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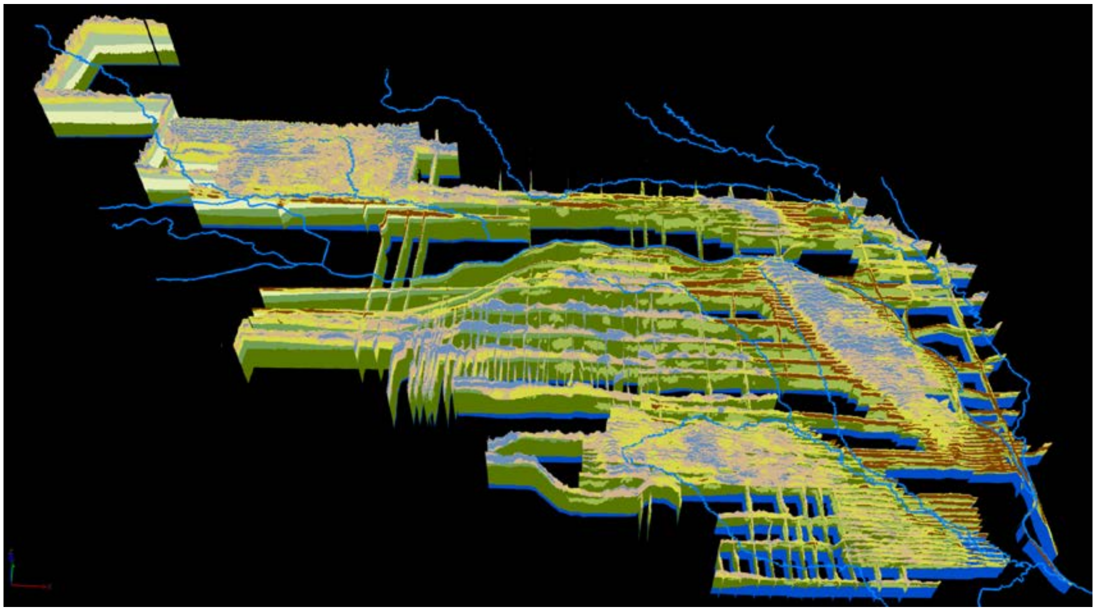
"Airborne Electromagnetic Mapping and Hydrogeologic Framework of Selected Regions of the Eastern Nebraska Water Resources Assessment Area" Chapter on the Lower Platte North Natural Resources District, v.3



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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 Lower Platte North 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) to collect, process, and interpret airborne electromagnetic (AEM) data, in conjunction with other available background information, to develop a 3D hydrogeologic framework of the Lower Platte North Natural Resources District (LPNNRD) 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 system was flown over the LPNNRD 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 and the ENWRA. This work included flight planning, database development, and review of hydrogeologic and geologic work for the area. The LPNNRD assisted in providing information such as power line maps, test hole databases, and related aquifer characteristic studies, if available.

1.3 Upon conclusion of the design process the LPNNRD reconnaissance flight lines had a maximum of approximately 52 miles (85 km) in length in the east-west direction and about 20 miles (33 km) at their longest in the north-south direction. The reconnaissance flight lines were separated by approximately 2.5 miles (4 km) in both east-west and north-south directions and block flight lines were separated by about 1500 feet to 2,000 feet (450 m – 600 m). Two block flight were flown in the area of Leshara Uplands and Waann with a line spacing of approximately 2,000 feet (~609 meters).

1.4 AGF acquired AEM data over the LPNNRD, commencing 26 June 2018 and finishing on 14 July 2018, to support development of the hydrogeological framework. During this time frame data were collected in other adjacent NRD's surrounding LPNNRD. Approximately 1,511 line-miles (2,447 line-kilometers) were acquired over the LPNNRD AEM survey area. Status reports of the flying were provided to the Contract Representative of ENWRA 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 1 – July 15, 2018. After final processing, 1,463-line-miles (2,371-line kilometers) were retained for inversion amounting to a retention rate of 96.9%. 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 LPNNRD with this report. After inversion, AGF derived 2D sections, 3D electrical models, and interpreted geologic and hydrogeologic surfaces of the surveyed area.

1.7 AGF is providing a hydrogeologic framework report that includes maps of aquifer 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 LPNNRD. The top of the undifferentiated Pennsylvanian (***IP***) was a challenging unit to interpret due to the highly variable resistivity of the IP. Top of the bedrock for the area was developed by inspection of the borehole logs that included consolidated geologic units and CSD (Nebraska Conservation and Survey Division) bedrock contacts. The CSD stratigraphic control was utilized to distinguish the ***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 ***Q***/***Kd*** contact when no resistivity contrast was present. The dependence on just boreholes for geologic interpretation also has its limitations because sometimes the boreholes 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. Very rarely 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. 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 (***To***), Cretaceous Niobrara (***Kn***), Cretaceous Carlile (***Kc***), Cretaceous Greenhorn Graneros (***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. 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. Given the known differences between the parameters of the 2014, 2015, 2016, and 2018 AEM surveys, it has become apparent that there needs to be integration work done to bring the results of all the years together in one package using the same parameters such as projection, model layer parameters, and lithologic nomenclature.

2.3 **Resistivity/Lithology Relationship** - Assessment of the sediment character in the Quaternary (***Q***) 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 numerically robust 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. 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 LPNNRD** - The 2018 LPNNRD AEM survey reveals variability in the Quaternary (***Q***) and Cretaceous Dakota Group (***Kd***) deposits across the LPNNRD AEM survey area that make up the aquifer materials. The ***Q*** make up the aquifer materials overlying the Cretaceous bedrock units of which the ***Kd*** Sandstone/Sand Dominant material are aquifers. 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 SQS1, SQS2, and Todd Valley areas.

Estimates of the groundwater in storage within the ***Q***-portion of the Leshara AEM Block of aquifer material below the 1995 CSD water table elevation is 3,487,506 acre-ft. The amount of extractable groundwater from aquifer material is 51,598 acre-ft and coarse aquifer material is 20,742. The amount of extractable groundwater from ***Kd*** Sandstone/Sand Dominant material is 228,244.

Estimates of the groundwater in storage within the ***Q***-portion of the SQS1 AEM Block of aquifer material below the 1995 CSD water table elevation is 3,625,684 acre-ft. The amount of extractable groundwater from aquifer material is 168,073 acre-ft and coarse aquifer material is 117,420. The amount of extractable groundwater from ***Kd*** Sandstone/Sand Dominant material is 1,091,837.

Estimates of the groundwater in storage within the ***Q***-portion of the SQS2 AEM Block of aquifer material below the 1995 CSD water table elevation is 6,184,486 acre-ft. The amount of extractable groundwater from aquifer material is 212,278 acre-ft and coarse aquifer material is 79,604. 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 Waann AEM Block of aquifer material below the 1995 CSD water table elevation is 7,451,998 acre-ft. The amount of extractable groundwater from aquifer material is 54,040 acre-ft and coarse aquifer material is 11,429. The amount of extractable groundwater from ***Kd*** Sandstone/Sand Dominant material is 403,012.

2.5 **Potential Recharge Zones within the LPNNRD AEM Survey Area** - The use of block flights for Leshara, Waann, SQS1 and SQS2 AEM Blocks illustrates 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 area throughout the Leshara Block has potential recharge that is limited in extent due to the ***Q*** aquifer materials (marginal and non-aquifer) at the land surface.

The exception is along the Platte River Valley and the south end of the Todd Valley. The area throughout the SQS1 Block has potential recharge that is limited in extent due to the ***Q*** aquifer materials at the land surface. The exception is near Octavia along the Platte River Valley. The area throughout the SQS2 Block has potential recharge that is limited in extent due to the ***Q*** aquifer materials at the land surface. The exception is the southern end of the SQS2 Block that is near the town of Columbus. The area throughout the Waann Block has potential recharge that is limited in extent due to the ***Q*** aquifer materials (marginal and non-aquifer) at the land surface. The exception is near the town of Ithaca and the south end of the Todd Valley.

Within the reconnaissance AEM flight area of the LPNNRD, 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.

2.6 Hydrologic connection between groundwater and surface water in the LPNNRD AEM Survey Area - The AEM data and interpretation provides detailed empirical data for determining earth materials at depth which 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 LPNNRD 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 LPNNRD about their management challenges.

3.1 **Integration of 2007-2018 AEM Hydrogeological Investigations** - The LPNNRD has acquired AEM data from 2007, 2014, 2015, 2016 and 2018 with several different AEM systems and contractors performing the work including USGS, XRI Geophysics and AGF with oversight from the ENWRA and the LPNNRD. With the completion of this current study there needs to be additional work done to bring all the work from previous years together in one seamless package using the same parameters such as the three different geographic projections NAD83 Zone 14N (meters), NAD83 Zone 14N (feet), and NAD83 Nebraska State Plane (feet), model layering structure, and hydrologic nomenclature. Recent communication with consultants and NE-DNR has also brought to light that additional effort is needed to quantify the NE-DNR boreholes relationship to the aquifer materials that the AEM has mapped. There apparently exists confusion on the use of “principal aquifer material” versus “aquifer material” versus “Principal Aquifer” as determined by NE-DNR. While these are apparently minor additions and changes, they can add to the overall usability and portability of the AEM analysis results within the LPNNRD.

3.2 **Additional AEM Mapping** - The AEM coverage of the district is nearly complete. At this time the only reason to gather additional AEM is to better understand the details of a specific area. Examples of those areas could be the Bellwood and Richland-Schuyler control areas.

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 LPNNRD 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 sedimentary 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 LPNNRD.

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 LPNNRD 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 LPNNRD exist and what additional information would be required for final selections of MAR sites. A detailed plan for locating and developing MAR sites would be beneficial to the LPNNRD 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 LPNNRD 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 flight Blocks *.xyz
- 2D Profiles and 3D fence diagrams of the AEM survey lines

Google Earth KMZs for LPNNRD AEM flight lines

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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
DOI	Depth of Investigation
DGPS	Differential global positioning system
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
LCI	Laterally-constrained Inversions
LENRD	Lower Elkhorn Natural Resources District
LLNRD	Lower Loup Natural Resources District
LPNNRD	Lower Platte North Natural Resources District
LPSNRD	Lower Platte South 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-DNR	Nebraska Department of Natural Resources
NESP83FT	Nebraska State Plane NAD 83 feet datum
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
SQS	Special Quantity Subareas
STD	Standard Deviation
TEM	Transient Electromagnetic
TDEM	Time-Domain Electromagnetic
Tx	Transmitter
UNL	University of Nebraska Lincoln
USGS	United States Geological Survey
UTM	Universal Transverse Mercator
VE	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: 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. Groundwater management strategies and policies implemented to address water quality concerns is another effort that can be improved with better understanding of 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. 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. Additional uses of this survey will be to determine potential areas of Managed Aquifer Recharge (MAR) for addition to current supplies of groundwater in areas if 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 high resolution framework to build the model.

This report describes the general hydrogeologic conditions, assessed using data collected from this AEM survey. 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 the block flight lines separated by about 1,500 ft to 2,000 ft (450 m – 600 m). This AEM survey was planned and selected by LPNNRD 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 LPNNRD, and in-kind service from CSD.

A location map showing the LPNNRD is presented in Figure 1-1. A Google Earth image of the 2018 "As-Flown" flight lines plus the 2016 SQS1 and SQS2 block flights are presented in Figure 1-2 and also included as a kmz in Appendix 3-Deliverables \KMZ\FlightLines. These are discussed in detail in Section 2. Also presented in Figure 1-2 is the boundary of this discussion of this report and the LPNNRD district boundary. The main AEM flight area was between Arlington, NE and Columbus, NE and continued to the northwest within the boundary of the LPNNRD.

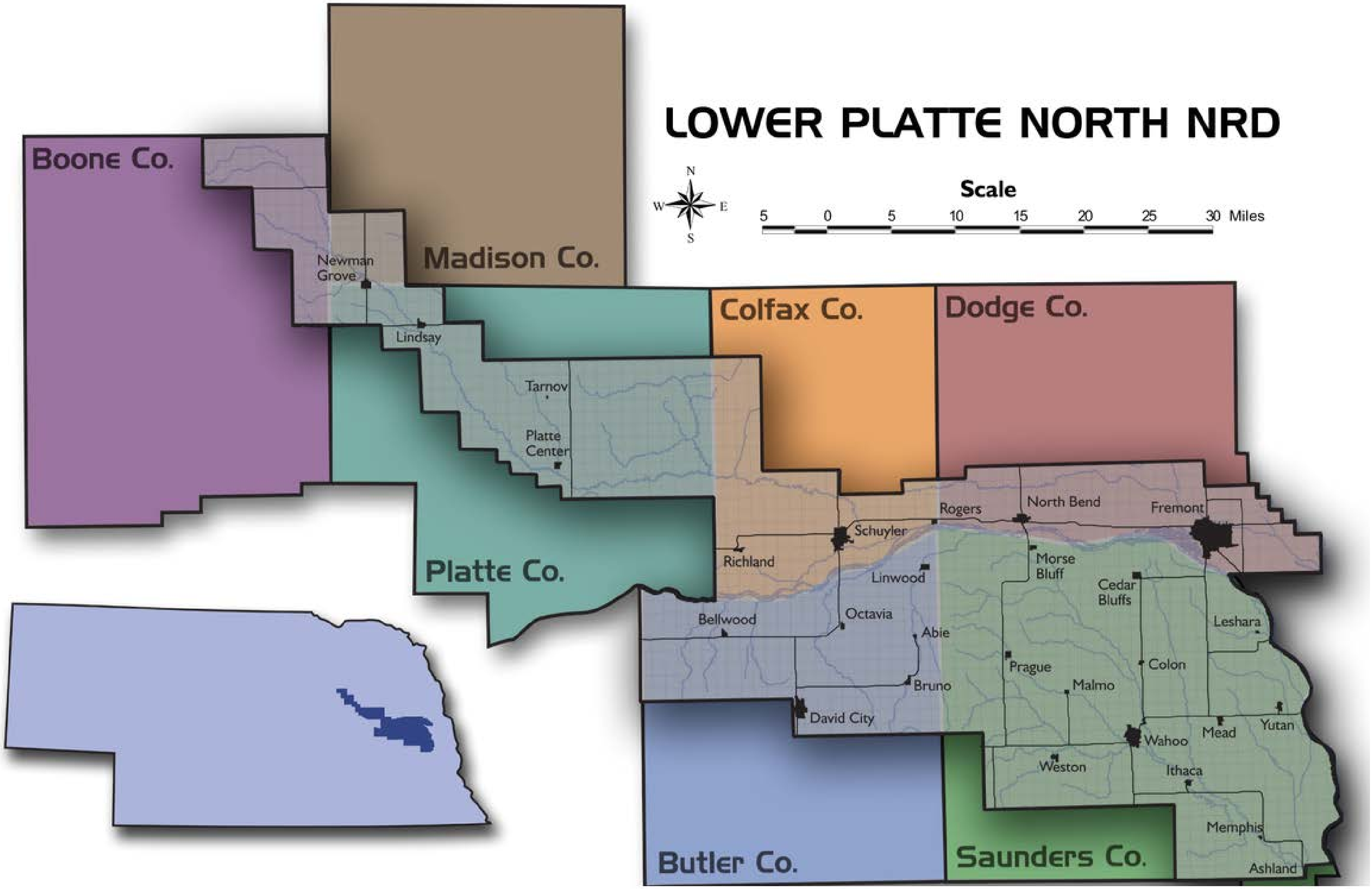


Figure 1-1. Map of the LPNNRD in eastern Nebraska (modified from https://lpnnrd.org/about/district-map/).

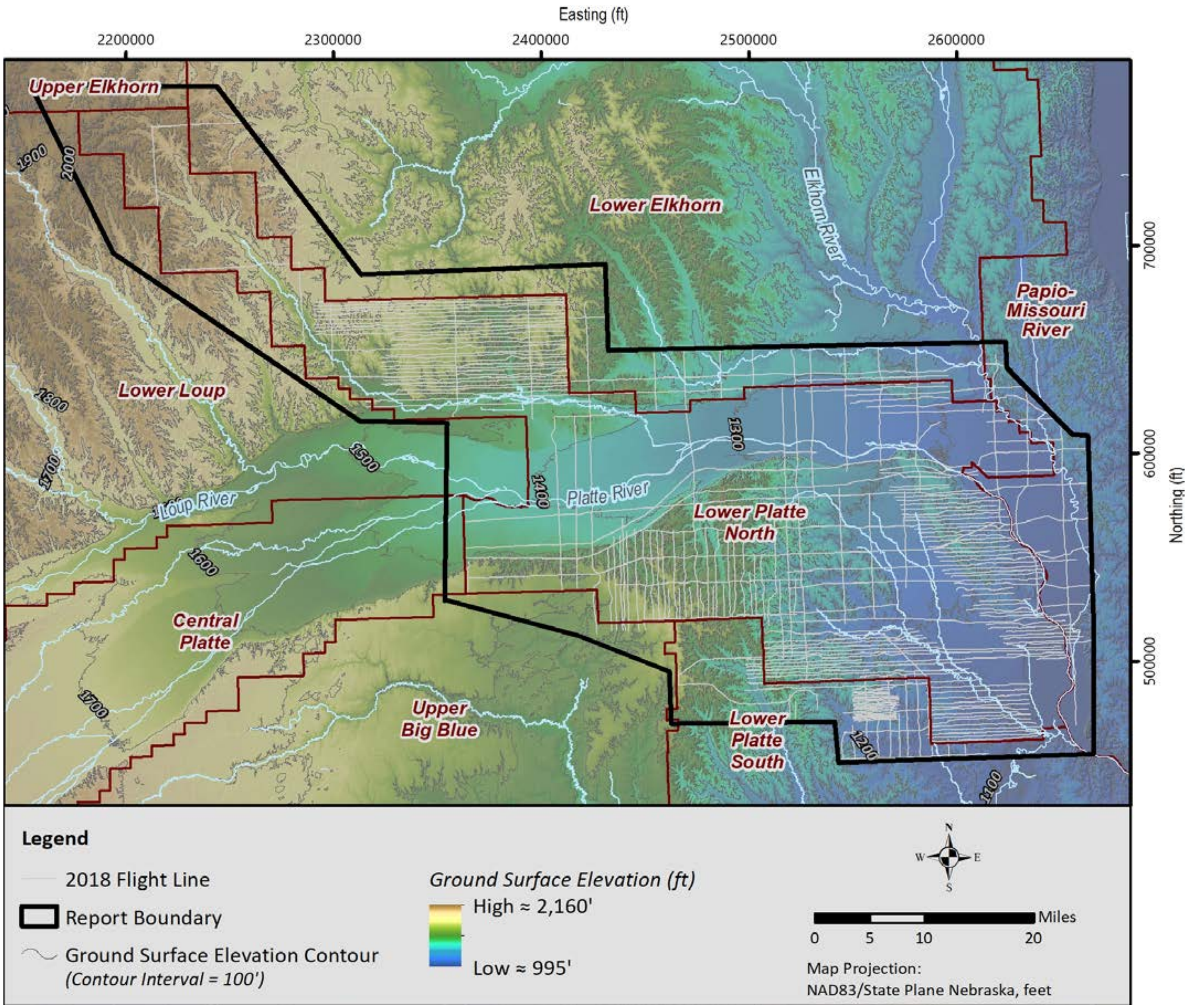


Figure 1-2. The LPNNRD 2018 AEM survey flight lines, the boundary of the LPNNRD AEM report, and the boundary of the LPNNRD over lying the DEM of the survey area.

1.2 Background

The LPNNRD has been a user of AEM technology for many years in Nebraska. In 2006 the ENWRA project was formed 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. In March 2007, ENWRA funded a study where AEM methods were implemented by the USGS to characterize the hydrogeologic conditions in the Platte River valley near Ashland, as well as in areas underlain by glacial till near Firth and Oakland, Nebraska (Smith et al., 2008). The Ashland area survey was split between the LPNNRD and the P-MRNRD. A CSD report on the interpretation of AEM in the Ashland area was released in 2012 (Hanson et al., 2012). In 2009, the LPNNRD funded the USGS and CSD for the development of a 3D hydrostratigraphic framework of the subsurface near Swedeburg, Nebraska using and AEM survey (Smith et al., 2009; Divine and Korus, 2013). As a way of identifying contamination pathways related to the former Nebraska Ordnance Plant near Mead, Nebraska, the USACE flew an AEM survey in 2011 that was later released in 2013 (USACE, 2013). In 2013, the LPSNRD funded XRI Geophysics to complete an AEM survey covering over 800 line-miles in Butler and Saunders counties near Valparaiso and Dwight, Nebraska (Carney et al., 2014). This survey revealed buried paleovalley aquifers beneath thick sequences of till. The LPSNRD survey is immediately south of the SQS#1 (also referred in this report as SQS1) area (Abraham et al., 2018). In 2014-2015 the ENWRA funded XRI Geophysics 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 flew an AEM survey over the areas of “Special Quantity Subareas” (SQS)1 and 2 to provide enhanced hydrostratigraphy to the areas (AGF, 2017). Through the previous work, and the current work presented in this report, much of the area of the LPNNRD has been mapped with AEM technology.

The District continues to monitor groundwater quality and quantity by collecting groundwater data each year at new and repeat locations. The conclusions from these studies indicated that groundwater aquifers continue to be contaminated to varying degrees with nitrate/nitrogen and that the causes were likely related to nonpoint source contamination due to leaching of nutrient applications, both from organic and inorganic sources, and irrigation practices.

In 2008, the LPNNRD declared the portions of the District as Hydrologically Connected Areas (HCAs) which have limited irrigation development allowed every year (www.lpnnrd.org). This determination was based on studies by Nebraska Department of Natural Resources (NE-DNR) and the LPNNRD in some areas of the District. The conclusions from these studies indicated that the aquifers appeared to be hydrologically connected to surface water in some of the district. The Restricted Development Areas (RDAs) in the LPNNRD (in Butler, Dodge and Saunders counties) are to address quantity management rules of the known aquifers of thin and limited size. Within SQS1 and SQS2 shown in Figure 1-3, the complex geology is related to highly volatile groundwater level changes related to the influence of drought and related increased in groundwater pumping during the irrigation season (www.lpnnrd.org).

1.3 Description of the LPNNRD 2018 AEM Project Area

The LPNNRD spans approximately 1,607 square miles (mi^2) in eastern Nebraska. The elevation of the area ranges from 995 ft to 1950 ft above sea level**.** It is underlain by parts of five of Nebraska's eight topographic regions—Rolling Hills, Plains, Valleys, Bluffs, and Escarpments (Elder et al., 1951).

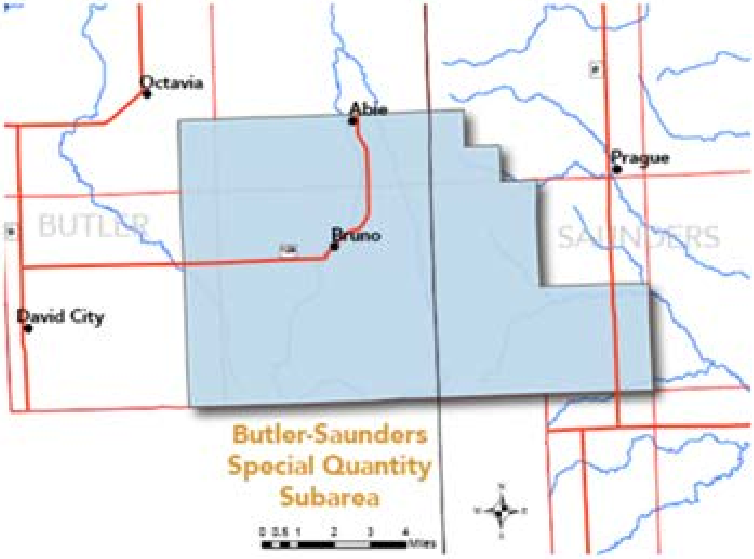
Principal cities within the project area, based on 2010 population estimates, include (alphabetically) David City (2,906), Fremont (26,397), North Bend (1,256), Schuyler (6,212) and Wahoo (4,471) (U.S. Census Bureau, 2013).

The LPNNRD website states that the Butler/Saunders counties area (SQS#1) covers approximately 56 square miles of east-central Butler County and 30 square miles of west-central Saunders County. The Platte/Colfax counties area (SQS#2) covers approximately 100 square miles of central Platte County and 32 square miles of west-central Colfax County (descriptions from https://lpnnrd.org/projects-and-programs/water-management/water-quantity/).

The AEM Block areas discussed in this report are presented in Figure 1-4. The sizes of these Block AEM survey areas, when during processing they are converted to voxels, are listed in Table 1-1. The naming conventions of the AEM Block areas discussed in this report are based on conversations with LPNNRD staff (Personal Communication, Darryl Andersen, LPNNRD Water Resource Manager, July 11, 2019)

Table 1-1. Areas of LPNNRD Block AEM data acquisition.

Voxel Block	Square Miles
Leshara Upland	166.4
SQS1	173.6
SQS2	257.4
Waann	157.1



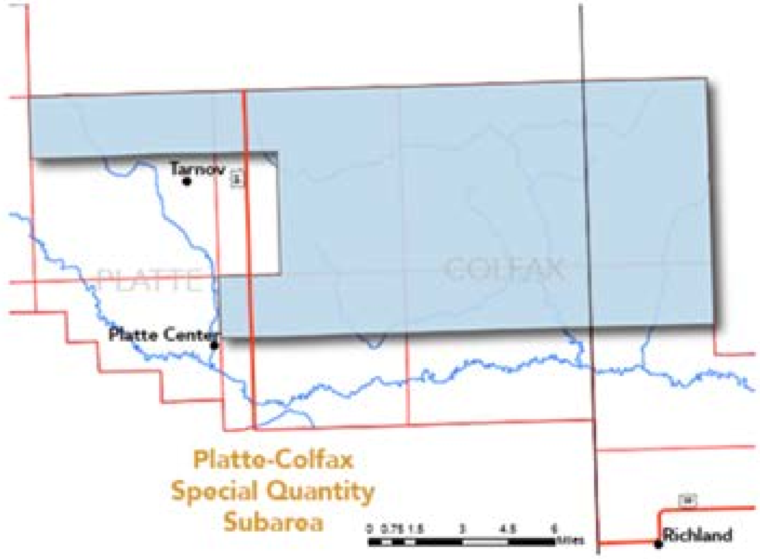


Figure 1-3. Map of the Special Quantity Subareas consisting of SQS#1 and SQS#2. The blue shaded area on the left is the Butler-Saunders Special Quantity Subarea (SQS#1) and the blue shaded area on the right is the Platte Colfax Special Quantity Subarea (SQS#2) (modified from https://lpnnrd.org/projects-and-programs/water-management/water-quantity/).

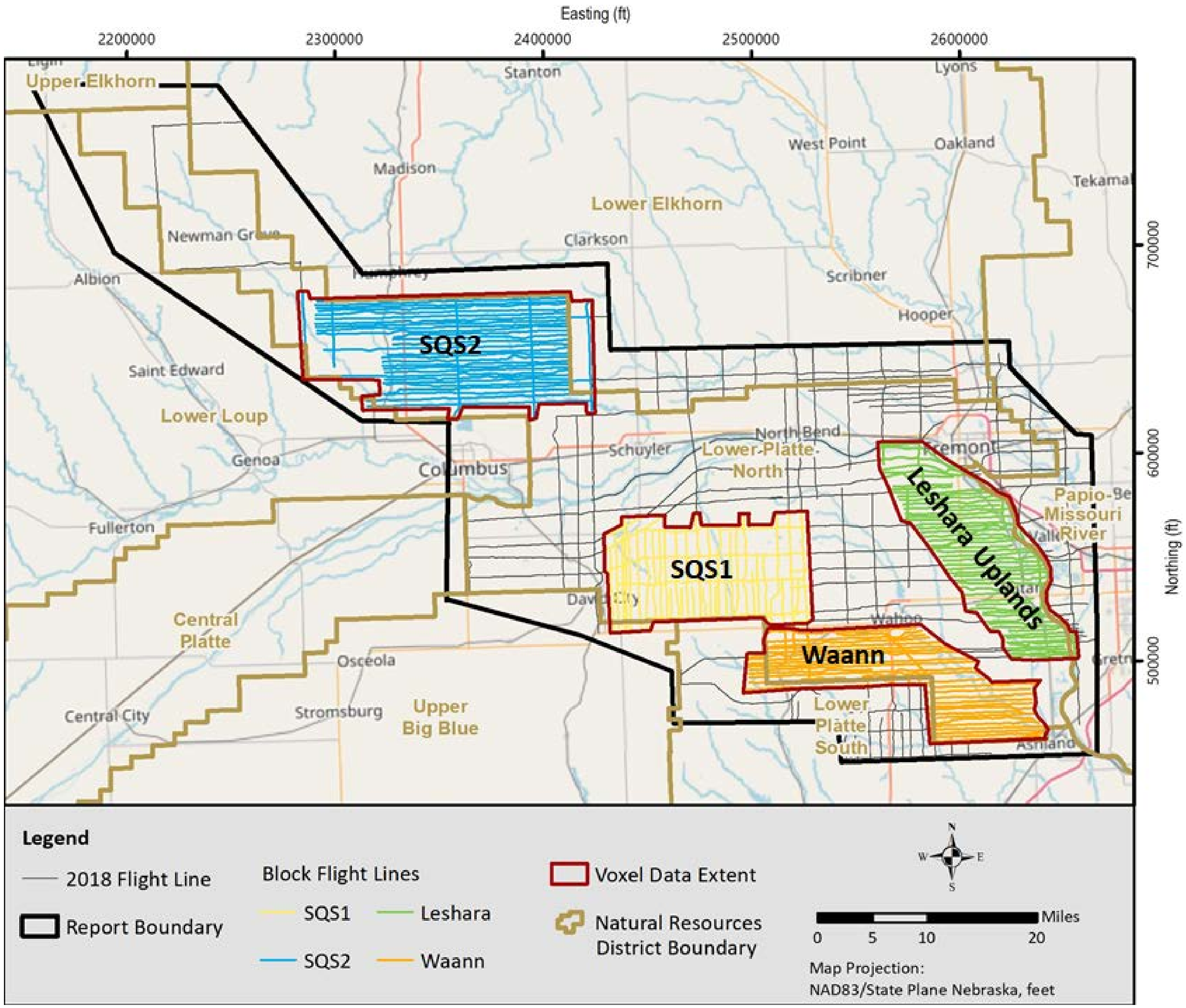


Figure 1-4. Locations of the Block AEM survey areas (brown boundaries, black labels) within the 2018 LPNNRD survey (thick black line) which includes areas outside the LPNNRD district boundary area (tan lines).

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.

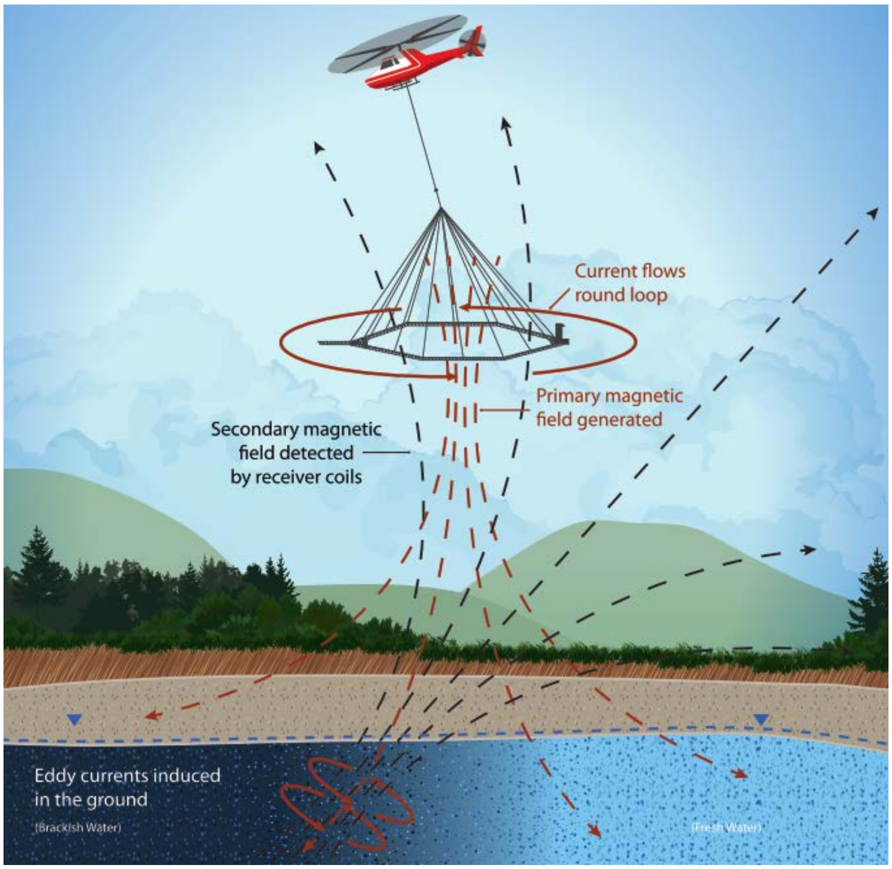
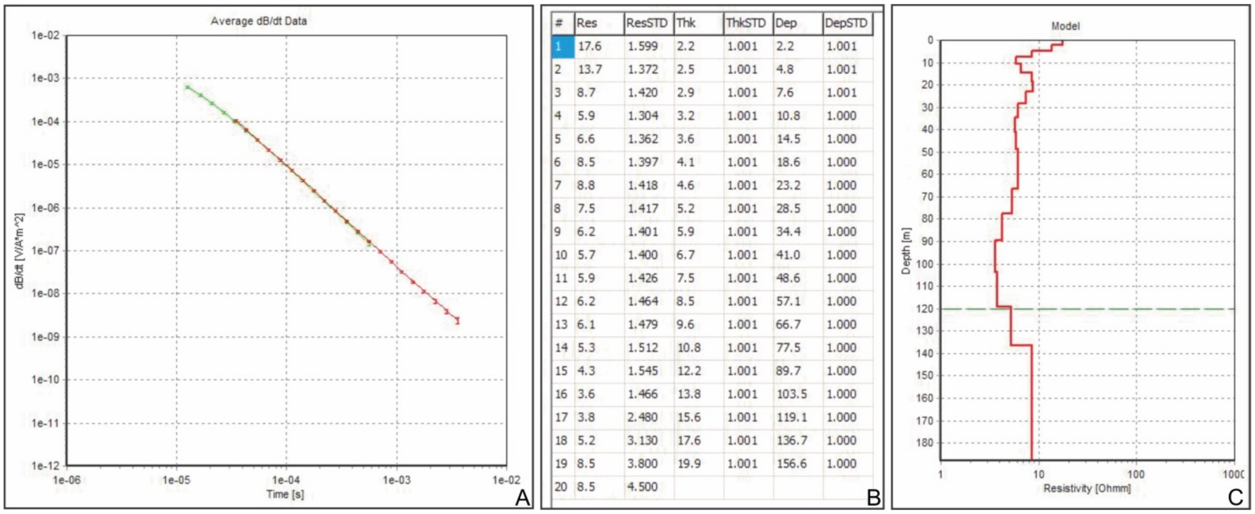


Figure 2-1. Schematic of an airborne electromagnetic survey, modified from Carney et al. (2015a).

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 LPNNRD, 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 LPNNRD reconnaissance flight lines had a maximum of approximately 52 miles (85 km) in length in the east-west direction and about 20 miles (33 km) at their longest in the north-south direction. The reconnaissance flight lines were separated by approximately 2.5 miles (4 km) in both east-west and north-south directions and block flight lines were separated by about 1500 feet to 2,000 feet (450 m – 600 m).

2.3 AEM Survey Instrumentation

AEM data were acquired using the SkyTEM304M (304M) airborne electromagnetic system (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 about 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 SkyTEM304M system utilizes an offset Rx positioned slightly behind the Tx resulting in a ‘null’ position which is a location where the intensity of the primary field from the system transmitter is minimized. This is desirable as to minimize the amplitude of the primary field at the Rx to maximize the sensitivity of the Rx to the secondary fields. The SkyTEM304M multi-turn Rx coil has an effective area of 105 m^2. In addition to the Tx and Rx that constitute the TEM instrument, the SkyTEM304M is also equipped with a Total Field magnetometer (MAG) and data acquisition systems for both instruments. The SkyTEM304M also includes two each of laser altimeters, inclinometers/tilt meters, and differential global positioning system (DGPS) receivers. Positional data from the frame mounted DGPS receivers are recorded by the AEM data acquisition system. The magnetometer includes a third DGPS receiver whose positional data is recorded by the magnetometer data acquisition system. Figure 2-3 gives a simple illustration of the SkyTEM304M frame and instrument locations. The image is viewed along the +z axis looking at the horizontal x-y plane. The axes for the image are labeled with distance in meters. The magnetometer is located on a boom off the front of the frame (right side of image). The Tx coil is located around the octagonal frame and the Rx Coil is located at the back of the frame (left side of image).

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

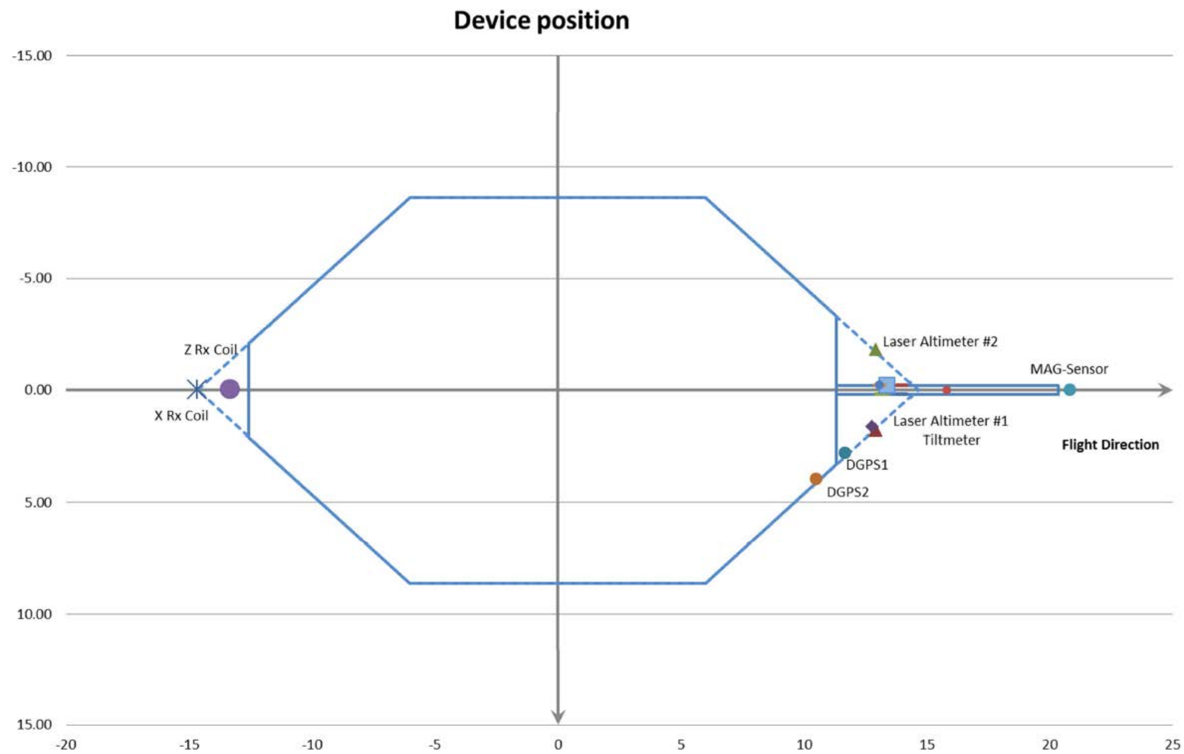


Figure 2-3. SkyTEM304M frame, including instrumentation locations and X and Y axes. Distances are in meters. Instrumentation locations listed in Table 2-1.

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

For this project, the 304M was flown at an average speed of 48 mi/hr (78 kilometers/hr) at an average flight height of 126.9 ft (38.7 m) above the land surface, using the sling-load cargo system of a Eurocopter AS350 helicopter. Figure 2-4 displays a couple of images of the 304M in operation.

Table 2-1. Positions of instruments on the SkyTEM304M frame, using the center of the frame as the origin, in feet.

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

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

Tx Corners	1	2	3	4	5	6	7	8
X	-41.16	-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.

Approximately 1,511 line-miles (3,073 line-kilometers) were acquired over the LPNNRD AEM survey area between 26 June 2018 and finishing on 14 July 2018 (Table 2-3). A data acquisition map is presented in Figure 2-5 with the flight lines grouped by acquisition date.

Table 2-3. LPNNRD AEM Data Acquisition Schedule and Totals

Date	# Flights	Feet	Miles	Km
22-Jun-19	1	23524.5	4.4	7.2
24-Jun-19	1	72818.0	13.7	22.2
26-Jun-18	2	167358.7	31.5	51.0
28-Jun-18	3	354592.4	66.7	108.1
30-Jun-18	3	823658.7	155.0	251.1
1-Jul-18	3	1624658.2	305.7	495.2
2-Jul-18	2	1226863.6	230.8	373.9
3-Jul-18	2	985948.9	185.5	300.5
4-Jul-18	3	1440385.4	271.0	439.0
5-Jul-18	3	826636.3	155.5	252.0
6-Jul-18	2	839832.5	158.0	256.0
7-Jul-18	2	519067.6	97.7	158.2
9-Jul-18	1	348400.5	65.6	106.2
12-Jul-18	3	530210.1	99.8	161.6
14-Jul-18	1	298637.4	56.2	91.0
Total	32	10082592.7	1897.0	3073.2

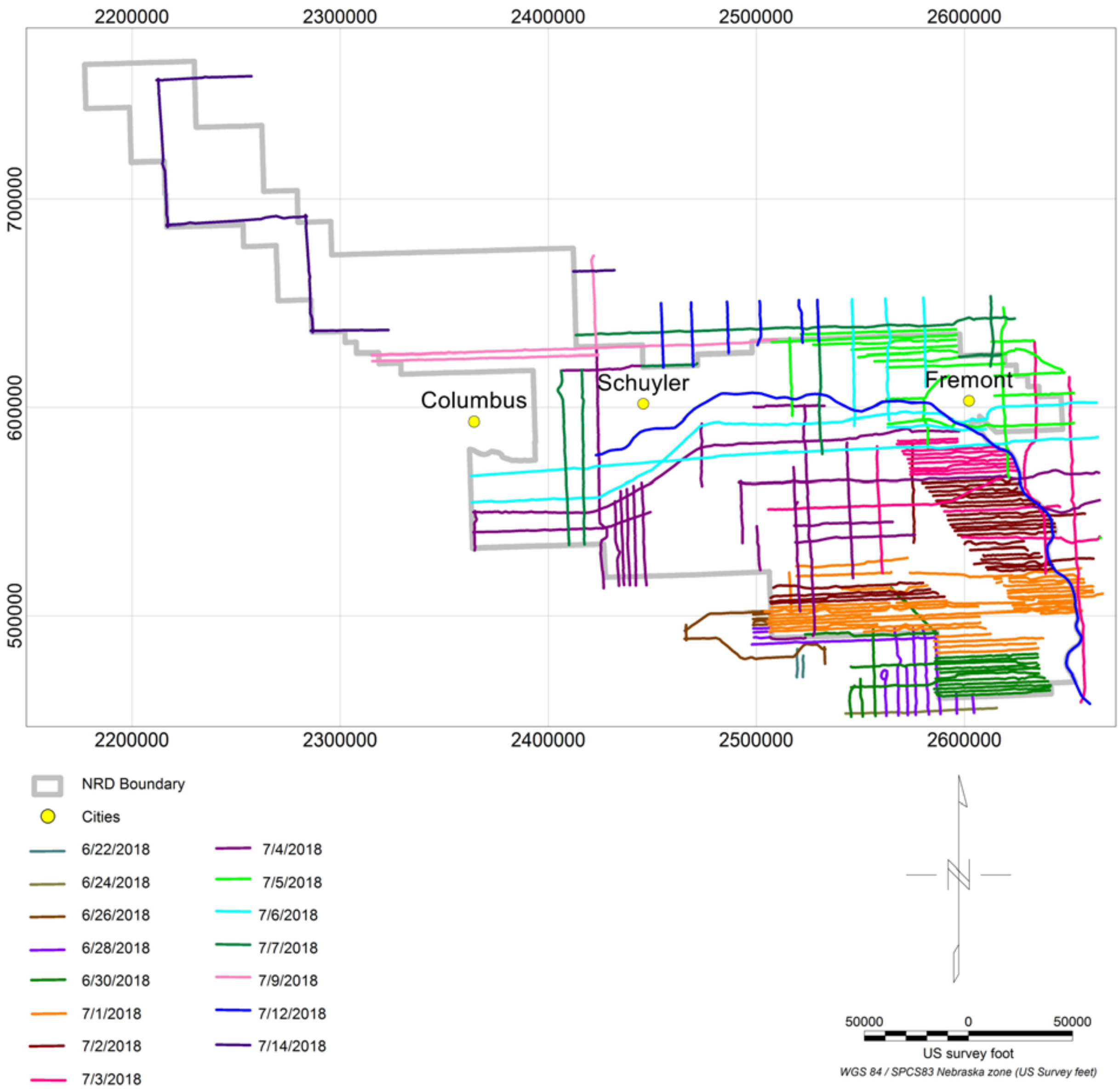


Figure 2-5. LPNNRD 2018 AEM flight lines grouped by acquisition date. Projection is Nebraska State Plane NAD83, feet.

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 $1.0x10^{-5}$ sec, $1.0x10^{-4}$ sec, and $1.0x10^{-3}$ sec with widths of 4, 7, and 18 seconds. The times used to define the trapezoid for the High Moment were $1.0x10^{-4}$ sec, $1.0x10^{-3}$ sec, and $1.0x10^{-2}$ sec with widths of 10, 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. 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.

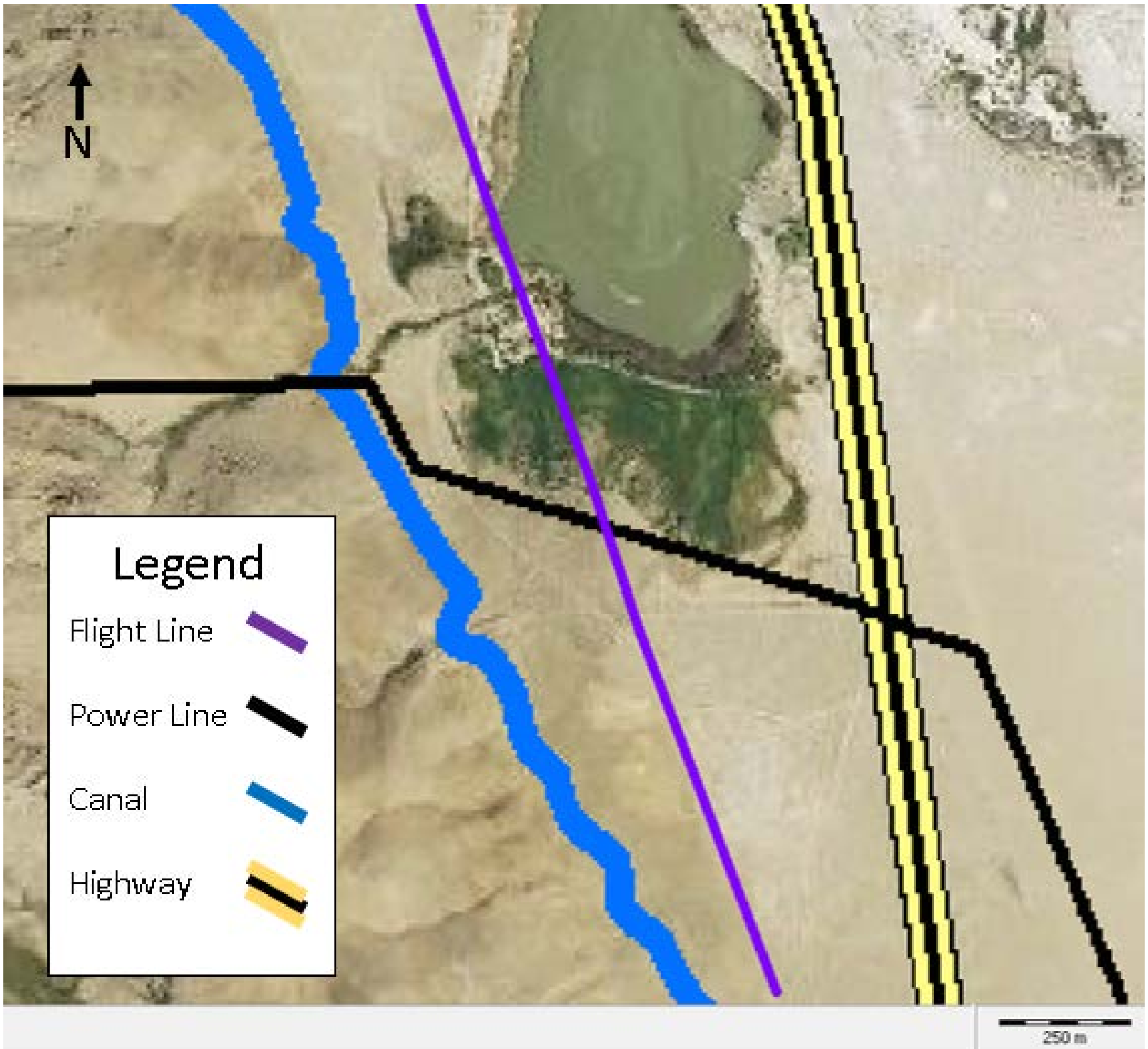


Figure 2-6. Example locations of electromagnetic coupling with pipelines or power lines.

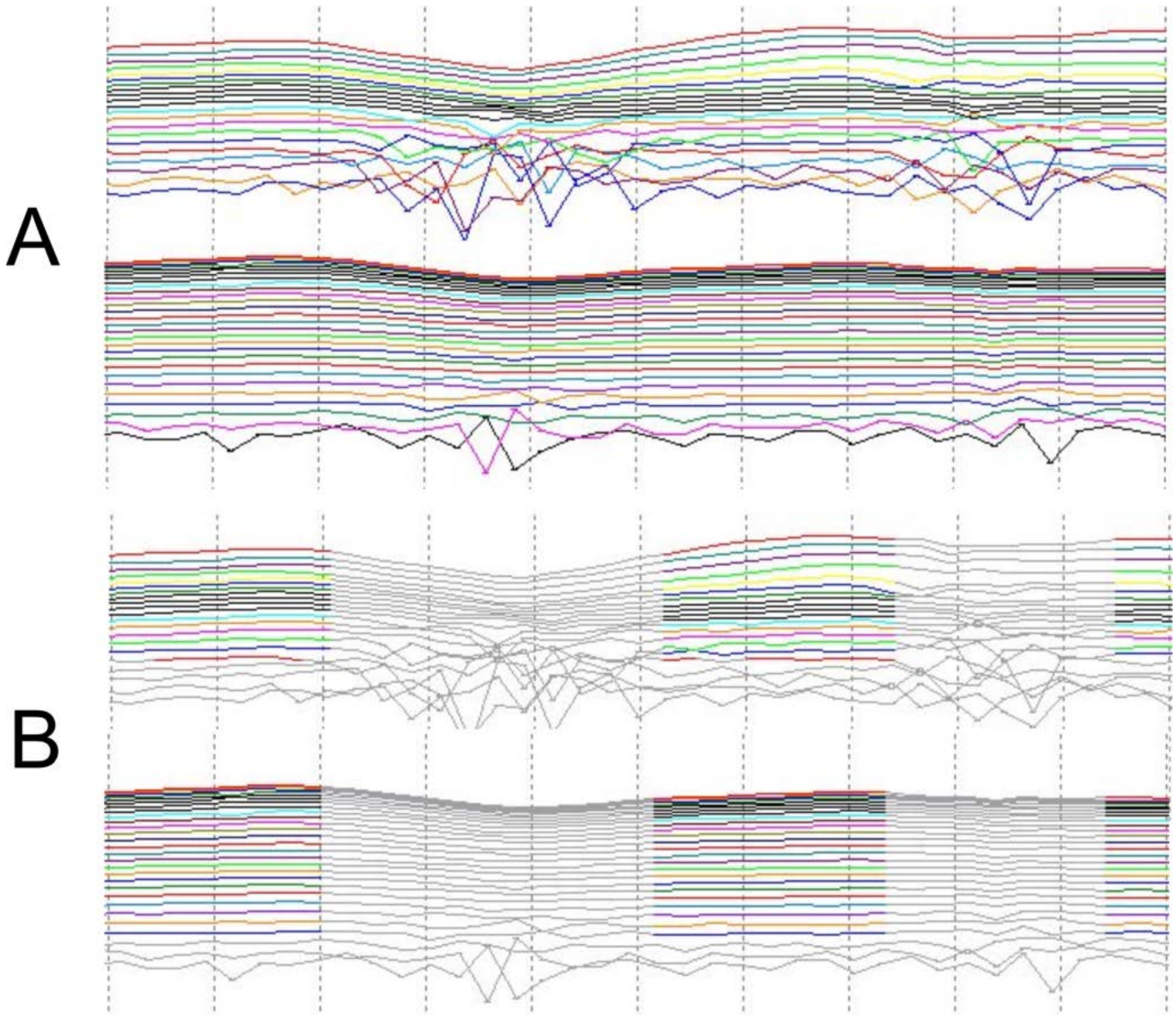


Figure 2-7. A) Example of AEM data affected by electromagnetic coupling as presented in the Aarhus Workbench editor. The top group of lines is the unedited data with the Low Moment on top and the High Moment on the bottom. The bottom group shows the same data after editing.

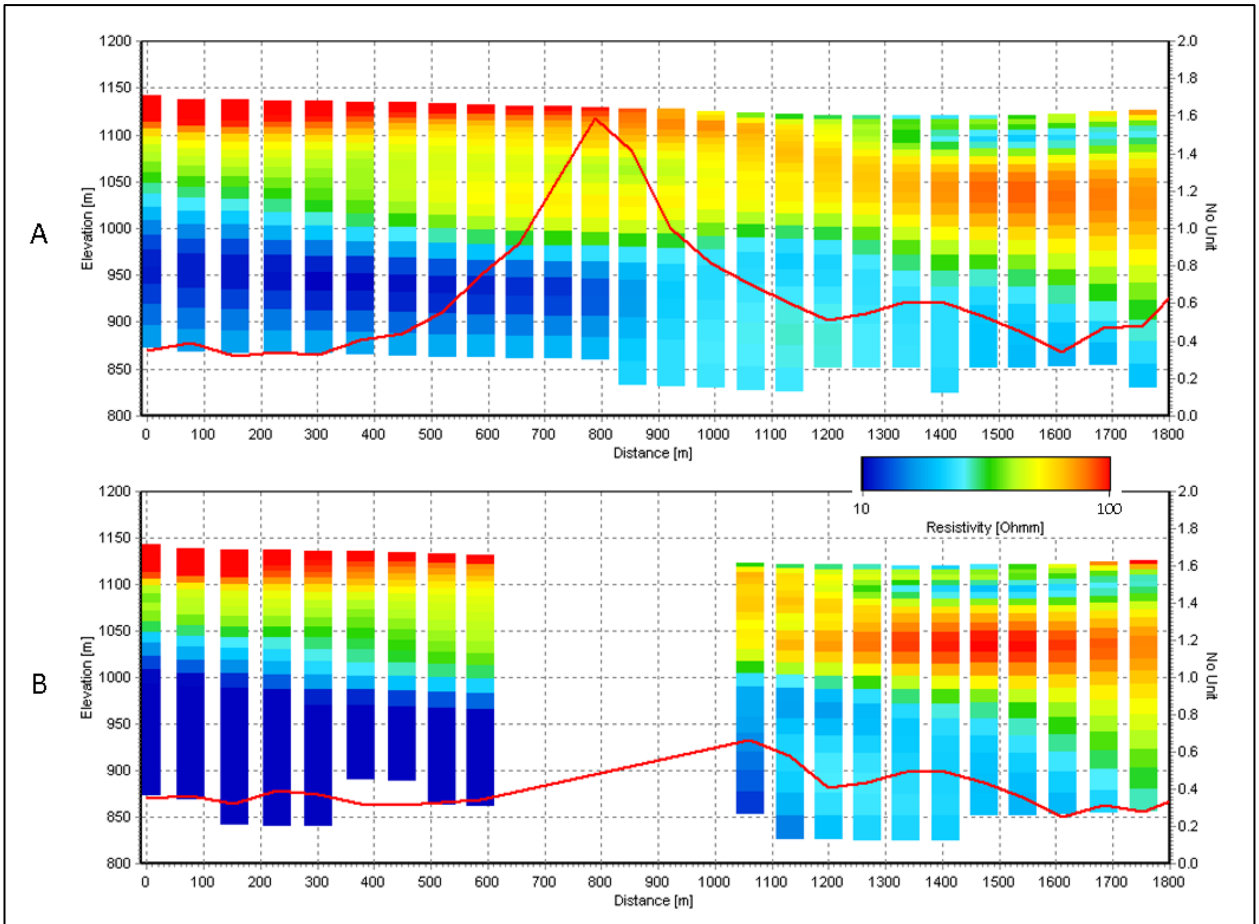


Figure 2-8. A) Example of Laterally-Constrained inversion results where AEM data affected by coupling with pipelines and power lines were not removed. B) Inversion results where AEM data affected by coupling were removed.

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 LPNNRD 2018 AEM survey is presented in Figure 2-9.

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 2-10 shows the residual magnetic Total Field intensity data for the LPNNRD AEM survey area after correcting for diurnal drift and removing the International Geomagnetic Reference Field (IGRF). This data is used in decoupling efforts.

