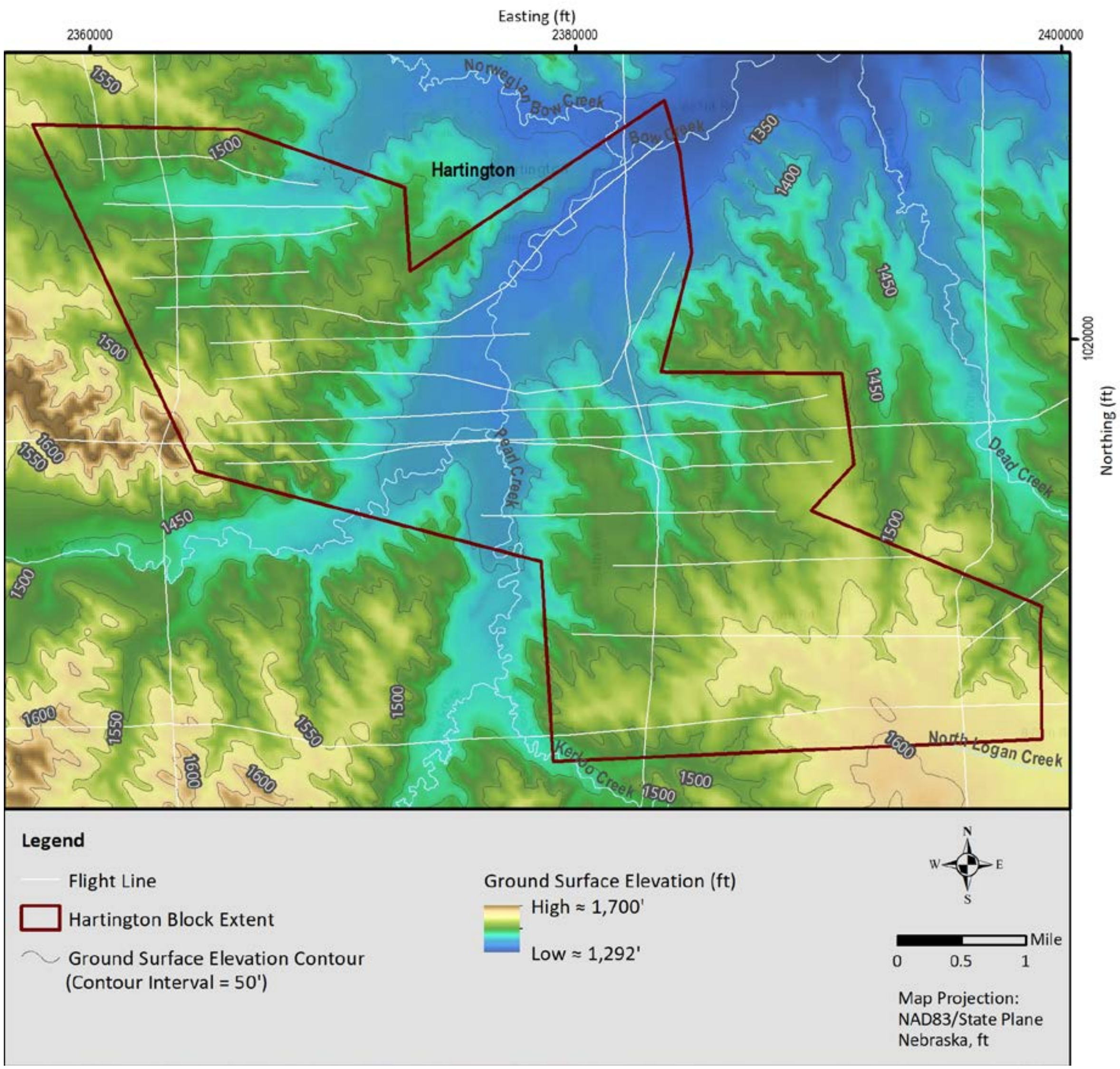


Figure 3-4. Map of the Digital Elevation Model for the Hartington Block AEM survey area. Flight lines are indicated with gray lines. Data source is the one (1) arc-second National Elevation Dataset (U.S. Geological Survey, 2018). North American Datum of 1983 (NAD 83) State Plane Nebraska (feet) and the elevation values are referenced to the North American Vertical Datum of 1988 (NAVD 88).

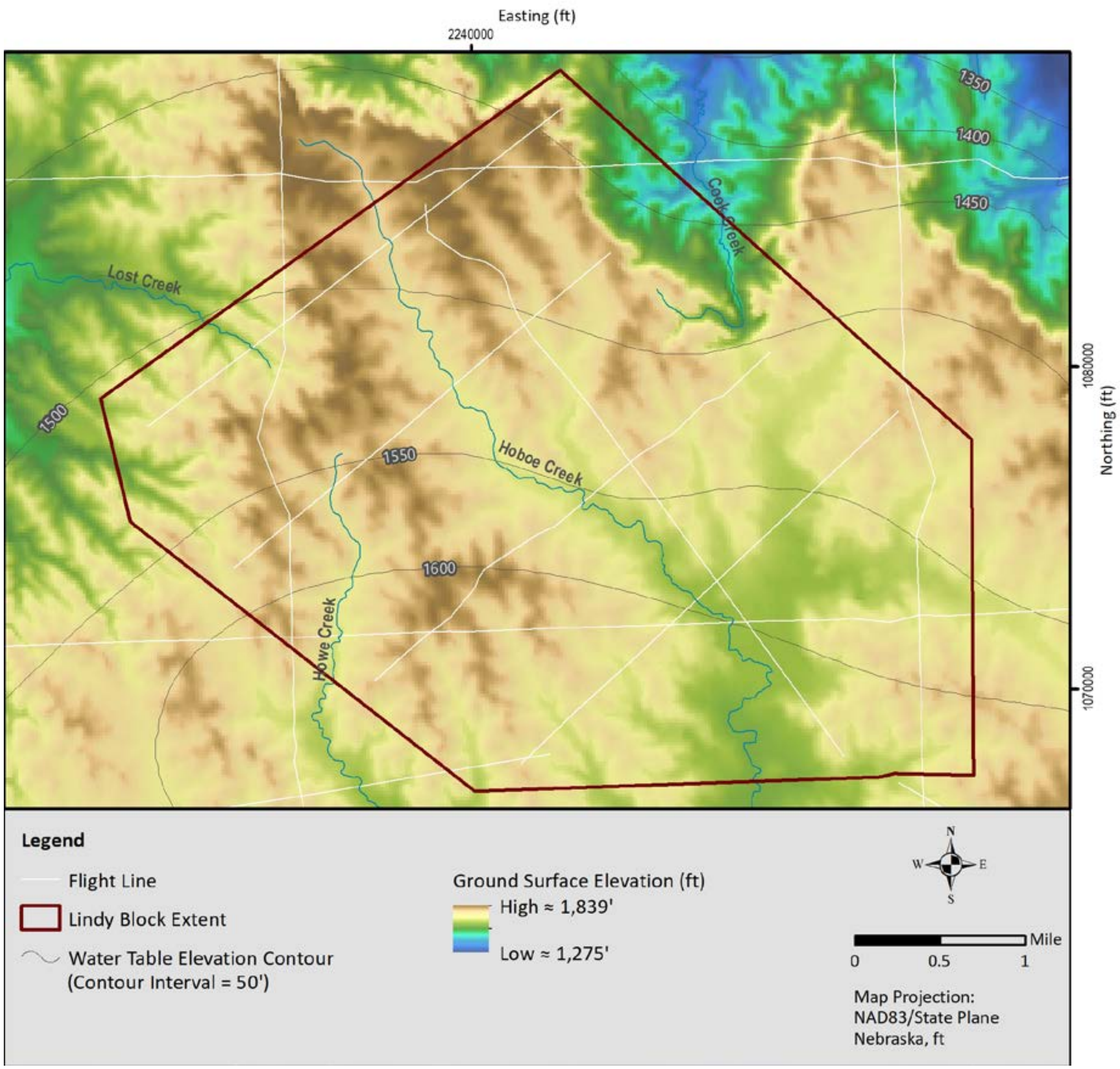


Figure 3-5. Map of the Digital Elevation Model for the Lindy Block AEM survey area. Flight lines are indicated with gray lines. Data source is the one (1) arc-second National Elevation Dataset (U.S. Geological Survey, 2018). North American Datum of 1983 (NAD 83) State Plane Nebraska (feet) and the elevation values are referenced to the North American Vertical Datum of 1988 (NAVD 88).

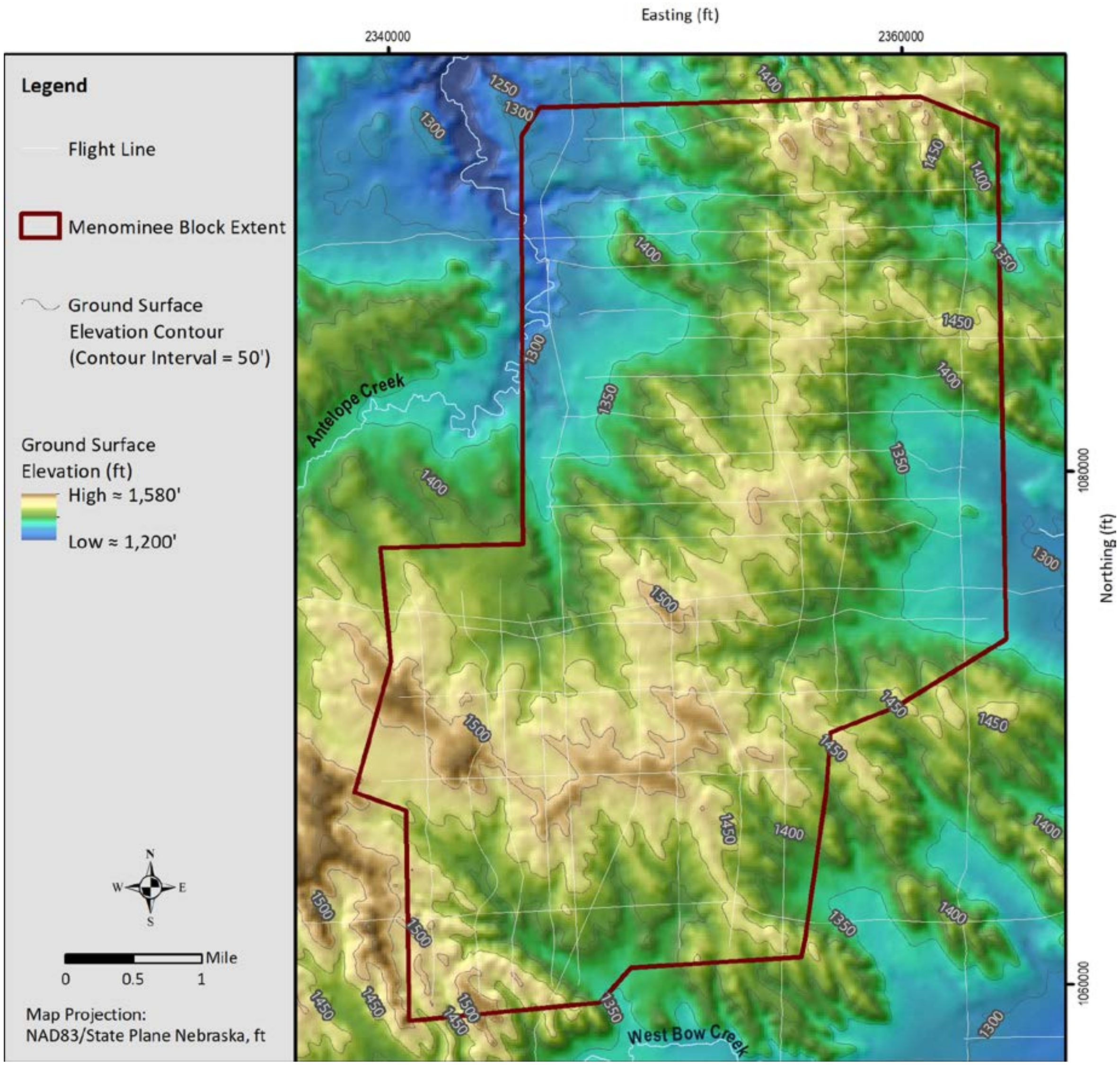


Figure 3-6. Map of the Digital Elevation Model for the Menominee Block AEM survey area. Flight lines are indicated with gray lines. Data source is the one (1) arc-second National Elevation Dataset (U.S. Geological Survey, 2018). North American Datum of 1983 (NAD 83) State Plane Nebraska (feet) and the elevation values are referenced to the North American Vertical Datum of 1988 (NAVD 88).

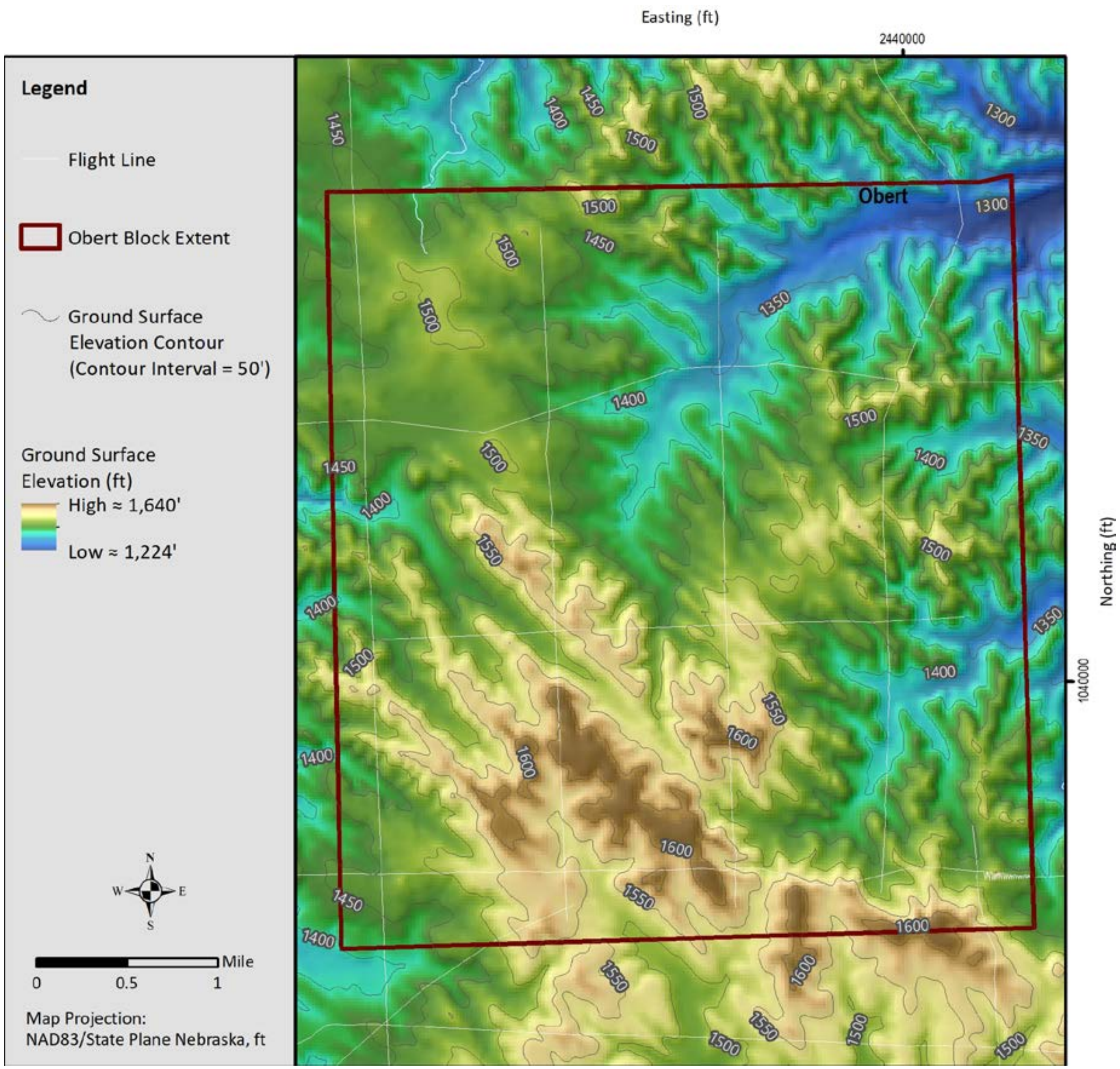


Figure 3-7. Map of the Digital Elevation Model for the Obert Block AEM survey area. Flight lines are indicated with gray lines. Data source is the one (1) arc-second National Elevation Dataset (U.S. Geological Survey, 2018). North American Datum of 1983 (NAD 83) State Plane Nebraska (feet) and the elevation values are referenced to the North American Vertical Datum of 1988 (NAVD 88).

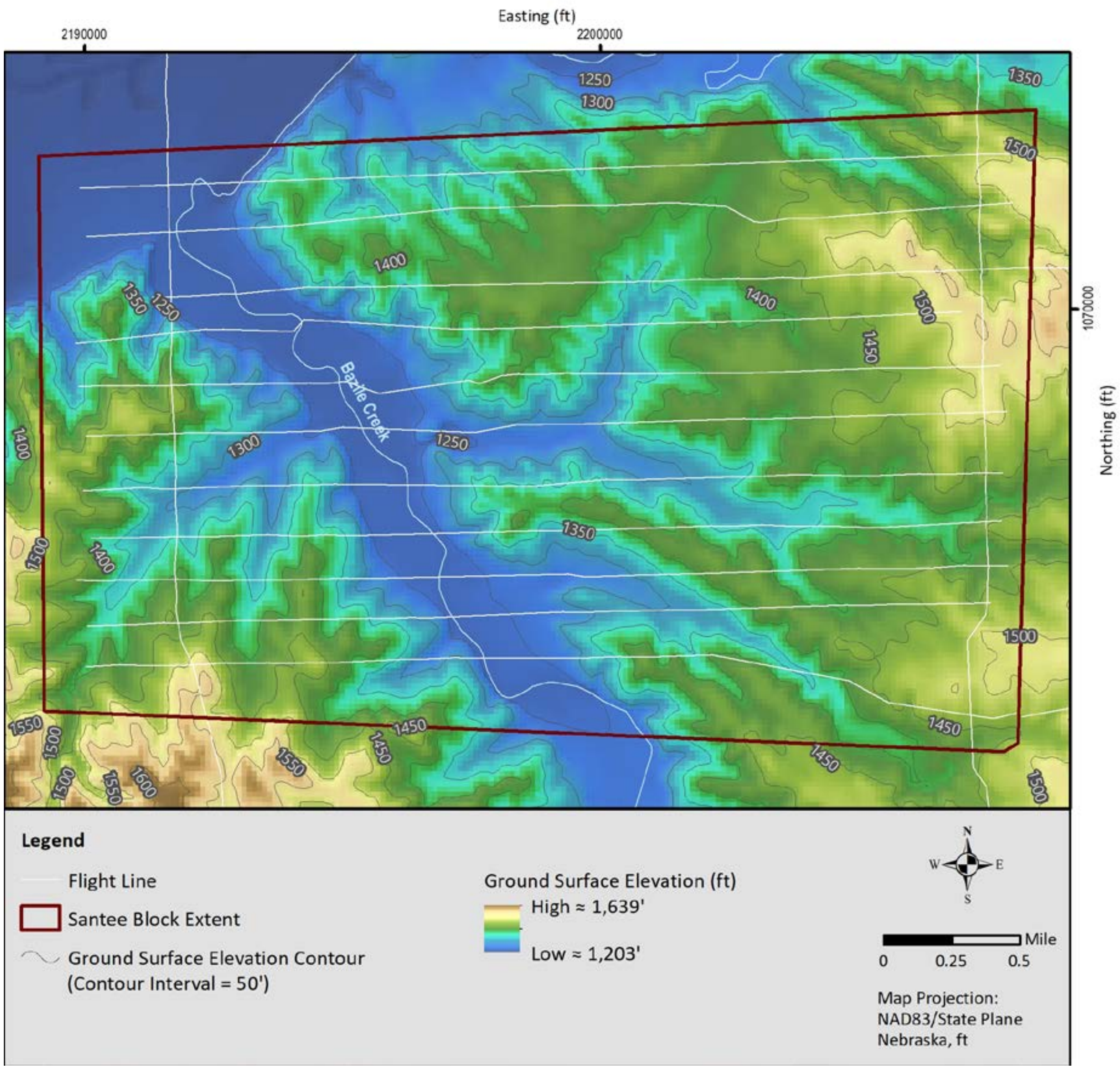


Figure 3-8. Map of the Digital Elevation Model for the Santee Block AEM survey area. Flight lines are indicated with gray lines. Data source is the one (1) arc-second National Elevation Dataset (U.S. Geological Survey, 2018). North American Datum of 1983 (NAD 83) State Plane Nebraska (feet) and the elevation values are referenced to the North American Vertical Datum of 1988 (NAVD 88).

3.1.3 Create Interpretative 2D Profiles

After final combination of the AEM data (described above in Section 3-1), characterization of the subsurface was performed in cross-section format using Datamine Discover Profile Analyst (PA) (Datamine Discover, 2019). 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 related to the area being interpreted. The first step in the interpretation is digitizing the contacts between the geologic units including: Quaternary (***Q***), Tertiary Ogallala Group (***To***), Cretaceous Pierre Shale (***Kp***), Cretaceous Niobrara Formation (***Kn***), Cretaceous Carlile Formation (***Kc***), Cretaceous Greenhorn Limestone and Graneros Shale (***Kgg***), Cretaceous Dakota Group (***Kd***), and the undifferentiated Pennsylvanian (***IP***). The interpretive process benefited from the use of CSD, NE-DNR, and NEOGCC borehole logs, which provided lithologic, stratigraphic, and geophysical information. The interpretations were simultaneously checked against the CSD's Nebraska bedrock geology map (Burchett, 1986), but may differ due to the final interpretation.

The interpretation began with picking the ***Kp***, ***Kc, Kn***, ***Kgg, Kd, IP*** contacts and then finally the ***To*** interface. The process worked iteratively around the eroded units due to the irregular boundary.

The interpretation of the ***To*** included examination of the CSD and NE-DNR boreholes and comparison with the AEM resistivities. Unlike the ***Kp/To*** and ***Kp/Q*** surface, there is not a strong resistivity contrast between the ***Q*** and the ***To***. The borehole information is critical in the determination of an estimated top of the ***To***. The following characteristics were used to locate the ***To*** top: 1) ***To*** indicated on the CSD borehole stratigraphic logs; 2) indication of sandstone, siltstone, or shale in the CSD borehole lithology logs; 3) indication of sandstone, siltstone, shale in the NE-DNR lithology logs; and a generally lower electrical resistivity than the overlying ***Q*** alluvial deposits. Patterns in the resistivity were also used to match the difference in the ***Q*** and the ***To***.

The interpretation of the ***Kp*** included examining the AEM profile section for a low electrical resistivity layer that was also indicated in the borehole logs as the base of aquifer. Many of the CSD as well as the NE-DNR borehole logs stop at the ***Kp*** due to that stratigraphic unit not being considered an aquifer composed predominantly of shale containing clay minerals. Many of the CSD boreholes have stratigraphic calls that assist in the location of the ***Kp***. For the profiles, the clipping distance from the flight line was set independently for the CSD boreholes and the NE-DNR boreholes. Typically, the CSD clipping distance was set to 1-mile or 5,280 ft, the NEOGCC wells were set to 2.84 miles or 15,000 ft, and the NE-DNR boreholes was set to a quarter mile or 1,320 ft. The inversion DOI was also inspected when interpreting the profiles, but was almost always below the top of the ***Kp*** in the western portion of the LCNRD flight area. In the east, the DOI was typically encountered when interpreting the base of the ***Kd***/top of the ***IP***.

The top of the ***Kn*** was a much more challenging unit to interpret when the ***Kp*** is eroded off the ***Kn***. This is due to the highly variable resistivity of the ***Kn***. The unit goes from a resistivity unit to a conductive unit based on the presence of clay minerals within the shale, chalk, and limestone unit. The best way to interpret the unit is to use the boreholes in the area and use the underlying ***Kc*** as a guide to the dip of the ***Kn***. Several of the CSD and the NE-DNR holes have shale, chalk, or limestone indicated at the bottom. This provides a clear indication of the ***Kn***. When the CSD holes contain stratigraphic information that boundary can be confidently interpreted. In some instances, there are no indications of the ***Kn*** at the bottom of the holes. Inspecting the area for the average depth of the NE-DNR holes provides another clue to the position of the ***Kn*** as many wells stop on top of the ***Kn***.

The ***Kc*** unit is identified as a low resistivity unit in the LCNRD. As the ***Kc*** is composed of shale containing clay minerals, the conductive nature of the unit is easily identified and interpreted. Additionally, CSD and NE-DNR wells provide further verification of the lithology and the stratigraphic contacts.

The ***Kgg*** can be difficult to detect depending on the depth. The ***Kgg*** is generally a thin unit <100 feet composed of resistive limestone and conductive shale. When detectable the resistive limestone of the Greenhorn is interrupted beneath the ***Kc***. The interpretation of the bottom of the ***Kgg*** is more challenging due to the variably resistivity of the ***Kd*** immediately below the conductive Graneros Shale. When the ***Kd*** contains resistive sands/sandstone the lower contact of the ***Kgg*** and the top of the ***Kd*** is identifiable. Deep CSD test holes and rare deep NE-DNR wells can assist in the verification of the position of the ***Kgg*** and ***Kd***. On the eastern edge of the survey area the ***Kgg*** is more common in the CSD wells.

The ***Kd*** general location is detectable when there are resistive sands/sandstones. Use of general thickness constraints can also assist in the interpretation of the ***Kd*** location. NEOGCC wells in the area also provide general stratigraphic control assisting in the location of the geologic units. When the ***Kd*** is the Cretaceous bedrock unit, much greater care needs to be taken due to the poor resistivity contrast of the ***Q*** and the ***Kd***. Many of the holes in the area indicate sand and/or sand and gravel at the bottom of the ***Q*** while the ***Kd*** is sand and or sandstone. The resistivity contrast between the ***Q*** sand and the ***Kd*** sand is almost nonexistent. Use of CSD stratigraphy calls and the presence of sandstone and shale in the NE- DNR registered wells were used to pick the ***Q/Kd*** contact when no resistivity contrast was present.

The top of the ***IP*** was a challenging unit to interpret due to the highly variable resistivity of the ***IP**.* The unit goes from a resistive unit to a conductive unit based on the presence of clay minerals within the shale and limestone units. The best way to interpret the unit is to use the boreholes in the area. Many of the CSD and the NE-DNR holes have shale, chalk, or limestone indicated at the bottom. This provides a clear indication of the ***IP***. When the CSD holes contain stratigraphic information, that boundary can be confidently interpreted. In some instances, there are no indications of the ***IP*** at the bottom of the holes. Inspecting the area for the average depth of the NE-DNR holes provides another clue to the position of the ***IP*** as many wells stop on top of the ***IP***. The borehole derived bedrock provided a useful interpretive tool to supplement the boreholes. The following images are selected examples of the interpreted resistivity profiles that illustrate the interpretation process with the use of the available boreholes.

Figure 3-9 is an approximately 70-mile-long merged line, L1101109, that was flown the east-west length of the LCNRD, south of the towns of Bloomfield, Hartington, and Ponca, Nebraska and north of Coleridge, Nebraska. The flight line crosses Bazile Creek, Little Bazile Creek, the North Fork of the

Elkhorn River, the confluence of Pearl and Kerloo Creeks, South Creek, and ends at the Missouri River. Many NE-DNR holes and several CSD holes are along this line. This line is composed of 2018 SkyTEM 312 and 2016 SkyTEM 304M (AGF, 2017a) data that was merged together. Several CSD test holes are projected onto the line that are within one mile. The ***Q*** sediments are composed of alluvium, glacial till outwash, and loess overlying the ***To***, ***Kp***, ***Kn***, ***Kc***, ***Kgg***, and ***Kd*** from west to east. The ***To*** is only a thin layer that occurs on the **Kp** and ***Kn***. The Cretaceous units are progressively eroded off toward the east. There is an excellent match of the resistivities with the lithologies in the CSD wells. However, this reconnaissance line is displayed at a scale for the complete NRD and many of the small changes cannot be seen over the 70 miles of this line at this scale. The DOI (gray dashed line on Figure 3-9) shows the minor differences in the DOI from 2016 and 2018. The gaps in the line indicate areas that were cut due to EM coupling. Many NE-DNR wells are within this line but are too numerous to show on this scale of a plot.

Figure 3-10 presents an approximately 28-mile-long, merged, north-south line, L1201800, that is south of Vermillion, South Dakota and west of Allen, Martinsburg, and Newcastle, Nebraska. The line starts in the south at Logan Creek and crosses Daily Branch and Aowa Creek and ends at the Missouri River. Several CSD test holes and many NE-DNR wells penetrate and/or stop at the top of the ***Kc***. This line is composed of 2018 SkyTEM 312 and 2016 SkyTEM 304M (AGF, 2017a) data that was merged together. Line L120180 is dominated by the glacial till and loess with and area of outwash sand and some alluvial deposits along the drainages. There are areas of resistors within the ***Kd*** that may indicate areas of sand or sandstone. There is an excellent match of the resistivities with the lithologies in the CSD wells. However, this reconnaissance line is displayed at a scale for the complete NRD and many of the small changes cannot be seen over the 70 miles of this line at this scale. The DOI (gray dashed line on the figure) shows the minor differences in the DOI from 2016 and 2018. The gaps in the line indicate areas that were cut due to EM coupling. Many NE-DNR wells are within this line but are too numerous to show at this scale of a plot.

Figure 3-11 is an approximately 6-mile-long east-west line, L1100101, that is just northeast of the town Aten, Nebraska within the Missouri River flood plain within the Aten Block. The line crosses Hwy-81. One CSD test hole, *03-LC-16*, penetrates the full depth of the ***Q*** materials down to the ***Kc.*** Several NE-DNR registered wells are also within 1,000 feet of the flight line; However, few penetrate the full depth of the ***Q***. The line is dominated by Missouri River alluvium that is deposited on the eroded ***Kc***. There is some outcropping ***Kn*** on the far eastern end of the line as the flight line ascends out of the flood plain. A bedrock high is located in approximately the middle of the flight line that divides the area into two compartments of ***Q*** materials with the coarsest of the two is on the west end of the line. The gaps in the line indicate areas that were cut due to EM coupling.

Figure 3-12 is an approximately 9-mile-long east-west line, L1100701, north of Bloomfield, Nebraska within the Bloomfield Block. This line was collected in 2014 using the SkyTEM 508 (Carney et al., 2015a). The line crosses West Bow Creek on the eastern end of the line. The line is dominated by the electrically conductive ***Kp*** and the glacial till and loess. On top of the ***Kp*** there is an obvious higher resistivity zone that contains an outwash sand or buried fluvial sand zone. Several NE-DNR registered wells as well as one CSD hole also indicated the sand rich areas. There is also a thin ***To*** layer. Several holes have sandstone in the logs which would indicate that the zone is within the ***To***. The gaps in the line indicate areas that were cut due to EM coupling.

Figure 3-13 is an approximately 2.75-mile-long east-west line, L901201, located in the center of the Menominee Block. The line is dominated by a paleovalley, possibly a tunnel valley that is co-located with a large EM coupling. The bedrock in the area is the ***Kp*** that is heavily eroded with the paleovalley eroded into the ***Kn***. Along line L901201 two NE-DNR registered wells indicate shallow depths to the ***Kn*** on the eastern end of the line. NE-DNR registered well *G-101606* indicates a deeper ***Q*** section. CSD hole *02-LC-19* indicated the ***Kp*** under sands while *03-LC-19* indicates a deeper ***Q*** section of sands on the ***Kn***. CSD test hole *02-LC-19* matches well with the AEM. Unfortunately, EM coupling precludes comparisons with *03-LC-19*. The gaps in the line indicate areas that were cut due to EM coupling.

Figure 3-14 is an approximately 4-mile-long north-south line, on the western edge of the Obert Block. This line was collected in 2014 using the SkyTEM 508 (Carney et al., 2015a). The line is parallel to and just west of NE-15. This short line indicates a very coarse zone in the ***Q*** that is sitting on the ***Kn***. The use of the NE-DNR wells was critical in making the interpretation of the ***Q*** sitting on the ***Kn***. Below the eroded ***Kn***, the ***Kc*** is easily detected as an electrically conductive layer. The gaps in the line indicate areas that were cut due to EM coupling.

All of the 2D profiles along the flight lines can be found in Appendix 1. The above profiles show examples of the interpretive process used in this LCNRD AEM interpretative report.

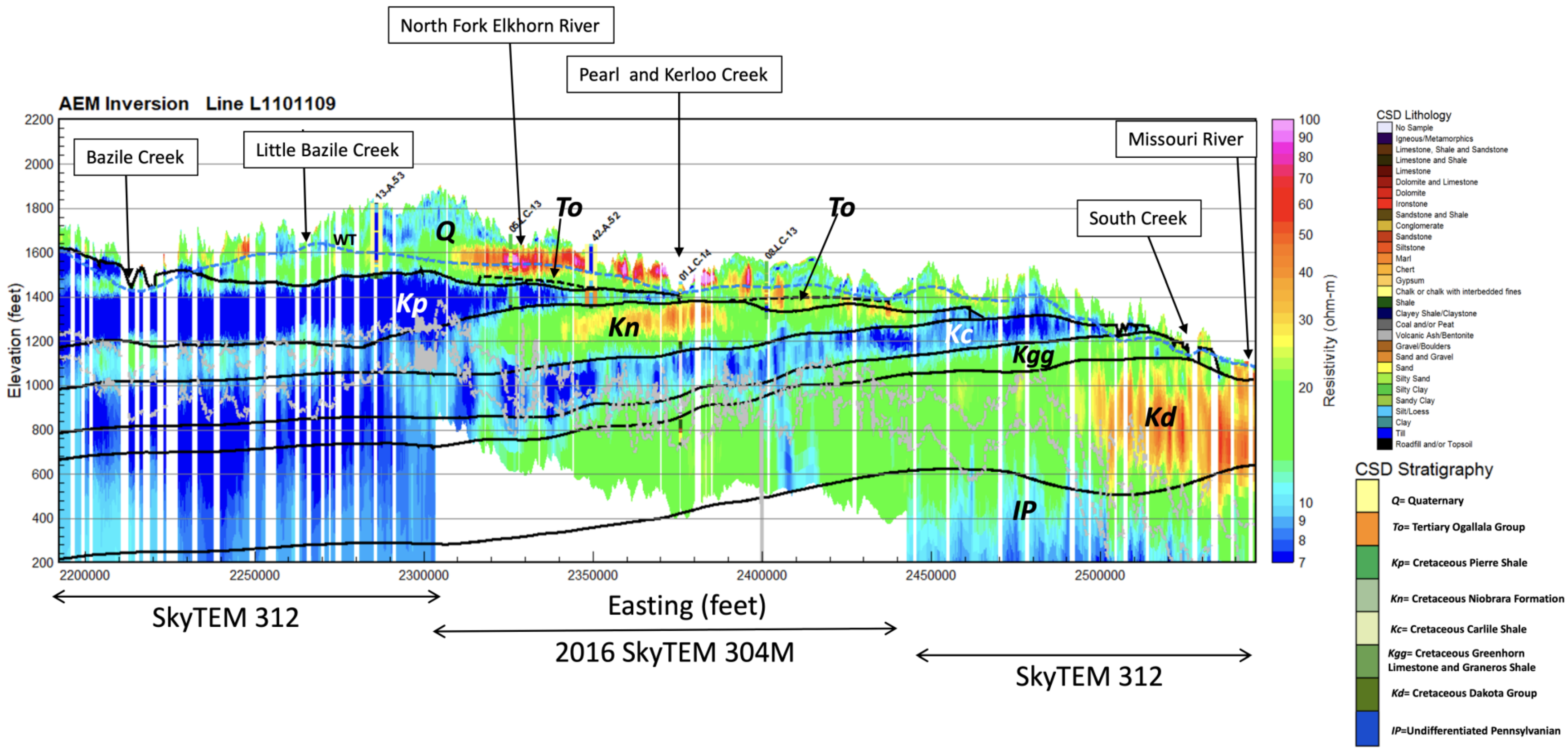


Figure 3-9. 70-mile merged east-west line L1101109. CSD (labeled) borehole lithology and stratigraphy logs are indicated on the AEM inverted earth models within 1-mile of flight line. Interpretations are indicated by lines black lines and are labeled with stratigraphic names. The dashed gray lines indicate the Depth of Investigation. Dashed blue line is the CSD 1995 water table.

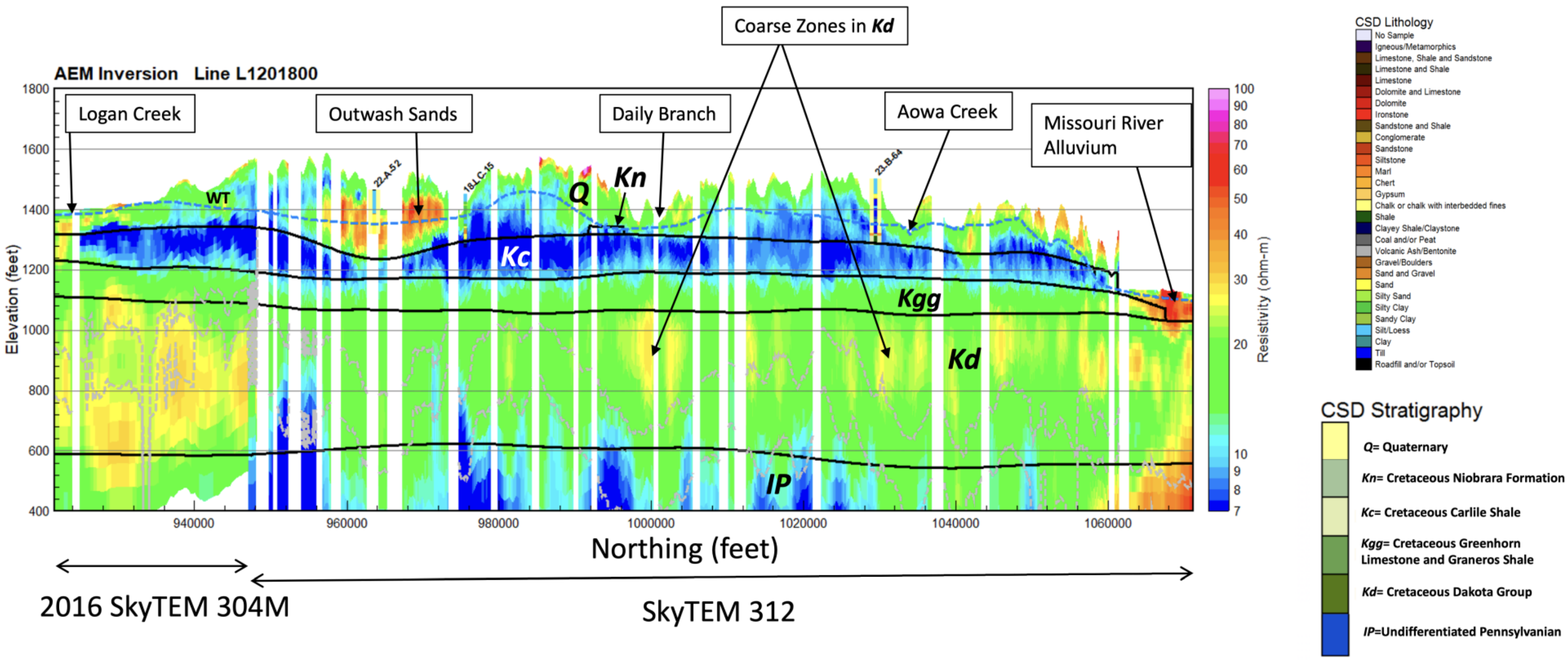


Figure 3-10. 28-mile merged north-south line L1201800. CSD (labeled) borehole lithology and stratigraphy logs are indicated on the AEM inverted earth models within one (1)-mile of flight line. Interpretations are indicated by lines black lines and are labeled with stratigraphic names. The dashed gray lines indicate the Depth of Investigation. Dashed blue line is the CSD 1995 water table.

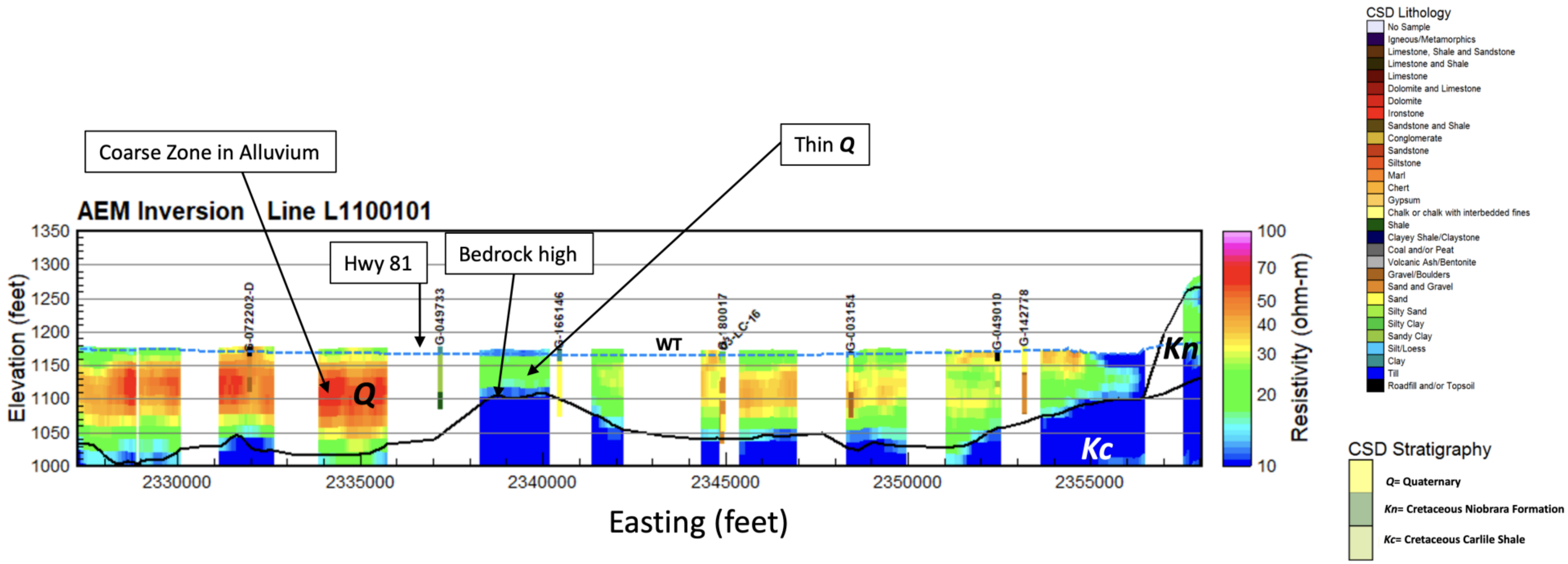


Figure 3-11. 6-mile east-west line L1100101 within the Aten AEM Block. CSD and NE-DNR (labeled) borehole lithology and stratigraphy logs are indicated on the AEM inverted earth models within 1,000-feet of flight line. Interpretations are indicated by lines black lines and are labeled with stratigraphic names. Dashed blue line is the CSD 1995 water table.

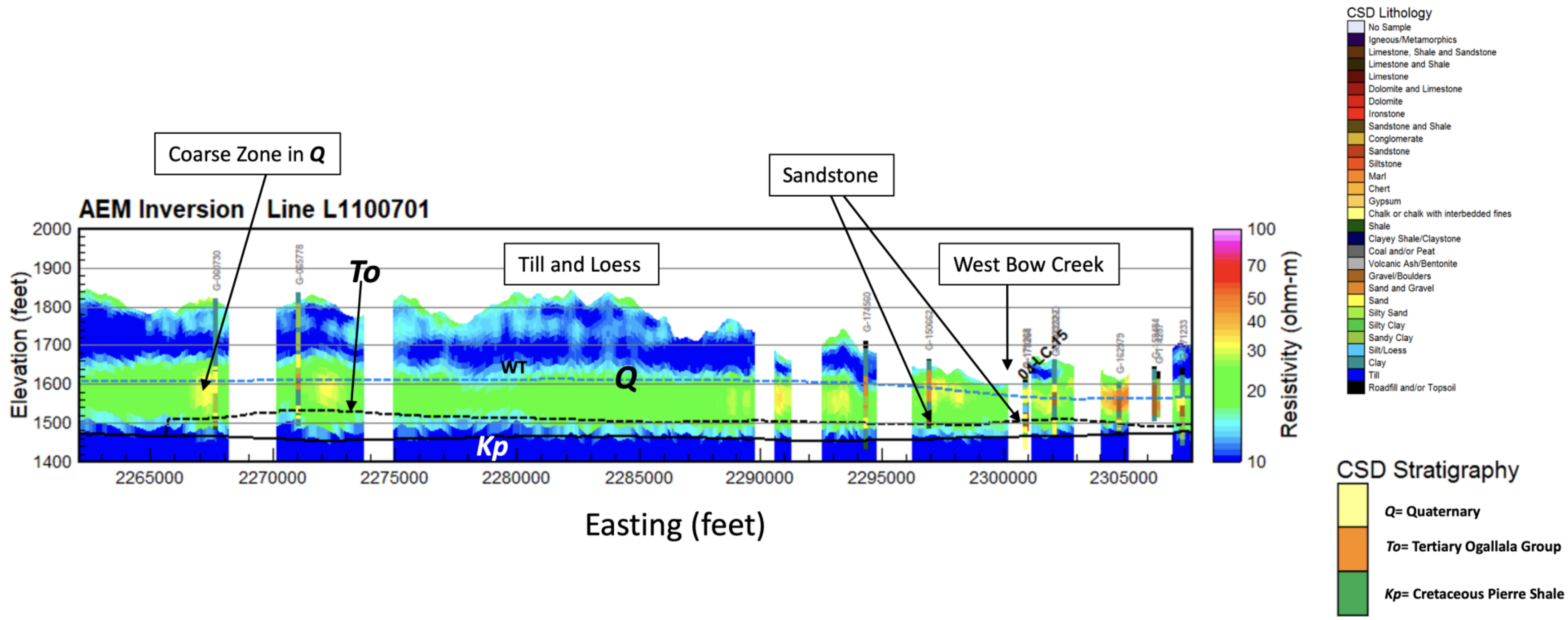


Figure 3-12. 9-mile east-west line L1100701 within the Bloomfield AEM Block. CSD and NE-DNR (labeled) borehole lithology and stratigraphy logs are indicated on the AEM inverted earth models within 1,000-feet of flight line. Interpretations are indicated by lines black lines and are labeled with stratigraphic names. Dashed blue line is the CSD 1995 water table.

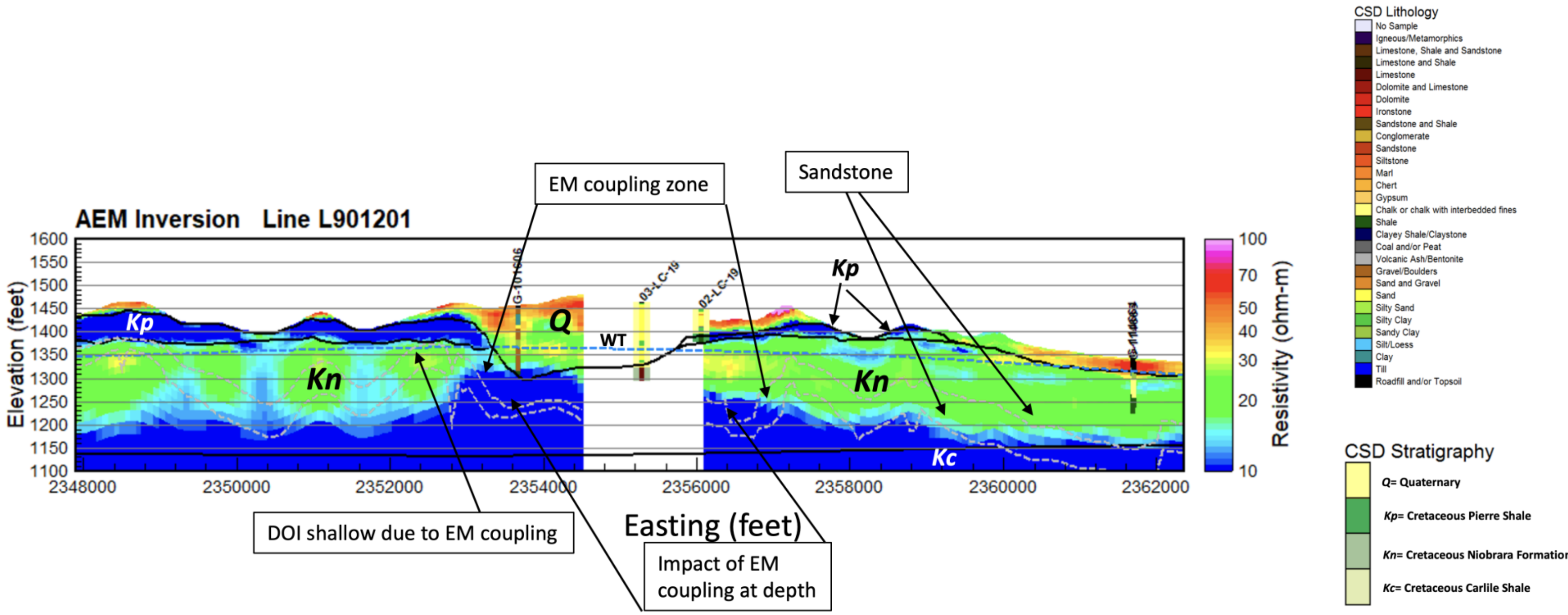


Figure 3-13. 2.75-mile east-west line L901201 within the Menominee AEM Block. CSD and NE-DNR (labeled) borehole lithology and stratigraphy logs are indicated on the inverted earth models within 1,000-feet of flight line. Interpretations are indicated by black lines and are labeled with stratigraphic names. The dashed gray lines indicate the Depth of Investigation. Dashed blue line is the CSD 1995 water table.

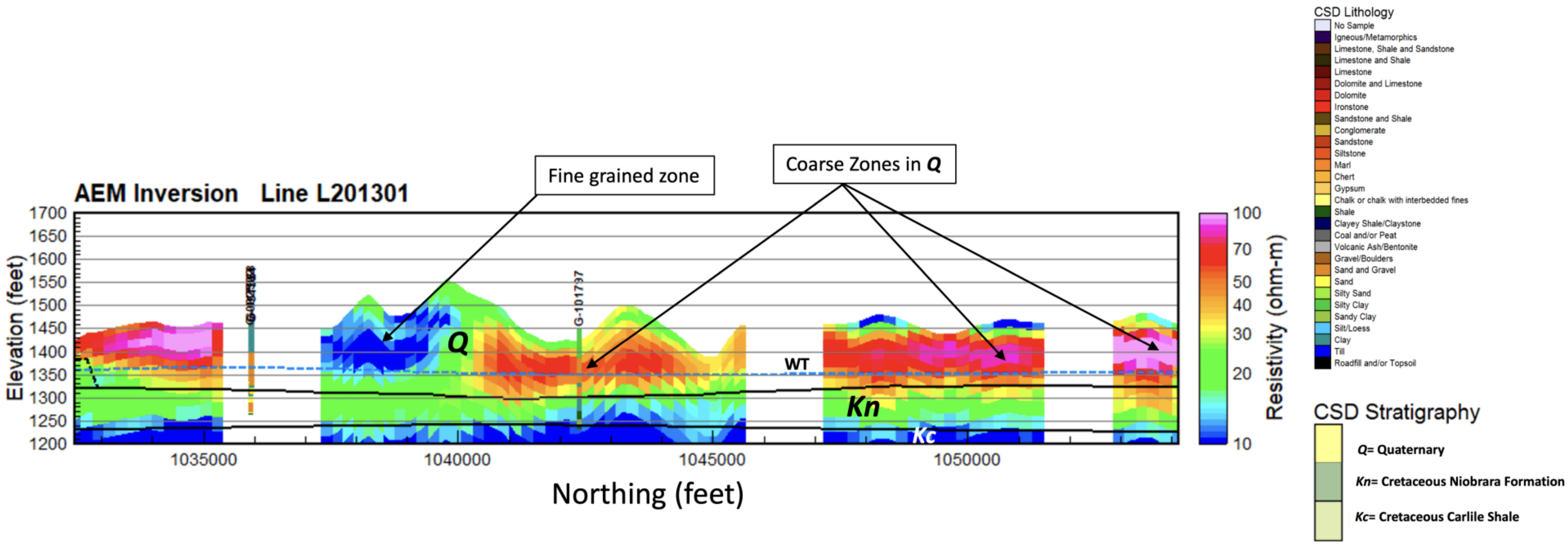


Figure 3-14. 4-mile east-west line L201301 within the Obert AEM Block. NE-DNR (labeled) borehole lithology are indicated on the AEM inverted earth models within 1,000-feet of flight line. Interpretations are indicated by black lines and are labeled with stratigraphic names. Dashed blue line is the CSD 1995 water table.

3.1.4 Create Interpretative Surface Grids

Grids have been produced for the LCNRD project area and the Aten, Bloomfield, Hartington, Lindy, Menominee, Obert, and Santee Block AEM survey areas including grids of elevations of the tops of the geologic units and geologic unit total thicknesses and saturated thicknesses. To create these grids, data such as a ground surface digital elevation model (DEM), water table elevation, data from CSD boreholes, and AEM interpreted point data of the survey area were imported and processed in ESRI's ArcMap along with the Spatial and Geostatistical Analyst extensions.

Raster grids of the elevations of the top of the Ogallala Group (***To***), Cretaceous Pierre (***Kp***), Cretaceous Niobrara (***Kn***), Cretaceous Carlile (***Kc***), Cretaceous Greenhorn Limestone/Graneros Shale (***Kgg***), Cretaceous Dakota Group (***Kd***), and undifferentiated Pennsylvanian (***IP***) for the LCNRD and the Block AEM survey areas were produced. Data used to create the grids included ≈22,000 data points with top elevation values extracted from the AEM interpretation and ≈250 CSD borehole data points, which provided control in areas between the flight lines. These data were input into a database and the database was imported into ESRI's ArcMap for processing. The elevation point data were interpolated into a continuous surface using the kriging geostatistical model and exported to a 100 ft cell size grid. Even though the average distance between AEM data points within the entire project area is almost 1,800 ft, a 100 ft cell size resolution was used so that the edges of the geologic units where the unit either outcrops or makes a surficial contact with another unit could be represented more accurately than if a larger cell size was used. The western extents of the raster grids for the lower geologic units including ***Kgg***, ***Kd***, and ***IP*** were clipped to the edge of the interpreted AEM data points even though the geologic units do continue to the west.

For discussion purposes, the grids created by this method will be called the top elevation raw grids herein. The top elevation raw grids were iteratively refined by the following methods:

- Identify geologic unit outcrops
- Revise geologic unit extents based on AEM data
- Re-interpolate top elevation raw grids at different scales

3.1.4.1 Identify Geologic Unit Outcrops

A geologic outcrop investigation was carried out to refine the top elevation raw grids, especially in areas where AEM point data were 2 or more miles apart at reconnaissance flight lines. The investigation included downloading previously published geologic maps showing the formation outcrops, digitizing and/or compiling the outcrop extents into a GIS, then revising the compiled outcrop extents as necessary. Figure 3-15 below shows the spatial distribution and sources of geologic maps that were used in the outcrop investigation. The six geologic quadrangles, Fordyce (Dillon et al., 2013), Wynot (Dillon et al., 2008), Obert (Dillon et al., 2009), Hartington (Dillon et al., 2012), Coleridge (Dillon et al., 2010), and Coleridge SE (Dillon et al., 2011), were provided as GIS shapefiles whereas the Geology of the Yankton Area, South Dakota and Nebraska (Simpson, 1960) and a bedrock geologic map showing the configuration of the bedrock surface in Nebraska part of Sioux City 1 degree x 2 degrees quadrangle (Burchett et al., 1988) were available as GeoTIFF images only.

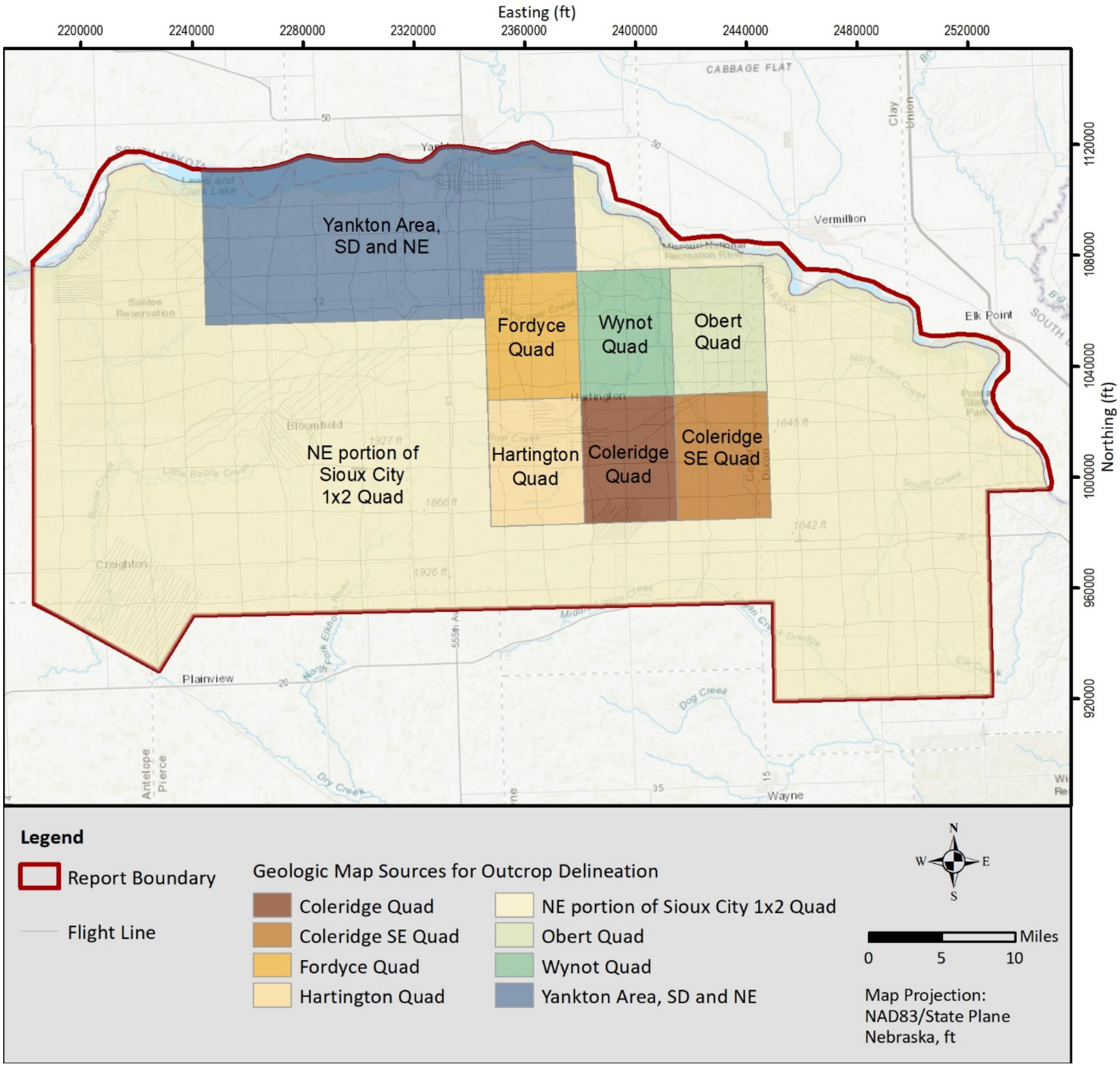


Figure 3-15. Map of the spatial distribution and sources of geologic maps that were used in the outcrop investigation within the LCNRD AEM survey area. The projection is NAD83 State Plane Nebraska (feet) and the elevation values are referenced to NAVD 88 (feet).

After the outcrops were digitized and compiled into a GIS, the top elevation raw grids as well as aerial imagery were used to revise the compiled outcrops. Revisions to the compiled outcrops were necessary since the scale of the geologic maps, especially the "Geology of the Yankton Area, South Dakota and Nebraska" (Simpson, 1960) and "Bedrock geologic map showing configuration of the bedrock surface in Nebraska part of Sioux City 1 degree x 2 degrees quadrangle" (Burchett et al., 1988) maps, was relatively small and therefore the outcrop extents were more generalized on the maps. To revise the outcrop extents two methods were carried out including: (1) comparison of compiled outcrop extents with aerial imagery and (2) comparison of compiled outcrop extents to the top elevation raw grids.

1. Inspection with aerial imagery
    a. The compiled outcrops were compared with aerial imagery in ArcMap using the ESRI world imagery base map.
    b. If a compiled outcrop extent existed in areas where outcrops were not apparent in the aerial imagery, such as irrigated farmland, the outcrop extent was removed or revised from the GIS shapefile.
2. Comparison of compiled outcrop extents to top elevation raw grids
    a. ArcMap's raster calculator was used to subtract the top elevation raw grid for each geologic unit from the DEM to determine where the top elevation raw grid was higher than the DEM.
    b. Areas where the top elevation raw grid was higher than the DEM indicated potential areas where the geologic unit could be outcropping.
    c. These potential outcrop areas were compared to the compiled outcrop extents in ArcMap.
        i. Any area where a potential outcrop, as determined by the raster calculator, existed inside a compiled outcrop extent that area was retained as an outcrop in the compiled outcrop shapefile.
        ii. Any area where a potential outcrop, as determined by the raster calculator, did not exist inside a compiled outcrop extent, especially where AEM data points existed, that area was removed or revised from the outcrop shapefile.

Figure 3-16 below shows an example of an area near Santee that compares the original published geologic map, digitized outcrops from the geologic map and aerial imagery, and the extent of the final outcrops after the outcrop investigation was complete.

After the outcrop extents were finalized, the top elevation raw grids were revised so that any area of the raw grid that was within the outcrop extent was set to the elevation of DEM minus one foot. A one-foot layer of soil was assumed to overlay most areas that are designated as outcrop.

3.1.4.2 Revise geologic unit extents based on AEM data

Based on the AEM point data some sections of the geologic unit extents delineated in the Geologic Bedrock Map of Nebraska (Burchett, 1986) were revised. The most notable revisions are within the Menominee Block AEM survey area as well as the southeastern portion of the project area. The currently mapped geologic extents presented in Burchett (1986) were retained in areas where an AEM survey was not conducted or where the AEM point data did not explicitly show a variation with the mapped extent. Figure 3-17 and Figure 3-18 below show the currently mapped geologic extent compared to the revised extent and AEM data within two significant areas. The general guideline that was followed to revise the geologic unit extents was that if an AEM-derived data point along a flight did not exist for that unit, then this indicated that the geologic unit was not present at that location and, therefore, the geologic unit should not extend into that area.

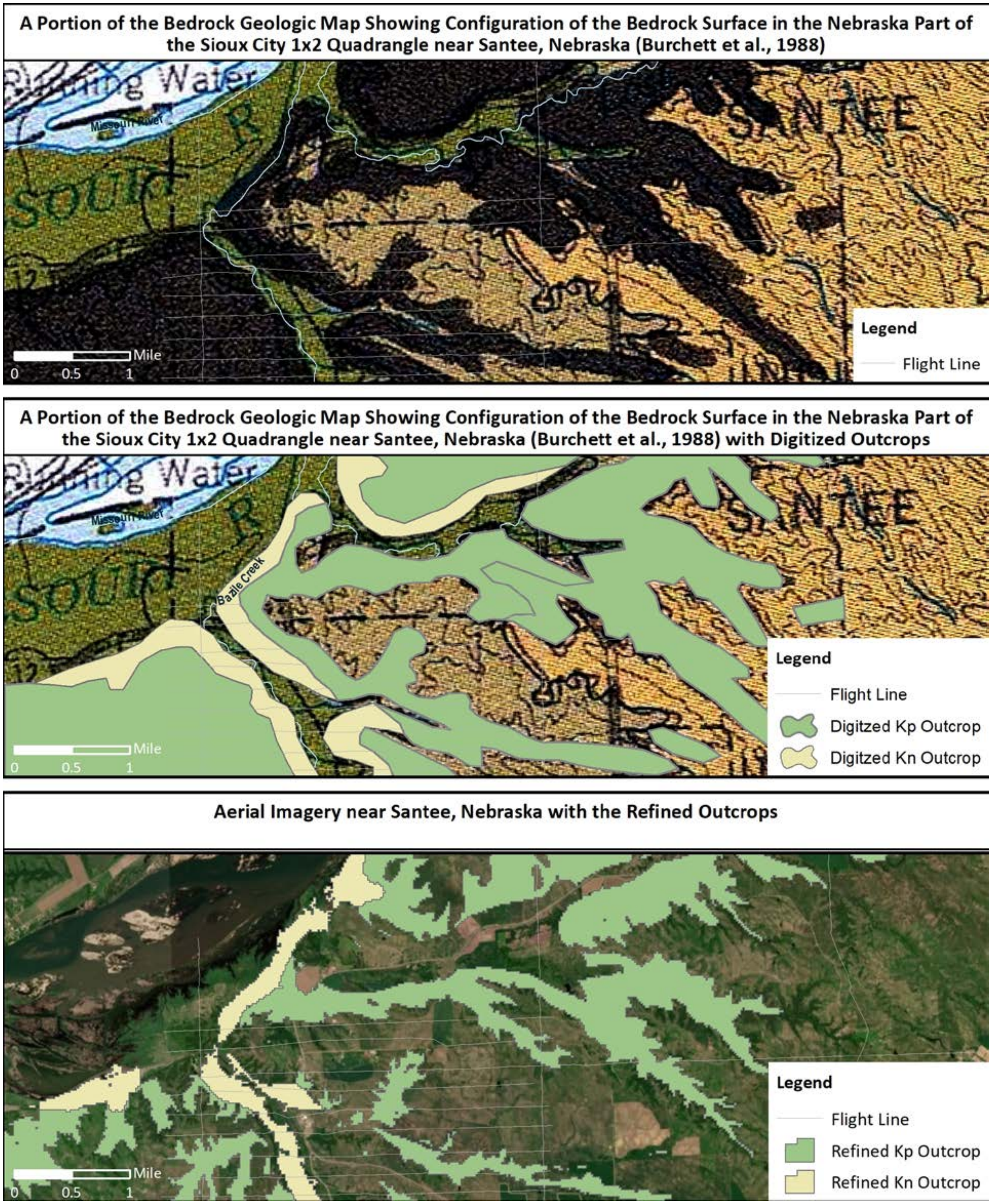


Figure 3-16. Map of an area near Santee that compares the original published geologic map (Bedrock geologic map showing configuration of the bedrock surface in Nebraska part of Sioux City 1 degree x 2 degrees quadrangle [Burchett et al., 1988), digitized outcrops from the geologic map and aerial imagery, and the extent of the final outcrops after the outcrop investigation was complete. The projection is NAD83 State Plane Nebraska (feet) and the elevation values are referenced to NAVD 88 (feet).

After the geologic unit extents were revised, the top elevation raw grids were clipped to the new extents. However, the western extents remained clipped to the western edge of the interpreted AEM data points even though the geologic units continue to the west.

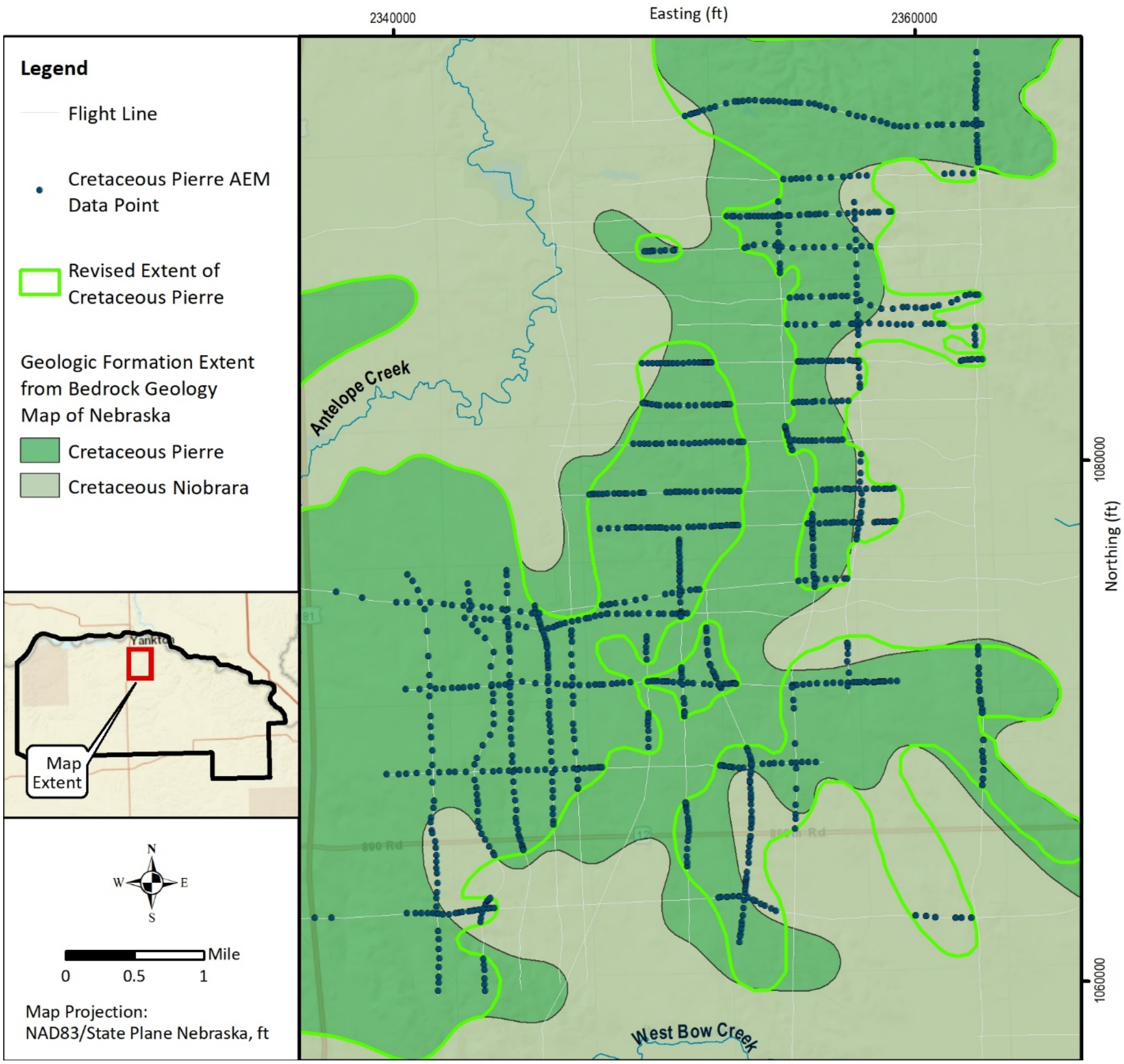


Figure 3-17. Map of the Menominee Block survey area showing the currently mapped geologic extent of the Cretaceous Pierre (*Kp*) as it is delineated in the Geologic Bedrock Map of Nebraska (Burchett, 1986) compared to the revised extent of the *Kp* and AEM data. The projection is NAD83 State Plane Nebraska (feet) and the elevation values are referenced to NAVD 88 (feet).

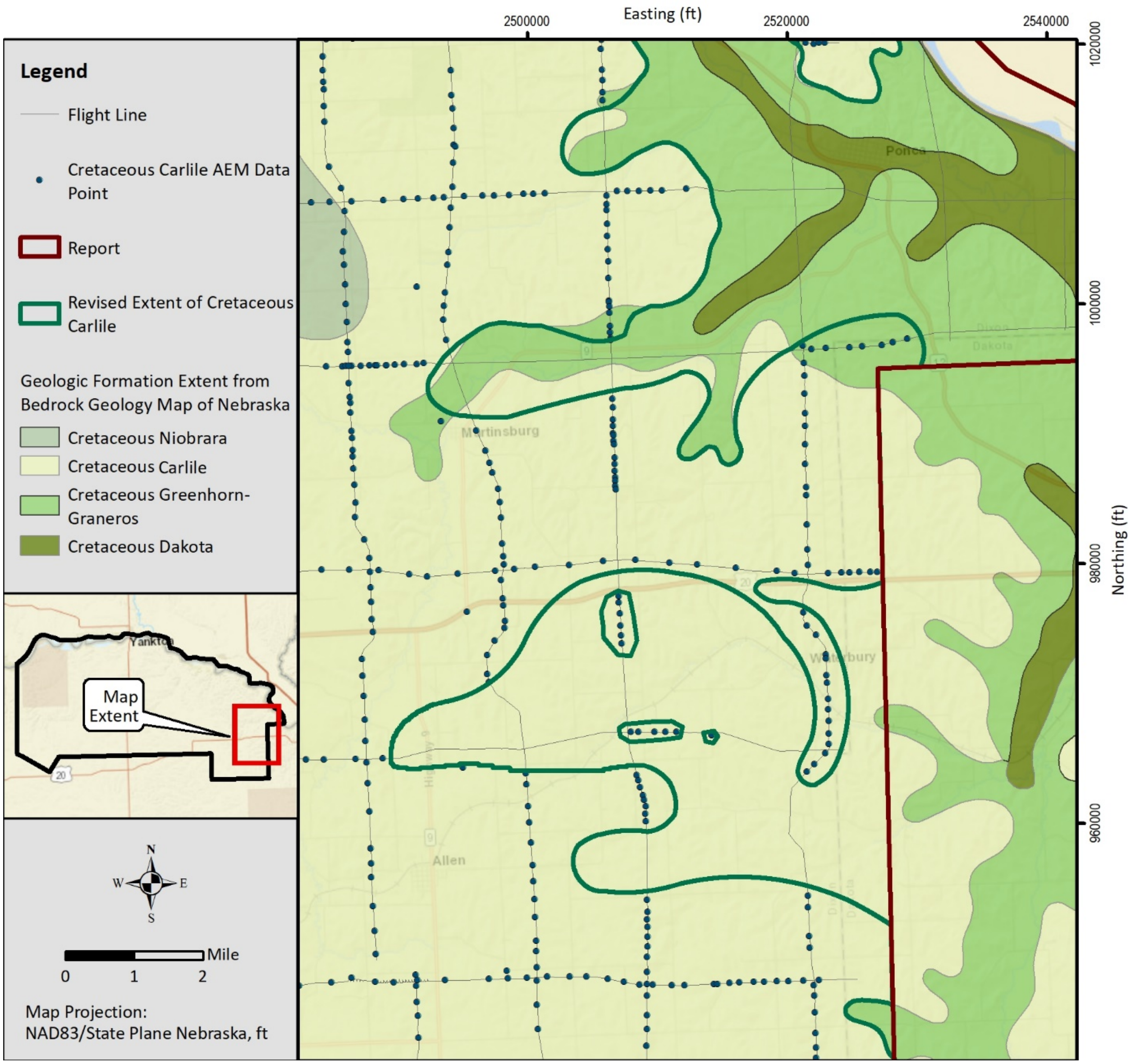


Figure 3-18. Map of the southeastern portion of the LCNRD survey area showing the currently mapped geologic extent of the Cretaceous Carlile (*Kc*) as it is delineated in the Geologic Bedrock Map of Nebraska (Burchett, 1986) compared to the revised extent of the *Kc* and AEM data. The projection is NAD83 State Plane Nebraska (feet) and the elevation values are referenced to NAVD 88 (feet).

3.1.4.3 Re-Interpolate Top Elevation Raw Grids at Larger Spatial Scale

The final refinement made to the elevation tops raw grids was to re-interpolate select shallow geologic unit surfaces at a spatially larger scale within some of the Block survey areas. Interpolating an area at a spatially large scale with dense data points, such as the block survey areas, essentially means that a smaller lag size, or distance between pairs of points that are used in the kriging model, may be used. A smaller lag size makes it possible to capture details of the fine, local variation between data points in the interpolation model. It was essential to capture the fine, local variations in the shallow geologic units such as the ***Kp*** and ***Kn*** in the Menominee Block and the ***Kc*** in the Aten block, in the raster grids to better represent the AEM data collected within those blocks. The Block areas where shallow geologic units were re-interpolated at a larger scale included Aten, Santee, and Menominee. To re-interpolate these areas, only those points within each Block AEM survey area as well as data points within a buffered area around the block survey were used in the kriging geostatistical model. The interpolated surface was exported to a 100 ft cell size, then mosaicked onto the whole project area tops elevation raw grid. Figure 3-19 below highlights the area where the ***Kc*** surface was re-interpolated at a larger scale within the Aten Block area. Edge effects, or areas where the elevation may vary slightly at a boundary, resulting from mosaicking the smaller scale interpolation to the larger scale interpolation were minimalized by re-interpolating an area slightly larger than the block area, then clipping the re-interpolated raster grid to the Block area extent to be mosaicked to the project area top elevation raw grid.

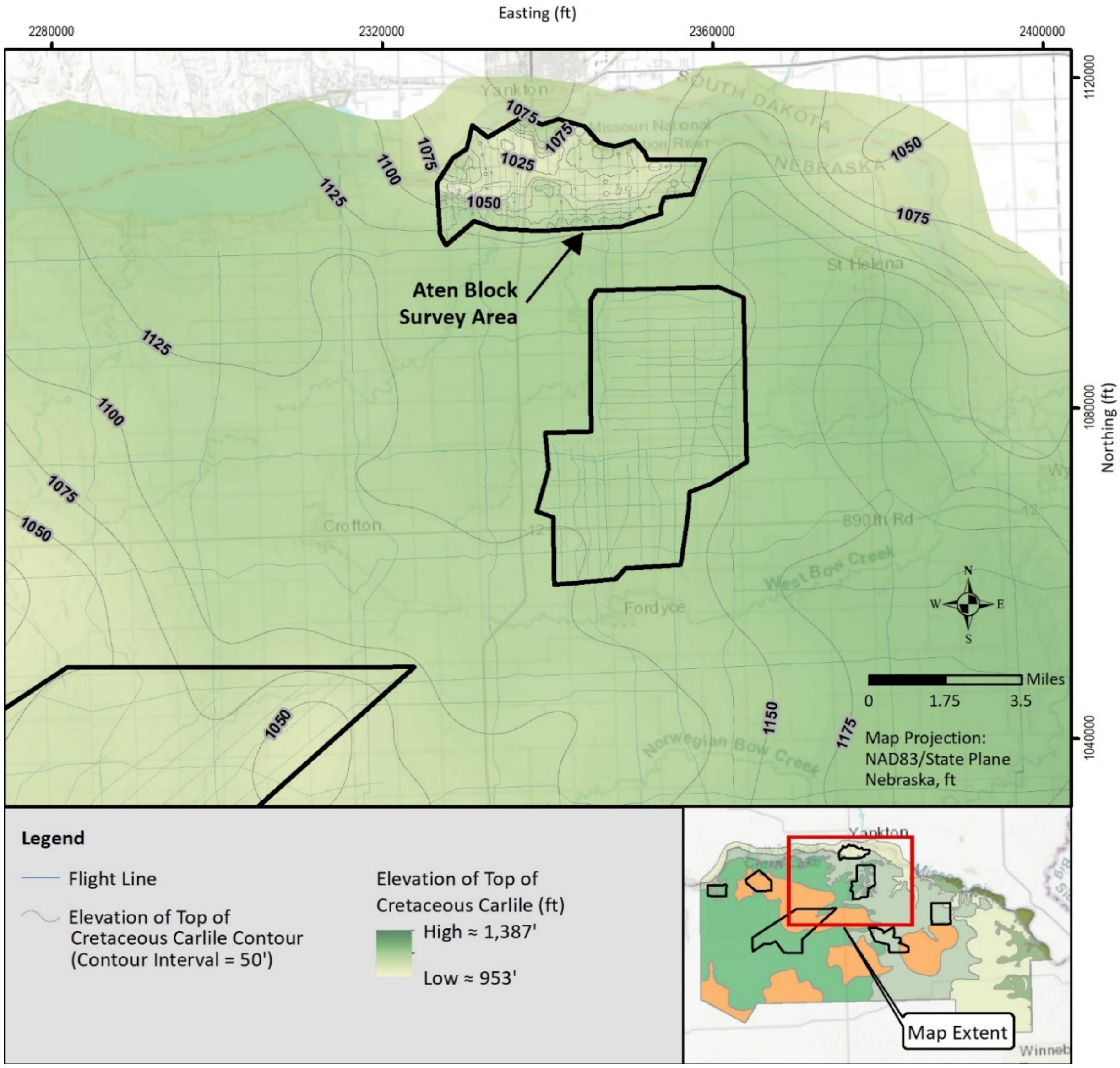


Figure 3-19. Map within the Aten and Menominee block survey areas that highlights the area where the *Kc* surface was re-interpolated at a larger scale within the Aten Block area. The projection is NAD83 State Plane Nebraska (feet) and the elevation values are referenced to NAVD 88 (feet).

3.1.5 Maps of the Geologic Units in the LCNRD AEM Survey Area

Figure 3-20 to Figure 3-58 are maps of the elevation of the top of the ***To*** (Figure 3-20 to Figure 3-22), ***Kp*** (Figure 3-23 to Figure 3-27), ***Kn*** (Figure 3-28 to Figure 3-34), ***Kc*** (Figure 3-35 to Figure 3-42), ***Kgg*** (Figure 3-43 to Figure 3-47), ***Kd*** (Figure 3-48 to Figure 3-53), and ***IP*** (Figure 3-54 to Figure 3-58) geologic units within the LCNRD survey area and the Aten, Bloomfield, Hartington, Lindy, Menominee, Obert, and Santee Block AEM survey areas, respectively, if present.

A raster grid of the elevation of the top of bedrock was produced for the LCNRD Reconnaissance and the Block AEM survey areas. To reduce the edge effects between contacts of geologic units, the bedrock surface was created by interpolating over 10,000 data points extracted from the AEM interpretation with the kriging geostatistical model rather than mosaicking each of the top elevation of geologic unit raster grids. The 100 ft cell size for the top of bedrock elevation grid was retained for the Block AEM survey areas as well as for the whole project area. Figure 3-59 to Figure 3-66 are maps of the elevation of the top of the bedrock surface within the LCNRD survey area and the Aten, Bloomfield, Hartington, Lindy, Menominee, Obert, and Santee Block AEM survey areas, respectively.

The total thickness and saturated thickness of Quaternary deposits (***Q***) were calculated for the LCNRD Reconnaissance and the Block AEM survey areas. The total ***Q*** thickness was calculated by subtracting the top of bedrock elevation from the DEM with ArcMap's raster calculator. The saturated ***Q*** thickness was calculated by subtracting the elevation of the top of bedrock from the 1995 water table. Both the total and saturated thickness grid cell sizes are 100 ft. Maps of ***Q*** total thickness are presented in Figure 3-67 to Figure 3-74. Alternating maps of ***Q*** total saturated thickness and ***Q*** saturated thickness combined with wells showing specific capacity are presented in Figure 3-75 to Figure 3-89 within the LCNRD Reconnaissance and Block AEM survey areas. Note that the Santee Block only has a total ***Q*** saturated thickness plot and no ***Q*** saturated thickness with wells showing specific capacity.

The total thickness ***Kd*** was calculated for the LCNRD Reconnaissance and the Aten Block survey areas. The ***Kd*** thickness was calculated by subtracting the top of ***IP*** from the top of ***Kd*** with ArcMap's raster calculator. The western extent of the ***Kd*** thickness raster grid differs from the western extent of the top elevation of ***Kd*** due to the western extent of the underlying IP that was used to determine the ***Kd*** thickness. Figure 3-90 to Figure 3-93 are maps of ***Kd*** total thickness within the LCNRD Reconnaissance and the Aten Block AEM survey areas and ***Kd*** total thickness within the LCNRD Reconnaissance and the Aten Block AEM survey area related to the specific capacity of wells screened within the ***Kd***, respectively.

Maps of the elevation of the 1995 water table in each of the LCNRD Reconnaissance and Block AEM survey areas are presented in Figure 3-94 to Figure 3-101.

Several of the thickness grids used to create these maps are included in *Appendix 3-Deliverables\Grids* in ArcView FLT grid format.

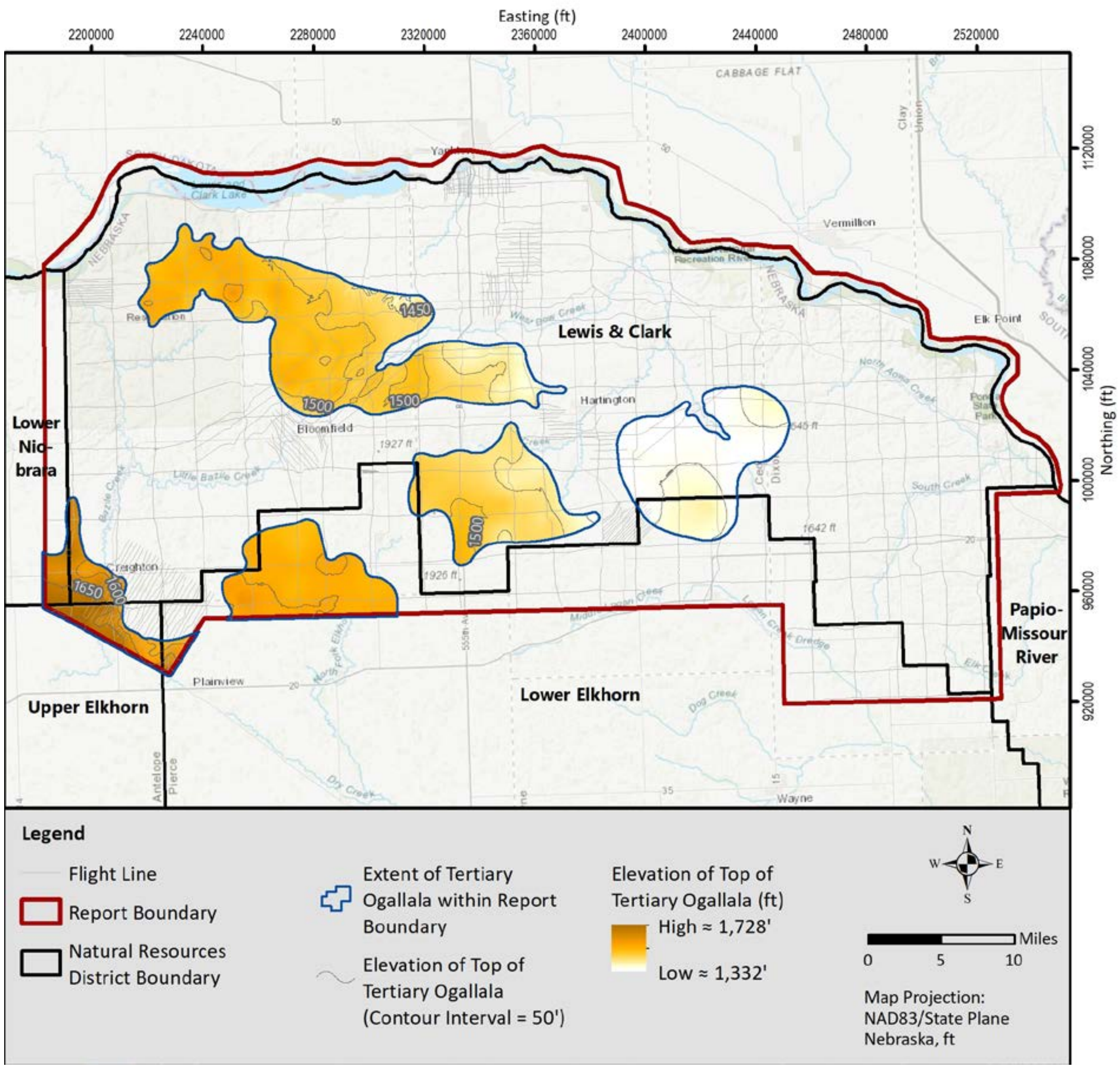


Figure 3-20. Map of the elevation of the top of the Tertiary Ogallala (*To*) within the LCNRD Reconnaissance AEM survey area. The projection is NAD83 State Plane Nebraska (feet) and the elevation values are referenced to NAVD 88 (feet).

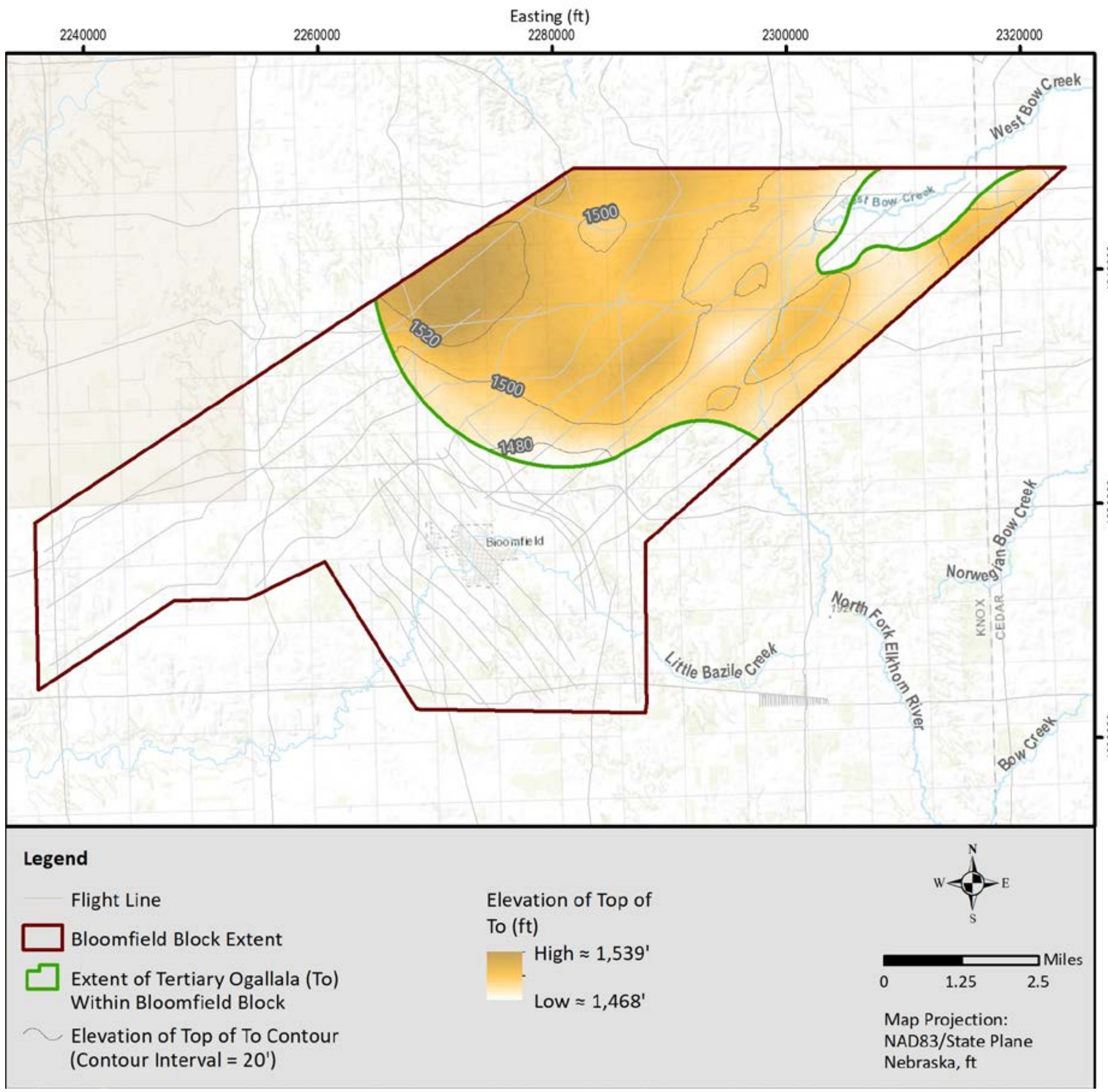


Figure 3-21. Map of the elevation of the top of the Tertiary Ogallala (*To*) within the Bloomfield Block AEM survey area. The projection is NAD83 State Plane Nebraska (feet) and the elevation values are referenced to NAVD 88 (feet).

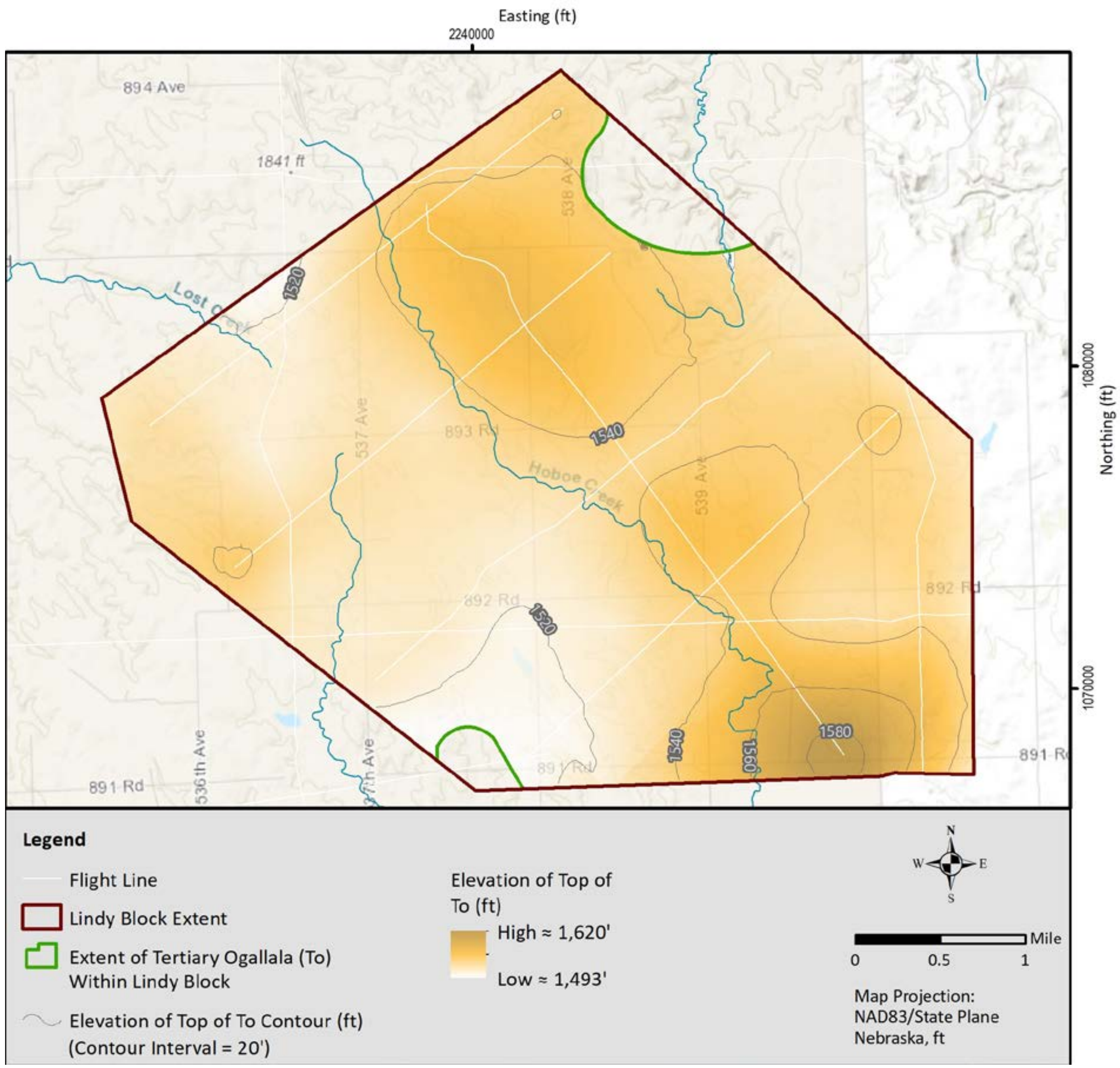


Figure 3-22. Map of the elevation of the top of the Tertiary Ogallala (*To*) within the Lindy Block AEM survey area. The projection is NAD83 State Plane Nebraska (feet) and the elevation values are referenced to NAVD 88 (feet).

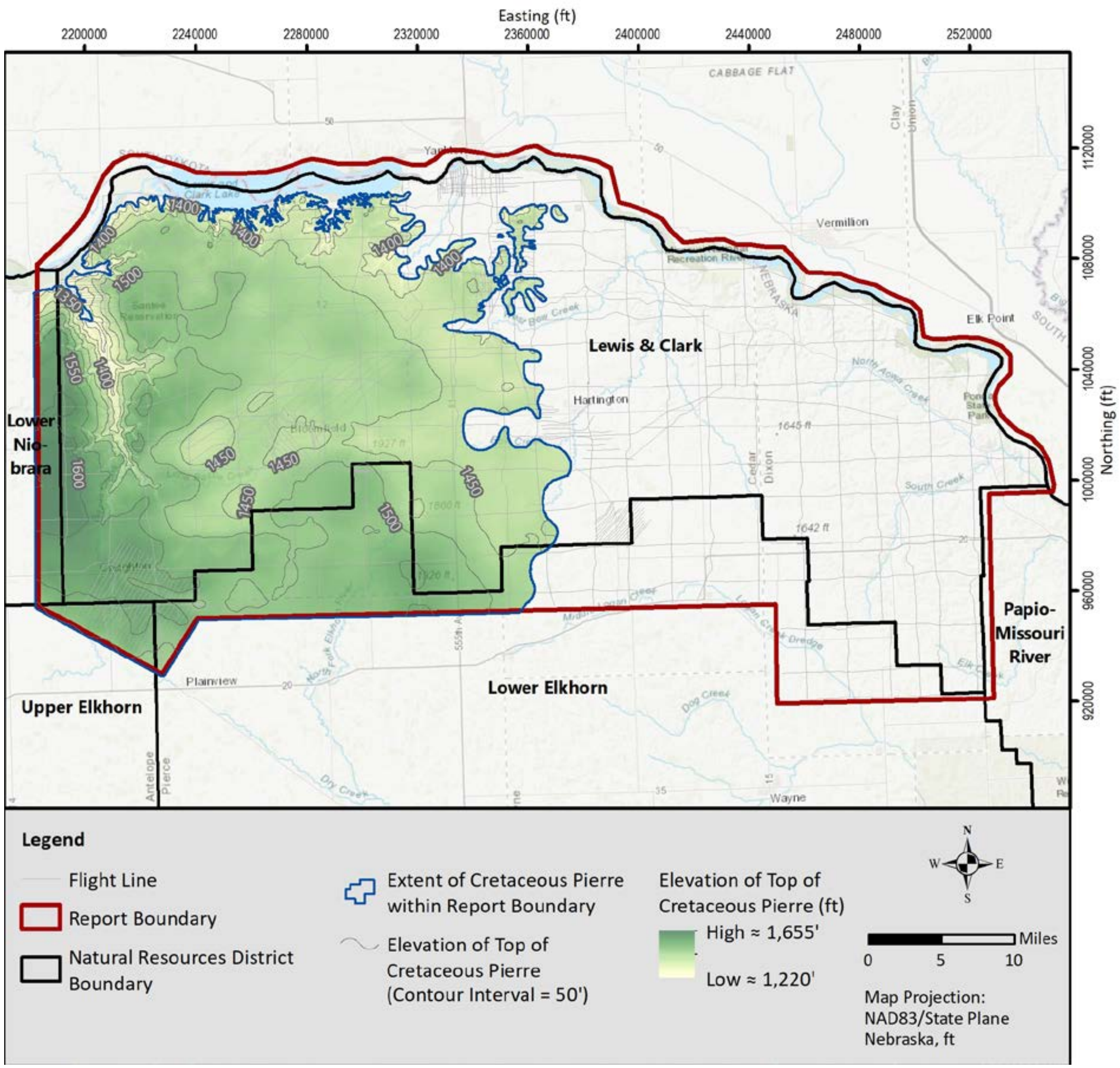


Figure 3-23. Map of the elevation of the top of the Cretaceous Pierre (*Kp*) within the LCNRD AEM survey area. The projection is NAD83 State Plane Nebraska (feet) and the elevation values are referenced to NAVD 88 (feet).

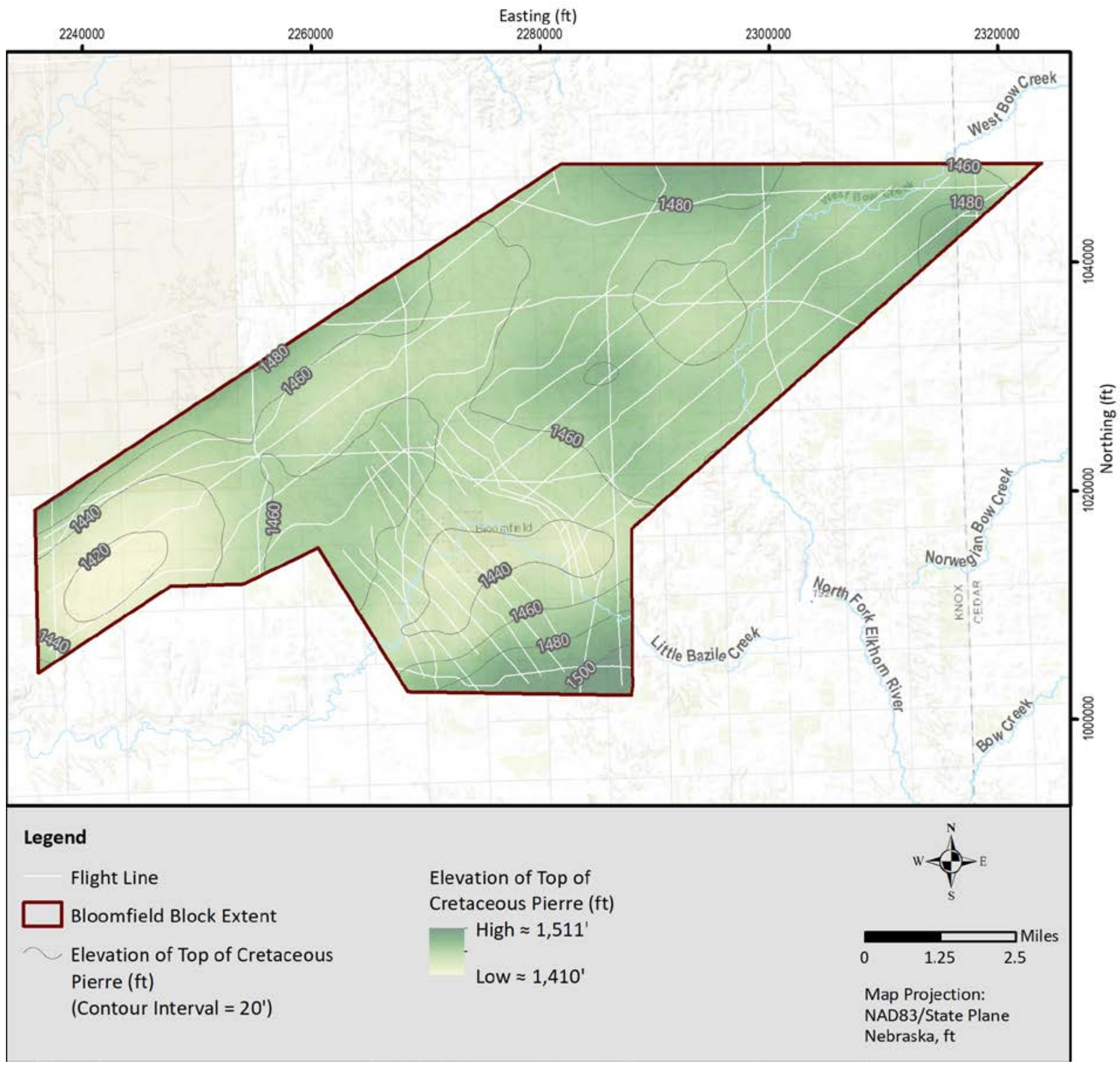


Figure 3-24. Map of the elevation of the top of the Cretaceous Pierre (*Kp*) within the Bloomfield Block AEM survey area. The projection is NAD83 State Plane Nebraska (feet) and the elevation values are referenced to NAVD 88 (feet).

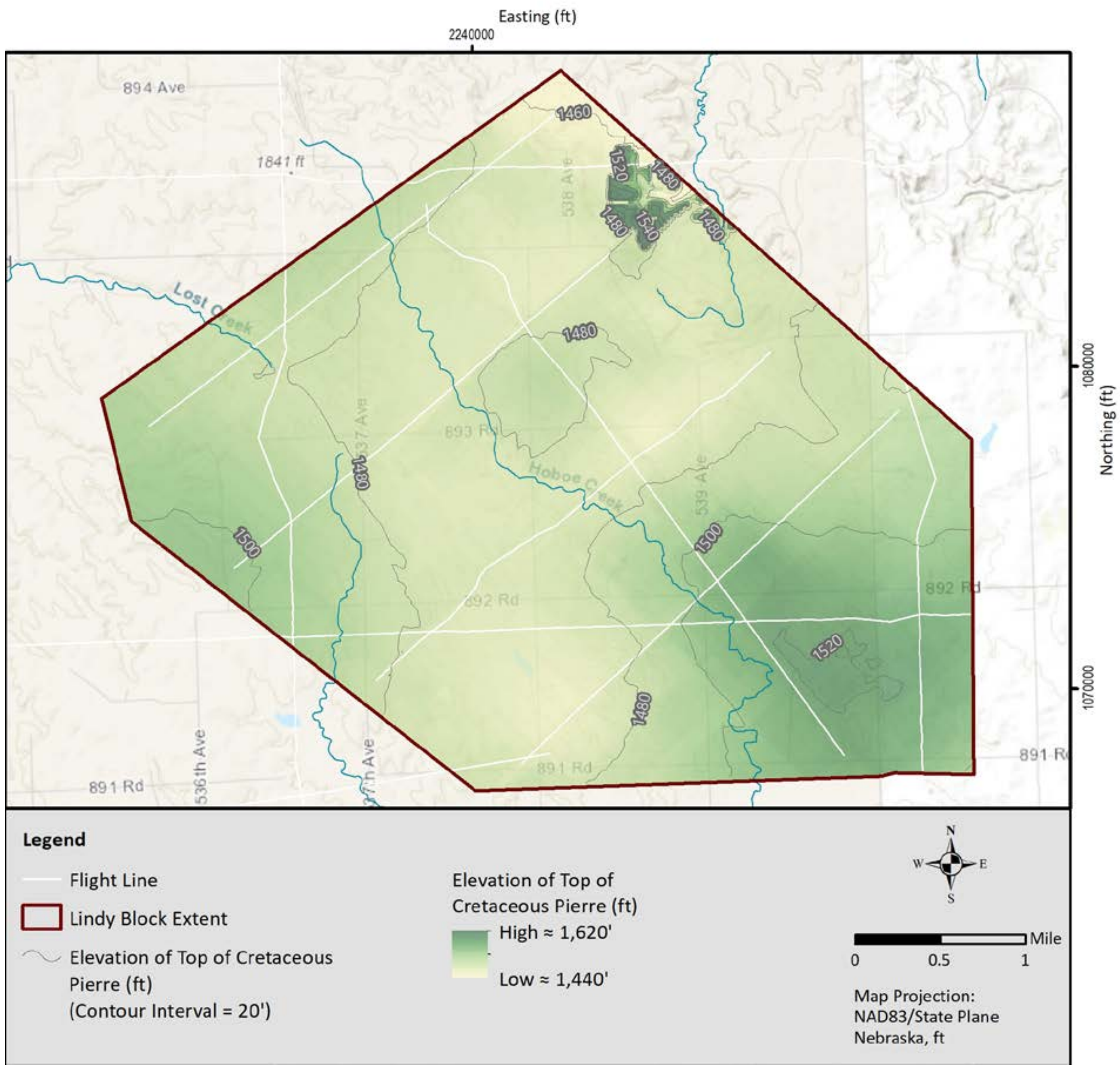


Figure 3-25. Map of the elevation of the top of the Cretaceous Pierre (*Kp*) within the Lindy Block AEM survey area. The projection is NAD83 State Plane Nebraska (feet) and the elevation values are referenced to NAVD 88 (feet).

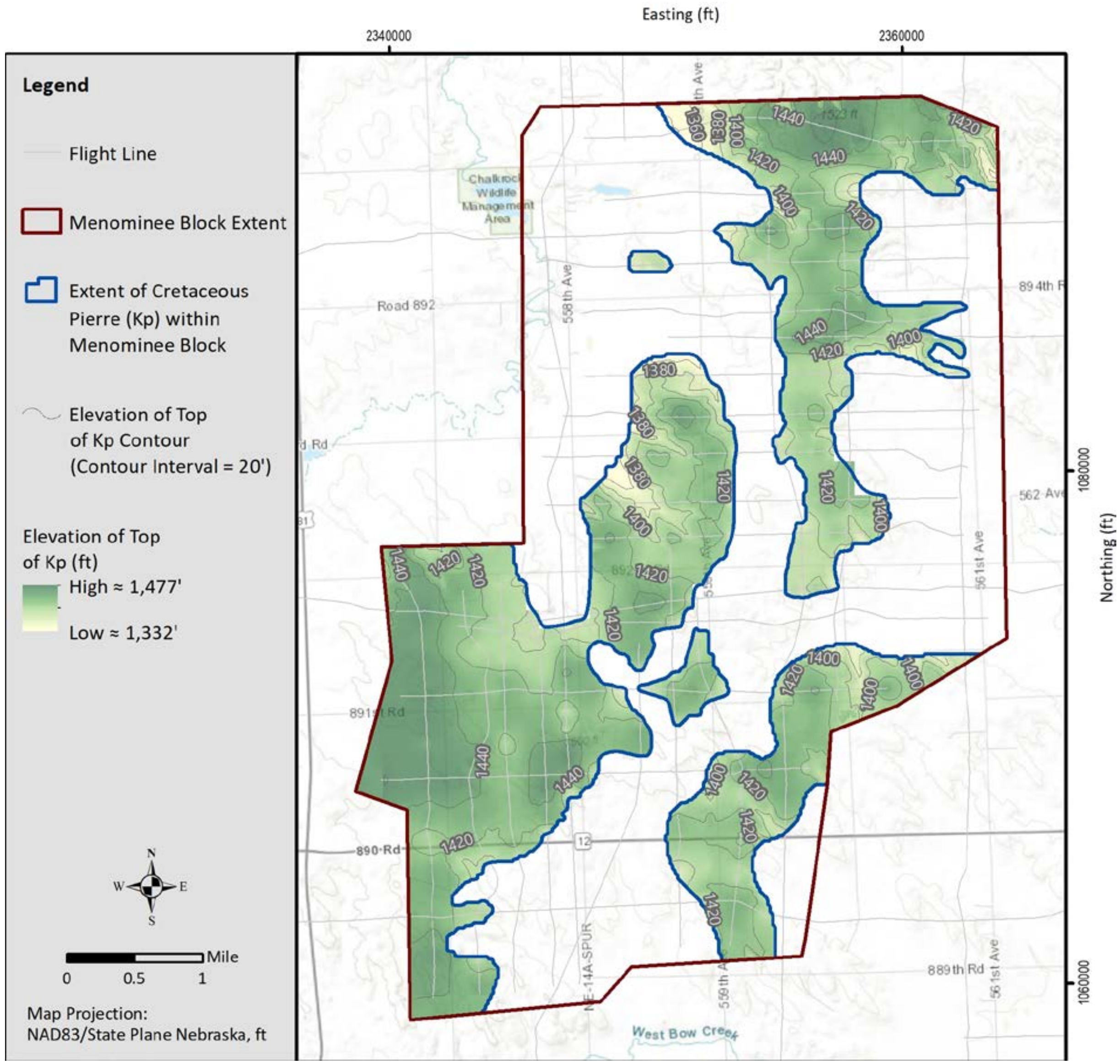


Figure 3-26. Map of the elevation of the top of the Cretaceous Pierre (*Kp*) within the Menominee Block AEM survey area. The projection is NAD83 State Plane Nebraska (feet) and the elevation values are referenced to NAVD 88 (feet).

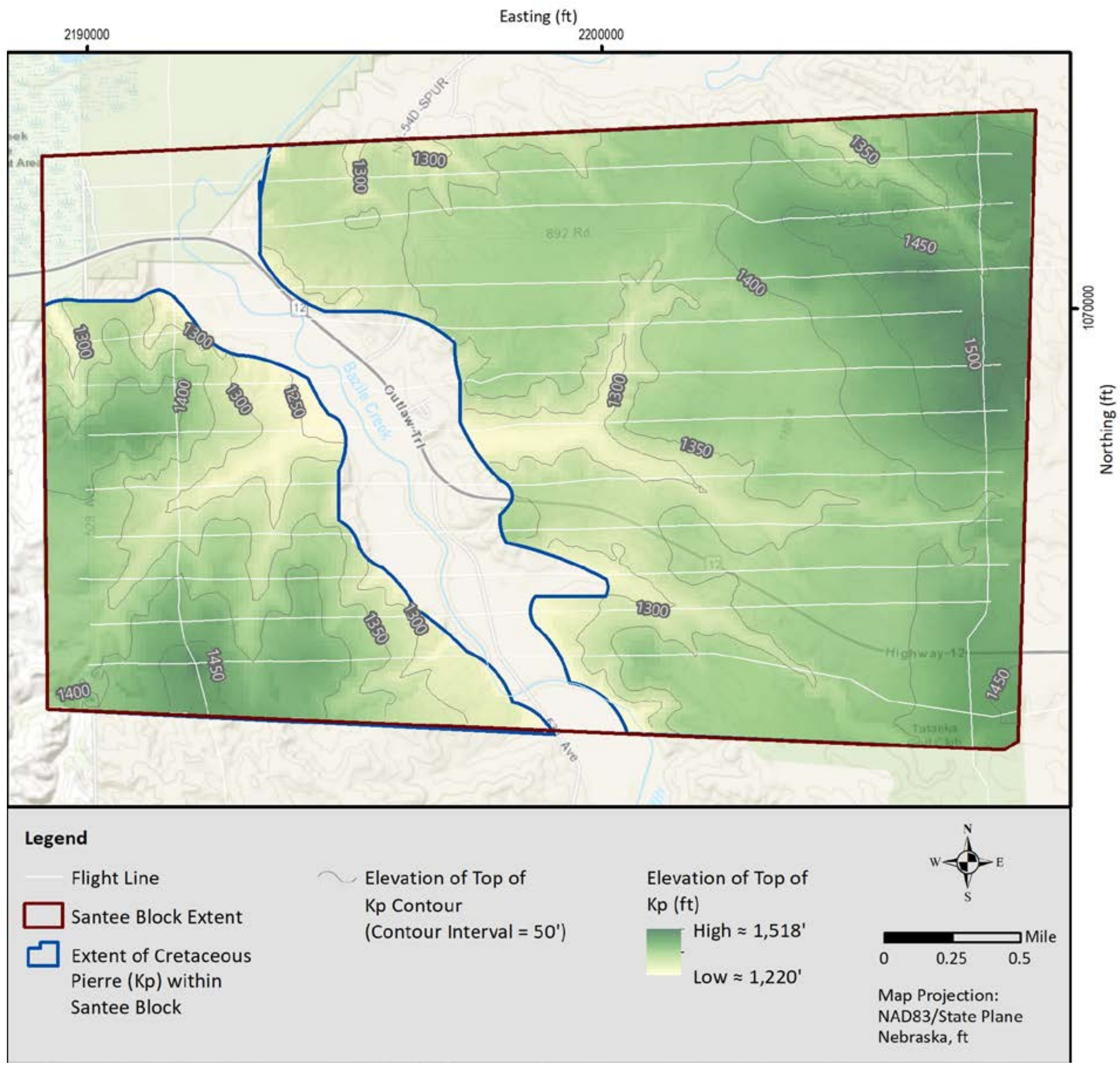


Figure 3-27. Map of the elevation of the top of the Cretaceous Pierre (*Kp*) within the Santee Block AEM survey area. The projection is NAD83 State Plane Nebraska (feet) and the elevation values are referenced to NAVD 88 (feet).

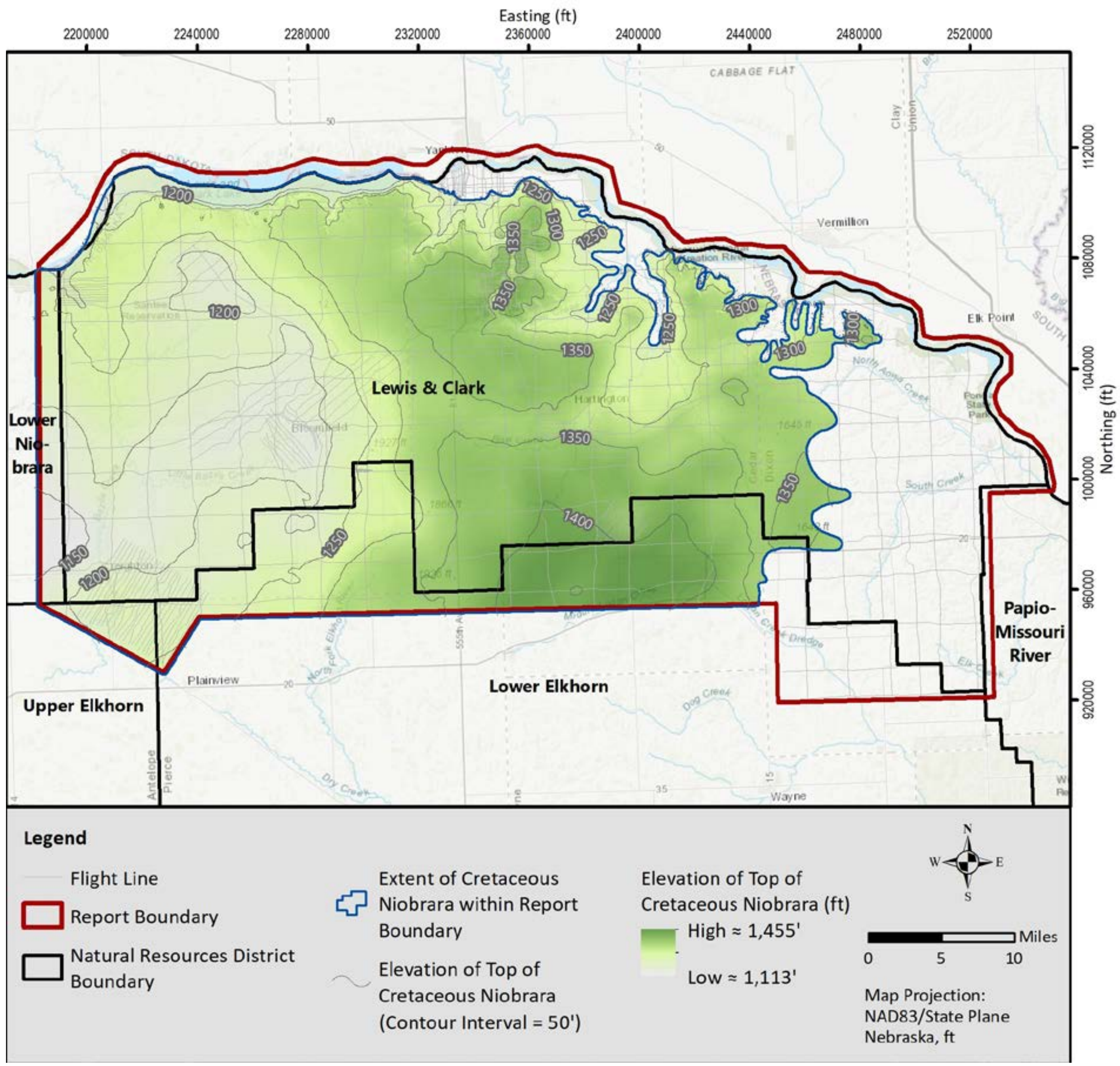


Figure 3-28. Map of the elevation of the top of the Cretaceous Niobrara (*Kn*) within the LCNRD Reconnaissance AEM survey area. The projection is NAD83 State Plane Nebraska (feet) and the elevation values are referenced to NAVD 88 (feet).

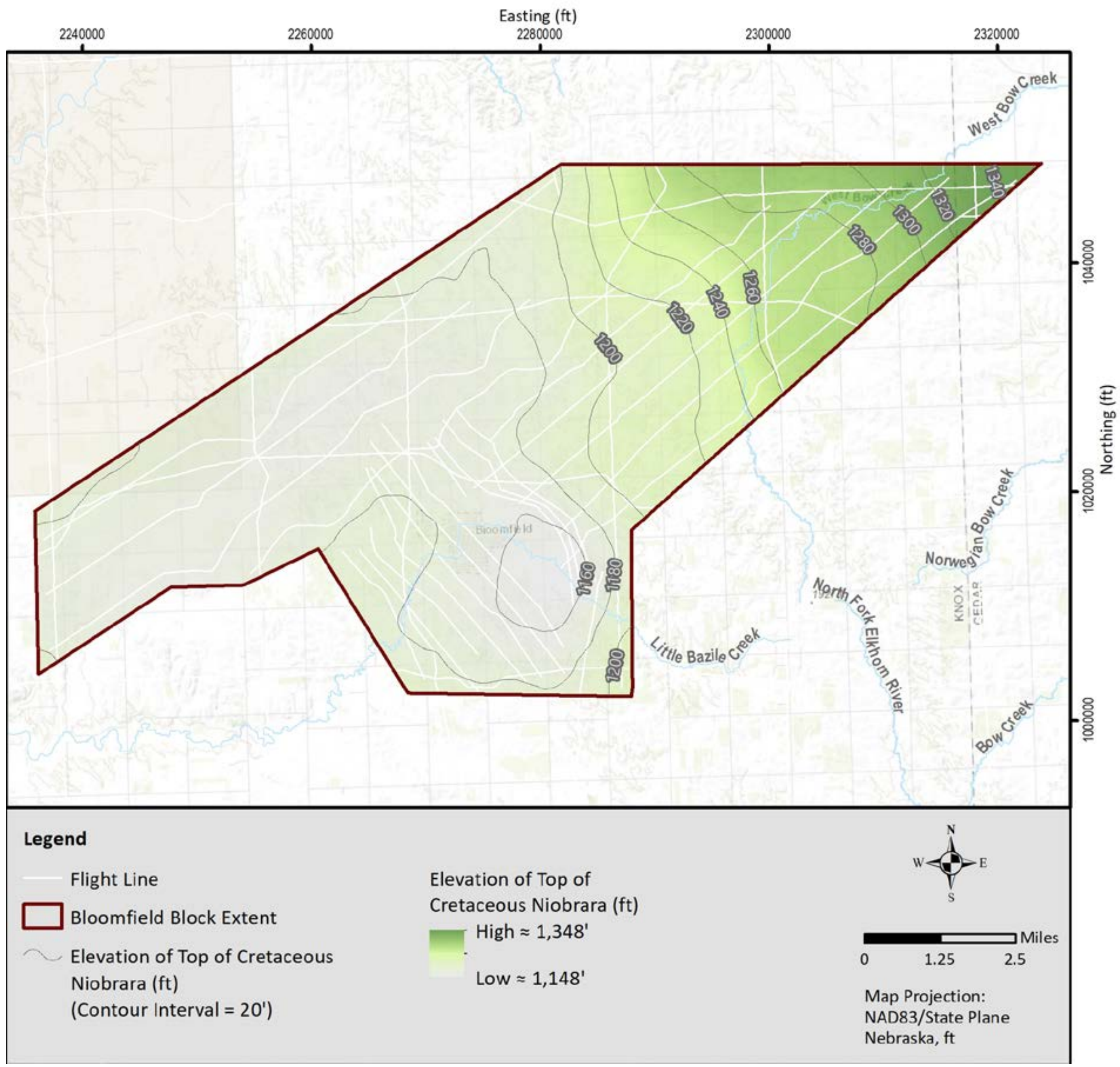


Figure 3-29. Map of the elevation of the top of the Cretaceous Niobrara (*Kn*) within the Bloomfield Block AEM survey area. The projection is NAD83 State Plane Nebraska (feet) and the elevation values are referenced to NAVD 88 (feet).

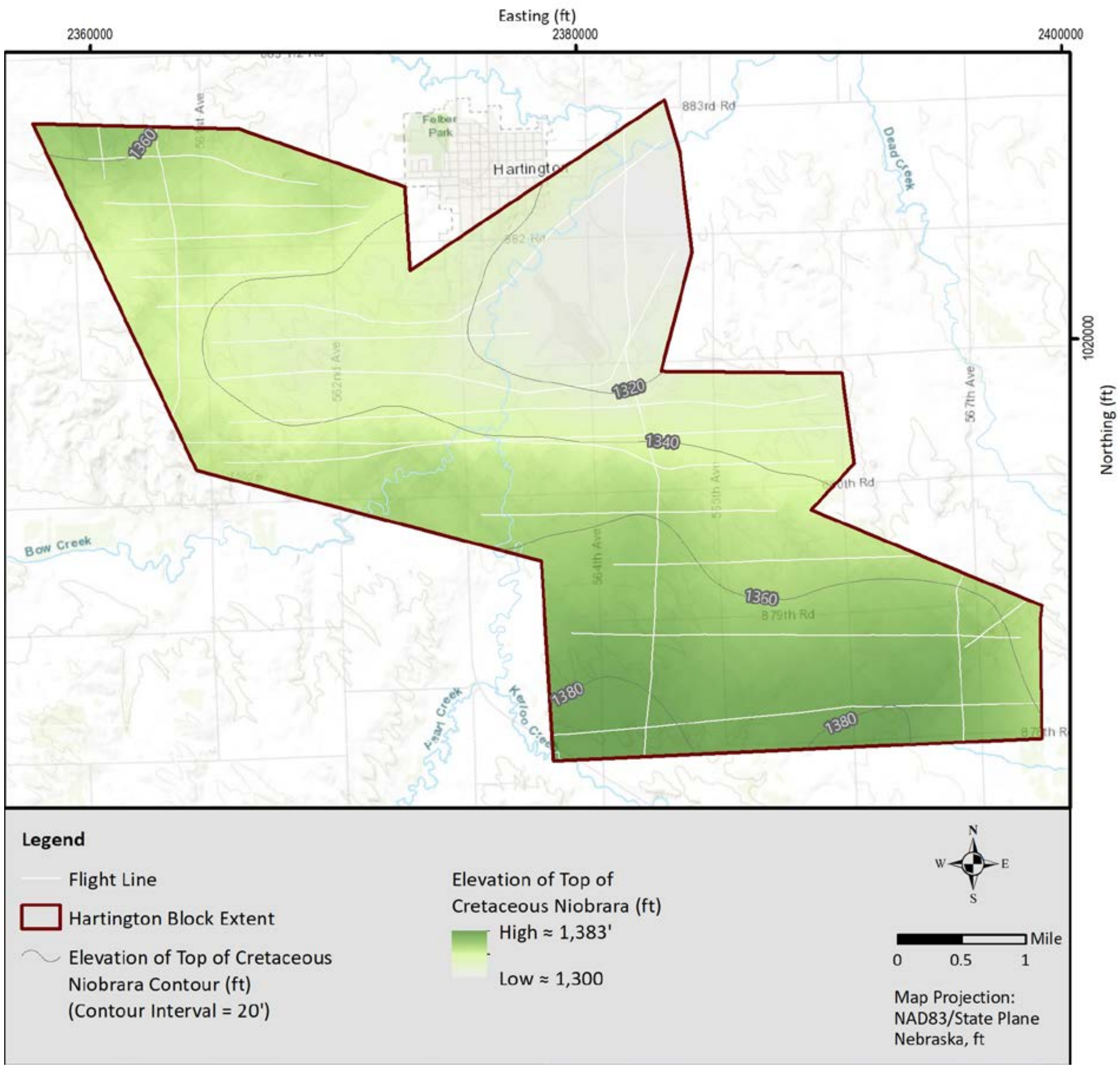


Figure 3-30. Map of the elevation of the top of the Cretaceous Niobrara (*Kn*) within the Hartington Block AEM survey area. The projection is NAD83 State Plane Nebraska (feet) and the elevation values are referenced to NAVD 88 (feet).

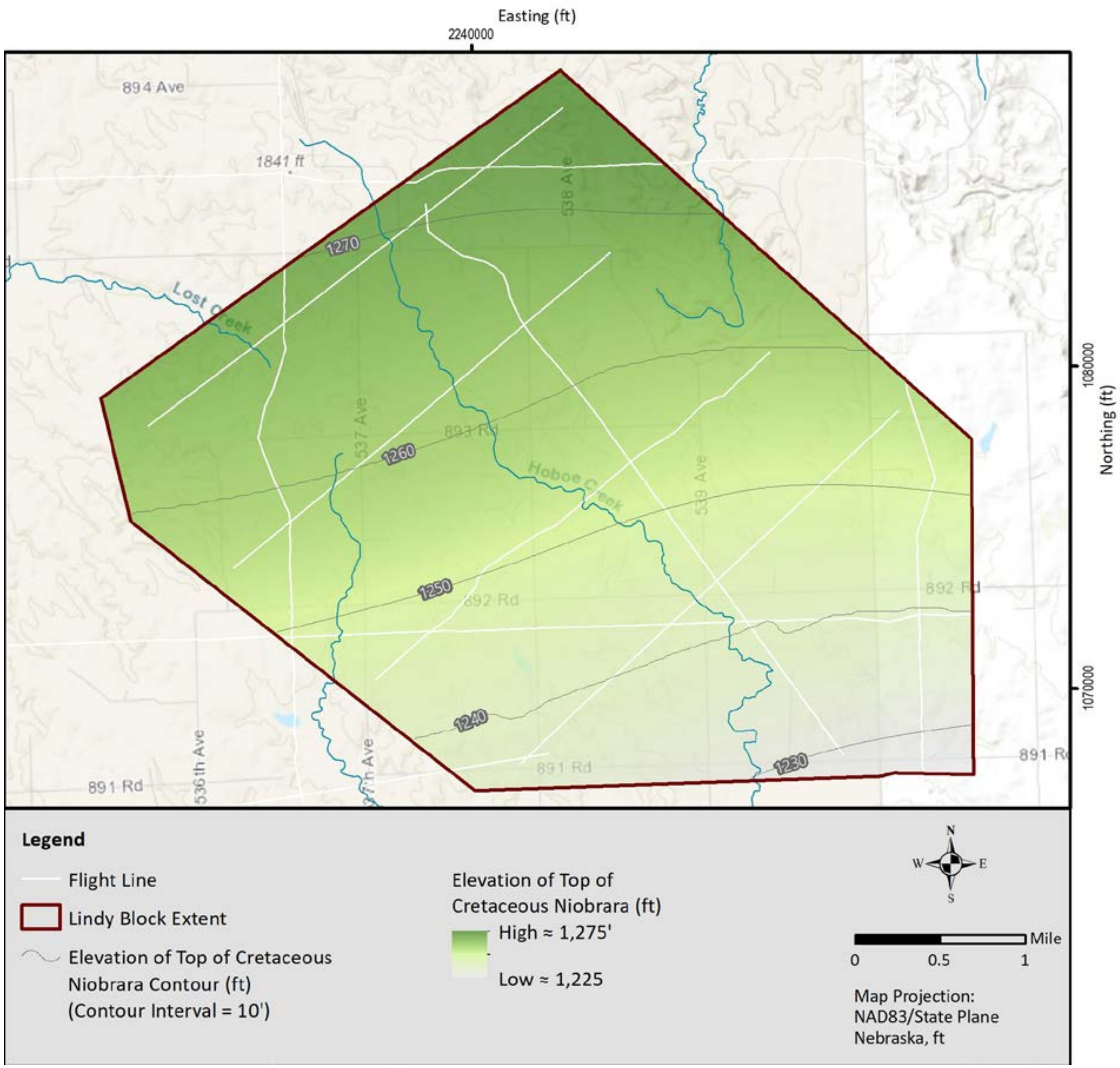


Figure 3-31. Map of the elevation of the top of the Cretaceous Niobrara (*Kn*) within the Lindy Block AEM survey area. The projection is NAD83 State Plane Nebraska (feet) and the elevation values are referenced to NAVD 88 (feet).

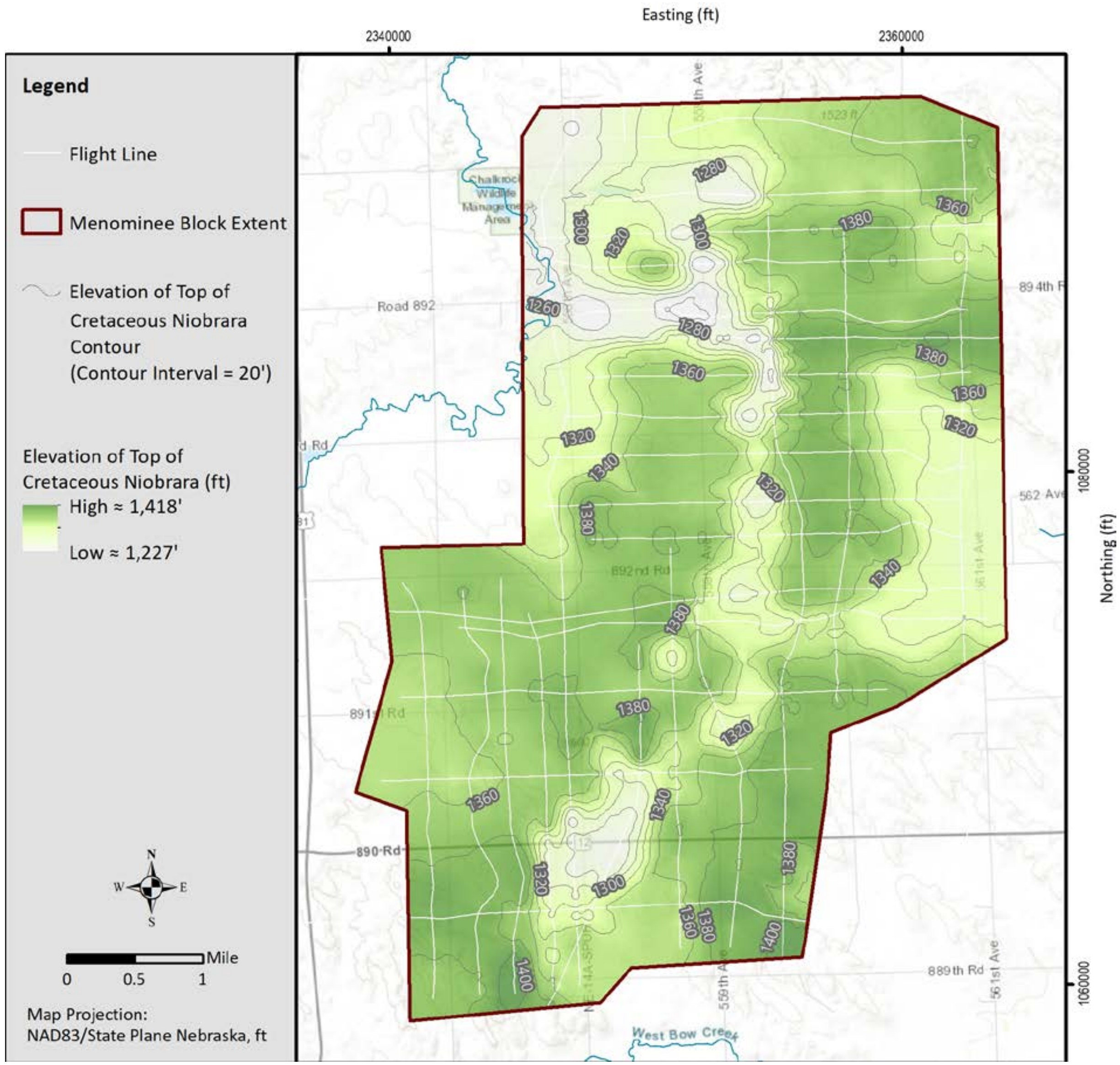


Figure 3-32. Map of the elevation of the top of the Cretaceous Niobrara (*Kn*) within the Menominee Block AEM survey area. The projection is NAD83 State Plane Nebraska (feet) and the elevation values are referenced to NAVD 88 (feet).

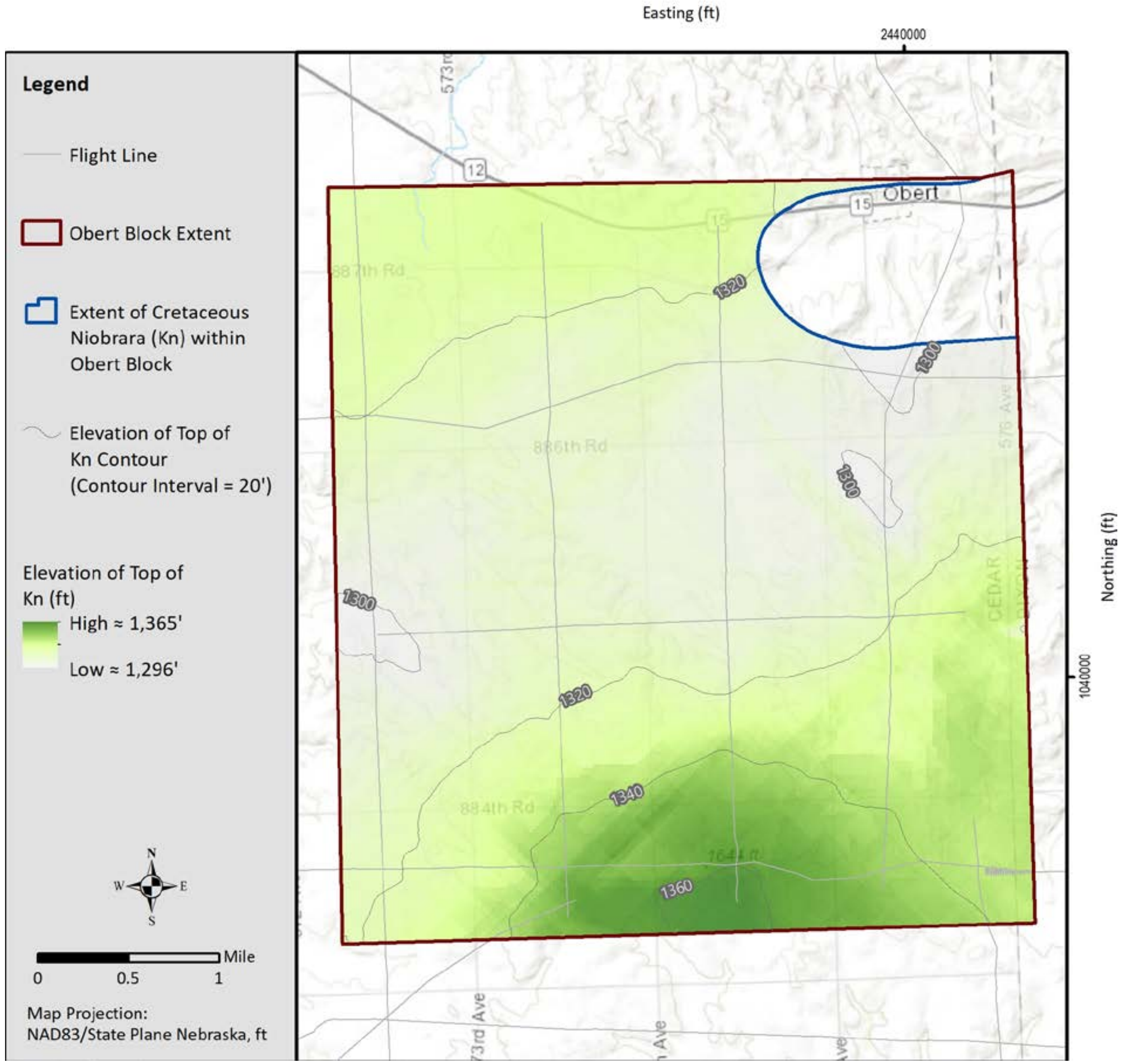


Figure 3-33. Map of the elevation of the top of the Cretaceous Niobrara (*Kn*) within the Obert Block AEM survey area. The projection is NAD83 State Plane Nebraska (feet) and the elevation values are referenced to NAVD 88 (feet).

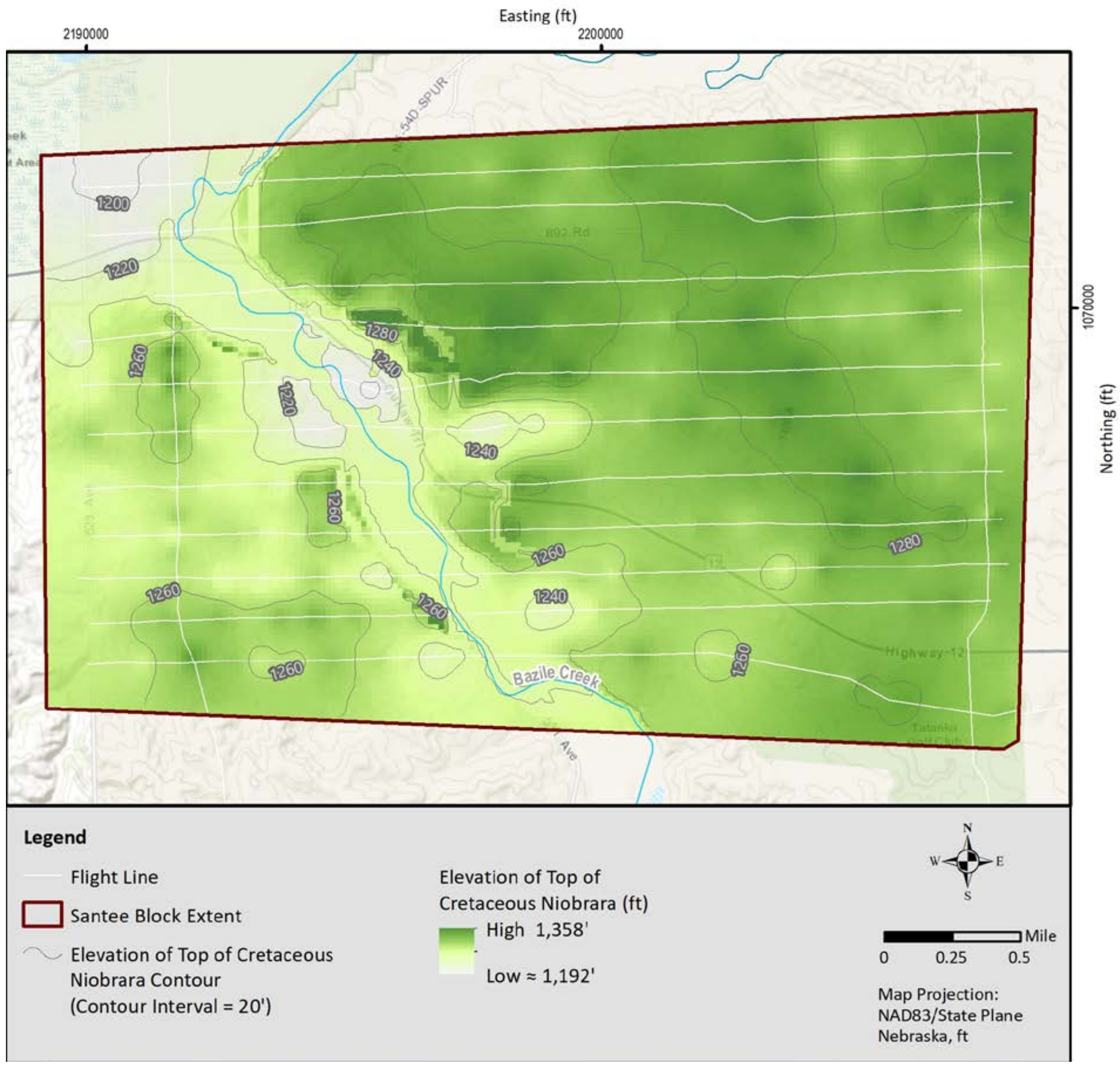


Figure 3-34. Map of the elevation of the top of the Cretaceous Niobrara (*Kn*) within the Santee Block AEM survey area. The projection is NAD83 State Plane Nebraska (feet) and the elevation values are referenced to NAVD 88 (feet).

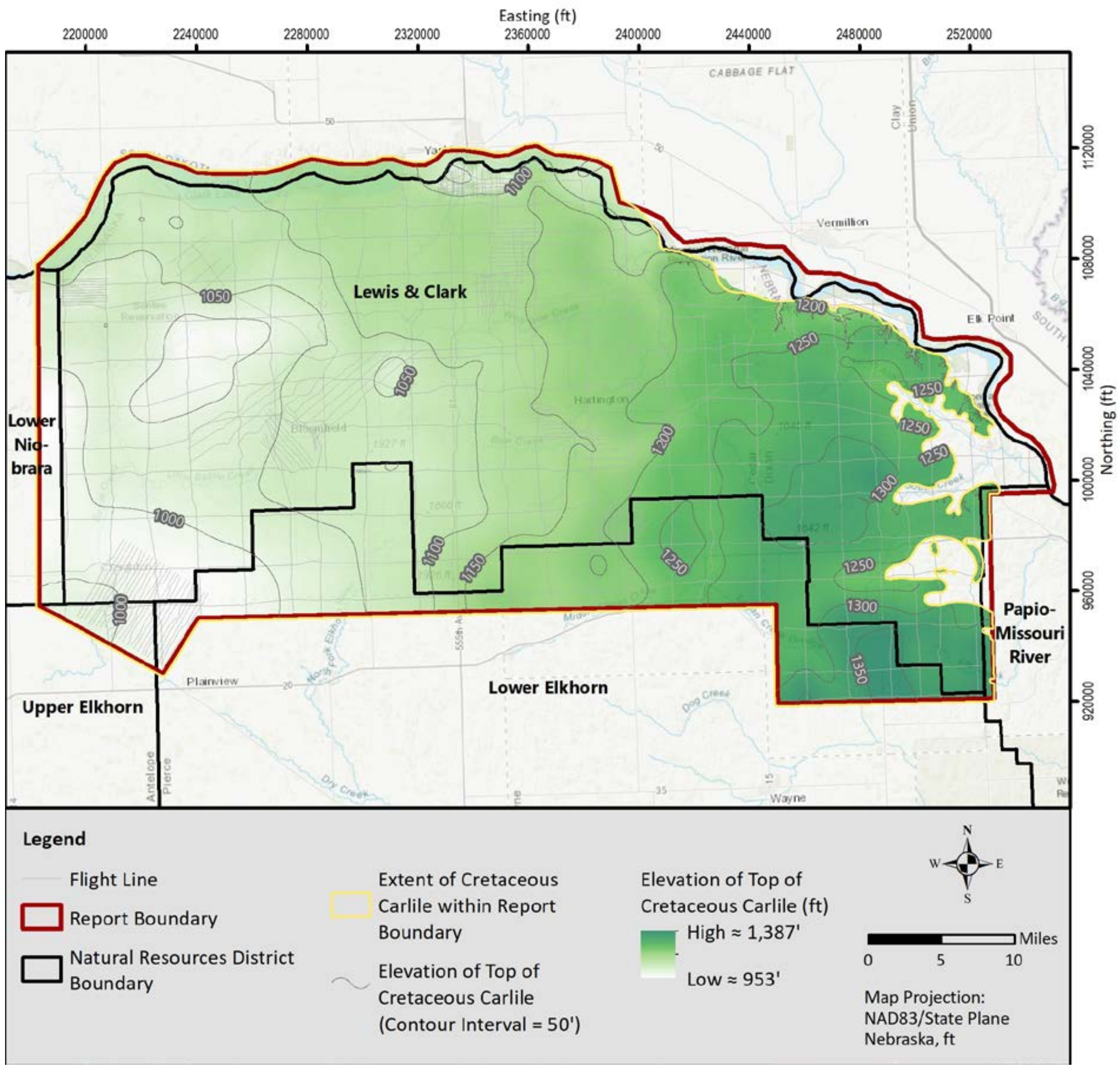


Figure 3-35. Map of the elevation of the top of the Cretaceous Carlile (*Kc*) within the LCNRD Reconnaissance AEM survey area. The projection is NAD83 State Plane Nebraska (feet) and the elevation values are referenced to NAVD 88 (feet).