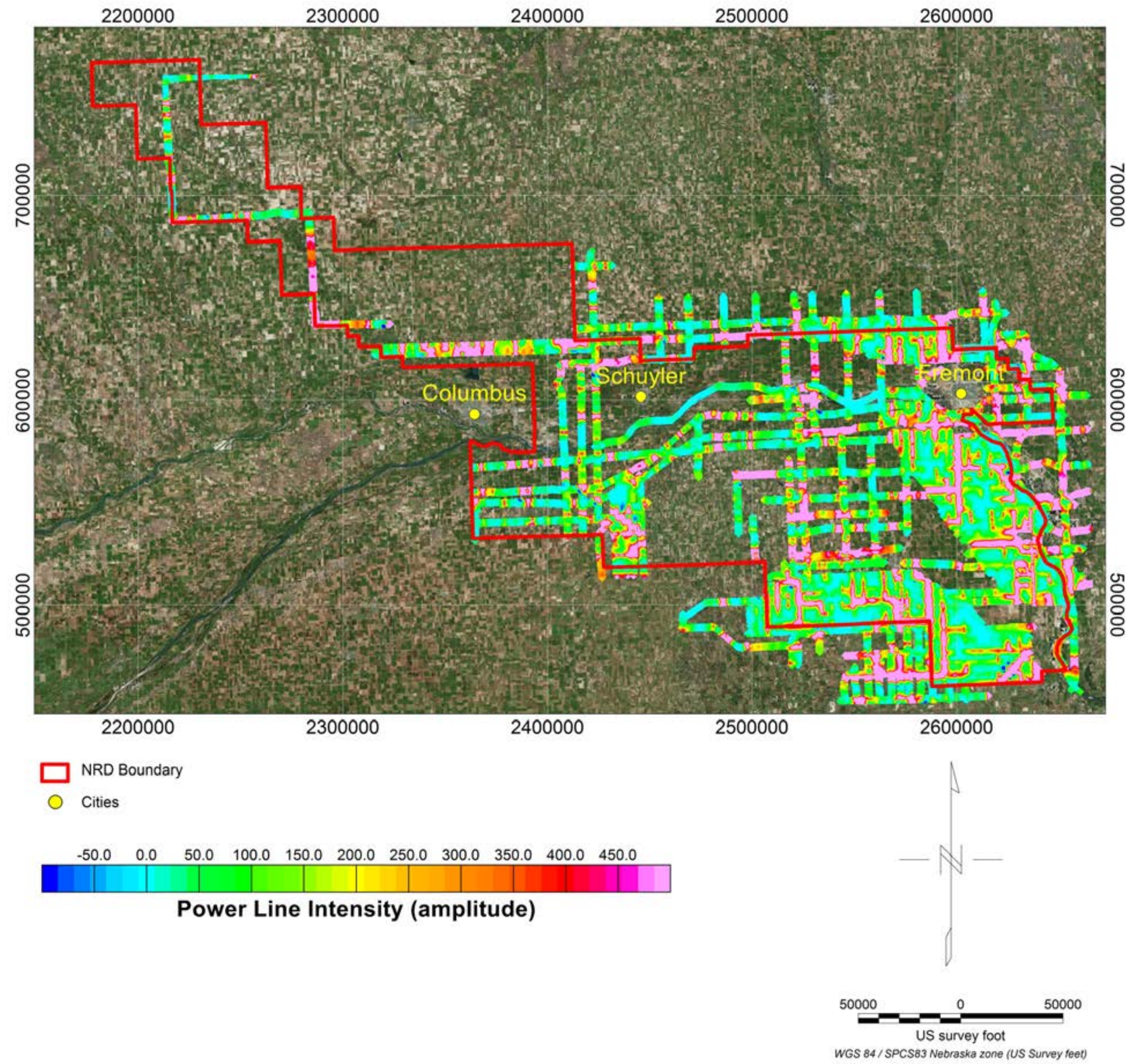


Figure 2-9. Power Line Noise Intensity (PLNI) map of the LPNNRD 2018 project area. Projection is Nebraska State Plane, NAD83, feet.

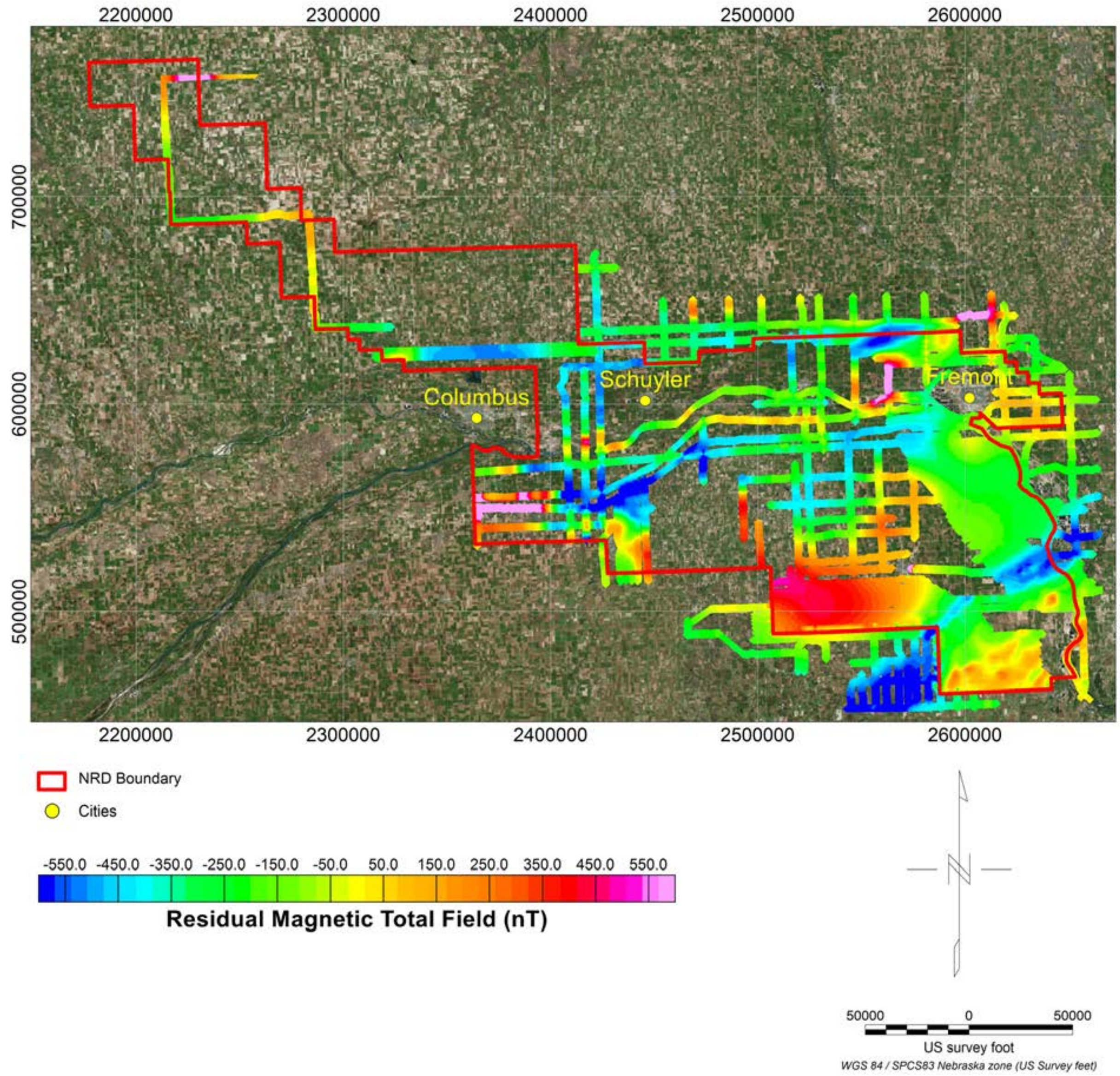


Figure 2-10. Residual magnetic Total Field intensity data for the LPNNRD 2018 survey area corrected for diurnal drift, with the International Geomagnetic Reference Field (IGRF) removed. Projection is Nebraska State Plane, NAD83, feet.

After final processing, 1,463-line-miles (2,371-line kilometers) were retained for inversion amounting to a retention rate of 96.9%. This high rate is the result of careful flight line planning and design given the infrastructure that was encountered during the acquisition. The LPNNRD-flight lines with blue colors representing the 96.6% of data retained for inversion and red lines representing data removed due to infrastructure and late time noise are presented in Figure 2-11.

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 LPNNRD 2018 AEM data were inverted using a 40-layer model structure. The SCI inversions used smooth models, each with a starting resistivity of 10 Ohm-m (equivalent to a 10 ohm-m halfspace). The thicknesses of the first layers of the models were about 3 ft (1 m) with the thicknesses of the consecutive layers increasing by a factor of 1.08. The depths to the bottoms of the 39th layers were set to 1,148 ft, with thicknesses up to about 85 ft. The thicknesses of the layers increase with depth (Table 2-4 and Figure 2-12) as the resolution of the technique decreases. The spatial reference distance, ***s***, for the constraints were set to 308 ft with power laws of 0.75. The vertical and lateral constraints, ***ResVerSTD*** and ***ResLatStD***, were set to 2.4 and 1.4, respectively, for all layers.

The areas that were flown for the P-MRNRD, LPNNRD, and LPSNRD districts were inverted together with some areas of LENRD along the borders of the other NRD's. Seven groups of inversions, with about 10-15 flights each, were required to invert the AEM data. This process provided adequate overlap and allowed for full advantage to be taken with the SCI. Table 2-5 lists the SCI inversion groups and the flights that were included in each group and Figure 2-13 presents Google Earth images of the different inversion groups.

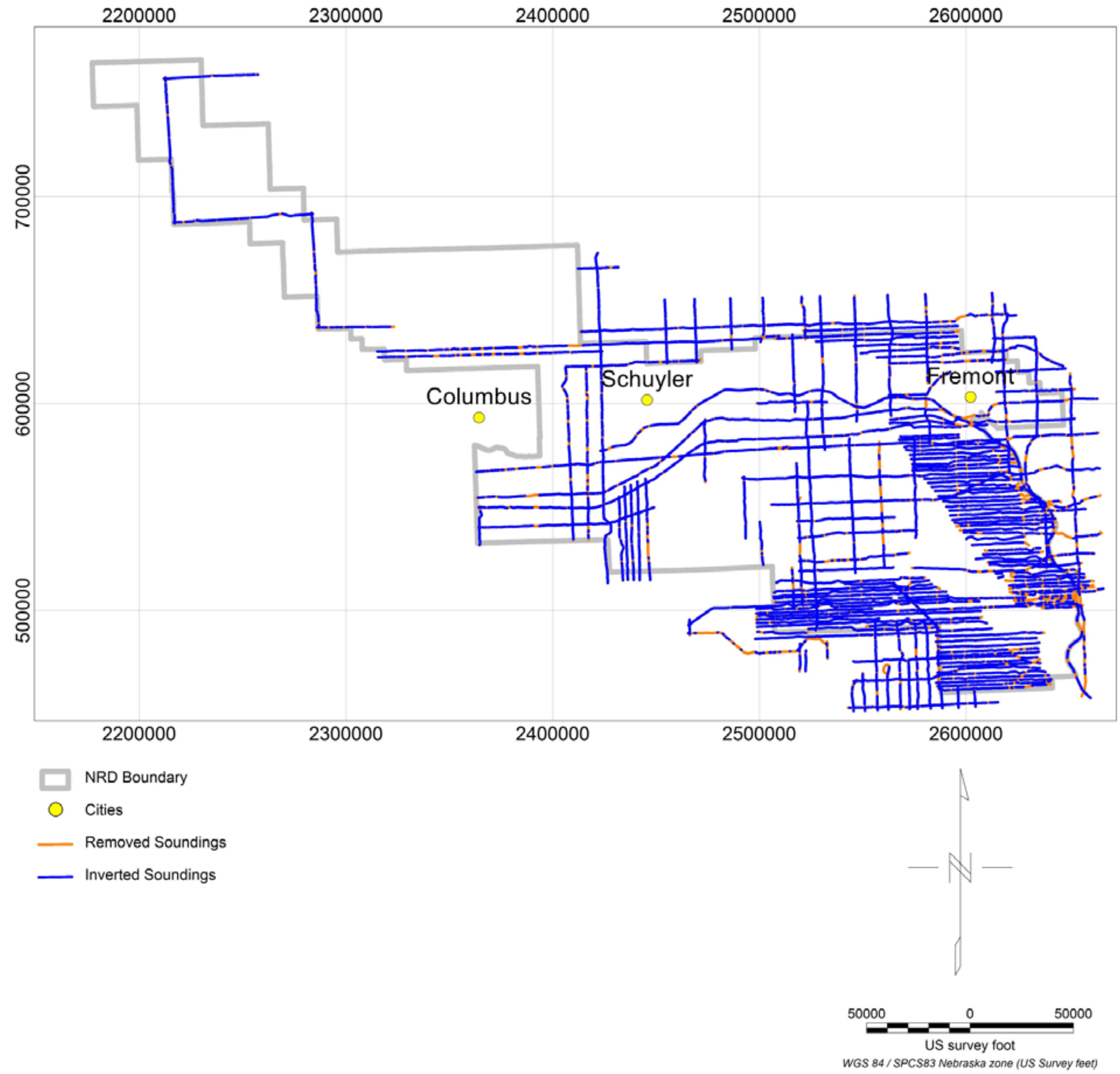


Figure 2-11. Locations of inverted data (blue lines) along the AEM flight lines (red lines) in the LPNNRD 2018 AEM survey area. Where blue lines are not present indicates decoupled (removed) data. 96.9% of the acquired data was retained for inversion and interpretation. Google Earth kmz's of the inverted data locations as well as the "as-flown" flight lines are included in Appendix 3\KMZ.

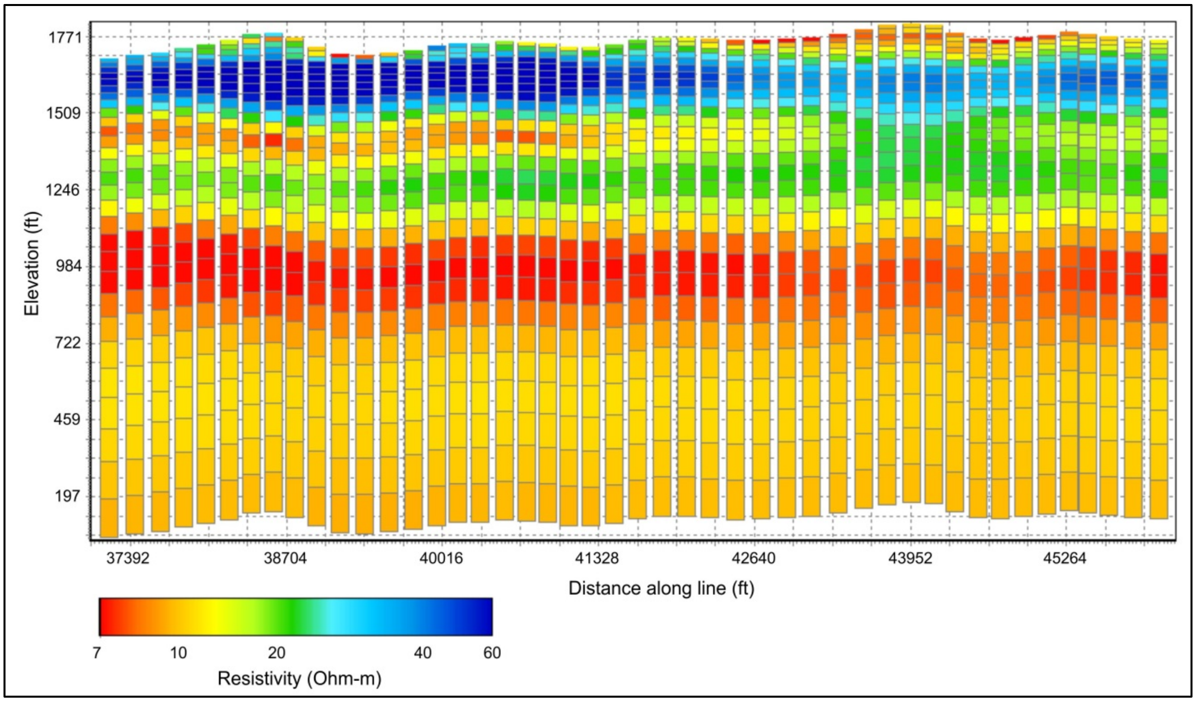


Figure 2-12: An example of an AEM profile illustrating increasing model layer thicknesses with depth.

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

Layer	Depth to Bottom (ft)	Thickness (ft)	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	197.8	20.0	60.3	6.1
2	6.9	3.6	2.1	1.1	22	219.8	22.0	67.0	6.7
3	10.8	3.9	3.3	1.2	23	243.7	23.9	74.3	7.3
4	15.1	4.3	4.6	1.3	24	269.9	26.2	82.3	8.0
5	19.7	4.6	6.0	1.4	25	298.8	28.9	91.1	8.8
6	24.9	5.2	7.6	1.6	26	330.3	31.5	100.7	9.6
7	30.5	5.6	9.3	1.7	27	364.7	34.4	111.2	10.5
8	36.7	6.2	11.2	1.9	28	402.5	37.7	122.7	11.5
9	43.6	6.9	13.3	2.1	29	443.8	41.3	135.3	12.6
10	51.2	7.5	15.6	2.3	30	489.0	45.3	149.0	13.8
11	59.4	8.2	18.1	2.5	31	538.6	49.5	164.2	15.1
12	68.2	8.9	20.8	2.7	32	593.0	54.4	180.7	16.6
13	78.1	9.8	23.8	3.0	33	652.4	59.4	198.8	18.1
14	88.6	10.5	27.0	3.2	34	717.3	64.9	218.6	19.8
15	100.4	11.8	30.6	3.6	35	788.5	71.2	240.3	21.7
16	113.2	12.8	34.5	3.9	36	866.6	78.1	264.1	23.8
17	127.3	14.1	38.8	4.3	37	951.9	85.3	290.1	26.0
18	142.7	15.4	43.5	4.7	38	1045.3	93.5	318.6	28.5
19	159.4	16.7	48.6	5.1	39	1147.7	102.3	349.8	31.2
20	177.8	18.4	54.2	5.6					

Table 2-5. AEM flights included in each of the SCI inversion groups.

Group 1	**0617FL2-0618FL1,2,3-0619FL1-0622FL1,2,3-0623FL1,2,3**
Group 2	**0622FL1,2,3-0623FL1,2,3-0624FL1,2,3-0626FL2-0628FL2,3-0630FL1**
Group 3	**0626FL1,2-0628FL1,2,3- 0630FL1,2,3- 0701FL1,2,3-0702FL1C-0704FL2**
Group 4	**0701FL3 - 0702FL1C,2A-0703FL1,2 - 0704FL1,2,3 - 0705FL2**
Group 5	**0703FL1,2-0704FL1,2,3-0705FL1-0706FL1,2-0707FL1**
Group 6	**0705FL1,2,3-0706FL1,2-0707FL1,2-0709FL1-0712FL1,2,3**
Group 7	**0711FL1-0714FL1,2-0718FL2-0720FL1**

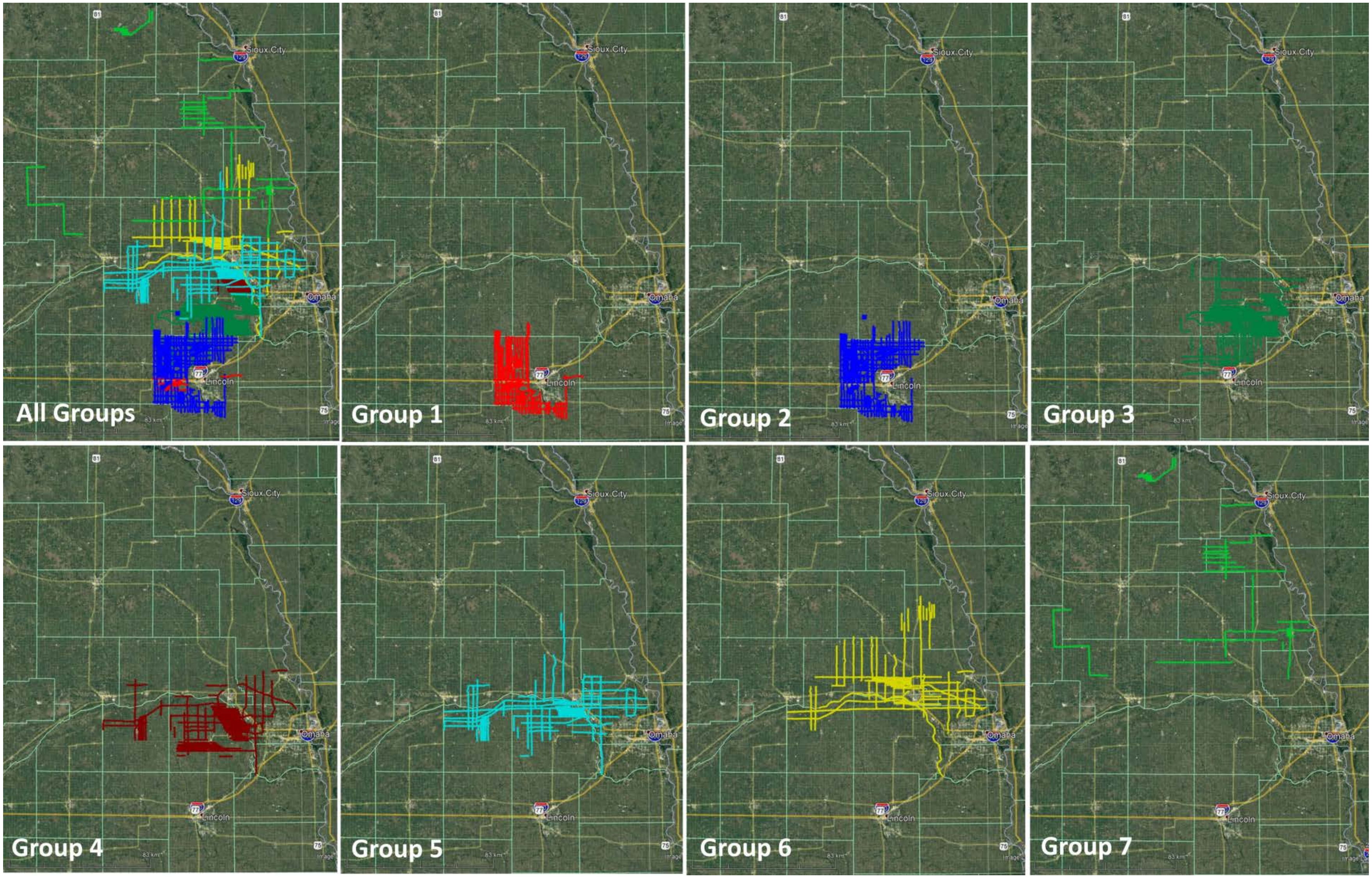


Figure 2-13. SCI inversion groups for the P-MRNRD, LPNNRD, and LPSNRD AEM data.

Figure 2-14 presents a histogram of the LPNNRD SCI inversion data/model residuals and a map of data to model error residuals comparison is presented in Figure 2-15.

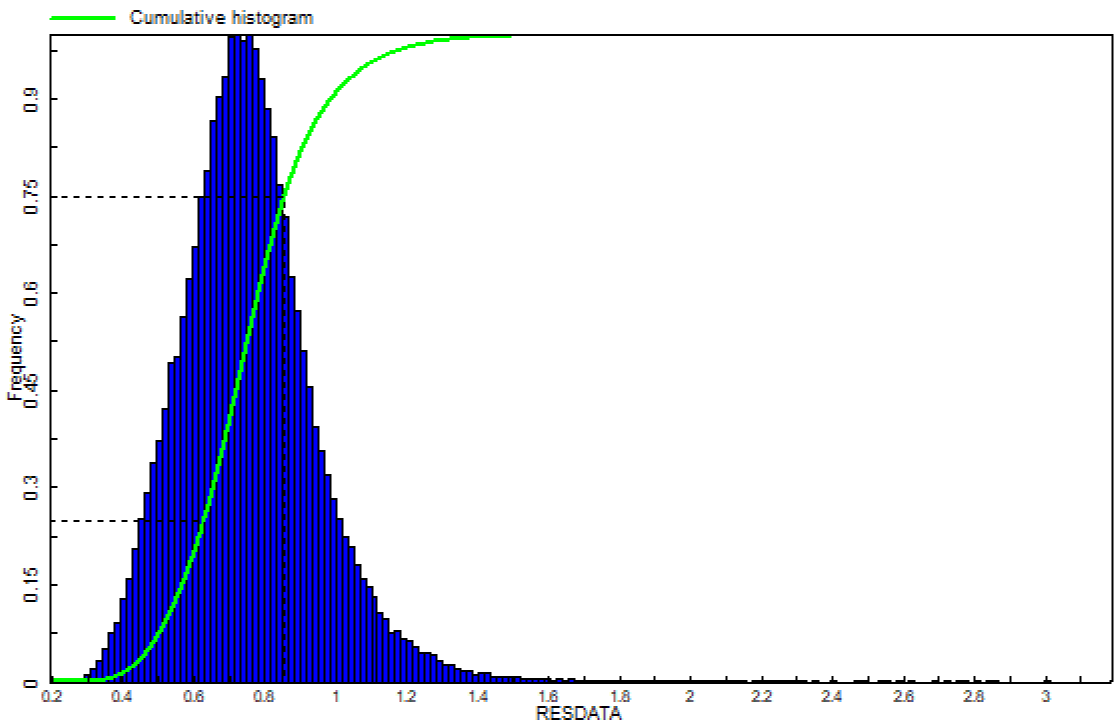


Figure 2-14: Data/model residual histogram for the LPNNRD 2018 SCI inversion results.

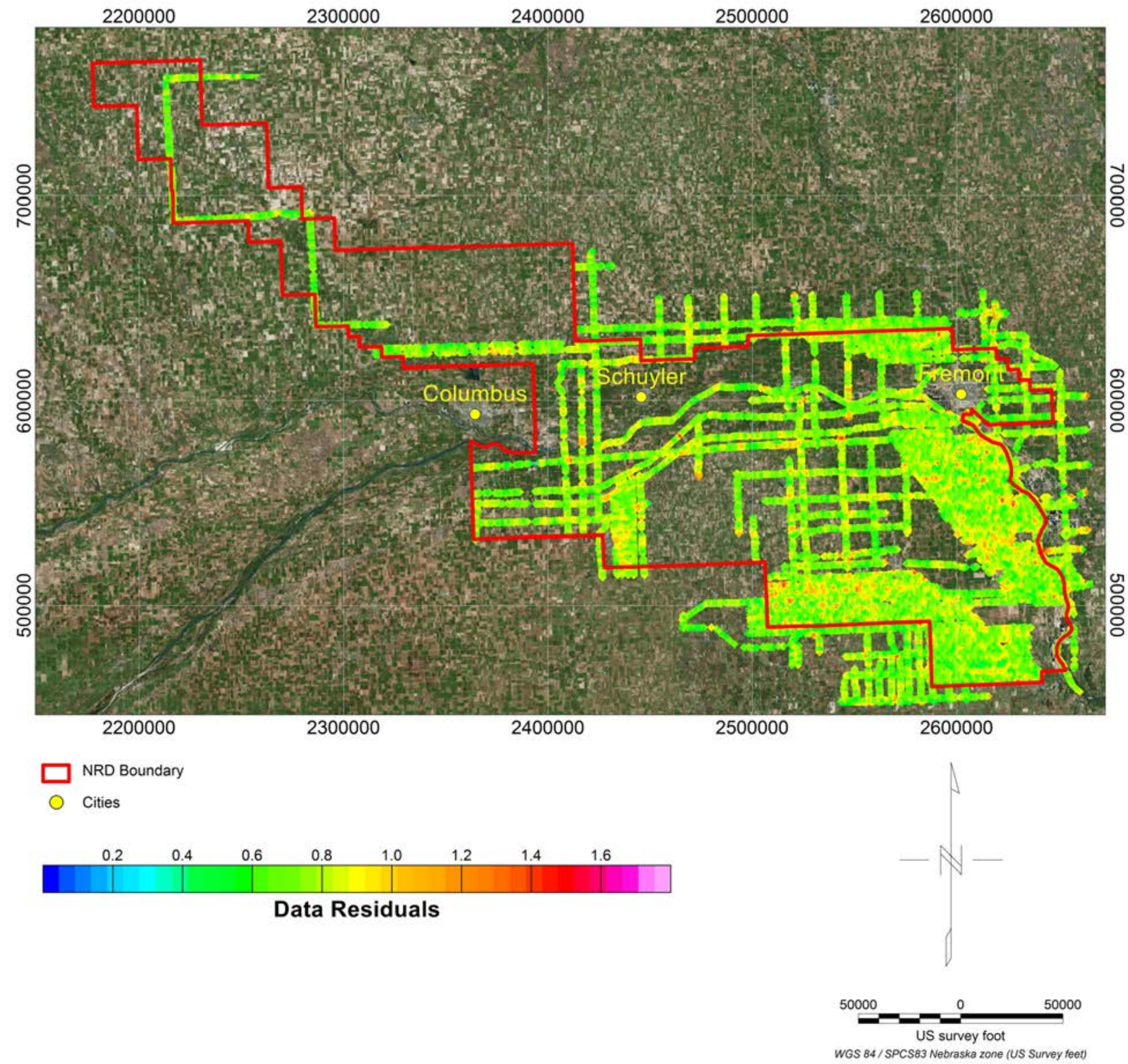


Figure 2-15. Map of data-inversion model residuals for the LPNNRD 2018 SCI inversion results.

2.6 Merge AEM Databases from Different Flights and Inversions

After the inversion process several lines segments were combined to form continuous lines within the survey area. This included lines that composed the block flights and reconnaissance grid lines. These continuous lines allow for improved viewing and interpretation of the AEM inversions results. As just discussed above, the areas that were flown for the P-MRNRD, LPNNRD, and LPSNRD AEM survey were inverted together with some areas of the LENRD. A consequence of this inversion procedure resulted in/provided multiple inversions of many lines. The lines that had multiple inversions were compared and the line-inversion with the lowest data-model residual was retained, and the other repeat line-inversions were deleted from the data base. At that point the segmented lines were merged to form continuous lines. Table 2-6 lists the original flown lines and the new combined lines.

Table 2-6. Combination of flight lines within the inversion areas.

Original Source Lines	New Line
Group 6 L160001.1, and Group 6 L160002	L160000
Group 3 L300101, Group 3 L507001, and Group 3 L508001	L300100
Group 3 L300201, Group 3 L507101, and Group 3 L508101	L300200
Group 3 L300301, and Group 3 L508201	L300300
Group 3 L300401, Group 3 L507301, and Group 3 L508301	L300400
Group 3 L300501, and Group 3 L508401	L300500
Group 3 L300601, and Group 3 L508601	L300600
Group 3 L300701, and Group 3 L508701	L300700
Group 3 L300801, and Group 3 L508901	L300800
Group 3 L301001, and Group 3 L509001	L301000
Group 3 L302101, and Group 3 L302102	L302100
Group 3 L302901, and Group 3 L509601	L302900
Group 3 L303701, and Group 3 L510001	L303700
Group 1 L303801, and Group 1 L303802	L303800
Group 1 L303901, Group 1 L304001, and Group 1 L304101	L303900
Group 1 L304301, and Group 1 L304302	L304300
Group 1 L305101, and Group 1 L305202	L305100
Group 1 L305301, and Group 1 L305401	L305300
Group 1 L305501, and Group 1 L305601	L305500
Group 1 L306001, and Group 1 L306101	L306000
Group 1 L306201, and Group 1 L306301	L306200
Group 1 L306401, and Group 1 L306501	L306400
Group 1 L306601, and Group 1 L306701	L306600
Group 1 L306901, and Group 1 L306902	L306900
Group 1 L307101, and Group 1 L307102	L307100
Group 2 L308301 and Group 2 L308401	L308300
Group 2 L308901, Group 2 L309001, and Group 2 L309002	L308900
Group 2 L309101, and Group 2 L309201	L309100
Group 2 L309301, and Group 2 L309401	L309300
Group 2 L310901, and Group 2 L310902	L310900
Group 2 L311101, and Group 2 L311201	L311100
Group 2 L311401, and Group 2 L311403	L311400

Original Source Lines	New Line
Group 1 L400811, and Group 1 L401301	**L400800**
Group 1 L400901, and Group 1 L401401	**L400900**
Group 1 L401101, Group 1 L402101, and Group 1 L402102	**L401100**
Group 1 L401501, and Group 1 L401901	**L401500**
Group 1 L402601, and Group 1 L402701	**L402600**
Group 1 L403001, Group 1 L403002, and Group 1 L403003	**L403000**
Group 3 L404101, and Group 1 L406801	**L404100**
Group 1 L404301, and Group 1 L404701	**L404300**
Group 3 L404501, and Group 1 L404801	**L404500**
Group 1 L404601, and Group 1 L404901	**L404600**
Group 1 L405201, and Group 1 L405301	**L405200**
Group 1 L405401, and Group 1 L405501	**L405400**
Group 1 L406001, and Group 1 L406201	**L406000**
Group 1 L406101, and Group 1 L406301	**L406100**
Group 3 L407801, and Group 1 L407901	**L407800**
Group 2 L407001, and Group 2 L407002	**L407000**
Group 2 L407601, and Group 1 L407602	**L407600**
Group 3 L409101, Group 3 L409102, Group 3 L409201, and Group 3 L413901	**L409100**
Group 2 L410201, Group 1 L405001, and Group 1 L406901	**L410200**
Group 2 L410601, and Group 2 L410701	**L410600**
Group 2 L410801, and Group 2 L410901	**L410800**
Group 2 L411001, and Group 2 L411101	**L411000**
Group 2 L411201, and Group 2 L411301	**L411200**
Group 3 L413801, Group 1 L414101, and Group 1 L402801	**L413800**
Group 2 L411401, and Group 2 L411501	**L411400**
Group 2 L411601, and Group 2 L411602	**L411600**
Group 2 L412101, and Group 3 L407401	**L412100**
Group 2 L412201, and Group 2 L412301	**L412200**
Group 2 L412401, and Group 2 L412501	**L412400**
Group 2 L413701, Group 3 L409701, and Group 3 L409702	**L413700**
Group 6 L500801, and Group 5 L700901	**L500800**
Group 6 L501100, Group 6 L701201, and Group 6 L908901	**L501100**
Group 5 L501401, Group 5 L501402, Group 5 L503101, and Group 5 L701101	**L501400**
Group 5 L501501, Group 5 L501601, Group 5 L501602, and Group 5 L701301	**L501500**
Group 5 L501901, and Group 5 L503201	**L501900**
Group 5 L502901, Group 5 L503001, Group 5 L701401, and Group 5 L702701	**L502900**
Group 4 L504201, and Group 4 L701501	**L504200**
Group 4 L6504401, Group 5 L504501, and Group 4 L702501	**L504500**
Group 5 L504801, and Group 5 L504901	**L504800**
Group 4 L505001, and Group 4 L701601	**L505000**
Group 4 L505601, and Group 4 L702601	**L505600**
Group 3 L505801, Group 3 L506001, Group 3 L506002, and Group 3 L701701	**L505800**
Group 3 L506101, Group 3 L506102, and Group 3 L701801	**L506100**
Group 3 L506301, Group 3 L506302, and Group 3 L701901	**L506300**
Group 3 L506501, and Group 3 L702001	**L506500**
Group 3 L506601, and Group 3 L702101	**L506600**
Group 3 L506701, and Group 3 L702201	**L506700**

Original Source Lines	New Line
Group 3 L506801, and Group 3 L702301	**L506800**
Group 3 L506901, and Group 3 L702401	**L506900**
Group 3 L507801, and Group 3 L507901	**L507800**
Group 5 L600401, and Group 5 L909001	**L600400**
Group 6 L601601, Group 5 L601701, and Group 5 L601702	**L601600**
Group 6 L601901, and Group 6 L1004801	**L601900**
Group 6 L602101, Group 6 L1004901, and Group 7 L1004902	**L602100**
Group 6 L602301, and Group 6 L1005001	**L602300**
Group 6 L602500, Group 4 L602601, and Group 6 L1005201	**L602500**
Group 6 L700701, and Group 6 L700702	**L700700**
Group 7 L700301, and Group 7 L906501	**L700300**
Group 7 L700501, and Group 7 L700502	**L700500**
Group 6 L800401, and Group 7 L800402	**L800400**
Group 5 L700801, and Group 6 L908801	**L908800**
Group 5 L600601, and Group 6 L1004001	**L1004000**
Group 5 L601201, and Group 6 L1004301	**L1004300**
Group 5 L601801, and Group 6 L1004701	**L1004700**
Group 7 L1004904, and Group 7 L1004905	**L1004900**

3 AEM Results and Interpretation

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

3.1 Interpretive Process

3.1.1 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) State Plane Nebraska (feet) and the elevation values are referenced to the North American Vertical Datum of 1988 (NAVD 88) (feet). The 100 ft grid cell size was used throughout the project and resulting products. Figure 3-1 is a map of the DEM for the LPNNRD survey area having a vertical relief of 930 ft with a minimum elevation of 1,040 ft and a maximum elevation of 1,970 ft. This DEM was used to reference all elevations within the AEM and borehole datasets. Figure 3-2 is a DEM of The Leshara Uplands Block and has a vertical relief of 314 ft with a minimum elevation of 1,071 ft and a maximum elevation of 1,385 ft. Figure 3-3 is a DEM of The SQS1 Block and has a vertical relief of 435 ft with a minimum elevation of 1,260 ft and a maximum elevation of 1,695 ft. Figure 3-4 is a DEM of The SQS2 Block and has a vertical relief of 353 ft with a minimum elevation of 1,391 ft and a maximum elevation of 1,744 ft. Figure 3-5 is a DEM of The Waann Block and has a vertical relief of 497 ft with a minimum elevation of 1,061 ft and a maximum elevation of 1,558 ft.

3.1.2 Borehole Derived Bedrock Surface

As a guide in the interpretation of the AEM, a bedrock surface was prepared using CSD and NE-DNR borehole logs. The process included the following steps:

1. Consolidated the NE-DNR lithology tables.
2. Categorized each borehole's lithology description as either "Bedrock" or 'Unconsolidated' based on the description type. For example:
    i. Sandstone, Shale, Siltstone, Limestone, Chalk, etc. = "Bedrock"
    ii. Clay, silt, sand, gravel/boulders, etc. = "Unconsolidated"
3. Reviewed the dataset and flagged those boreholes where an "Unconsolidated" lithologic description was underlying a "Bedrock" description.
4. Revised categorized lithology, as needed, or flagged boreholes for removal from final dataset to be used for interpolation of the bedrock surface.
    a. In general, those boreholes flagged for removal contained unclear lithologic descriptions, making it uncertain where the depth to the top of the bedrock is located.

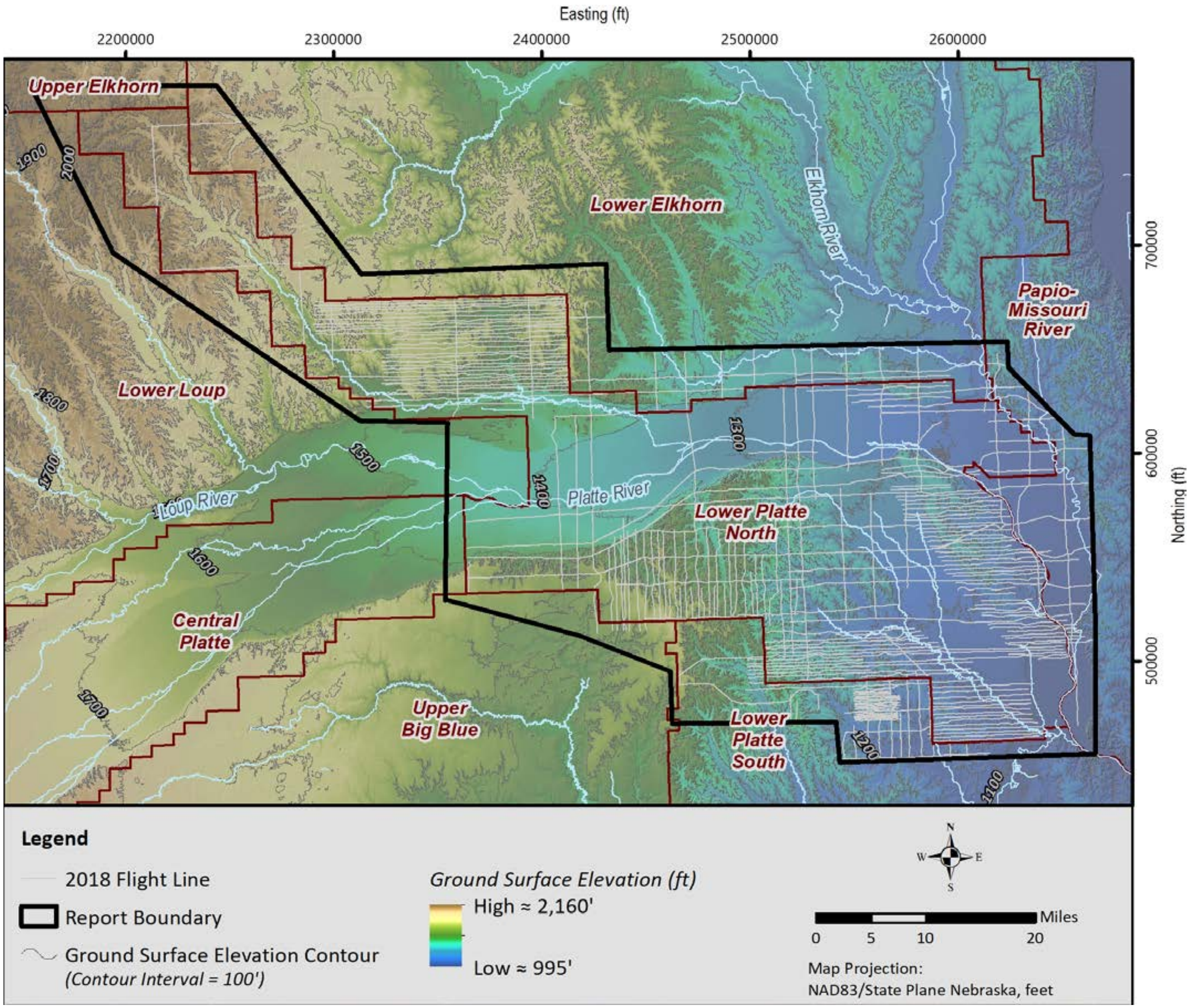


Figure 3-1. Map of the Digital Elevation Model for the 2018 LPNNRD study area. 2018 flight lines as well as SQS1 and SQS2 are indicated with gray lines. Data source is the one (1) arc-second National Elevation Dataset (U.S. Geological Survey, 2018).

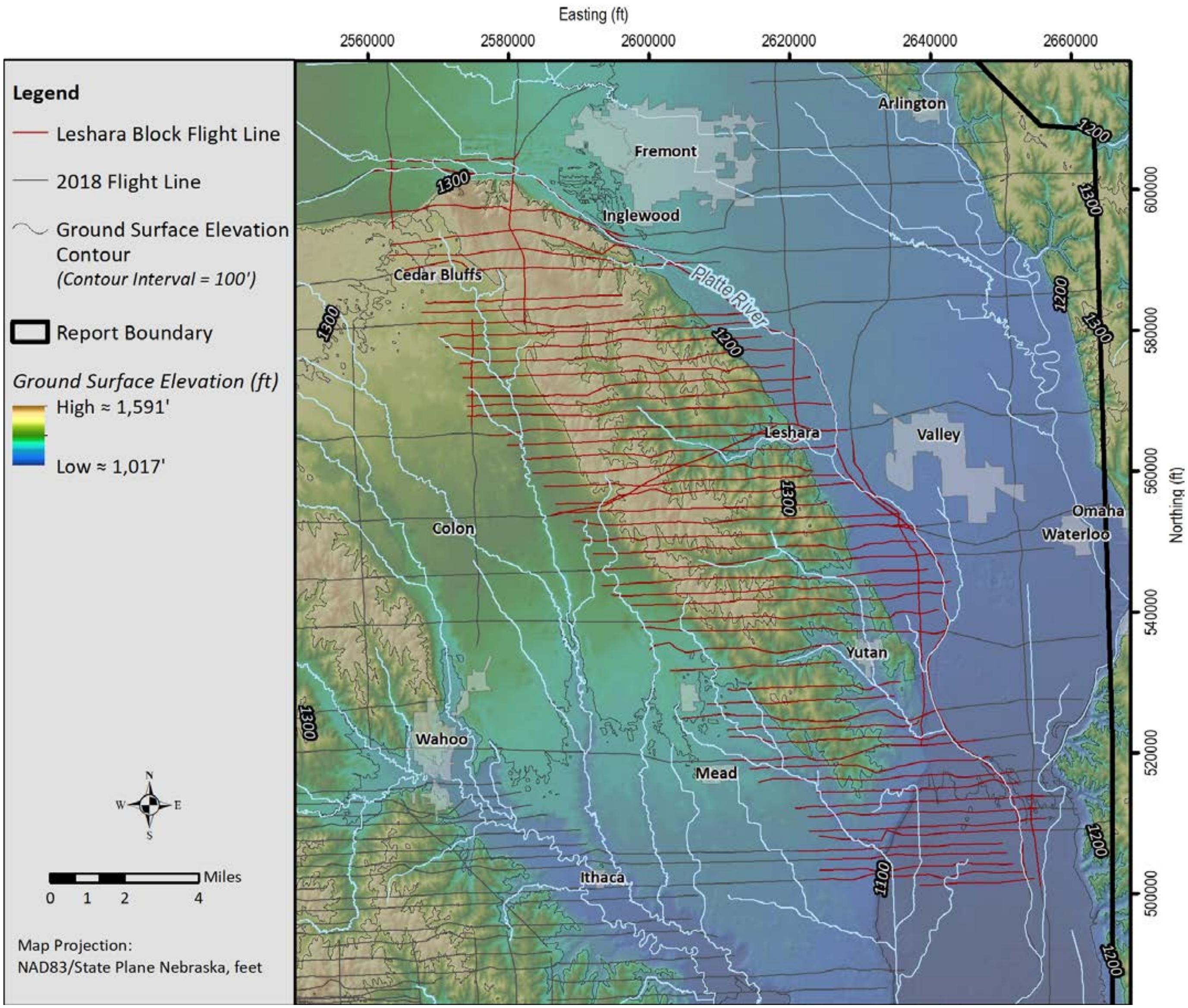


Figure 3-2. Map of the Digital Elevation Model for the Leshara Upland Block. Block flight lines are indicated with maroon lines and 2018 flight lines are indicated with gray lines. Data source is the one (1) arc-second National Elevation Dataset (U.S. Geological Survey, 2018).

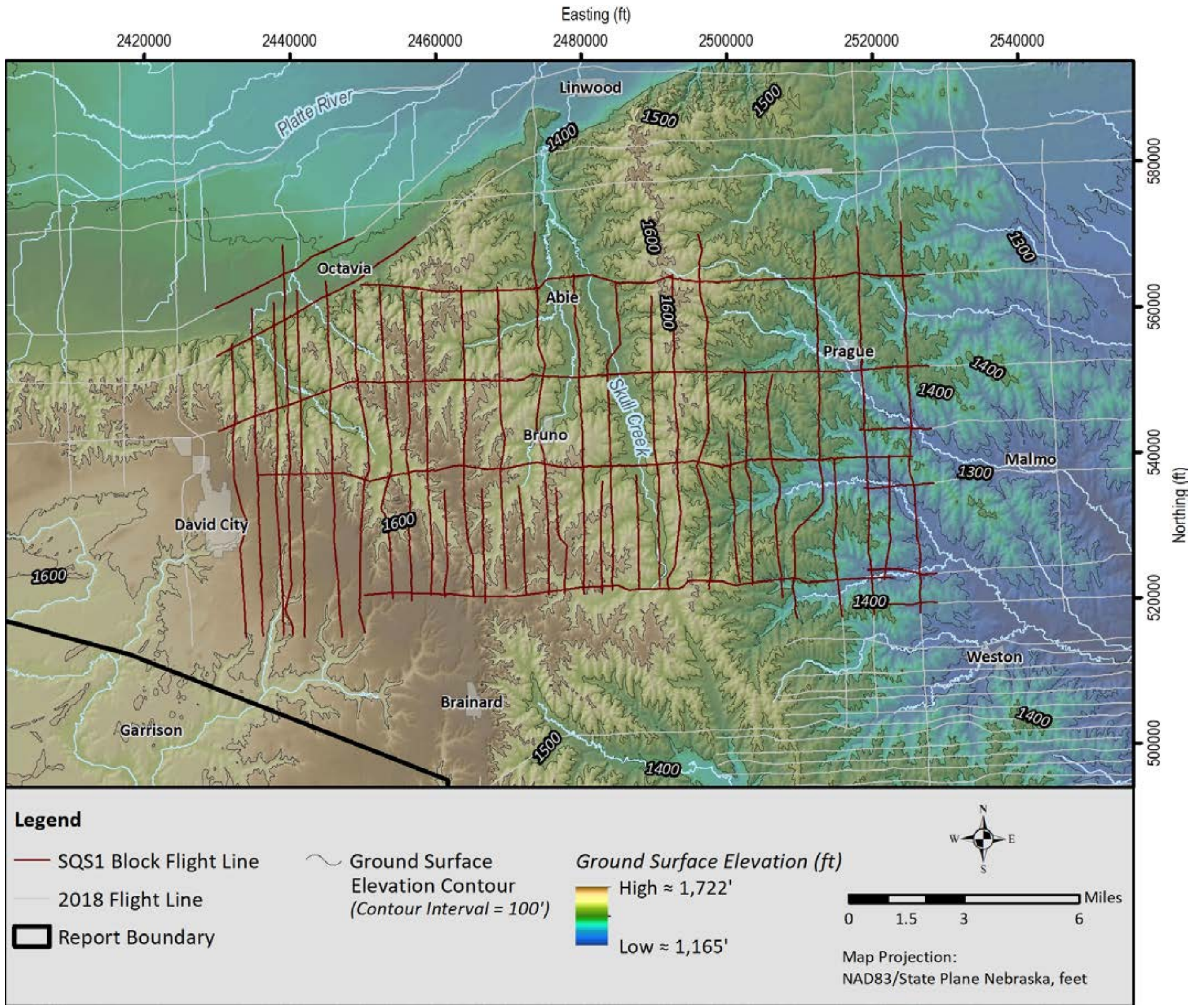


Figure 3-3. Map of the Digital Elevation Model for the SQS1 Block AEM survey area. Block flight lines are indicated with maroon lines and 2018 flight lines are indicated with gray lines. Data source is the one (1) arc-second National Elevation Dataset (U.S. Geological Survey, 2018).

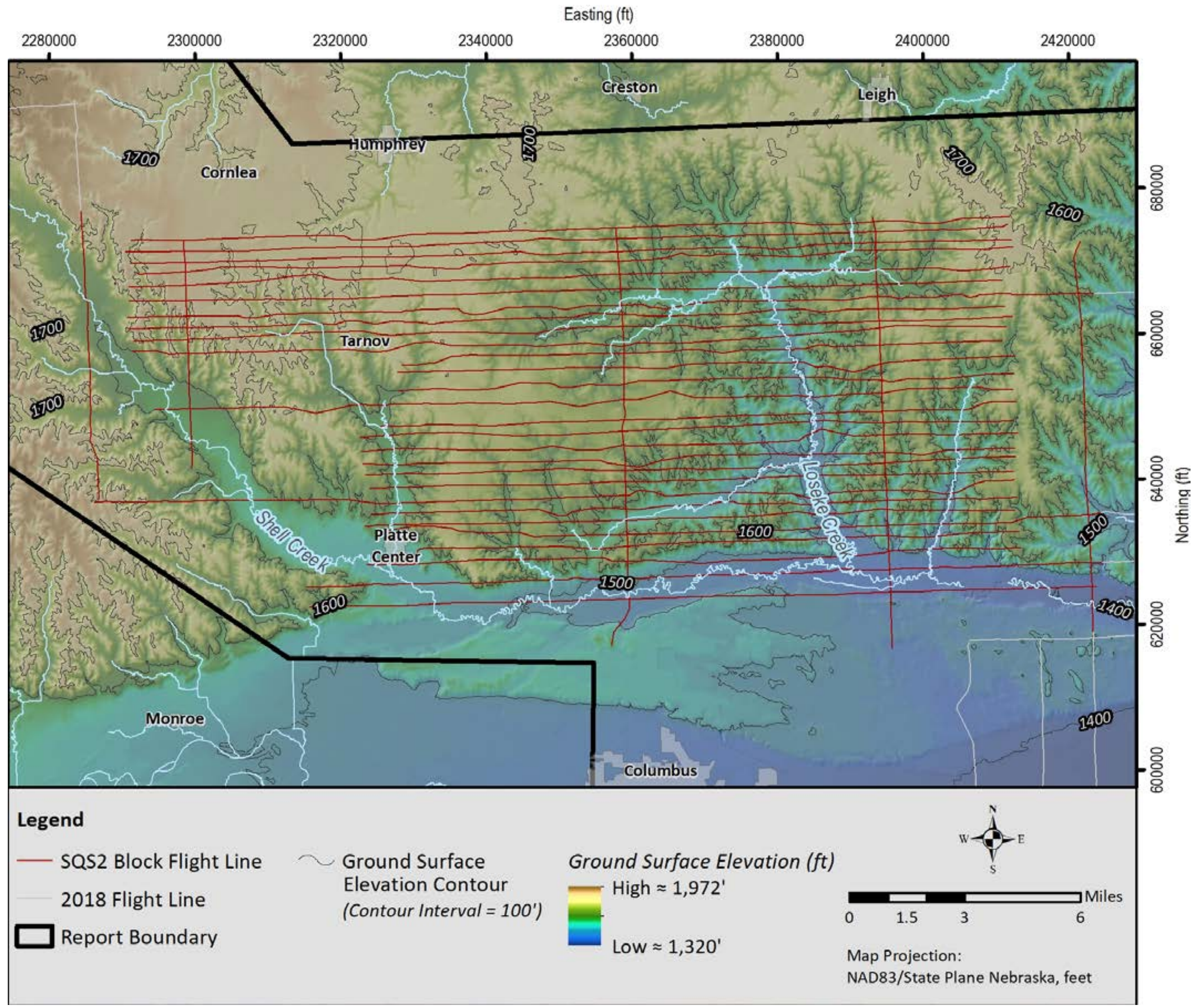


Figure 3-4. Map of the Digital Elevation Model for the SQS2 Block AEM survey area. Block flight lines are indicated with maroon lines and 2018 flight lines are indicated with gray lines. Data source is the one (1) arc-second National Elevation Dataset (U.S. Geological Survey, 2018).

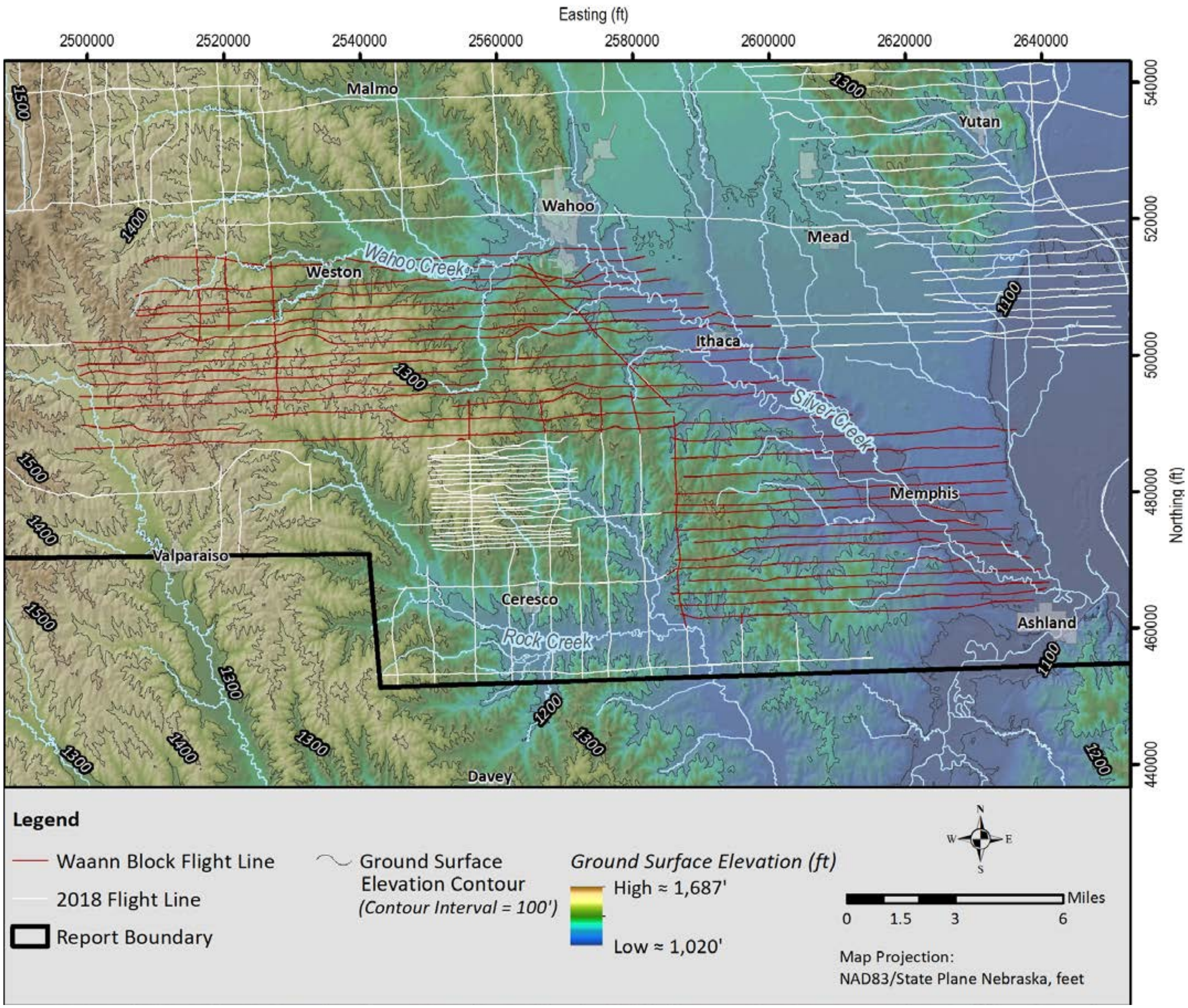


Figure 3-5. Map of the Digital Elevation Model for the Waann Block AEM survey area. Block flight lines are indicated with maroon lines and 2018 flight lines are indicated with gray lines. Data source is the one (1) arc-second National Elevation Dataset (U.S. Geological Survey, 2018).

5. Added the CSD borehole stratigraphy table to updated borehole lithology dataset, imported final dataset into ESRI's ArcCatalog, and exported as a borehole point shapefile. The borehole shapefile contained 7,203 data points.
6. Extracted the project's 100 ft cell size DEM into the borehole point shapefile and calculated the top of bedrock elevation by subtracting the depth to the top of bedrock from the ground surface elevation.
7. Interpolated the borehole point shapefile into a continuous raster dataset using the kriging geostatistical model and exported to a 300 ft cell size grid.
8. Calculated the residuals of the actual measured top of bedrock elevation to the interpolated top of bedrock elevation.
9. Reviewed any borehole where the residual was > 30 ft or < -30 ft. The value of 30 was used because it is a general representation of the degree of error while logging a borehole with mud rotary drilling techniques as it is approximately one drill stem length. Flagged those boreholes that appeared to be an anomaly.
    a. Boreholes were flagged as an "anomaly" if the following was observed:
        i. A borehole in a cluster of boreholes where the actual measured bedrock elevation varied more than ~ 75 ft from adjacent wells' actual measured bedrock elevation, or
        ii. a borehole's actual measured bedrock elevation varied more than ≈ 75 ft from an adjacent CSD well.
10. Compared the interpolated top of bedrock elevation surface to bottom of Quaternary deposits in CSD boreholes. Areas where the top of bedrock elevation was below the bottom of Quaternary deposits were reviewed for either anomalous boreholes in the area, or over-smoothing of the 300 ft cell size.
11. After reviewing and revising the borehole point shapefile, 285 data points that were flagged an "anomaly" were removed, leaving 6,918 data points for a second bedrock surface interpolation.
12. Re-interpolated the borehole point shapefile into a continuous raster dataset using the kriging geostatistical model and exported to a 300 ft cell size grid.
13. The interpolated bedrock surface raster dataset was compared to the DEM and anywhere the bedrock surface was greater than the DEM was set to the elevation of the DEM.
14. Calculated the residuals of the actual measured top of bedrock elevation to the interpolated top of bedrock elevation.
    b. Found that 535 boreholes had actual measured bedrock elevations differing more than 30 ft from the interpolated bedrock elevation.
    c. The majority of these 535 points fell within the range of +/- 30 to +/-50 ft variation of actual versus interpolated top of bedrock elevation.
    d. These relatively differences between actual and interpolated bedrock elevation in these boreholes could be attributed to inconsistent logging of boreholes

This surface is utilized as a guide in the interpretation of the bedrock within the AEM data profiles described next.