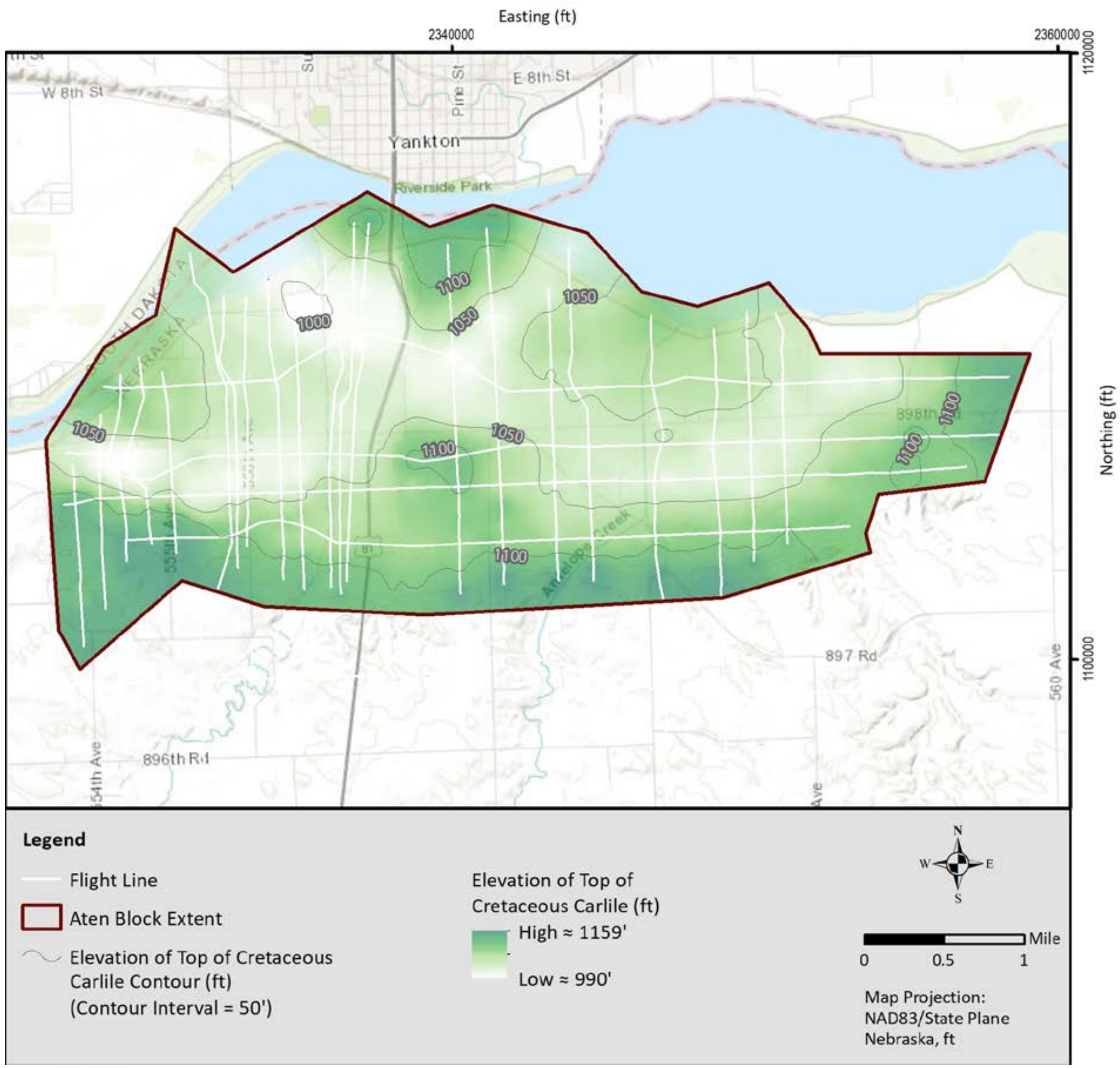


Figure 3-36. Map of the elevation of the top of the Cretaceous Carlile (*Kc*) within the Aten Block AEM survey area. The projection is NAD83 State Plane Nebraska (feet) and the elevation values are referenced to NAVD 88 (feet).

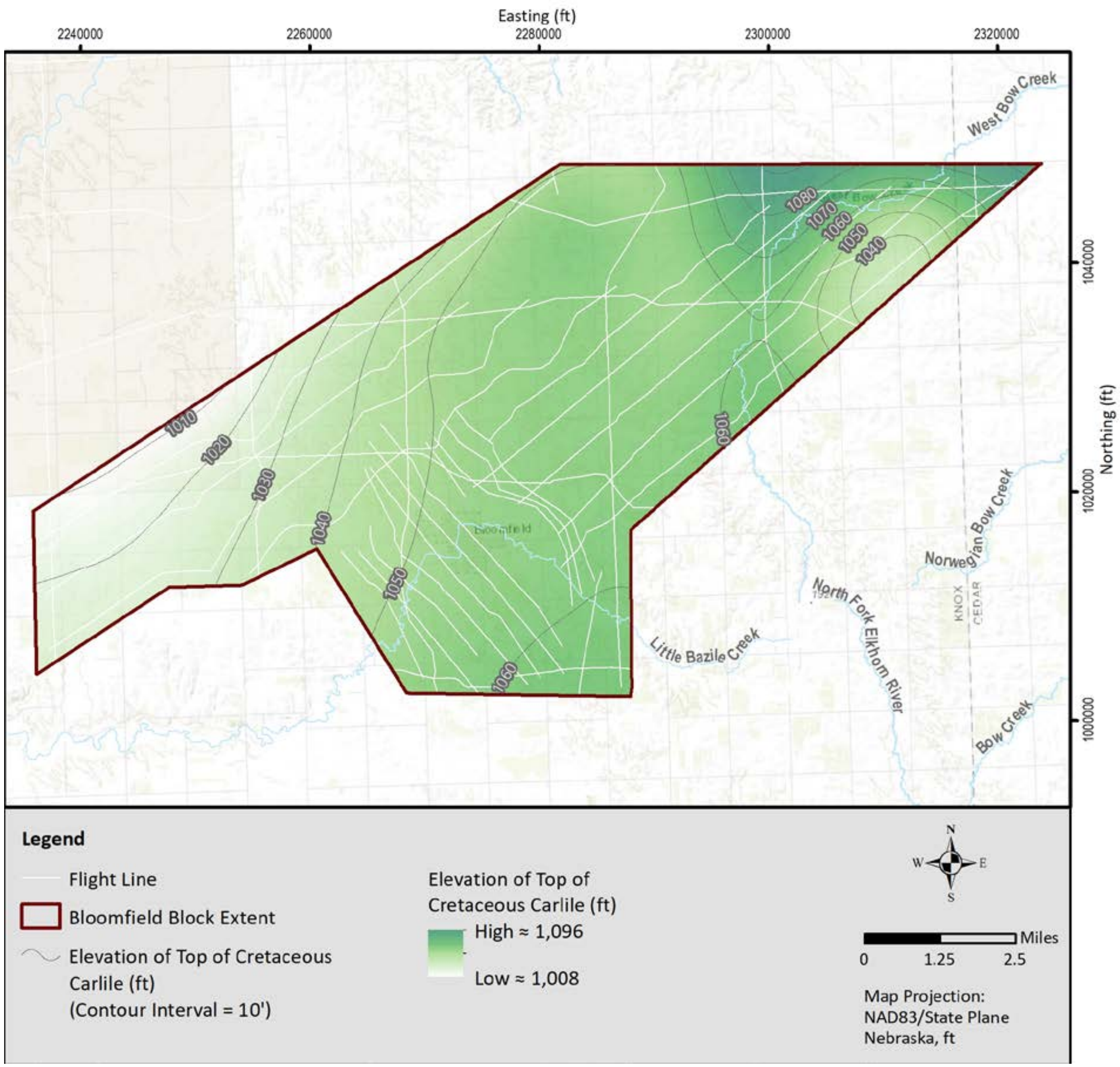


Figure 3-37. Map of the elevation of the top of the Cretaceous Carlile (*Kc*) within the Bloomfield Block AEM survey area. The projection is NAD83 State Plane Nebraska (feet) and the elevation values are referenced to NAVD 88 (feet).

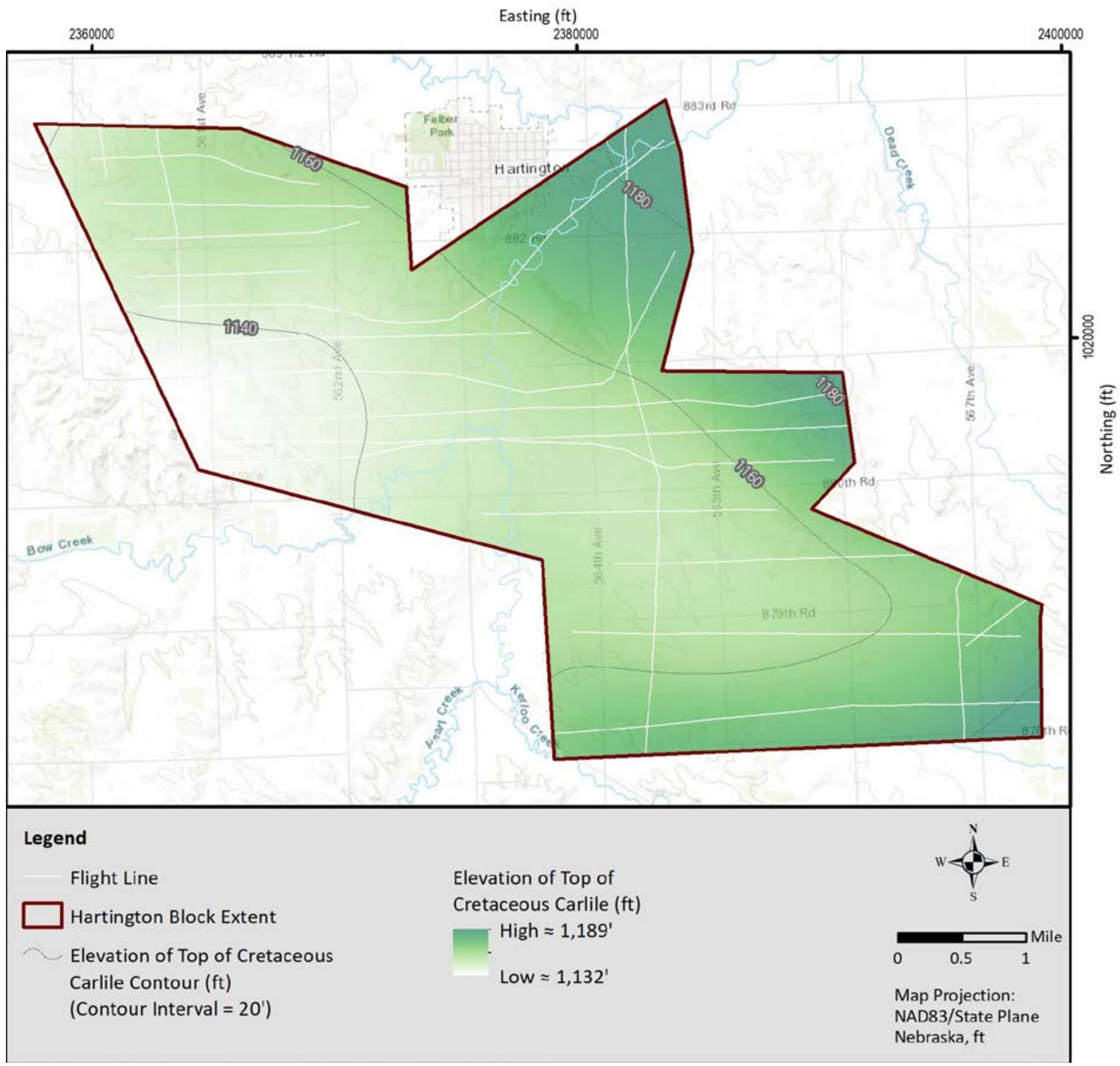


Figure 3-38. Map of the elevation of the top of the Cretaceous Carlile (*Kc*) within the Hartington Block AEM survey area. The projection is NAD83 State Plane Nebraska (feet) and the elevation values are referenced to NAVD 88 (feet).

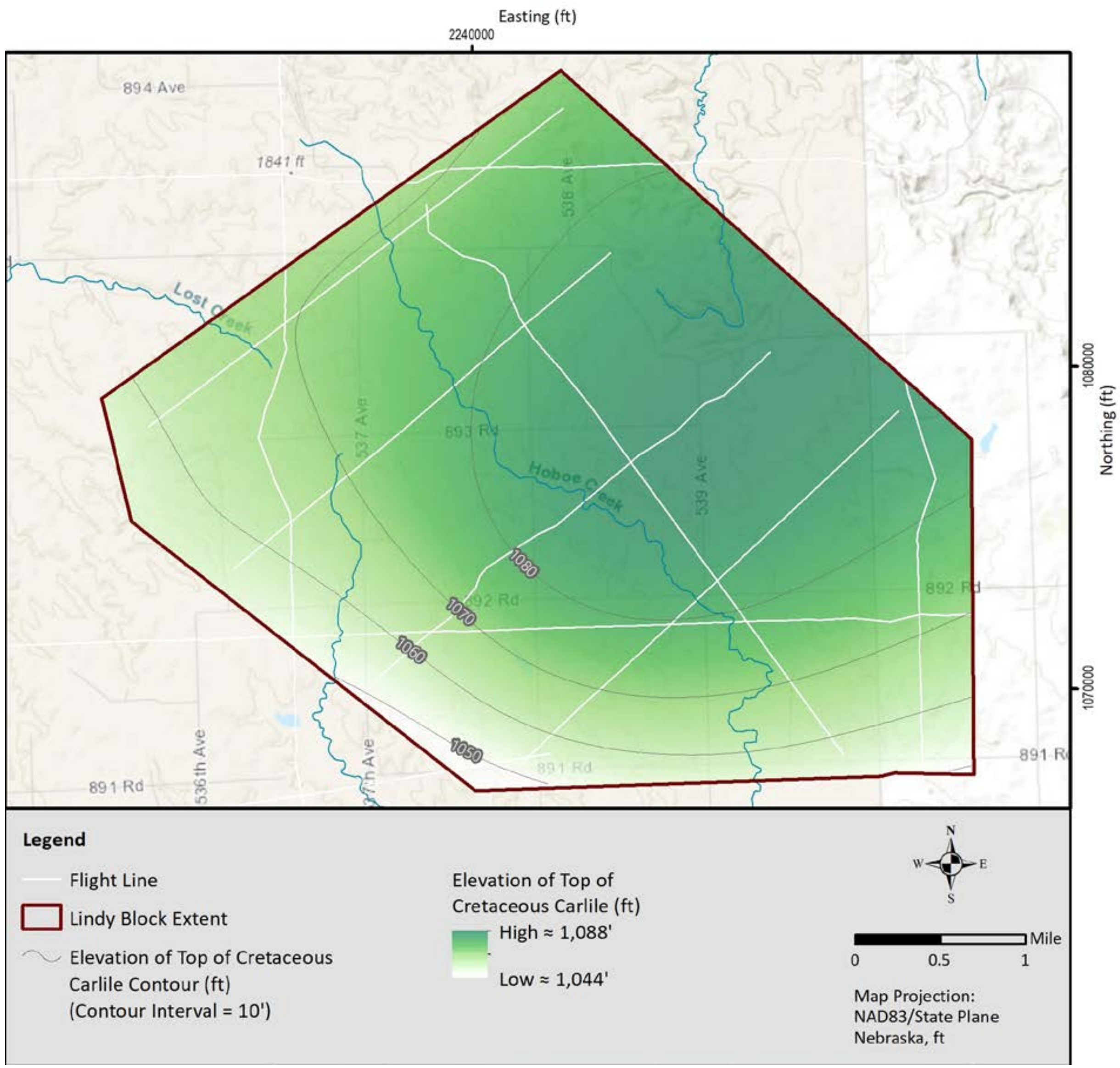


Figure 3-39. Map of the elevation of the top of the Cretaceous Carlile (*Kc*) within the Lindy Block AEM survey area. The projection is NAD83 State Plane Nebraska (feet) and the elevation values are referenced to NAVD 88 (feet).

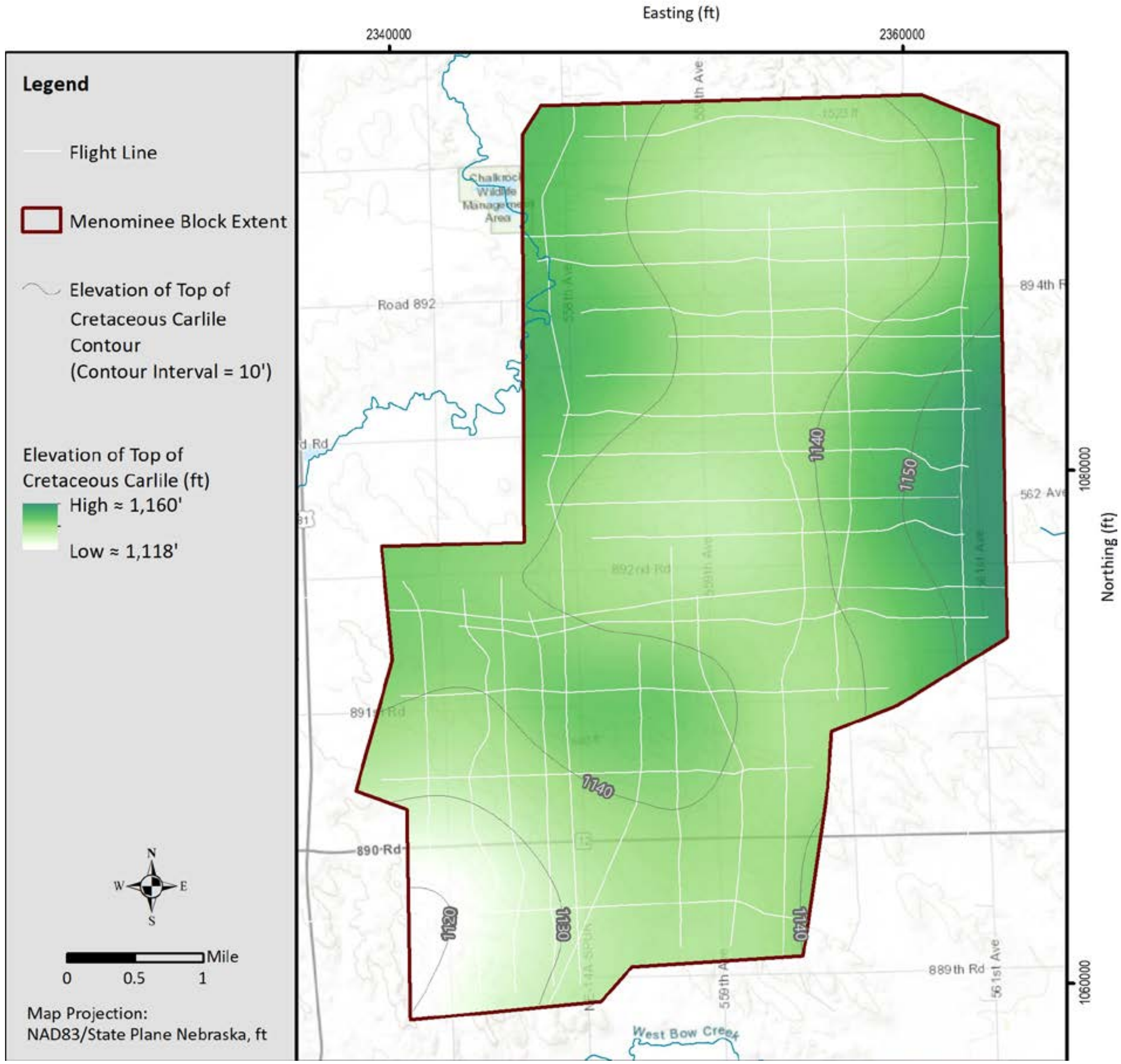


Figure 3-40. Map of the elevation of the top of the Cretaceous Carlile (*Kc*) within the Menominee Block AEM survey area. The projection is NAD83 State Plane Nebraska (feet) and the elevation values are referenced to NAVD 88 (feet).

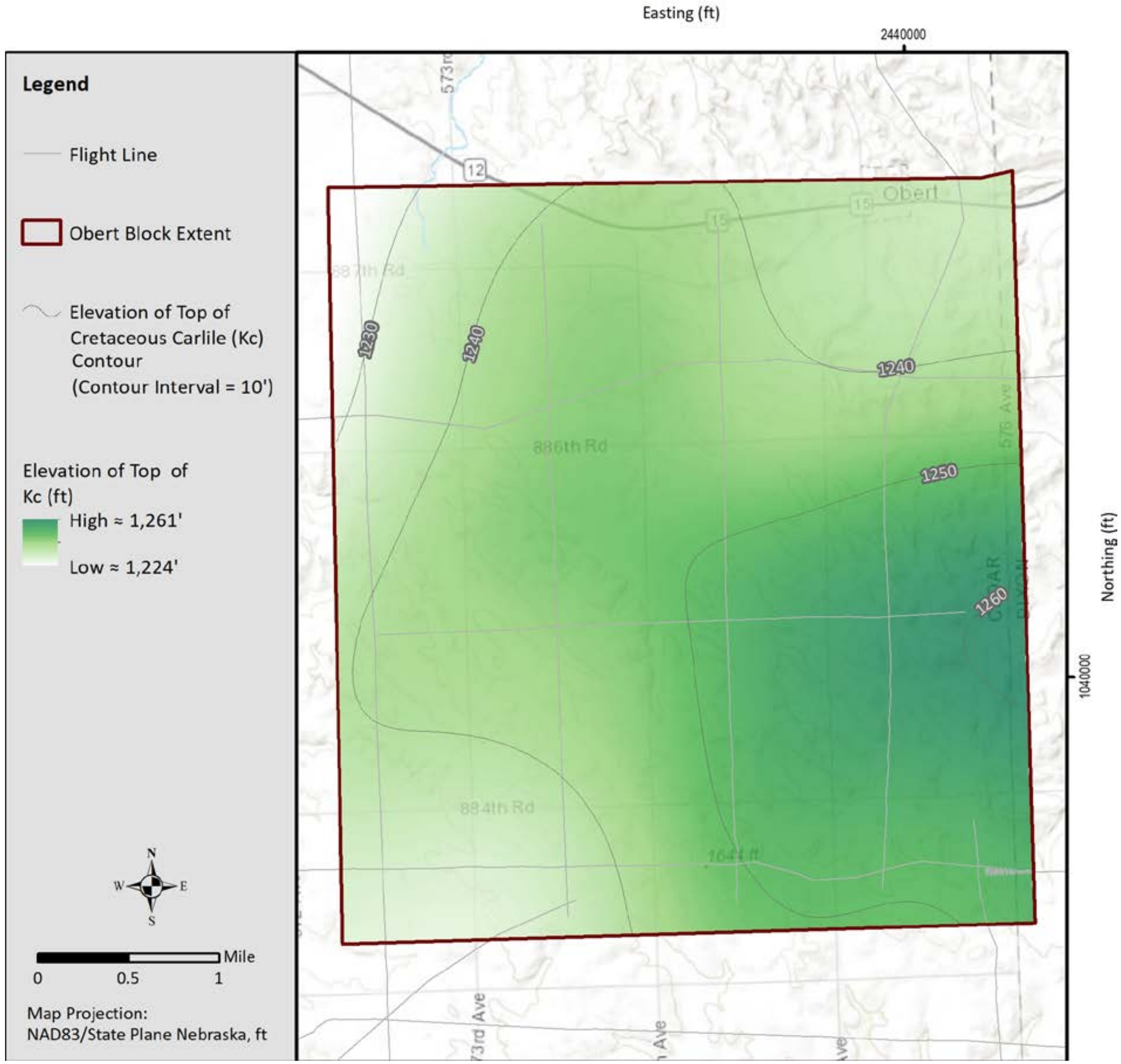


Figure 3-41. Map of the elevation of the top of the Cretaceous Carlile (*Kc*) within the Obert Block AEM survey area. The projection is NAD83 State Plane Nebraska (feet) and the elevation values are referenced to NAVD 88 (feet).

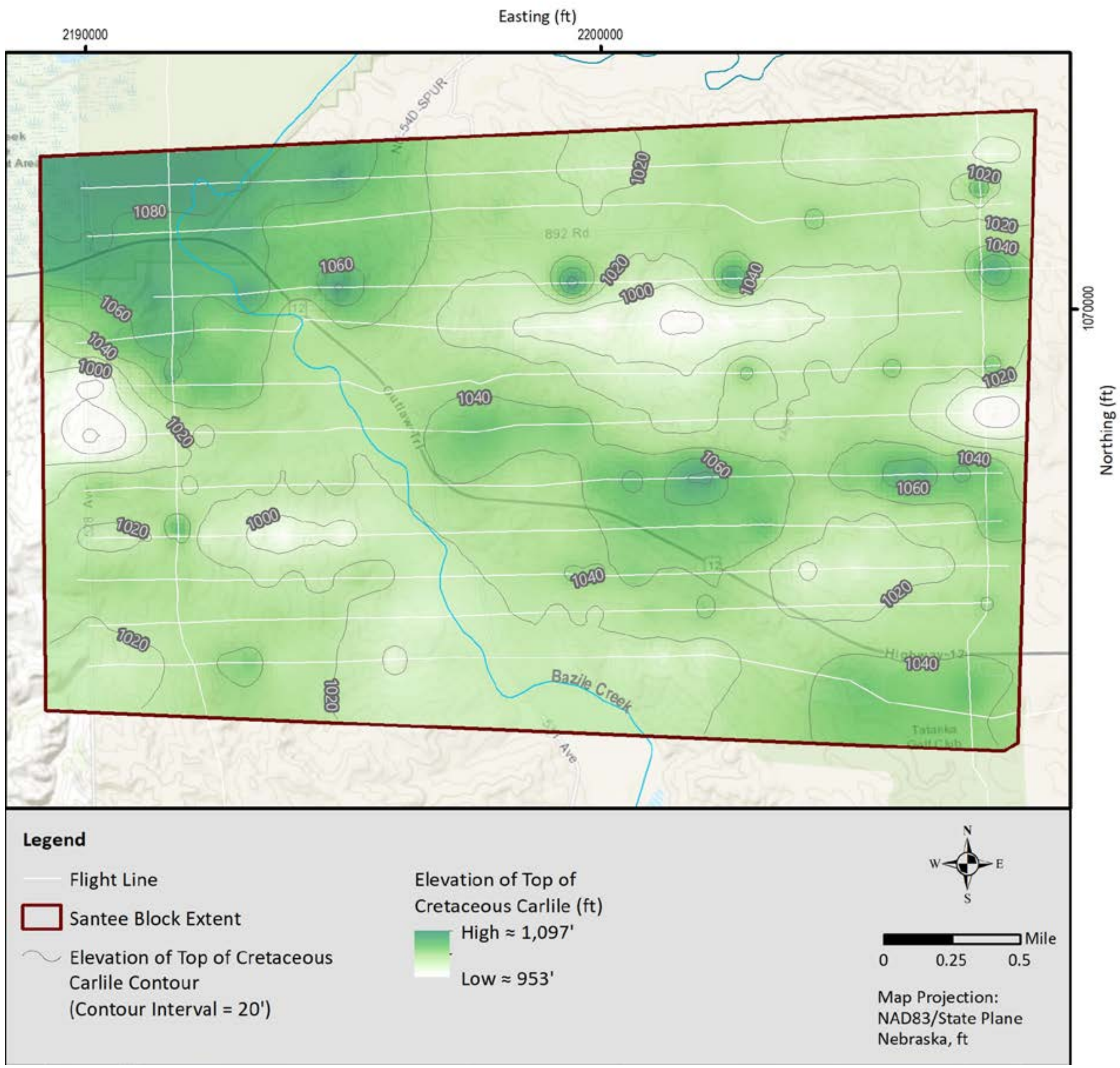


Figure 3-42. Map of the elevation of the top of the Cretaceous Carlile (*Kc*) within the Santee Block AEM survey area. The projection is NAD83 State Plane Nebraska (feet) and the elevation values are referenced to NAVD 88 (feet).

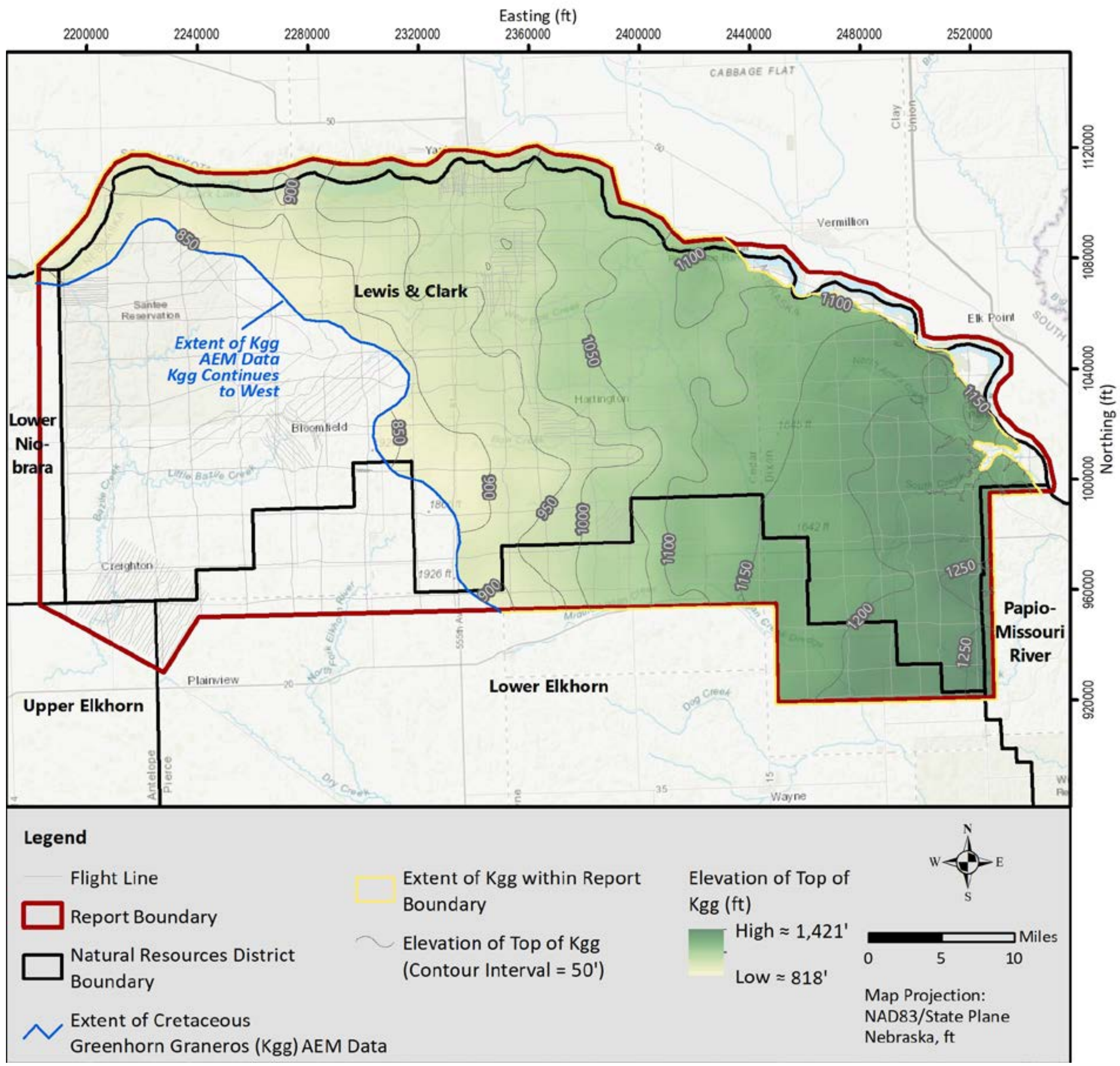


Figure 3-43. Map of the elevation of the top of the Cretaceous Greenhorn-Graneros (*Kgg*) within the LCNRD Reconnaissance AEM survey area. The projection is NAD83 State Plane Nebraska (feet) and the elevation values are referenced to NAVD 88 (feet).

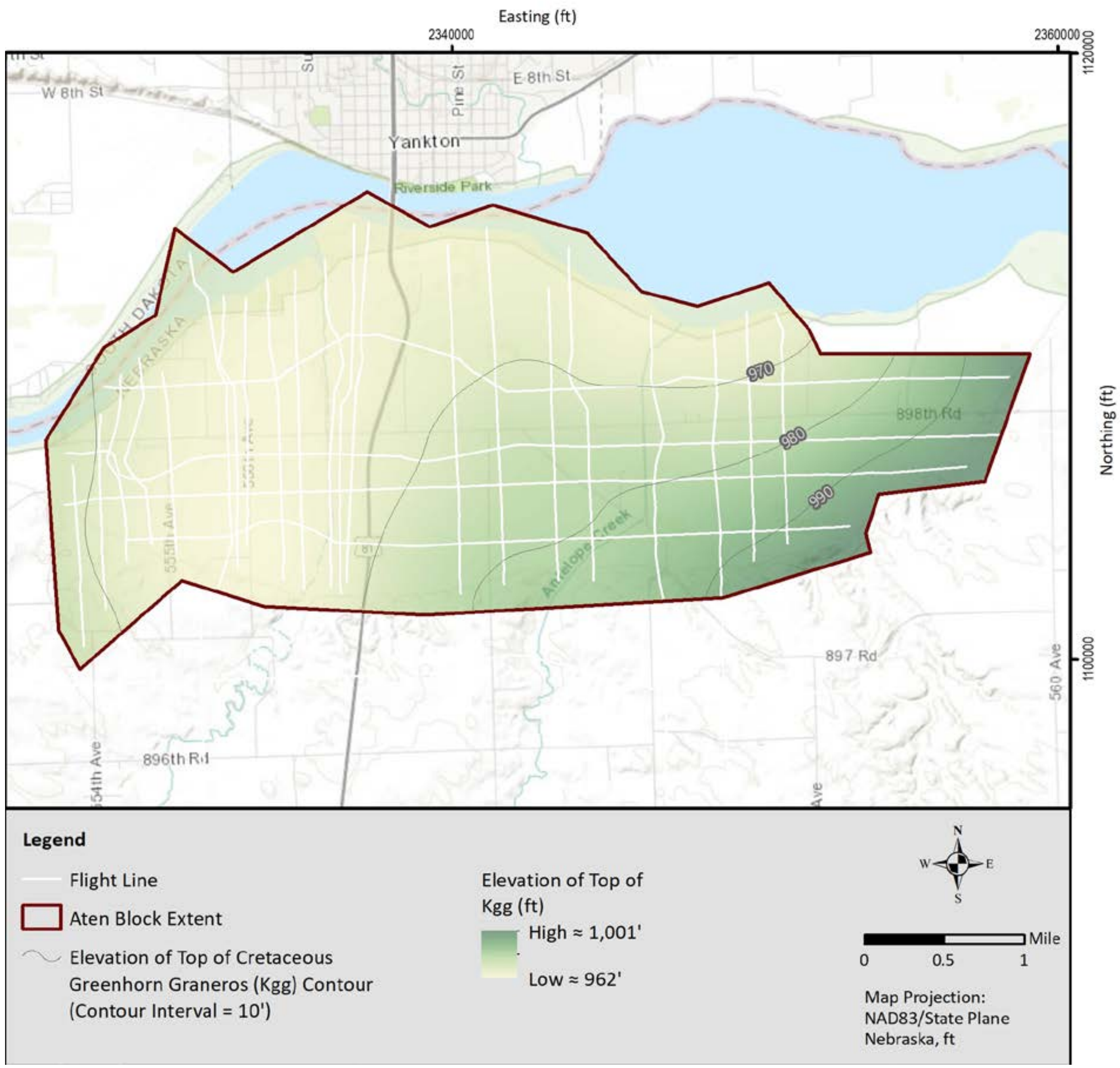


Figure 3-44. Map of the elevation of the top of the Cretaceous Greenhorn-Graneros (*Kgg*) within the Aten Block AEM survey area. The projection is NAD83 State Plane Nebraska (feet) and the elevation values are referenced to NAVD 88 (feet).

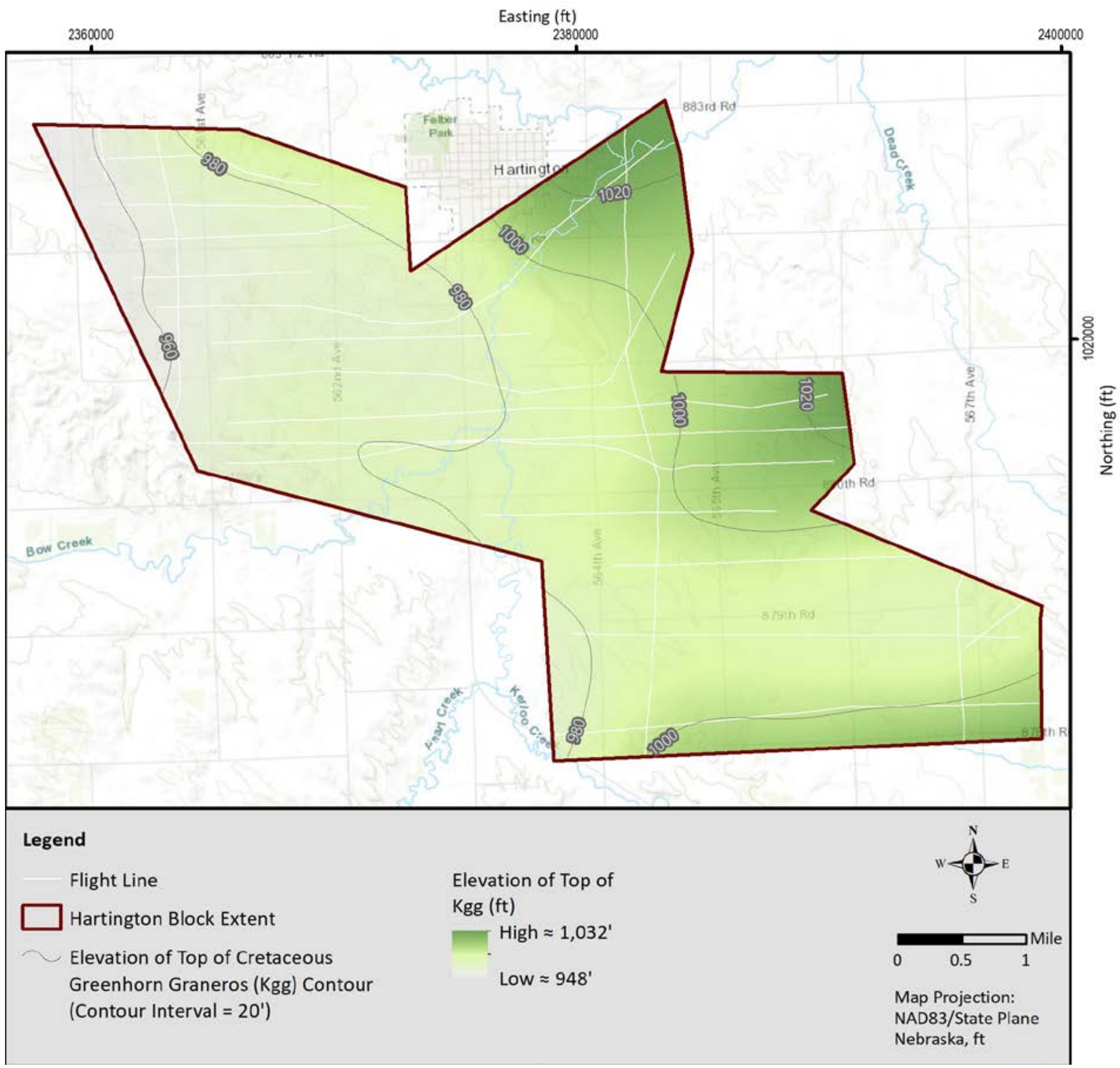


Figure 3-45. Map of the elevation of the top of the Cretaceous Greenhorn-Graneros (*Kgg*) within the Hartington Block AEM survey area. The projection is NAD83 State Plane Nebraska (feet) and the elevation values are referenced to NAVD 88 (feet).

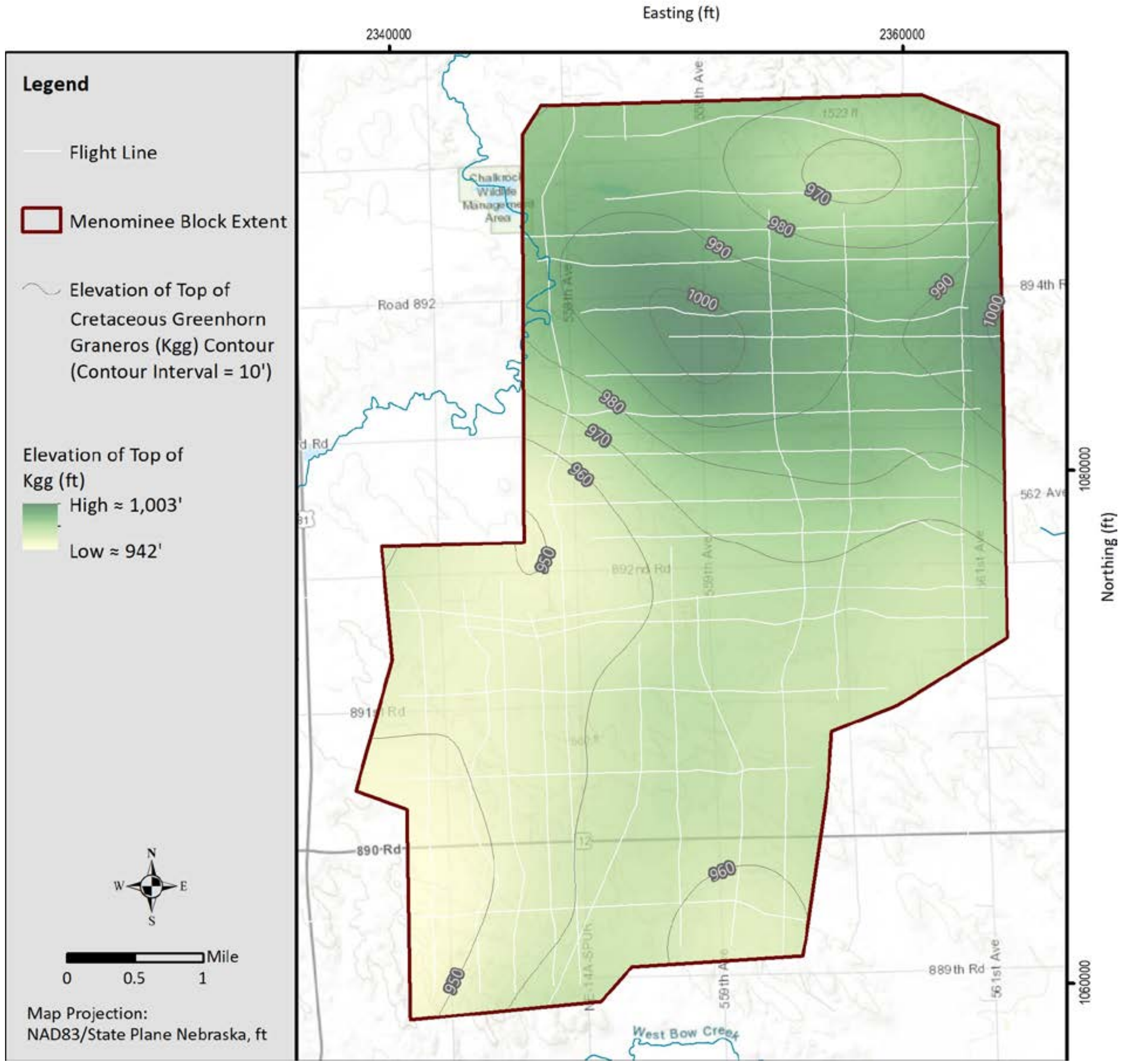


Figure 3-46. Map of the elevation of the top of the Cretaceous Greenhorn-Graneros (*Kgg*) within the Menominee Block AEM survey area. The projection is NAD83 State Plane Nebraska (feet) and the elevation values are referenced to NAVD 88 (feet).

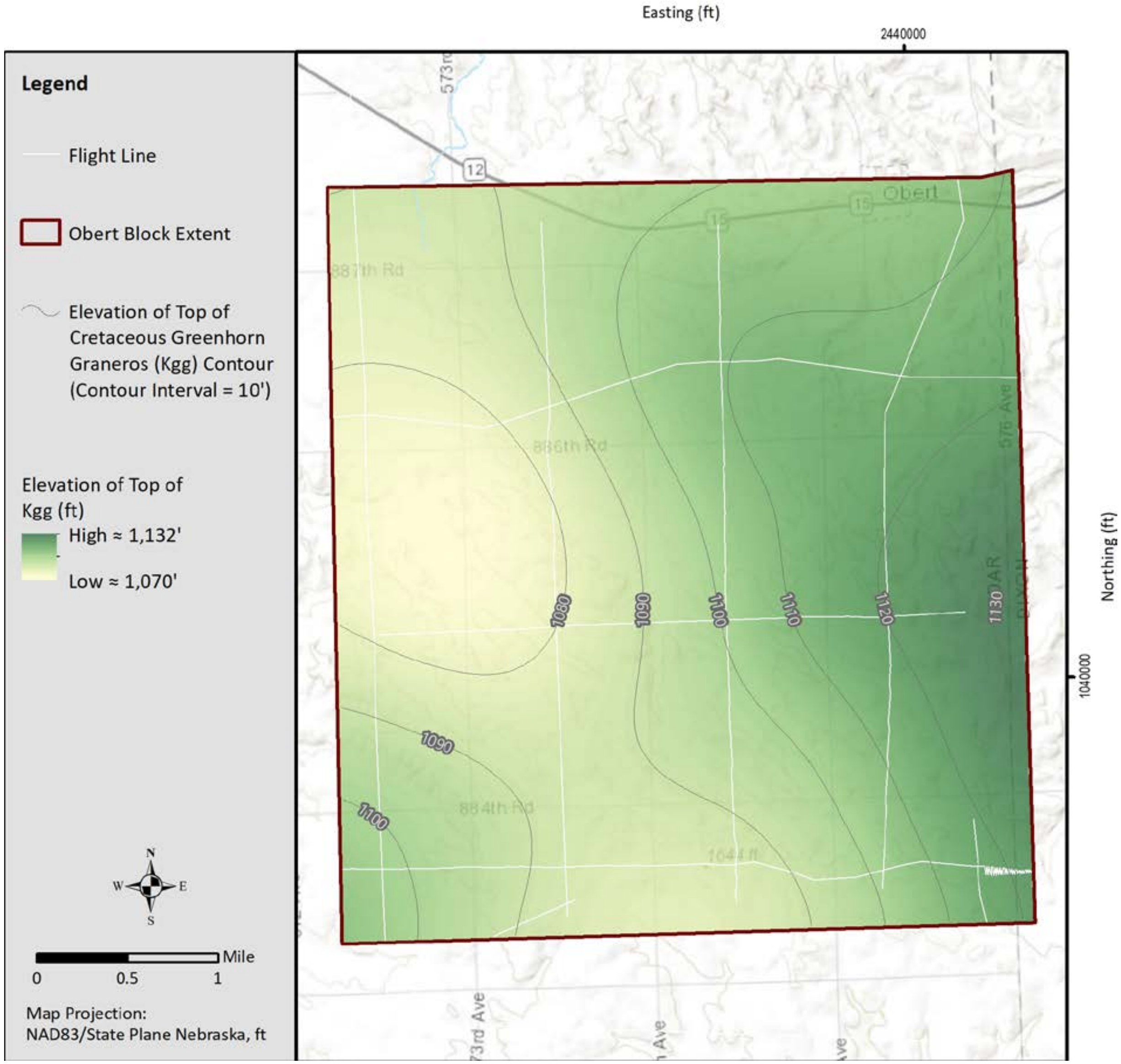


Figure 3-47. Map of the elevation of the top of the Cretaceous Greenhorn-Graneros (*Kgg*) within the Obert Block AEM survey area. The projection is NAD83 State Plane Nebraska (feet) and the elevation values are referenced to NAVD 88 (feet).

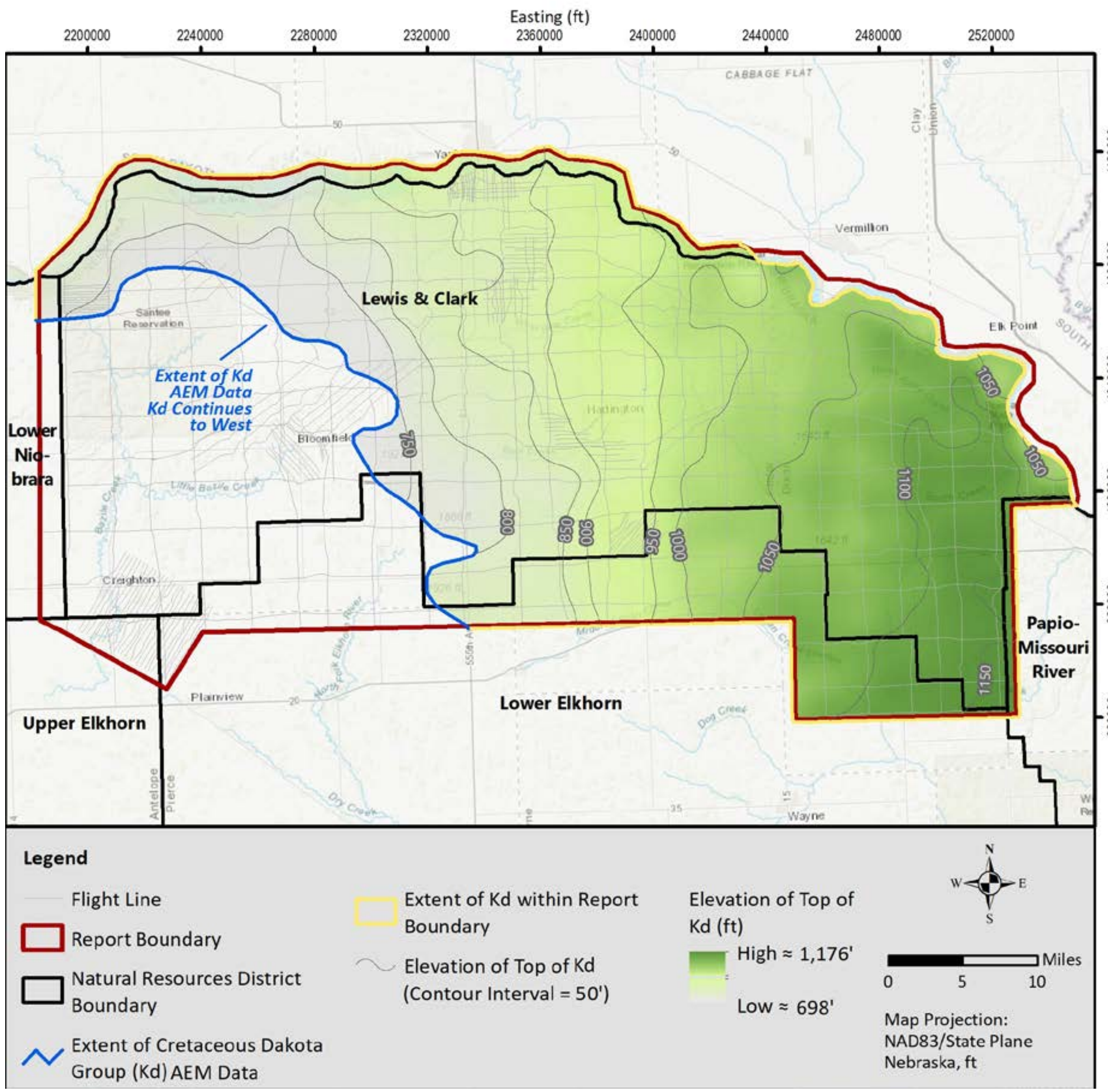


Figure 3-48. Map of the elevation of the top of the Cretaceous Dakota Group (*Kd*) within the LCNRD Reconnaissance AEM survey area. The projection is NAD83 State Plane Nebraska (feet) and the elevation values are referenced to NAVD 88 (feet).

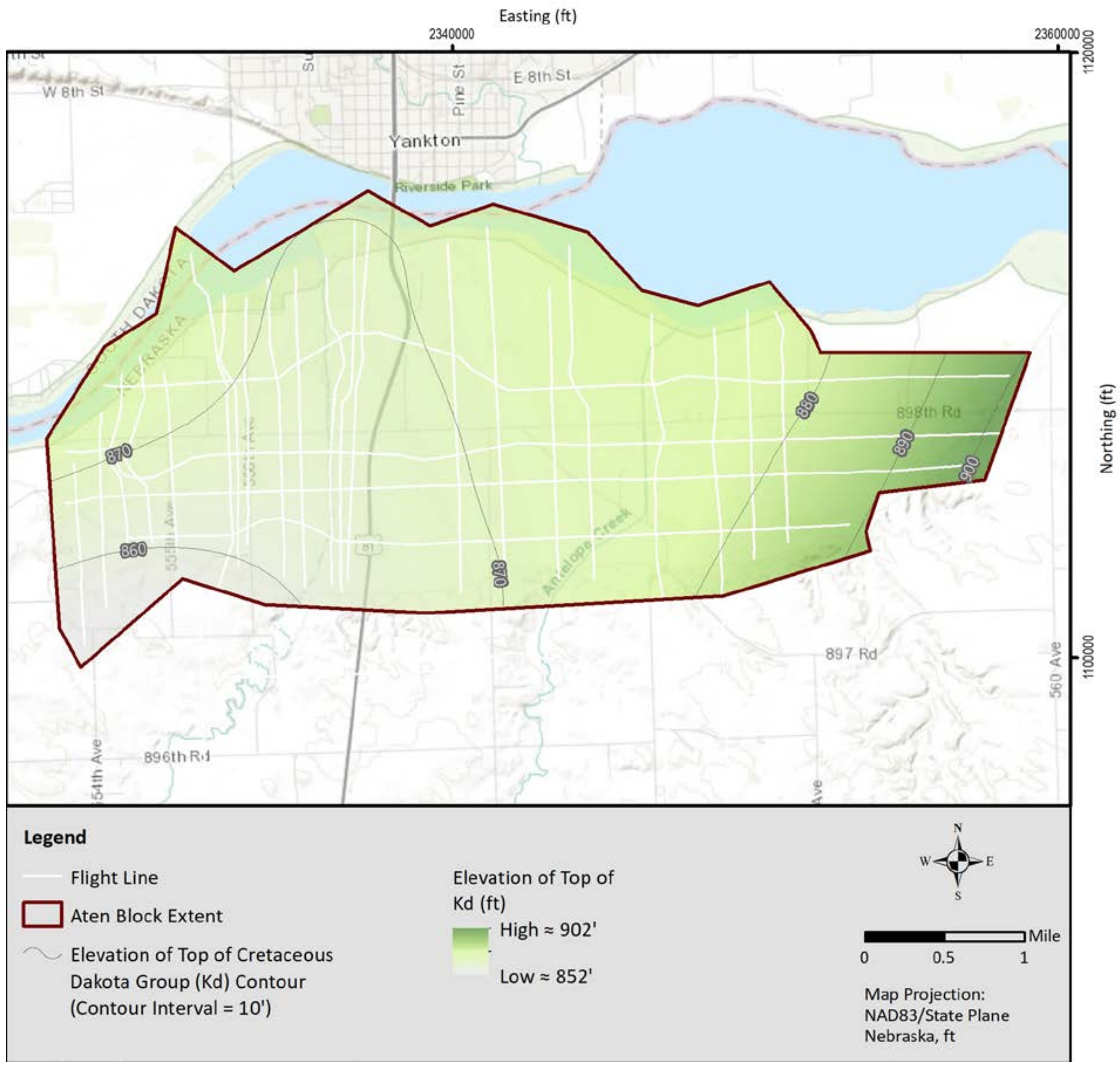


Figure 3-49. Map of the elevation of the top of the Cretaceous Dakota Group (*Kd*) within the Aten Block AEM survey area. The projection is NAD83 State Plane Nebraska (feet) and the elevation values are referenced to NAVD 88 (feet).

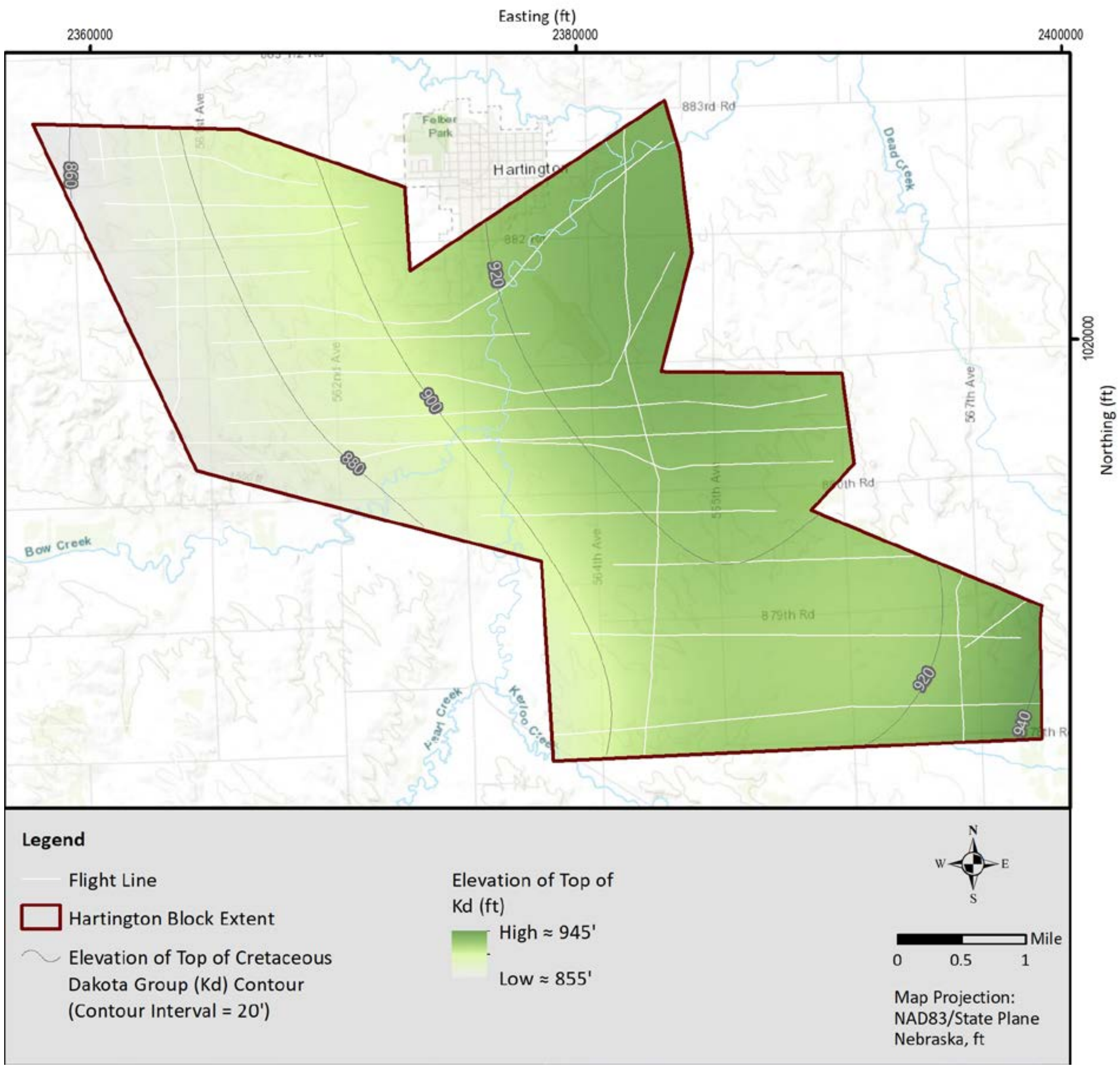


Figure 3-50. Map of the elevation of the top of the Cretaceous Dakota Group (*Kd*) within the Hartington Block AEM survey area. The projection is NAD83 State Plane Nebraska (feet) and the elevation values are referenced to NAVD 88 (feet).

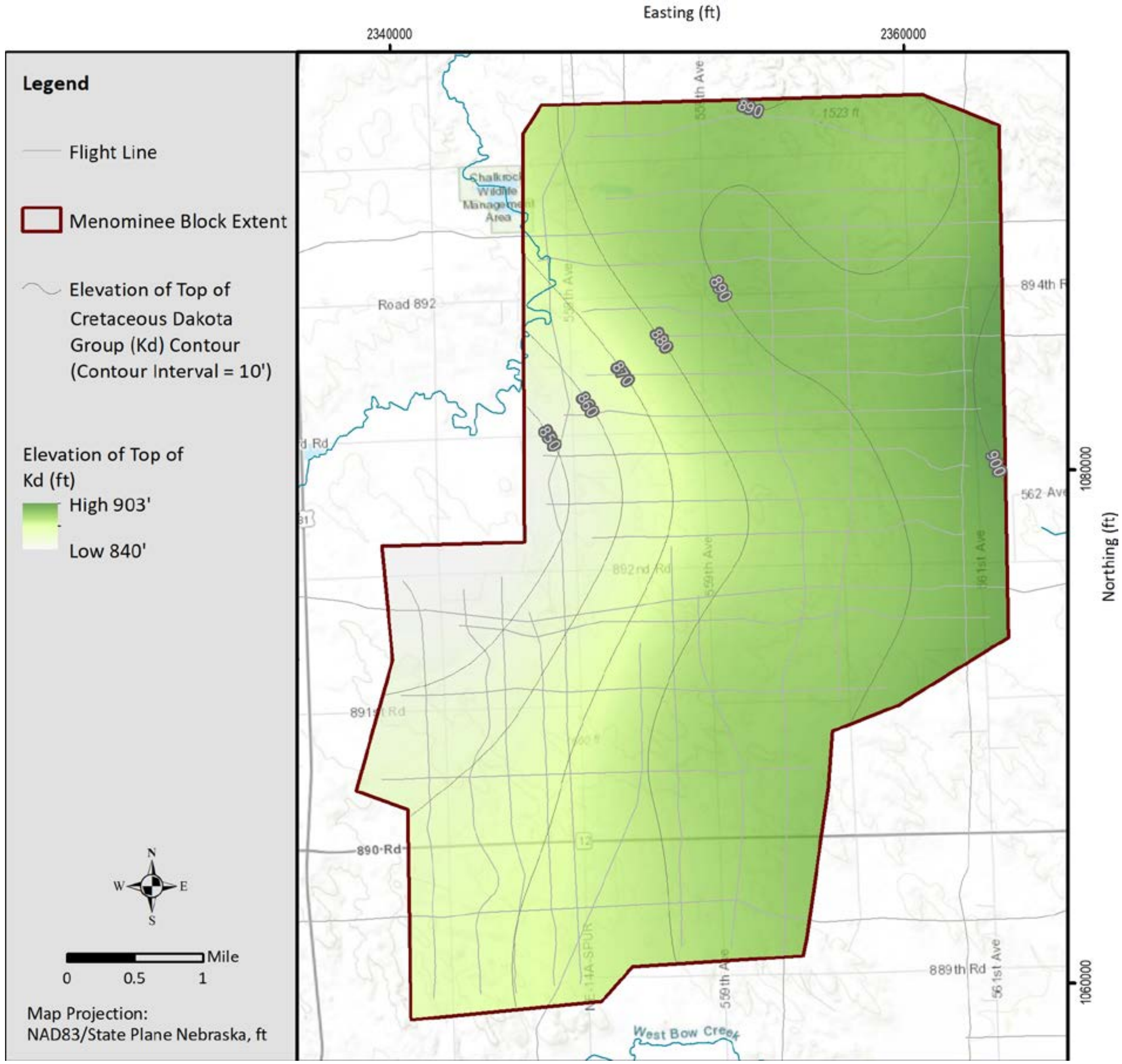


Figure 3-51. Map of the elevation of the top of the Cretaceous Dakota Group (*Kd*) within the Menominee Block AEM survey area. The projection is NAD83 State Plane Nebraska (feet) and the elevation values are referenced to NAVD 88 (feet).

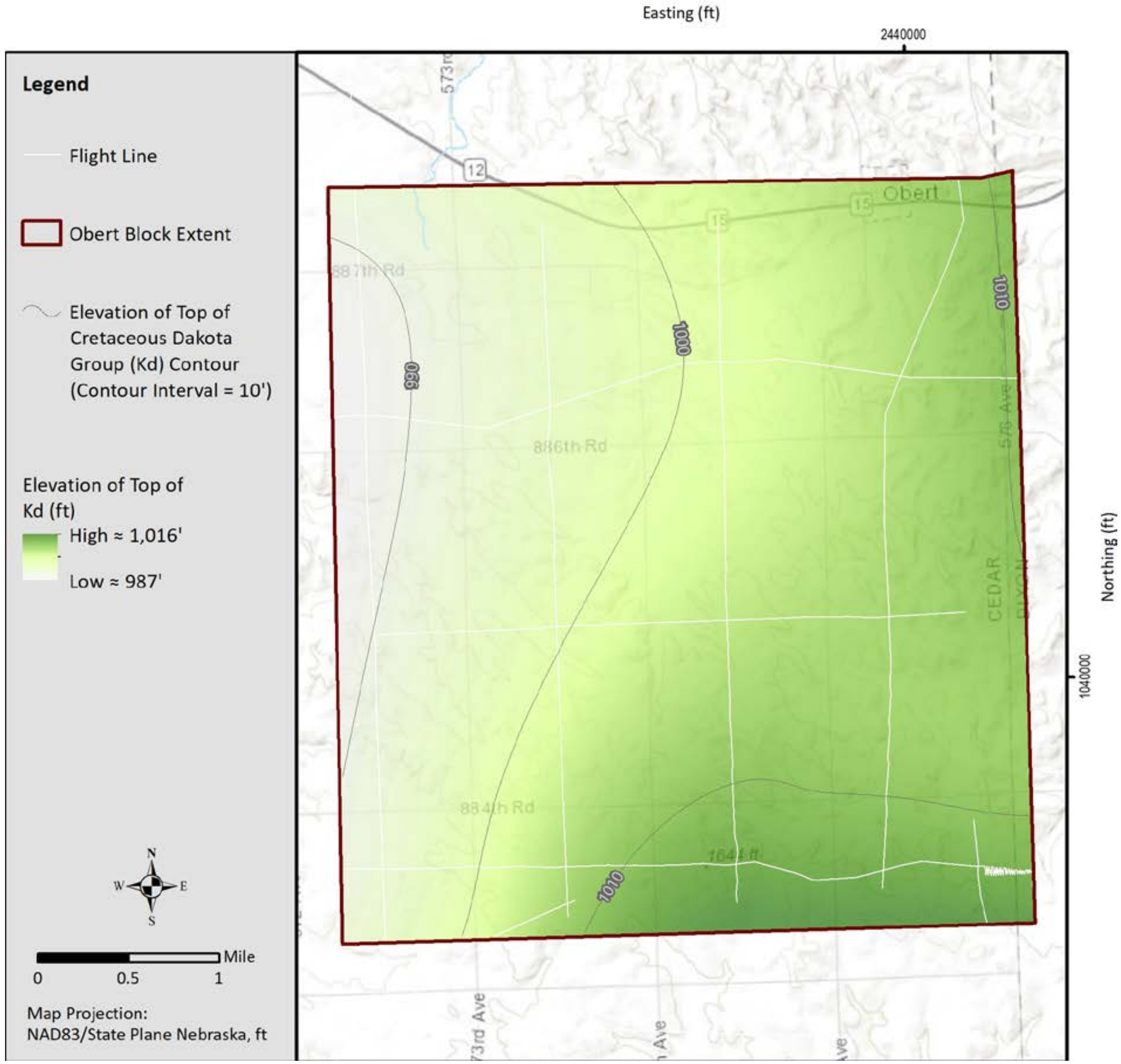


Figure 3-52. Map of the elevation of the top of the Cretaceous Dakota Group (*Kd*) within the Obert Block AEM survey area. The projection is NAD83 State Plane Nebraska (feet) and the elevation values are referenced to NAVD 88 (feet).

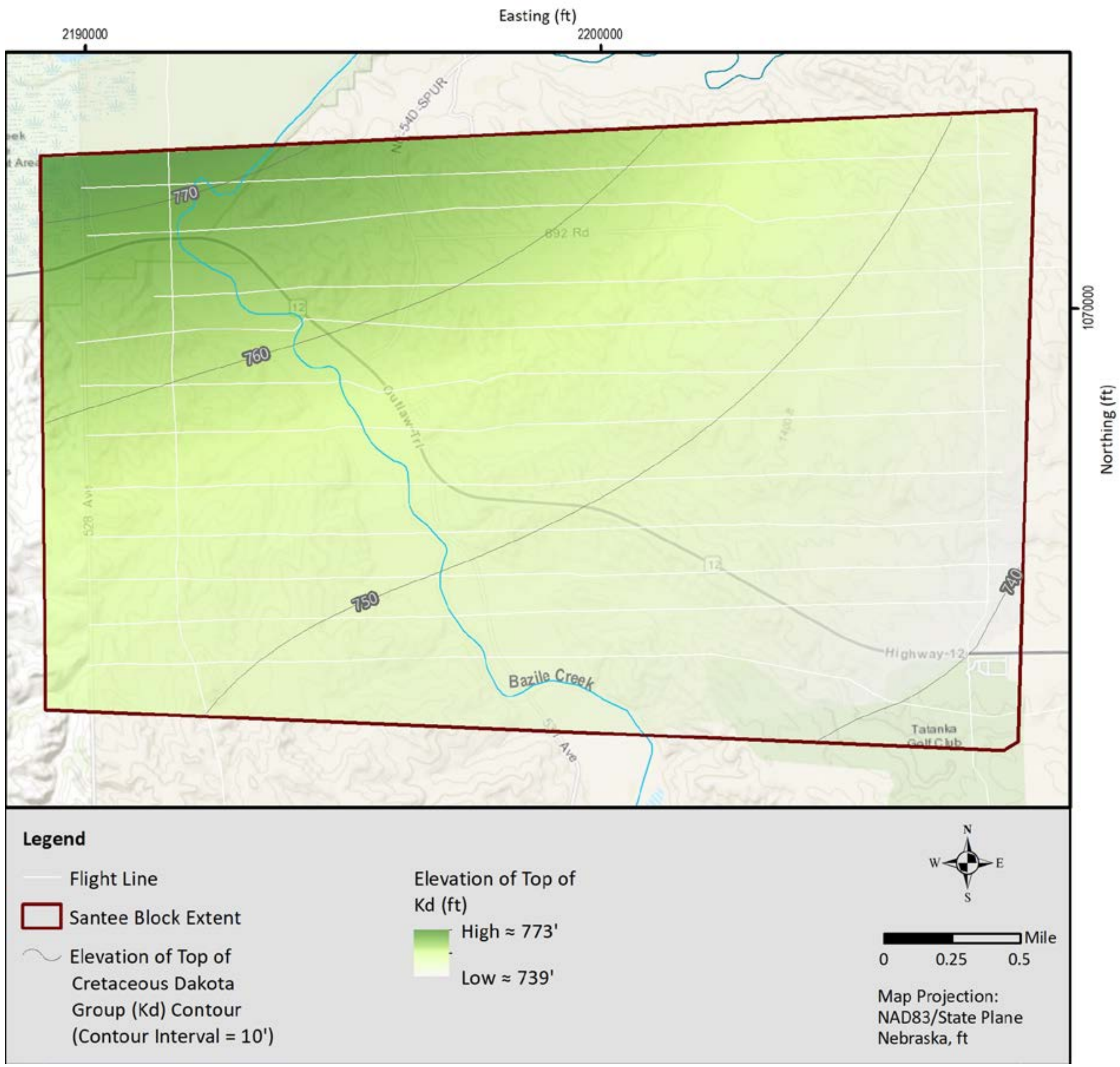


Figure 3-53. Map of the elevation of the top of the Cretaceous Dakota Group (*Kd*) within the Santee Block AEM survey area. The projection is NAD83 State Plane Nebraska (feet) and the elevation values are referenced to NAVD 88 (feet).

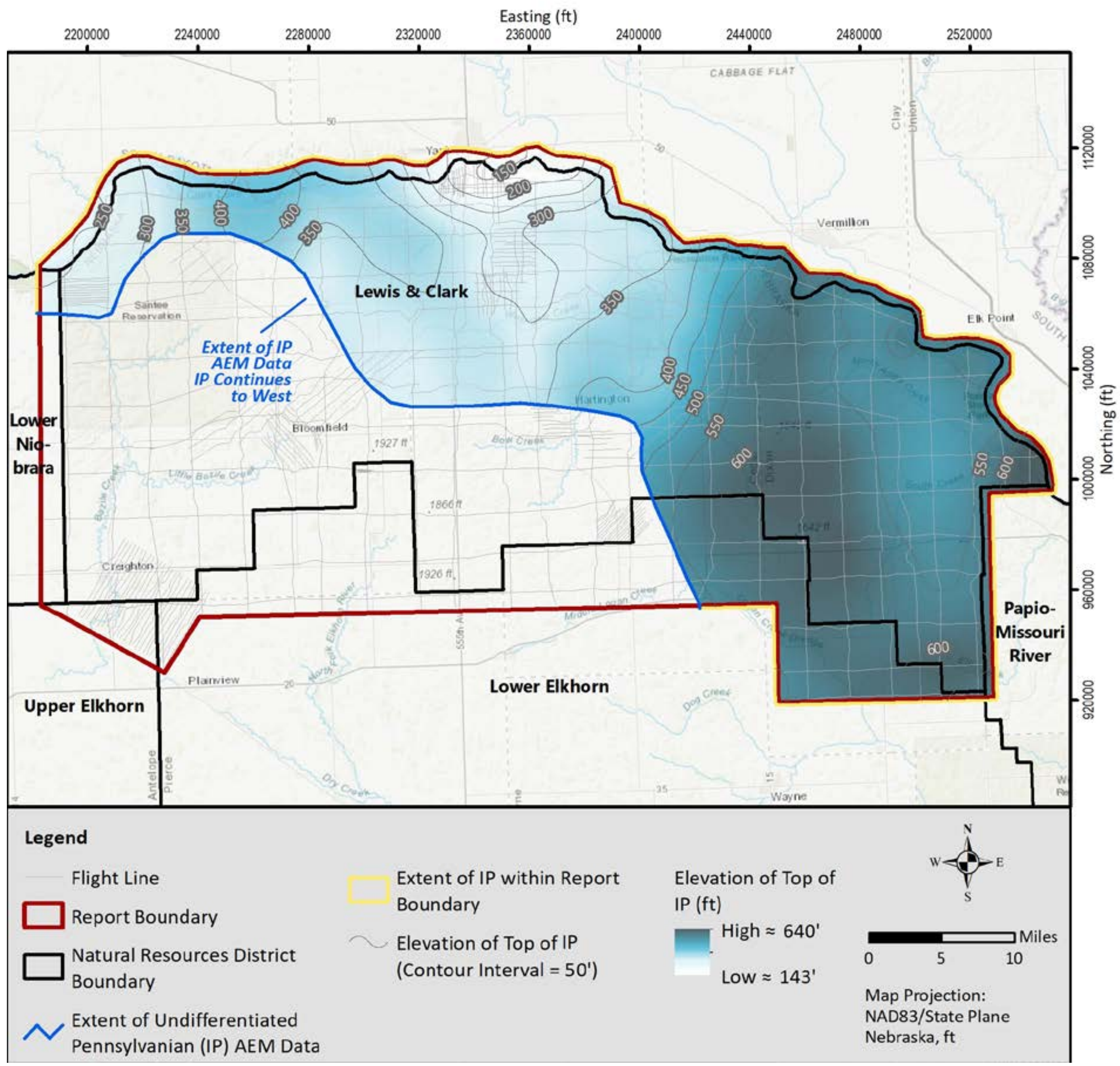


Figure 3-54. Map of the elevation of the top of the undifferentiated Pennsylvanian (*IP*) within the LCNRD Reconnaissance AEM survey area. The projection is NAD83 State Plane Nebraska (feet) and the elevation values are referenced to NAVD 88 (feet).

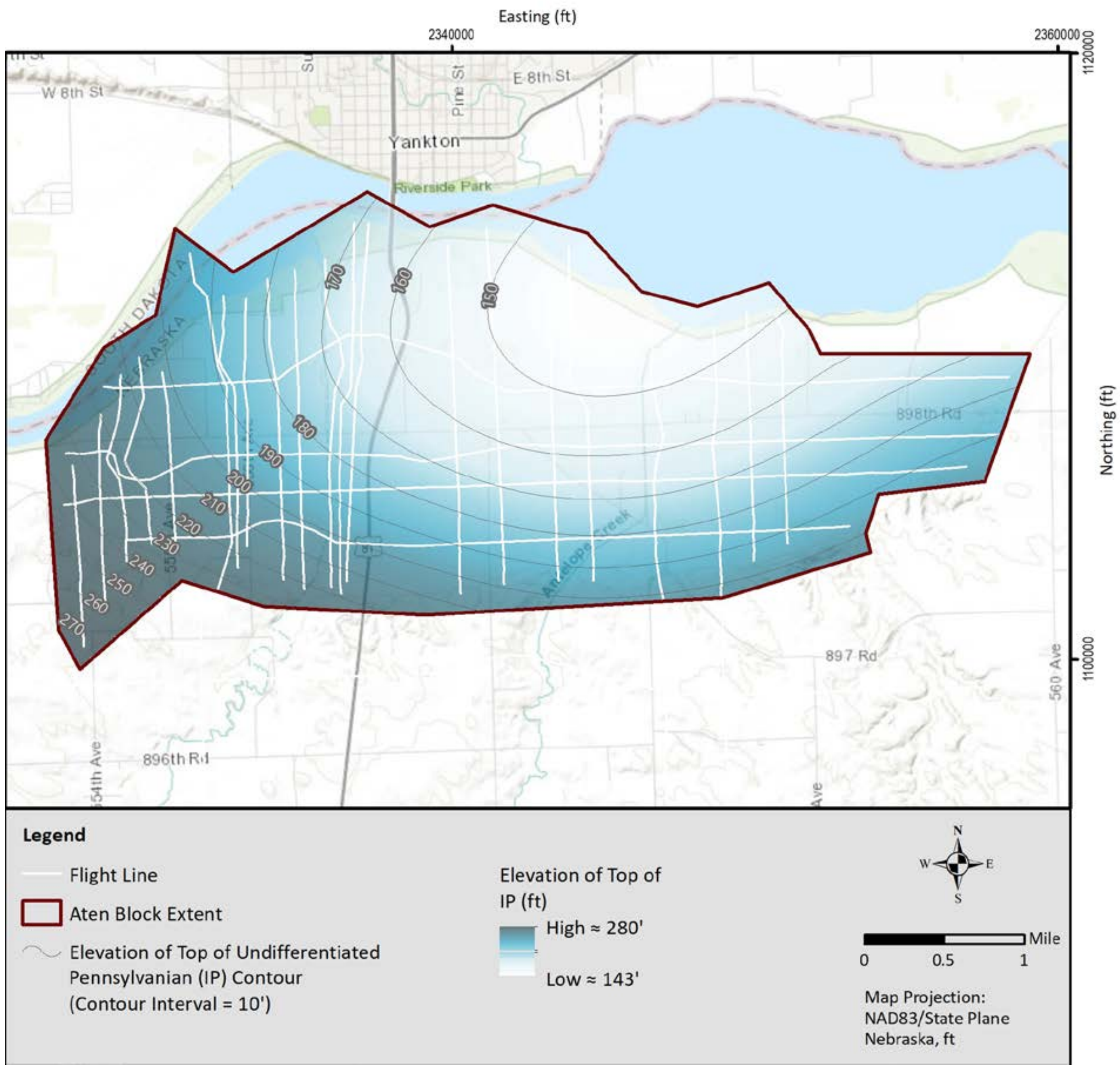


Figure 3-55. Map of the elevation of the top of the undifferentiated Pennsylvanian (*IP*) within the Aten Block AEM survey area. The projection is NAD83 State Plane Nebraska (feet) and the elevation values are referenced to NAVD 88 (feet).

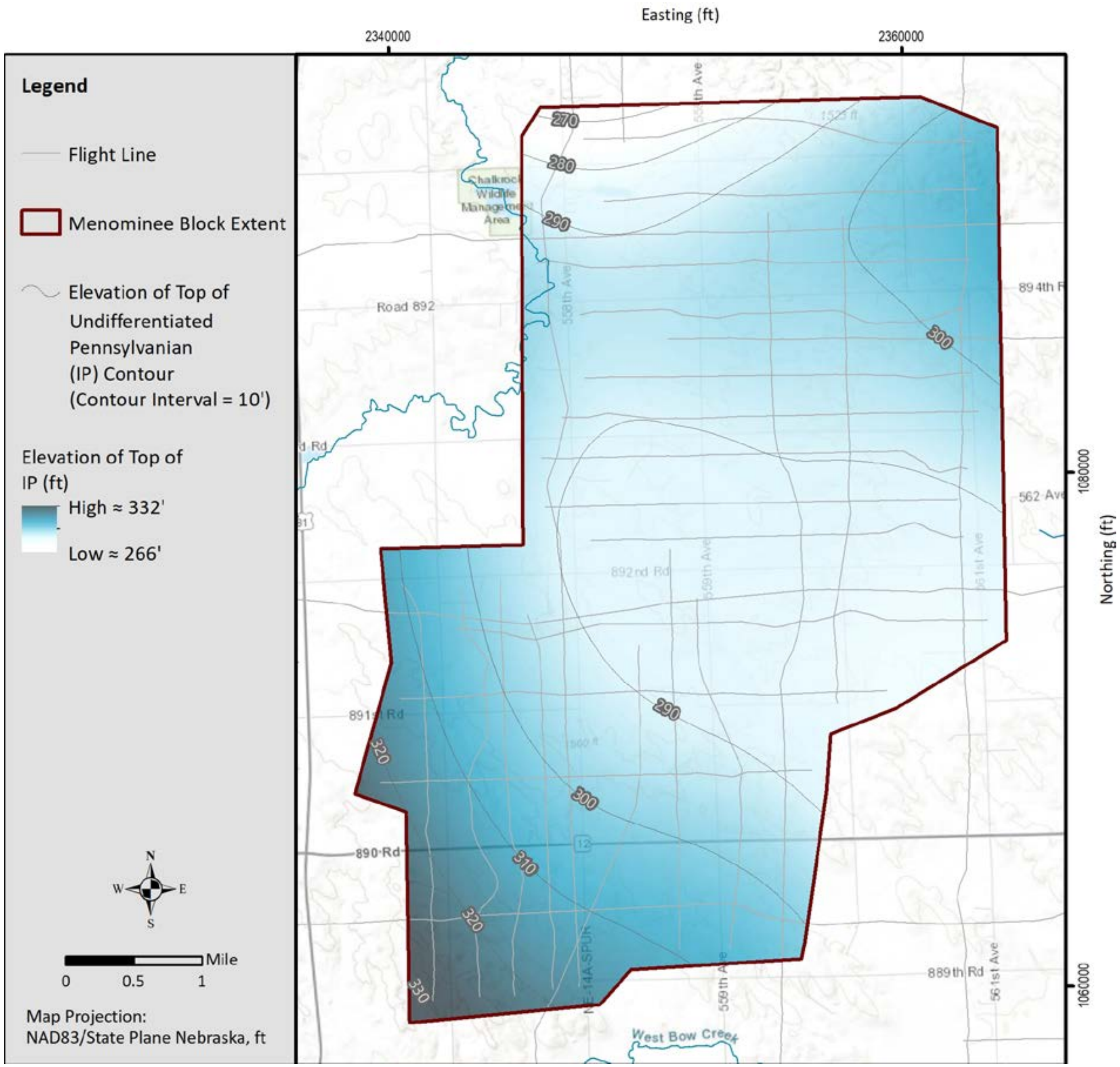


Figure 3-56. Map of the elevation of the top of the undifferentiated Pennsylvanian (*IP*) within the Menominee Block AEM survey area. The projection is NAD83 State Plane Nebraska (feet) and the elevation values are referenced to NAVD 88 (feet).

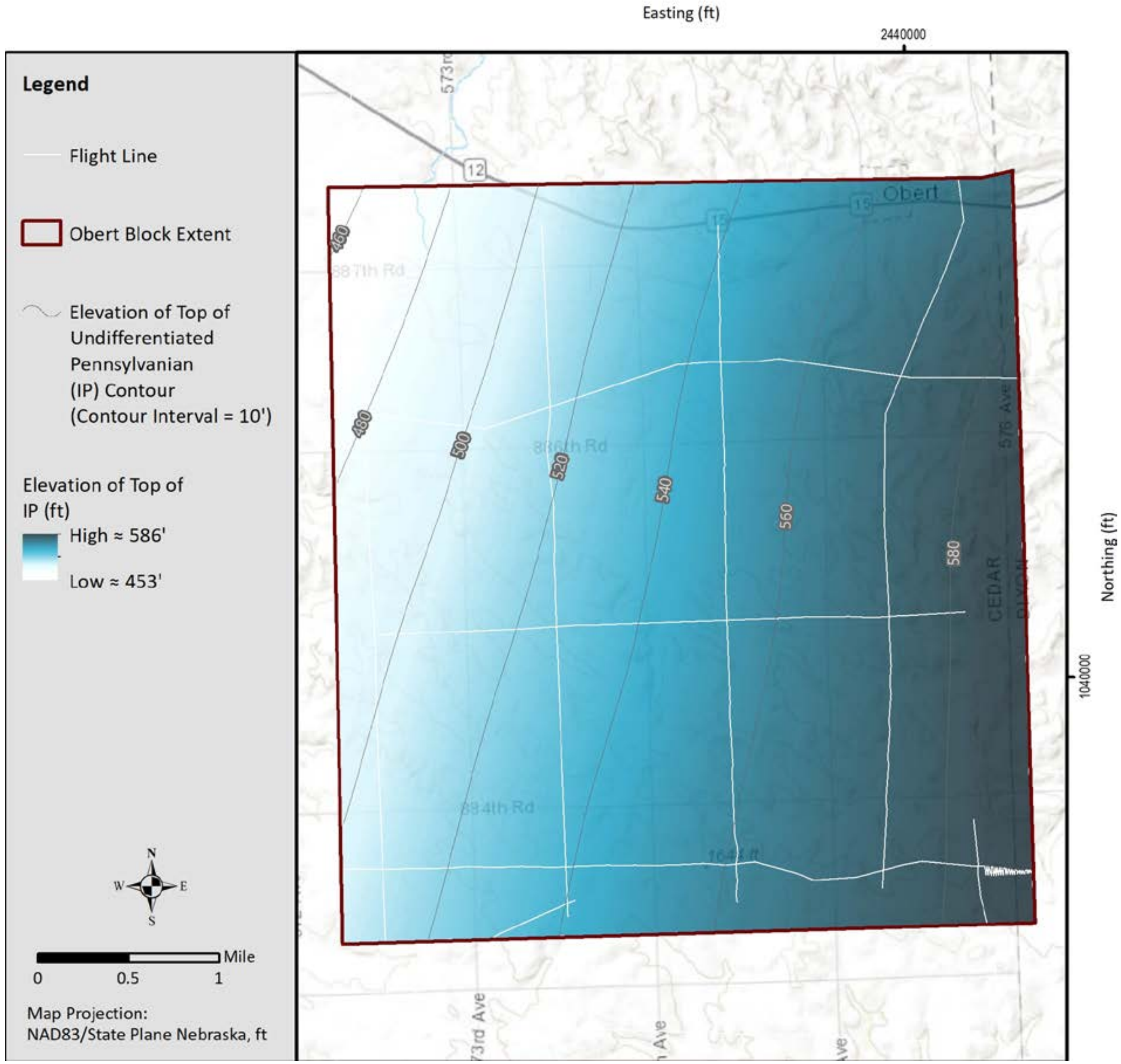


Figure 3-57. Map of the elevation of the top of the undifferentiated Pennsylvanian (*IP*) within the Obert Block AEM survey area. The projection is NAD83 State Plane Nebraska (feet) and the elevation values are referenced to NAVD 88 (feet).

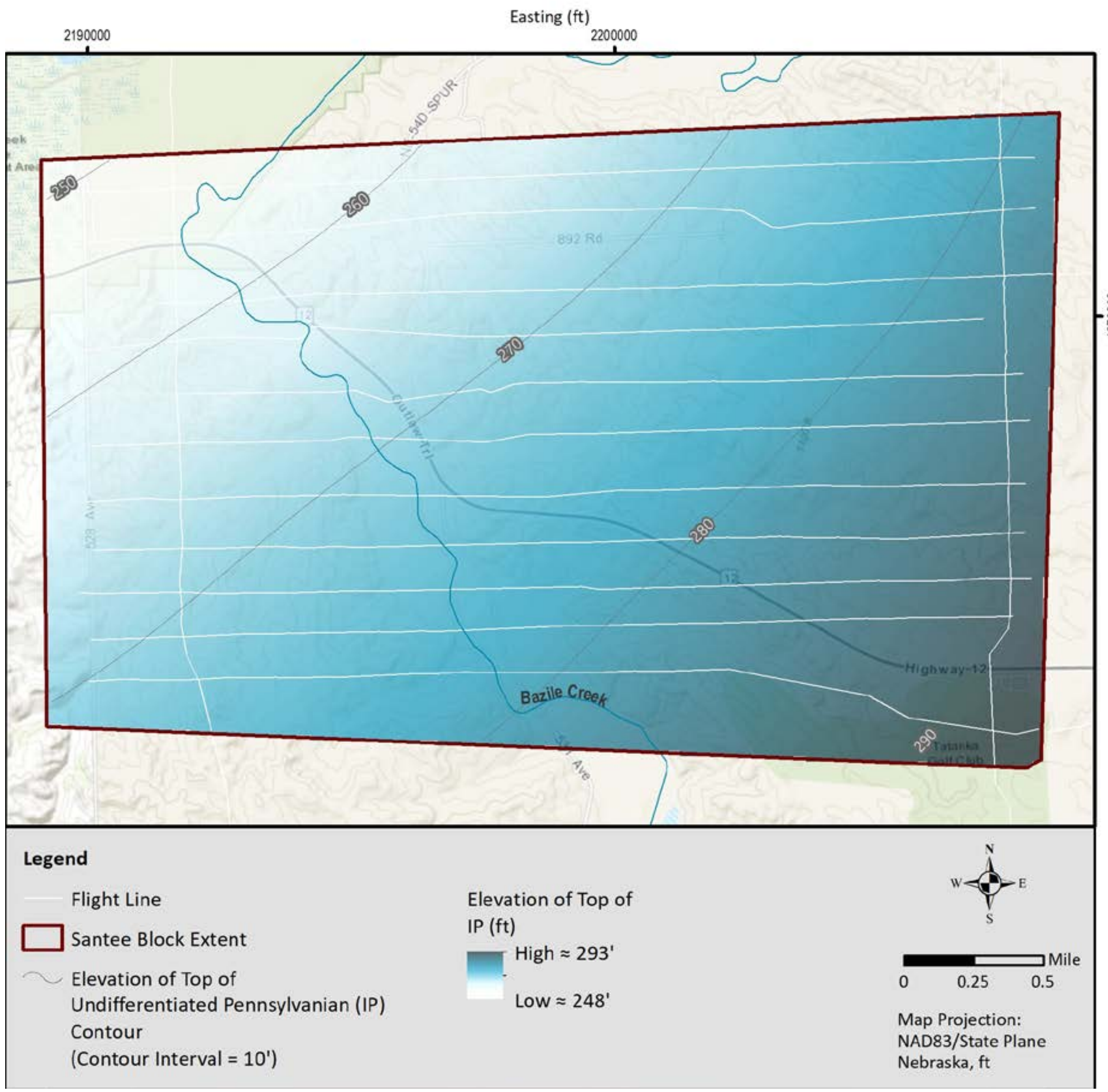


Figure 3-58. Map of the elevation of the top of the undifferentiated Pennsylvanian (*IP*) within the Santee Block AEM survey area. The projection is NAD83 State Plane Nebraska (feet) and the elevation values are referenced to NAVD 88 (feet).

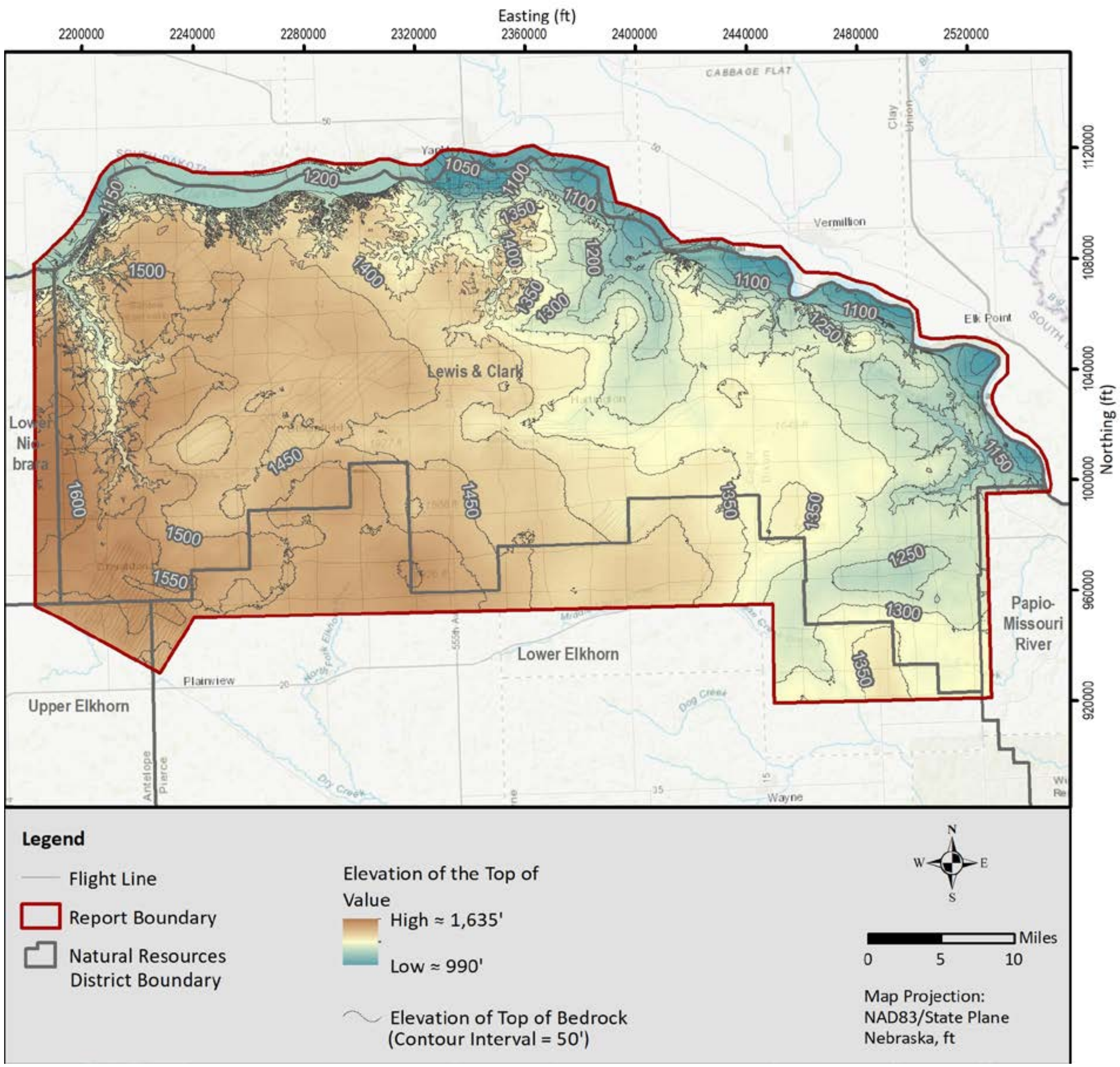


Figure 3-59. Map of the elevation of the top of bedrock surface within the LCNRD Reconnaissance AEM survey area. The projection is NAD83 State Plane Nebraska (feet) and the elevation values are referenced to NAVD 88 (feet).

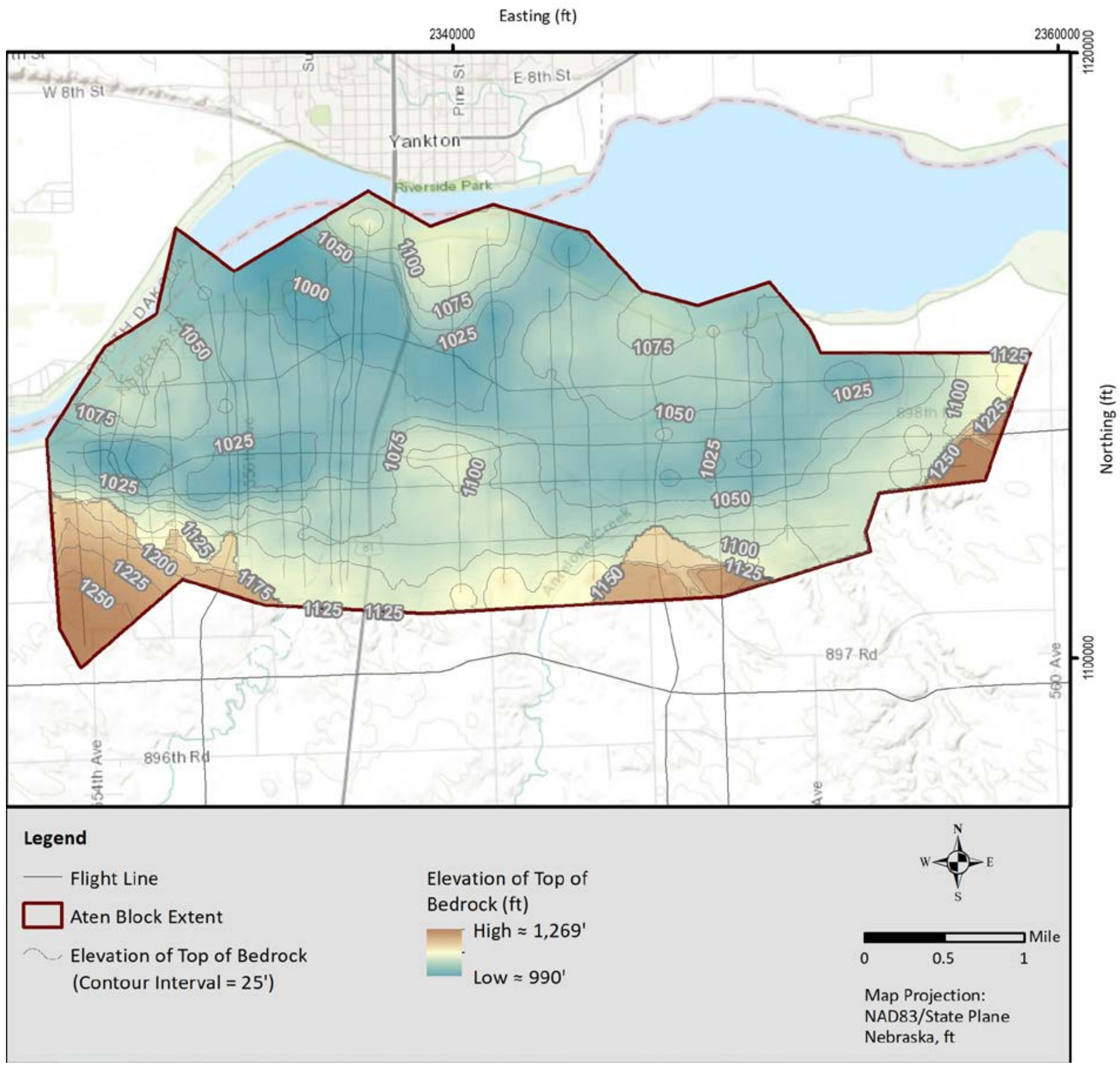


Figure 3-60. Map of the elevation of the top of bedrock surface within the Aten Block AEM survey area. The projection is NAD83 State Plane Nebraska (feet) and the elevation values are referenced to NAVD 88 (feet).

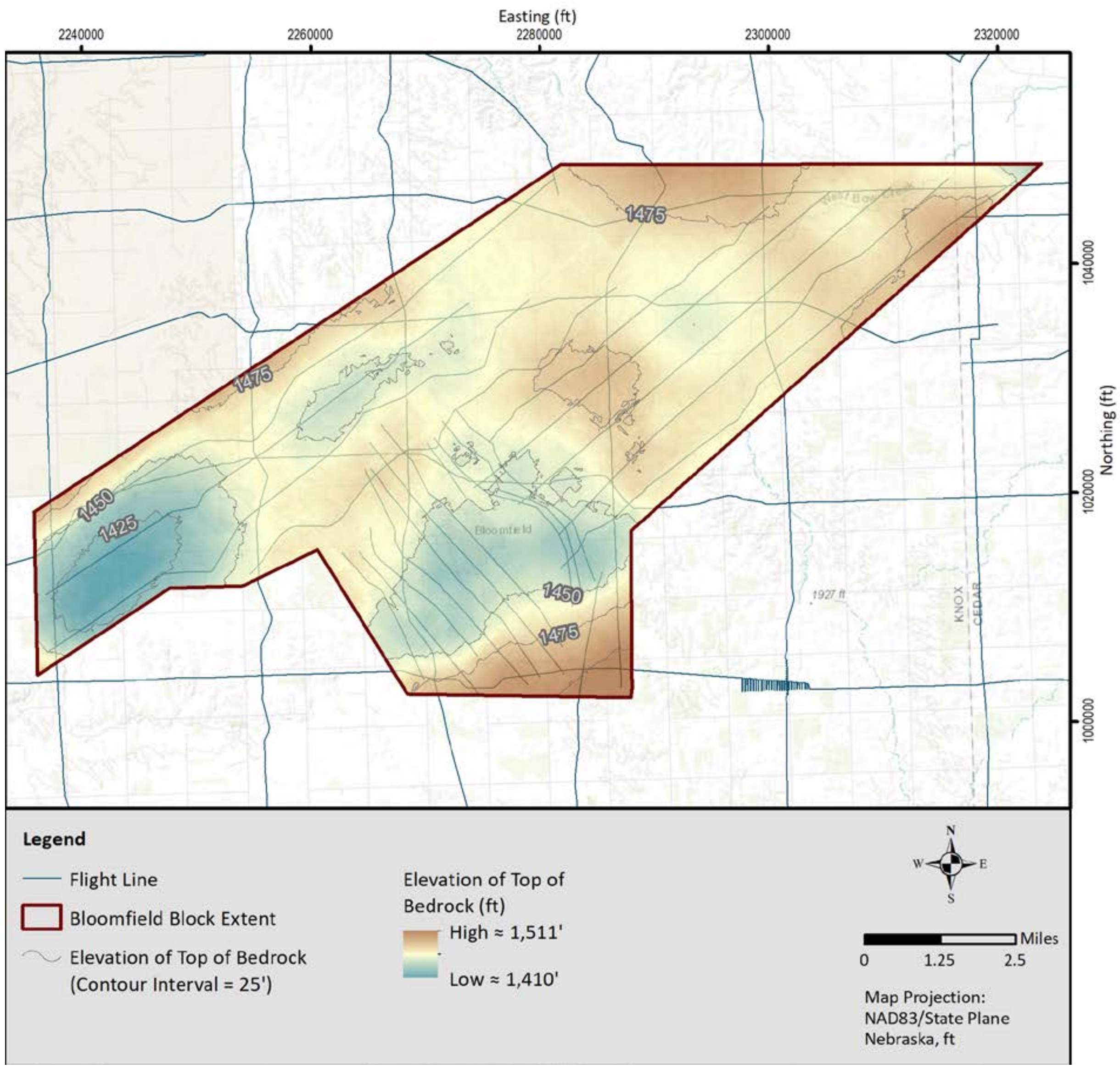


Figure 3-61. Map of the elevation of the bedrock surface top within the Bloomfield Block AEM survey area. The projection is NAD83 State Plane Nebraska (feet) and the elevation values are referenced to NAVD 88 (feet).

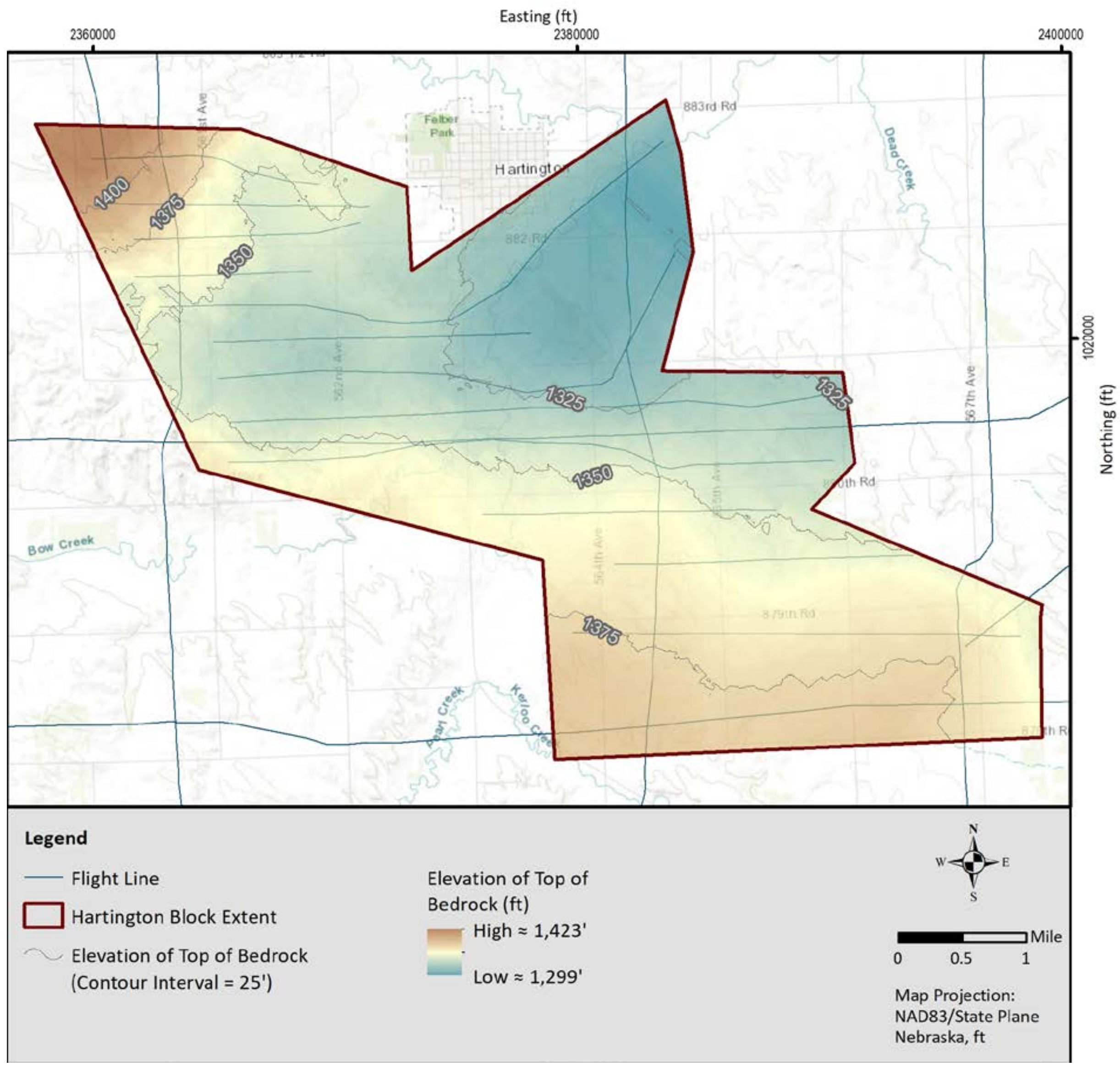


Figure 3-62. Map of the elevation of the top of bedrock surface within the Hartington Block AEM survey area. The projection is NAD83 State Plane Nebraska (feet) and the elevation values are referenced to NAVD 88 (feet).

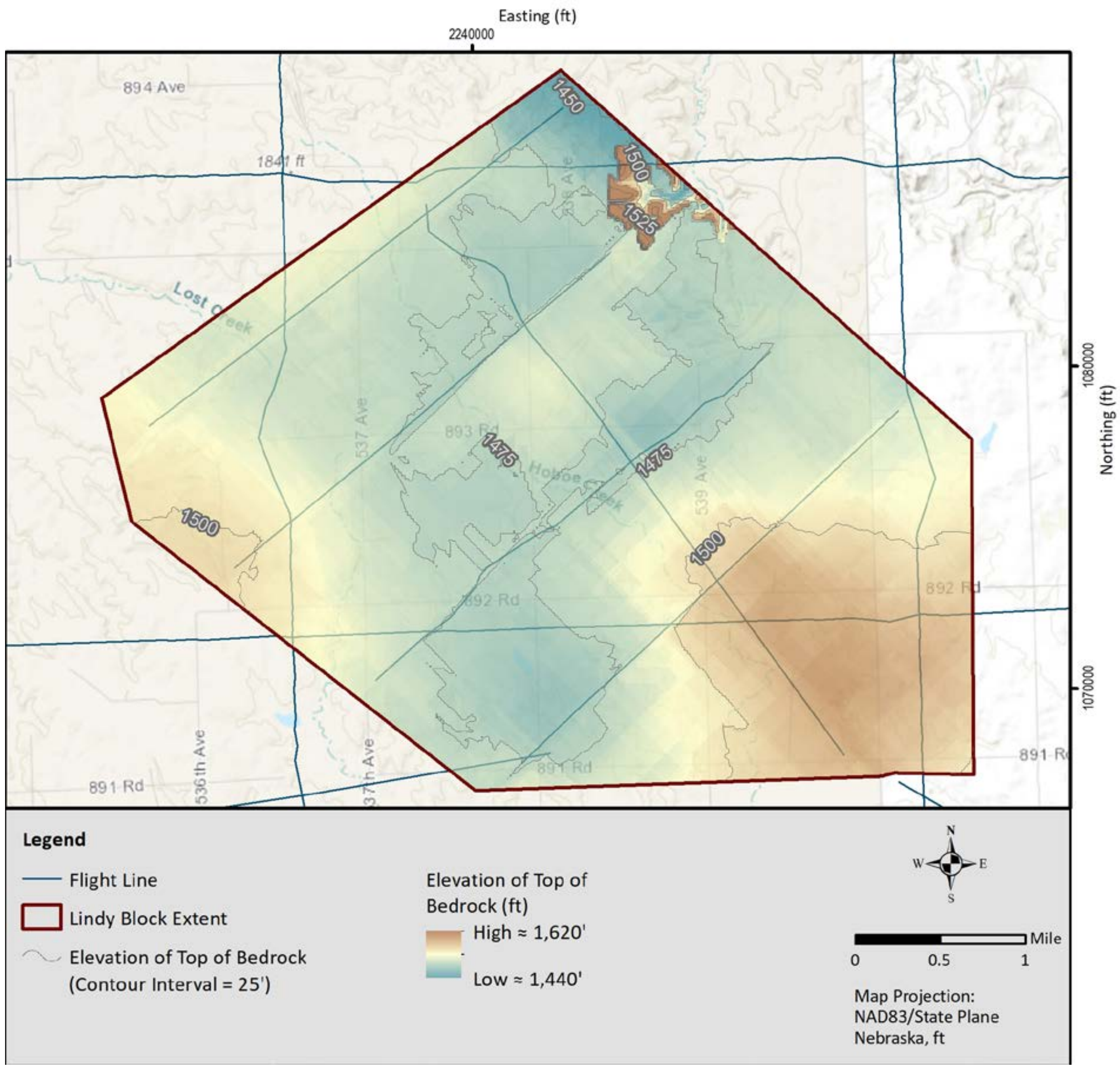


Figure 3-63. Map of the elevation of the top of bedrock surface within the Lindy Block AEM survey area. The projection is NAD83 State Plane Nebraska (feet) and the elevation values are referenced to NAVD 88 (feet).

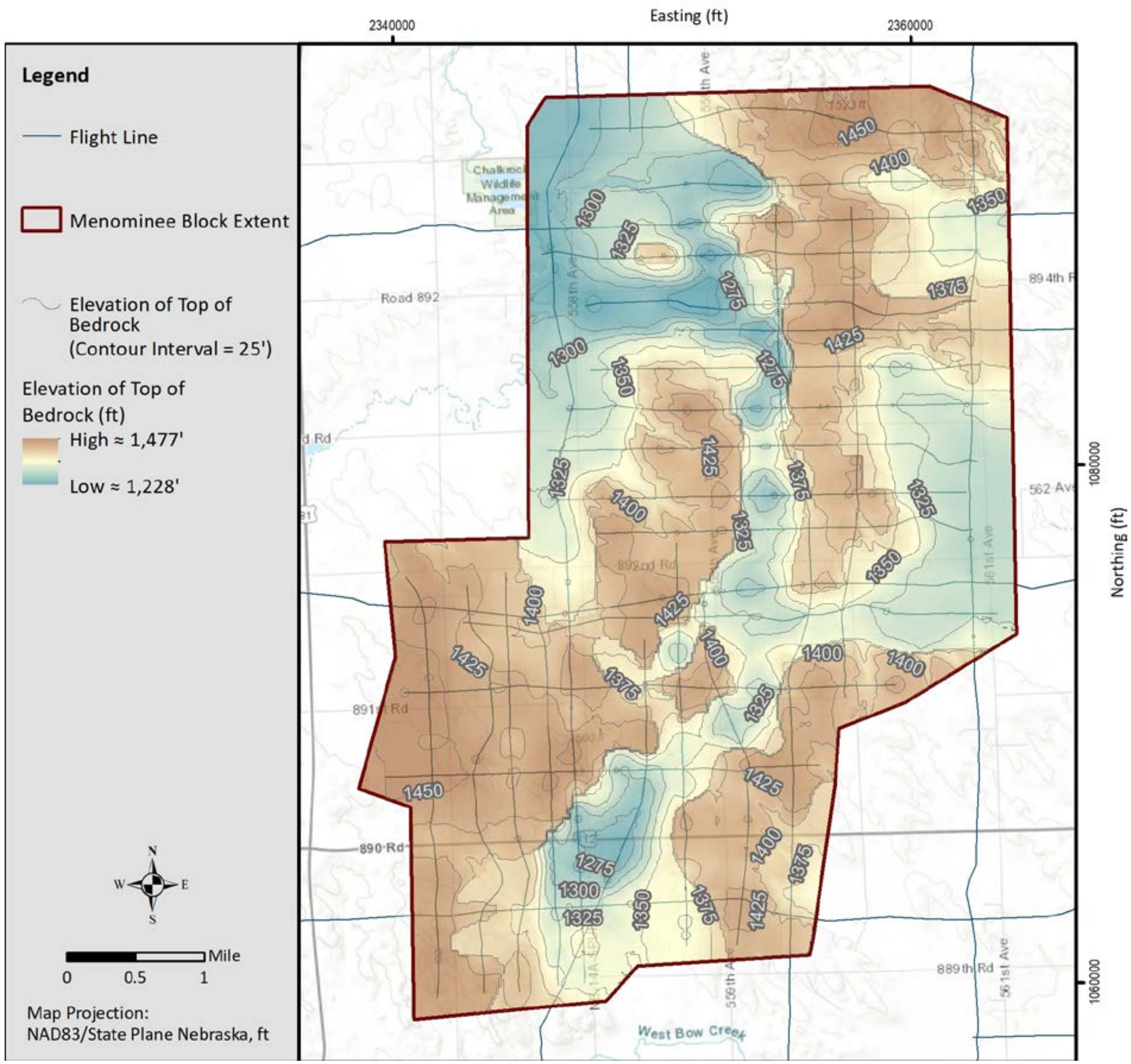


Figure 3-64. Map of the elevation of the top of bedrock surface within the Menominee Block AEM survey area. The projection is NAD83 State Plane Nebraska (feet) and the elevation values are referenced to NAVD 88 (feet).

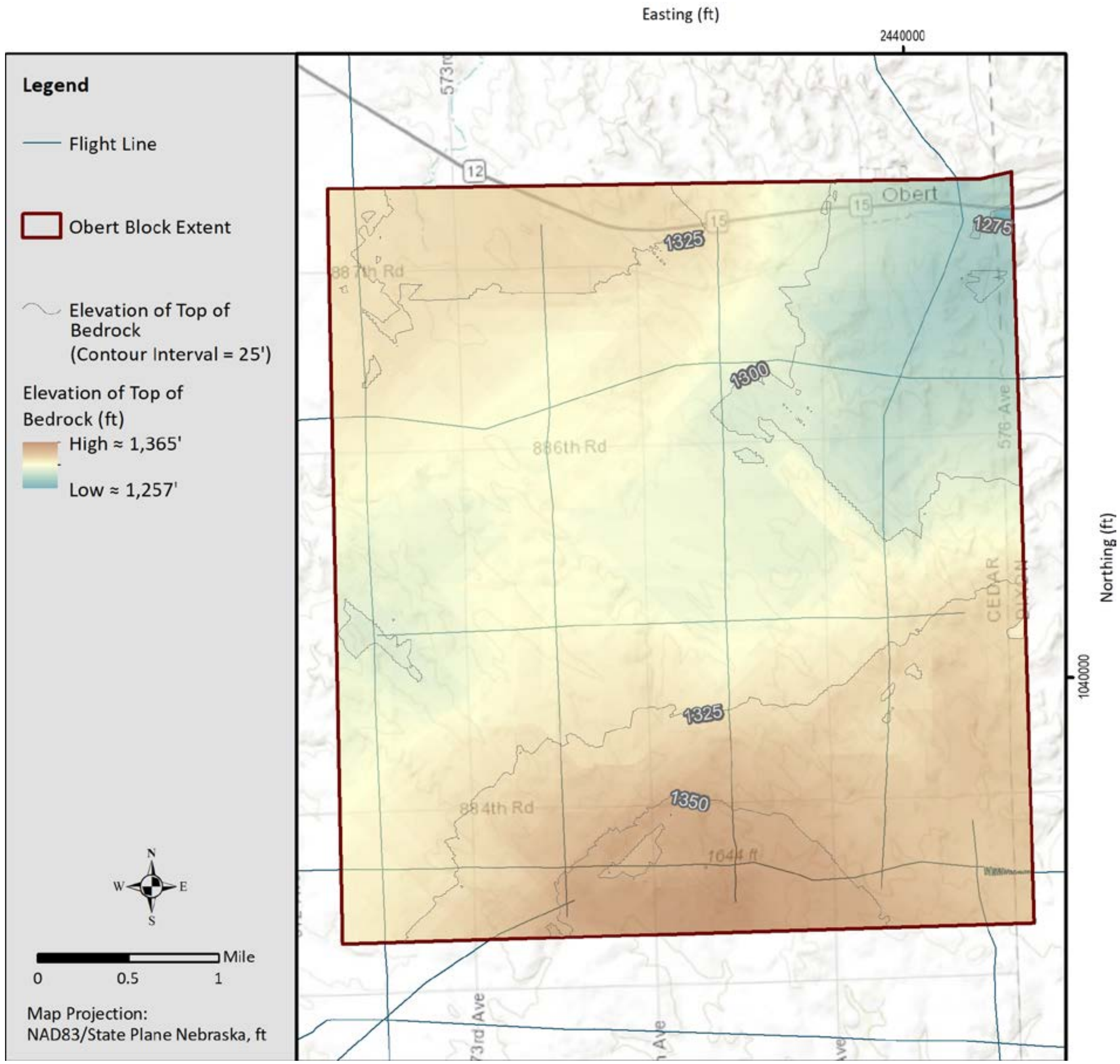


Figure 3-65. Map of the elevation of the top of bedrock surface within the Obert Block AEM survey area. The projection is NAD83 State Plane Nebraska (feet) and the elevation values are referenced to NAVD 88 (feet).

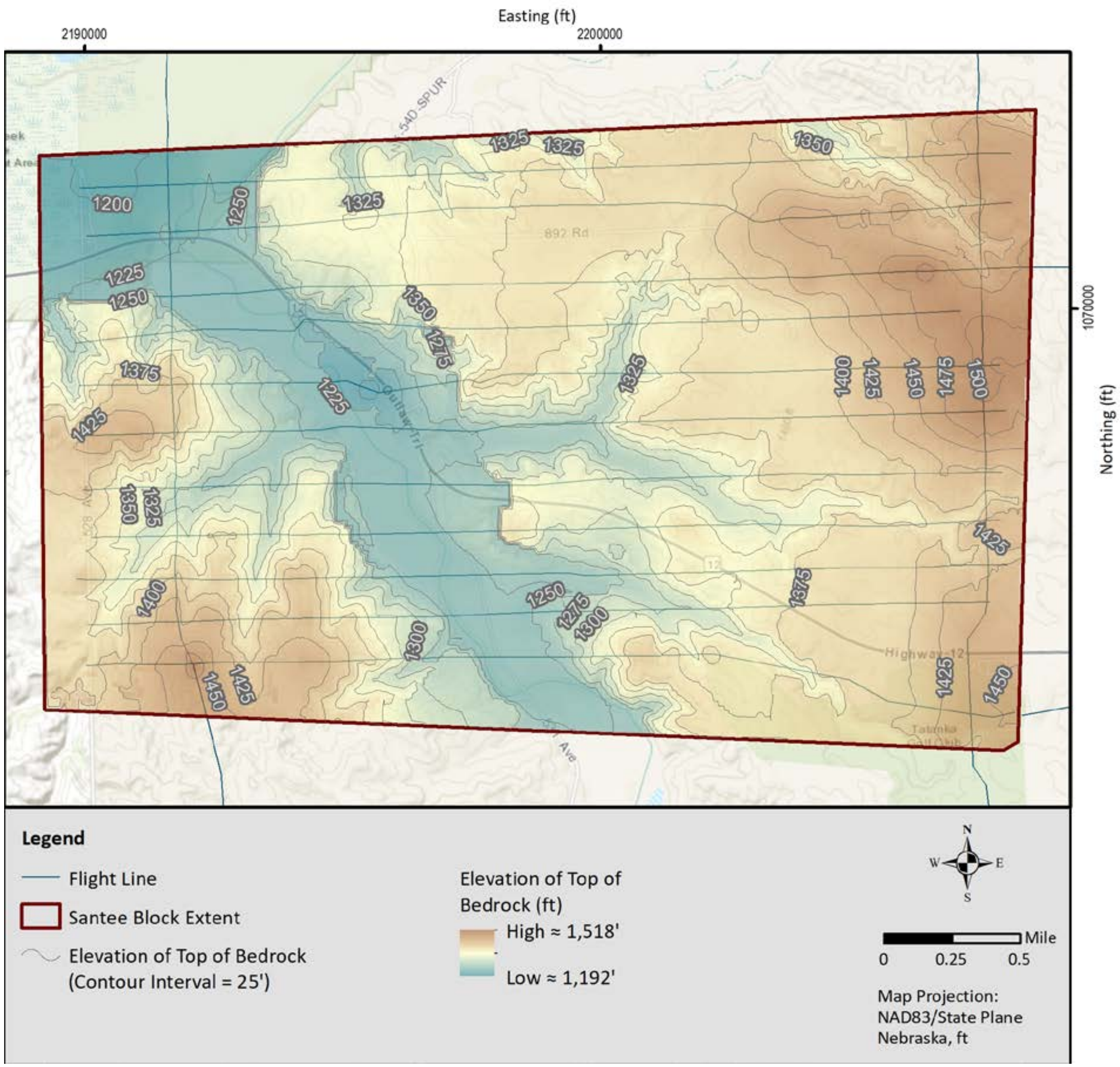


Figure 3-66. Map of the elevation of the top of the bedrock surface within the Santee Block AEM survey area. The projection is NAD83 State Plane Nebraska (feet) and the elevation values are referenced to NAVD 88 (feet).

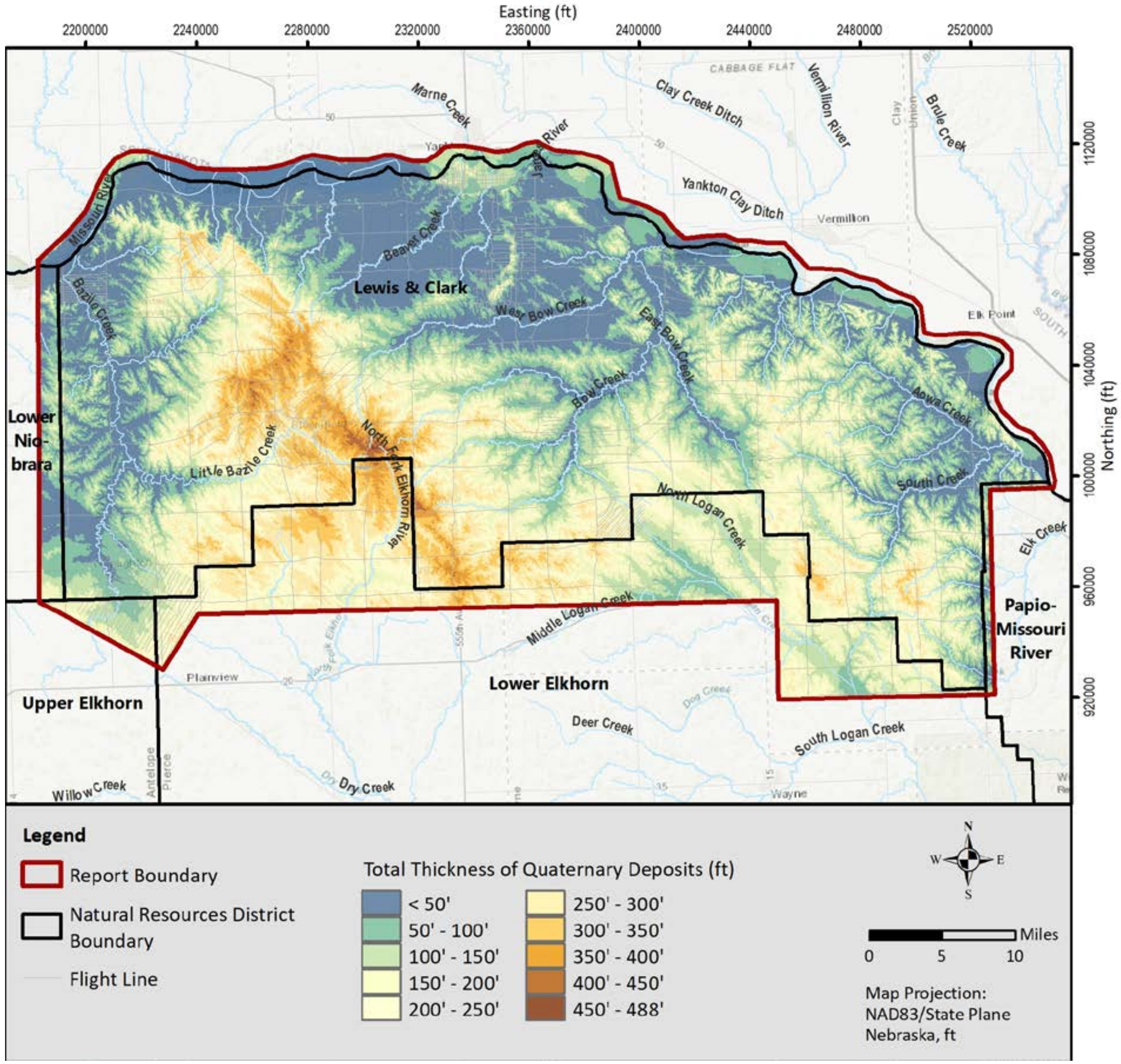


Figure 3-67. Map of the thickness (in feet) of the Quaternary (*Q*) and Tertiary Ogallala Group (*To*) deposits within the LCNRD Reconnaissance AEM survey area. The projection is NAD83 State Plane Nebraska (feet).

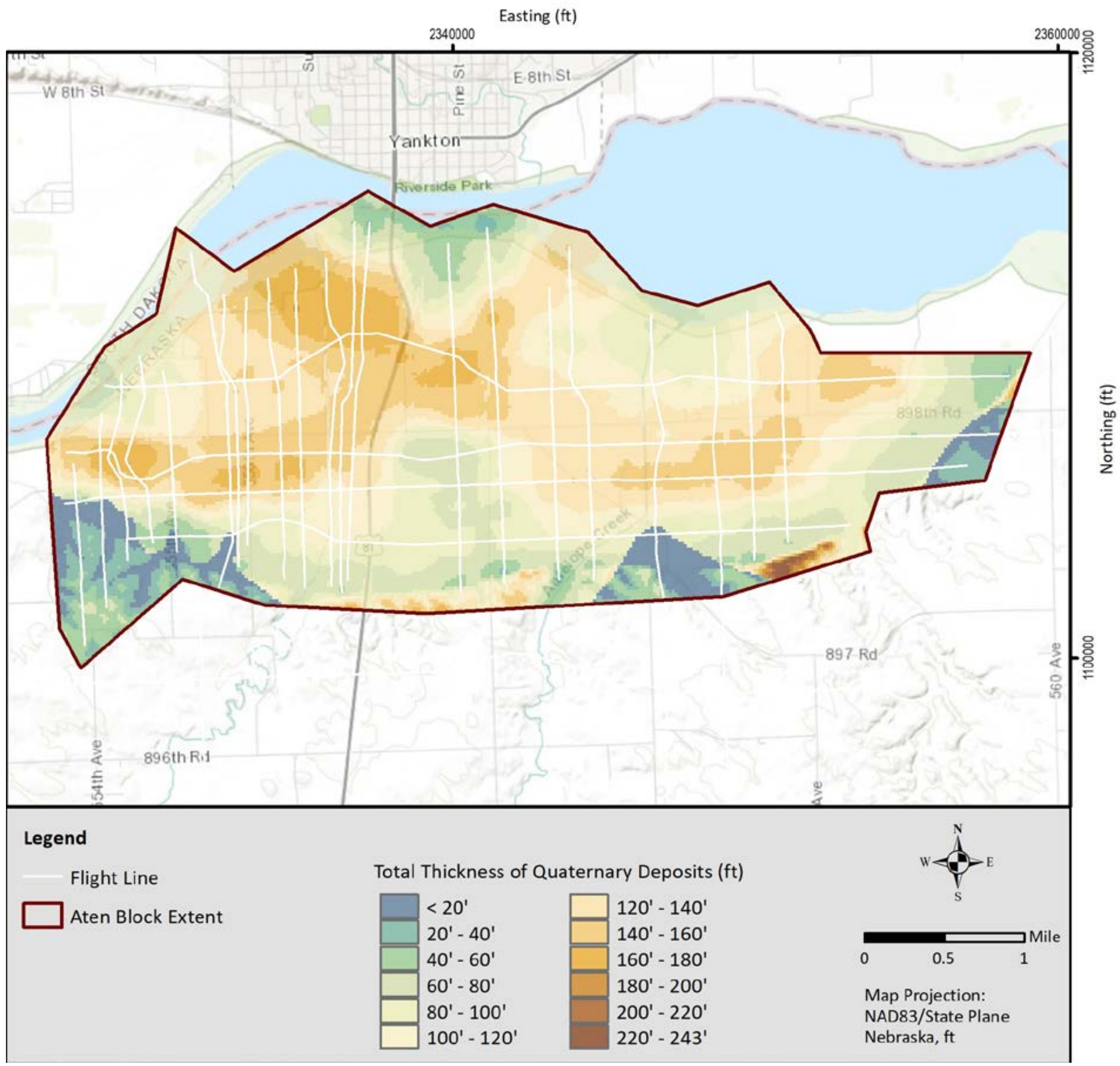


Figure 3-68. Map of the thickness (in feet) of the Quaternary (*Q*) deposits within the Aten Block AEM survey area. The projection is NAD83 State Plane Nebraska (feet).

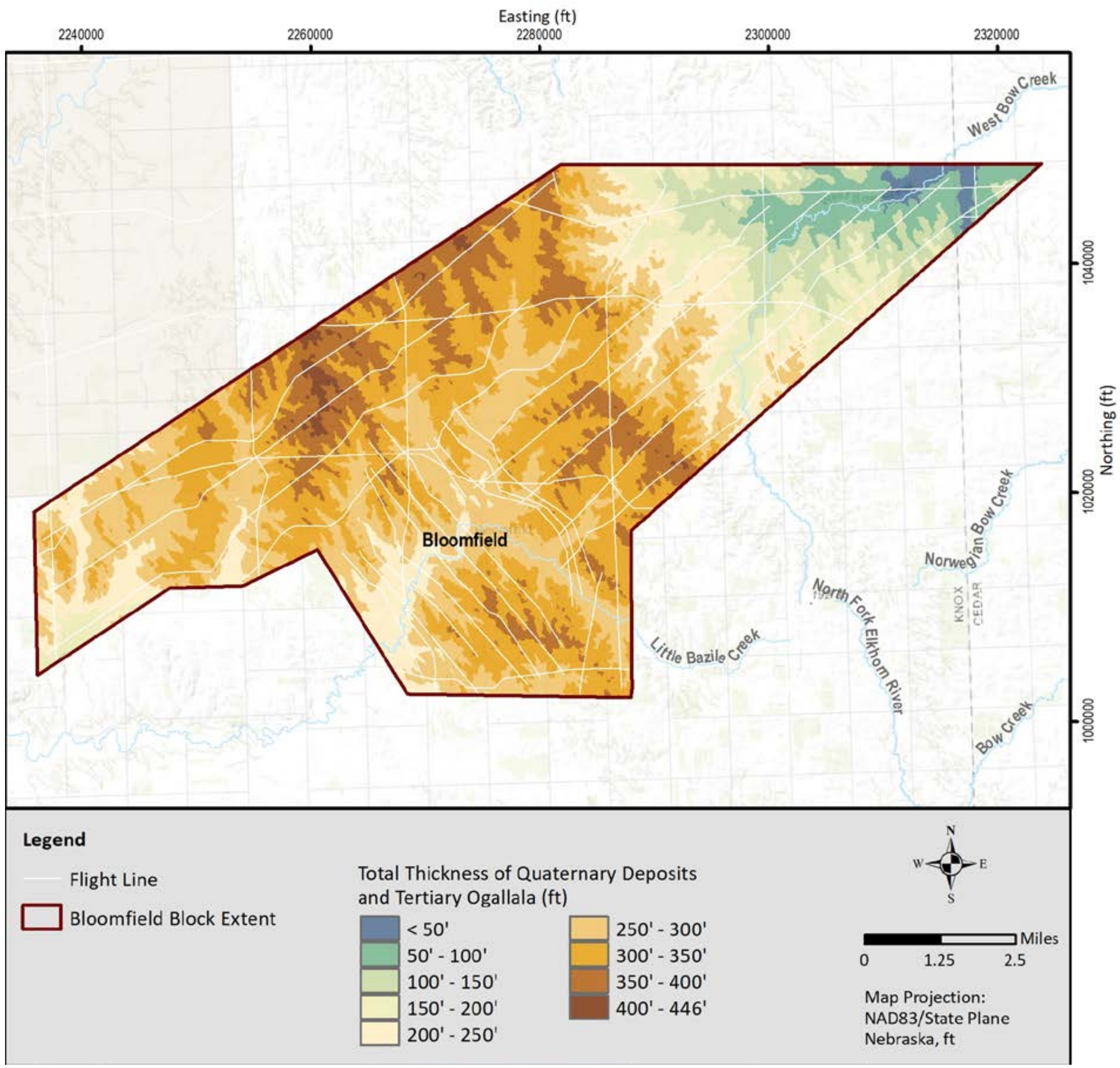


Figure 3-69. Map of the thickness (in feet) of the Quaternary (*Q*) and Tertiary Ogallala Group (*To*) deposits within the Bloomfield Block AEM survey area. The projection is NAD83 State Plane Nebraska (feet).

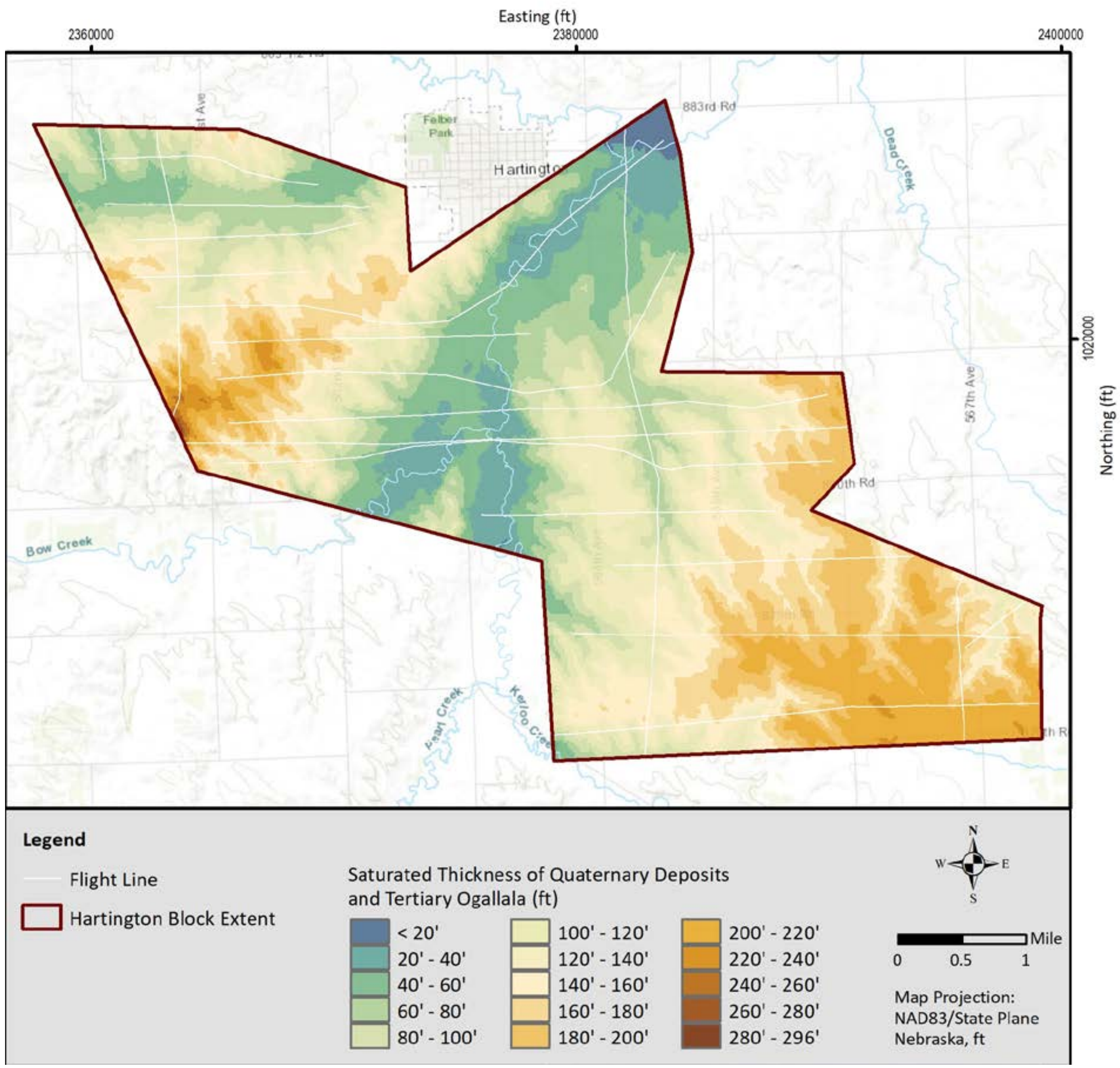


Figure 3-70. Map of the thickness (in feet) of the Quaternary (*Q*) and Tertiary Ogallala Group (*To*) deposits within the Hartington Block AEM survey area. The projection is NAD83 State Plane Nebraska (feet).

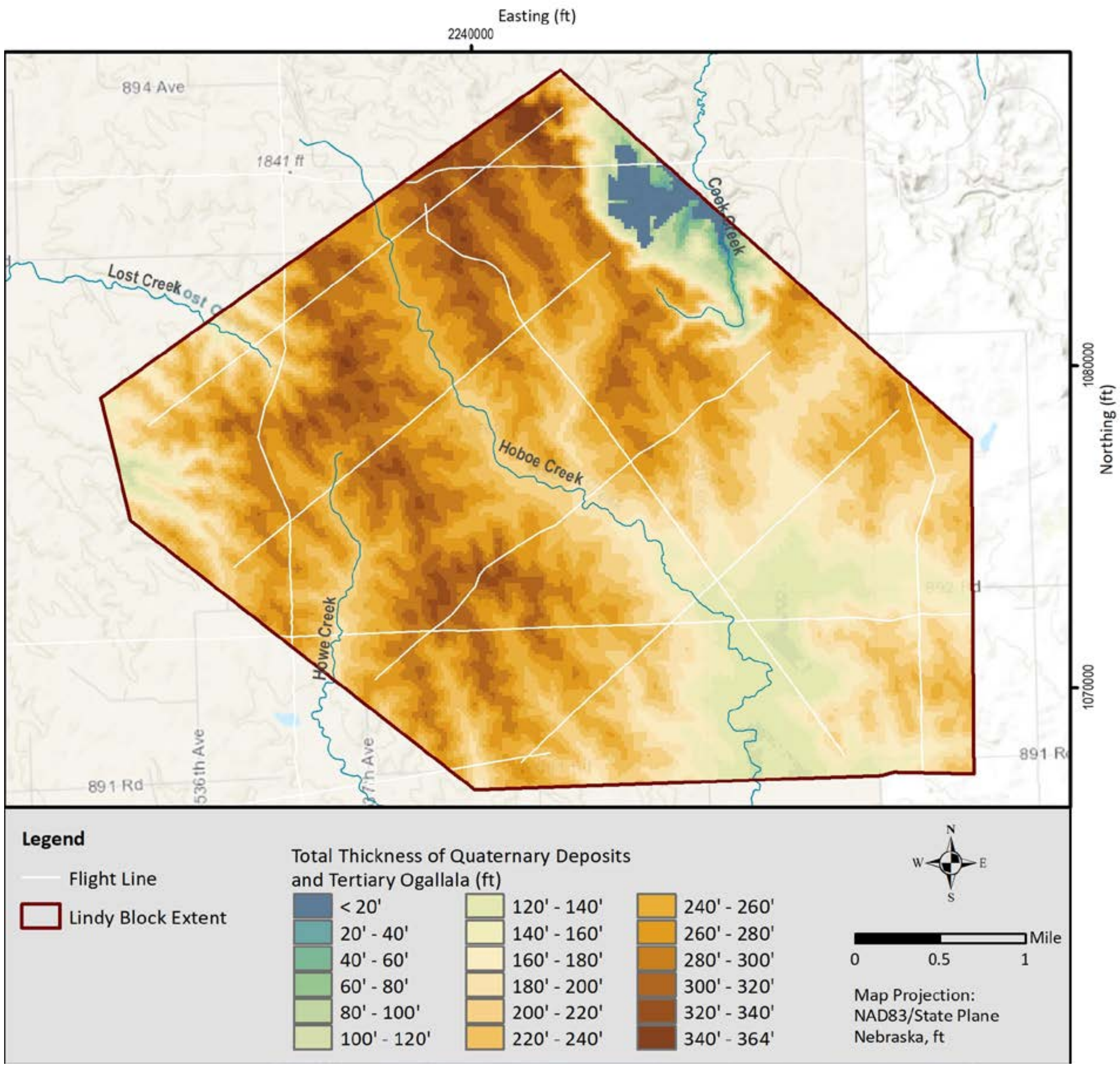


Figure 3-71. Map of the thickness (in feet) of the Quaternary (*Q*) and Tertiary Ogallala Group (*To*) deposits within the Lindy Block AEM survey area. The projection is NAD83 State Plane Nebraska (feet).

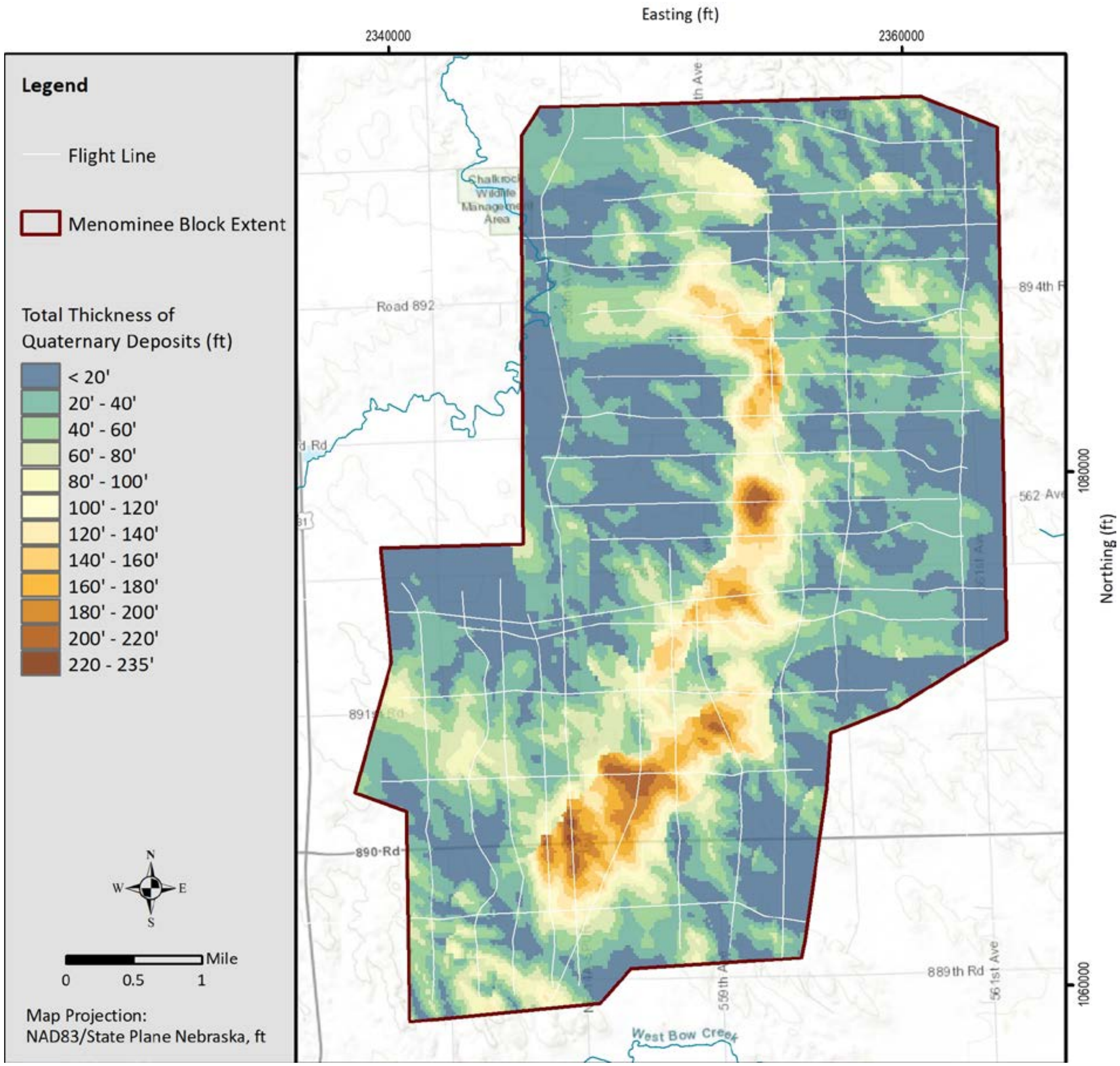


Figure 3-72. Map of the thickness (in feet) of the Quaternary (*Q*) deposits within the Menominee Block AEM survey area. The projection is NAD83 State Plane Nebraska (feet).

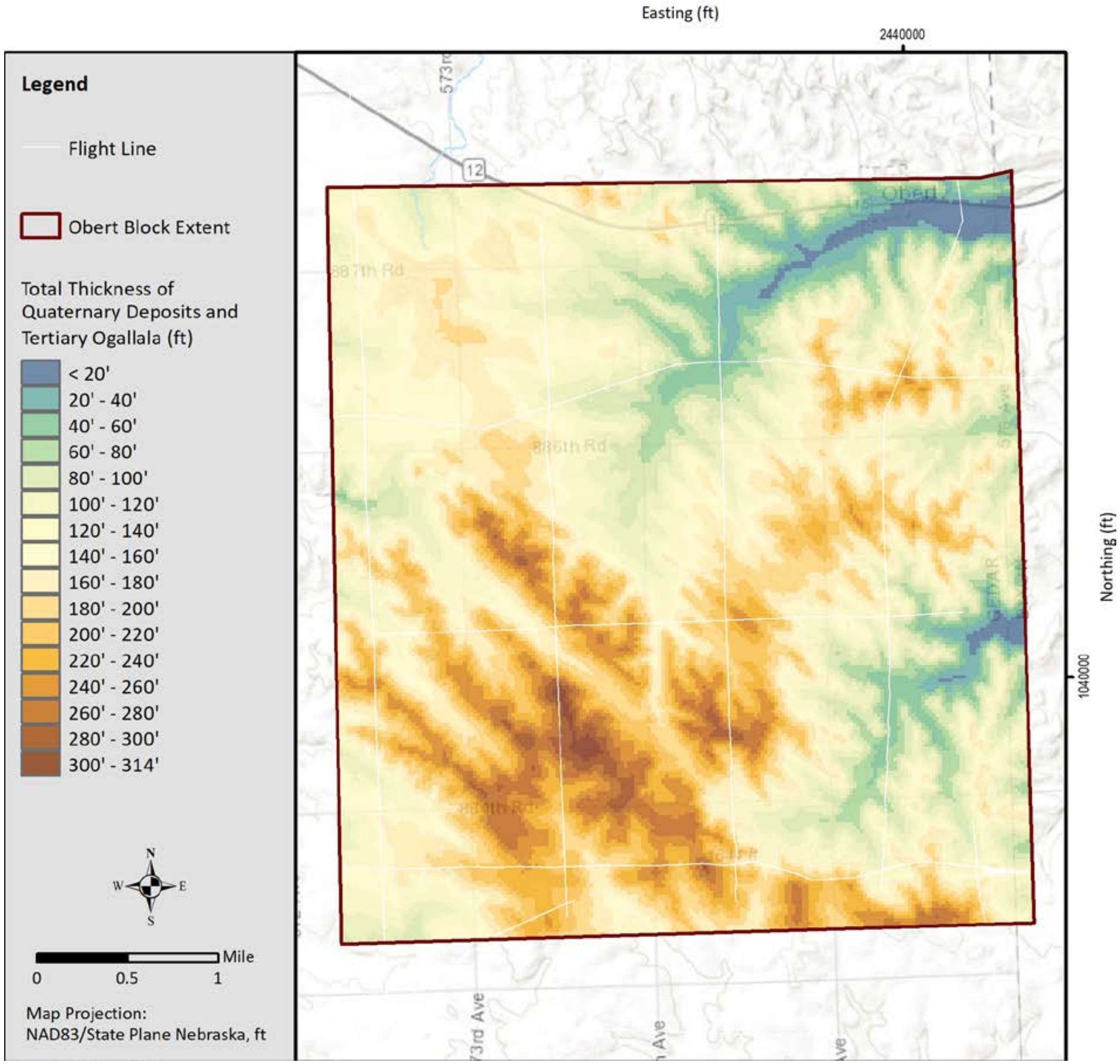


Figure 3-73. Map of the thickness (in feet) of the Quaternary (*Q*) and Tertiary Ogallala Group (*To*) deposits within the Obert Block AEM survey area. The projection is NAD83 State Plane Nebraska (feet).

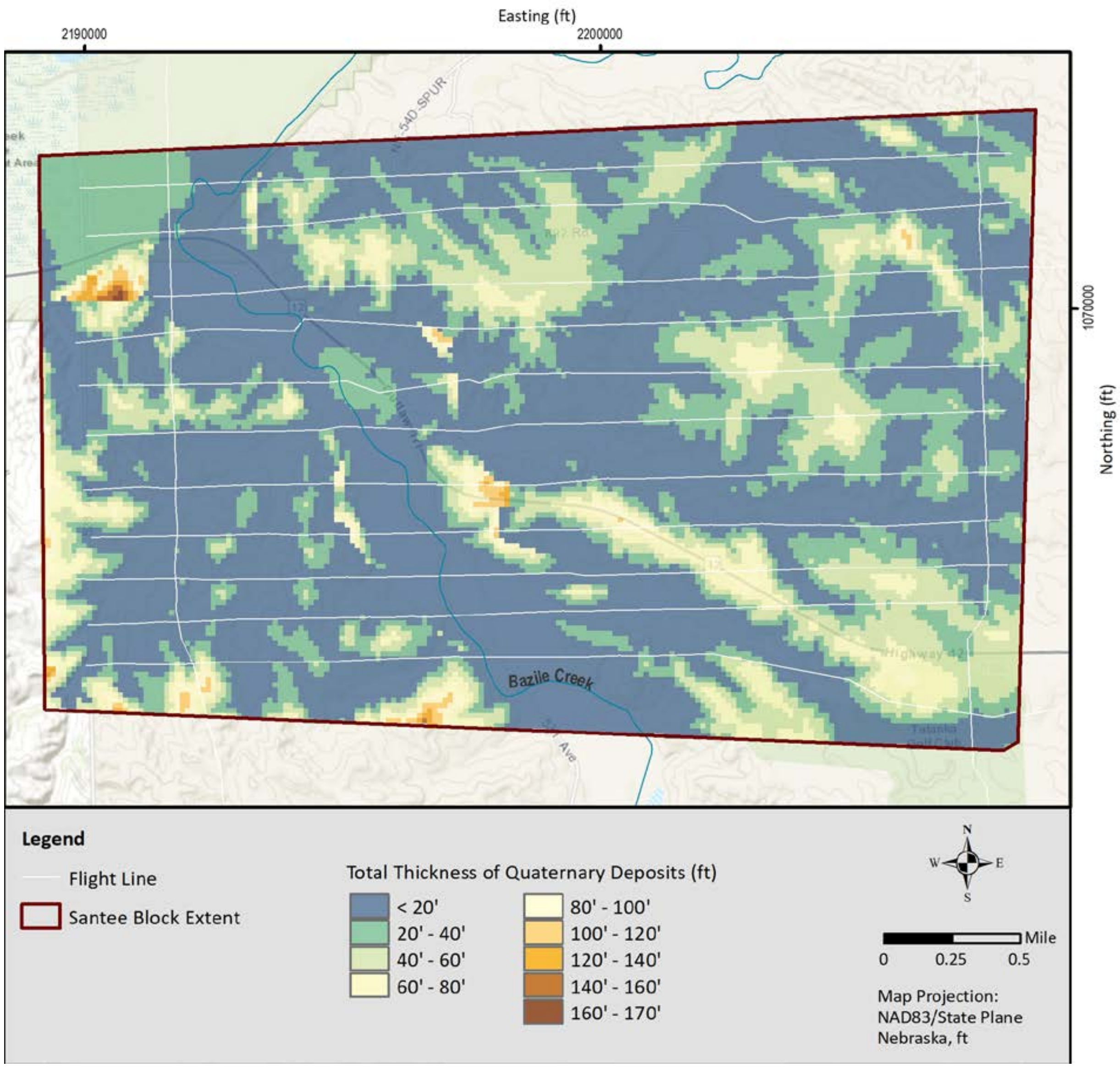


Figure 3-74. Map of the thickness (in feet) of the Quaternary (*Q*) deposits within the Santee Block AEM survey area. The projection is NAD83 State Plane Nebraska (feet).

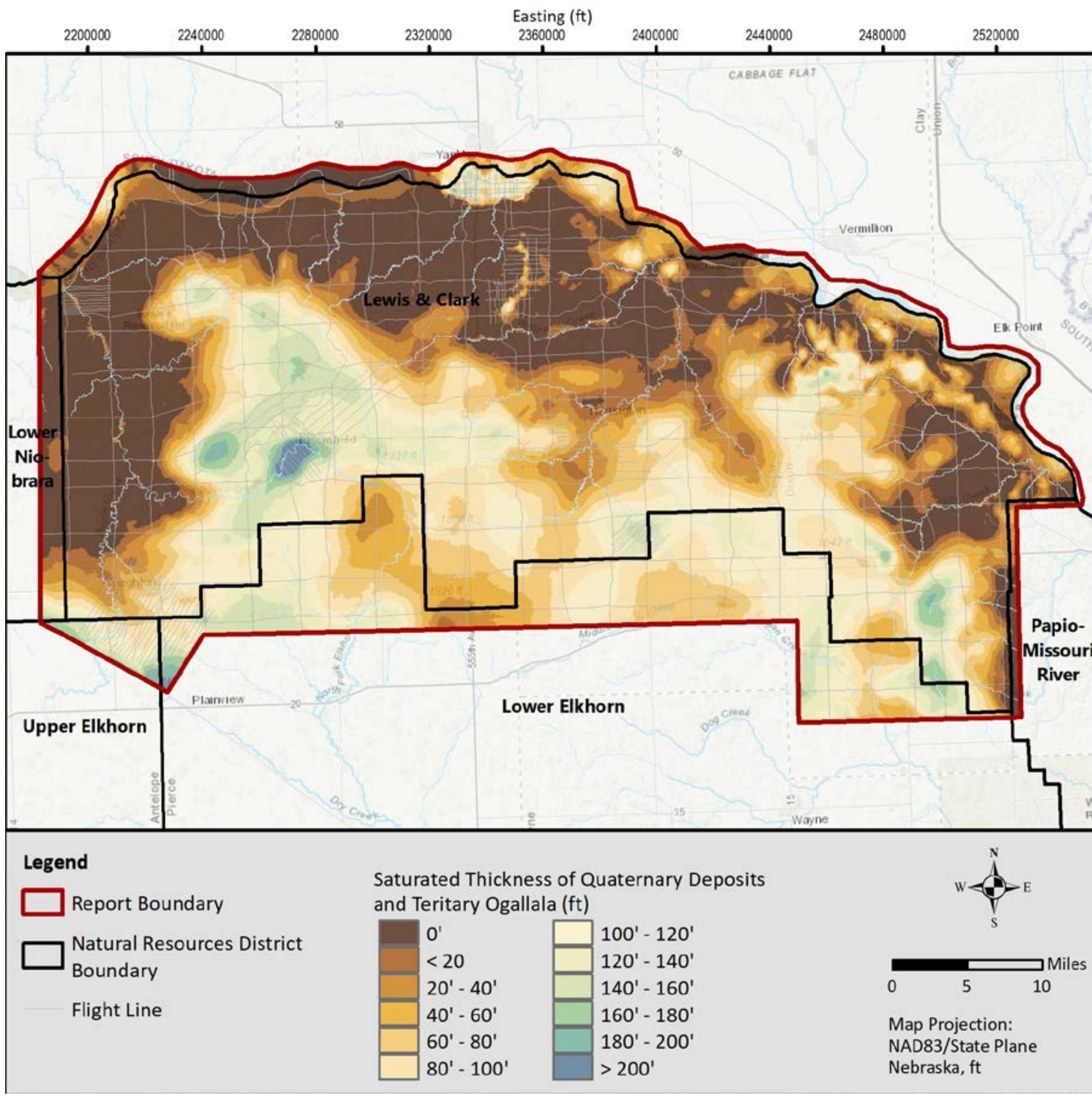


Figure 3-75. Map of the saturated thickness (in feet) of the Quaternary (*Q*) and Tertiary Ogallala Group (*To*) deposits within the LCNRD Reconnaissance AEM survey area. The projection is NAD83 State Plane Nebraska (feet).

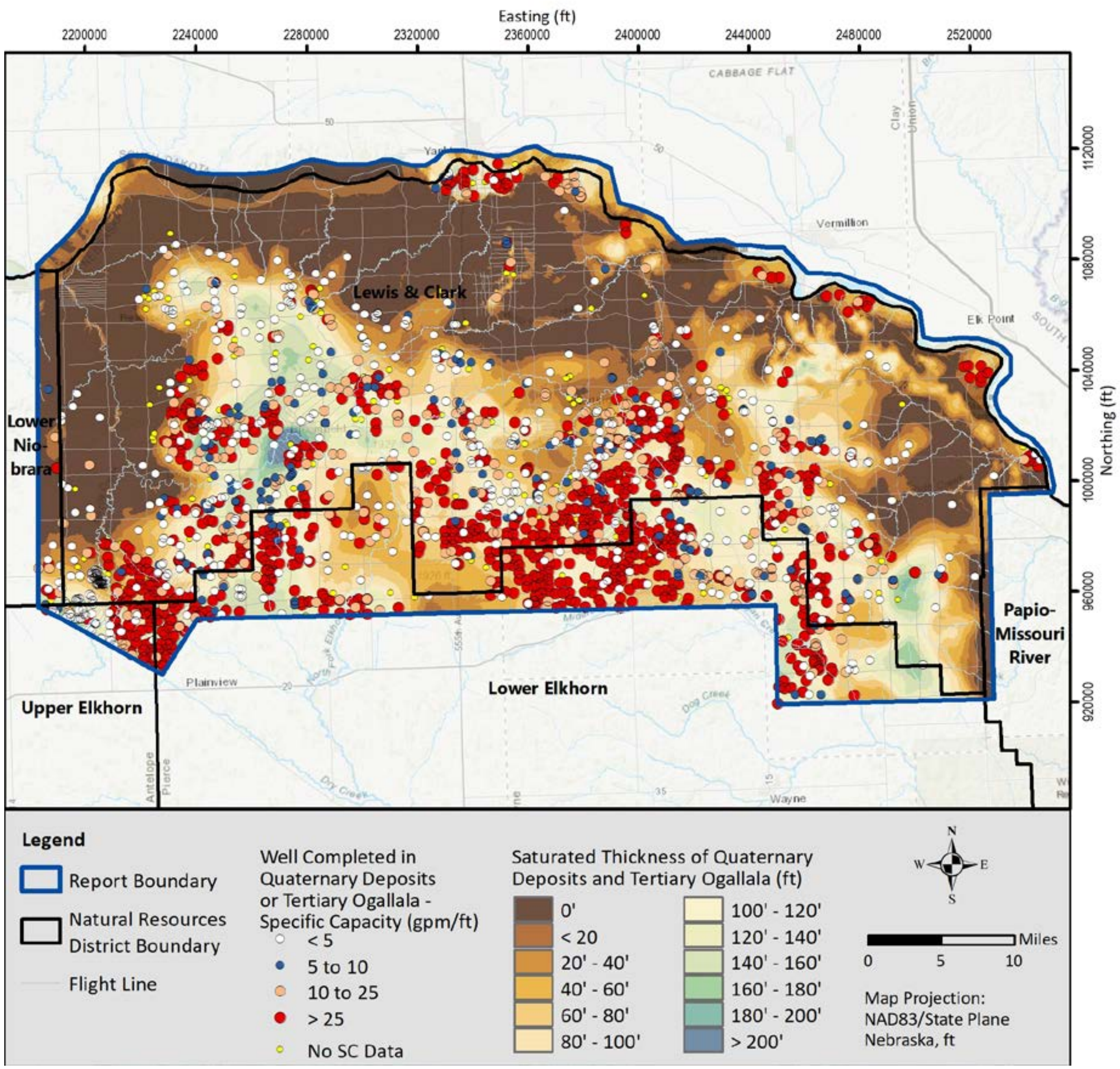


Figure 3-76. Map of the saturated thickness (in feet) of the Quaternary (*Q*) and Tertiary Ogallala Group (*To*) deposits related to the specific capacity of the wells screened within *Q* within the LCNRD Reconnaissance AEM survey area. The projection is NAD83 State Plane Nebraska (feet).

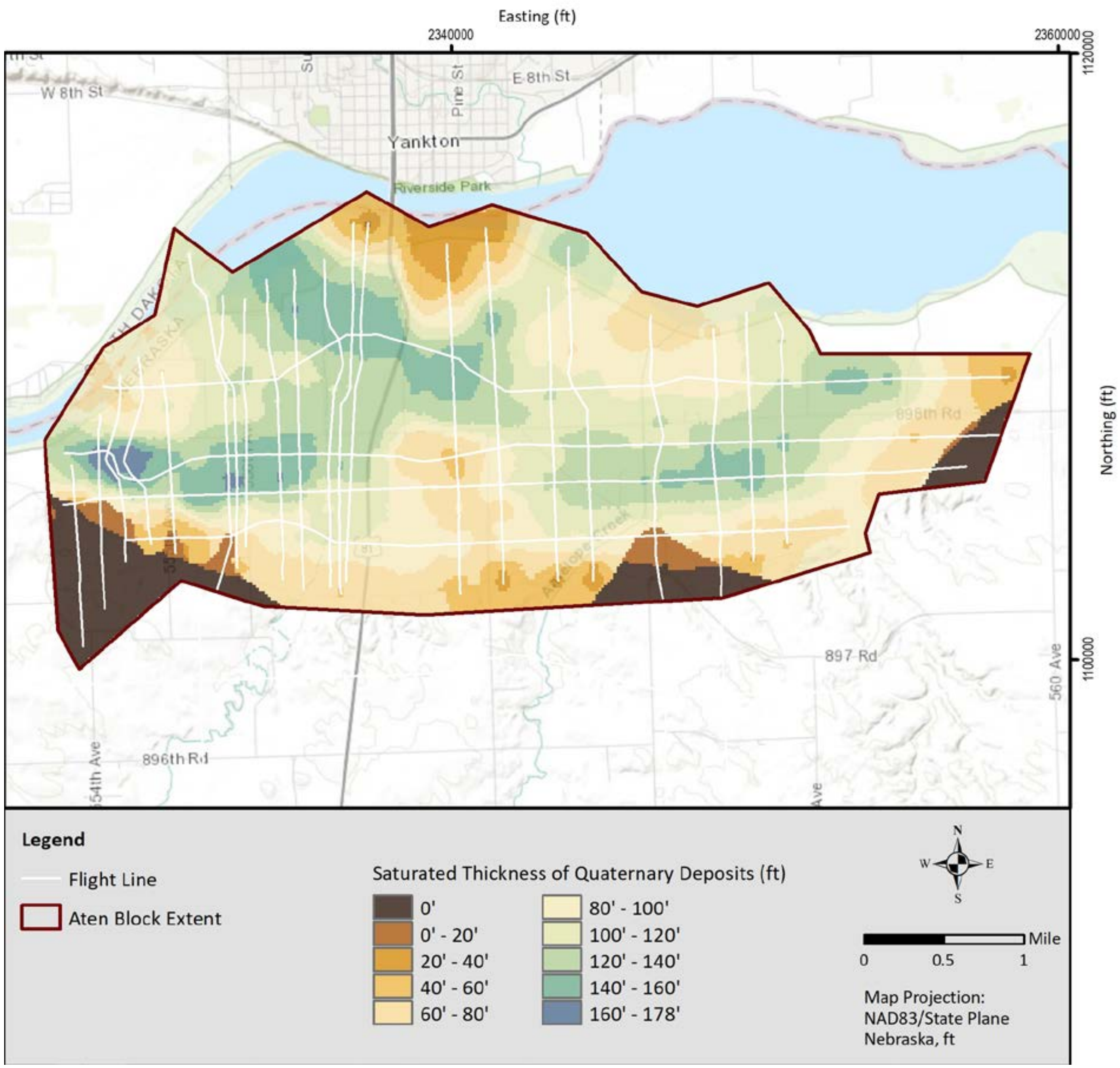


Figure 3-77. Map of the saturated thickness (in feet) of the Quaternary (*Q*) deposits within the Aten Block AEM survey area. The projection is NAD83 State Plane Nebraska (feet).

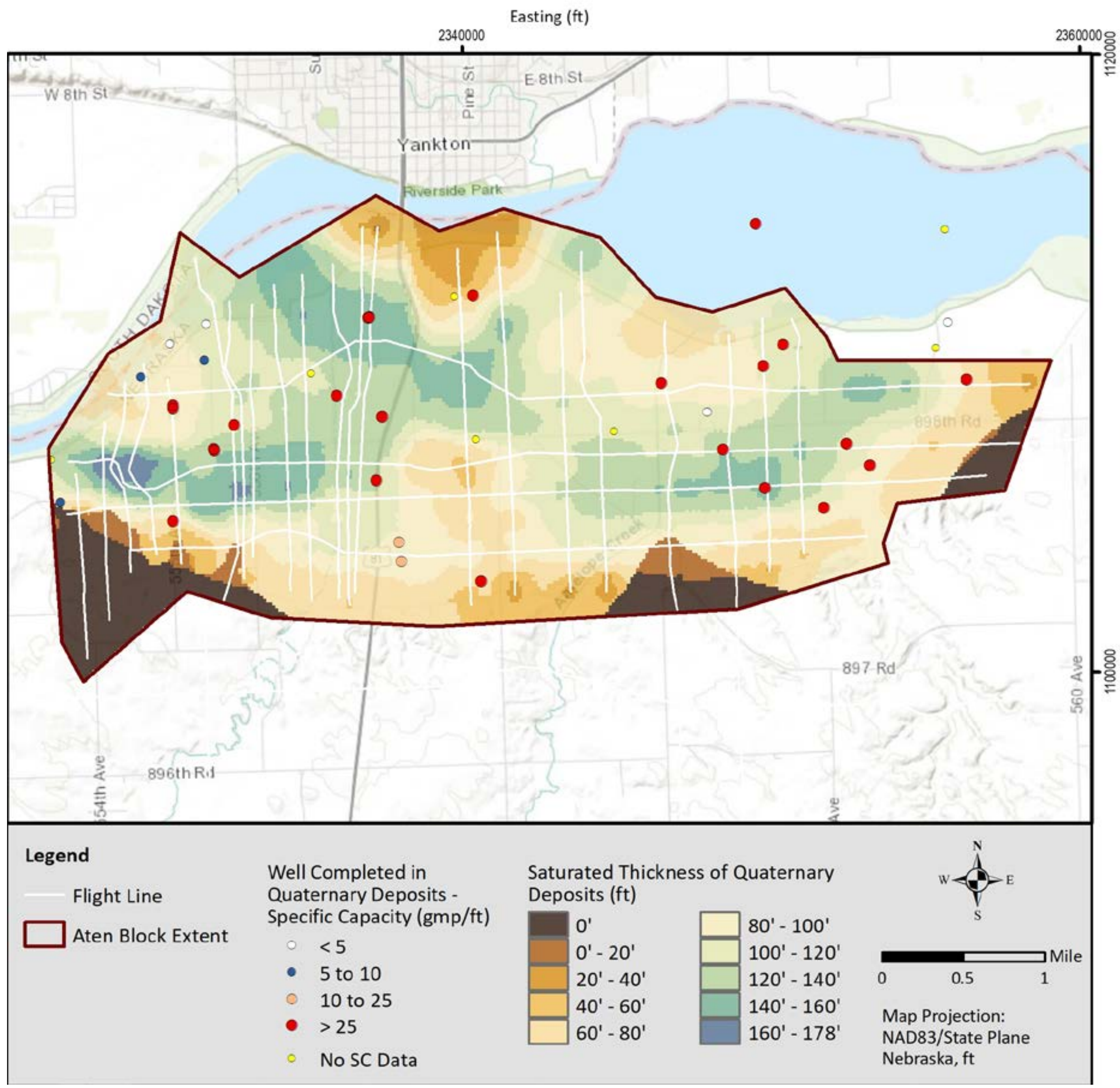


Figure 3-78. Map of the saturated thickness (in feet) of the Quaternary (*Q*) deposits related to the specific capacity of the wells screened within *Q* within the Aten Block AEM survey area. The projection is NAD83 State Plane Nebraska (feet).

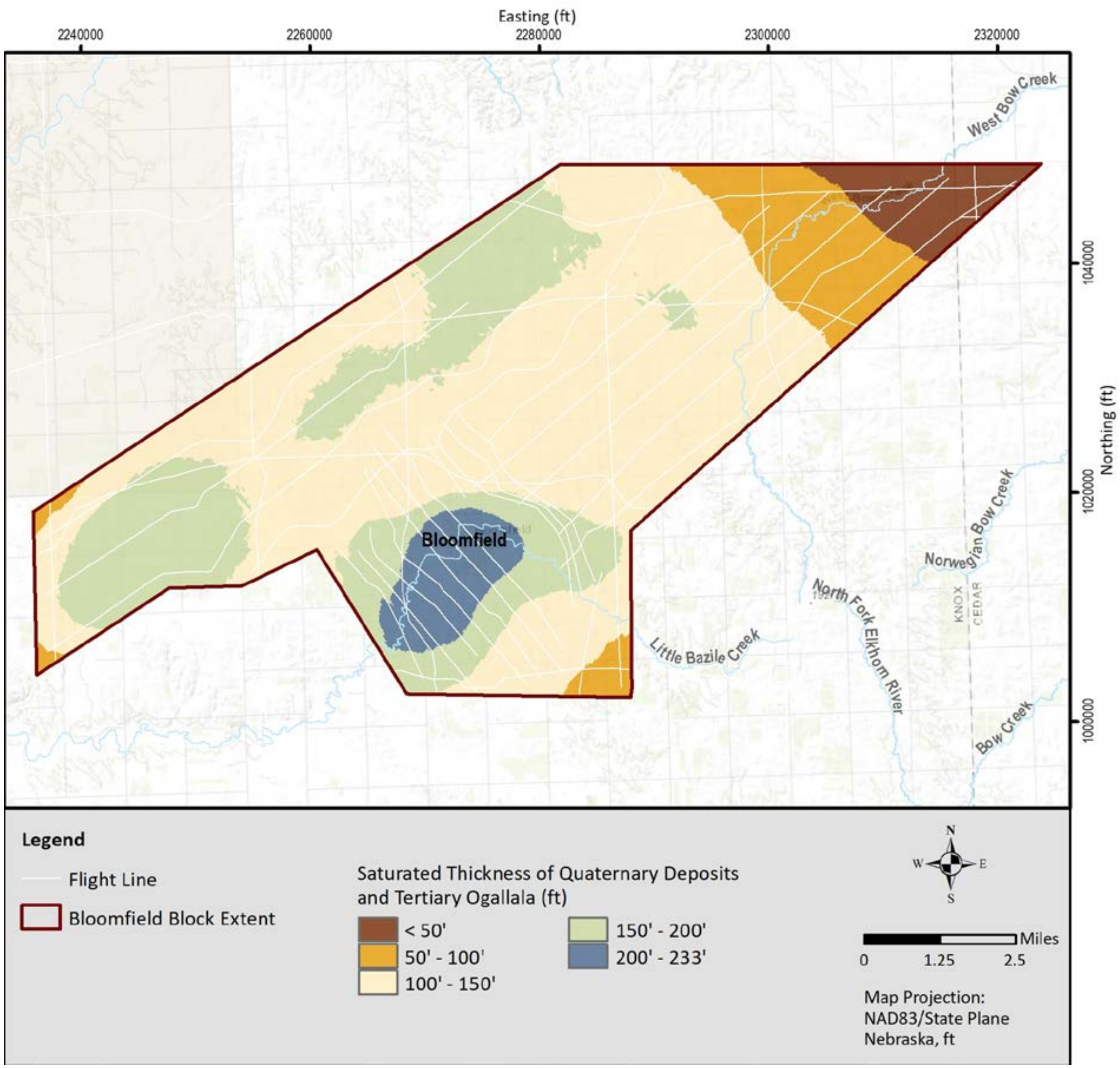


Figure 3-79. Map of the saturated thickness (in feet) of the Quaternary (*Q*) and Tertiary Ogallala Group (*To*) deposits within the Bloomfield Block AEM survey area. The projection is NAD83 State Plane Nebraska (feet).

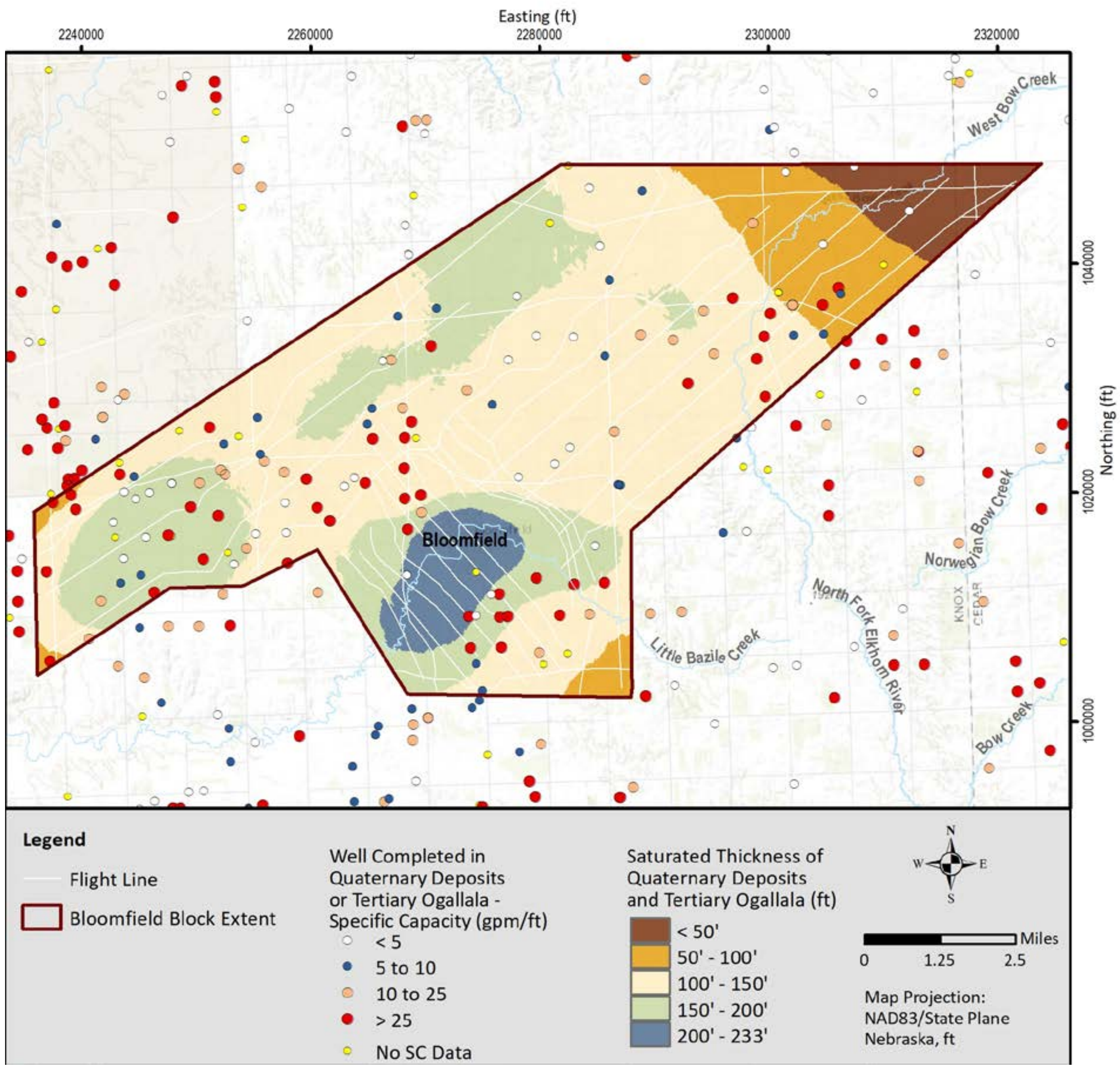


Figure 3-80. Map of the saturated thickness (in feet) of the Quaternary (*Q*) and Tertiary Ogallala Group (*To*) deposits related to the specific capacity of the wells screened within *Q* within the Bloomfield Block AEM survey area. The projection is NAD83 State Plane Nebraska (feet).

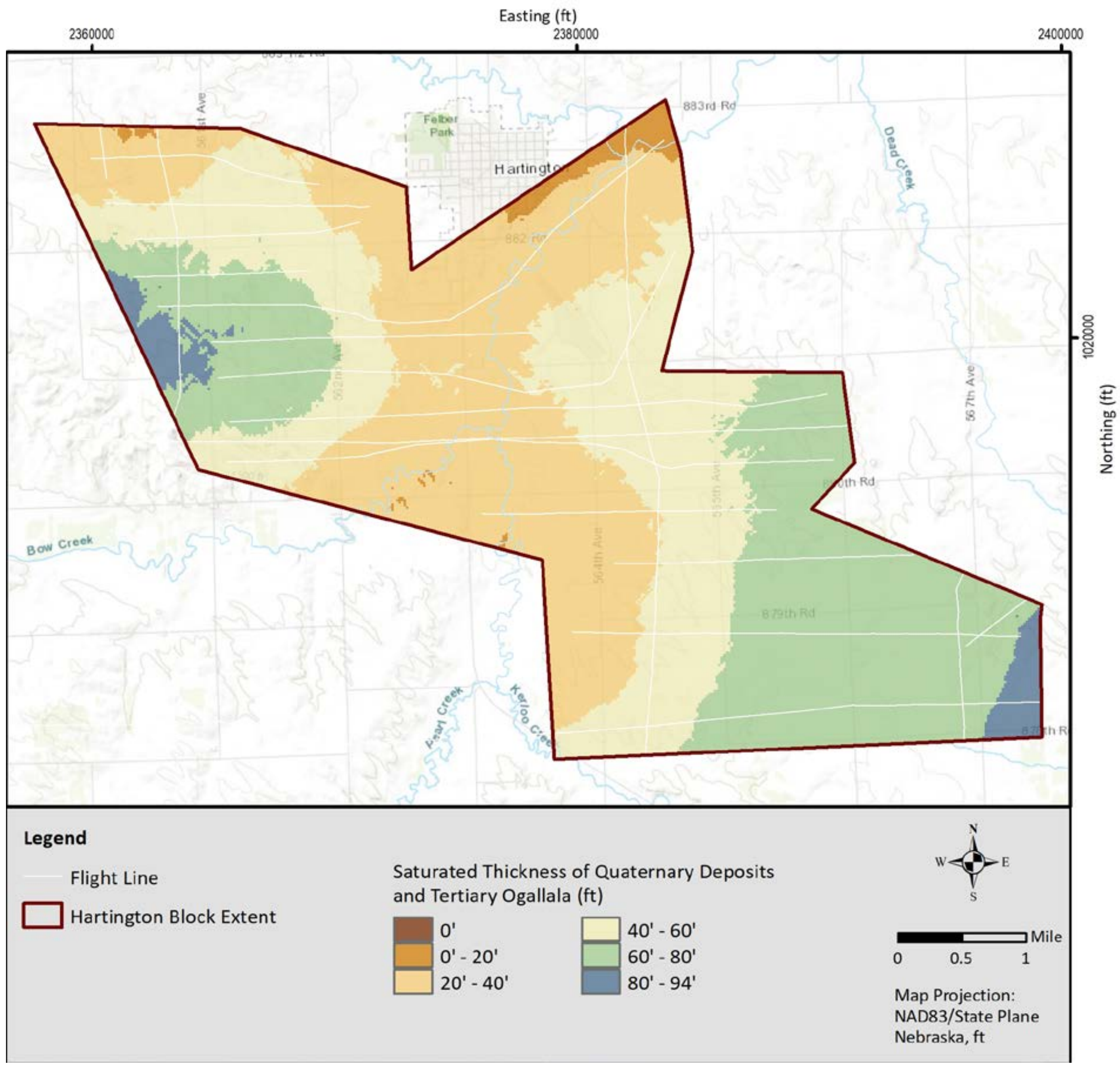


Figure 3-81. Map of the saturated thickness (in feet) of the Quaternary (*Q*) and Tertiary Ogallala Group (*To*) deposits within the Hartington Block AEM survey area. The projection is NAD83 State Plane Nebraska (feet).

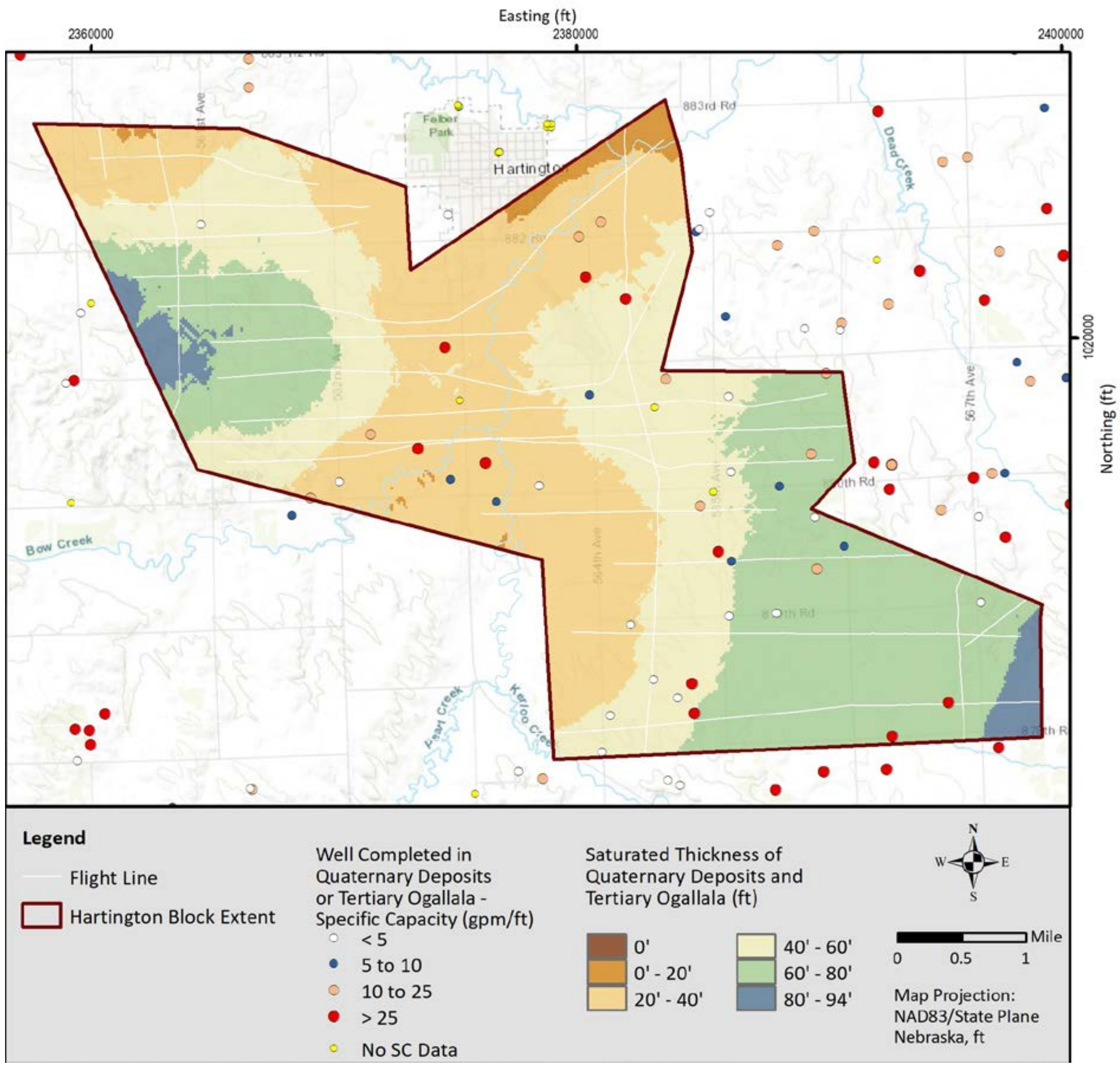


Figure 3-82. Map of the saturated thickness (in feet) of the Quaternary (*Q*) and Tertiary Ogallala Group (*To*) deposits related to the specific capacity of the wells screened within *Q* within the Hartington Block AEM survey area. The projection is NAD83 State Plane Nebraska (feet).

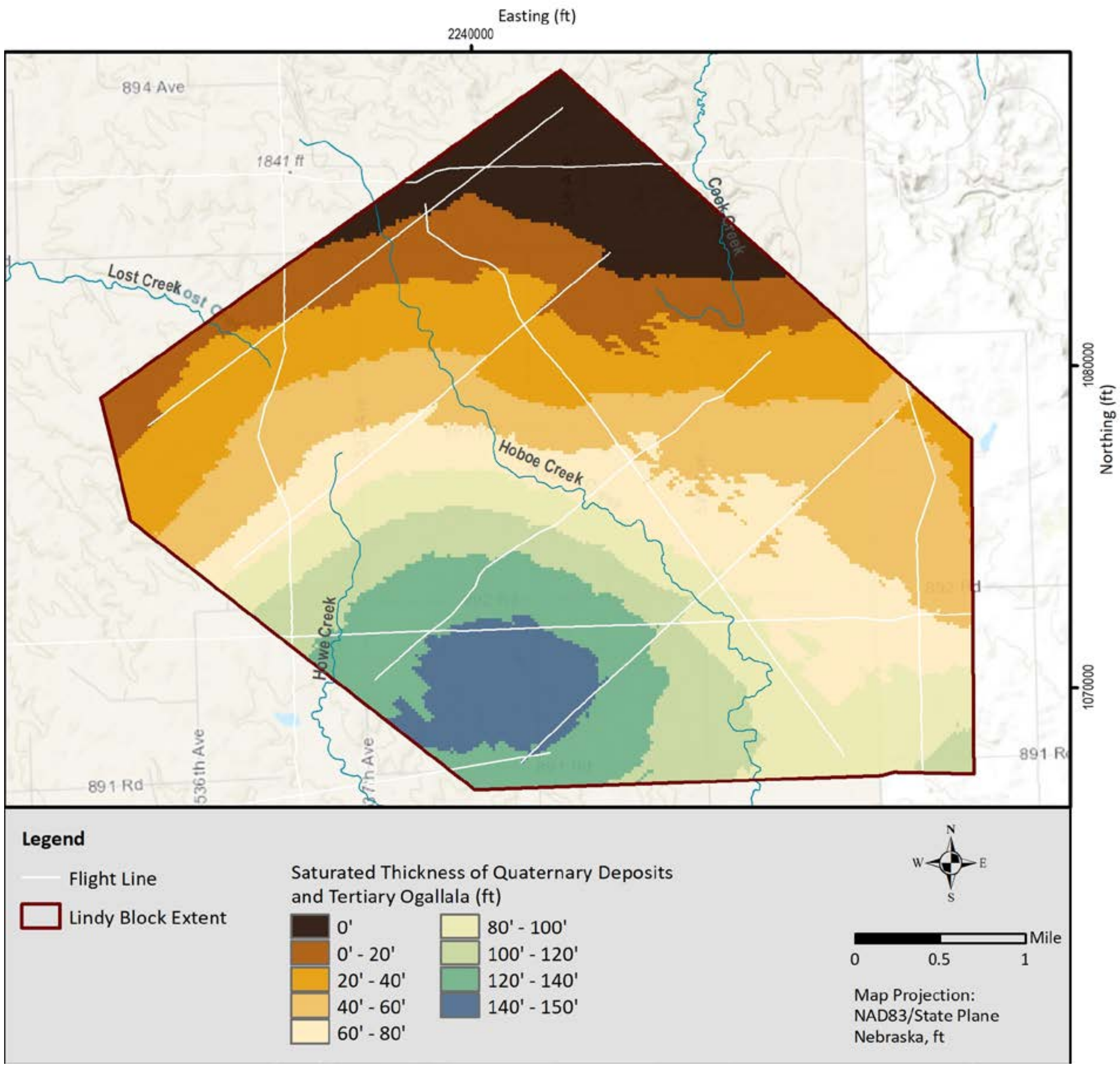


Figure 3-83. Map of the saturated thickness (in feet) of the Quaternary (*Q*) and Tertiary Ogallala Group (*To*) deposits within the Lindy Block AEM survey area. The projection is NAD83 State Plane Nebraska (feet).

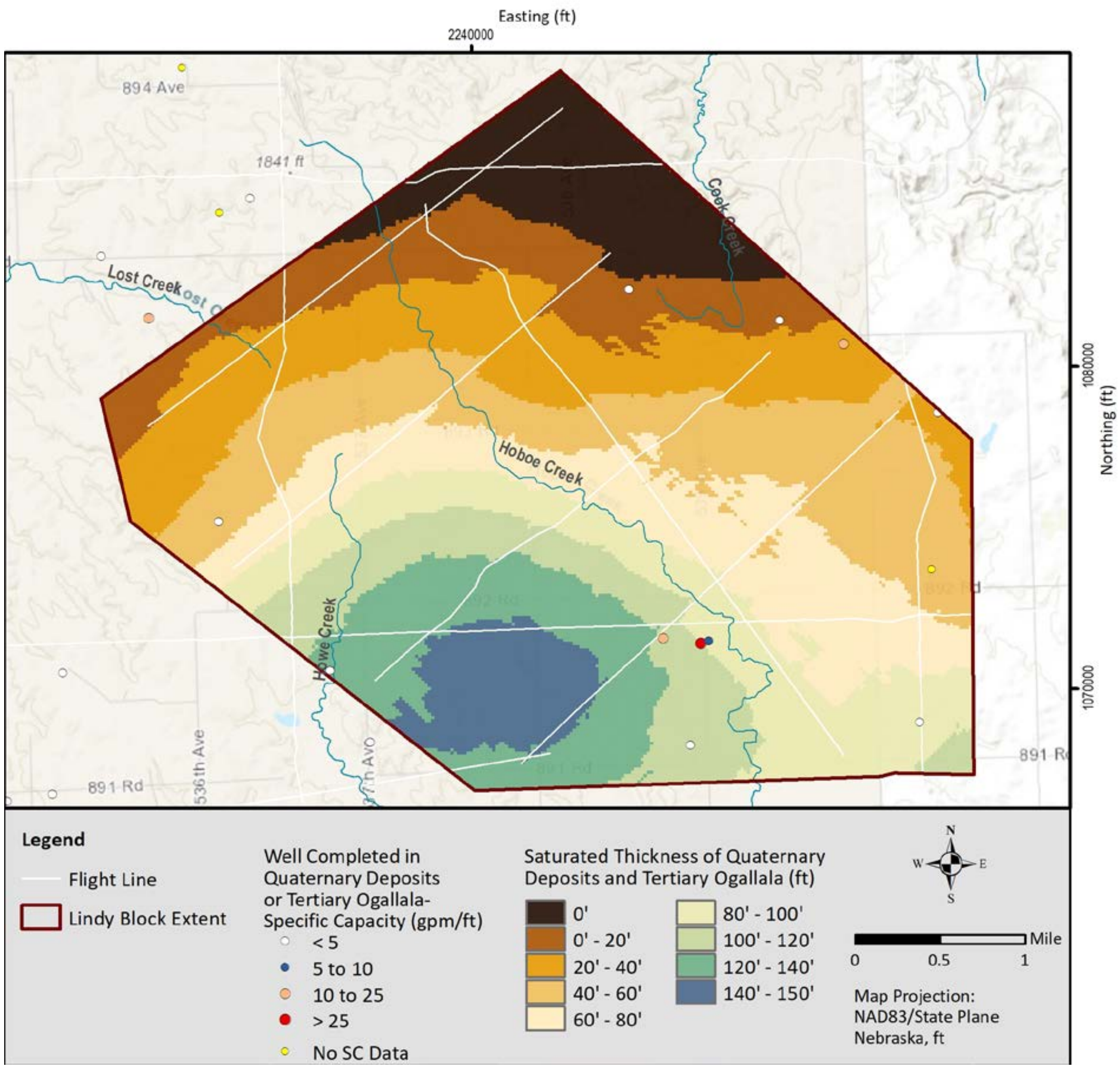


Figure 3-84. Map of the saturated thickness (in feet) of the Quaternary (*Q*) and Tertiary Ogallala Group (*To*) deposits related to the specific capacity of the wells screened within *Q* within the Lindy Block AEM survey area. The projection is NAD83 State Plane Nebraska (feet).

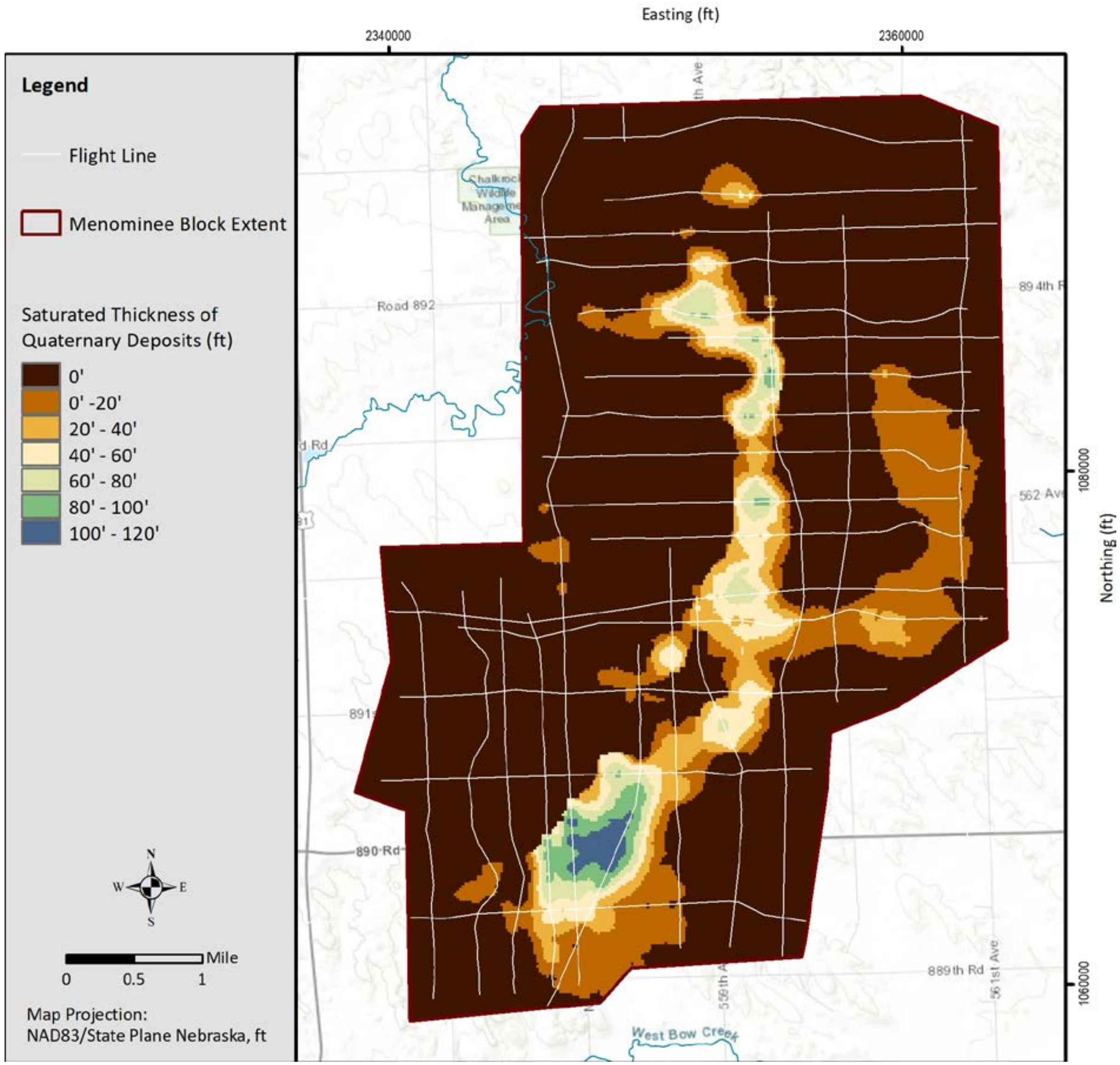


Figure 3-85. Map of the saturated thickness (in feet) of the Quaternary (*Q*) deposits within the Menominee Block AEM survey area. The projection is NAD83 State Plane Nebraska (feet).

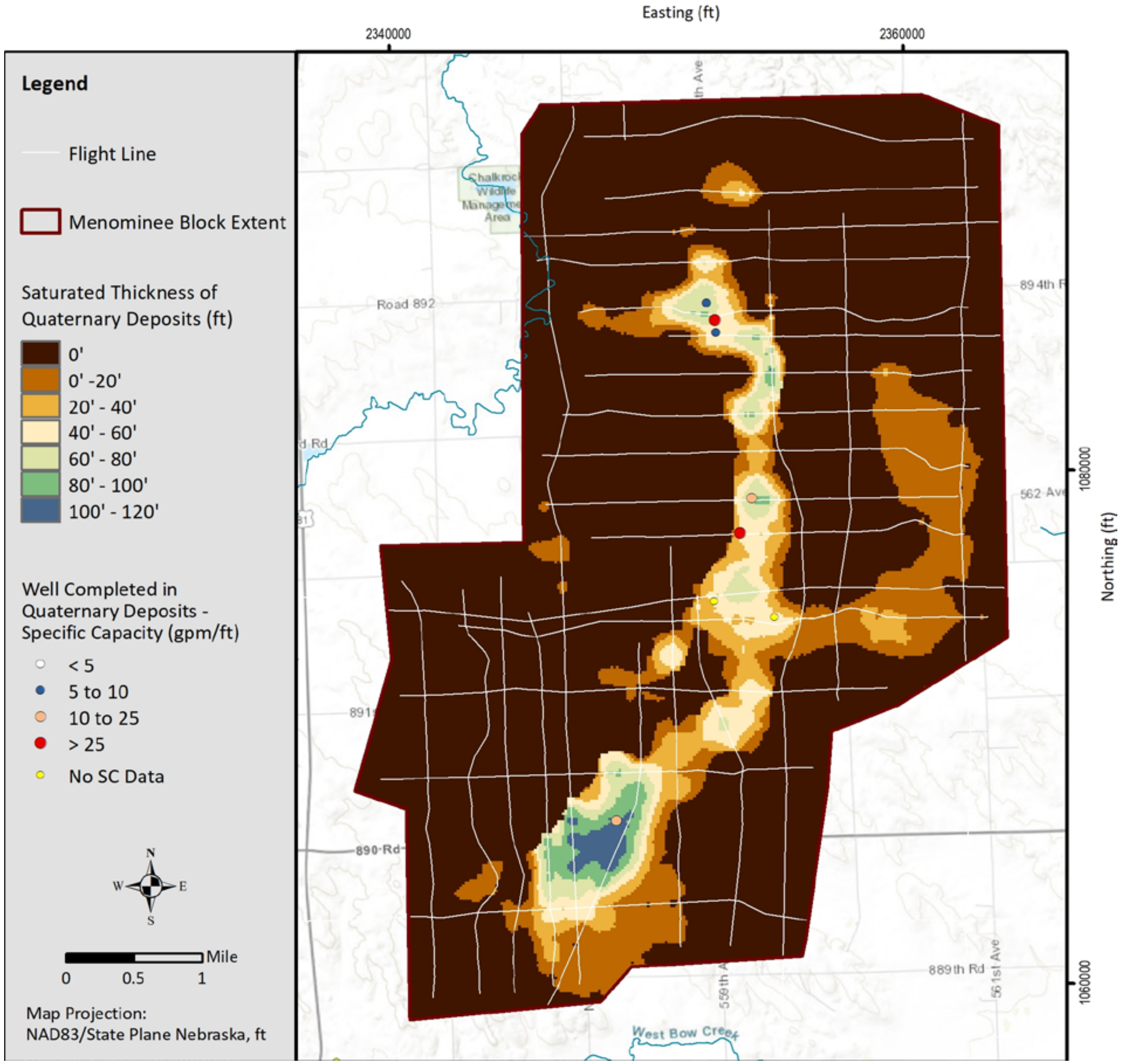


Figure 3-86. Map of the saturated thickness (in feet) of the Quaternary (*Q*) deposits related to the specific capacity of the wells screened within *Q* within the Menominee Block AEM survey area. The projection is NAD83 State Plane Nebraska (feet).

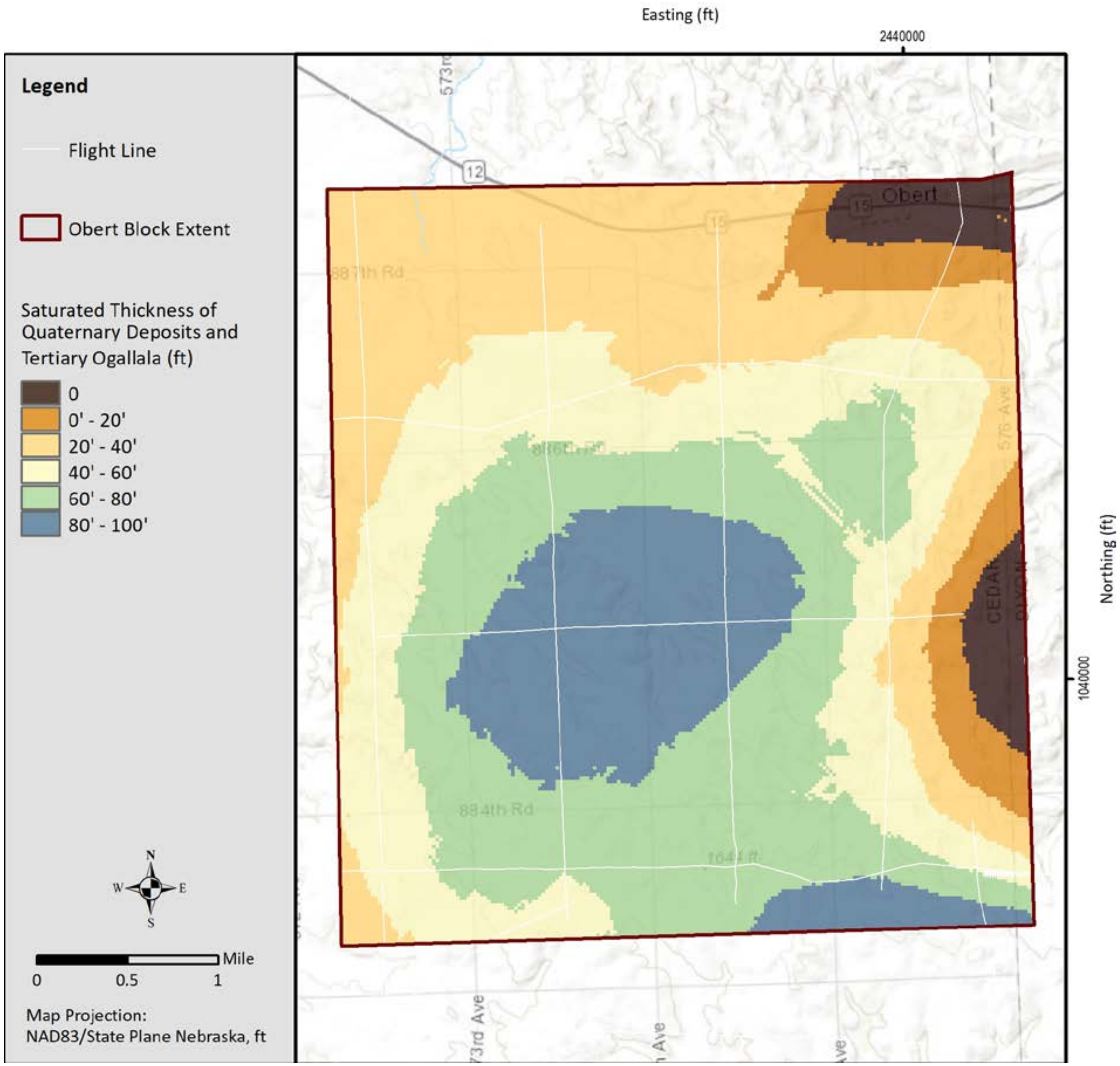


Figure 3-87. Map of the saturated thickness (in feet) of the Quaternary (*Q*) and Tertiary Ogallala Group (*To*) deposits within the Obert Block AEM survey area. The projection is NAD83 State Plane Nebraska (feet).

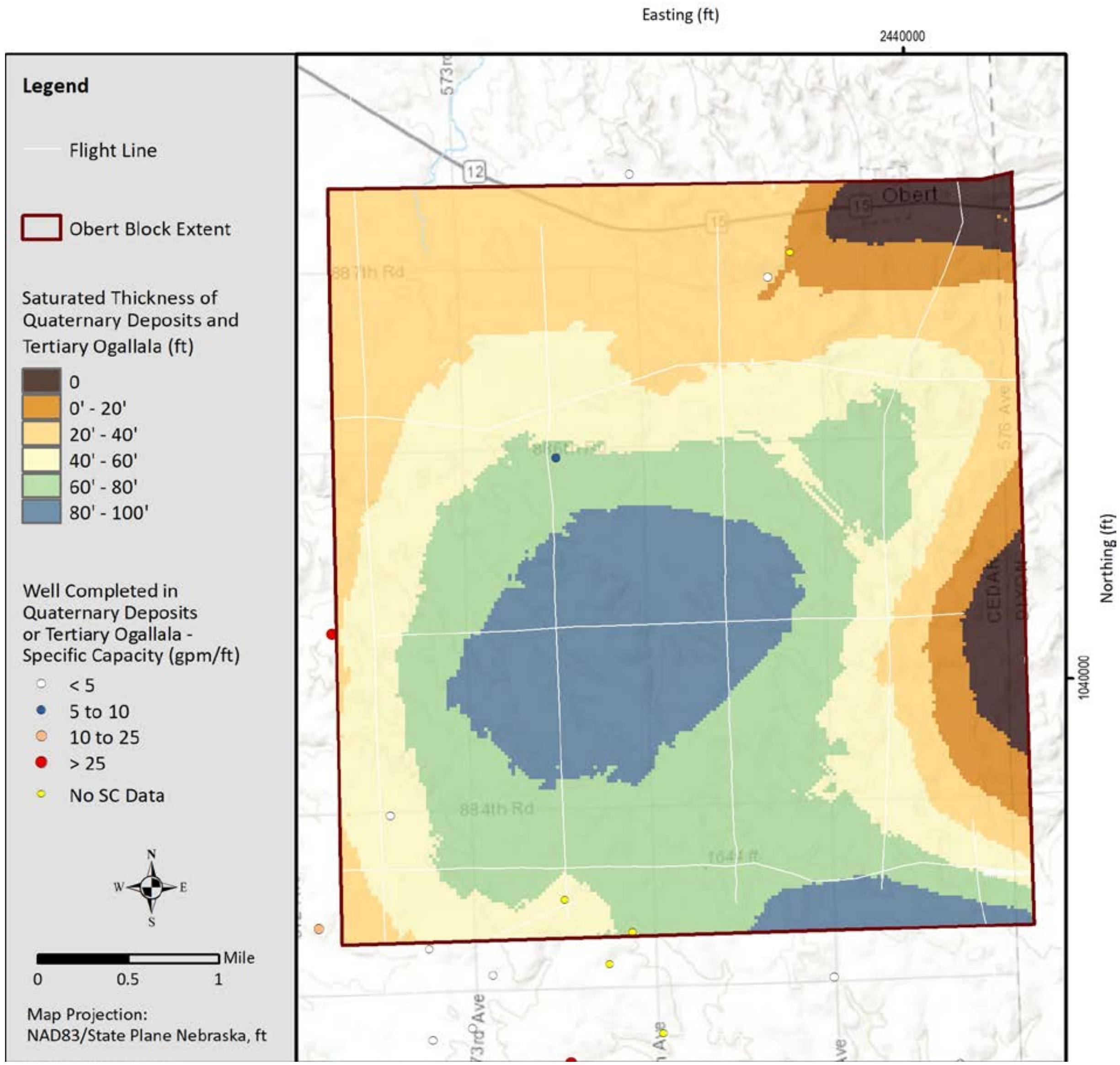


Figure 3-88. Map of the saturated thickness (in feet) of the Quaternary (*Q*) and Tertiary Ogallala Group (*To*) deposits related to the specific capacity of the wells screened within *Q* within the Obert Block AEM survey area. The projection is NAD83 State Plane Nebraska (feet).

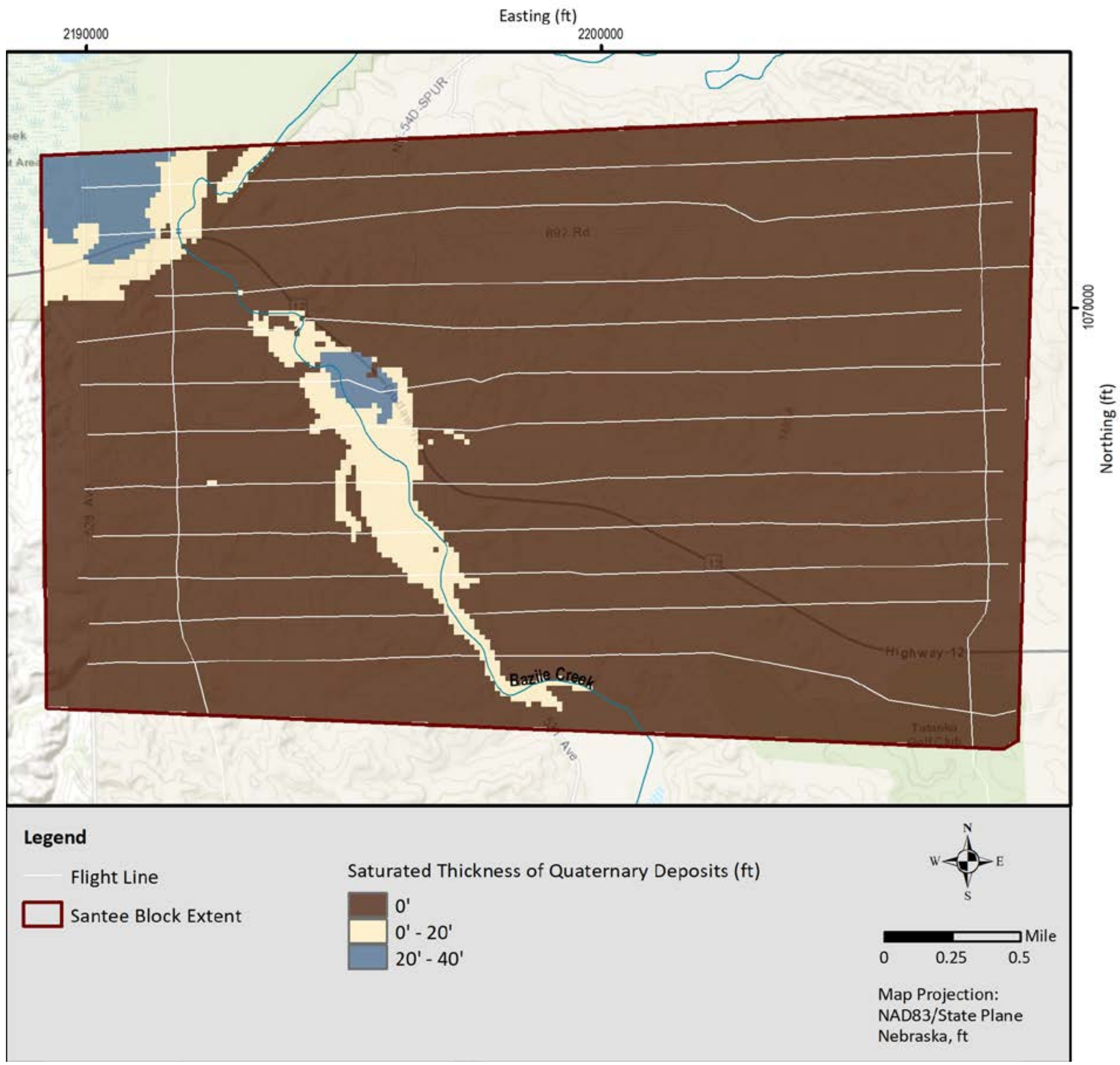


Figure 3-89. Map of the saturated thickness (in feet) of the Quaternary (*Q*) deposits within the Santee Block AEM survey area. The projection is NAD83 State Plane Nebraska (feet).

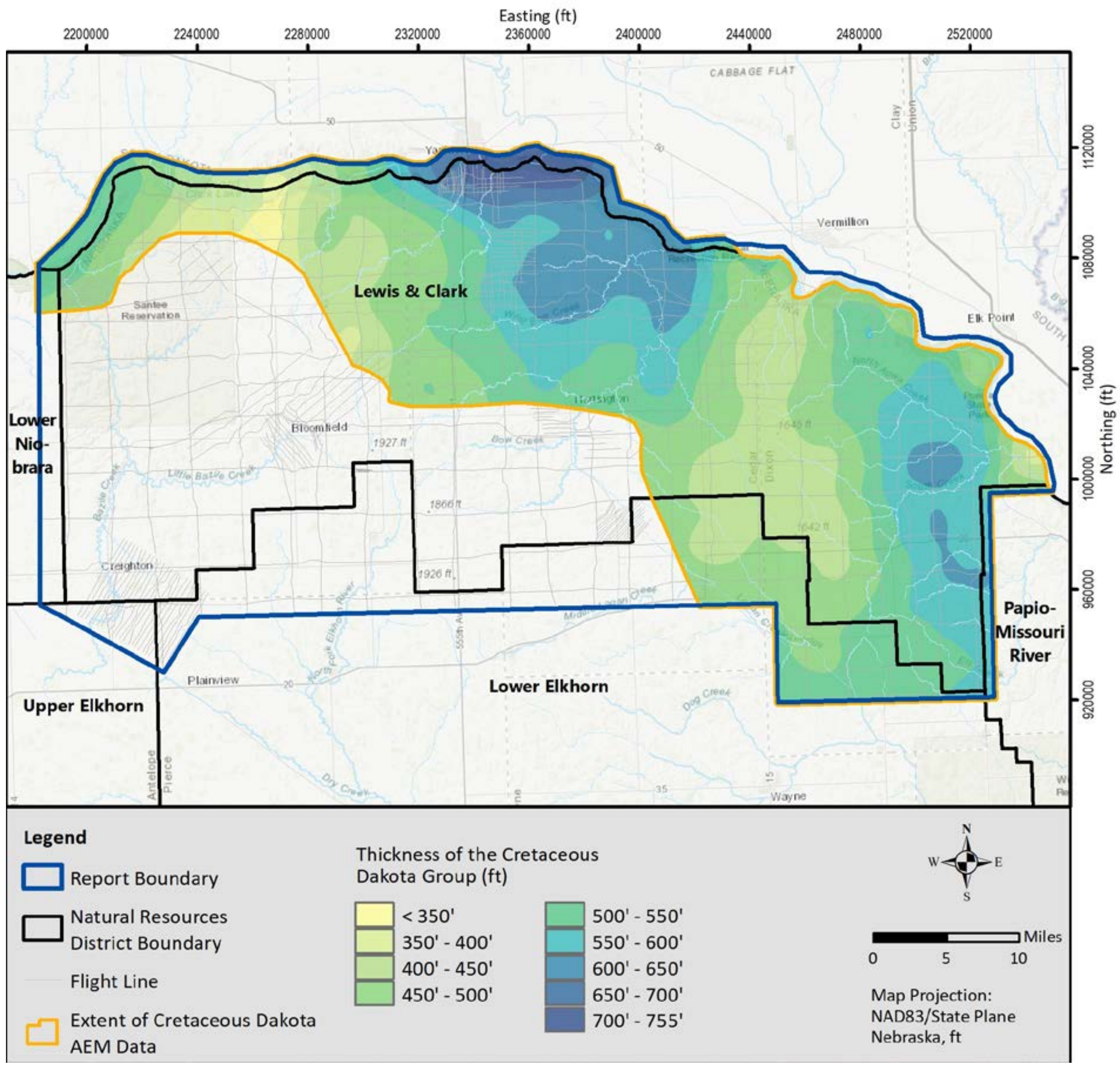


Figure 3-90. Map of the thickness (in feet) of the Cretaceous Dakota Group (*Kd*) within the LCNRD Reconnaissance AEM survey area. The projection is NAD83 State Plane Nebraska (feet).

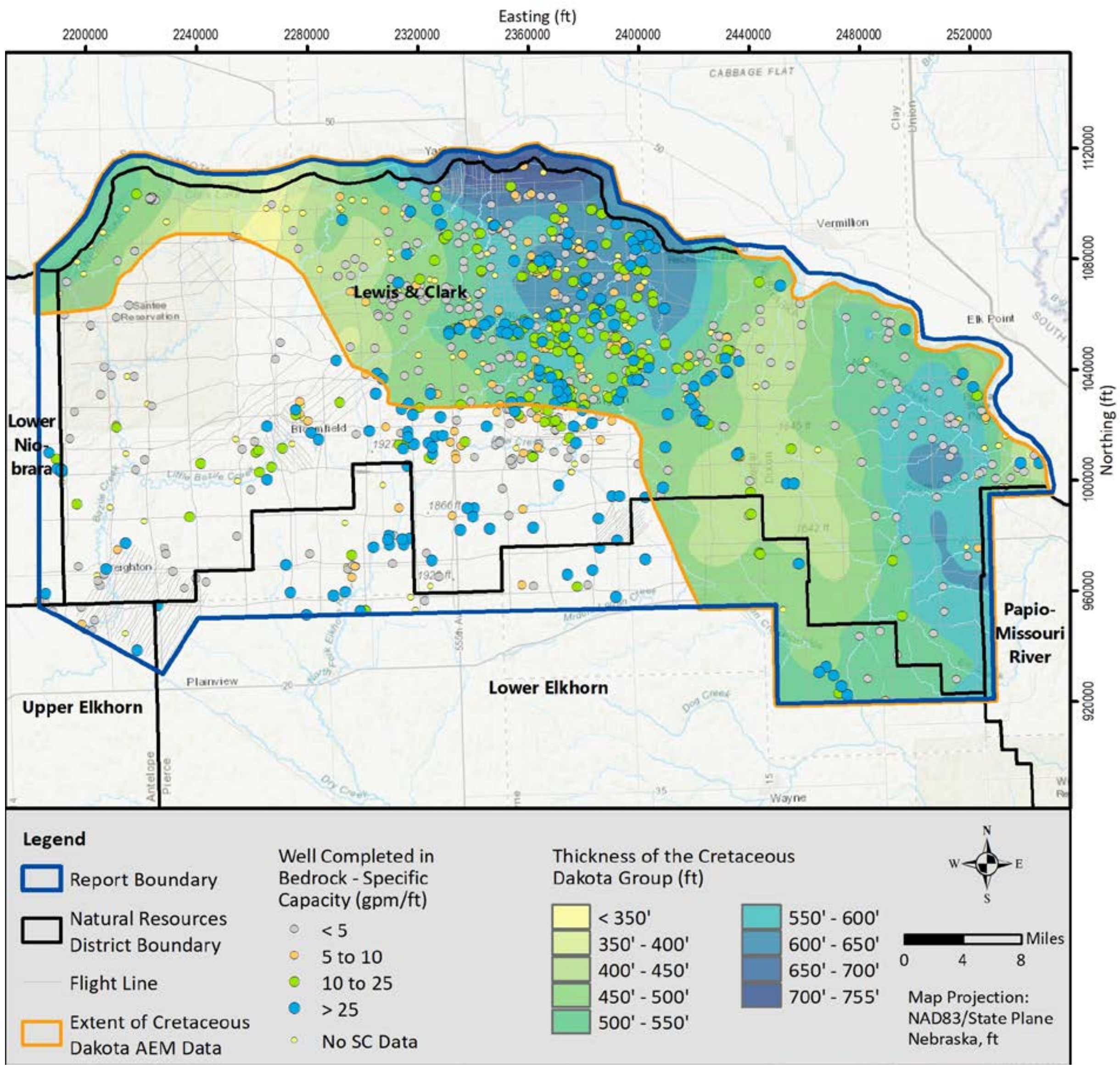


Figure 3-91. Map of the thickness (in feet) of the Cretaceous Dakota Group (*Kd*) related to the specific capacity of the wells screened within *Kd* within the LCNRD Reconnaissance AEM survey area. The projection is NAD83 State Plane Nebraska (feet).

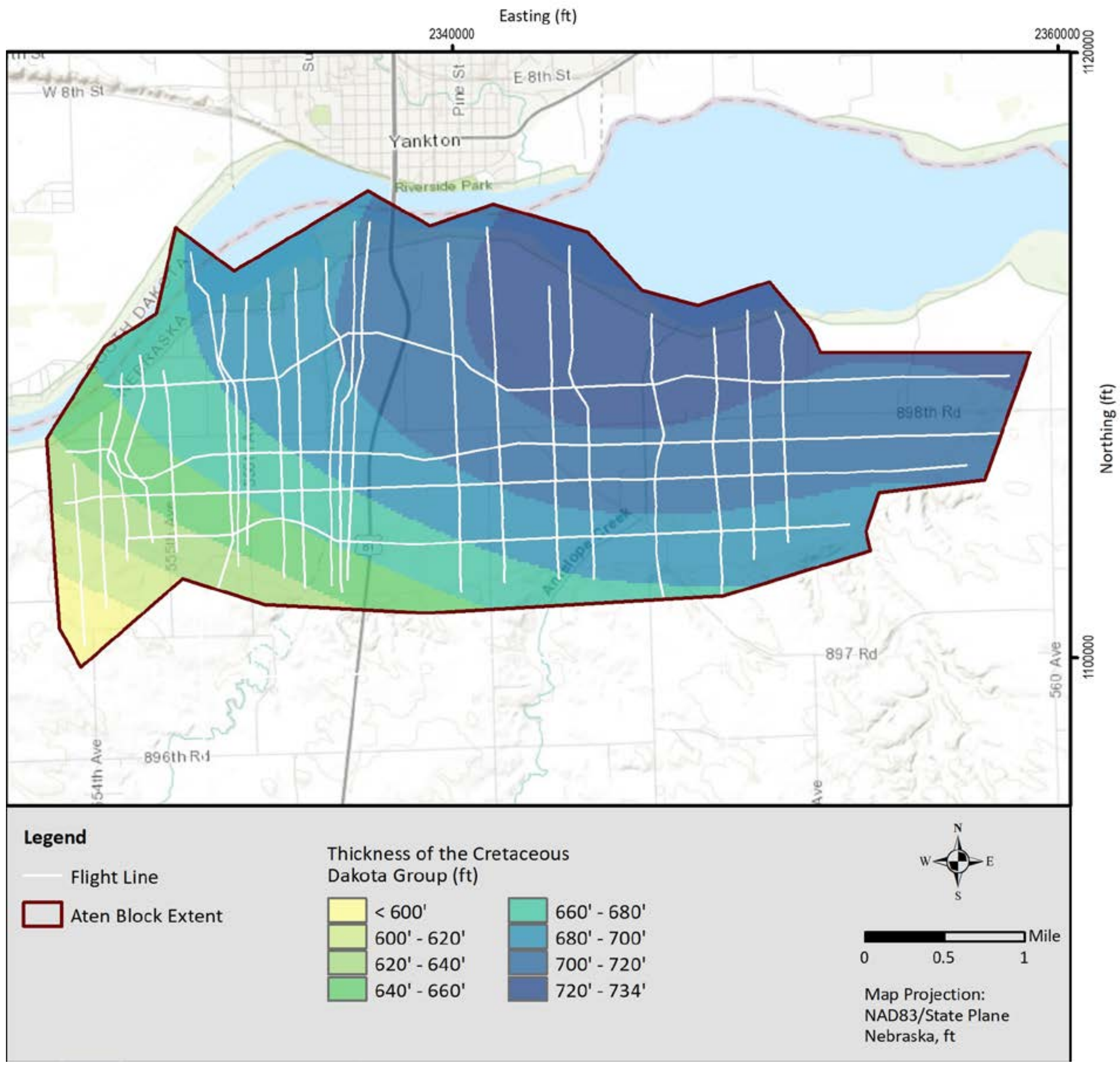


Figure 3-92. Map of the thickness (in feet) of the Cretaceous Dakota Group (*Kd*) within the Aten Block AEM survey area. The projection is NAD83 State Plane Nebraska (feet).

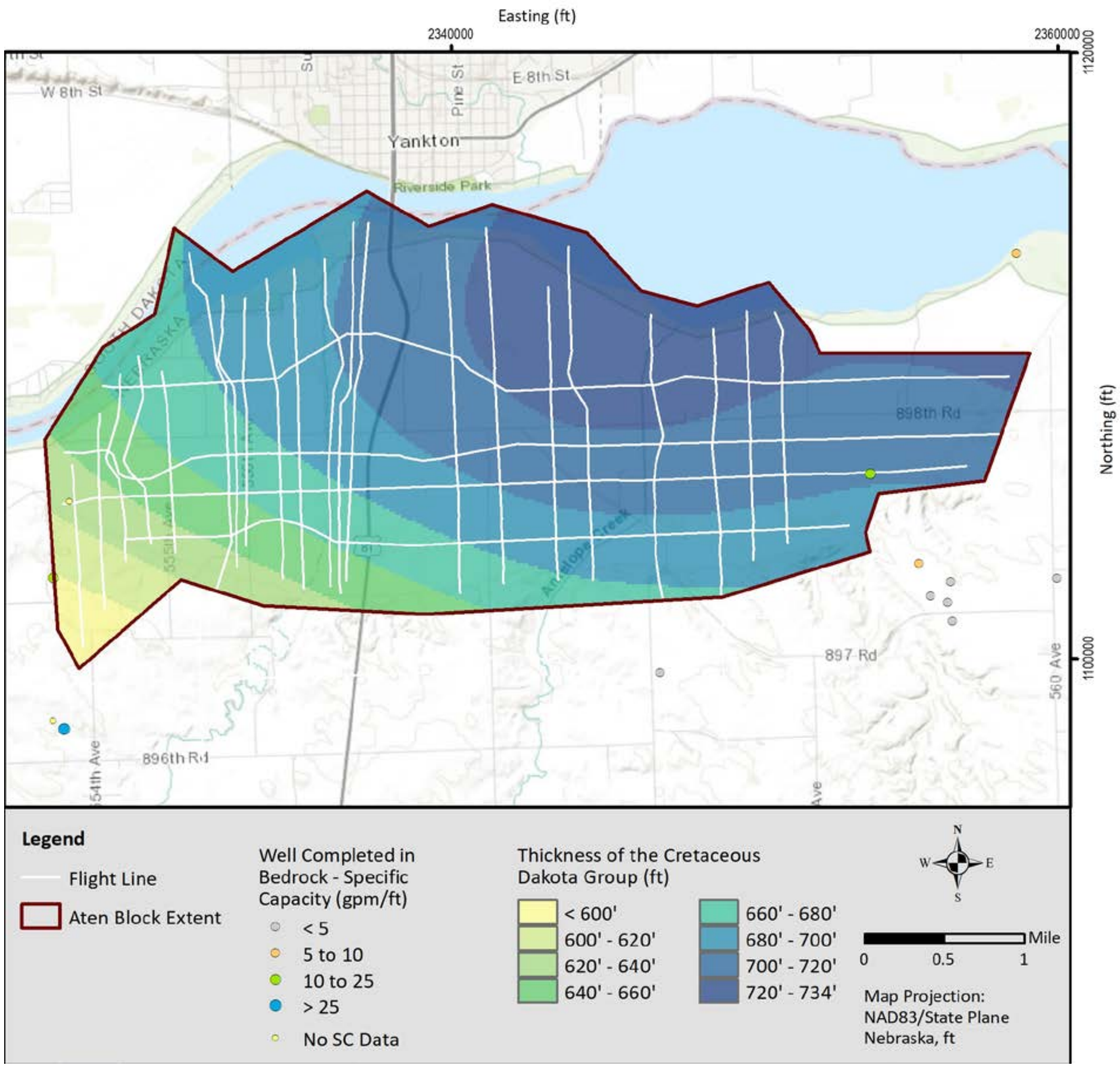


Figure 3-93. Map of the thickness (in feet) of the Cretaceous Dakota Group (*Kd*) related to the specific capacity of the wells screened within *Kd* within the Aten Block AEM survey area. The projection is NAD83 State Plane Nebraska (feet).

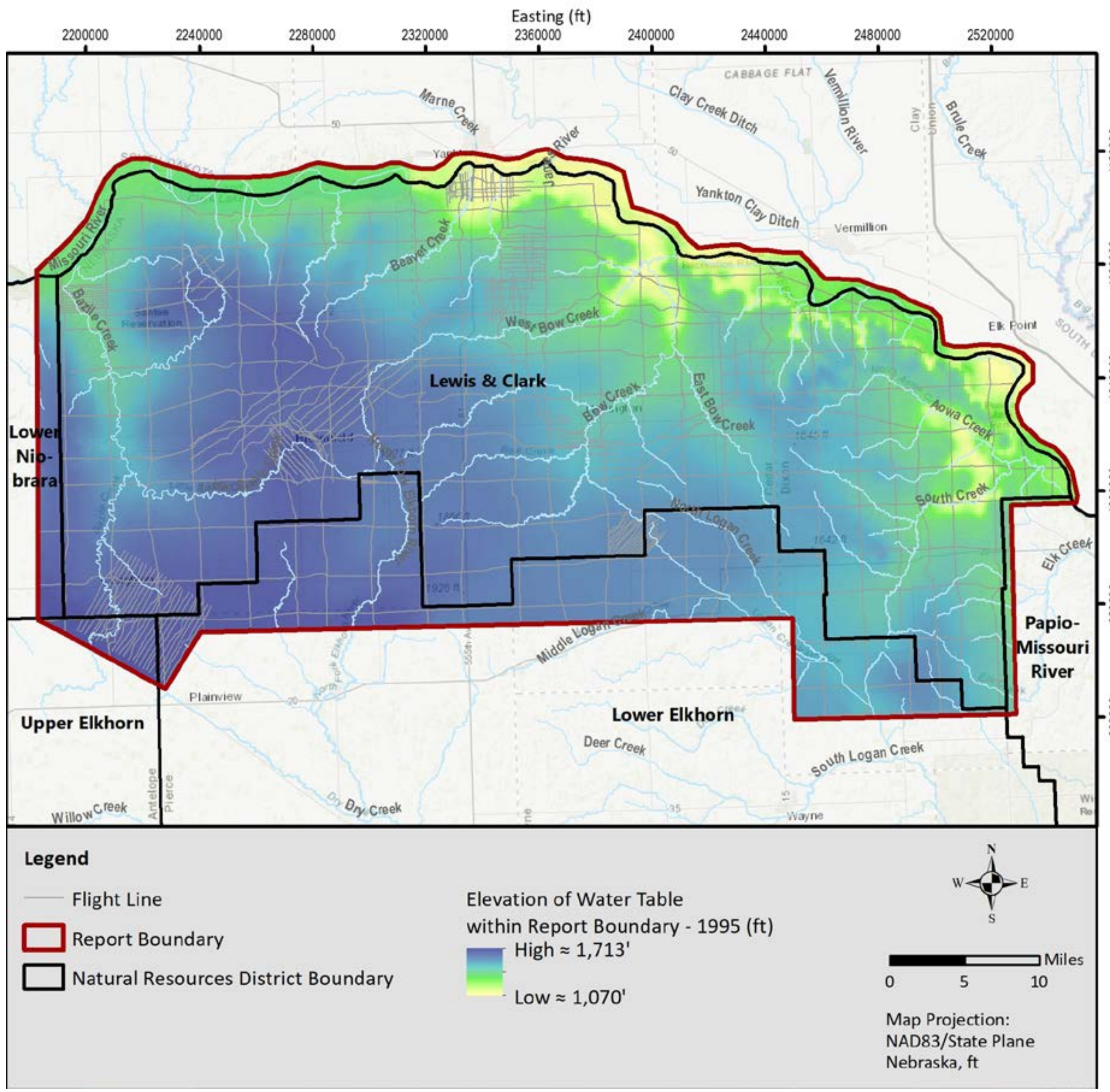


Figure 3-94. Map of the elevation (in feet) of the 1995 CSD water table within the LCNRD Reconnaissance AEM survey area. The projection is NAD83 State Plane Nebraska (feet).

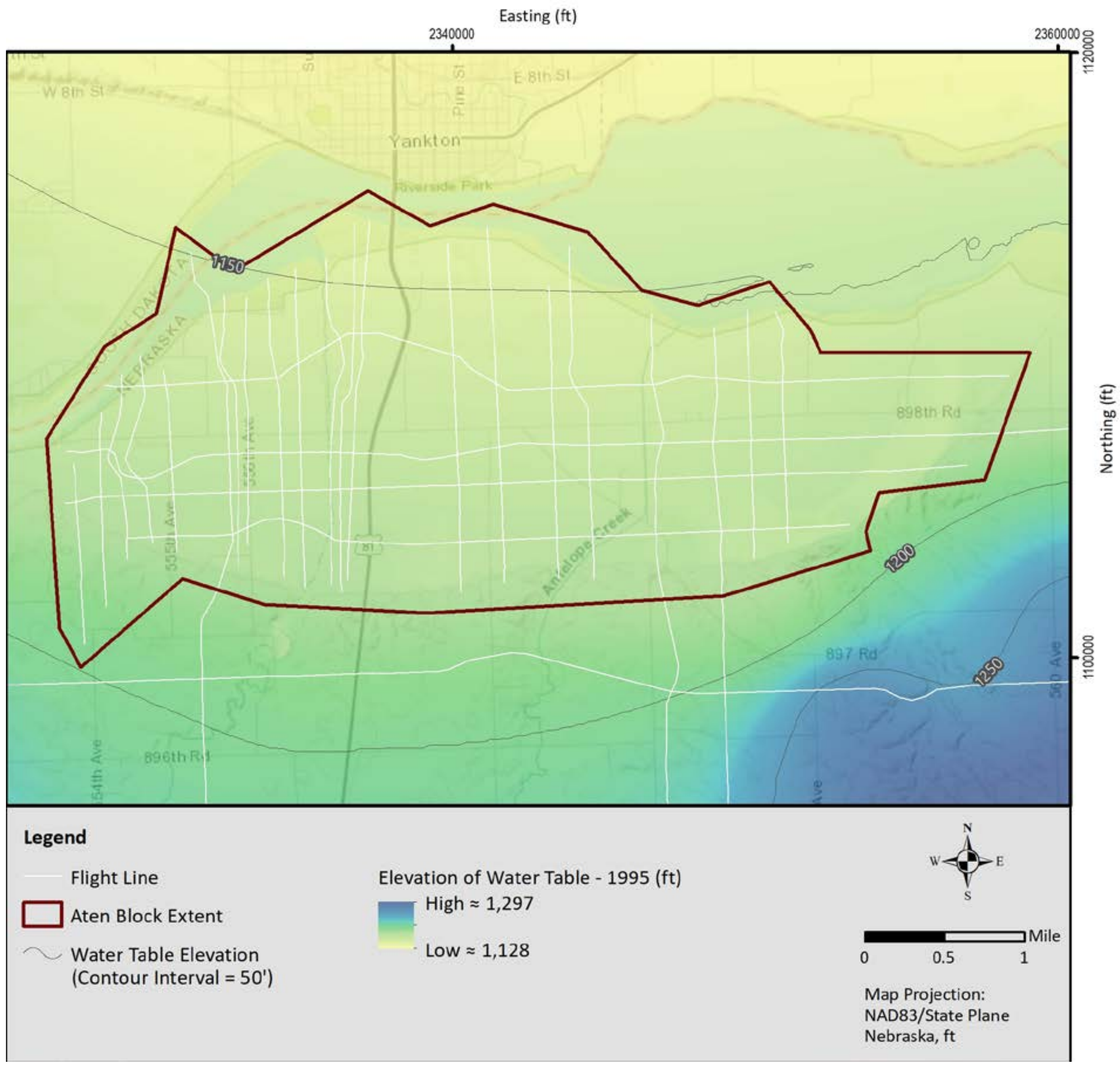


Figure 3-95. Map of the elevation (in feet) of the 1995 CSD water table within the Aten Block AEM survey area. The projection is NAD83 State Plane Nebraska (feet).

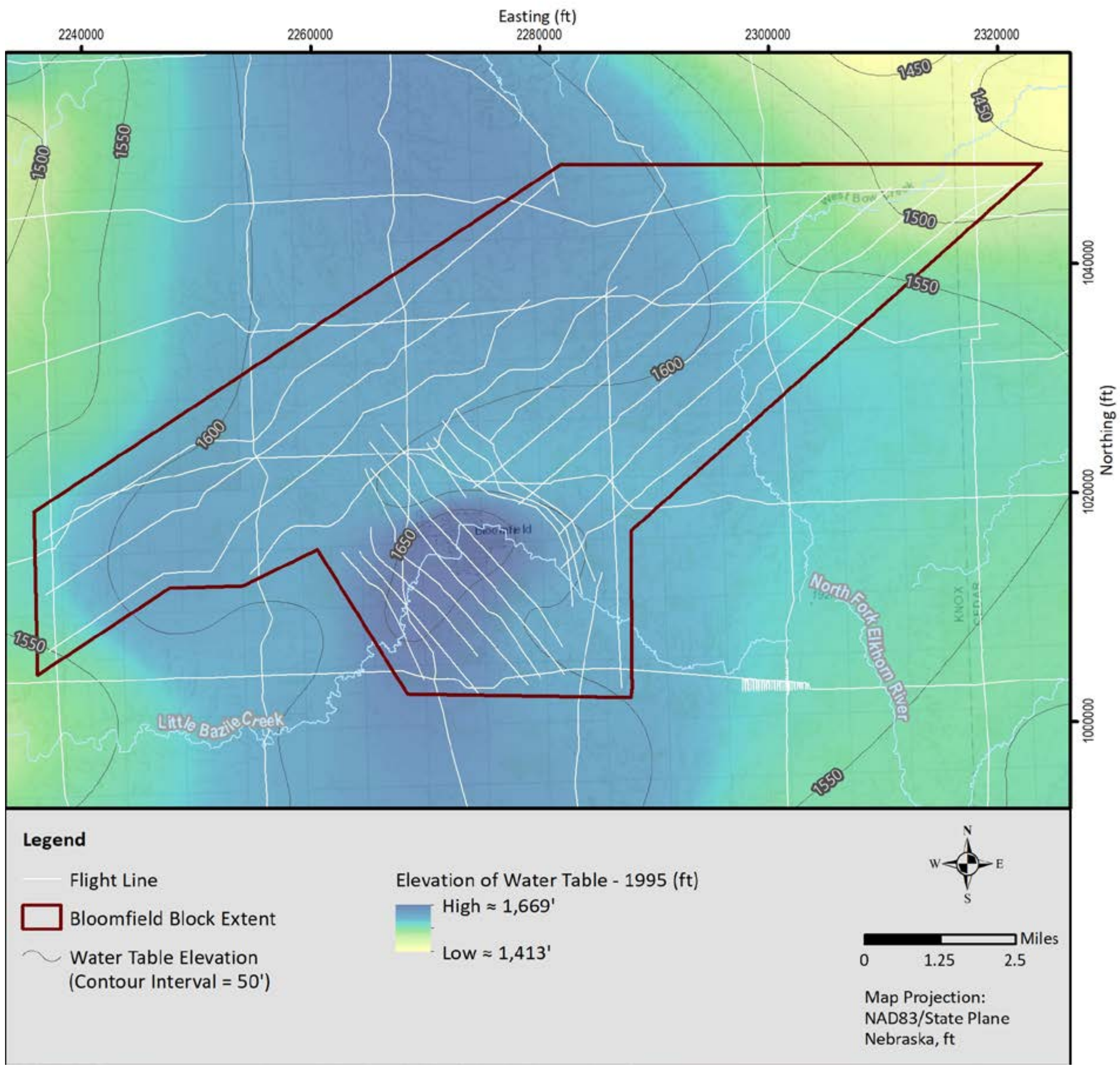


Figure 3-96. Map of the elevation (in feet) of the 1995 CSD water table within the Bloomfield Block AEM survey area. The projection is NAD83 State Plane Nebraska (feet).

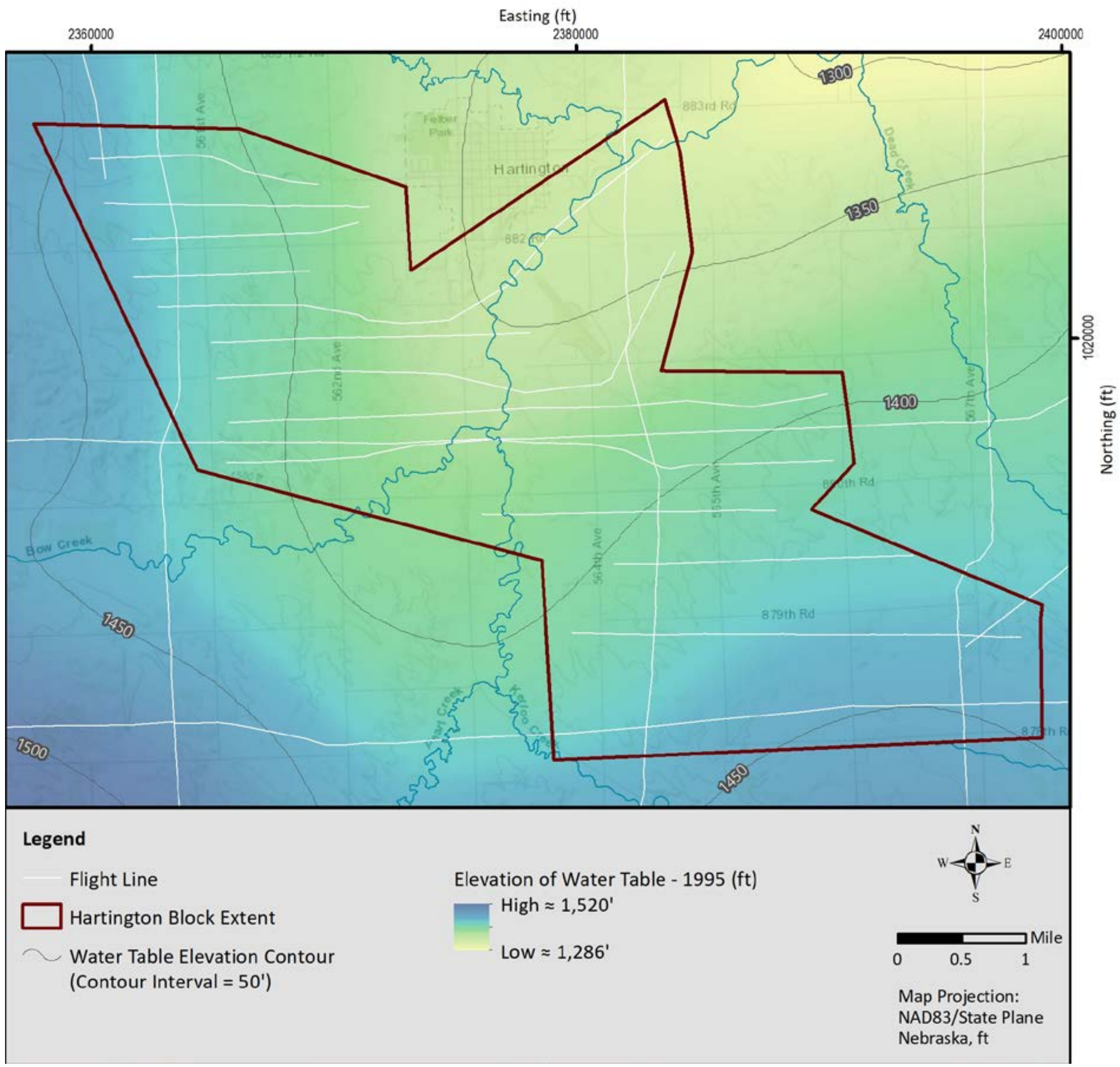


Figure 3-97. Map of the elevation (in feet) of the 1995 CSD water table within the Hartington Block AEM survey area. The projection is NAD83 State Plane Nebraska (feet).

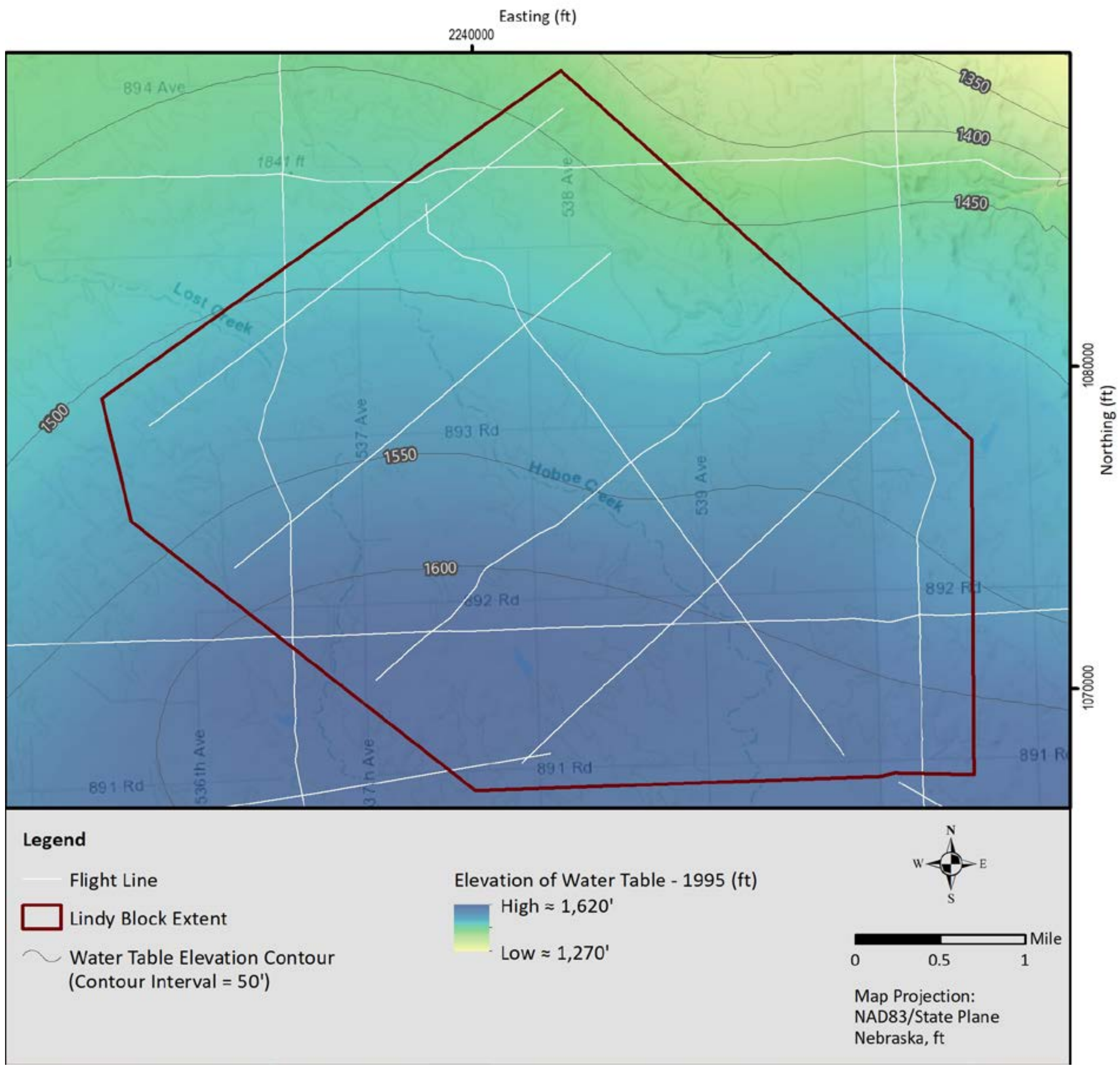


Figure 3-98. Map of the elevation (in feet) of the 1995 CSD water table within the Lindy Block AEM survey area. The projection is NAD83 State Plane Nebraska (feet).

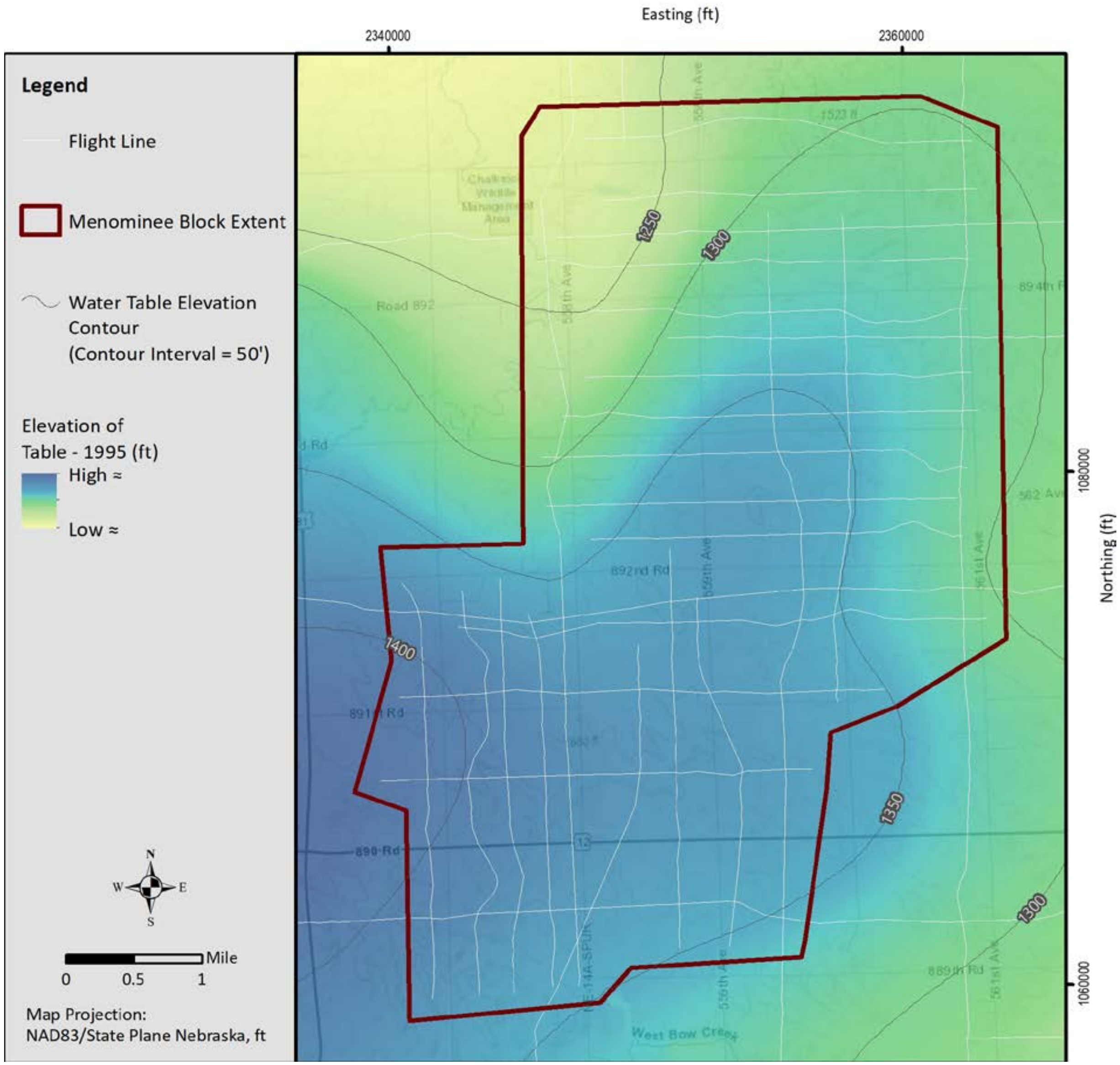


Figure 3-99. Map of the elevation (in feet) of the 1995 CSD water table within the Menominee Block AEM survey area. The projection is NAD83 State Plane Nebraska (feet).

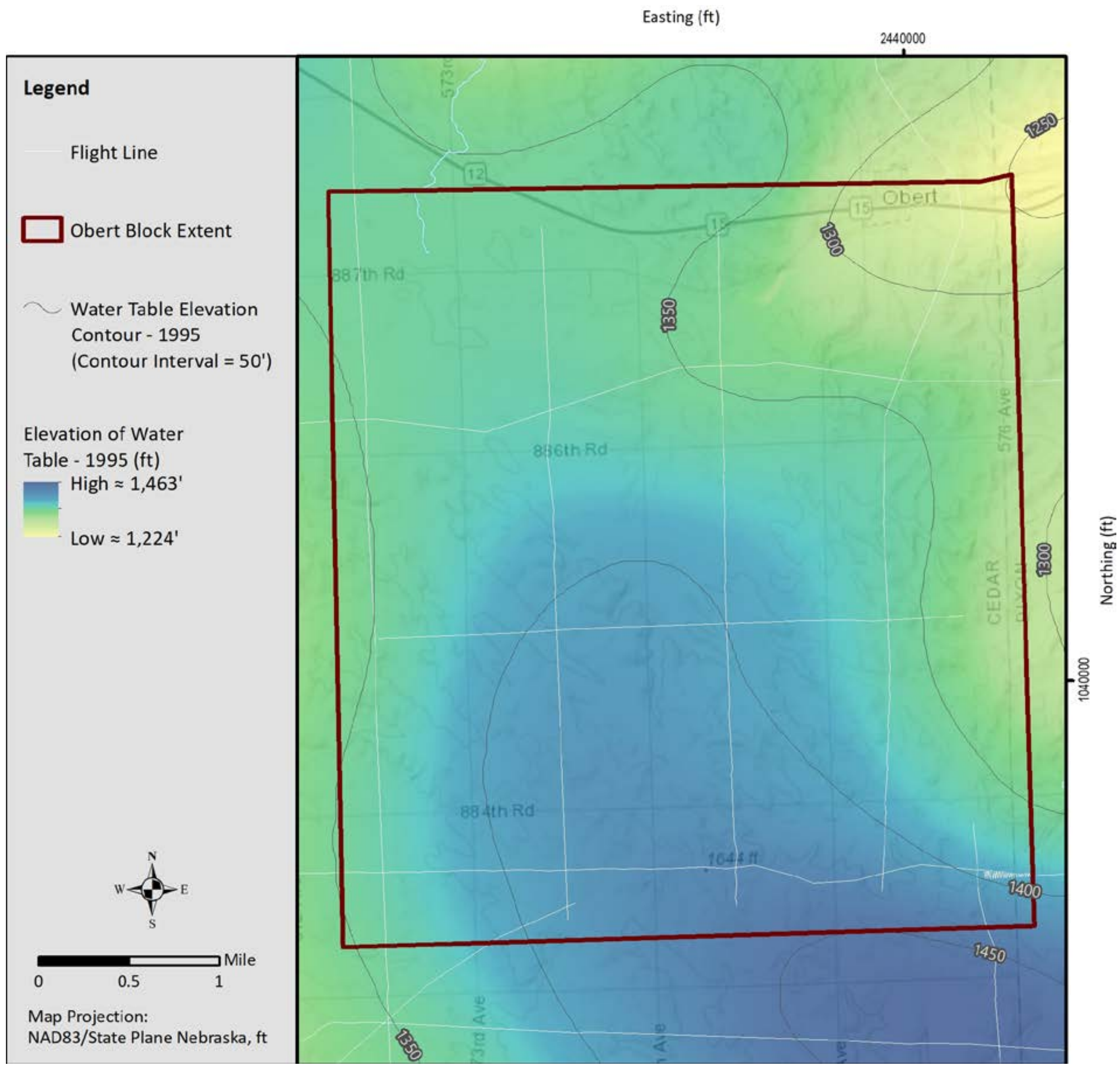


Figure 3-100. Map of the elevation (in feet) of the 1995 CSD water table within the Obert Block AEM survey area. The projection is NAD83 State Plane Nebraska (feet).

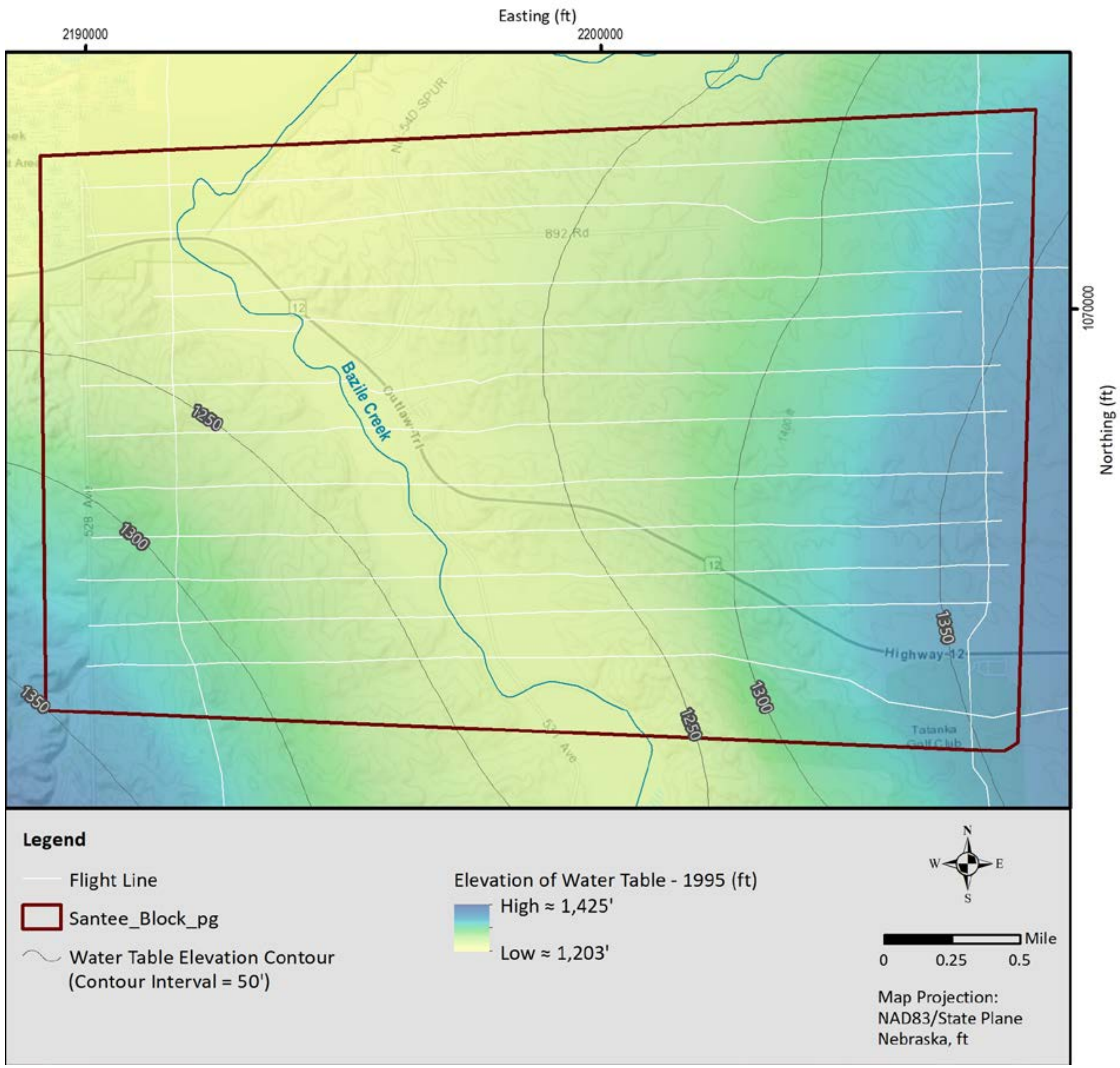


Figure 3-101. Map of the elevation (in feet) of the 1995 CSD water table within the Santee Block AEM survey area. The projection is NAD83 State Plane Nebraska (feet).

3.1.6 Resistivity/Lithology Relationship in the Quaternary Aquifer System

A critical aspect of a geophysical survey, for whatever purpose, is assessing the nature of the material detected by the geophysical method applied in the investigation. In regard to the LCNRD survey, assessment of the sediment character in both the Quaternary aquifer system and the consolidated bedrock strata was conducted to determine the overall composition of the major categories used to define the aquifer and aquitards in eastern Nebraska. A numerically robust assessment of the resistivity thresholds used to characterize non-aquifer, marginal, and aquifer, including sand-rich intervals was calculated. This allows for the characterization of the ranges of resistivities present in the major geologic units described in this report. It should be noted that this analysis encompasses all Quaternary/Tertiary Ogallala (***Q/To***) aquifer system and bedrock data from both the ENWRA project area (Carney et al., 2015a, 2015b). The original analysis that was completed as part of Carney et al. (2015a, 2015b) included some of the LCNRD. This analysis has been used in the current report for the categorization of the Quaternary aquifer system.

Data for this analysis was utilized from locations across the ENWRA reconnaissance line area (Carney et al., 2015a, 2015b). The relationship between resistivity and lithology type was assessed by performing an association function that linked nine lithologic descriptor codes for ***Q/To*** sediments used in the CSD test hole lithologic characterization with the resistivity values across that depth interval as indicated in the 58 high-graded resistivity logs applied in the AEM data inversion (25 from the southern area, 33 from the northern area). With this approach, several thousand points became available for each lithologic description in the test holes used in this analysis. From this list of associated resistivity levels and pre-categorized lithologies, statistical analyses were performed to aide in defining the various thresholds used to determine the aquifer material type in the project area subsurface. Details of the analysis can be found in Carney et al. (2015a, 2015b). A summary of the resistivities and the color scale is shown in Figure 3-102.

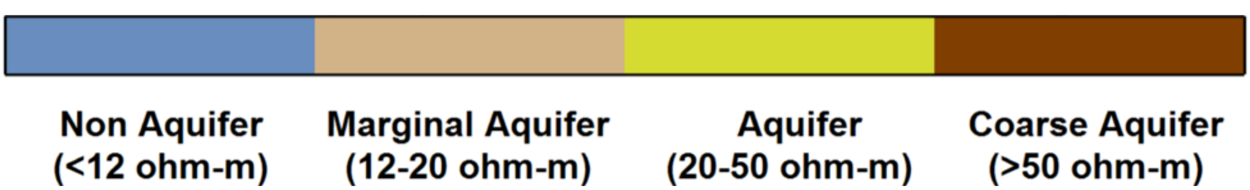


Figure 3-102. Plot displaying the resistivities by major aquifer material color categories: blue- non-aquifer materials, tan- marginal aquifer materials, yellow- aquifer materials, brown- coarse aquifer materials (Carney et al., 2015b).

3.1.7 Resistivity/Lithology Relationship in the Bedrock

The Cretaceous bedrock in the LCNRD analyzed in this study includes the ***Kp, Kn, Kc, Kgg,*** and ***Kd.*** These were included to demonstrate the overall distribution in resistivity of bedrock materials across the entire LCNRD. The median resistivity values for each unit are 9 ohm-m for the ***Kp***, 38 ohm-m for the ***Kn,*** 16 ohm-m for the combined ***Kc*** and ***Kgg***, and 35 ohm-m for the ***Kd*** (Carney et al., 2015a). Note that for the ENWRA study, the ***Kc*** and the ***Kgg*** were interpreted together. The proximity of the ***Kgg*** to the surface allows for a more accurate interpretation. The low resistivity character of 3 to 9 ohm-m for the ***Kc*** made the interpretation of the ***Kc*** relatively straight forward while the ***Kgg*** showed a more resistive character on the order of 15 ohm-m. The ***Kd*** within the LCNRD displayed some low resistivities on the order of 9 to 20 ohm-m indicating either clay/shale dominant lithology or the presence of saline waters. In the western portions of the LCNRD the resistivities were typically below 20 ohm-m. Above 20 ohm-m the ***Kd*** displays characteristics of sand and sandstone dominant materials. (Carney et al., 2015b). The ***IP*** has a wide range of resistivity from 1 to 80 ohm-m with a median at 16 Ohm-m (Carney et al., 2015b).

3.1.8 Create 3D Interpretative Voxel Grids

Voxel grids were completed for the Aten, Bloomfield, Hartington, Menominee, and Santee Block AEM survey areas. The voxel grids were made using a 250 feet grid cell size and the model layer thickness (Table 2-3 and Table 2-4 in the previous section) for the Aten, Bloomfield, Hartington, and Santee Blocks. A 100-foot cell size was used for Menominee due to the steep erosional patterns of the paleochannel. A minimum curvature method was used within Discover PA (Datamine Discover, 2019). All layers were referenced to their depth from the surface and then projected on the area DEM. After the grid was calculated, the grid was split at the top of the Bedrock, Cretaceous Pierre (***Kp***), Cretaceous Niobrara (***Kn***); Cretaceous Carlile Shale (***Kc***); Cretaceous Greenhorn Limestone and Graneros Shale (***Kgg***); Cretaceous Dakota Group (***Kd***); and the undifferentiated Pennsylvanian (***IP***). The units were also split at the 1995 CSD water table. These resulting voxel grids can be used to explore the distribution of the aquifer materials within the area in 3D. Specifically, these grids can allow for visual inspection of the volume of materials above the bedrock as well as the ***Kd***, and the ***Q*** materials. The ***Q*** and materials can be separated by the thresholds developed above for the four lithology classes. Utilizing the voxel grids of the ***Q*** analysis can be made of the volume of the different materials within the section. Additionally, the ***Kd*** can be divided into the Sandstone/Sand dominant versus the Shale/Clay dominant portions. Within the ***Kd*** Sandstone/Sand dominant a higher resistive zone can be illustrated that is greater than 40 ohm-m. Figure 3-103 is an example voxel plot of the Aten Block showing ***Q*** material (separated into the different aquifer materials discussed above) overlying Cretaceous ***Kn***, ***Kc***, ***Kgg***, ***Kd***, and ***IP***, looking to the northeast. Additional examples of the interpretative voxel models for each Block AEM area are discussed below in Section 3.2. The images of the voxel grids can be found in *Appendix 2-3D Images* and the voxel grids themselves are located in *Appendix 3-Deliverables\Voxels*.

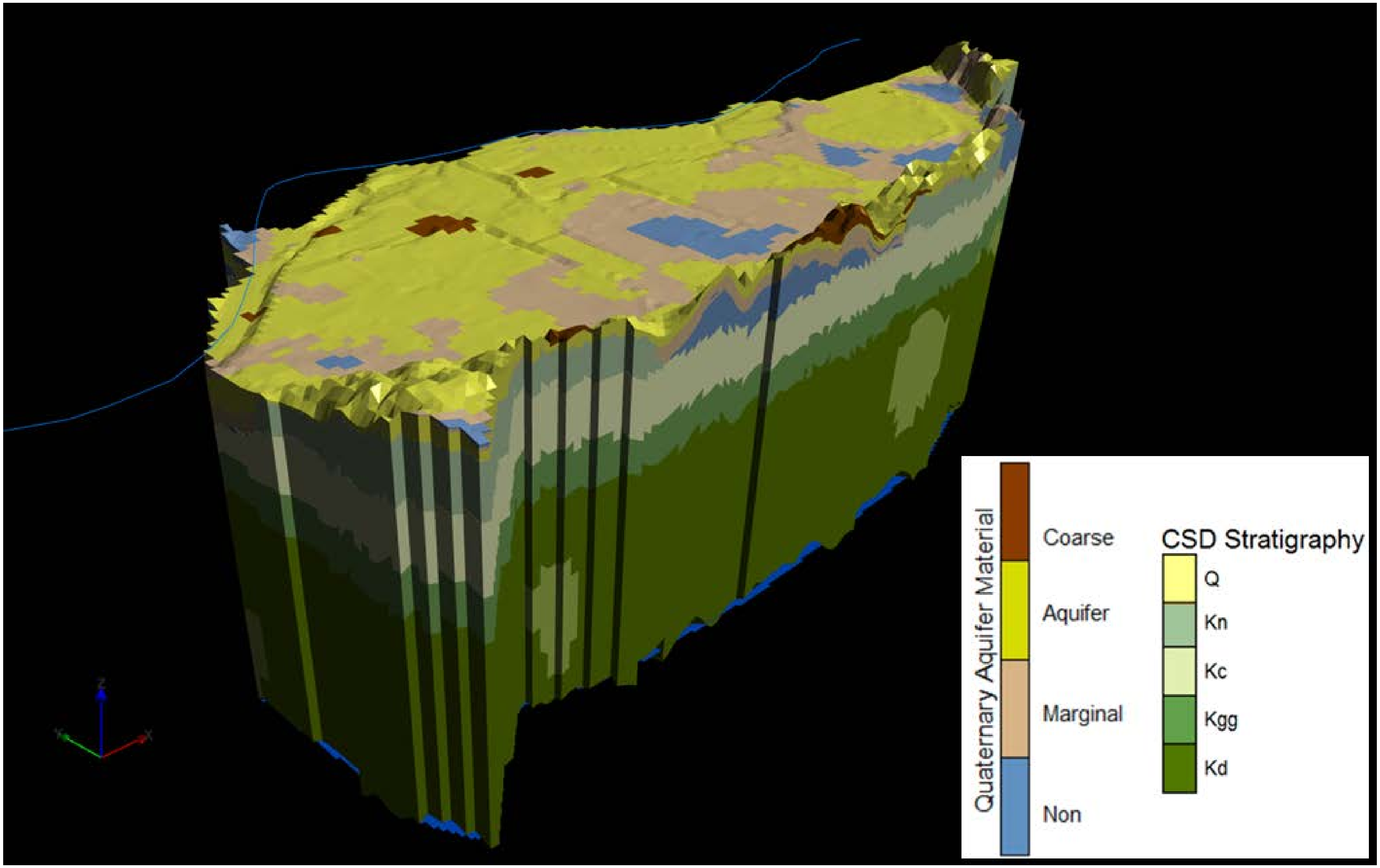


Figure 3-103. Example voxel model of the aquifer material types for the Aten Block consisting of Quaternary (*Q*) sediments overlying Cretaceous and undifferentiated Pennsylvanian units. Not to scale. Streams are indicated by blue lines.

3.1.9 Comparison of Borehole Resistivity Logs to Inverted AEM Resistivity Soundings

Two CSD borehole geophysical resistivity logs were selected from the LCNRD AEM survey area for comparison with the AEM inversions: CSD test holes *01-LC-18* and *1-LE-03*. 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 has been a long-standing issue with using geophysical logs as ground truths when comparing to AEM inversions that are well calibrated using modern techniques. 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 recognizing the proper operation of a calibrated sonde or in the ability to recognize high contact resistances 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 relatively indicate an increase or a decrease in the formation resistivity. Not accurately, but relatively. Thus, 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-Cooper and Davis, 2010).

Figure 3-104 is a plot of the *01-LC-18* 16-inch short normal and 64-inch long normal resistivity logs plotted with the inverted AEM resistivities for flight line L201801, which is 379 feet away. The AEM soundings selected are from the closest points to the location of the borehole geophysical log. The agreement in the resistivity is generally good. The general trend of the 16-inch and 65-inch logs follow that of the AEM inversion except at ~75 ft depth. Note that it is likely that some averaging is happening.

It is a similar case with the borehole logs from *1-LE-03*. Figure 3-105 presents the 16-inch short normal and 64-inch long normal resistivity logs plotted with the inverted AEM resistivity for flight line L1101909 which is located 1,619 feet from *1-LE-03* at its closest point. The agreement in the resistivity is generally fair except for the zone between ~125 feet and ~160 feet. The nature of the resistivity logs in this zone indicate that there is an issue in the extremely high resistivity zone in the 16-inch and 64-inch logs. Saturated sand should not have a resistivity approaching 1000 ohm-m

The 16-inch short normal log from borehole *01-LC-18* is presented in situ on the 2D inverted AEM resistivity profile sections for flight line L201801 in Figure 3-106. Again, the resistivity comparison between *01-LC-18* and the AEM is generally pretty good.

Similarly, Figure 3-107 presents inverted AEM resistivities on a 2D profile of flight line L1101909 with borehole *1-LE-03* displaying the 16-inch short normal log overlaid in the center. They compare well.

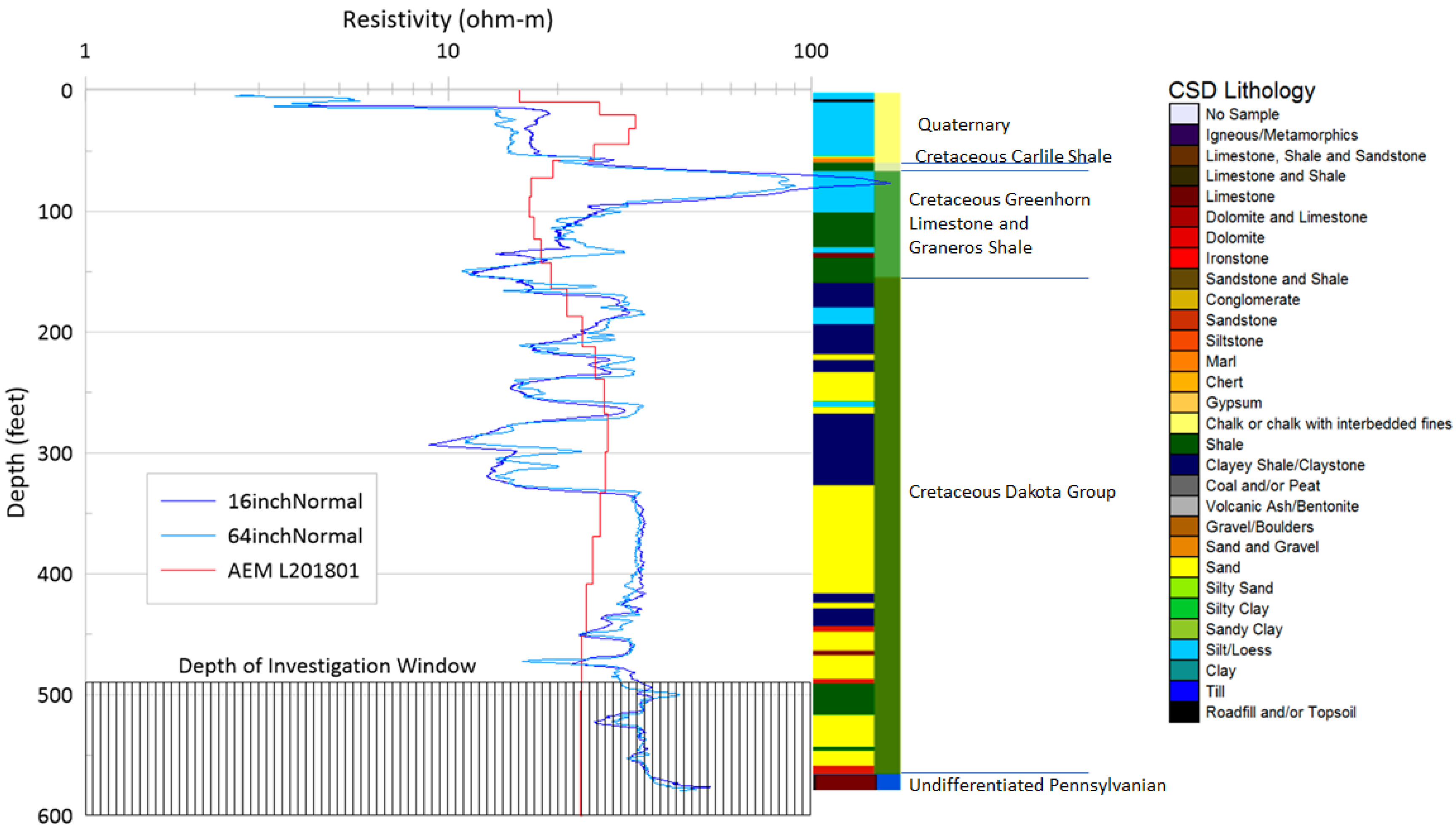


Figure 3-104. Graph of the *01-LC-18* 16-inch normal (purple line) and 64-inch long normal (light blue line) resistivity log values and the inverted airborne electromagnetic resistivity values for flight line L201801(red line). Also included are the lithology and stratigraphy logs from *01-LC-18*.

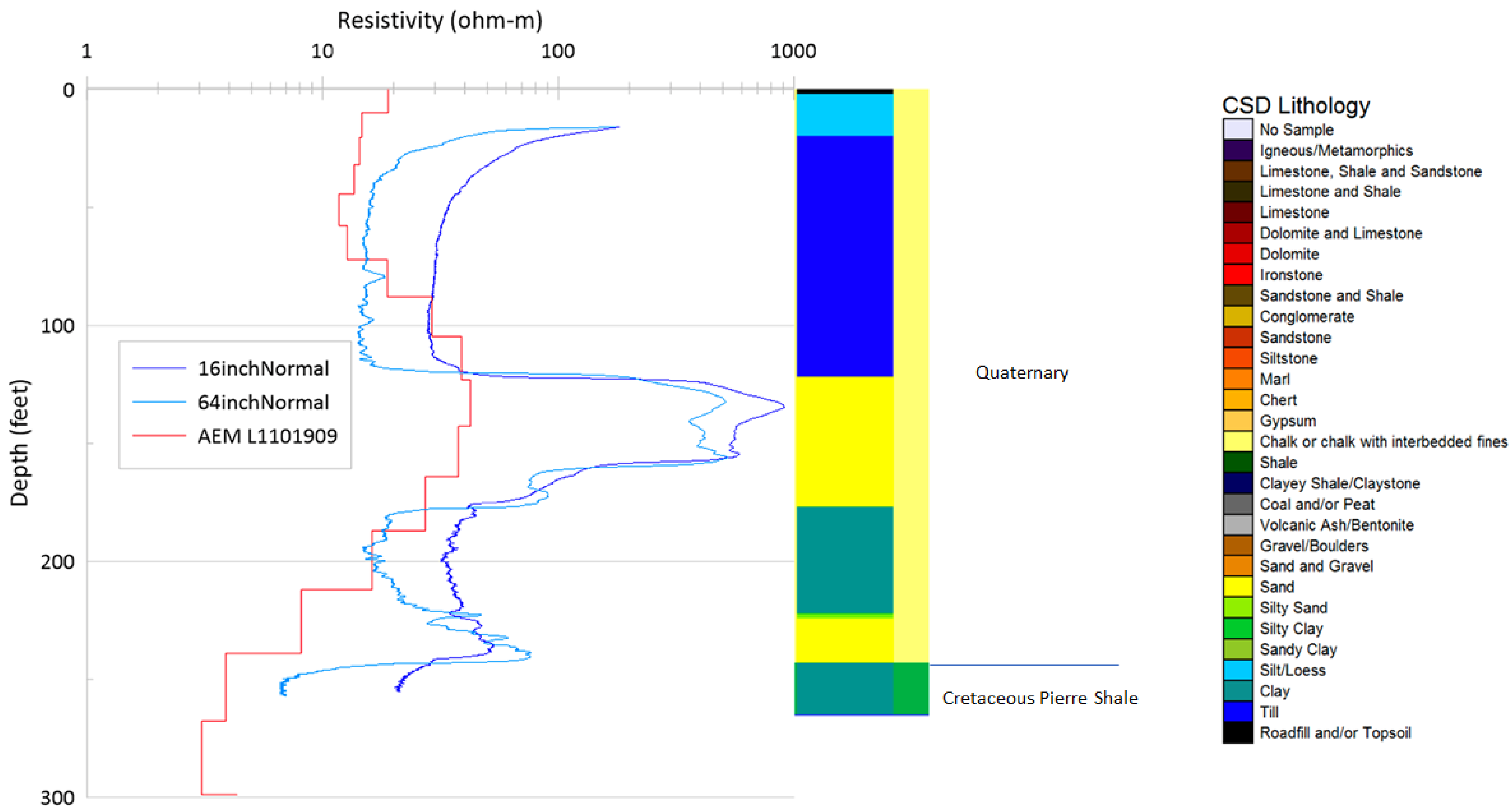


Figure 3-105. Graph of the *1-LE-03* 16-inch short normal (purple line) and 64-inch long normal (light blue line) resistivity log values and the inverted airborne electromagnetic resistivity values for flight line L1101909 (red line). Also included are the lithology and stratigraphy logs from *1-LE-18*.

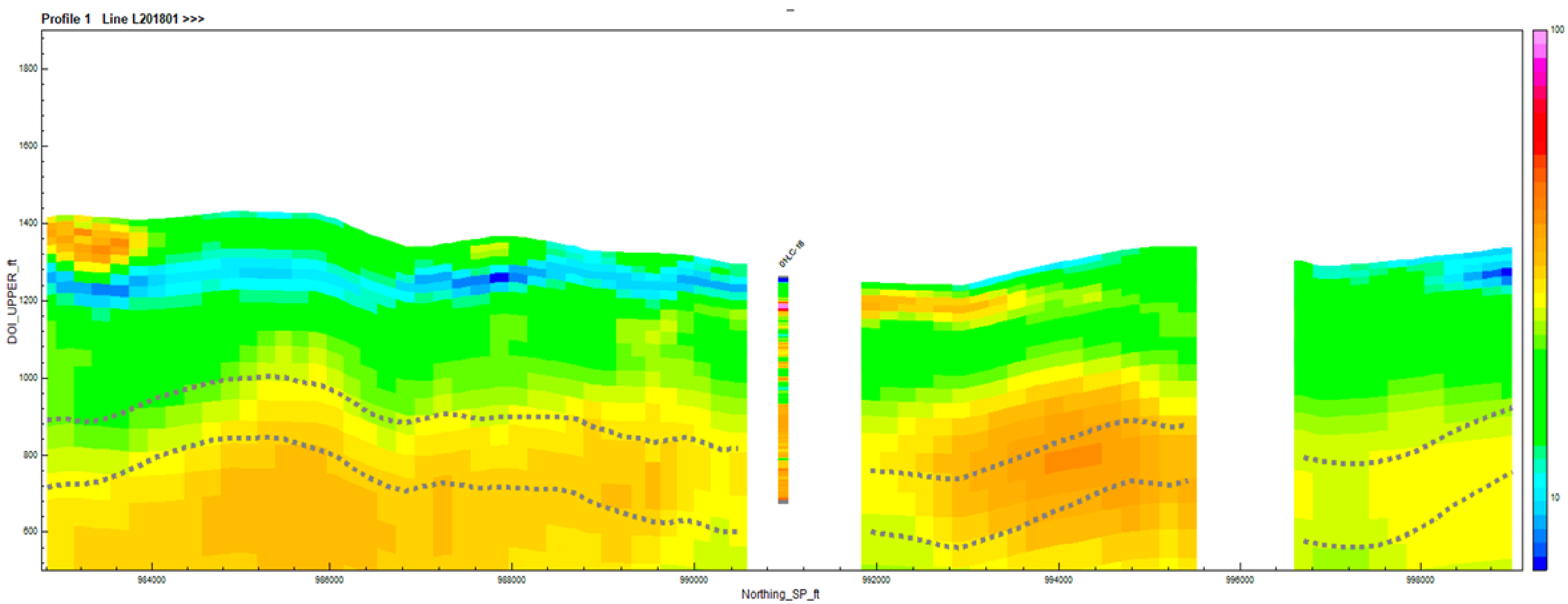


Figure 3-106. Inverted AEM resistivities for flight line L201801 with borehole *01-LC-18* overlaid on the left. They compare well.

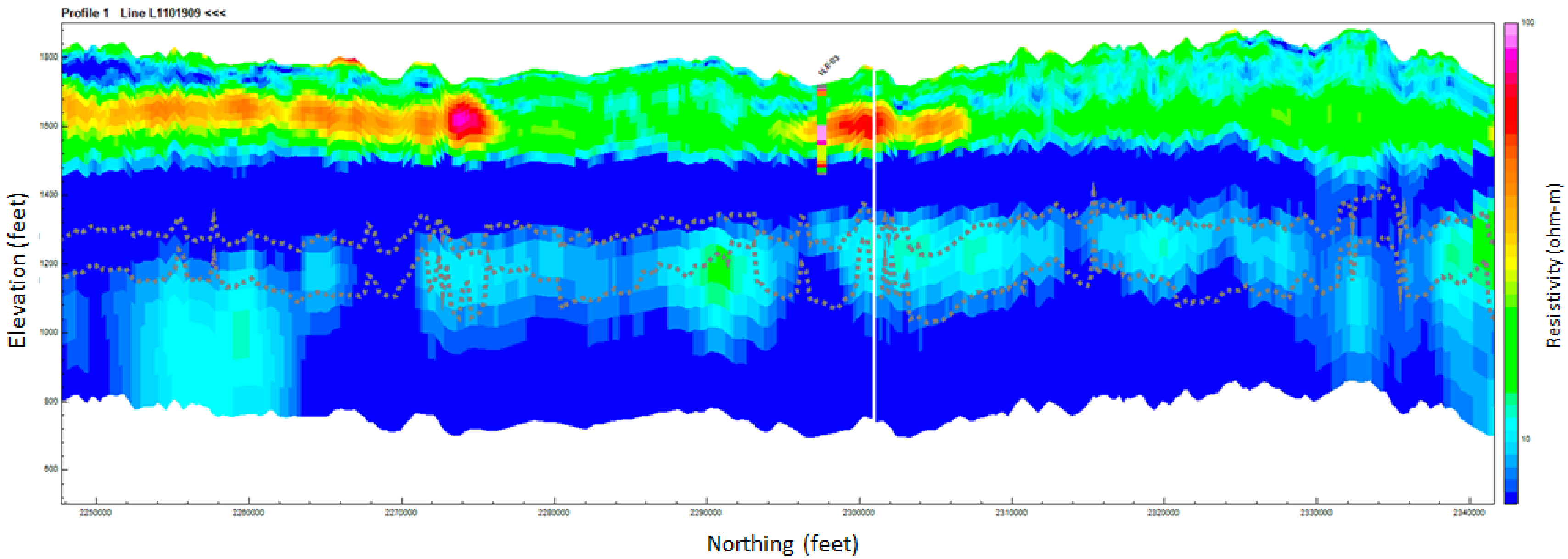


Figure 3-107. Inverted AEM resistivities for flight line L1101909 with borehole *1-LE-03* overlaid on the right. They also compare well.

3.2 Hydrogeological Framework of the LCNRD 2018 AEM Survey Area

The 2018 survey continues to build upon the previous AEM survey efforts within LCNRD beginning in 2014-15 with the ENWRA Reconnaissance survey (Abraham et al., 2015; Carney et al., 2015a; Carney et al., 2015b), and continuing into 2016-17 with the Bazile Creek Groundwater Management Area (BGMA) (AGF, 2017b) and with the ENWRA project which funded the 2017 Hydrogeologic Framework of Selected Areas of the Lewis and Clark Natural Resources District, Nebraska (AGF, 2017a). The hydrogeology of the Coleridge Block AEM flight area is discussed in more detail in the LCNRD 2017 report (AGF, 2017a) and that for the Creighton Block AEM flight area is discussed in more detail in the BGMA 2017 report (AGF, 2017b). In the current 2019 report new updated profiles and KMZs have been developed for the Creighton and Coleridge Block areas and are included in appendices 1 (2D Profiles) and 3 (Deliverables\KMZ). These 2018 AEM-derived results provide new information on the hydrogeology in areas that was previously unknown to the LCNRD or were only known to a limited extent from just the borehole information. The merged AEM survey data provides the basis for this section of the report.

3.2.1 The Hydrogeologic Framework of the LCNRD Reconnaissance Survey Area

The hydrogeologic framework for entire LCNRD survey area based on the reconnaissance flight lines will be described first, then the Block areas in the following order: Aten, Bloomfield, Hartington, Lindy, Menominee, Obert, and Santee. Creighton and Coleridge have been discussed previously in AGF (2017a and 2017b). The AEM reveals the variability in the Quaternary, Tertiary, and Cretaceous deposits which make up the aquifers across the AEM survey area. Figure 3-108 shows the CSD bedrock geology map of the area. For purposes of this section the ***Q, To***, ***Kn***, and ***Kd*** contain the aquifer units in the survey area. The ***Q*** and ***To*** are treated as the same aquifer for this report when in contact with each other and contain aquifer materials composed of non-aquifer (blue color in figures), marginal aquifer (tan color in figures), aquifer (yellow color in figures), and coarse aquifer (brown color in figures) materials. These materials are composed predominantly of glacial, pre-glacial alluvial (paleochannel deposits and ***To***), and alluvial deposits related to the current drainages.

The dominant hydrogeologic features that are in the LCNRD Reconnaissance survey area are ***Q*** alluvial deposits found in the modern drainages and paleochannels and the till deposits which are a mix of all aquifer materials types including outwash deposits of sand and gravel. The ***To*** found in the west part of the project area are a mix of all aquifer materials. The ***Kn*** can be an aquifer for shallow wells in the northern part of Cedar County (Joeckel et al., 2017) but is typically considered an aquitard for the rest of the project area. The ***Kd*** Sandstone/ Sand Dominant deposits are found on the eastern and northern side of the project area and are considered bedrock aquifers which can be hydrologically connected to streams where the overlying units have been eroded. Figure 3-109 is a 3D image of the AEM interpretation as a fence diagram, looking to the north, showing the geologic formations across the survey area. Figure 3-110 is a 3D image of the AEM interpretation as a fence diagram, looking to the southwest, showing the geologic formations across the survey area and highlights the ***Kd*** sandstone/sand dominant areas including where they are hydrologically connected and not hydrologically connected to surface water. Figure 3-111 is the total ***Q*** and ***To*** thickness containing all interpreted non-aquifer, marginal aquifer, aquifer, and coarse aquifer materials. The thick areas of ***Q*** and ***To*** are found in the uplands of the project area and the thin areas are in the drainages. ***Q*** thickness ranges from <50 feet to 575 feet.

Figure 3-112 shows the total ***Kd*** thickness including the Shale/Clay Dominant and Sandstone/Sand Dominant materials. The ***Kd*** ranges in thickness from greater than 350 feet to 755 feet near Yankton, South Dakota. The ***Kd*** contains both Sandstone/Sand dominant and Shale/Clay dominant materials. The Sandstone/Sand dominant materials are the aquifer materials in the ***Kd***.

The water table map for the LCNRD 2018 AEM survey area is shown on Figure 3-113 and is used in all calculations for saturated Thickness and hydrologic connection to surface water.

Examining the 3D fence diagrams provides a spatial understanding of the distribution of aquifer materials within the LCNRD 2018 AEM survey area. Figure 3-114 is a 3D fence diagram looking to the west. The figure includes the surface of the undifferentiated Pennsylvanian (***IP***) as well as some of the major streams. The AEM aquifer material classifications illuminate the areas of the ***Q*** (which covers the survey area) and ***To*** (the extent of which is shown on Figure 3-115) with the yellow and brown colors of the aquifer and coarse aquifer materials. The ***Kd*** is a secondary aquifer made up of ***Kd*** Sandstone/Sand Dominant materials and exists mostly in the eastern half of the survey area. Figure 3-114 shows where the ***Kd*** Sandstone/Sand Dominant materials are hydrologically connected to surface water near the Missouri River valley and that they quickly become non-hydrologically connected and confined units where the ***Kd*** Shale/Clay, ***Kgg***, ***Kc***, and ***Kn*** are on top. In areas where there are no paleochannels or alluvial channels, the dominate aquifer material type is a mix of marginal (tan areas) and non-aquifer (blue areas) materials.

It is important to note that the marginal aquifer material areas may have wells that produce, just at a lower rate due to the interlayered nature of the marginal materials that contain large portions of silt and clay but may also contain thin layers of sand and gravel and/or silty sand. Discussion on the materials that were found to be within the marginal aquifer materials resistivity range can be found in Carney et al. (2015a).

In some areas of the survey the paleochannels are discrete and have very sharp transitions from non-aquifer and marginal aquifer materials to aquifer and coarse aquifer materials. East-west line L900901 (Figure 3-116) is oriented west to east across the Menominee Paleochannel, southeast of the town of Aten, Nebraska in the north central portion of the LCNRD Reconnaissance AEM survey area and illustrates the discrete nature of the paleochannel deposits. The paleochannel lies under an upland area made up of two hills flanking the east and west sides of the paleochannel which contains mostly coarse aquifer and aquifer material with minor amounts of marginal aquifer material. This aquifer geometry provides for sharp flow boundaries within the aquifer system which are made up of ***Kp*** and ***Kn***. Note the elevation change from the top of the hill (~1,450-foot elevation) to the bottom of the paleochannel (~1,275-foot elevation) is ~175 feet.

North-south line L200801 (Figure 3-117), near Fordyce, Nebraska, displays the subsurface deposits of geologic units of the uplands area inclusive of Bow Creek Valley at the northern end of the profile which is also in the Menominee paleovalley area. The ***Q*** deposits are flanked to the north and south by dissected hills made up of glacial outwash and till deposits capped by loess (Joeckel et al., 2017). The ***Q*** is thick to the south and thins to the north upon a gently sloping Cretaceous bedrock surface. Beneath the upland, near easting 1020000, is a paleovalley with a thickness of ~100 ft cut into the ***Kp*** that includes basal sand deposits of aquifer material that are capped by marginal aquifer material. There is a second paleochannel near Bow Creek (easting 1060000) and is eroded into the ***Kn*** ~100 feet and contains sand deposits of aquifer material. The ***Kd*** is the basal Cretaceous unit resting upon the ***IP*** and is ~420 feet thick. It is composed of Sandstone/Sand dominant and Shale/Clay dominant materials that have no hydrologic connection with surface water because there is ***Kd*** Shale/Clay dominant material, ***Kgg***, ***Kc***, ***Kd*** and discontinuous ***Kp*** above this zone to the just below the ***Q*** impeding any groundwater flow vertically and horizontally.