3.1.3 Create Interpretative 2D Profiles

After final combination of the AEM data and clipping of the data the general area of the LPNNRD (described above in Section 2.6) and the borehole-only bedrock surface was calculated, characterization of the subsurface was performed in cross-section format using Discover PA (Datamine, 2019). During interpretation, the horizontal and vertical scales of the profiles were adjusted to facilitate viewing. The color scale of the resistivity data was iteratively adjusted to illuminate subtle differences in the resistivity structure within the inverted AEM resistivity data related to the specific 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 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. Additionally, the bedrock borehole-only surface as developed was used as a guide for the interpretation in areas with low to no electrical resistivity contrast and no boreholes.

The ***To*** only occurs on the farthest northwestern portions of the survey on a few reconnaissance lines. The ***Kc*** and the ***Kgg*** only occurred on the western portions of the survey area along the reconnaissance lines and in survey blocks SQS1 and SQS2. The ***Kd*** exists throughout most of the LPNNRD survey area with the exception of the far southeastern corner where the ***Q*** is sitting directly on the IP. On the far western portions of the survey area, the AEM system was unable to penetrate to the depth of the ***Kd*** and the ***IP*** due to the system's Depth Of Investigation (DOI), discussed in Section 2.5. CSD stratigraphic control was utilized to distinguish the ***Q*** from the underlining formations. The ***To*** and the ***Q*** are difficult units to differentiate due to the similarities in resistivity. CSD and DNR wells were used to identify areas of consolidated materials (i.e. sandstone) to provide an estimate of the ***To*** location. The ***Kn*** is typically a resistive unit that is composed of shale and limestone. In areas of resistive ***Q*** materials sitting on the ***Kn***, the contrast is muted or non-existent. CSD test holes and DNR wells were critical in determining the presence of ***Kn***. Many of the NE-DNR wells stop at the top of the ***Kn***; this can be used as a clue that the overlying materials are not aquifer materials and would be the limestone, shale, and chalk of the ***Kn***. The ***Kc*** is a marine shale and is distinguished by its electrically conductive nature and is easily interpreted. The ***Kgg*** is typically observed as a resistor from the inclusion of the Greenhorn Limestone, but is masked in many locations by the low resistivity Graneros Shale unit that causes a bulk averaging effect. Depending on the depth of the ***Kgg*** interpretations can be made. In areas where the resolution of the AEM drops due to the depth the ***Kgg*** can be challenging and needs to be inferred from borehole control and regional patterns of thickness and dip.

The general location of ***Kd*** is detectable when there are resistive sands/sandstones. Use of general thickness constraints can also assist in the interpretation of the location of ***Kd***. NEOGCC and CSD wells in the area also provide 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 wells 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 borehole derived bedrock provided a useful interpretive tool to supplement the boreholes.

The top of the ***IP*** was another challenging unit to interpret due to the highly variable resistivity of the ***IP***. The unit varies from a resistive unit to a conductive unit based on the presence of clay minerals within the shale and limestone units with the additional complication of conductive saltwater in some areas. The best way to interpret the unit is to use the boreholes in the area. Many of the CSD and 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, the 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 are selected examples of the interpreted resistivity profiles that illustrate the process of interpretation with the use of the boreholes.

Figure 3-6 presents an approximately 58-mile-long east-west line, L501500, that was flown south of the Platte River from approximately Columbus to Fremont, Nebraska where the flight line extends east crossing the Platte River and ending near Elk City, Nebraska. Note that this line is combined from two flight lines with overlapping ends and the data have been sorted and interleaved together in the overlapping region. Several CSD test holes are projected onto the line that are within ½ mile. NE-DNR wells are also projected onto the line if they are within ¼ mile. The ***Q*** sediments are composed of Platte River alluvium and Todd Valley alluvium with areas of glacial till and glaciotectonic deposits. These ***Q*** materials are overlying the ***Kc*** and the ***Kgg*** that have been eroded off towards the east. The ***Kd*** occurs over the full flight line and is also eroded on the eastern end of the flight line with ***Q*** sediments directly deposited on the ***Kd***. Within the ***Kgg*** the difference between the resistive Cretaceous Greenhorn Limestone versus the conductive Cretaceous Graneros Shale can be observed. The color scale is set to a range that shows the resistive material within the ***Kd*** that is in direct contact with the resistive materials within the ***Q***. There is an excellent match between the AEM resistivities with the lithologies in the CSD wells. In the area of the glaciotectonic deposits the resistive outwash sands have been thrust up by the glacier.

Figure 3-7 presents an approximately 30-mile-long north-south line, L1004000, that is just east of David City, Nebraska and crosses the Platte River. Several CSD test holes and many NE-DNR wells are along the line. The bedrock is a combination of eroded ***Kc*** and ***Kgg*** on top of ***Kd*** that is found along the entire line. A paleochannel that is eroded down into the ***Kd*** is present just west of David City. Several terrace systems can be seen along the north bank of the Platte River as indicated by the resistive deposits in those locations.

Figure 3-8 presents an approximately 25-mile-long east-west line, L505800, that runs through the town of Wahoo, Nebraska and crosses the Platte River on the east. There is a gap in the line associated with the town of Wahoo as no data were collected in the town due to EM interference and FAA flight rules.

Several CSD test holes penetrate the ***Kd*** and/or stop at the top of the ***IP*** in the area of Todd Valley. This line is dominated by high resistivity materials in eastern portion of the flight line associated with the Platte River alluvium and the alluvial deposits within the Todd Valley. Several areas in the ***Kd*** show the change in resistivity associated with sand/sandstone units versus the clay/shale units. On the eastern portion of the line there are resistive materials associated with ***Q*** sands.

Figure 3-9 presents an approximately 22-mile-long east-west line, L301000, that is south of the Swedeburg, Nebraska area. The line crosses Oak, Rock, and Wahoo Creeks. Several NE-DNR registered wells penetrate the ***Kd*** and indicate sandstone in these areas that corelate with increased resistivity zones in the AEM. The ***Q*** material is predominantly till with sand zones associated with Rock and Wahoo Creeks. The sand zones are generally larger than the alluvial deposits and may be related to glacial outwash. In the Oak Creek area, these larger sand deposits are not observed.

Figure 3-10 presents an approximately 35-mile-long east-west line, L300100, that is north of the Swedeburg, Nebraska area and south of the town of Wahoo, Nebraska. Several CSD test holes (plotted within ½ mile) and many NE-DNR wells (plotted within ¼ mile) penetrate the ***Kd***. On the western end of the line, the bedrock is eroded ***Kgg***, most likely the Graneros Shale. The ***Kd*** is progressively more eroded towards the east. The line is dominated by the resistive materials in Todd Valley.

Figure 3-11 presents an approximately 12-mile-long east-west line, L500201, that is north of the town of Lindsay, Nebraska and crosses Shale Creek. Several NE-DNR registered wells penetrate the ***To***. CSD borehole 34-A-55 also penetrates the ***To*** and also indicates ***Kn***. The Quaternary (***Q***) material is predominantly loess on top of more resistive sands and sands/gravels that overlie the ***To***. The Cretaceous bedrock here is composed of ***Kn*** material.

The above profiles serve as examples of the interpretation of the AEM profiles. All of the 2D profiles that show the relationship of the CSD test holes to the interpreted AEM for the complete study area can be found in Appendix 1 – 2D Profiles.

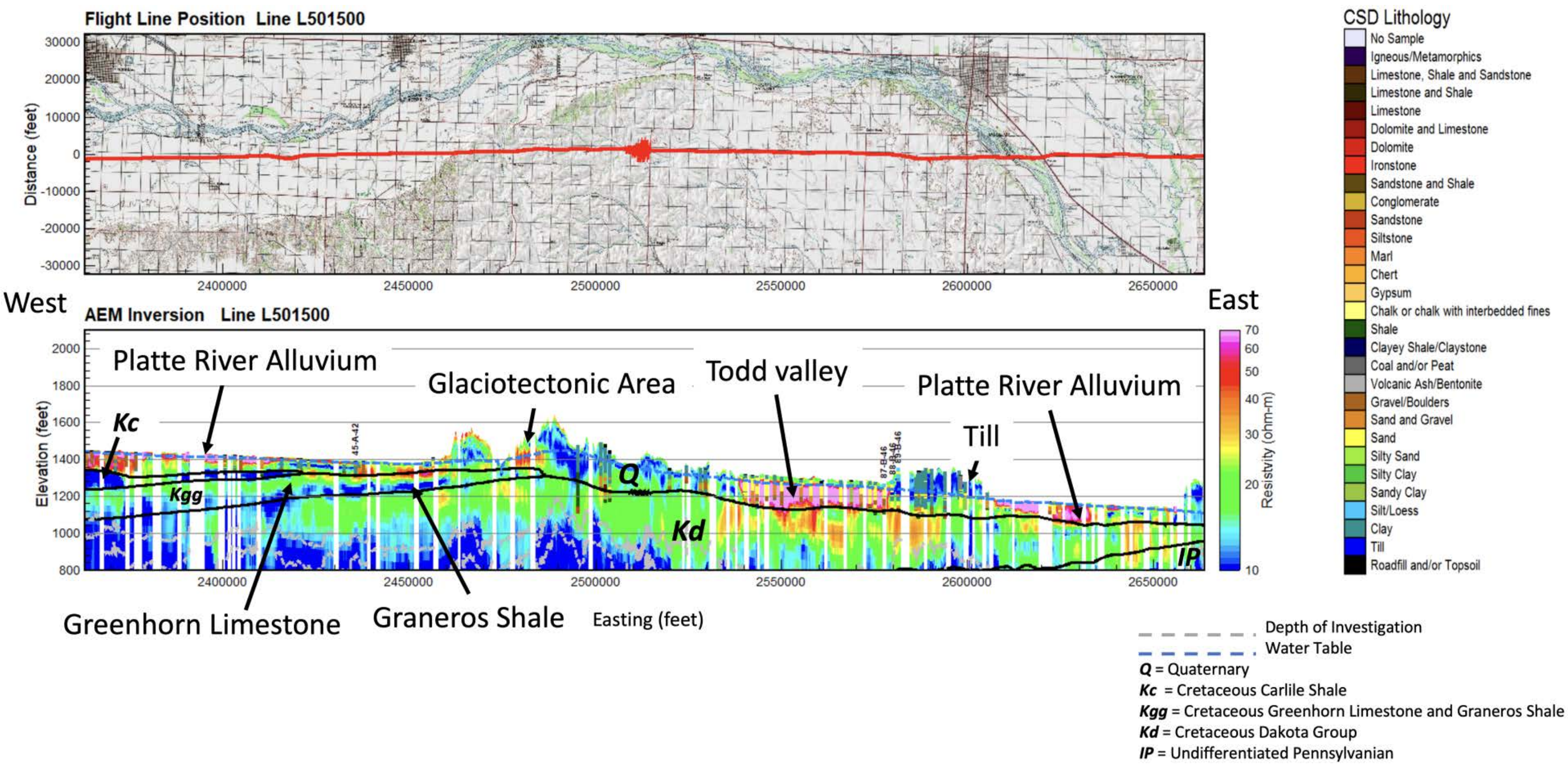


Figure 3-6. 58-mile-long east-west line L501500 that is flown south of the Platte River from approximately Columbus to Fremont, Nebraska where it extends east crossing the Platte River ending near Elk City, Nebraska. Borehole lithology logs are indicated on the AEM inverted earth models if they are within ½ mile for CSD holes and ¼ mile for NE-DNR wells of the flight line. Interpretations of the top of the geologic units are indicated by the black lines. Gaps indicate areas removed due to coupling. The horizontal datum is NAD83 State Plane (feet).

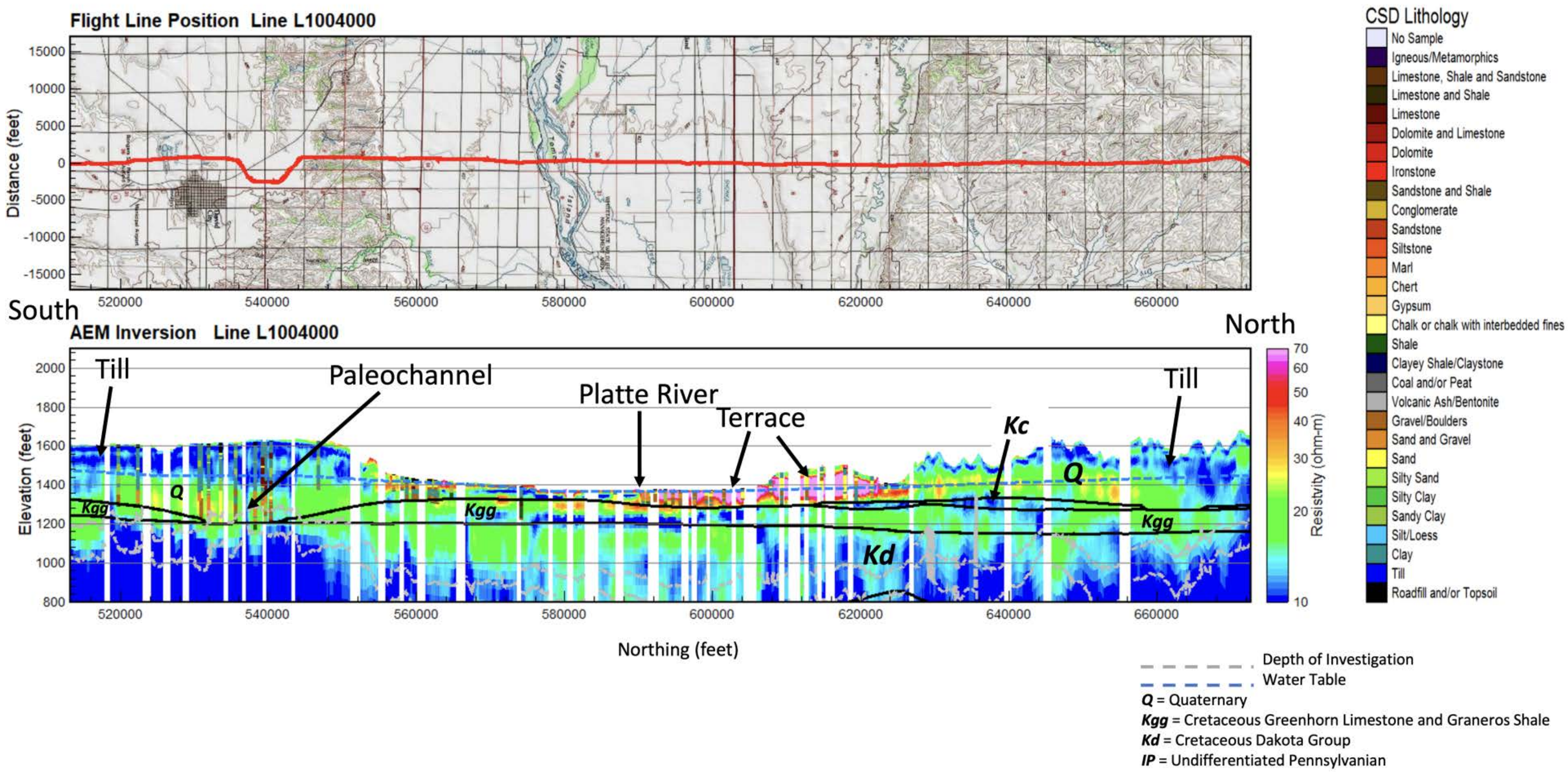


Figure 3-7. 30-mile-long north-south line L1004000. CSD (within ½ mile) and Nebraska DNR (within ¼ mile) boreholes lithology logs are indicated on the AEM inverted earth model. Interpretations of the top of the geologic units are indicated by the black lines. The Quaternary (*Q*) material is predominantly glacial deposits with Platte River alluvium in the center and a paleochannel deposit at the southern end of the line. Gaps indicate areas removed due to coupling. The horizontal datum is NAD83 State Plane (feet).

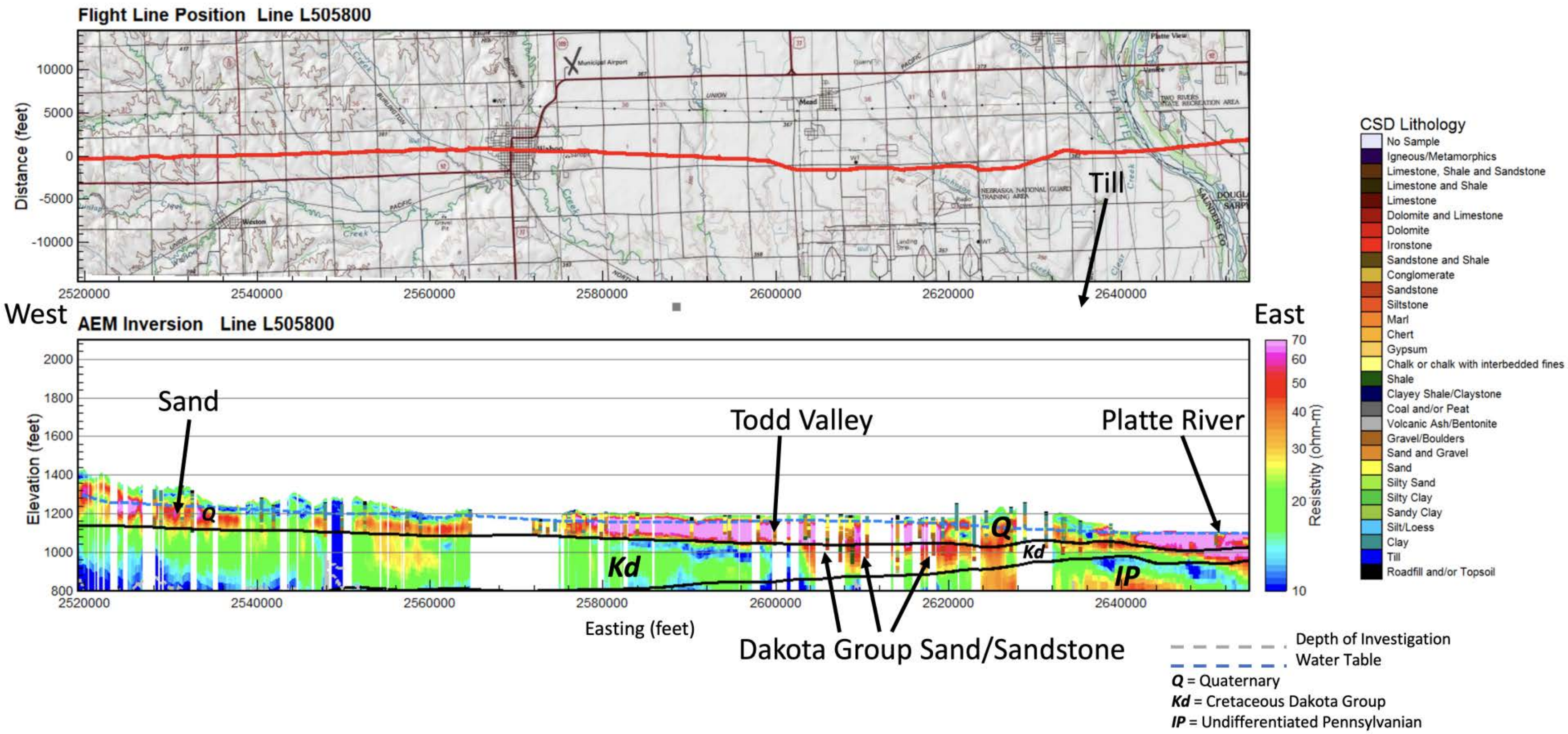


Figure 3-8. 25-mile-long east-west line L505800 that runs through Wahoo, Nebraska. CSD (within ½ mile) and Nebraska DNR (within ¼ mile) boreholes lithology logs are indicated on the AEM inverted earth model. Interpretations of the top of the geologic units are indicated by the black lines. Gaps indicate areas removed due to coupling. The horizontal datum is NAD83 State Plane (feet).

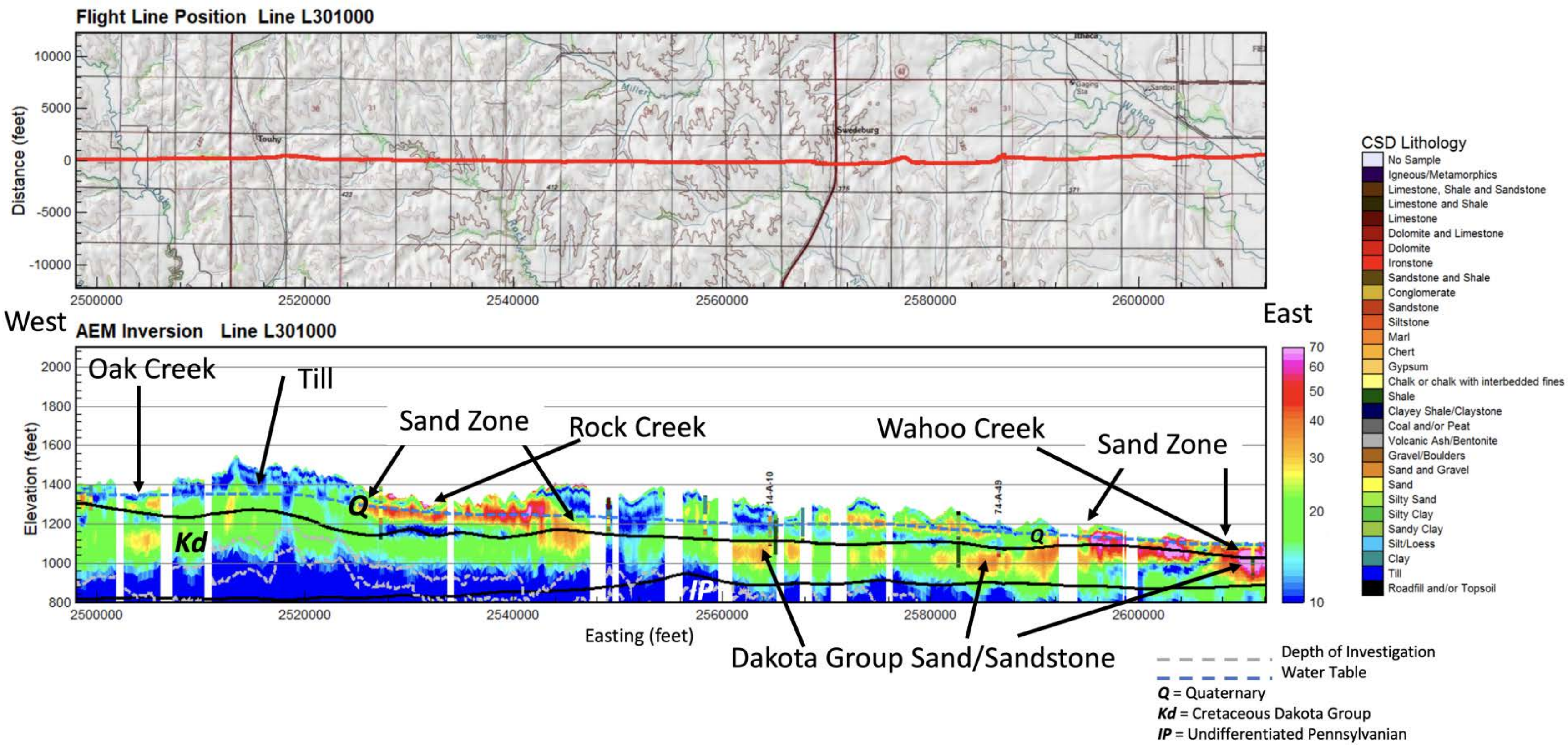


Figure 3-9. 22-mile-long east-west line L301000 that is south of Swedeburg, Nebraska. Nebraska DNR borehole lithology logs are indicated on the AEM inverted earth models if they are within ¼ mile of the flight line. CSD test holes are within ½ mile. Interpretations of the top geologic units are indicated by the black lines. The Quaternary (*Q*) material is predominantly till with sand zones associated with Rock and Wahoo Creeks. Gaps indicate areas removed due to coupling. The horizontal datum is NAD83 State Plane (feet).

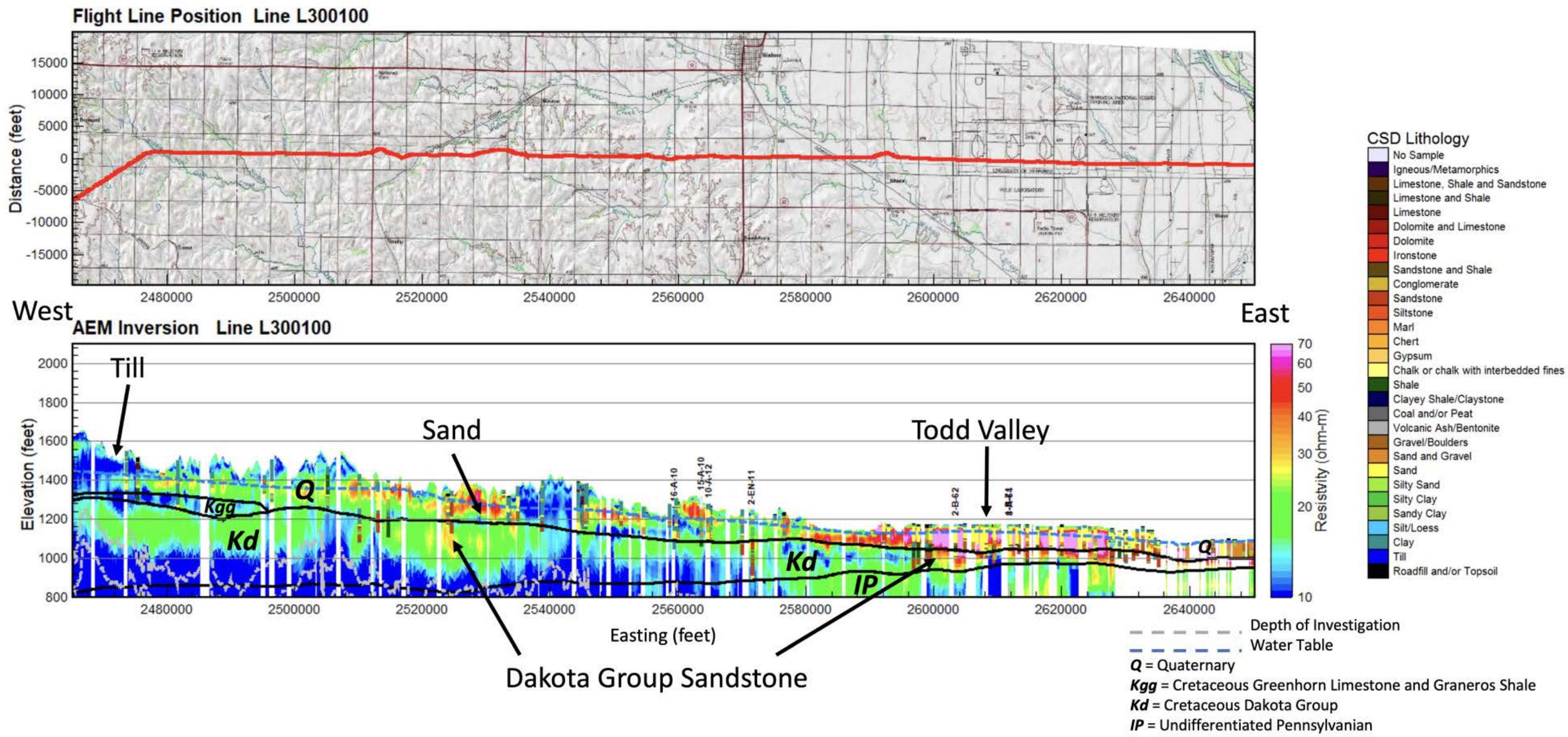


Figure 3-10. 35-mile-long east-west line L300100 that is south of Wahoo, Nebraska. CSD and Nebraska DNR borehole lithology logs are indicated on the AEM inverted earth models if they are within ½ and ¼ mile of the flight line, respectively. Interpretations of the top geological units are indicated by the black lines. Gaps indicate areas removed due to coupling. The horizontal datum is NAD83 State Plane (feet).

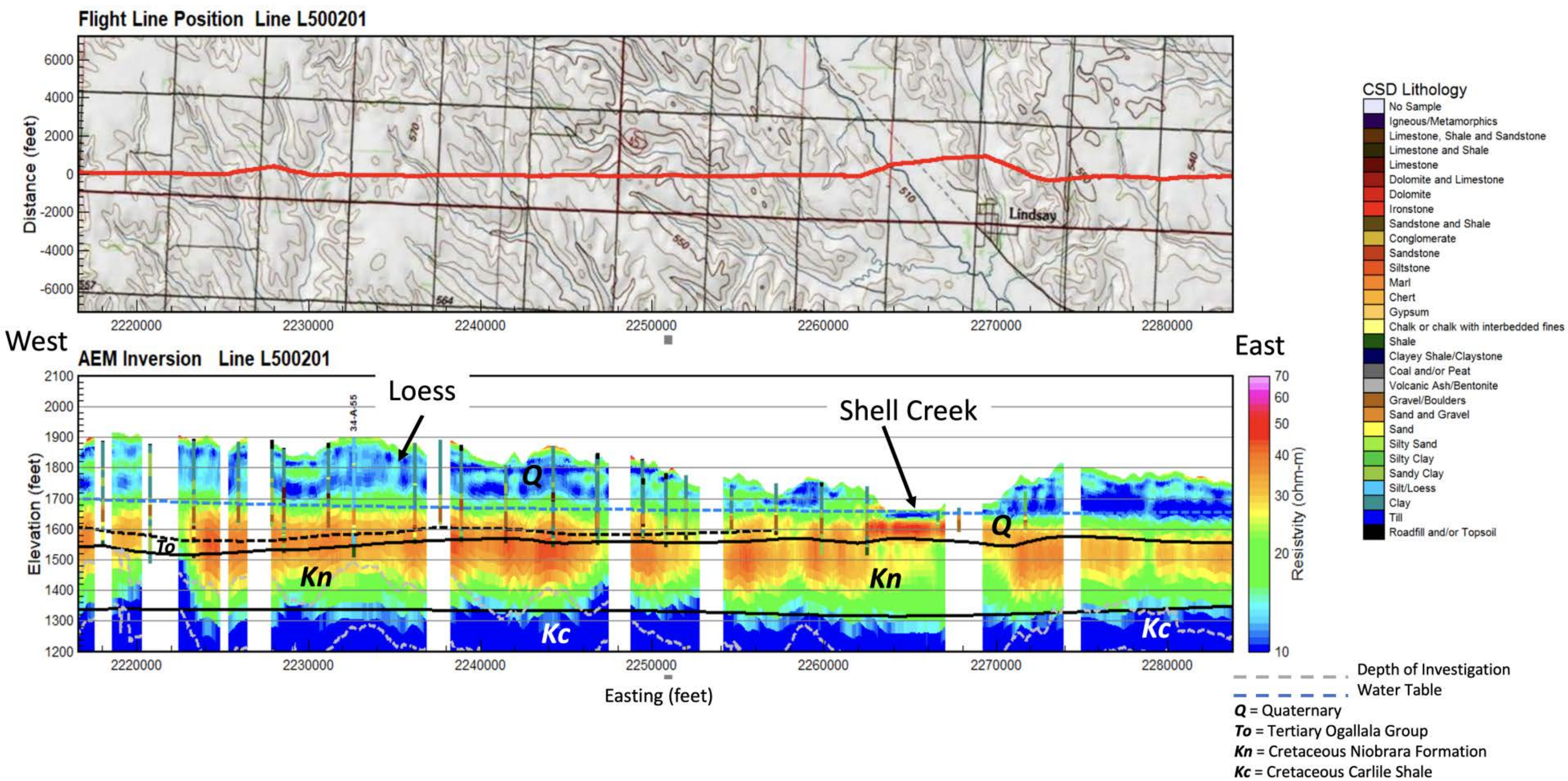


Figure 3-11. 12-mile-long east-west line L500201. Nebraska DNR borehole lithology logs are indicated on the AEM inverted earth models if they are within ¼ mile of the flight line and CSD test holes if they are within ½ mile. Interpretations of the top geologic units are indicated by the black lines. The Quaternary (*Q*) material is predominantly Loess with sand and gravel deposited on the Tertiary Ogallala Group (*To*). Gaps indicate areas removed due to coupling. The horizontal datum is NAD83 State Plane (feet).

3.1.4 Create Interpretative Surface Grids

Grids have been produced for the LPNNRD 2018 project area and the Block survey areas (the Leshara Upland, SQS1, SQS2, and Waann) including grids of the elevations of the tops of the geologic units, geologic unit thicknesses, and the saturated thicknesses of the geologic units. To create these grids, data such as the ground surface digital elevation model (DEM), the 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 elevation of the top of the Tertiary Ogallala Group (***To***), Cretaceous Niobrara Formation (***Kn***), Cretaceous Carlile Shale (***Kc***), Cretaceous Greenhorn Limestone and Graneros Shale (***Kgg***), Cretaceous Dakota Group (***Kd***), and undifferentiated Pennsylvanian (***IP***) for the LPNNRD and the Block AEM survey areas were produced. To create the grids, ~ 33,000 data points with top elevation values were extracted from the AEM interpretation and input into a database. Additionally, ~400 CSD borehole data points with depth to top of geologic units were added to the database which was then input into ESRI's ArcMap for processing. The CSD borehole data provided control in areas between flight lines. The elevation point data were interpolated into a continuous surface using the kriging geostatistical model and exported to a 500 ft cell size grid. The grid for the 2018 LPNNRD survey area and SQS2 AEM Block survey area was then resampled in ArcGIS to a 1,000 ft cell size using the cubic convolution resampling technique. The grids created for the remaining AEM Block survey areas were developed by the same kriging method except they were not resampled, but instead kept at the 500 ft cell size based on the denser AEM flight line spacing. Figures 3-12 to 3-30 are maps of top elevation of ***To, Kn, Kc, Kgg, Kd,*** and ***IP*** within the 2018 LPNNRD AEM survey area and the Leshara Upland, SQS1, SQS2, and Waann Block AEM survey areas, respectively.

Raster grids of the elevations of the tops of bedrock were produced for the 2018 LPNNRD and the Block AEM survey areas. First, a comparison was made between the geologic contacts interpreted on the geologic map (Burchett, 1986) and where the AEM data show the contact to exist. Small adjustments were made to the mapped contact based on this comparison. Next, the grids of the elevations of the tops of ***To, Kn, Kc, Kgg, Kd,*** and ***IP*** were masked to the extents of each unit based on the revised geologic map. Finally, the grids were mosaicked in ArcMap to create one continuous top of bedrock elevation grid. The 500 ft cell size for the top of bedrock elevation grids was retained for the Leshara Upland, SQS2, and Waann AEM Block survey areas, but was resampled to 1,000 ft cell size using the cubic convolution resampling technique for the 2018 LPNNRD and SQS1 AEM Block survey areas. Figures 3-31 to 3-35 are maps of the elevations of the tops of the bedrock surfaces within the 2018 LPNNRD survey area and the Leshara Upland, SQS1, SQS2, and Waann Blocks AEM survey areas, respectively.

Quaternary deposits (***Q***), and ***To, Kn, Kc, Kgg,*** and ***Kd*** thicknesses were calculated for the 2018 LPNNRD and the Block AEM survey areas using the tops of elevation grids with ArcMap's raster calculator. For the ***Q*** thickness grid, the elevation of the top of bedrock was subtracted from the DEM. For the ***To*** thickness grid, the elevation of the top of ***Kn*** was subtracted from the elevation of the top of ***To*** and then the resultant grid was masked with a ***To-Kn*** contact line polygon. For the ***Kn*** thickness grid, the elevation of the top of ***Kc*** was subtracted from the elevation of the top of ***Kn*** and then the resultant grid was masked with the ***Kn-Kc*** contact line polygon. Similarly, for the ***Kc*** thickness grid, the elevation of the top of ***Kgg*** was subtracted from the elevation of the top of ***Kc*** and then the resultant grid was masked with the ***Kc-Kgg*** contact line polygon. For the ***Kgg*** thickness, the elevation of the top of ***Kd*** was subtracted from the elevation of the top of ***Kgg***, and then the resultant grid was masked with the ***Kgg-Kd*** contact line polygon. Finally, for the ***Kd*** thickness, the elevation of the top of ***IP*** was subtracted from the elevation of the top of ***Kd*** and then the resultant grid was masked with the ***Kd-IP*** contact line polygon. The grids produced for the 2018 LPNNRD and SQS1 Block AEM survey areas were calculated using the 1,000 ft cell size top elevation grids, whereas the grids produced for the Leshara Upland, SQS2, and Waann, AEM Block survey areas were calculated using the 500 ft cell size top elevation grids. Figures 3-36 to 3-51 are maps of ***Q, To, Kn, Kc, Kgg,*** and ***Kd*** thickness within the 2018 LPNNRD and Block AEM survey areas, respectively.

To assist in the approximation of the saturated materials along the surveyed AEM flight lines, the 1995 CSD statewide water table (Nebraska CSD, 1995) was utilized. It should be noted that this inclusion provides only a generalized characterization of the saturated thickness of the aquifer as the CSD's dataset is two decades old at the time of the 2018 LPNNRD AEM survey and local conditions likely deviate in areas with variable topography. The water table in the LPNNRD area is close to the surface in some of the areas. To this end a topographic correction was required to ensure that the water table height was below the surface topography. The original water table contour lines were gridded at a 1,000 ft cell size using the Geosoft Oasis Montaj's Minimum Curvature Grid (MCG) and a blanking distance of 5,000 ft. The cells were set 'to extend beyond' to 50. The resulting grid was then re-gridded at a 100 ft cell size and compared with the DEM (Figure 3-52) of the LPNNRD 2018 AEM survey area. In areas where the water table was greater than the topography, the water table was set to an elevation of the topography minus three feet. The grid was then clipped to the southern reconnaissance AEM survey area. A water table was also prepared for the Leshara Upland, SQS1, SQS2, and Waann Block AEM survey area (Figures 3-53 to 3-56).

Saturated thicknesses of ***Q*** and ***Kd*** were calculated for the 2018 LPNNRD and the Block AEM survey areas with the top elevation and 1995 CSD water table grids using ArcMap's raster calculator. For the ***Q*** saturated thickness grid, the elevation of the top of bedrock was subtracted from the 1995 water table. For the ***Kd*** saturated thickness grid, the elevation of the top of ***IP*** was subtracted from the 1995 water table. Then the ***Q*** saturated thickness was subtracted from the resultant grid. The grids produced for the 2018 LPNNRD and SQS1 AEM Block survey areas were calculated using the 1,000 ft cell size top elevation grids, whereas the grids produced for the Leshara, Waann, and SQS2 AEM Block survey areas were calculated using the 500 ft cell size top elevation grids. All resultant saturated thickness grids were masked, as necessary, to the geologic contact lines. Figures 3-57 to 3-65 are maps of ***Q*** and ***Kd*** saturated thickness both with and without well points displaying estimated specific capacity within the 2018 LPNNRD and Block AEM survey areas, respectively.

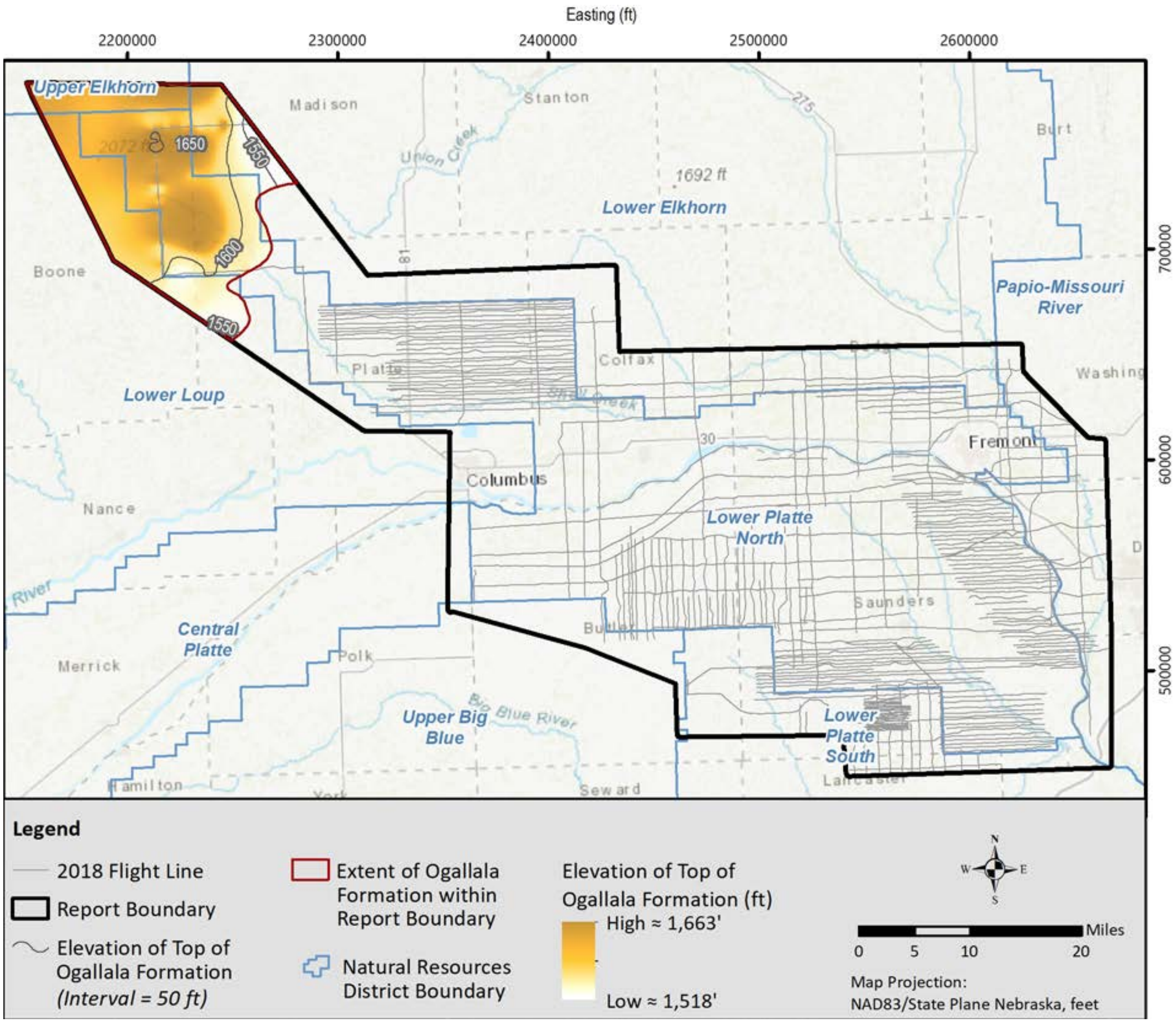


Figure 3-12. Map of the elevation of the top of the Tertiary Ogallala Group (*To*) within the 2018 LPNNRD AEM survey area.

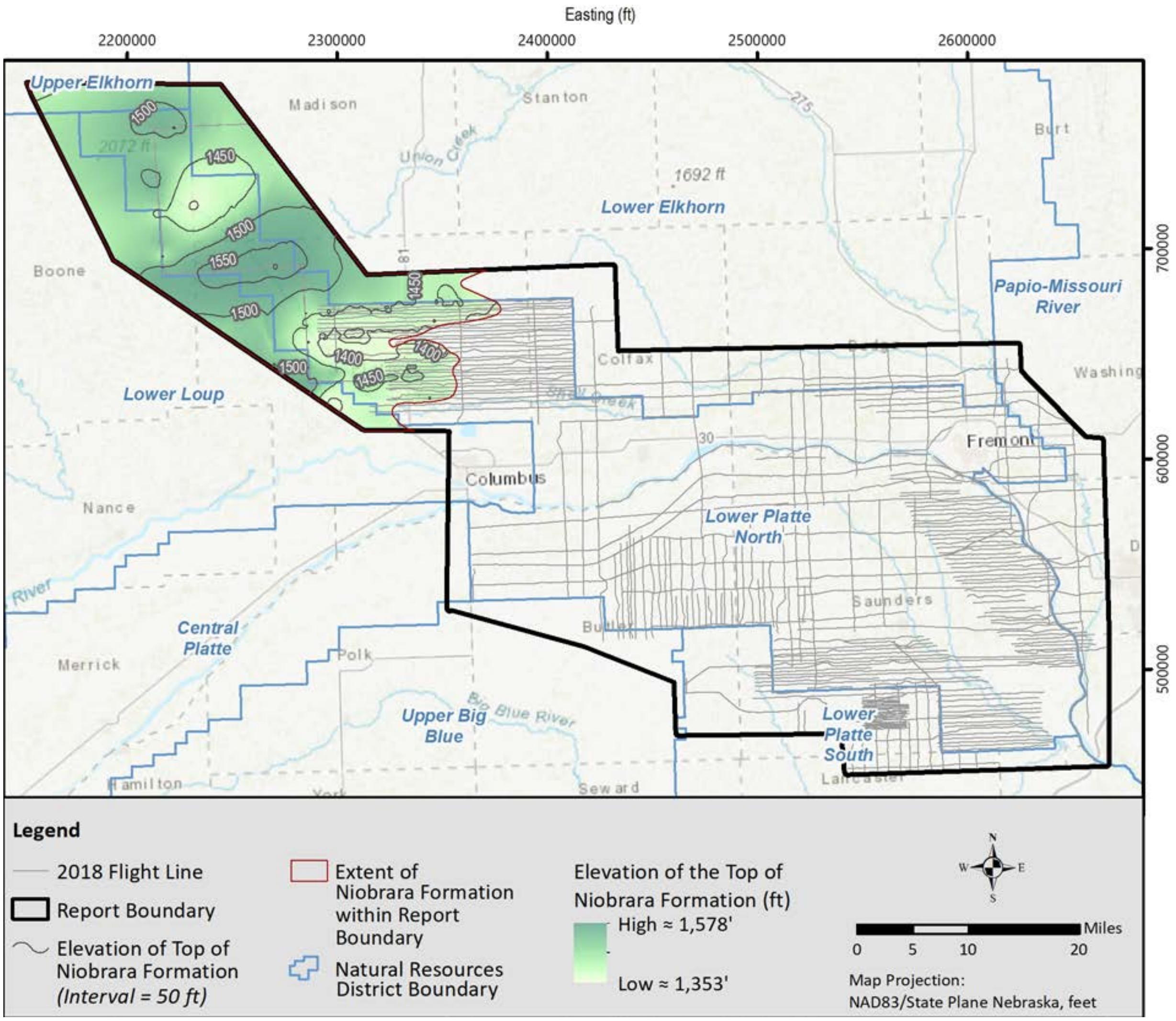


Figure 3-13. Map of the elevation of the top of the Cretaceous Niobrara Formation (*Kn*) within the 2018 LPNNRD AEM survey area.

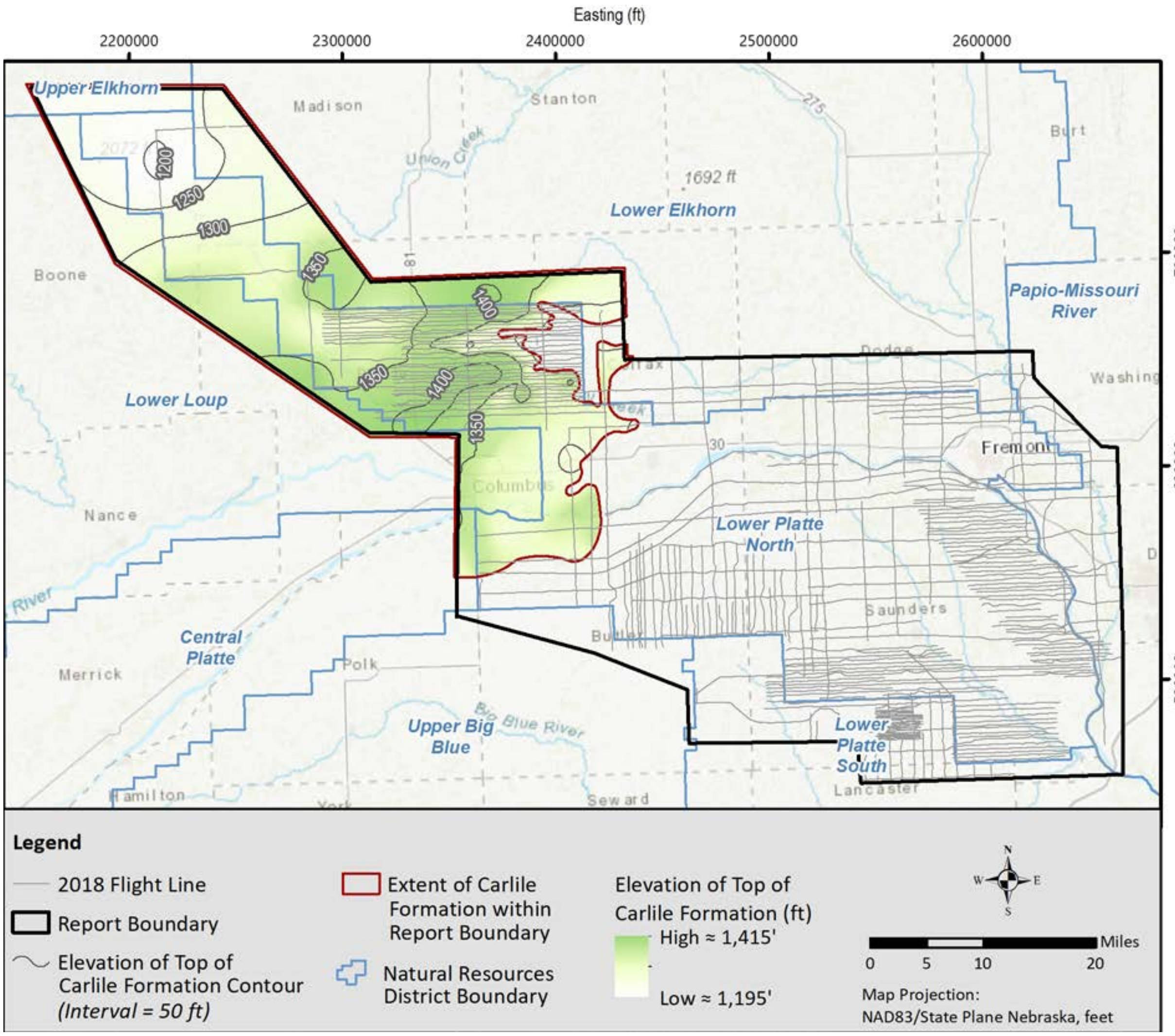


Figure 3-14. Map of the elevation of the top of the Cretaceous Carlile Shale (*Kc*) within the 2018 LPNNRD AEM survey area.

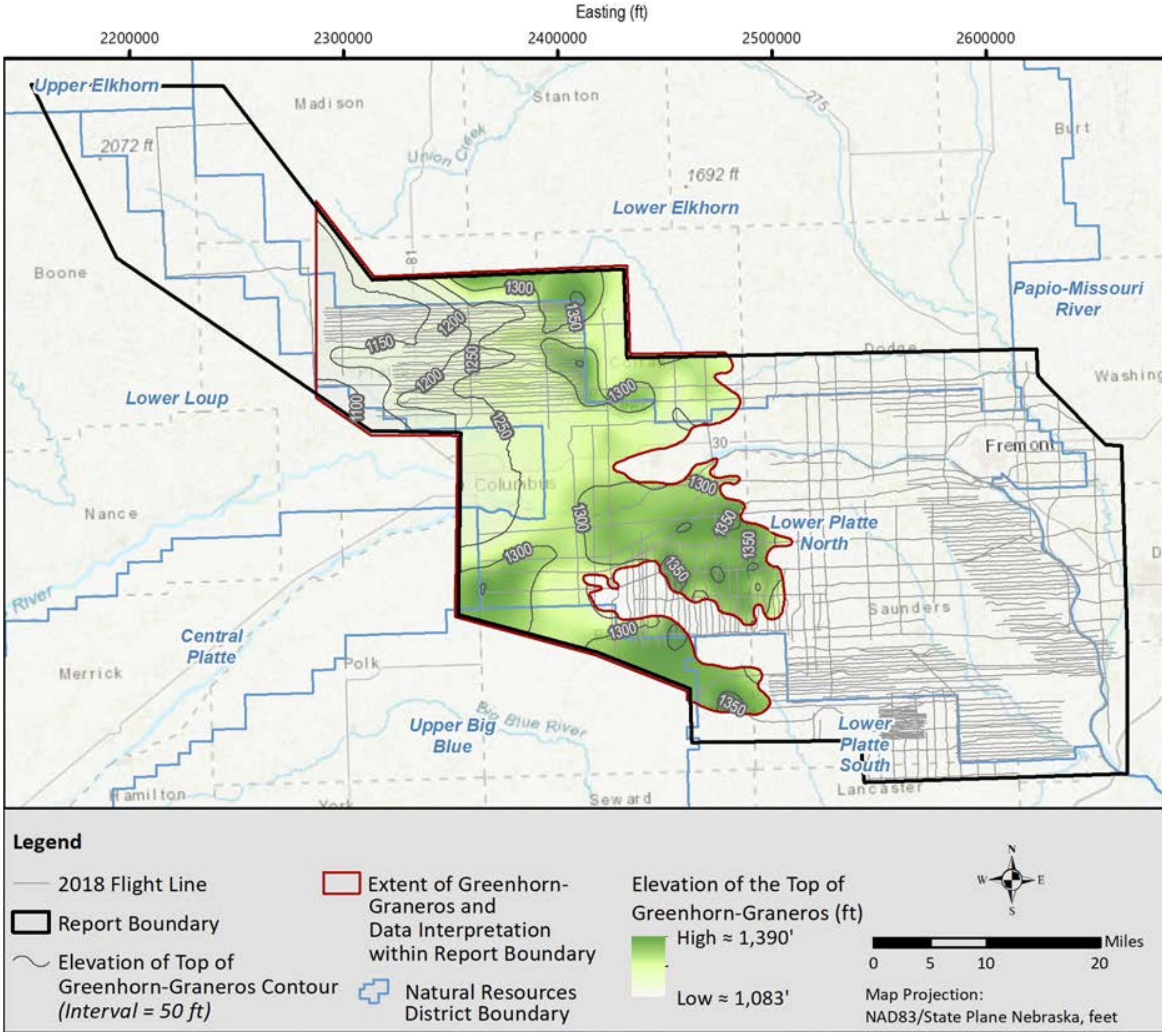


Figure 3-15. Map of the elevation of the top of the Cretaceous Greenhorn Limestone and Graneros Shale (*Kgg*) within the 2018 LPNNRD AEM survey area.

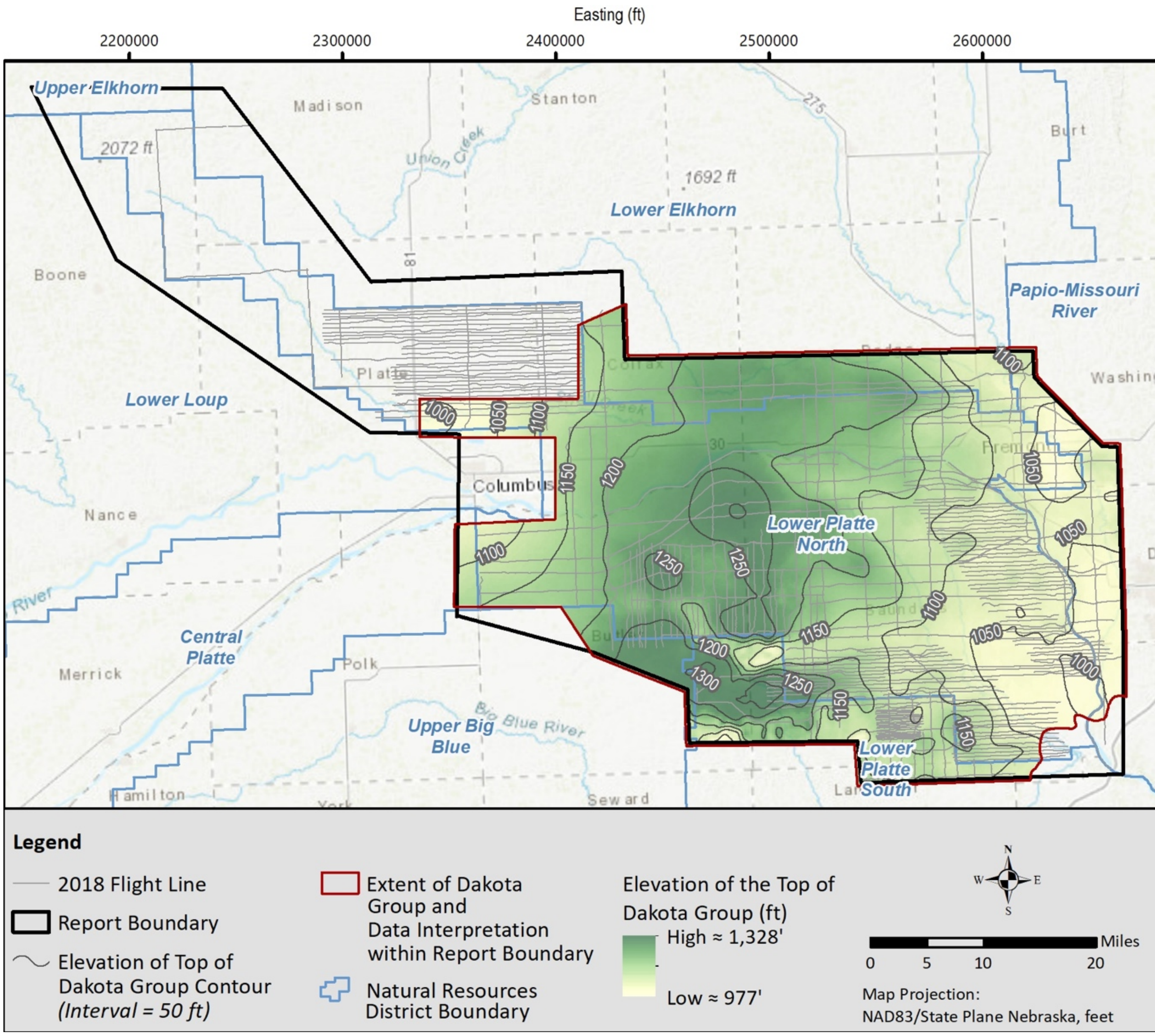


Figure 3-16. Map of the elevation of the top of the Cretaceous Dakota Group (*Kd*) within the 2018 LPNNRD AEM survey area.