East-west line L1100101 (Figure 3-118) lies in the Missouri River flood plain with a small hill ~1,300 feet in elevation which is mostly ***Kn*** outcrop with a small cap of ***Q*** material at its very top. The Missouri River flood plain which bends around the ***Kn*** outcrop varies in elevation from ~1,180 feet in the west to ~1,150 feet in the east. The ***Q*** sediments, which average ~40-100 feet thick, are within the flood plain and are made up of all aquifer material types including coarse aquifer, aquifer, marginal aquifer, and non-aquifer. Beneath the ***Q*** of the flood plain lies ***Kn*** and ***Kc*** which in turn lie upon the ***Kgg***. The ***Kc*** and ***Kgg*** has a poor hydrologic connection due to its material make up (limestone and shale). The ***Q*** material has strong hydrologic connection to surface water across the flood plain.

North-south line 1202101 (Figure 3-119) is near the towns Waterbury and Ponca, Nebraska. It starts in the dissected hills in the south and continues north to the Missouri River. The ***Q*** till in the south is continuous to near northing 1000000 where it outcrops into a valley. The till is composed of aquifer, marginal, and non-aquifer materials with the southern end being predominately marginal and non-aquifer. It lies upon the ***Kc*** to approximately northing 960000 where the ***Kc*** is eroded off and the ***Kgg*** is now the bedrock below the ***Q***. The ***Kgg*** continues as the bedrock until it nears northing 970000 where the ***Kc*** is and begins again as the bedrock until it reaches approximately northing 100000 where it subcrops in a valley wall. The ***Kgg*** continues as the bedrock unit until it reaches the Missouri River flood plain where it subcrops and the ***Kd*** becomes the bedrock unit. The ***Kd*** is composed of both the Sandstone/Sand dominant and Shale/Clay dominant material. There are outcrops of ***Kc*** and ***Kgg*** along the northern part of the line. The bedrock outcrops that were mapped by CSD were included in this interpretation and required considerable effort to make them useable. Along this line it does not appear the ***Kd*** Sandstone/Sand dominant material is hydrologically connected to the surface water.

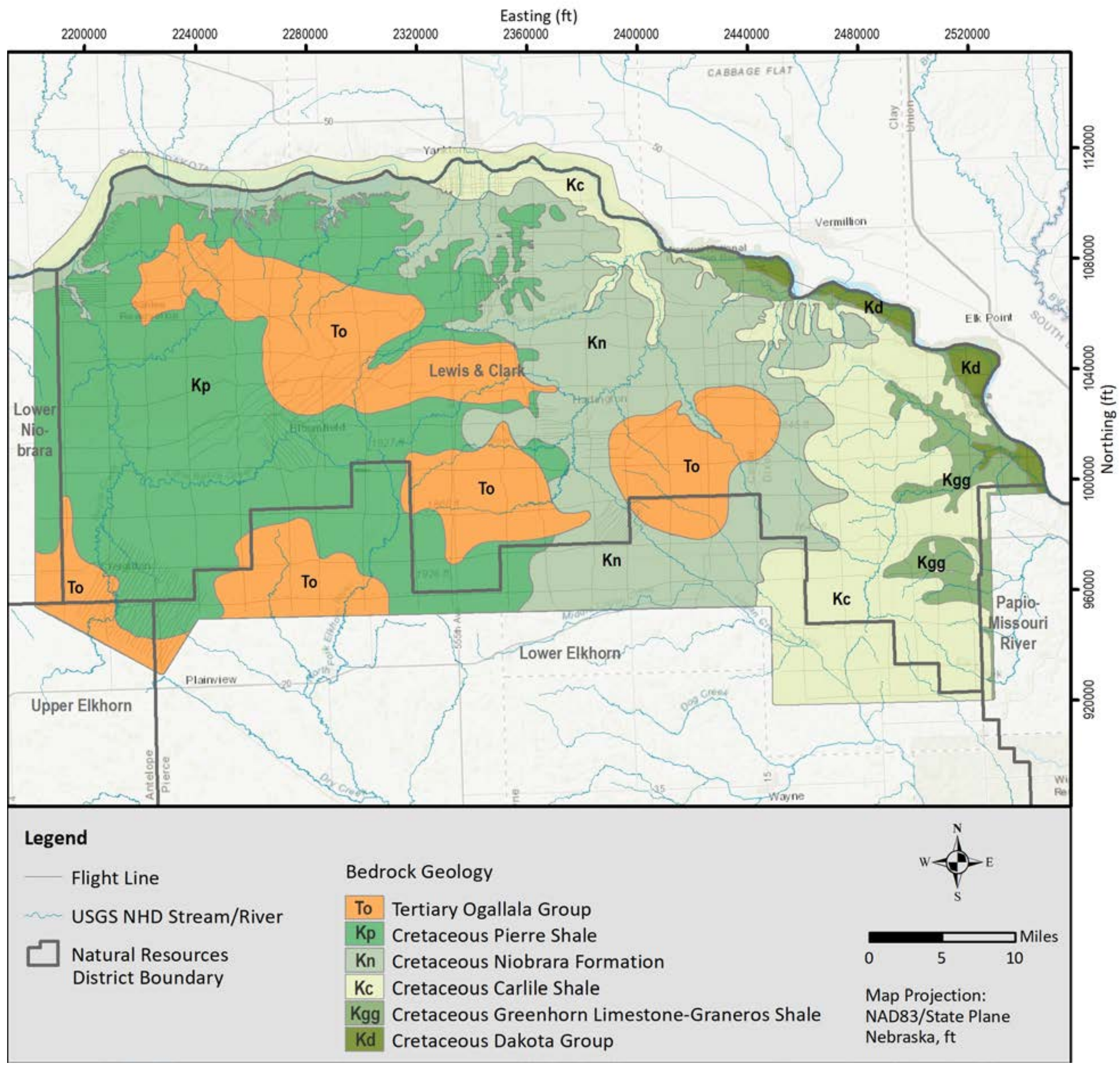


Figure 3-108. Map showing the CSD bedrock geology map for the entire project area, modified from Burchett (1986).

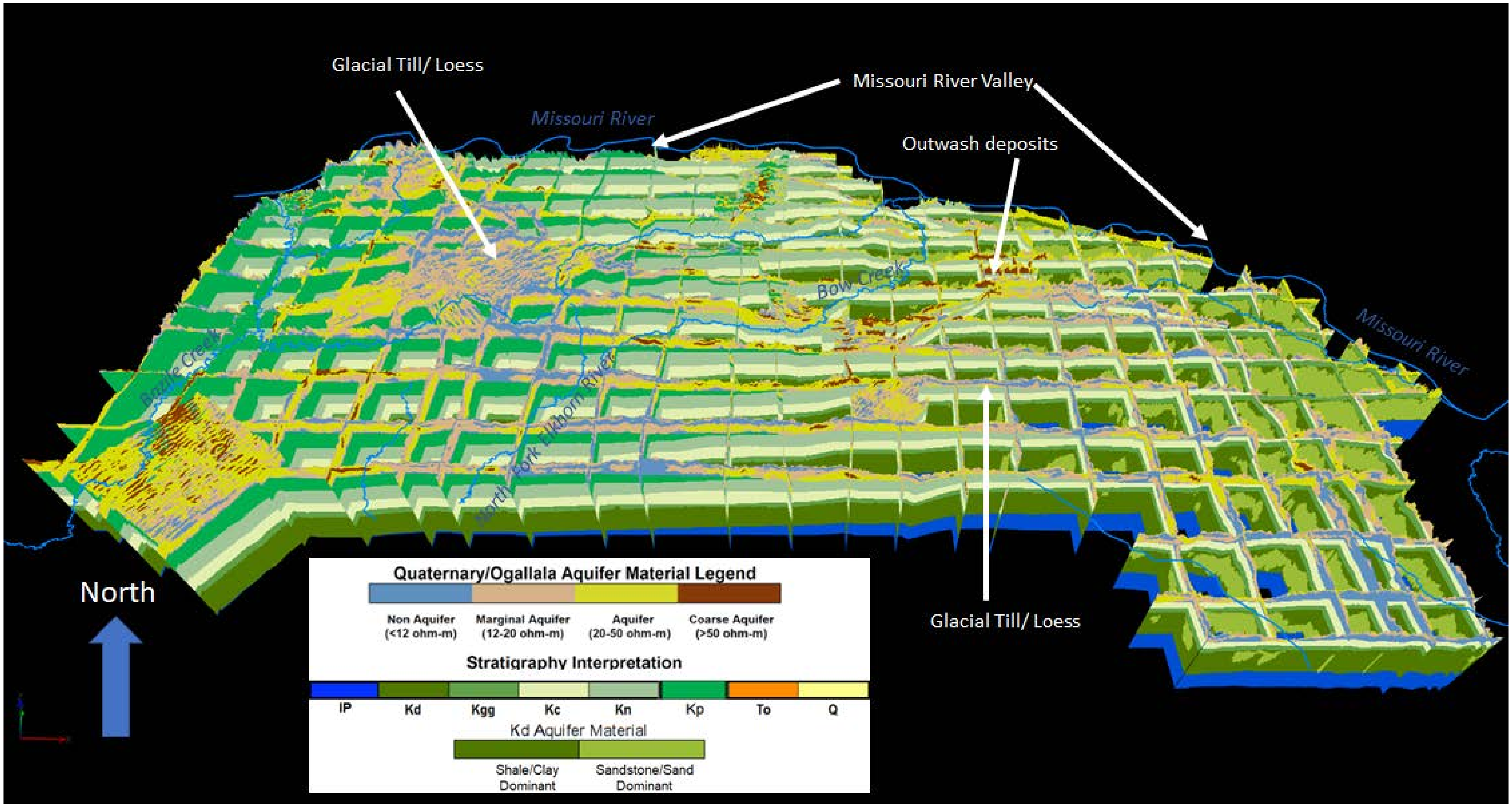


Figure 3-109. 3D fence diagram of the LCNRD 2018 lines looking north showing Quaternary and Tertiary Ogallala Group aquifer materials. Cretaceous units are colored in shades of green. Dark green is Shale/Clay Dominant and light green is Sandstone/Sand Dominant units of the Cretaceous Dakota. The blue area in the fence diagrams is the undifferentiated Pennsylvanian. The geologic units present in this survey area include *Q*= Quaternary, *To*=Tertiary Ogallala Group, *Kp*=Cretaceous Pierre Shale, *Kn*=Cretaceous Niobrara Formation, *Kc*= Cretaceous Carlile Shale, *Kgg*= Cretaceous Greenhorn Limestone and Graneros Shale, *Kd*= Cretaceous Dakota Group, *IP*=Undifferentiated Pennsylvanian. Vertical exaggeration (VE) = 20x.

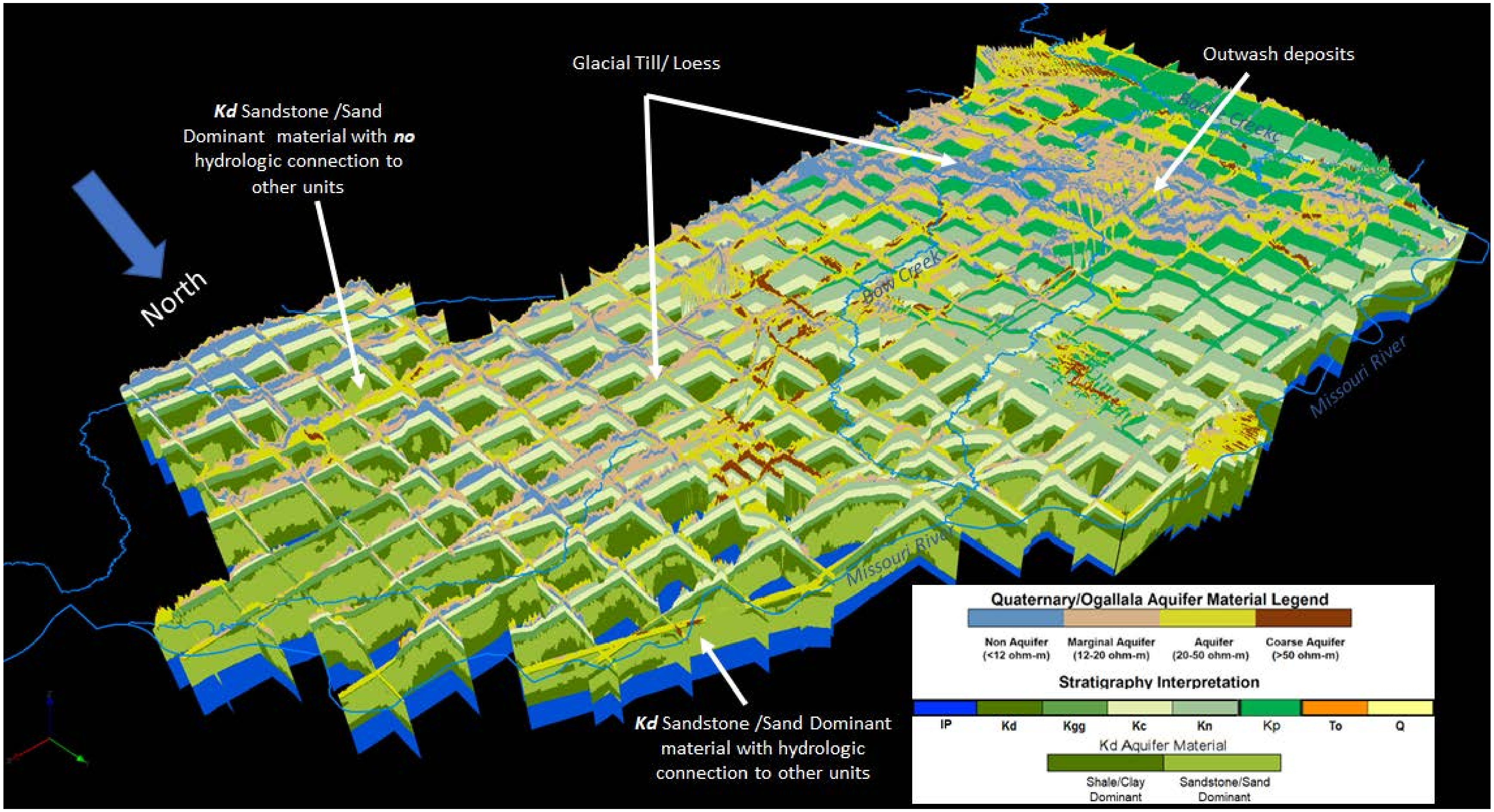


Figure 3-110. 3D fence diagram of the LCNRD 2018 lines looking southwest showing Quaternary and Tertiary Ogallala Group aquifer materials. Cretaceous units are colored in shades of green. Dark green is Shale/Clay Dominant and light green is Sandstone/Sand Dominant units of the Cretaceous Dakota. The blue area in the fence diagrams is the undifferentiated Pennsylvanian. The geologic units present include in this survey area *Q*= Quaternary, *To*=Tertiary Ogallala Group, *Kp*=Cretaceous Pierre Shale, *Kn*=Cretaceous Niobrara Formation, *Kc*= Cretaceous Carlile Shale, *Kgg*= Cretaceous Greenhorn Limestone and Graneros Shale, *Kd*= Cretaceous Dakota Group, *IP*=Undifferentiated Pennsylvanian. Vertical exaggeration (VE) = 20x.

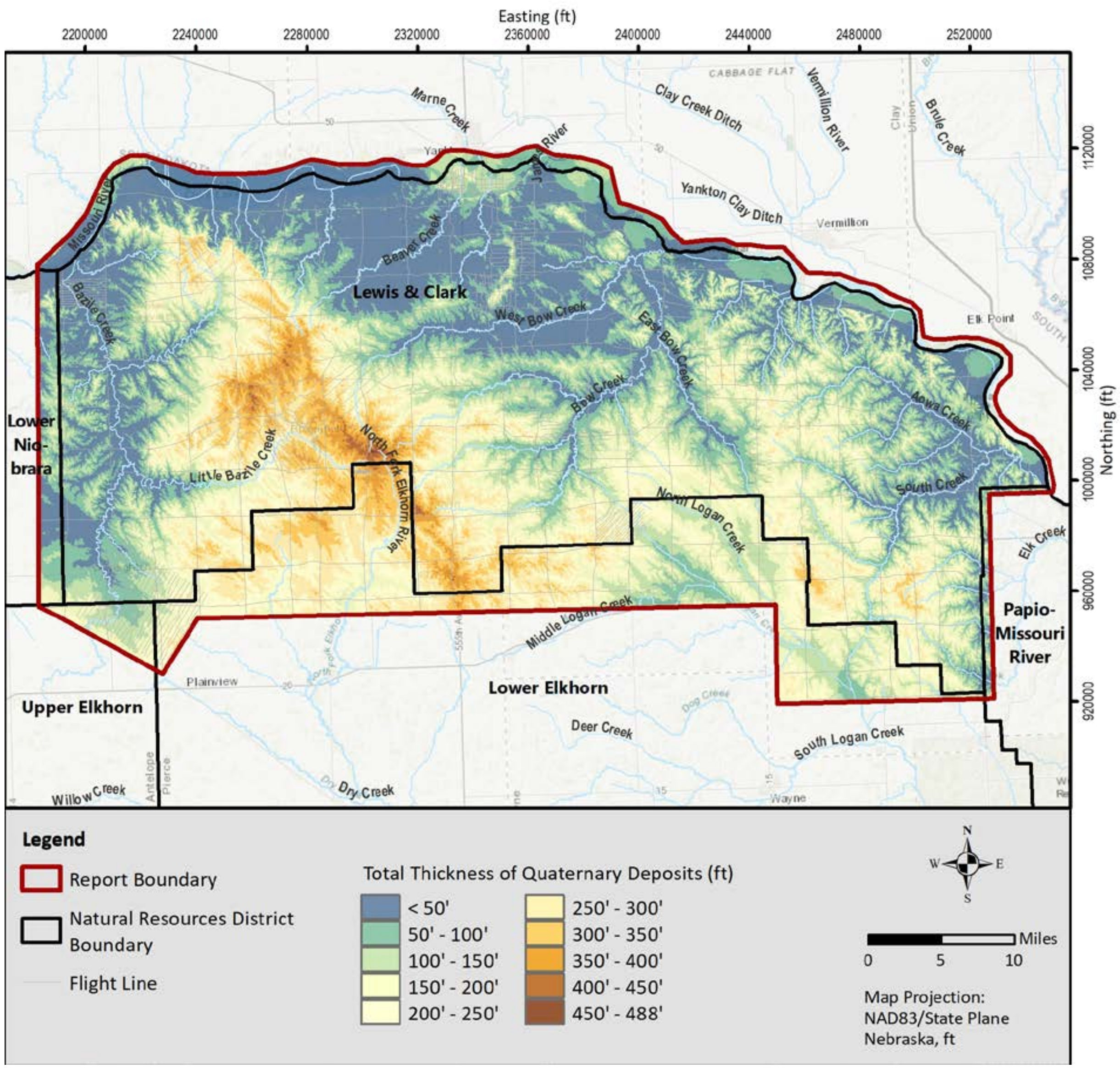


Figure 3-111. Map of the total Quaternary and the Tertiary Ogallala Group thickness of the AEM aquifer material thickness LCNRD 2018 Reconnaissance survey area. Note the thick areas are in the upland and the thin areas are in the stream valleys.

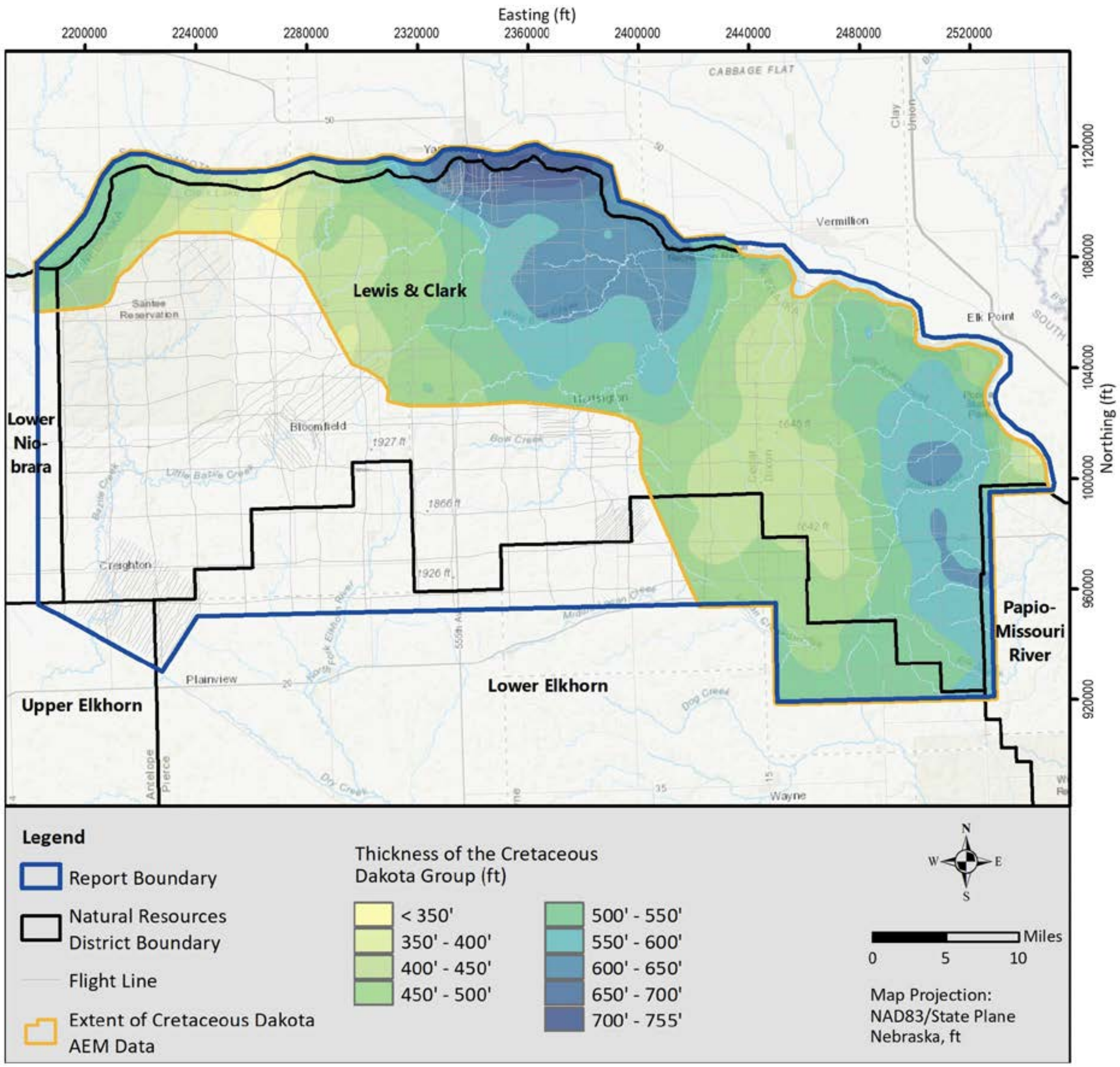


Figure 3-112. Map of the AEM total Cretaceous Dakota Group (*Kd*) thickness LCNRD 2018 Reconnaissance survey area. Note the thick areas near Yankton, South Dakota.

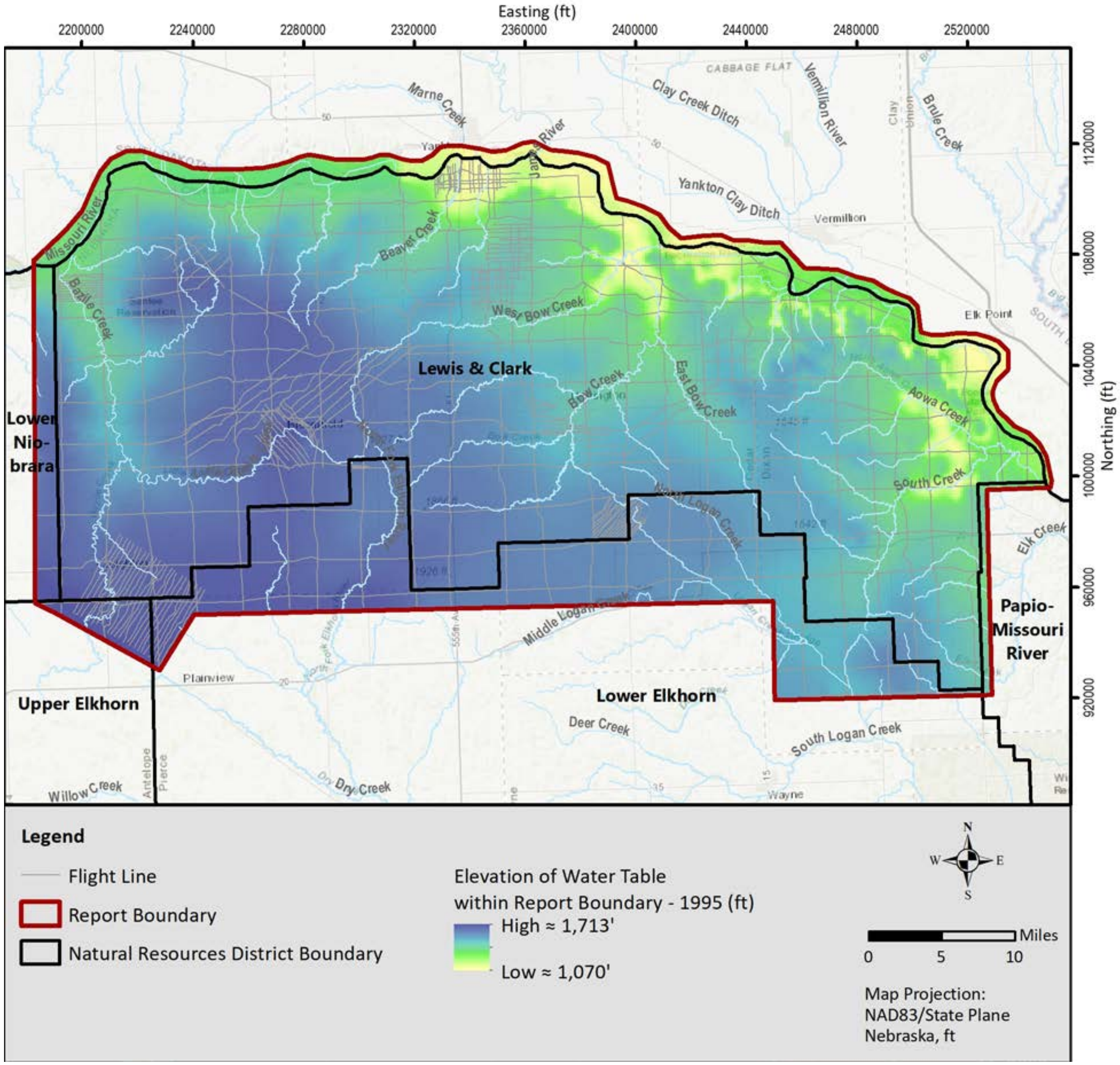


Figure 3-113. Map of the CSD 1995 water table within the LCNRD 2018 Reconnaissance survey area. Flight lines are indicated by grey lines.

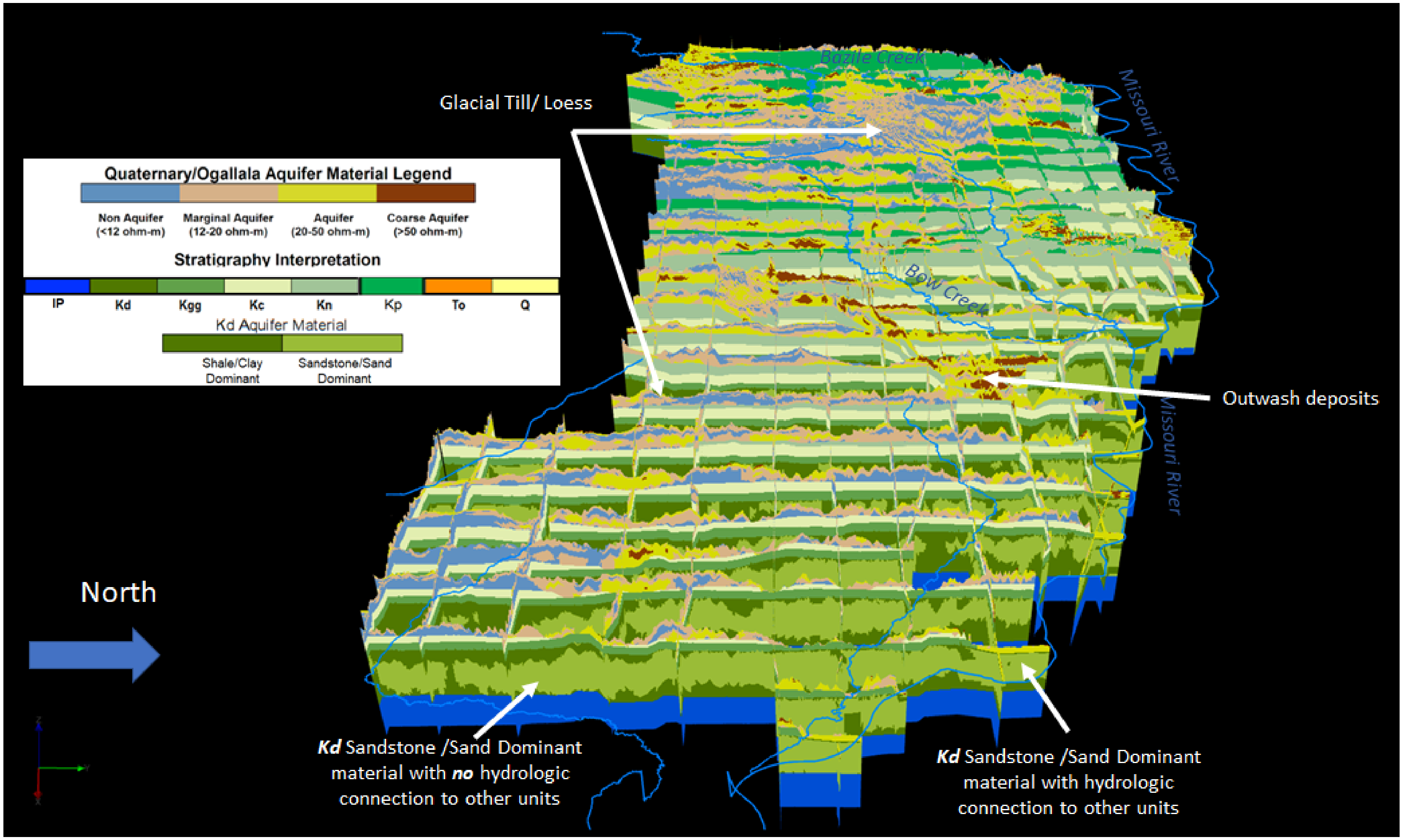


Figure 3-114. 3D fence diagram of the LCNRD 2018 Reconnaissance lines looking west showing Quaternary and Tertiary Ogallala Group aquifer materials. Cretaceous units are colored in shades of green. Dark green is Shale/Clay Dominant and light green is Sandstone/Sand Dominant units of the Cretaceous Dakota Group. Note the abundance of Kd sandstone/sand dominant materials on the east end of the area (bottom of image). The blue area in the fence diagrams is the undifferentiated Pennsylvanian. The geologic units present in this survey area include *Q*= Quaternary, *To*=Tertiary Ogallala Group, *Kp*= Cretaceous Pierre Shale, *Kn*=Cretaceous Niobrara Formation, *Kc*= Cretaceous Carlile Shale, *Kgg*= Cretaceous Greenhorn Limestone and Graneros Shale, *Kd*= Cretaceous Dakota Group, *IP*=Undifferentiated Pennsylvanian. Vertical exaggeration (VE) = 20x.

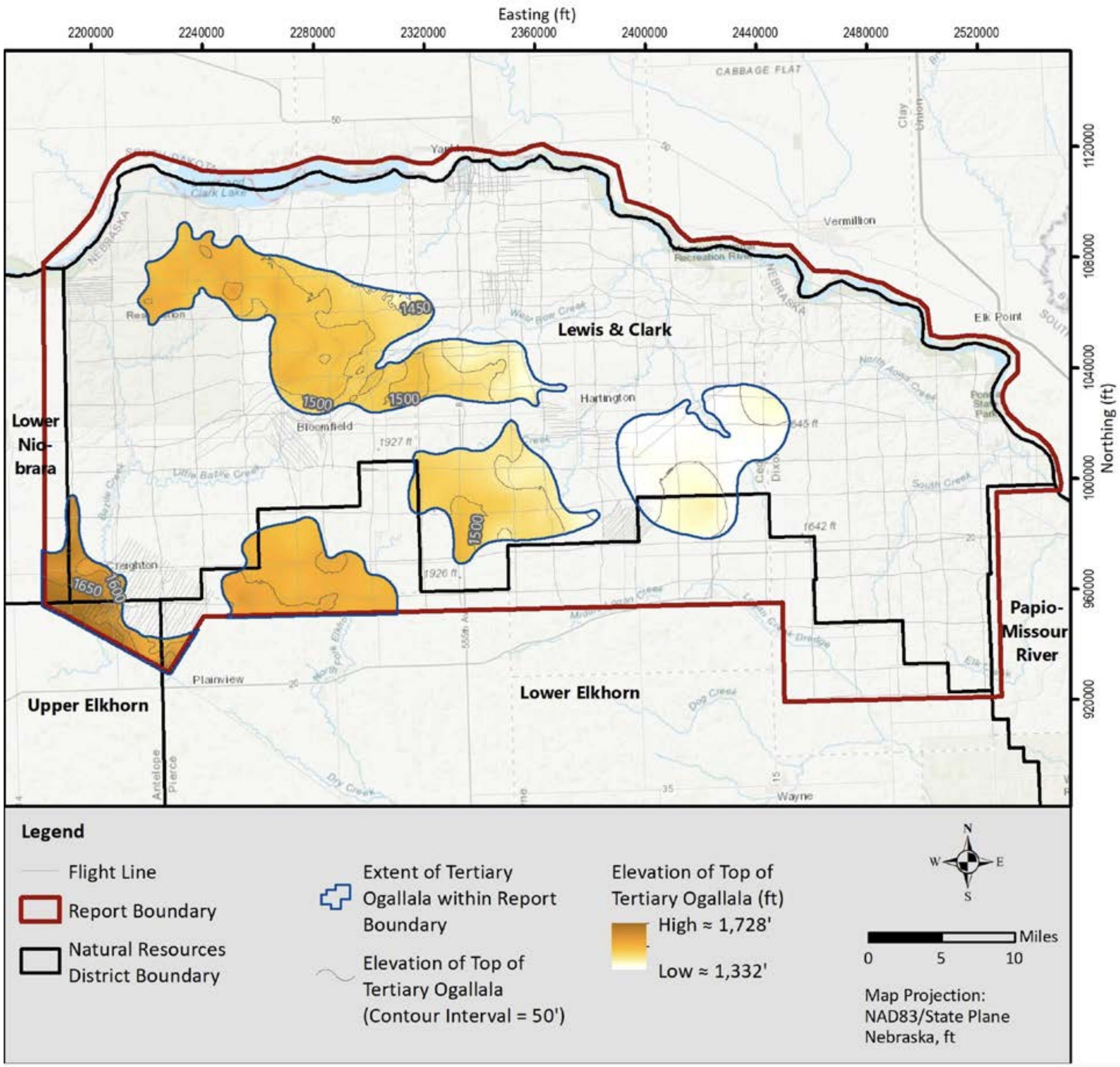


Figure 3-115. Map of the extent of the Tertiary Ogallala (*To*) within the LCNRD Reconnaissance AEM survey area.

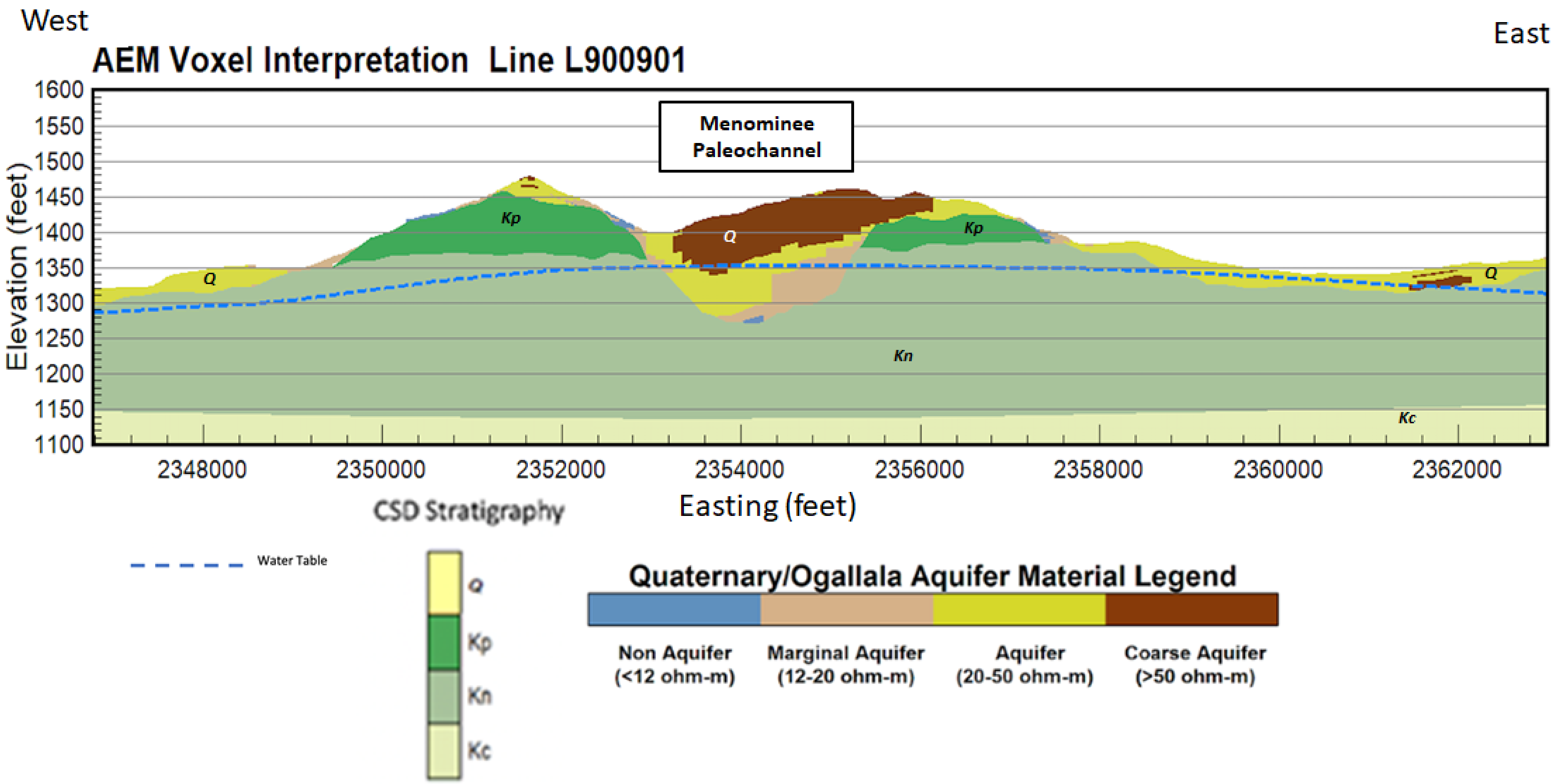


Figure 3-116. Interpreted east-west line L900901 crosses the Menominee paleochannel near West Bow Creek. This is a paleochannel that is imaged by the AEM as well as by NE-DNR registered wells and CSD test holes. Note the sharp incision through the Cretaceous Pierre Shale (*Kp*) and Niobrara Formation (*Kn*). The CSD 1995 water table is indicated with a dashed blue line. The geologic units present on this image include *Q*= Quaternary, *Kp*= Cretaceous Pierre Shale, *Kn*=Cretaceous Niobrara Formation, *Kc*= Cretaceous Carlile Shale. Horizontal datum is NAD83 State Plane Nebraska (feet).

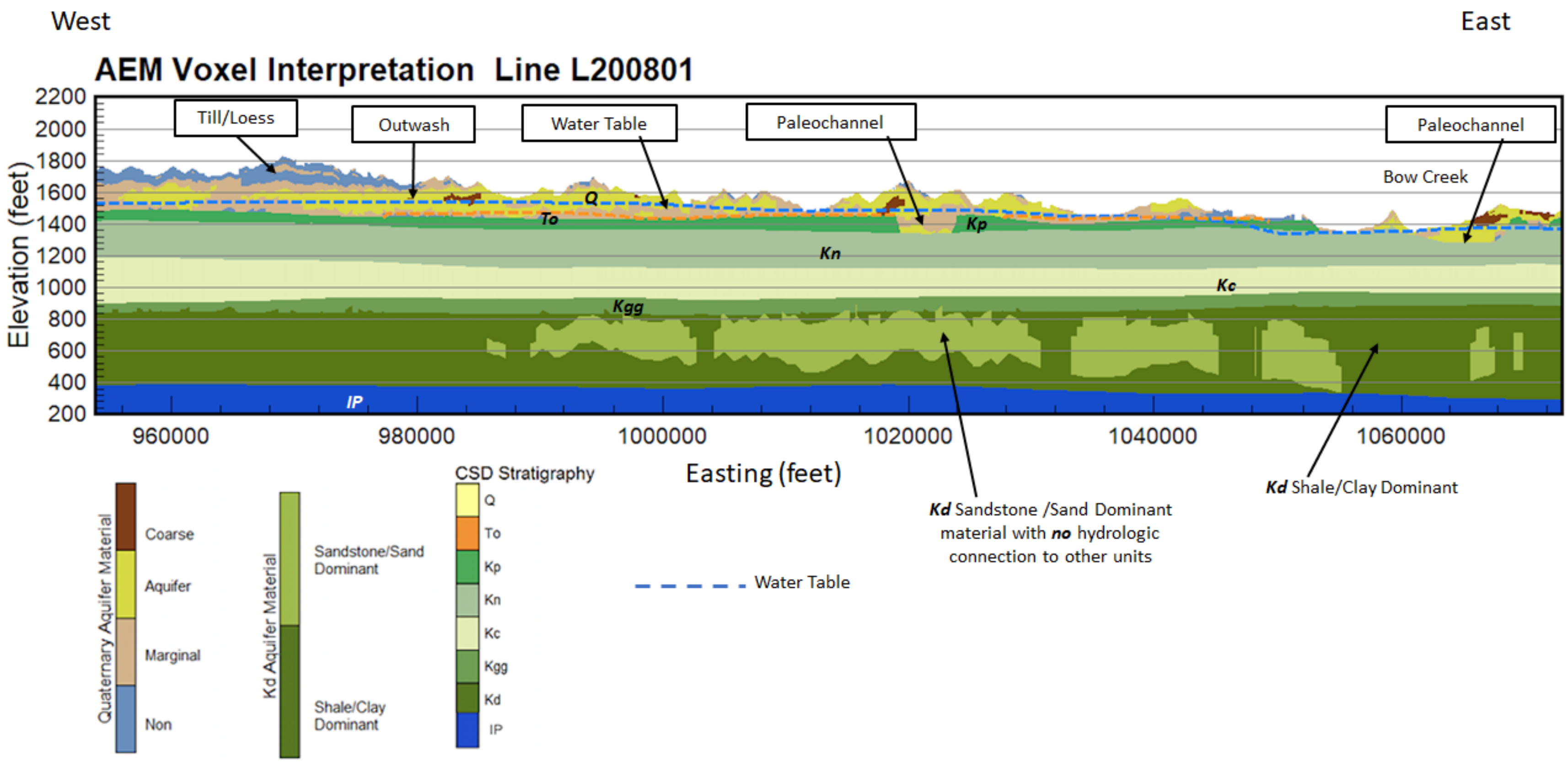


Figure 3-117. Interpreted north-south line L200801 near Fordyce, Nebraska displays the subsurface deposits of geologic units of the uplands area inclusive of Bow Creek Valley at the northern end of the profile which is also near the Menominee paleovalley area. The geologic units present in the AEM survey area include the *Q*= Quaternary, *To*=Tertiary Ogallala Group, *Kp*= Cretaceous Pierre Shale, *Kn*=Cretaceous Niobrara Formation, *Kc*= Cretaceous Carlile Shale, *Kgg*= Cretaceous Greenhorn Limestone and Graneros Shale, *Kd*= Cretaceous Dakota Group, *IP*=Undifferentiated Pennsylvanian. Note the small amount of Sandstone/Sand Dominant material in the *Kd*. The CSD 1995 water table is indicated with a dashed blue line. Horizontal datum is NAD83 State Plane Nebraska (feet).

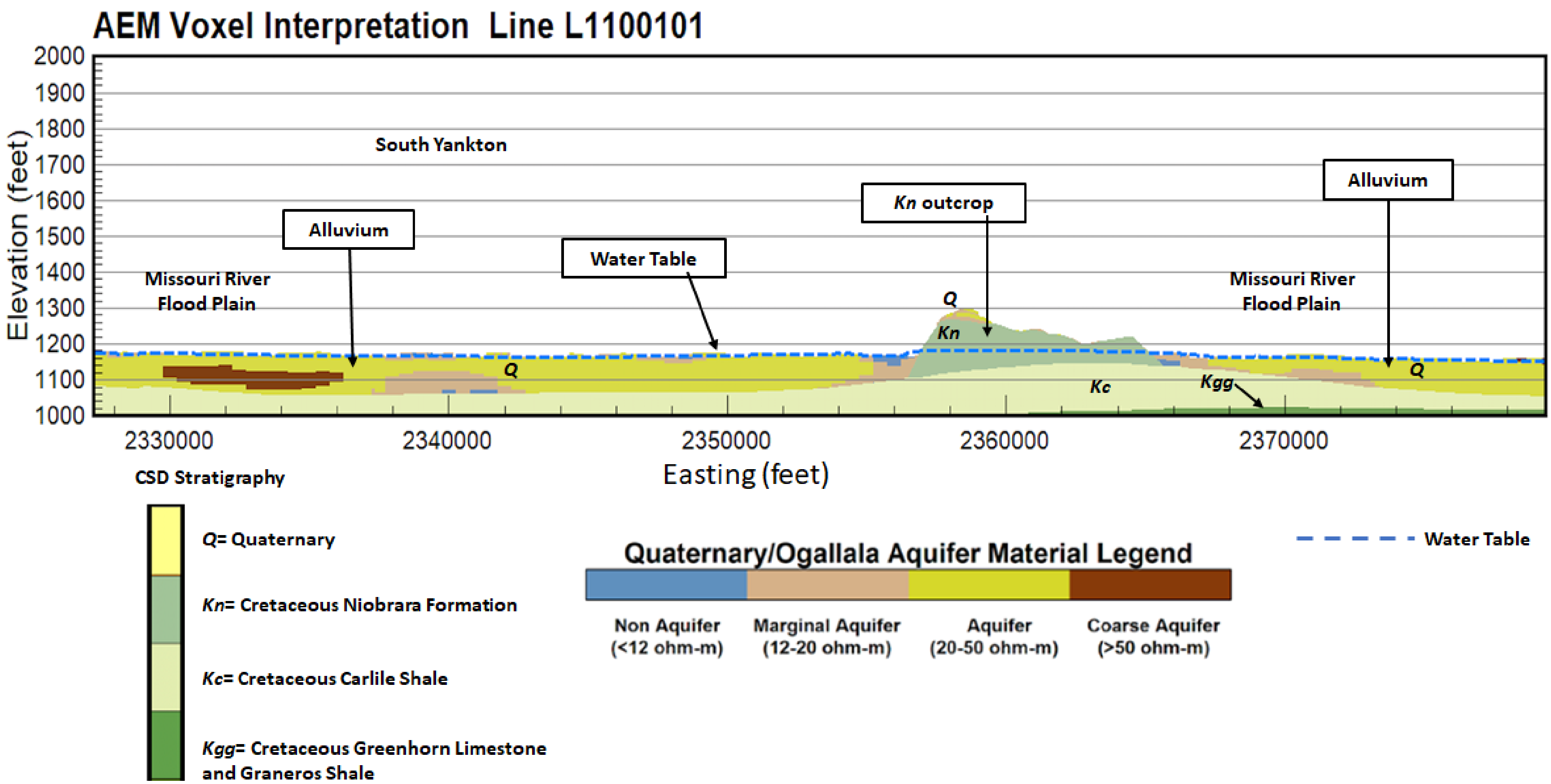


Figure 3-118. Interpreted east-west line L1100101 lies in the Missouri River flood plain. The Quaternary (*Q*) sediments average ~20-100 feet thick in this area and rest upon the Cretaceous Niobrara Formation (*Kn*)and Carlile Shale (*Kc*) and. There is a small outcrop of *Kn* near the center of the line that forms a small hill. The geologic units present in this image include *Q*= Quaternary, *Kn*=Cretaceous Niobrara Formation, *Kc*= Cretaceous Carlile Shale, and *Kgg*= Cretaceous Greenhorn Limestone and Graneros Shale. The CSD 1995 water table is indicated with a dashed blue line. Horizontal datum is NAD83 State Plane Nebraska (feet).

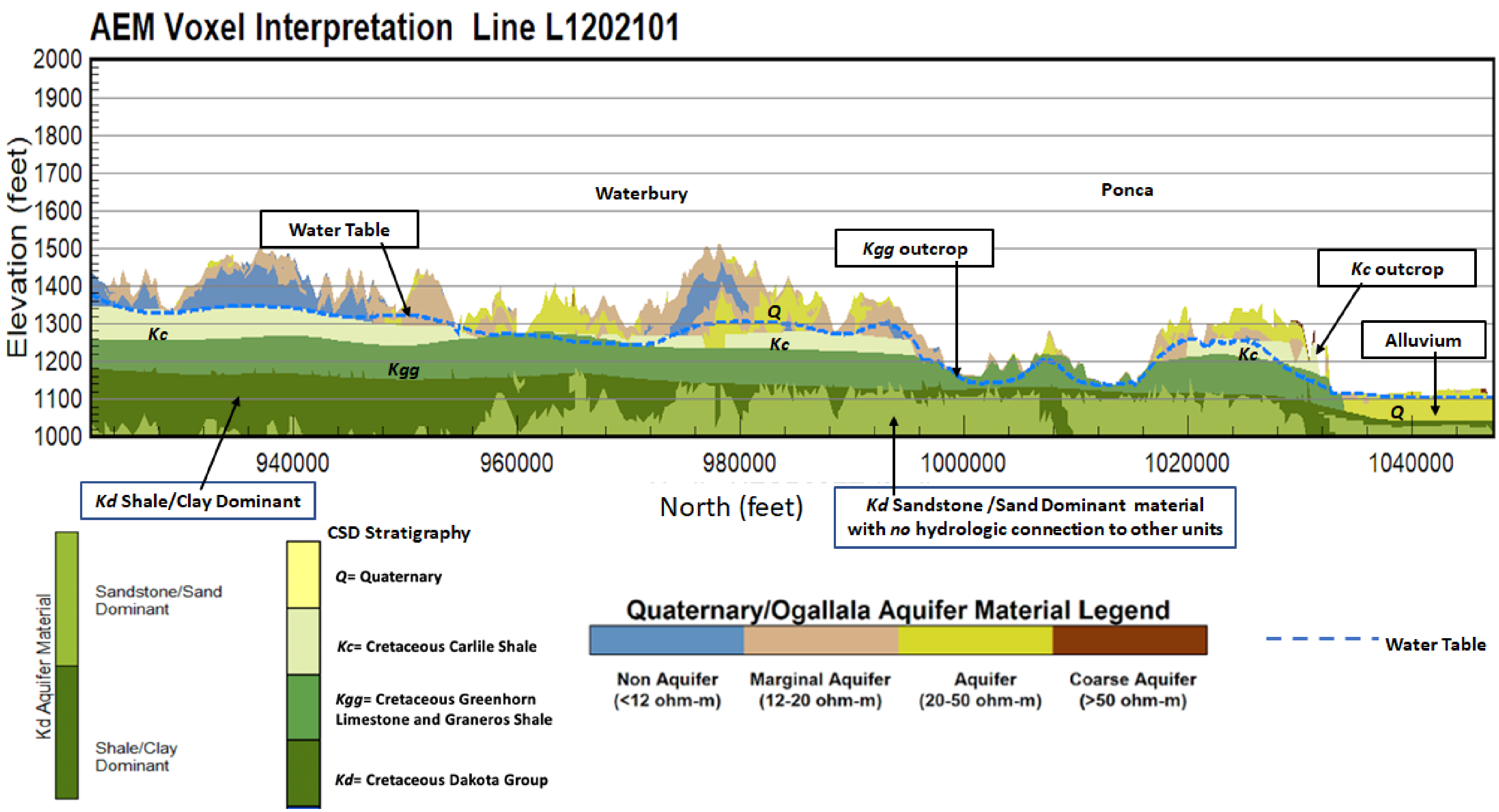


Figure 3-119. Interpreted north-south line L1202101 near the towns Waterbury and Ponca, Nebraska. It starts in the dissected hills in the south and continues north to the Missouri River flood plain. The geologic units present in this image include the Quaternary (*Q)* sediments lying upon the *Kc*= Cretaceous Carlile Shale, *Kgg*= Cretaceous Greenhorn Limestone and Graneros Shale, and *Kd*= Cretaceous Dakota Group. Cretaceous Dakota (*Kd*) which is composed of a mix of Sandstone/Sand Dominant and Shale/Clay Dominant material and has no hydrologic connection where the *Kd* Sand/Sandstone Dominant materials are in contact with the *Q* materials. The CSD 1995 water table is indicated with a dashed blue line.

Using the interpretive surfaces and grids that were produced as described above (in Section 3.1.4), an enhanced understanding of the hydrogeological framework of the LCNRD AEM survey area can be achieved. Referring back to Figure 3-111 which shows the total thickness of all ***Q*** aquifer materials, the ***Q*** alluvial fill in the valleys tend to be thinner than the till/loess covered hills surrounding the valleys. When the 1995 CSD water table is used to separate the total thickness of aquifer materials into saturated and unsaturated materials, and calculation of the saturated thickness can be determined (Figure 3-120), the Menominee paleochannel has a thickness of ~20-100 feet of ***Q*** materials.

Across the project area the various Cretaceous formations make up the bedrock of the area and come in contact with the ***Q*** sediments and ***To*** where they coexist. The youngest Cretaceous unit is in the western part of the project area and is ***Kp.*** The extent of the top of the ***Kp*** surface is shown in Figure 3-121 and it varies in elevation from 1,220 to 1,655 feet. Note the bedrock high to the west by Bazile Creek next to the incised drainage of the creek. The discontinuous nature of the ***Kp*** south of Yankton, South Dakota is the extent of the shale from west to east.

Figure 3-122 presents the elevation of the upper surface of the ***Kn*** which lies below the ***Kp***. The elevation varies from 1,113 to 1,455 feet with the lowest elevation to the west near Bazile Creek. There is a channel in the top surface of the ***Kn*** near Bloomfield, Nebraska which extends west towards Creighton, Nebraska. The highest elevation of the ***Kn*** is south of Hartington, Nebraska

Figure 3-123 presents the elevation of the upper surface of the ***Kc*** which lies below the ***Kn***. The elevation varies from 956 to 1,386 feet with the lowest elevation to the west near Creighton, Nebraska. There is a channel in the top surface of the ***Kc*** near Creighton, Nebraska which extends west. The yellow line on the map shows the easternmost extent of the ***Kc***. The highest elevation of the ***Kc*** is near the boundary with Papio-Missouri River NRD.

Figure 3-124 presents the elevation of the upper surface of the ***Kgg*** which lies below the ***Kc***. The elevation varies from 818 to 1,421 feet with the lowest elevation to the west near the extent of the ***Kgg*** AEM data. The blue line on the map shows the westernmost extent of the ***Kgg***.

Figure 3-125 is the elevation of the upper surface of the ***Kd*** which lies below the ***Kgg***. The elevation varies from 698 feet to 1,176 feet with the lowest elevation near the extent of the ***Kd*** AEM data on the west side and highest elevation to the eastside of the project area. The blue line on the map shows the westernmost extent of the ***Kd***. Figure 3-126 shows the thickness of the ***Kd*** in the area which varies from <350 feet 15 miles west of Yankton, South Dakota to 755 feet at Yankton.

Using the data within the NE-DNR well database, plots of the specific capacity of wells can be overlain on a map of the thickness of the **Q**/***To*** combined, as well as the ***Kd*** deposits. Utilizing the new interpretation presented within this report on the position of the top of the ***Kd***, the NE-DNR wells were split between areas that had screens within the ***Q*** and within the ***Kd***. The magnitudes of the specify capacities as reported within the database were plotted and provide affirmation of the interpretations provided by the AEM aquifer material separations and categories.

Figure 3-127 is a map of the thickness of saturated **Q**/***To*** combined over the LCNRD 2018 Reconnaissance AEM survey area. The areas of the Missouri River Flood Plain along with the west and southern uplands are easy to see with the many wells with specific capacities of 25 gpm/ft or greater. Also indicated are areas of paleochannels and outwash on the uplands. To the west, the impact of the ***To*** near Creighton can also be observed.

Figure 3-128 is a map of the thickness of saturated ***Kd*** material with the specific capacity of the wells that are screened in that zone shown. What is easily seen is the areas that have Sandstone/Sand Dominant materials which are the aquifer materials and their approximate locations throughout the area. The majority of these areas are in the middle portion of the project area stretching from Yankton, South Dakota to boundary with Lower Elkhorn NRD (red shaded area in Figure 3-129).

These areas provide a couple of possible reasons for being where the higher specific capacities are found: 1) These area have had the overlaying Cretaceous sediments eroded off allowing for water exchange and input from water sources from the pre-Pleistocene and younger water through recharge; and 2) These areas have had cementation removed from exposure to weathering allowing for flow enhancements due to dissolution of the cementation associated with these original ***Kd*** deposits.

To better understand the ***Kd*** deposits, an improved understanding of the depositional system of the ***Kd*** needs to be put forward. Witzke and Ludvigson (1994) published a cartoon depicting a prograding deltaic environment during deposition of the ***Kd*** as a way to understand the deposits (Figure 3-130).

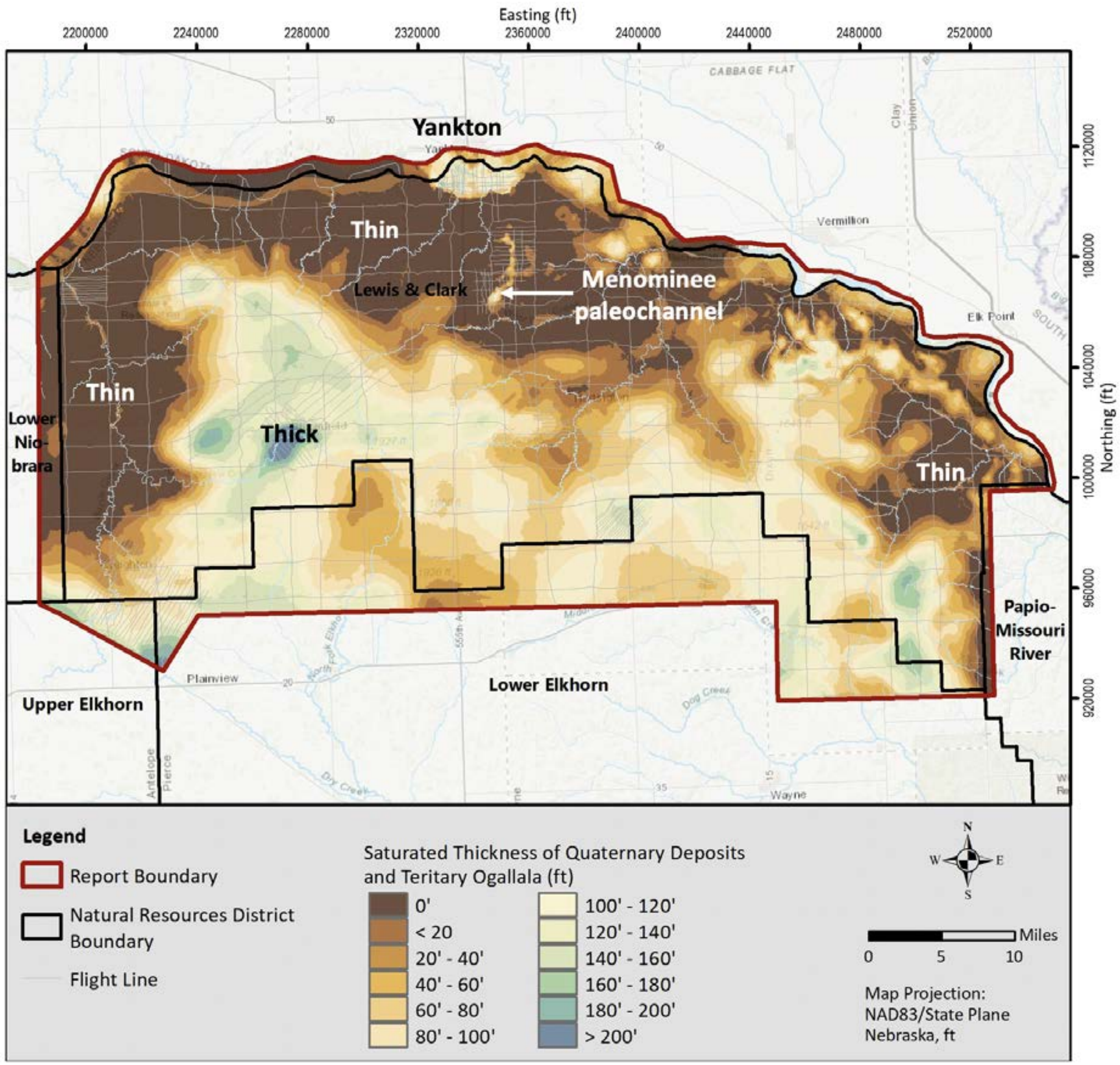


Figure 3-120. Map of the saturated thickness of Quaternary (*Q*) and Tertiary Ogallala Group (*To*) aquifer materials within the 2018 LCNRD Reconnaissance survey area. Saturated thickness varies from 0 to 406 feet. Flight lines are indicated by the grey lines.

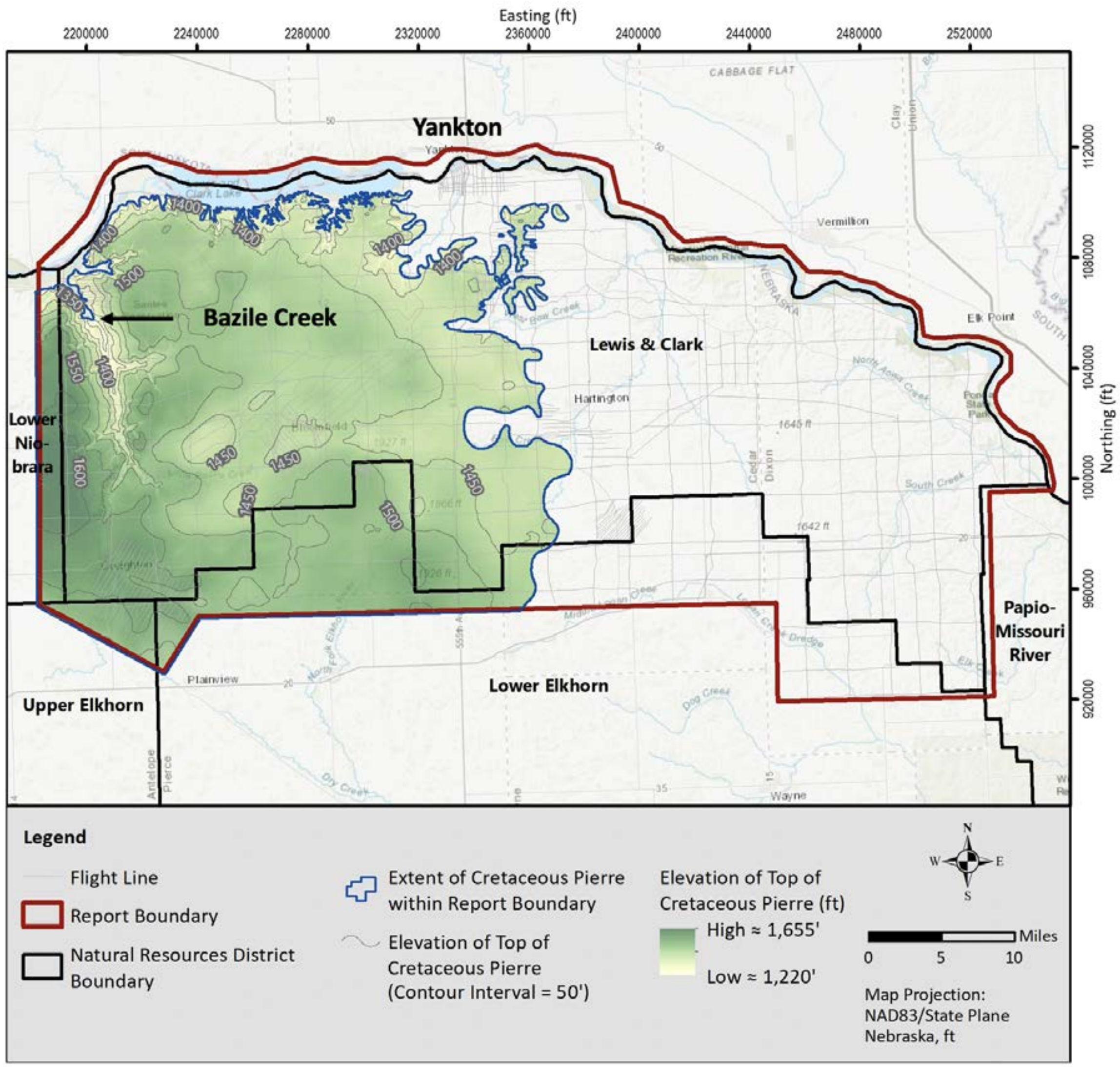


Figure 3-121. Map of the top surface of the Cretaceous Pierre Shale (*Kp*) within the 2018 LCNRD Reconnaissance AEM survey area. Flight lines are indicated by the grey lines. The *Kp* is only present in the western part of the area and varies in elevation from 1,220 to 1,655 feet from east to west. Note the channel formed by Bazile Creek.

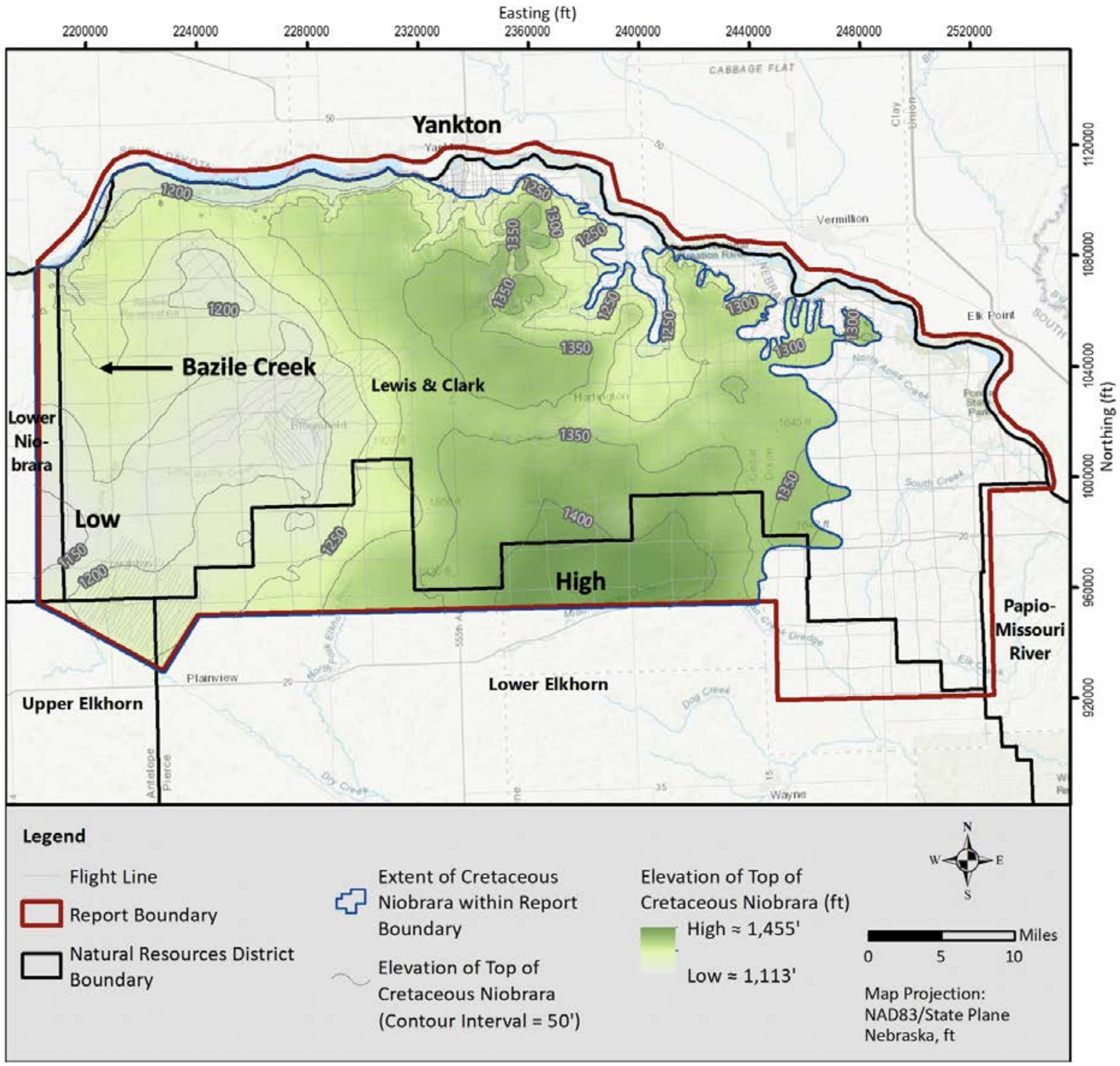


Figure 3-122. Map of the top surface of the Cretaceous Niobrara Formation (*Kn*) within the 2018 LCNRD Reconnaissance AEM survey area. Flight lines are indicated by the grey lines. The elevation varies from 1,113 to 1,455 feet from east to west.

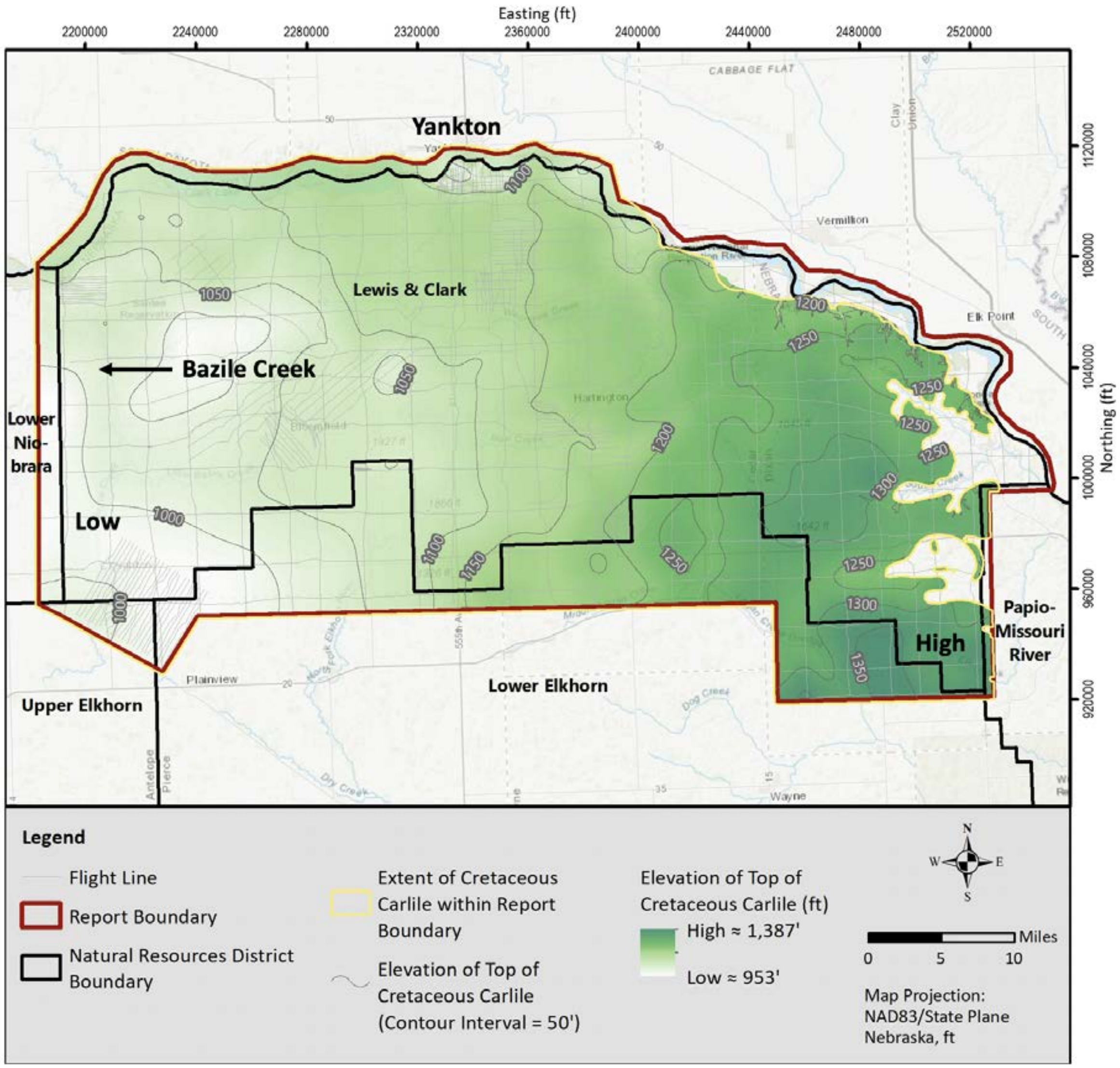


Figure 3-123. Map of the top surface of the Cretaceous Carlile Formation (*Kc*) within the 2018 LCNRD Reconnaissance AEM survey area. Flight lines are indicated by the grey lines. The *Kc* is present across the area except the east side of the area and varies in elevation from 956 to 1,386 feet from west to east.

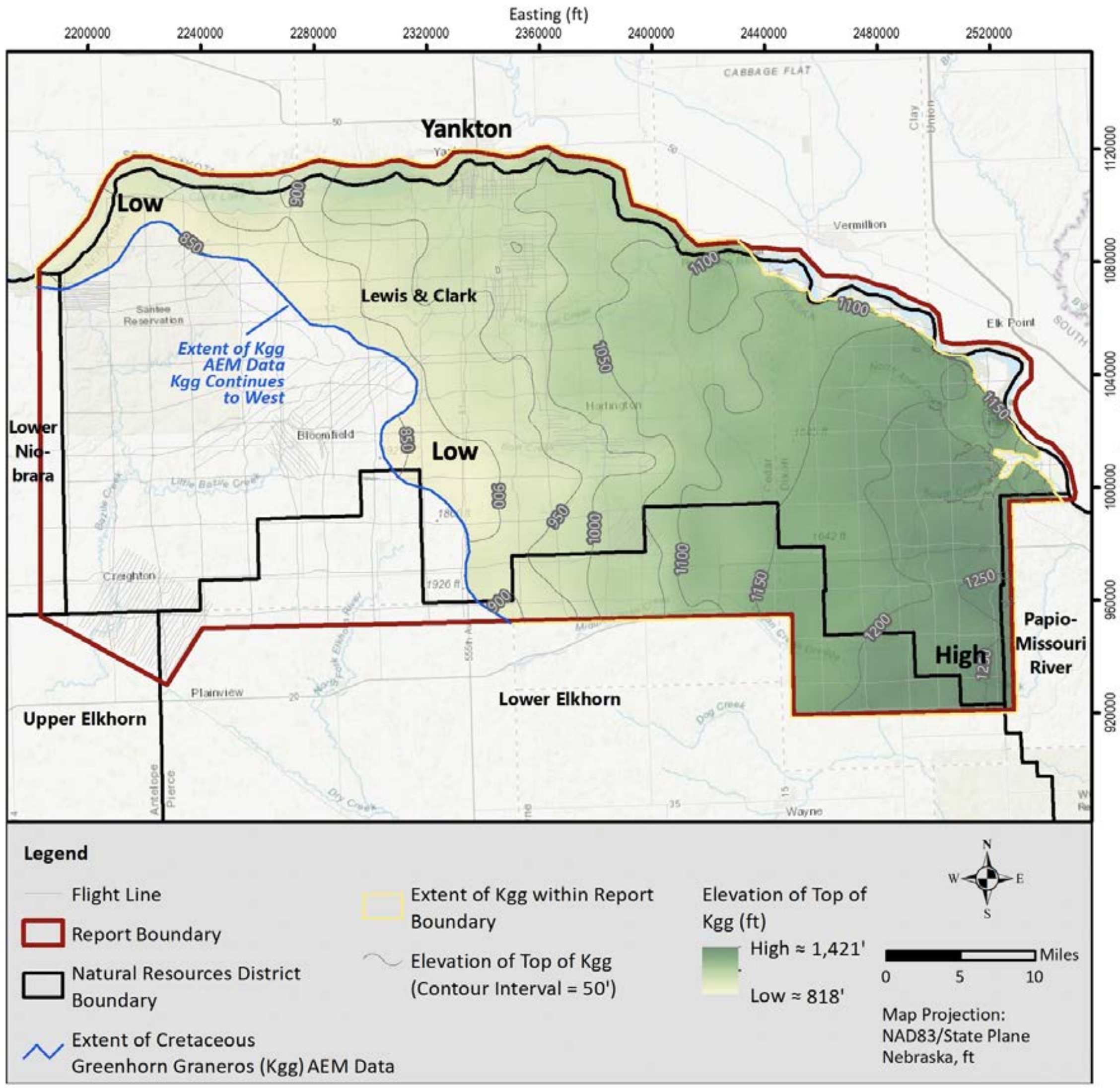


Figure 3-124. Map of the top surface of the of Cretaceous Greenhorn-Graneros Formation (*Kgg*) within the 2018 LCNRD Reconnaissance AEM survey area. Flight lines are indicated by the grey lines. The *Kgg* is only mapped in the eastern part of the area and varies in elevation 818 to 1,421 feet from east to west.

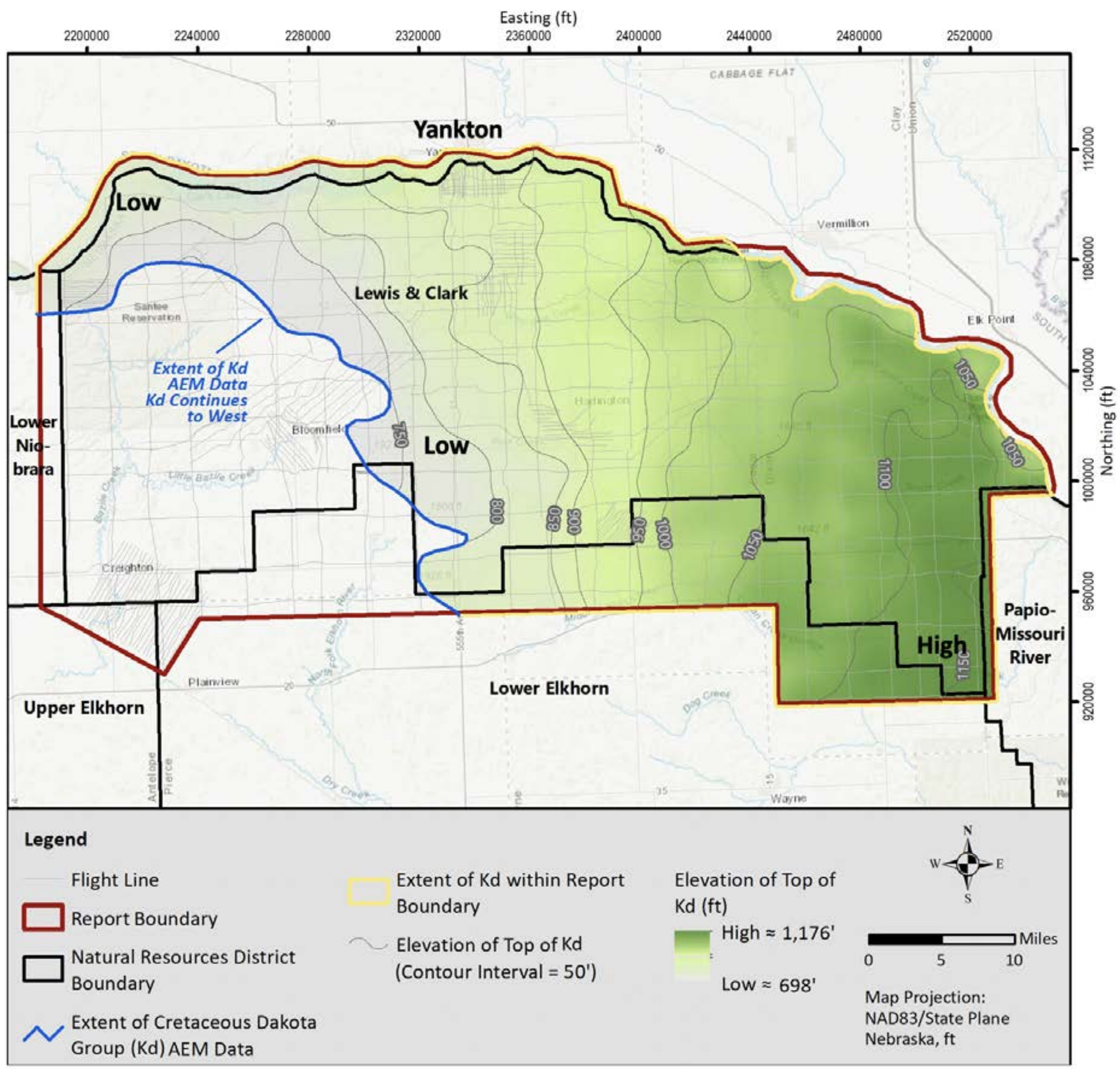


Figure 3-125. Map of the top surface of the of Cretaceous Dakota Group (*Kd*) within the 2018 LCNRD Reconnaissance AEM survey area. Flight lines are indicated by the grey lines. The *Kd* is present in most of the LCNRD AEM survey area and varies in elevation 698 to 1,176 feet.

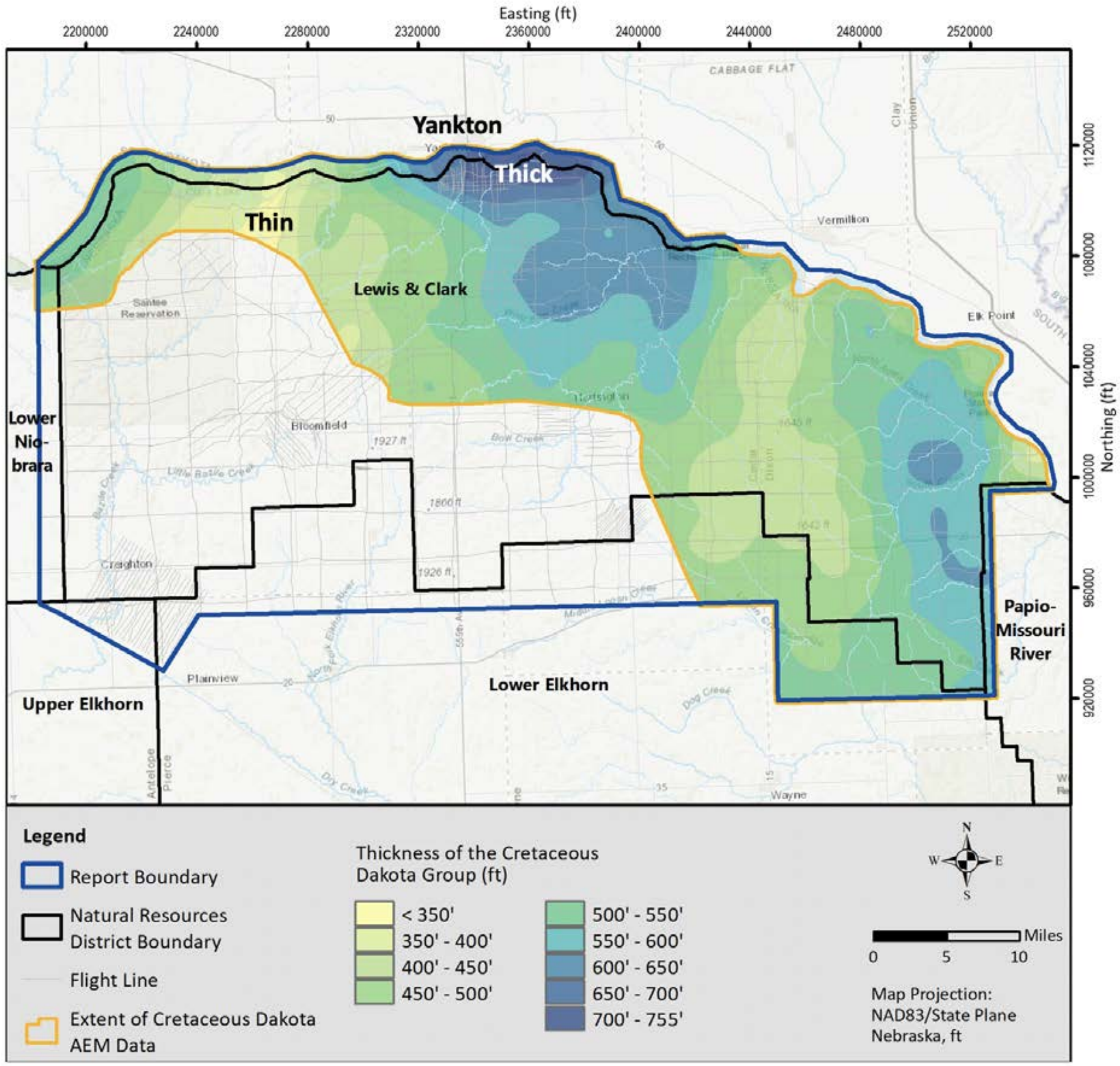


Figure 3-126. Map of the thickness of the Cretaceous Dakota Group (*Kd*) within the 2018 LCNRD Reconnaissance AEM survey area. Flight lines are indicated by the grey lines. The thickness varies from <350-775 feet with the thickest are near Yankton, South Dakota.

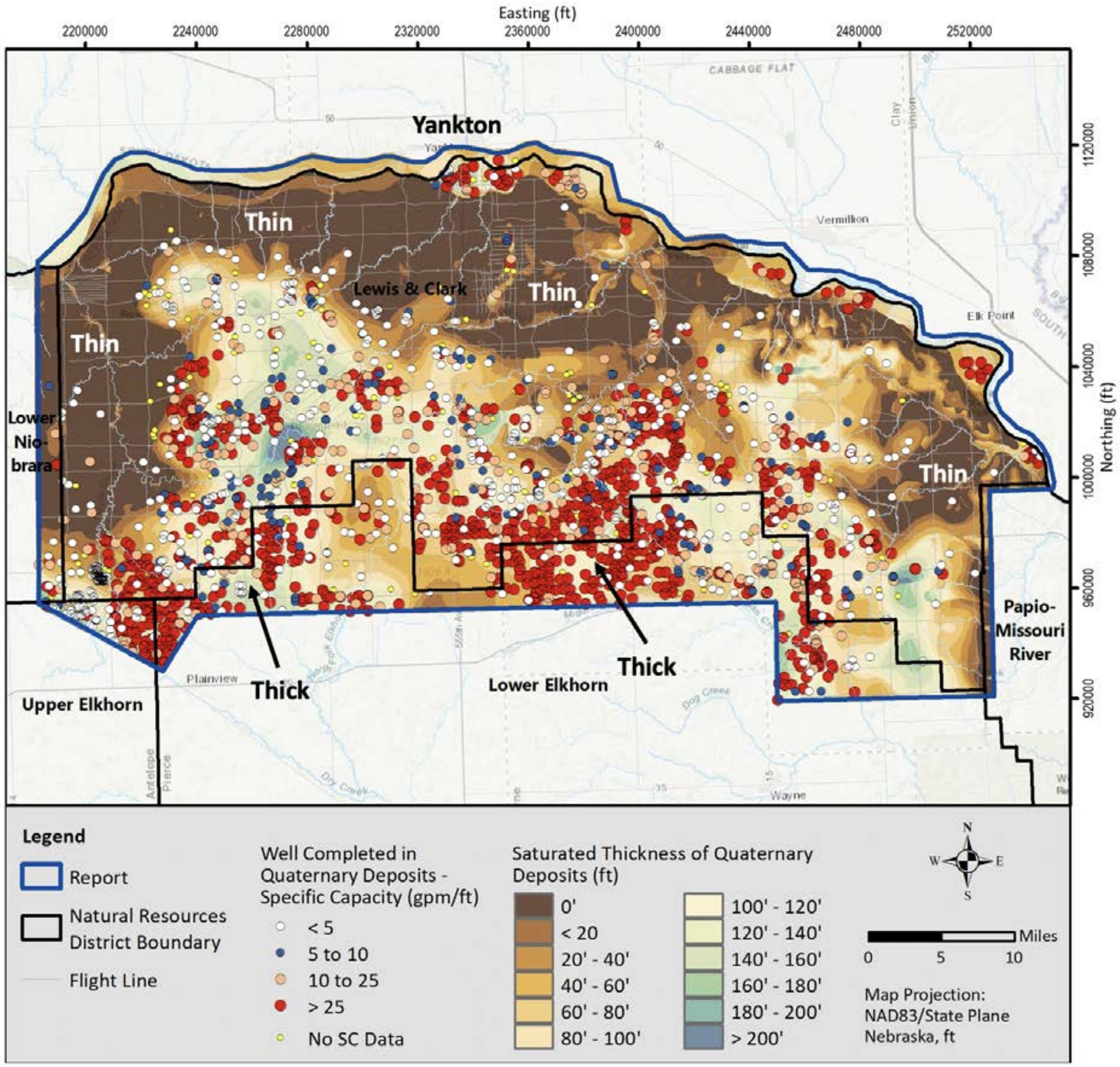


Figure 3-127. Map of the saturated Quaternary and Tertiary Ogallala Group thickness for the LCNRD 2018 Reconnaissance AEM survey area plus the specific capacity of wells screened within the Quaternary from the NE-DNR registered well database.

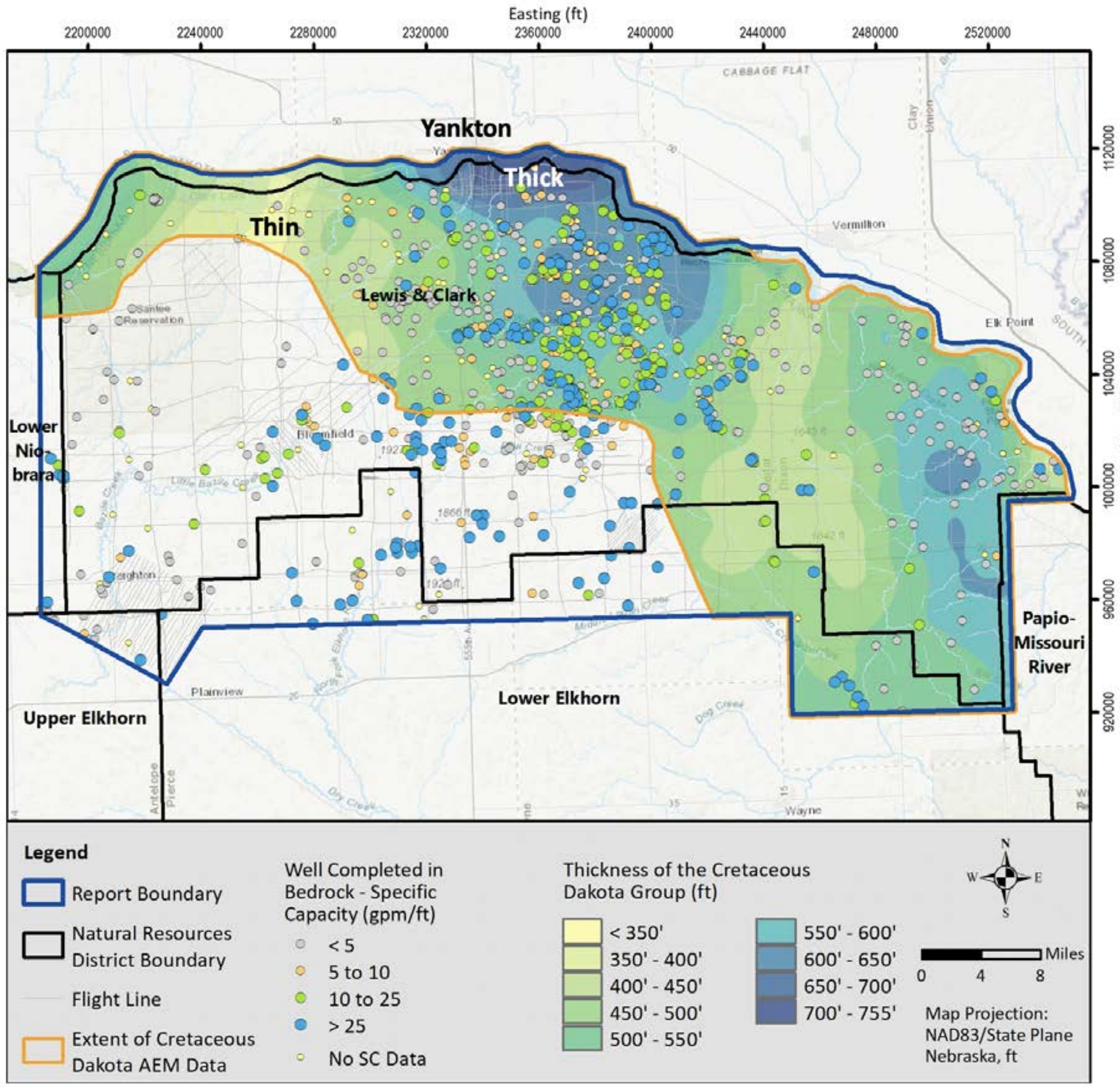


Figure 3-128. Map of the thickness of saturated Cretaceous Dakota Group for the LCNRD 2018 Reconnaissance AEM survey area plus the specific capacity of wells screened within the Cretaceous Dakota Group from the NE-DNR registered well database.

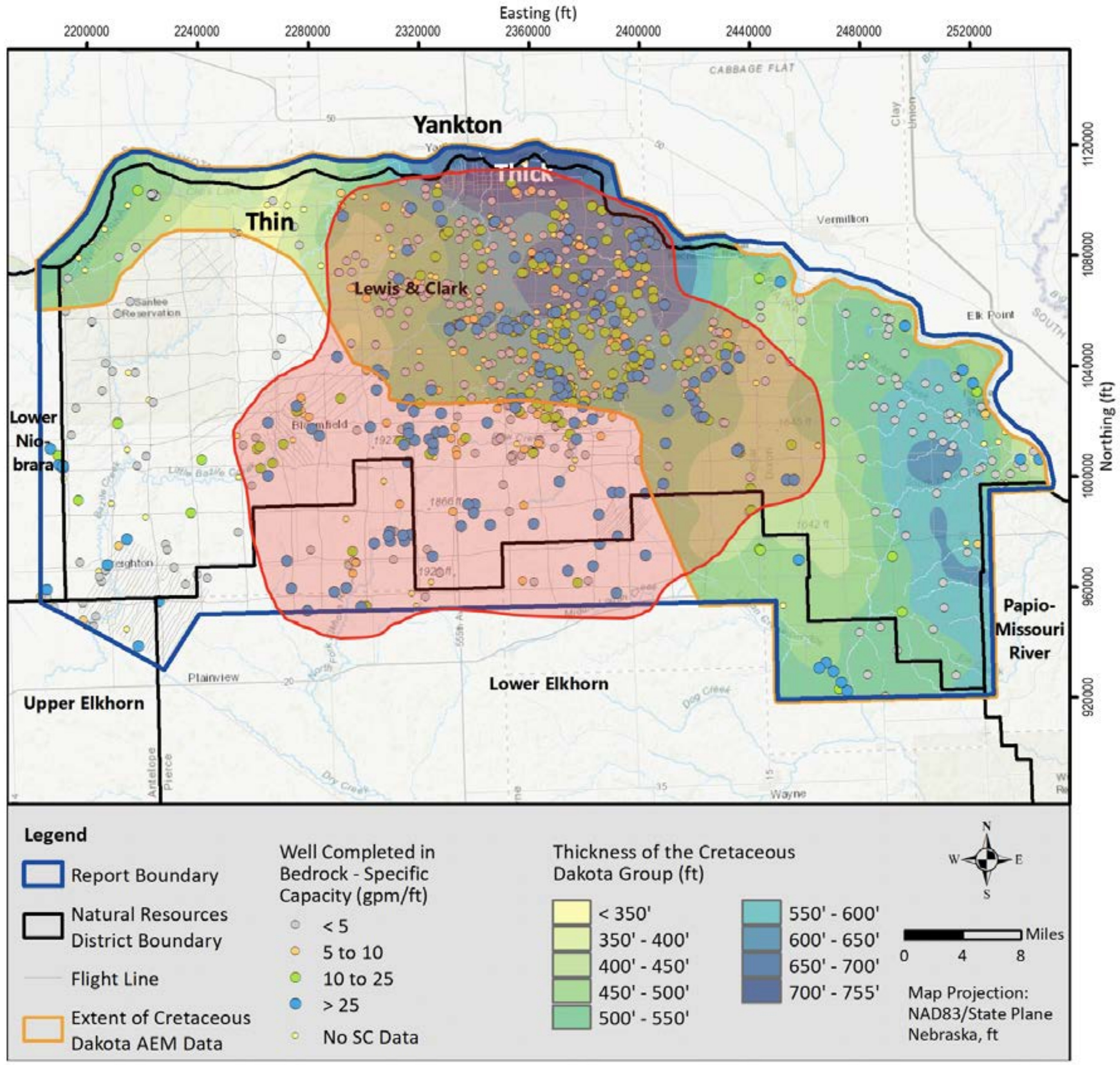


Figure 3-129. Map of the thickness of saturated Cretaceous Dakota Group in the LCNRD 2018 Reconnaissance AEM survey area plus the specific capacity of wells screened within the Cretaceous Dakota Group (*Kd*) from the NE-DNR registered well database. The red-shaded polygon denotes the highest concentration of *Kd* wells with >25 gpm capacity.

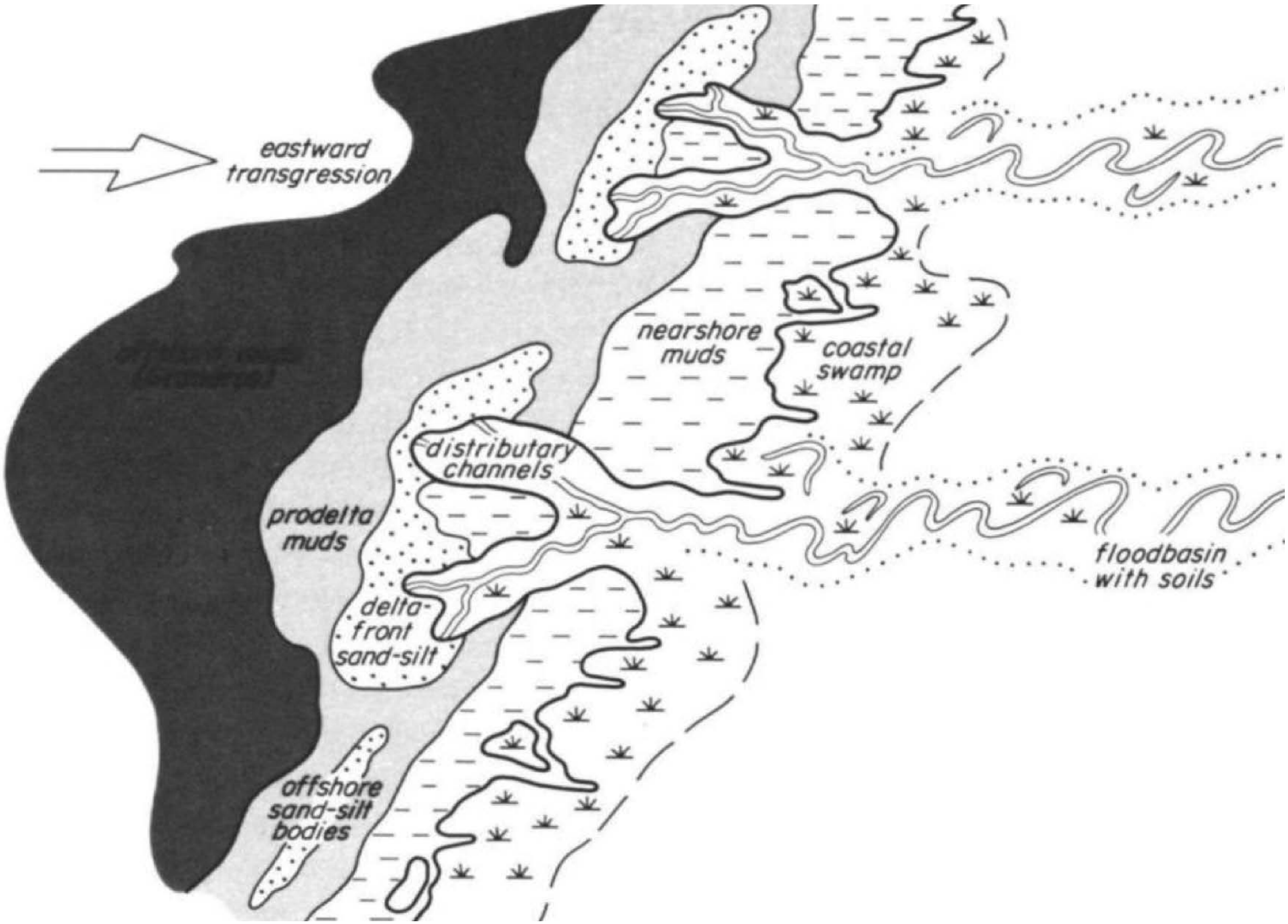


Figure 3-130. Depositional environment of the Cretaceous Dakota Group sediments in eastern Nebraska and western Iowa (Witzke and Ludvigson, 1994).

3.2.2 Hydrogeologic Framework of the Aten Block AEM Survey Area

The AEM provided insight into the geographic distribution and extent of the unconsolidated material in the Aten Block AEM survey area. The ***Q*** materials within the Aten Block are composed of unconsolidated alluvial silt, sand, that overlie the consolidated ***Kc*** bedrock. The ***Q*** material in the Aten Block AEM survey area is identified through interpretation of the AEM data as non-aquifer (blue), marginal aquifer (tan), aquifer material (yellow), and coarse aquifer (brown) material as discussed in Section 3.1. Figure 3-131 is the flight line location map including roads, streams and towns. Generally, the flight block is bounded by the cut bank of the abandoned meander of the Missouri River south of the active river channel which can be seen on the ground surface elevation map (Figure 3-132). Figure 3-133 displays a deep 3D fence diagram of the Aten Block AEM survey area, looking to the north, with the flight lines and the interpreted hydrostratigraphic profiles along with CSD and NE-DNR borehole lithology data. The area generally contains a mix of all ***Q*** aquifer materials lying upon the ***Kc*** within the flood plain area surrounded by small areas of ***Kn*** subcrop and outcrop on the southern edge. Beneath the ***Kc*** lies the following sequence of Cretaceous units ***Kgg*** and ***Kd*** which contains a mix of Shale/Clay Dominant and Sandstone/Sand Dominant materials. Figure 3-134 presents 2D profile L1100101, located east of the town of Aten. The figure shows the subsurface of the Missouri river flood plain and the Q materials that fill the abandoned oxbow. The east side of the line where it is bounded by the ***Kn*** outcrop. The CSD 1995 water table is also on the profile Figure 3-135 shows the water table for the area.

The total thickness of the ***Q*** material in the Aten Block AEM survey area (Figure 3-136) was gridded by subtracting the bedrock elevation from the ground surface elevation. The greatest thickness is in the 2 paleochannels that cross each other just south of Yankton, South Dakota. The ***Q*** material varies in thickness from <20 to 243 feet. It is important to understand the distribution of the various ***Q*** aquifer materials in relation to the hydrologic connection of those materials to the surface water of the area. The aquifer and coarse aquifer materials which make up the bulk of aquifer materials present provide the greatest connection for water movement through all of the ***Q*** aquifer materials. Of equal importance is the saturated thickness of the ***Q*** materials calculated by the bedrock elevation subtracted from the gridded 1995 CSD water table surface elevation (NE-CSD, 1995) to obtain the total saturated thickness of ***Q*** material. All aquifer material thickness is shown for the Aten Block (Figure 3-137). The thickness of these materials varies between 0, where there is no aquifer material near the ***Kn*** outcrops and the greatest thickness up to 178 feet within the identified paleochannels.

Figure 3-138 shows, underlying the ***Kd*** surface elevation which is generally highest at 902 feet in the east and lowest at 852 feet in the southwest areas of the survey. The ***Kd*** is a relatively flat lying surface sloping from east to southwest. These high and low elevations correlate with the thickness map of the ***Kd*** shown in Figure 3-139. An area with a thin ***Kd*** material thickness of <600 feet is located in the southwest corner of the area. The saturated thickness of the ***Kd*** varies from <600 feet to 734 feet with the thickest section central-northeast of the area near the town of Yankton, South Dakota.

Figure 3-140 shows the interpreted 2D profile L1201101 which is a north-south line which parallels Antelope Creek to the west across the Missouri River flood plain. Near northing 1106000 is a paleochannel of the Missouri River. The ***Q*** is mostly aquifer material with a thin intermittent layer of marginal aquifer material lying on the ***Kc***. The ***Kn*** outcrops to the south and bounds the ***Q*** material valley fill which is hydrologically connected to the Missouri River. The ***Kc*** lies atop the ***Kgg***, ***Kd*** and the ***IP***. The ***Kd*** along this line contains the largest percentage of Sandstone/Sand dominant material in the Aten block. The ***Kd*** is not hydrologically connected to the Missouri River.

Figure 3-141 is 2D profile L900301 which is an east-west profile in the along the southern end of the Aten area showing a complex mix of ***Q*** lying atop ***Kc***, ***Kgg*** and ***Kd***. The ***Kd*** has a small area of Sandstone/Sand Dominant material on the east side which is not hydrologically connected to the Missouri River.

An exploded view of the voxel model showing the ***Q***, both saturated and unsaturated, the ***Kc***, ***Kgg***, ***Kd***, and the ***IP*** formations is presented in Figure 3-142. The ***Q*** materials show mostly aquifer and coarse aquifer materials beneath the flood plain with some marginal and non-aquifer materials near the base of the ***Q*** and along the edges of the flood plain. Nearly all of the materials shown are saturated because of the water table being in close proximity to the land surface across the flood plain. Because of the near land-surface water table conditions in the Aten block (Figure 3-143) there is no ability for managed aquifer recharge (MAR) sites to be located within. Figure 3-144 shows the saturated thickness of the ***Q*** aquifer and coarse aquifer materials. The saturated aquifer and coarse aquifer materials range in thickness from <20 feet near the edges of the flood plain to 154 feet in the paleochannels.

The map of saturated thickness for ***Q*** deposits and specific capacity of wells in the ***Q*** (Figure 3-145) shows the relationship between specific capacity in gpm/ft and the saturated thickness. Careful evaluation of the map shows a trend of 10 to >25 gpm/ft that follows the paleochannels where there are 80 to 178 ft thick ***Q*** deposits. The lack of more wells in this area may be related more to farming practice rather than any lack of high capacity wells for irrigation.

Different views of 3D voxel models of the Aten Block AEM survey area are presented in Figure 3-146 to Figure 3-152. Figure 3-146 presents a view to the southwest of the shallow portion of the Aten Block to emphasize the areas of the ***Q*** aquifer material types. Figure 3-147 presents a similar shallow view of the Aten Block to the southwest but with the modification of the ***Q*** material types displayed as a 3D Fence diagram and the addition of NE-CSD and NE-DNR lithology logs. Figure 3-148 presents a view to the north of the shallow Aten Block showing 3D voxels of the ***Q*** Coarse Aquifer material near the Missouri River and the underlying bedrock units with a 3D Fence diagram of all the ***Q*** aquifer material types. Figure 3-149 presents a view to the south of the shallow Aten Block showing a 3D voxel of both the ***Q*** Aquifer Material and the Coarse Aquifer material and the underlying bedrock units. Figure 3-150 is a view to the northwest of a 3D voxel of the ***Q*** Coarse Aquifer Material overlying a surface depicting the topography/elevation of the top of the bedrock surface. Figure 3-151 presents the same 3D voxel as in Figure 3-150 from another view but with CSD and NE-DNR lithology logs. Figure 3-152 has the same contents as in Figure 3-151 but with a surface overlay of the 1995 Water Table (NE-CSD, 1995). This makes apparent the unsaturated areas and saturated areas of the ***Q*** Coarse Aquifer Materials in the Aten Block.

Figure 3-153 presents a map of the saturated thickness for ***Kd*** Sandstone/Sand Dominant deposits. Figure 3-154 shows the relationship between the thickness of ***Kd*** and the specific capacities, in gpm/ft, for wells completed in the ***Kd***. Careful evaluation of the wells in Figure 3-154 shows only one well in the Aten block with a specific capacity of 10-25 gpm/ft range following the 700 to 720 ft thick saturated ***Kd*** Sandstone/Sand Dominant deposits. The best locations for well development are in the thick Sandstone/Sand Dominant zones of the ***Kd***.

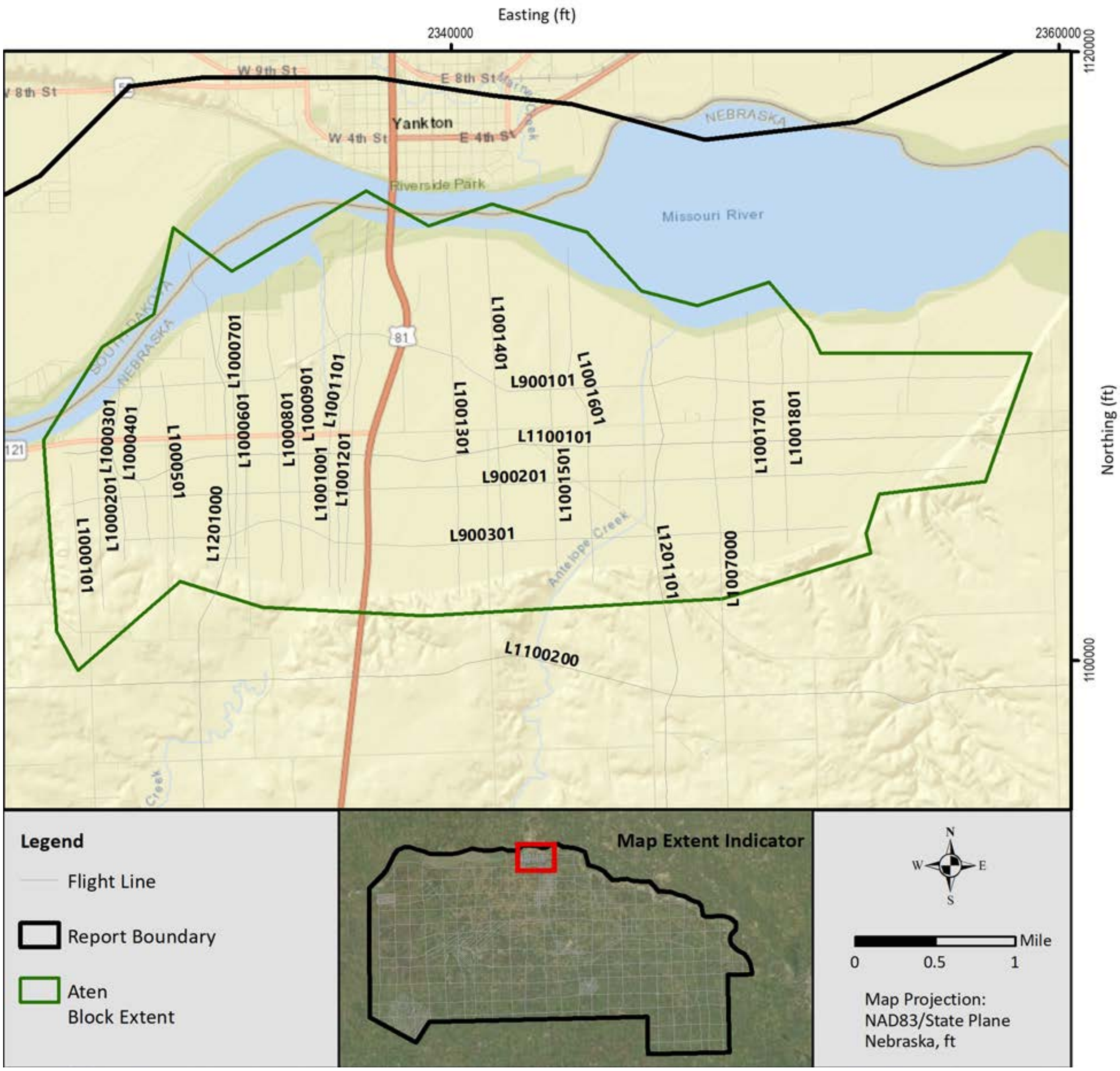


Figure 3-131. Location map of the Aten Block indicating AEM flight lines, local roads, and streams.

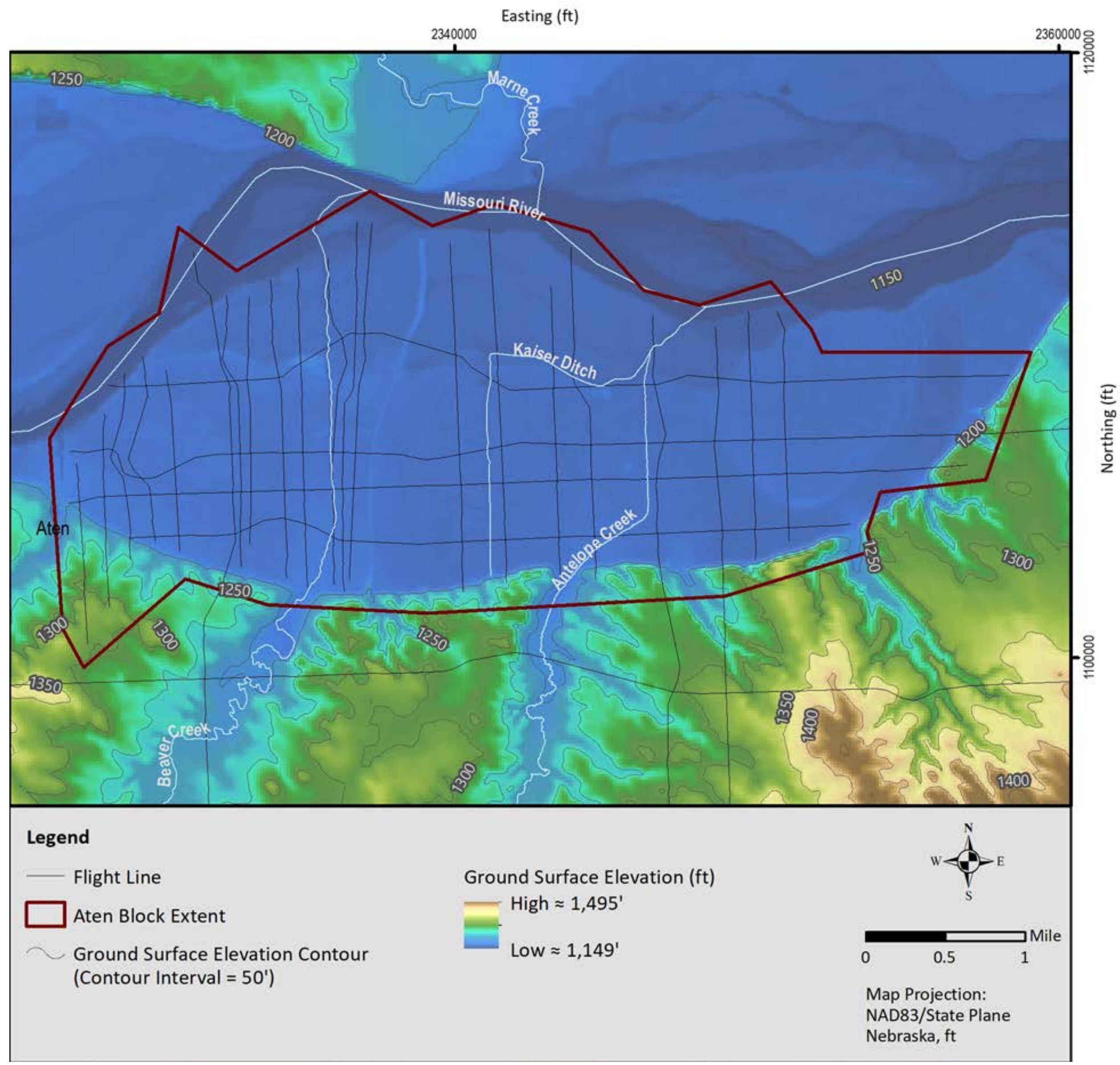


Figure 3-132. Map showing the Missouri River flood plain bounded by the cut bank areas.

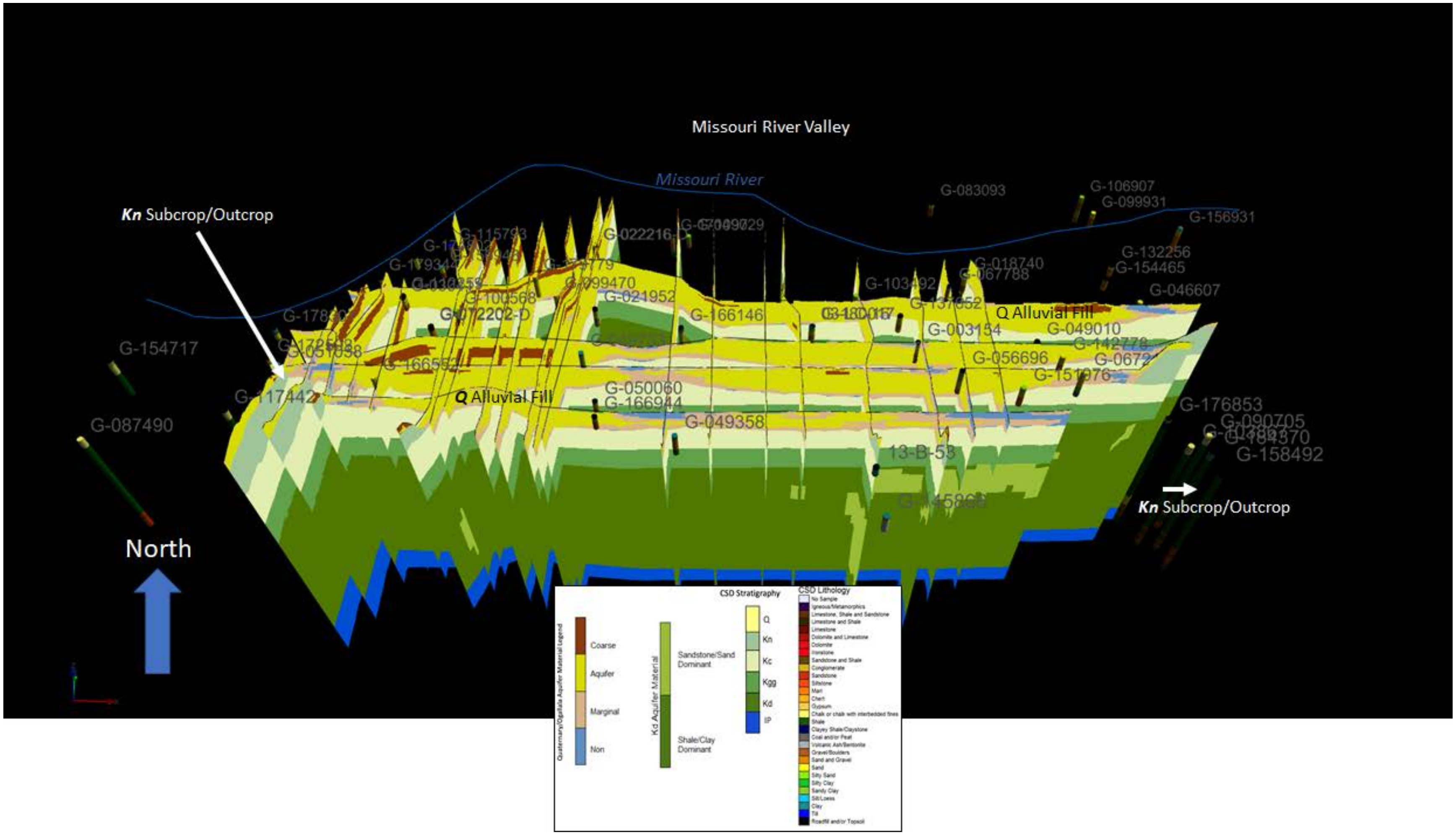


Figure 3-133. 3D fence diagram of interpreted AEM hydrostratigraphic profiles within the 2018 Aten Block AEM survey area. CSD and NE-DNR wells are labeled. VE = 15x.

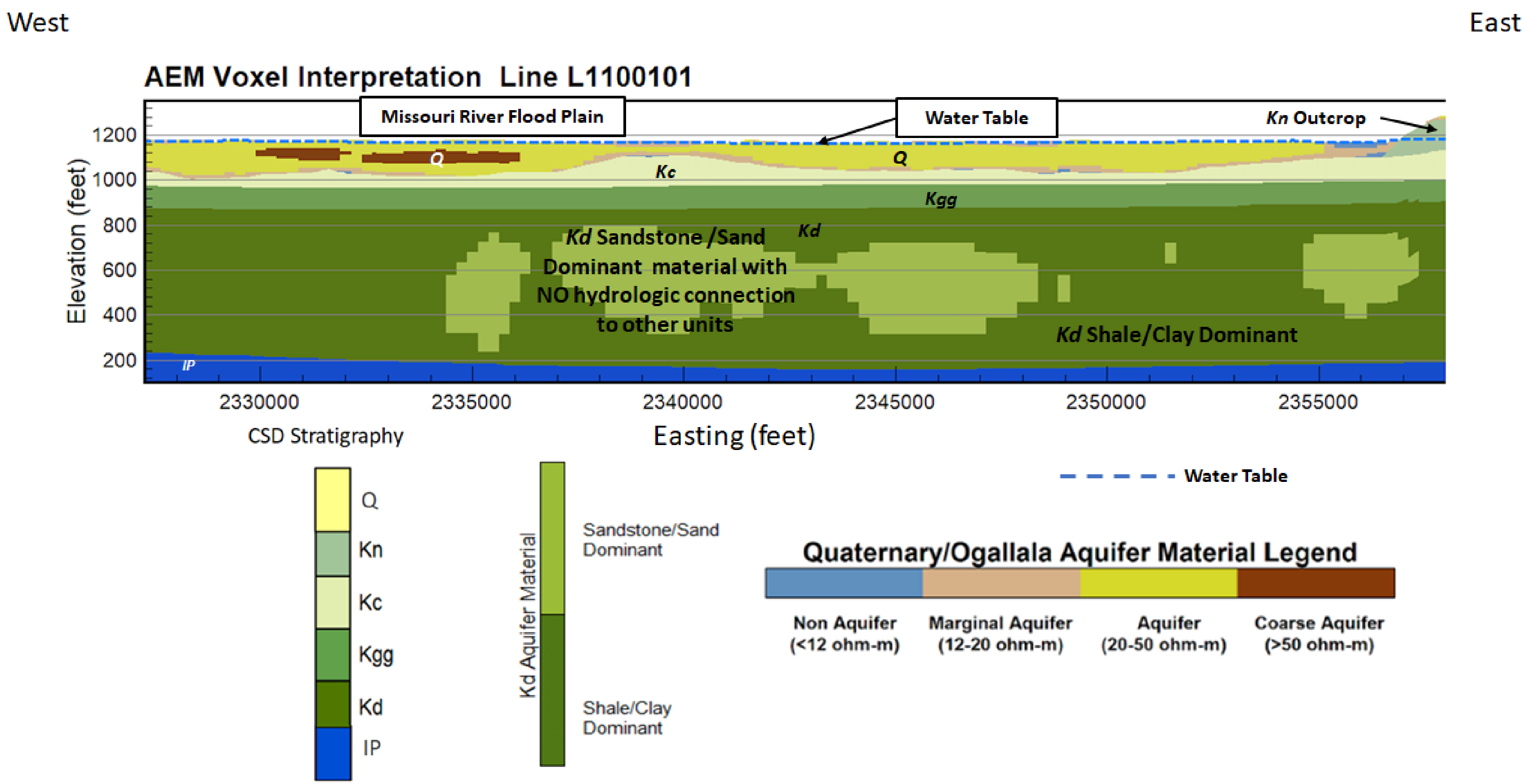


Figure 3-134. Profile of the east-west line L1100101 showing the relationship of the AEM interpretations to the CSD lithology and stratigraphy logs. The CSD 1995 water table is indicated as a dashed blue line on the profiles. Horizontal datum is NAD83 State Plane Nebraska (feet).

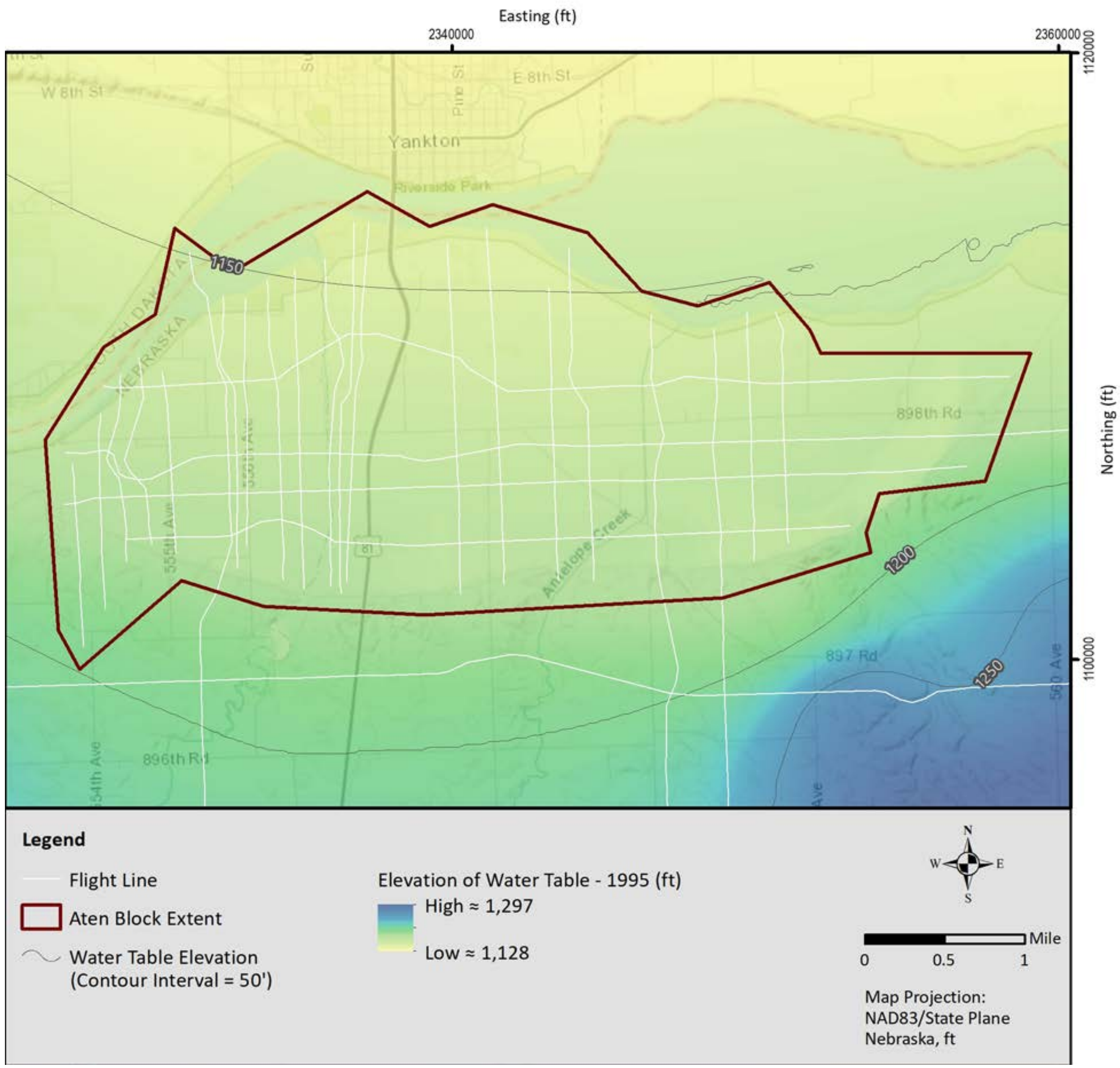


Figure 3-135. Map of the CSD 1995 water table within the 2018 Aten Block AEM survey area. Block flight lines are indicated by white lines.

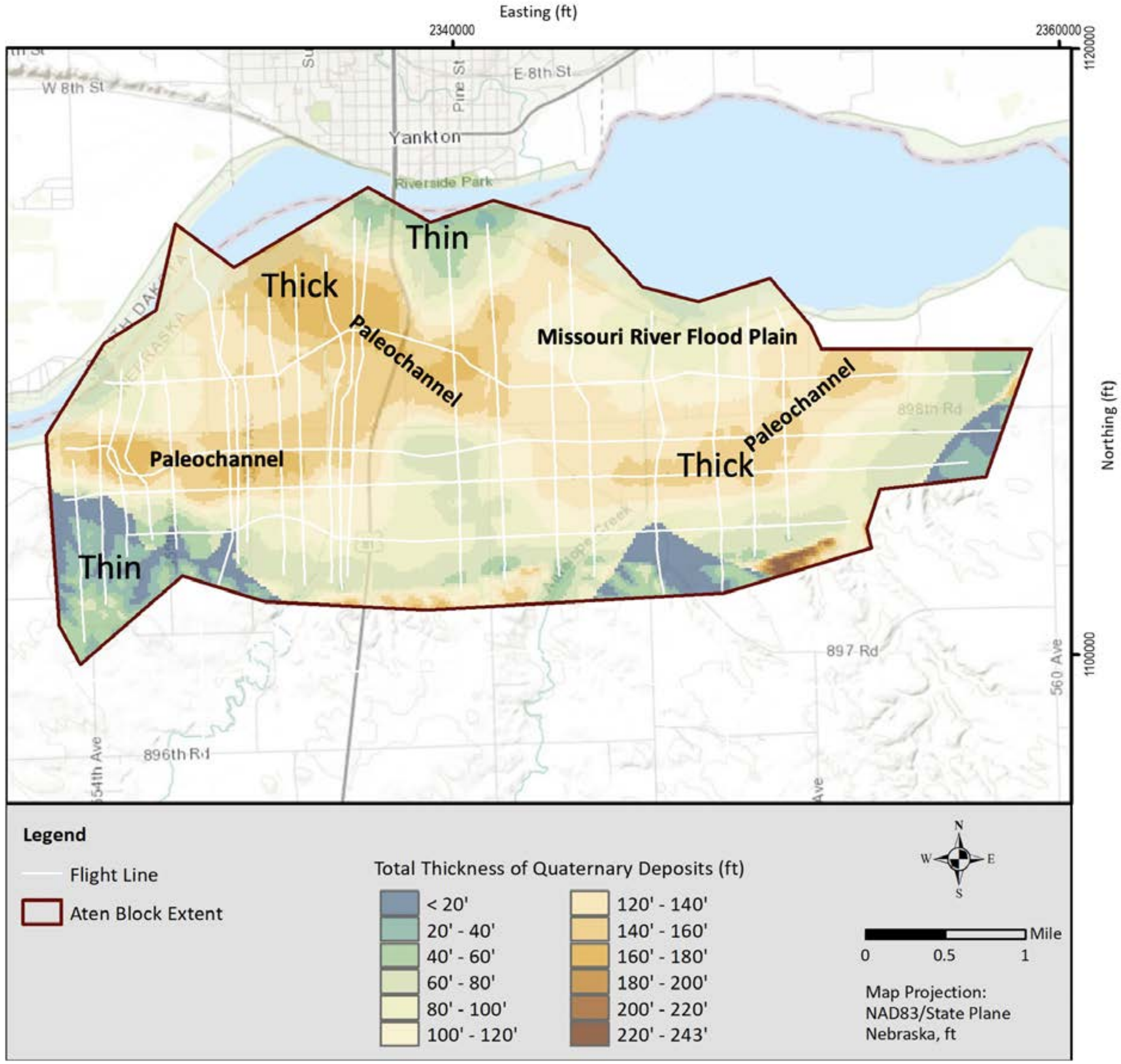


Figure 3-136. Map of the total thickness of the Quaternary (*Q*) deposits within the 2018 Aten Block AEM survey area. Block flight lines are indicated by white lines.

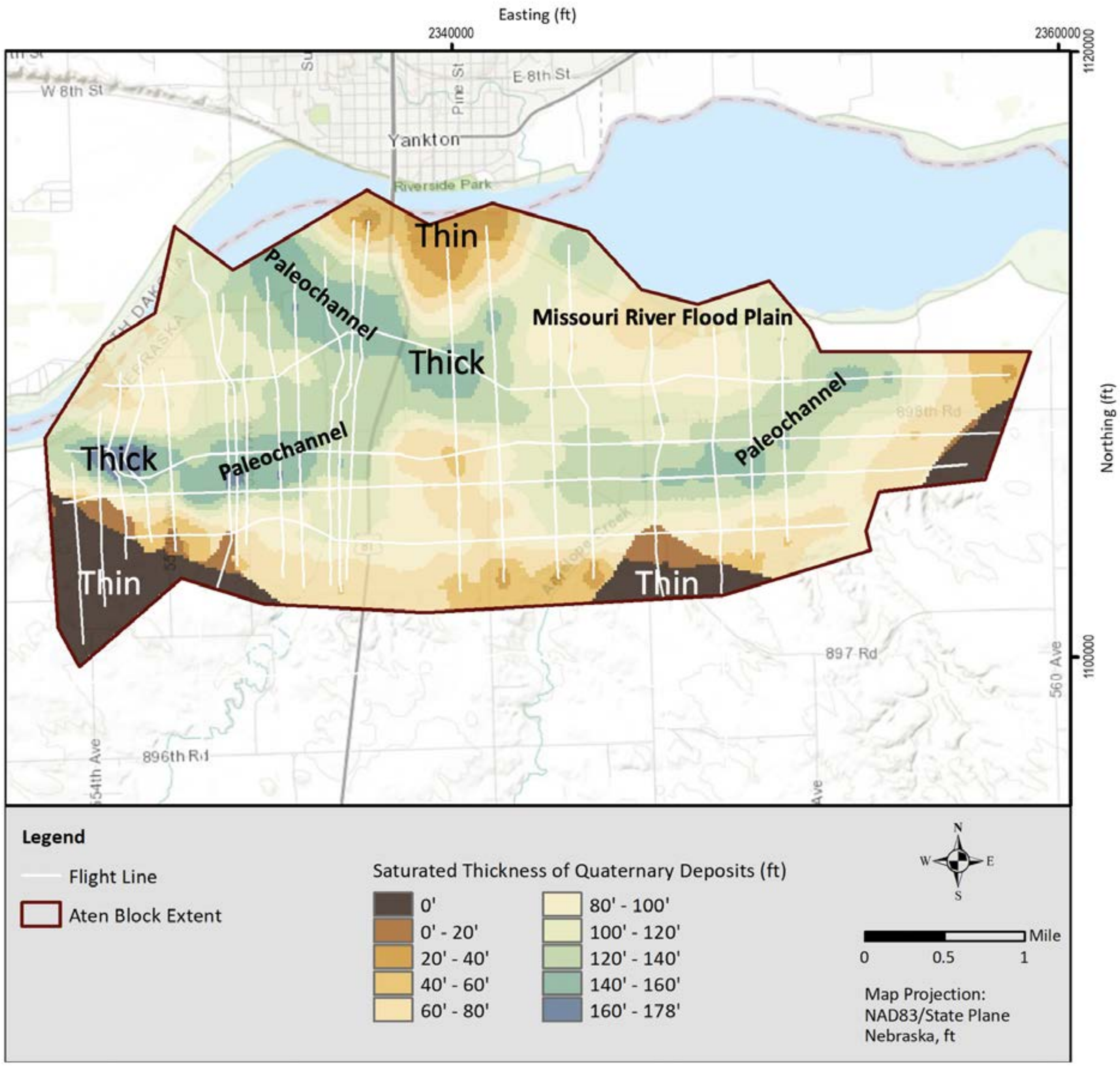


Figure 3-137. Map of the thickness of the Quaternary (*Q*) saturated aquifer and coarse aquifer materials within the 2018 Aten Block AEM survey area. Block flight lines are indicated by white lines.

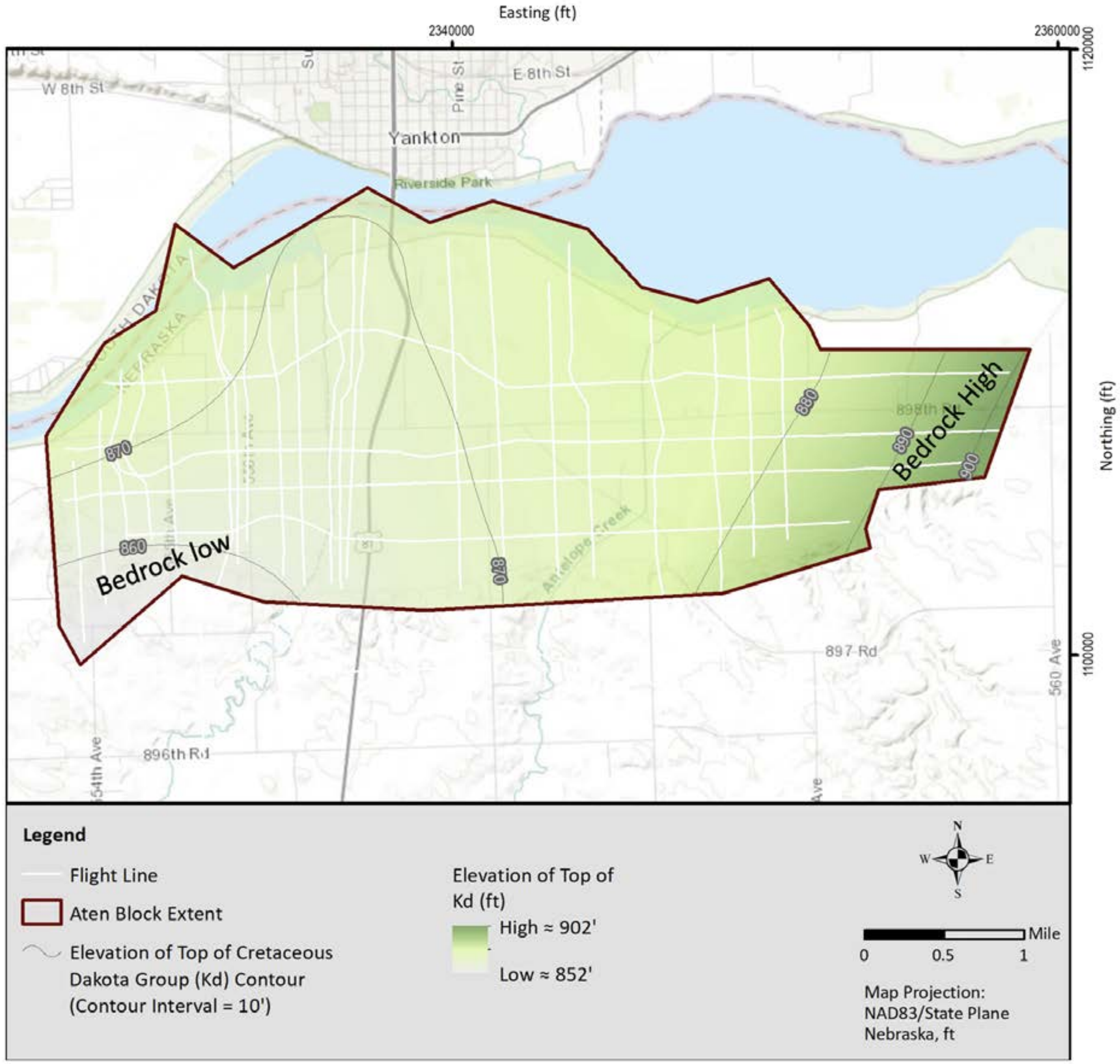


Figure 3-138. Map of the elevation of the top of the Cretaceous Dakota Group (*Kd*) within the 2018 Aten Block AEM survey area. Block flight lines are indicated by the white lines.

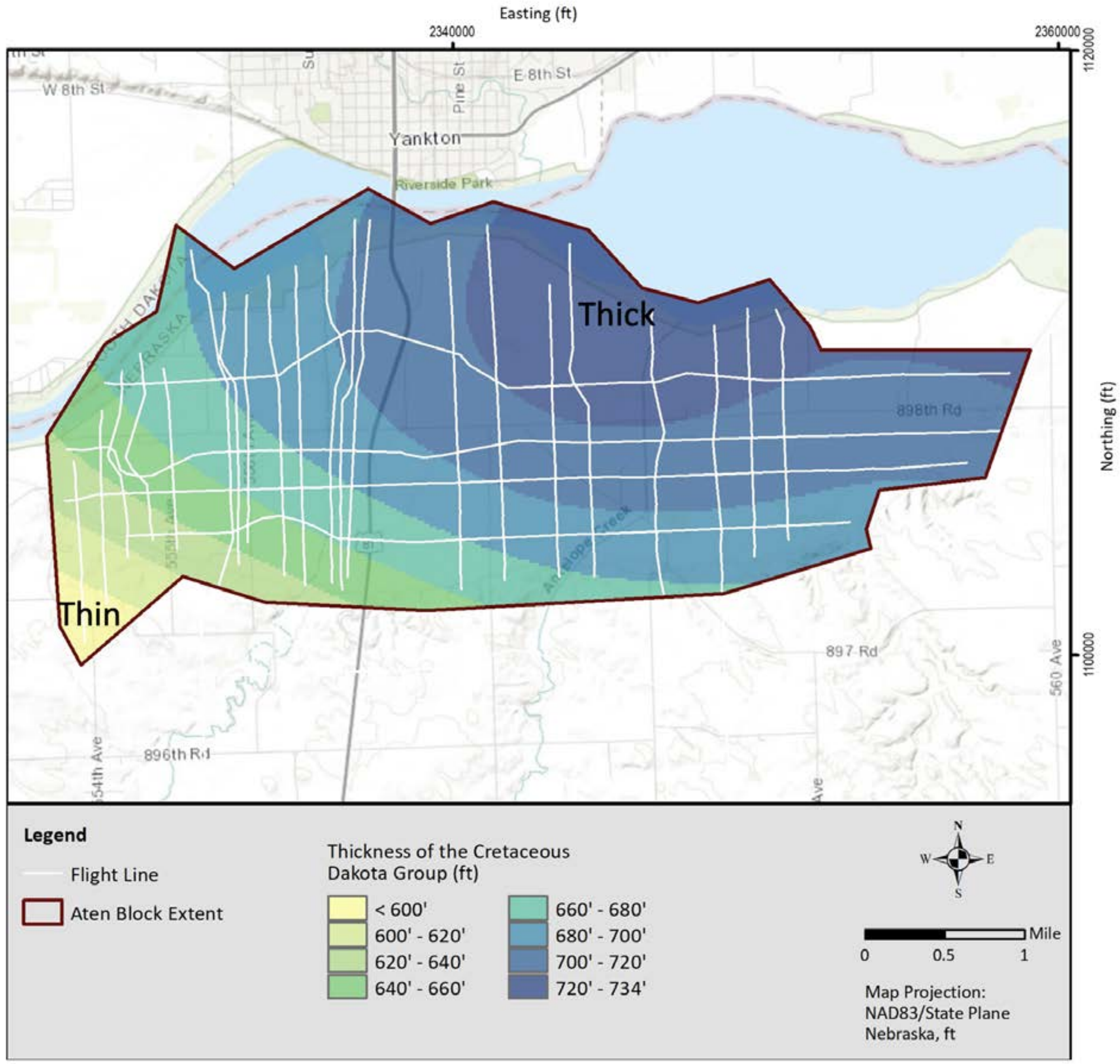


Figure 3-139. Map of the thickness of the Cretaceous Dakota Group (*Kd*) within the 2018 Aten Block AEM survey area. Block flight lines are indicated by the white lines.

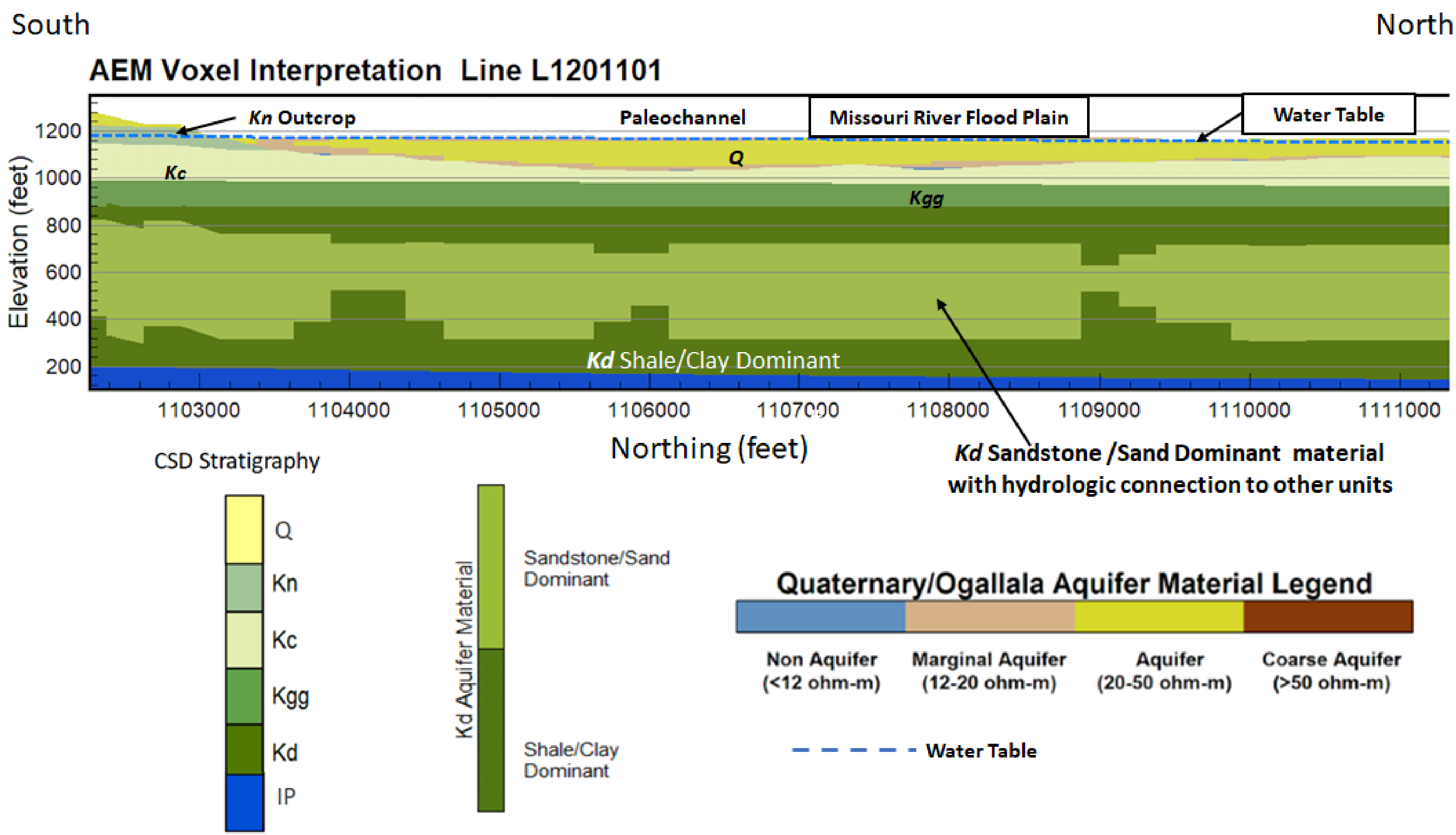


Figure 3-140. Interpreted profile of the north-south line L1201101 showing the relationship of the AEM interpretations across the area. The CSD 1995 water table is indicated as a dashed blue line on the profiles. Horizontal datum is NAD83 State Plane Nebraska (feet).