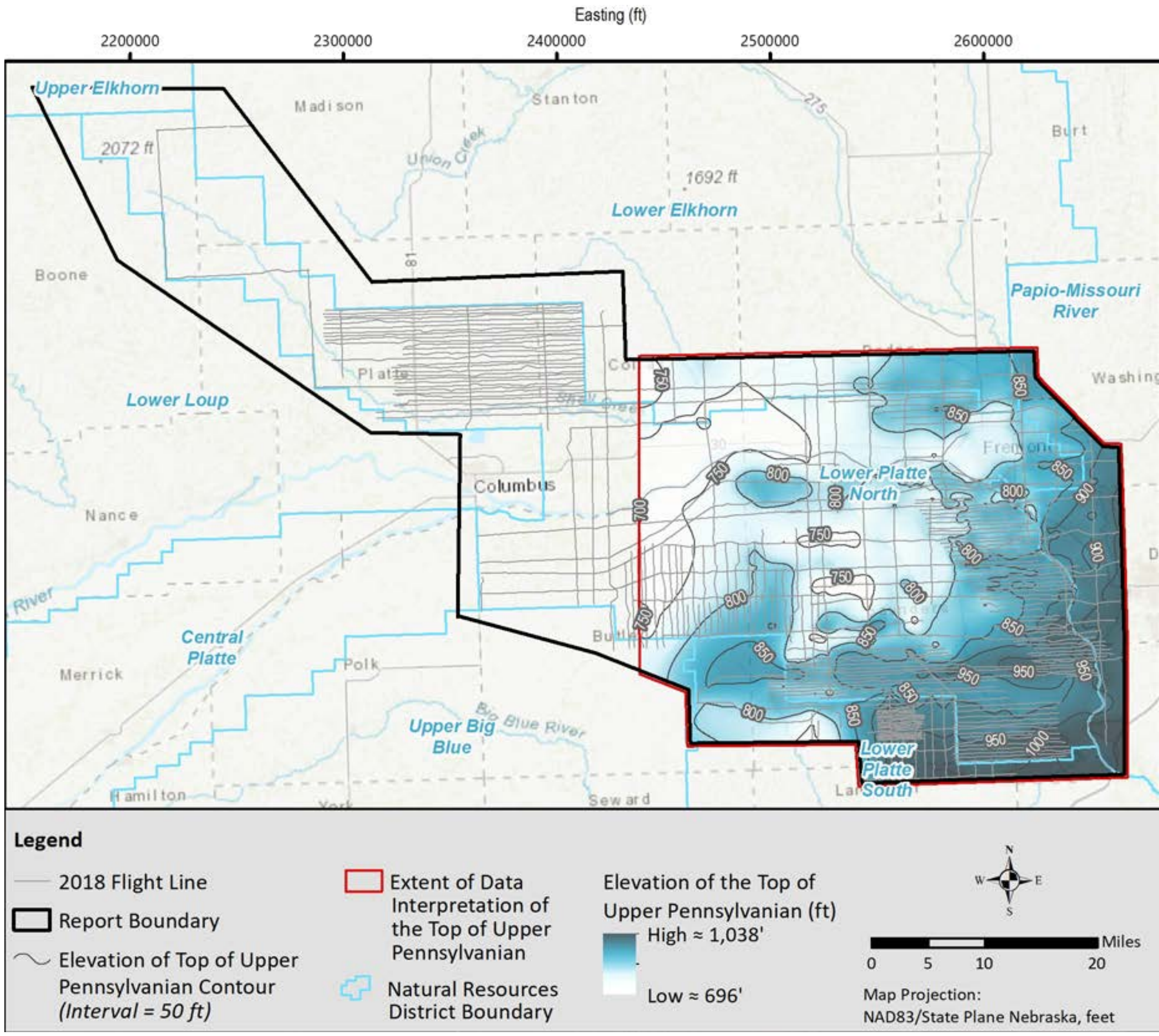


Figure 3-17. Map of the elevation of the top of the Undifferentiated Pennsylvanian (*IP*) within the 2018 LPNNRD AEM survey area.

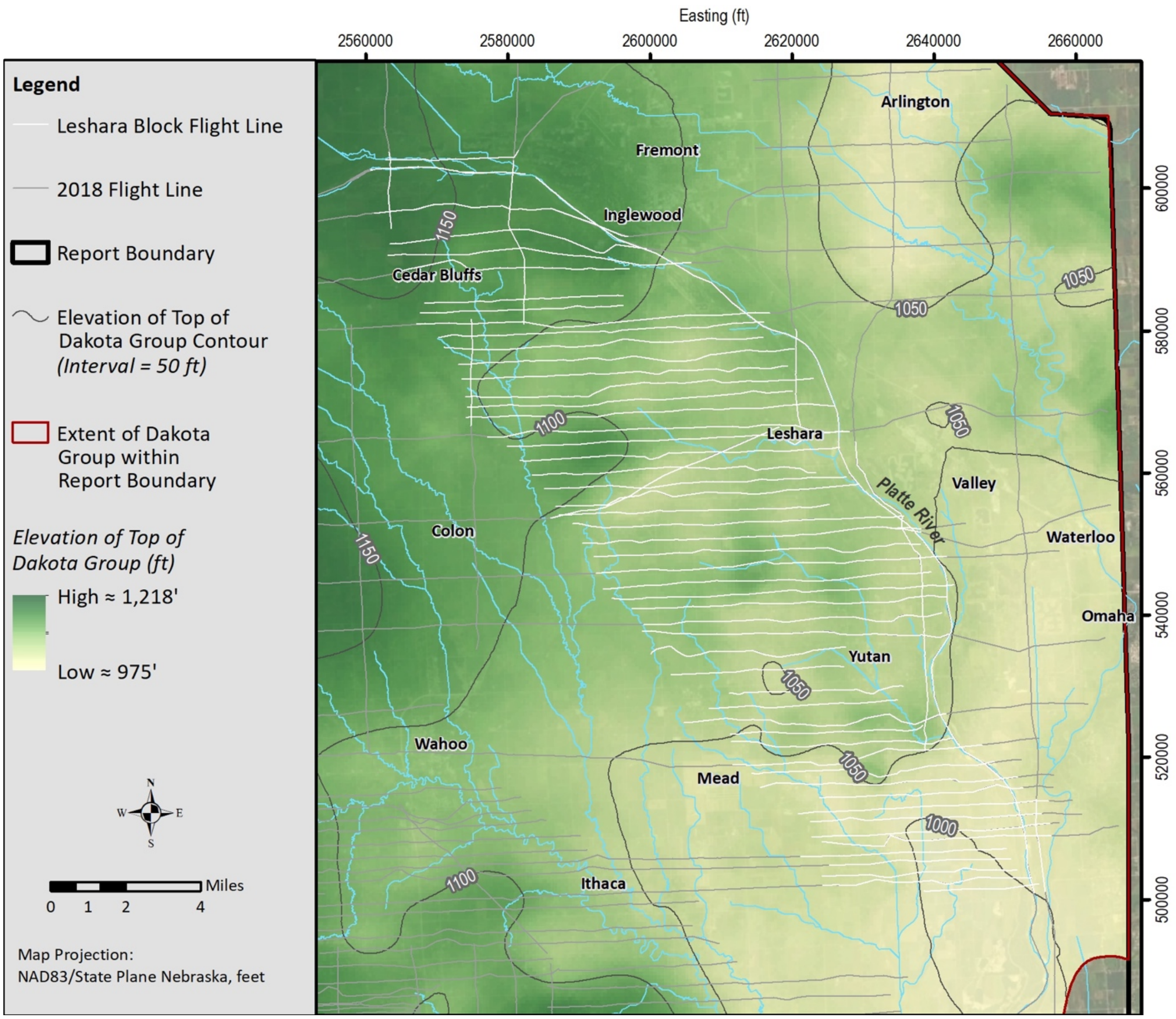


Figure 3-18. Map of the elevation of the top of the Cretaceous Dakota Group (*Kd*) within the Leshara Upland Block survey area.

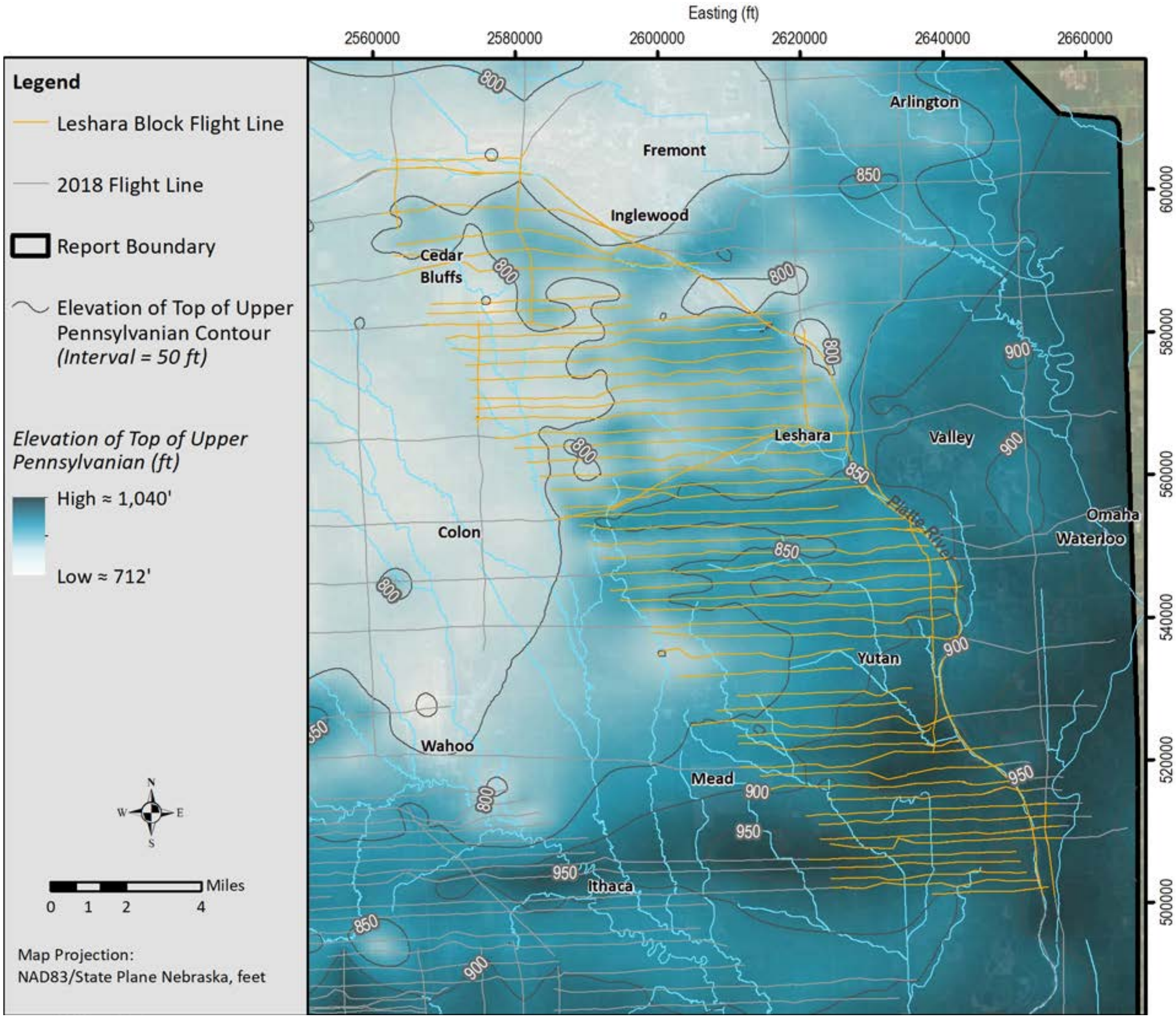


Figure 3-19. Map of the elevation of the top of the Undifferentiated Pennsylvanian (*IP*) within the Leshara Upland Block survey area.

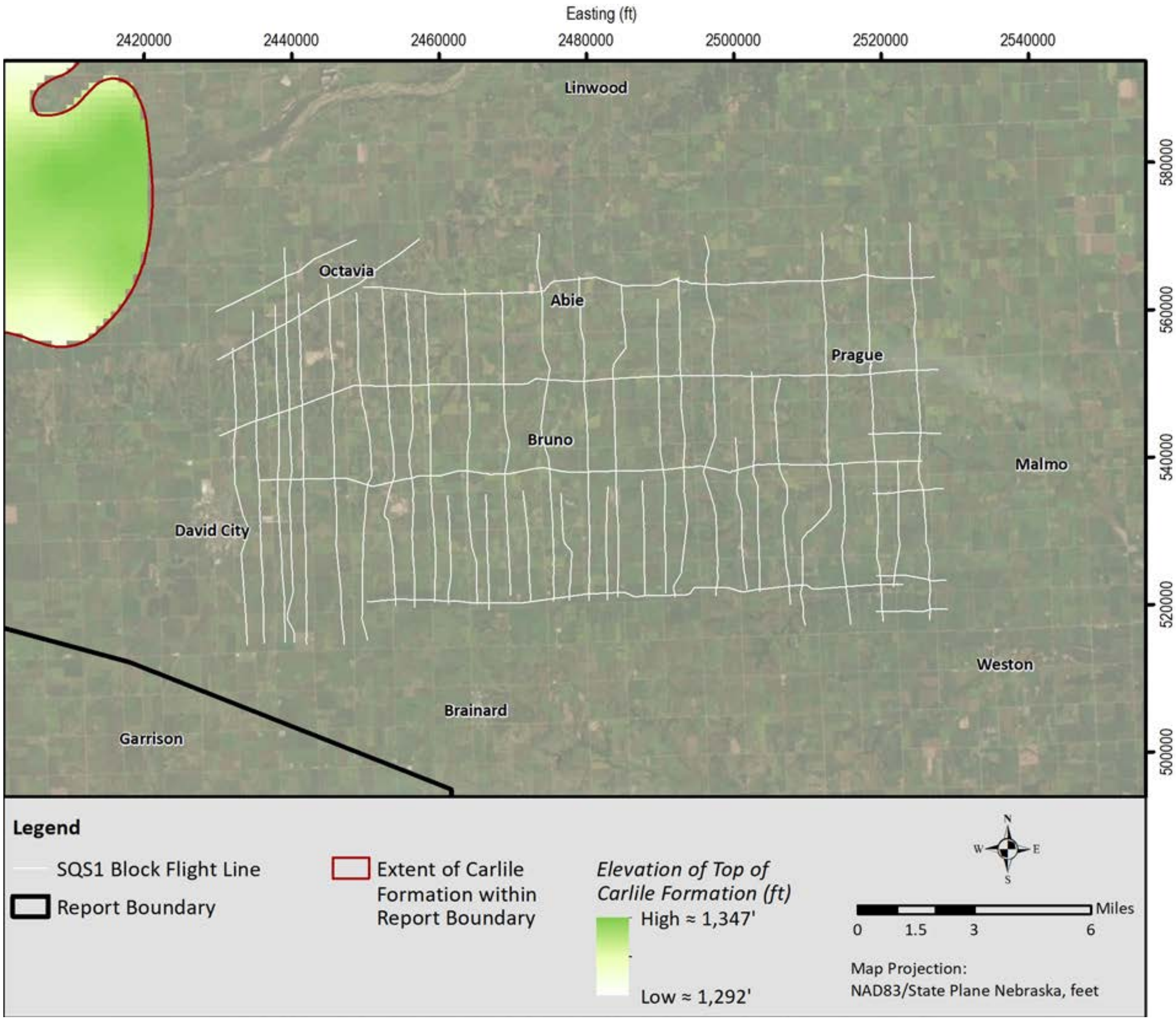


Figure 3-20. Map of the elevation of the top of the Cretaceous Carlile Shale (*Kc*) within the SQS1 Block AEM survey area.

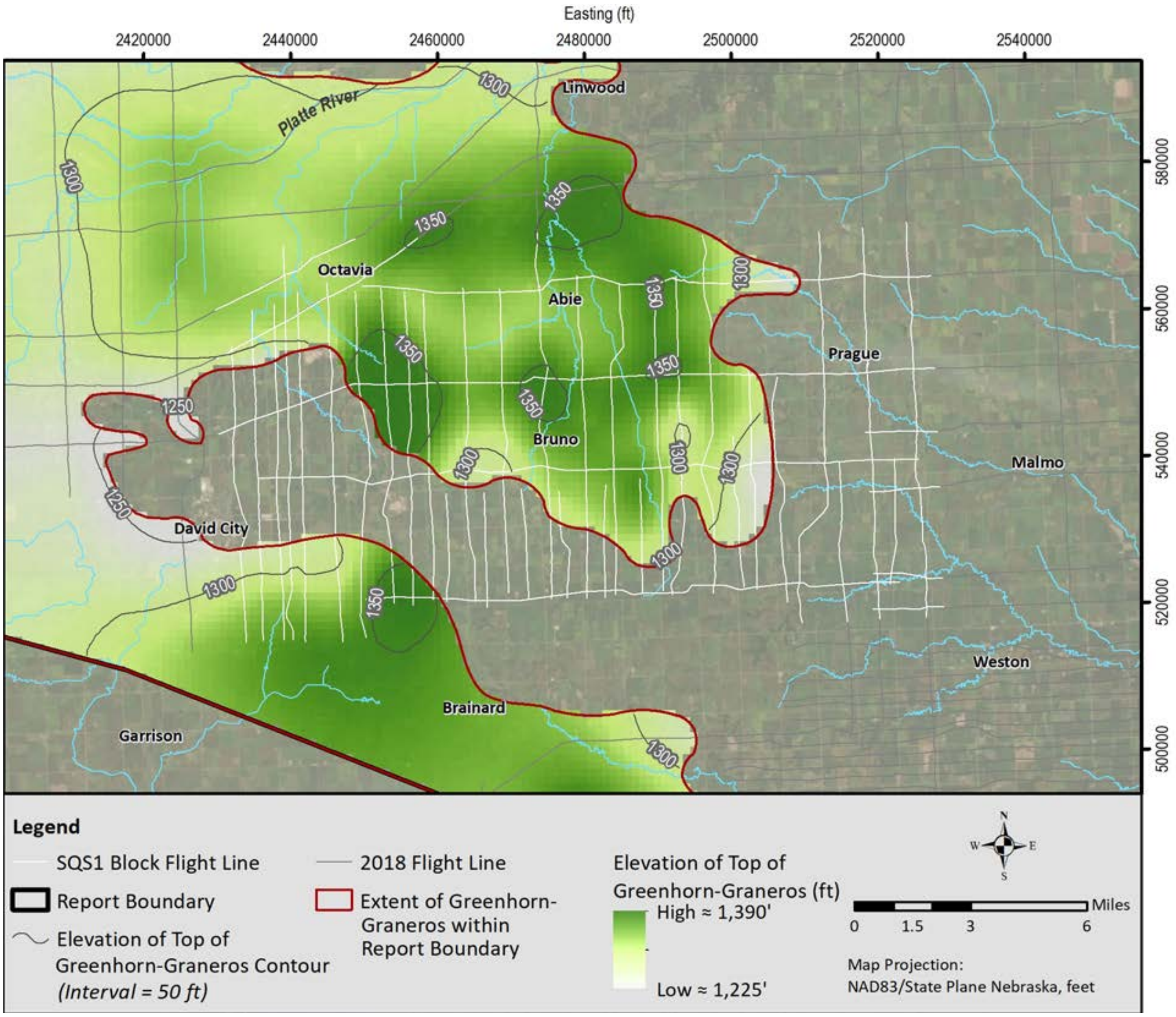


Figure 3-21. Map of the elevation of the top of the Cretaceous Greenhorn Limestone and Graneros Shale (*Kgg*) within the SQS1 Block AEM survey area.

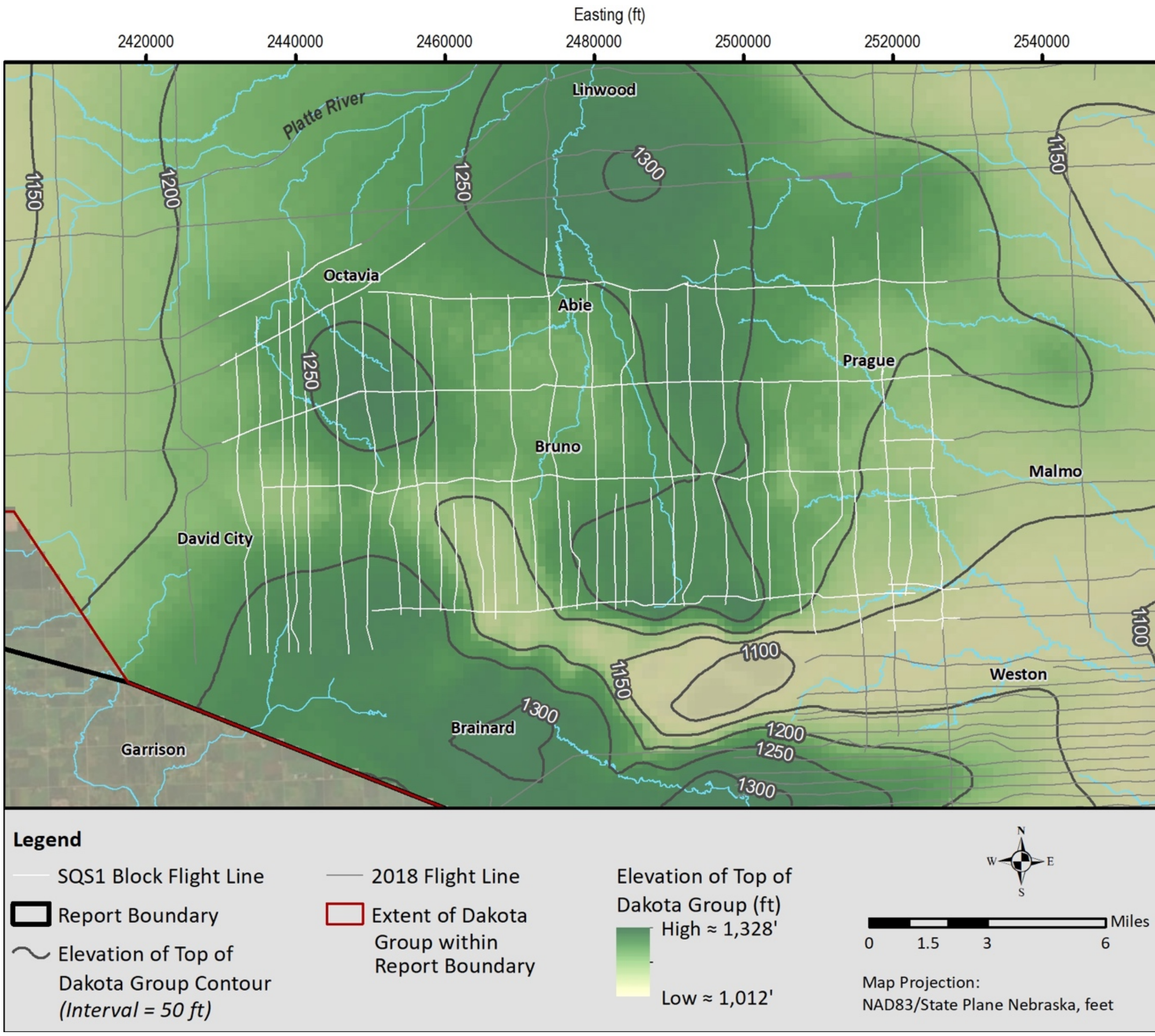


Figure 3-22. Map of the elevation of the top of the Cretaceous Dakota Group (*Kd*) within the SQS1 Block AEM survey area.

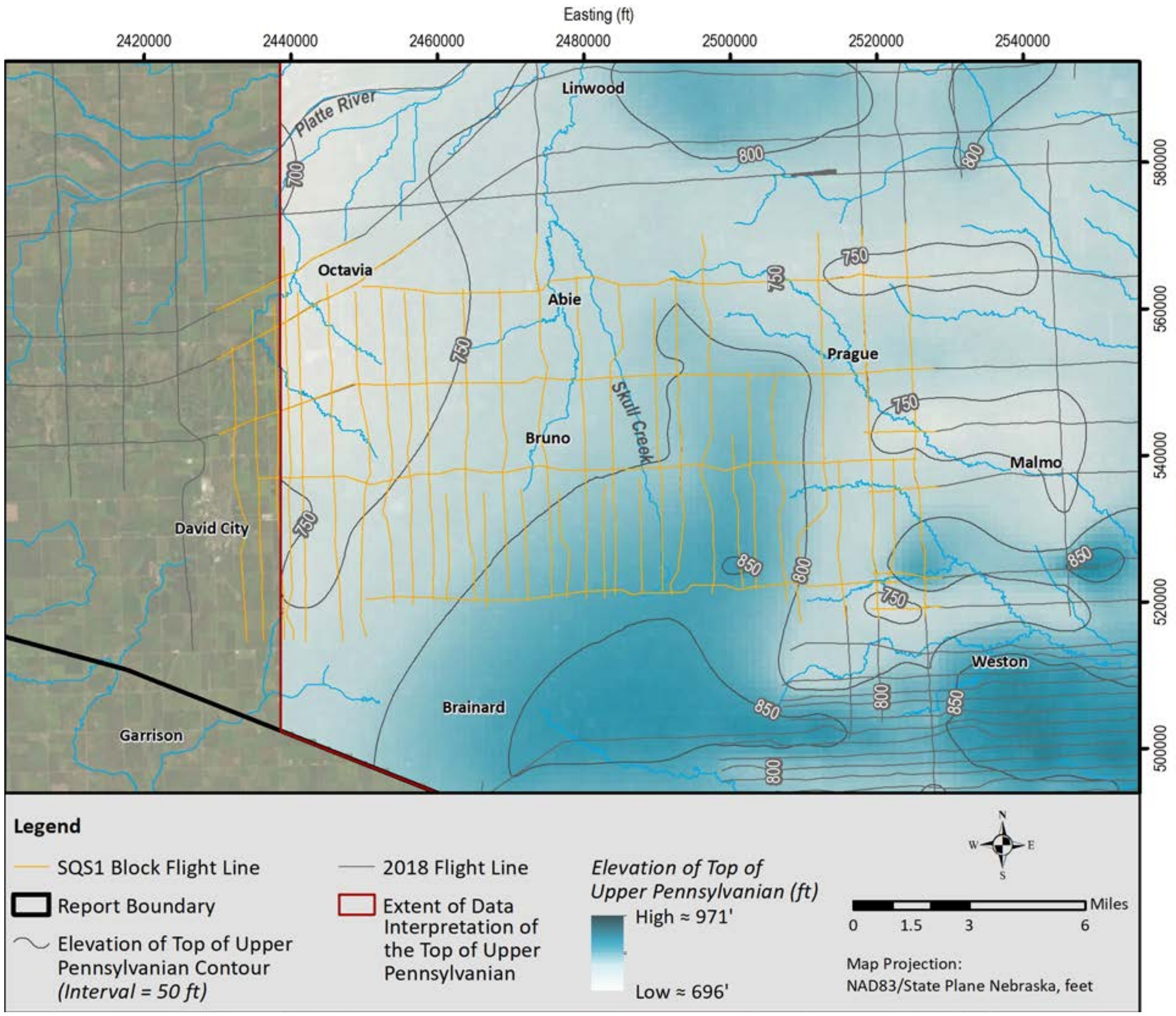


Figure 3-23. Map of the elevation of the top of the Undifferentiated Pennsylvanian (*IP*) within the SQS1 Block AEM survey area.

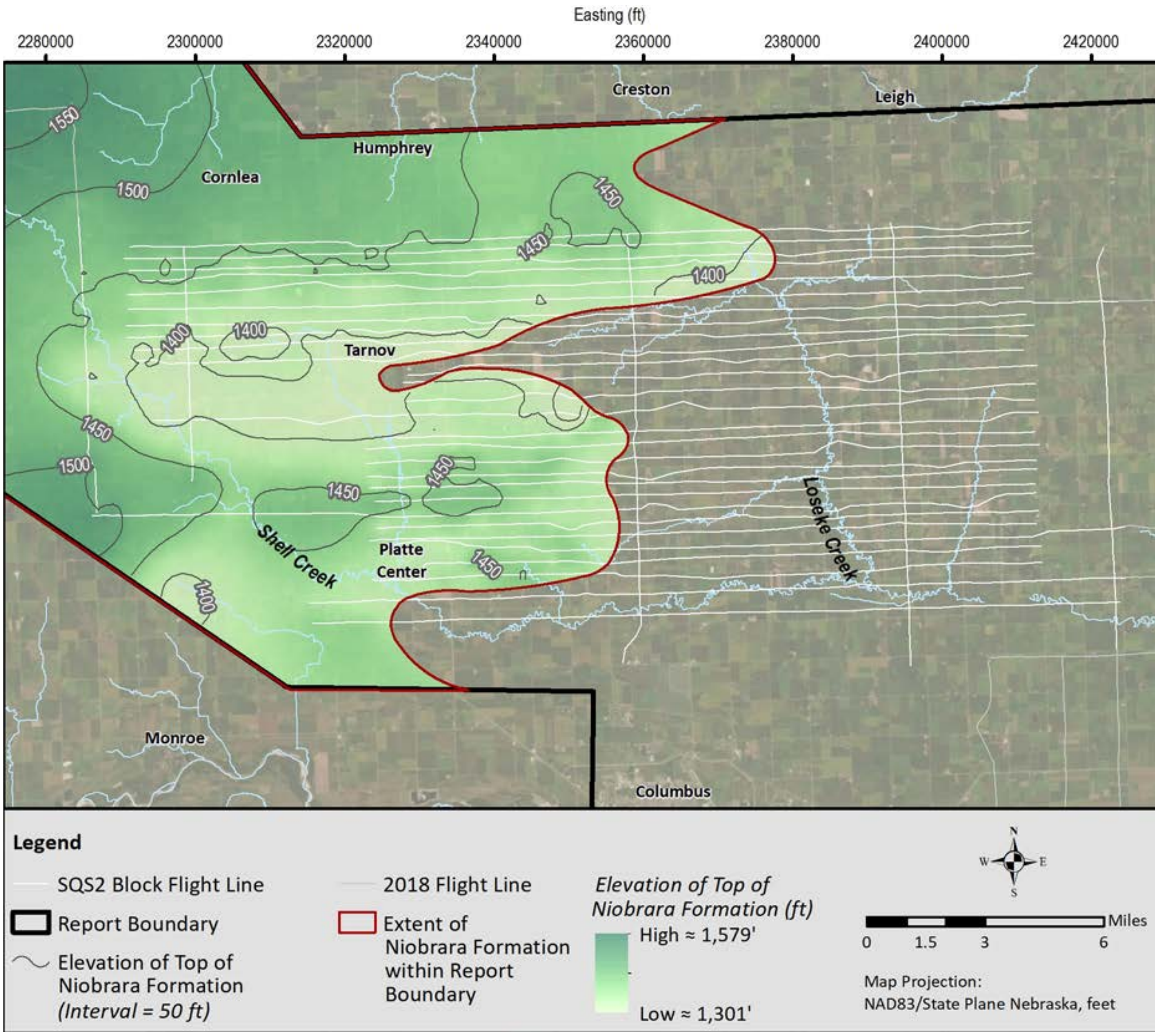


Figure 3-24. Map of the elevation of the top of the Cretaceous Niobrara Formation (*Kn*) within the SQS2 Block AEM survey area.

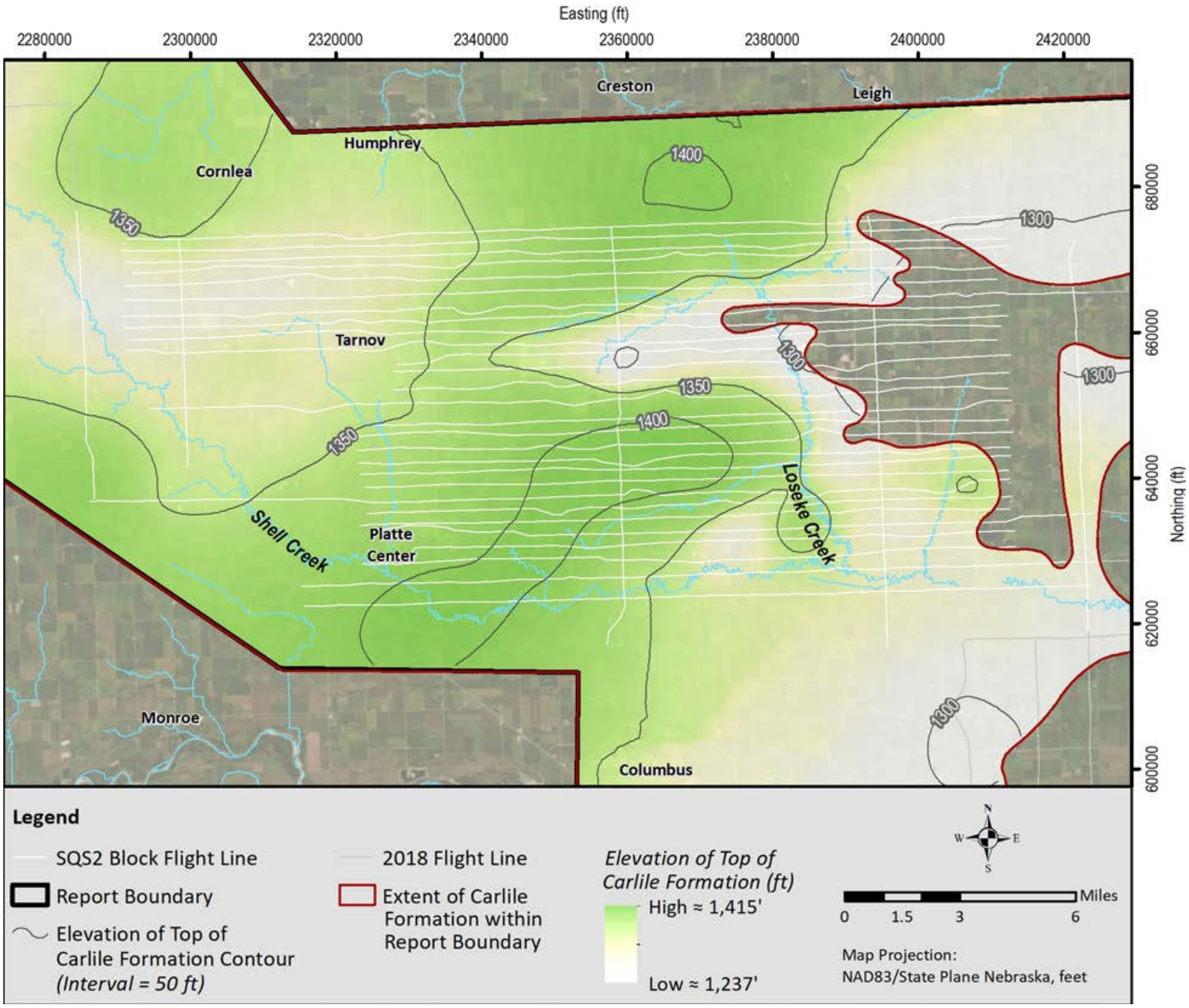


Figure 3-25. Map of the elevation of the top of the Cretaceous Carlile Shale (*Kc*) within the SQS2 Block AEM survey area.

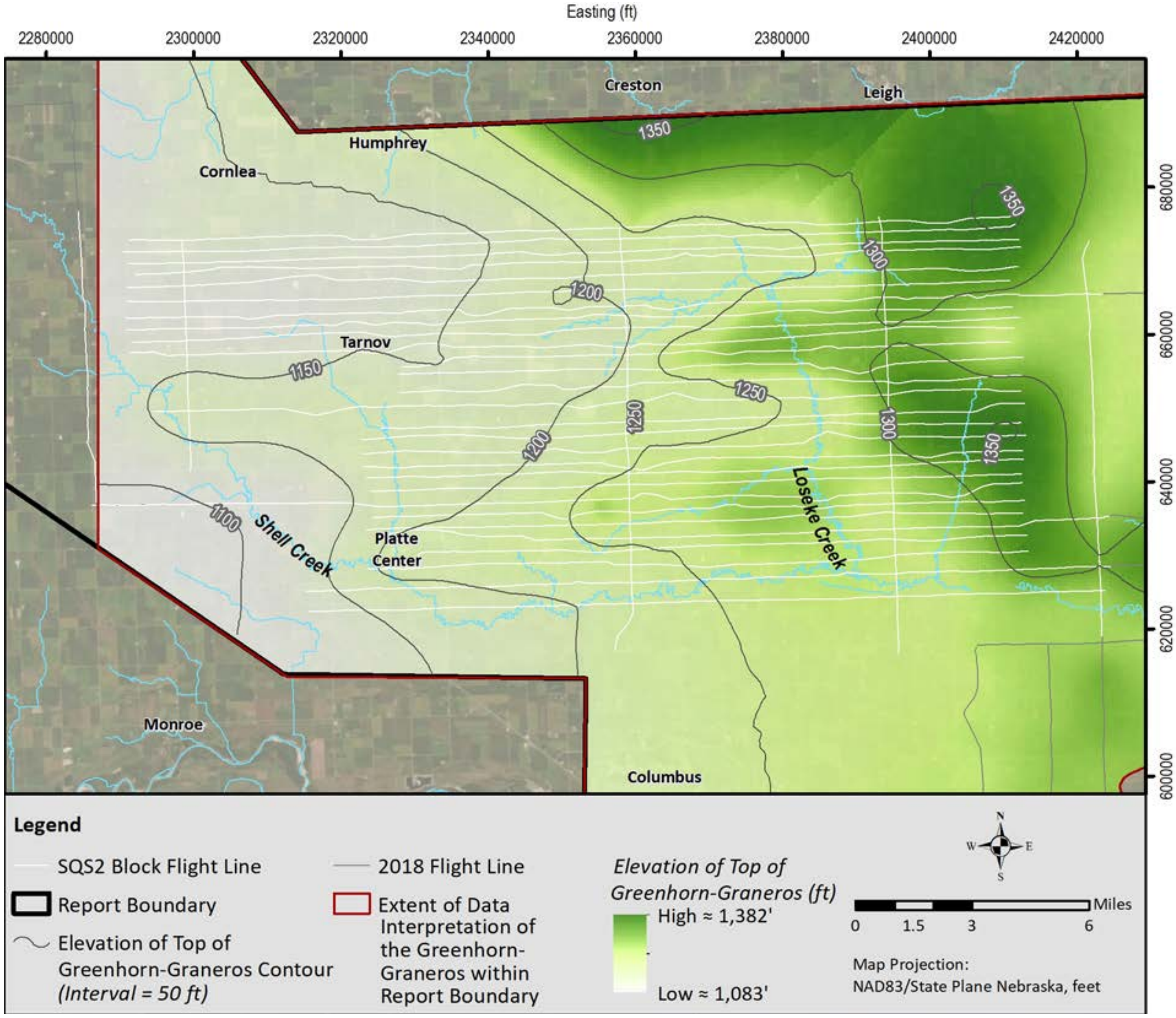


Figure 3-26. Map of the elevation of the top of the Cretaceous Greenhorn Limestone and Graneros Shale (*Kgg*) within the SQS2 Block AEM survey area.

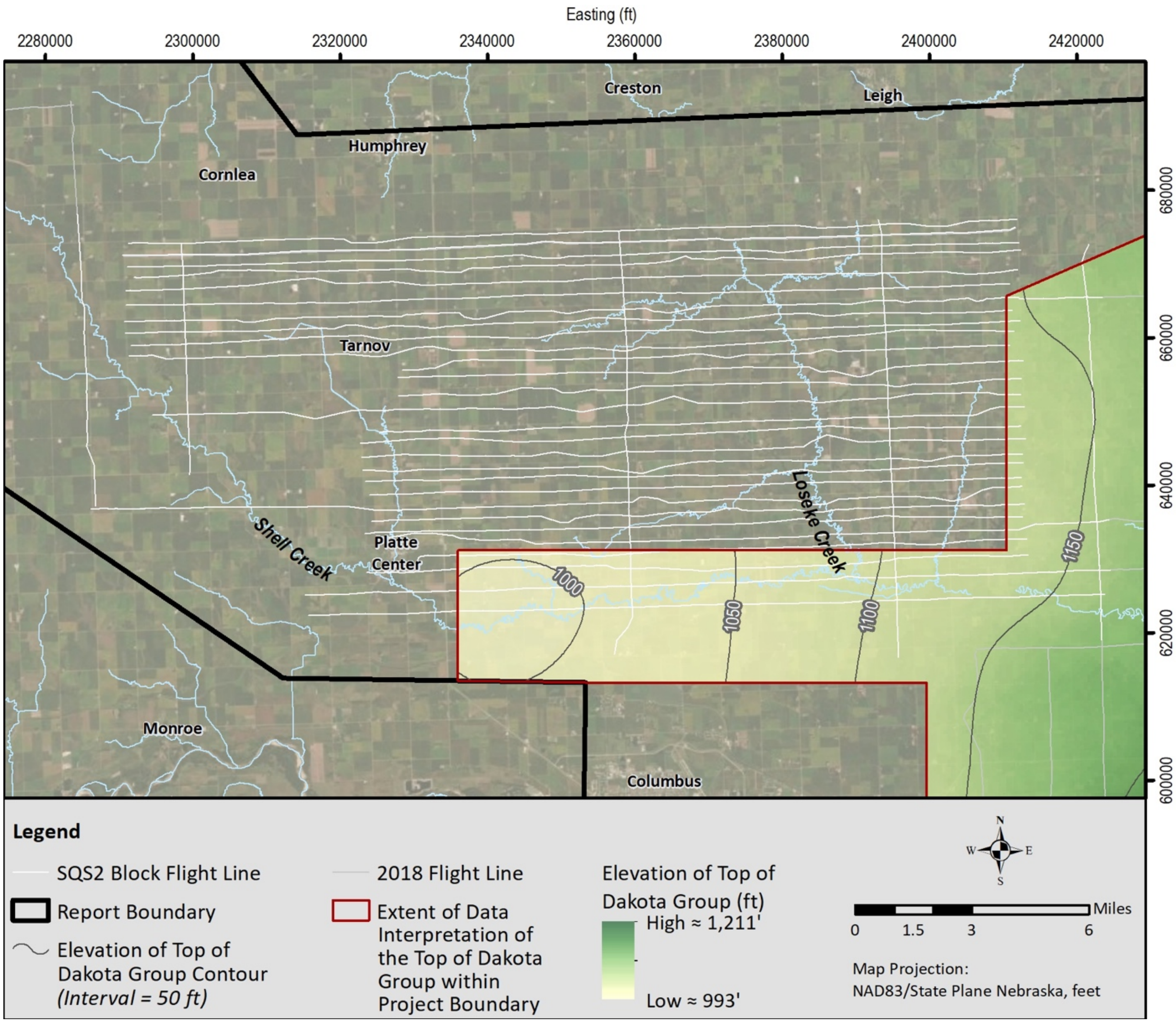


Figure 3-27. Map of the elevation of the top of the Cretaceous Dakota Group (*Kd*) within the SQS2 Block AEM survey area.

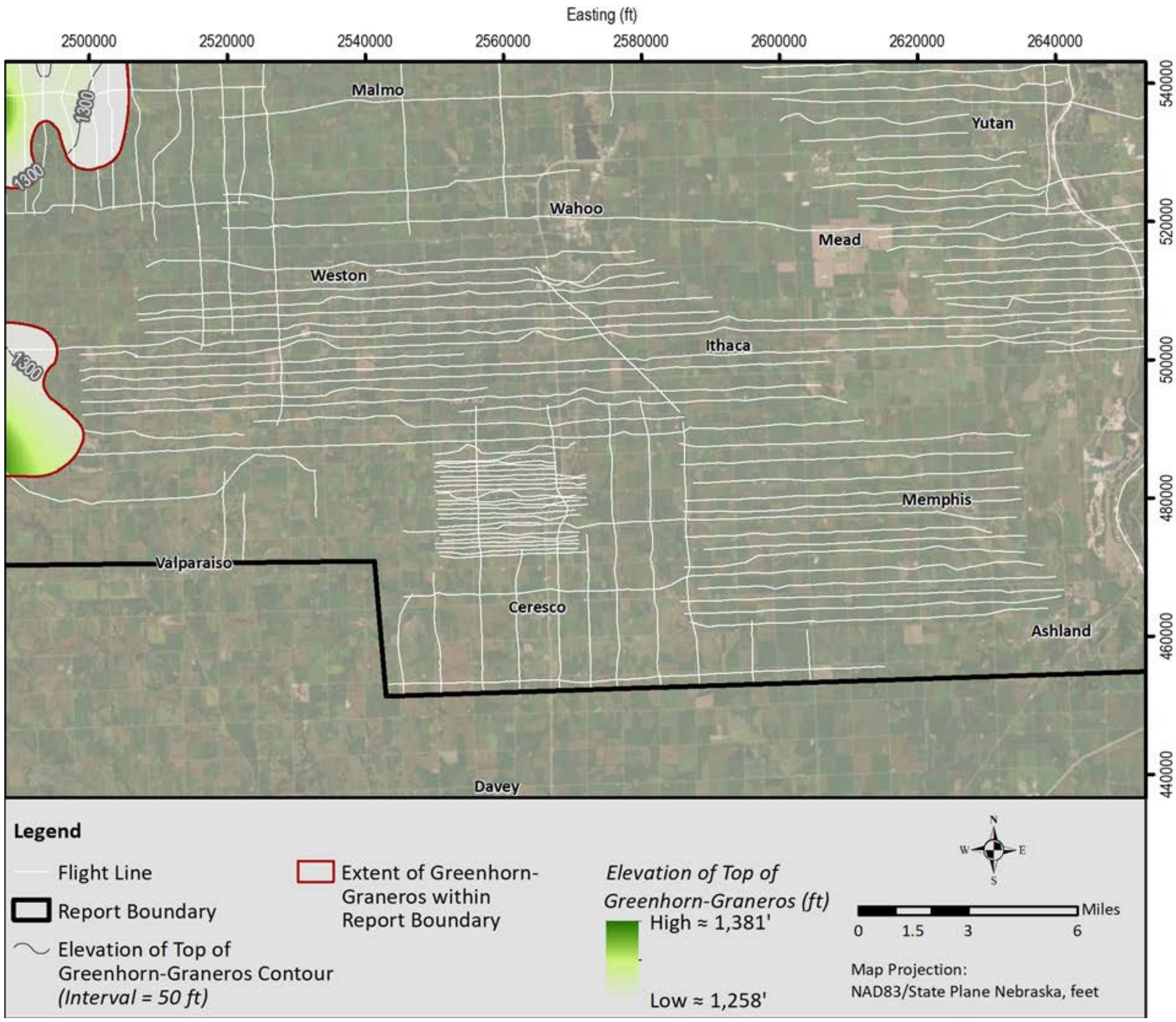


Figure 3-28. Map of the elevation of the top of the Cretaceous Greenhorn Limestone and Graneros Shale (*Kgg*) within the Waann Block AEM survey area.

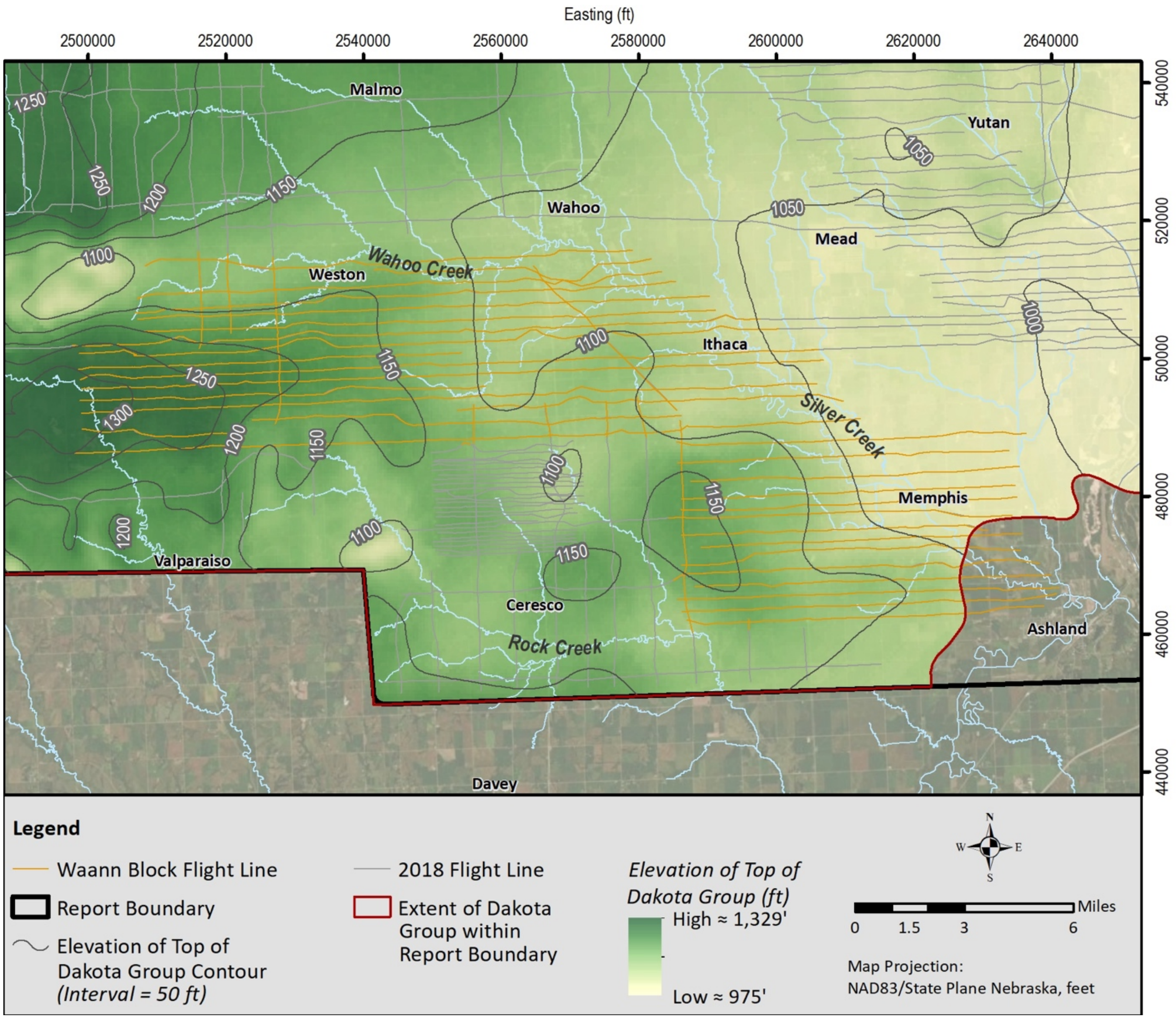


Figure 3-29. Map of the elevation of the top of the Cretaceous Dakota Group (*Kd*) within the Waann Block AEM survey area.

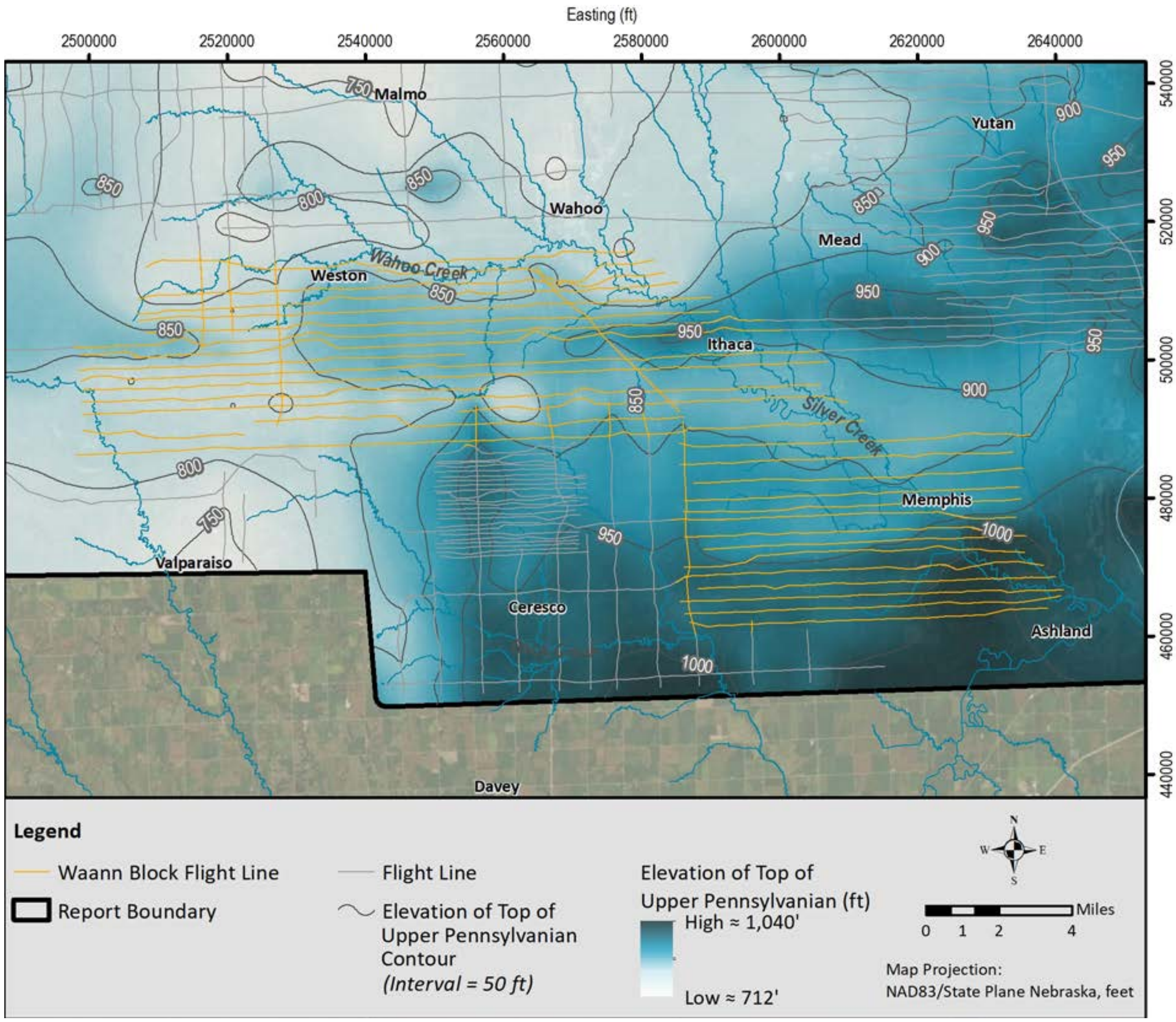


Figure 3-30. Map of the elevation of the top of the Undifferentiated Pennsylvanian (*IP*) within the Waann Block AEM survey area.

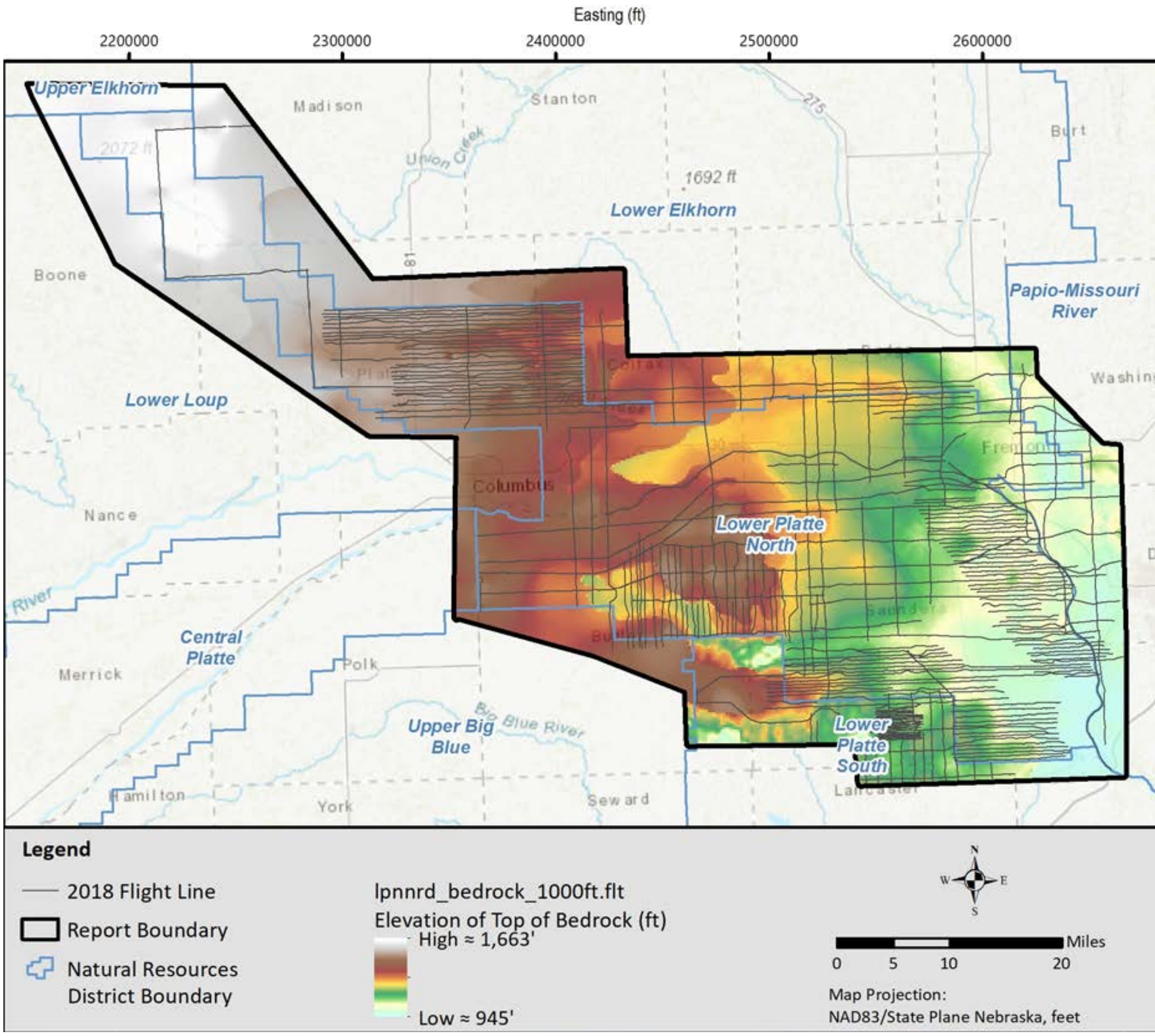


Figure 3-31. Map of the elevation of the top of the bedrock within the LPNNRD AEM survey area.

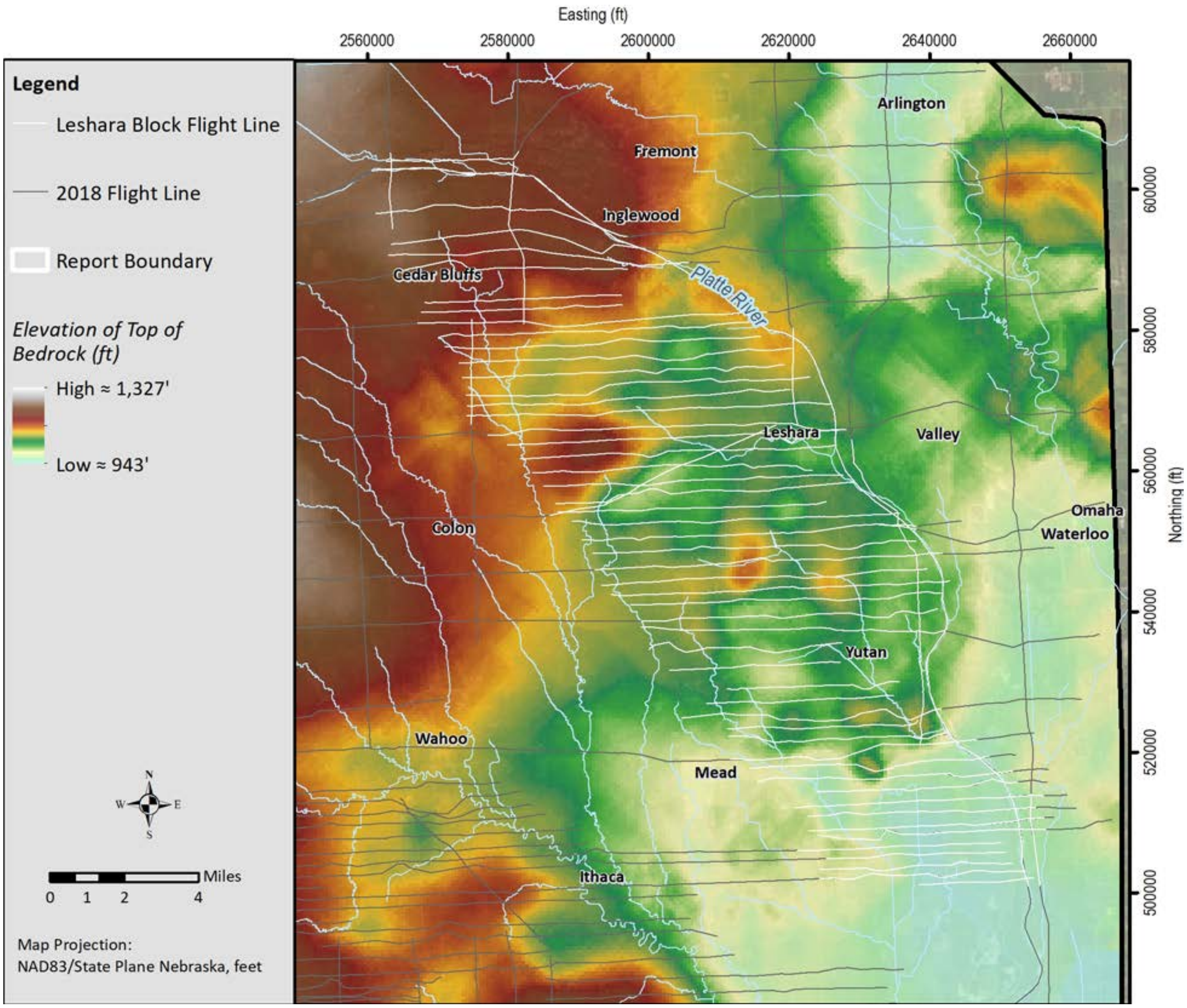


Figure 3-32. Map of the elevation of the top of the bedrock within the Leshara Upland Block AEM survey area.

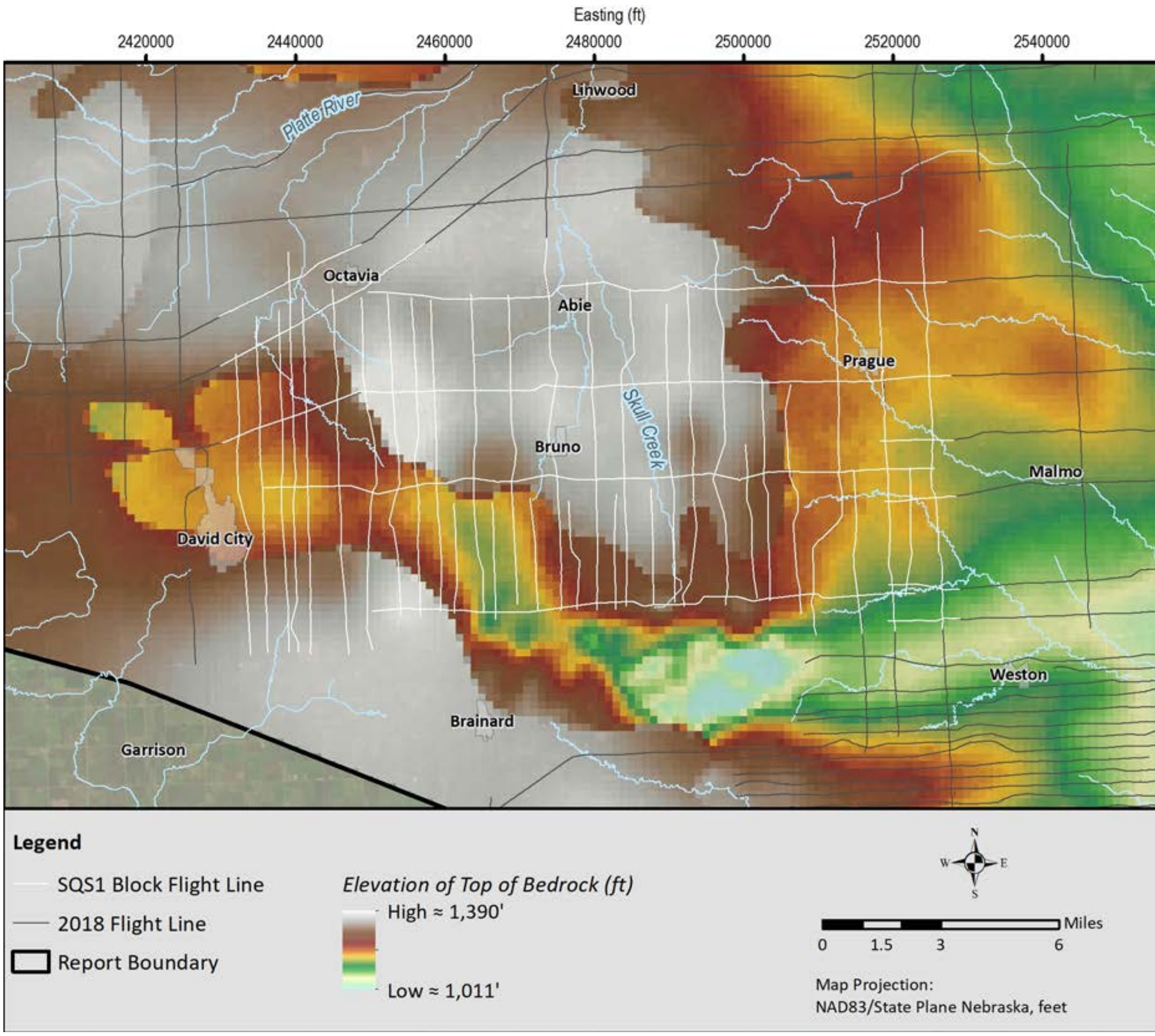


Figure 3-33. Map of the elevation of the top of the bedrock within the SQS1 Block AEM survey area.

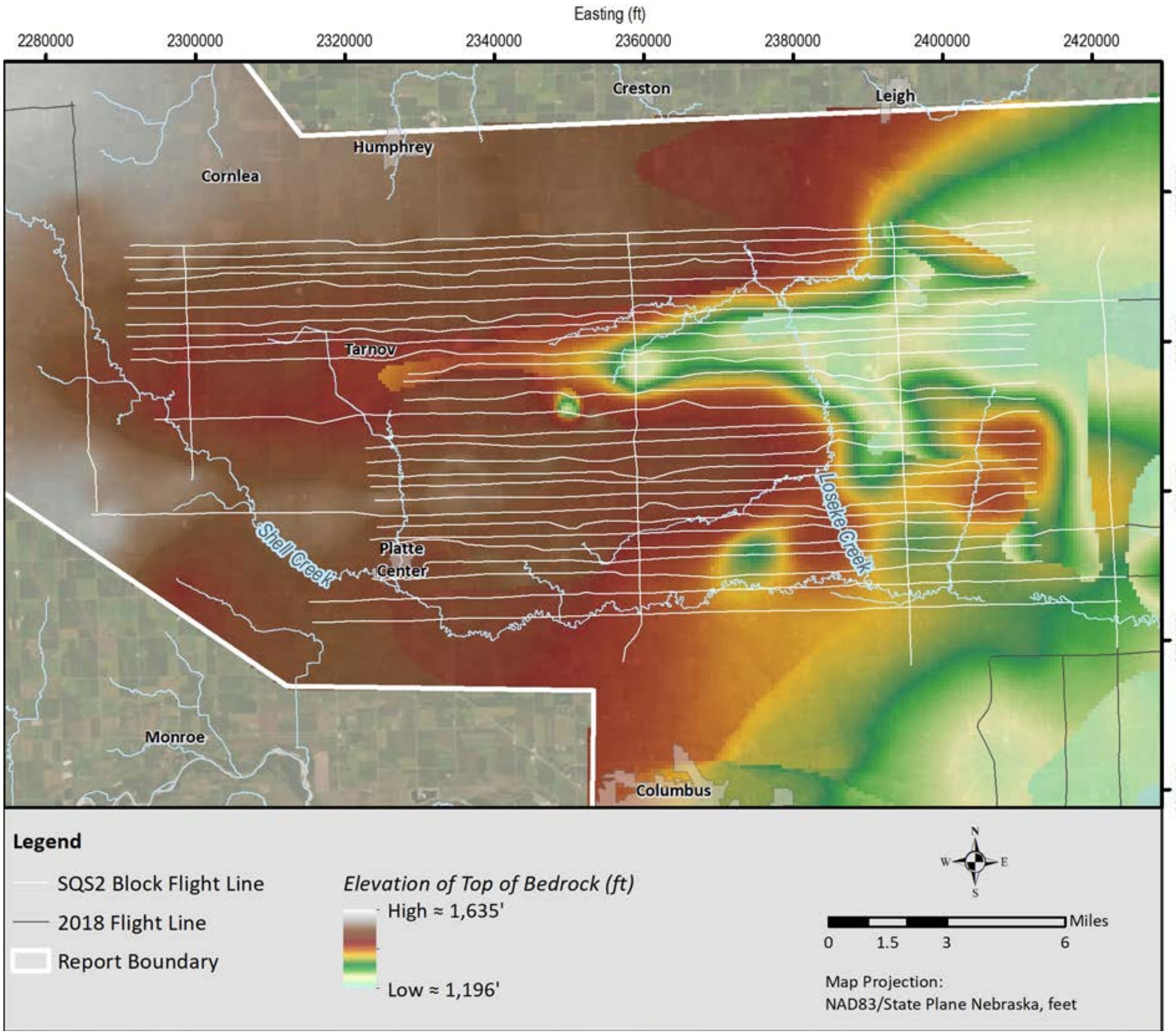


Figure 3-34. Map of the elevation of the top of the bedrock within the SQS2 Block AEM survey area.

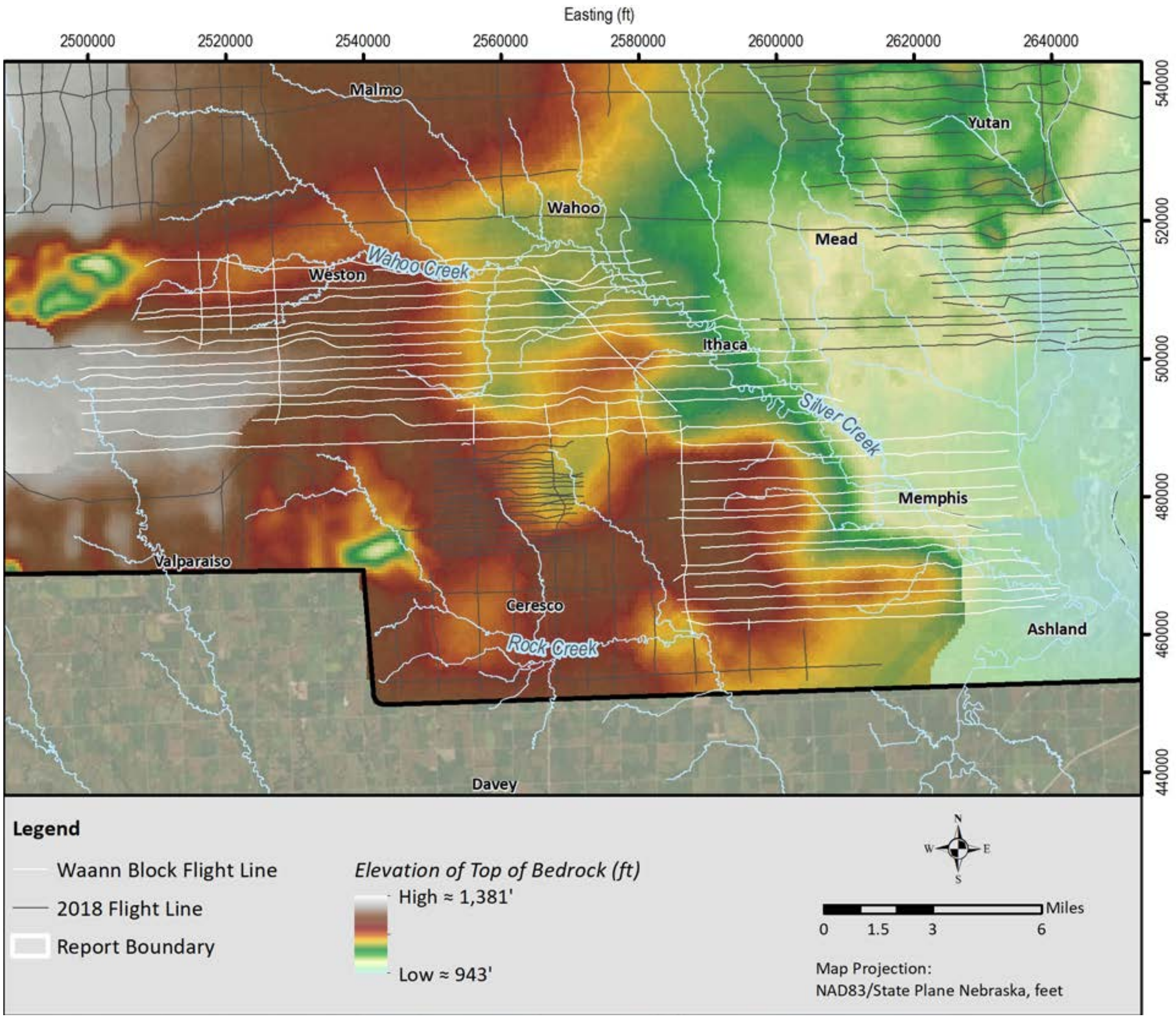


Figure 3-35. Map of the elevation of the top of the bedrock within the Waann Block AEM survey area.

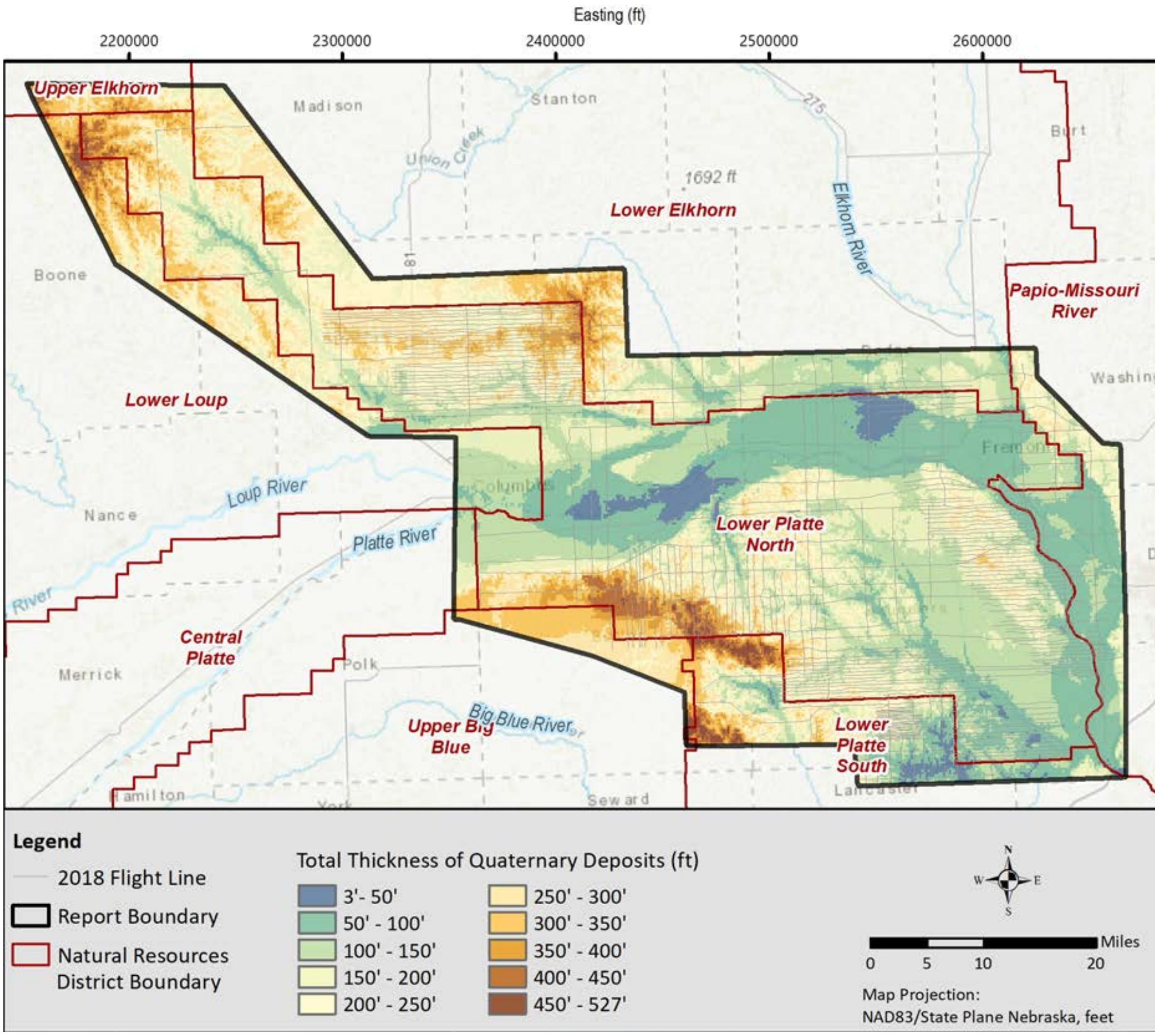


Figure 3-36. Map of the thickness (in feet) of Quaternary (*Q*) deposits within the LPNNRD AEM survey area.

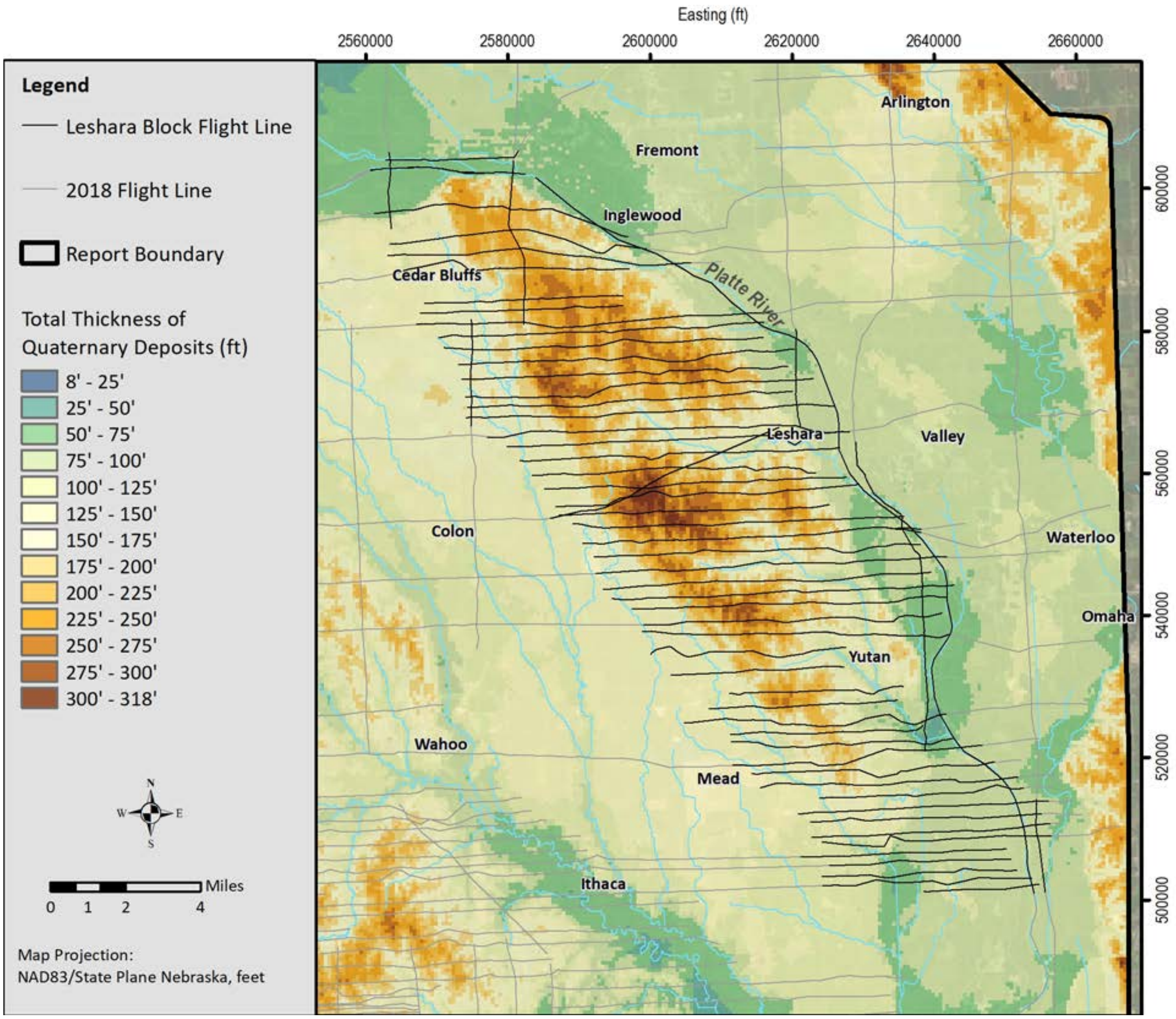


Figure 3-37. Map of the thickness (in feet) of Quaternary (*Q*) deposits within the Leshara Block AEM survey area.

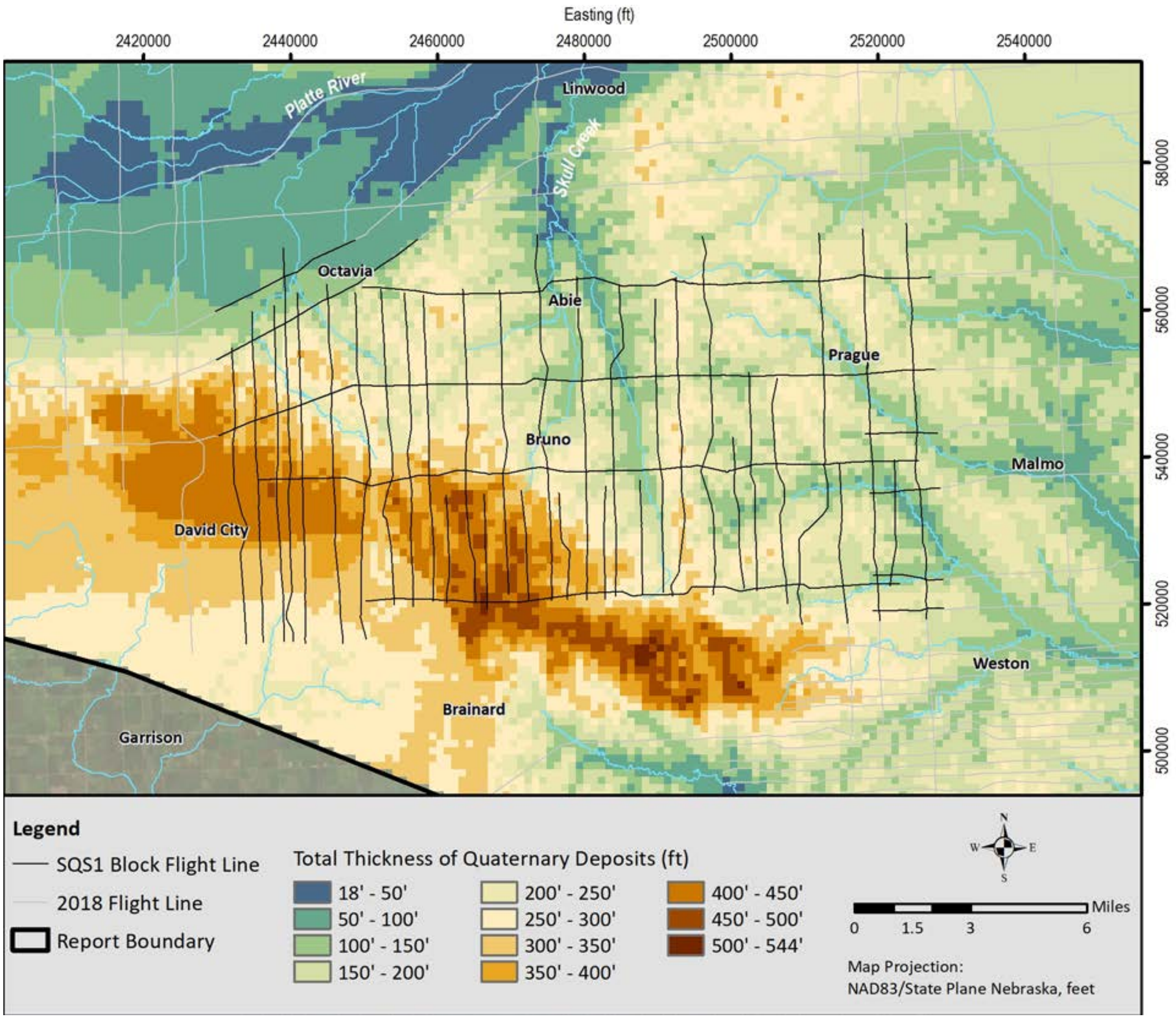


Figure 3-38. Map of the thickness (in feet) of Quaternary (*Q*) deposits within the SQS1 Block AEM survey area.

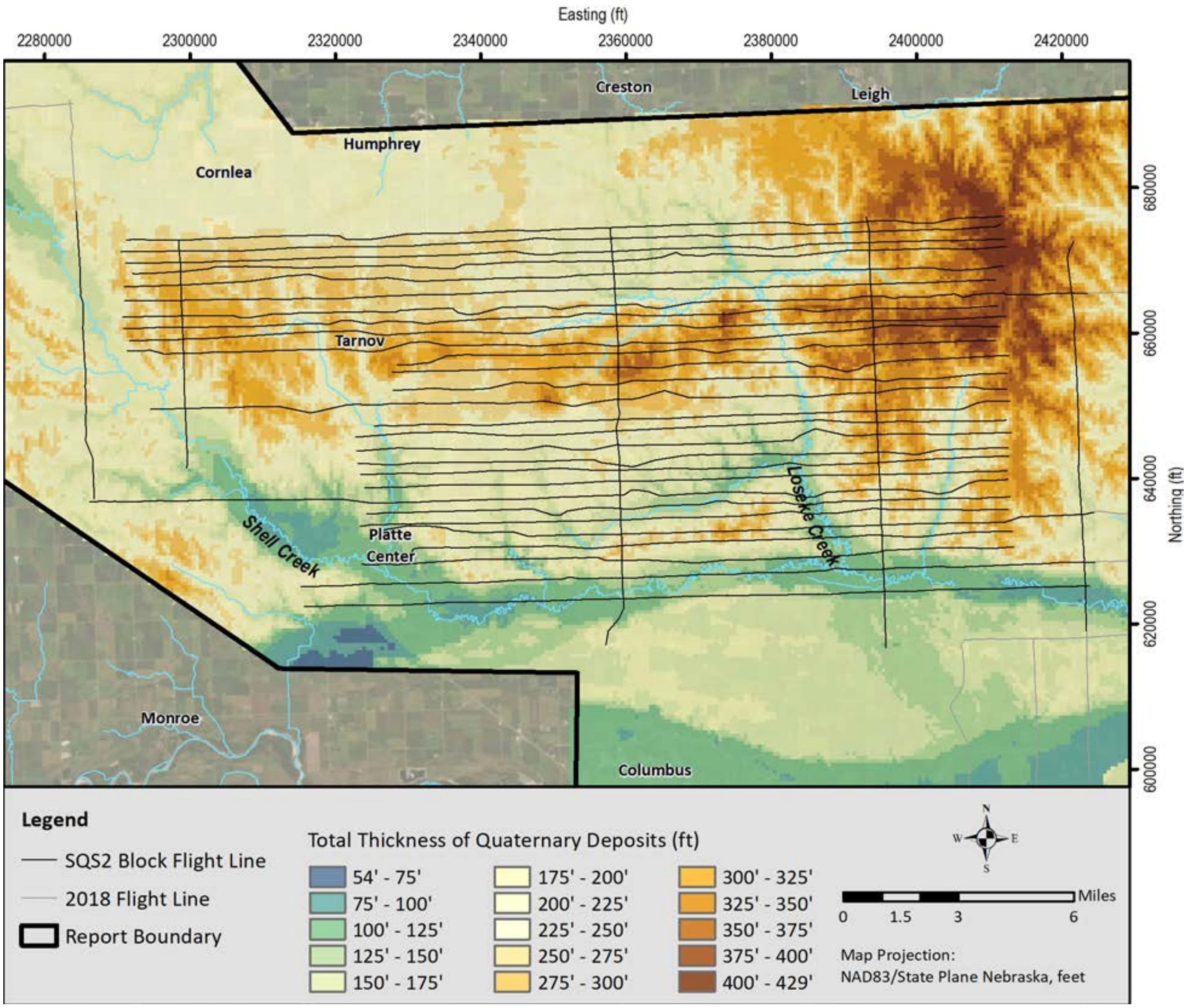


Figure 3-39. Map of the thickness (in feet) of Quaternary (*Q*) deposits within the SQS2 Block AEM survey area.

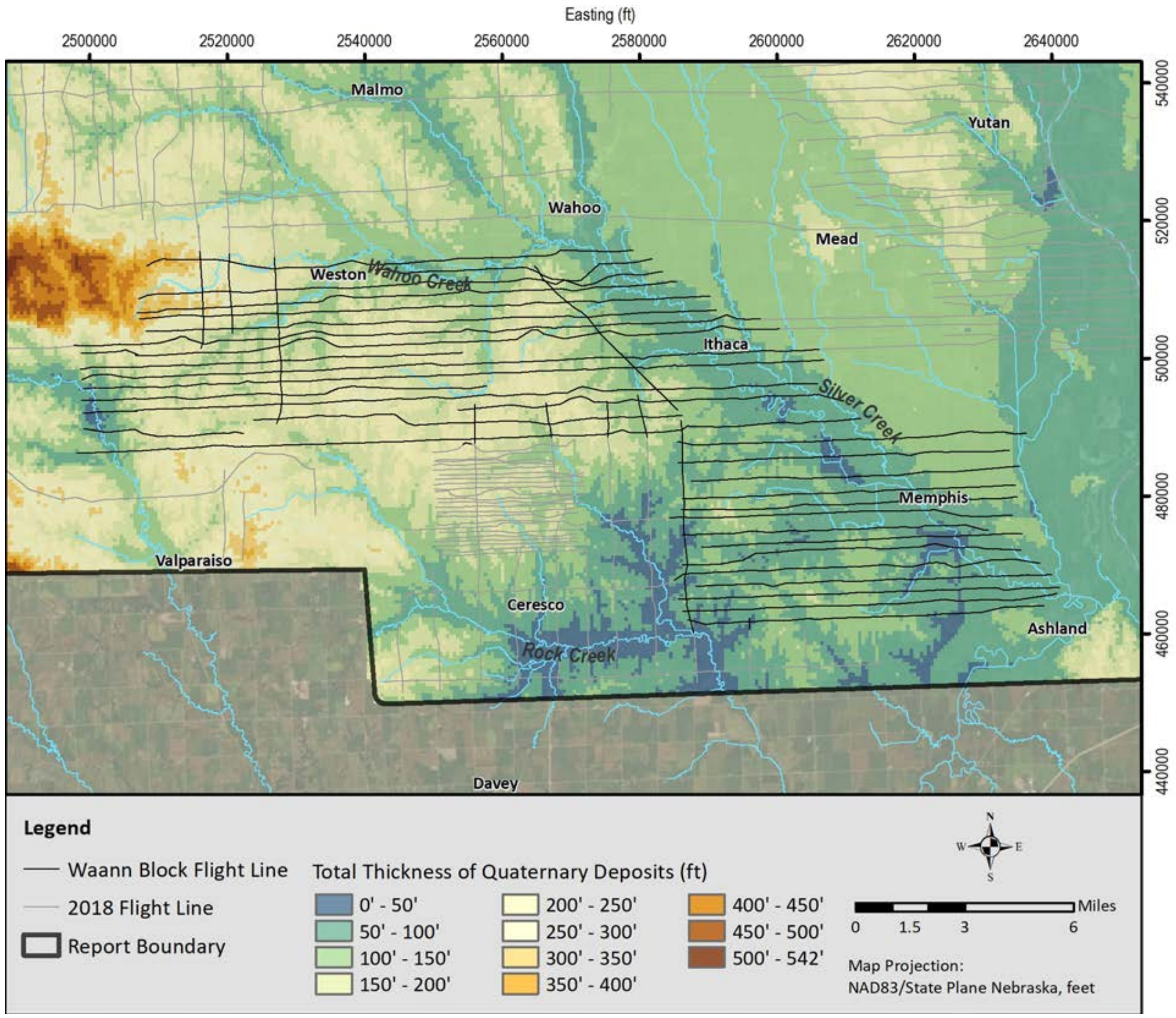


Figure 3-40. Map of the thickness (in feet) of Quaternary (*Q*) deposits within the Waann Block AEM survey area.

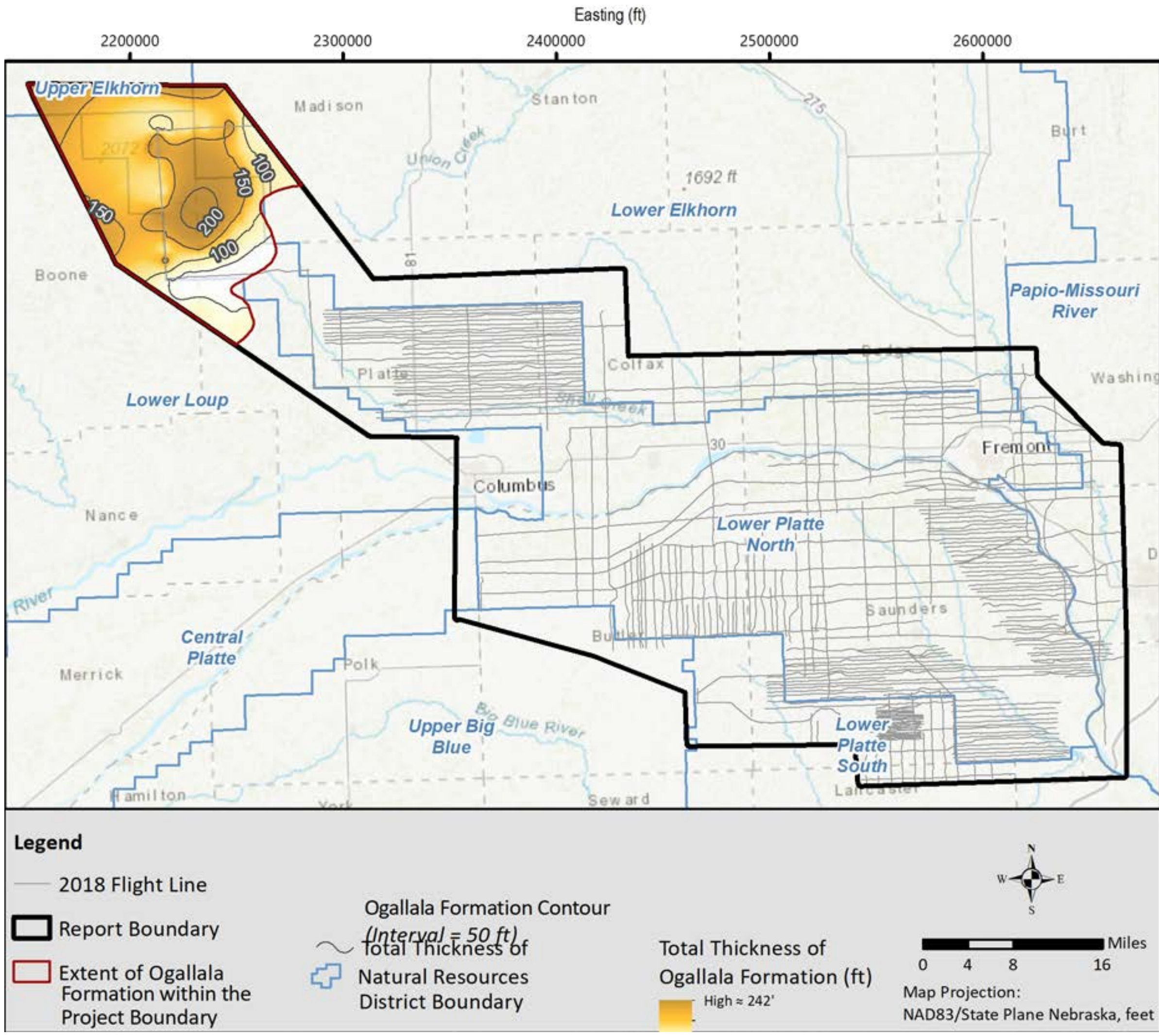


Figure 3-41. Map of the thickness (in feet) of the Ogallala Group (*To*) within the LPNNRD AEM survey area.

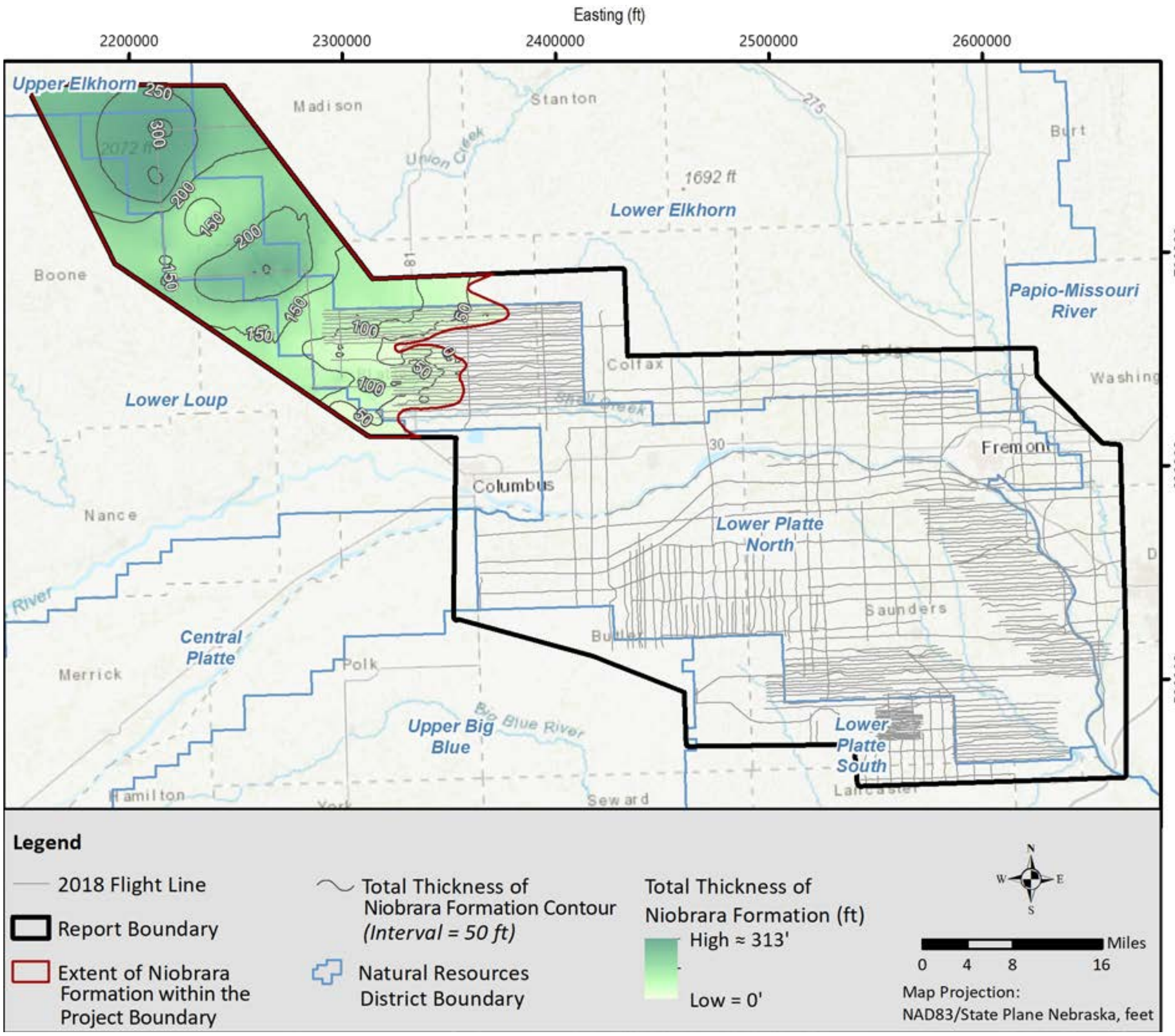


Figure 3-42. Map of the thickness (in feet) of the Niobrara Formation (*Kn*) within the LPNNRD AEM survey area.

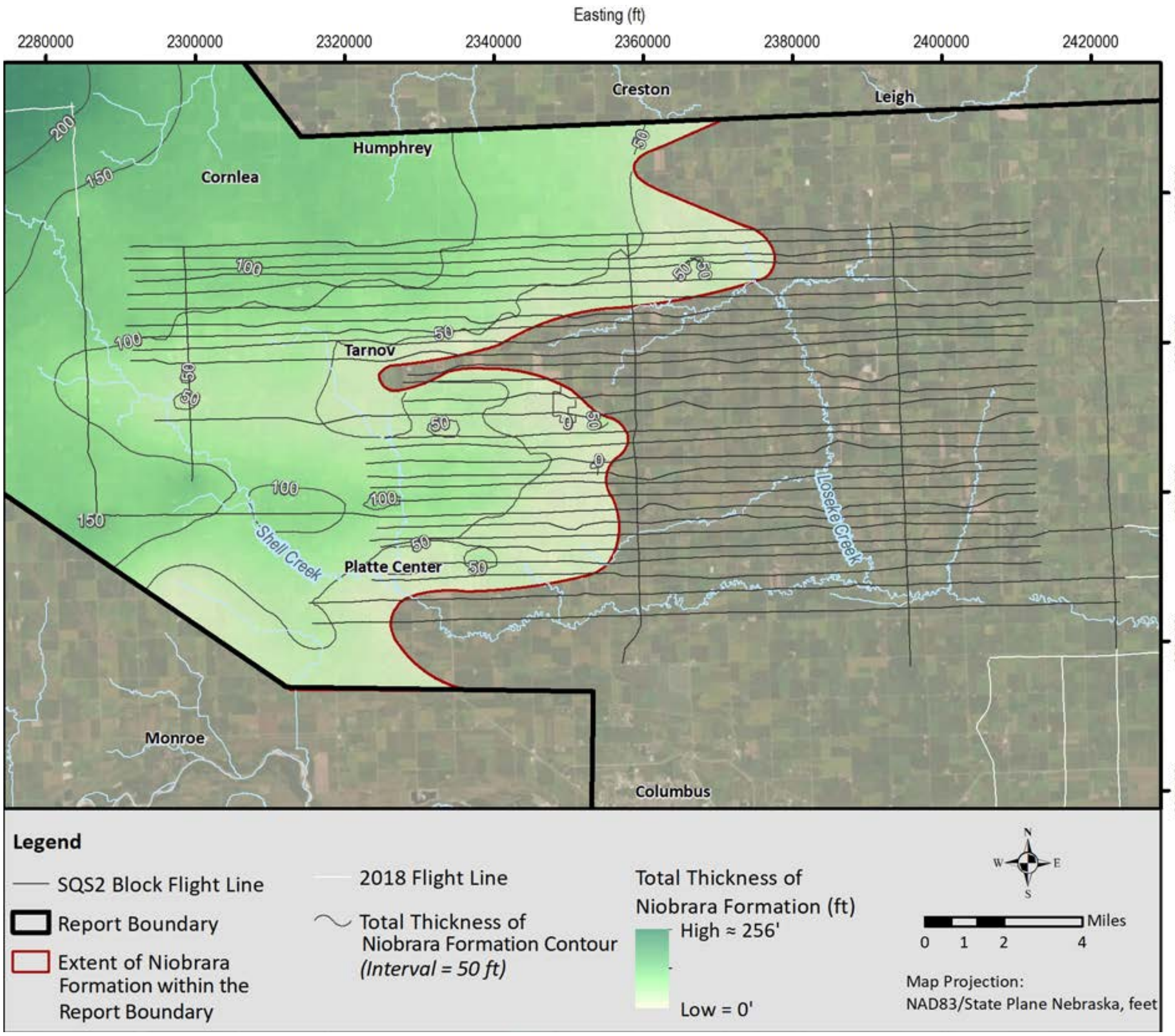


Figure 3-43. Map of the thickness (in feet) of the Niobrara Formation (*Kn*) within the SQS2 Block AEM survey area.

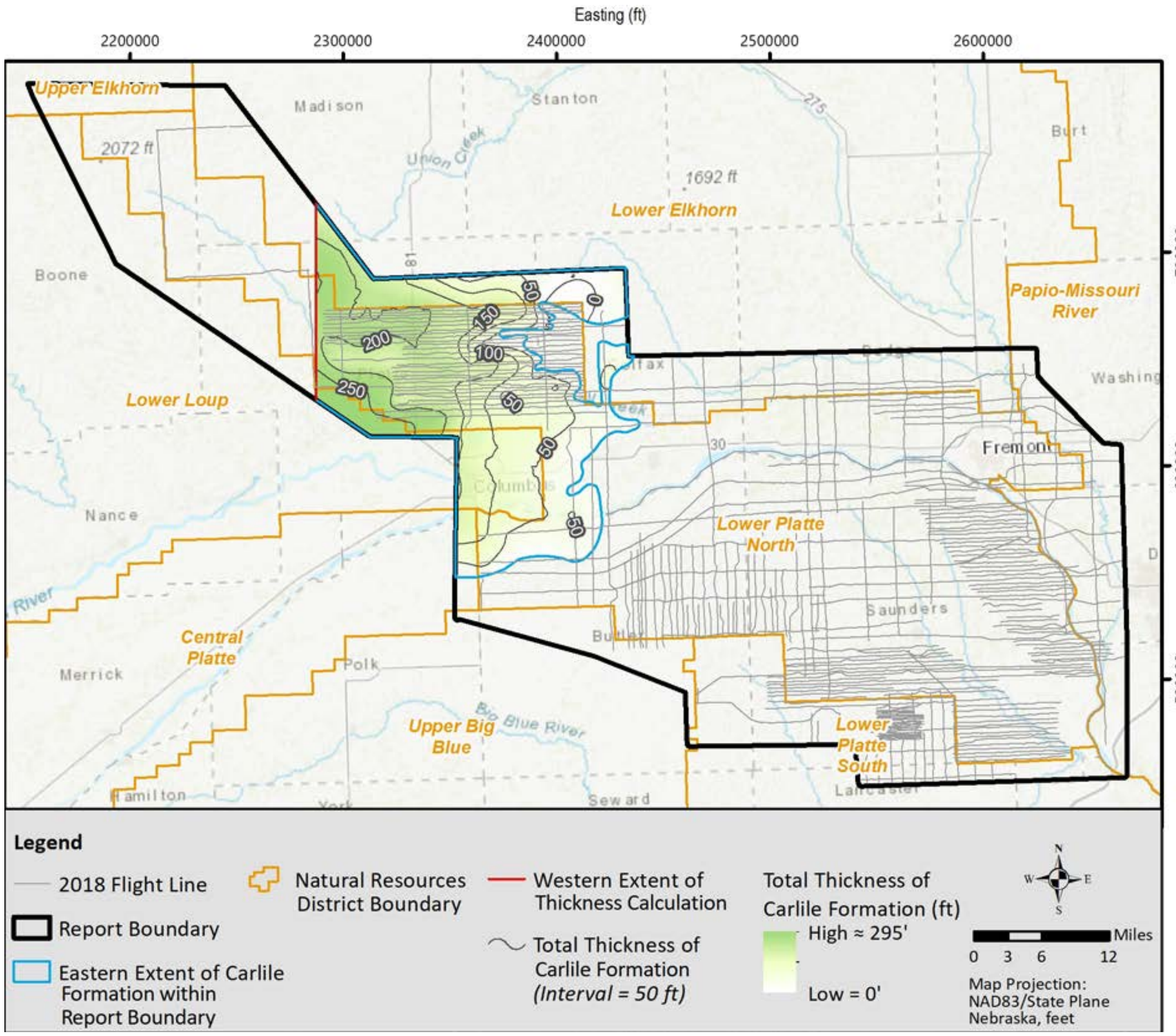


Figure 3-44. Map of the thickness (in feet) of the Carlile Shale (*Kc*) within the LPNNRD AEM survey area.

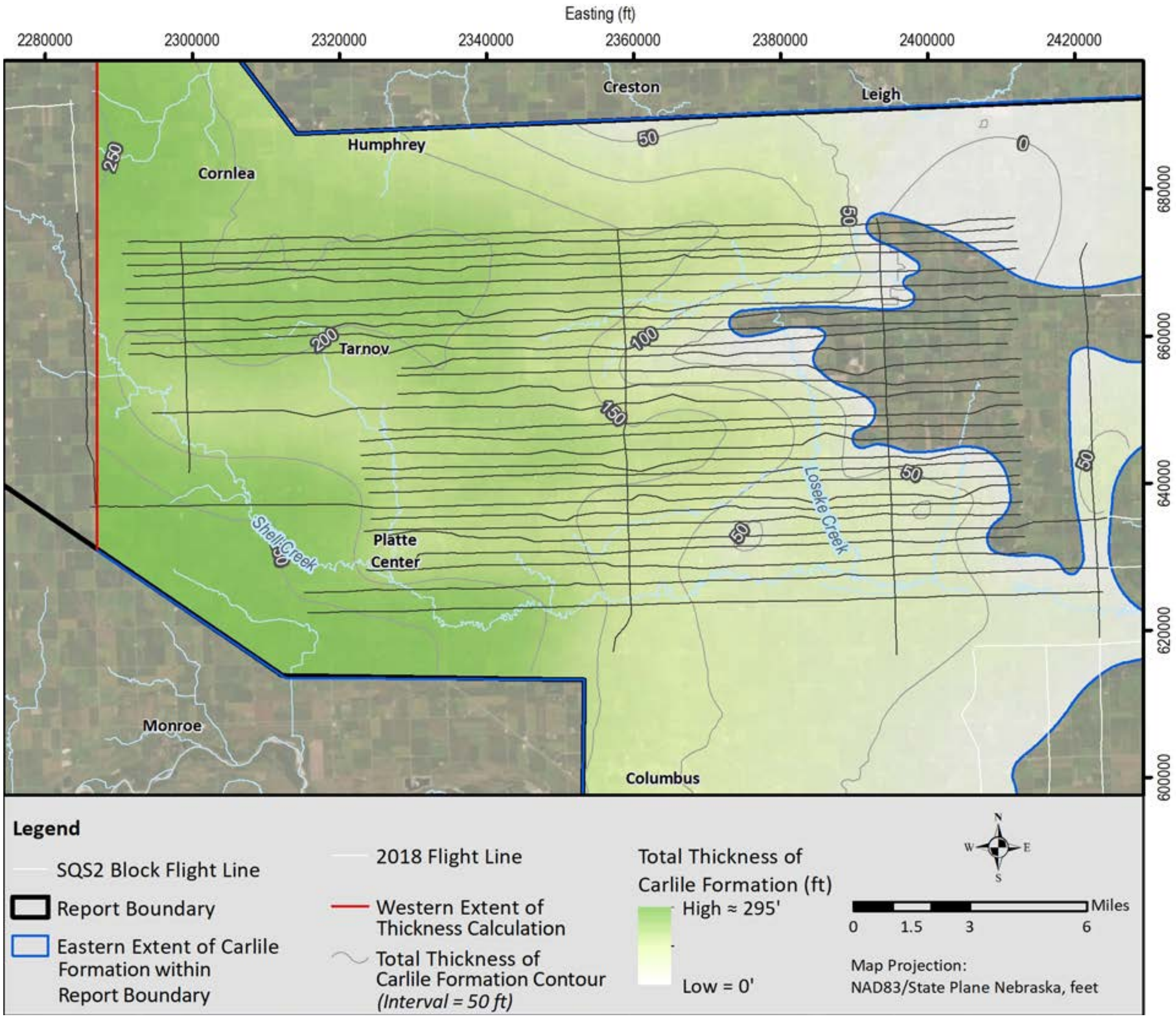


Figure 3-45. Map of the thickness (in feet) of the Carlile Shale (*Kc*) within the SQS2 Block AEM survey area.

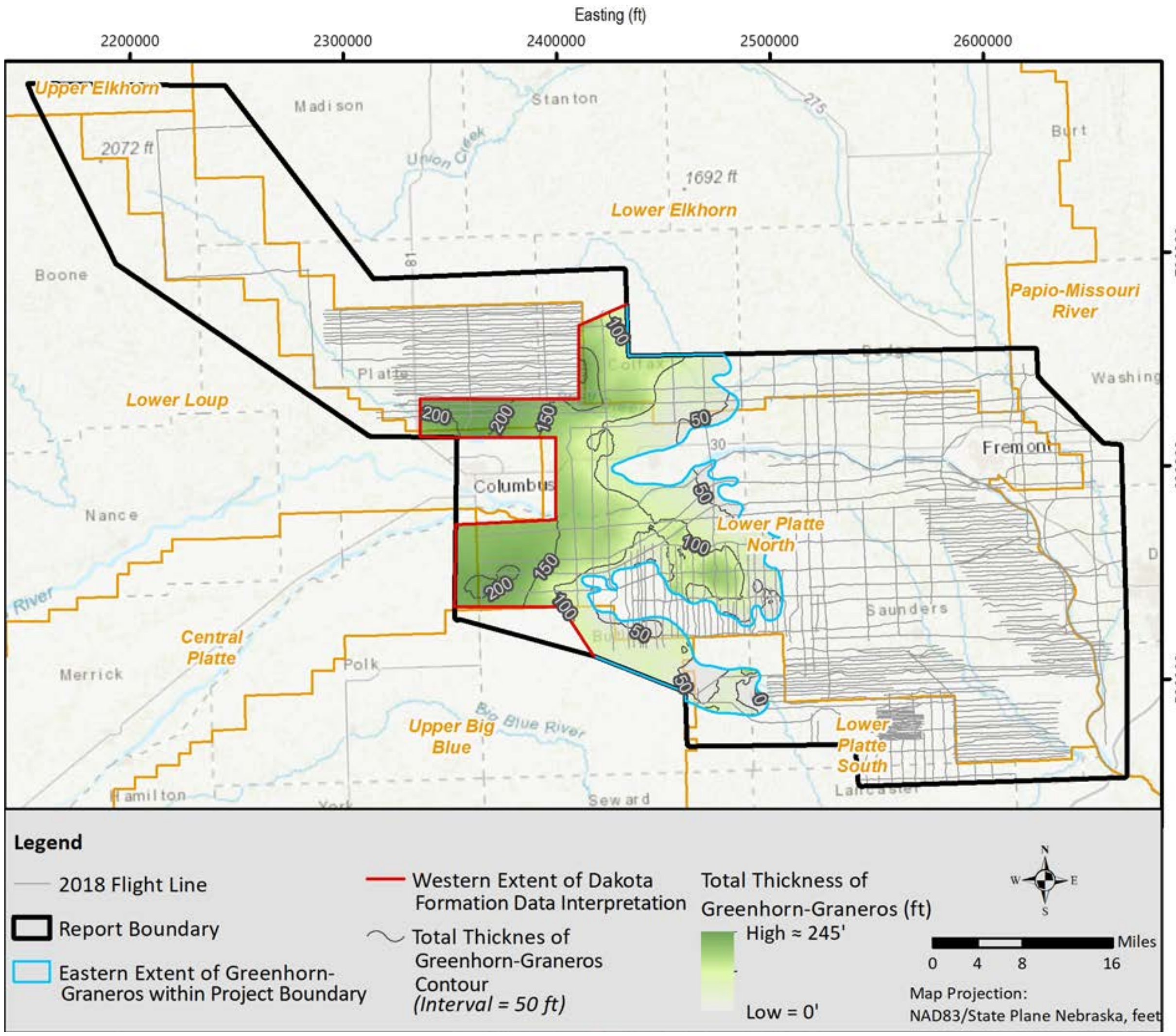


Figure 3-46. Map of the thickness (in feet) of the Greenhorn Limestone/Graneros Shale (*Kgg*) within the LPNNRD AEM survey area.

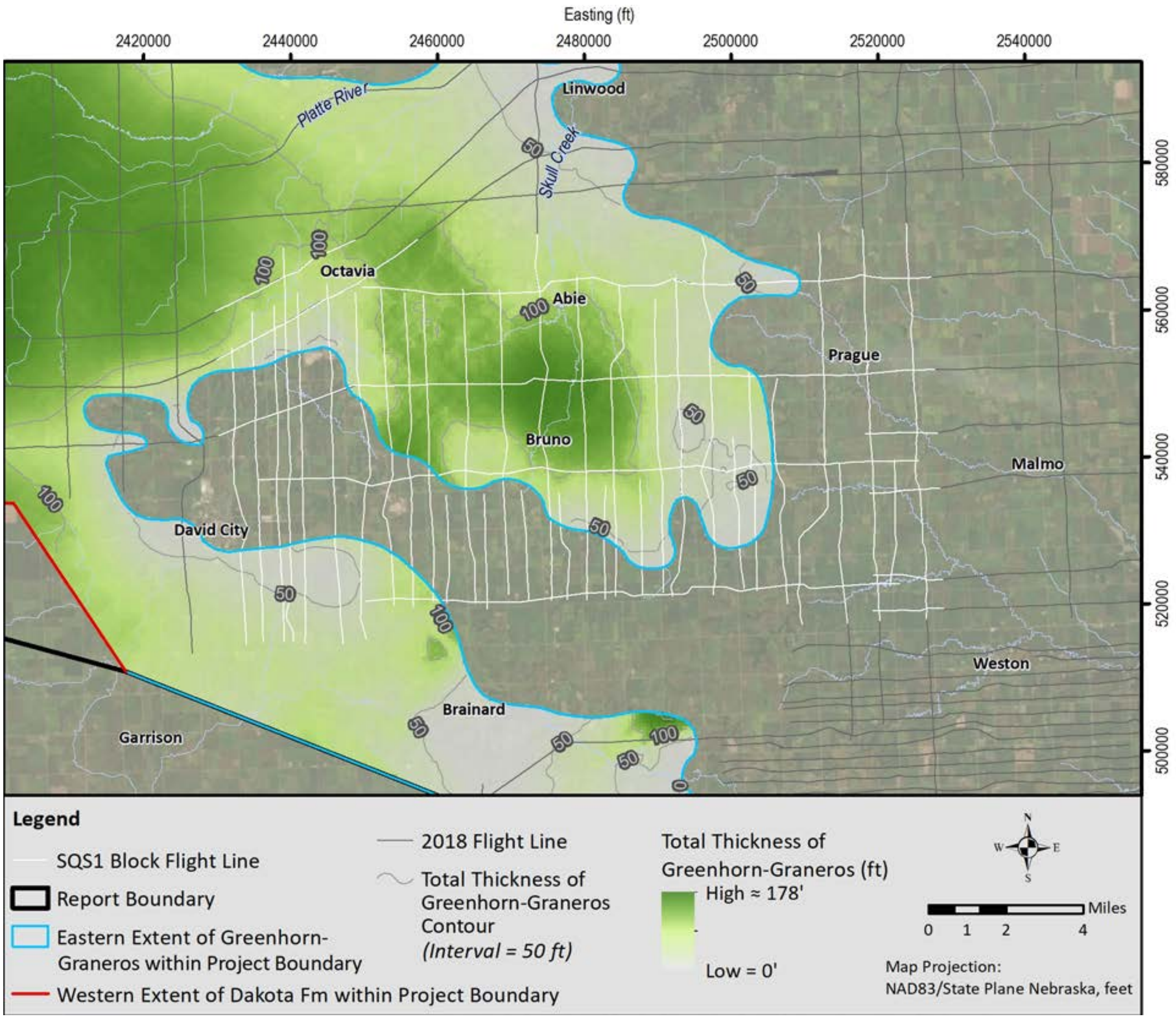


Figure 3-47. Map of the thickness (in feet) of the top of the Greenhorn Limestone/Graneros Shale (*Kgg*) within the SQS1 Block AEM survey area.