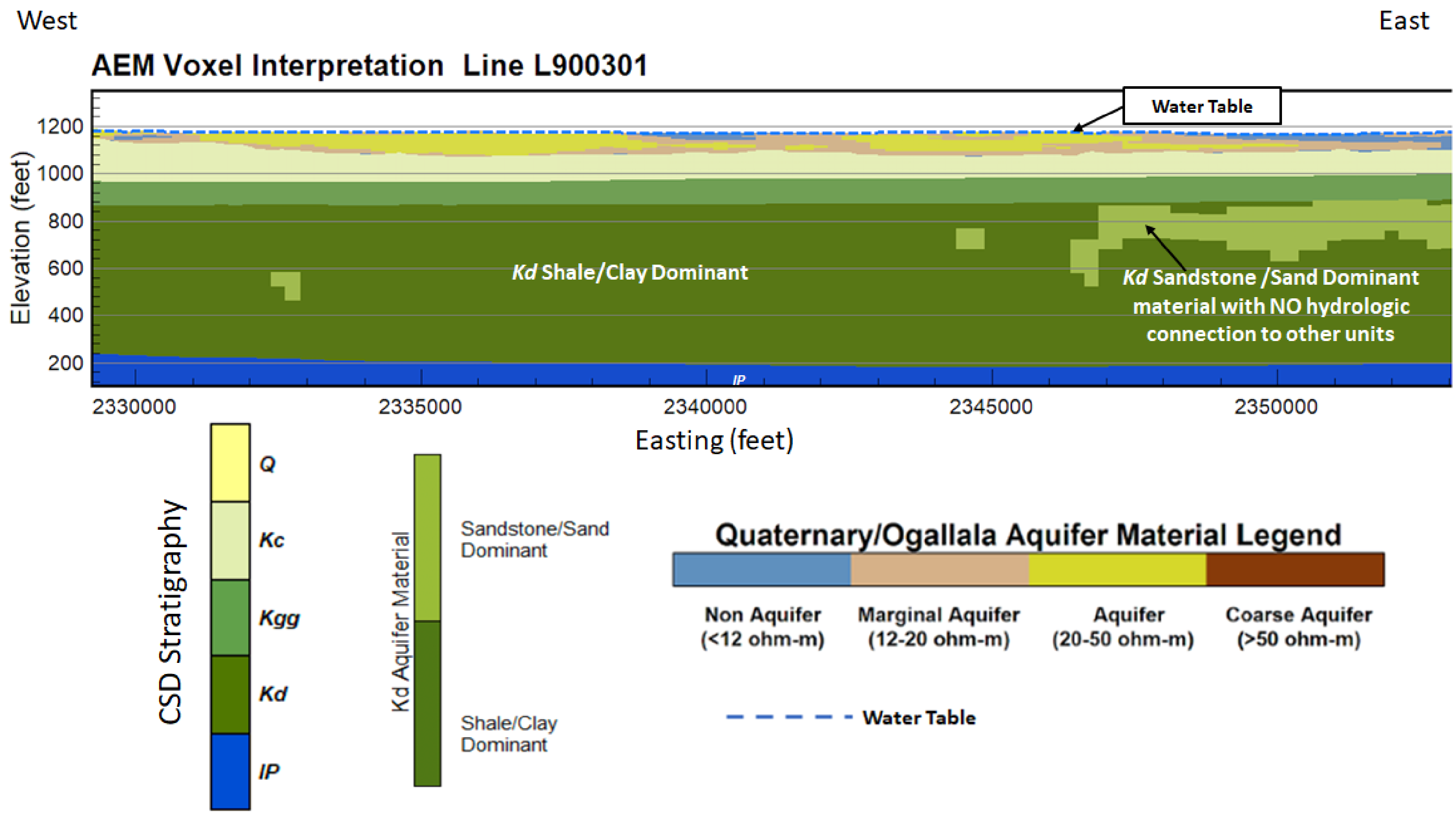


Figure 3-141. Interpreted profile of the east-west line L900301 showing the relationship of the AEM interpretations across the area. The CSD 1995 water table is indicated as a dashed blue line on the profiles. Horizontal datum is NAD83 State Plane Nebraska (feet).

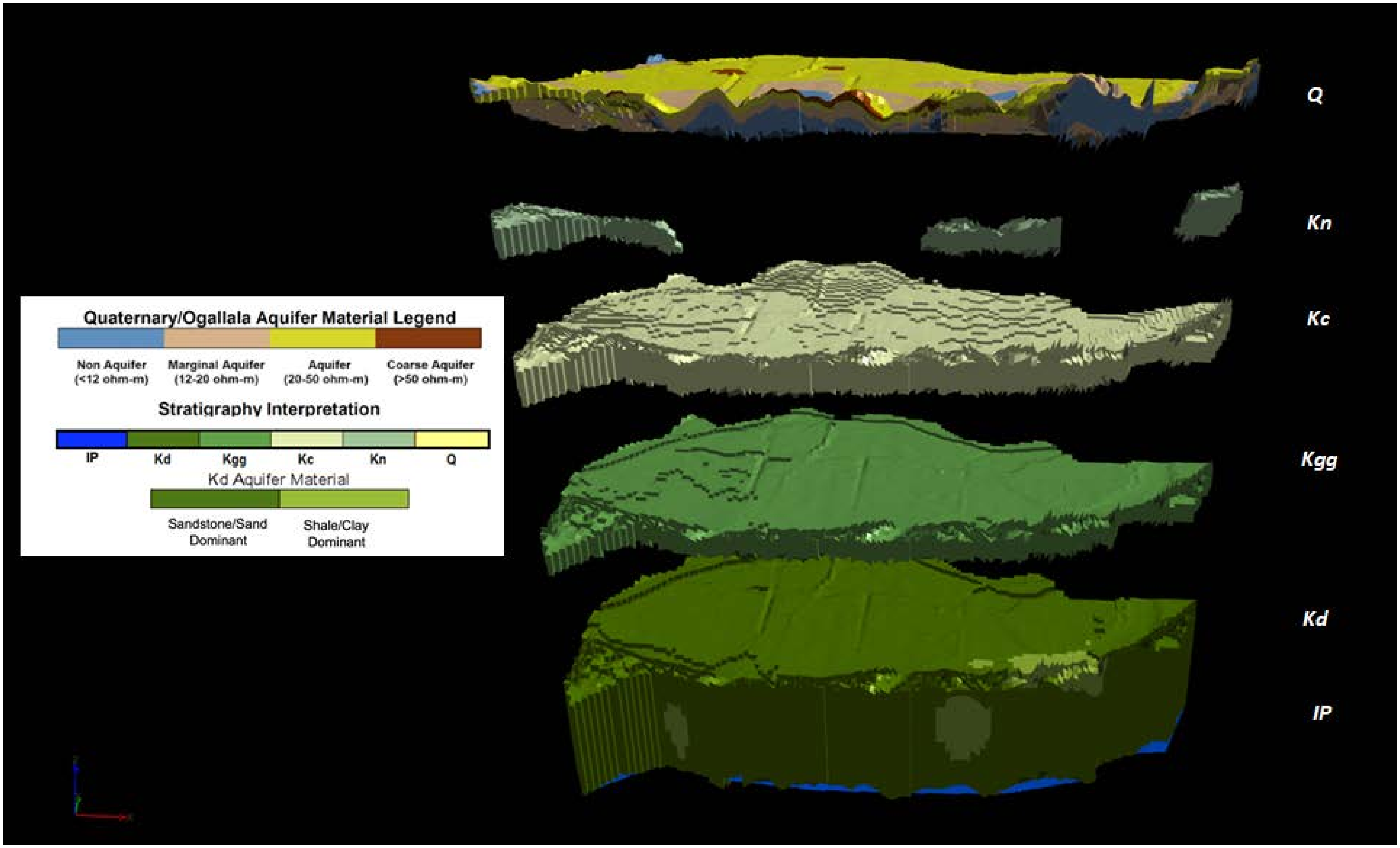


Figure 3-142. 3D exploded voxel model of the Aten Block showing *Q*= Quaternary, *Kn*=Cretaceous Niobrara Formation, *Kc*= Cretaceous Carlile Shale, *Kgg*= Cretaceous Greenhorn Limestone and Graneros Shale, *Kd*= Cretaceous Dakota Group, *IP*=Undifferentiated Pennsylvanian. V.E. = 10x. Not to scale.

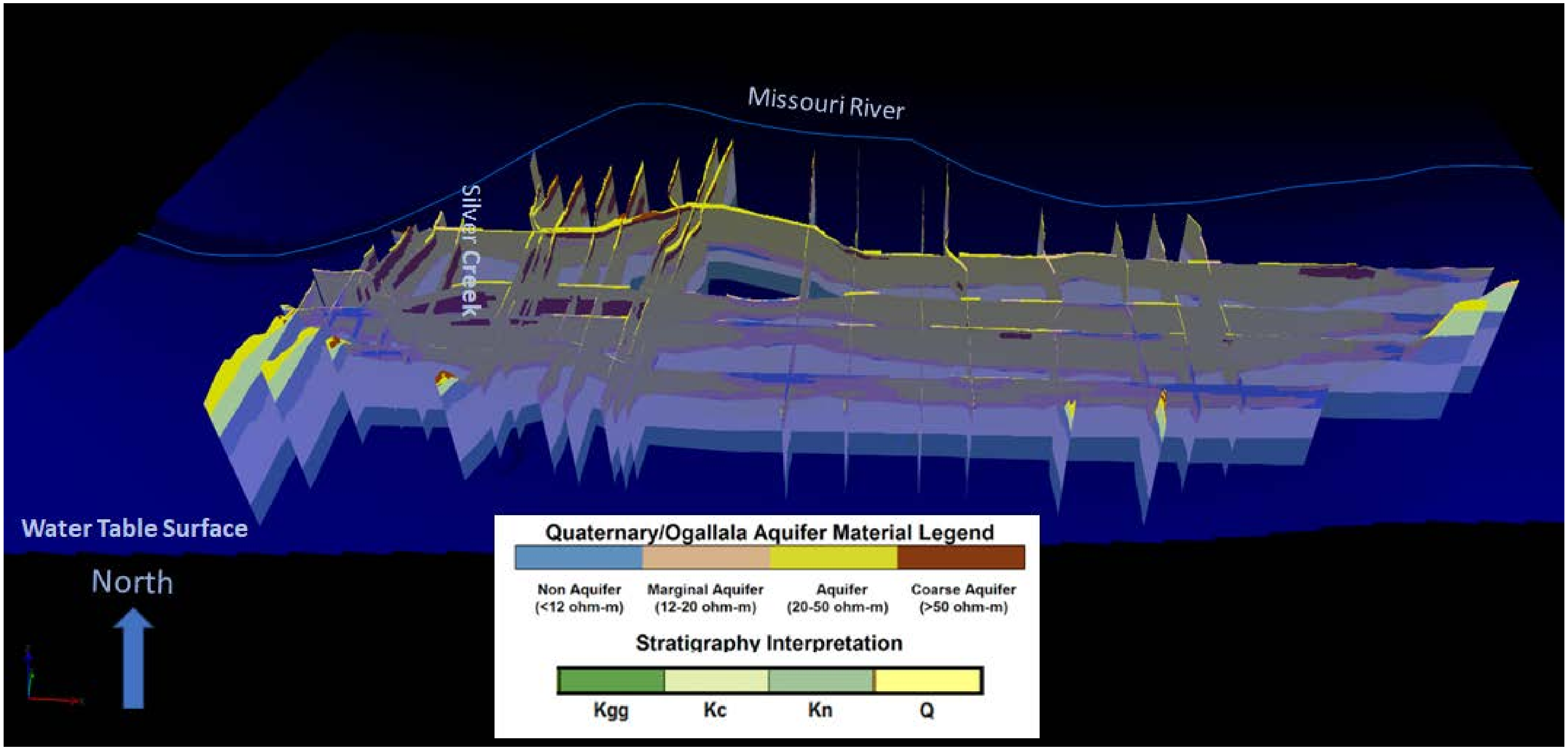


Figure 3-143. 3D fence diagram of the unsaturated and saturated Quaternary (*Q*) aquifer and coarse aquifer materials for the Aten Block, looking to the north. Note the thin amount of unsaturated material. The CSD 1995 water table is indicated as a blueish surface. Vertical scale is 10x.

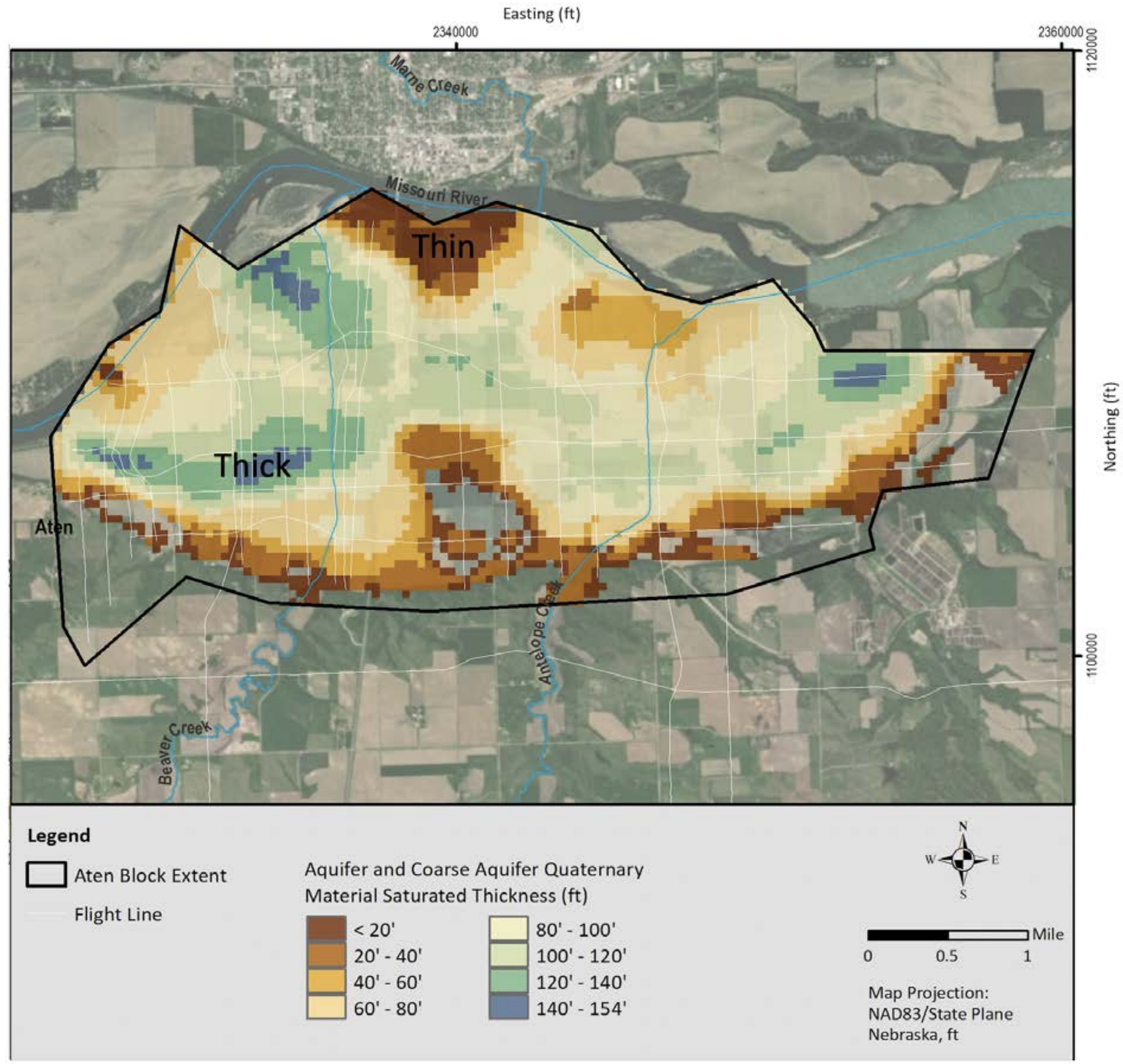


Figure 3-144. Map of saturated Quaternary (*Q*) aquifer materials for the Aten Block. Thickest areas are in the paleochannels. CSD 1995 water table is indicated as a blueish surface.

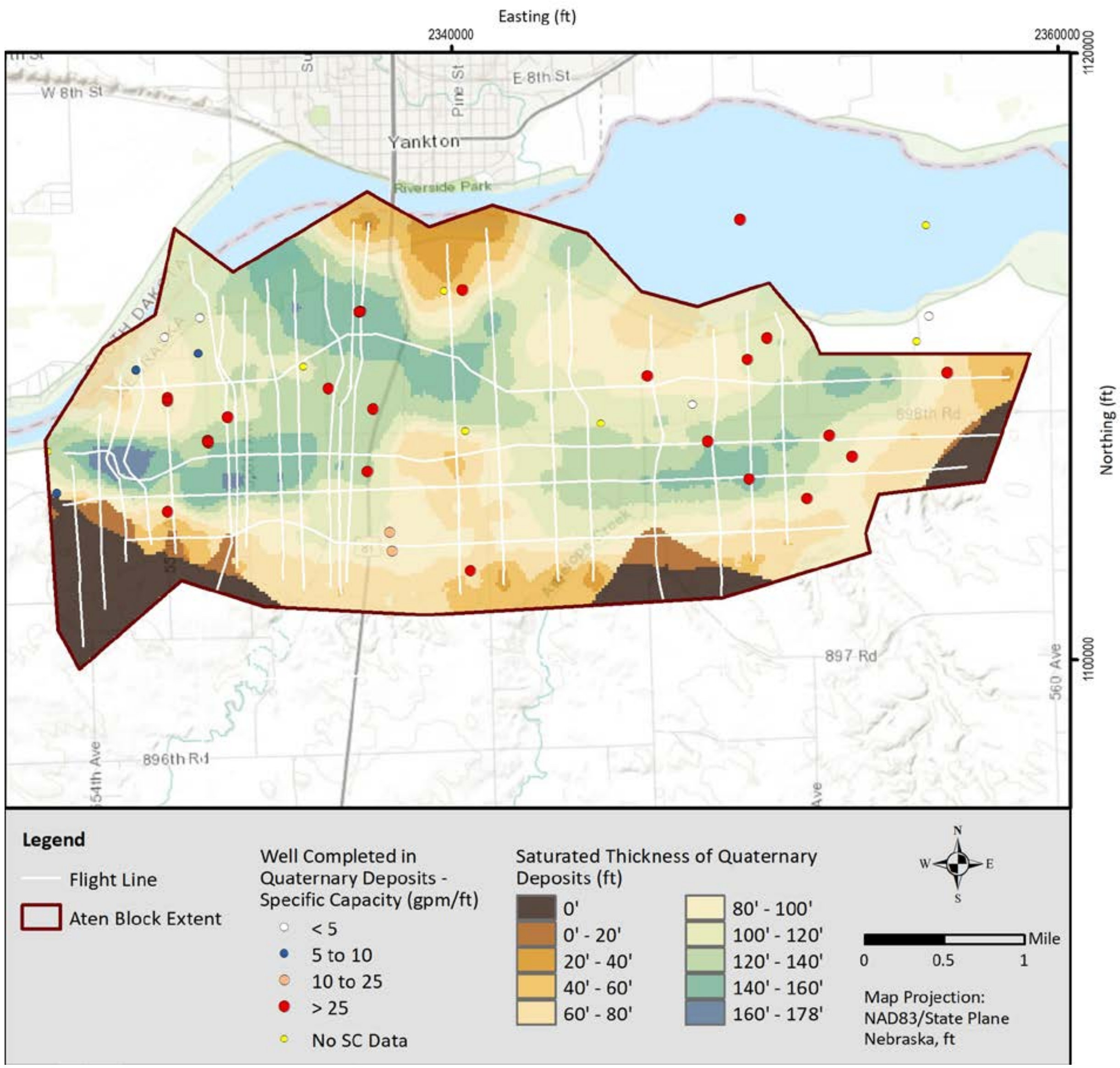


Figure 3-145. Map of saturated thickness of Quaternary (*Q*) deposits and the specific capacity measured in wells completed in the *Q* deposits. Note the wells are coincident with the paleovalleys.

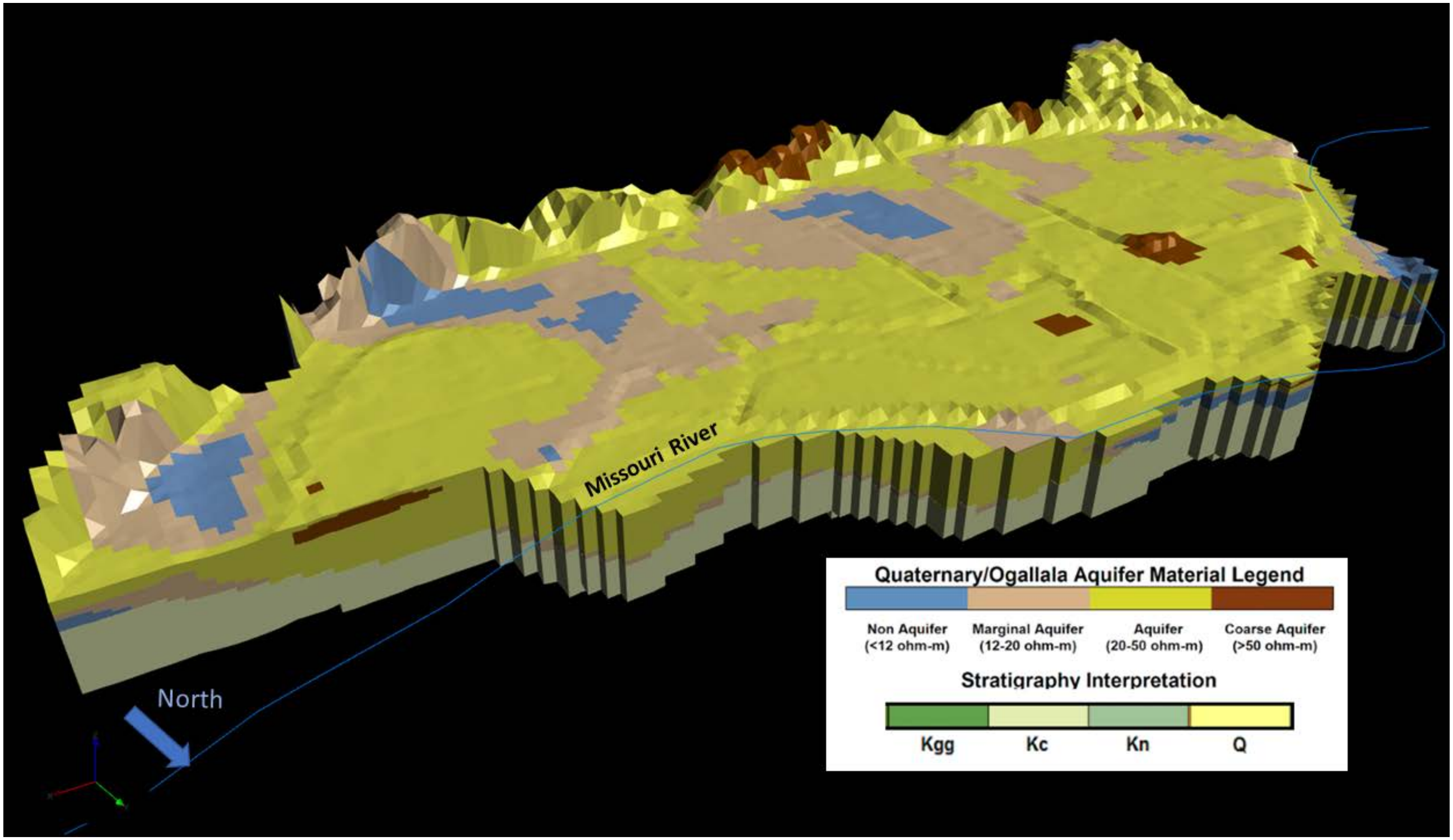


Figure 3-146. A view to the southwest of the shallow portion of the 3D voxel of the Aten Block AEM survey area emphasizing areas of Quaternary (*Q*) aquifer material types. V.E. = x10.

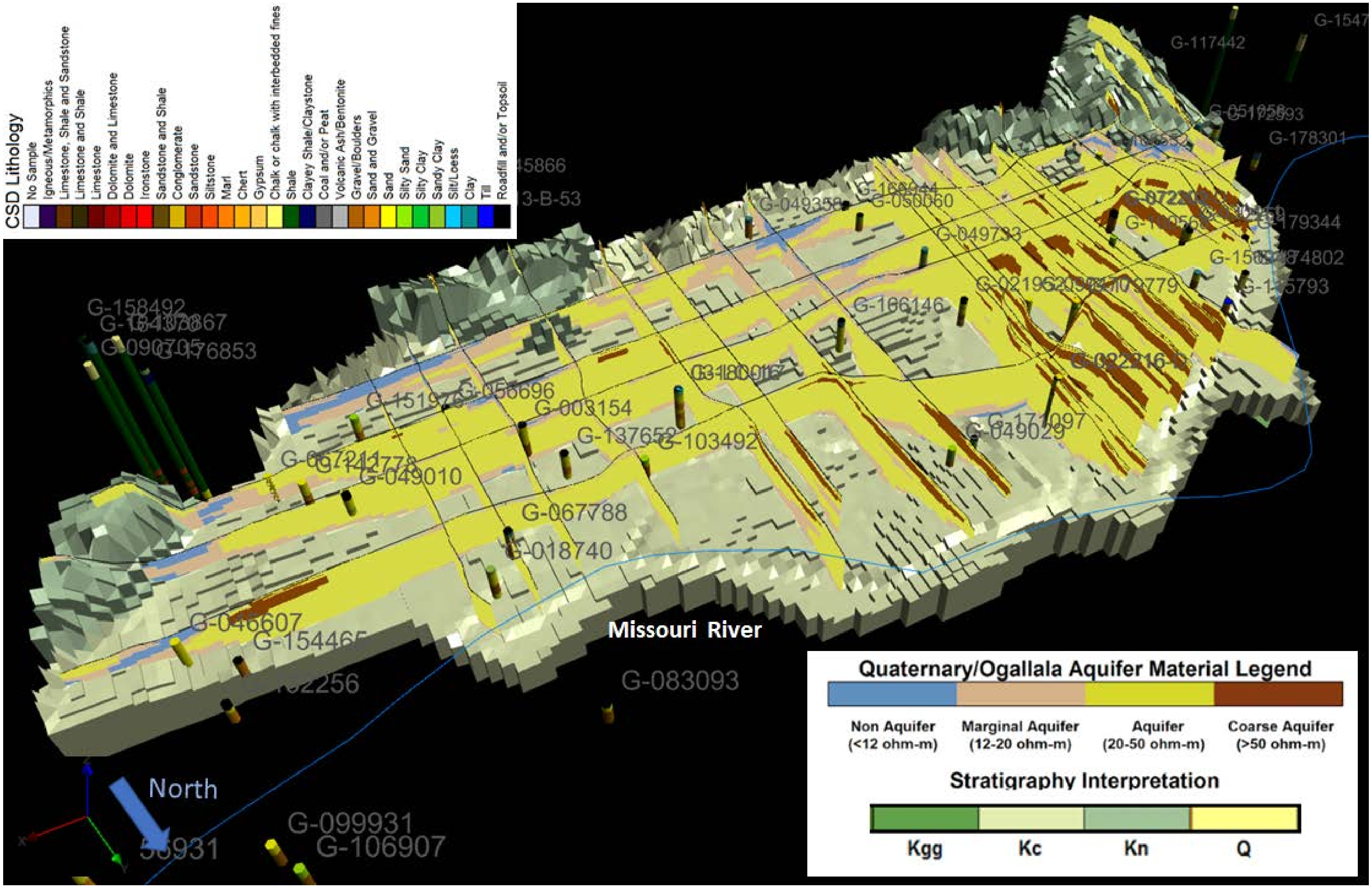


Figure 3-147. A view to the southwest of the shallow portion of the Aten Block AEM survey area showing a 3D voxel of the bedrock units with an emphasis of Quaternary (*Q*) aquifer material types in the form of a 3D Fence Diagram along with CSD and NE-DNR lithology logs. V.E. = x10.

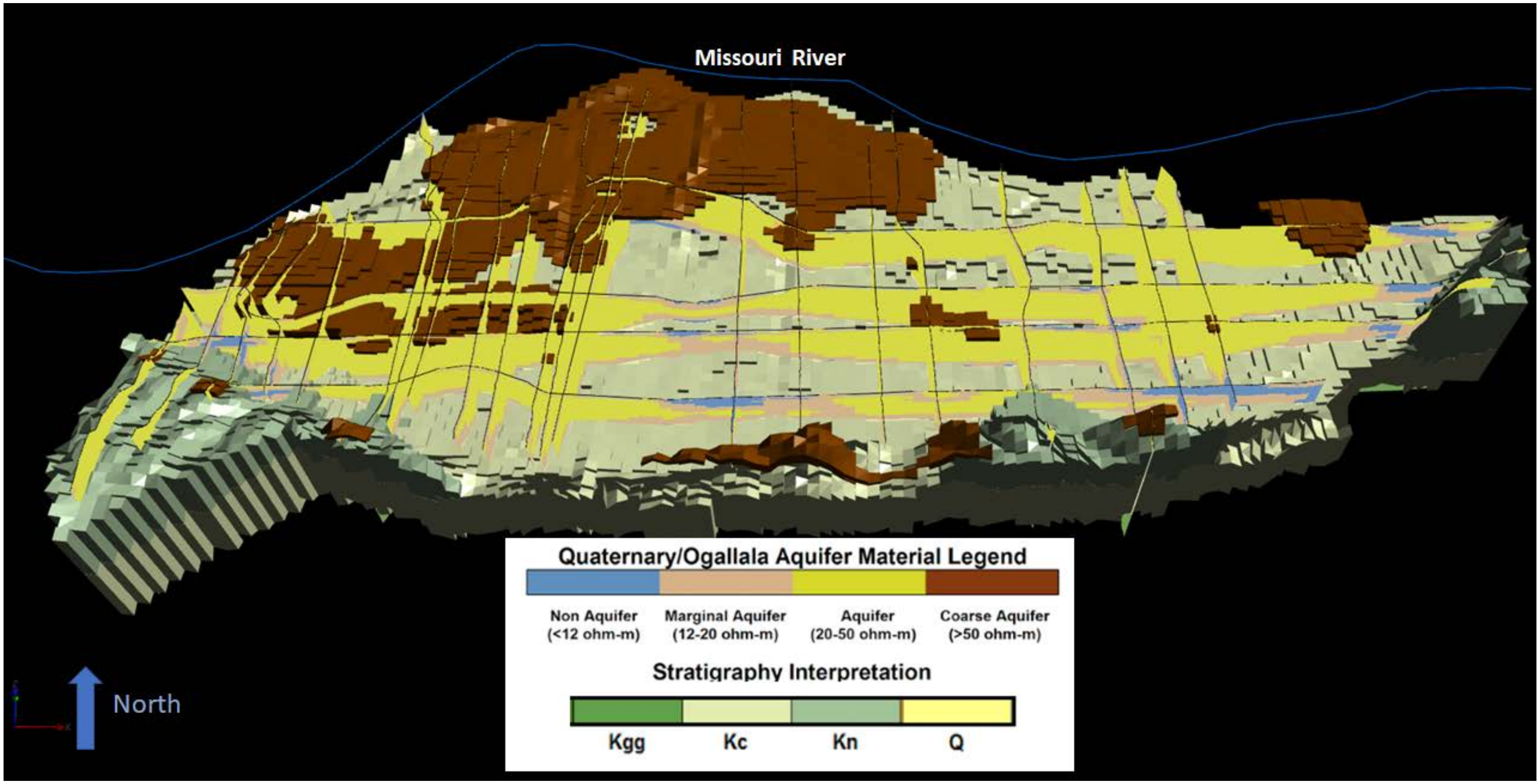


Figure 3-148. A view of the shallow portion of the Aten Block AEM survey area, to the north, showing a 3D voxel of the Quaternary (*Q*) Coarse Aquifer material near the Missouri River and the underlying bedrock units with the Quaternary (*Q*) aquifer material types also presented in the form of a 3D Fence Diagram. V.E. = x10.

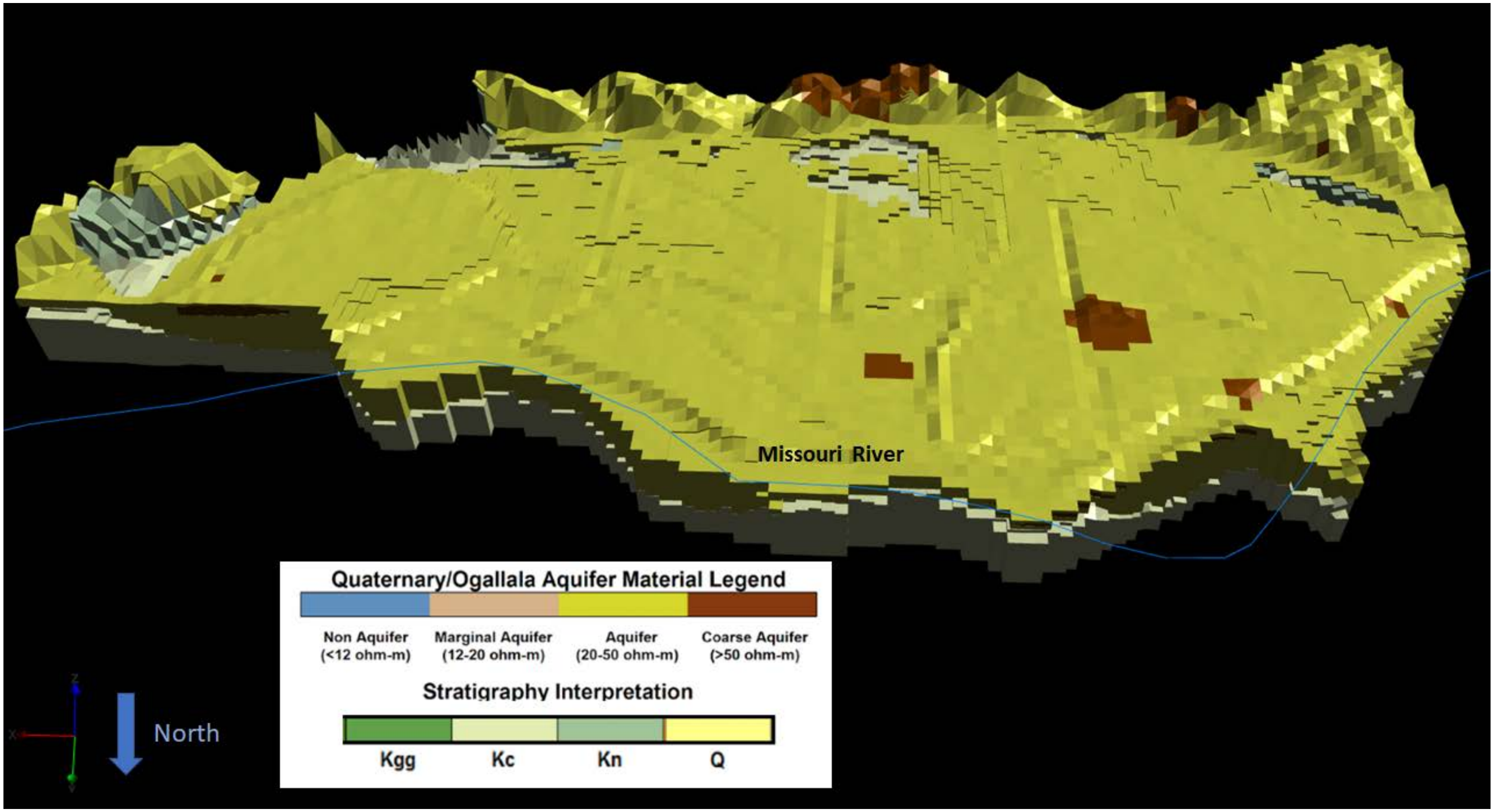


Figure 3-149. A view of the shallow portion of the Aten Block AEM survey area, to the south, showing a 3D voxel of the Quaternary (*Q*) aquifer material and the coarse aquifer material and the underlying bedrock units. V.E. = x10.

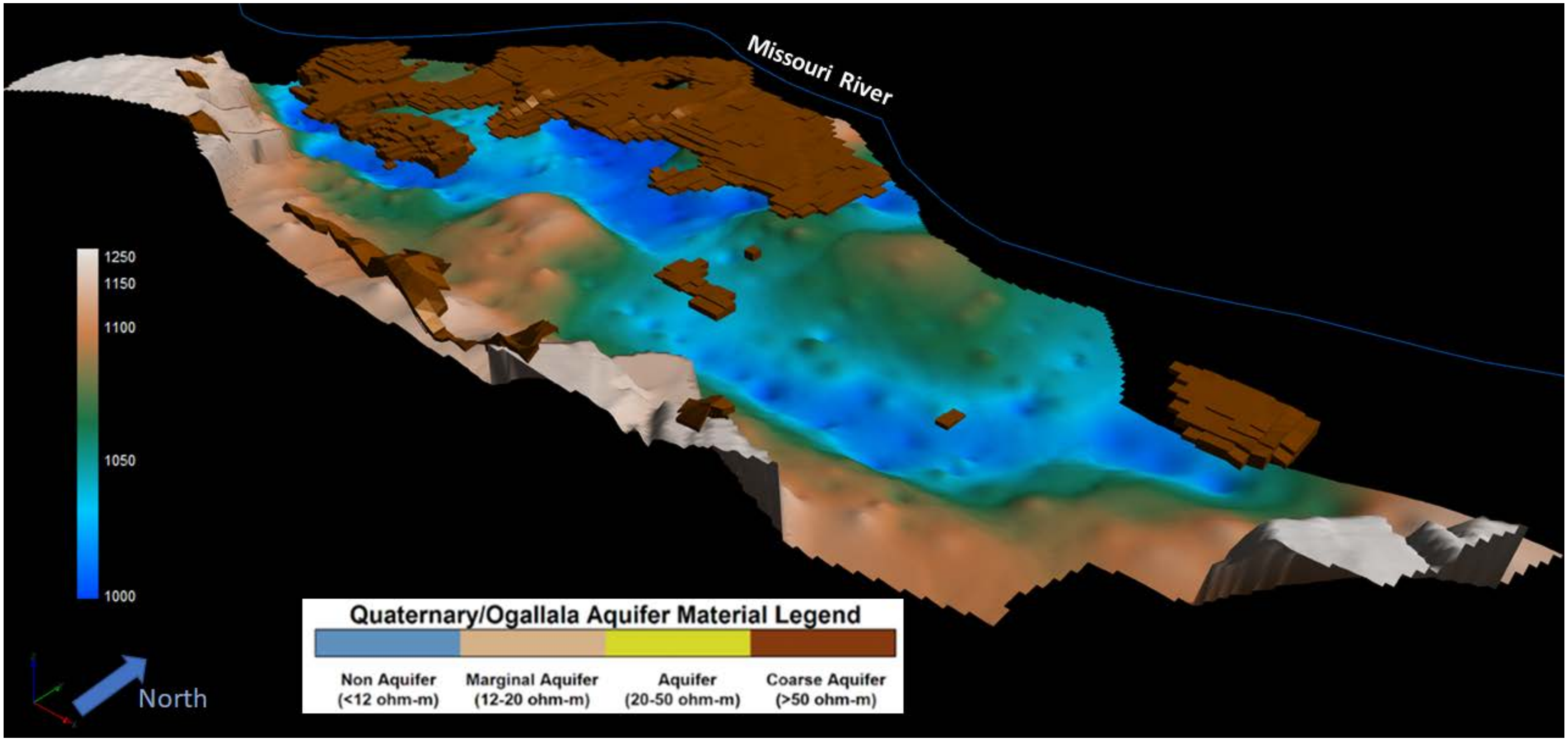


Figure 3-150. A view to the northwest of the Aten Block AEM survey area of a 3D voxel of the Quaternary (*Q*) coarse aquifer material overlying a surface depicting the topography/elevation of the top of the bedrock surface. V.E. = x10.

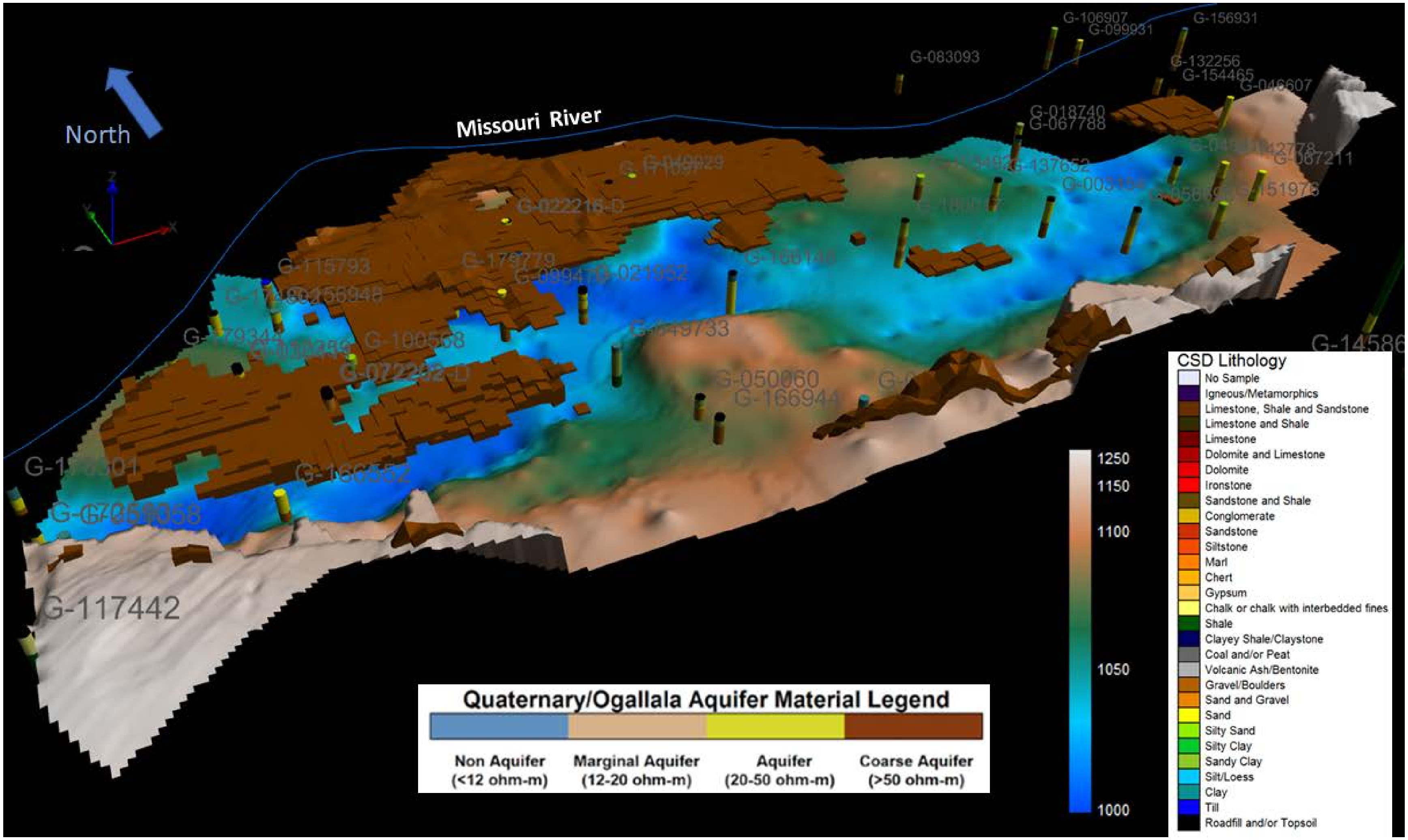


Figure 3-151. A view to the northeast of the Aten Block AEM survey area of a 3D voxel of the Quaternary (*Q*) Coarse Aquifer Material overlying a surface depicting the topography/elevation of the top of the bedrock surface with CSD and NE-DNR lithology logs. V.E. = x10.

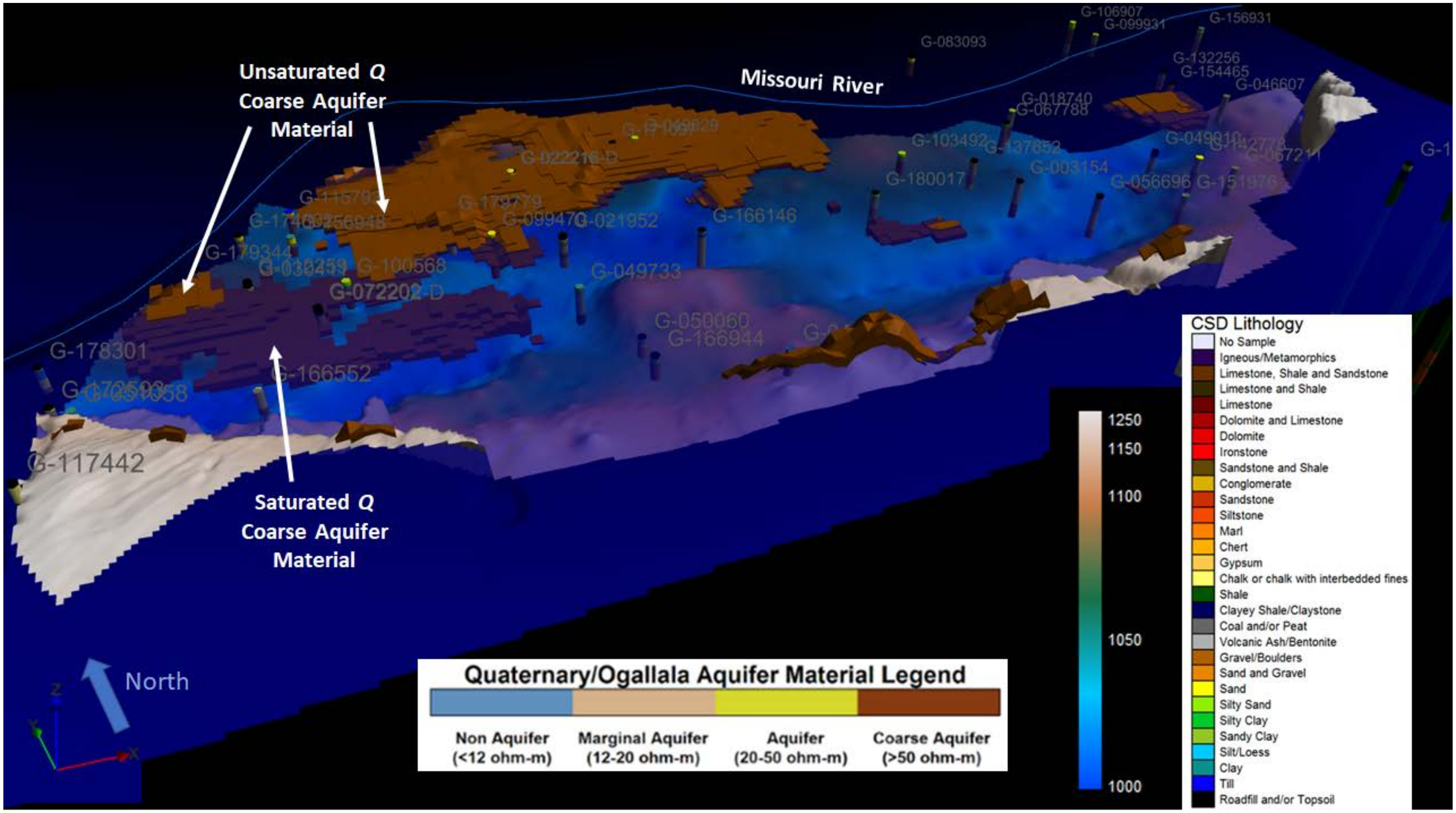


Figure 3-152. Same view to the northeast as in Figure 3-151 of the Aten Block AEM survey area showing a 3D voxel of the Quaternary (*Q*) Coarse Aquifer Material overlying a surface depicting the topography/elevation of the top of the bedrock surface with CSD and NE-DNR lithology logs but with the 1995 Water Table surface (NE-CSD, 1995). This makes apparent the unsaturated areas and saturated areas of the Quaternary (*Q*) coarse aquifer materials in the Aten Block. V.E. = x10.

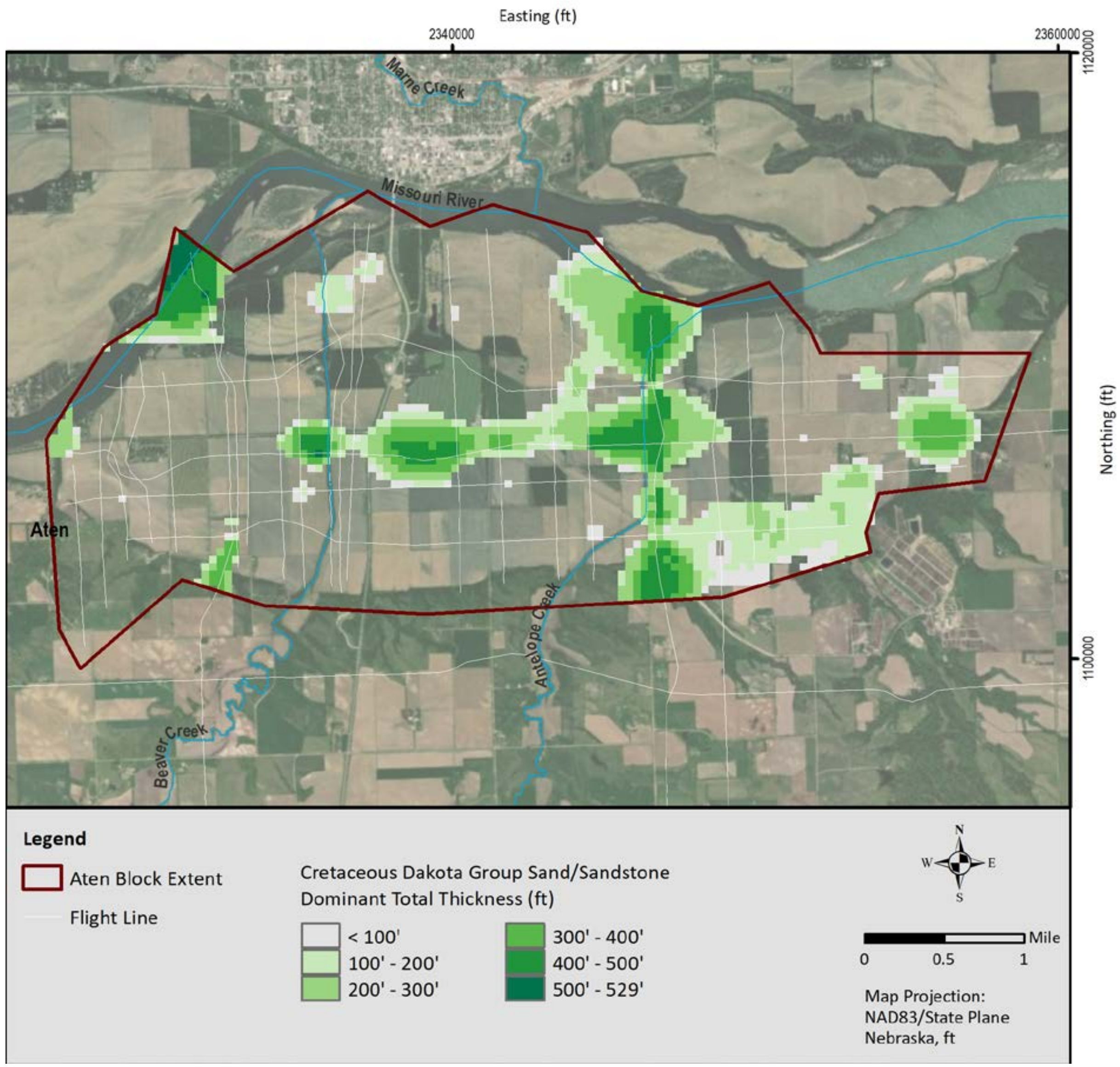


Figure 3-153. Map of the saturated thickness of the Sandstone/Sand Dominant portion of the Cretaceous Dakota Group (*Kd*) in the 2018 Aten Block AEM survey area.

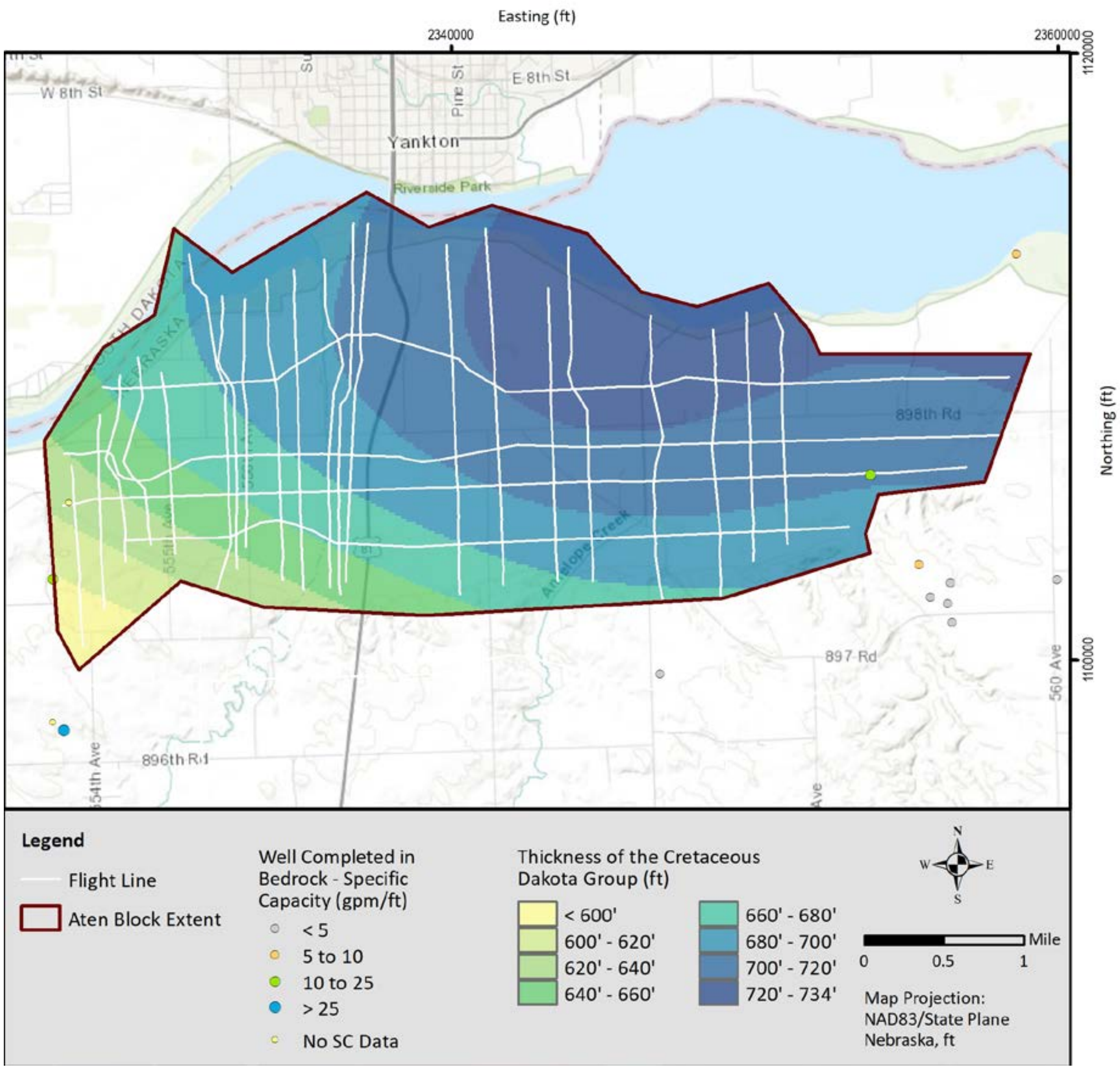


Figure 3-154. Map of the saturated thickness of the Cretaceous Dakota Group (*Kd*) Sandstone/Sand Dominant material in the 2018 Aten Block AEM survey area with specific capacity indicated in wells completed in the bedrock. The well yielding 10-25 gpm/ft follow is located on the eastern side of the Aten Block AEM survey area.

3.2.3 Hydrogeologic Framework of the Bloomfield Block AEM Survey Area

The AEM provided insight into the geographic distribution and extent of the unconsolidated material in the 2018 Bloomfield Block AEM survey area. The ***Q*** materials within the Bloomfield AEM Block are composed of unconsolidated alluvial silt, sand, and gravel generally in the form of loess and glacial till that overlie the ***To*** in the northeast and both are treated as one unit for purposes of this report. The ***To*** found in the project area is a mix of all aquifer materials. The ***Q*** and ***To*** lie on the ***Kp*** throughout the Bloomfield Block AEM area. The ***Q*** material in the Bloomfield Block AEM survey area is identified through interpretation of the AEM data as non-aquifer (blue), marginal aquifer (tan), aquifer material (yellow), and coarse aquifer (brown) material as discussed in Section 3.1.6. Generally, the flight block (Figure 3-155) is bounded 8 miles west of Bloomfield along Highway 84, just east of Highway 121 in the east, 2 miles south of Bloomfield and 5 miles north of Bloomfield, Nebraska.

Figure 3-156 displays a 3D fence diagram, looking to the north, of the interpreted hydrostratigraphic profiles with CSD and NE-DNR borehole lithology data. The area generally contains a mix of all ***Q*** and ***To*** aquifer-type materials lying upon the ***Kp***. The boreholes in the area indicate a mix of silty clay, sandy clay, and sand and gravel in the Block area. As can be seen on Figure 3-156, a large portion of the Block area is covered in glacial till/loess made up of marginal and non-aquifer materials. This makes for poor recharge across most of the area because the permeability of these materials is low, limiting the amount of infiltration. There are many areas of glacial out wash and fluvial deposits made up of mostly aquifer material and minor amounts coarse aquifer material.

Figure 3-157 presents profile L903801, located south of the town of Broomfield, Nebraska and extending southwest to northeast in the block. The CSD 1995 water table (NE-CSD, 1995) is on the profile and shows the change in water table elevation from the southwest to the northeast and changes in elevation from ~1600 to ~1480 feet. Depth to water changes from ~250 to ~30 feet below land surface and is independent to the change in topography. There is no evidence along this profile of any hydrologic connection to surface water due to the depth to the water table and the ***Q*** marginal and non-aquifer materials present. The CSD 1995 water table is also on the profile Figure 3-158 shows the water table for the area.

Figure 3-159 is a map of the top of the bedrock, composed of ***Kp*** that indicates the presence of bedrock lows and highs across the area ranging from 1,410 to 1,511 feet. The area is covered with ***Q*** aquifer material and ***To*** aquifer material, where it exists. Figure 3-160 shows where the elevation of the top of the ***To***, where it exists, northeast of Bloomfield, Nebraska and ranges in elevation from 1,468 to 1,539 feet. The total thickness of the ***Q*** and ***To*** material in the Bloomfield AEM block area (Figure 3-161) was calculated by subtracting the bedrock elevation from the ground surface elevation. The ***Q*** and ***To*** varies in thickness from <50 to 450 feet. It is important to understand the distribution of the various ***Q*** and ***To*** aquifer materials in relation to their hydrologic connection to both the surface water. Generally, the water table is deep below the land surface or bounded by marginal and non-aquifer materials which limits the connection to surface water. An example of where there is a hydrologic connection to surface water is near the Bloomfield airport along line L1002001 (Figure 3-162). The aquifer and coarse aquifer materials provide the greatest connection for water movement through all of the ***Q*** and ***To*** aquifer materials present in the area. The ***Q*** and ***To*** aquifer and coarse aquifer materials generally are confined by surrounding marginal and non-aquifer material. Of equal importance is the saturated thickness of the ***Q*** and ***To*** materials calculated by the bedrock elevation subtracted from the 1995 CSD water table surface elevation (NE-CSD, 1995). By separating the aquifer and coarse aquifer material from the total voxel model, the thickness of those units (Figure 3-163) is indicated to vary between 0, where there is no aquifer and coarse aquifer material, to a maximum thickness of about 195 feet near Bloomfield, NE. Figure 3-164 is another view of the ***Q*** and ***To*** aquifer and coarse aquifer material thickness, this time as a 3D voxel model showing the aquifer and coarse aquifer material volume in the Bloomfield Block AEM survey area in relation to the ***Kp*** bedrock.

Figure 3-165 presents interpreted Line L9033000, a southwest to northeast line west of Bloomfield, Nebraska. It is mostly ***Q*** glacial till/loess made up of marginal aquifer material and non-aquifer material. However, there are deposits of aquifer and minor coarse aquifer materials that are outwash deposits of the glacial material. The ***To*** is present below the ***Q*** on the east end of the line. Due to depth of the water table there is no hydrologic connection to surface water.

Figure 3-166 presents interpreted Line L1101109, an east-west line south of Bloomfield, Nebraska. It is mostly ***Q*** glacial till/loess made up of marginal aquifer material and non-aquifer material. However, there are deposits of aquifer material that are outwash deposits of the glacial material. Due to depth of the water table there is no hydrologic connection to surface water.

Figure 3-167 shows an exploded view voxel showing the volumes of material for ***Q*** and ***To*** aquifer materials and ***Kp*** across the entire Bloomfield Block AEM survey area***.*** The ***Q*** aquifer and coarse aquifer materials being the main aquifers with ***Kp*** being an aquitard. Figure 3-168 shows an exploded view voxel showing the volumes of ***Q*** aquifer materials including coarse aquifer, aquifer, marginal aquifer and non-aquifer. Note the marginal and non-aquifer materials consist of most of the ***Q*** volume with aquifer material next in total volume and coarse aquifer material being a minor part of the total. Figure 3-169 shows a voxel model of the ***Q*** coarse aquifer and aquifer materials with the water table in relation to the ***Kp***. As can be seen the water table is often deep below the land surface limiting the hydrologic connection to surface water. Figure 3-170 shows the saturated thickness of the ***Q*** deposits related to the specific capacity of the NE-DNR registered wells screened within the ***Q***. With the exception of the area near West Bow Creek and the North Fork of the Elkhorn River, most of the large capacity wells between 10 and >25 gpm lie near Bloomfield, Nebraska and then west to the boundary of the survey area.

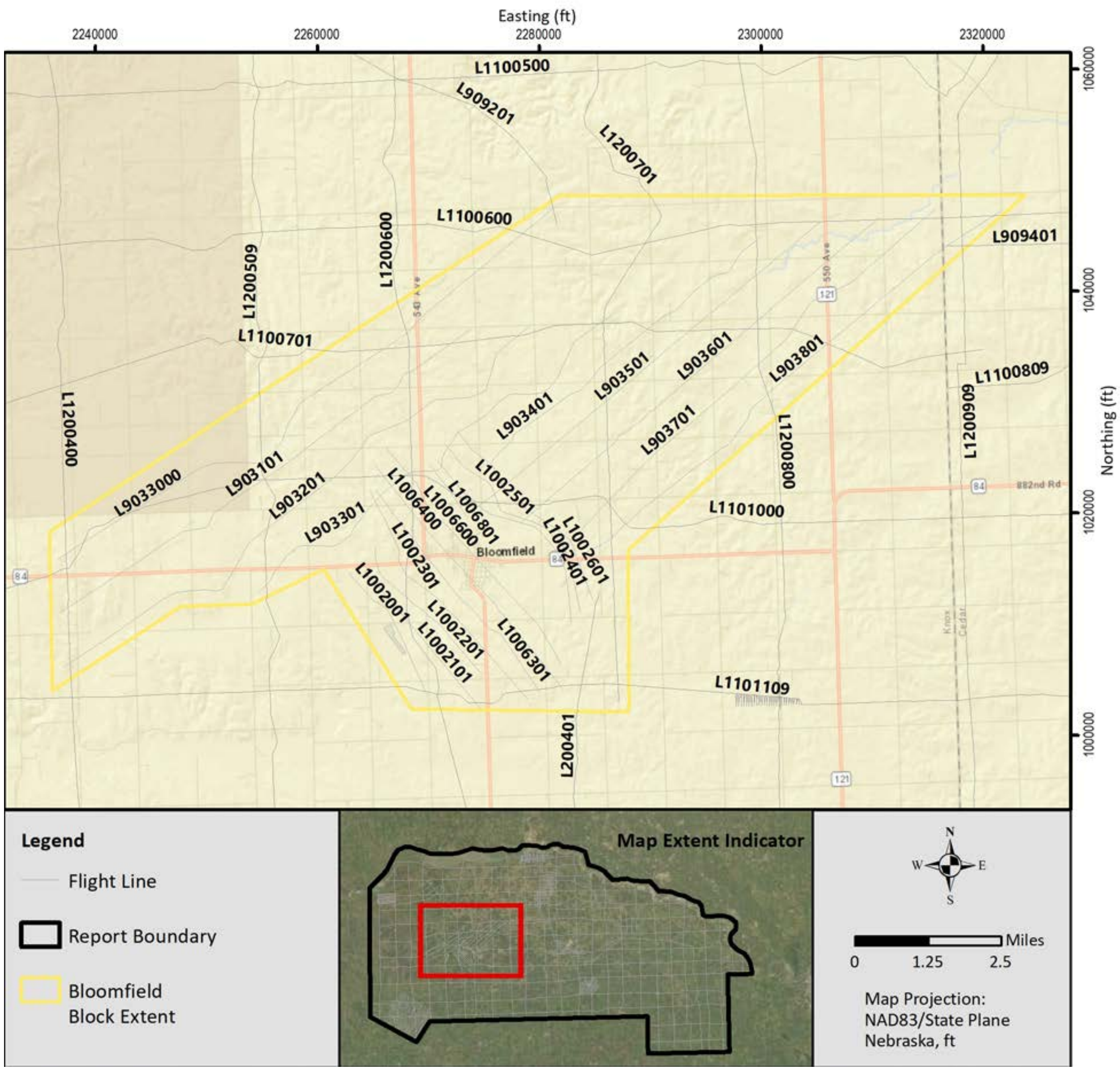


Figure 3-155. Location map of the Bloomfield Block indicating AEM flight lines, local roads, and streams.

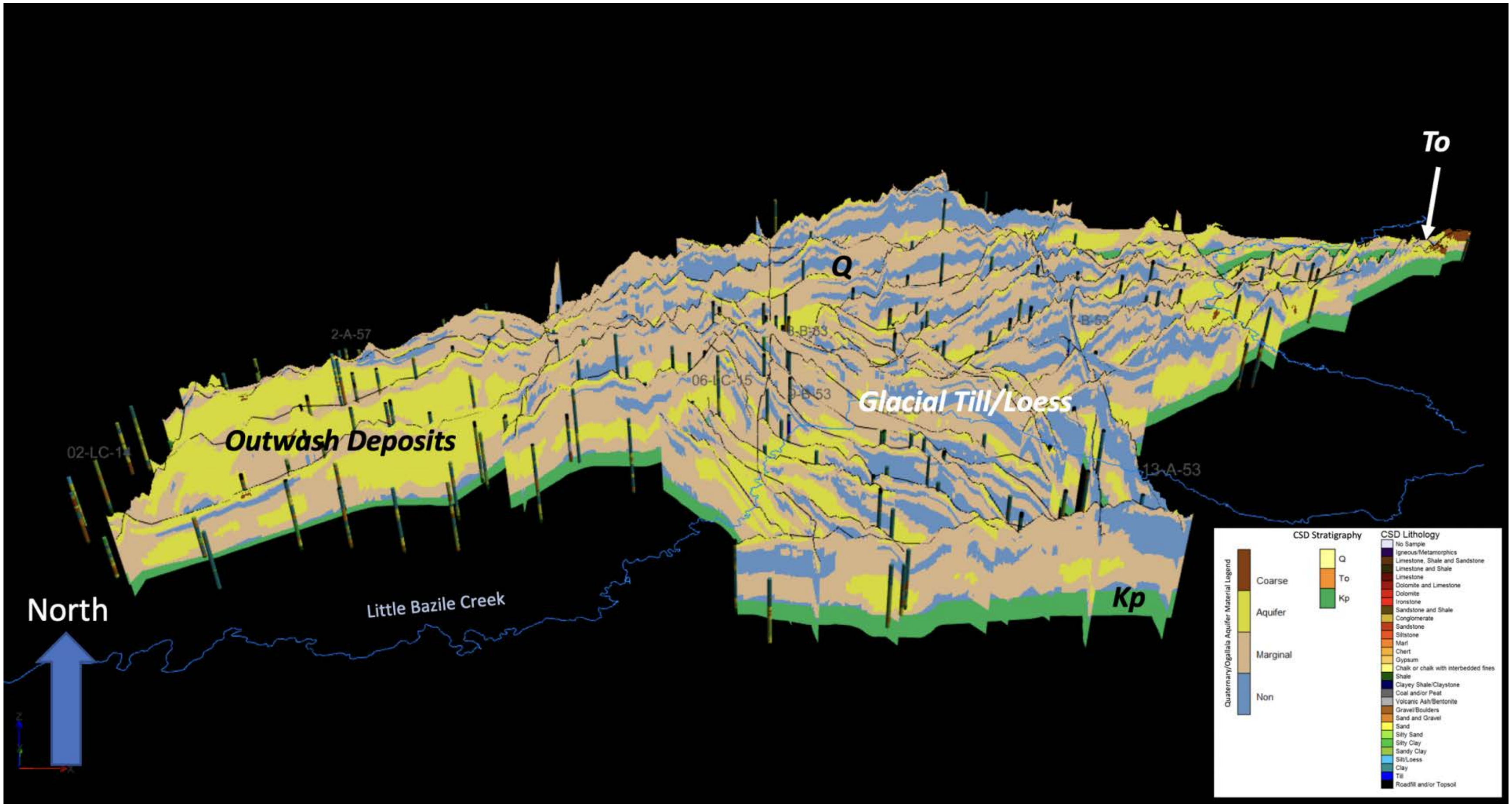


Figure 3-156. 3D fence diagram of interpreted AEM hydrostratigraphic profiles within the Bloomfield Block showing *Q*= Quaternary, *Kp*=Cretaceous Pierre Shale. Note the majority of the area is covered in marginal to non-aquifer materials. CSD test holes and NE-DNR registered wells are indicated on the plot. V.E. = 15x.

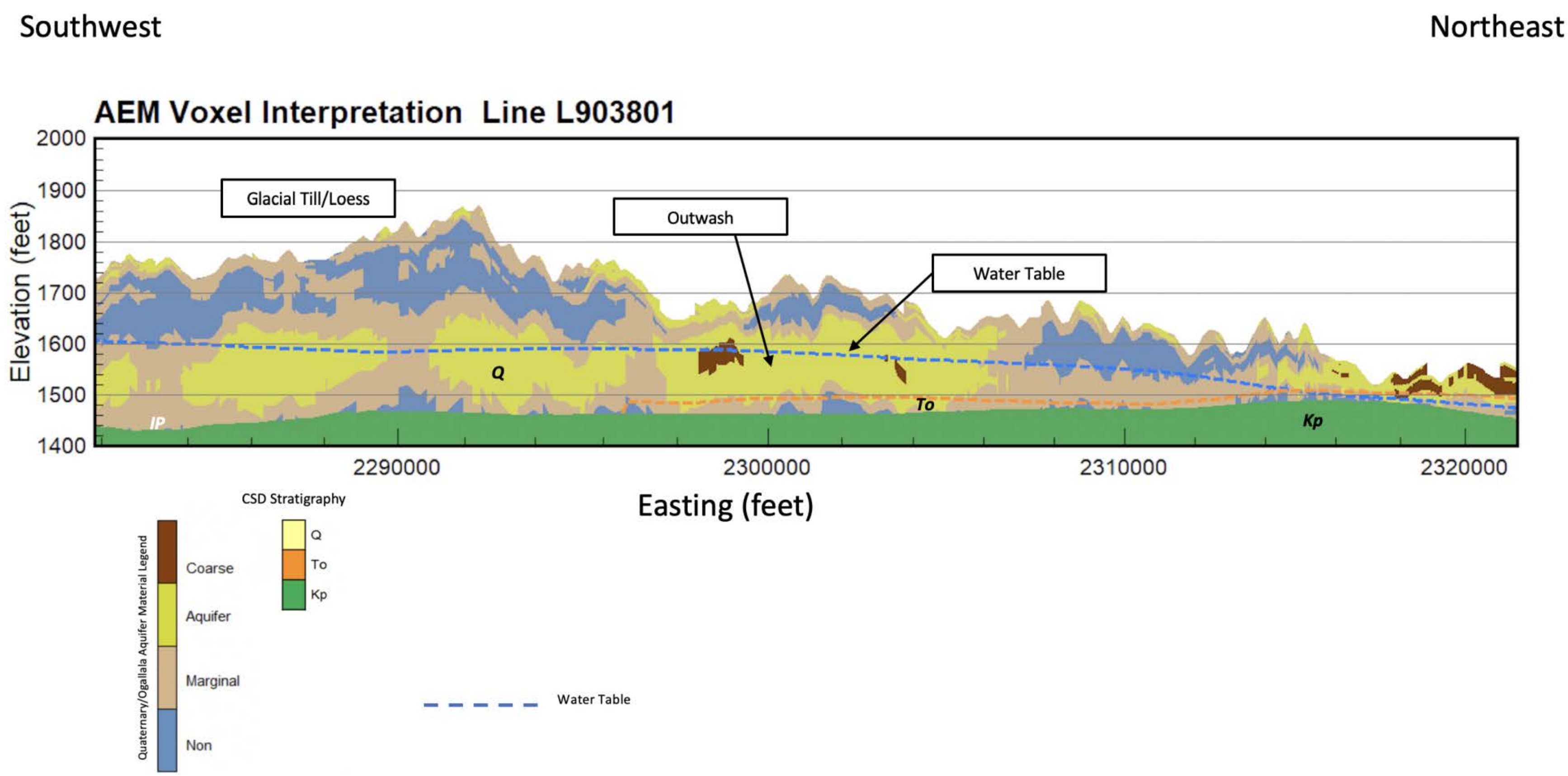


Figure 3-157. Profile of the east-west line L903801 showing the AEM interpretation. The CSD 1995 water table is indicated as a dashed blue line on the profiles. Note the isolated nature of the Quaternary (*Q*) and Tertiary Ogallala Group (*To*) aquifer materials. Horizontal datum is NAD83 State Plane Nebraska (feet).

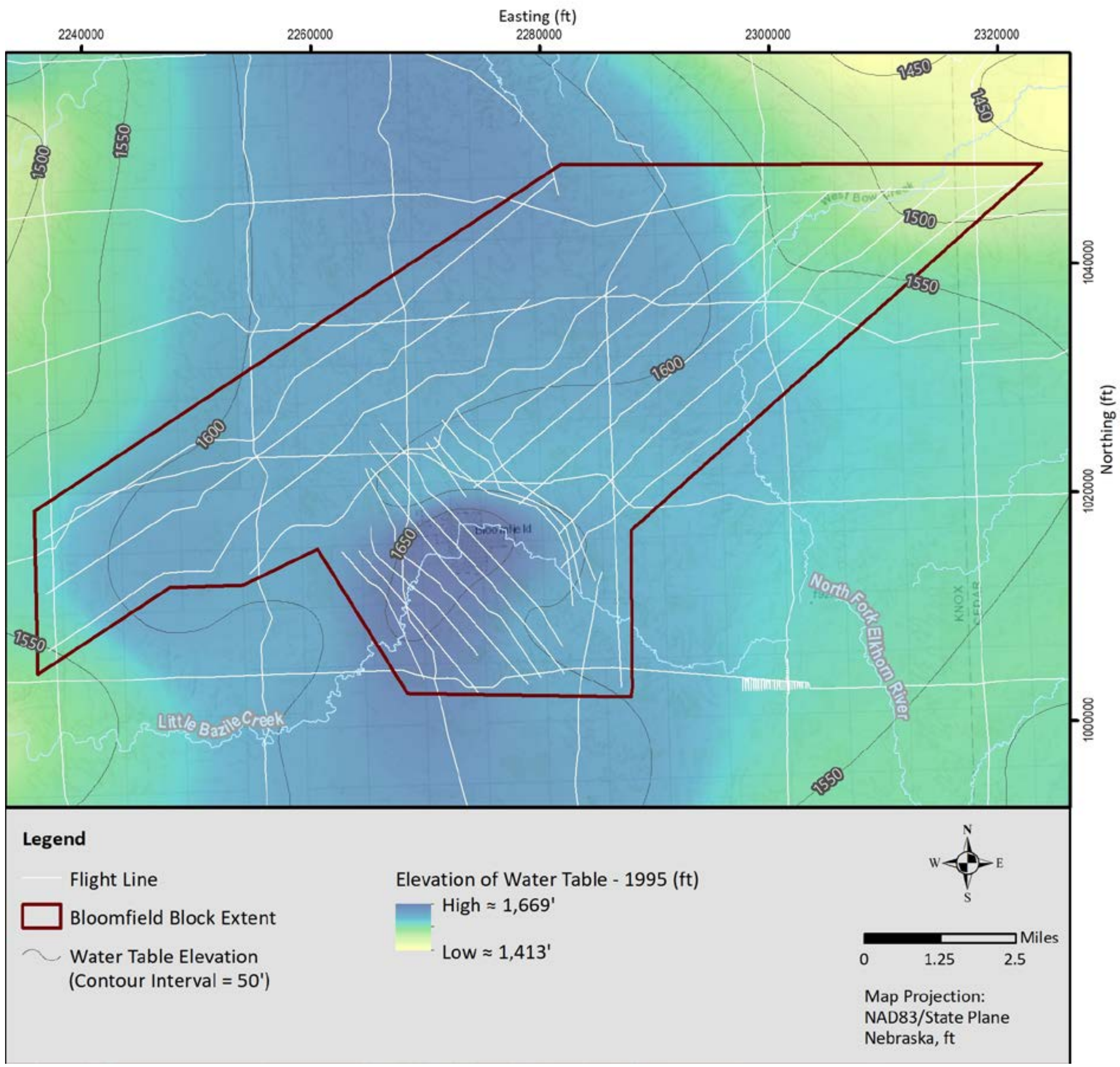


Figure 3-158. Map of the CSD 1995 water table within the 2018 Bloomfield Block AEM survey area. Block flight lines are indicated by white lines.

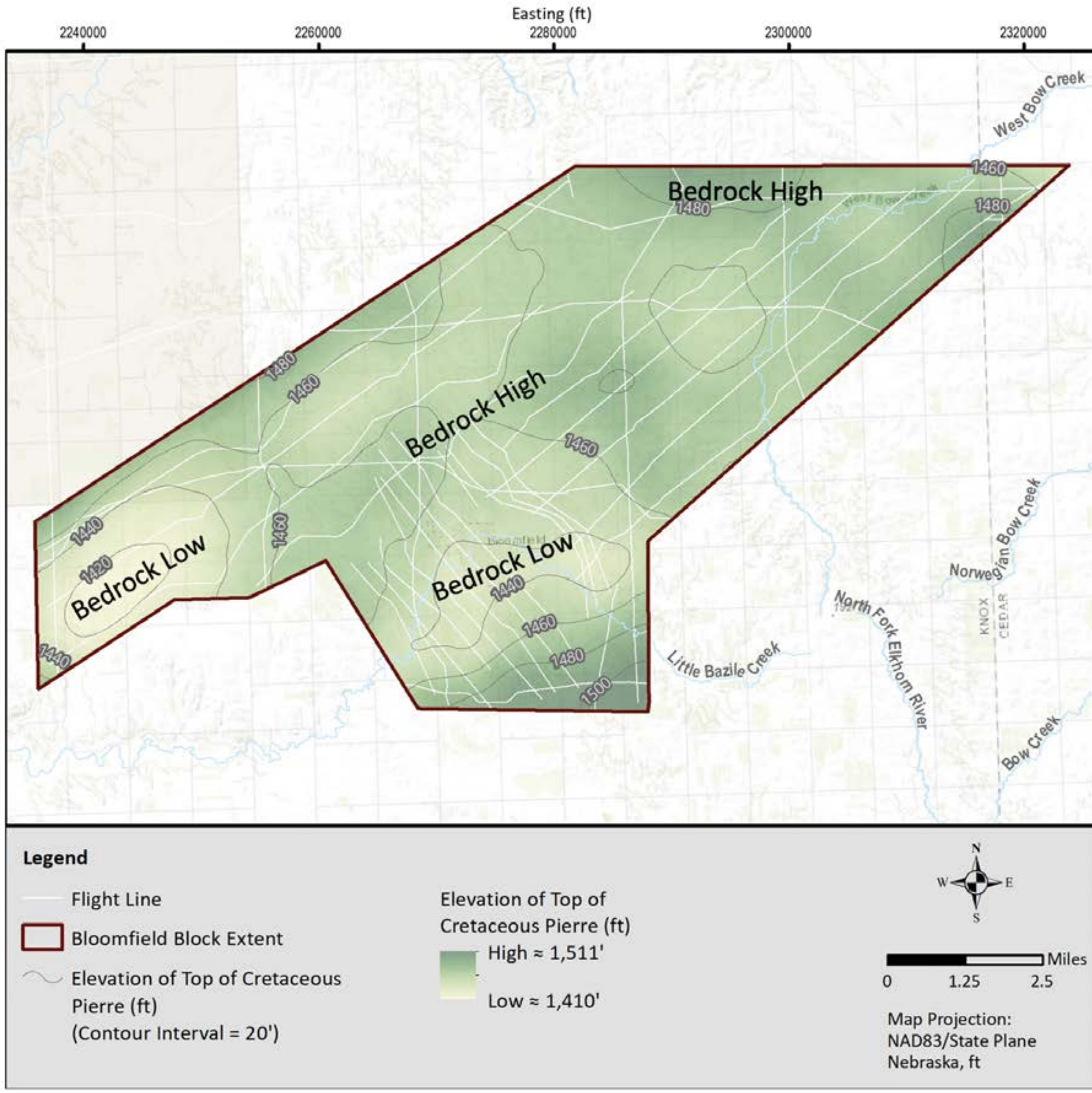


Figure 3-159. Map of the Cretaceous Pierre Shale (*Kp*) bedrock surface elevation within the Bloomfield Block. Flight lines are indicated by white lines. Note the paleovalley by David City, Nebraska and the bedrock high to each side.

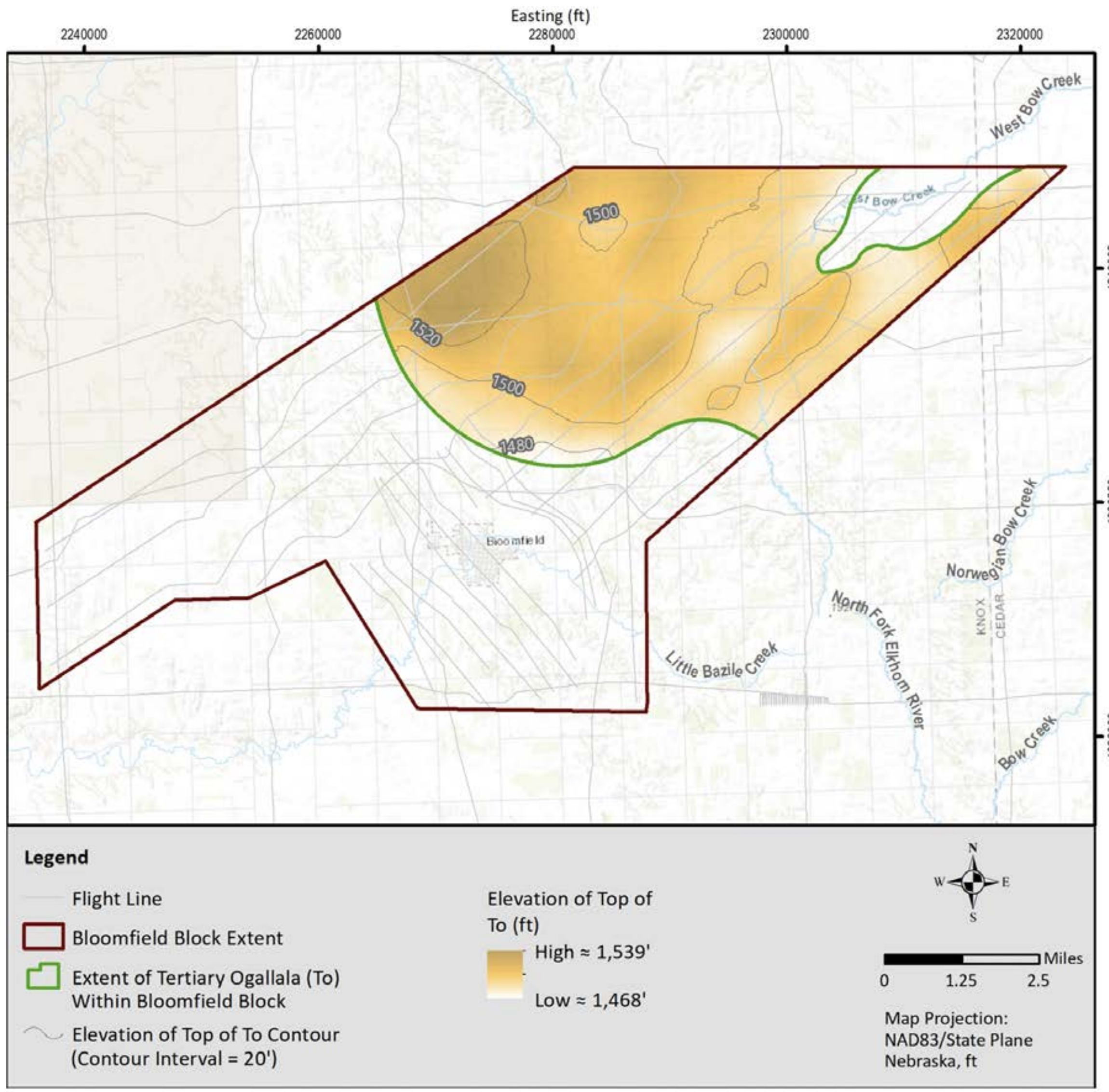


Figure 3-160. Map of the elevation of the top of the Tertiary Ogallala (*To*) within the Bloomfield Block AEM survey area. Note that *To* exists in the Northeast part of the survey area and its extent is bounded by the green lines. Block flight lines are indicated by black lines.

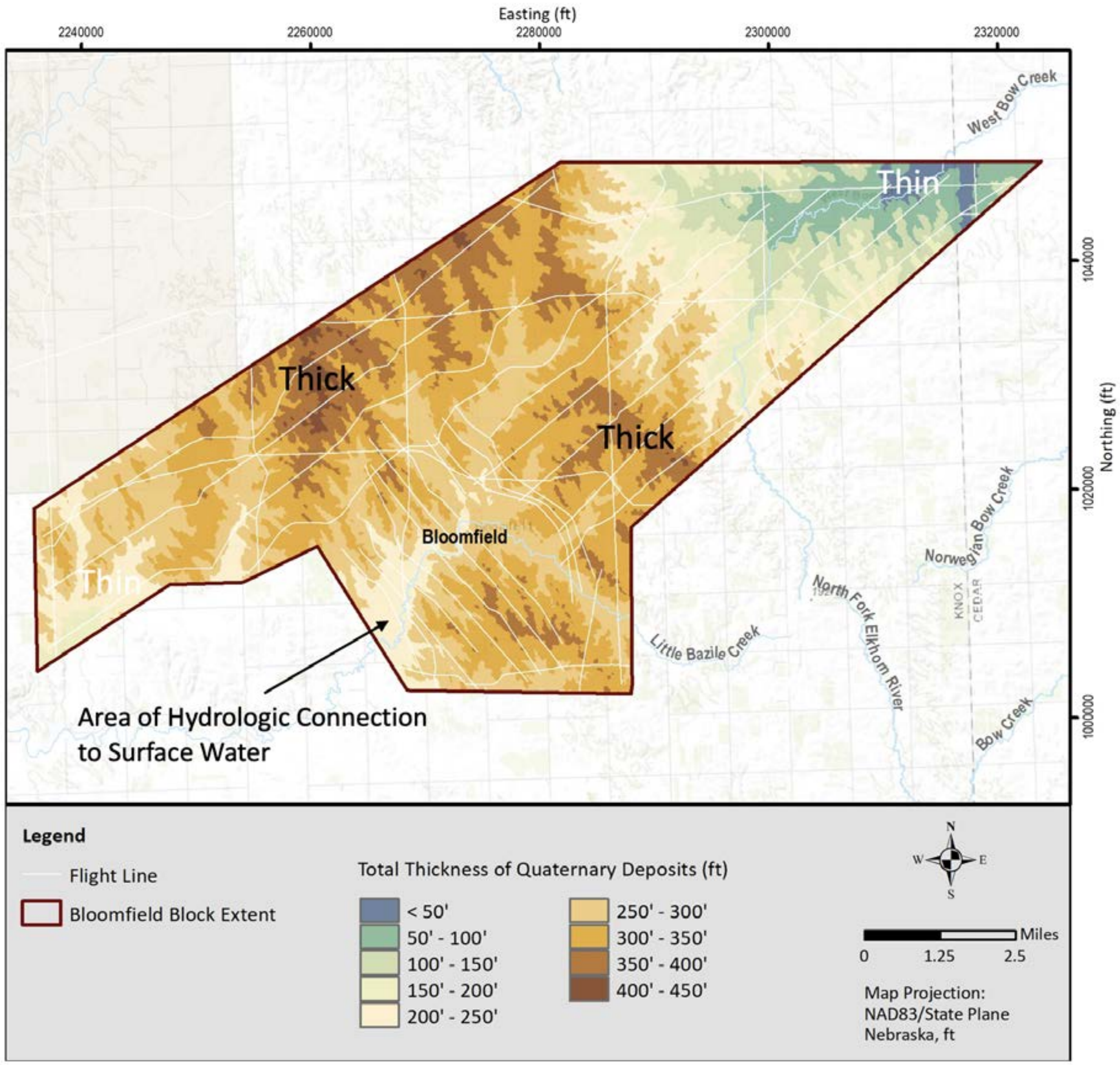


Figure 3-161. Map of the total thickness of the Quaternary (*Q*) and Tertiary Ogallala Group (To) comprised of all aquifer materials within the Bloomfield Block AEM survey area. *Q* aquifer materials include coarse aquifer, aquifer, marginal aquifer and non-aquifer materials. Note the example of hydrologic connection to surface water on Little Bazile Creek. Block flight lines are indicated by black lines.

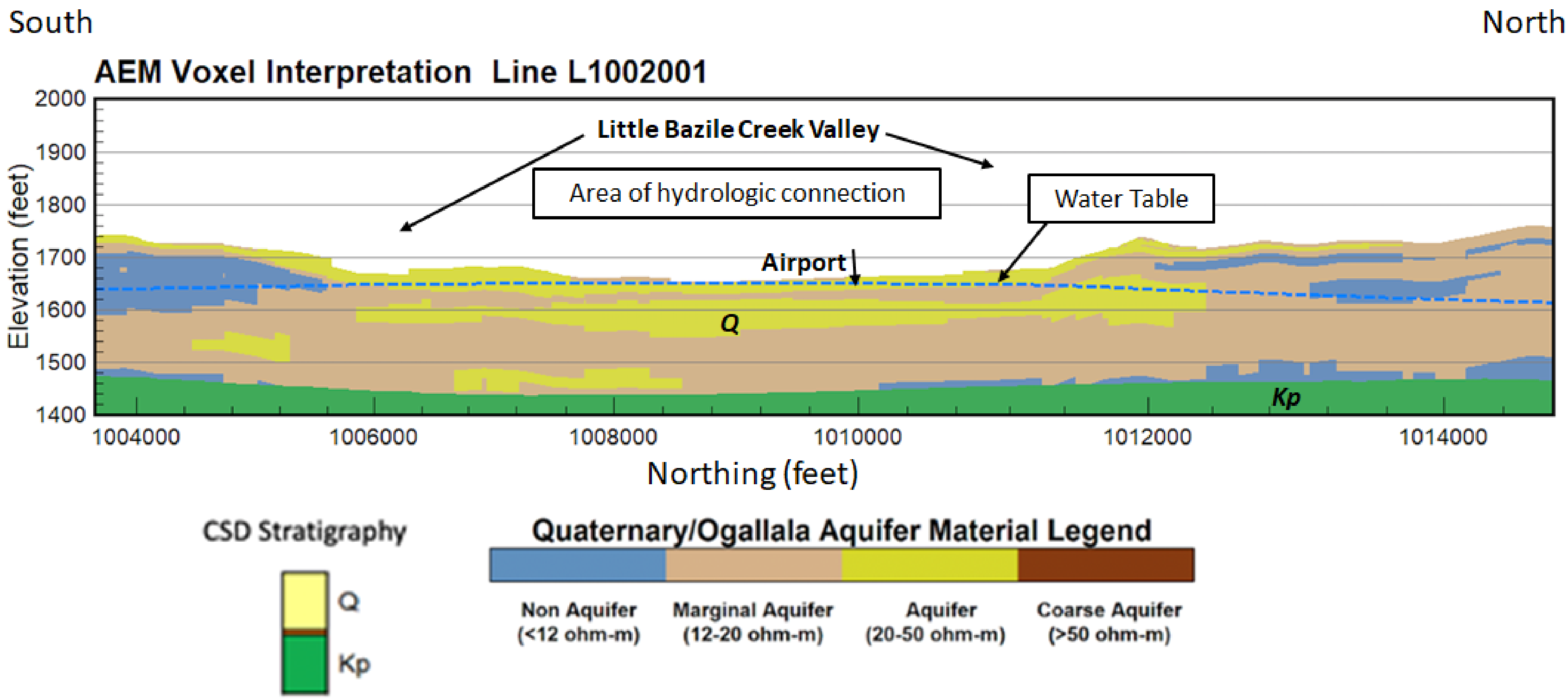


Figure 3-162. Profile of the east-west line L1002001 showing the AEM interpretation. The CSD 1995 water table is indicated as a dashed blue line on the profiles. Note the isolated nature of the Quaternary (*Q*) and Tertiary Ogallala Group (*To*) aquifer materials except for immediately below the Little Bazile Creek Valley where there is a hydrologic connection to surface water. Horizontal datum is NAD83 State Plane Nebraska (feet).

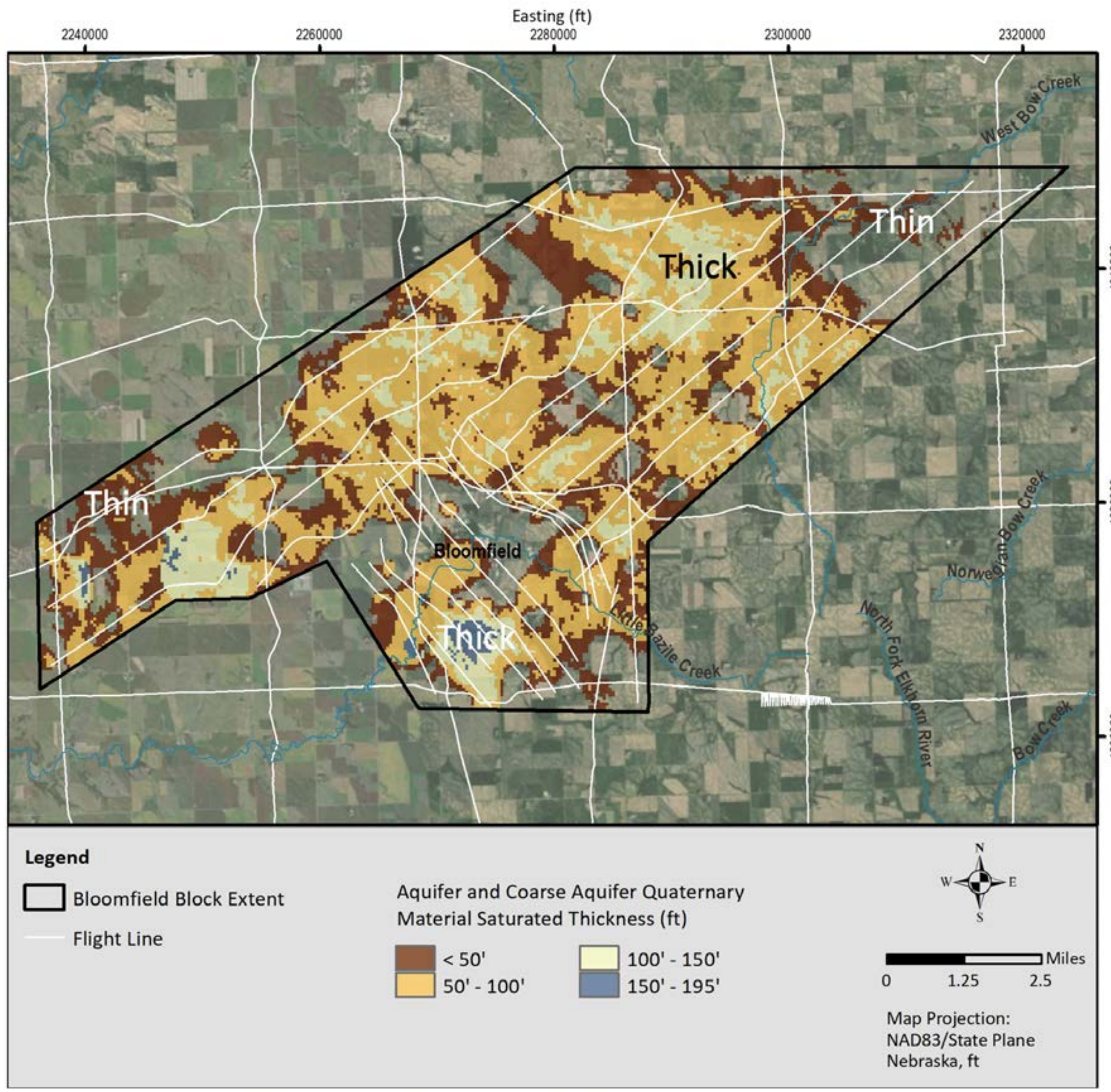


Figure 3-163. Map of the saturated thickness of the Quaternary (*Q*) and Tertiary Ogallala Group (*To*) aquifer and coarse aquifer materials within the Bloomfield Block AEM survey area. Block flight lines are indicated by the white lines. Note the discontinuous nature of the coarse aquifer and aquifer materials and the variation of their thickness.

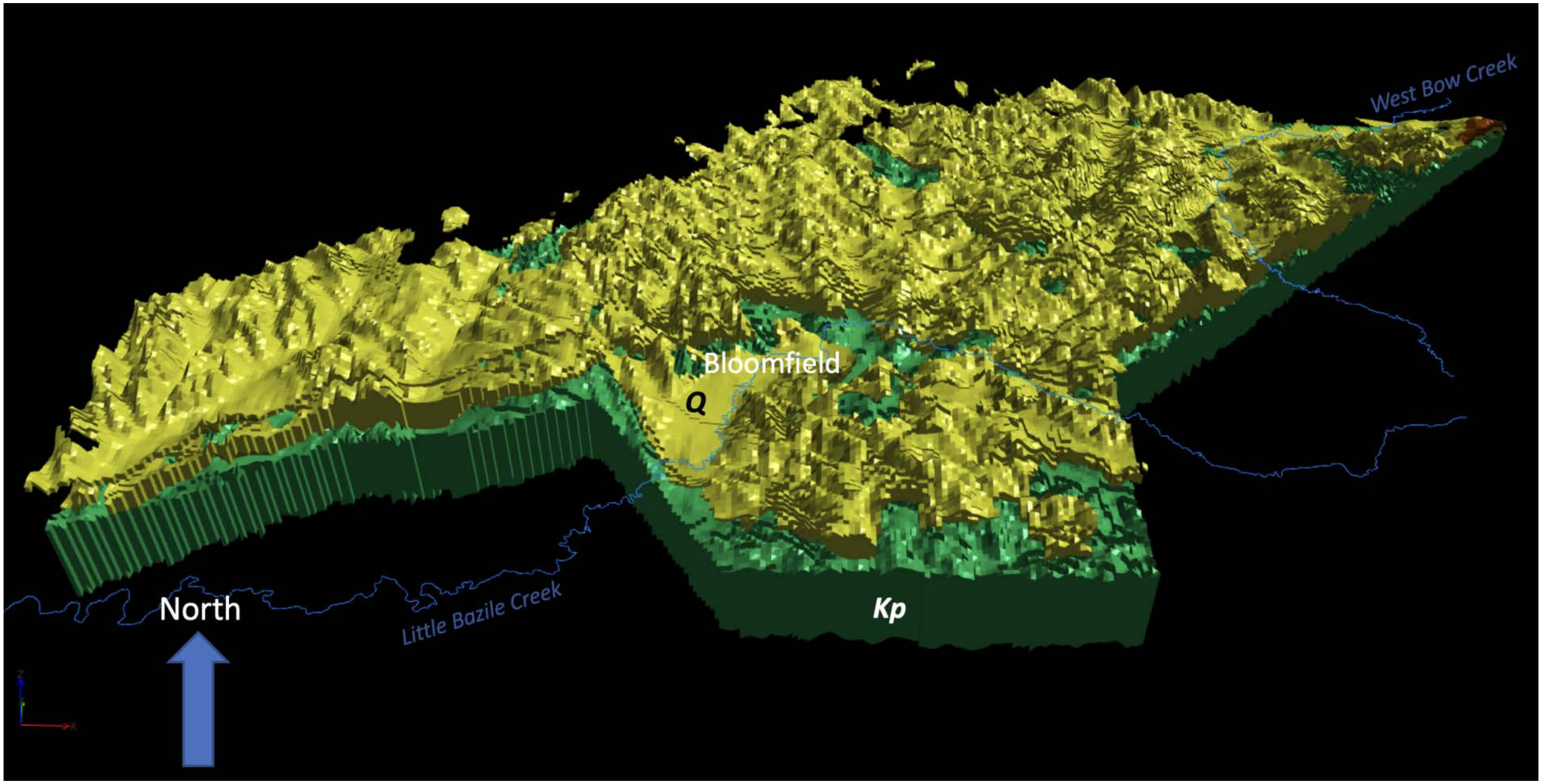


Figure 3-164. 3D voxel plot of the Quaternary (*Q*) and Tertiary Ogallala Group (*To*) coarse aquifer and aquifer materials and their relationship to the *Kp*. Note the discontinuous nature of this unit. V.E. = 15x.

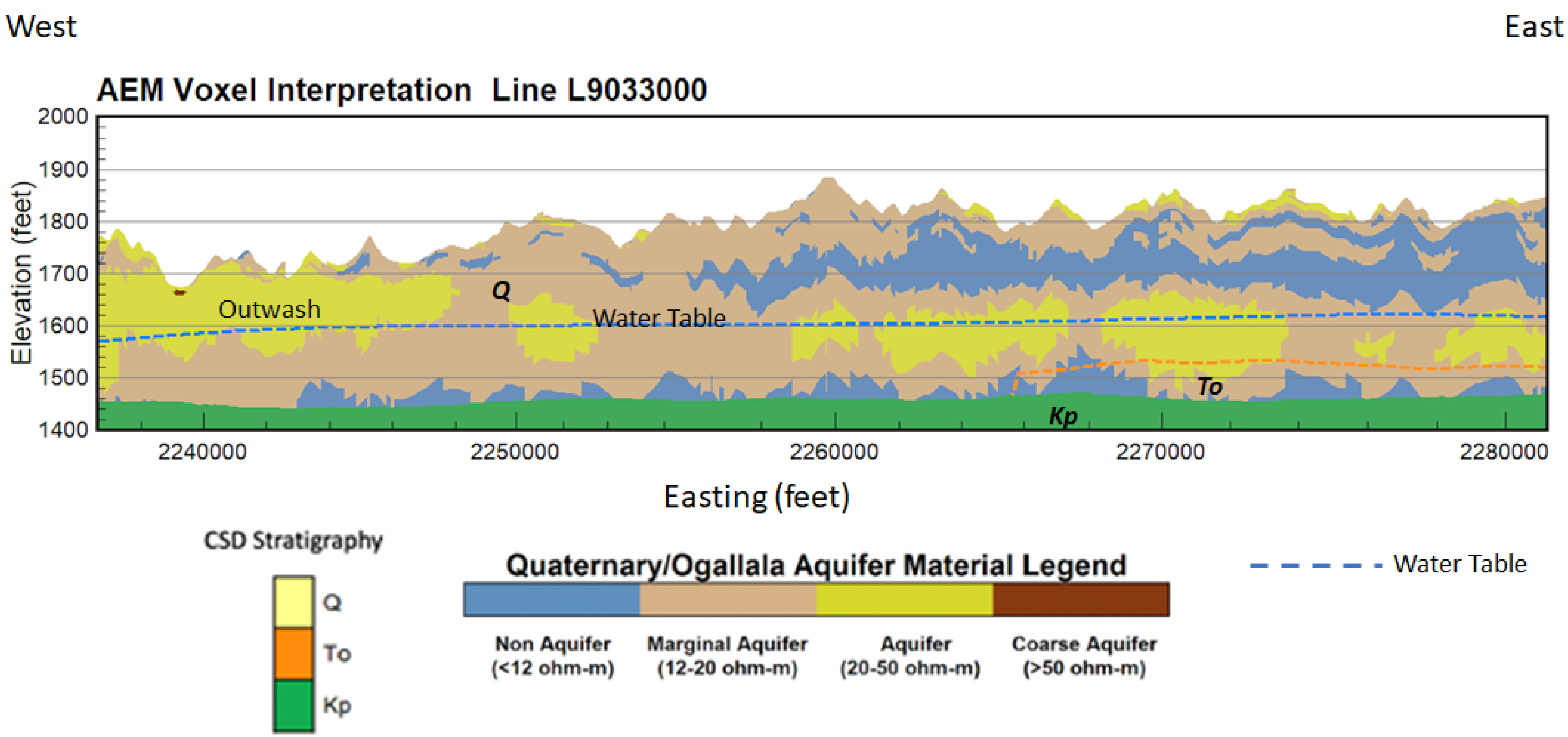


Figure 3-165. Profile of the east-west line L9033000 showing the AEM interpretation of the Quaternary (*Q*) and Tertiary Ogallala Group (*To*) aquifer materials. Note the multiple *Q* aquifer material outwash deposits across the profile. The CSD 1995 water table is indicated as a dashed blue line. Horizontal datum is NAD83 State Plane Nebraska (feet).

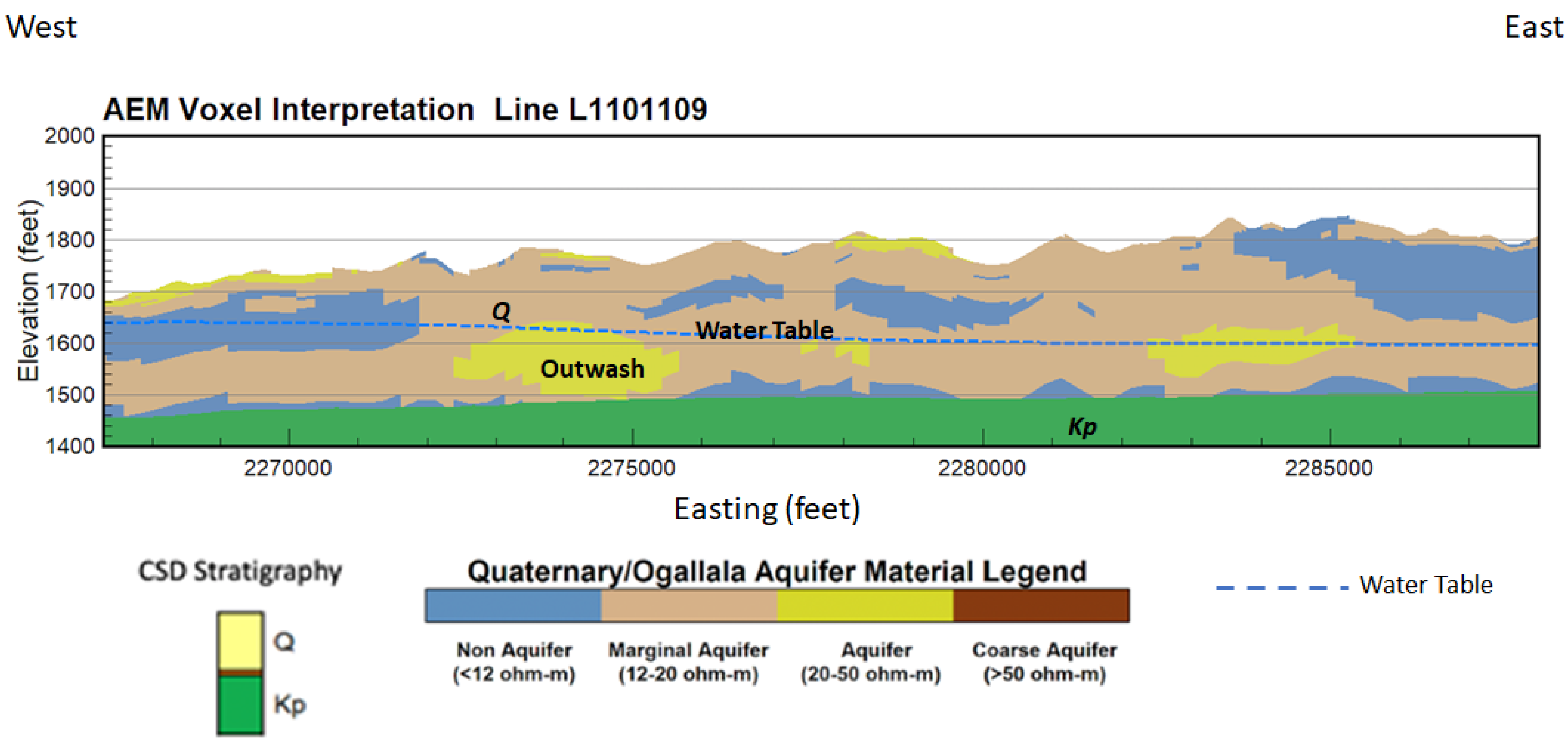


Figure 3-166. Profile of the east-west line L1101109 showing the AEM interpretation of the Quaternary (*Q*) and Tertiary Ogallala Group (*To*) aquifer materials. Note the multiple small *Q* aquifer material outwash deposits across the profile. The CSD 1995 water table is indicated as a dashed blue line. Horizontal datum is NAD83 State Plane Nebraska (feet).

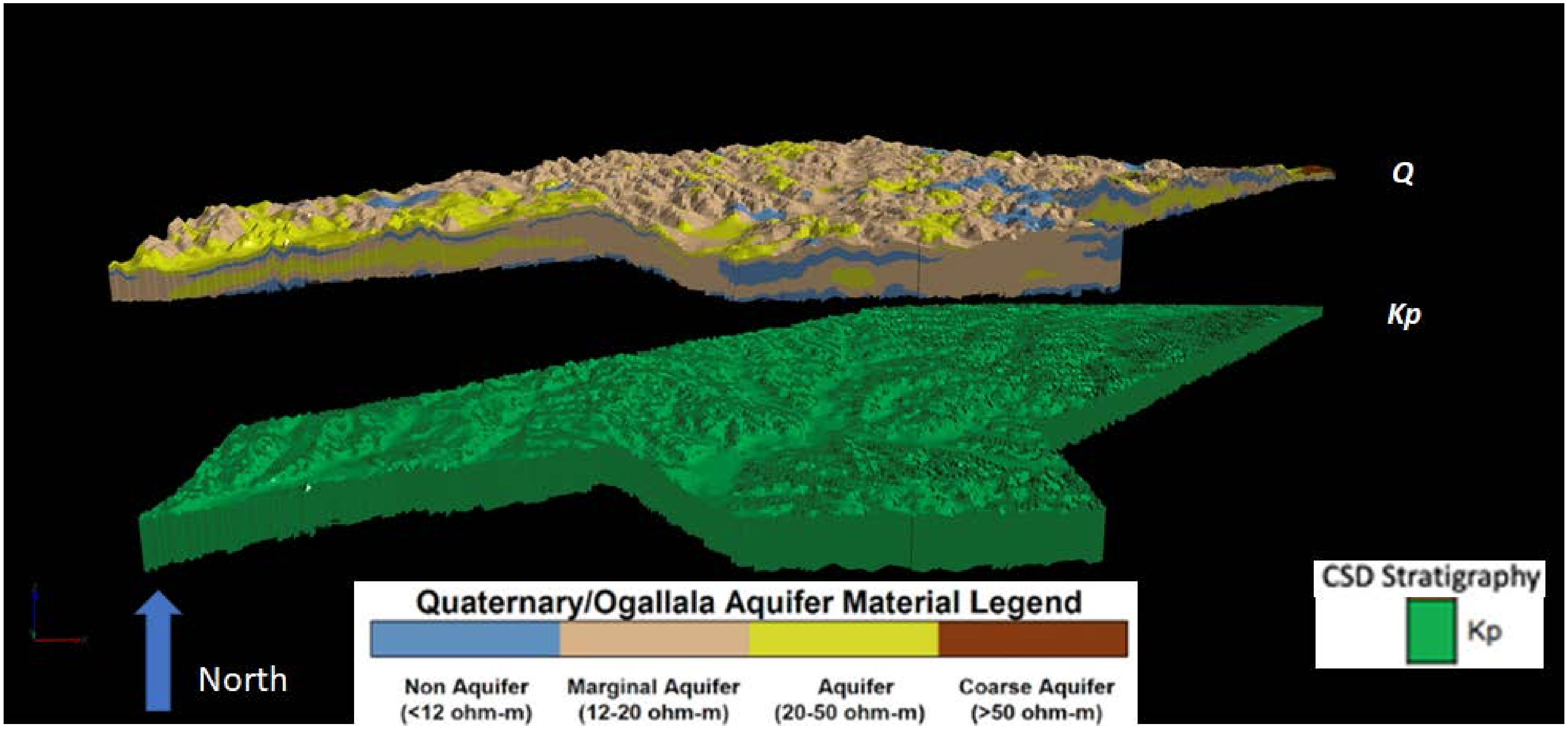


Figure 3-167. 3D 'exploded' voxel model of the Bloomfield Block AEM survey area showing *Q*= Quaternary, *To*= Tertiary Ogallala Group, *Kp*=Cretaceous Pierre Shale. V.E. = 15x. Note that the image is not to scale.

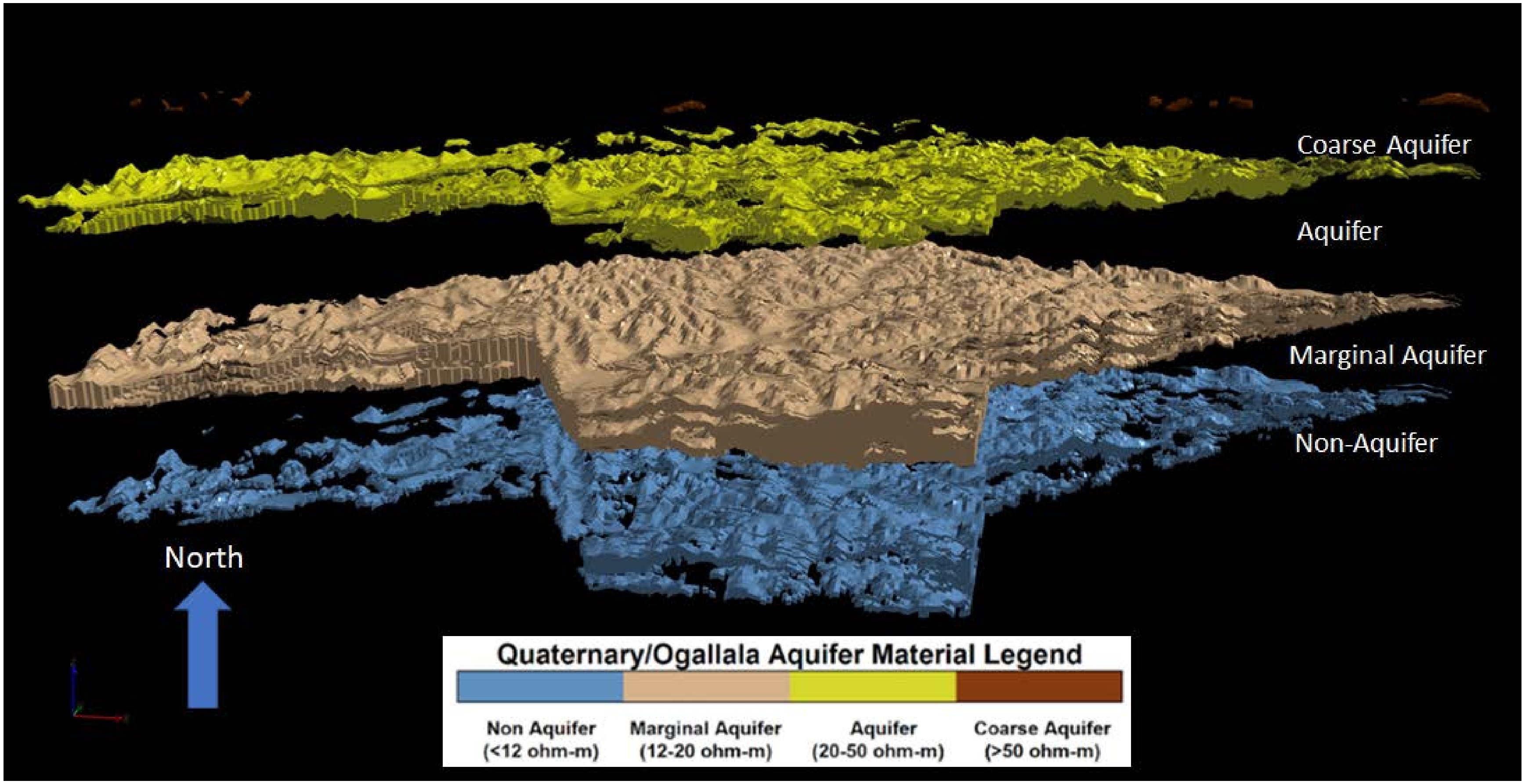


Figure 3-168. 3D 'exploded' voxel model of the Bloomfield Block AEM survey area showing Quaternary (*Q*) aquifer materials divided into coarse aquifer, aquifer, marginal aquifer and non-aquifer. Note the majority of the *Q* material is made up of marginal and non-aquifer material. V.E. =15x, but the image is not to scale.

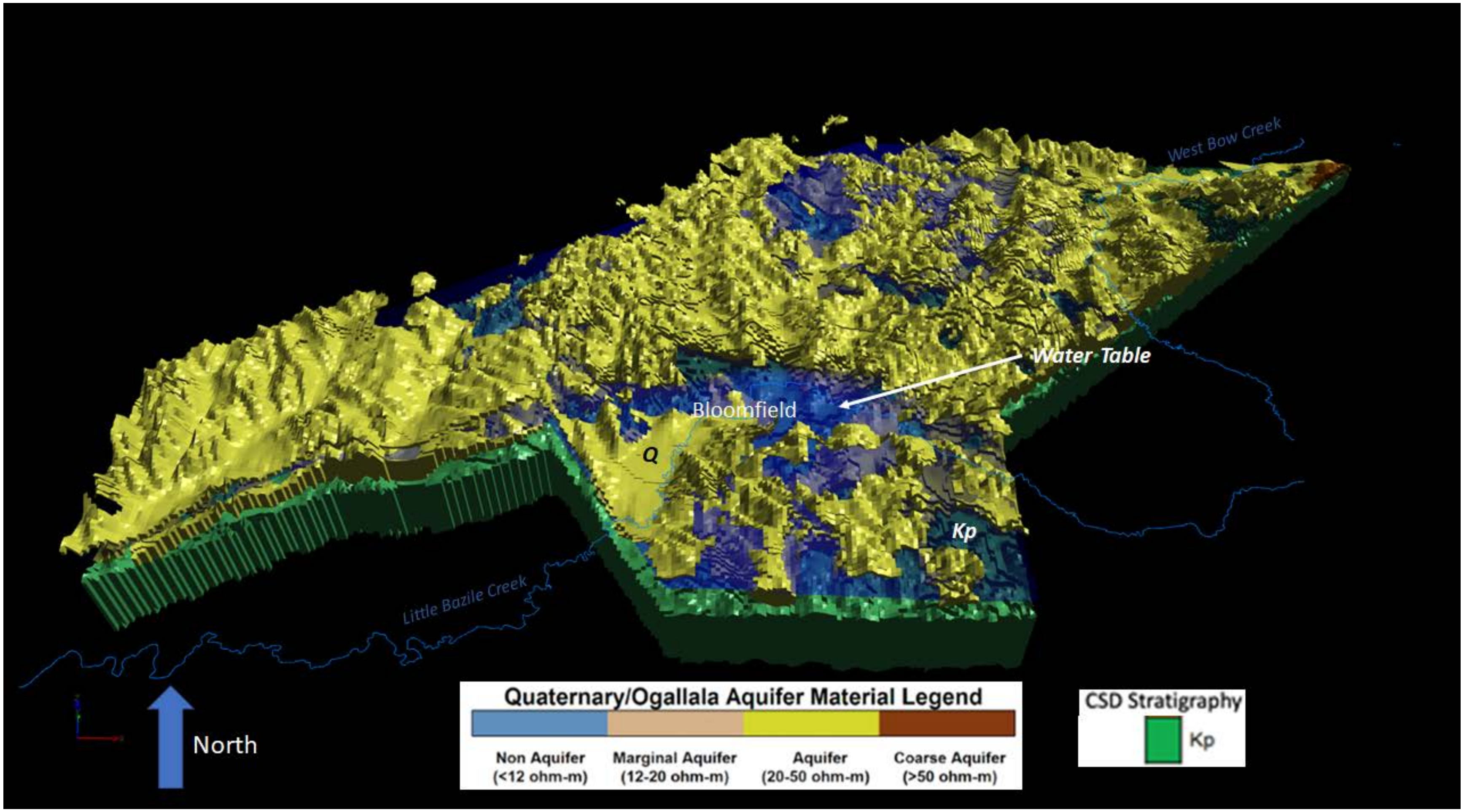


Figure 3-169. 3D voxel model of the Bloomfield Block AEM survey area showing Quaternary (*Q*) aquifer and coarse aquifer with the water table surface and the Cretaceous Pierre Shale (*Kp*) bedrock. Note the connection between the unsaturated aquifer material and saturated aquifer material. V.E. =15x. Not to scale.

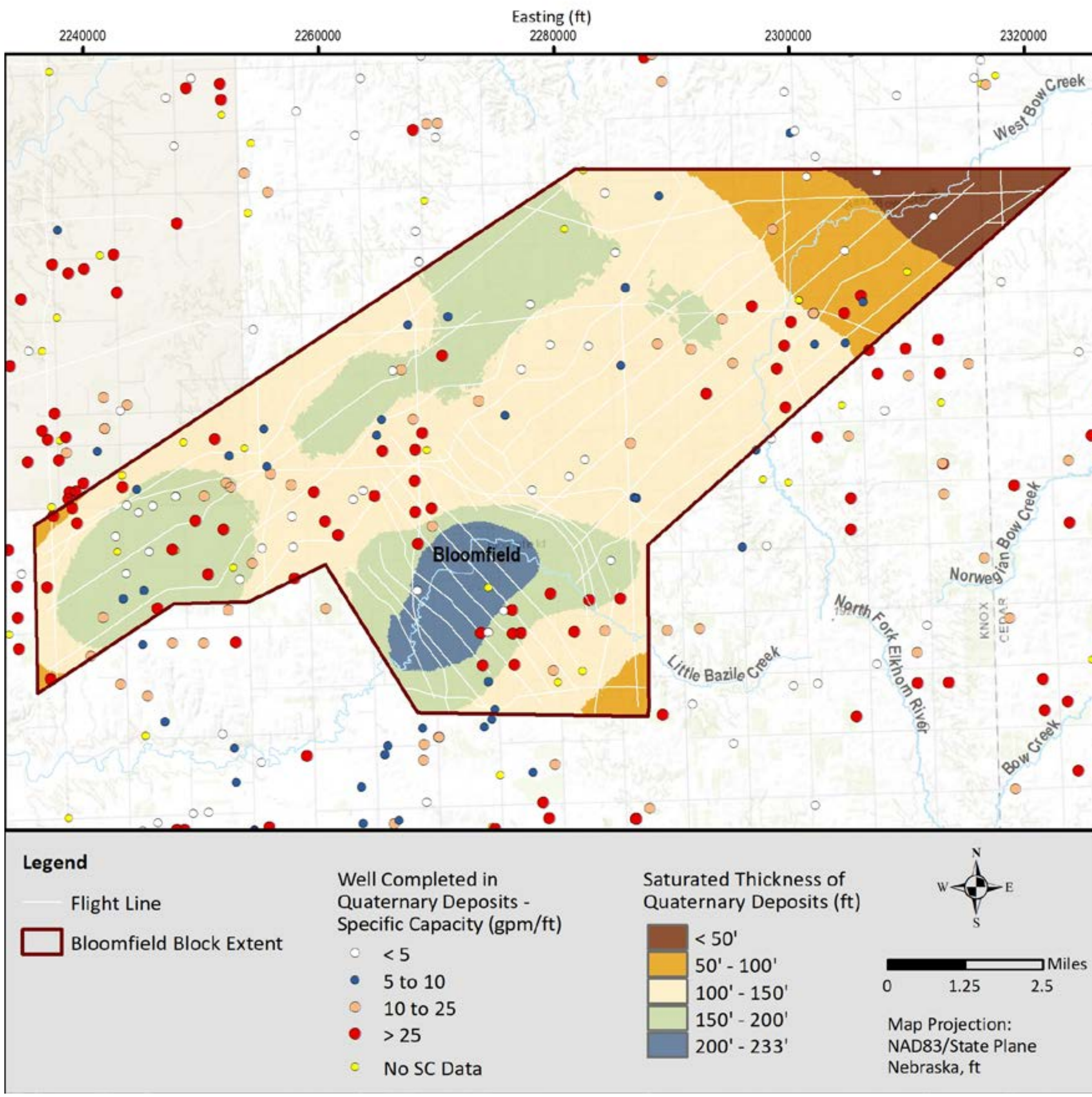


Figure 3-170. Map of the saturated thickness of the Quaternary (*Q*) and Tertiary Ogallala Group (*To*) deposits related to the specific capacity of the wells screened within the *Q/To*. Note the majority of high capacity wells are in the vicinity of Bloomfield, Nebraska extending west to the block flight boundary. Block flight lines are indicated by the white lines.

3.2.4 Hydrogeologic Framework of the Hartington Block AEM Survey Area

The AEM provided insight into the geographic distribution and extent of the unconsolidated material in the Hartington Block AEM survey area. The ***Q*** materials within the Hartington Block are composed of unconsolidated alluvial silt, sand, and gravel generally in the form of loess and glacial till that overlie the ***To*** in the southeast and southwest and both are treated as one unit for purposes of this report. The ***To*** found in the project area is a mix of all aquifer materials. The ***Q*** and ***To*** lie on the ***Kp*** in northwest part of the Hartington Block AEM area and on the ***Kn*** throughout most of the area. The ***Q*** material in the Hartington Block AEM survey area is identified through interpretation of the AEM data as non-aquifer (blue), marginal aquifer (tan), aquifer material (yellow), and coarse aquifer (brown) material as discussed in Section 3.1.6. Generally, the flight block (Figure 3-171) is bounded 3 miles west of Hartington along Highway 84, 3 miles east of Hartington, 2 miles south of Hartington and ~5 miles south of Hartington, Nebraska near Pearl Creek.

Figure 3-172 displays a 3D fence diagram, looking to the south, of the interpreted hydrostratigraphic profiles with CSD and NE-DNR borehole lithology data. The area generally contains a mix of all ***Q*** and ***To*** aquifer-type materials lying upon the ***Kp*** in the northwest part of the area and on the ***Kn*** throughout the rest of the block. The boreholes in the area indicate a mix of silty clay, sandy clay, and sand and gravel in the block area. As can be seen on Figure 3-172, approximately half of the block area is covered in glacial till/loess made up of marginal and non-aquifer materials. This makes for poor recharge across most of the area because the permeability of these materials is low, limiting the amount of infiltration. The other half of the area is covered in glacial outwash and fluvial deposits made up of mostly aquifer material and coarse aquifer material which makes for good recharge areas.

Figure 3-173 presents profile L910601, located west of the town of Hartington, Nebraska and extending from the west side of the Block to just west of Hartington. The CSD 1995 water table (NE-CSD, 1995) is on the profile and shows the change in water table elevation from the east to the west and changes in elevation from ~1,450 to ~1,400 feet. Depth to water changes from ~50 to ~150 feet below land surface and is independent to the change in topography. There is no evidence along this profile of any hydrologic connection to surface water due to the depth to the water table and the ***Q*** marginal and non-aquifer materials present. The CSD 1995 water table is also on the profile Figure 3-174 shows the water table for the area.

Figure 3-175 is a map of the top of the bedrock, composed of ***Kn*** that indicates the presence of bedrock lows and highs across the area ranging from 1,383 to 1,300 feet. The area is covered with ***Q*** aquifer material and ***To*** aquifer material where it exists.

The total thickness of the ***Q*** and ***To*** material in the Hartington AEM block area (Figure 3-176) was calculated by subtracting the bedrock elevation from the ground surface elevation. The ***Q*** and ***To*** varies in thickness from <20 to 296 feet. It is important to understand the distribution of the various ***Q*** and ***To*** aquifer materials in relation to their hydrologic connection to both the surface water. Generally, the water table is deep below the land surface or bounded by marginal and non-aquifer materials which limits the connection to surface water. An example of where there is a hydrologic connection to surface water is near the Hartington airport along line L1201300 (Figure 3-177). The aquifer and coarse aquifer materials provide the greatest connection for water movement through all of the ***Q*** and ***To*** aquifer materials present in the area. The ***Q*** and ***To*** aquifer and coarse aquifer materials generally are confined by surrounding marginal and non-aquifer material. As can be seen on the profile the aquifer material that fills the Bow Creek valley is bounded to the north by ***Kn*** and to the south by marginal and non-aquifer materials. The area along the profile is mostly coarse aquifer and aquifer material to the land surface which makes for a good recharge area. Of equal importance is the saturated thickness of the ***Q*** and ***To*** materials calculated by the bedrock elevation subtracted from the 1995 CSD water table surface elevation (NE-CSD, 1995). By separating the aquifer and coarse aquifer material from the total voxel model, the thickness of those units (Figure 3-178) is indicated to vary between 0, where there is no aquifer and coarse aquifer material, to a maximum thickness of about 103 feet near east side of the area. Figure 3-179 is another view of the aquifer and coarse aquifer material thickness, this time as a 3D voxel model showing the aquifer and coarse aquifer material volume in the Hartington Block in relation to the water table and the ***Kp*** and ***Kn*** bedrock.

Figure 3-180 presents interpreted Line L910201, an east-west line south of Hartington, Nebraska. It is mostly ***Q*** glacial till/loess made up of marginal aquifer material and non-aquifer material. However, there are deposits of aquifer and coarse aquifer materials that are outwash deposits of the glacial material. The shallow water table in Bow Creek valley has a hydrologic connection to surface water.

Figure 3-181 presents interpreted Line L1101109, an east-west line south of Hartington, Nebraska near the south area border. It is mostly ***Q*** glacial till/loess made up of marginal aquifer material and non-aquifer material. There is also ***To*** materials below the ***Q*** in the east in of the line. However, there are deposits of aquifer material that are outwash deposits of the glacial material. Due to depth of the water table and the presence of marginal to non-aquifer material that acts as a boundary there is no hydrologic connection to surface water.

Figure 3-182 shows an exploded view voxel showing the volumes of material for ***Q*** and ***To*** aquifer materials, ***Kp***, ***Kn***, and ***Kc*** across the entire Hartington Block AEM survey area**.** The ***Q*** and ***To*** aquifer and coarse aquifer materials being the main aquifers of the Block with ***Kp***, ***Kn***, and ***Kc*** being an aquitard. Figure 3-183 shows an exploded view voxel showing the volumes of ***Q*** aquifer materials including coarse aquifer, aquifer, marginal aquifer and non-aquifer. Note the marginal and non-aquifer materials consist of most of the ***Q*** volume with aquifer material next in total volume and coarse aquifer material being a minor part of the total. Figure 3-184 shows a voxel model of the ***Q*** coarse aquifer and aquifer materials with the water table in relation to the ***Kp*** and ***Kn*** bedrock. As can be seen, the water table is often deep below the land surface limiting the hydrologic connection to surface water.

Figure 3-185 shows the saturated thickness of the ***Q*** deposits related to the specific capacity of the NE-DNR registered wells screened within the ***Q***. Most of the large capacity wells between 10 and >25 gpm lie near Bow Creek south of Hartington, Nebraska and then west to the boundary of the survey area.

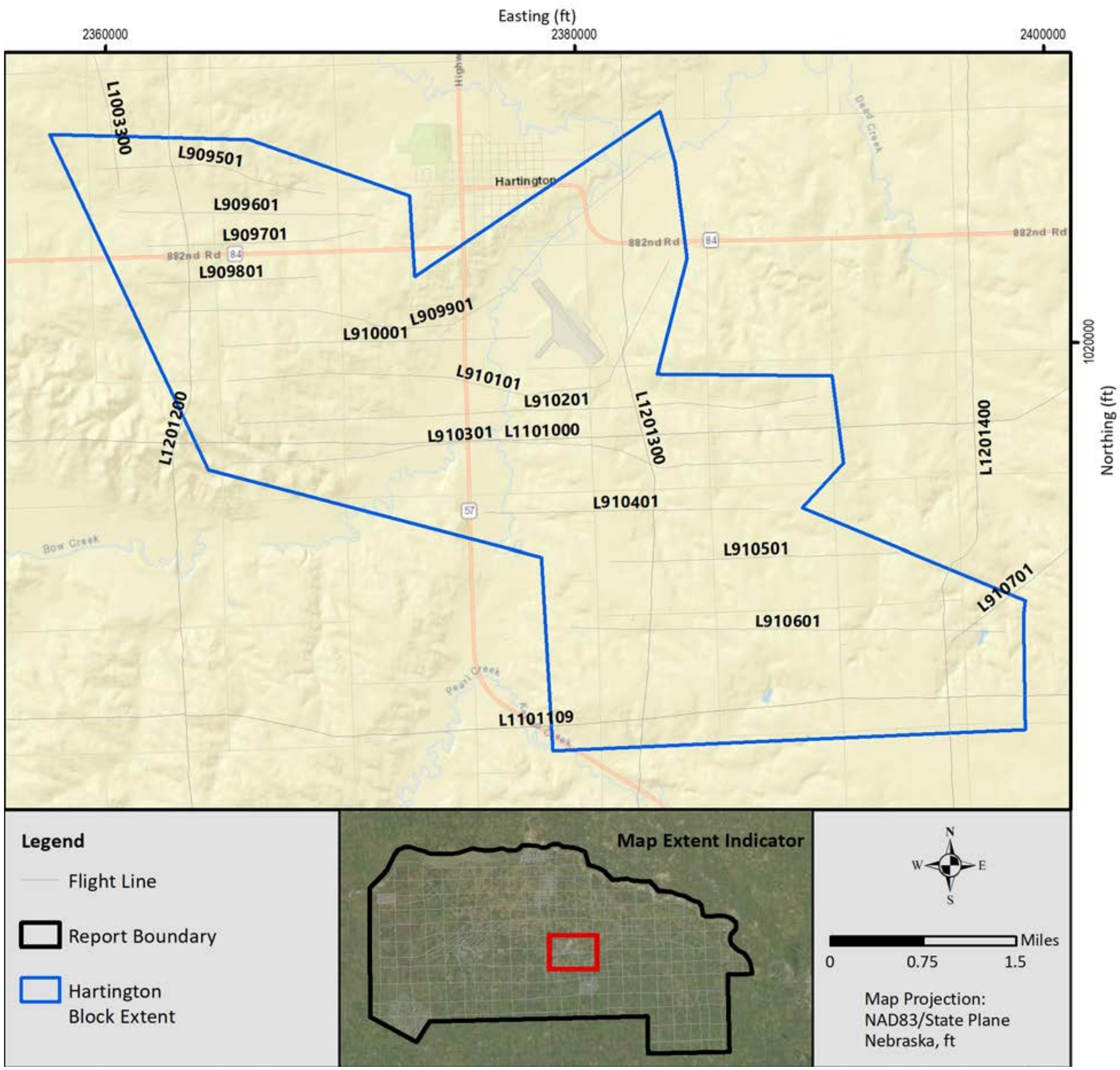


Figure 3-171. Location map of the Hartington Block indicating AEM flight lines local roads and streams.

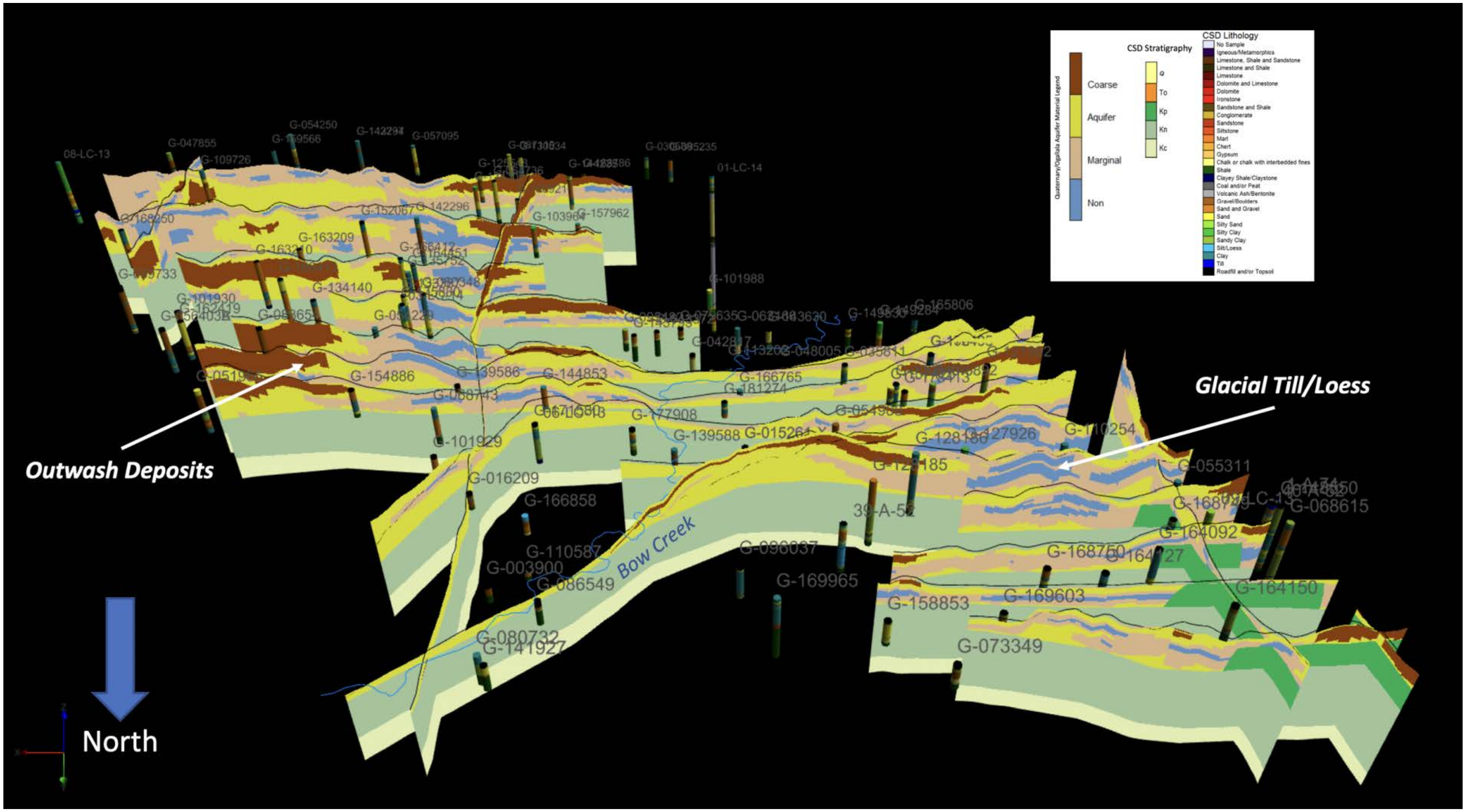


Figure 3-172. 3D fence diagram of interpreted AEM hydrostratigraphic profiles within the Hartington Block showing *Q*= Quaternary, *Kp*=Cretaceous Pierre Shale, *Kn*=Cretaceous Niobrara Formation, *Kc*= Cretaceous Carlile Shale. Note the majority of the area is covered in an even mix of coarse aquifer, aquifer, marginal and non-aquifer materials. There is limited amounts of Tertiary Ogallala Group (*To*) in the area beneath the *Q.* Bedrock is Cretaceous Niobrara Formation (*Kn*) with an isolated area of Cretaceous Pierre Shale (*Kp*) in northwest corner of area. CSD test holes and NE-DNR registered wells are indicated on the plot. V.E. = 10x.

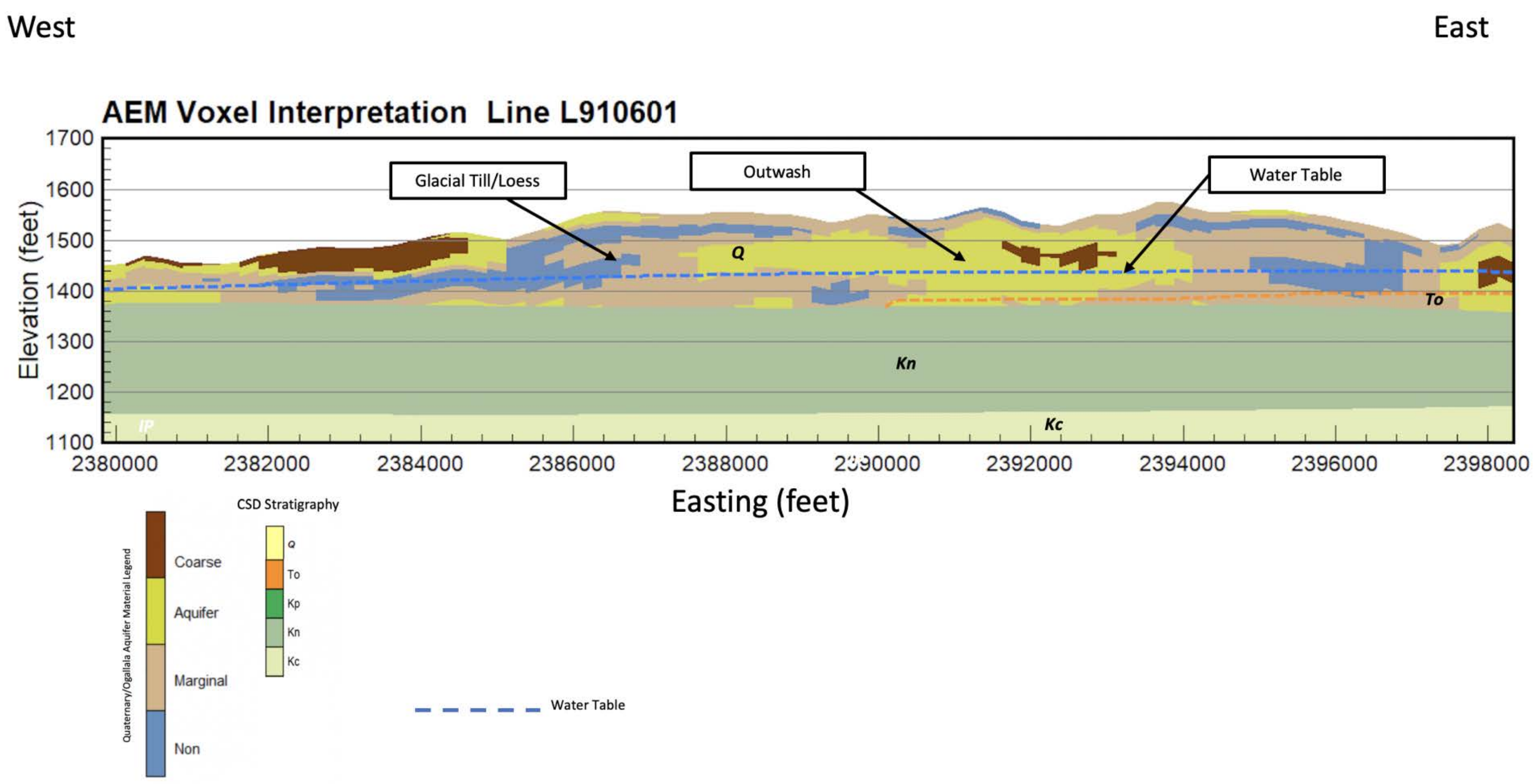


Figure 3-173. Profile of the east-west line L910601 showing the AEM interpretation. The CSD 1995 water table is indicated as a dashed blue line on the profiles. Note the isolated nature of the Quaternary (*Q*) and Tertiary Ogallala Group (*To*) coarse aquifer and aquifer material. Horizontal datum is NAD83 State Plane Nebraska (feet).

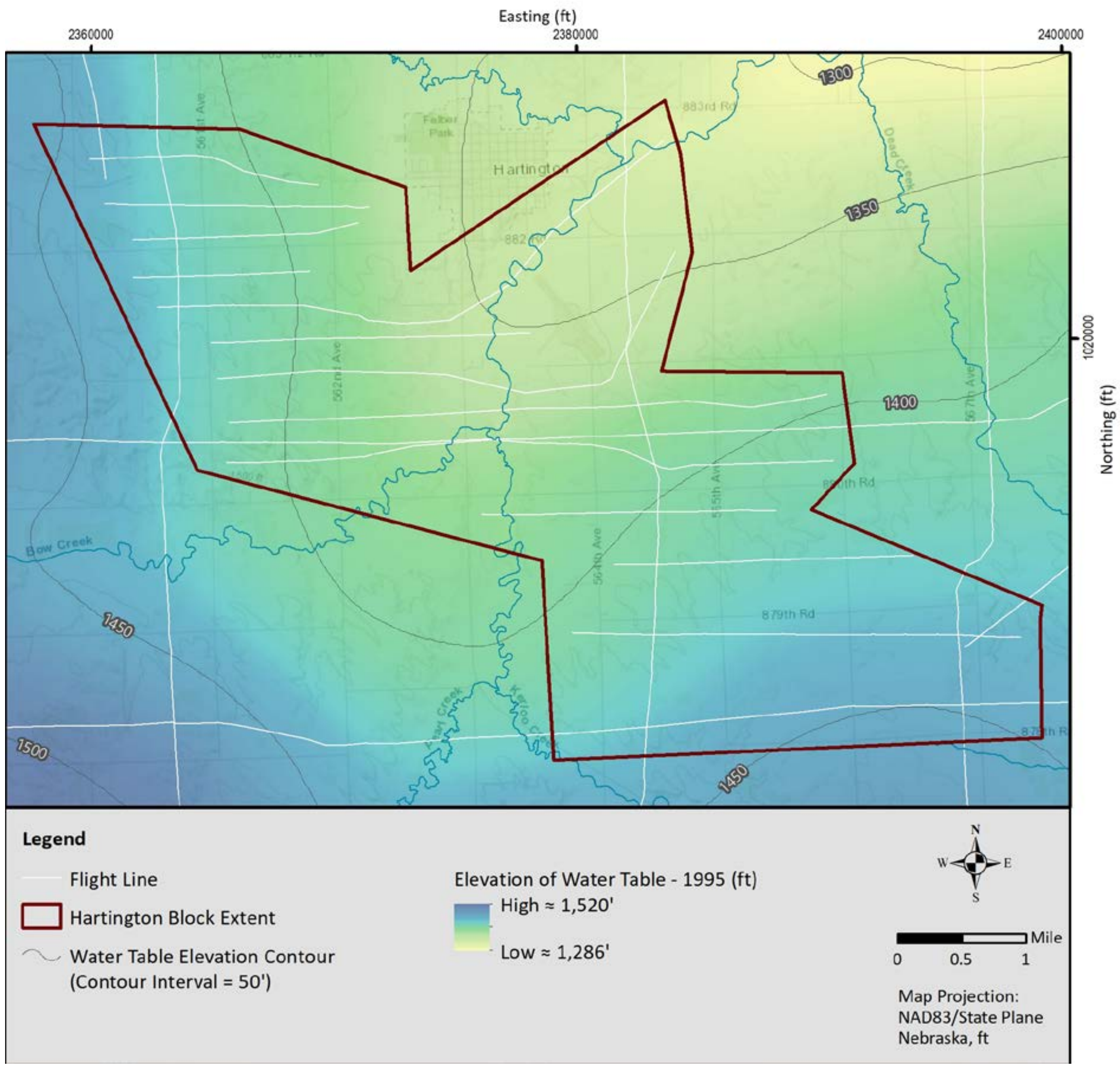


Figure 3-174. Map of the CSD 1995 water table within the 2018 Hartington Block AEM survey area. Block flight lines are indicated by white lines.

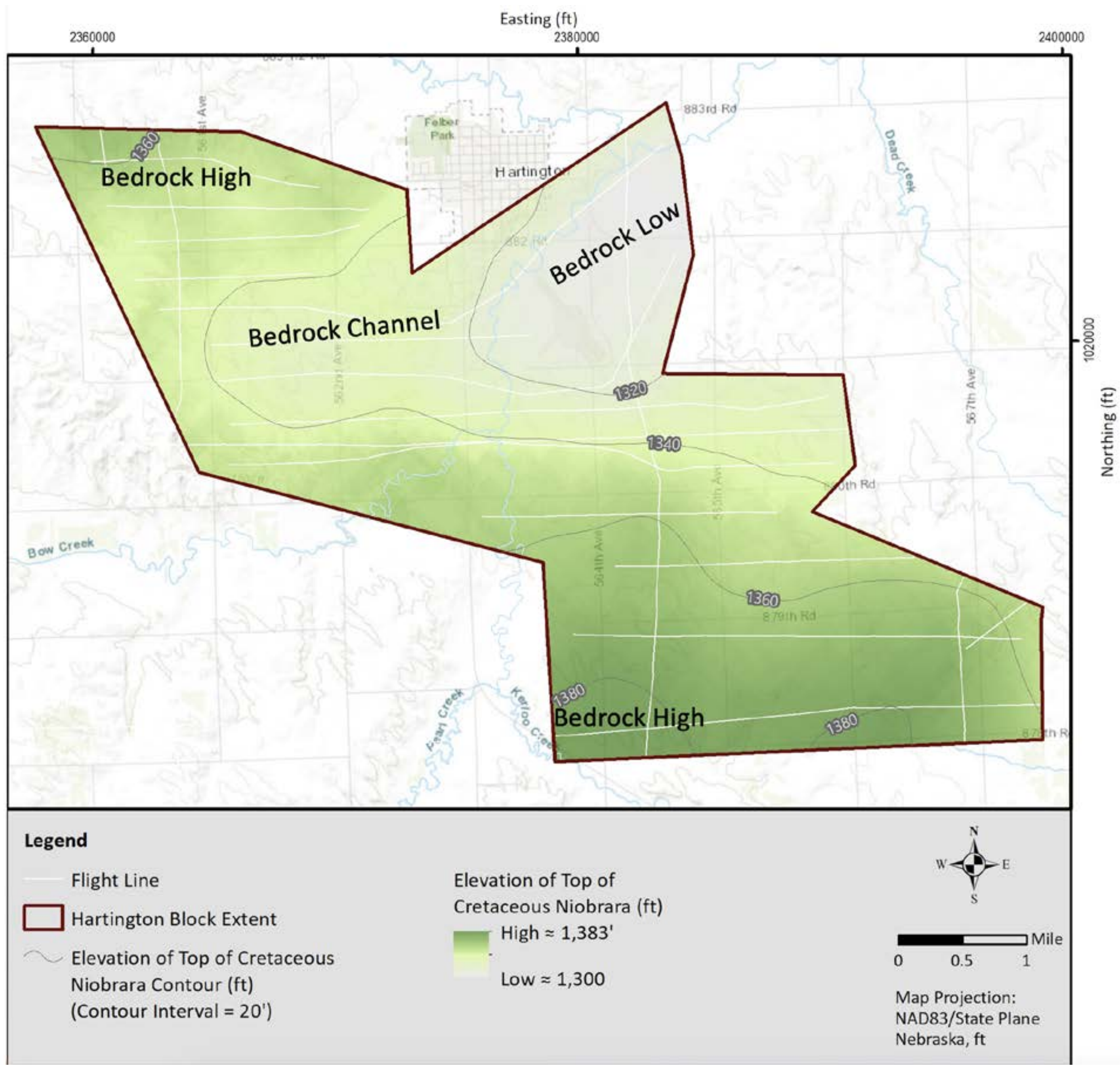


Figure 3-175. Map of the Cretaceous Niobrara Formation (*Kn*) bedrock surface elevation within the Hartington Block. Flight lines are indicated by white lines. Note the bedrock channel south of Hartington, Nebraska and the bedrock high to each side.

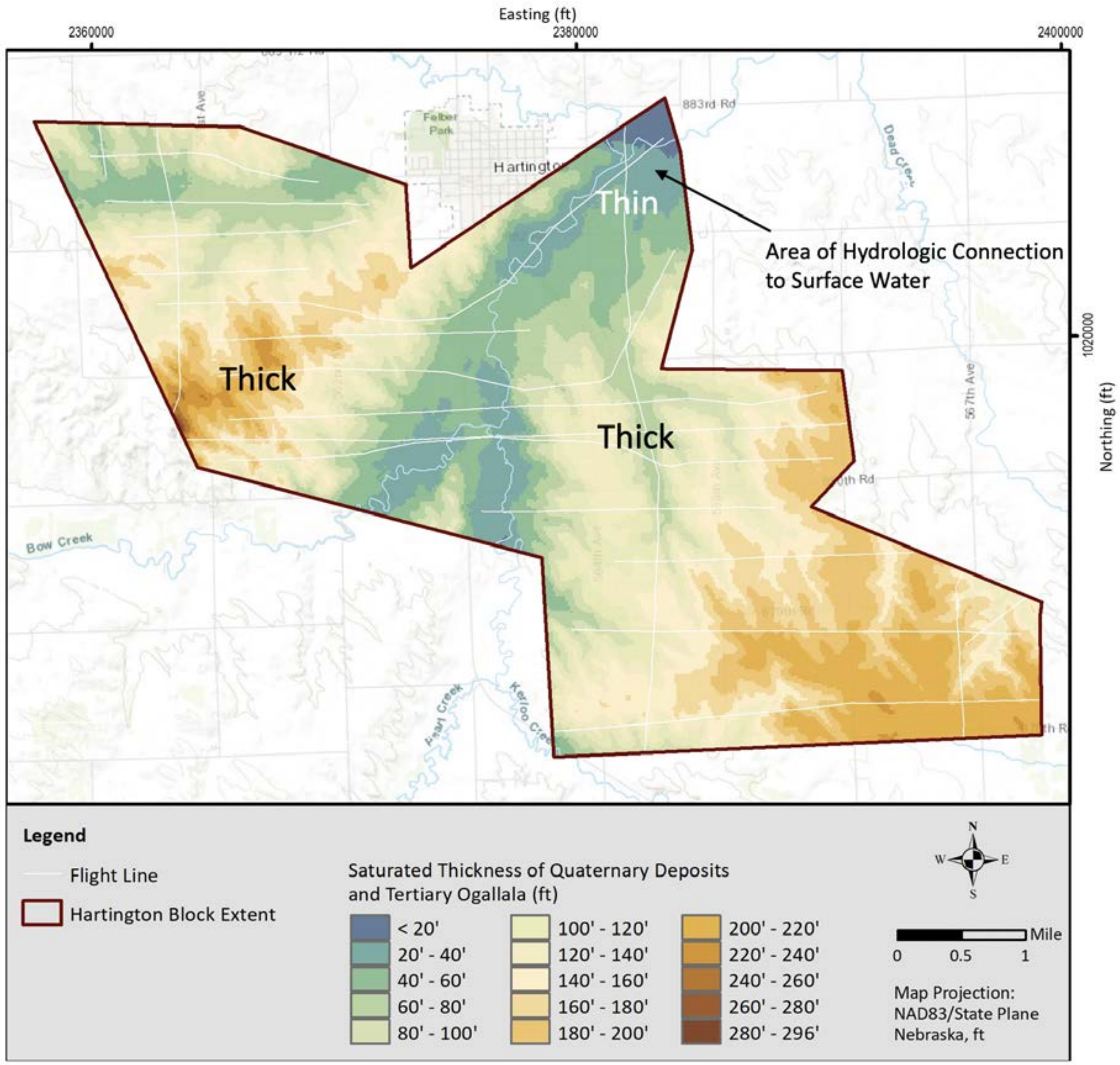


Figure 3-176. Map of the total thickness of the Quaternary (*Q*) and Tertiary Ogallala Group (*To*) comprised of all aquifer materials within the Hartington Block AEM survey area. Note the example of hydrologic connection to surface water on Little Bazile Creek. Block flight lines are indicated by black lines.

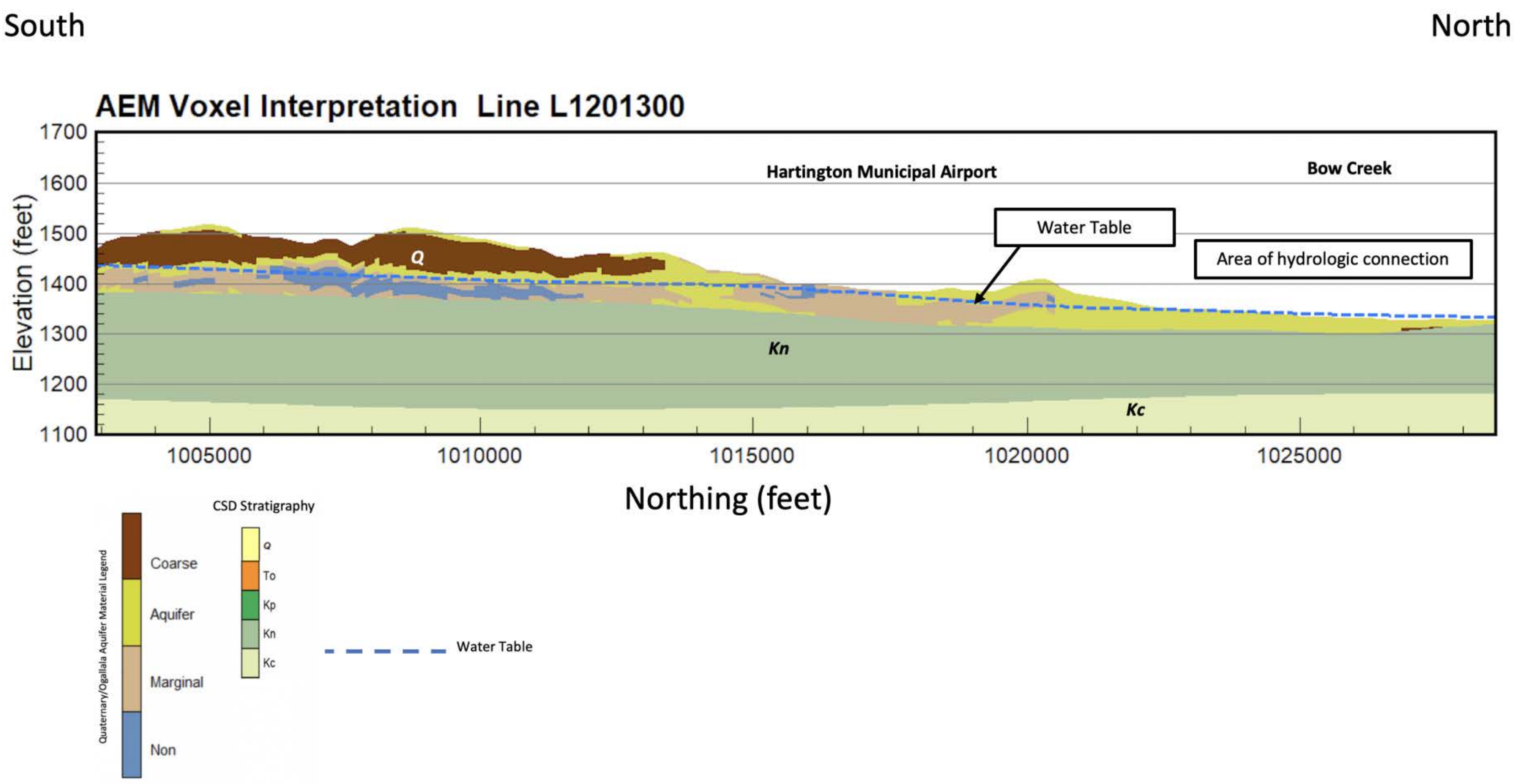


Figure 3-177. Profile of the east-west line L1201300 showing the AEM interpretation. The CSD 1995 water table is indicated as a dashed blue line on the profiles. Note the isolated nature of the Quaternary (*Q*) aquifer materials except for immediately below Bow Creek where there is a hydrologic connection to surface water. Horizontal datum is NAD83 State Plane Nebraska (feet).

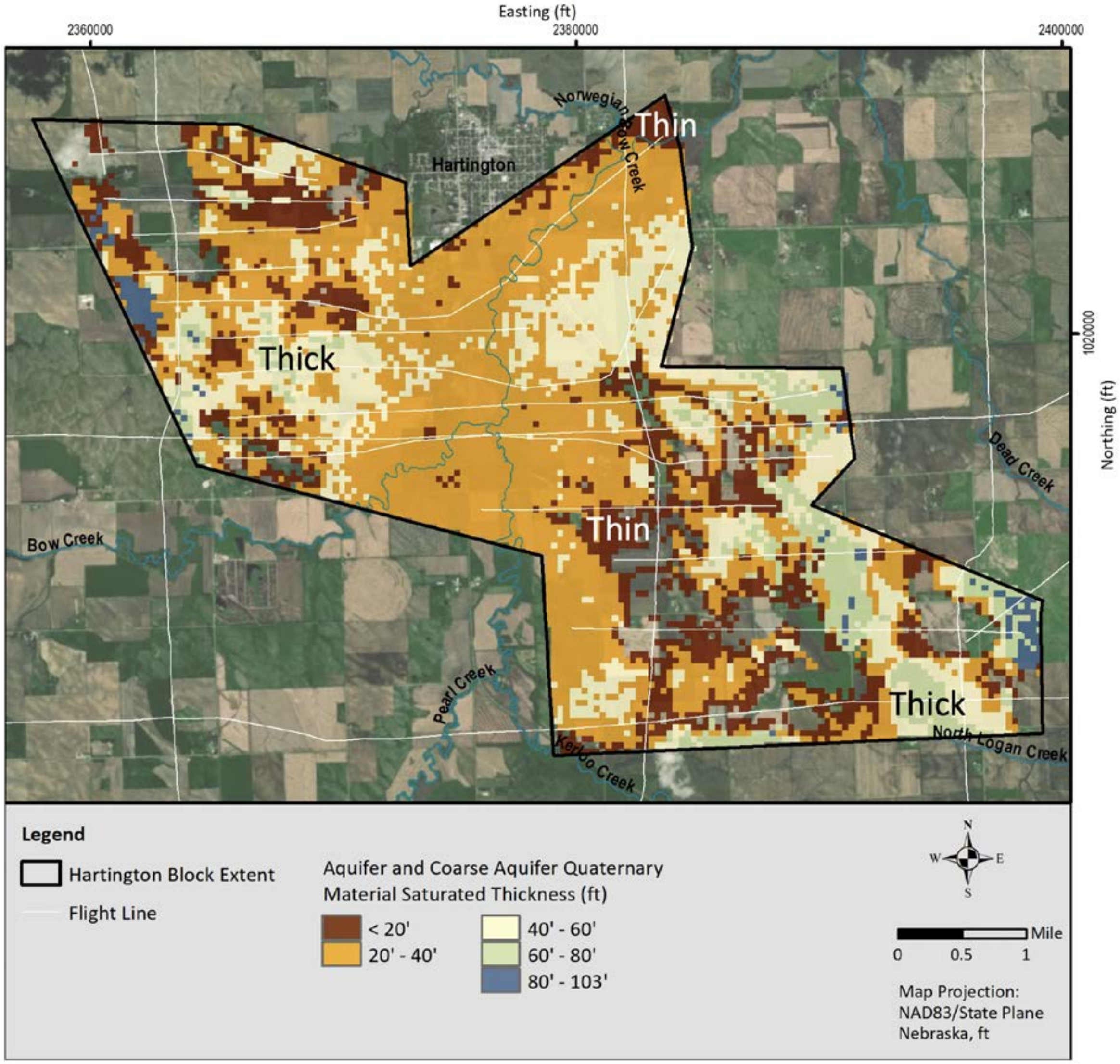


Figure 3-178. Map of the saturated thickness of the Quaternary (*Q*) and Tertiary Ogallala Group (*To*) coarse aquifer and aquifer materials within the Hartington Block AEM survey area. Block flight lines are indicated by the white lines. Note the discontinuous nature of the coarse aquifer and aquifer materials and the variation of their thickness.

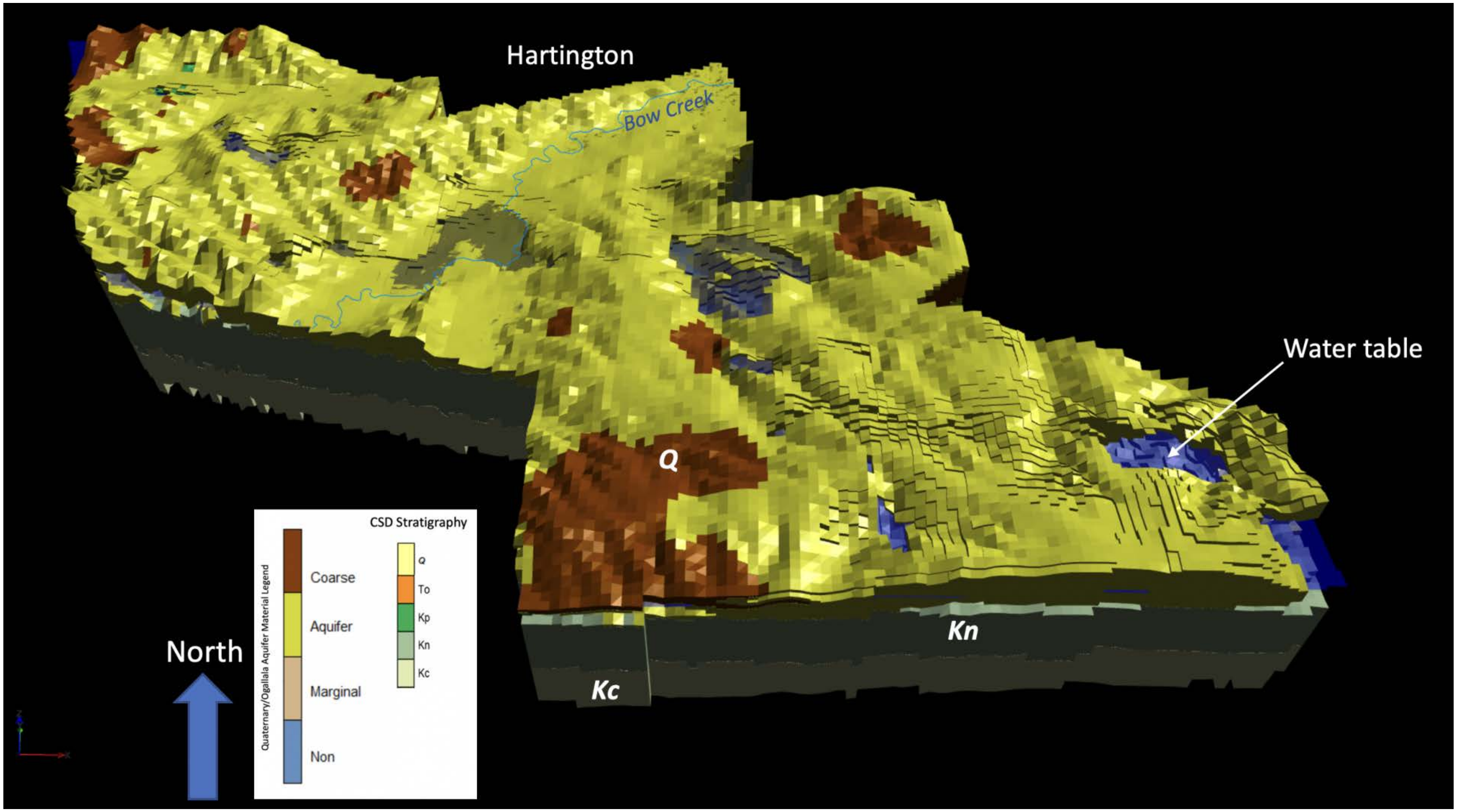


Figure 3-179. 3D voxel plot of the Quaternary (*Q*) and Tertiary Ogallala Group (*To*) coarse aquifer and aquifer materials and their relationship to the water table and the Cretaceous Pierre Shale (*Kp*) and Cretaceous Niobrara Formation (*Kn*). Note the discontinuous nature of this unit. V.E. = 10x.

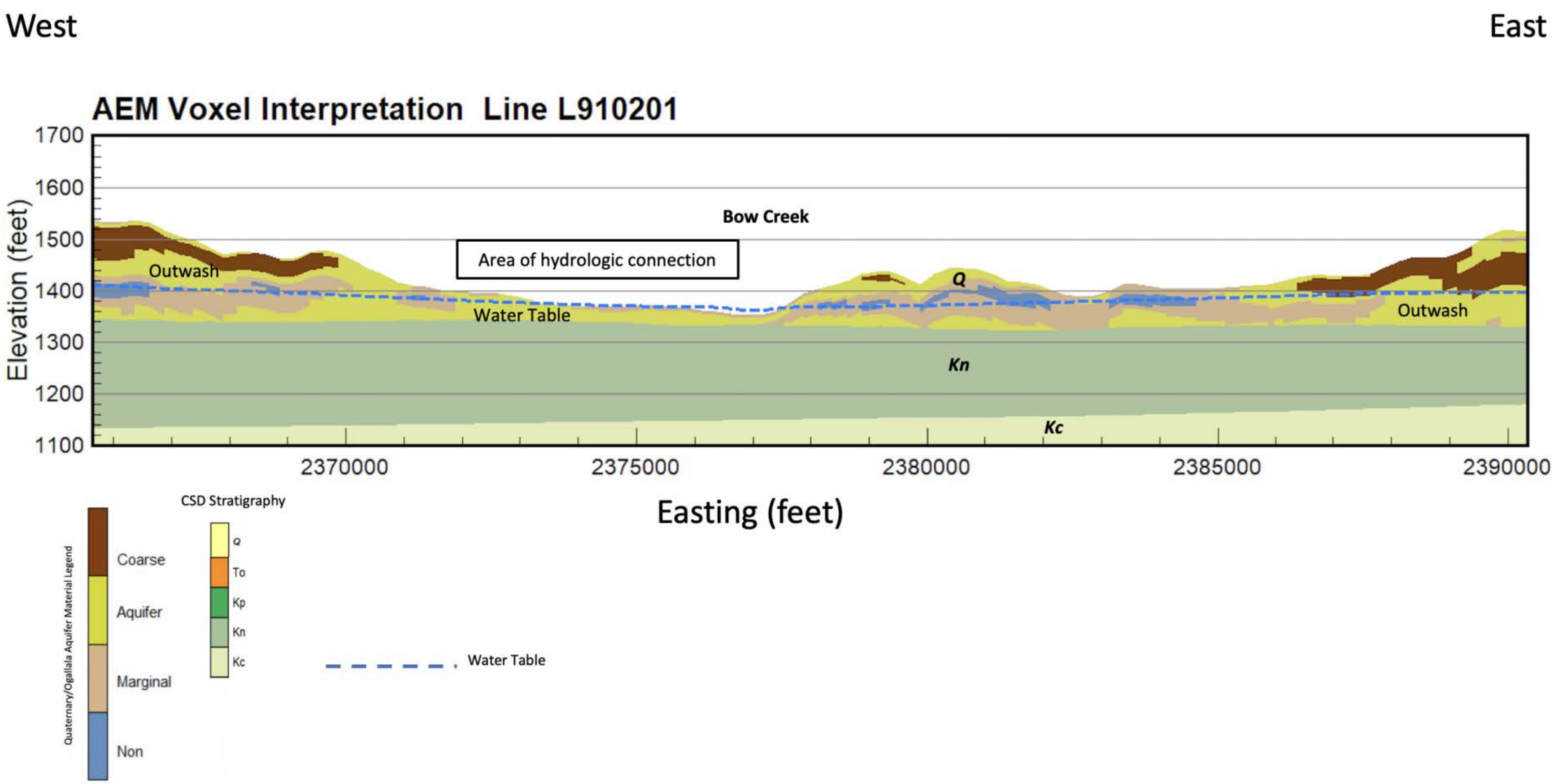


Figure 3-180. Profile of the east-west line L910201 showing the AEM interpretation of the Quaternary (*Q*) aquifer materials. Note the multiple *Q* aquifer material outwash deposits across the profile. There is an area hydrologic connection along Bow Creek to surface water. The CSD 1995 water table is indicated as a dashed blue line. Horizontal datum is NAD83 State Plane Nebraska (feet).

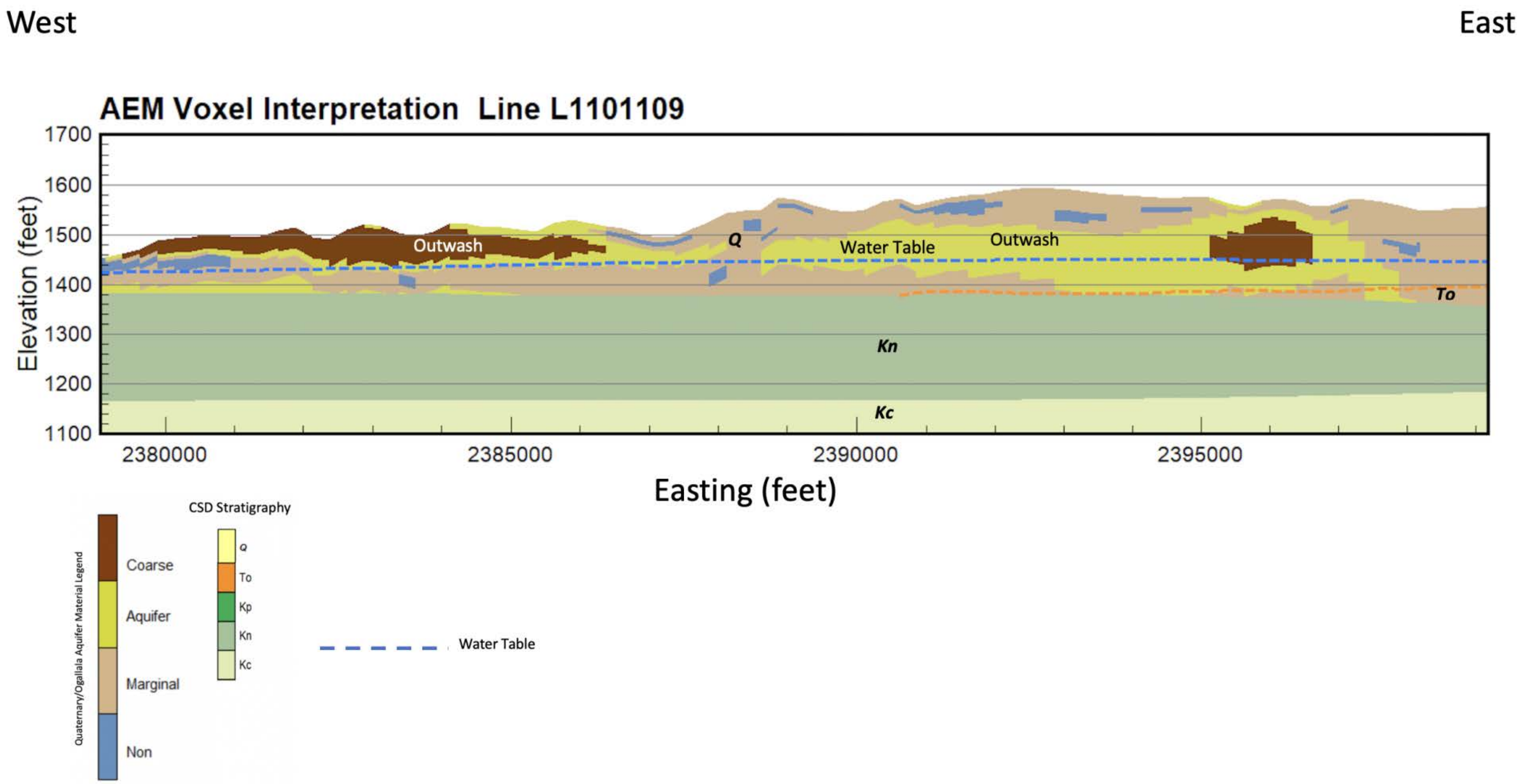


Figure 3-181. Profile of the east-west line L1101109 showing the AEM interpretation of the Quaternary (*Q*) and Tertiary Ogallala Group (*To*) aquifer materials. Note the multiple small *Q* aquifer material outwash deposits across the profile. There is a small amount of *To* in the east end of the line. CSD 1995 water table is indicated as a dashed blue line. Horizontal datum is NAD83 State Plane Nebraska (feet).

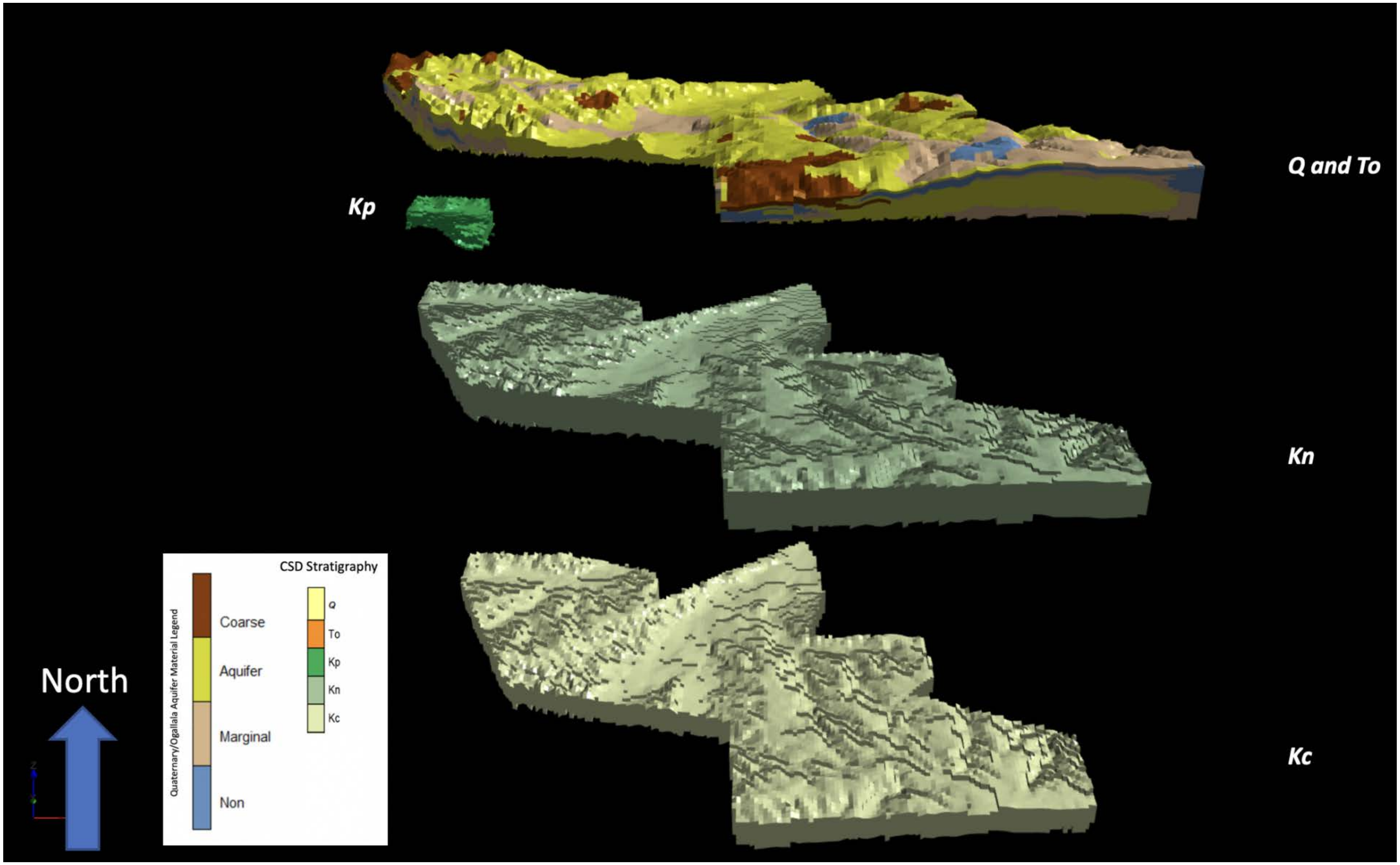


Figure 3-182. 3D 'exploded' voxel model of the Hartington Block AEM survey area showing Quaternary (*Q*) and Tertiary Ogallala Group (*To*), Cretaceous Pierre Shale (*Kp*), Cretaceous Niobrara Formation (*Kn*), and Cretaceous Carlile Shale (*Kc*). V.E. =10x. Not to scale.

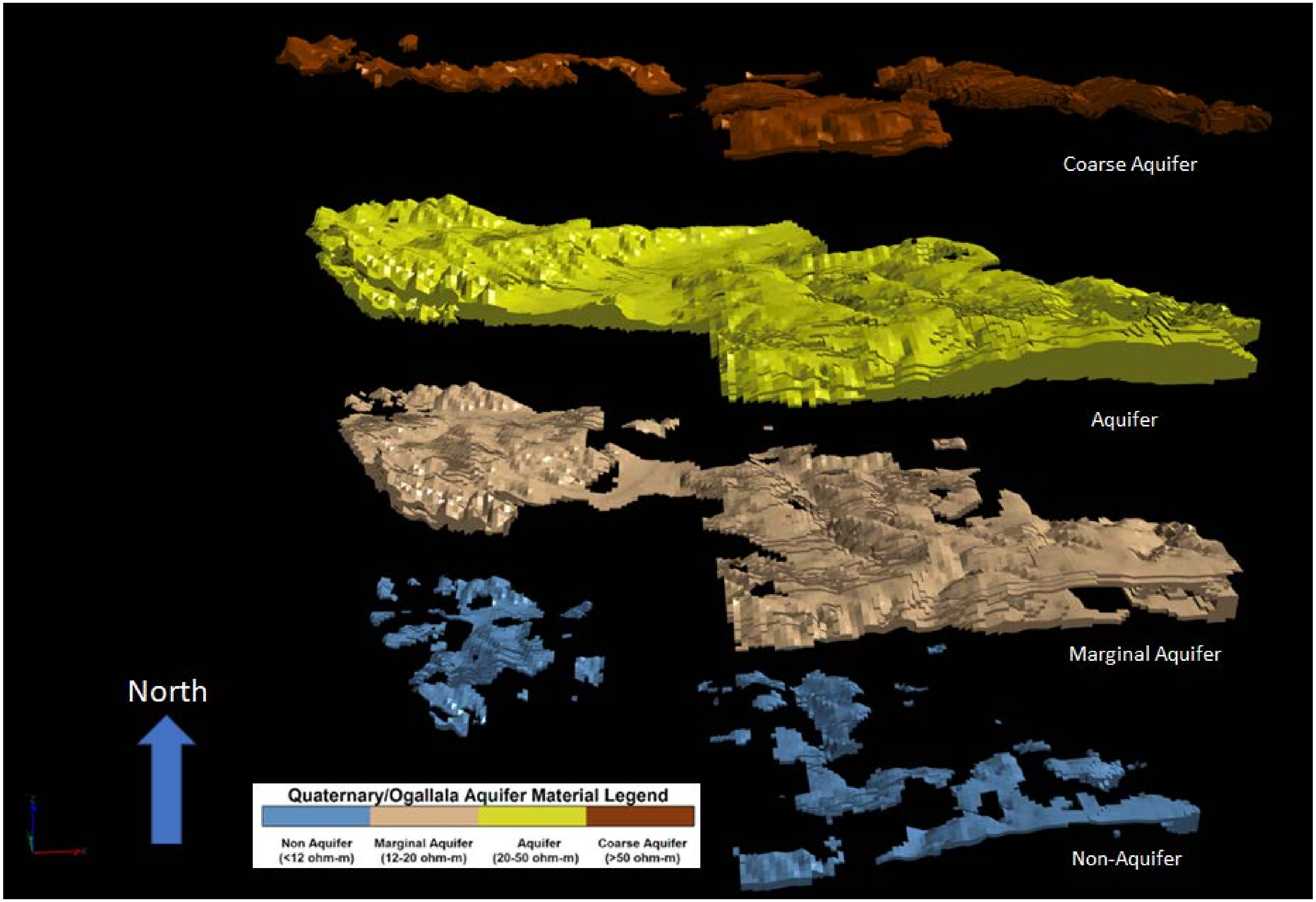


Figure 3-183. 3D 'exploded' voxel model of the Hartington Block AEM survey area showing Quaternary (*Q*) aquifer materials divided into coarse aquifer, aquifer, marginal aquifer and non-aquifer. Note the majority (~50%) of the *Q* material is made up of coarse aquifer and aquifer materials. V.E. =10x. Not to scale.

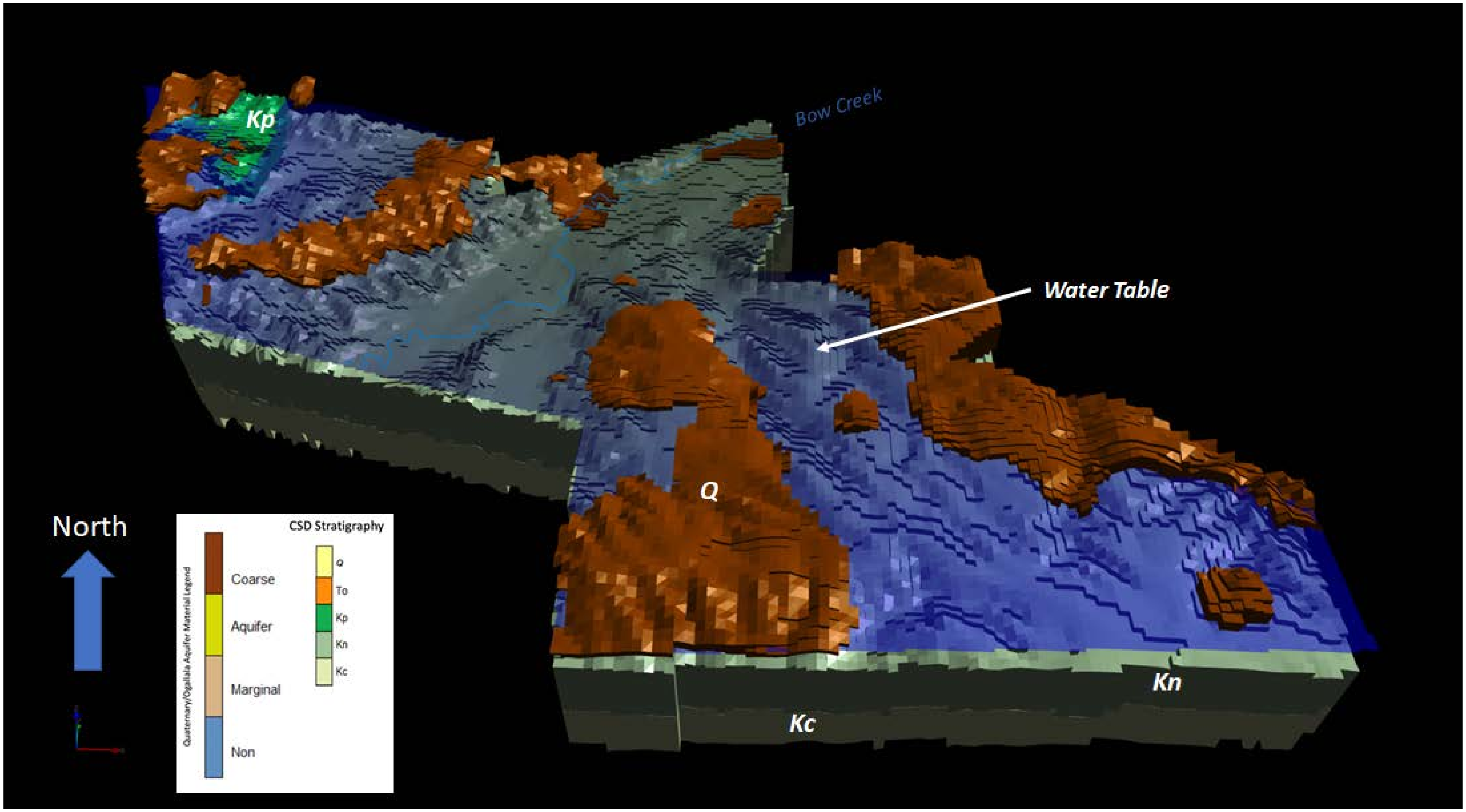


Figure 3-184. 3D voxel model of the Hartington Block AEM survey area showing Quaternary (*Q*) coarse aquifer with the water table surface and the Cretaceous Pierre Shale (*Kp*) and Cretaceous Niobrara Formation (*Kn*) bedrock. V.E. =10x.

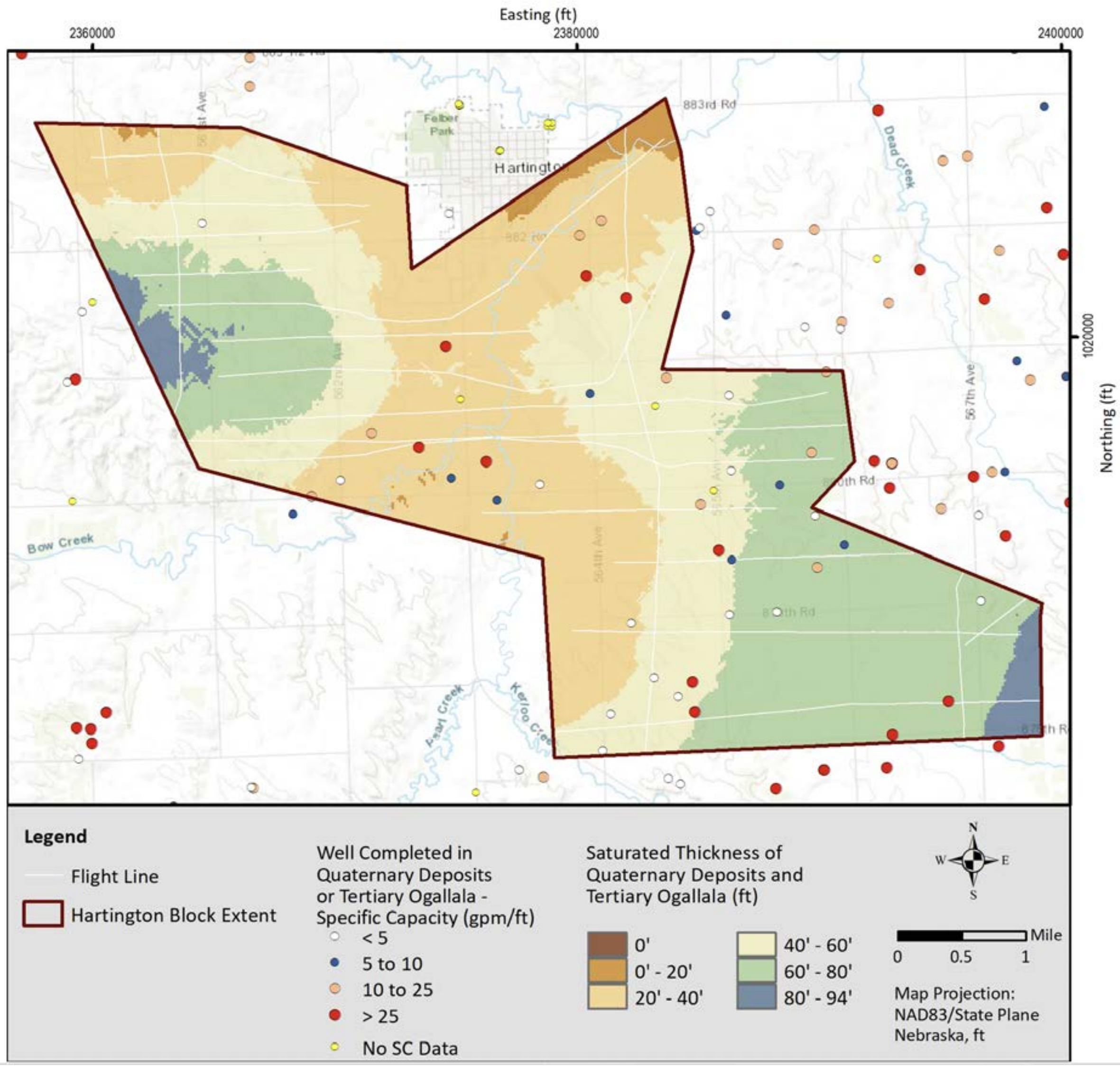


Figure 3-185. Map of the saturated thickness of the Quaternary (*Q*) deposits related to the specific capacity of the wells screened within the *Q*. Note the majority of high capacity wells are in the vicinity of Hartington, Nebraska extending southeast to the block flight boundary. Block flight lines are indicated by the white lines.

3.2.5 Hydrogeologic Framework of the Lindy Block AEM Survey Area

The AEM provided insight into the geographic distribution and extent of the unconsolidated ***Q*** and ***To*** in the Lindy Block AEM survey area. The ***Q*** materials within the Lindy Block are composed of unconsolidated alluvial silt, sand, and gravel as well as loess and glacial till and outwash that overlie the ***To*** fluvial deposits made up of all aquifer materials seen in the ***Q***. The ***Q*** material in the Lindy Block AEM survey area is identified through interpretation of the AEM data as non-aquifer (blue), marginal aquifer (tan), aquifer material (yellow), and coarse aquifer material (brown) as discussed in Section 3.1.6. Generally, the flight block is located in the uplands east of Santee, Nebraska (Figure 3-186).

Figure 3-187 displays a 3D fence diagram, looking to the north, of the interpreted hydrostratigraphic profiles with CSD and NE-DNR borehole lithology data. The area generally contains a mix of all ***Q*** and ***To*** aquifer materials lying upon the ***Kp***. The boreholes in the area indicate a mix of silty clay, sandy clay, and sand and gravel in the block area. As can be seen on Figure 3-187, the Lindy Block area is covered in glacial till/loess and glacial outwash and ***To*** fluvial deposits and is a mix of all aquifer materials. The presence of marginal and non-aquifer materials across most of the area makes for poor recharge across most of the area because the permeability of these materials is low, limiting the amount of infiltration.

Figure 3-188 presents profile L1001901, located in the center of the Lindy Block AEM survey area and extending from the northwest side of the block to just southeast. The CSD 1995 water table (NE-CSD, 1995) is on the profile and shows the change in water table elevation from the east to the west and changes in elevation from ~1,475 to ~1,600 feet. Depth to water changes from ~50 to ~325 feet below land surface and is independent to the change in topography. There is no evidence along this profile of any hydrologic connection to surface water due to the depth to the water table and the ***Q*** and ***To*** marginal and non-aquifer materials present. There are areas of good recharge to the outwash coarse aquifer and aquifer materials between northings 1070000 and 1075000. The rest of the area has poor recharge because of a cover of marginal and non-aquifer materials. The CSD 1995 water table is also on the profile and shows the near flat nature of the water table elevation (Figure 3-189).

Figure 3-190 is a map of the top of the bedrock in the Lindy Block which is composed of ***Kp*** that indicates bedrock lows including a shallow channel, and highs across the area ranging from 1,440 to 1,620 feet. The area is covered with ***Q*** aquifer material and ***To*** aquifer material (except in small areas on the north and south sides of the area).

Figure 3-191 shows the elevation of the top of ***To***. The ***To*** is at its highest elevation at 1,620 feet in the southeast corner of the area and is lowest at 1,493 in its south-southwest corner. The total thickness of the ***Q*** and ***To*** material in the Lindy AEM block area (Figure 3-192) was calculated by subtracting the bedrock elevation from the ground surface elevation. The ***Q*** and ***To*** varies in thickness from <20 to 364 feet. It is important to understand the distribution of the various ***Q*** and ***To*** aquifer materials in relation to their hydrologic connection to both the surface water. Generally, the water table is deep below the land surface or bounded by marginal and non-aquifer materials which limits the connection to surface water. There is no hydrologic connection along the line and there is a cap of marginal and non-aquifer materials at the land surface preventing recharge to the outwash and fluvial ***To*** coarse aquifer and aquifer material which is present between ~1,500 to 1,650 feet across line L902801 (Figure 3-193). The aquifer and coarse aquifer materials provide the greatest connection for water movement through all of the ***Q*** and ***To*** aquifer materials present in the area. The ***Q*** and ***To*** aquifer and coarse aquifer materials generally are confined by surrounding marginal and non-aquifer material. Of equal importance is the saturated thickness of the ***Q*** and ***To*** materials calculated by the bedrock elevation subtracted from the 1995 CSD water table surface elevation (NE-CSD, 1995)and is shown on Figure 3-194 is indicated to vary between 0, where there is no saturated aquifer materials, to a maximum thickness of about 150 feet near south side of the area. It is mostly ***Q*** glacial till/loess made up of marginal aquifer material and non-aquifer material and outwash deposits lying on ***To*** sediments. The glacial outwash deposits are made up of aquifer material.

Figure 3-195 presents interpreted Line L1200509, a north-south line near the east border of the area. It is mostly ***Q*** glacial till/loess made up of marginal aquifer material and non-aquifer material. There is also ***To*** materials below the ***Q*** in the across the line. However, there are deposits of aquifer material that are outwash deposits of the glacial material. Due to depth of the water table and the presence of marginal to non-aquifer material that acts as a boundary there is no hydrologic connection to surface water.

Figure 3-196 presents interpreted Line L1100300, an east-west line on the north side of the area. It is mostly ***Q*** glacial till/loess made up of marginal aquifer material and non-aquifer material. There is a thick continuous outwash deposit on the west end of the line. There is also ***To*** materials below the ***Q*** in the west to near easting 2244000 in of the line where the ***To*** is eroded off. There is a steep topographic drop near the easting 2244000 and most of the glacial material eroded off replaced by a mix of ***Q*** alluvial deposits. are deposits of aquifer material that are outwash deposits of the glacial material. The water table is below the ***Q*** and ***To- Kp*** contact and therefore all ***Q*** and ***To*** materials are unsaturated so there is no hydrologic connection to surface water.

Figure 3-197 shows the saturated thickness of the ***Q*** deposits related to the specific capacity of the NE-DNR registered wells screened within the ***Q***. There are two large capacity wells between 10 and >25 gpm in the south-central area near the boundary of the survey area. The remaining wells in the area produce <5 gpm and are scattered throughout the area.

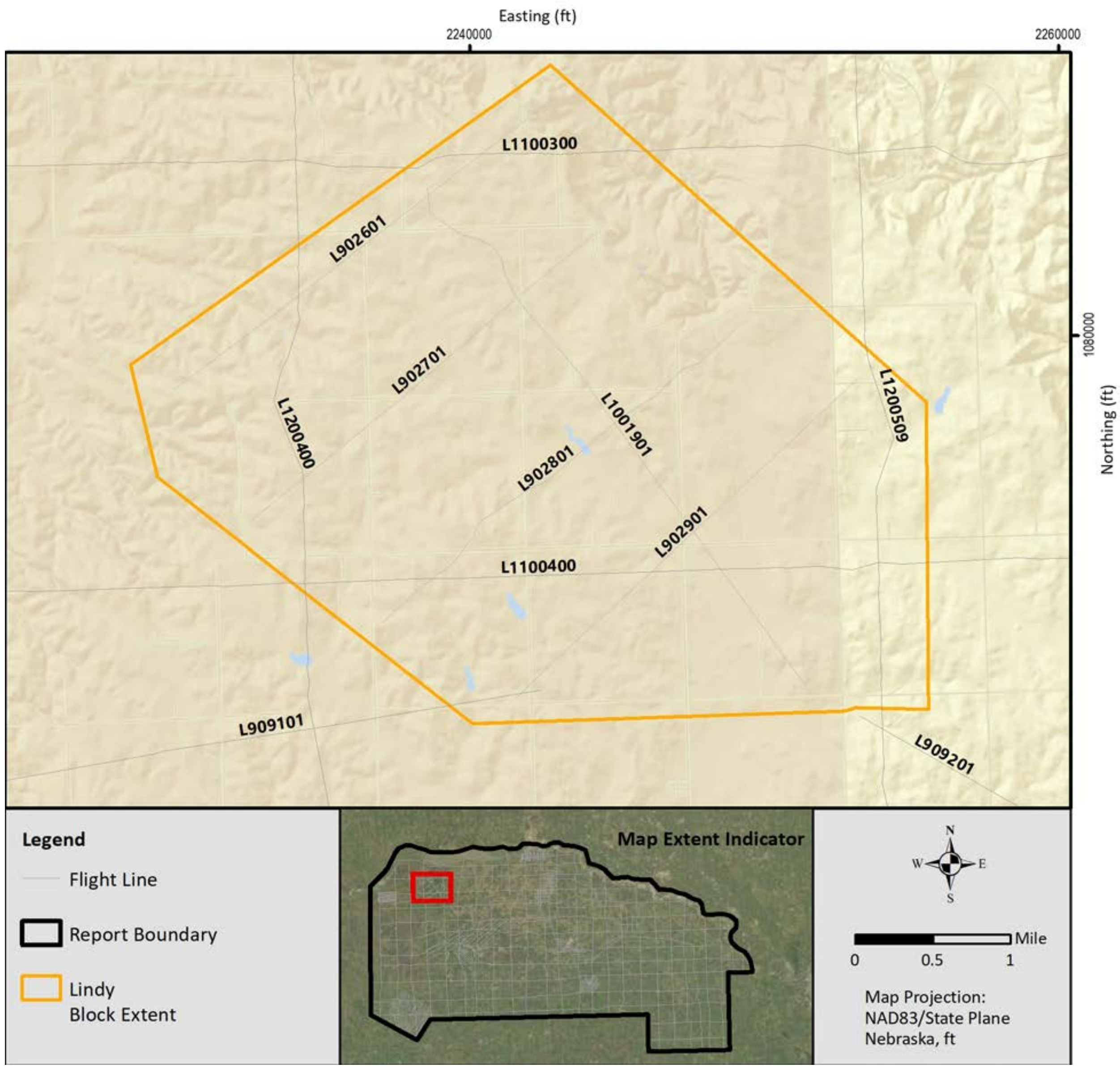


Figure 3-186. Location map of the Lindy Block indicating AEM flight lines local roads.

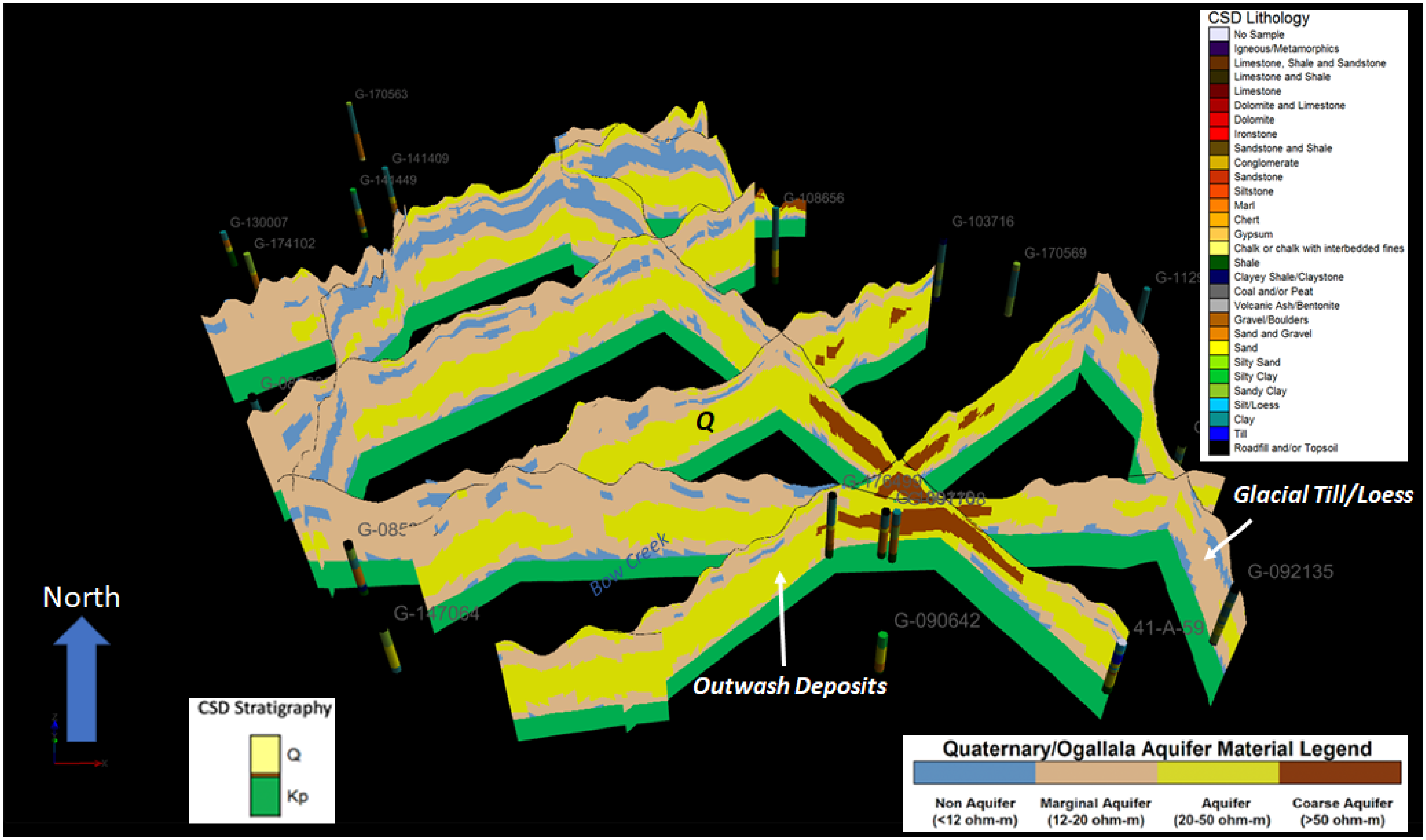


Figure 3-187. 3D fence diagram of interpreted AEM hydrostratigraphic profiles within the Lindy Block showing *Q*= Quaternary, *To*= Tertiary Ogallala Group, *Kp*= Cretaceous Pierre Shale. Note the majority of the area is covered in a mix of Quaternary (*Q*) coarse aquifer, aquifer, marginal and non-aquifer materials with Tertiary Ogallala Group (*To*) in the area beneath the *Q*. Bedrock is Cretaceous Pierre Shale (*Kp*). CSD test holes and NE-DNR registered wells are indicated on the plot. V.E. = 10x.

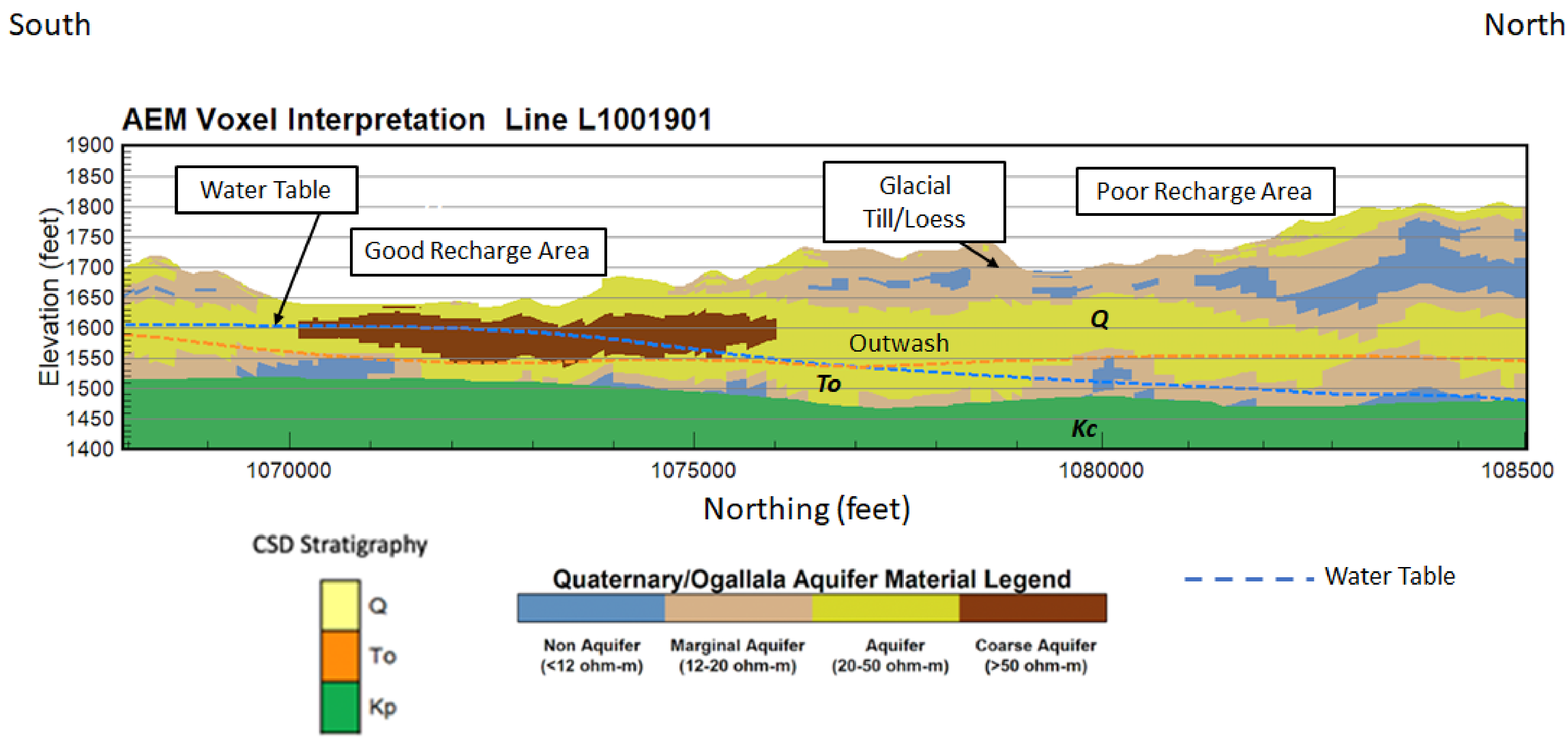


Figure 3-188. Profile of the east-west line L1001901 showing the AEM interpretation. The CSD 1995 water table is indicated as a dashed blue line on the profiles. Note the isolated nature of the Quaternary (*Q*) and Tertiary Ogallala Group (*To*) aquifer materials which do not have a hydrologic connection to the surface water. Horizontal datum is NAD83 State Plane Nebraska (feet).

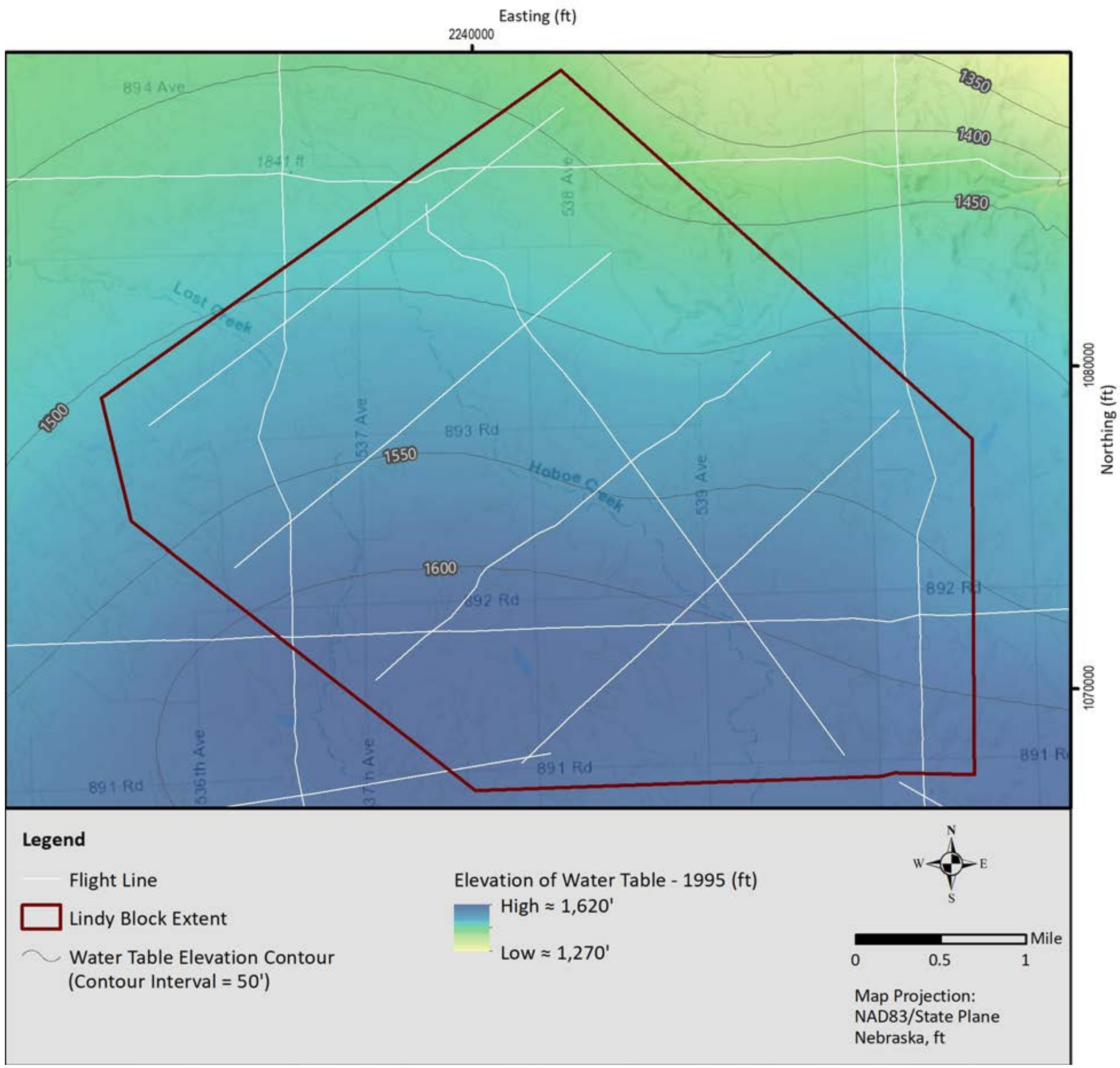


Figure 3-189. Map of the CSD 1995 water table within the 2018 Lindy Block AEM survey area. Block flight lines are indicated by white lines.

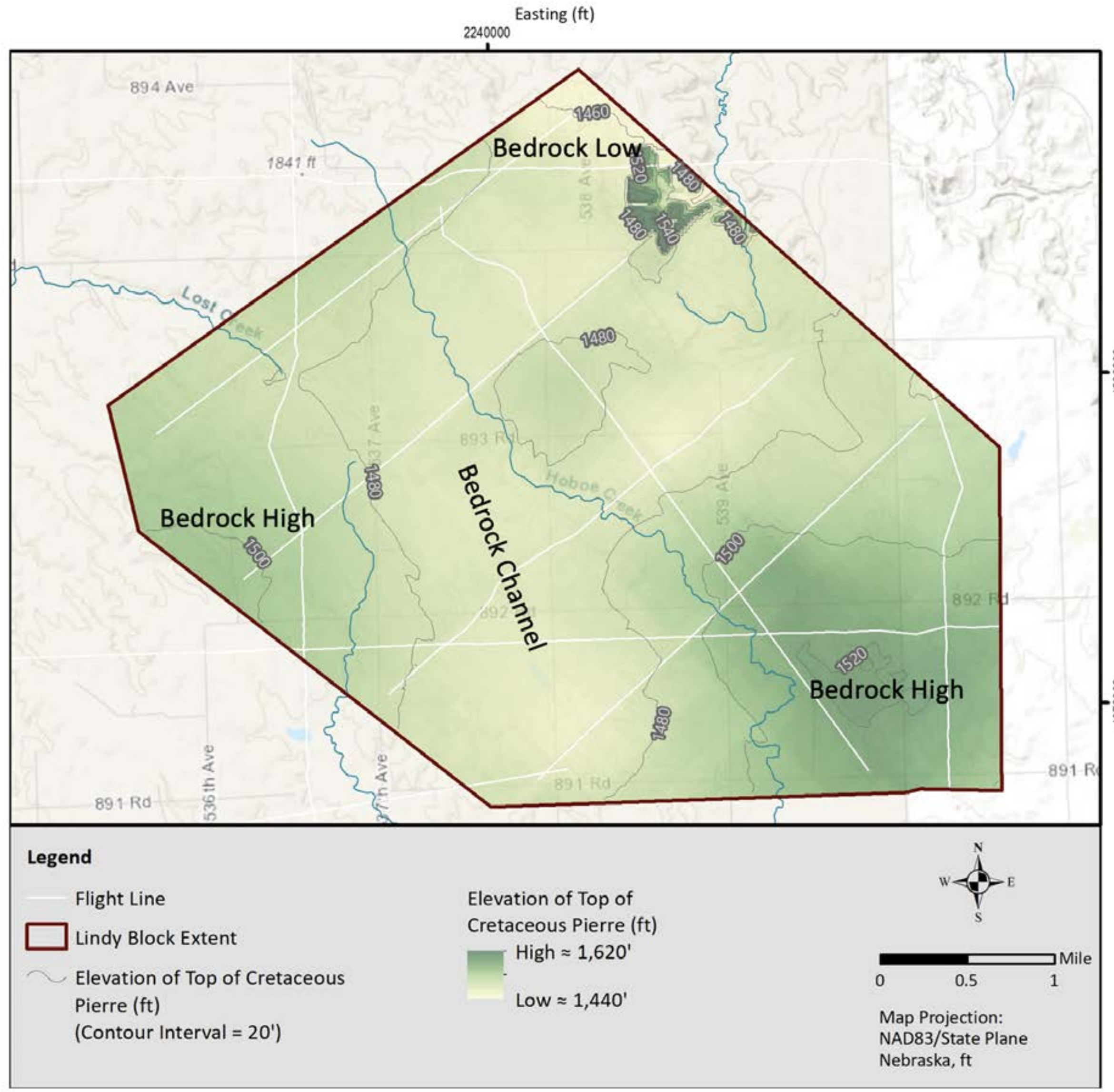


Figure 3-190. Map of the Cretaceous Pierre Shale (*Kp*) bedrock surface elevation within the Lindy Block AEM survey area. Flight lines are indicated by white lines. Note the shallow bedrock channel trending south to north and the bedrock high to each side.

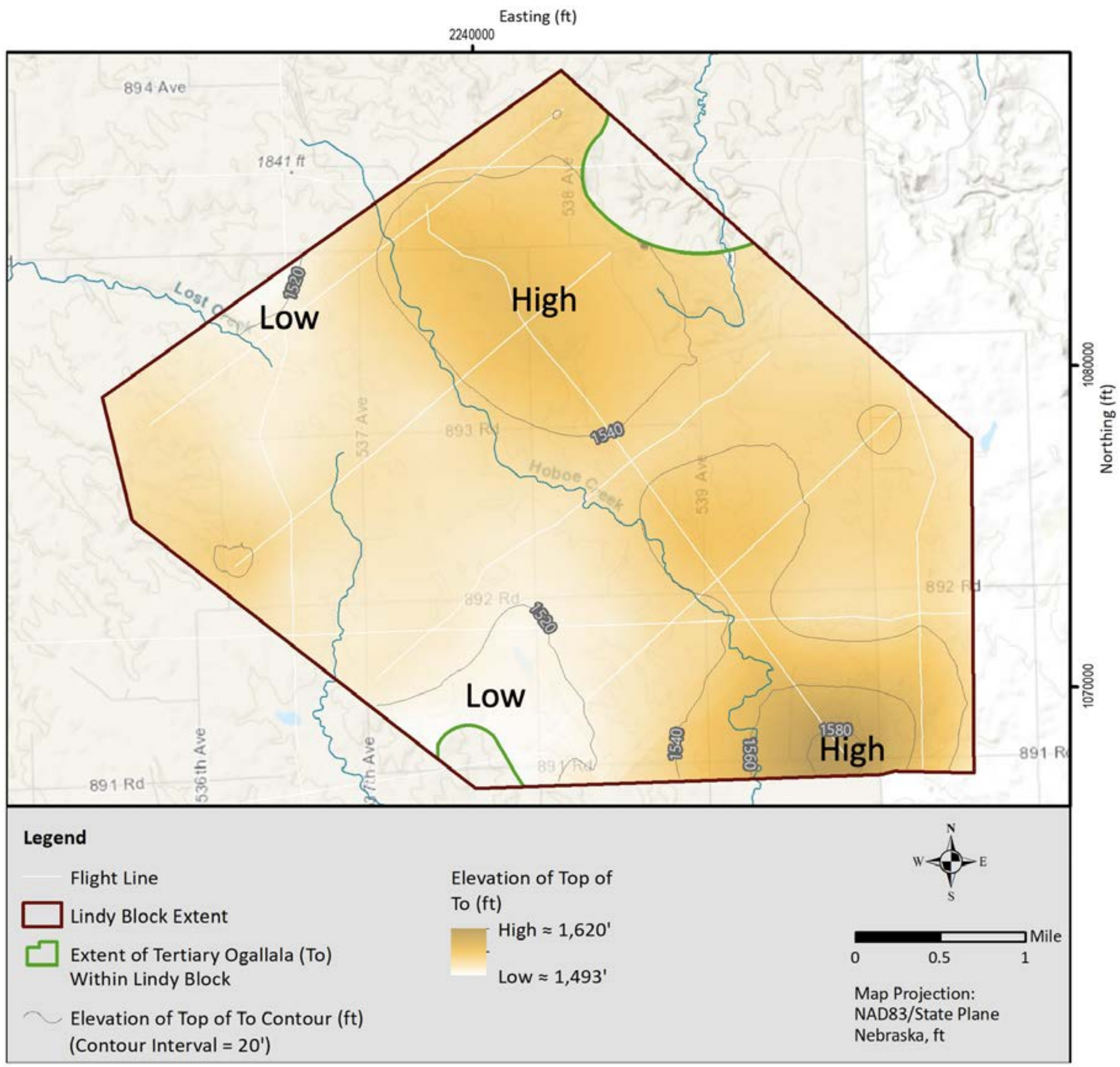


Figure 3-191. Map of the elevation of the top of the Tertiary Ogallala (*To*) within the Lindy Block AEM survey area. Note that *To* exists throughout the area except in small areas in the north and the south of the survey area and its extent is bounded by the green lines. Block flight lines are indicated by white lines.

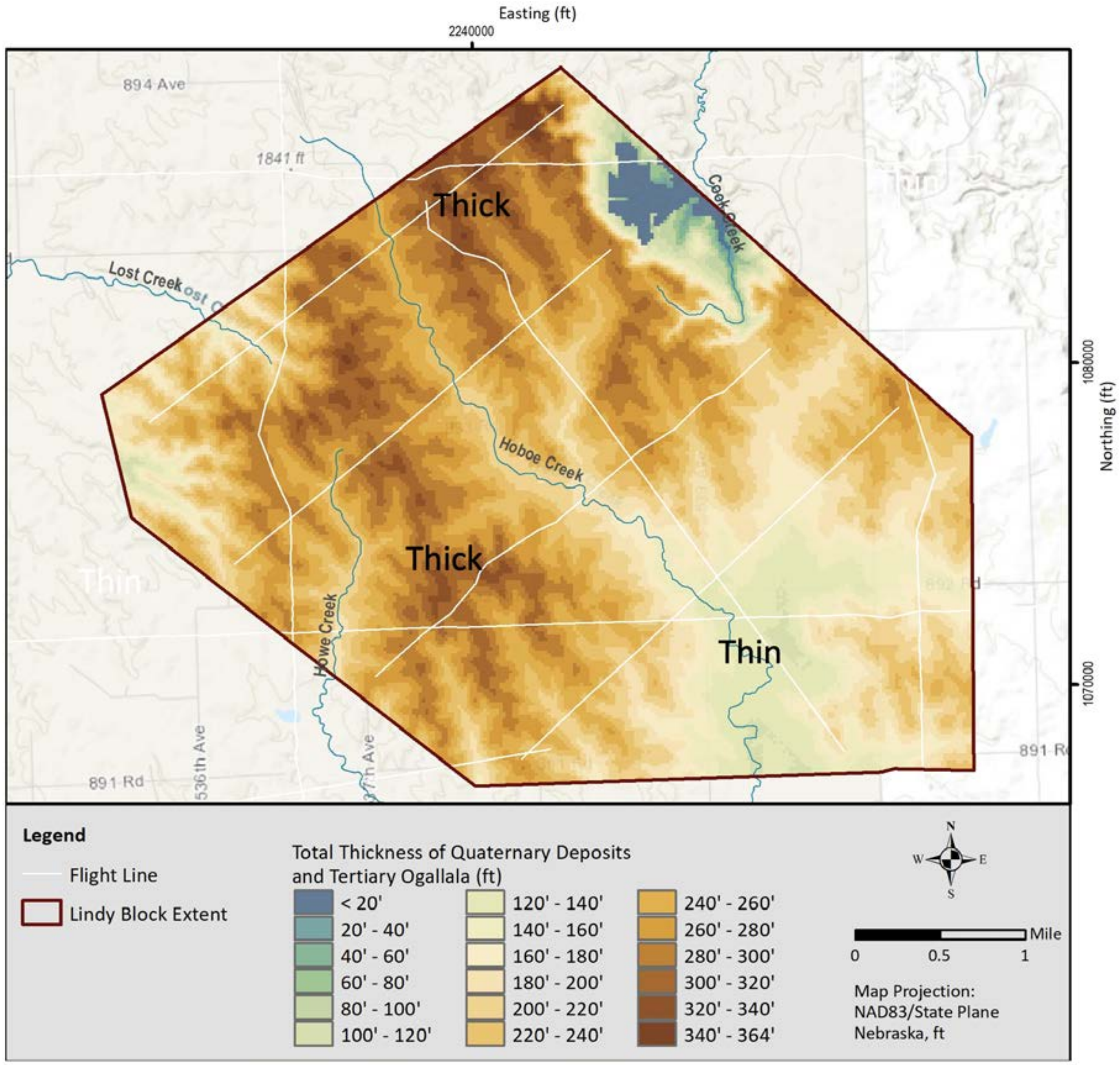


Figure 3-192. Map of the total thickness of the Quaternary (*Q*) and Tertiary Ogallala Group (*To*) map comprised of all aquifer materials within the Lindy Block AEM survey area. *Q* and *To* aquifer materials include coarse aquifer, aquifer, marginal aquifer and non-aquifer materials. Note there is no hydrologic connection to surface water. Block flight lines are indicated by white lines.

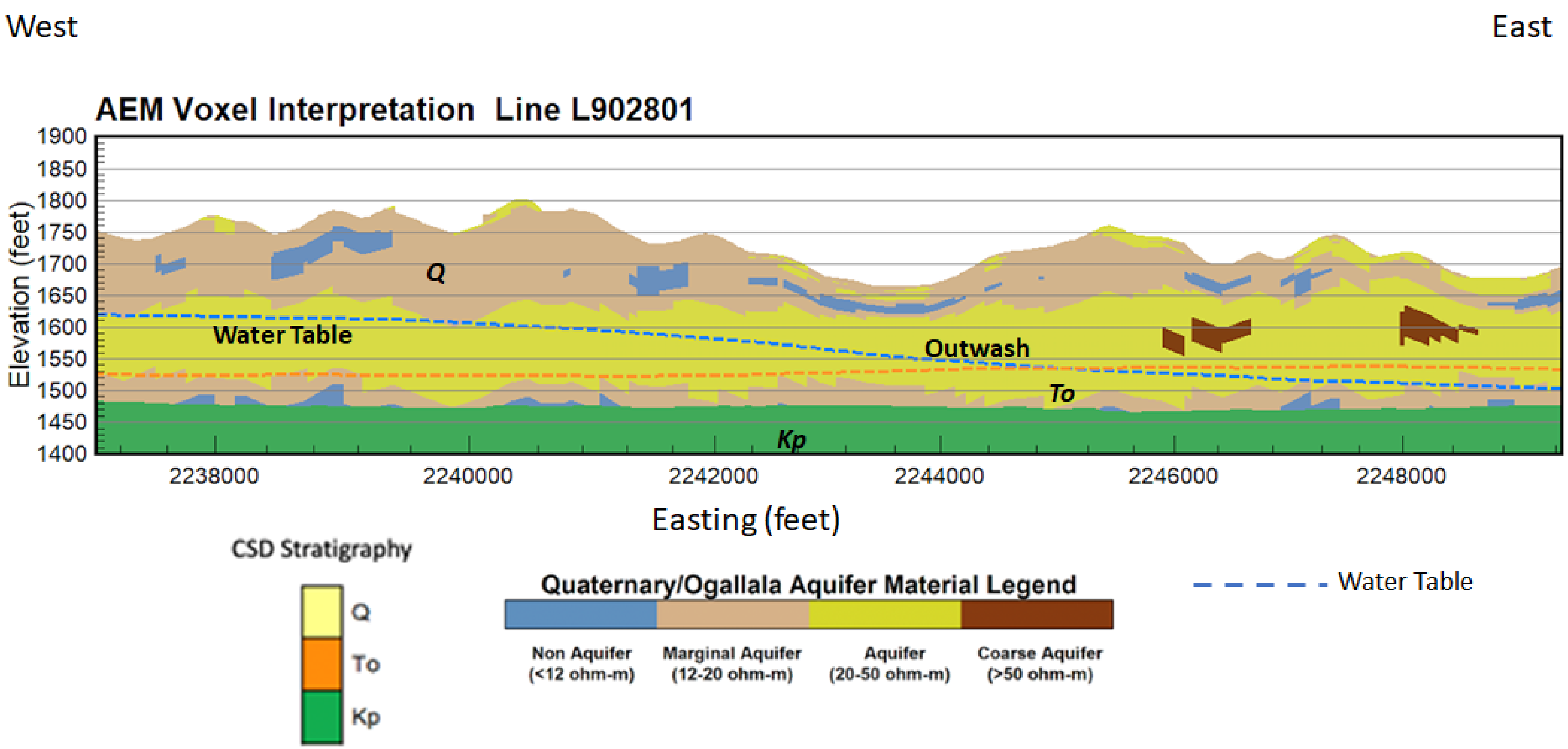


Figure 3-193. Profile of the east-west line L902801 showing the AEM interpretation. The CSD 1995 water table is indicated as a dashed blue line on the profiles. Note the isolated nature of the Quaternary (*Q*) and Tertiary Ogallala Group (*To*) aquifer materials and no hydrologic connection to surface water. Horizontal datum is NAD83 State Plane Nebraska (feet).

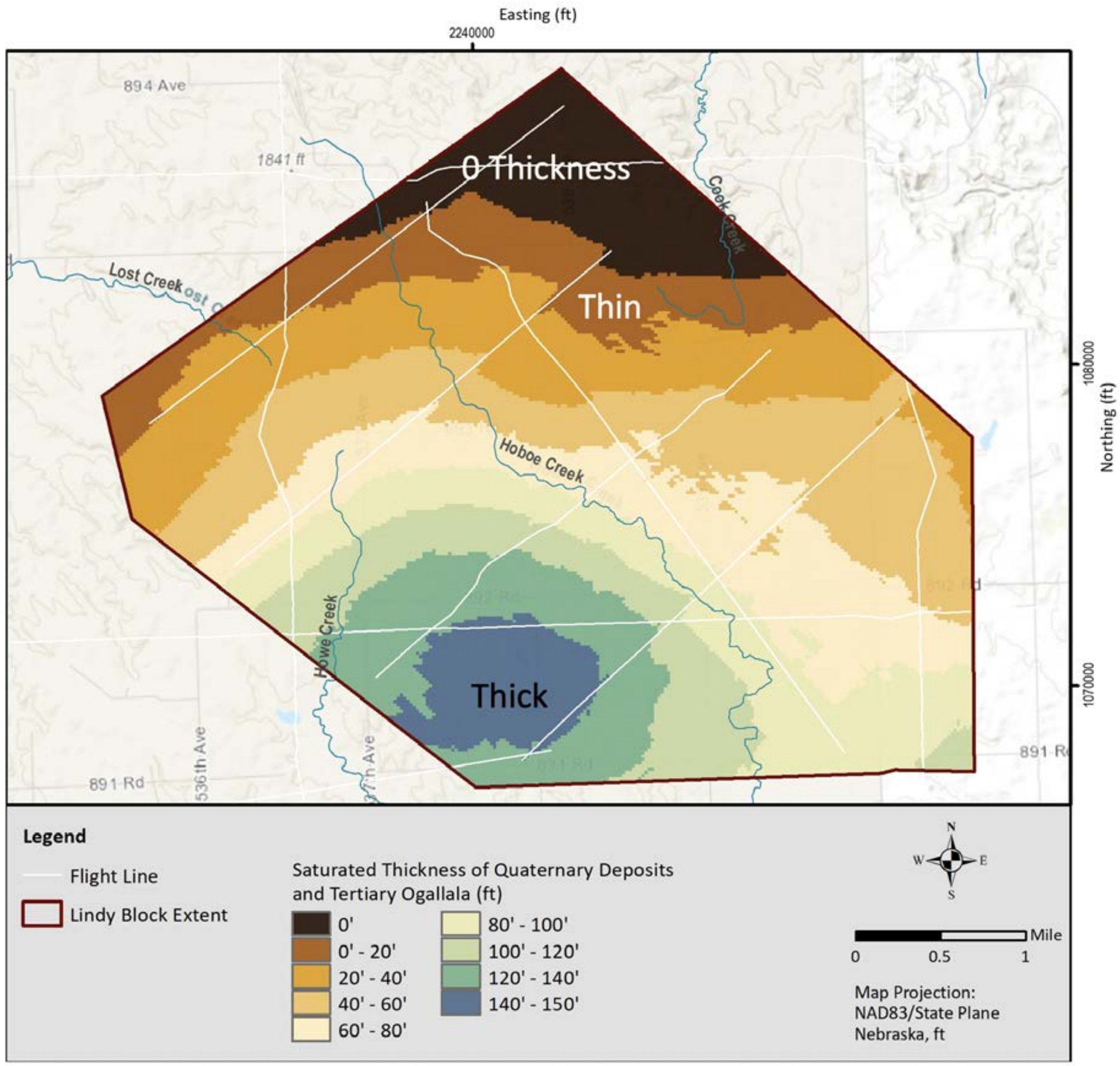


Figure 3-194. Map of the saturated thickness of the Quaternary (*Q*) and Tertiary Ogallala Group (*To*) aquifer materials within the Lindy Block AEM survey area. Block flight lines are indicated by the white lines. Note the lack of saturated Q and To materials in the north part of the area.

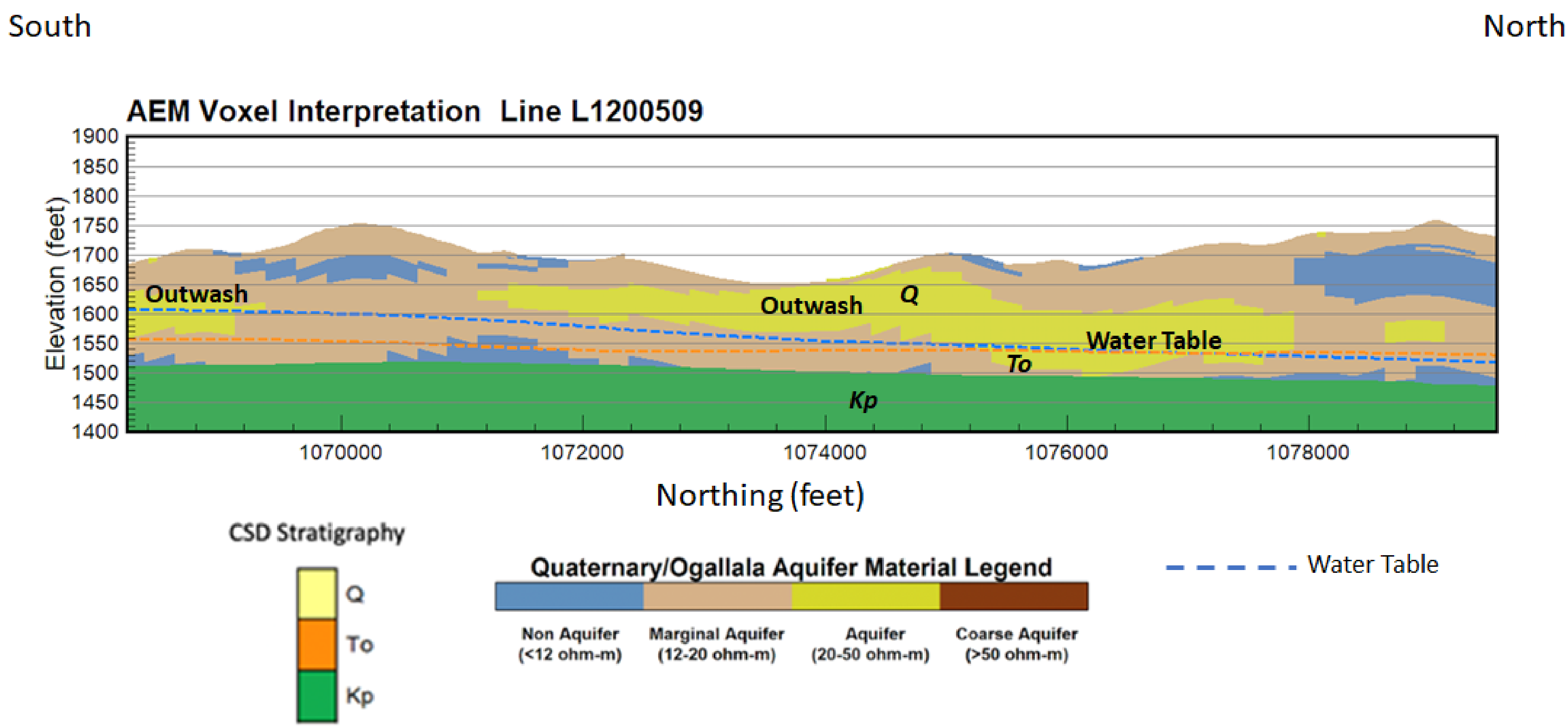


Figure 3-195. Profile of the north-south line L1200509 showing the AEM interpretation of the Quaternary (*Q*) and Tertiary Ogallala Group (*To*) aquifer materials. Note the multiple *Q* aquifer material outwash deposits across the profile. There is no hydrologic connection to surface water. CSD 1995 water table is indicated as a dashed blue line. Horizontal datum is NAD83 State Plane Nebraska (feet).

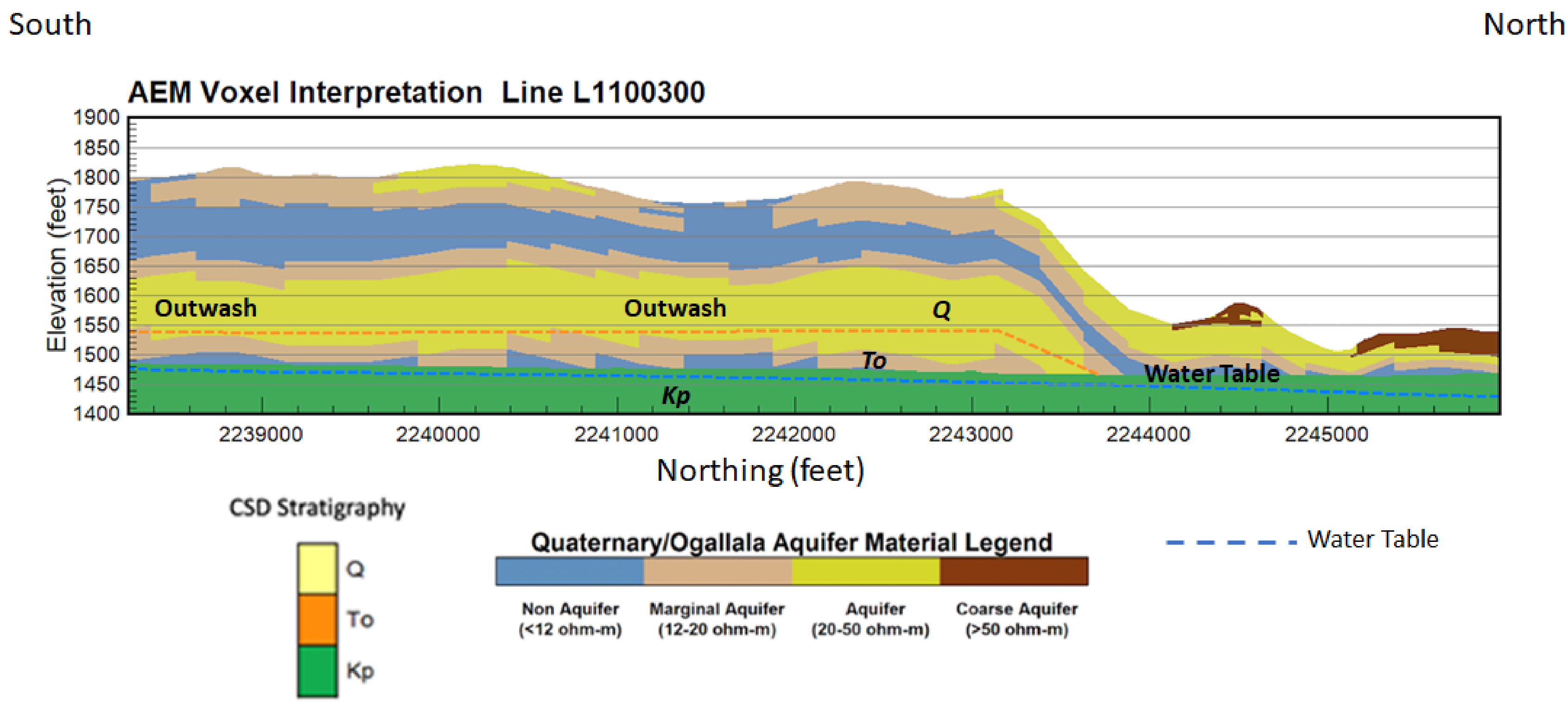


Figure 3-196. Profile of the east-west line L1100300 showing the AEM interpretation of the Quaternary (*Q*) and Tertiary Ogallala Group (*To*) aquifer materials which lie upon Cretaceous Pierre Shale (*Kp*). Note the continuous *Q* aquifer material outwash deposits lying on the *To* materials across the west half of the line. CSD 1995 water table is indicated as a dashed blue line. Horizontal datum is NAD83 State Plane Nebraska (feet).

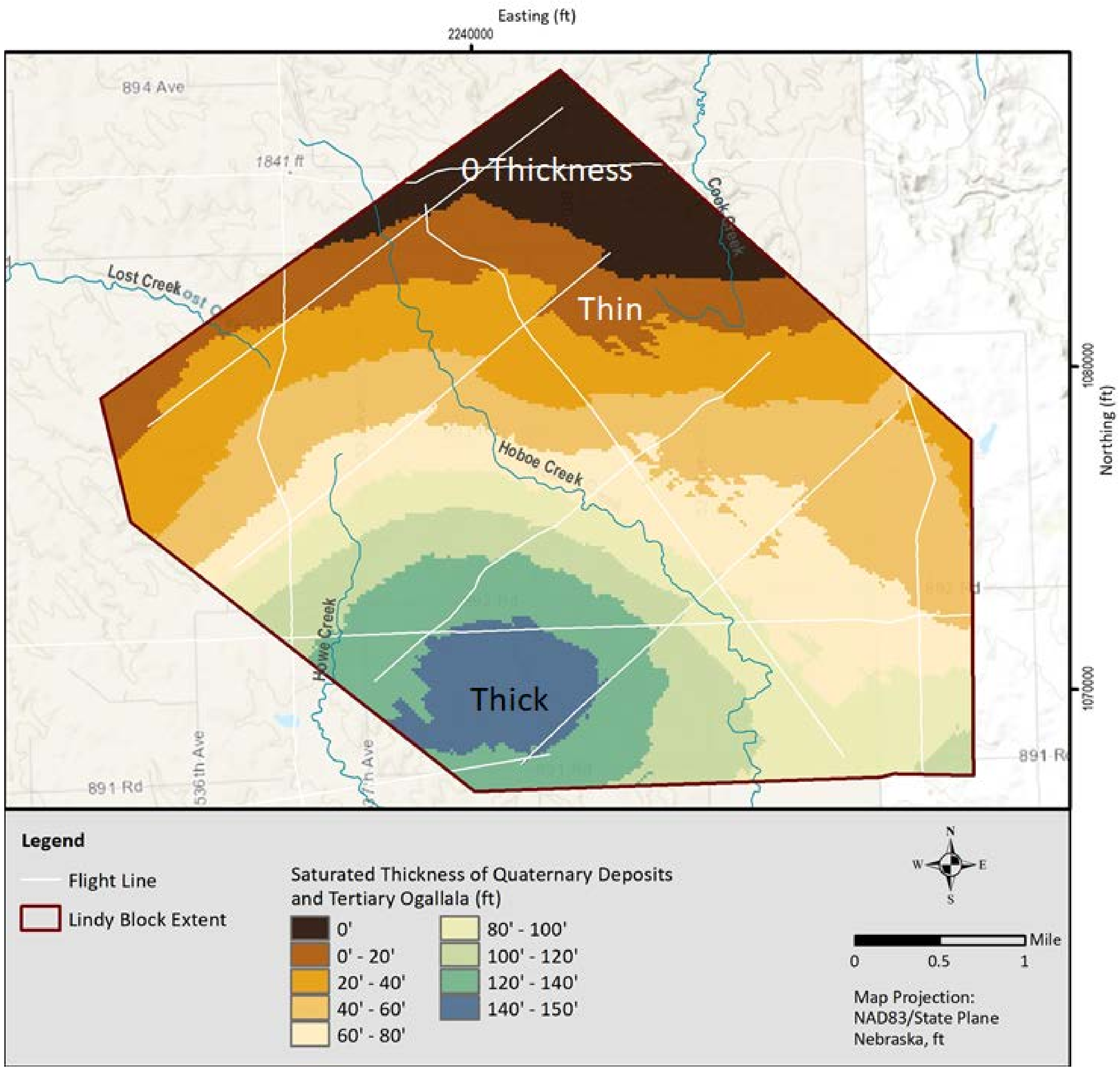


Figure 3-197. Map of the saturated thickness in the Lindy Block of the Quaternary (*Q*) and Tertiary Ogallala Group (*To*) deposits related to the specific capacity of the wells screened within them. Note the two high capacity wells lie to the south-central part of the area. Block flight lines are indicated by the white lines.

3.2.6 Hydrogeologic Framework of the Menominee Block AEM Survey Area

The AEM provided insight into the geographic distribution and extent of the unconsolidated material in the Menominee Block AEM survey area. The ***Q*** materials within the Menominee Block are composed of unconsolidated alluvial silt, sand, and gravel generally in the form of loess and glacial till and alluvial deposits that overlie the ***Kp*** and ***Kn*** bedrock. The main paleochannel feature may be related to a tunnel valley. The ***Q*** material in the Menominee Block AEM survey area is identified through interpretation of the AEM data as non-aquifer (blue), marginal aquifer (tan), aquifer material (yellow), and coarse aquifer (brown) material as discussed in Section 3.1.6. Generally, the flight block (Figure 3-198) is bounded ~1 mile east of Highway 81, just east of Highway 121 in the west, ~1 mile south of Highway 12 and ~6 miles northeast of the intersection of highways 81 and 12. The area was severely impacted by EM-coupling in the area of the paleochannel (Figure 2-7 and Figure 3-13)

Figure 3-199 displays a 3D fence diagram, looking to the southeast, of the interpreted hydrostratigraphic profiles with CSD and NE-DNR borehole lithology data. The area generally contains a mix of all ***Q*** aquifer-type materials lying upon the ***Kp*** and ***Kn***. The boreholes in the area indicate a mix of silty clay, sandy clay, and sand and gravel in the block area. As can be seen on Figure 3-199, some of the block area is covered in glacial till/loess made up of marginal and non-aquifer materials. This makes for poor recharge across most of the area because the permeability of these materials is low, limiting the amount of infiltration. There are areas of glacial tunnel valley deposits, outwash, and fluvial deposits made up of mostly coarse aquifer material and aquifer material and are present mostly as fill for the paleochannel located in the center-north of the AEM survey area.

Figure 3-200 presents profile L901101, located in the center of the survey area, which extends from west to east across a paleovalley likely formed by a tunnel valley which trends from south to north. The CSD 1995 water table (NE-CSD, 1995) is on the profile and shows the shape of the water table to be a mound with the center below the paleochannel with the highest elevation along the line at ~1,370. The elevation of the water table on the flanks of the mound are ~1,340 feet. Depth to water changes from ~20 to ~140 feet below land surface and is similar to the change in topography. There is no evidence along this profile of any hydrologic connection to surface water due to the depth to the water table and the incised nature of the paleochannel into the ***Kp*** and ***Kn*** providing a boundary to groundwater flow. The CSD 1995 water table is also on the profile Figure 3-201 shows the water table for the area.

Maps of the top surfaces of the bedrock ***Kp*** (Figure 3-202) and ***Kn*** (Figure 3-203) units both show effects of incision of the same paleochannel into both surfaces. Figure 3-202, the map of the top of the ***Kp***, also indicates the presence of bedrock lows and highs across the area ranging from 1,332 to 1,477 feet as well as indicating that much of the ***Kp*** has eroded off. The top of the ***Kn*** surface map (Figure 3-203) indicates the presence of bedrock lows and highs across the area ranging from 1,227 to 1,418 feet. The area is covered with ***Q*** aquifer material and can be thin across most of the area except in the paleochannel area.

The total thickness of the ***Q*** material in the Menominee AEM block area (Figure 3-204) was calculated by subtracting the bedrock elevation from the ground surface elevation. The ***Q*** varies in thickness from <20 feet to 235 feet. It is important to understand the distribution of the various ***Q*** aquifer materials in relation to their hydrologic connection to both the surface water. Generally, the water table is at a moderate to shallow depth below the land surface and is bounded by marginal and non-aquifer materials and bedrock materials which does not allow hydrologic connection to surface water. The aquifer and coarse aquifer materials provide the greatest connection for water movement through all of the ***Q*** aquifer materials present in the area. The ***Q*** aquifer and coarse aquifer materials generally are confined by surrounding marginal and non-aquifer material and confining bedrock units. Of equal importance is the saturated thickness of the ***Q*** materials calculated by the bedrock elevation subtracted from the 1995 CSD water table surface elevation (NE-CSD, 1995). By separating the aquifer and coarse aquifer material from the total voxel model, the saturated thickness of those units (Figure 3-205) is indicated to vary between 0, where there is no aquifer and coarse aquifer material, to a maximum thickness of about 120 feet within or near the paleochannel. Figure 3-206 is another view of the aquifer and coarse aquifer material thickness ranging from <20 to 123 feet this time as a 3D voxel model showing the aquifer and coarse aquifer material volume in the Menominee Block in relation to the paleochannel. Figure 3-207 is a voxel model of the bedrock units ***Kp*** and ***Kn*** with a fence diagram of the flight lines showing the ***Q*** aquifer materials. As mentioned above the ***Q*** aquifer materials are thickest in the paleochannel.

Figure 3-208 presents interpreted Line L1003300, a north-south line near the center of the area. It shows ***Q*** glacial till/loess made up of marginal aquifer material and non-aquifer material. However, there are deposits of aquifer and minor coarse aquifer materials that are outwash deposits of the glacial material much of which occupy the paleochannel. Due to depth of the water table there is no hydrologic connection to surface water.

Figure 3-209 shows an exploded view voxel showing the volumes of material for ***Q*** aquifer materials and ***Kp*** and ***Kn*** across the entire Menominee AEM survey block**.** The ***Q*** aquifer and coarse aquifer materials being the main aquifers of the Block with ***Kp*** and ***Kn*** being an aquitard. Figure 3-210 shows an exploded view voxel showing the volumes of ***Q*** aquifer materials including coarse aquifer, aquifer, marginal aquifer and non-aquifer. Note the marginal and non-aquifer materials consist of ~50% of the ***Q*** volume with aquifer material next in total volume and coarse aquifer material being a similar part of the total.

Figure 3-211 presents a 3D voxel of the bedrock units (***Kp*** and ***Kn***) and the coarse aquifer material component of the ***Q*** deposits along the paleochannel in the Menominee Block along with a 3D fence diagram of all the ***Q*** deposits.

Figure 3-212 shows a voxel model of the ***Q*** aquifer materials with the water table in relation to the ***Kp*** and ***Kn***. As can be seen the water table is below the land surface and bounded by the bedrock aquitards limiting the hydrologic connection to surface water. Figure 3-213 shows the saturated thickness of the ***Q*** deposits related to the specific capacity of the NE-DNR registered wells screened within the ***Q***. Only the fill of the paleochannel has the large capacity wells between 10 and >25 gpm.

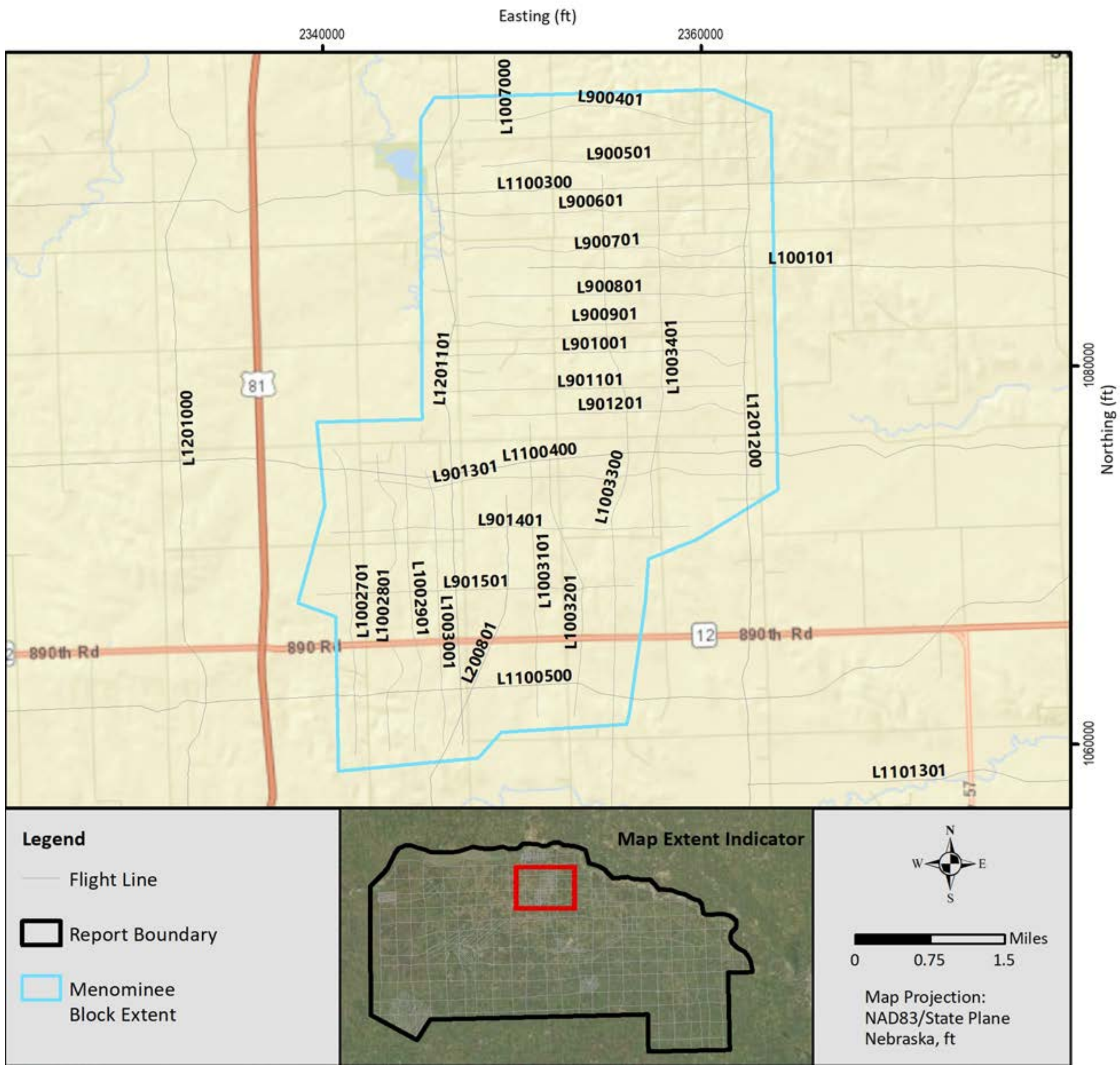


Figure 3-198. Location map of the Menominee Block indicating AEM flight lines local roads and streams.

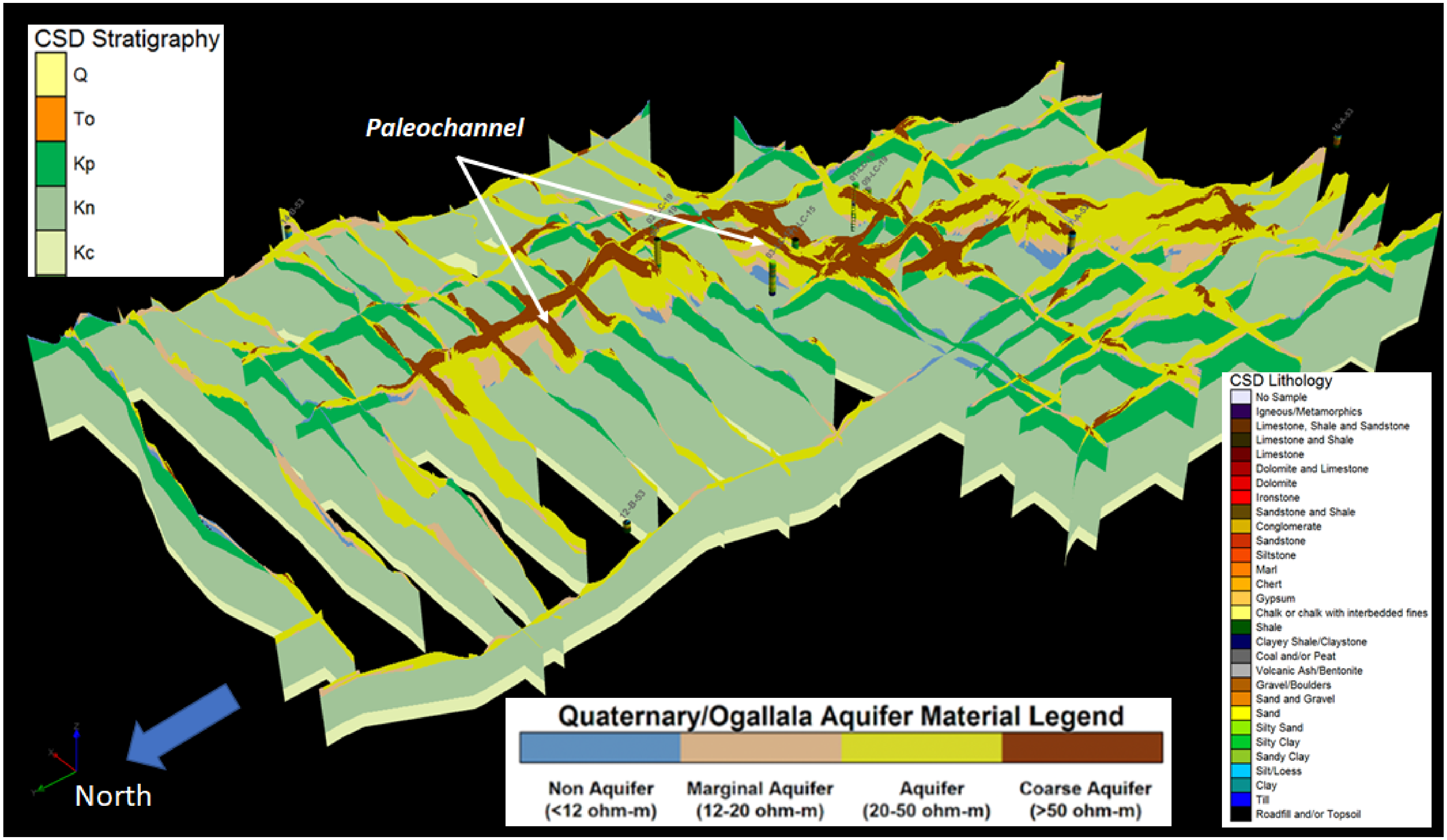


Figure 3-199. 3D fence diagram of interpreted AEM hydrostratigraphic profiles within the Menominee Block AEM survey area include the *Q*= Quaternary, *Kp*= Cretaceous Pierre Shale, *Kn*=Cretaceous Niobrara Formation, *Kc*= Cretaceous Carlile Shale. Note the majority of the area is covered in Quaternary (*Q*) coarse aquifer and aquifer materials mostly in the paleochannel. CSD test holes and NE-DNR registered wells are indicated on the plot. V.E. = 10x.

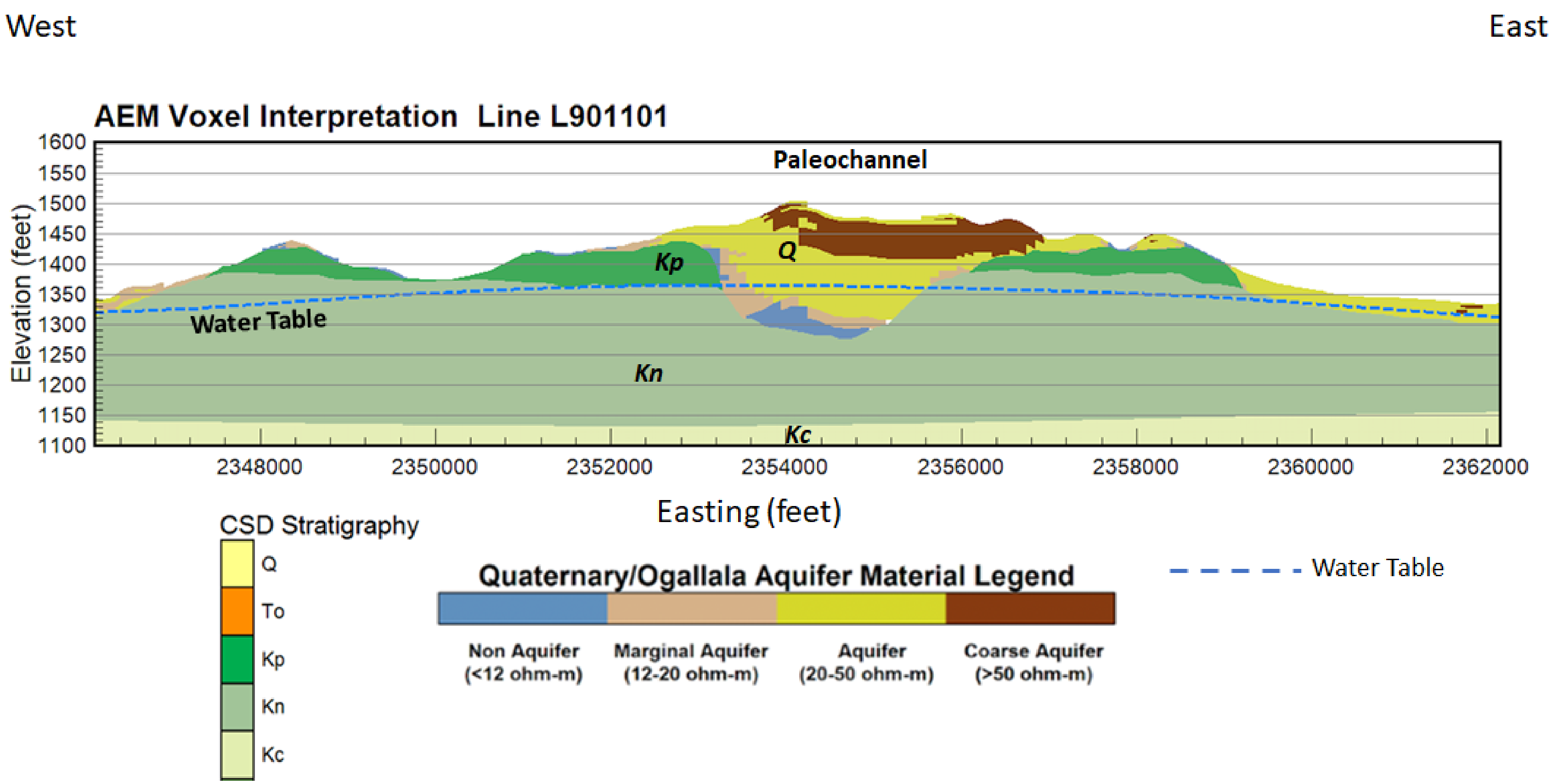


Figure 3-200. Profile of the east-west line L901101 in the Menominee Block showing the AEM interpretation. The CSD 1995 water table is indicated as a dashed blue line on the profiles. Note the isolated nature of the Quaternary (*Q*) aquifer materials within the paleochannel which incised into the Cretaceous Pierre Shale (*Kp*) and Cretaceous Niobrara Formation (*Kn*). Horizontal datum is NAD83 State Plane Nebraska (feet).

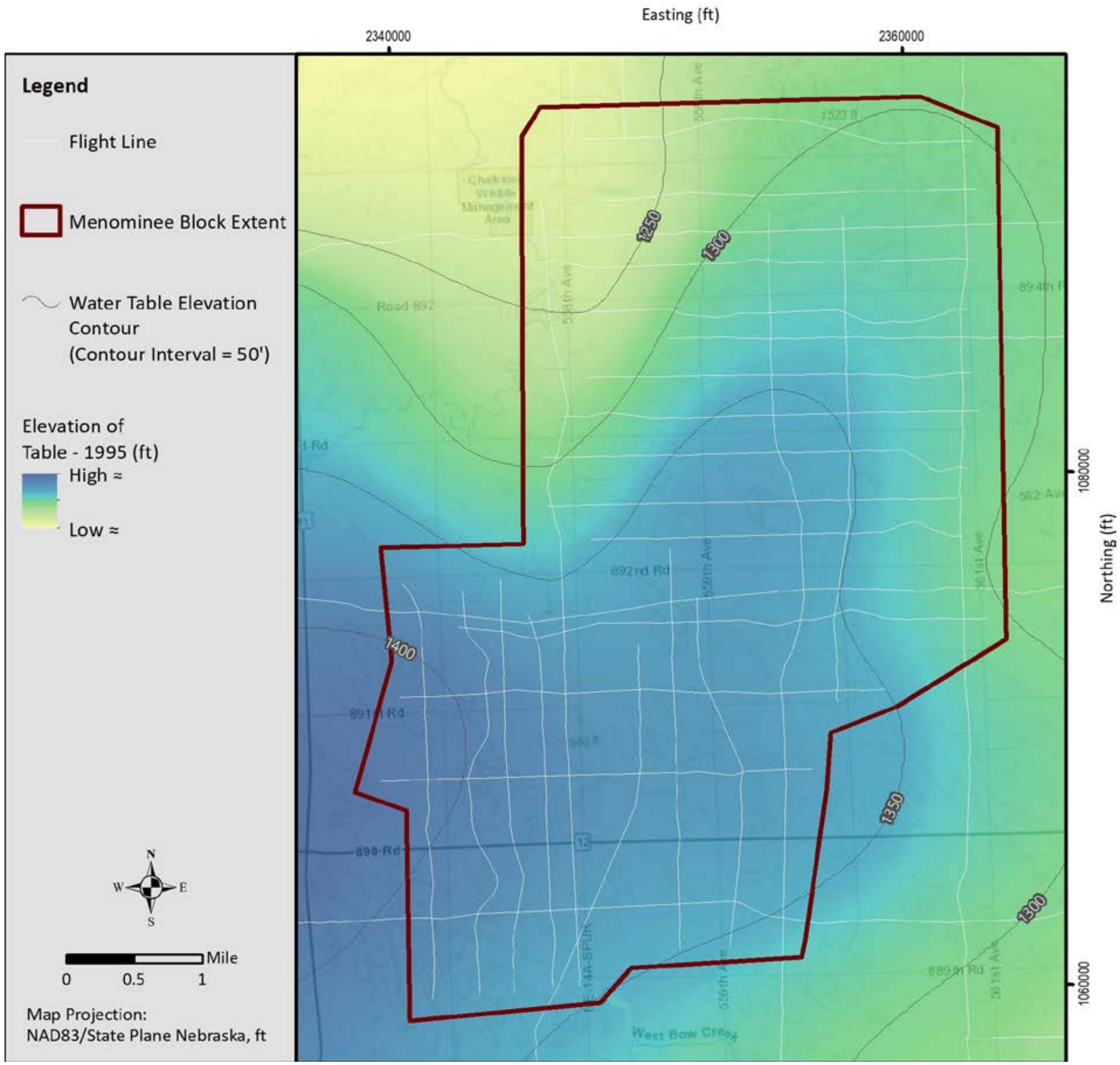


Figure 3-201. Map of the CSD 1995 water table (NE-CSD, 1995) within the 2018 Menominee Block AEM survey area. Block flight lines are indicated by white lines.

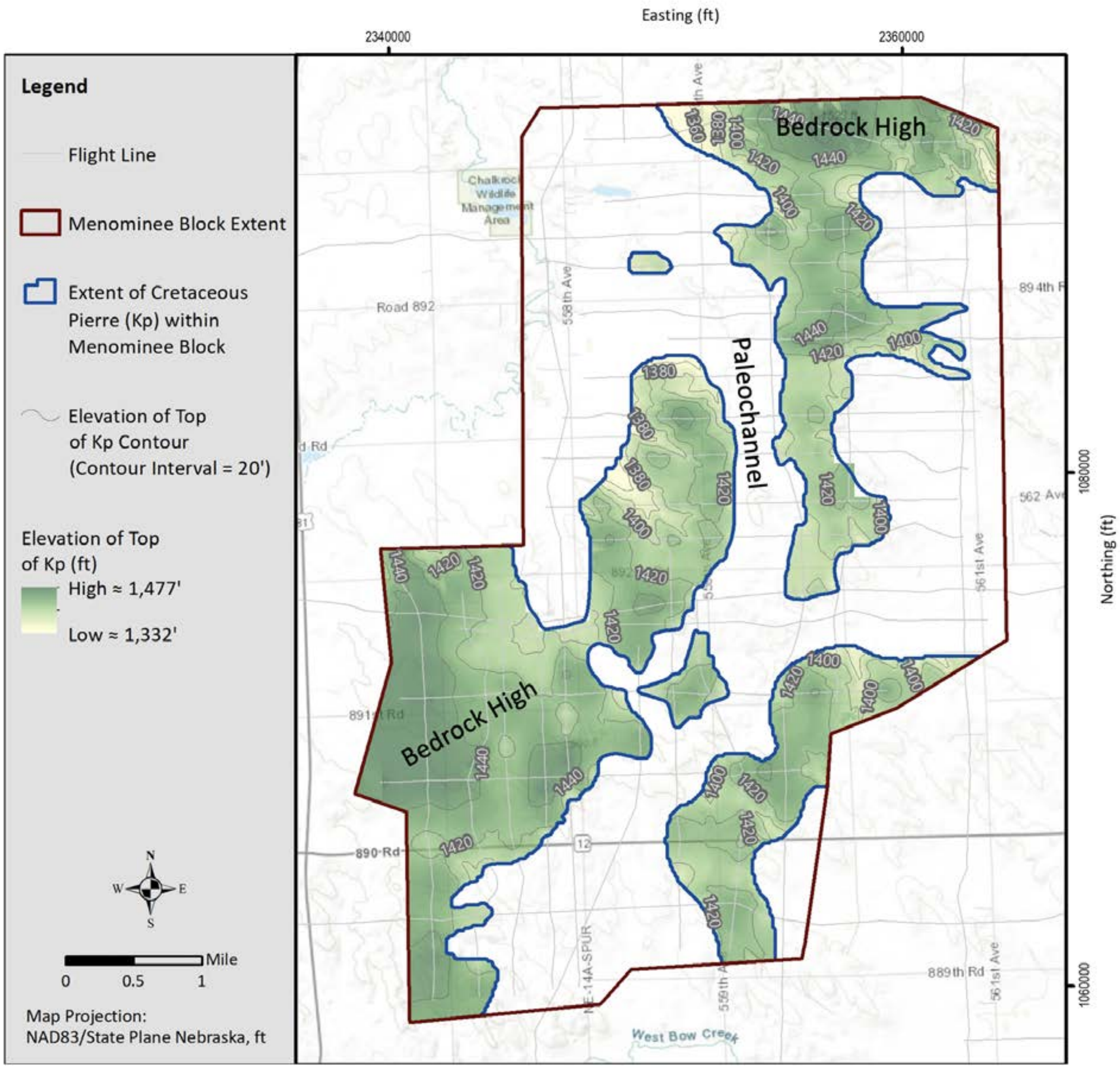


Figure 3-202. Map of the Cretaceous Pierre Shale (*Kp*) bedrock surface elevation within the Menominee Block AEM survey area. Flight lines are indicated by grey lines. Note the paleovalley where the Cretaceous Pierre Shale (*Kp*) is removed and the bedrock high to each side.

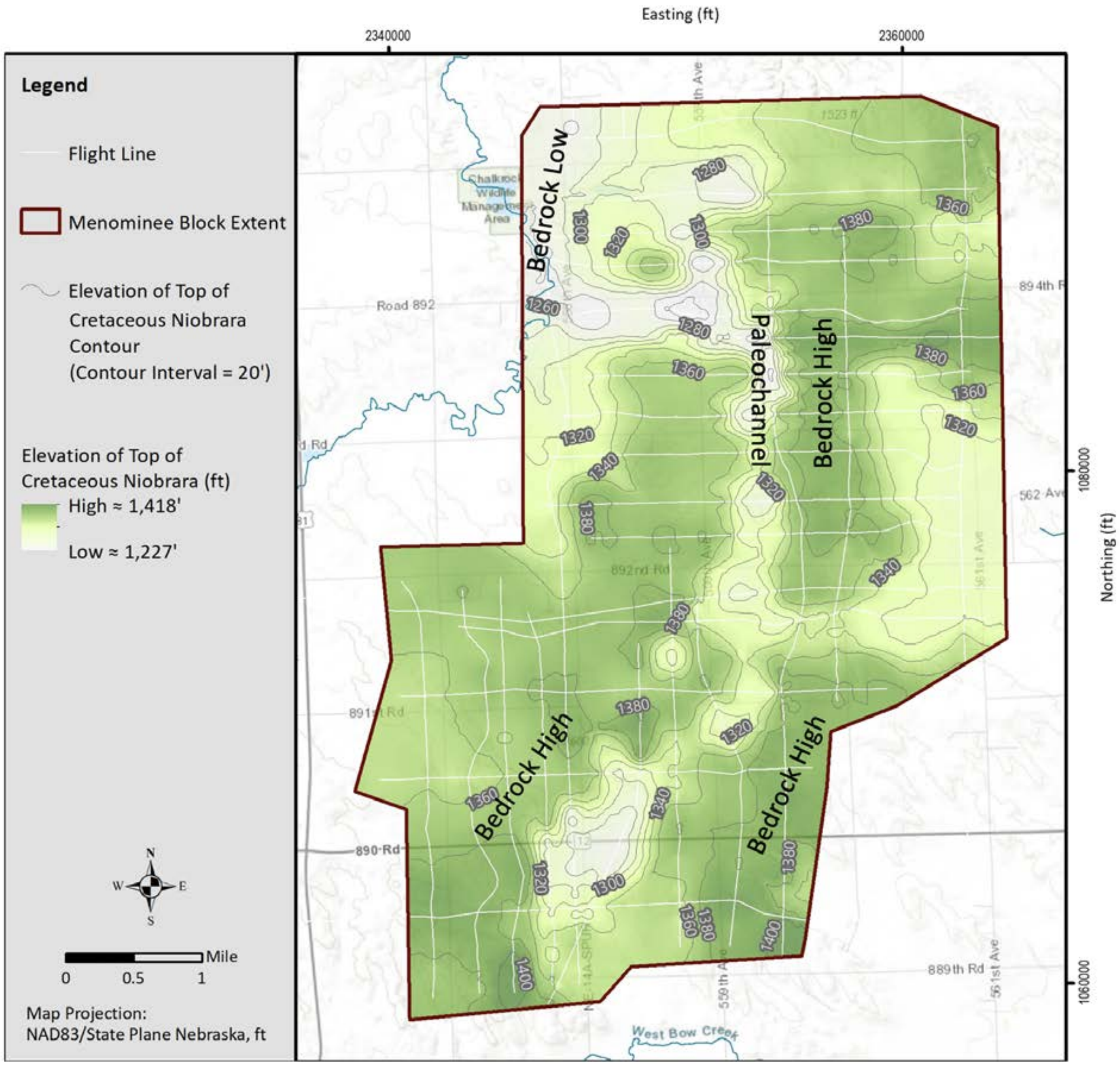


Figure 3-203. Map of the Cretaceous Niobrara Formation (*Kn*) bedrock surface elevation within the Menominee Block AEM survey area. Flight lines are indicated by white lines. Note the paleovalley where the *Kn* is eroded into the bedrock and the bedrock high to each side.

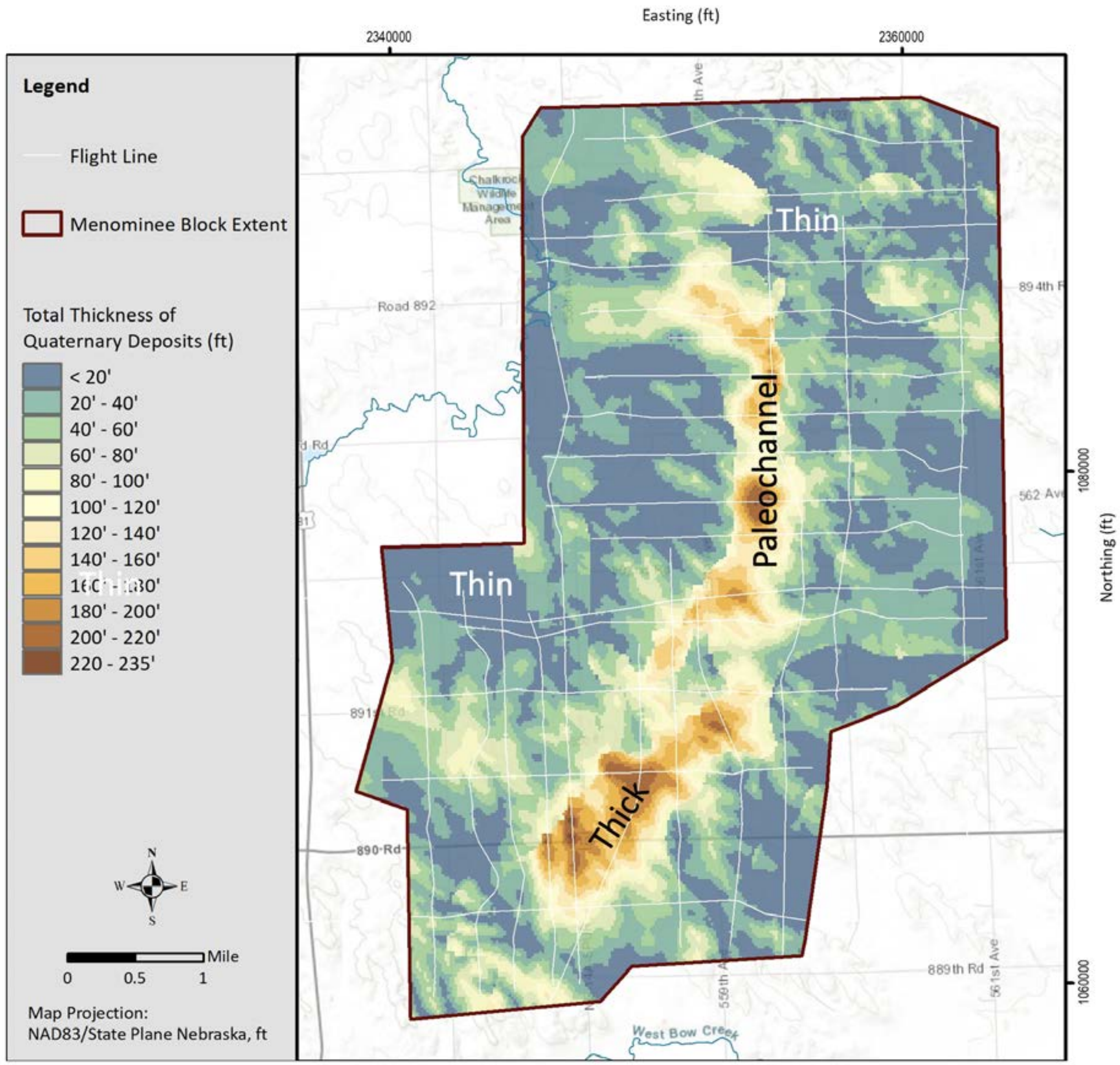


Figure 3-204. Map of the total thickness of the Quaternary (*Q*) comprised of all aquifer materials within the Menominee Block AEM survey area. *Q* aquifer materials include coarse aquifer, aquifer, marginal aquifer and non-aquifer materials. Note the paleochannel contains the greatest thickness of *Q* materials. Block flight lines are indicated by white lines.

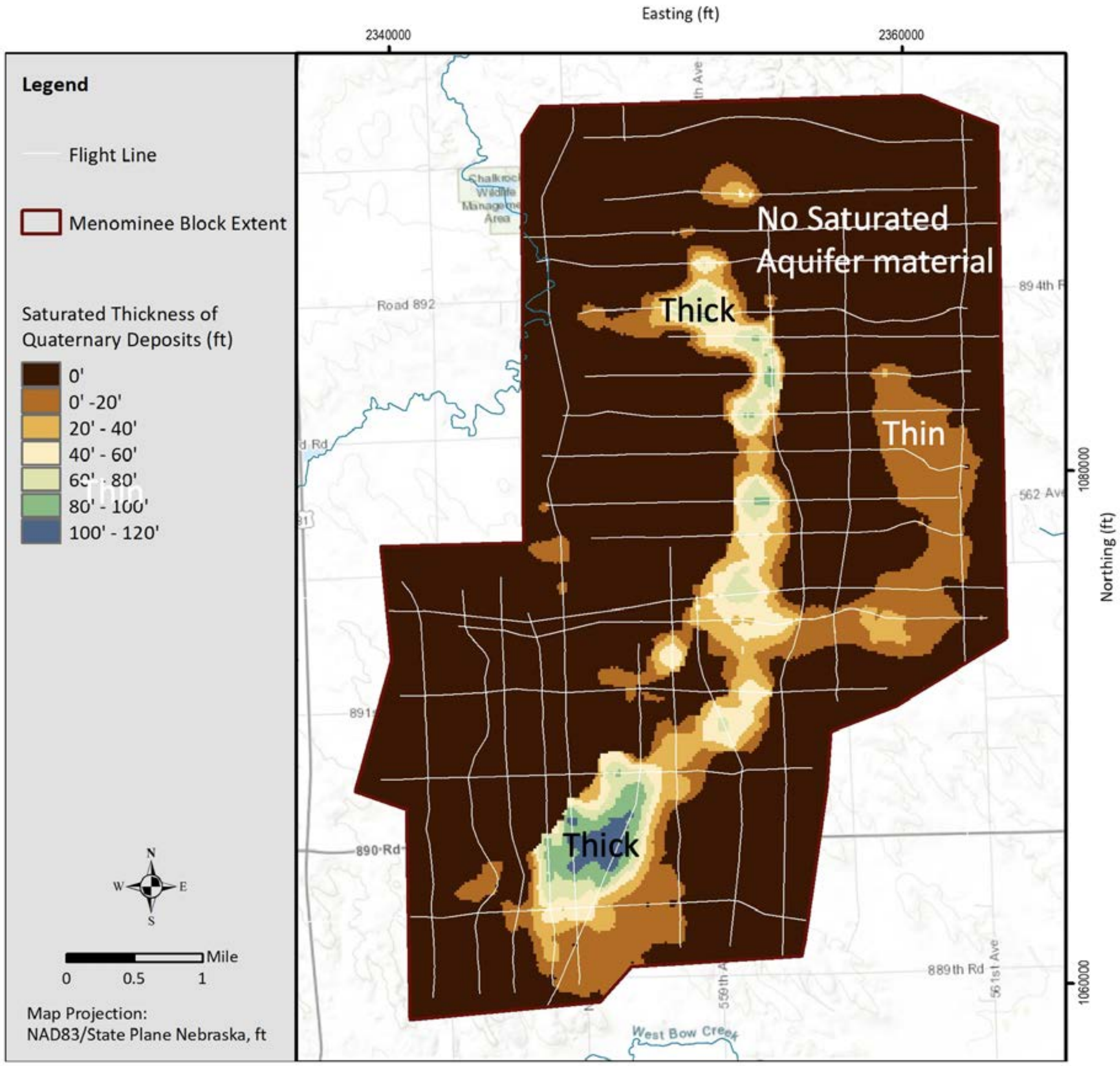


Figure 3-205. Map of the saturated thickness of the Quaternary (*Q*) aquifer materials within the Menominee Block AEM survey area. Block flight lines are indicated by the white lines. Note the saturated thickness for the *Q* materials is limited to paleochannel and small areas nearby.

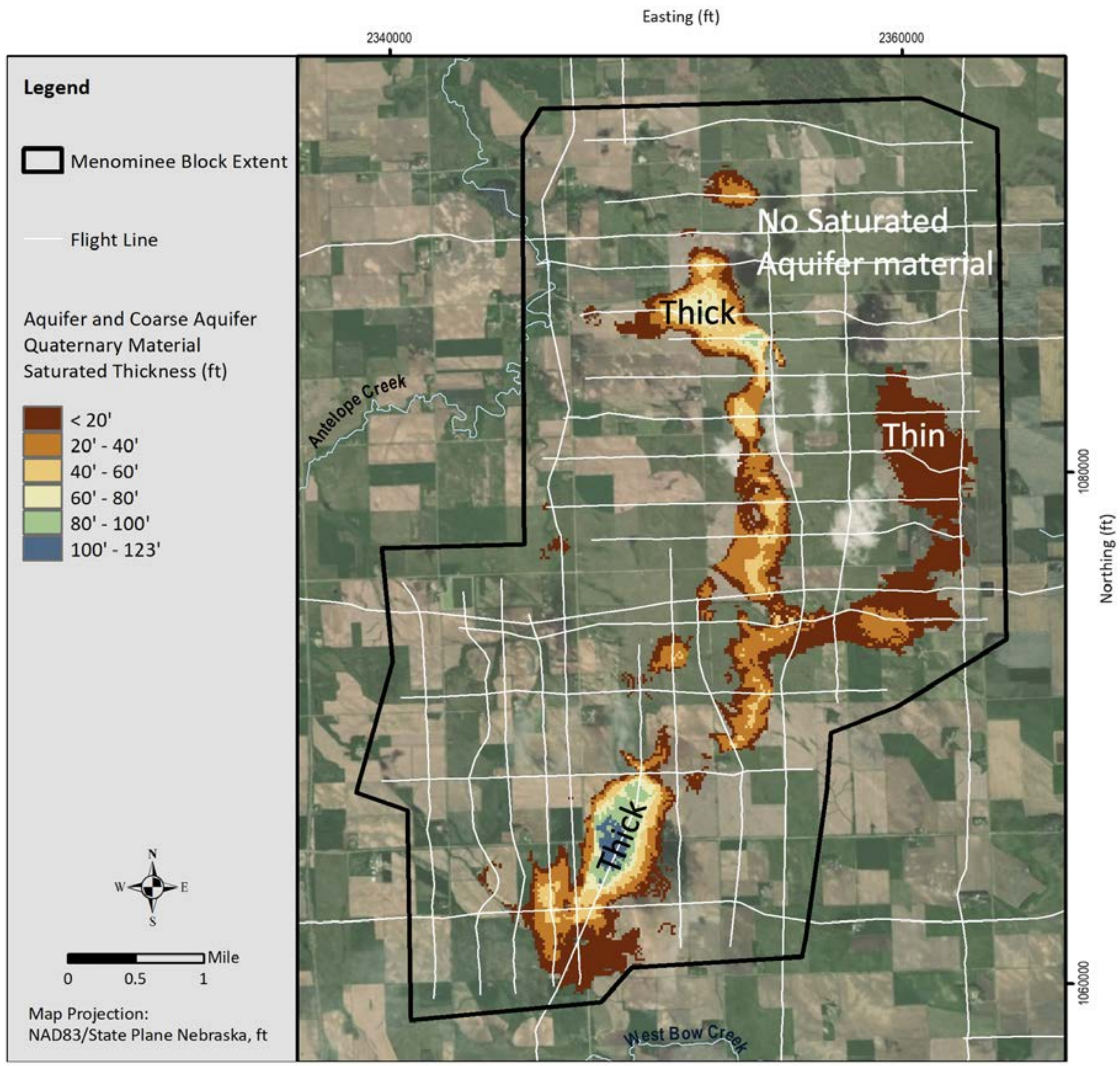


Figure 3-206. Map of the saturated thickness of the Quaternary (*Q*) aquifer and coarse aquifer materials within the Menominee Block AEM survey area. Block flight lines are indicated by the white lines. Note the discontinuous nature of the coarse aquifer and aquifer materials and the variation of their thickness within the paleochannel area.

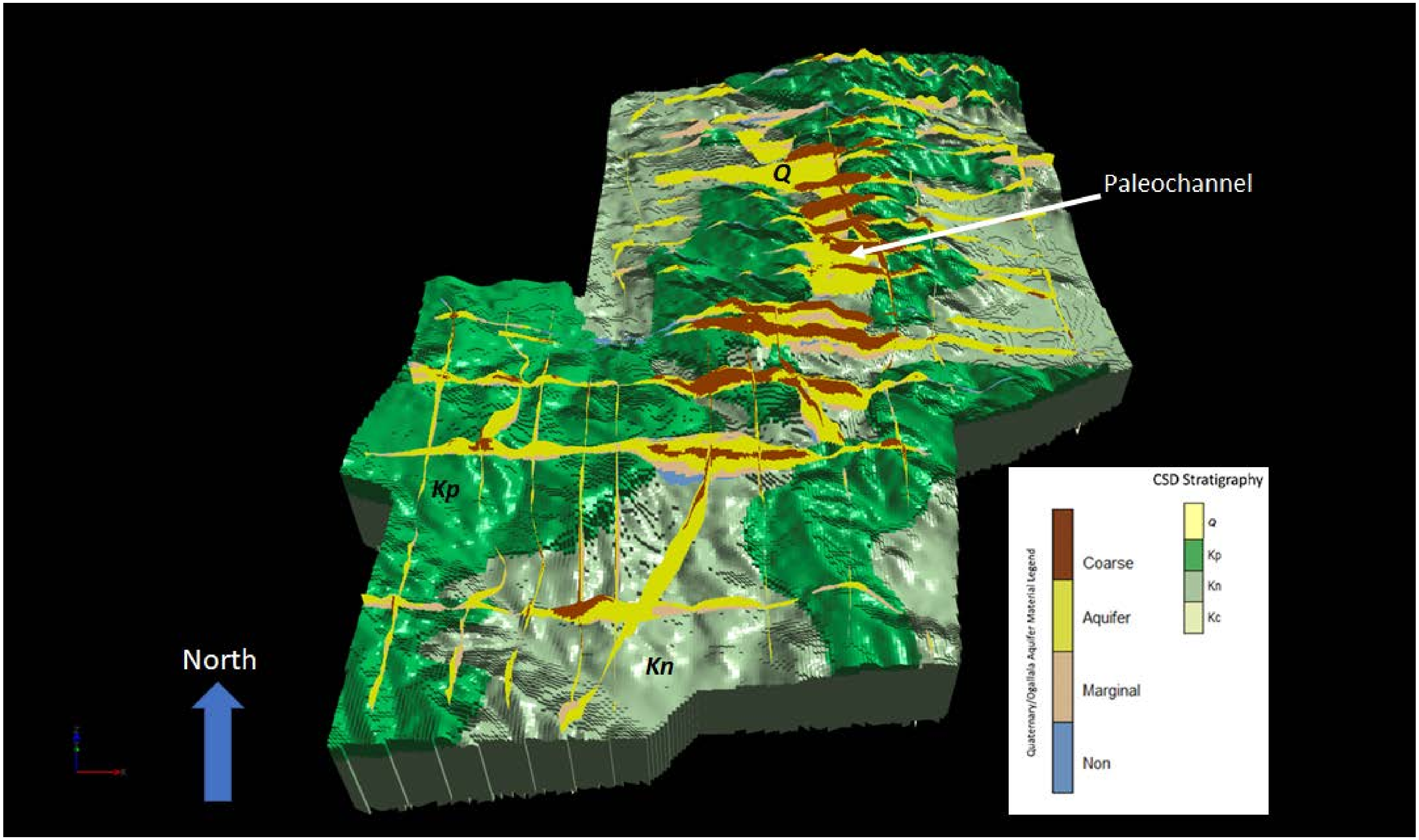


Figure 3-207. 3D voxel plot of the bedrock Cretaceous Pierre Shale (*Kp*) and Cretaceous Niobrara Formation (*Kn*) with a 3D fence diagram of the Quaternary (*Q*) aquifer materials. Note the *Q* aquifer materials are contained within the paleochannel. V.E. = 10x.

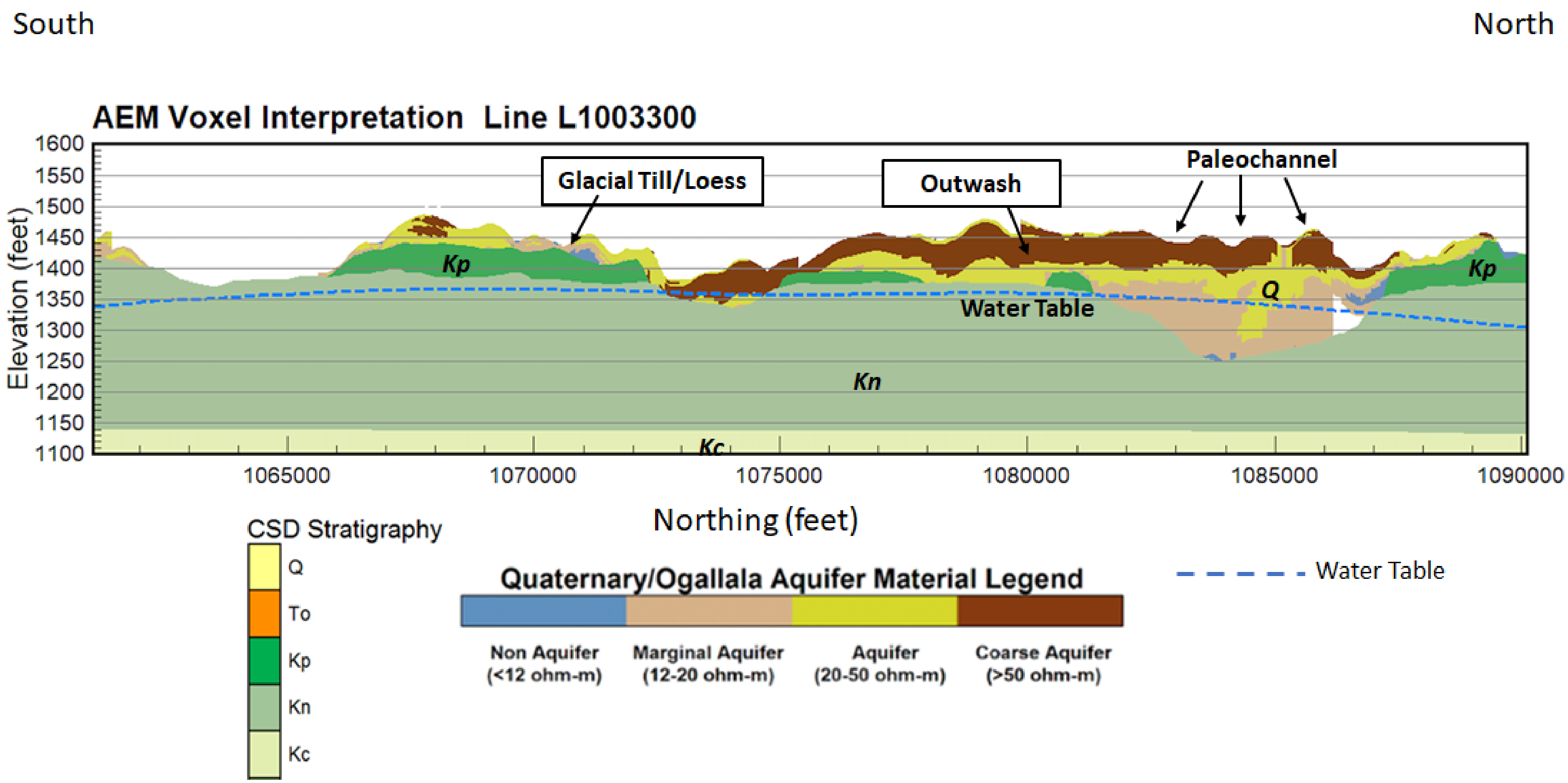


Figure 3-208. Profile of the north-south line L1003300 in the Menominee Block parallel to the paleochannel showing the AEM interpretation of the Quaternary (*Q*) aquifer materials in relation to the Cretaceous Pierre Shale (K*p*) and Cretaceous Niobrara Formation (*Kn*). Note the multiple *Q* aquifer material outwash deposits across the profile. The CSD 1995 water table is indicated as a dashed blue line. Horizontal datum is NAD83 State Plane Nebraska (feet).