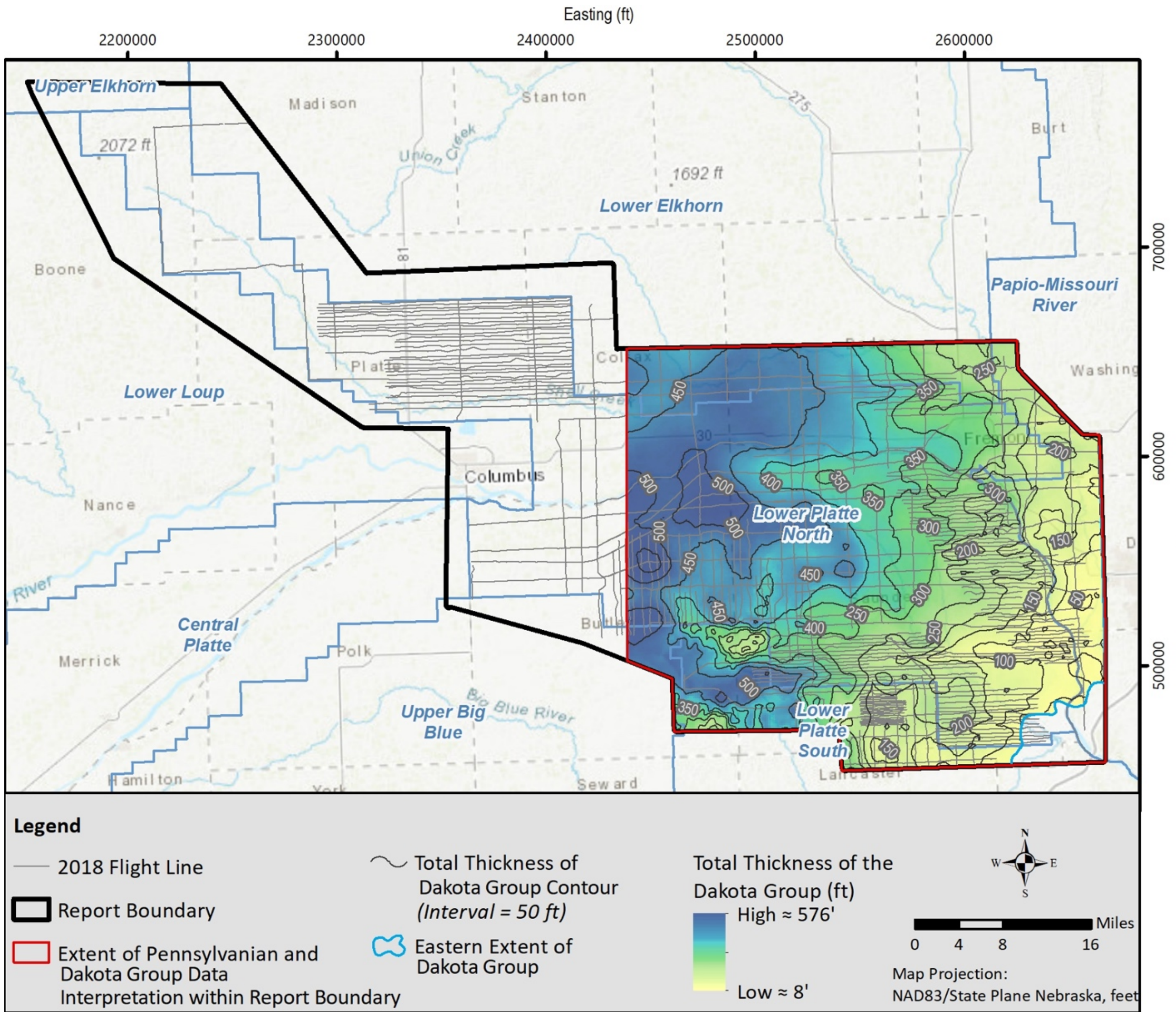


Figure 3-48. Map of the thickness (in feet) of the Cretaceous Dakota Group (*Kd*) within the LPNNRD AEM survey area.

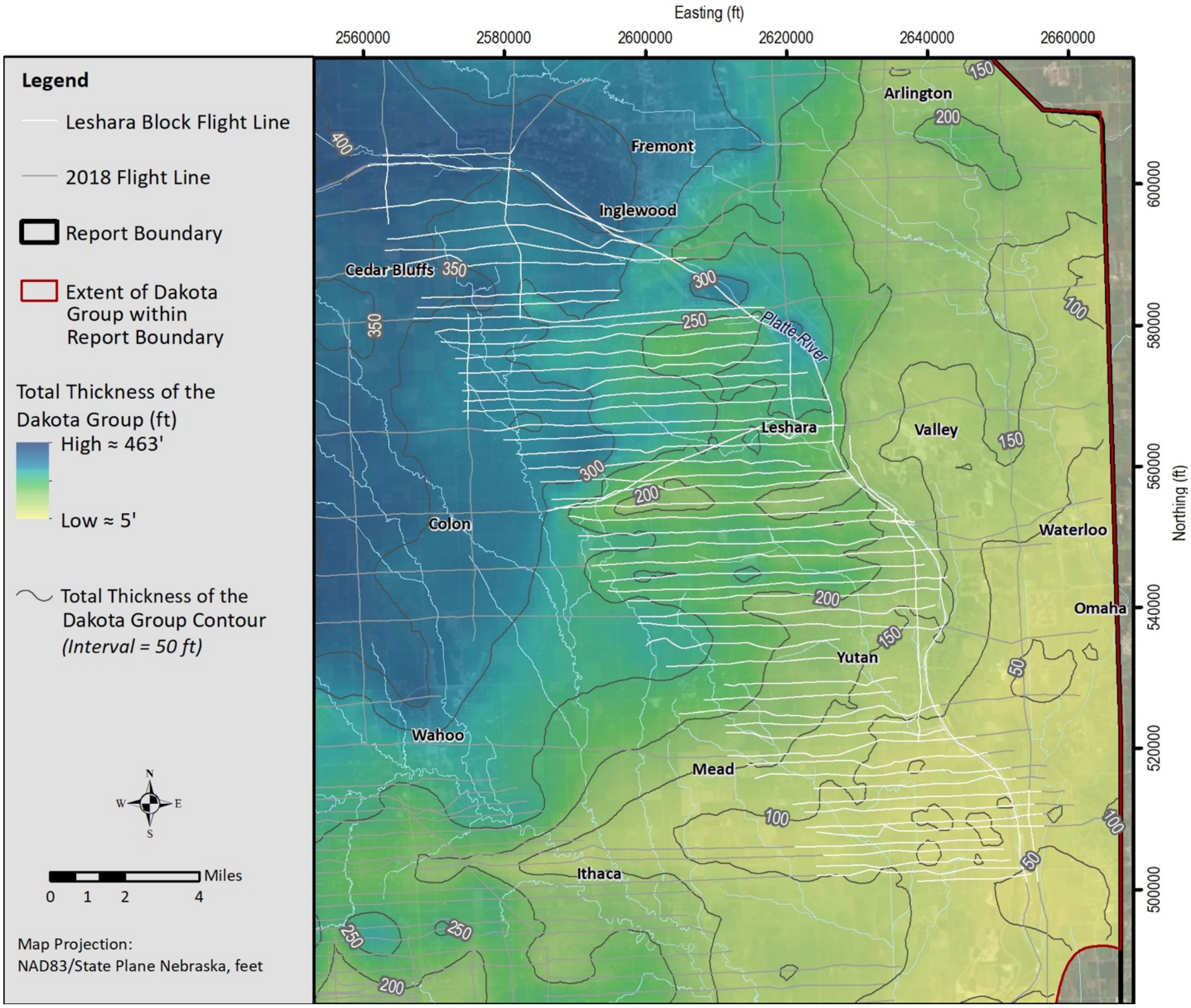


Figure 3-49. Map of the thickness (in feet) of the top of the Cretaceous Dakota Group (*Kd*) within the Leshara Upland Block AEM survey area.

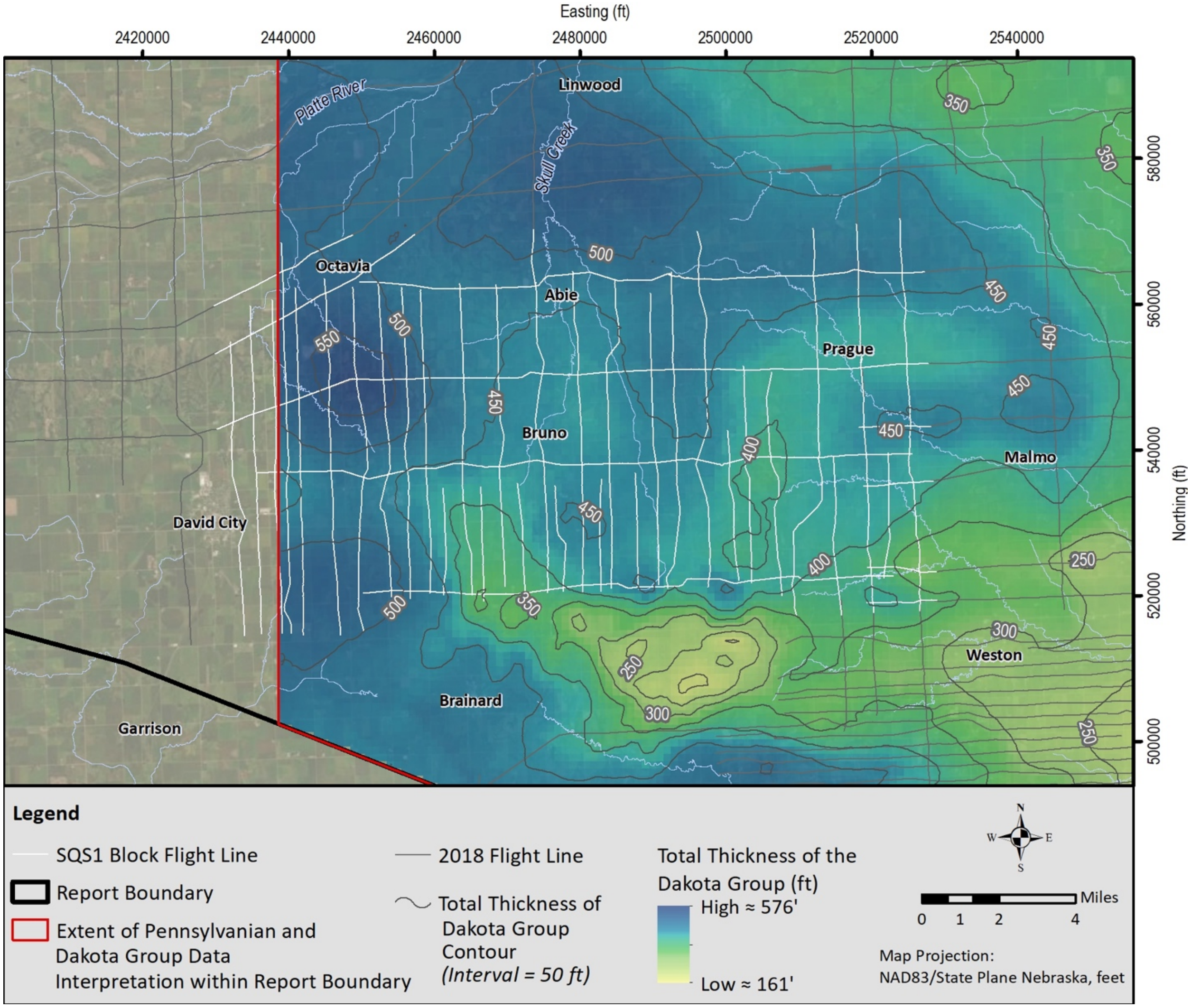


Figure 3-50. Map of the thickness (in feet) of the top of the Cretaceous Dakota Group (*Kd*) within the SQS1 Block AEM survey area.

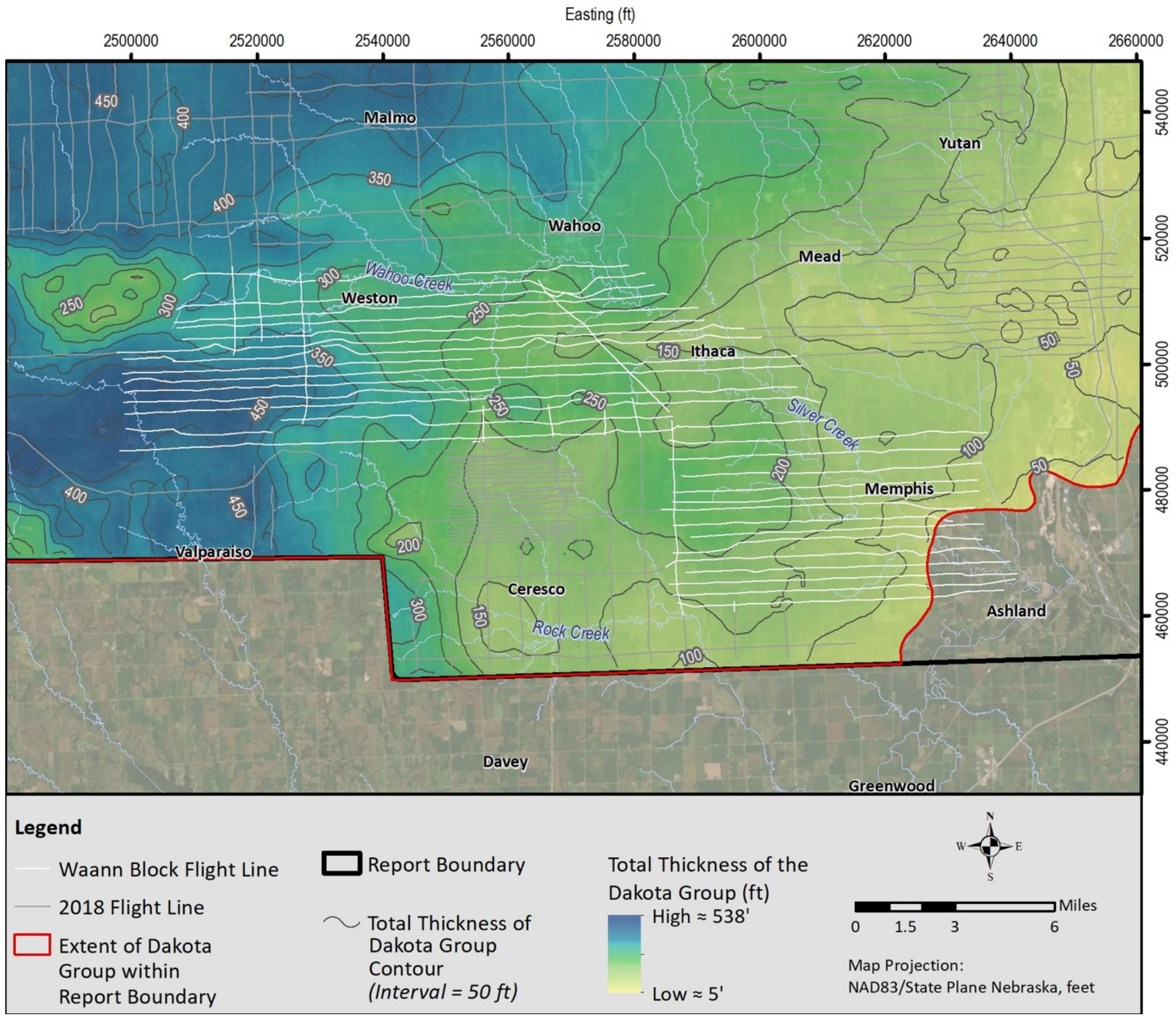


Figure 3-51. Map of the thickness (in feet) of the top of the Cretaceous Dakota Group (*Kd*) within the Waann Block AEM survey area.

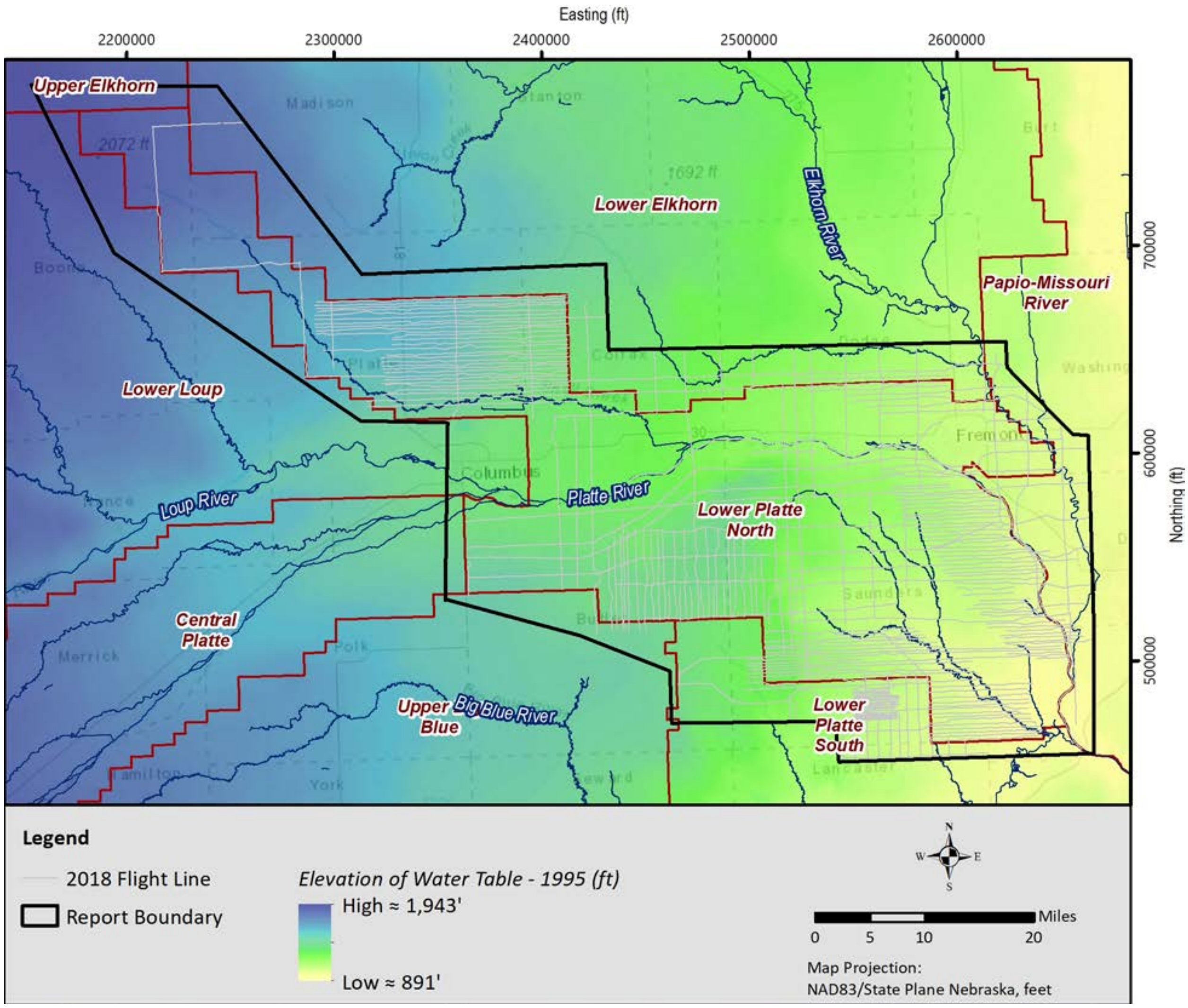


Figure 3-52. Map of the elevation (in feet) of the 1995 CSD water table within the 2018 LPNNRD AEM survey area.

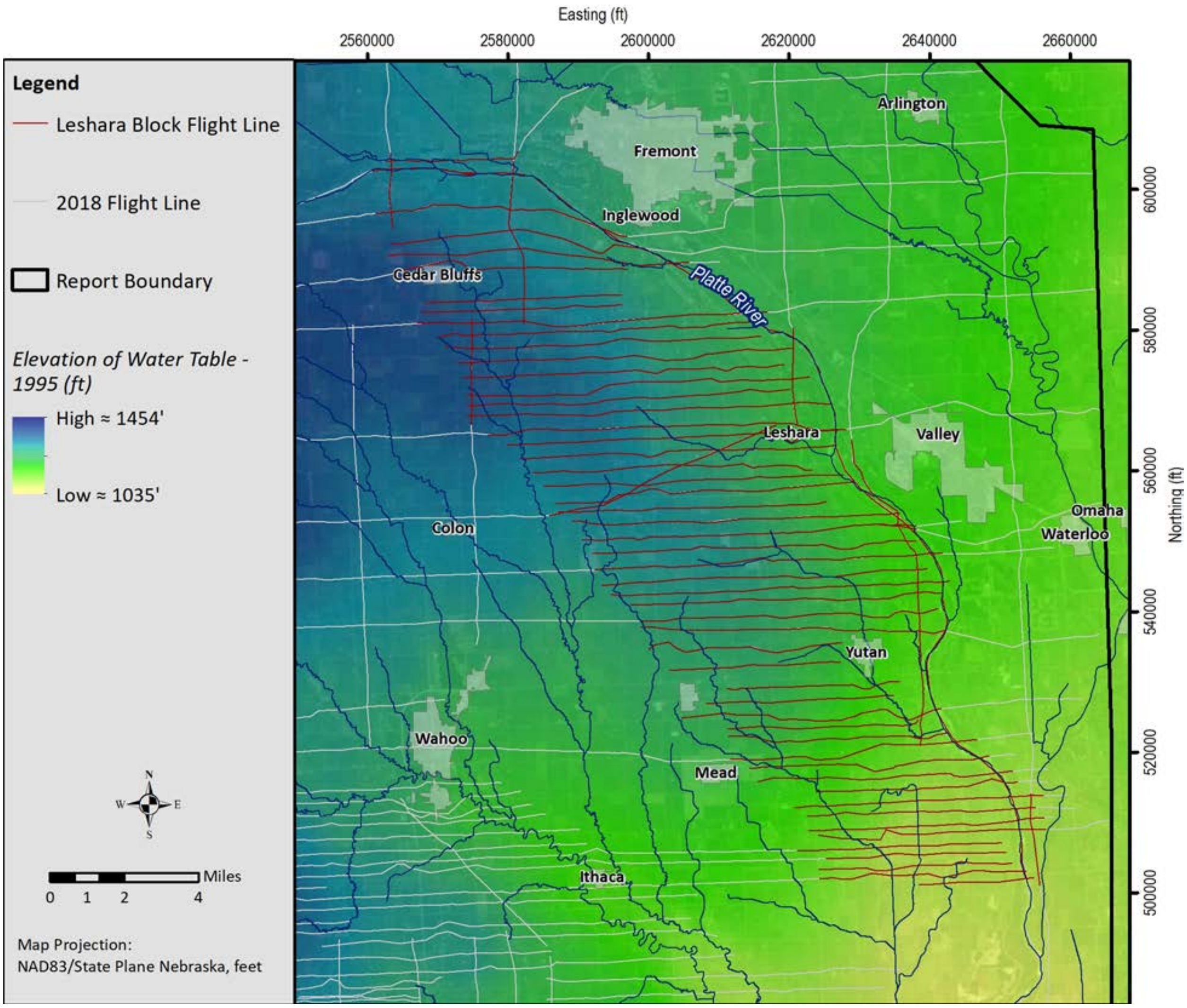


Figure 3-53. Map of the elevation (in feet) of the 1995 CSD water table within the Leshara Upland Block AEM survey area.

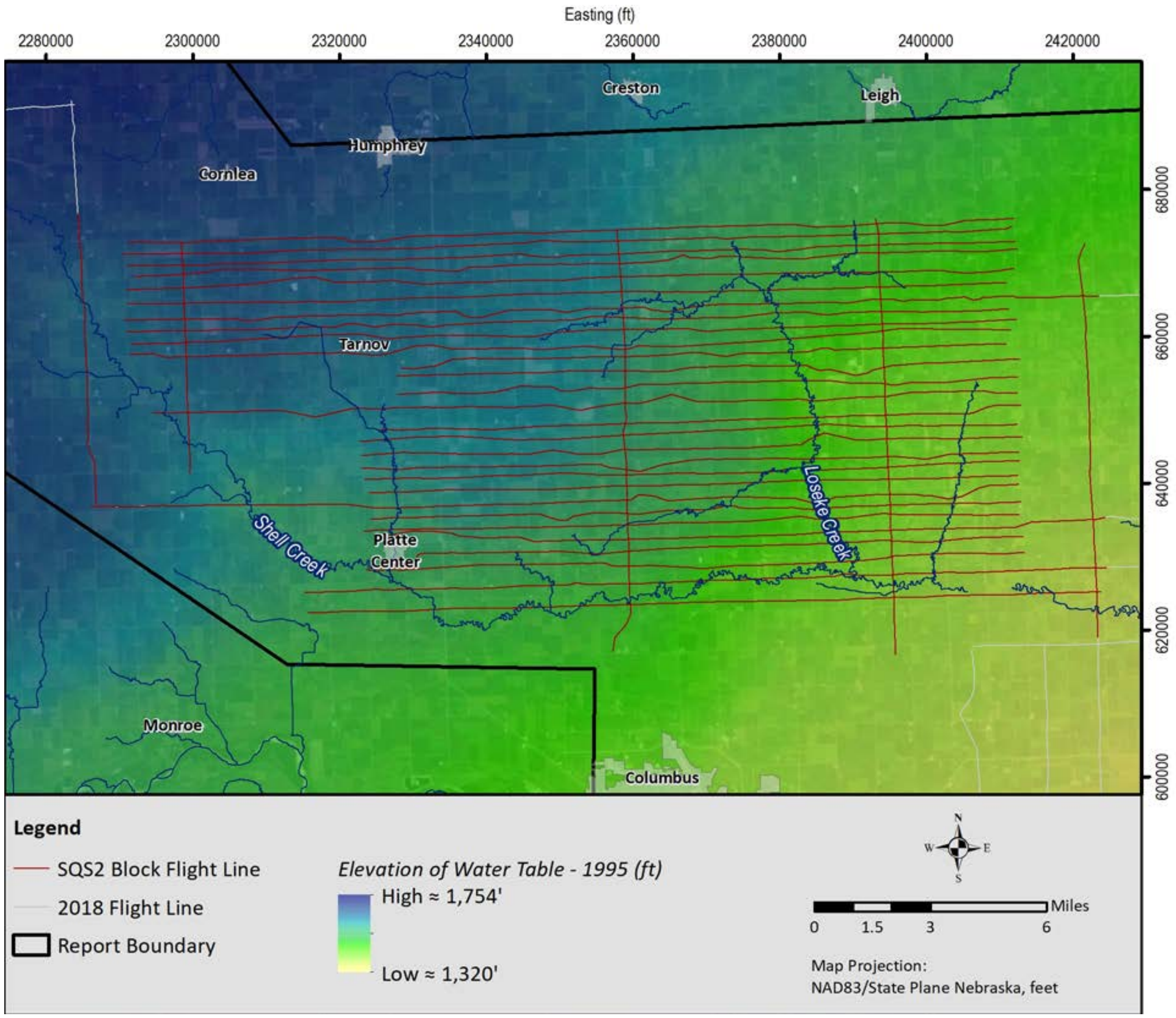


Figure 3-54. Map of the elevation (in feet) of the 1995 CSD water table within the SQS1 Block AEM survey area.

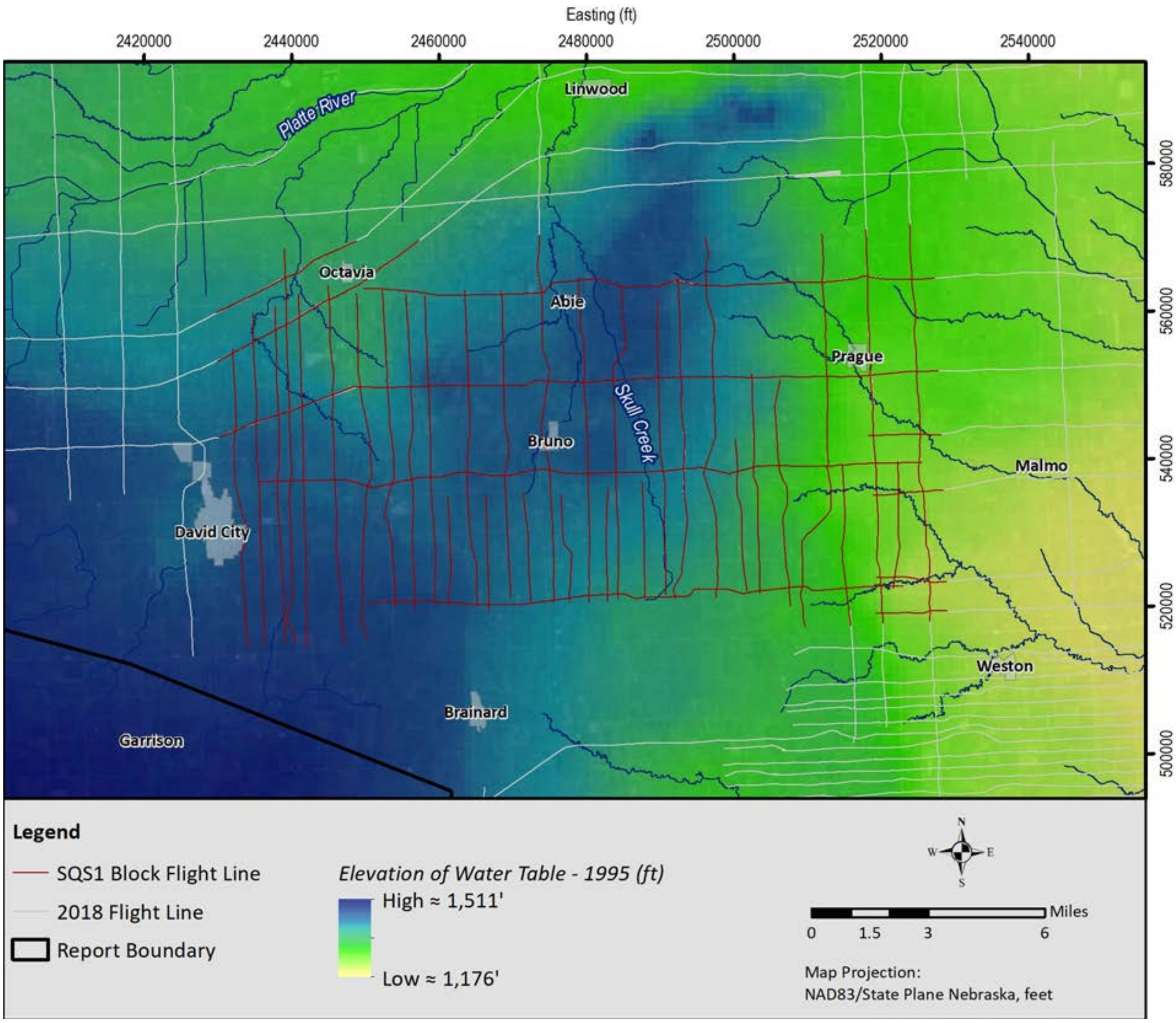


Figure 3-55. Map of the elevation (in feet) of the 1995 CSD water table within the SQS2 Block AEM survey area.

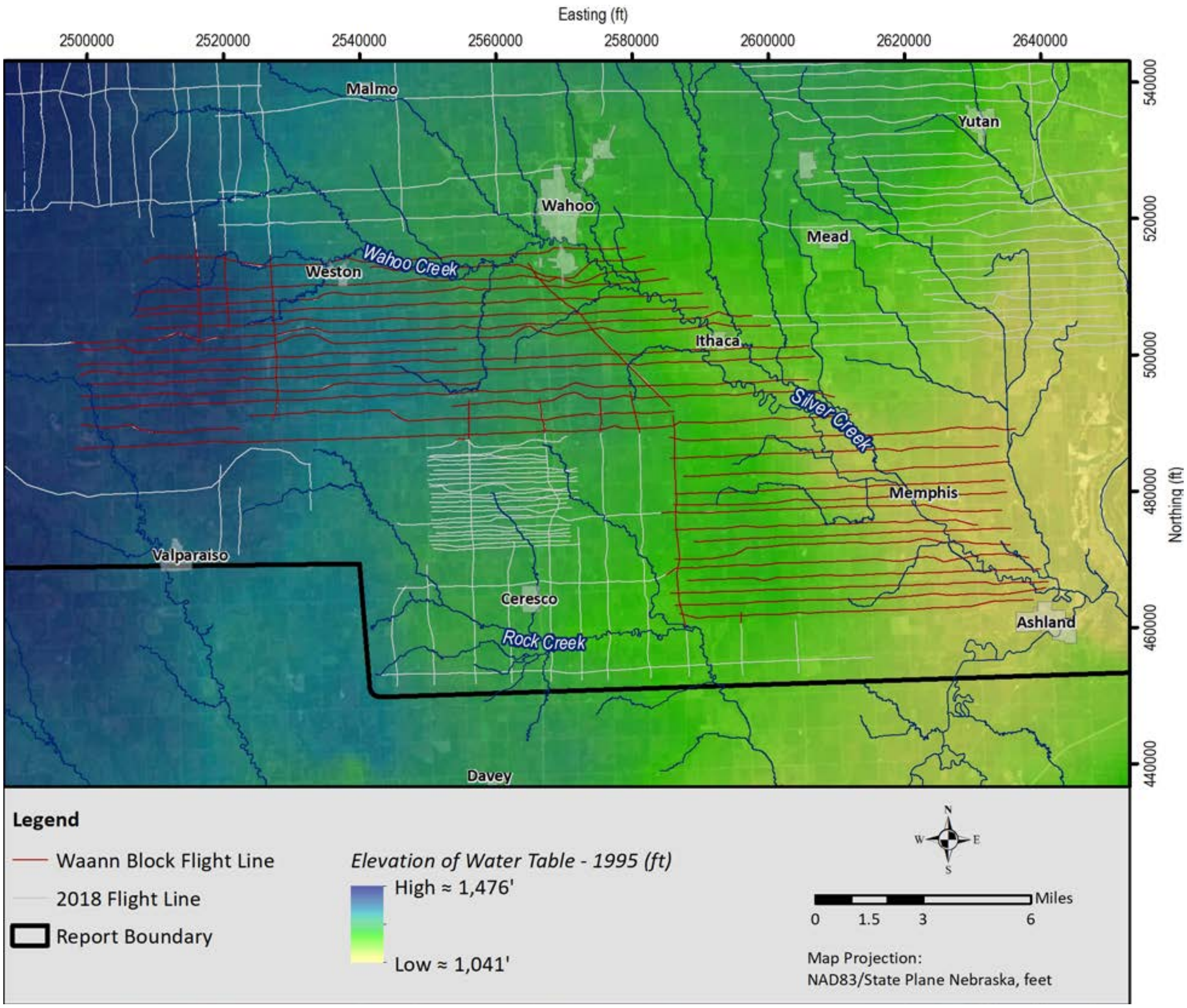


Figure 3-56. Map of the elevation (in feet) of the 1995 CSD water table within the Waann Block AEM survey area.

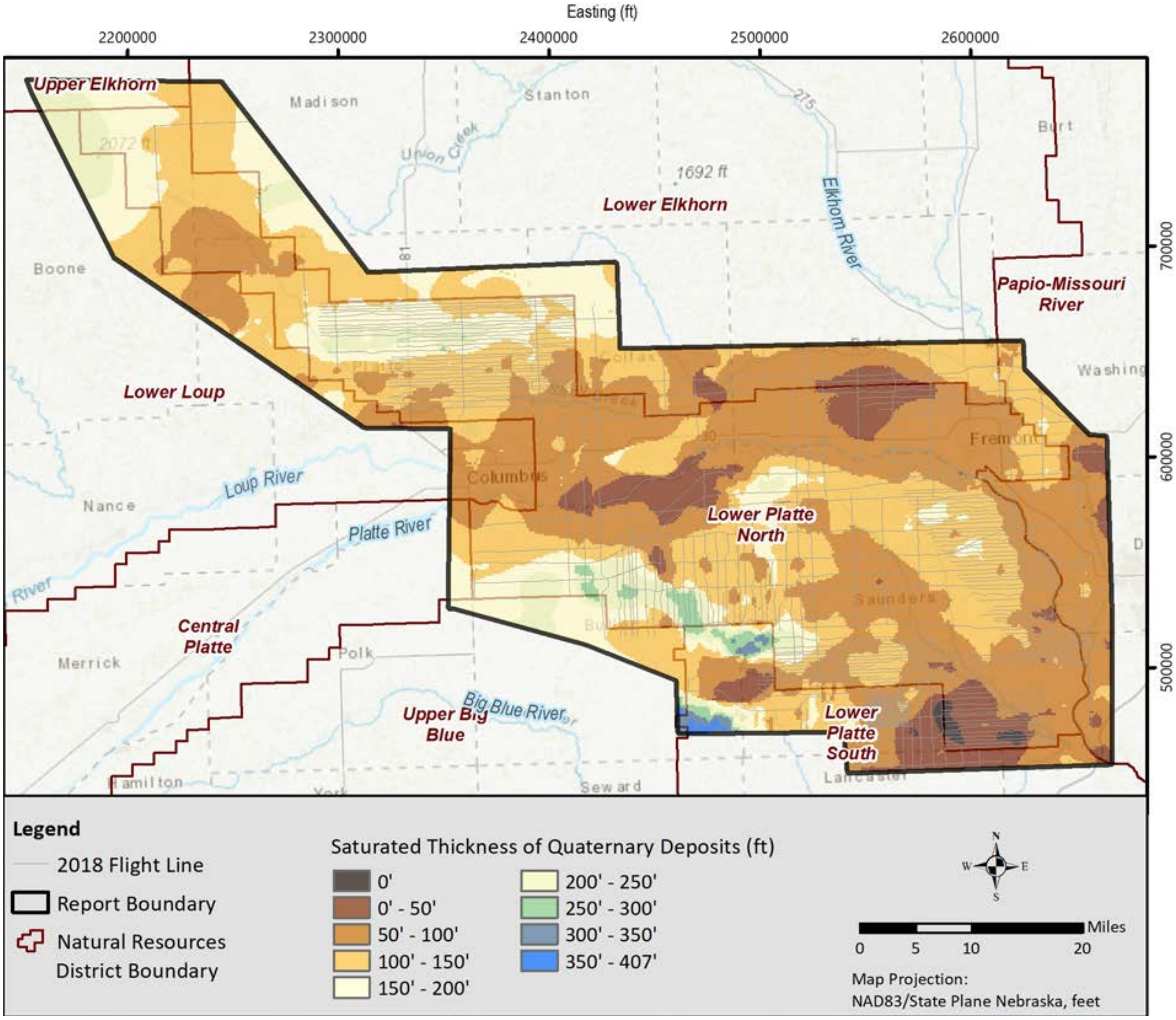


Figure 3-57. Map of the saturated thickness of Quaternary (*Q*) materials within the 2018 LPNNRD AEM survey area. Flight lines are indicated by the gray lines.

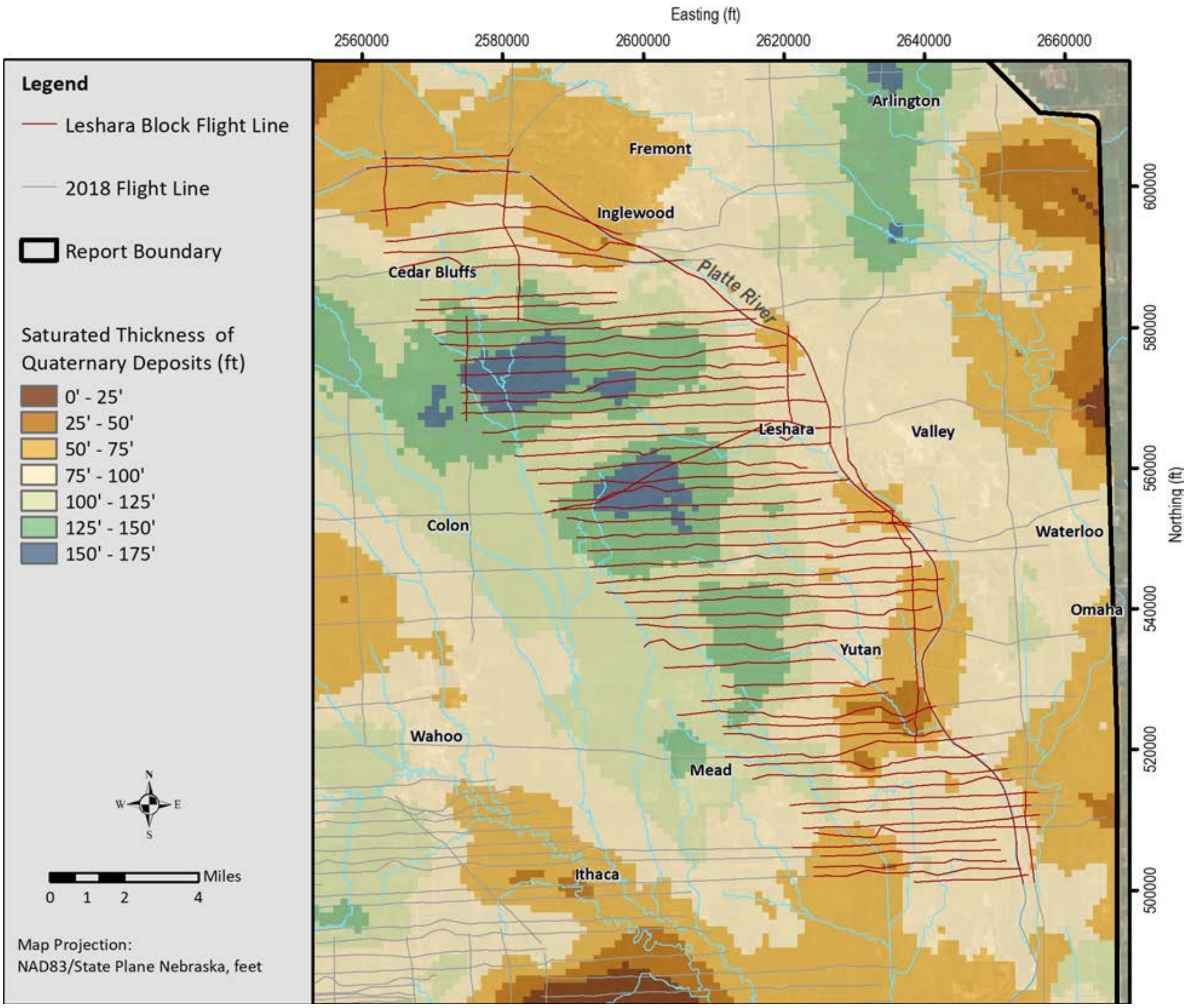


Figure 3-58. Map of the saturated thickness of Quaternary (*Q*) materials within the Leshara Upland Block AEM survey area. Flight lines are indicated by the gray lines.

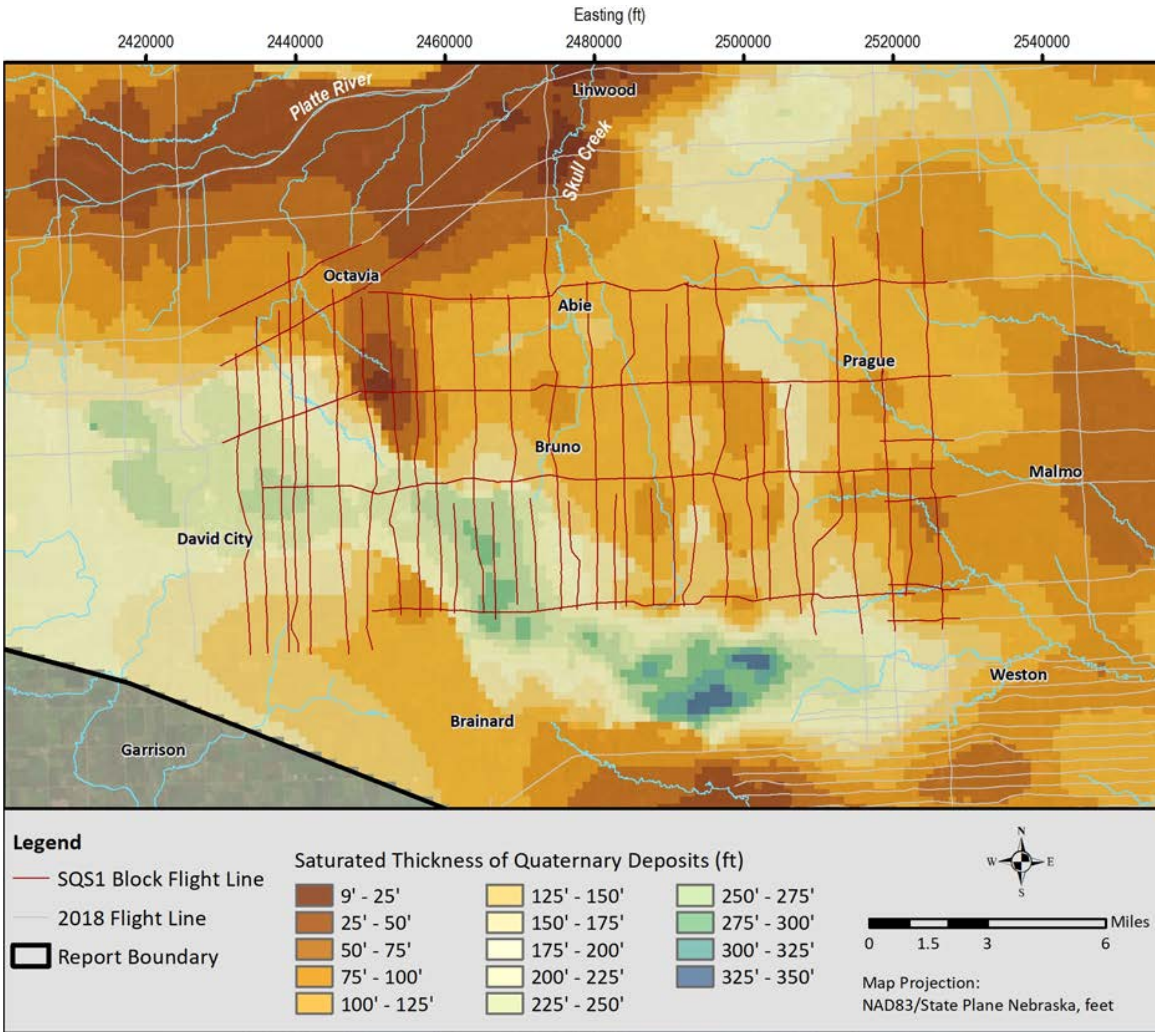


Figure 3-59. Map of the saturated thickness of Quaternary (*Q*) materials within the SQS1 Block AEM survey area. Flight lines are indicated by the gray lines.

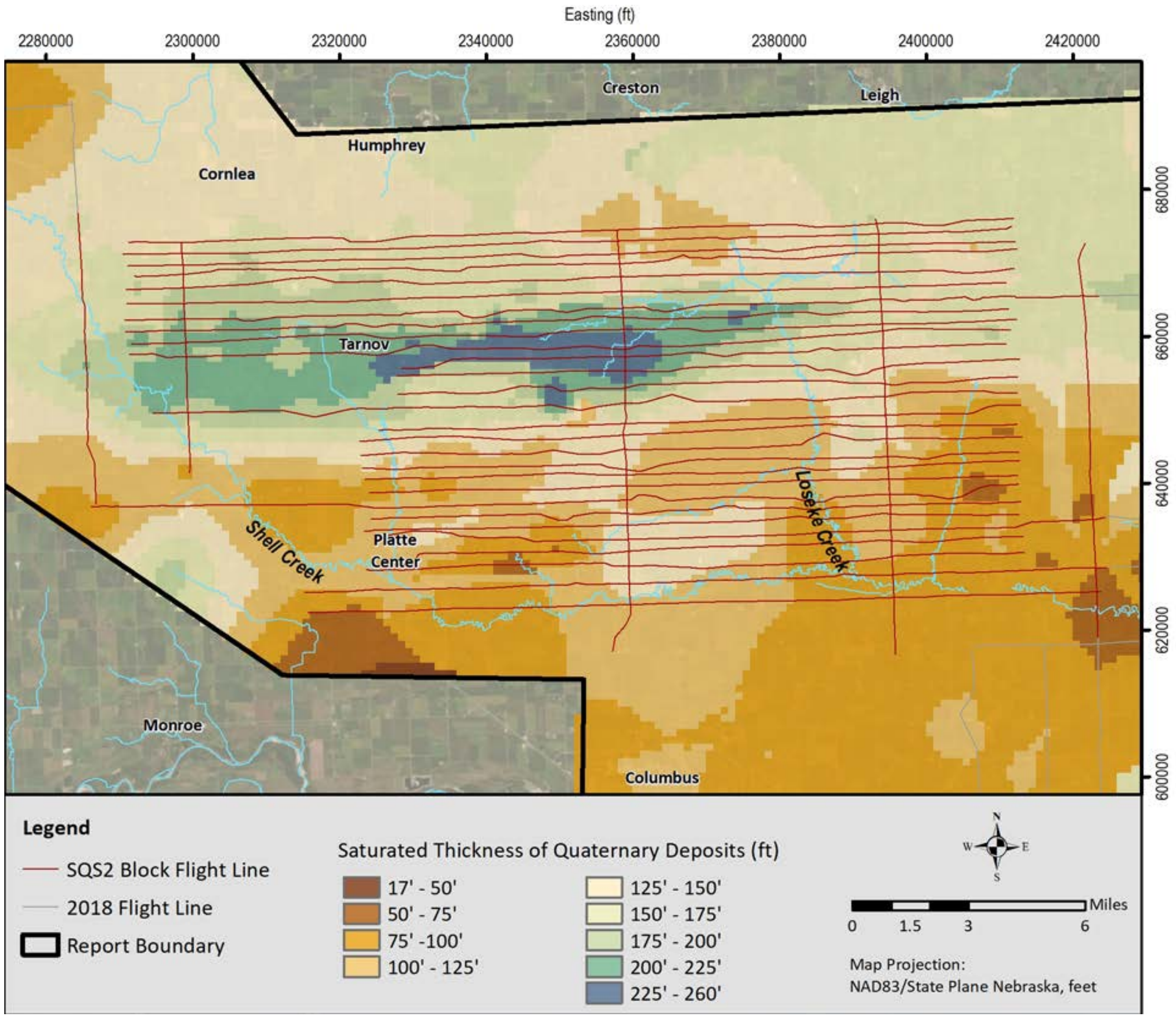


Figure 3-60. Map of the saturated thickness of Quaternary (*Q*) materials within the SQS2 Block AEM survey area. Flight lines are indicated by the gray lines.

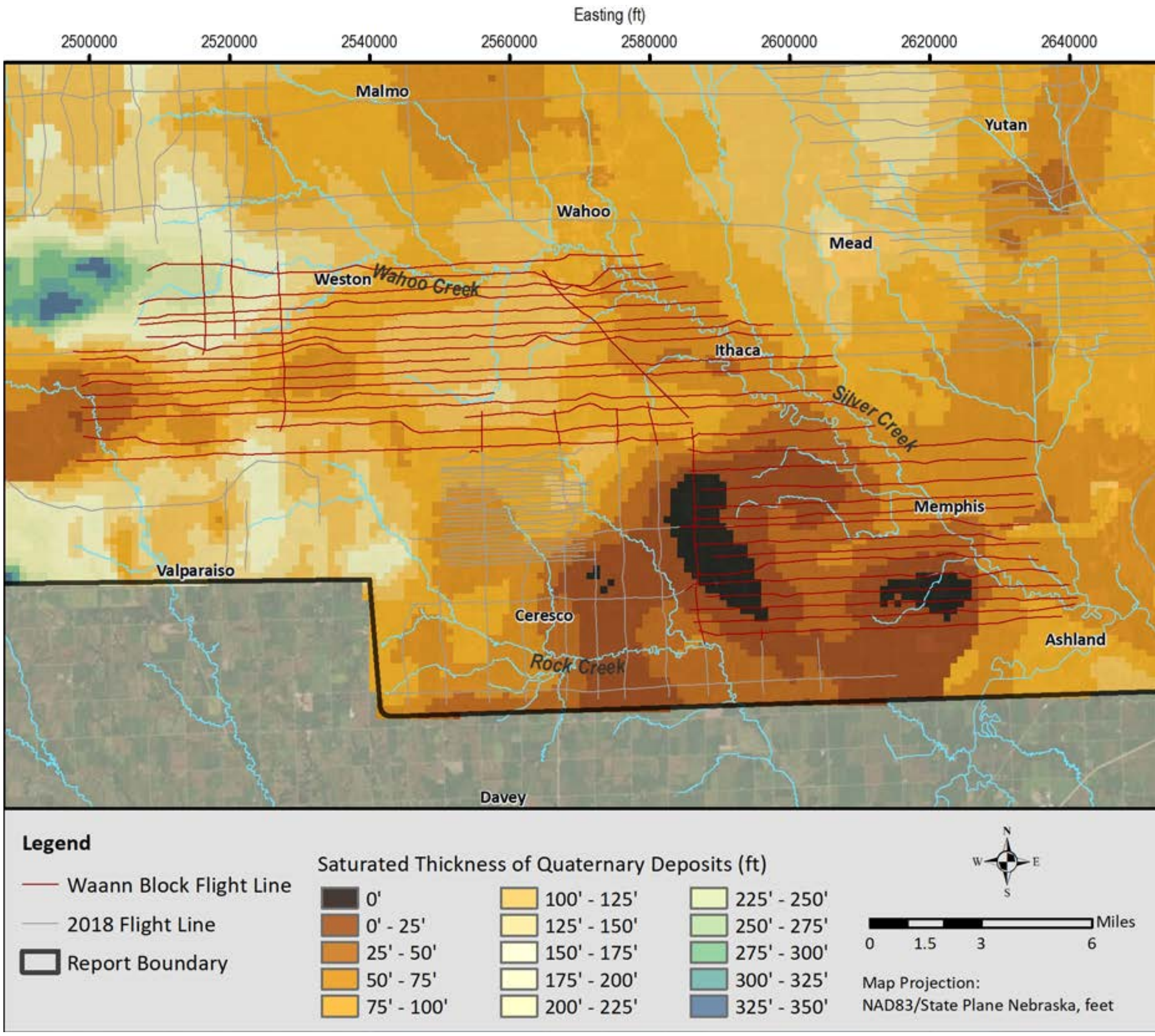


Figure 3-61. Map of the saturated thickness of Quaternary (*Q*) materials within the Waann Block AEM survey area. Flight lines are indicated by the gray lines.

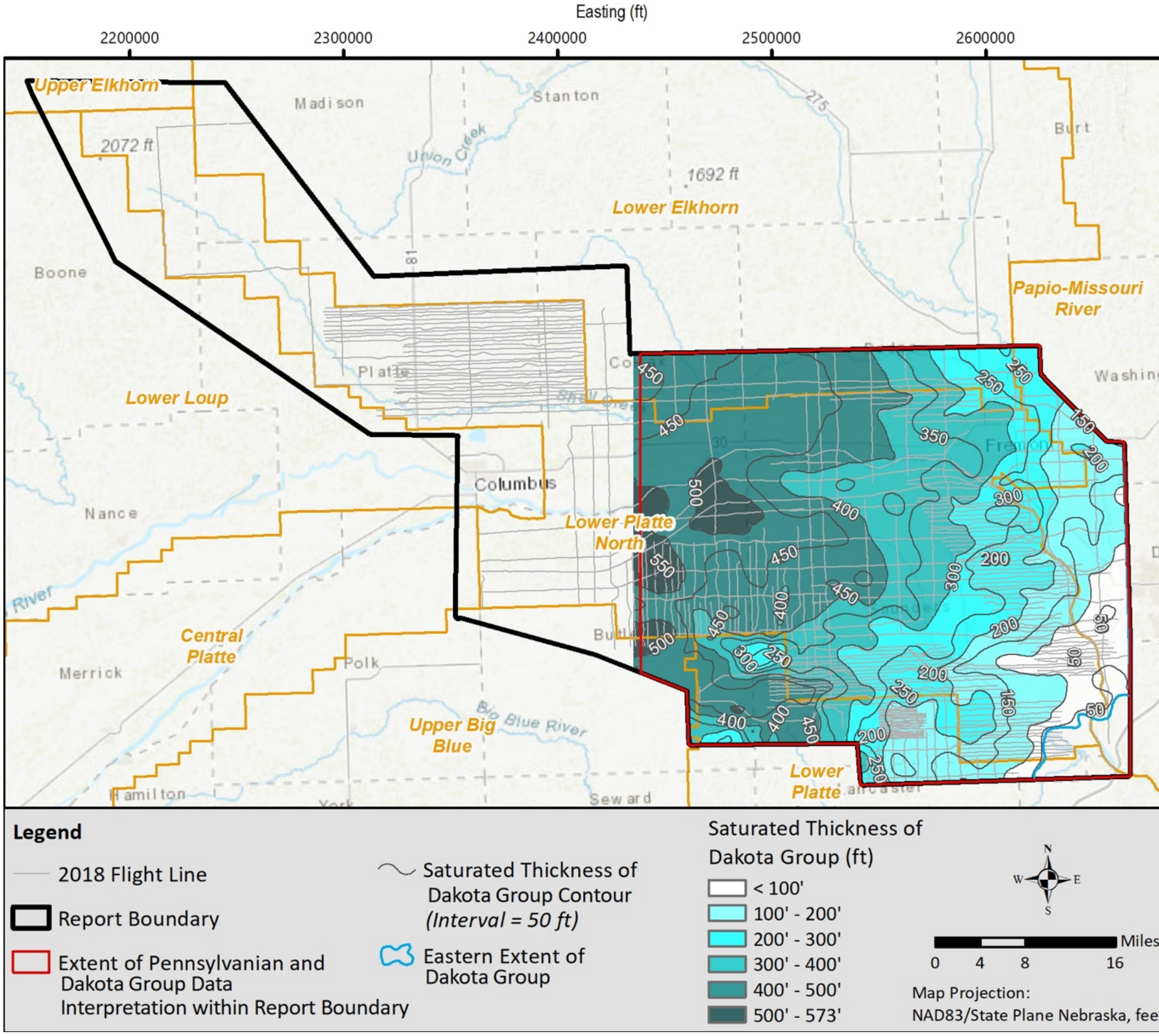


Figure3-62. Map of the saturated thickness of Cretaceous Dakota Group (*Kd*) within the 2018 LPNNRD AEM survey area. Flight lines are indicated by the gray lines.