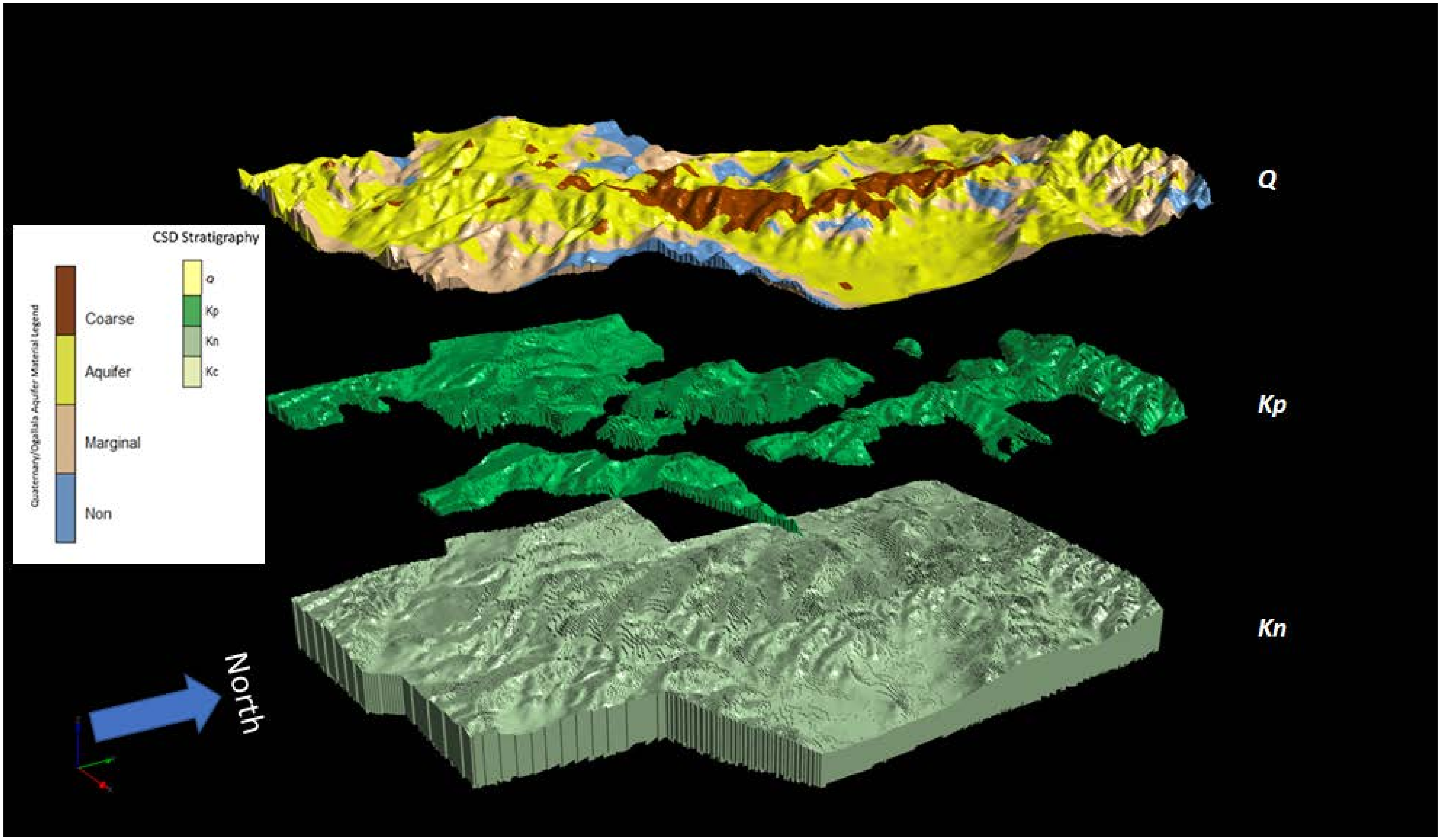


Figure 3-209. 3D 'exploded' voxel model of the Menominee Block AEM survey area showing Quaternary (*Q*), Cretaceous Pierre Shale (*Kp*), Cretaceous Niobrara Formation (*Kn*), and Cretaceous (*Kc*). V.E. =10x. Not to scale.

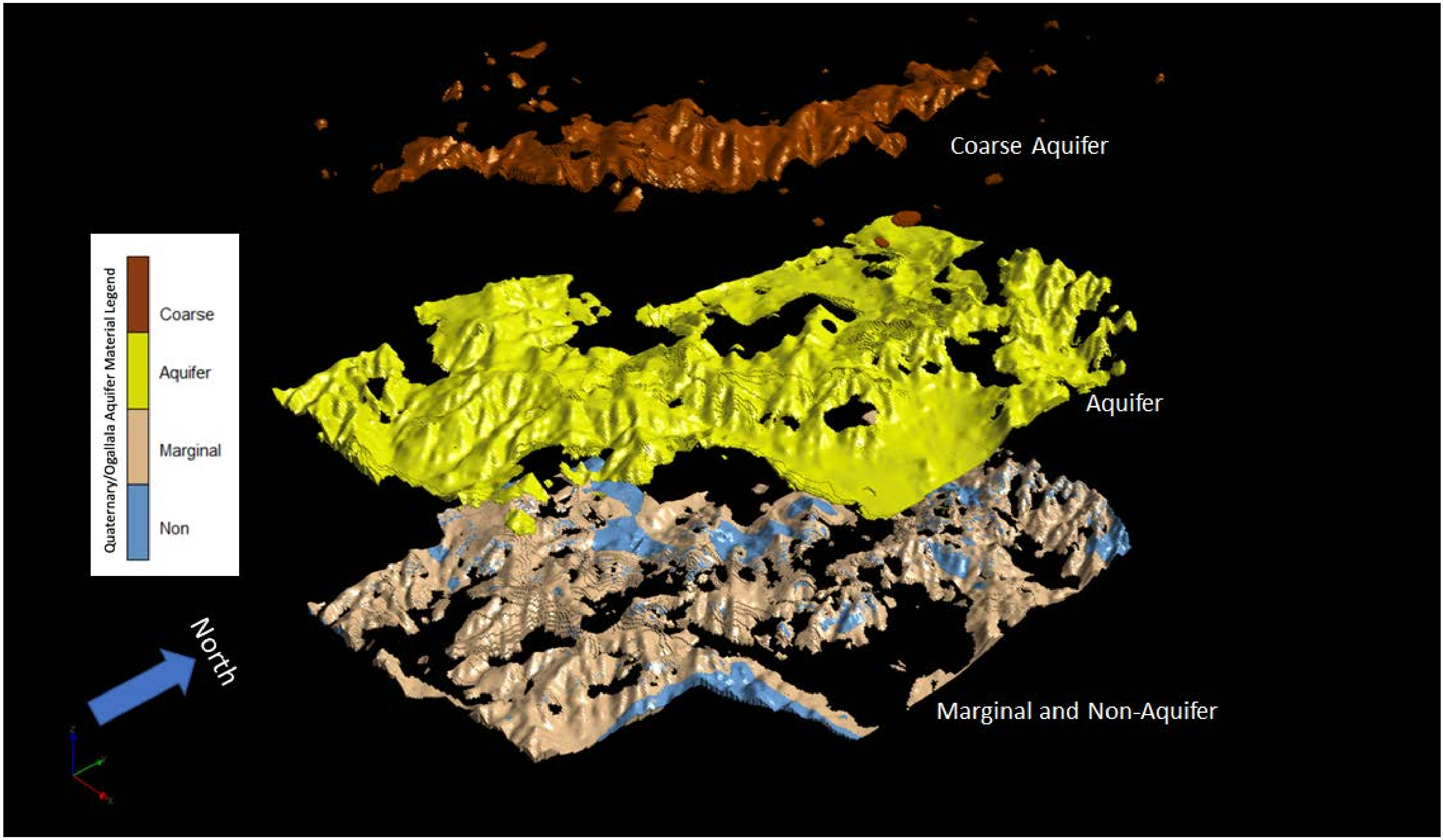


Figure 3-210. 3D 'exploded' voxel model of the Menominee Block AEM survey area showing Quaternary (*Q*) aquifer materials divided into coarse aquifer, aquifer, marginal aquifer and non-aquifer. Note the majority of the *Q* material is made up of coarse aquifer and aquifer material. V.E. =10x. Not to scale.

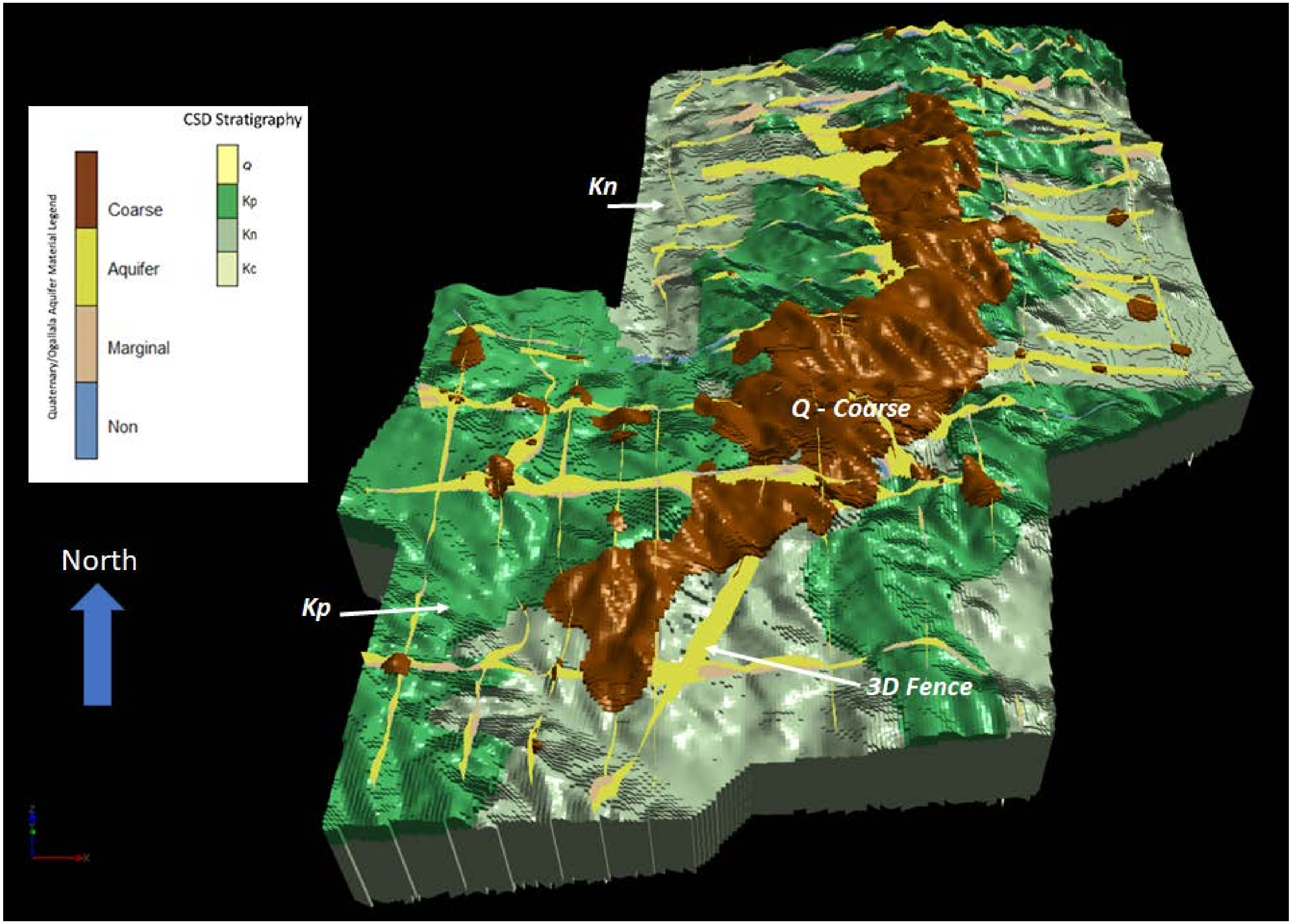


Figure 3-211. 3D voxel of the Cretaceous bedrock (Pierre *Kp* and Niobrara *Kn* Shale) and Quaternary (*Q*) coarse aquifer material and 3D fence diagram of *Q* aquifer materials. V.E.=10x.

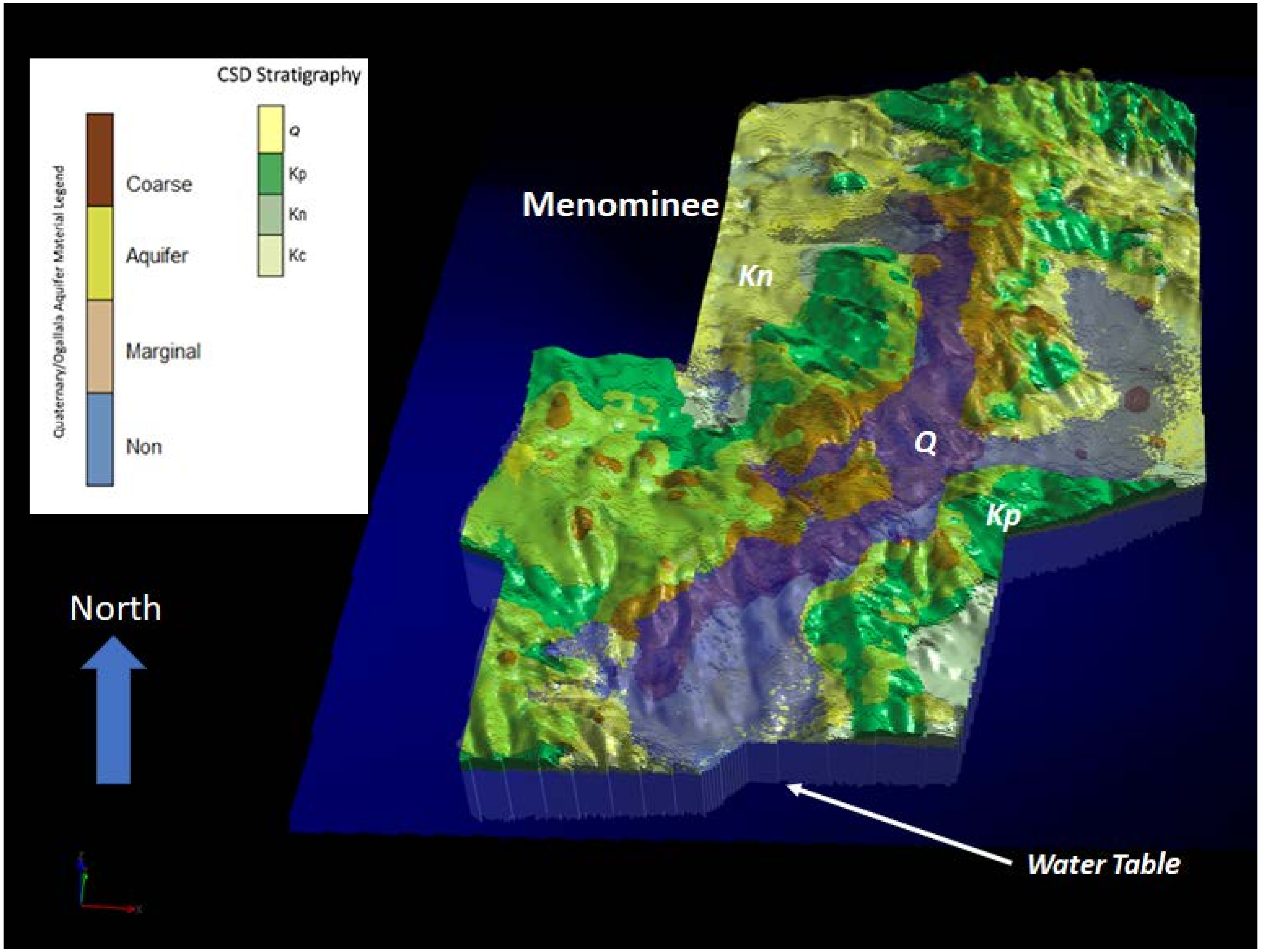


Figure 3-212. 3D voxel model of the Menominee Block AEM survey area showing Quaternary (*Q*) aquifer material, Cretaceous Pierre Shale (*Kp*), Cretaceous Niobrara Formation (*Kn*), and Cretaceous (*Kc*) with the 1995 CSD water table surface showing the saturated nature of the sediments in the paleochannel. V.E. =10x.

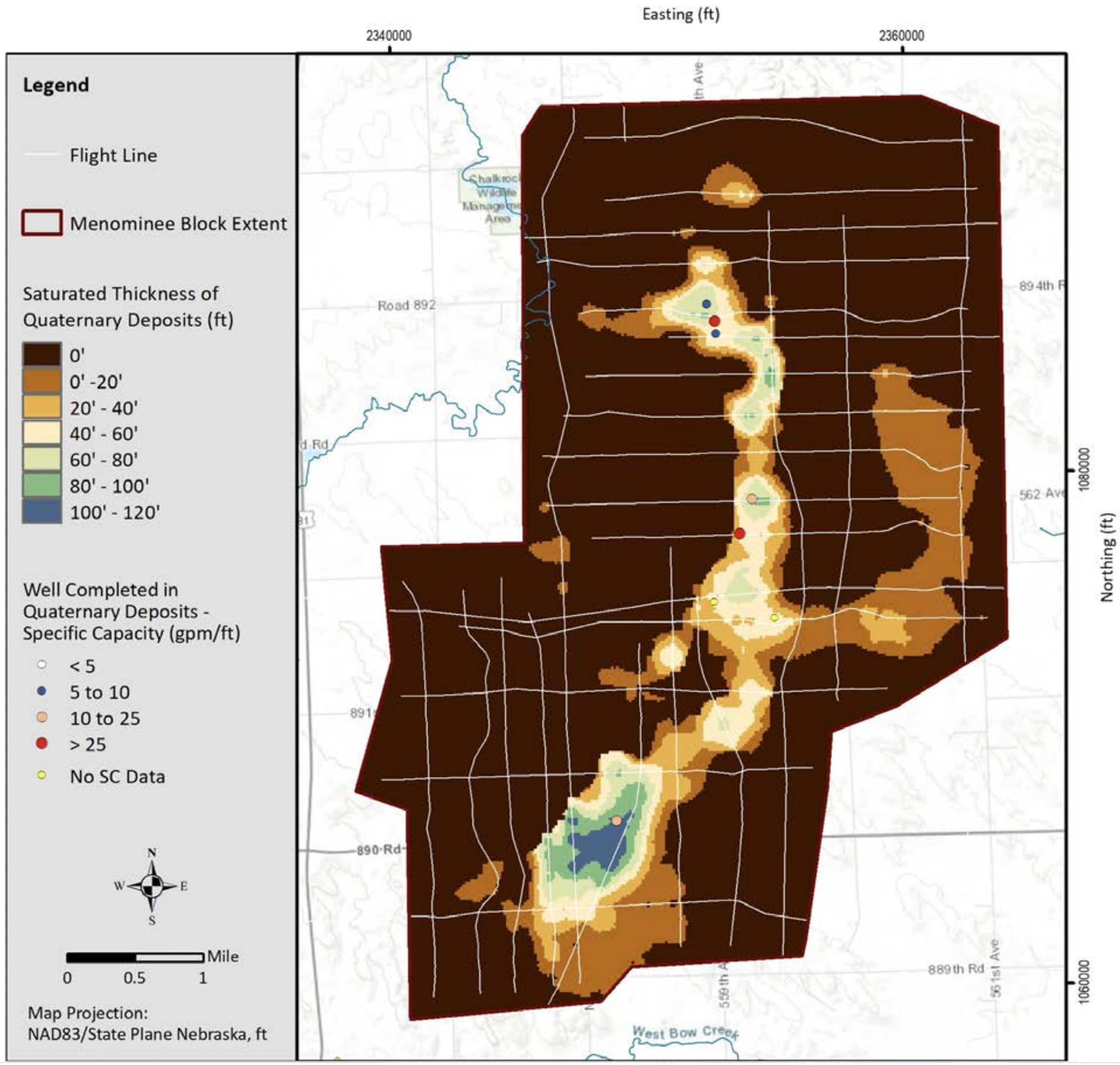


Figure 3-213. Map of the saturated thickness of the Quaternary (*Q*) deposits related to the specific capacity of the wells screened within the *Q*. Note the high capacity wells are in the paleochannel. Block flight lines are indicated by the white lines.

3.2.7 Hydrogeologic Framework of the Obert Block AEM Survey Area

The AEM provided insight into the geographic distribution and extent of the unconsolidated ***Q*** and ***To*** in the Obert Block AEM survey area. The ***Q*** materials within the Obert Block are composed of unconsolidated alluvial silt, sand, and gravel as well as loess and glacial till and outwash that overlie the ***To*** fluvial deposits made up of all aquifer materials seen in the ***Q***. The ***Q*** and ***To*** material in the Obert Block AEM survey area is identified through interpretation of the AEM data as non-aquifer (blue), marginal aquifer (tan), aquifer material (yellow), and coarse aquifer material (brown) as discussed in Section 3.1.6. Generally, the flight block is located near the Cedar-Dixon county boundary near highways 15 and 12 (Figure 3-214).

Figure 3-215 displays a 3D fence diagram, looking to the North, of the interpreted hydrostratigraphic profiles with CSD and NE-DNR borehole lithology data. The area generally contains a mix of all ***Q*** and ***To*** aquifer materials lying upon the ***Kn*** bedrock which lies upon the ***Kc***. The boreholes in the area indicate a mix of silty clay, sandy clay, and sand and gravel in the block area. As can be seen on Figure 3-215, the block area is covered in glacial till/loess and glacial outwash and ***To*** fluvial deposits and is a mix of all aquifer materials. The presence of coarse aquifer and aquifer materials across most of the area makes for good recharge across most of the area because the permeability of these materials is high.

Figure 3-216 presents profile L1003601, located in the center of the Obert Block AEM survey area and oriented north-south. The CSD 1995 water table (NE-CSD, 1995) is on the profile and shows the change in water table elevation from the east to the west and changes in elevation from ~1,350 to ~1,440 feet. Depth to water changes from ~0 to 220 feet below land surface and is similar to the change in topography. There is evidence along this profile of hydrologic connection to surface water due to the depth to the water table and the ***Q*** coarse aquifer and aquifer materials present. There are areas of good recharge to the outwash coarse aquifer and aquifer materials at Northing 1042000. The rest of the area has poor recharge because of a cover of marginal and non-aquifer materials. Note the small amount of ***To*** at the southern end of the profile. The CSD 1995 water table is also on the profile Figure 3-217 shows the water table for the area.

Figure 3-218 is a map of the top of the bedrock, composed of ***Kn*** that indicates the presence of bedrock lows and highs across the area ranging from 1,296 to 1,365 feet. There is a shallow paleochannel in the center of the area trending west to east. The entire area is covered with ***Q*** aquifer material and ***To*** aquifer material (only in small area on the south side of area). The total thickness of the ***Q*** and ***To*** material in the Obert Block AEM survey area (Figure 3-219) was calculated by subtracting the bedrock elevation from the ground surface elevation. The ***Q*** and ***To*** varies in thickness from <20 to 314 feet. It is important to understand the distribution of the various ***Q*** and ***To*** aquifer materials in relation to their hydrologic connection to both the surface water. Generally, the water table is deep below the land surface or bounded by marginal and non-aquifer materials which limits the connection to surface water.

Figure 3-220 shows line L1100600 where there is ***Q*** materials overlying ***Kn***. here is hydrologic connection along the line near the center and the discontinuous caps of marginal and non-aquifer materials to the west and the east near the land surface limiting recharge. The coarse aquifer and aquifer materials which are outwash deposits provide the greatest connection for water movement through all of the ***Q*** and ***To*** aquifer materials present in the area. Of equal importance is the saturated thickness of the ***Q*** materials calculated by the bedrock elevation subtracted from the 1995 CSD water table surface elevation (NE-CSD, 1995). The thickness of the saturated ***Q*** is shown on Figure 3-221 and varies between 0, where there is no saturated aquifer materials, to a maximum thickness of about 101 feet near south side of the area. It is mostly ***Q*** glacial till/loess made up of coarse aquifer material and aquifer material outwash deposits lying on small localized areas of ***To*** sediments. The glacial outwash deposits are made up of coarse aquifer and aquifer material.

Figure 3-222 presents interpreted Line L201301, a north-south line on the north side of the area. It is mostly ***Q*** glacial till/loess made up of coarse aquifer material and aquifer material. There are also marginal and non-aquifer materials located on some of the hill tops and a thick deposit near Northing 1040000. There is a small localized deposit of ***To*** materials below the ***Q*** in the west. There are deposits of aquifer material that are outwash deposits of the glacial material across the line. The water table is relatively flat at ~1,360 feet elevation and there is no hydrologic connection to surface water. Figure 3-223 is a 3D fence diagram with the water table surface. Note the water table has a gently sloping mound in the south that moves to lower elevation to the east-west and north.

Figure 3-224 shows the saturated thickness of the ***Q*** deposits related to the specific capacity of the NE-DNR registered wells screened within the ***Q***. There is 1 large capacity well >25 gpm that lie west-central area near the boundary of the survey area. The remaining wells in the area produce <5 gpm and are scattered throughout the area.

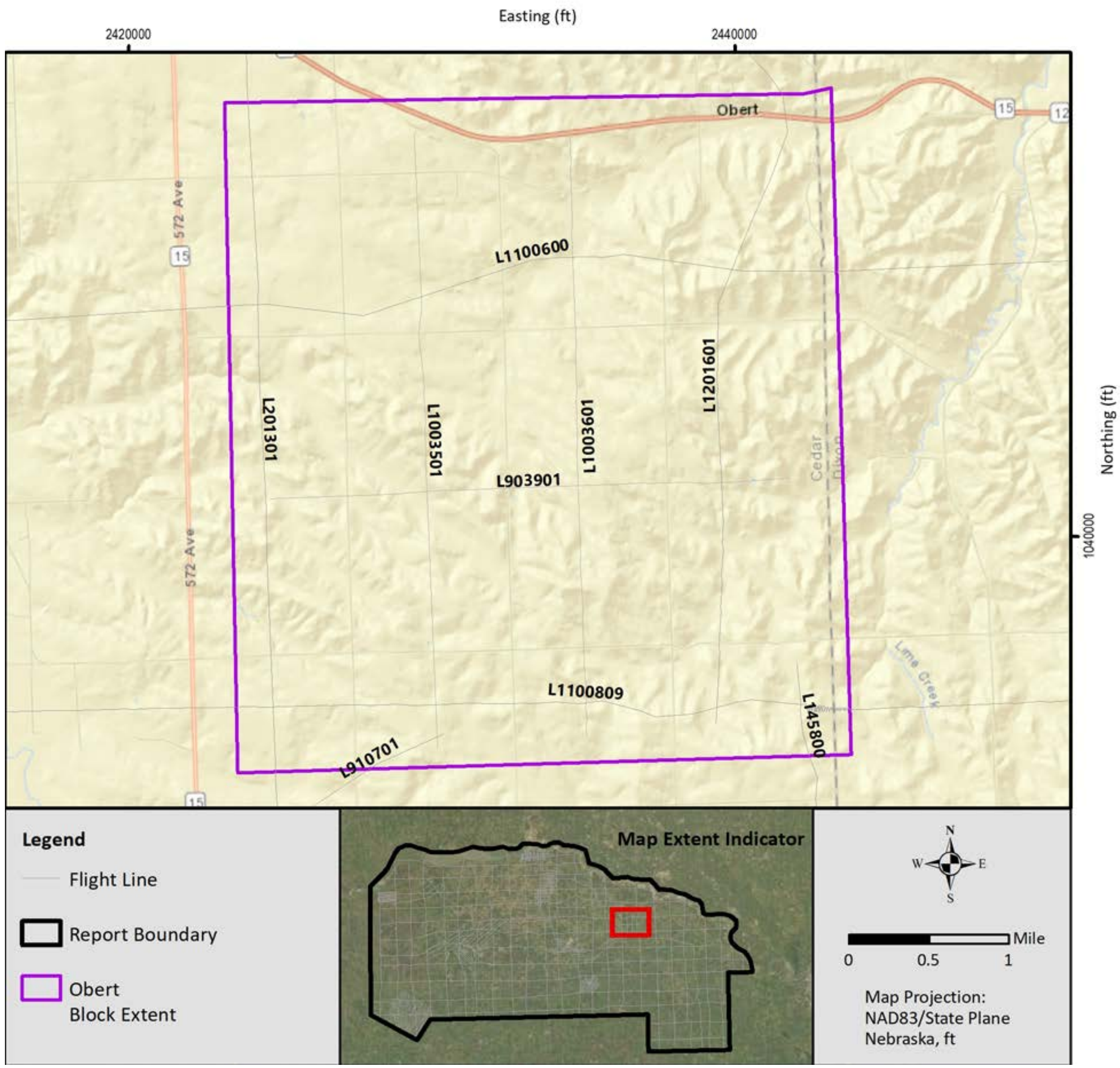


Figure 3-214. Location map of the Obert Block indicating AEM flight lines local roads.

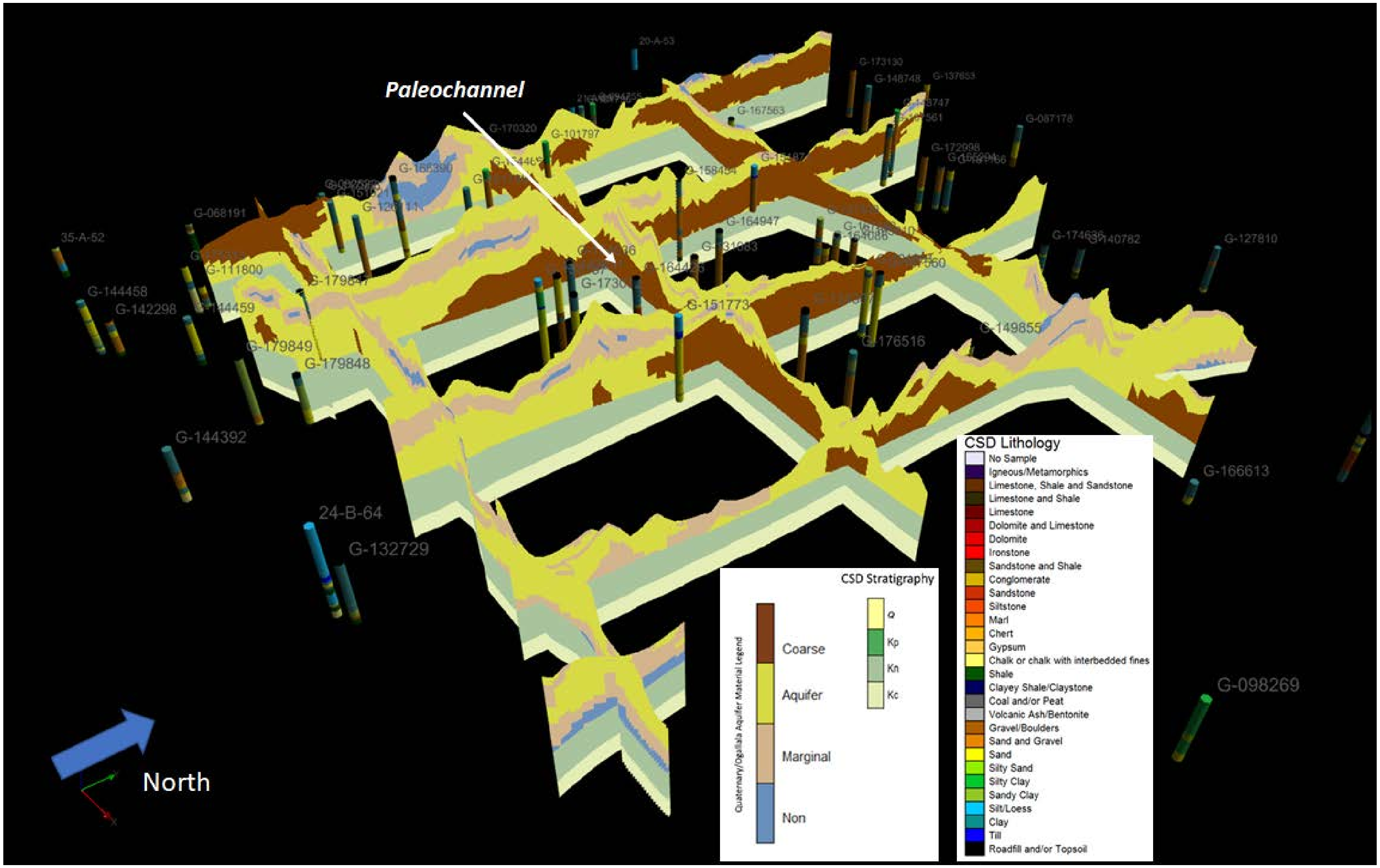


Figure 3-215. 3D fence diagram of interpreted AEM hydrostratigraphic profiles within the Obert Block AEM survey area include the *Q*= Quaternary, *To*=Tertiary Ogallala Group, *Kn*=Cretaceous Niobrara Formation, *Kc*= Cretaceous Carlile Shale. Note the majority of the area is covered in a mix of Quaternary (*Q*) coarse aquifer, aquifer, marginal, and non-aquifer materials with a small area of Tertiary Ogallala Group (*To*) in the south along Line 1003601. Bedrock is Cretaceous Niobrara Formation (*Kn*) over most of the area and Cretaceous Carlile Shale (*Kc*) in the northeast corner of area. CSD test holes and NE-DNR registered wells are indicated on the plot. V.E. = 10x.

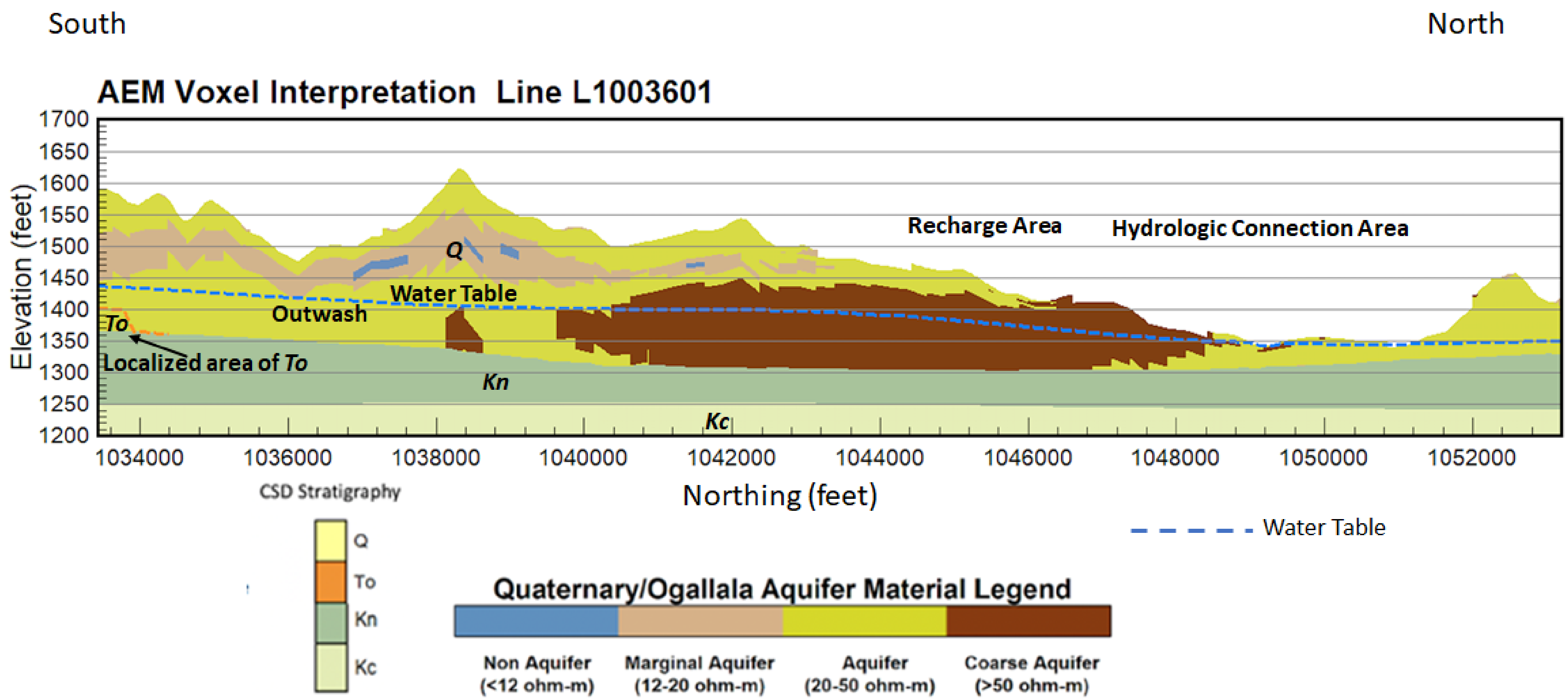


Figure 3-216. Profile of the east-west line L1003601 in the Obert Block showing the AEM interpretation. The CSD 1995 water table is indicated as a dashed blue line on the profiles. Note the intermittent isolated nature of the Quaternary (*Q*) coarse aquifer and aquifer materials which do not have a hydrologic connection to the surface water until Northing 1048000. Note the small area of *To* in the south. Horizontal datum is NAD83 State Plane Nebraska (feet).

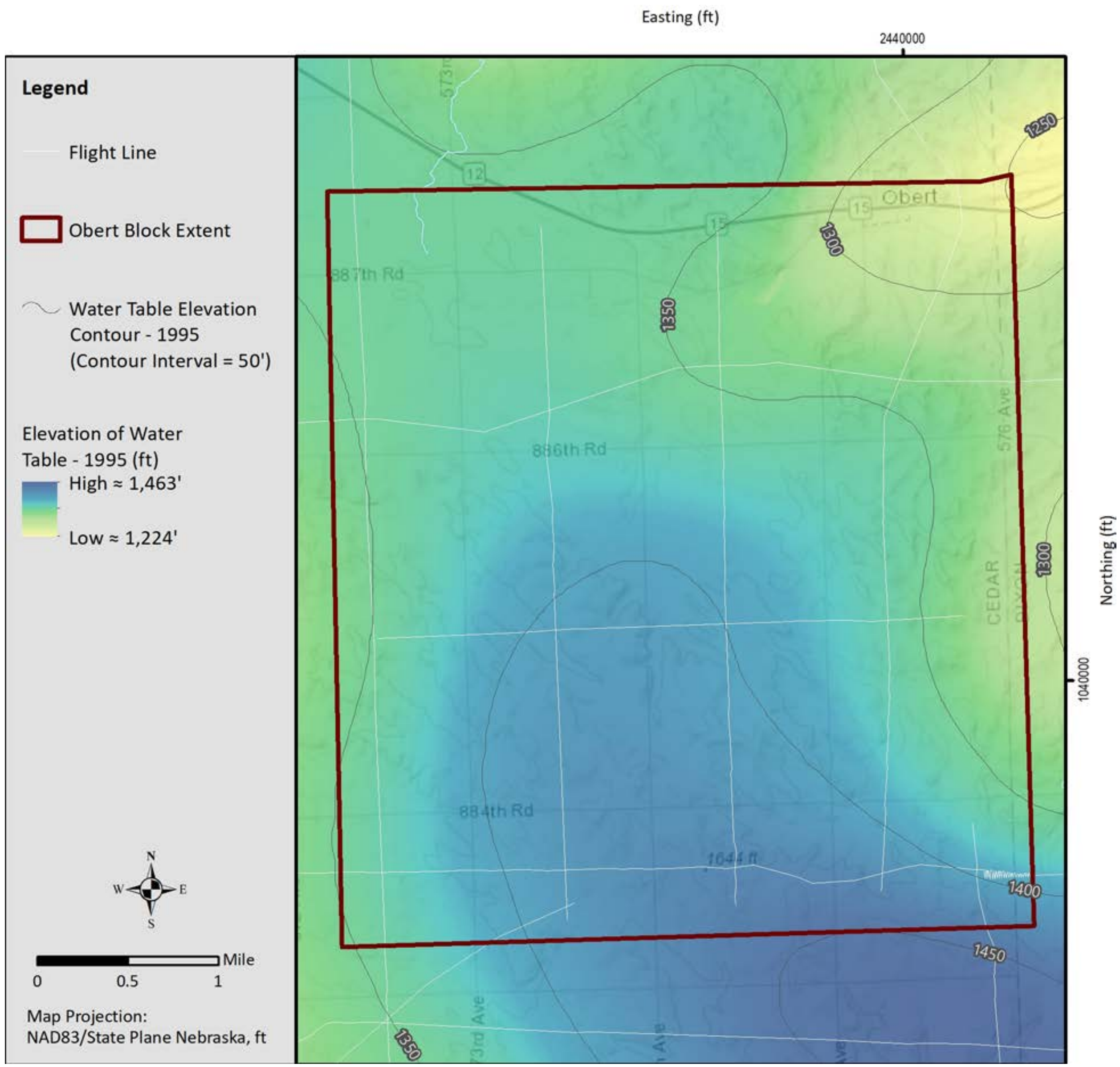


Figure 3-217. Map of the CSD 1995 water table within the 2018 Obert Block AEM survey area. Block flight lines are indicated by white lines.

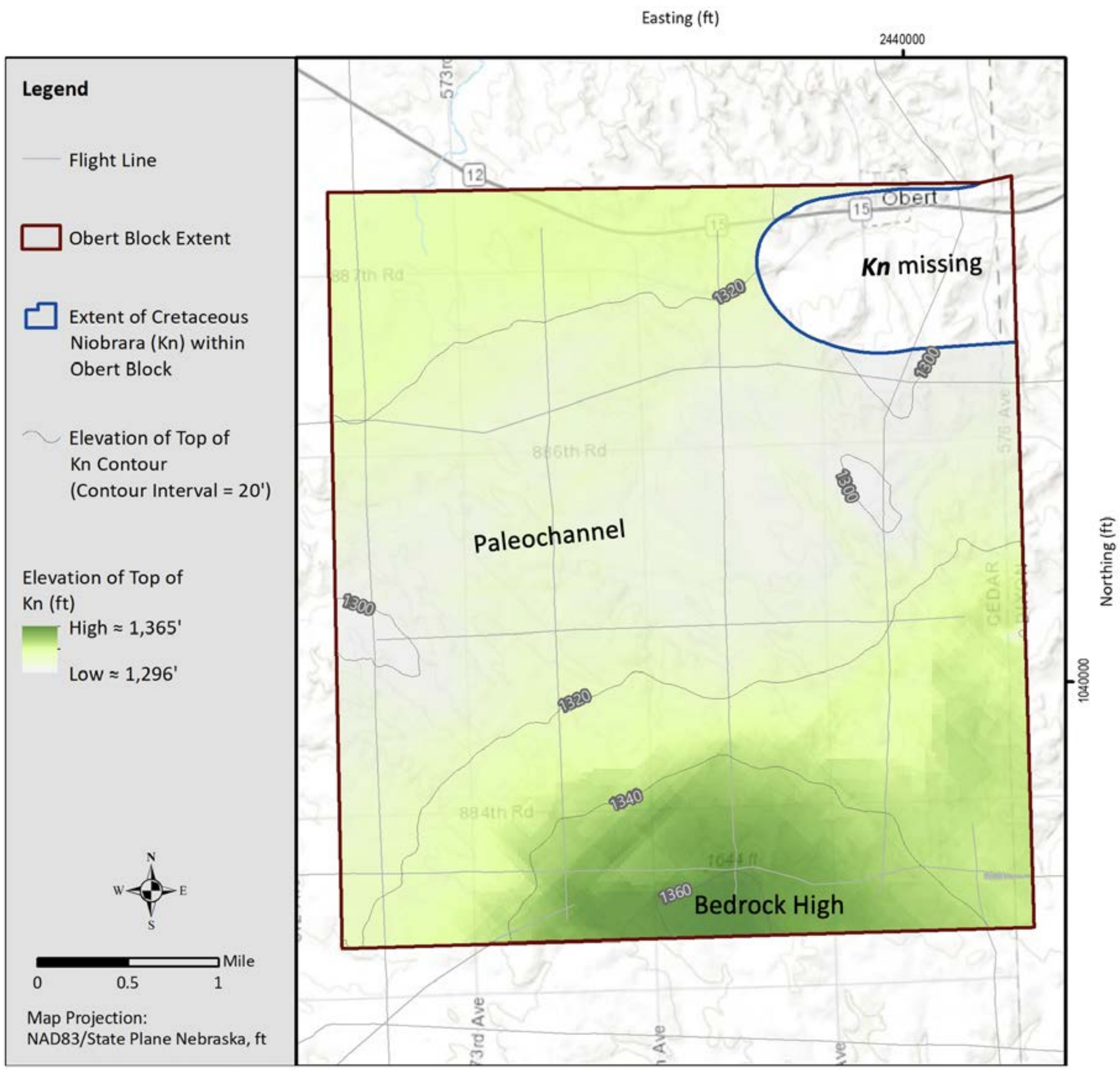


Figure 3-218. Map of the Cretaceous Niobrara Formation (*Kn*) bedrock surface elevation within the Obert Block AEM survey area. Flight lines are indicated by white lines. Note the bedrock channel trending east-west and the bedrock high to each side. In the northeast corner the Kn is eroded off and the bedrock is Cretaceous Carlile (*Kc*).

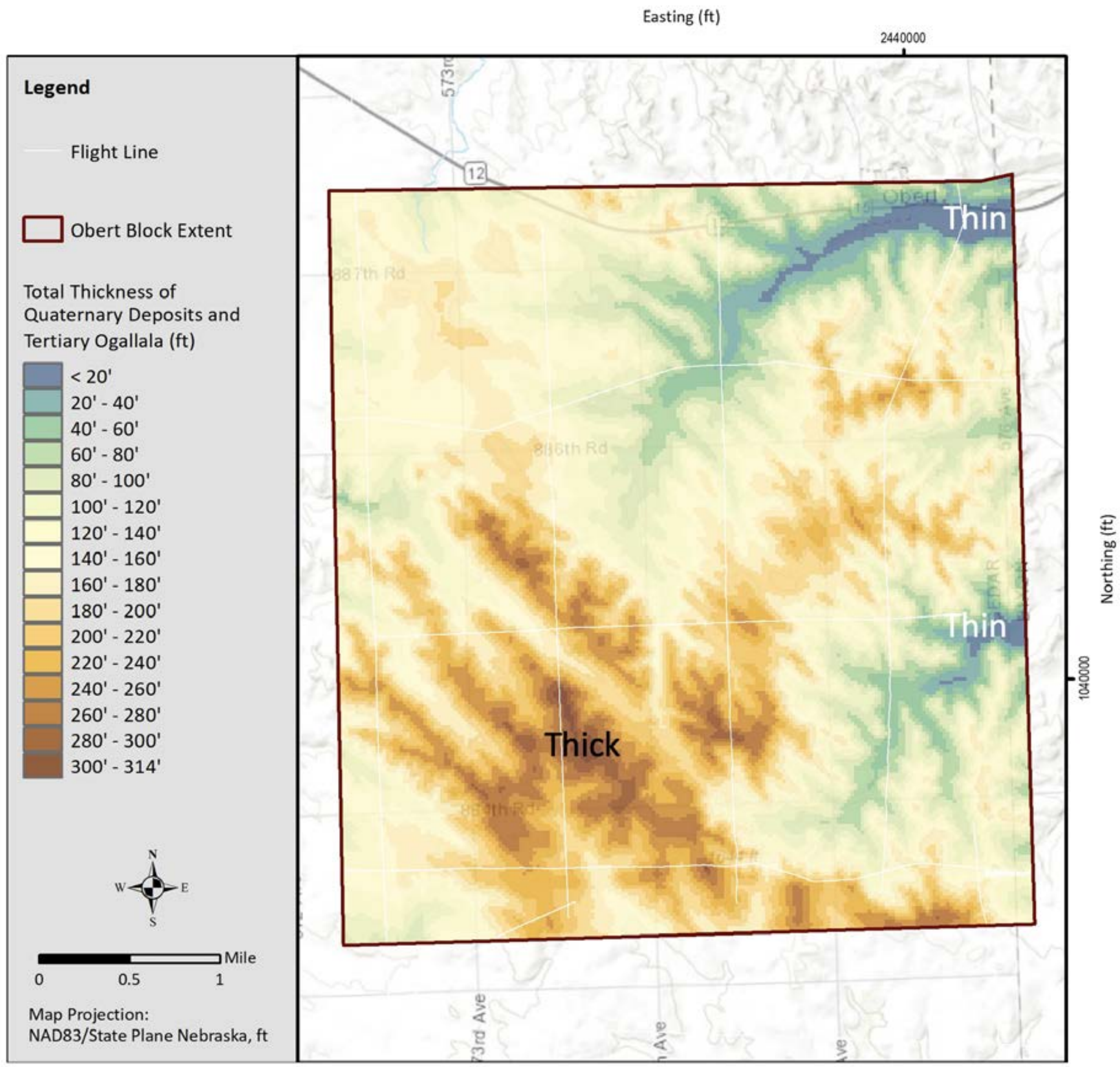


Figure 3-219. Map of the total thickness of the Quaternary (*Q*) and Tertiary Ogallala Group (*To*) comprised of all aquifer materials within the Obert Block AEM survey area. *Q* and *To* aquifer materials include coarse aquifer, aquifer, marginal aquifer, and non-aquifer materials. Note there is a hydrologic connection to surface water in the northeast. Block flight lines are indicated by white lines.

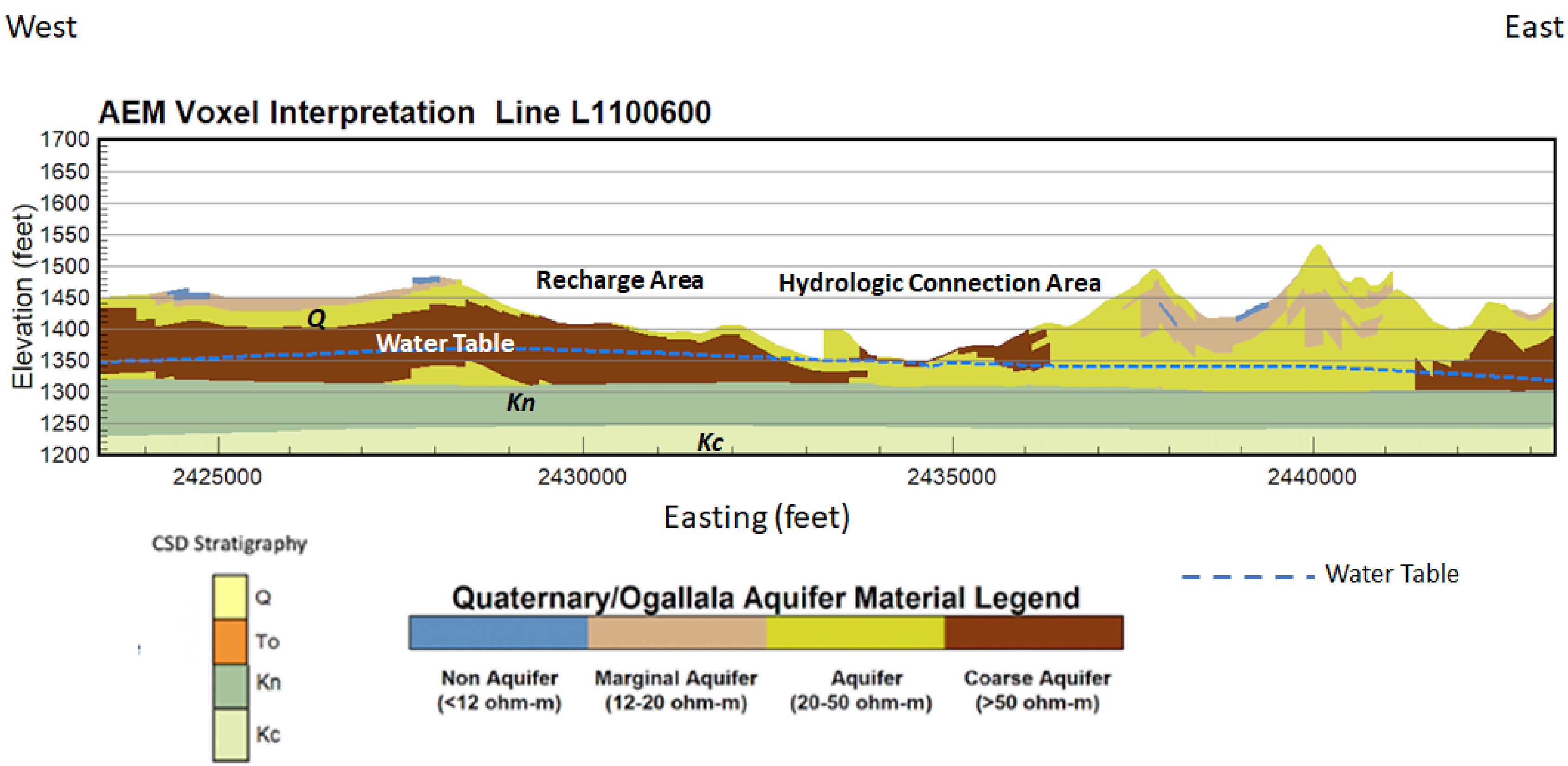


Figure 3-220. Profile of the east-west line L1100600 in the Obert Block showing the AEM interpretation. The CSD 1995 water table is indicated as a dashed blue line on the profiles. Note the intermittent isolated nature of the Quaternary (*Q*) and Tertiary Ogallala Group (*To*) aquifer materials and a hydrologic connection to surface water near easting 2435000. Horizontal datum is NAD83 State Plane Nebraska (feet).

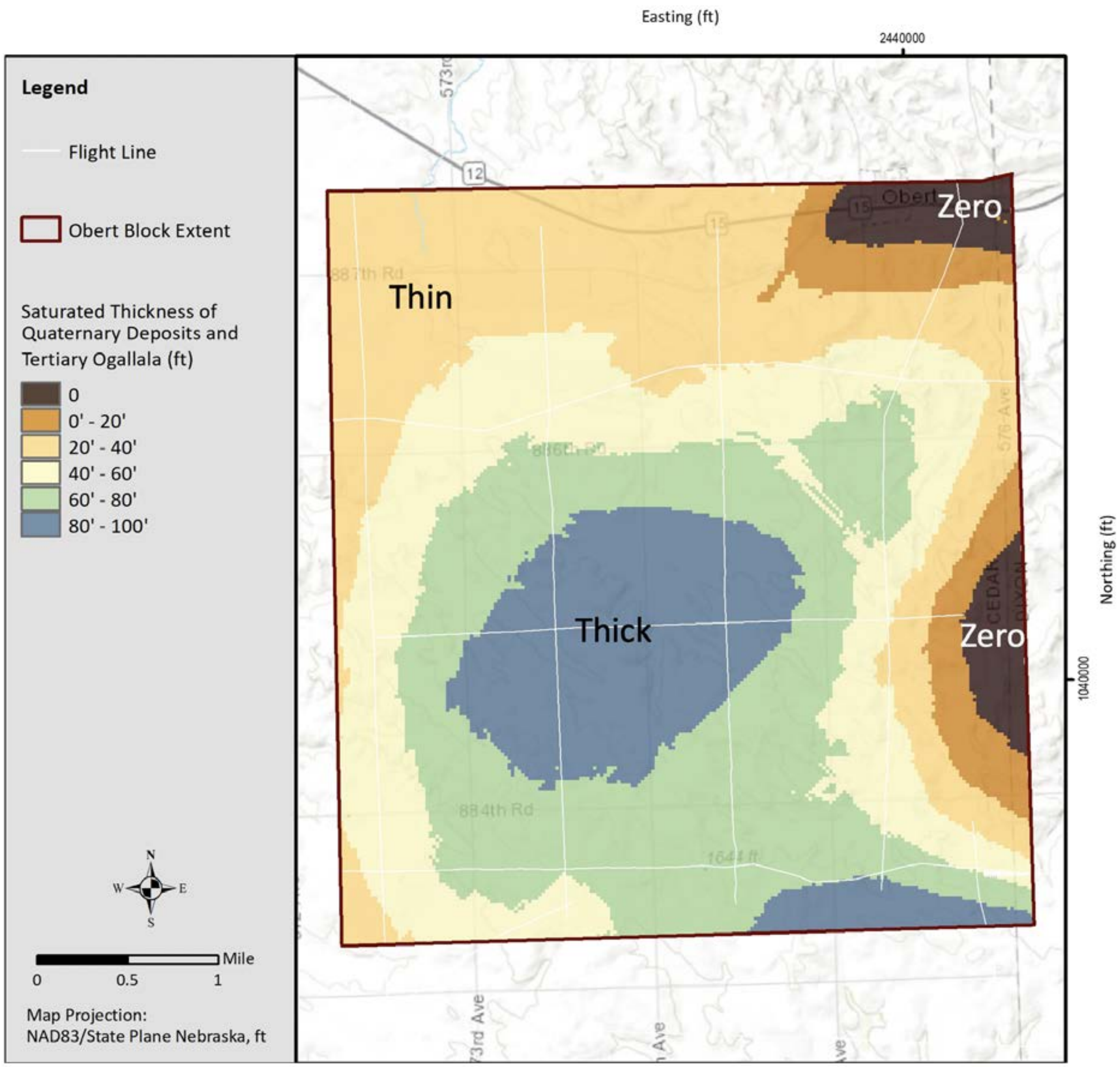


Figure 3-221. Map of the saturated thickness of the Quaternary (*Q*) and Tertiary Ogallala Group (*To*) aquifer materials within the Obert Block AEM survey area. Block flight lines are indicated by the white lines. Note the lack of saturated *Q* and *To* materials in the east part of the area.

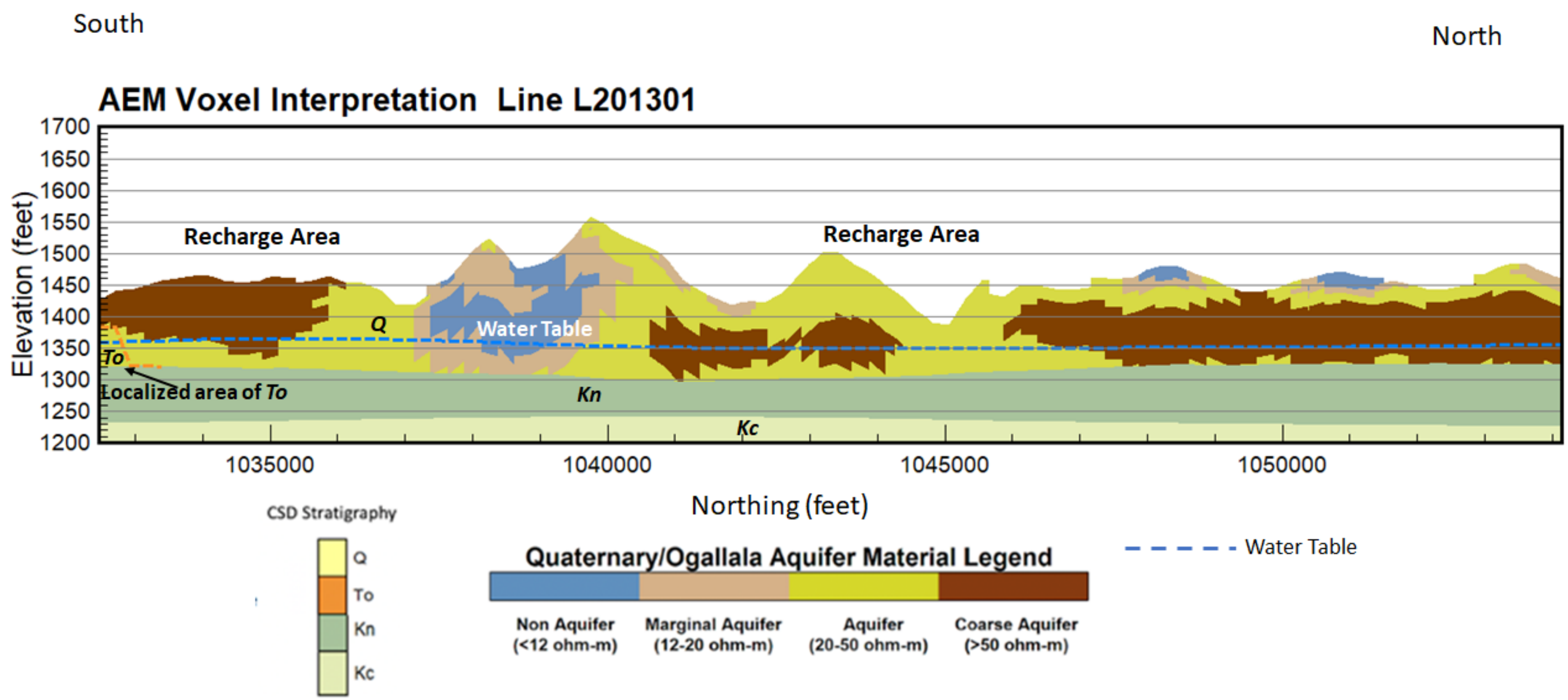


Figure 3-222. Profile of the north-south line L201301 in the Obert Block showing the AEM interpretation of the Quaternary (*Q*) and Tertiary Ogallala Group (*To*) (seen in south part) aquifer materials. Note the multiple *Q* aquifer material outwash deposits across the profile. There is no hydrologic connection to surface water. There are multiple recharge areas along the line. CSD 1995 water table is indicated as a dashed blue line. Horizontal datum is NAD83 State Plane Nebraska (feet).

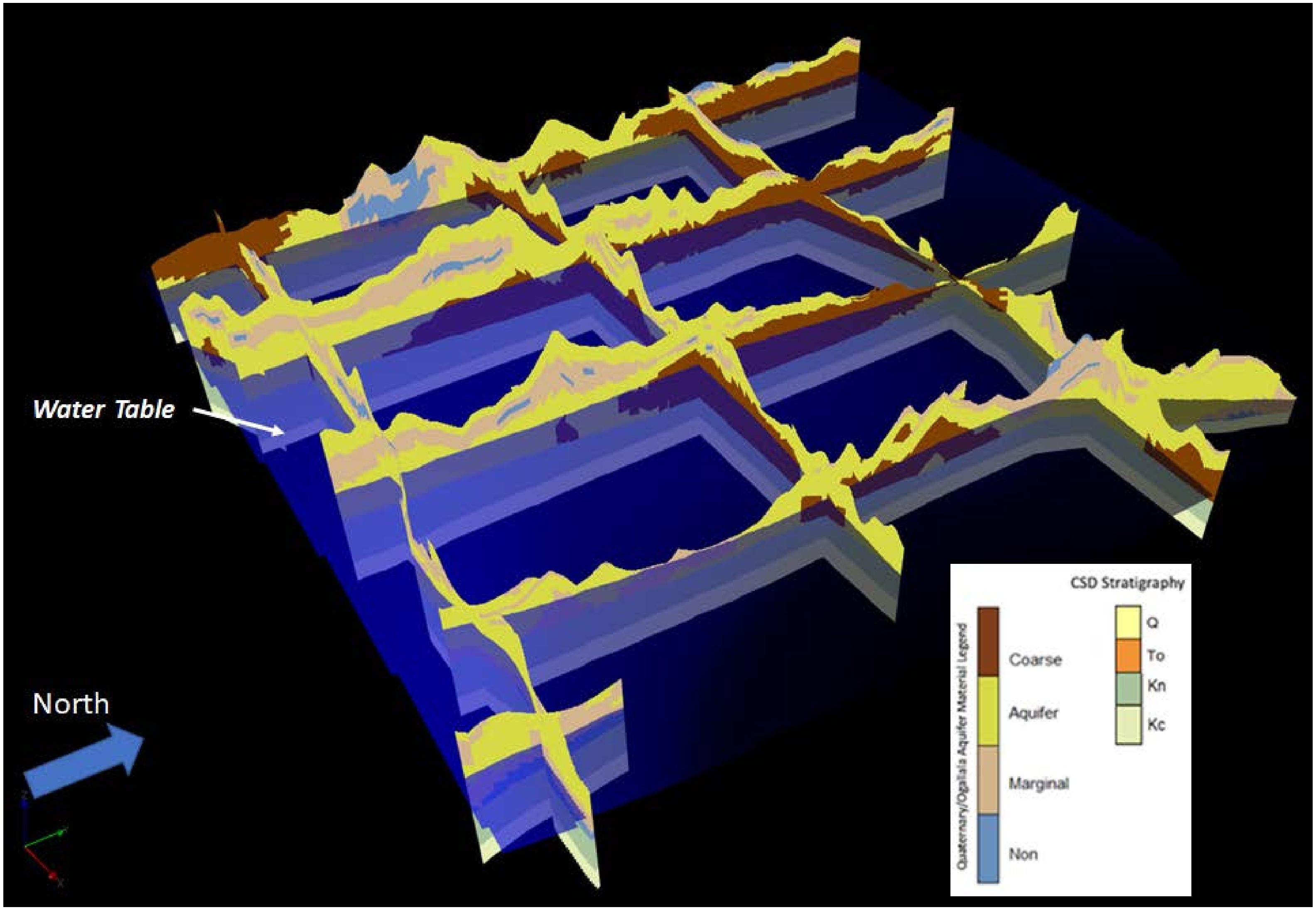


Figure 3-223. 3D fence diagram of interpreted AEM hydrostratigraphic profiles within the Obert Block AEM survey area. Note the majority of the area is covered in a mix of Quaternary (*Q*) coarse aquifer, aquifer, marginal, and non-aquifer materials with a small area of Tertiary Ogallala Group (*To*) in the south. The CSD 1995 water table is shown as a blue surface. CSD test holes and NE-DNR registered wells are indicated on the plot. V.E. = 10x.

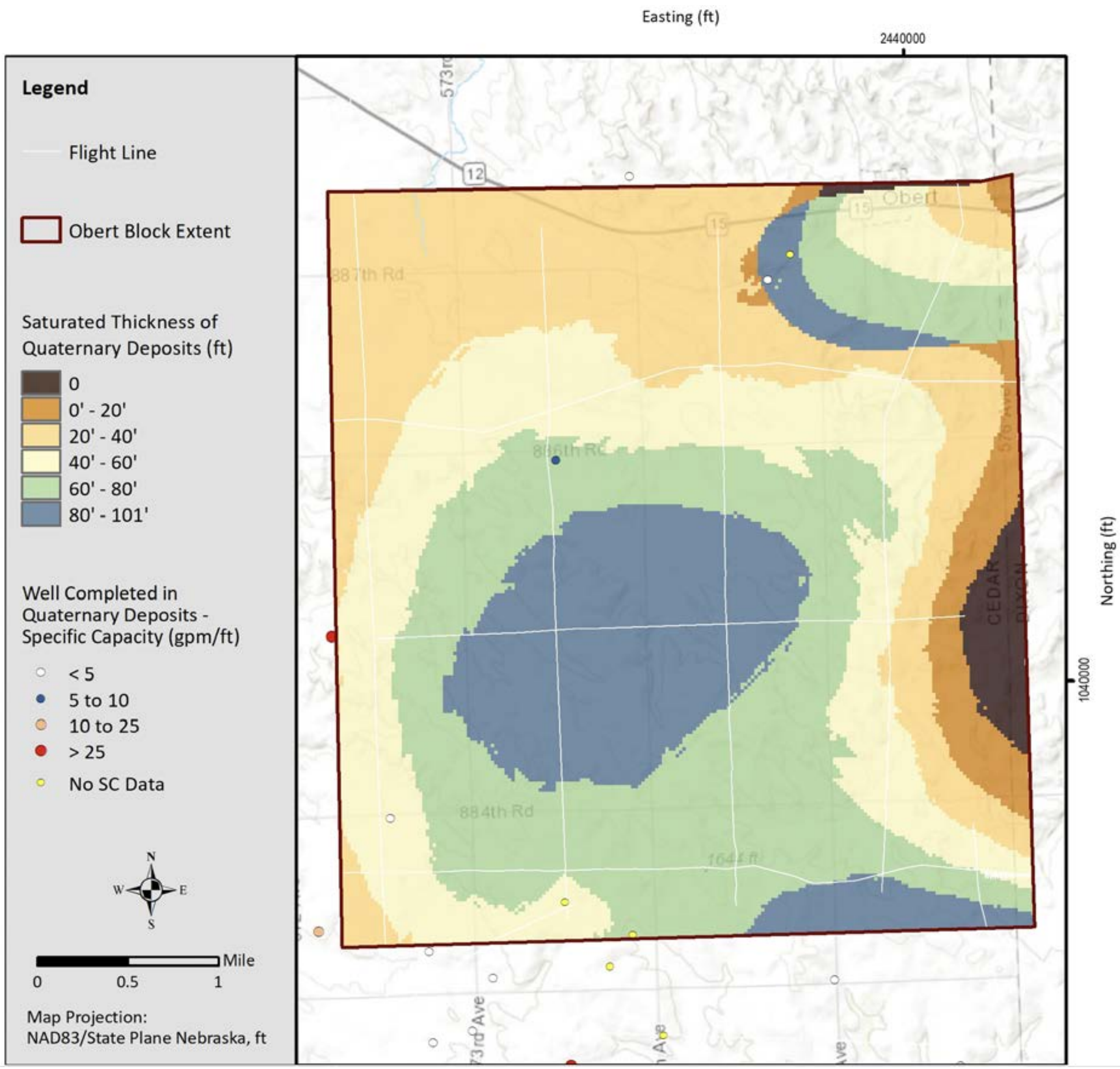


Figure 3-224. Map of the saturated thickness of the Quaternary (*Q*) and Tertiary Ogallala Group (*To*) deposits in the Obert Block related to the specific capacity of the wells screened within them. Note the one high capacity well in the west central part of the area. Block flight lines are indicated by the white lines.

3.2.8 Hydrogeologic Framework of the Santee Block AEM Survey Area

The AEM provided insight into the geographic distribution and extent of the unconsolidated ***Q*** and ***To*** in the Santee Block AEM survey area. The ***Q*** materials within the Santee Block are composed of unconsolidated alluvial silt, sand, and gravel as well as loess and glacial till and outwash that overlie the ***To*** fluvial deposits made up of all aquifer materials seen in the ***Q***. The ***Q*** and ***To*** material in the Santee Block AEM survey area is identified through interpretation of the AEM data as non-aquifer (blue), marginal aquifer (tan), aquifer material (yellow), and coarse aquifer material (brown) as discussed in Section 3.1.6. Generally, the flight block is located near Bazile Creek near highway 12 (Figure 3-225).

Figure 3-226 displays a 3D fence diagram, looking to the north, of the interpreted hydrostratigraphic profiles with CSD and NE-DNR borehole lithology data. The area generally contains minor amounts of a mix of all ***Q*** aquifer materials lying upon the ***Kp*** bedrock on the hill tops and ***Kn*** in the creek valley with the ***Kn*** lying on the ***Kc***. The boreholes in the area indicate a thin mix of silty clay, sandy clay, and sand and gravel in the block area but is mostly bedrock material. As can be seen on Figure 3-226, the block area is lightly covered in glacial till/loess and glacial outwash and is a mix of all aquifer materials. The presence of coarse aquifer and aquifer materials across most of the area makes for good recharge across these areas because the permeability of these materials is high. Unfortunately, there is little thickness of the ***Q*** materials and it makes recharge negligible. However, the thin nature and no connection to the water table makes this area makes groundwater a difficult resource to find and develop.

Figure 3-227 presents the same information as the 3D fence diagram in Figure 3-226, but as a 3D voxel with a view to the southeast, of the interpreted AEM results within the Santee Block AEM survey area. Note that the majority of the area is covered in a thin mix of *Q* coarse aquifer, aquifer, marginal and non-aquifer materials*.* Bedrock is ***Kp*** and ***Kn*** over most of the area and ***Kc*** in the northeast corner of area. Figure 3-228 presents the same 3D voxel of the Santee Block AEM survey area as in Figure 3-227, but only showing the ***Q*** aquifer and coarse aquifer material and the bedrock units The view is to the southeast along Bazile Creek where the ***Kp*** has been eroded off.

Figure 3-229 presents profile L902001, located in the center of the Santee Block AEM survey area and oriented east-west. The CSD 1995 water table (NE-CSD, 1995) is on the profile and shows the change in water table elevation from the east and west sides of the line to the center near Bazile Creek. Changes in elevation from west (~1,480 feet) to bottom of Bazile Creek valley (~1,240 feet) to the east side (~1,520 feet). The water table is mostly in the bedrock and its' shape is similar to the change in topography. There is evidence along this profile of no hydrologic connection to surface water due to the depth to the water table and the water table in the bedrock. There are areas of good recharge to the outwash coarse aquifer and aquifer materials near easting 1042000 and the rest of the area has poor recharge because of a cover of marginal and non-aquifer materials but there is little ***Q*** thickness to saturate. The CSD 1995 water table is also on the profile Figure 3-230 shows the water table for the area.

Figure 3-231 is a map of the top of the bedrock, composed of ***Kp*** that indicates the presence of bedrock lows and highs across the area ranging from 1,220 to 1,518 feet. Parts of the area are covered with ***Q*** aquifer material, mostly on the hill tops. Bazile Creek is deeply eroded into the area and has cut through the ***Kp*** entire length and into the top of the ***Kn***. Figure 3-232 shows the top of the ***Kn*** bedrock in the area. The total thickness of the ***Q*** material in the Santee Block AEM survey area (Figure 3-233) was calculated by subtracting the bedrock elevation from the ground surface elevation. It is important to understand the distribution of the various ***Q*** aquifer materials in relation to their hydrologic connection to both the surface water. The saturated thickness map is shown in Figure 3-234 and generally, the water table is deep below the land surface or bounded by bedrock or marginal and non-aquifer materials which limits the connection to surface water, however a narrow deposit of aquifer materials in Bazile Creek allows minimal saturation and connection to surface water. There is hydrologic connection along the line L901901 in the creek sediments and there is a cap of ***Q*** aquifer materials to the west and east of the creek at the land surface (Figure 3-235). The aquifer and coarse aquifer materials provide the greatest connection for water movement through all of the ***Q*** aquifer materials present in the area. The ***Q*** aquifer and coarse aquifer materials generally are limited in thickness and are intermittent across the area.

Figure 3-236 is a 3D fence diagram with the water table surface. Note the water table has a gently sloping mound in the south that moves to lower elevation to the east-west and north. Figure 3-237 is a 3D voxel of the Santee Block AEM survey area showing only the ***Q*** aquifer and coarse aquifer material and the bedrock units, ***Kp*** and ***Kn***, and the water table as a surface. The view is to the southeast along Bazile Creek where the ***Kp*** has been eroded off.

Figure 3-238 shows an exploded view voxel showing the volumes of material for ***Q*** aquifer materials and ***Kp*** and ***Kn*** across the entire Menominee AEM survey block***.*** The ***Q*** aquifer and coarse aquifer materials being the main aquifers of the Block with ***Kp*** and ***Kn*** being an aquitard. Figure 3-239 shows an exploded view voxel showing the volumes of ***Q*** aquifer materials including coarse aquifer, aquifer, marginal aquifer and non-aquifer. Note the aquifer, marginal, and non-aquifer materials consist of ~90% of the ***Q*** volume with aquifer material next in total volume and coarse aquifer material being ~10% of the total. There are no registered wells in the area that can be used to calculate specific capacity.

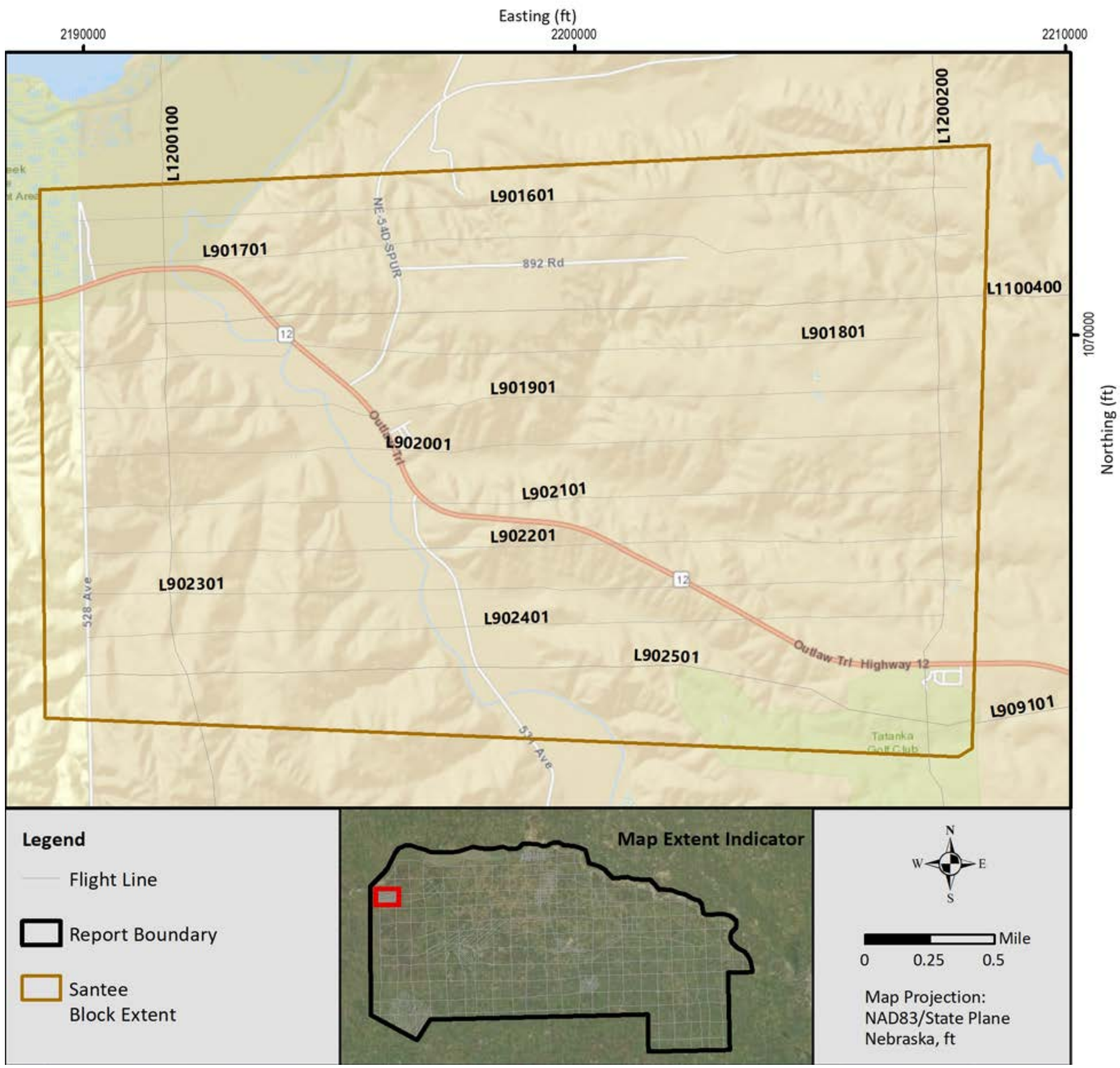


Figure 3-225. Location map of the Santee Block indicating AEM flight lines local roads.

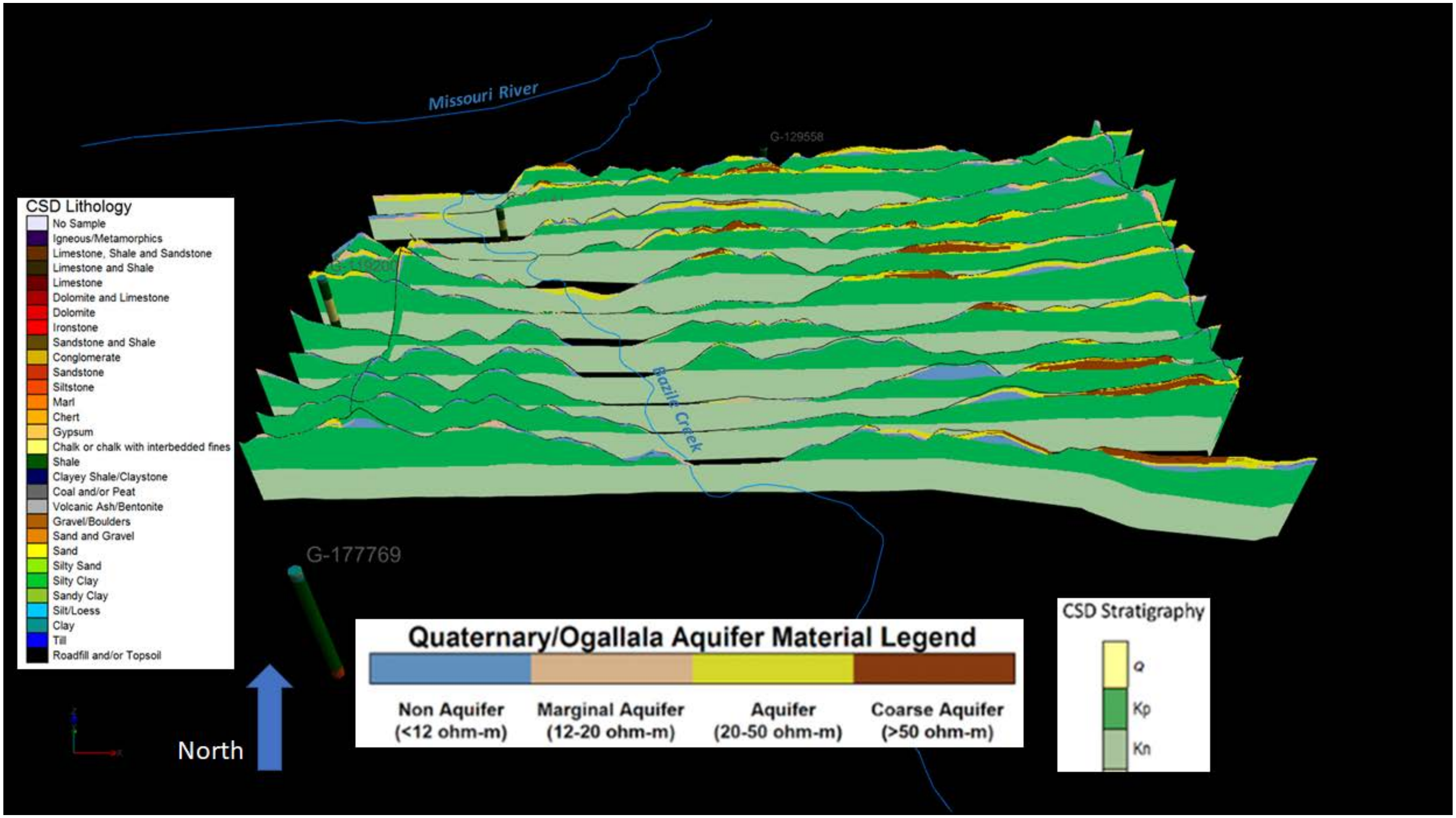


Figure 3-226. 3D fence diagram of interpreted AEM hydrostratigraphic profiles within the Santee Block AEM survey area include the *Q*= Quaternary, *Kp*= Cretaceous Pierre Shale, *Kn*=Cretaceous Niobrara Formation. Note the majority of the area is covered in a thin mix of Quaternary (*Q*) coarse aquifer, aquifer, marginal and non-aquifer materials. Bedrock is Cretaceous Pierre Shale (*Kp*) and Cretaceous Niobrara Formation (*Kn*) over most of the area and Cretaceous Carlile Shale (*Kc*) in the northeast corner of area. CSD test holes and NE-DNR registered wells are indicated on the plot. V.E. = 10x.

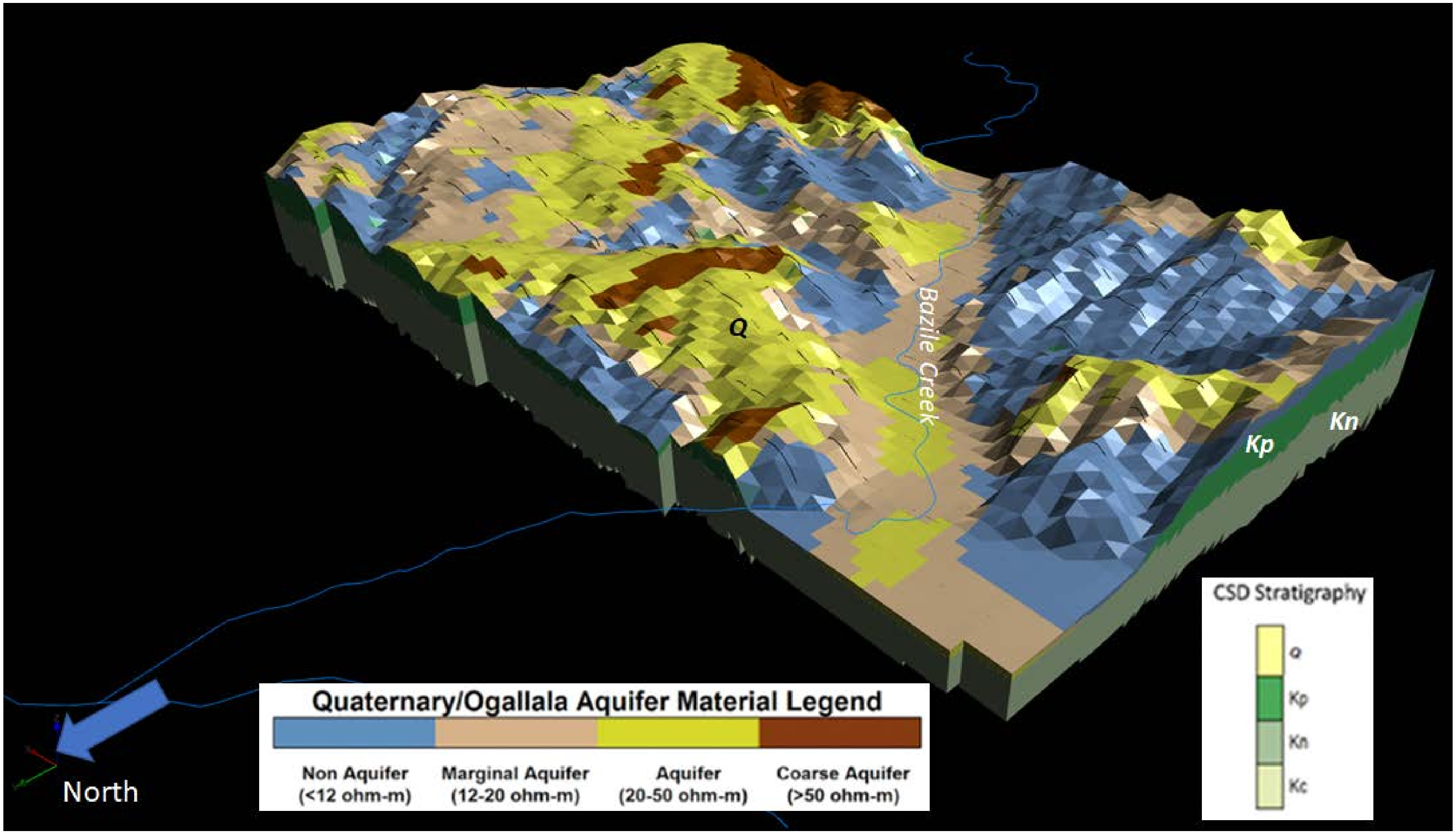


Figure 3-227. 3D voxel, with a view to the southeast, of interpreted AEM results within the Santee Block AEM survey area include the *Q*= Quaternary, *Kp*= Cretaceous Pierre Shale, *Kn*=Cretaceous Niobrara Formation. Note the majority of the area is covered in a thin mix of Quaternary (*Q*) coarse aquifer, aquifer, marginal and non-aquifer materials. Bedrock is Cretaceous Pierre Shale (*Kp*) and Cretaceous Niobrara Formation (*Kn*) over most of the area and Cretaceous Carlile Shale (*Kc*) in the northeast corner of area. V.E. = 10x

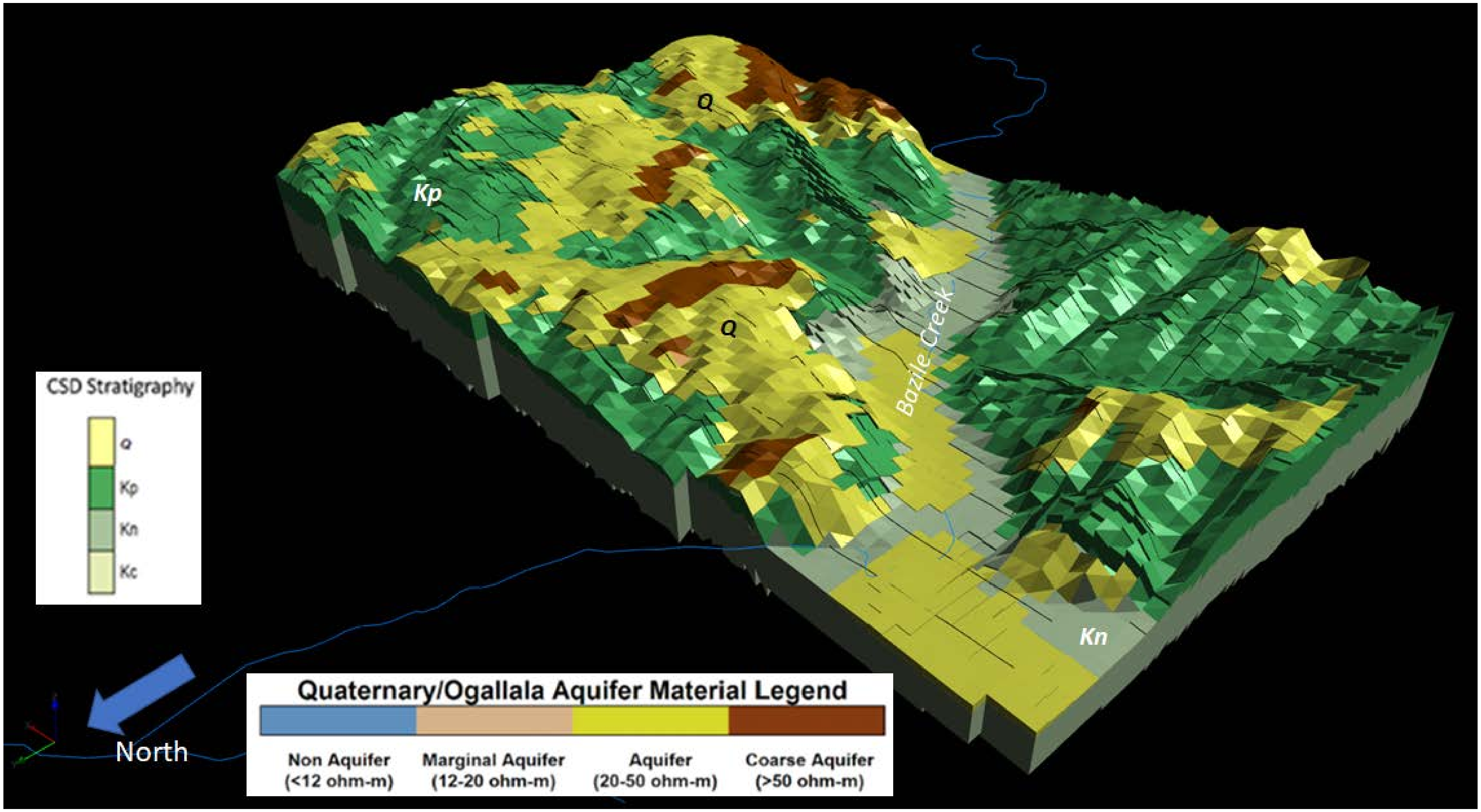


Figure 3-228. 3D voxel of the Santee Block AEM survey area, similar to Figure 3-227, but only showing the Quaternary (*Q*) aquifer and coarse aquifer material and the bedrock units, Cretaceous Pierre Shale (*Kp*) and Niobrara Shale (*Kn*). The view is to the southeast along Bazile Creek where the Cretaceous Pierre Shale (*Kp*) has been eroded off. V.E.=5x.

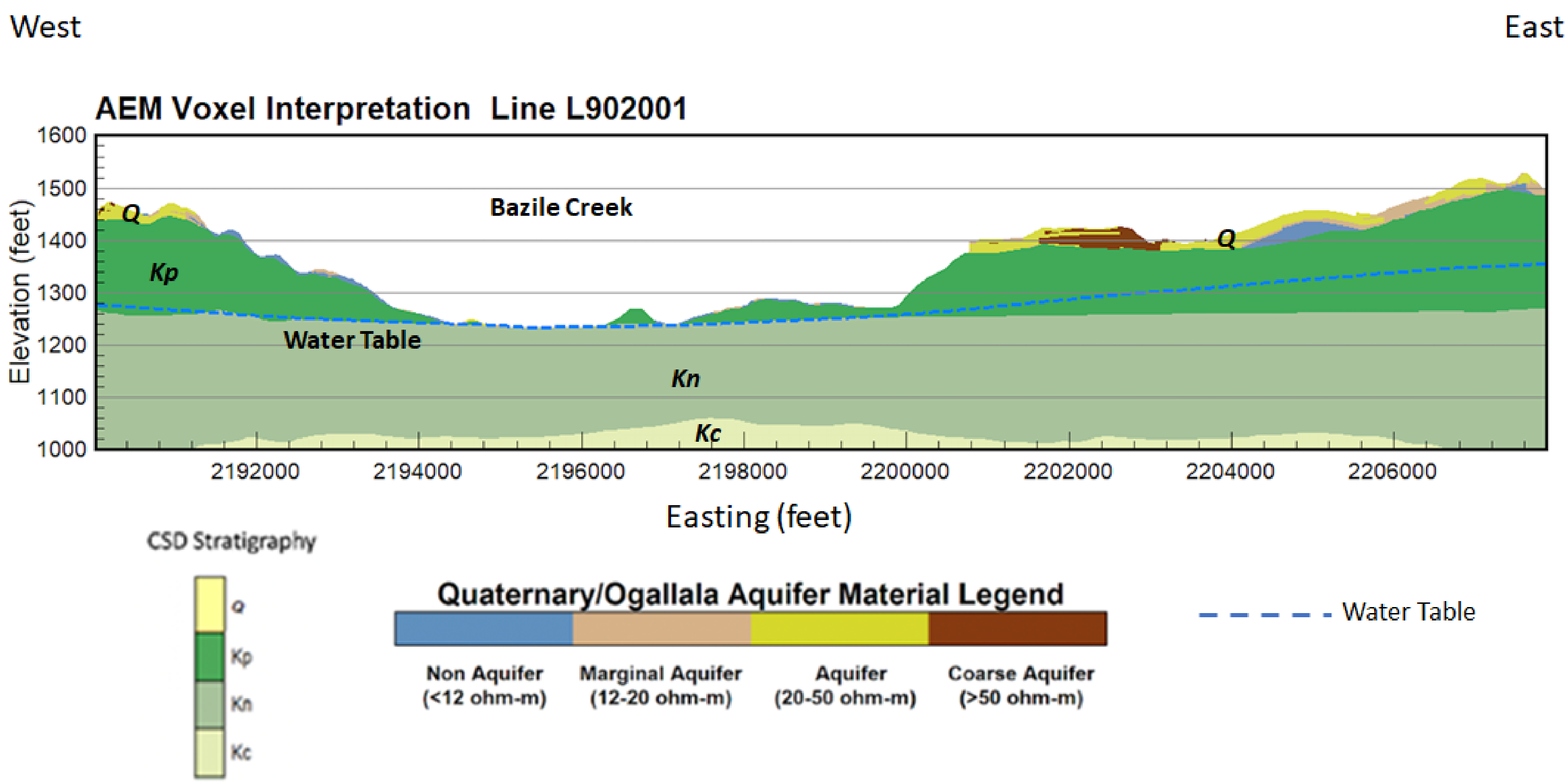


Figure 3-229. Profile of the east-west line L902001 in the Santee Block showing the AEM interpretation. The CSD 1995 water table is indicated as a dashed blue line on the profiles. Note the intermittent isolated nature of the Quaternary (*Q*) aquifer materials which do not have a hydrologic connection to the surface water. Horizontal datum is NAD83 State Plane Nebraska (feet).

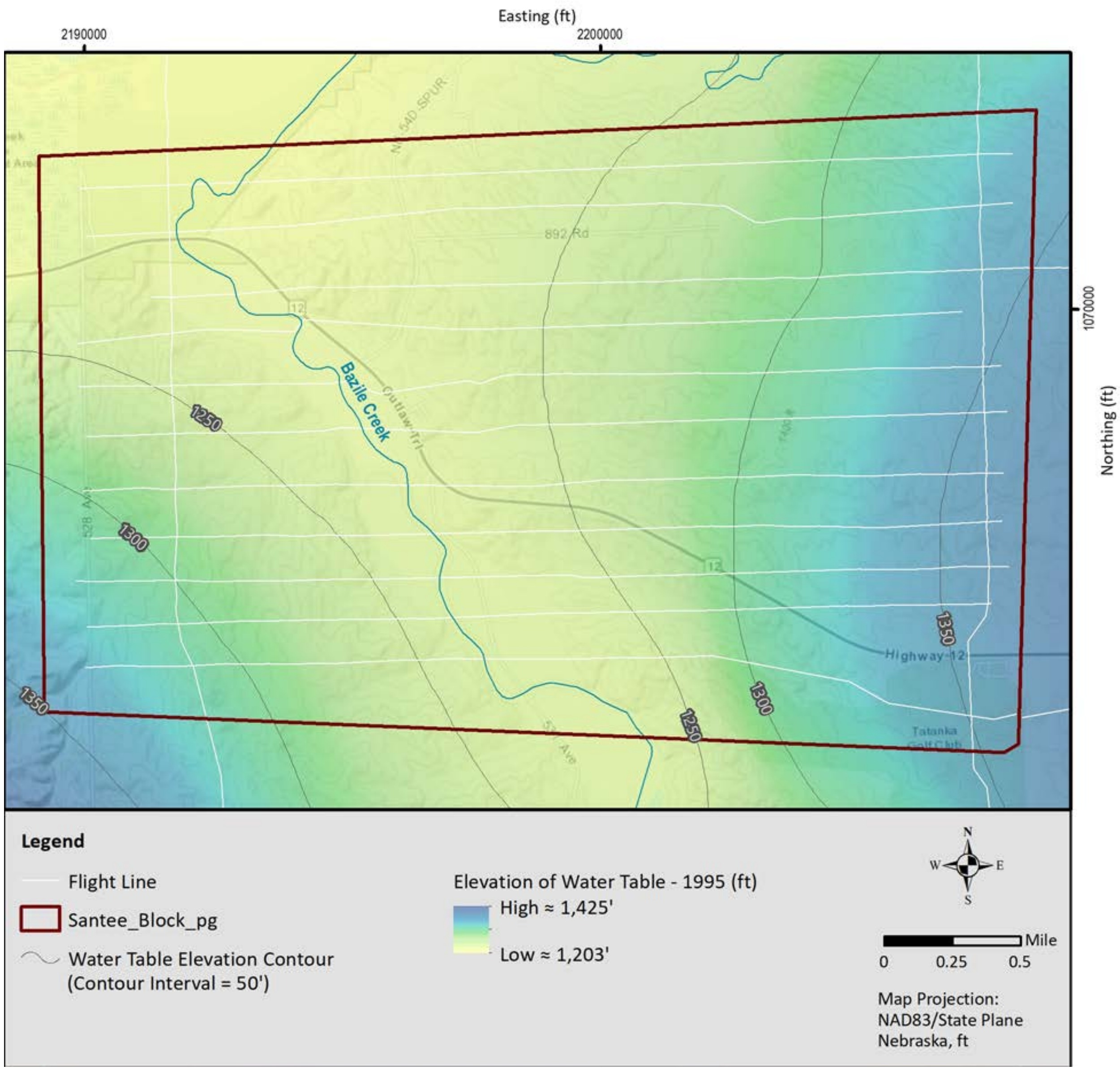


Figure 3-230. Map of the CSD 1995 water table within the 2018 Santee Block AEM survey area. Block flight lines are indicated by white lines.

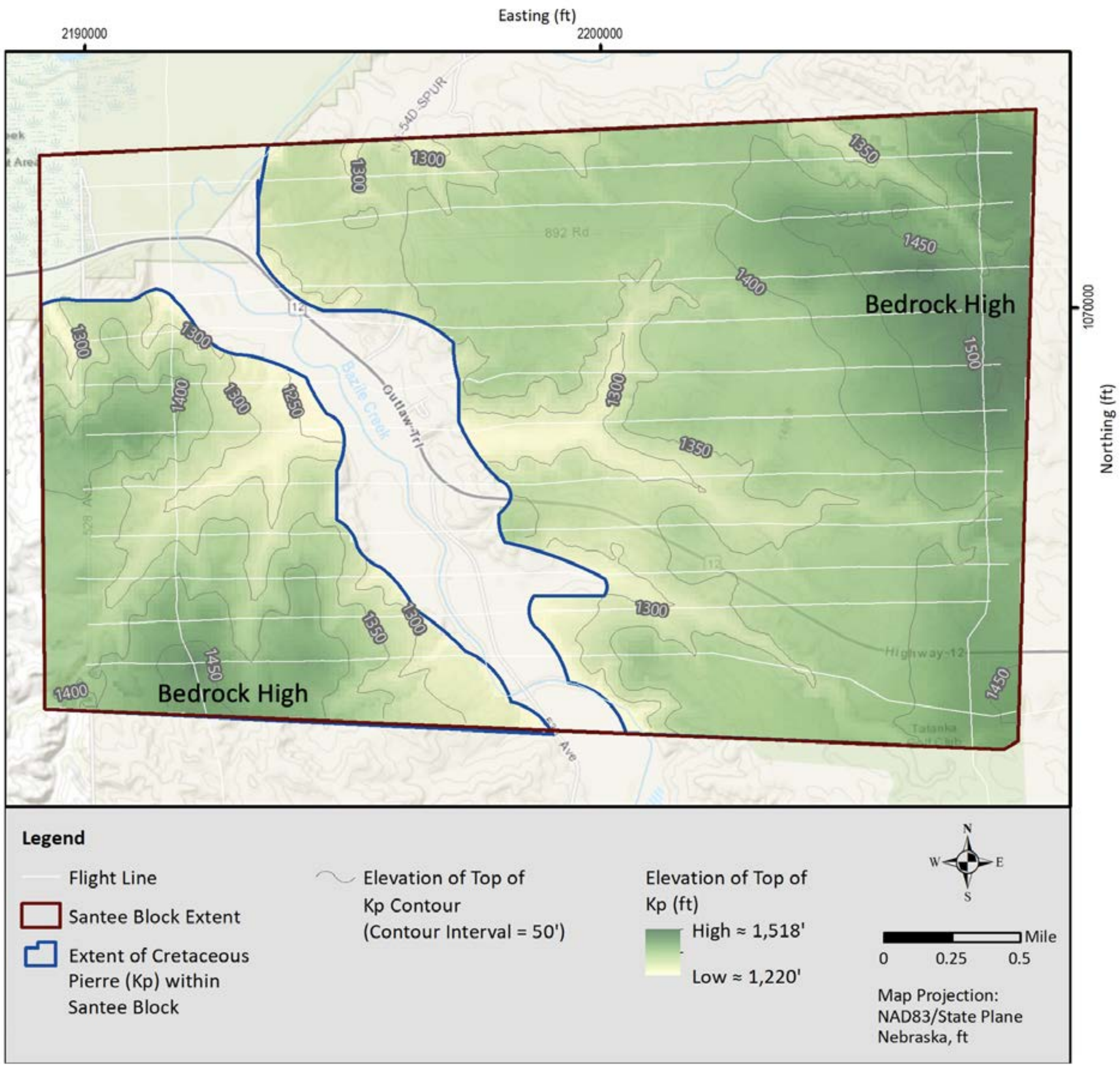


Figure 3-231. Map of the Cretaceous Pierre Shale (*Kp*) bedrock surface elevation within the Santee Block AEM survey area. Flight lines are indicated by white lines. Note Bazile Creek has completely cut through the *Kp* along its route.

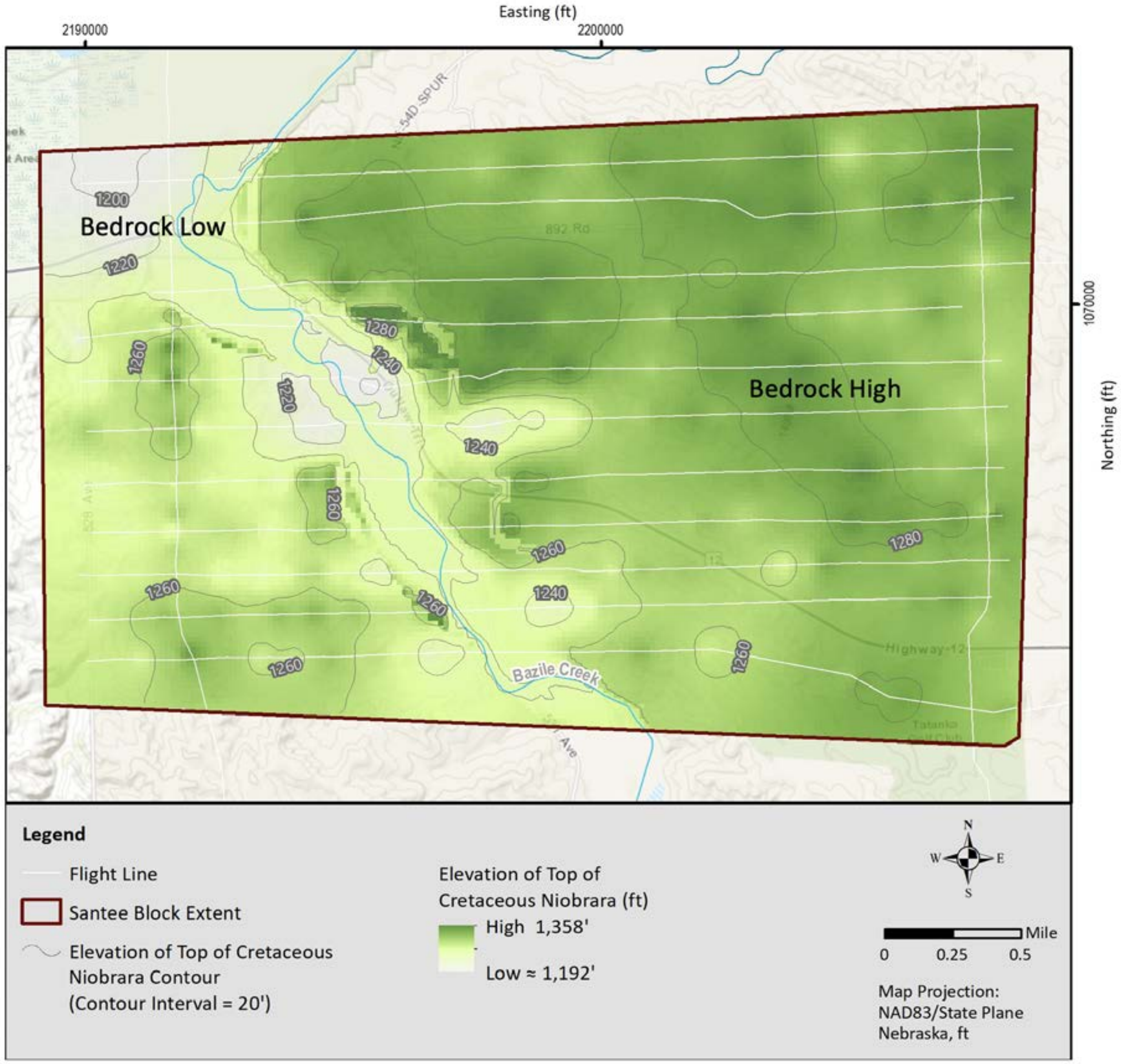


Figure 3-232. Map of the Cretaceous Niobrara Formation (*Kn*) bedrock surface elevation within the Santee Block AEM survey area. Flight lines are indicated by white lines. Note Bazile Creek has eroded into the *Kn* creating a bedrock channel trending east-west and bedrock highs on each side.

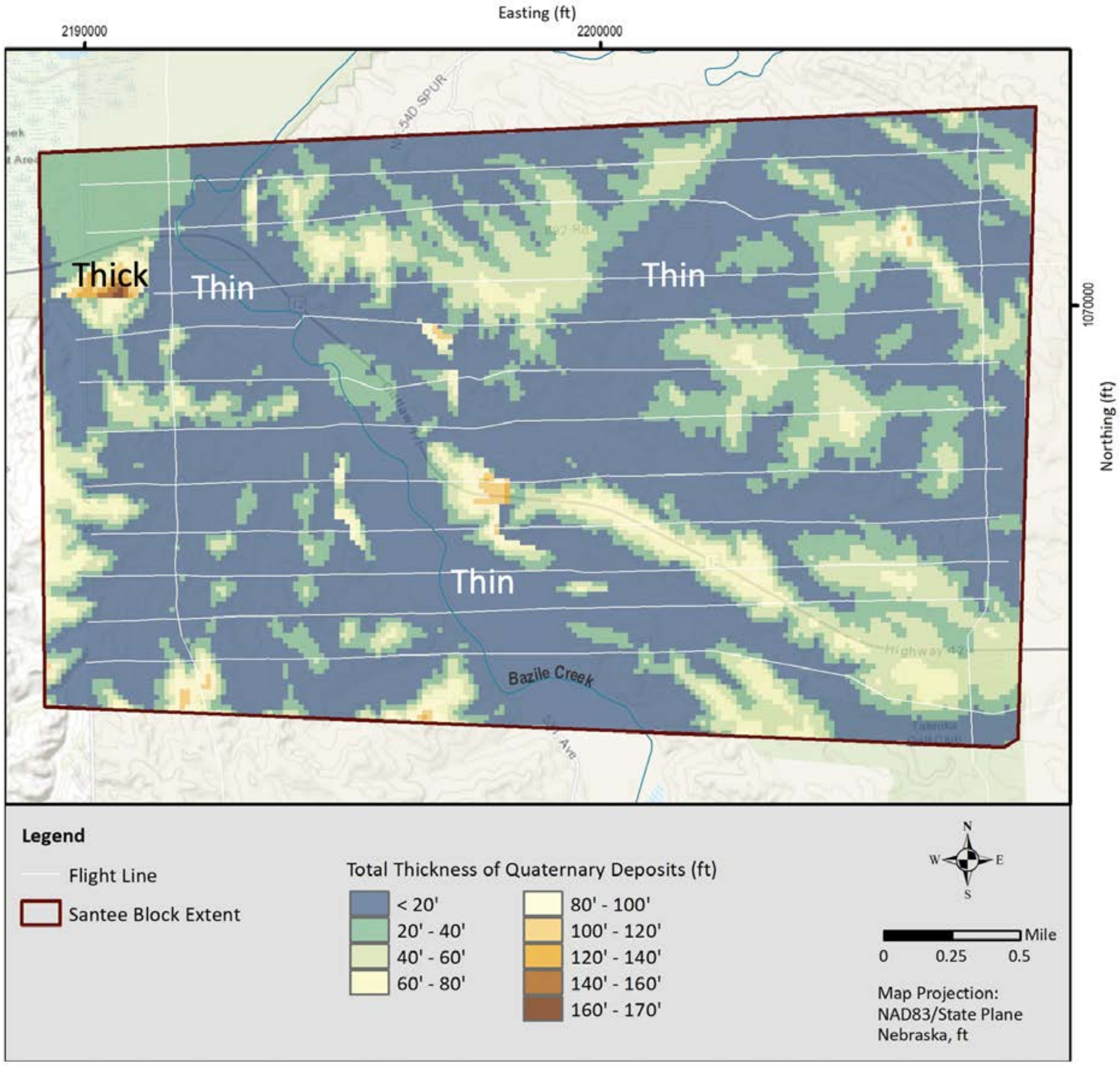


Figure 3-233. Map of the total thickness of the Quaternary (*Q*) comprised of all aquifer materials within the Santee Block AEM survey area. *Q* aquifer materials include coarse aquifer, aquifer, marginal aquifer and non-aquifer materials. Block flight lines are indicated by white lines.

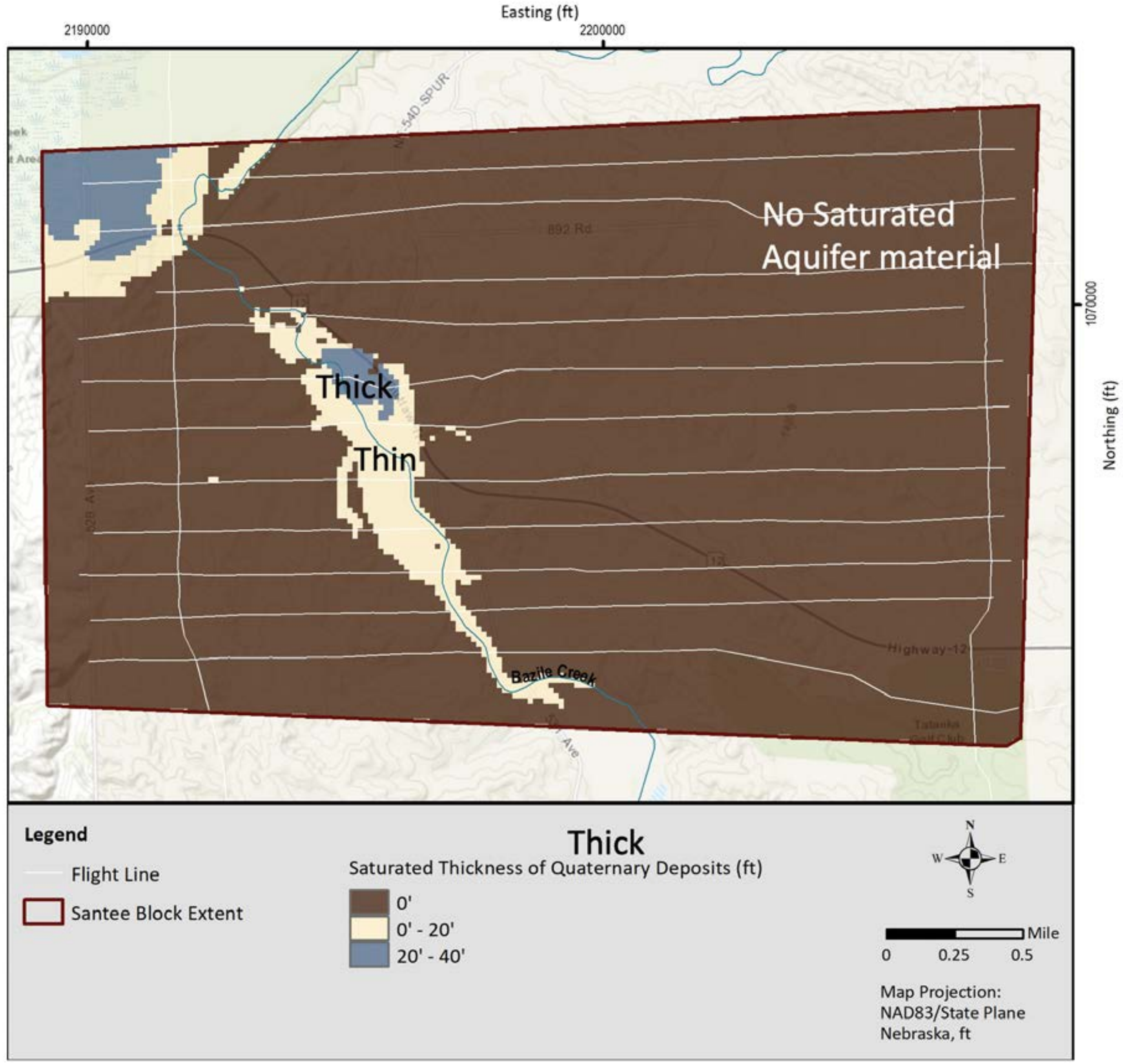


Figure 3-234. Map of the saturated thickness of the Quaternary (*Q*) aquifer materials within the Santee Block AEM survey area. Block flight lines are indicated by the white lines. Note the lack of saturated *Q* materials except along Bazile Creek (trending northwest-southeast) and the Missouri Flood Plain in the northwest corner.

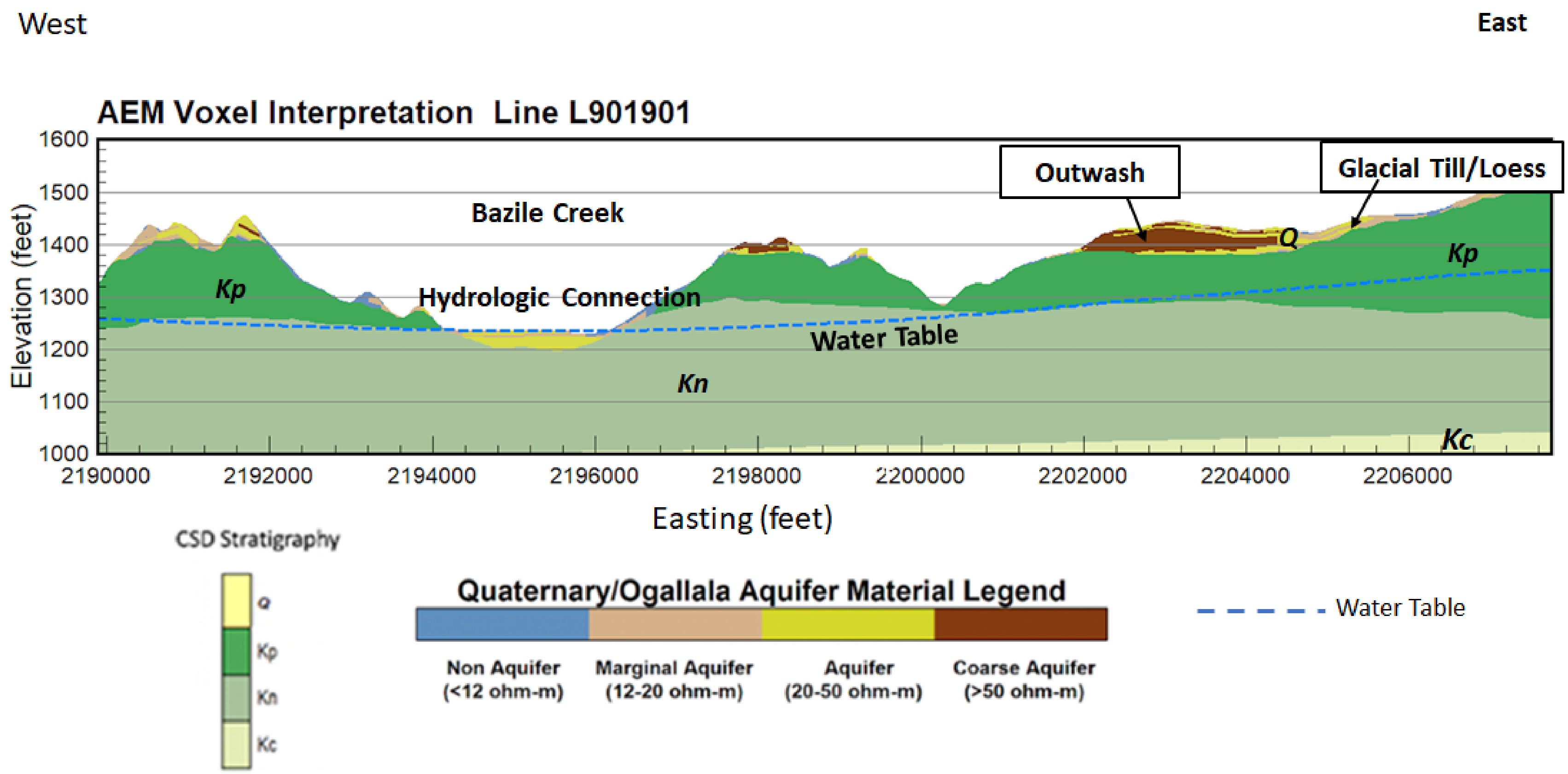


Figure 3-235. Profile of the east-west line L901901 in the Santee Block showing the AEM interpretation of the Quaternary (*Q*) aquifer materials and bedrock. Note the *Q* aquifer material outwash deposits on the east side the line that is unsaturated. There is hydrologic connection of the *Q* in Bazile Creek to surface water. There are multiple recharge areas along the line however there is little thickness of the *Q* material to saturate. CSD 1995 water table is indicated as a dashed blue line. Horizontal datum is NAD83 State Plane Nebraska (feet).

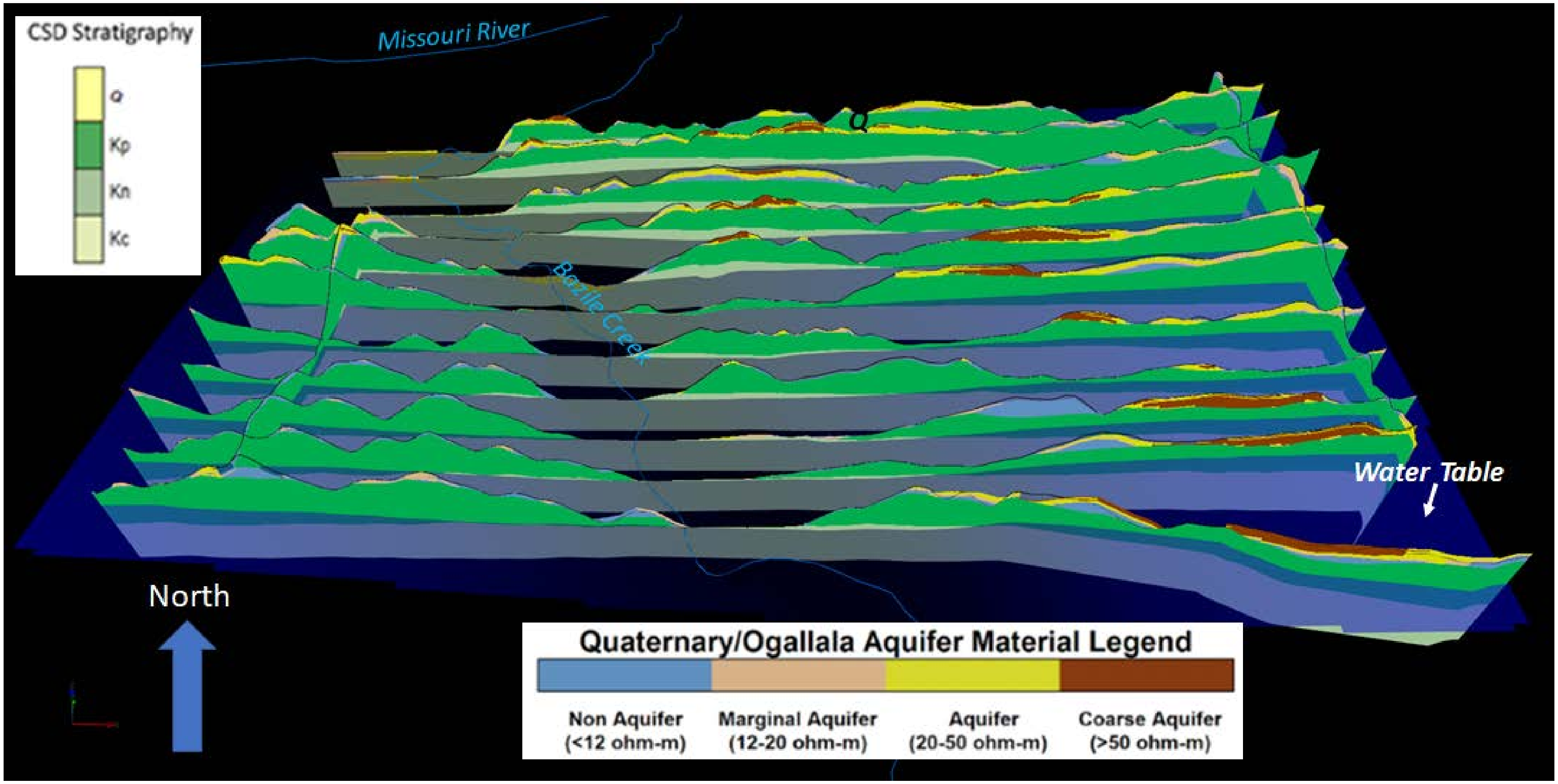


Figure 3-236. 3D fence diagram of interpreted AEM hydrostratigraphic profiles within the Santee Block AEM survey area. Note the majority of the area is covered in a thin mix of Quaternary (*Q*) coarse aquifer, aquifer, marginal, and non-aquifer materials. The water table is shown as a blue surface. CSD test holes and NE-DNR registered wells are indicated on the plot. V.E. = 10x.

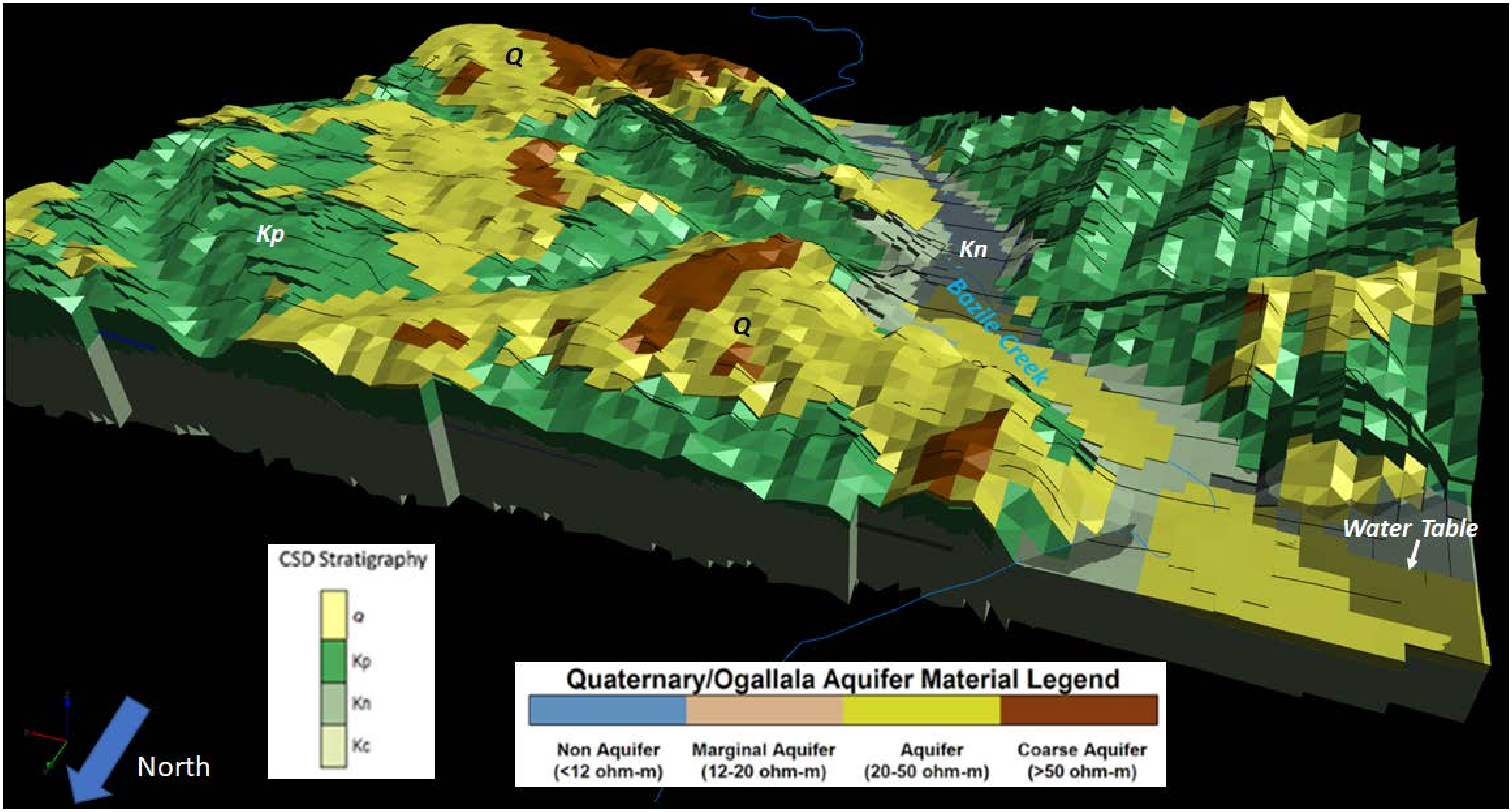


Figure 3-237. 3D voxel of the Santee Block AEM survey area showing only the Quaternary (*Q*) aquifer and coarse aquifer material and the bedrock units, Cretaceous Pierre Shale (*Kp*) and Niobrara Shale (*Kn*), and the water table as a surface. The view is to the southeast along Bazile Creek where the Cretaceous Pierre Shale (*Kp*) has been eroded off. V.E.=5x.

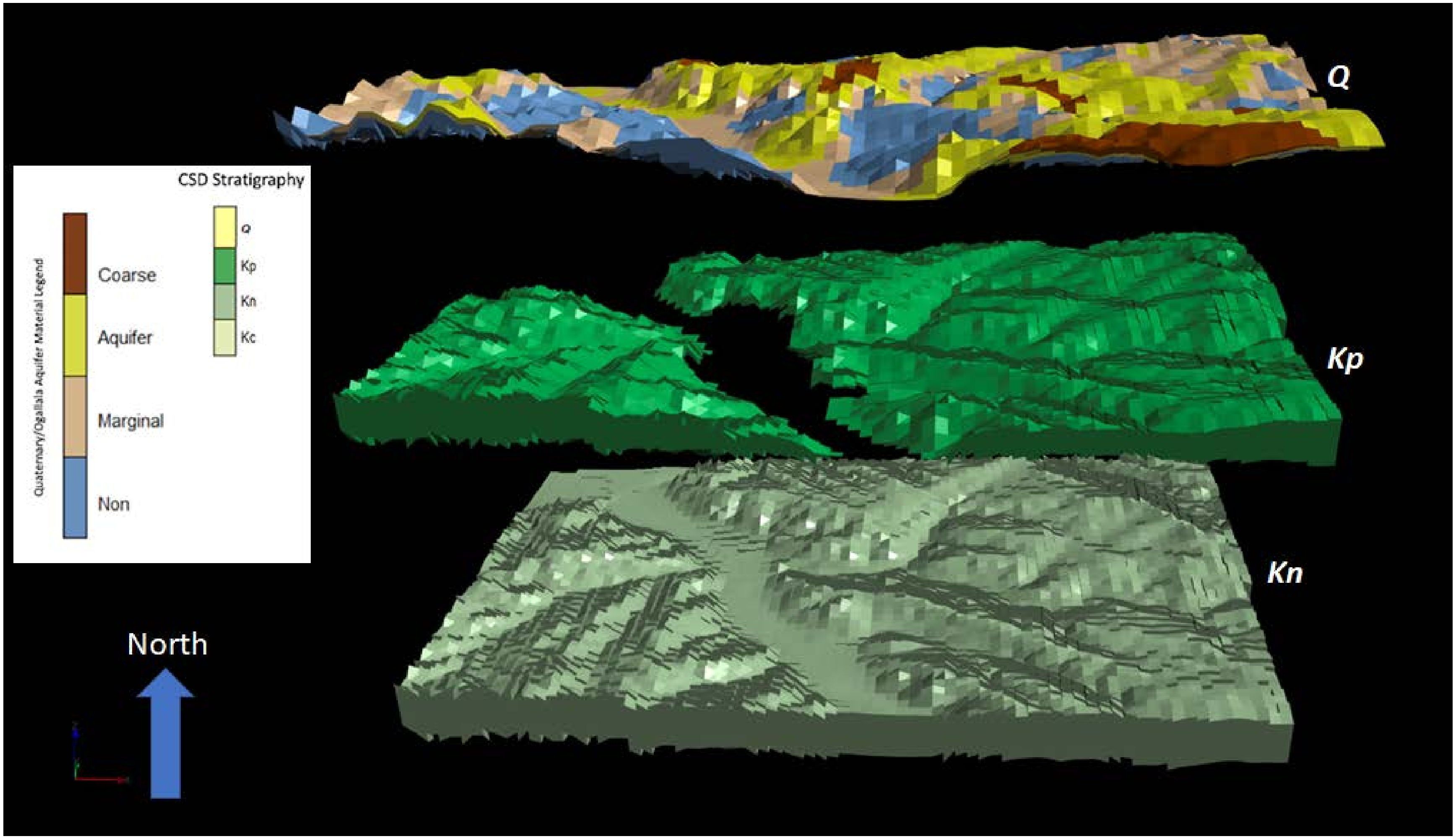


Figure 3-238. 3D 'exploded' voxel model of the Santee Block AEM survey area showing Quaternary (*Q*) and Cretaceous Pierre Shale (*Kp*) and Cretaceous Niobrara Shale (*Kn*) and Cretaceous Carlile Shale (*Kc*). V.E. =10x. Not to scale.

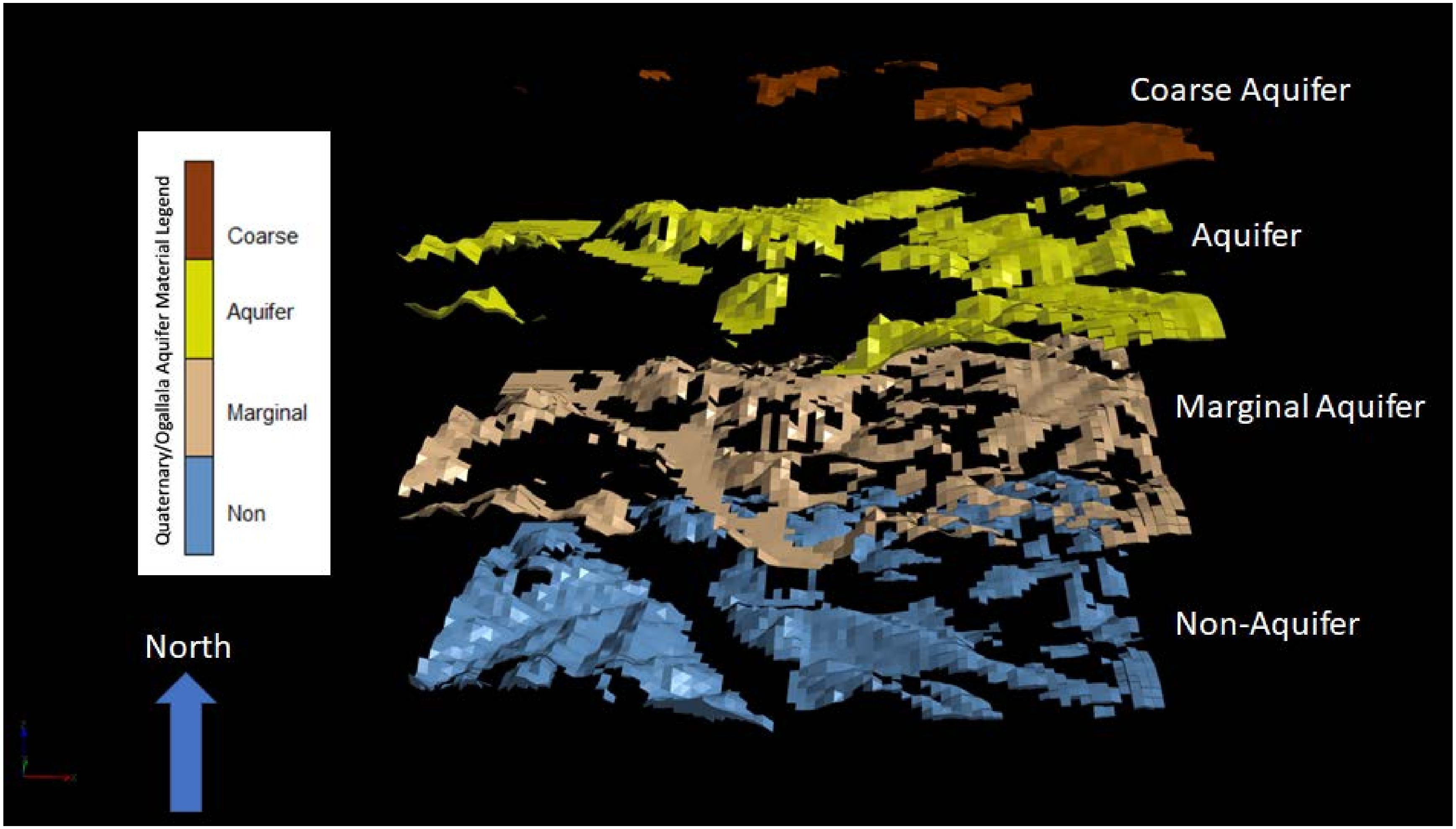


Figure 3-239. 3D 'exploded' voxel of the Quaternary (*Q*) aquifer materials present in the Santee Block AEM survey area. The dominant units are the non-aquifer (blue) and marginal aquifer (tan) materials with shallow and thin aquifer (yellow) materials and coarse (brown) aquifer materials. V.E. =10x. Not to scale.

3.2.9 Estimation of Aquifer Volume and Water in Storage for the LCNRD Reconnaissance AEM area and the Aten, Bloomfield, Harington, Menominee, and Santee AEM Block Areas

The 3D digital representation of the subsurface resulting from the AEM method provides users the ability to more accurately estimate total unsaturated and saturated aquifer volume and the amount of extractable water present. The Aten, Bloomfield, Harington, Menominee and Santee Block AEM survey areas were mapped at high resolution for this purpose. The Aten Block area covers approximately 11.4 mi^2 (7,281 acres), the Bloomfield Block area covers approximately 120.2 mi^2 (46,903 acres), the Harington Block area covers approximately 19.8 mi^2 (12,671 acres), the Menominee approximately 23.3 mi^2 (14,902 acres), and the Santee Block area covers approximately 7.9 mi^2 (5,090 acres) (Figure 3-240). The grid spacing was also changed affecting the volume calculations and explained in Section 3.1.8. In 2018 the Menominee Block AEM used a 100 ft grid size due to the high gradients in the paleochannel. The remaining blocks used a 250 ft grid size. In 2016 grids for the Coleridge and Creighton Blocks used a 250 ft grid size for voxel calculations (AGF, 2017a).

The criteria for determining the bases for the ranges of resistivity values used in calculating the volumes of interpreted aquifer material are provided in Section 3.1.6 and are presented in many of the figures for the Block AEM survey areas in the preceding sections. This report provides information on unsaturated and saturated volumes of non-aquifer, marginal aquifer, aquifer, and coarse aquifer materials. The Cretaceous Dakota Group (***Kd***) Sandstone/Sand-Dominant material has resistivities >20 ohm-m and the Shale/Clay-Dominant material has resistivities < 20 ohm-m.

As a reminder, 3D voxel models for the Aten Block (Figure 3-241), the Bloomfield Block (Figure 3-242), the Hartington Block (Figure 3-243), the Menominee Block (Figure 3-244), and the Santee Block (Figure 3-245) show the distribution of the volumes of all saturated and unsaturated ***Q*** aquifer materials and the saturated and unsaturated ***Kd*** sand/sandstone and shale/clay dominant materials. These figures show the complex nature of each area. From these voxels only the volumes of ***Q*** and ***Kd*** aquifer materials have been calculated for each block and are used in the calculation for aquifer volume in ft^3, aquifer volume in acre-ft, groundwater in storage volume acre-ft, and extractable water volume acre-ft.

All aquifer materials 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.

Specific yield values for Aten, Bloomfield, Hartington, and Menominee AEM block areas were estimated after discussion with LCNRD staff for the AGF 2017 report (AGF, 2017a) (Personal communication, Susan Olafsen-Lackey, January 5, 2017). No aquifer test information was available for this report for the AEM block areas. Estimates of specific yield were made for all aquifer materials. Specific yield for non-aquifer

(<12 ohm-m) materials was set at 0.02 and for marginal aquifer materials (12-20 ohm-m) a value of 0.05 was selected (Heath, 1983). Aquifer material (20-50 ohm-m) ranges from 0.1 to 0.2 with an average of 0.15 and estimates of specific yield for the coarse aquifer material (>50 ohm-m) ranges from 0.10 to 0.20 with an average of 0.15.

Porosity and Specific Yield values for the ***Kd*** Sandstone/Sand-Dominant and the Shale/Clay-Dominant materials were taken from published values by Heath (1983) and O'Connor (1987). The Sandstone value for porosity is 0.11 of volume and specific yield is 0.06. The Shale/Clay materials for the ***Kd*** have a porosity value of 0.40 of volume and specific yield is 0.02 for calculating groundwater storage/yield.

Tables have been created that describe the volumes of ***Q*** aquifer materials that are both saturated and unsaturated. Tables describing the volumes of ***Kd*** aquifer materials are also both saturated and unsaturated. Total volumes of all materials listed in the table are included in the "**TOTAL**" row at the bottom of each column. The tables are presented in alphabetic order by AEM Block name (Aten, Bloomfield, Hartington, and Menominee) in the following order: ***Q*** unsaturated, ***Q*** saturated, ***Kd*** unsaturated, and ***Kd*** saturated. Note that not all AEM Block areas contain all 4 classifications of aquifer materials.

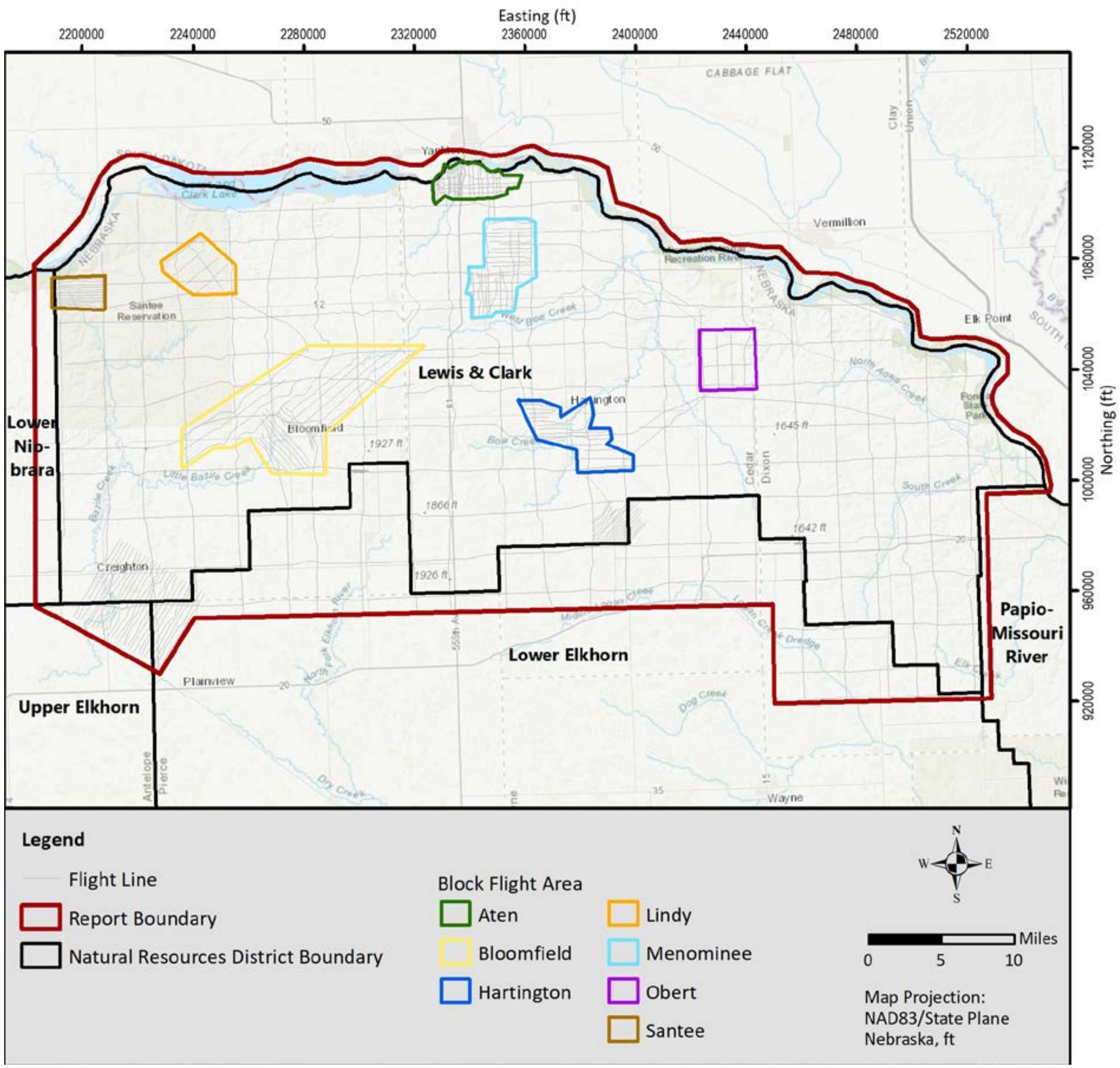


Figure 3-240. Map of the Aten (green polygon), Bloomfield (yellow polygon), Hartington (dark blue polygon), Menominee (light blue polygon), and Santee Block (brown polygon) AEM locations. The projection is NAD83 State Plane Nebraska (feet).

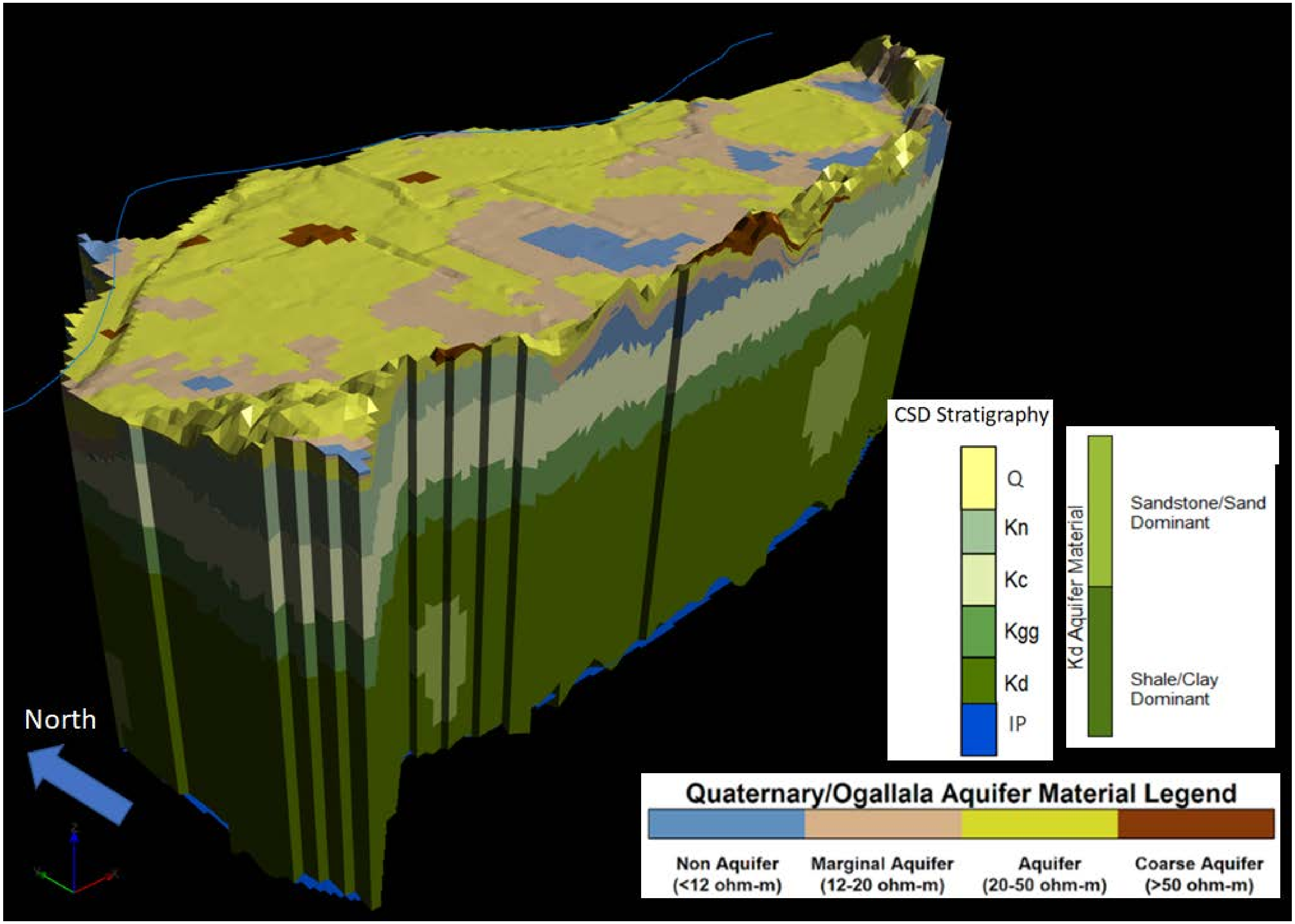


Figure 3-241. Voxel model of the Aten AEM block area looking northeast showing all Quaternary (*Q*) and Cretaceous Dakota Formation (*Kd*) aquifer materials. Note the complexity of aquifer materials distributed across the area. V.E.=10x.