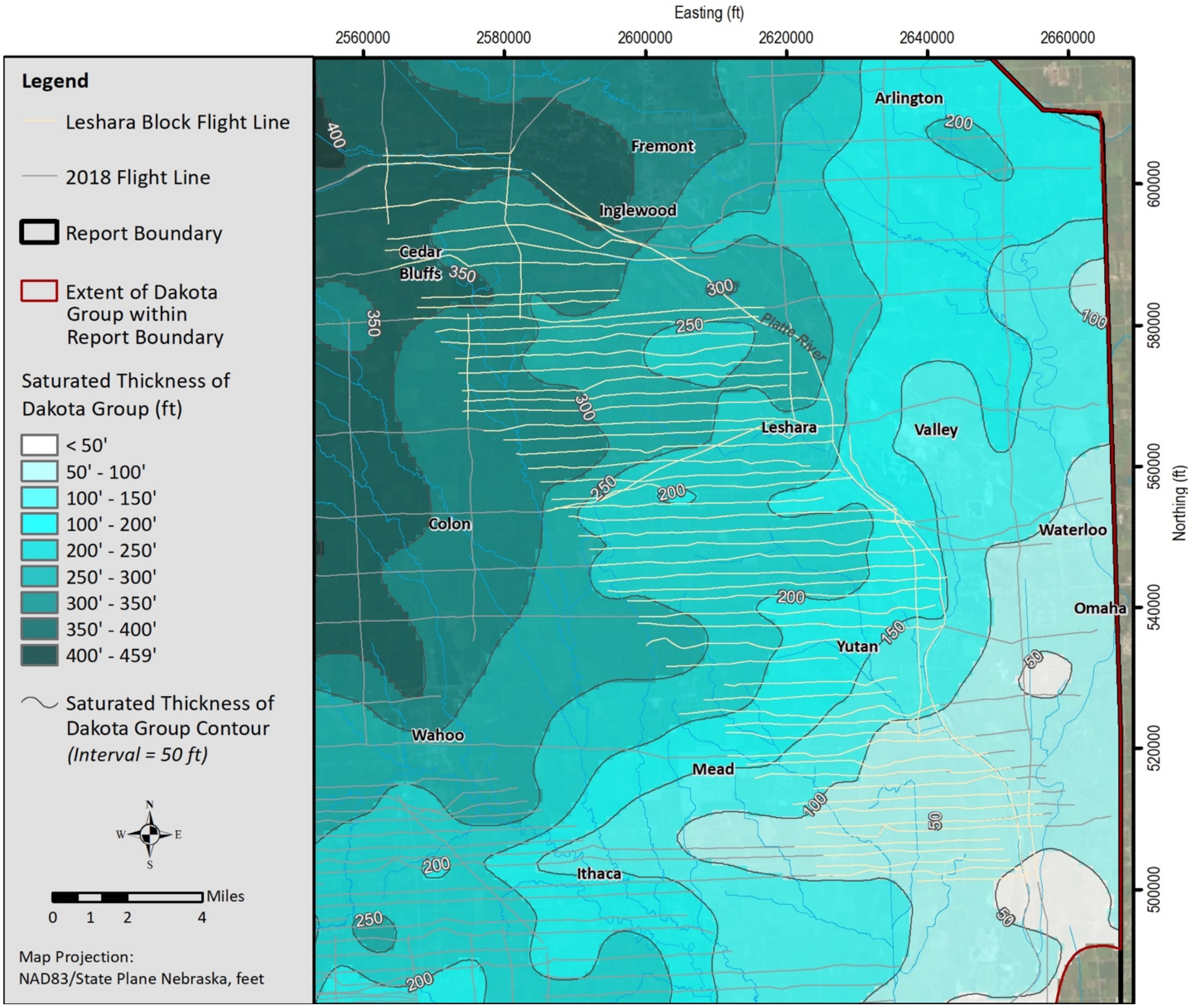


Figure 3-63. Map of the saturated thickness of Cretaceous Dakota Group (*Kd*) within the Leshara Block AEM survey area. Flight lines are indicated by the gray lines.

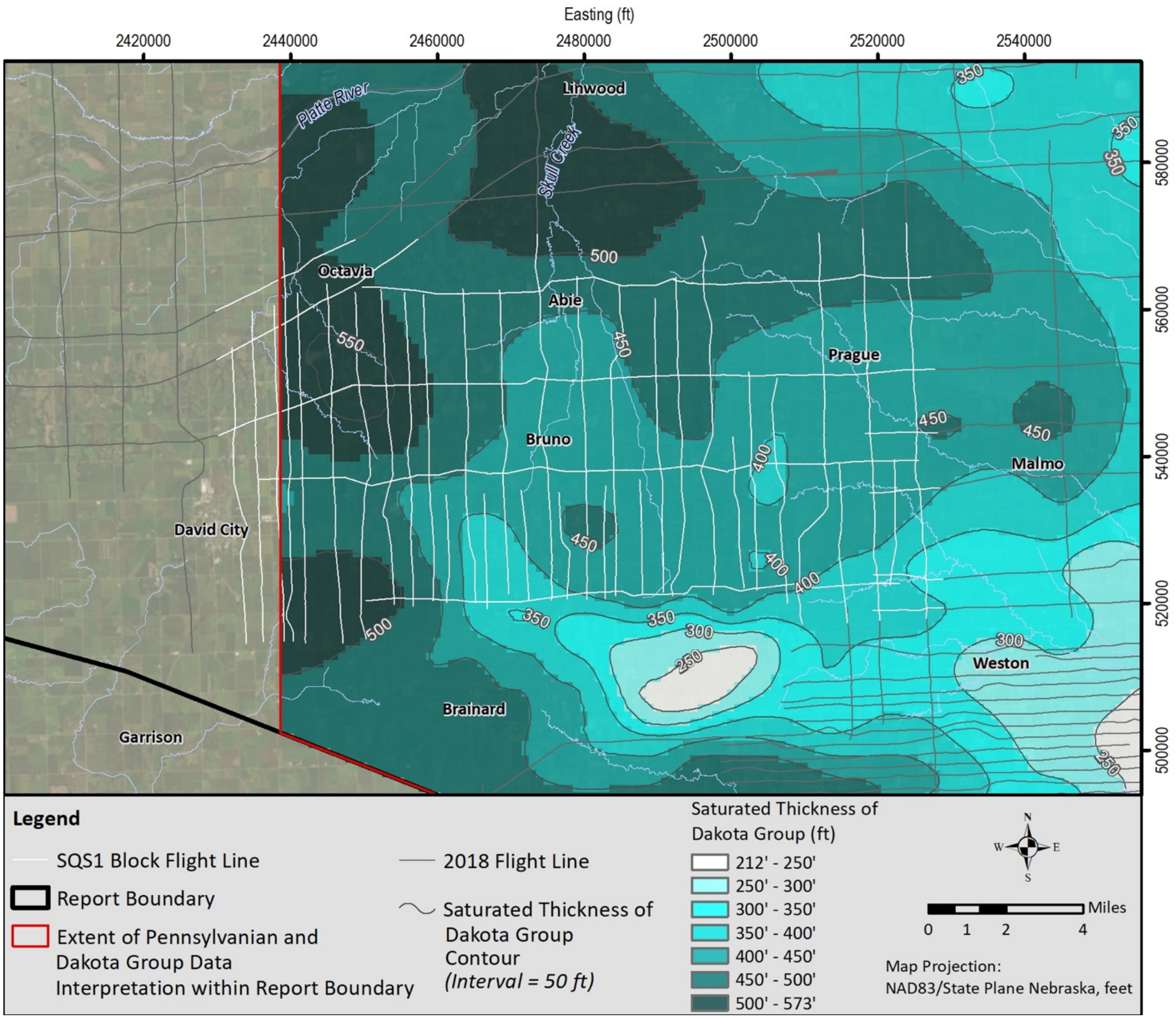


Figure 3-64. Map of the saturated thickness of Cretaceous Dakota Group (*Kd*) within the SQS1 Block AEM survey area. Flight lines are indicated by the gray lines.

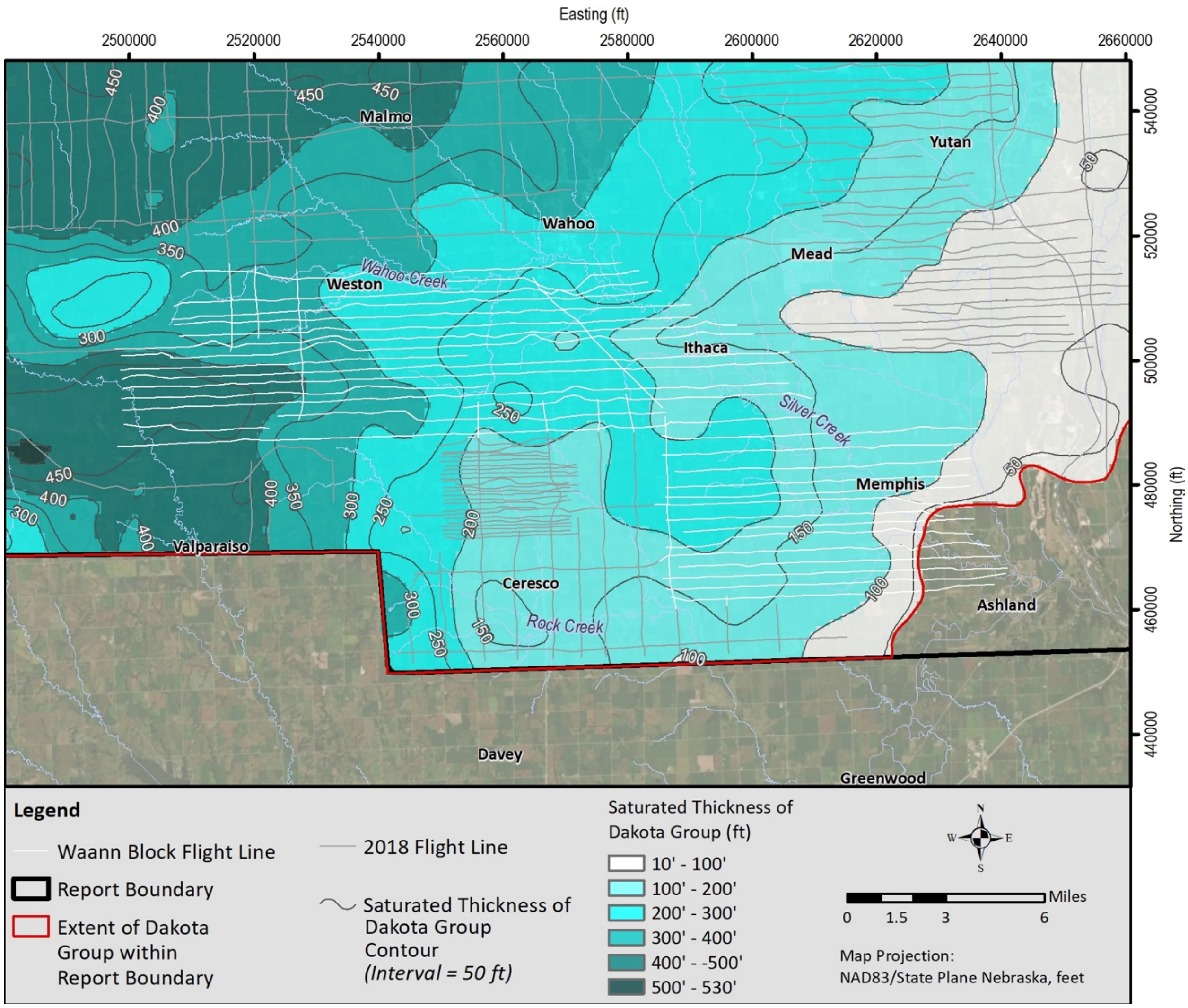


Figure 3-65. Map of the saturated thickness of Cretaceous Dakota Group (*Kd*) within the Waann Block AEM survey area. Flight lines are indicated by the gray lines.

3.1.5 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 LPNNRD 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 the overall area of the LPNNRD. 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 3-66.

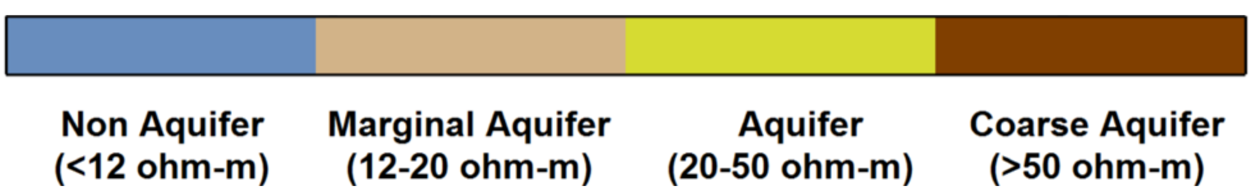


Figure 3-66. Plot displaying the resistivities by major aquifer material color categories: blue- non-aquifer materials, tan- marginal aquifer materials, yellow- aquifer materials, brown- coarse aquifer materials (Carney et al., 2015b).

3.1.6 Resistivity/Lithology Relationship in the Bedrock

The Cretaceous bedrock in the LPNNRD 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 LPNNRD. 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 LPNNRD 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 mostly in the western portions of the LPNNRD. 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).

3.1.7 Create 3D Interpretative Voxel Grids

A voxel grids were completed for the Leshara Upland, SQS1, SQS2, and Waann Blocks. The voxel grids were made using a 500 feet grid cell size and the model layer thickness (Table 2-5 in the previous section) for the Leshara Upland, SQS2, and Waann Blocks. SQS1 was gridded using a 1,000 feet cell size. This is an increased cell size from the 2016 report (AGF, 2017) due to the concern of over-interpolation of the widely spaced lines. 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 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 3-67 is a plot of the exploded diagram of the solid model for the ***Q*** material separated from the ***Kd*** above the ***IP*** bedrock looking to the north for the Leshara Upland Block as an example. 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\Voxel*.

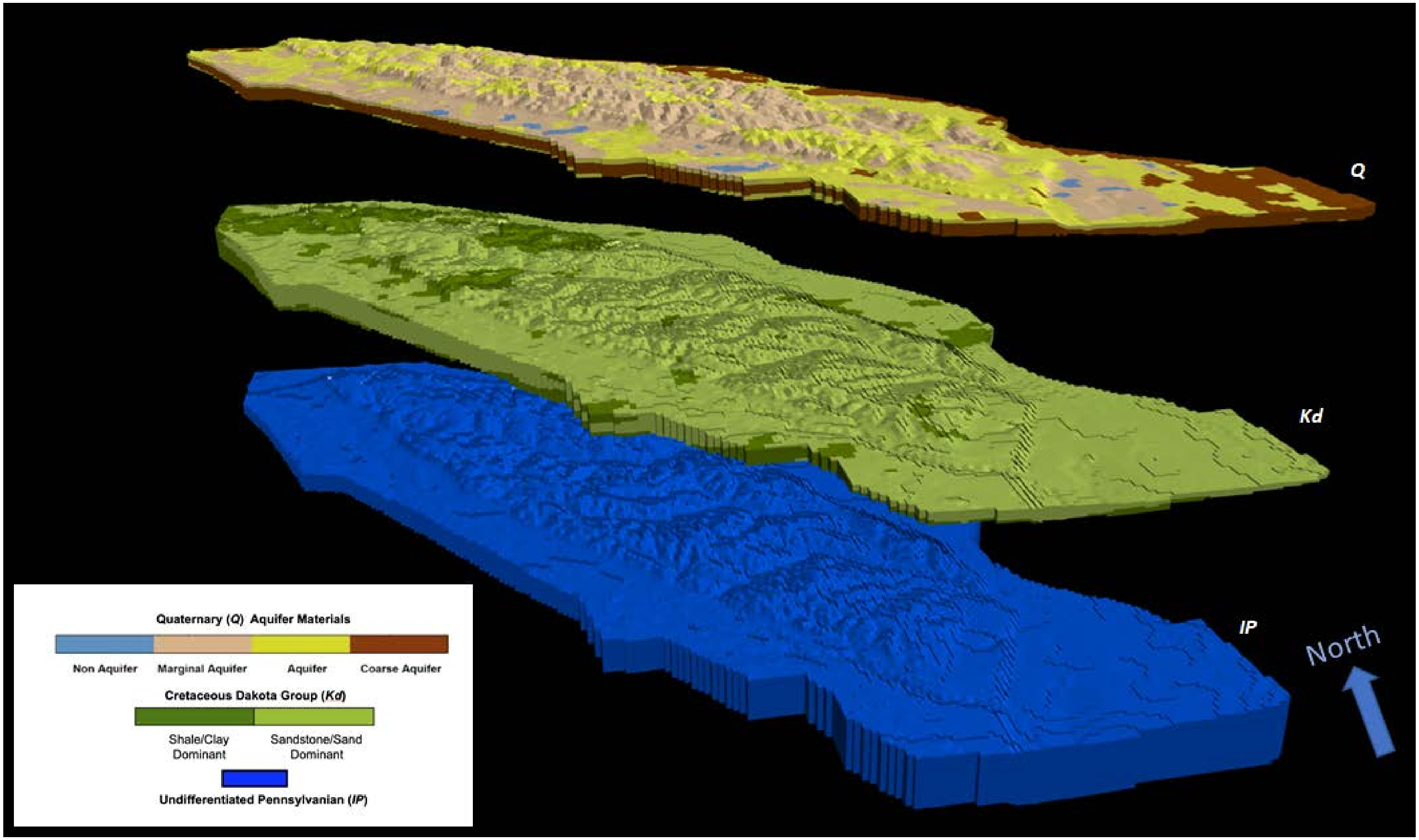


Figure 3-67. 'Exploded' voxel model of the aquifer material types for the Leshara Uplands Block: the Quaternary (*Q*), separated from the two types of Cretaceous Dakota Group (*Kd*) separated from the undifferentiated Pennsylvanian (*IP*). Not to scale.

3.1.8 Comparison of Borehole Resistivity Logs to Inverted AEM Resistivity Soundings

Three recent CSD borehole geophysical resistivity logs were selected from the LPNNRD AEM survey area for comparison with the AEM inversions: CSD test holes *02-LPN-15, 03-LPN-15,* and *05-LPN-15*.

Figure 3-68 is a plot of the *02-LPN-15* 16-inch short and the 64-in long normal resistivity log plotted with the inverted AEM resistivities for flight line L504800, which is ~900 feet away. The AEM sounding selected is from the closest point to the location of the borehole geophysical log. The 16-inch and the 64-inch track each other well and indicate relatively little variation away from the borehole. The agreement in the resistivity is generally good. The downhole resistivity logs indicate a slightly higher resistivity overall compared with the AEM. The sand zone around ~50 feet in the ***Q*** is indicated by the AEM but at a lower resistivity than the downhole resistivity logs. The higher resistivity peaks are not well imaged by the AEM which presents a rather broad increase in the resistivity. This encompasses the zones of the claystone in the ***Kd***. The sand zone at ~400 is not detected by the AEM. This also overlaps with the Depth of Investigation (DOI) window of the AEM.

Figure 3-69 presents the 16-inch short normal resistivity log for borehole *03-LPN-15* plotted with the inverted AEM resistivity for flight line L502900 which is located 608 feet from *03-LPN-15* at its closest point. The 64-inch long normal resistivity log for this hole indicated negative resistivity values and was not included due to an obvious malfunction. The agreement in the resistivity is generally good down to the DOI window of the AEM. The AEM indicates a low resistivity zone at the top of the hole within the ***Q*** and a subdued increase in resistivity in the area of the sand also within the ***Q***. Within the ***Kd***, the AEM and the 16-inch short normal resistivity log match well down to approximately 450 feet.

Figure 3-70 presents the 16-inch short and the 64-in long normal resistivity logs for borehole *05-LPN-15* plotted with the inverted AEM resistivities for flight line L504800, which is ~734 feet away.

The 16-inch short normal log and the 64-in long normal resistivity log indicate an abrupt increase in resistivity at ~ 125 feet. These values exceed 100 ohm-m and look suspect compared to the typical response of a resistivity systems within the sediments of eastern Nebraska (Carney et al., 2015a; Carney et al., 2015b). These values are particularly suspect within the ***Kd***. These comparisons indicate that there was a malfunction within the logging system when log 05-LPN-15 was collected and cannot be used in any qualitative, let alone quantitative, manner.

Borehole *02-LPN-15* is presented projected on the 2D inverted AEM resistivity profile sections for flight lines L504800 (Figure 3-71). Again, the resistivity comparison between *02-LPN-15* and the AEM is generally good. Similarly, Figure 3-72 presents inverted AEM resistivities on a 2D profile of flight line L502900 with borehole *03-LPN-15* displaying the 16-inch short normal log overlaid in the center. They compare well. As indicated above the log from *05-LPN-15* does not compare to the AEM (Figure 3-73).

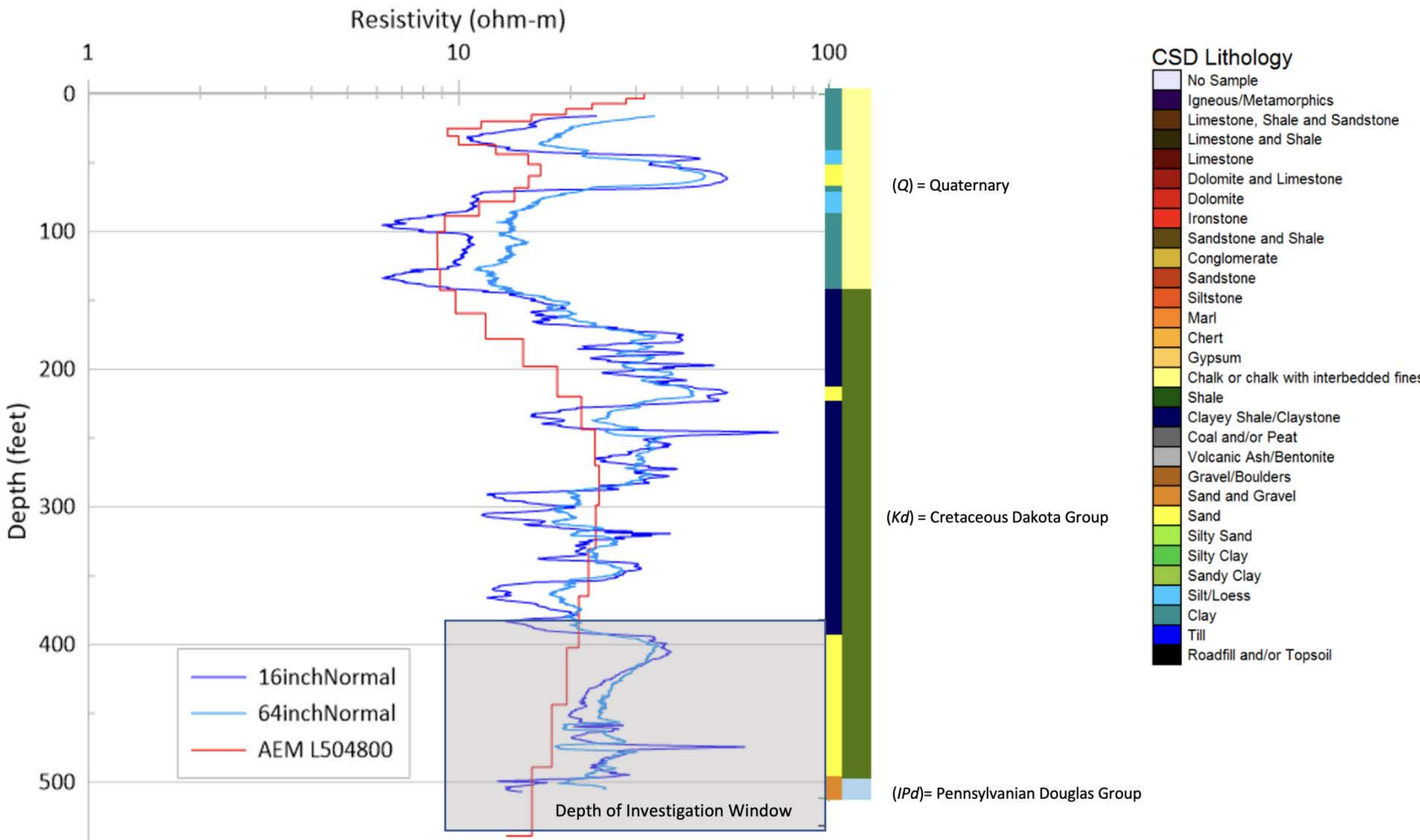


Figure 3-68. Graph of the *02-LPN-15* 16-inch short normal (dark blue line) and 64-inch long normal (light blue line) resistivity logs values and the inverted airborne electromagnetic resistivity values for flight line L504800 (red line). CSD lithology and Stratigraphy are indicated.

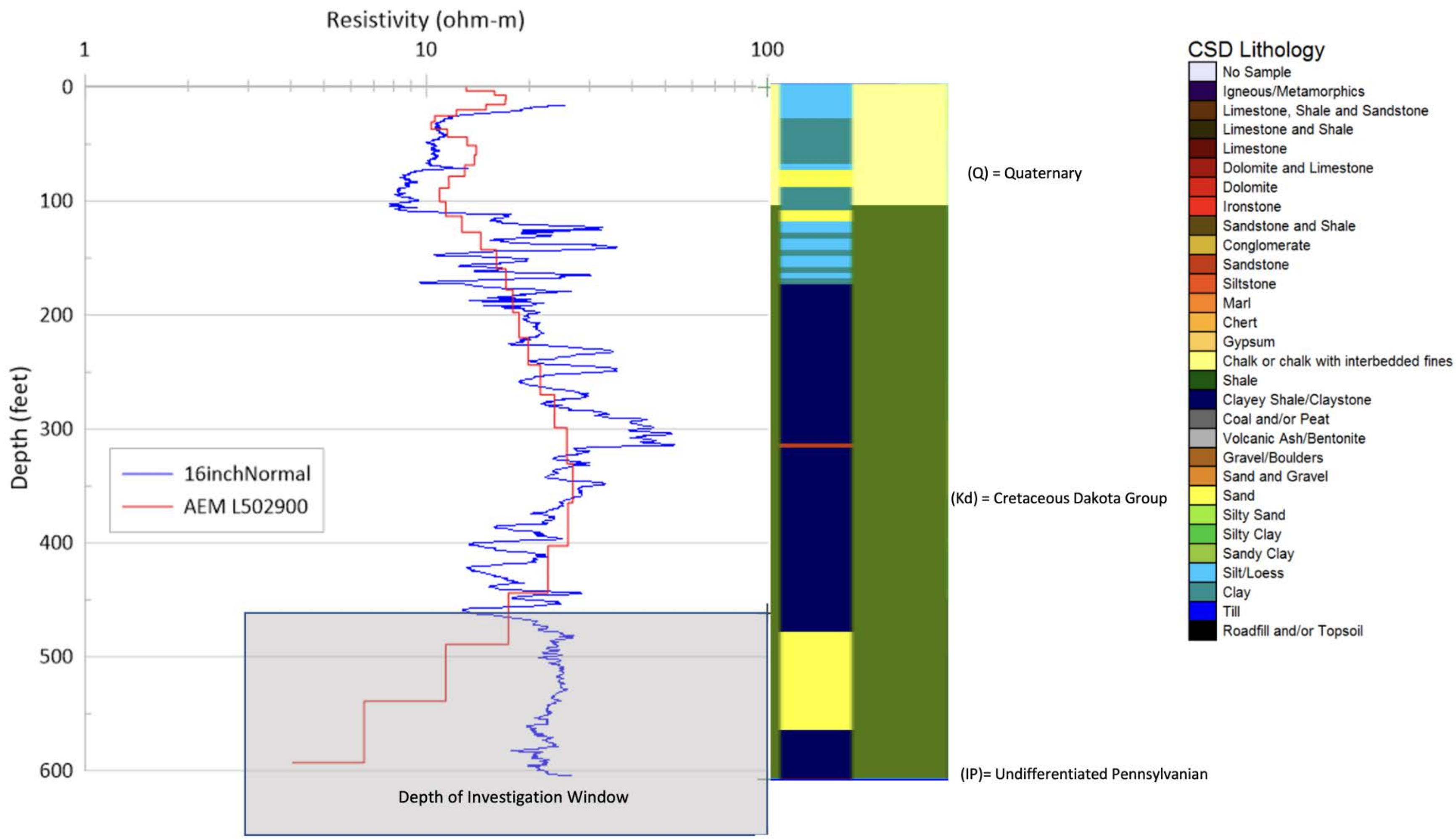


Figure 3-69. Graph of the *03-LPN-15* 16-inch short normal (dark blue line) resistivity log values and the inverted airborne electromagnetic resistivity values for flight line L502900 (red line). CSD lithology and Stratigraphy are indicated.

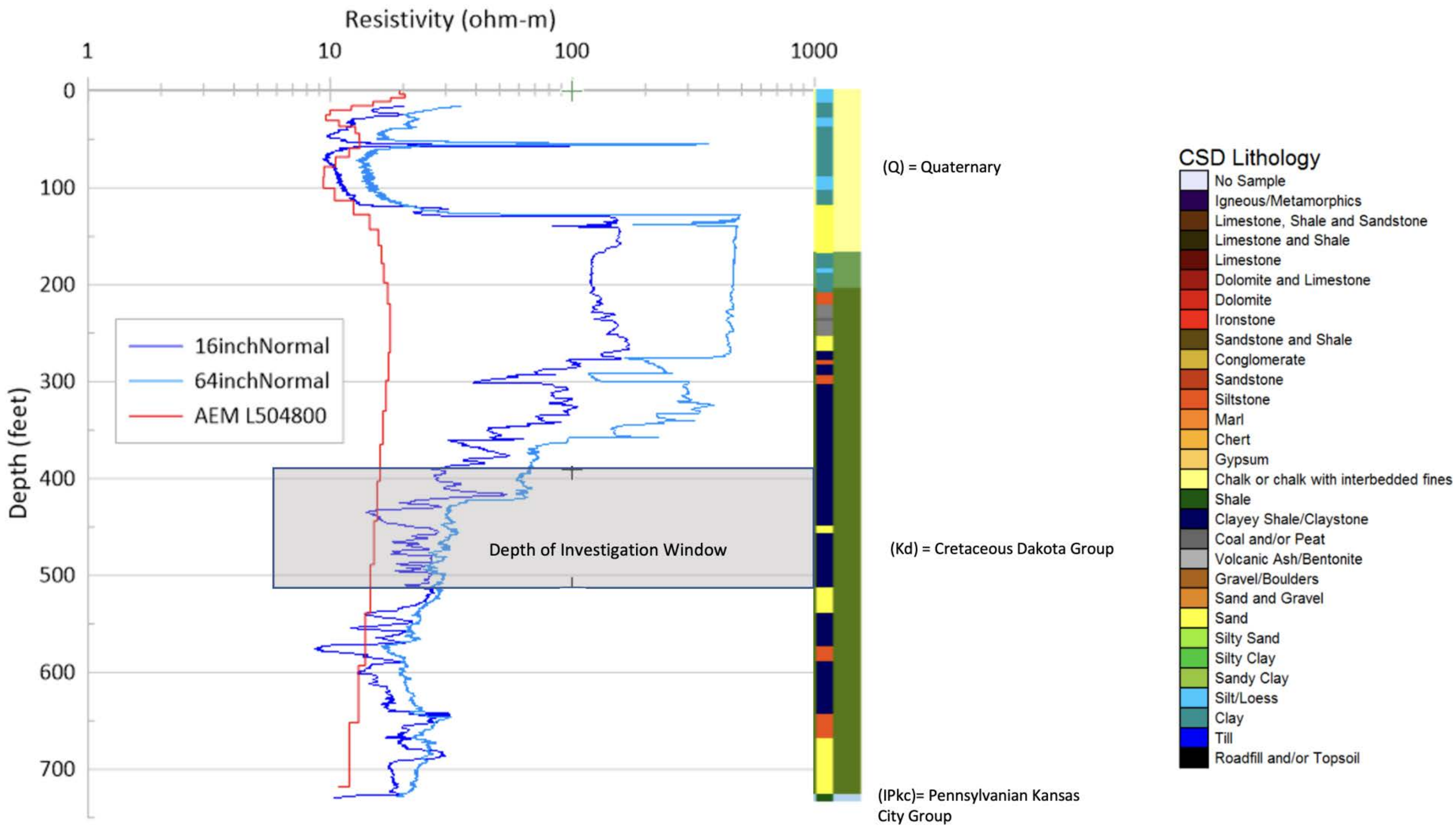


Figure 3-70. Graph of the *05-LPN-15* 16-inch short normal (dark blue line) resistivity log values and the inverted airborne electromagnetic resistivity values for flight line L504800 (red line). CSD lithology and Stratigraphy are indicated.

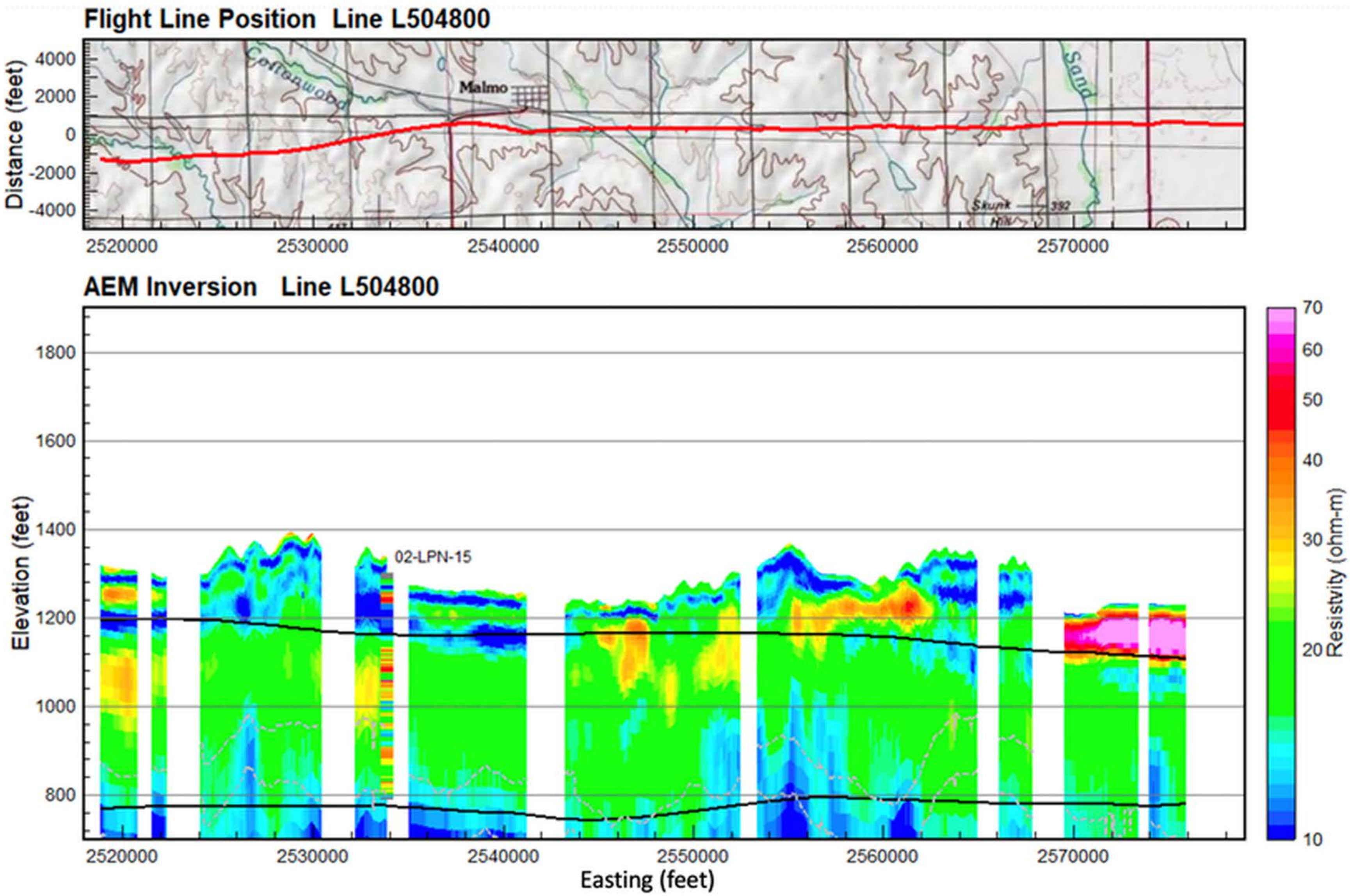


Figure 3-71. Inverted AEM resistivities for flight line L504800 with borehole *02-LPN-15* overlaid on the profile. Horizontal datum is NAD83 State Plane Nebraska (feet).

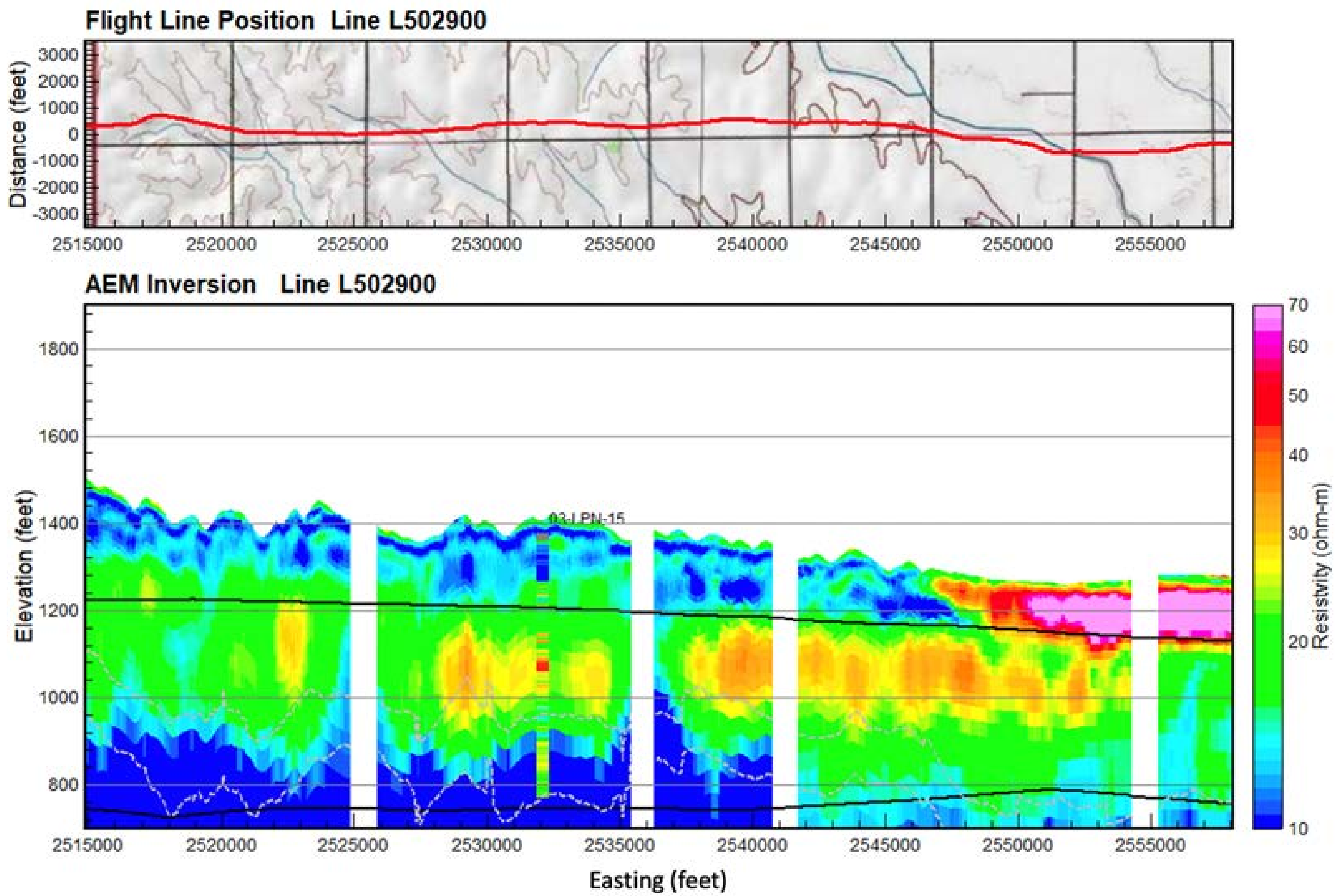


Figure 3-72. Inverted AEM resistivities for flight line L502900 with borehole *03-LPN-15* overlaid in the profile.

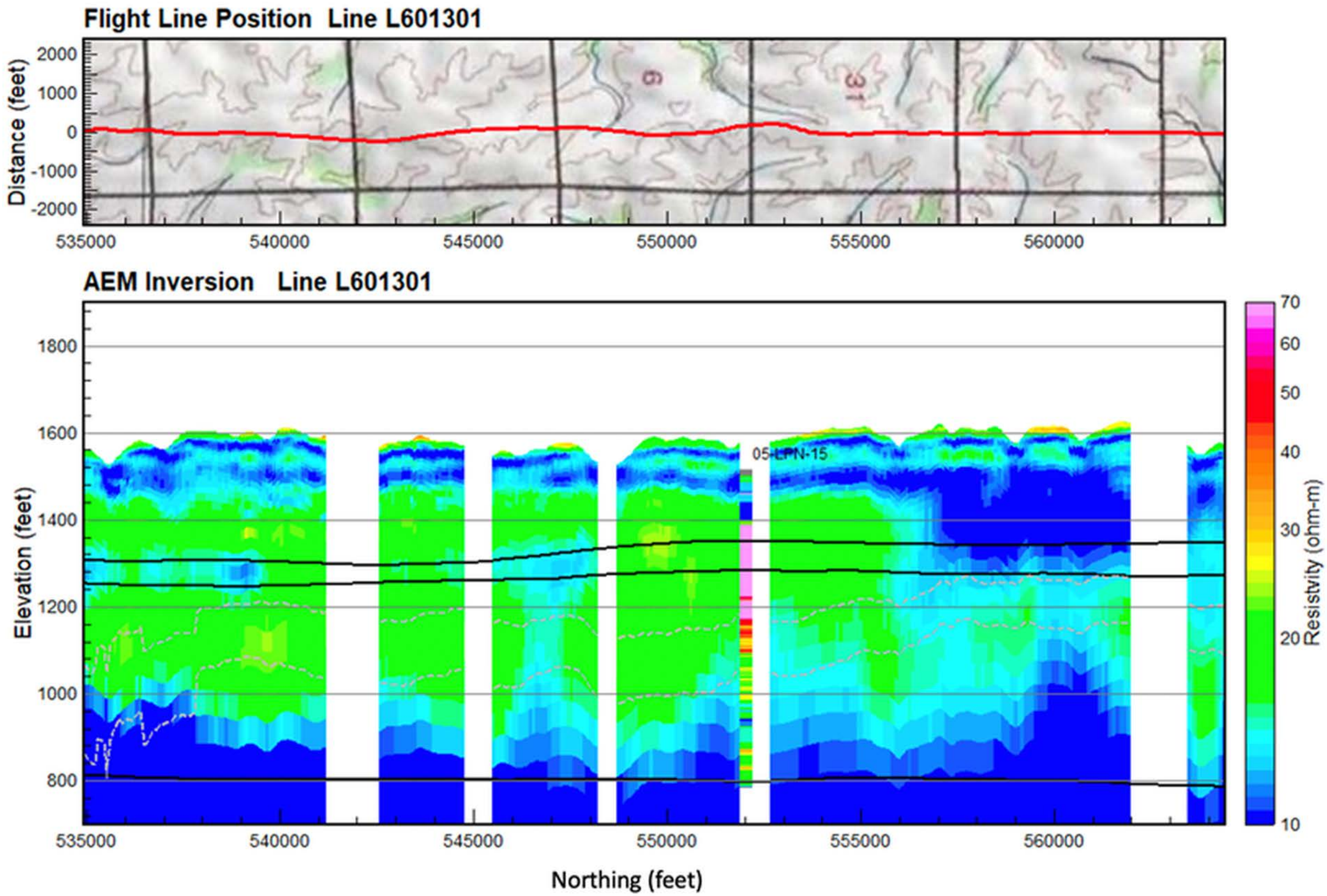


Figure 3-73. Inverted AEM resistivities for flight line L504800 with borehole *05-LPN-15* overlaid in the profile. Note the obvious mismatch between the AEM earth model and the resistivity log from *05-LPN-15*.

3.2 Hydrogeological Framework of the LPNNRD 2018 AEM Survey Area

The 2018 survey continues to build upon the previous AEM survey efforts within LPNNRD beginning in 2007 with the Ashland survey (Smith et al., 2008) and continuing into 2016 with the AEM surveys of Special Quantity Subareas (SQS) SQS1 and SQS2 (AGF, 2017). These AEM-derived results provide new information on the hydrogeology in areas that was previously unknown to the LPNNRD or were only known to a limited extent from just the borehole information. The survey completed in 2018 by AGF provides the basis for this section of the report. The following highlights the additions to the current multi-year project being conducted by the LPNNRD and ENWRA.

3.2.1 The Hydrogeologic Framework of the LPNNRD AEM Survey Area

The hydrogeologic framework for entire LPNNRD survey area will be described first, then the block areas in the following order: Leshara Upland, SQS1, SQS2, and Waann. The AEM reveals the variability in the Quaternary, Tertiary, and Cretaceous deposits which make up the aquifers across the AEM survey area. For purposes of this section the ***Q, To***, 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 alluvial deposits related to the current drainages. The dominant hydrogeologic features that are in the LPNNRD 2018 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. The ***To*** found in the northwest corner of the project area deposits are a mix of all aquifer materials. The ***Kd*** Sandstone/ Sand Dominant deposits are considered bedrock aquifers. Figure 3-74 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 3-75 is the total ***Q*** thickness containing all interpreted non-aquifer, marginal aquifer, aquifer, and coarse aquifer materials. Figure 3-76 shows the total ***Kd*** thickness including the Shale/Clay Dominant and Sandstone/Sand Dominant materials.

Examining the 3D fence diagrams provides a spatial understanding of the distribution of aquifer materials within the LPNNRD 2018 AEM survey area. Figure 3-77 is a 3D fence diagram looking to the southwest. The figure includes the surface of the undifferentiated Pennsylvanian (***IP***) as well as some of the major streams and towns. The AEM aquifer material classifications illuminate the areas of the ***Q*** which covers the survey area and ***To*** which is only in far northwest corner making up the main aquifers 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 part of the survey area. The boreholes also provide additional evidence as the area of sand and sand/gravel are shown as yellow and brown respectively. In areas where there are no paleochannels or alluvial channels, the dominate aquifer material type is marginal (tan areas). ***Q*** non-aquifer materials and ***Kd*** Shale/Clay Dominant materials do exist in the area. These areas have few to no boreholes completed in them.

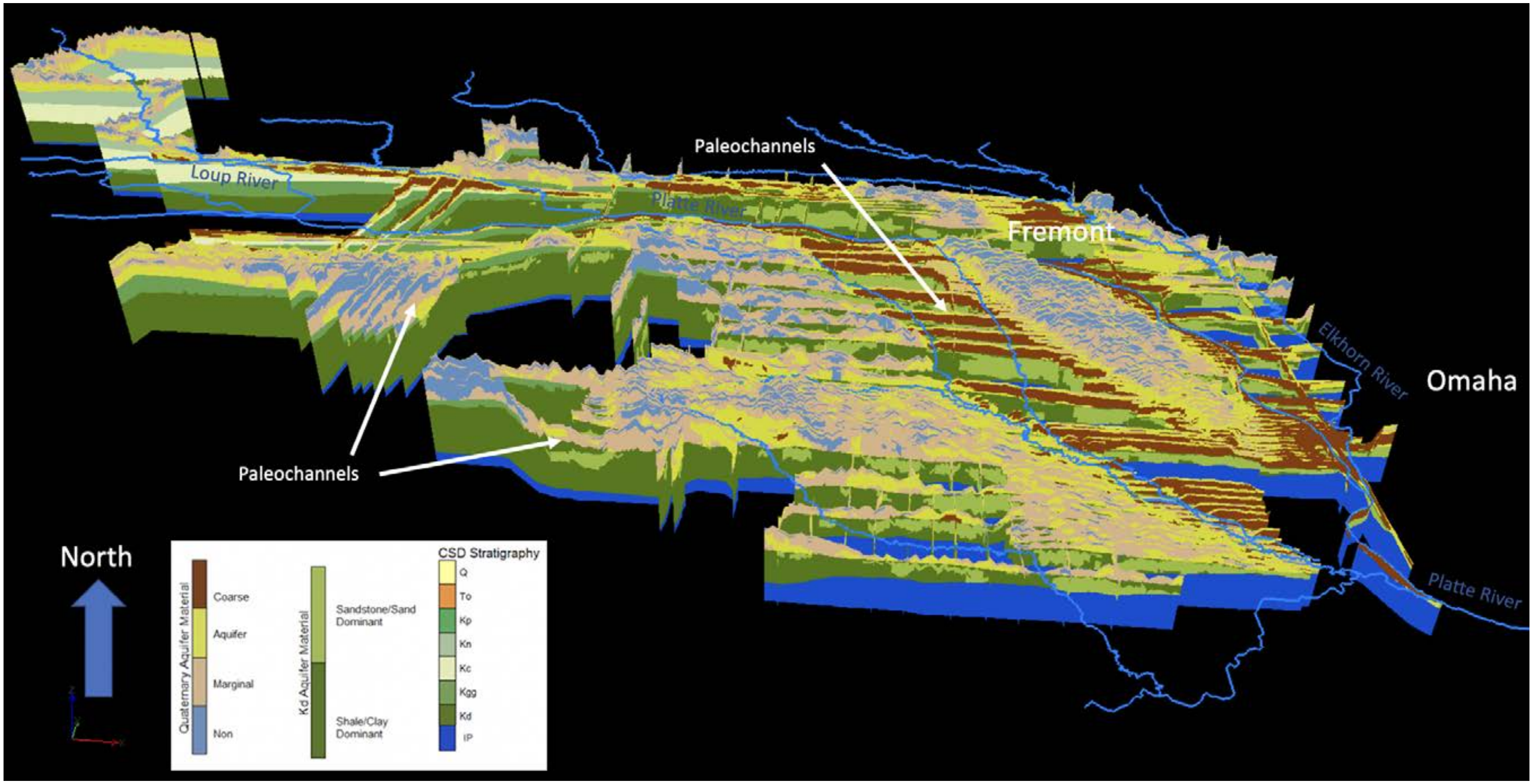


Figure 3-74. 3D fence diagram of the LPNNRD 2018 lines looking north showing Quaternary aquifer materials. Note the highlighted paleochannels across the project area. Cretaceous units are colored in shades of green. Dark green is Shale/Clay Dominant and light green is Sand/Sandstone Dominant units of the Cretaceous Dakota. The blue area in the fence diagrams is the undifferentiated Pennsylvanian. *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) = 25x.

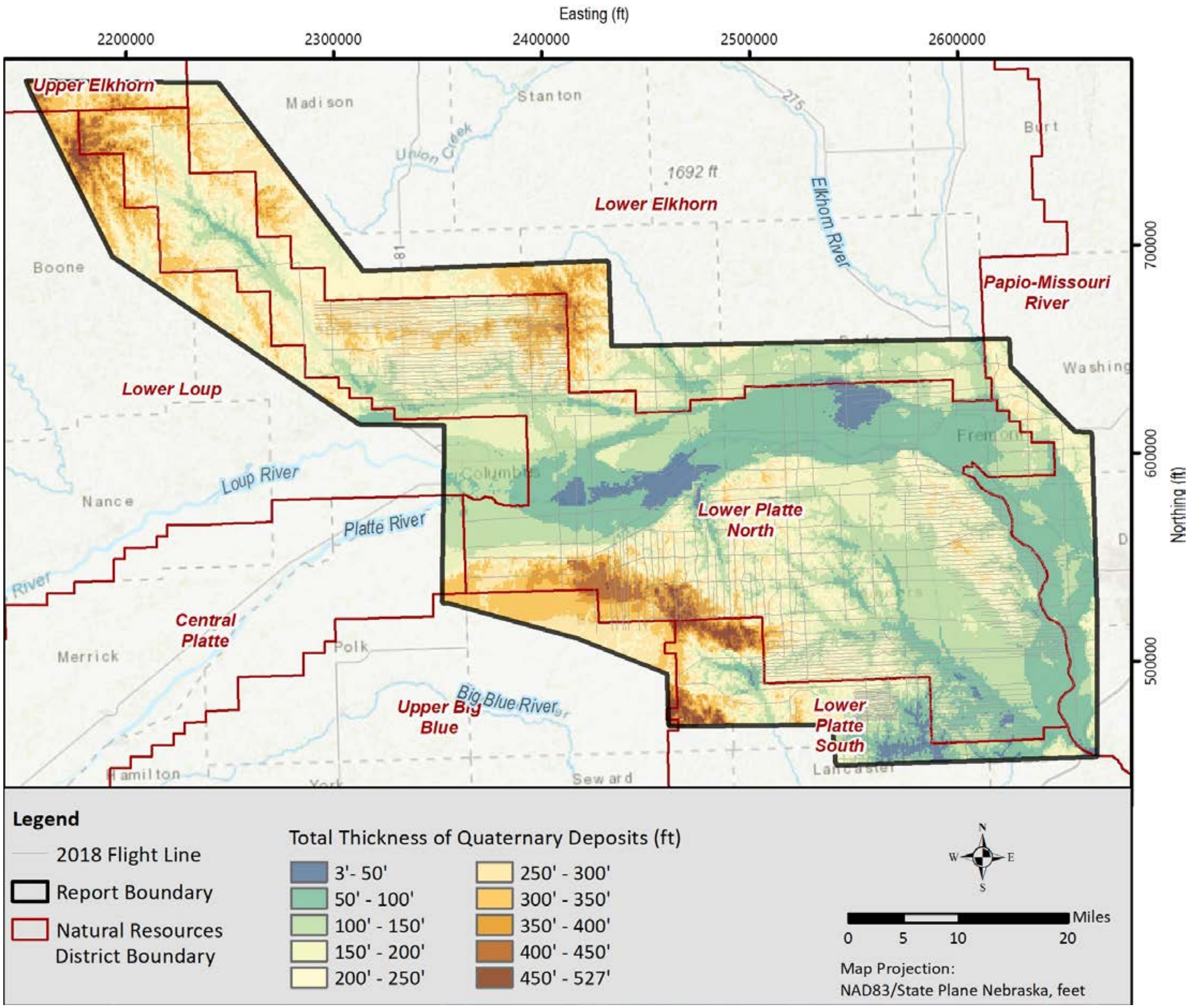


Figure 3-75. Map of the total Quaternary thickness of the AEM aquifer material thickness LPNNRD2018 survey area.

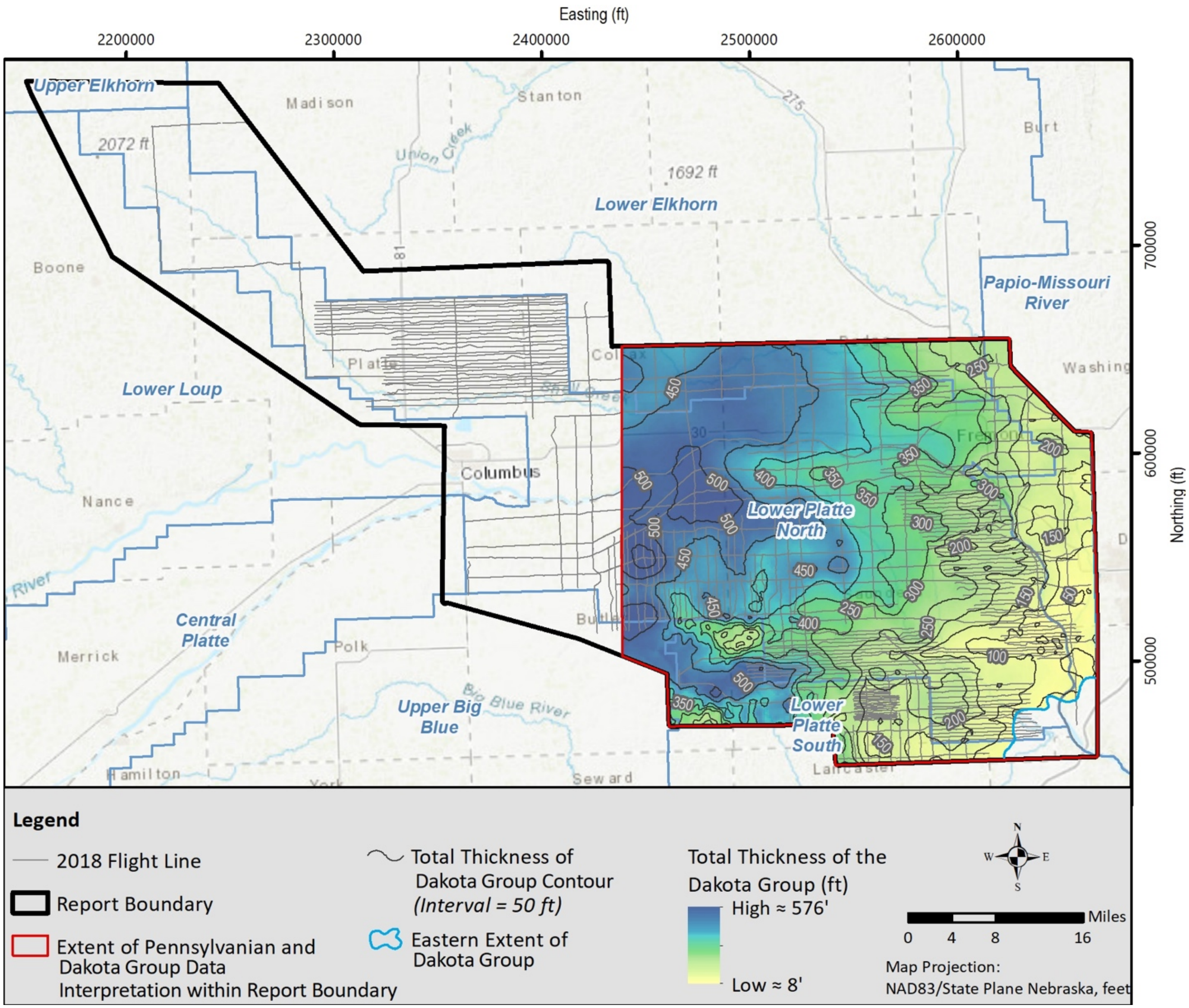


Figure 3-76. Map of the total thickness of the Cretaceous Dakota Group including the Shale/Clay dominant and sand/sandstone dominant units.