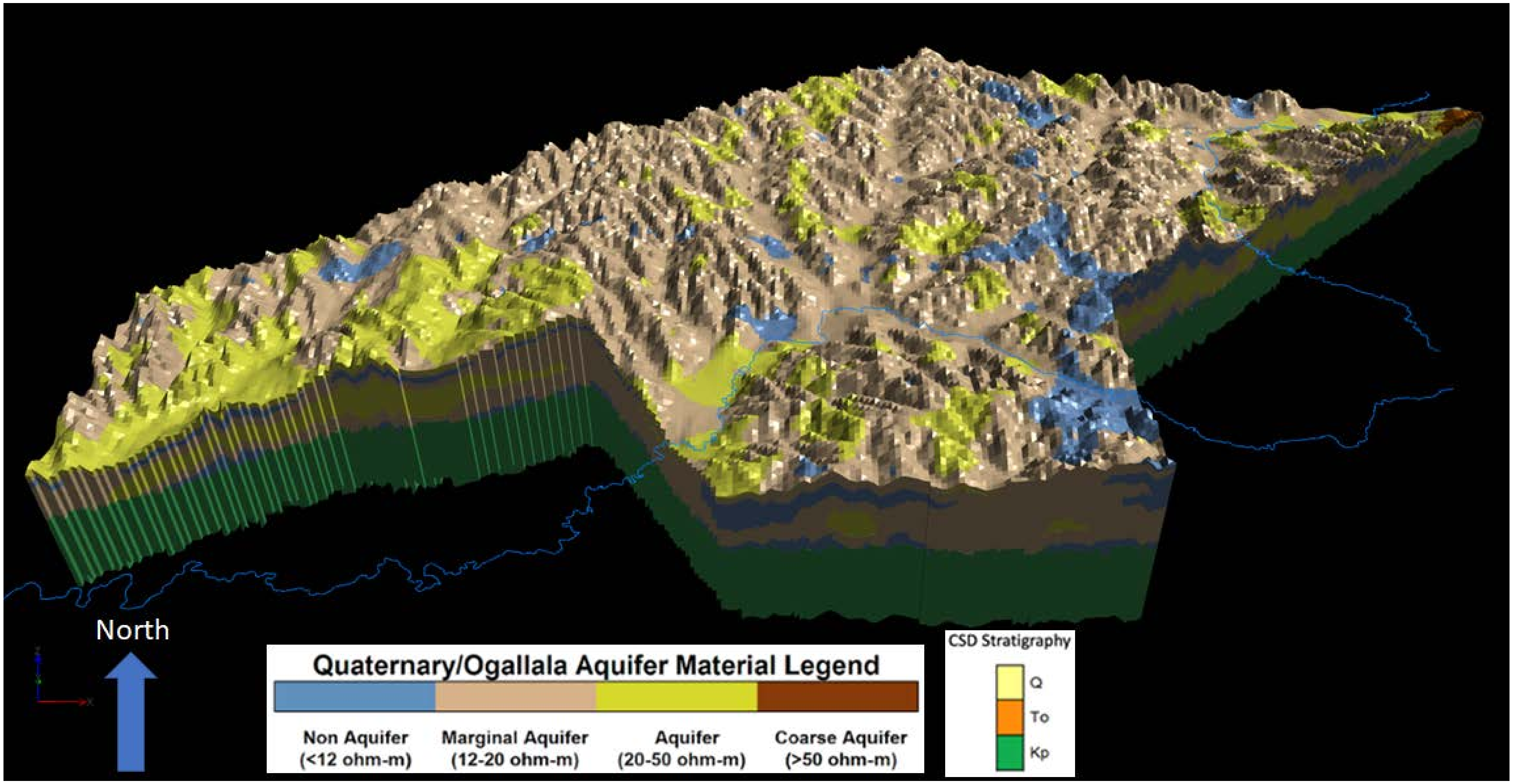


Figure 3-242. Voxel model of the Bloomfield AEM block area facing north showing all Quaternary (*Q*) aquifer materials. Note the complexity of aquifer materials distributed across the area. V.E.=10x.

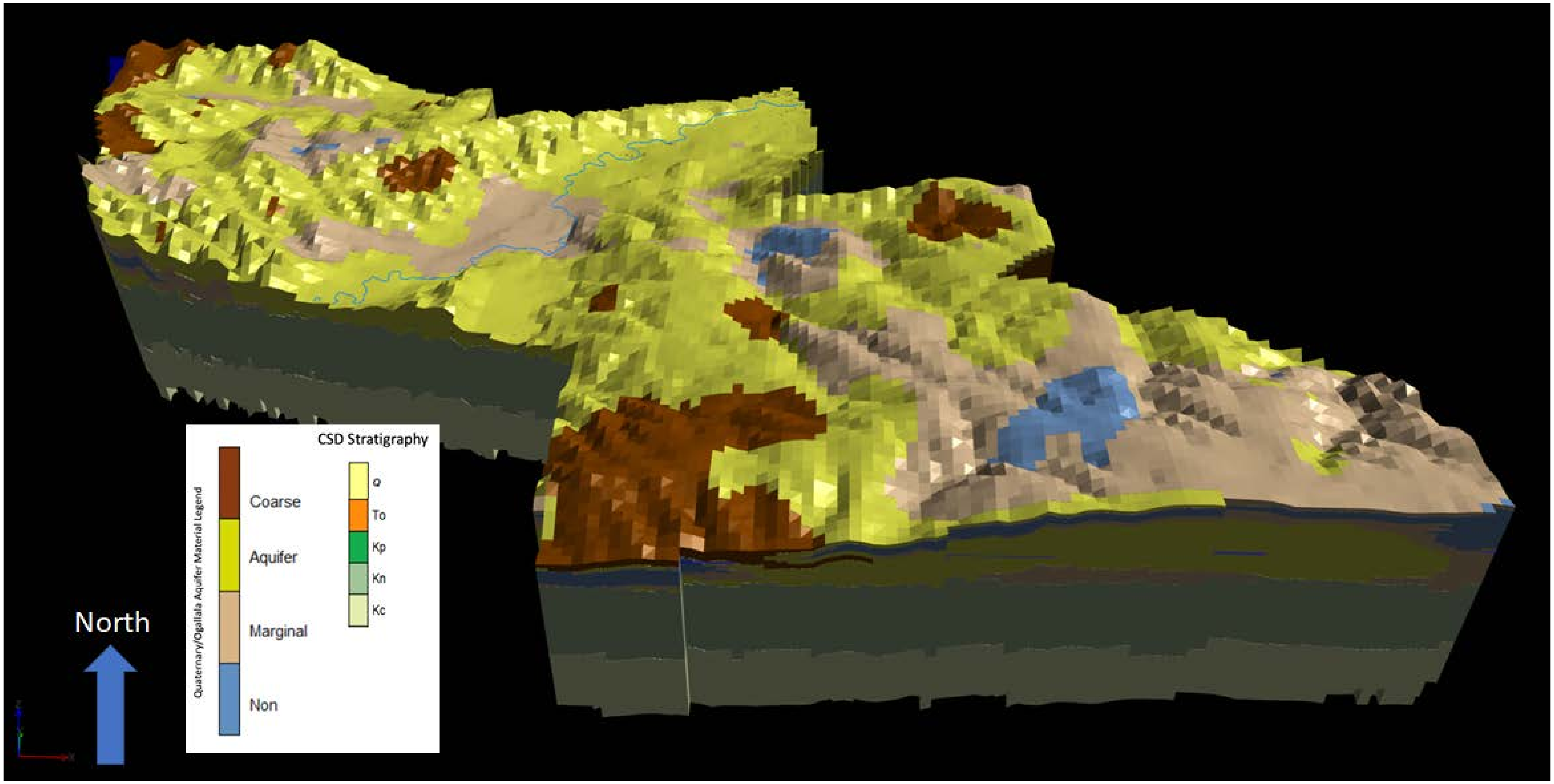


Figure 3-243. Voxel model of the Hartington AEM block area facing north showing all Quaternary (*Q*) aquifer materials. Note the complexity of aquifer materials distributed across the area. V.E.=10x.

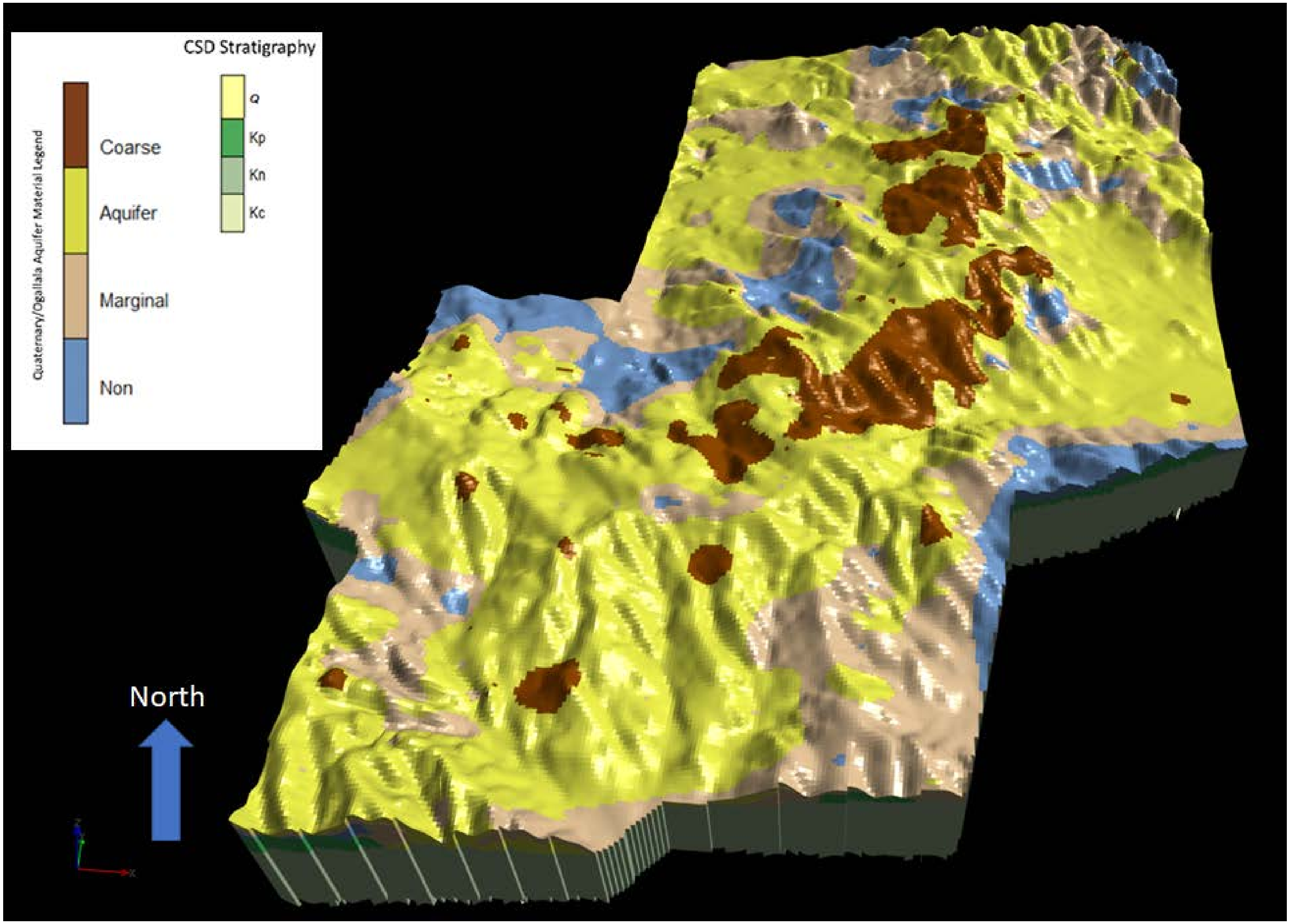


Figure 3-244. Voxel model of the Menominee AEM block area facing north showing all Quaternary (*Q*) aquifer materials. Note the complexity of aquifer materials distributed across the area. V.E.=10x.

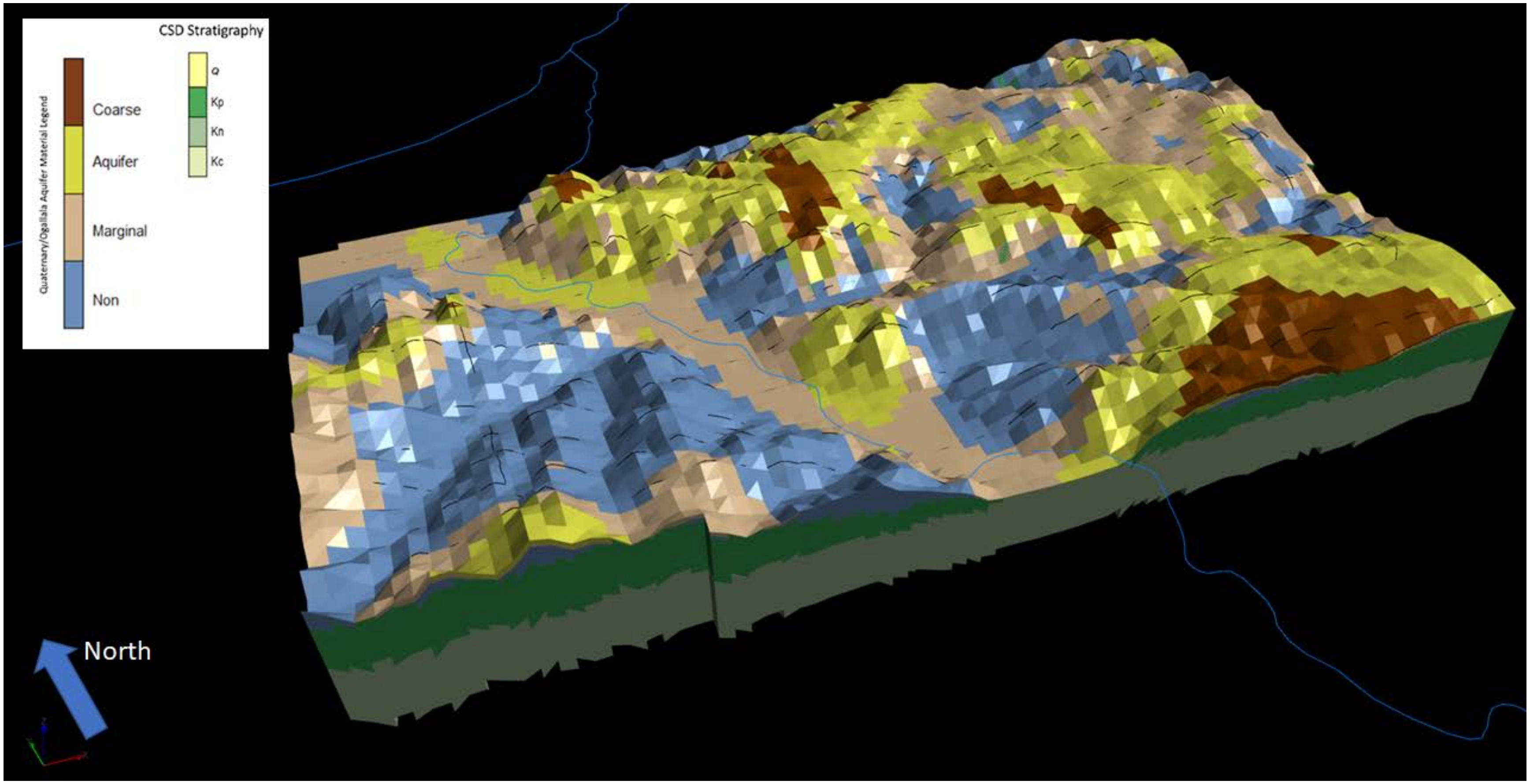


Figure 3-245. Voxel model of the Santee AEM block area facing north showing all Quaternary (*Q*) aquifer materials. Note the complexity of aquifer materials distributed across the area. V.E.=5x.

Aten AEM Block Area

Table 3-3. Unsaturated Quaternary (*Q)* aquifer materials underlying the Aten AEM Block 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)
Coarse	2,105,228,750	48,329	0.40	19,331	0.02	386
Aquifer	21,981,884,375	504,635	0.35	176,622	0.05	8,831
Marginal	7,596,504,063	174,392	0.20	34,878	0.10	3,487
Non-Aquifer	2,005,959,063	46,050	0.25	11,512	0.15	1,726
TOTAL	33,689,576,250	773,407		242,343		14,430

Table 3-4. Saturated Quaternary (*Q)* aquifer materials underlying the Aten AEM Block 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)
Coarse	1,412,250,938	32,420	0.40	12,968	0.02	259
Aquifer	19,454,234,688	446,608	0.35	156,312	0.05	7,815
Marginal	7,054,229,063	161,493	0.20	32,298	0.10	3,229
Non-Aquifer	1,729,965,313	39,741	0.25	9,935	0.15	1,490
TOTAL	29,650,680,000	680,686		211,513		12,793

Table 3-5. Saturated Cretaceous Dakota Group (*Kd*) aquifer materials underlying the Aten AEM Block 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)
Sandstone/ Sand	19,417,048,125	445,754	0.11	49,032	0.02	980
Shale/Clay	201,479,350,938	4,625,336	0.40	1,850,134	0.06	111,008
TOTAL	220,896,399,063	5,071,091		1,899,166		111,988

Bloomfield Aten AEM Block Area

Table 3-6. Unsaturated Quaternary (*Q*) aquifer materials underlying the Bloomfield AEM Block 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)
Coarse	521,324,063	11,967	0.40	4,786	0.02	95
Aquifer	155,744,066,875	3,575,397	0.35	1,251,388	0.05	62,569
Marginal	291,297,104,063	6,687,271	0.20	1,337,454	0.10	133,745
Non-Aquifer	110,692,117,813	2,541,145	0.25	635,286	0.15	95,292
TOTAL	558,254,612,813	12,815,781		3,228,914		291,701

Table 3-7. Saturated Quaternary (*Q*) aquifer materials underlying the Bloomfield AEM Block 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)
Coarse	136,601,875	3,135	0.40	1,254	0.02	25
Aquifer	97,073,309,063	2,228,499	0.35	779,974	0.05	38,998
Marginal	143,488,935,938	3,294,057	0.20	658,811	0.10	65,881
Non-Aquifer	36,682,752,500	842,121	0.25	210,530	0.15	31,579
TOTAL	277,381,599,375	6,367,814		1,650,569		136,483

Hartington AEM Block Area

Table 3-8. Unsaturated Quaternary (*Q)* aquifer materials underlying the Hartington AEM Block 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)
Coarse	7,169,549,688	164,590	0.40	65,836	0.02	1,316
Aquifer	34,698,273,750	769,563	0.35	269,347	0.05	13,467
Marginal	21,005,337,813	482,217	0.20	96,443	0.10	9,644
Non-Aquifer	3,679,602,188	84,472	0.25	21,118	0.15	3,167
TOTAL	66,552,763,438	1,527,843		452,844		27,594

Table 3-9. Saturated Quaternary (*Q)* aquifer materials underlying the Hartington AEM Block 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)
Coarse	308,749,375	7,087	0.40	2,834	0.02	56
Aquifer	15,894,398,125	364,886	0.35	127,710	0.05	6,385
Marginal	10,544,153,125	242,060	0.20	48,412	0.10	4,841
Non-Aquifer	933,004,688	21,418	0.25	5,354	0.15	803
TOTAL	27,680,305,313	635,453		184,310		12,085

Menominee AEM Block Area

Table 3-10. Unsaturated Quaternary (*Q)* aquifer materials underlying the Menominee AEM Block 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)
Coarse	3,394,322,300	77,923	0.40	31,169	0.02	623
Aquifer	16,570,546,800	380,408	0.35	133,142	0.05	6,657
Marginal	6,726,158,250	154,411	0.20	30,882	0.10	3,088
Non-Aquifer	2,276,271,600	52,256	0.25	13,064	0.15	1,959
TOTAL	28,967,298,950	664,998		208,257		12,327

Table 3-11. Saturated Quaternary (*Q)* aquifer materials underlying the Menominee AEM Block 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)
Coarse	21,201,950	487	0.40	194	0.02	4
Aquifer	2,663,351,500	61,142	0.35	21,399	0.05	1,069
Marginal	1,257,401,250	28,866	0.20	5,773	0.10	577
Non-Aquifer	275,507,250	6,325	0.25	1,581	0.15	237
TOTAL	4,217,461,950	96,820		28,947		1,887

Santee AEM Block Area

Table 3-12. Unsaturated Quaternary (*Q)* aquifer materials underlying the Santee AEM Block 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)
Coarse	485,820,313	11,152	0.40	4,460	0.02	89
Aquifer	1,107,286,875	25,419	0.35	8,896	0.05	444
Marginal	922,715,938	21,182	0.20	4,236	0.10	423
Non-Aquifer	2,168,449,375	49,780	0.25	12,445	0.15	1,866
TOTAL	4,684,272,500	107,536		30,037		2,822

Table 3-13. Saturated Quaternary (*Q)* aquifer materials underlying the Santee AEM Block 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)
Coarse	0	0	0.40	0	0.02	0
Aquifer	131,358,750	3,015	0.35	1,055	0.05	52
Marginal	41,065,625	942	0.20	188	0.10	19
Non-Aquifer	16,940,625	388	0.25	58	0.15	9
TOTAL	189,365,000	4,347		2,602		80

3.3 Recharge Areas in the LCNRD Reconnaissance and Block 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 for the LCNRD area incorporating all of the AEM Reconnaissance lines (2014, 2016, and 2018), Aten, Bloomfield, Hartington, Lindy, Menominee, Obert, and Santee 2018 AEM survey areas as well as the 2016 Coleridge and Creighton Block AEM survey areas. The near-surface maps present the results of the resistivity to lithology relationship described in Section 3.1.6 over an average of the first three (3) layers of the AEM inverted earth model, down to a depth of -10.8 feet. From the discussion around Table 2-3 (SkyTEM304 system) and Table 2-4 (SkyTEM312 system), each model layer represents an average of the earth's resistivities within those depths, based on the physics of the electromagnetic exploration technique. Maps of the first layers show aquifer materials and indicate the areas at the land surface and just below that can potentially transmit water to the groundwater aquifers in the area. These model layers, near the ground surface, provide a visualization of whether the sediments are made up of aquifer material (yellow - "good") to coarse aquifer material (brown - "very good"). The coarse aquifer material can transmit the largest volume of water. By viewing layers at depth an understanding of the heterogeneity of the aquifer materials and their distribution can be achieved. There is not always a direct path downwards to the aquifer from the land surface. Often there is no path available for the water to move through.

Maps of the ***Q*** surface sediments indicating recharge capabilities are presented as aquifer material types for the total LCNRD AEM survey area and the Block AEM survey areas in Figure 3-246, recharge for the Aten Block AEM survey area in Figure 3-247, recharge for the Bloomfield Block AEM survey area in Figure 3-248, recharge for the 2016 Coleridge Block AEM survey area in Figure 3-249, recharge for the 2016 Creighton Block AEM survey area in Figure 3-250, recharge for the Hartington Block AEM survey area in Figure 3-251, recharge for the Lindy Block AEM survey area in Figure 3-252, recharge for the Menominee Block AEM survey area in Figure 3-253, recharge for the Obert Block AEM survey area in Figure 3-254, and recharge for the Santee Block AEM survey area in Figure 3-255.

Note that 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 LCNRD AEM survey areas are the alluvial valley floors in valleys. In other areas, the best possible locations for recharge would be where there is a combination of aquifer and coarse aquifer materials at the land surface with little relief in elevation with a pathway of similar materials down to the saturated aquifer at depth. A more in-depth recharge analysis could be performed using slope and run-off analysis combined with detailed soils maps with the addition of the AEM interpretation.

The recharge layers shown are included as Google Earth kmz's in Appendix 3-Deliverables\KMZ\Recharge.

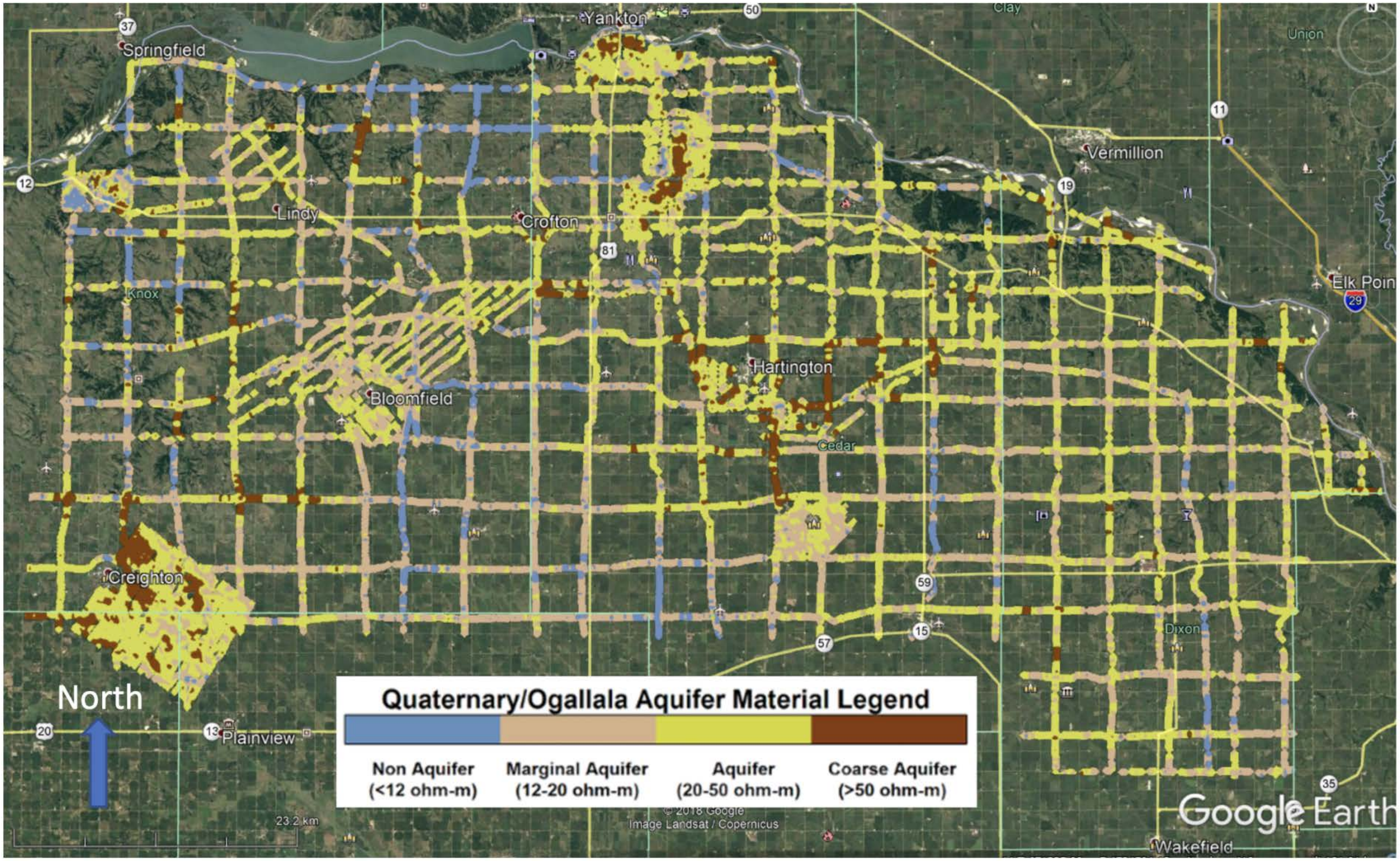


Figure 3-246. Map of near-surface aquifer materials in the 2018 LCNRD Reconnaissance AEM survey area.

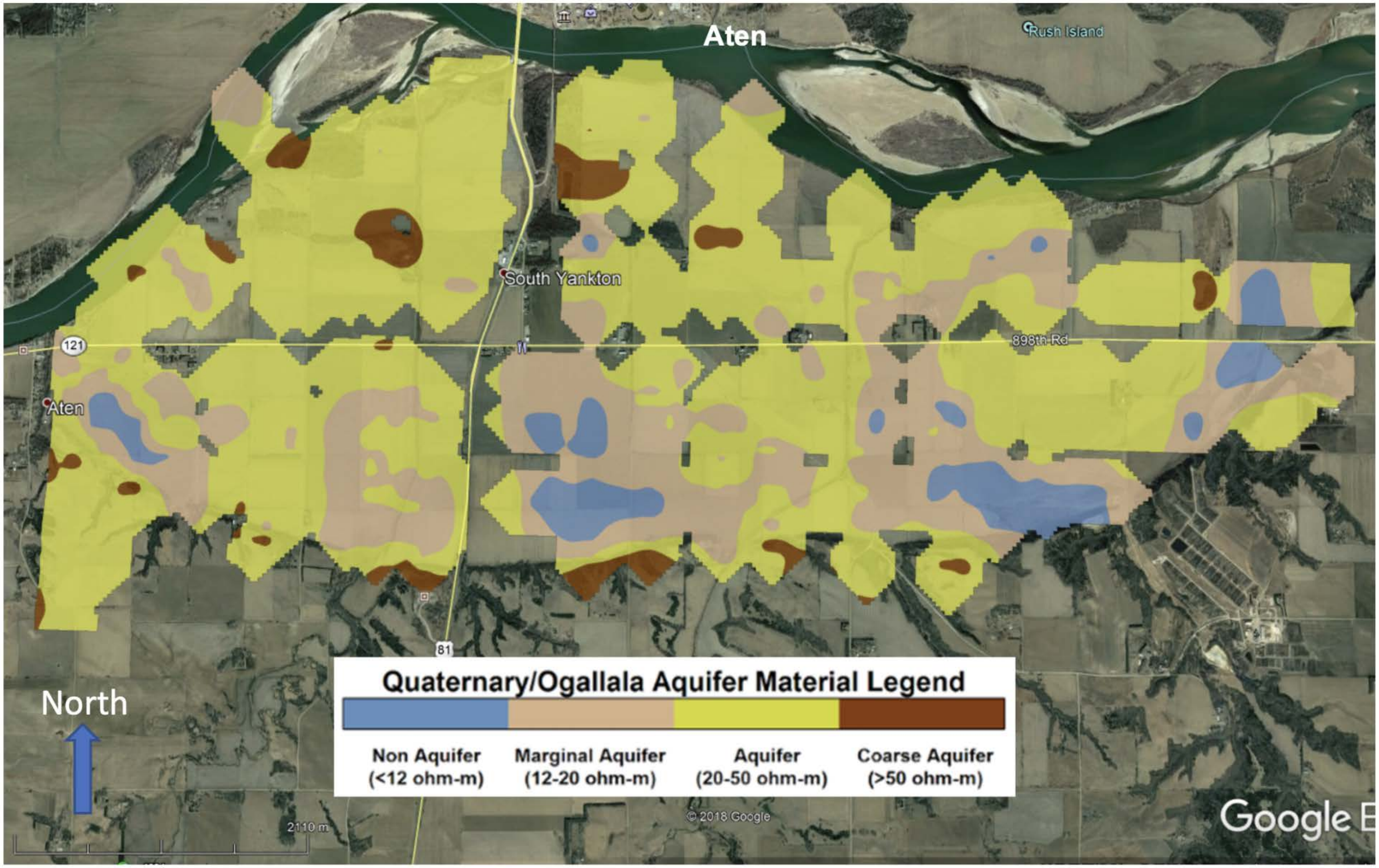


Figure 3-247. Map of near-surface aquifer materials in the Aten Block AEM survey area. Note the presence of aquifer and coarse aquifer material in the Missouri River Flood Plain.

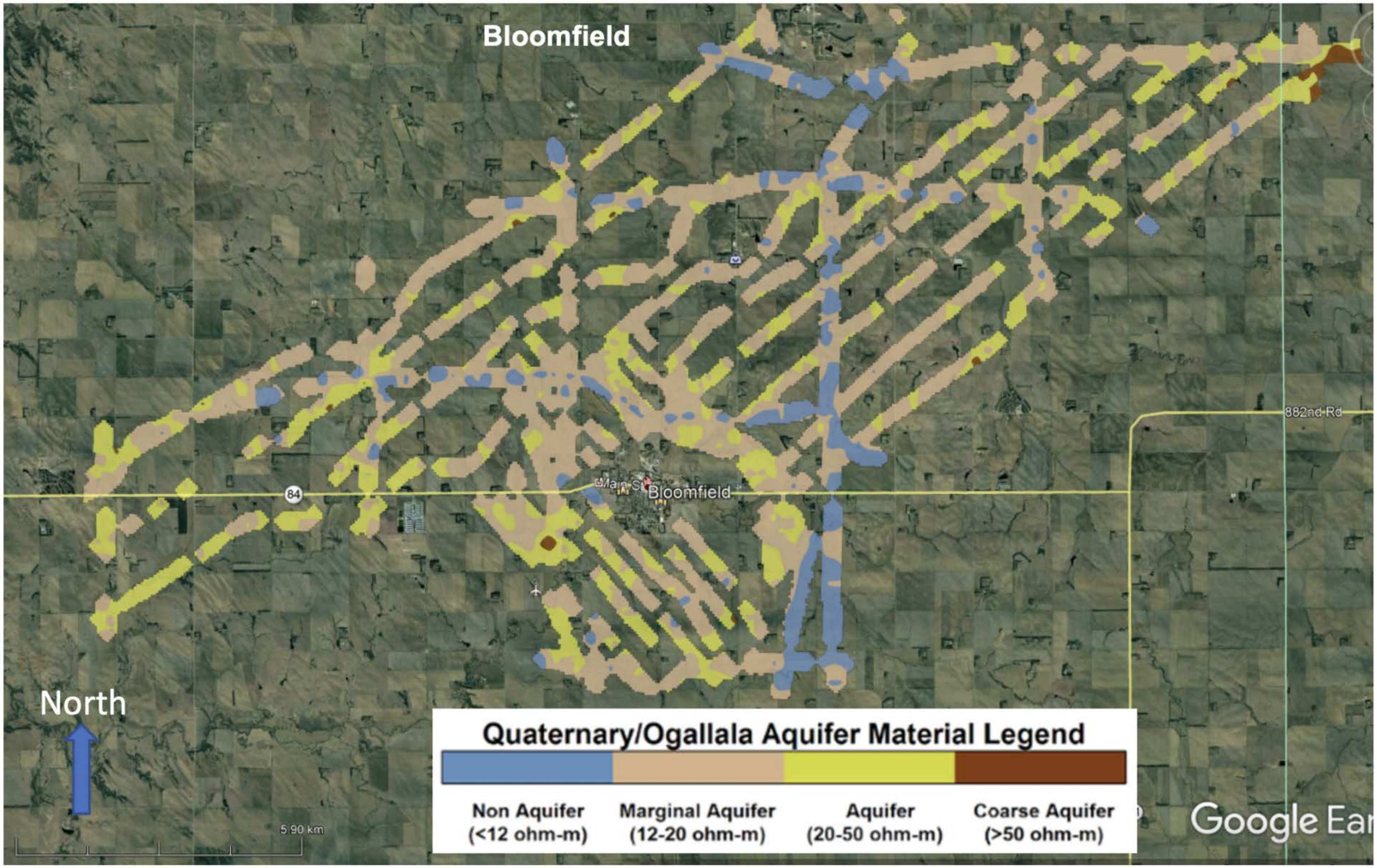


Figure 3-248. Map of near-surface aquifer materials in the Bloomfield Block AEM survey area. The majority of the material is non-aquifer (blue) and marginal aquifer (tan) material.

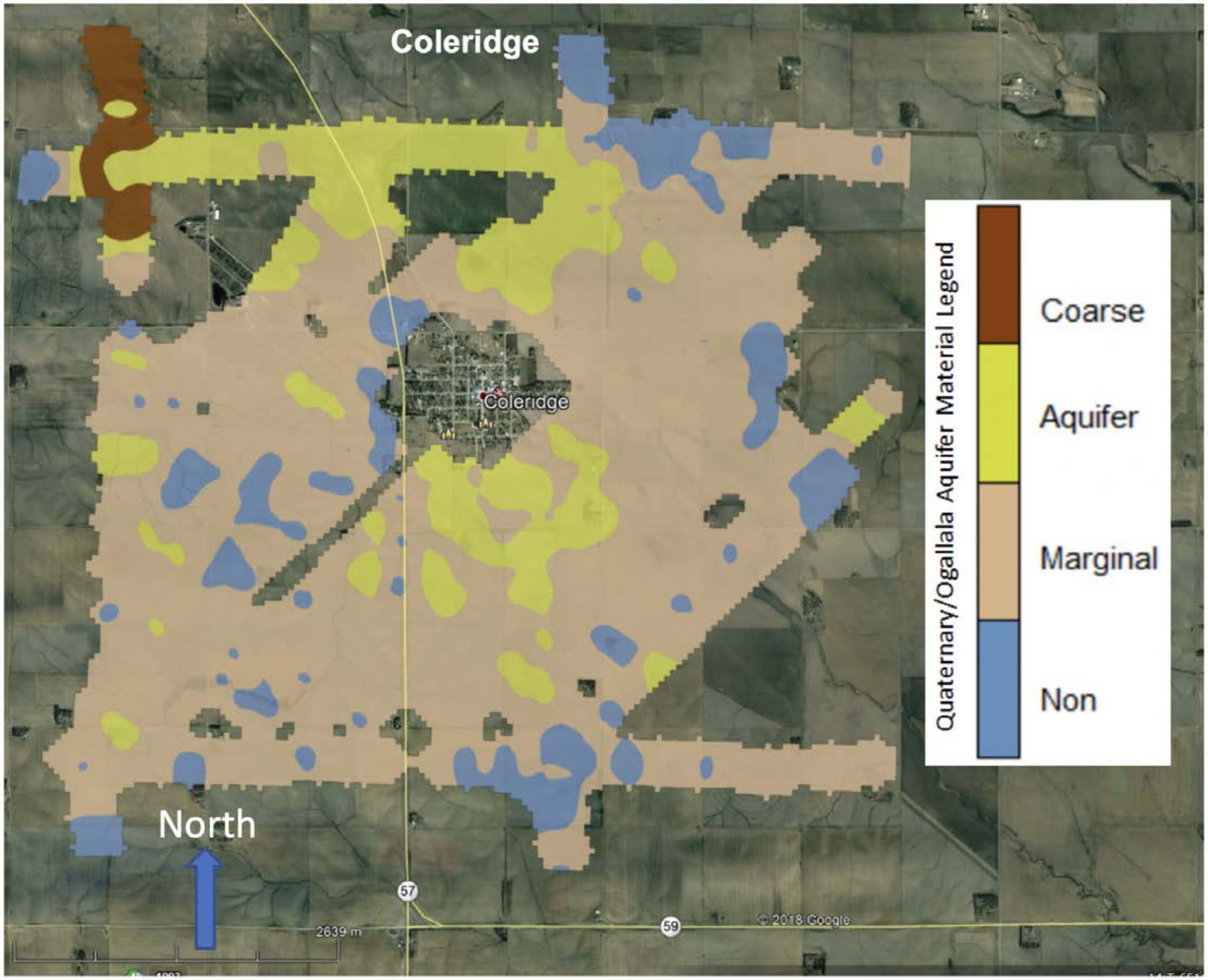


Figure 3-249. Map of near-surface aquifer materials in the Coleridge Block AEM survey area. The majority of the material is non-aquifer (blue) and marginal aquifer (yellow) material with small sub-areas of aquifer material (yellow) and coarse aquifer material (brown).

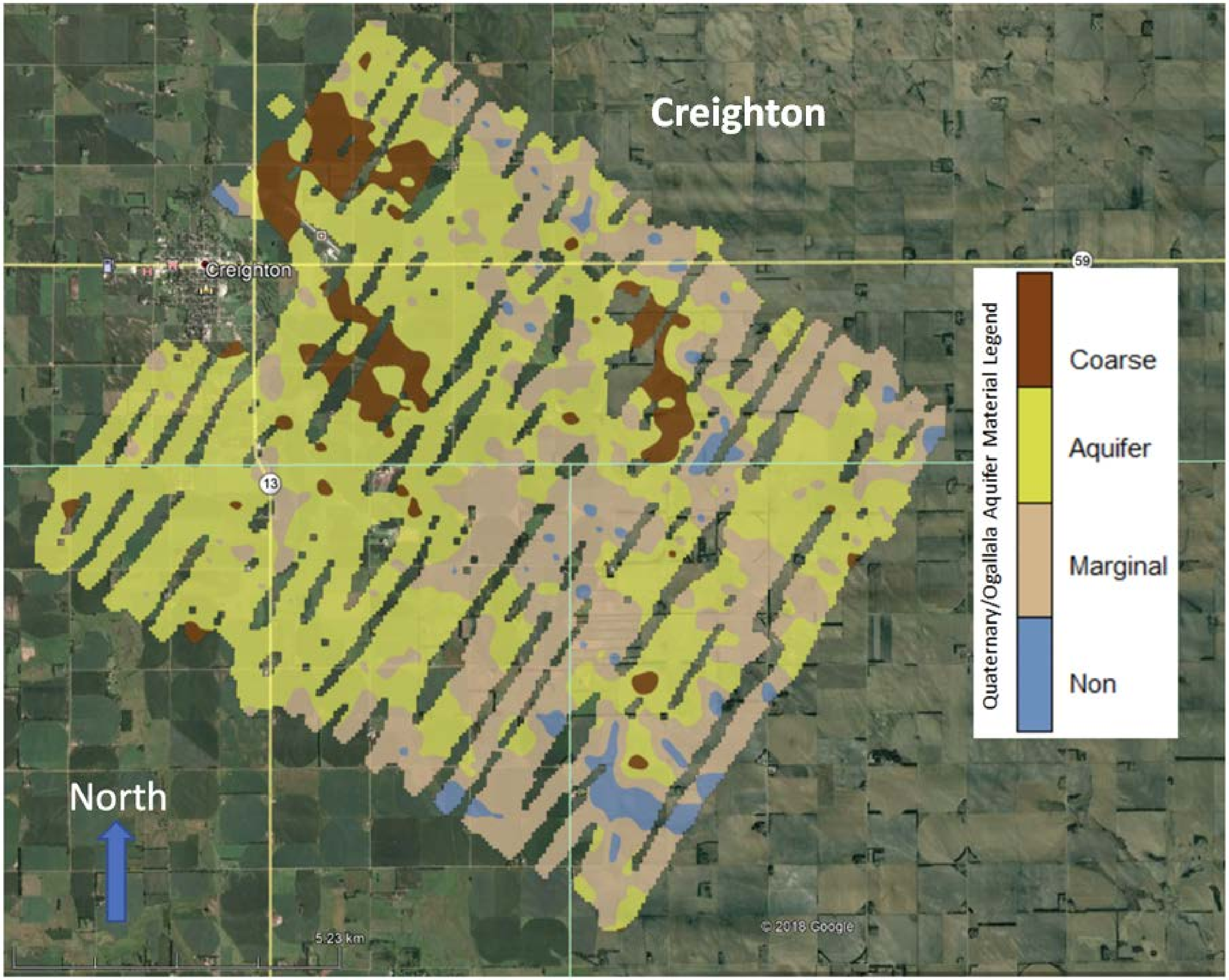


Figure 3-250. Map of near-surface aquifer materials in the Creighton Block AEM survey area. The majority of the material is aquifer (yellow) and coarse aquifer (brown) material.

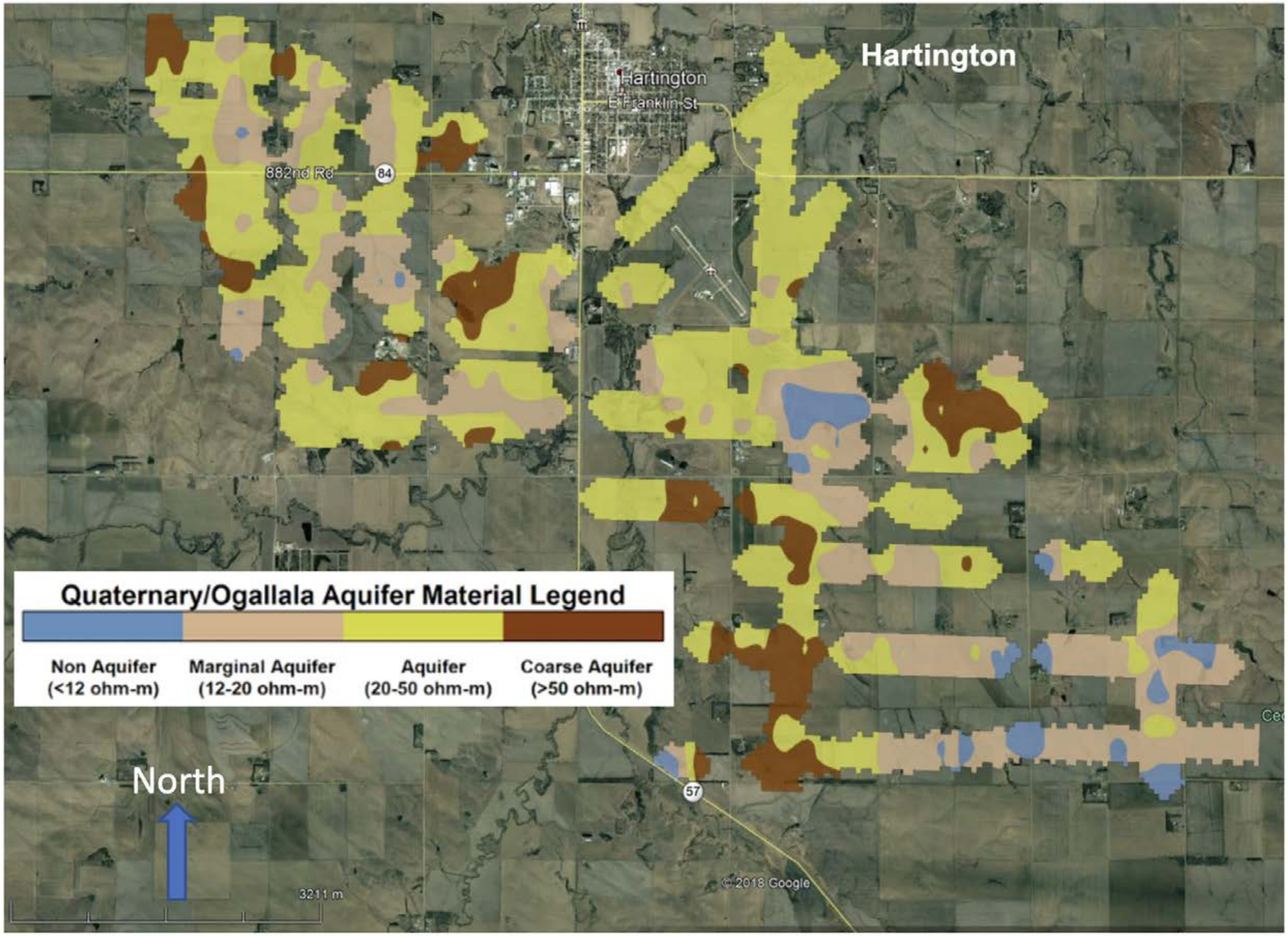


Figure 3-251. Map of near-surface aquifer materials in the Hartington Block AEM survey area. Note the presence of the mix of all aquifer materials across the area.

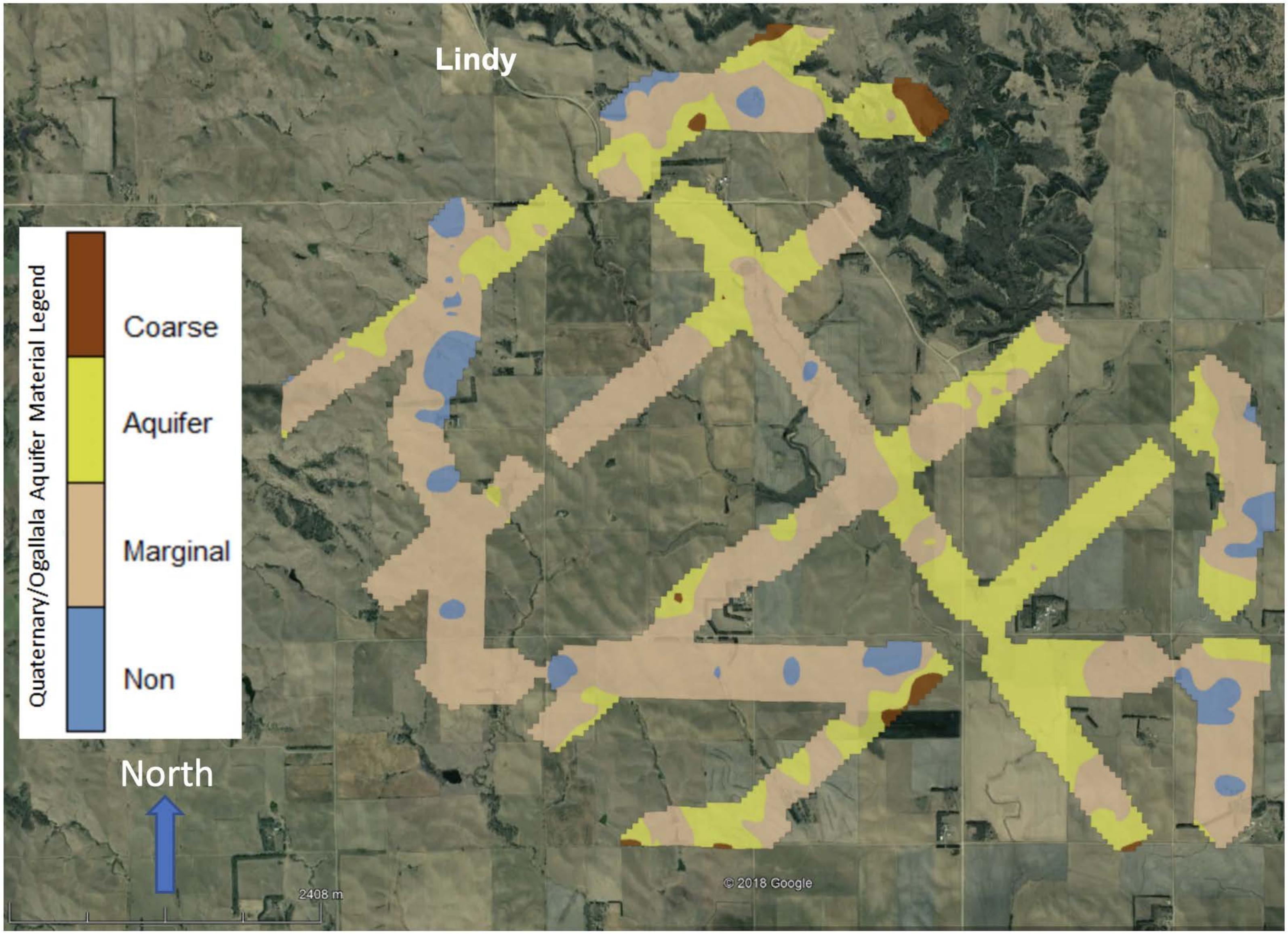


Figure 3-252. Map of near-surface aquifer materials in the Lindy Block AEM survey area. The majority of the aquifer material is non-aquifer (blue) and marginal aquifer (tan) material.

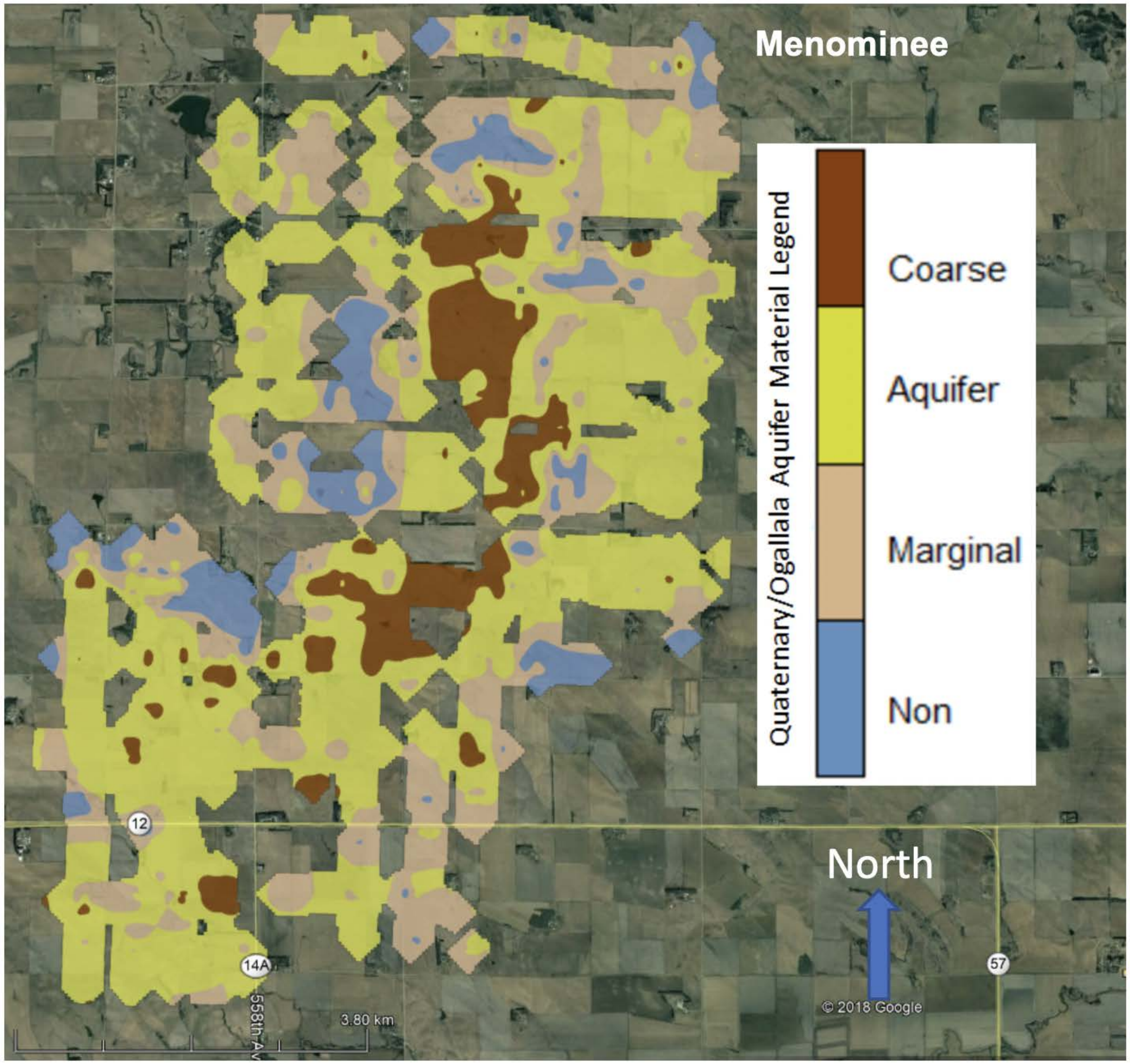


Figure 3-253. Map of near-surface aquifer materials in the Menominee Block AEM survey area. The majority of the material is aquifer (yellow) and coarse aquifer (brown). Note the concentration of coarse aquifer material along the paleochannel in center of the survey area.

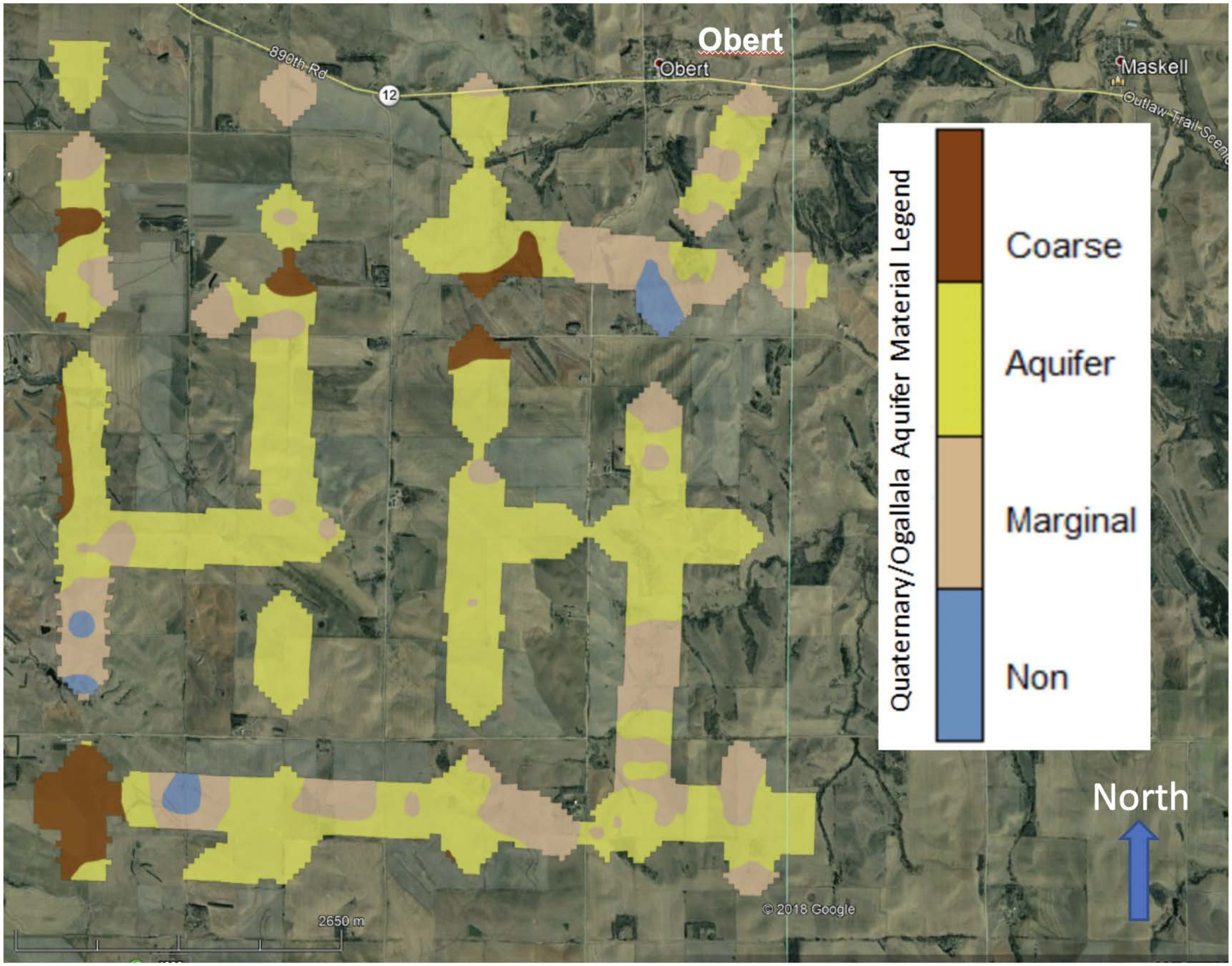


Figure 3-254. Map of near-surface aquifer materials in the Obert Block AEM survey area. The majority of the material is aquifer (yellow) and coarse aquifer (brown) material.

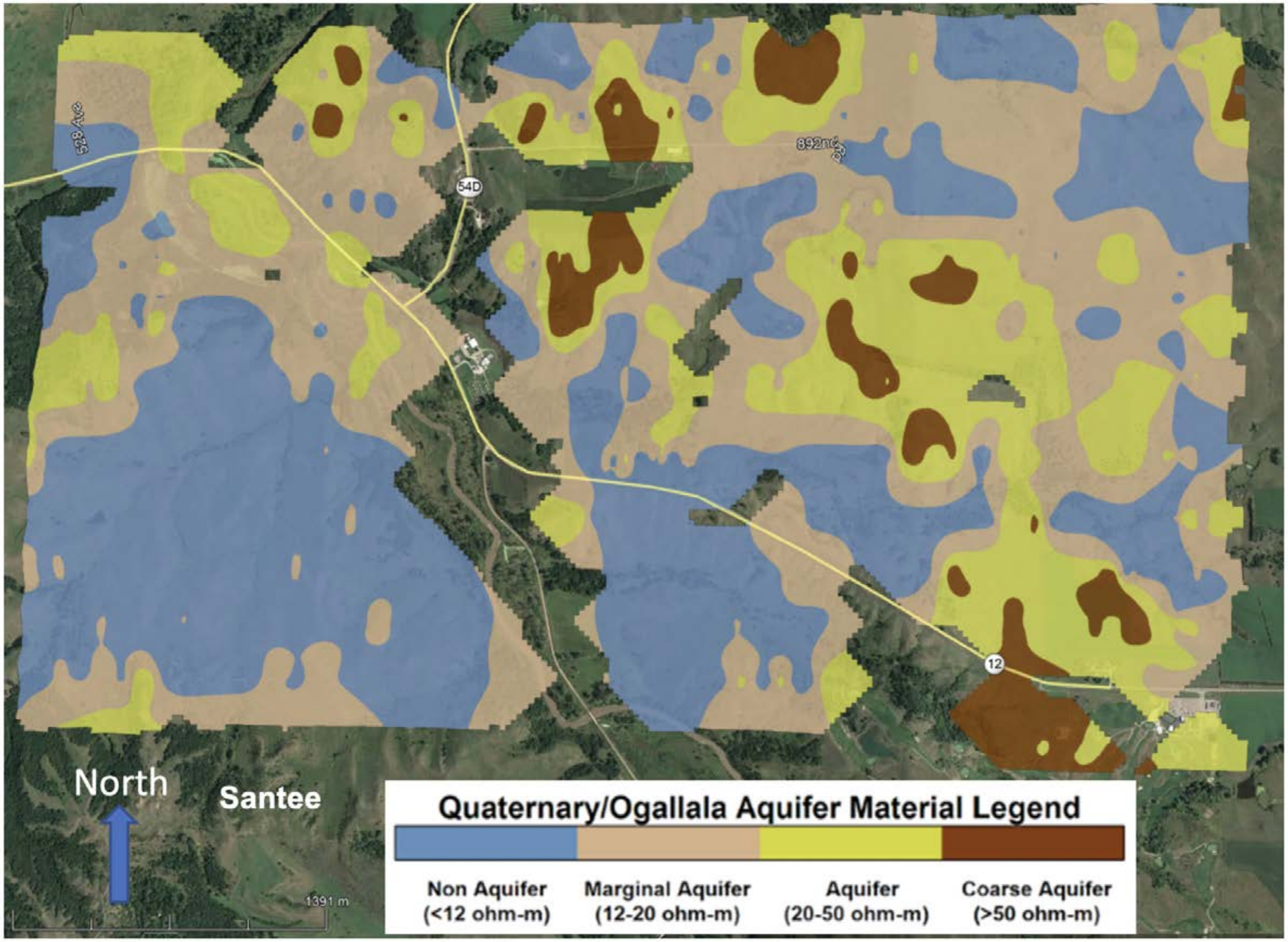


Figure 3-255. Map of near-surface aquifer materials in the Santee Block AEM survey area. The majority of the material are marginal aquifer (tan) and non-aquifer (blue) material. Where coarse and aquifer material exist, they are only a thin cover over bedrock with little ability to store recharge water.

3.4 Key AEM Findings

3.4.1 Boreholes

Information from boreholes was used to analyze the AEM inversion results and was important for all areas in the LCNRD. The CSD stratigraphic control was utilized to distinguish the ***Kp, Kn***, ***Kc***, ***Kgg,*** and ***Kd***. Contacts between the Quaternary (***Q***) Tertiary Ogallala (***To***)***,*** and Cretaceous Dakota Group (***Kd***) can have limited or no contrast in the electrical resistivity between the different geologic formations. Use of CSD stratigraphy calls and the presence of sandstone and shale in the NE- DNR (Nebraska Department of Natural Resources) registered wells were used to pick the contact when no resistivity contrast was present. The dependence on just boreholes for geologic interpretation also has its limitations because sometimes the borehole logs are wrong, improperly located, have improper stratigraphic/lithology picks, and/or other errors. These errors in the boreholes are usually encountered in the NE-DNR registered wells. Rare inconsistencies are encountered in the oldest of the NE- CSD wells. The limited errors in the CSD wells may very well be due to poor positioning from a time before GPS and modern survey methods. As a guide in the interpretation of the AEM***,*** a bedrock surface was prepared using the of CSD and NE-DNR borehole logs and surface maps of the geologic outcrops. As in all surveys of this nature the use of boreholes with AEM needs to be approached in a thoughtful and considered manner as to the value of information from an individual borehole.

3.4.2 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***), Cretaceous Pierre Shale (***Kp***), Cretaceous Niobrara Formation (***Kn***), Cretaceous Carlile Shale (***Kc***), Cretaceous Greenhorn Limestone and Graneros Shale (***Kgg***), Cretaceous Dakota Group (***Kd***), and undifferentiated Pennsylvanian (***IP***). The interpretive process benefited from the use of CSD, Nebraska Oil and Gas Conservation Commission (NEOGCC), and NE-DNR borehole logs. Geologic maps of surface outcrops and geologic maps contributed to the understanding of geologic interpretation. Surface grids of the interpreted geologic formations were then produced. Each flight line profile with interpretation including the Quaternary (***Q***) aquifer material mapping is included in the appendices as well as interpretative surface grids.

3.4.3 Resistivity/Lithology Relationship

Assessment of the sediment character in the Quaternary aquifer system and the bedrock strata was conducted to determine the overall composition of the major categories used to define the aquifer and aquitards in eastern Nebraska. A statistical assessment of the resistivity thresholds was used to characterize non-aquifer (<12 ohm-m), marginal (12-20 ohm-m), and aquifer (20-50 ohm-m), including coarse sand-rich intervals (>50 ohm-m) was determined in 2015 (Carney et al., 2015a). This allowed for the characterization of the ranges of resistivities present in the major geologic units described in this report.

3.4.4 Hydrogeological Framework of the LCNRD AEM Survey Areas

The 2018 LCNRD AEM survey reveals variability in the Quaternary (***Q***), Tertiary Ogallala (***To***) and Cretaceous Dakota Group (***Kd***) deposits across the LCNRD AEM survey area that make up the aquifer materials. The ***Q*** and ***To*** make up the aquifer materials overlying the Cretaceous bedrock units of which the ***Kd*** Sandstone/Sand Dominant material is the aquifer material. In the north and south parts of the AEM survey area, the aquifer material and coarse aquifer material exist in paleovalleys and glacial outwash deposits that are separated by ***Q*** deposits. These separating Q deposits consist predominantly of marginal to non-aquifer materials that are glacial till and loess and that can be more than 400 ft thick. ***Q*** aquifer and coarse aquifer materials are thick in the paleovalleys located in Aten, Menominee, and Obert 2018 survey areas.

Estimates of the groundwater in storage within the ***Q***-portion of the Aten AEM Block of aquifer material below the 1995 CSD water table elevation is 211,513 acre-ft. The amount of extractable groundwater from aquifer material is 8,831 acre-ft and coarse aquifer material is 386 acre-ft. The amount of extractable groundwater from ***Kd*** Sandstone/Sand Dominant material is 111,988 acre-ft.

Estimates of the groundwater in storage within the ***Q***-portion of the Bloomfield AEM Block of aquifer material below the 1995 CSD water table elevation is 1,650,569 acre-ft. The amount of extractable groundwater from aquifer material is 38,998 acre-ft and coarse aquifer material is 25 acre-ft.

Estimates of the groundwater in storage within the ***Q***-portion of the Hartington AEM Block of aquifer material below the 1995 CSD water table elevation is 184,310 acre-ft. The amount of extractable groundwater from aquifer material is 6,385 acre-ft and coarse aquifer material is 56. While these materials will produce water, the yields and specific capacity will be reduced.

Estimates of the groundwater in storage within the ***Q***-portion of the Menominee AEM Block of aquifer material below the 1995 CSD water table elevation is 28,947 acre-ft. The amount of extractable groundwater from aquifer material is 1,069 acre-ft and coarse aquifer material is 4.

Estimates of the groundwater in storage within the ***Q***-portion of the Santee AEM Block of aquifer material below the 1995 CSD water table elevation is 2,602 acre-ft. The amount of extractable groundwater from aquifer material is 52 acre-ft and coarse aquifer material is 0.

3.4.5 Potential Recharge Zones within the LCNRD AEM Survey Area

Within the LCNRD Reconnaissance AEM flight area the highest rate of recharge can be expected along the river and stream valleys due to the presence of aquifer and coarse aquifer materials from the land surface down to the water table and beyond. Areas with aquifer and coarse aquifer materials at the surface can also become conduits for infiltration of nitrates into the groundwater system. These areas exist in the river and stream areas of the survey area where the reconnaissance lines are the basis for this determination. It should be noted that in these areas the results shown in the recharge maps are based on actual AEM data. A potential solution for any nonpoint source water quality contamination is adding additional fresh surface water as recharge to select areas of rangeland that can dilute any potential nitrate contaminant problem occurring from cropland. Additional work can be done to identify where the best locations are for these type of management efforts. The current recharge analysis allows for more accurate representation of the aquifer materials in the first 10 feet from the land surface downward.

The use of Block flights for Aten, Bloomfield, Hartington, Lindy, Menominee, Obert, and Santee 2018 AEM survey areas as well as the 2016 AEM Block survey areas Coleridge and Creighton illustrate the preferred method of using AEM to identify areas where the potential for recharge to the aquifer can be high and low. Locations where the flight lines are closely spaced showing either aquifer or coarse aquifer material at the land surface should be considered as locations for higher likelihood for recharge because of the 2D and 3D spatial nature of the aquifer material distribution. The opposite is also true where AEM data analysis shows non-aquifer or marginal aquifer material. Those areas will likely not be optimal recharge locations. The areas throughout the Aten, Creighton, Hartington, Menominee, and Obert AEM survey areas have potential recharge that is good across most of the area due to the ***Q*** aquifer and coarse aquifer materials at the land surface. The areas throughout the Bloomfield, Coleridge, Lindy, and Santee AEM survey areas have potential recharge that is limited in extent due to the ***Q*** marginal and non-aquifer aquifer materials at the land surface.

3.4.6 Hydrologic Connection Between Groundwater and Surface Water in the LCNRD AEM Survey Area

The AEM data and interpretation provides detailed empirical data for determining earth materials at depth that are related to aquifer characteristics. The ***Q*** aquifer materials are a guide with coarse aquifer and aquifer materials being the most able to recharge, store, and provide groundwater flow. The marginal aquifer material provides limited groundwater flow with poor recharge and the non-aquifer material provides virtually no groundwater flow. The areas mapped and presented in this report show areas that contain large amounts of marginal and non-aquifer deposits. These areas can be boundary conditions between different parts of the groundwater system and the surface water of the area. Any planning or detailed analysis related to groundwater and surface water relationships should take this information into account.

3.5 Recommendations

Recommendations provided to the LCNRD 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 the LCNRD about their management challenges.

3.5.1 Preparing the Results from AEM Hydrogeological Investigations for Groundwater Modeling

The LCNRD has acquired AEM data for groundwater management purposes. With the completion of this current AEM study there needs to be additional work done to integrate any additional data and geologic modeling to create optimal datasets for input into groundwater models and water quality studies.

3.5.2 Additional AEM Mapping

No additional reconnaissance-level AEM mapping is needed for the LCNRD at this time. Future additional Block data acquisition should be considered as needed depending on future projects by the LCNRD.

3.5.3 Update the Water Table map

The groundwater data used in the analyses presented in this report utilized the 1995 CSD water table map which is now 24 years old. Additional water level measurement locations would improve the water table map where groundwater conditions are unconfined. The areas of glacial till and loess covering the parts of the district will need great care in developing a water level map of potentiometric heads due to the confined to semiconfined nature of the area. Use of the data collected in this survey and future surveys will provide the best possible water table and conditions map for the district.

3.5.4 Siting new test holes and production wells

The AEM hydrogeological framework profiles, maps, and surfaces provided in this report provide great 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 LCNRD area was used in building the framework maps and profiles. Additional information from previous groundwater reports were helpful in this work. 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 more 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. A good example of this would be confined aquifers with large volumes of coarse aquifer and aquifer material with minimal aquiclude boundary conditions. The previous AEM studies have already found use by CSD and local well drillers to locate test wells and production wells within the LCNRD.

3.5.5 Aquifer testing and borehole logging

Aquifer tests are recommended to improve estimates of aquifer characteristics. Limited aquifer properties from previous reports 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. Examples of additional logging would be flow meter logs and geophysical logs including gamma, neutron, electrical, and induction logs. Detailing aquifer characteristics can be accomplished with nuclear magnetic resonance logging (NMR) at a reduced cost when compared to traditional aquifer tests. 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.

3.5.6 Recharge Zones

The LCNRD hydrogeologic framework in this report provides areas of recharge from the ground surface to the groundwater aquifer. Reconnaissance-level AEM investigations provide limited detailed information between the lines for understanding recharge throughout the survey area. It is recommended that future work integrate new soils and land use 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. A potential solution to water quality, quantity, and stream depletions is adding additional fresh surface water as recharge to select areas of rangeland or other areas. Additional work can be done to identify where the best locations are for these type of management efforts. This information can and has been used in Nebraska to improve Well Head Protection Areas by refining the estimated travel time estimates and the boundary areas.

3.5.7 Managed Aquifer Recharge

The areas which may have potential for managed aquifer recharge (MAR) can be approximately located by the interpreted results from AEM reconnaissance line interpretations. Detailed analysis for this purpose would need to be done to determine where viable opportunities for the LCNRD exist and what additional information would be required for final selections of MAR sites. Additional AEM mapping in new block flight locations and along the streams in the LCNRD would also be beneficial in locating potential MAR locations. A detailed plan for locating and developing MAR sites would be beneficial to the LCNRD for storage and release of water for stream flow and other uses.

3.5.8 Updating previous groundwater reports and Groundwater Management Plans

The groundwater reports and management plans should be updated with the AEM information. The addition of estimates of groundwater in storage, recharge areas, hydrologic connection to streams and consideration of managed aquifer recharge sites will greatly improve and groundwater management plan.

3.5.9 Assist the LCNRD staff with additional interpretation and data analysis for groundwater management needs

The AEM reports provided to the district are complete, but there is always a need to extract and analyze the AEM data in conjunction with a particular management need or area. Examples include using the AEM data to define areas for management practices related to water quality problems, use the AEM data to site water well development, assist groundwater modelers with input data sets for groundwater modeling, and define hydrologic connections between groundwater and surface water to name a few.

4 Description of Data Delivered

4.1 Tables Describing Included Data Files

Table 4-1 describes the raw data files included in Appendix 3_Deliverables \Raw_Data. As discussed above, eighteen (18) flights were required to acquire the LCNRD AEM data (Figure 2-5). Grouped by flight date, there are four (4) data flies included in Appendix 3\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 2.4.1). 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.

Table 4-2 describes the data columns in the ASCII *.xyz files LCNRD2018_304_EM_MAG.xyz and LCNRD2018_312_EM_MAG.xyz. These files contain the electromagnetic data, plus the magnetic and navigational data, as supplied directly from SkyTEM.

The results of the Spatially-Constrained Inversions (SCI) are included in LCNRD2018_312_SCI_Inv_v1.xyz, LCNRD2018_304_SCI_Inv_pt1.xyz, and LCNRD2018_304_SCI_Inv_pt2.xyz. The columns of these databases are described in Table 4-3.

The interpretation results are included in the data files LCNRD Recon Interpretation.xyz, Aten Block Interpretation.xyz, Bloomfield Block Interpretation.xyz, Coleridge Block Interpretation.xyz, Creighton Block Interpretation.xyz, Hartington Block Interpretation.xyz, Lindy Block Interpretation.xyz, Menominee Block Interpretation.xyz, Obert Block Interpretation.xyz, and Santee Block Interpretation.xyz in ASCII format. Table 4-4 describes the data columns in these files.

A new table of data has been compiled (Table 4-5) that lists, model layer by model layer, the top, middle, and bottom depths and elevations of each model cell layer along with the inverted model resistivity for that cell.

ESRI Arc View Binary 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 4-6. And stored in Appendix 3_Deliverables\Grids.

The format of the voxel grids that have been created from the AEM data in the Aten, Bloomfield, Hartington, Menominee, and Santee Blocks is described in Table 4-7. The voxel grids are presented as xyz files.

In summary, the following are included as deliverables:

- Raw Data Files - SkyTEM files *.gex, *skb, *.lin
- Raw EM Mag data as ASCII *.xyz
- SCI inversion as ASCII *.xyz in array and an individual column format by model layer.
- Interpretations as ASCII *.xyz
- ESRI ArcView files – surface, topo, etc

- Voxel Grids in *.csv format
- 2D profiles and 3D fence diagrams of the AEM survey inversion results

KMZs for LCNRD AEM flight lines (Discussed in Section 4.2).

Table 4-1. 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 divided into SkyTEM 312 and 304M sub-folders
Geo	20180823_312_DualWaveform_60Hz_skb.gex 20180823_304_DualWaveform_60Hz_skb.gex 20181002_304_446_Nebraska_skb_SR2.gex 20181002_304_446_Nebraska_skb_SR2.sr2	304M, 312 System Description
Mask	20180613_446_NE304_LCNRD.lin 20180613_446_NE312_LCNRD.lin	Production file listing dates, flights, and assigned line numbers

Table 4-2: Channel name, description, and units for LCNRD2018_312_EM_MAG.xyz and LCNRD2018_304_EM_MAG.xyz with DEM, 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]
E_NESP83_ft	Easting, NAD83 Nebraska State Plane	Feet [ft]
N_NESP83N_ft	Northing, NAD83 Nebraska State Plane	Feet [ft]
DEM	Digital Elevation	Meters [m]
Alt	DGPS Altitude above sea level	Meters [m]
GDSpeedL	Ground Speed	Kilometers/hour [km/h]
Curr_LM	Current, Low Moment	Amps [A]
Curr_HM	Current, High Moment	Amps [A]
LMZ_G01	Normalized (PFC-Corrected) Low Moment Z-RxCoil values array	$pV/(m^4*A)$
HMZ_G01	Normalized (PFC-Corrected) High Moment Z-RxCoil values array	$pV/(m^4*A)$
HMX_G01	Normalized (PFC-Corrected) High Moment X-RxCoil values array	$pV/(m^4*A)$
PLNI	Power Line Noise Intensity monitor	V/m^2
Bmag	Raw Base Station Mag Data filtered	nanoTesla [nT]
MAG_Raw	Raw Mag Data	nanoTesla [nT]
Mag_ED	Mag filtered	nanoTesla [nT]
Diurnal	Diurnal Mag Data	nanoTesla [nT]
Mag_Cor	Mag Data Corrected for Diurnal Drift	nanoTesla [nT]
RMF	Residual Magnetic Field	nanoTesla [nT]
TMI	Total Magnetic Intensity	nanoTesla [nT]

Table 4-3. Channel name, description, and units for LCNRD2018_312_SCI_INV_v1.xyz and LCNRD2018_304_SCI_INV_pt1.xyz and …_pt2.xyz (from the LENRD) with EM inversion results.

/Parameter	Description	Unit
LINE	Line Number	
East_NESP83FT	Easting NAD83, Nebraska State Plane	Feet (ft)
North_NESP83FT	Northing NAD83, Nebraska State Plane	Feet [ft]
DEM_FT	DEM from 100 ft grid NED NAVD88	Feet [ft]
East_UTM_M	Easting NAD83, UTM Zone 14	Meters [m]
North_UTM_M	Northing NAD83, UTM Zone 14	Meters [m]
DEM_M	DEM from survey	Meters [m]
ALT_M	Altitude of system above ground	Meters [m]
INVALT_M	Inverted Altitude of system above ground	Meters [m]
RESDATA	Residual of individual sounding	
RESTOTAL	Total residual for inverted section	
RHO_I_0 THROUGH RHO_I_38	Inverted resistivity of each layer	Ohm-m
RHO_I_STD_0 THROUGH RHO_I_STD_38	Inverted resistivity error per layer	
SIGMA_I_0 THROUGH SIGMA_I_38	Conductivity	S/m
DEP_TOP_0_FT THROUGH DEP_TOP_38_FT	Depth to the top of individual layers	Feet [ft]
DEP_BOT_0_FT THROUGH DEP_BOT_38_FT	Depth to the bottom of individual layers	Feet [ft]
THK_0_FT THROUGH THK_38_FT	Thickness of individual layers	Feet [ft]
DEP_TOP_0_M THROUGH DEP_TOP_38_M	Depth to the top of individual layers	Meters [m]
DEP_BOT_0_M THROUGH DEP_BOT_38_M	Depth to the bottom of individual layers	Meters [m]
THK_0_M THROUGH THK_38_M	Thickness of individual layers	Meters [m]
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]

Table 4-4. Channel name description and units for the interpretation results files LCNRD 2018 InterpSurfaces *.xyz files.

Parameter	Description	Unit
LINE	Line Number	
East_M	Easting NAD83, UTM Zone 14N	Meters (m)
North_M	Northing NAD83, UTM Zone 14N	Meters (m)
East_ft	Easting NAD83, Nebraska State Plane	Feet [ft]
North_ft	Northing NAD83, Nebraska State Plane	Feet [ft]
DEM_ft	Topography at 100ft sampling (NAVD 1988)	Feet [ft]
RHO [0] through RHO [38]	Array of Inverted model resistivities of each layer	Ohm-m
RESDATA	Inversion model residuals of each individual sounding	
RESTOTAL	Inversion model average of all residuals	
DEP_TOP_FT [0] through DEP_TOP_FT [38]	Depth to the top of 39 individual layers (not all arrays have 39 values)	Feet [ft]
DEP_BOT_FT [0] through DEP_BOT_FT [38]	Depth to the bottom of 39 individual layers (not all arrays have 39 values)	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]
SoilRecharge	1 = Surficial layer Aquifer Material or Coarse Aquifer Material; 0 = Non-Aquifer or Marginal Material	
WaterTable1995	Elevation of the top of the water table from the Nebraska School of Natural Resources Configuration Report, 1995.	Feet [ft]
NAT[0] through NAT[38]	Array of model cell top elevations of the Non-Aquifer Material (<12 ohm-m), if present	Feet [ft]
NAB[0] through NAB[38]	Array of model cell bottom elevations of the Non-Aquifer Material (<12 ohm-m), if present	Feet [ft]
ThkTot_NAq	Total Thickness of Non-Aquifer Material (<12 ohm-m) above bedrock	Feet [ft]
ThkWT_NAq	Total Thickness of Non-Aquifer Material (<12 ohm-m) below the water table and above bedrock	Feet [ft]
MAT[0] through MAT[38]	Array of model cell top elevations of the Marginal-Aquifer Material (12 - 20 ohm-m), if present	Feet [ft]
MAB[0] through MAB[38]	Array of model cell bottom elevations of the Marginal-Aquifer Material (12 - 20 ohm-m), if present	Feet [ft]
ThkTot_MAq	Total Thickness of Marginal-Aquifer Material (12 - 20 ohm-m) above bedrock	Feet [ft]
AMT[0] through AMT[38]	Array of model cell top elevations of the Aquifer Material (20 - 50 ohm-m), if present	Feet [ft]
AMB[0] through AMB[38]	Array of model cell bottom elevations of the Aquifer Material (20 - 50 ohm-m), if present	Feet [ft]
ThkTot_AqM	Total Thickness of Aquifer Material (20 - 50 ohm-m) above bedrock	Feet [ft]
CAT[0] through CAT[38]	Array of model cell top elevations of the Coarse Aquifer Material (>50 ohm-m), if present	Feet [ft]
CAB[0] through CAB[38]	Array of model cell bottom elevations of the Coarse Aquifer Material (>50 ohm-m), if present	Feet [ft]
ThkTot_CAq	Total Thickness of Coarse Aquifer Material (>50 ohm-m) above bedrock	Feet [ft]
ThkTot_Aq_CA	Sum of Total Thicknesses of Aquifer Material (20 - 50 ohm-m) and Coarse Aquifer Material (>50 ohm-m) above bedrock	Feet [ft]
ThkWT_Aq_CA	Sum of Total Thicknesses of Aquifer Material (20 - 50 ohm-m) and Coarse Aquifer Material (>50 ohm-m) below the water table and above bedrock	Feet [ft]
To	Elevation of the top of the Tertiary Ogallala Fm., if present	Feet [ft]

Bedrock	Elevation of interpreted bedrock surface	Feet [ft]
Kp	Elevation of the top of the Cretaceous Pierre Shale, if present	Feet [ft]
Kn	Elevation of the top of the Cretaceous Niobrara Shale, if present	Feet [ft]
Kc	Elevation of the top of the Cretaceous Carlile Shale, if present	Feet [ft]
Kgg	Elevation of the top of the Cretaceous Greenhorn Limestone and Graneros Shale, if present	Feet [ft]
Kd	Elevation of the top of the Cretaceous Dakota Group, if present	Feet [ft]
IP	Elevation of the top of the Undifferentiated Pennsylvanian, if present	Feet [ft]

Table 4-5. LCNRD Inverted Model Structure with DEM and Layer Top-, Bottom-, and Mid-points in Depth and Elevation plus Inverted Cell Resistivities (LCNRD_XYDEM_Dep_Elev_Rho.xyz).

Parameter	Description	Unit
Line	Line number	
East_ft	Easting NAD83, Nebraska State Plane	Feet [ft]
North_ft	Northing NAD83, Nebraska State Plane	Feet [ft]
DEM_ft	Topography at 100ft sampling (NAVD 1988)	Feet [ft]
Dep_Top_ft		Feet [ft]
Dep_Mid_ft		Feet [ft]
Dep_Bot_ft		Feet [ft]
Elev_Top_ft		Feet [ft]
Elev_Mid_ft		Feet [ft]
Elev_Bot_ft		Feet [ft]
RHO	Cell Resistivity	Ohm-m

Table 4-6. Files containing ESRI ArcView Binary Grids *.flt (Nebraska State Plane, NAD83, feet)

Grid File Name	Description	Grid Cell Size (feet)
LCRND_DEM_ft	Digital Elevation Model (ground surface elevation) (NAVD88 feet) of the LCNRD survey area, NAD83/State Plane Nebraska, feet	100
LCNRD_WT_1995	Elevation (NAVD88 feet) of water table (1995) for the LCNRD survey area, NAD83/State Plane Nebraska, feet	100
LCNRD_Top_Bedrock	Elevation (NAVD88 feet) of top of bedrock for the LCNRD survey area, NAD83/State Plane Nebraska, feet	100
LCNRD_Top_To	Elevation (NAVD88 feet) of top of Tertiary Ogallala (To) for the LCNRD survey area, NAD83/State Plane Nebraska, feet	100
LCNRD_Top_Kp	Elevation (NAVD88 feet) of top of Cretaceous Pierre (Kp) for the LCNRD survey area, NAD83/State Plane Nebraska, feet	100
LCNRD_Top_Kn	Elevation (NAVD88 feet) of top of Cretaceous Niobrara (Kn) for the LCNRD survey area, NAD83/State Plane Nebraska, feet	100
LCNRD_Top_Kc	Elevation (NAVD88 feet) of top of Cretaceous Carlile for the LCNRD survey area, NAD83/State Plane Nebraska, feet	100
LCNRD_Top_Kgg	Elevation (NAVD88 feet) of top of Cretaceous Greenhorn-Graneros (Kgg) for the LCNRD survey area, NAD83/State Plane Nebraska, feet	100
LCNRD_Top_Kd	Elevation (NAVD88 feet) of top of Cretaceous Dakota Group (Kd) for the LCNRD survey area, NAD83/State Plane Nebraska, feet	100
LCNRD_Top_IP	Elevation (NAVD88 feet) of top of undifferentiated Pennsylvanian (IP) for the LCNRD survey area, NAD83/State Plane Nebraska, feet	100
LCNRD_Thickness_Q	Thickness (feet) of Quaternary Deposits for the LCNRD survey area, NAD83/State Plane Nebraska, feet	100
LCNRD_SaturatedThickness_Q	Saturated Thickness (feet) of Quaternary Deposits for the LCNRD survey area, NAD83/State Plane Nebraska, feet	100
LCNRD_Thickness_Kd	Thickness (feet) of Cretaceous Dakota Group (Kd) for the LCNRD survey area, NAD83/State Plane Nebraska, feet	100

Aten_Coarse_Aquifer_SaturatedThickness	Saturated thickness (feet) of aquifer and coarse aquifer Quaternary material for the Aten Block survey area, NAD83/State Plane Nebraska, feet	100
Aten_Coarse_Aquifer_TotalThickness	Total thickness (feet) of aquifer and coarse aquifer Quaternary material for the Aten Block survey area, NAD83/State Plane Nebraska, feet	100
Aten_Coarse_TotalThickness	Total thickness (feet) of coarse aquifer Quaternary material for the Aten Block survey area, NAD83/State Plane Nebraska, feet	100
Aten_Kd_Sandstone_Sand_Thickness	Total thickness (feet) of Cretaceous Dakota Group sand/sandstone dominant material for the Aten Block survey area, NAD83/State Plane Nebraska, feet	100
Aten_Non_Marginal_SaturatedThickness	Saturated thickness (feet) of non-aquifer and marginal Quaternary material for the Aten Block survey area, NAD83/State Plane Nebraska, feet	100
Aten_Non_Marginal_TotalThickness	Total thickness (feet) of non-aquifer and marginal Quaternary material for the Aten Block survey area, NAD83/State Plane Nebraska, feet	100
Bloomfield_Coarse_Aquifer_SaturatedThickness	Saturated thickness (feet) of aquifer and coarse aquifer Quaternary material for the Bloomfield Block survey area, NAD83/State Plane Nebraska, feet	100
Bloomfield_Coarse_Aquifer_TotalThickness	Total thickness (feet) of aquifer and coarse aquifer Quaternary material for the Bloomfield Block survey area, NAD83/State Plane Nebraska, feet	100
Bloomfield_Non_Marginal_SaturatedThickness	Saturated thickness (feet) of non-aquifer and marginal Quaternary material for the Bloomfield Block survey area, NAD83/State Plane Nebraska, feet	100
Bloomfield_Non_Marginal_TotalThickness	Total thickness (feet) of non-aquifer and marginal Quaternary material for the Bloomfield Block survey area, NAD83/State Plane Nebraska, feet	100
Hartington_Coarse_Aquifer_SaturatedThickness	Saturated thickness (feet) of aquifer and coarse aquifer Quaternary material for the Hartington Block survey area, NAD83/State Plane Nebraska, feet	100
Hartington_Coarse_Aquifer_TotalThickness	Total thickness (feet) of aquifer and coarse aquifer Quaternary material for the Hartington Block survey area, NAD83/State Plane Nebraska, feet	100
Hartington_Coarse_TotalThickness	Total thickness (feet) of coarse aquifer Quaternary material for the Hartington Block survey area, NAD83/State Plane Nebraska, feet	100

Hartington_Non_Marginal_SaturatedThickness	Saturated thickness (feet) of non-aquifer and marginal Quaternary material for the Hartington Block survey area, NAD83/State Plane Nebraska, feet	100
Menominee_Coarse_Aquifer_SaturatedThickness	Saturated thickness (feet) of aquifer and coarse aquifer Quaternary material for the Menominee Block survey area, NAD83/State Plane Nebraska, feet	100
Menominee_Coarse_Aquifer_TotalThickness	Total thickness (feet) of aquifer and coarse aquifer Quaternary material for the Menominee Block survey area, NAD83/State Plane Nebraska, feet	100
Menominee_Coarse_TotalThickness	Total thickness (feet) of coarse aquifer Quaternary material for the Menominee Block survey area, NAD83/State Plane Nebraska, feet	100
Menominee_Non_Marginal_SaturatedThickness	Saturated thickness (feet) of non-aquifer and marginal Quaternary material for the Menominee Block survey area, NAD83/State Plane Nebraska, feet	100
Menominee_Non_Marginal_TotalThickness	Total thickness (feet) of non-aquifer and marginal Quaternary material for the Menominee Block survey area, NAD83/State Plane Nebraska, feet	100
Santee_AquiferMaterial_SaturatedThickness	Saturated thickness (feet) of aquifer Quaternary material for the Santee Block survey area, NAD83/State Plane Nebraska, feet	100
Santee_Coarse_Aquifer_TotalThickness	Total thickness (feet) of aquifer and coarse aquifer Quaternary material for the Santee Block survey area, NAD83/State Plane Nebraska, feet	100
Santee_Coarse_TotalThickness	Total thickness (feet) of coarse aquifer Quaternary material for the Santee Block survey area, NAD83/State Plane Nebraska, feet	100
Santee_Non_Marginal_SaturatedThickness	Saturated thickness (feet) of non-aquifer and marginal Quaternary material for the Santee Block survey area, NAD83/State Plane Nebraska, feet	100
Santee_Non_Marginal_TotalThickness	Total thickness (feet) of non-aquifer and marginal Quaternary material for the Santee Block survey area, NAD83/State Plane Nebraska, feet	100

Table 4-7. Voxel channel name, description, and units for Aten, Bloomfield, Hartington, Menominee, and Santee voxel *.xyz. The cell size is 100 feet for Menominee and 250 feet for the remaining voxels.

Parameter	Description	Unit
X	Easting NAD83, State Plane Nebraska	feet [ft]
Y	Northing NAD83, State Plane Nebraska	feet [ft]
Z	Depth of Voxel Node	feet [ft]
Resistivity	Voxel cell resistivity value	Ohm-m

4.2 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\KMZ\FlightLines*".

Unique KMZ files were created for each individual flight line in approximately 10-mile segments or shorter. 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 as well as bedrock and the 1995 water table. These KMZ files are located within the "*Appendix_3_Deliverables\KMZ\Interpretation\LCNRD_Profiles*" folder. In this folder is a "*GoogleE_Readme.pdf*" file that provides instructions regarding 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. This LCNRD GoogleE_Readme.pdf file is repeated below as a convenience. All the LCNRD interpretation KMZ's are presented in Figure 4-1 and interpretation dialogue boxes for the individual block flight areas and the recon flights follow.

4.2.1 Included README for the LCNRD Interpretation KMZ's

README for:

LCNRD Reconnaissance Interpretative kmz (in 3 part)
Aten_Interpretative.kmz
Bloomfield_Interpretative.kmz
Coleridge_Interpretative.kmz
Creighton_Interpretative.kmz
Hartington_Interpretative.kmz
Lindy_Interpretative.kmz
Menominee_Interpretative.kmz
Obert_Interpretative.kmz
Santee_Interpretative.kmz

Data Files - Please copy the folder *LCNRD_Profiles* to your C:\ drive. Do not rename any of the images 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 2018 Interpretation kmz files within the folder named *LCNRD_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 State Plane, in feet

North (ft) – Northing coordinate in NAD83, Nebraska State Plane, in feet

Elevation (ft) – Digital Elevation Model (DEM) elevation in feet

Soil Recharge – 1=Non-Aquifer Material on Surface; 2 = Margin Aquifer Material on Surface, 3 = Aquifer Material on Survey, 4 = Coarse Aquifer Material on Surface.

WaterTable1995 Elev (ft) – 1995 Water Table elevation, in feet

ThkTot_NAq (ft) – Total Thickness of Non-Aquifer Material (<12 ohm-m) above bedrock

ThkWT_NAq (ft) – Total Thickness of Non-Aquifer Material (<12 ohm-m) below the water table and above bedrock

ThkTot_MAq (ft) – Total Thickness of Marginal-Aquifer Material (12 - 20 ohm-m) above bedrock

ThkTot_AqM (ft) – Total Thickness of Aquifer Material (20 - 50 ohm-m) above bedrock

ThkTot_CAq (ft) – Total Thickness of Coarse Aquifer Material (>50 ohm-m) above bedrock

ThkTot_Aq_CA (ft) – Total Thicknesses of Aquifer Material (20 - 50 ohm-m) and Coarse Aquifer Material (>50 ohm-m) above bedrock.

ThkWT_Aq_CA (ft) - Total Thicknesses of Aquifer Material (20 - 50 ohm-m) and Coarse Aquifer Material (>50 ohm-m) below the water table and above bedrock

Elevation To (ft) – Elevation of Tertiary Ogallala Fm (if present), in feet

Bedrock (ft) – Elevation of Bedrock surface, in feet

Elevation Kp (ft) – Elevation of Cretaceous Pierre Shale (if present), in feet

Elevation Kn (ft) – Elevation of Cretaceous Niobrara Shale (if present), in feet

Elevation Kc (ft) – Elevation of Cretaceous Carlile Shale (if present), in feet.

Elevation Kgg (ft) – Elevation of Cretaceous Greenhorn Limestone and Graneros Shale Formation (if present), in feet.

Elevation Kd (ft) – Elevation of Cretaceous Dakota Group, in feet.

Elevation IP (ft) – Elevation of Undifferentiated Pennsylvanian units, in feet.

Profile – Link to Interpreted AEM profile images.

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

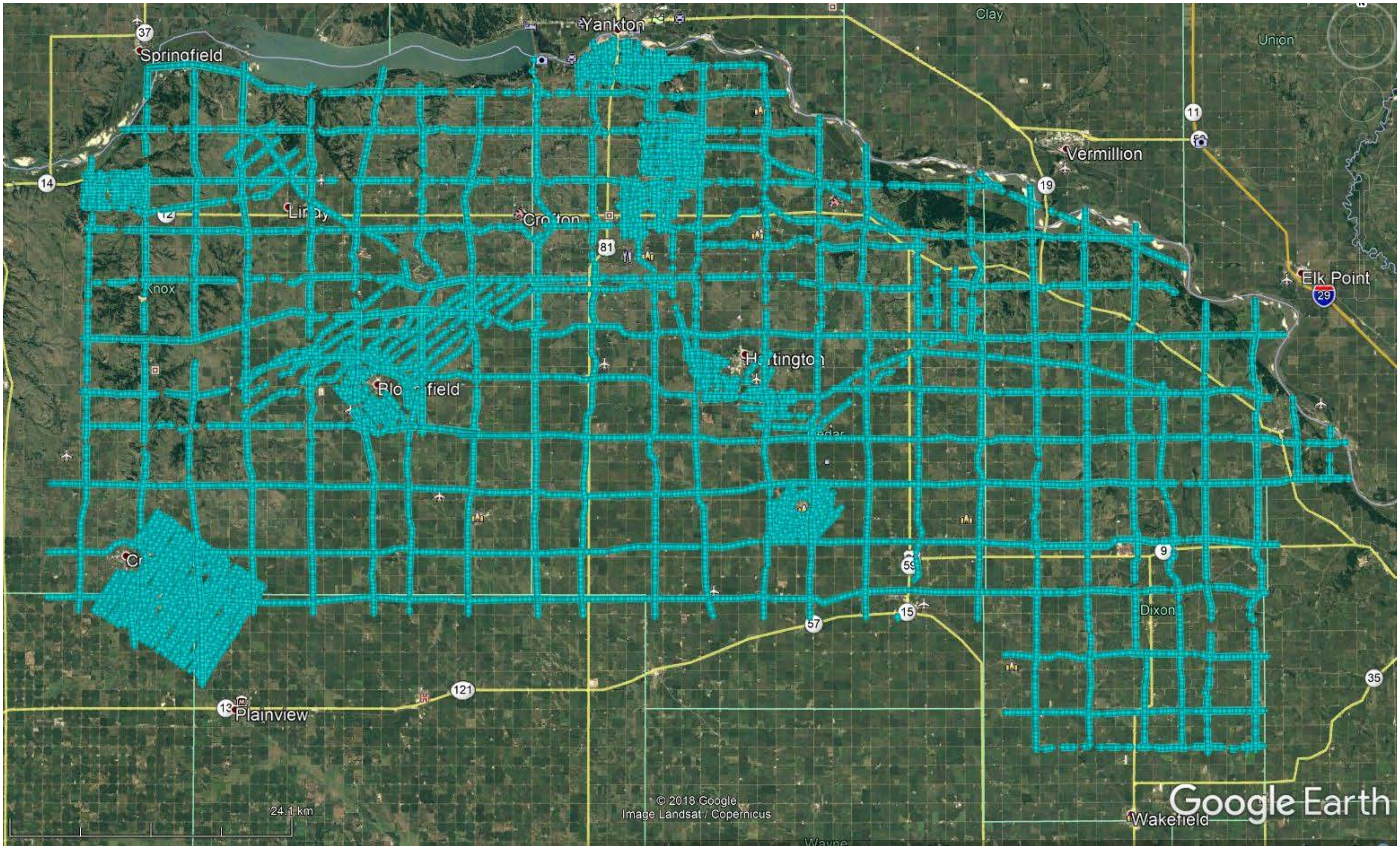


Figure 4-1. Google Earth image of the 2018 LCNRD Interpretation kmz's.

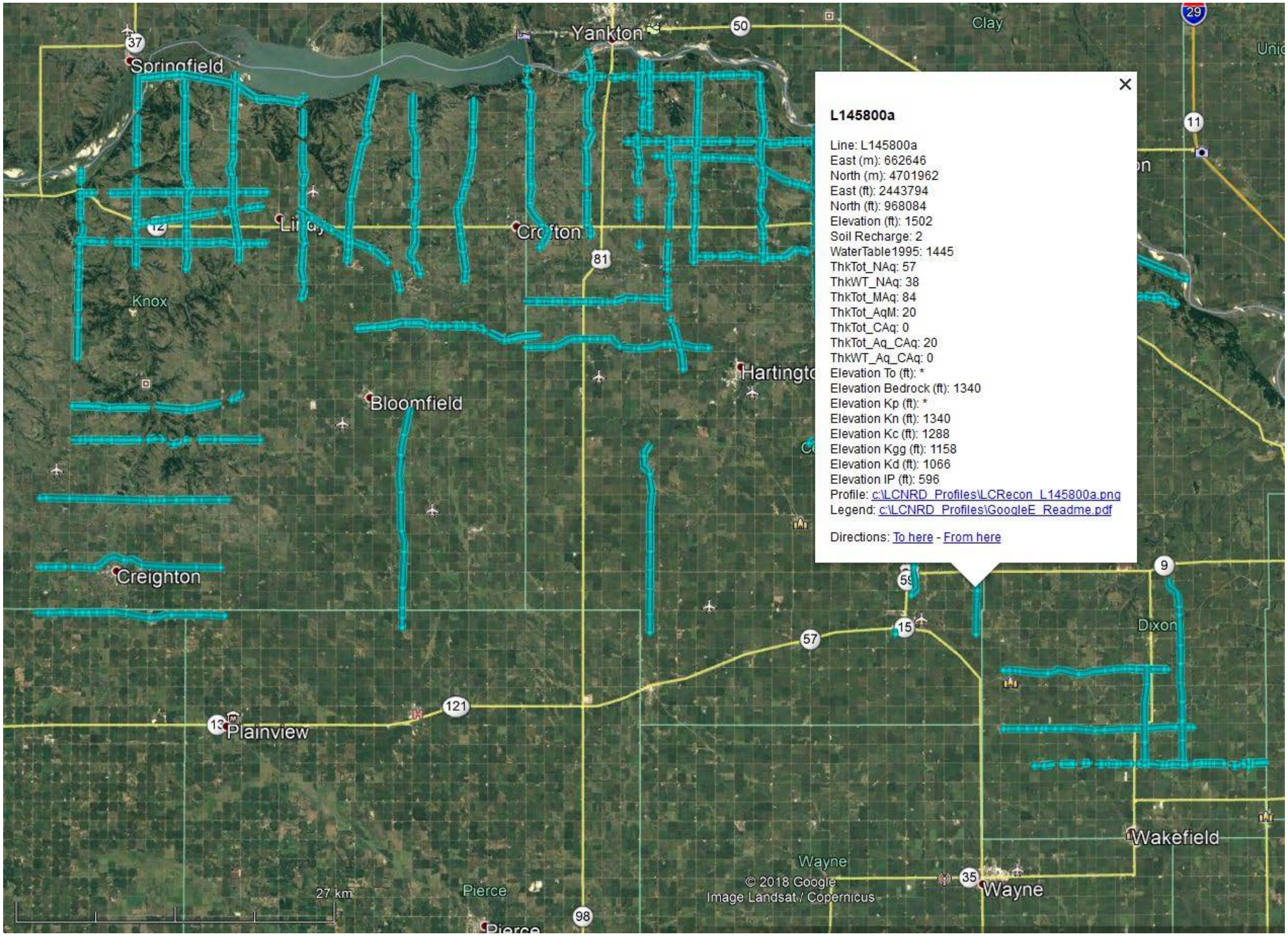


Figure 4-2. Example Google Earth image for the LCNRD Reconnaissance Interpretation kmz, part 1, showing location attributes.

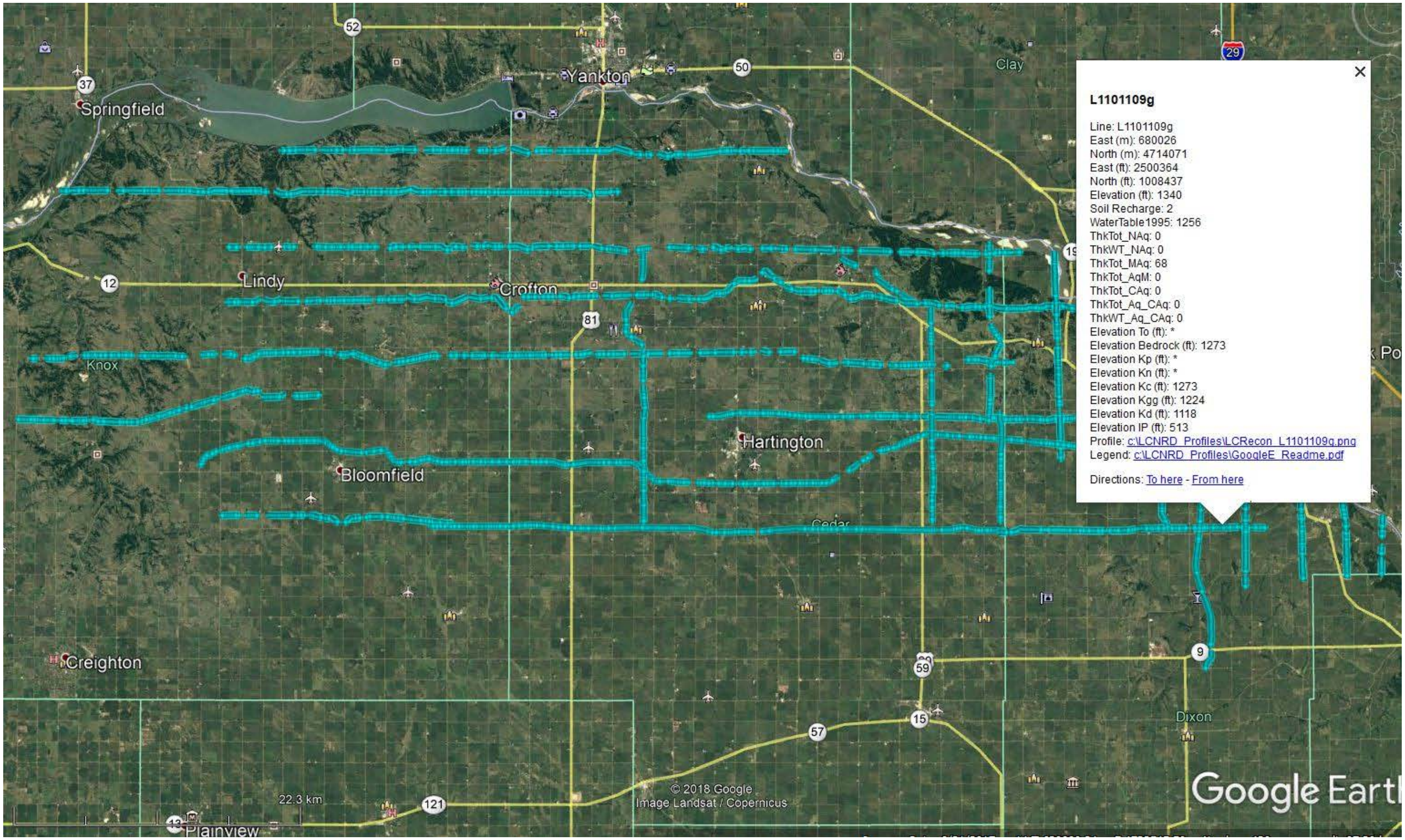


Figure 4-3. Example Google Earth image for the LCNRD Reconnaissance Interpretation kmz, part 2, showing location attributes.

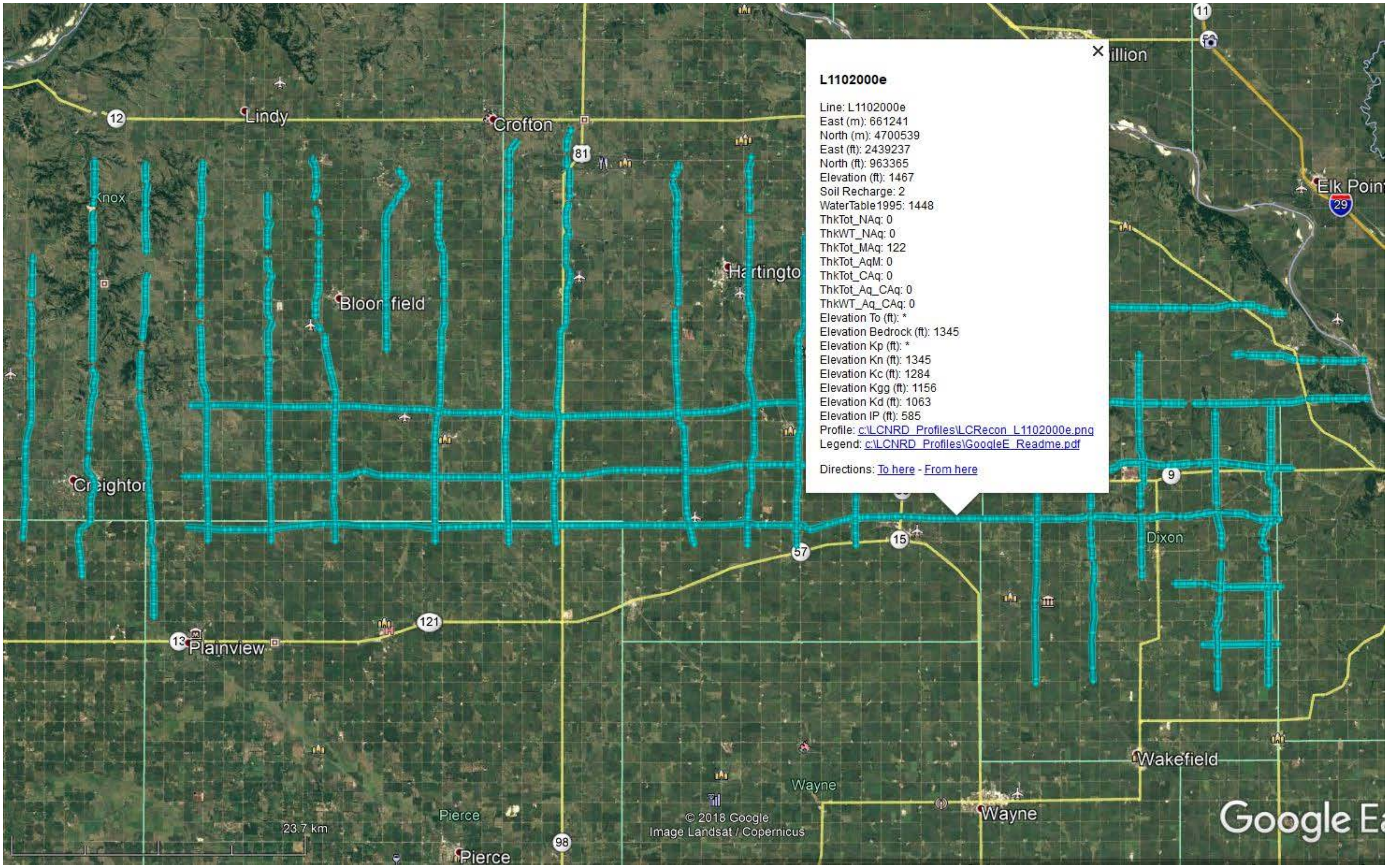


Figure 4-4. Example Google Earth image for the LCNRD Reconnaissance Interpretation kmz, part 3, showing location attributes.

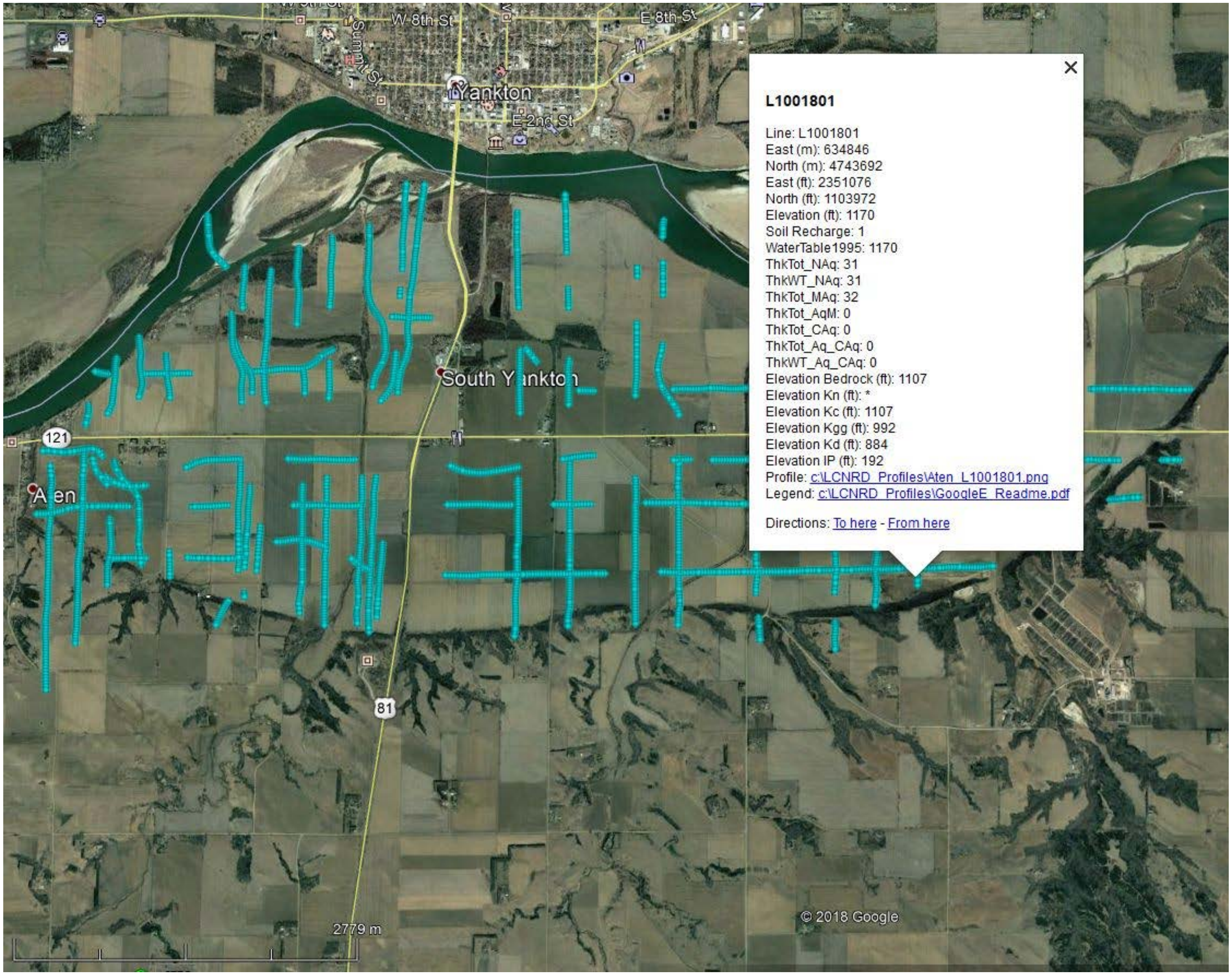


Figure 4-5. Example Google Earth image for the Aten Block Interpretation kmz showing location attributes.

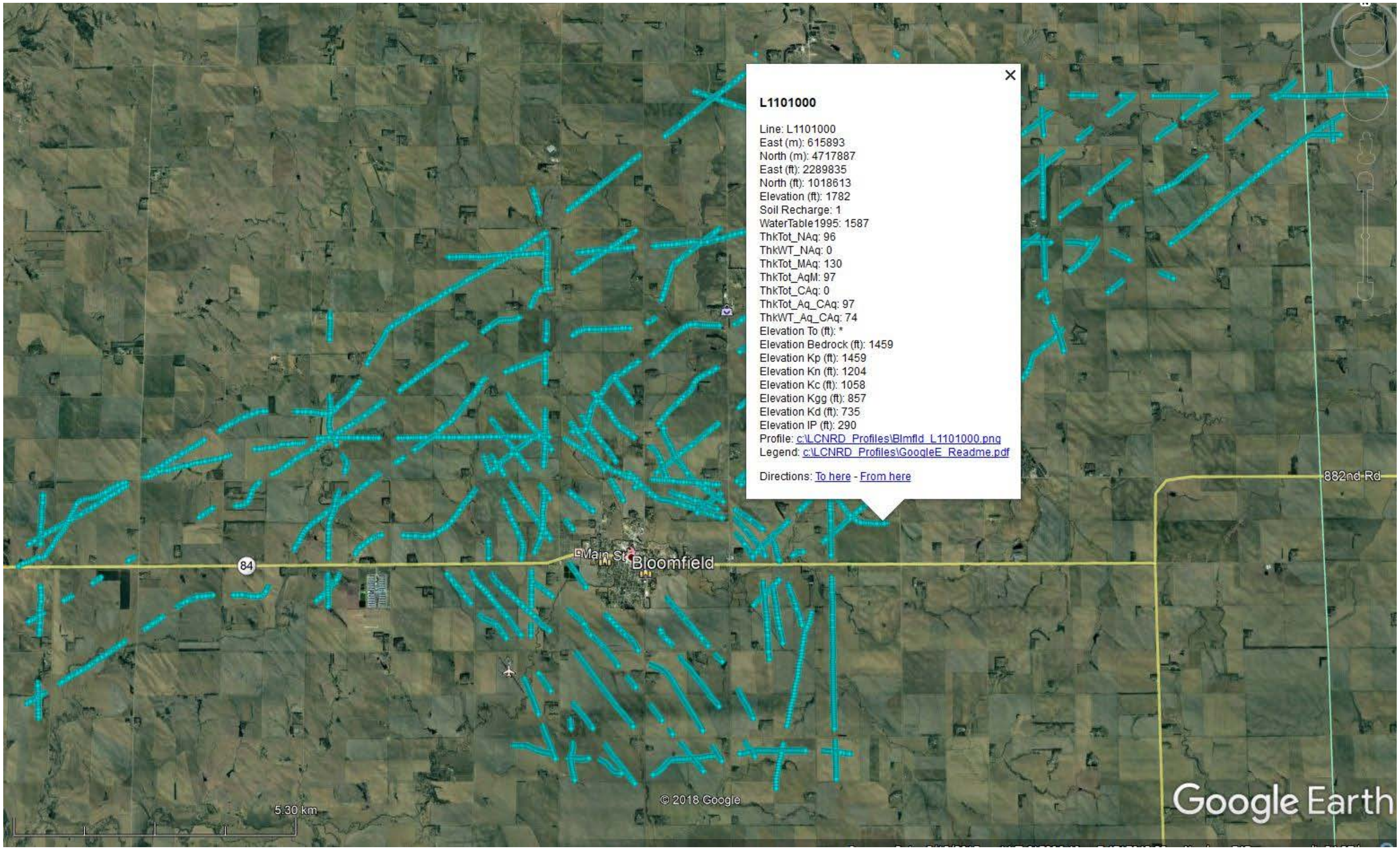


Figure 4-6. Example Google Earth image for the Bloomfield Block Interpretation kmz showing location attributes.

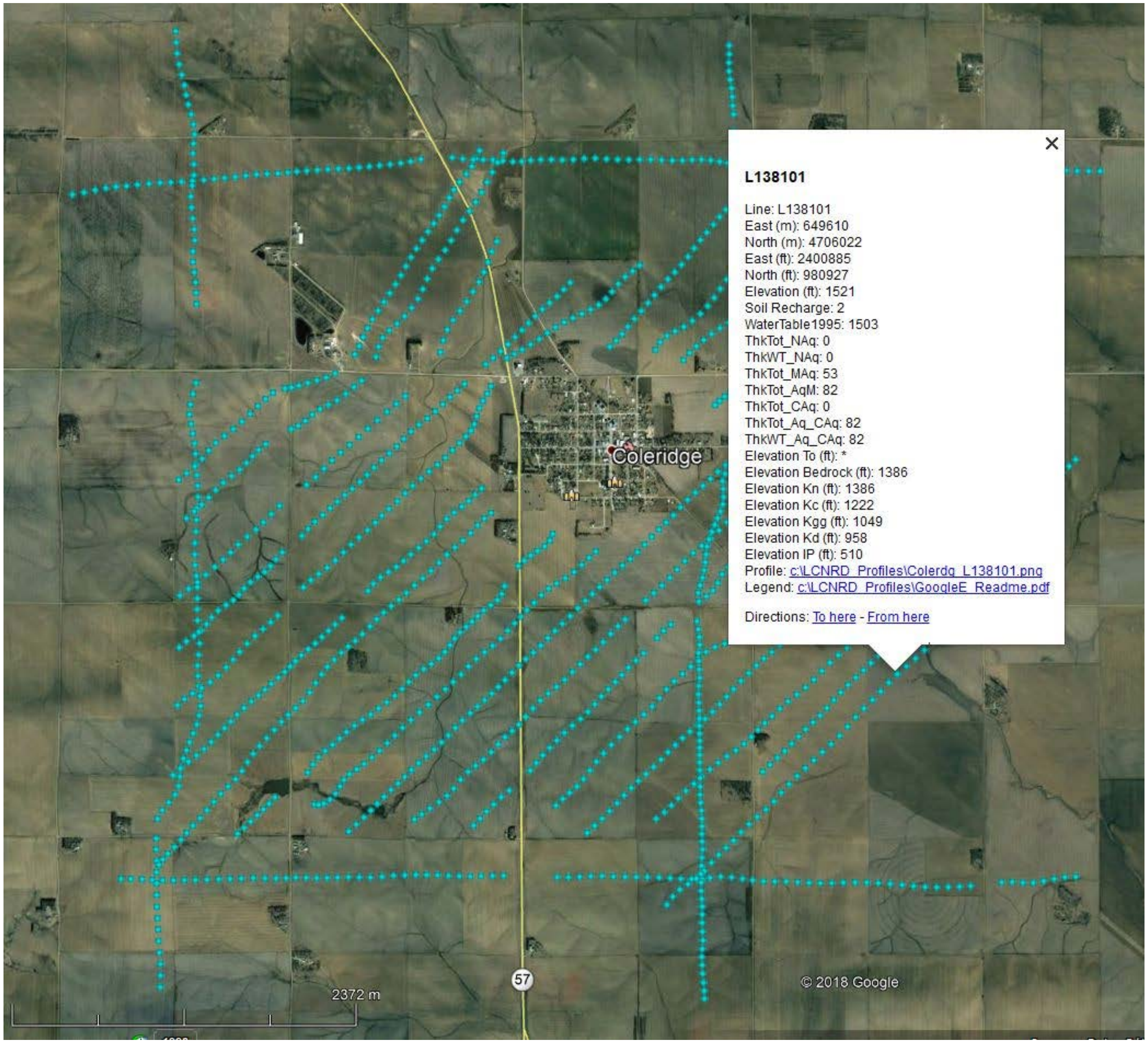


Figure 4-7. Example Google Earth image for the Coleridge Block Interpretation kmz showing location attributes.

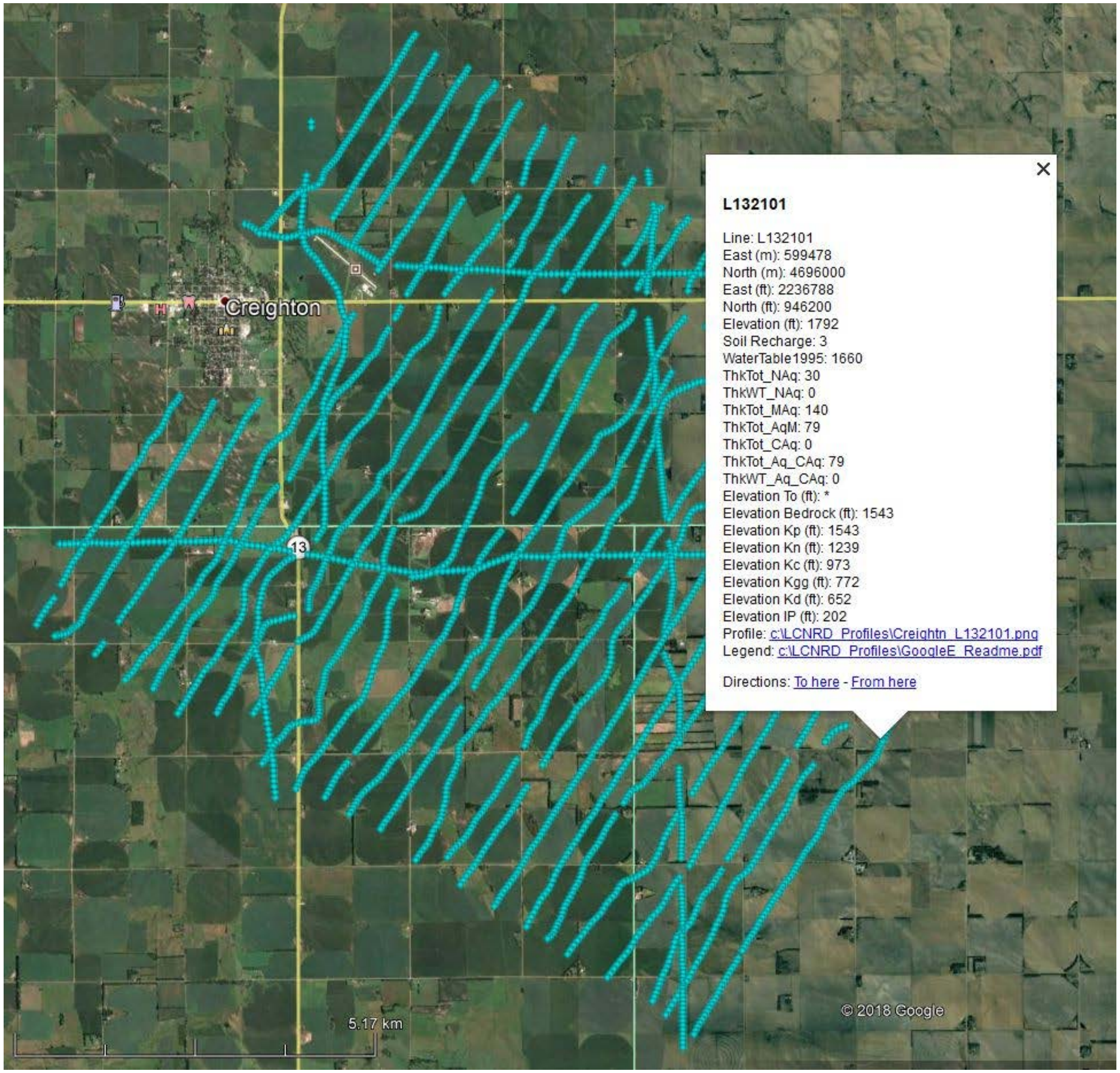


Figure 4-8. Example Google Earth image for the Creighton Block Interpretation kmz showing location attributes.

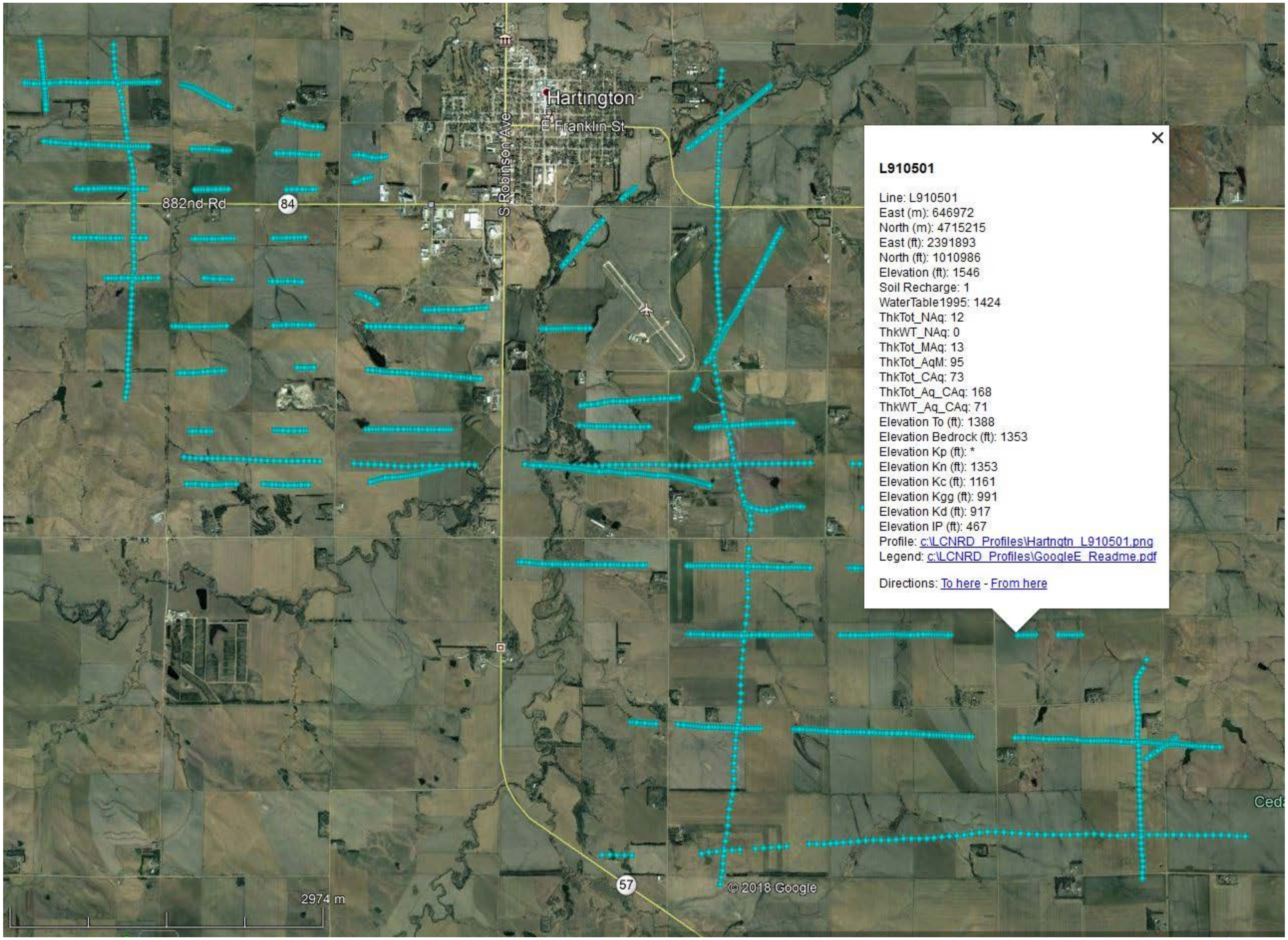


Figure 4-9. Example Google Earth image for the Hartington Block Interpretation kmz showing location attributes.

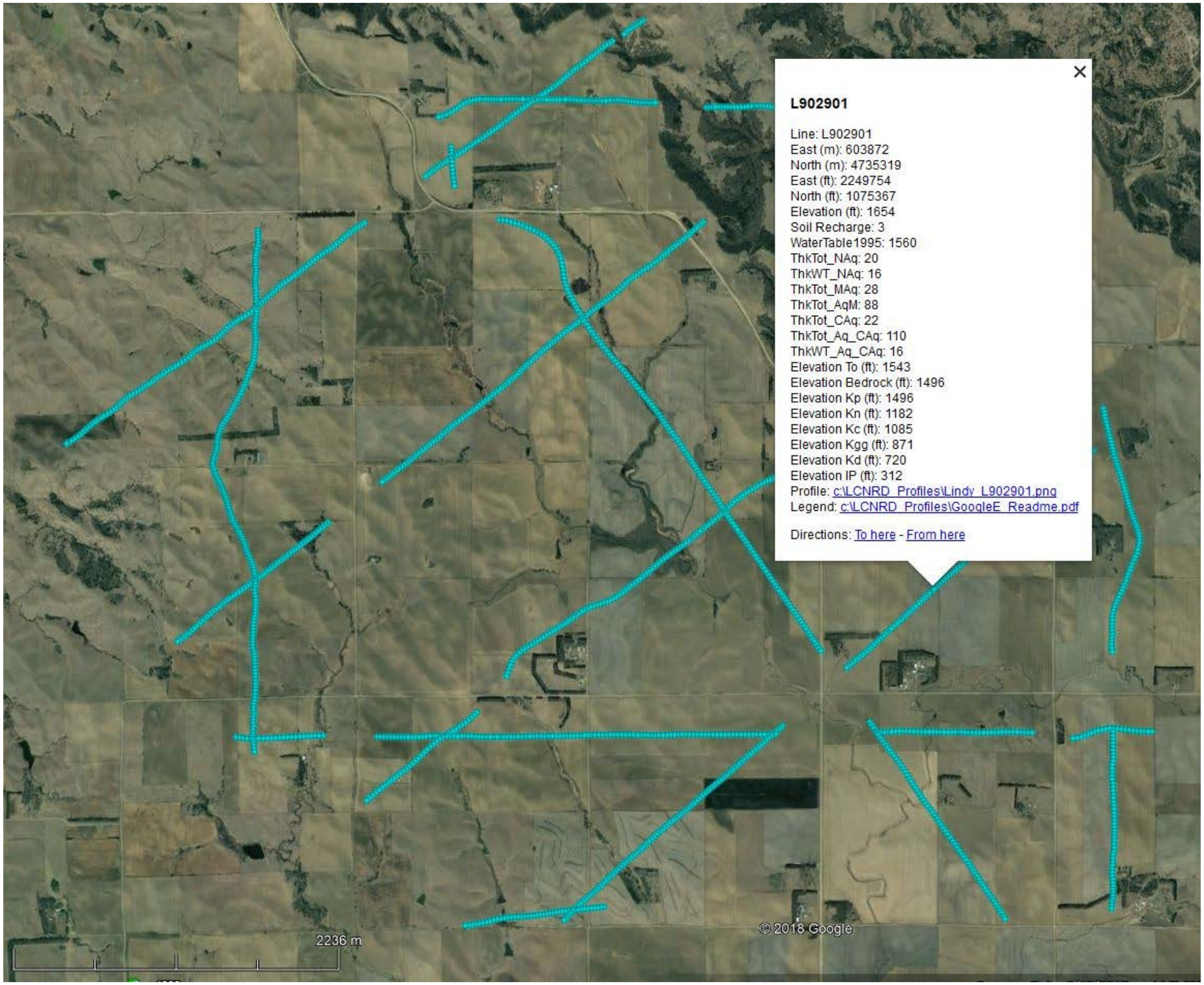


Figure 4-10. Example Google Earth image for the Lindy Block Interpretation kmz showing location attributes.

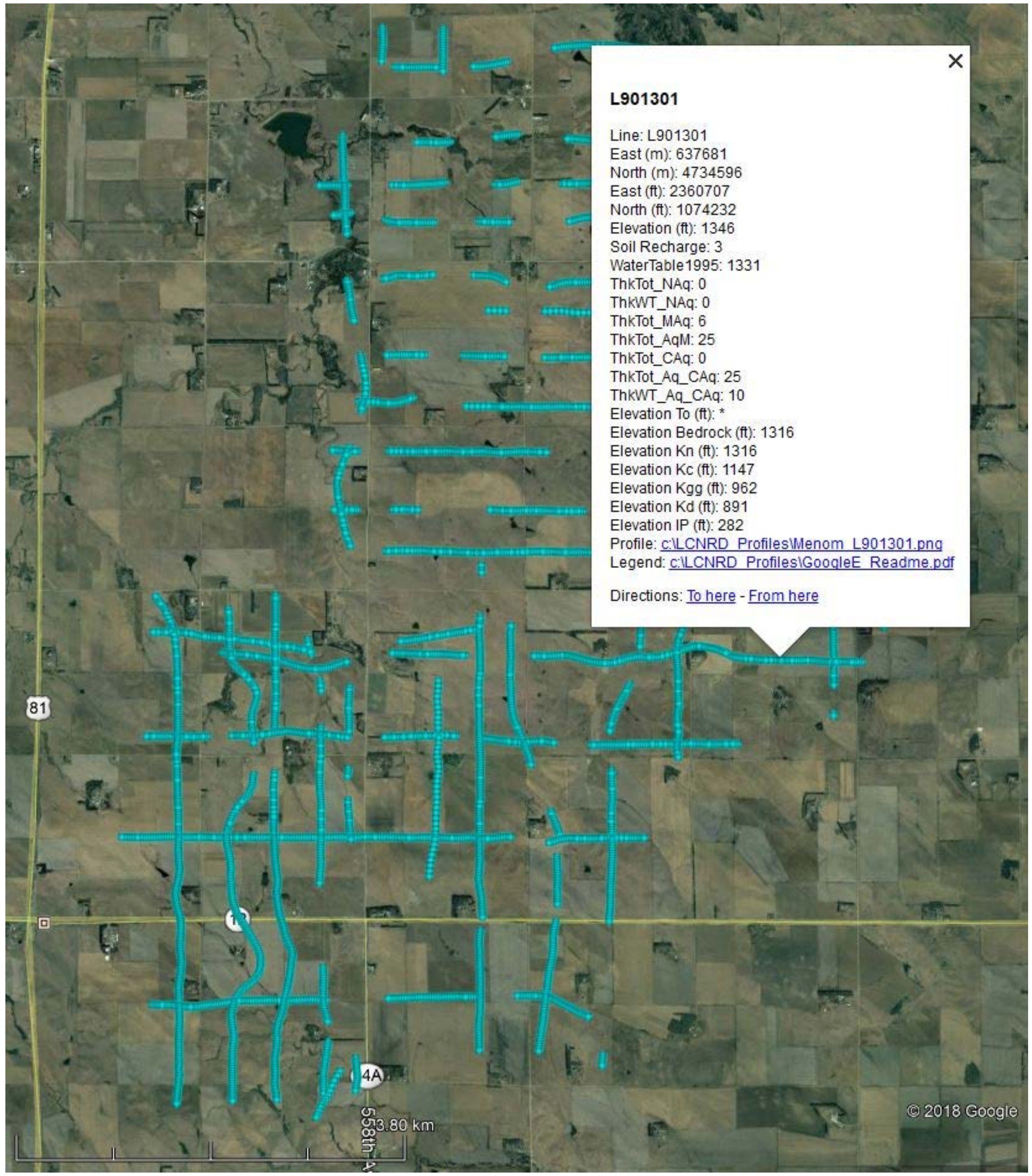


Figure 4-11. Example Google Earth image for the Menominee Block Interpretation kmz showing location attributes.

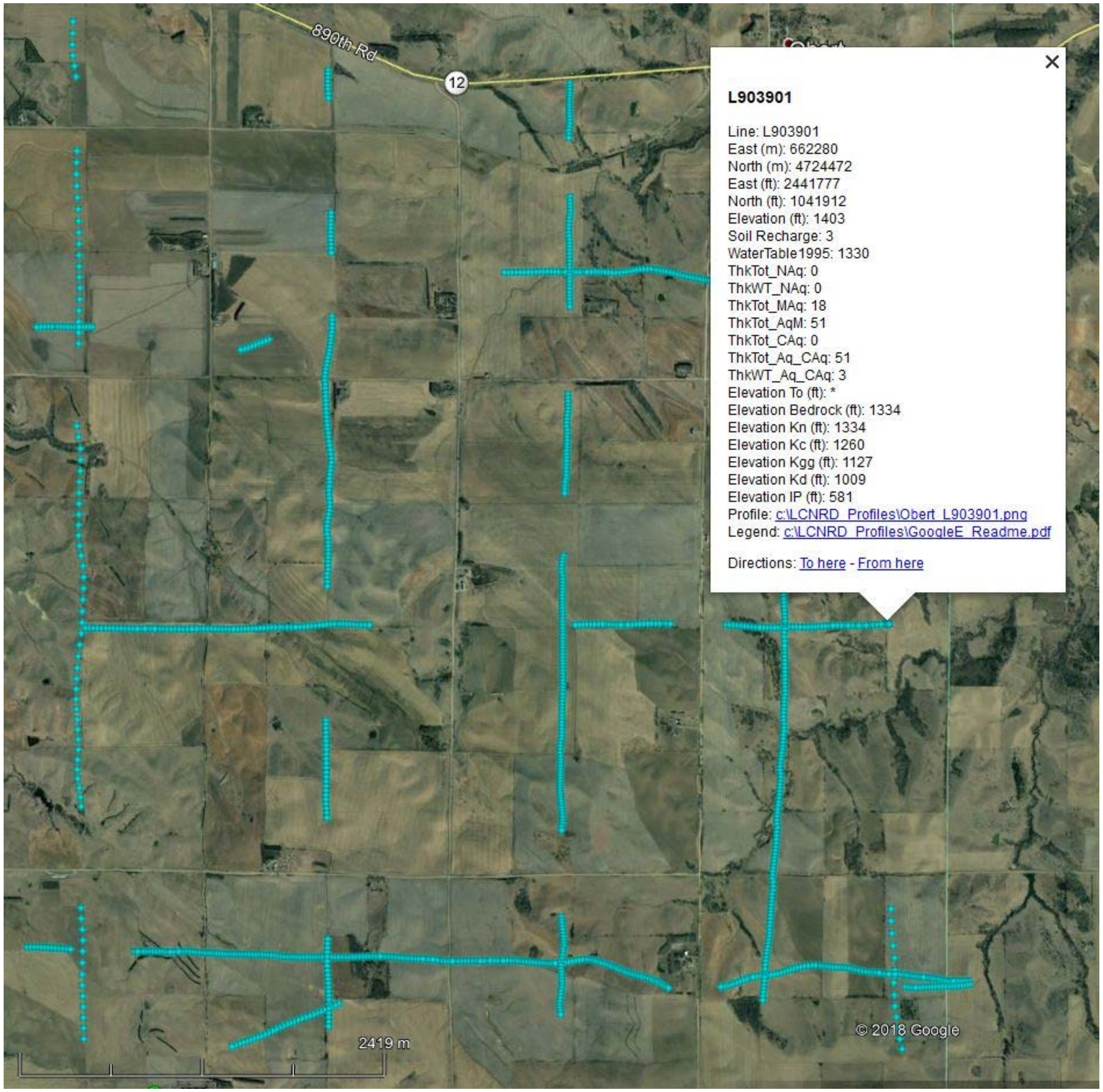


Figure 4-12. Example Google Earth image for the Obert Block Interpretation kmz showing location attributes.

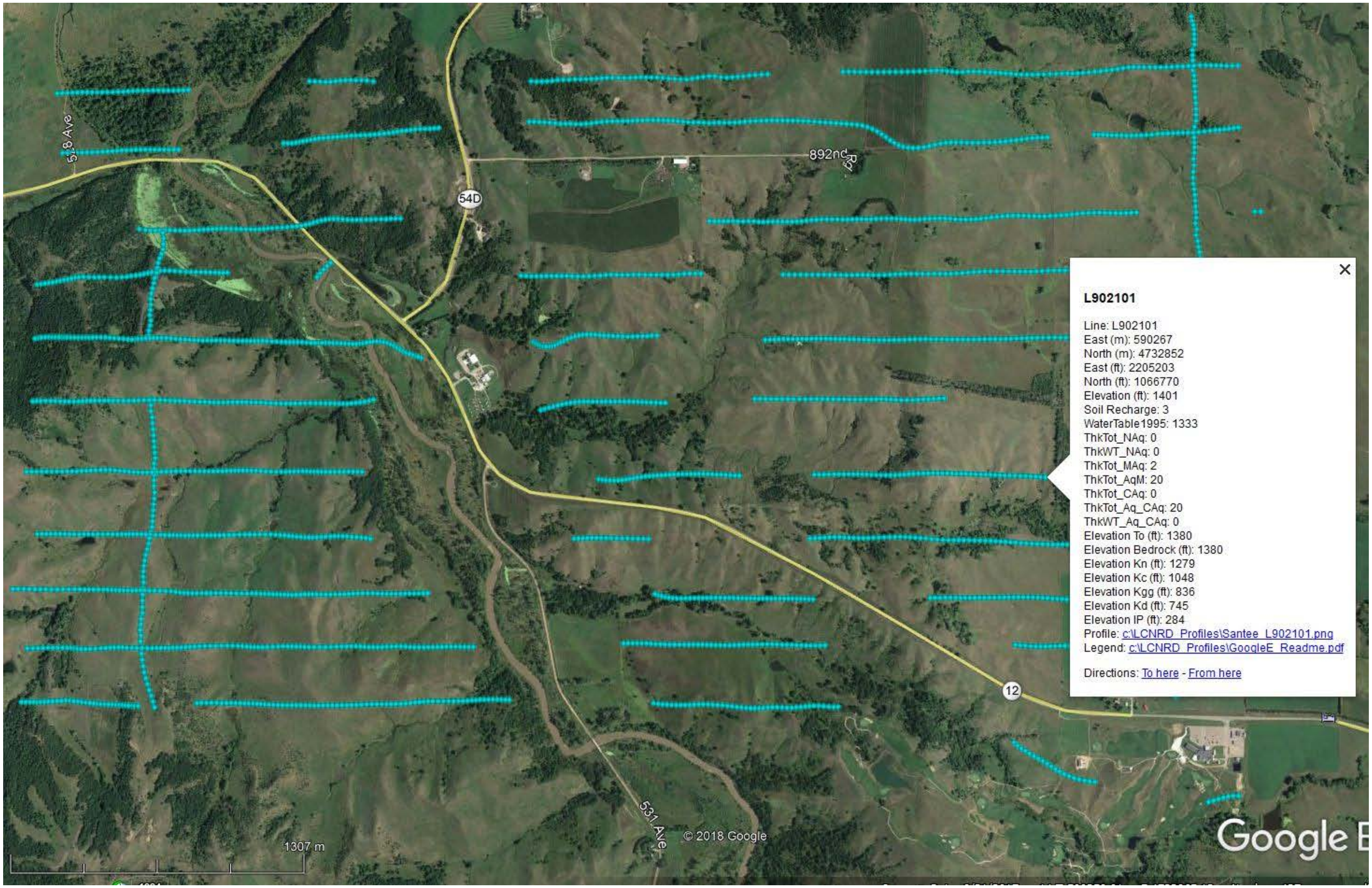


Figure 4-13. Example Google Earth image for the Santee Block Interpretation kmz showing location attributes.

5 References

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