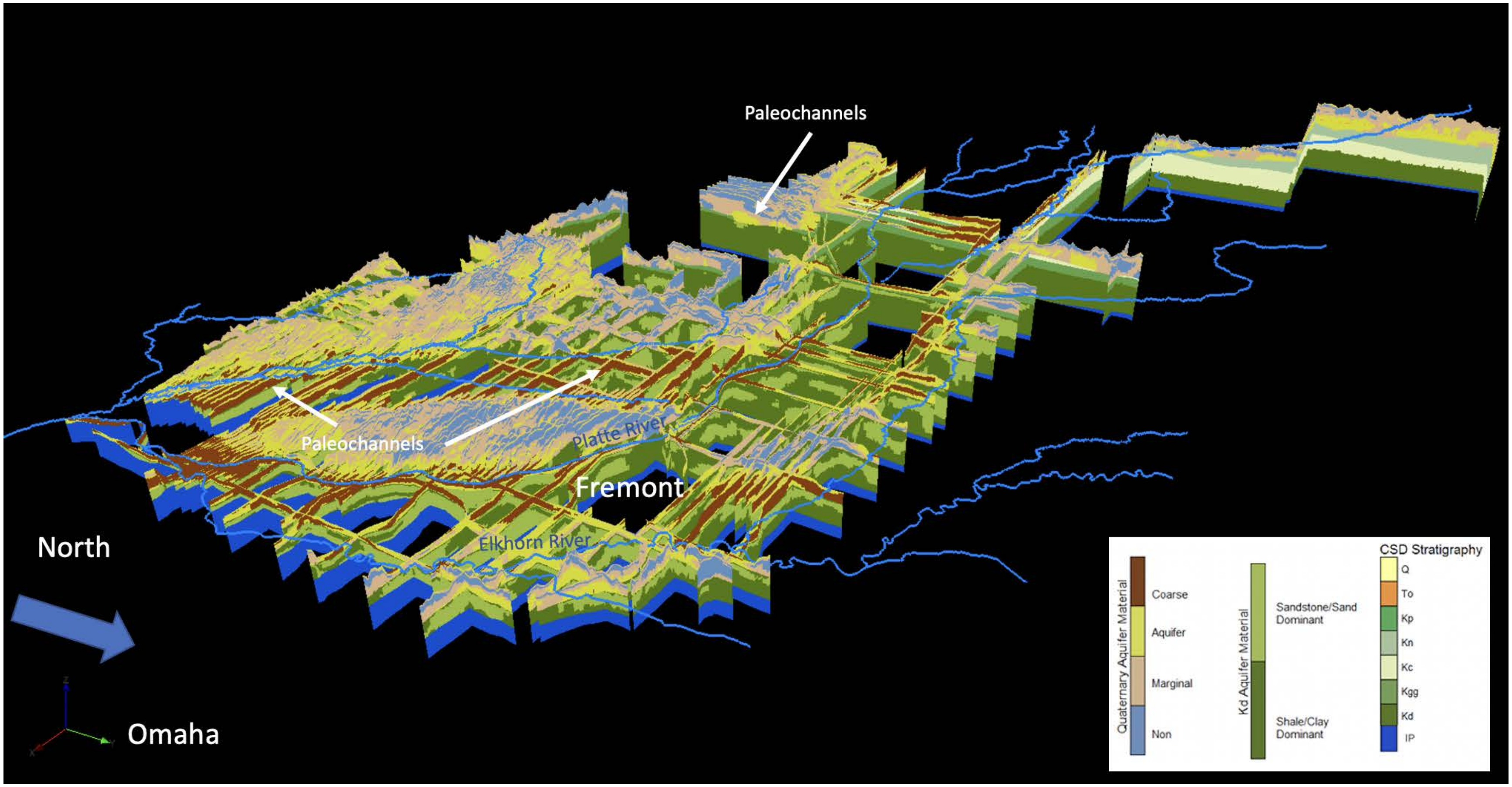


Figure 3-77. 3D fence diagram of the 2018 LPNNRD AEM survey looking southwest showing Quaternary aquifer materials. Note the highlighted paleochannels across the project area. Cretaceous units are colored in shades of green. Dark green is shale/clay dominant and light green is sand/sandstone dominant units of the Cretaceous Dakota. Blue area in the fence diagrams is the undifferentiated Pennsylvanian. *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. VE = 25x.

It is important to note that the marginal aquifer 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 L504500 (Figure 3-78) is oriented west to east across the Todd Valley, east of the town of Valley, Nebraska in the eastern portion of the LPNNRD 2018 survey area and illustrates the discrete nature of the paleochannel deposits. In the western end of Line L504500 a paleochannel is detected by the AEM as well as by NE-DNR registered wells and CSD test holes. Note the transition from the from the Rolling Uplands to the Todd Valley and then back to Rolling Uplands continuing to the transition to the Platte River Valley. This aquifer geometry provides for sharp flow boundaries within the aquifer system. Note the elevation change from Todd Valley (~1,200-foot elevation) in the west to the Platte River Valley in the east (~1,100-foot elevation). The base of both the Todd Valley paleochannel and alluvial channel deposits of the Platte River lies in direct contact with the ***Kd***. The ***Kd*** bedrock surface slopes from ~1,200 feet in the west to ~1,000 feet in the east. Where the ***Q*** coarse aquifer, aquifer and marginal aquifer overlie the ***Kd*** sandstone/sand dominant materials you have hydrologic connection between the ***Q*** and ***Kd***. This connection includes recharge from land surface through the ***Q*** down into the ***Kd***.

North-south line L1004000 (Figure 3-79), north of David City, Nebraska displays the Platte River channel system in the center portion of the line. These deposits are flanked to the north and south by dissected hills made up of glacial outwash deposits capped by loess (Young et al., 2011). The transition from the hills to the Platte Valley is sharp on the south side but is not as sharp to the north. Beneath the south upland is a paleovalley with a thickness of ~400 ft that includes sand deposits of aquifer material that are embedded in marginal and non-aquifer material. The sediment package that makes up the valley fill of the Platte River valley is thin near the river (~20 ft) and is also made up of coarse aquifer, aquifer, marginal aquifer, and non-aquifer materials. Near the valley sides, the sediments thicken to ~100 feet to the south and ~120 feet to the north near a terrace deposit. North of the valley the dissected rolling hills are similar to those of the south upland composed of all aquifer materials and are glacial outwash covered in loess.

East-west line L160000 (Figure 3-80) lies in the Platte River channel and follows the boundary between Colfax and Butler counties. The Platte River flood plain varies in elevation from ~1,380 feet in the west to ~1,280 feet in the east near School Island. The ***Q*** sediments which average ~20-80 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 ***Kgg*** and ***Kd*** which in turn lie upon the ***IP***. The ***Kgg*** has a poor hydrologic connection due to its material- make up (limestone and shale), but the ***Kd*** sandstone/sand dominant material has strong hydrologic connection to the ***Q*** material on the east end of the profile.

East-west line 700500 (Figure 3-81) goes through the town Wahoo, Nebraska. It starts in the Rolling Uplands and continues east across the Todd Valley and transitions into the Platte River.

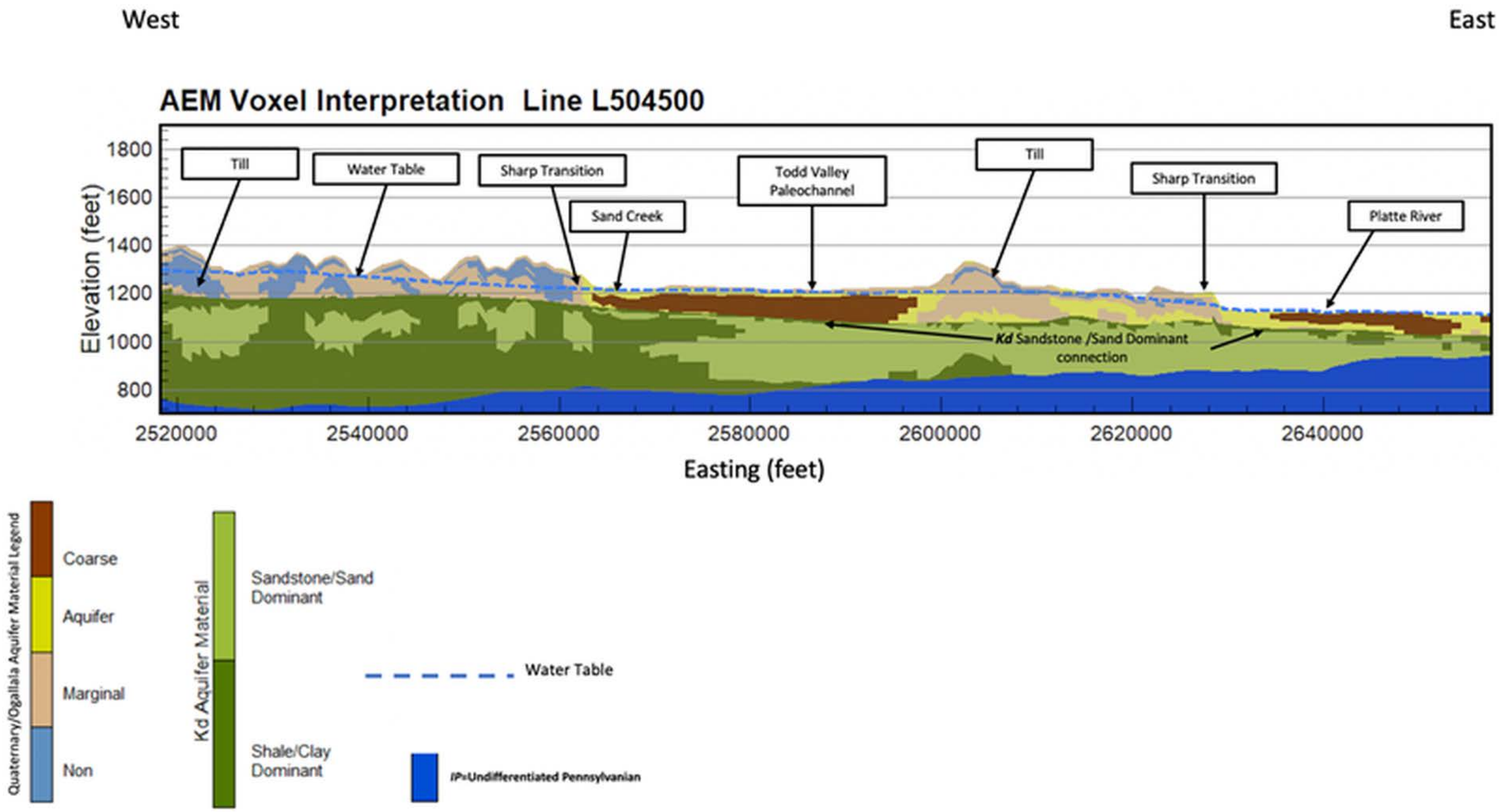


Figure 3-78. East-west line L504500 crosses the Todd Valley east of the town of Valley, Nebraska. The Todd Valley is a major paleochannel that is detected by the AEM as well as by NE-DNR registered wells and CSD test holes. In many areas the Cretaceous Dakota Sandstone/Sand Dominant materials are in connection with the Quaternary coarse aquifer and aquifer materials. The CSD 1995 water table is indicated with a dashed blue line. Horizontal datum is NAD83 State Plane Nebraska (feet).

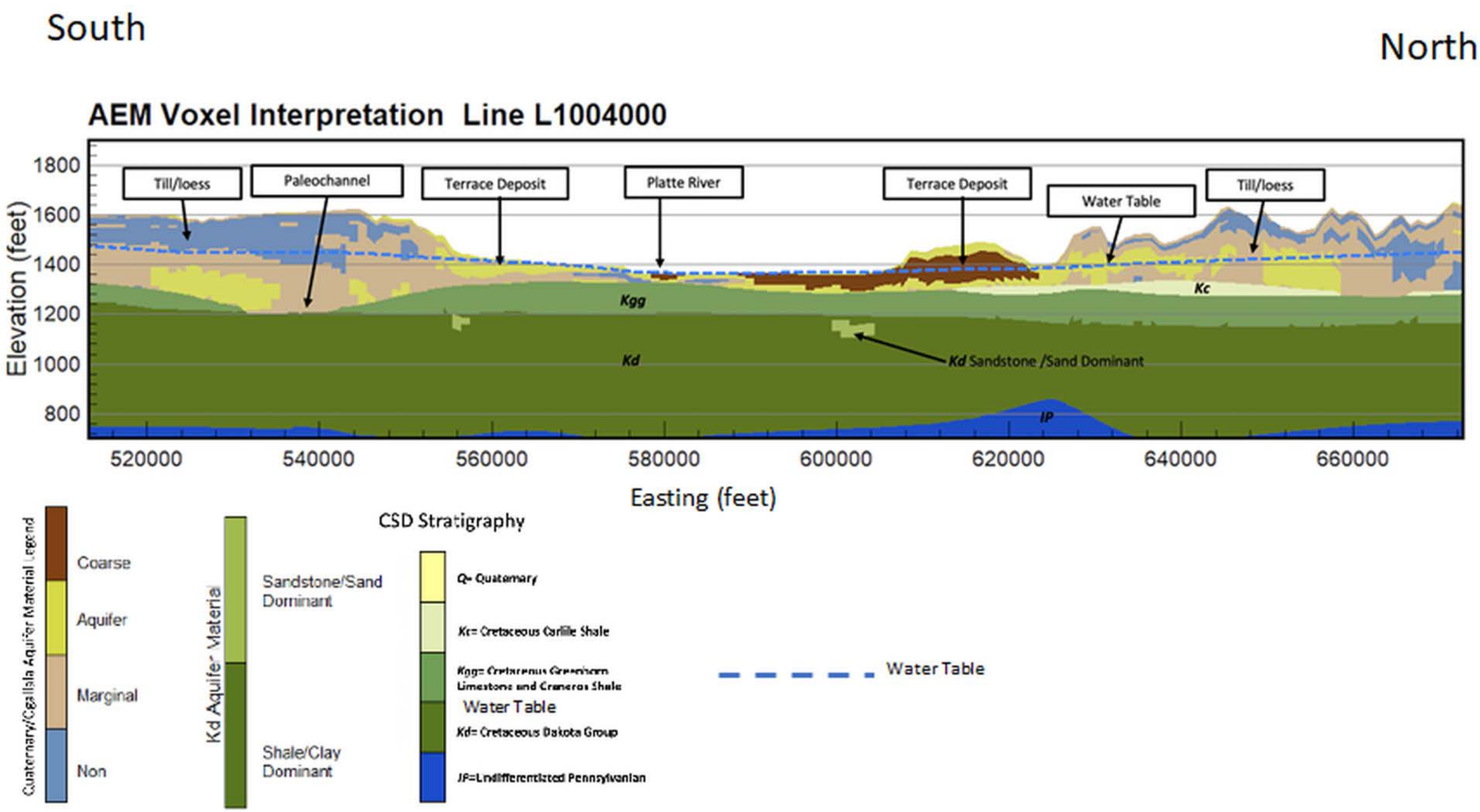


Figure 3-79. North-south line L1004000 north of David City, Nebraska displays the Platte River channel system in the center portion of the line flanked by glacial deposits and loess which make up the sharp transition to the valley floor. Bedrock is Cretaceous Carlile (*Kc*), Cretaceous Greenhorn-Graneros (*Kgg*), and Cretaceous Dakota (*Kd*). 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).

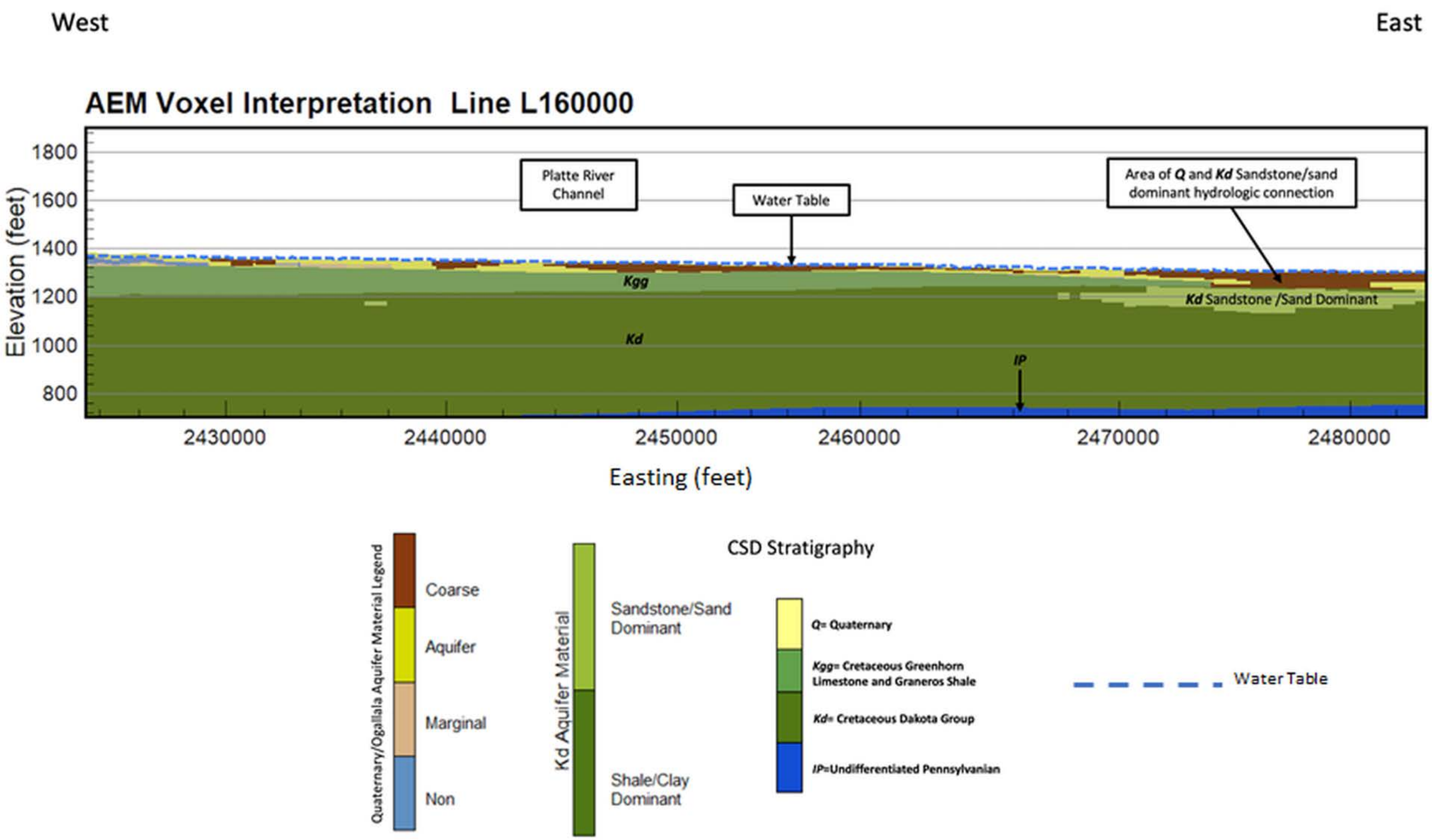


Figure 3-80. East-west line 160000 lies in the Platte River channel and follows the boundary between Colfax and Butler counties. The Quaternary (*Q*) sediments average ~20-80 feet thick in this area and rest upon the Cretaceous Greenhorn-Graneros (*Kgg*) in the west and on the Cretaceous Dakota (*Kd*) in the east. There is poor hydrologic connection with the Quaternary sediments between the *Kgg* and *Kd* in the west and a strong connection with the *Kd* Sandstone/Sand Dominant material in the east. The CSD 1995 water table is indicated with a dashed blue line. Horizontal datum is NAD83 State Plane Nebraska (feet).

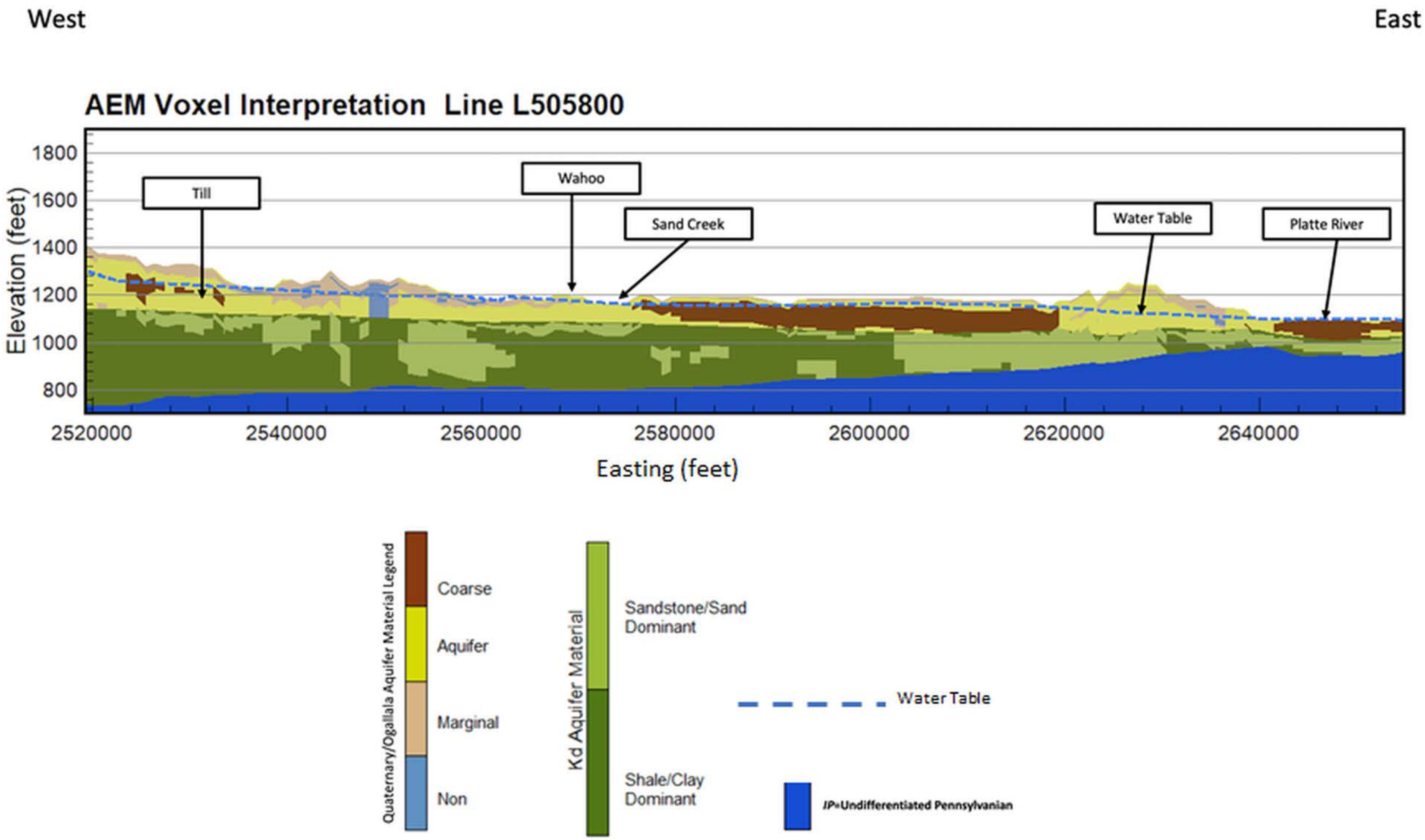


Figure 3-81. East-west line 700500 passes through the town of Wahoo, Nebraska. It starts in the Rolling Uplands continues east across the Todd Valley Paleochannel and transitions into the Platte River Valley. Quaternary (*Q)* sediments lie upon the Cretaceous Dakota (*Kd*) which is composed of a mix of Sandstone/Sand Dominant and Shale/Clay Dominant material and has a strong hydrologic connection where the *Kd* Sand/Sandstone Dominant materials are in contact. The CSD 1995 water table is indicated with a dashed blue line. *Q*= Quaternary, *Kc*= Cretaceous Carlile Shale, *Kgg*= Cretaceous Greenhorn Limestone and Graneros Shale, *Kd*= Cretaceous Dakota Group, *IP*=Undifferentiated Pennsylvanian.

The till in Figure 3-81 lies upon the ***Kd*** which is composed of a mix of Sandstone/Sand Dominant and Shale/Clay Dominant materials under the till which pinches out under the floodplain on the east. Beneath the ***Q*** fill of the flood plain lies the ***Kd***. The ***Kd*** Sandstone/Sand Dominant material has a good hydrologic connection to the overlying ***Q*** materials of the Rolling Uplands, the Todd Valley paleochannel, and the Platte Valley. This connection is strongest in the east where near continuous ***Kd*** Sandstone/Sand Dominant material exists.

Using the interpretive surfaces and grids that were produced as described above (in Section 3.1.3), an enhanced understanding of the hydrogeological framework of the LPNNRD 2018 AEM survey area can be achieved. Referring back to Figure 3-75 which shows the total thickness of all ***Q*** aquifer materials, the ***Q*** alluvial fill in the valleys tend to be thinner than the till 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 thickness can be determined (Figure 3-82), the paleochannel system near the town of Fremont, Nebraska has a thickness of ~100-150 feet and near David City, Nebraska the paleochannel has up to ~400 feet of ***Q*** materials. The paleochannel north of Columbus, Nebraska can have greater than 300 feet of saturated thickness and the paleochannel in the Todd Valley can have ~150-200 feet of saturated thickness.

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 ***Kn.*** The extent of the ***Kn*** top elevation surface is shown in Figure 3-83 and it varies in thickness from 1,304 to 1,578 feet. Note the bedrock high and the channel in the surface. The thickness of the ***Kn*** shown on Figure 3-84 varies from 0 to 313 feet with the greatest thickness in the northwest portion of the study area.

Figure 3-85 presents the elevation of the upper surface of the ***Kc*** which lies below the ***Kn***. The elevation varies from 1,415 to 1,195 feet with the lowest elevation to the northwest. There is a channel in the top surface of the ***Kc*** north of Columbus. The red line on the map shows the easternmost extent of the ***Kc***. Figure 3-86 shows the thickness of the ***Kc*** in the area which varies from 9 to 295 feet and thins from west to east. The thickest section is northwest of Columbus.

Figure 3-87 presents the elevation of the upper surface of the ***Kgg*** which lies below the ***Kc***. The elevation varies from 1,083 feet to 1,390 feet with the lowest elevation to the northwest. There are channels in the top surface of the ***Kgg*** northwest of Columbus and north of David City, Nebraska. The red line on the map shows the easternmost extent of the ***Kgg***. Figure 3-88 shows the thickness of the ***Kgg*** in the area which varies from 0 to 245 feet and thins from east to west. The thickest section is northwest of Columbus, Nebraska.

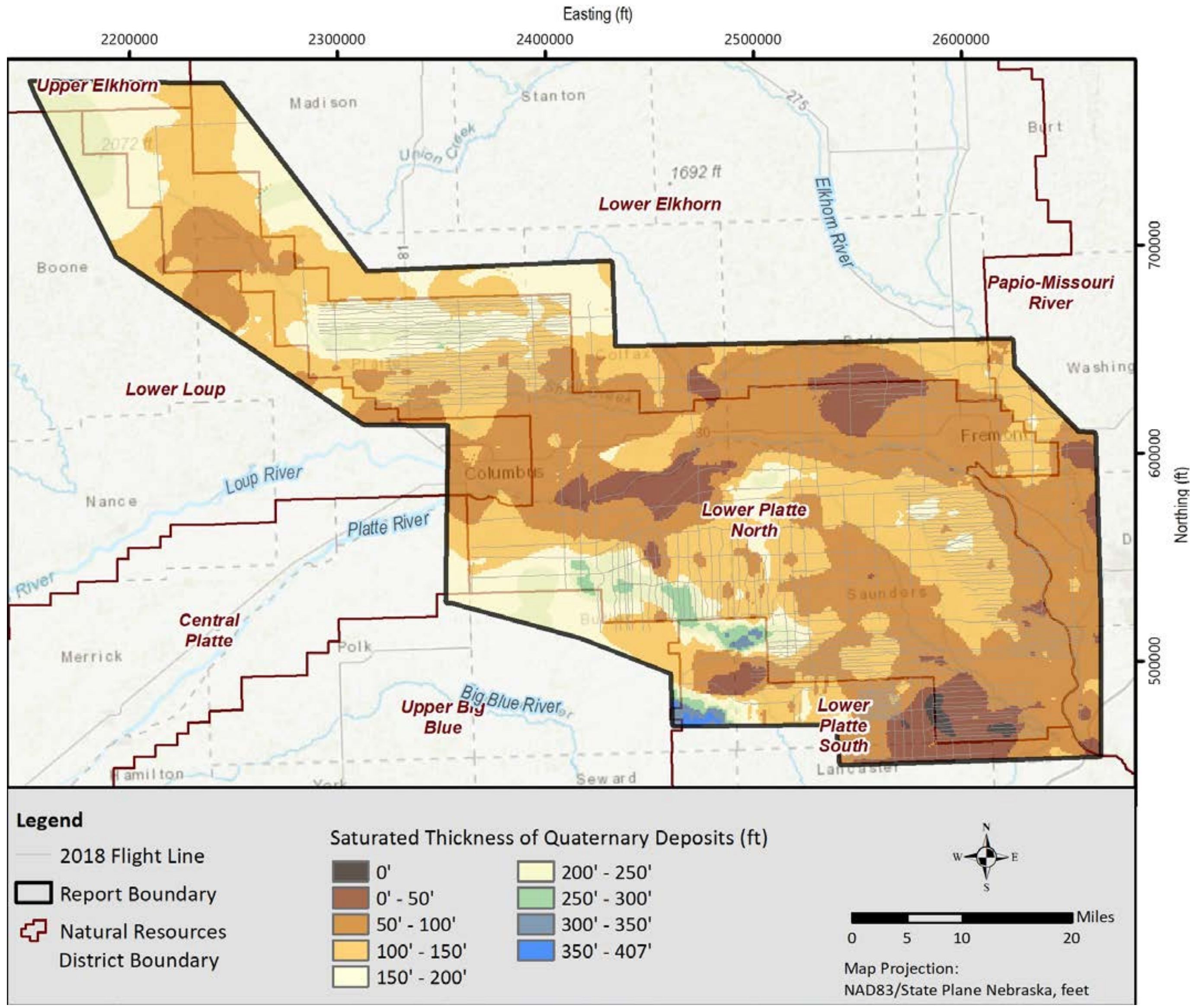


Figure 3-82. Map of the saturated thickness of Quaternary (*Q*) aquifer materials within the 2018 LPNNRD survey area. Saturated thickness varies from 0 to 406 feet. Flight lines are indicated by the grey lines.

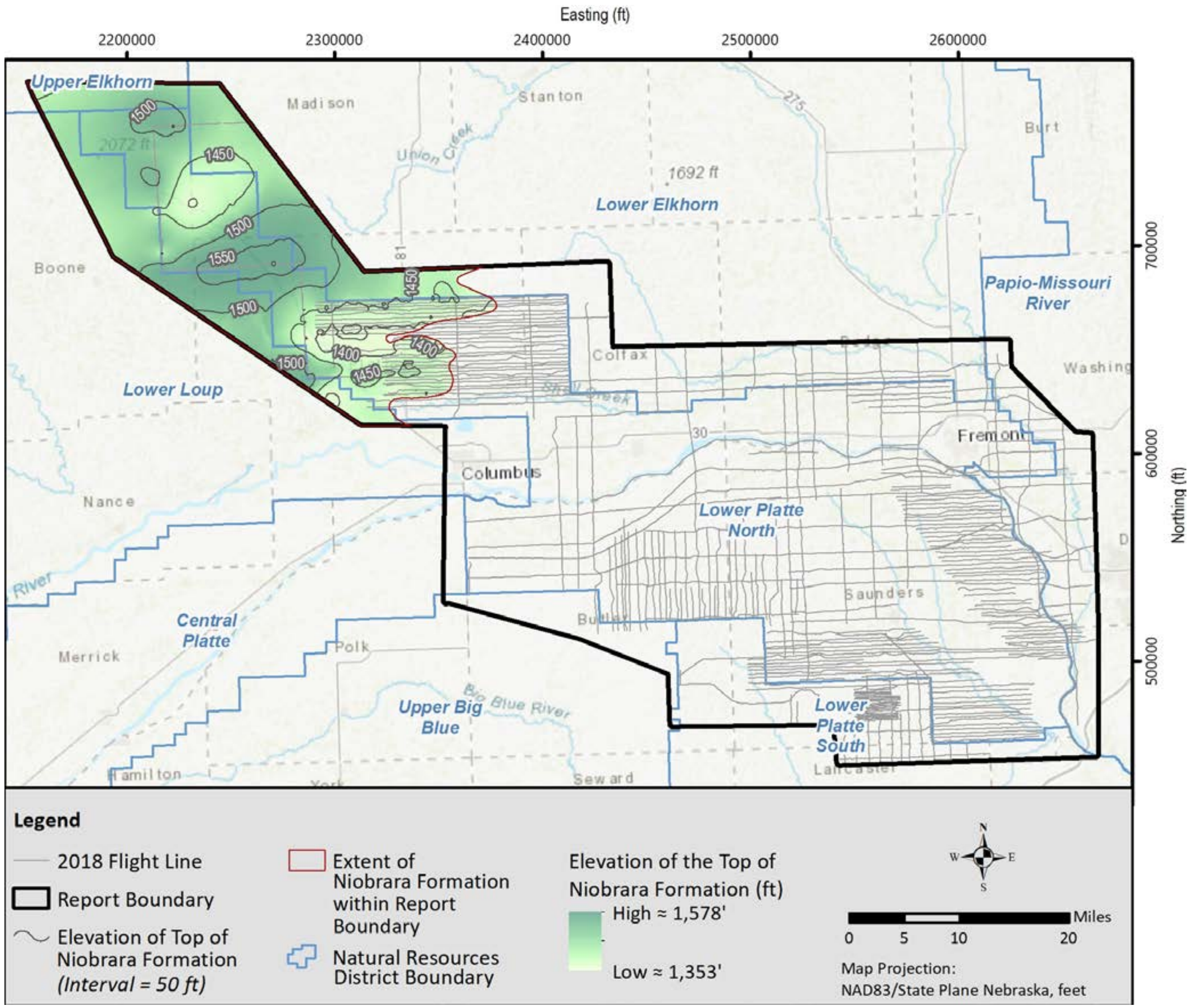


Figure 3-83. Map of the top surface of the Cretaceous Niobrara Formation (*Kn*) within the 2018 LPNNRD AEM survey area. Flight lines are indicated by the grey lines. The *Kn* is only present in the western part of the area and varies in elevation from 1,304 to 1,578 feet from east to west. Note the channel northwest of Columbus, Nebraska.

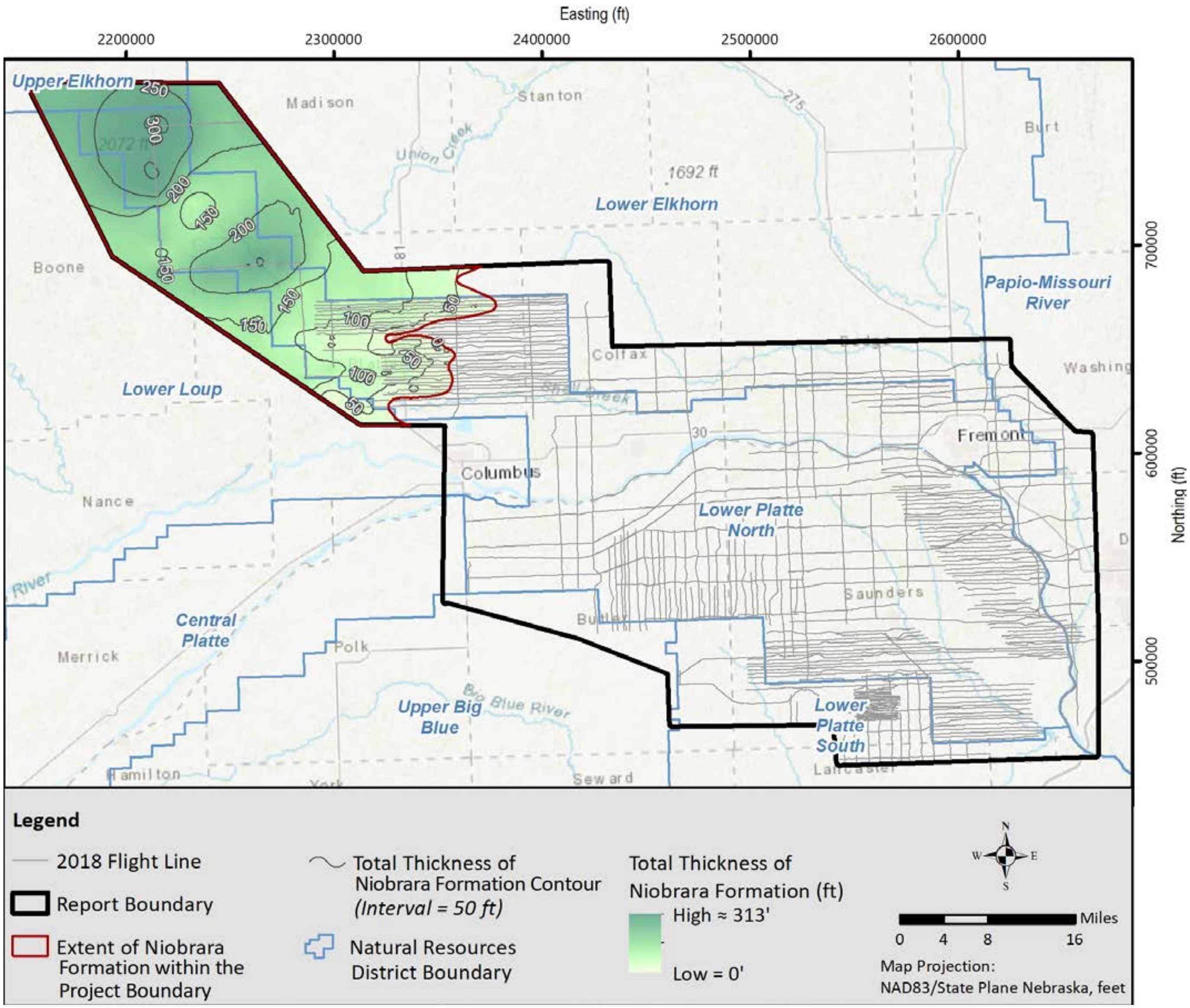


Figure 3-84. Map of the thickness of the Cretaceous Niobrara Formation (*Kn*) within the 2018 LPNNRD AEM survey area. Flight lines are indicated by the grey lines. The thickness varies from 0 to 313 feet from east to west.

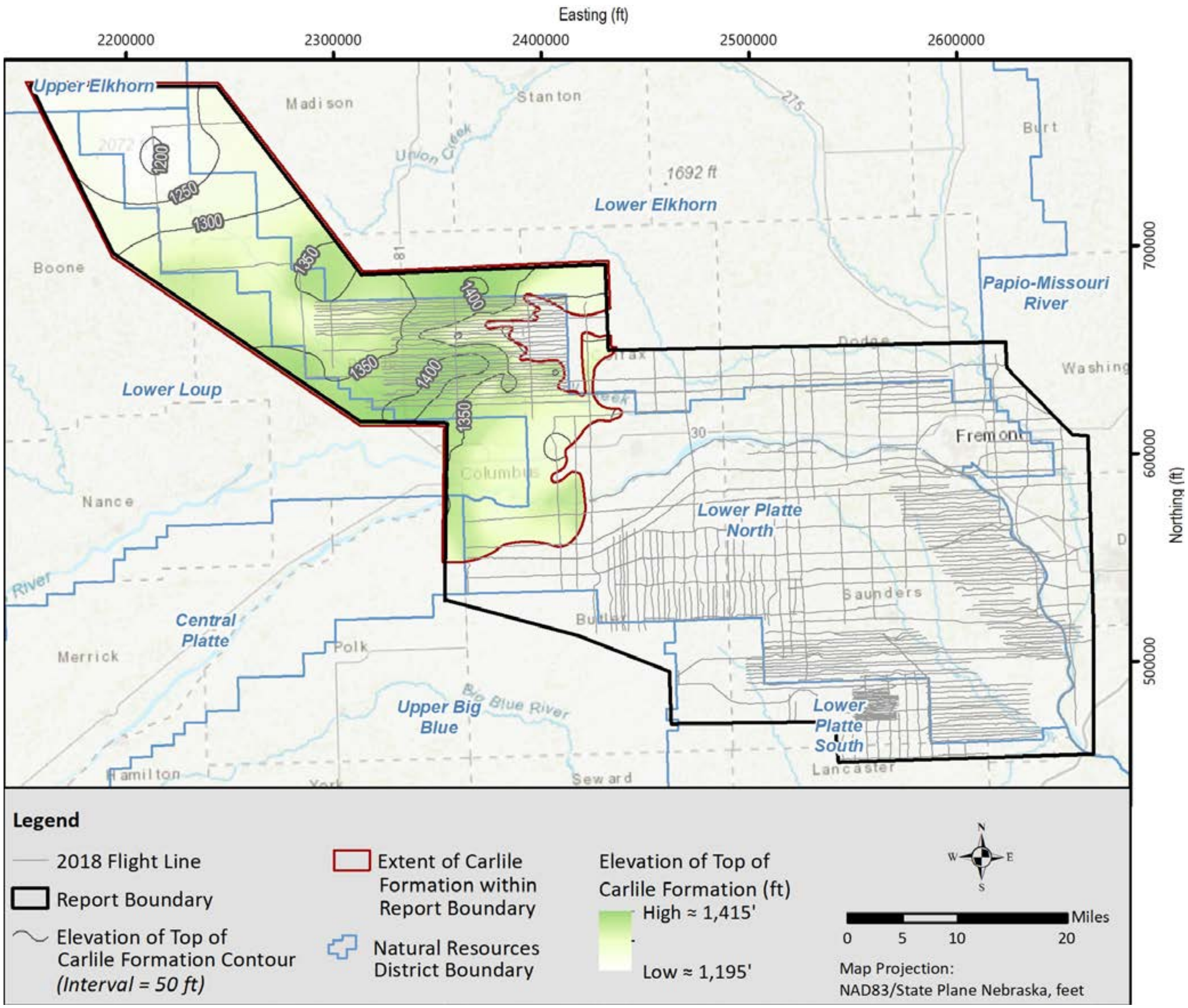


Figure 3-85. Map of the top surface of the Cretaceous Carlile Formation (*Kc*) within the 2018 LPNNRD AEM survey area. Flight lines are indicated by the grey lines. The *Kc* is only present in the western part of the area and varies in elevation from 1,195 to 1,415 feet from east to west. Note the channel northwest of Columbus, Nebraska.

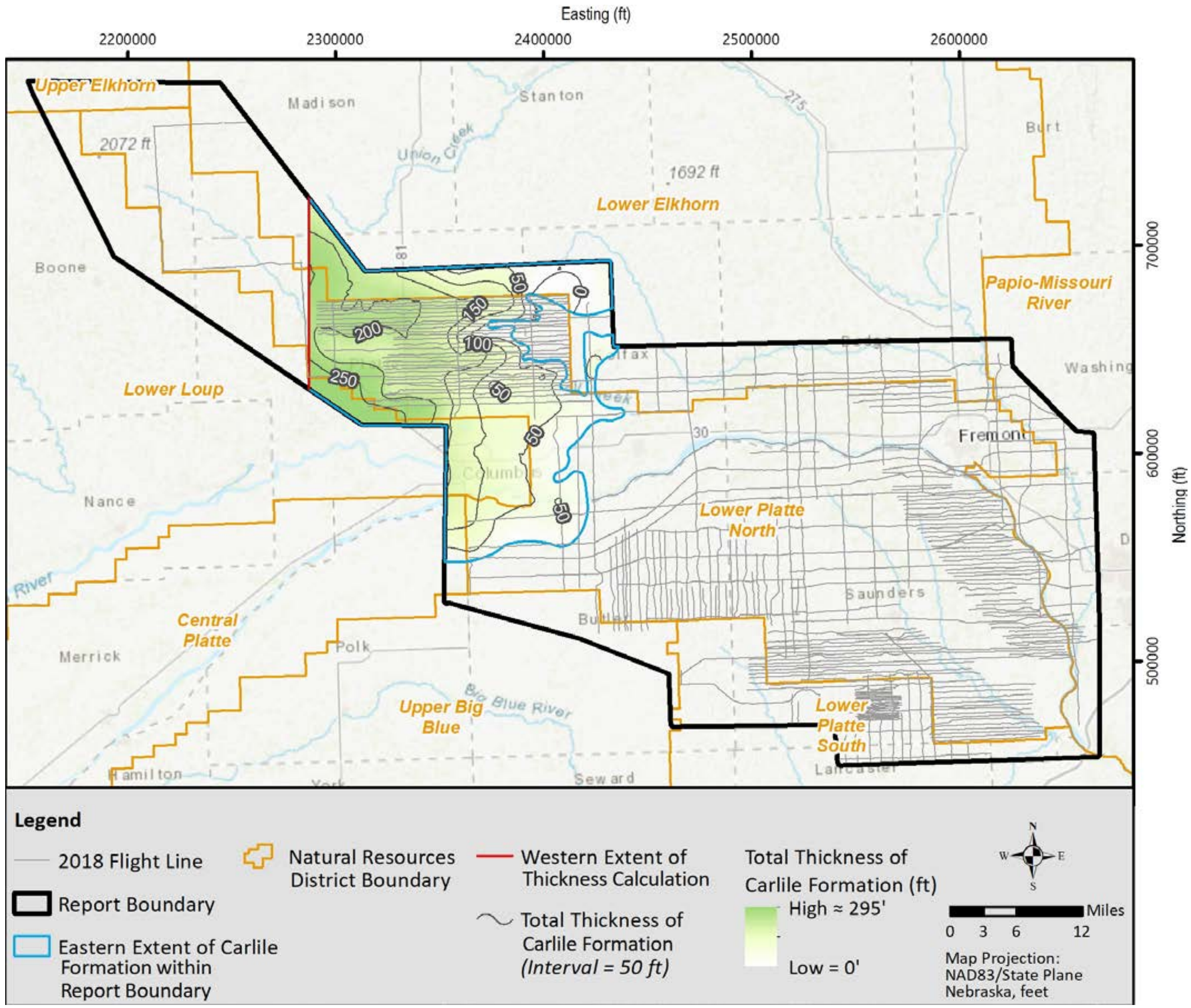


Figure 3-86. Map of the thickness of Cretaceous Carlile Formation (*Kc*) within the 2018 LPNNRD AEM survey area. Flight lines are indicated by the grey lines. The thickness varies from 0 to 295 feet from east to west. Note the channel northwest of Columbus, Nebraska.

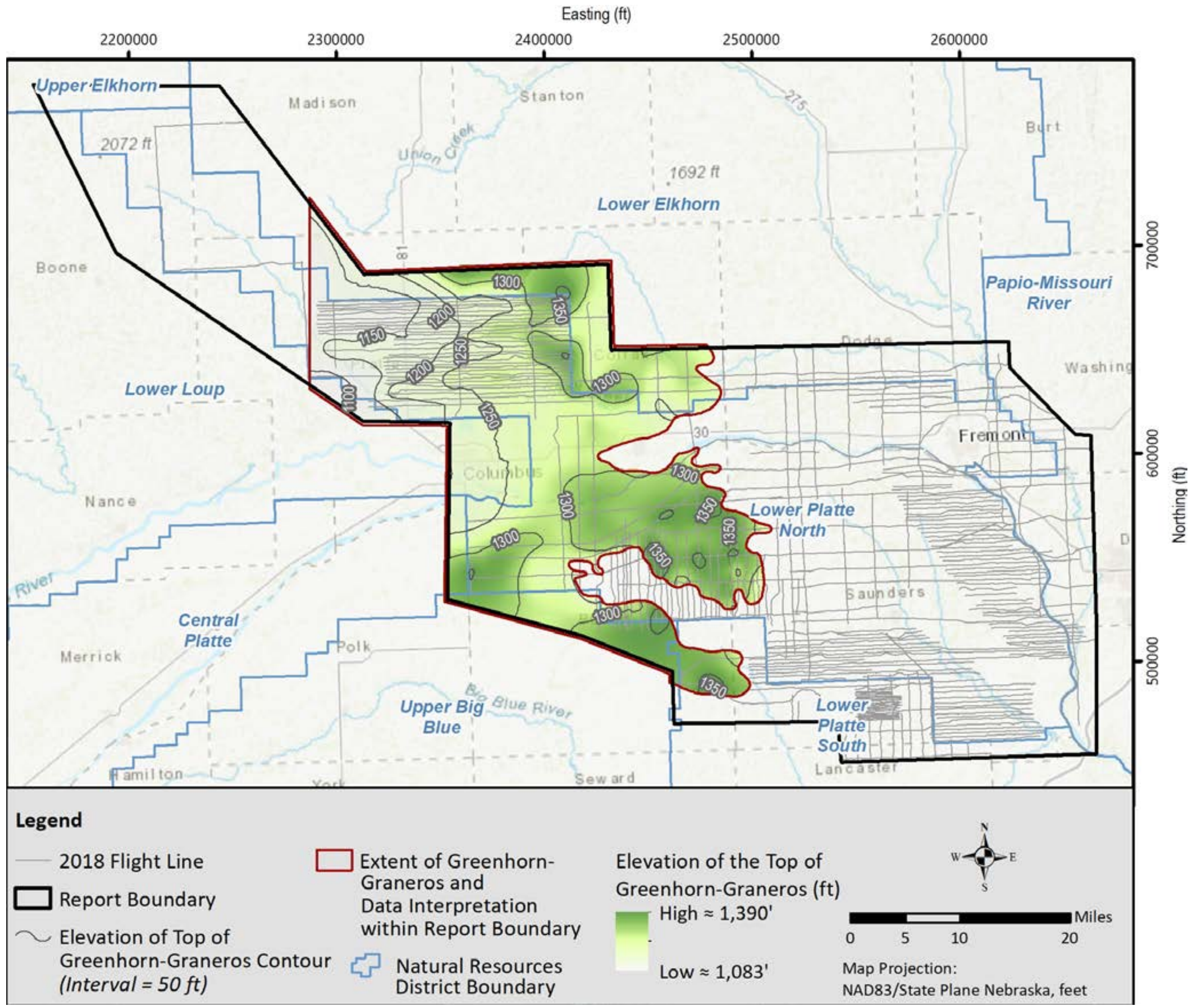


Figure 3-87. Map of the top surface of the of Cretaceous Greenhorn-Graneros Formation (*Kgg*) within the 2018 LPNNRD AEM survey area. Flight lines are indicated by the grey lines. The *Kgg* is only present in the western part of the area and varies in elevation 1,083 to 1,390 feet from east to west. Note the channels near David City, Nebraska.

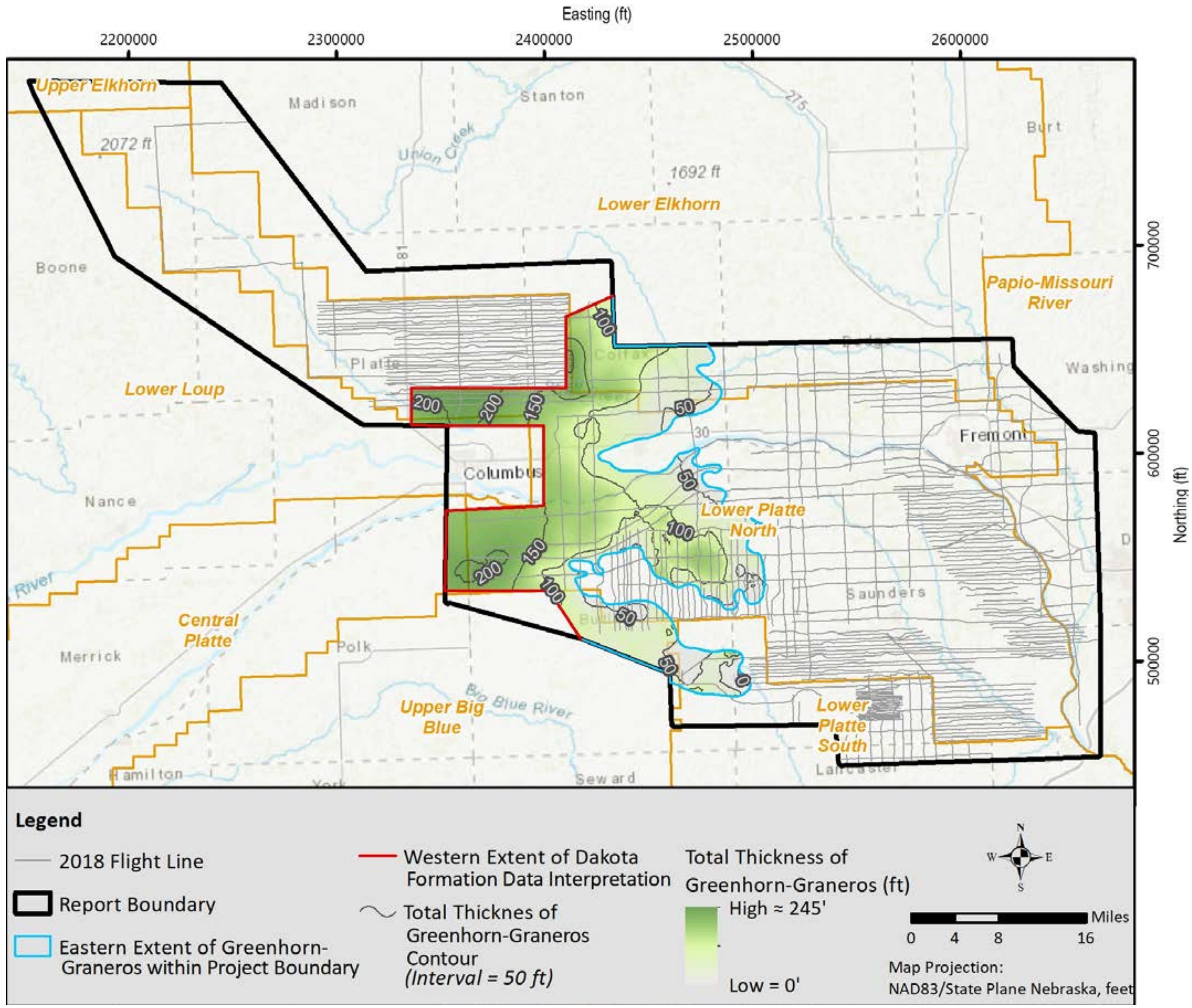


Figure 3-88. Map of the thickness of Cretaceous Greenhorn-Graneros Formation (*Kgg*) within the 2018 LPNNRD survey area. Flight lines are indicated by the grey lines. The thickness varies from 0-245 feet from east to west. Note the channels north of David City, Nebraska.

Figure 3-89 is the elevation of the upper surface of the ***Kd*** which lies below the ***Kgg***. The elevation varies from 977 feet to 1,328 feet with the lowest elevation on the west and east sides of the project area. There are channels in the top surface of the ***Kd*** east of Columbus and David City, Nebraska with bedrock highs in between. The red line on the map shows the easternmost and westernmost extent of the ***Kd***. Figure 3-90 shows the thickness of the ***Kd*** in the area which varies from 8 to 576 feet and thins from west to east. The thickest section is north of David City, Nebraska.

The impact of glaciotectonic features can be observed within the LPNNRD 2018 AEM survey area. As indicated in Section 3.1.3, line L501500 has deposits of aquifer material that are pushed up on the end of a moraine (Figure 3-91). These deposits are similar to the simplified diagrams in Aber and Ber (2011) that show the deposits that are likely found in an area of glacial thrusting. In the 2018 LPNNRD AEM survey area these deposits are found higher up on the moraine than most typical outwash deposits. When saturated these can serve as local aquifers but are discontinuous and limited in extent.

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 Quaternary (**Q**) and the Cretaceous Dakota Group (***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 3-92 is a map of the saturated Quaternary (***Q***) Thickness for the LPNNRD 2018 AEM survey area. The area of the Platte River and the Todd Valley 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 related to the glacial moraine position. To the west, the impact of the Tertiary Ogallala Group (***To***) and the thick alluvial deposits can also be observed.

Figure 3-93 is a map of the thickness of saturated Cretaceous Dakota Group (***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 (as well indicated in Figure 3-74 and Figure 3-75) and their approximate locations throughout the area. The majority of these areas are in the east parts of the LPNNRD with some of the area showing erosion of paleochannel structure to the west. The paleo channels 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 of the ***Kd*** as a way to understand the deposits (Figure 3-94). A 3D fence diagram of only the ***Kd*** including the Sandstone/Sand Dominant and the Shale/Clay Dominant portions sitting on undifferentiated Pennsylvanian (*IP*) is presented in Figure 3-95.

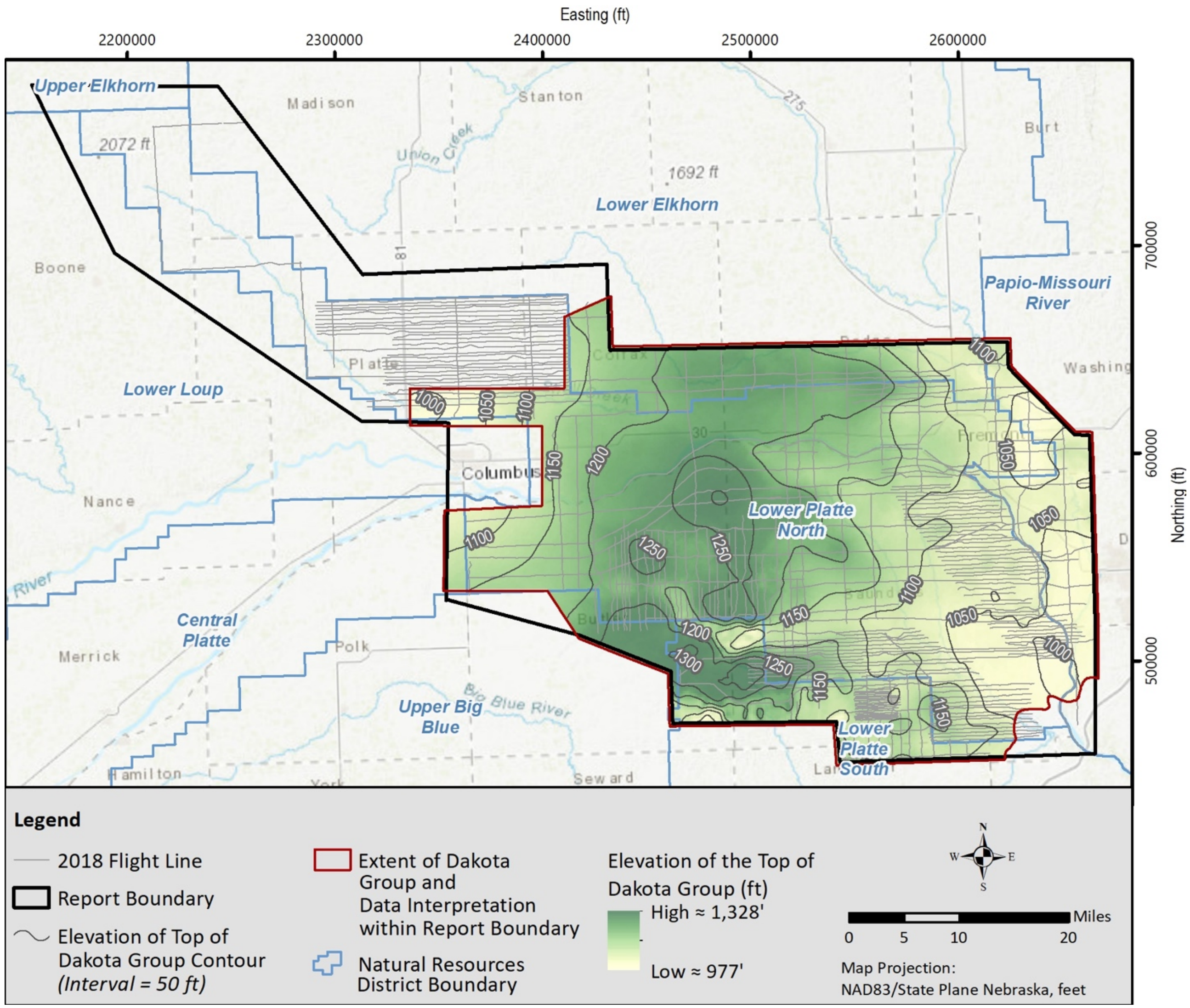


Figure 3-89. Map of the top surface of the of Cretaceous Dakota Group (*Kd*) within the 2018 LPNNRD AEM survey area. Flight lines are indicated by the grey lines. The *Kd* is present in most of the LPNNRD AEM survey area and varies in elevation 977 to 1,328 feet. The *Kd* is missing from the southeast corner of the survey area and cannot be calculated west of Columbus, Nebraska. Note the channels across the *Kd*, northwest of Columbus, Nebraska.

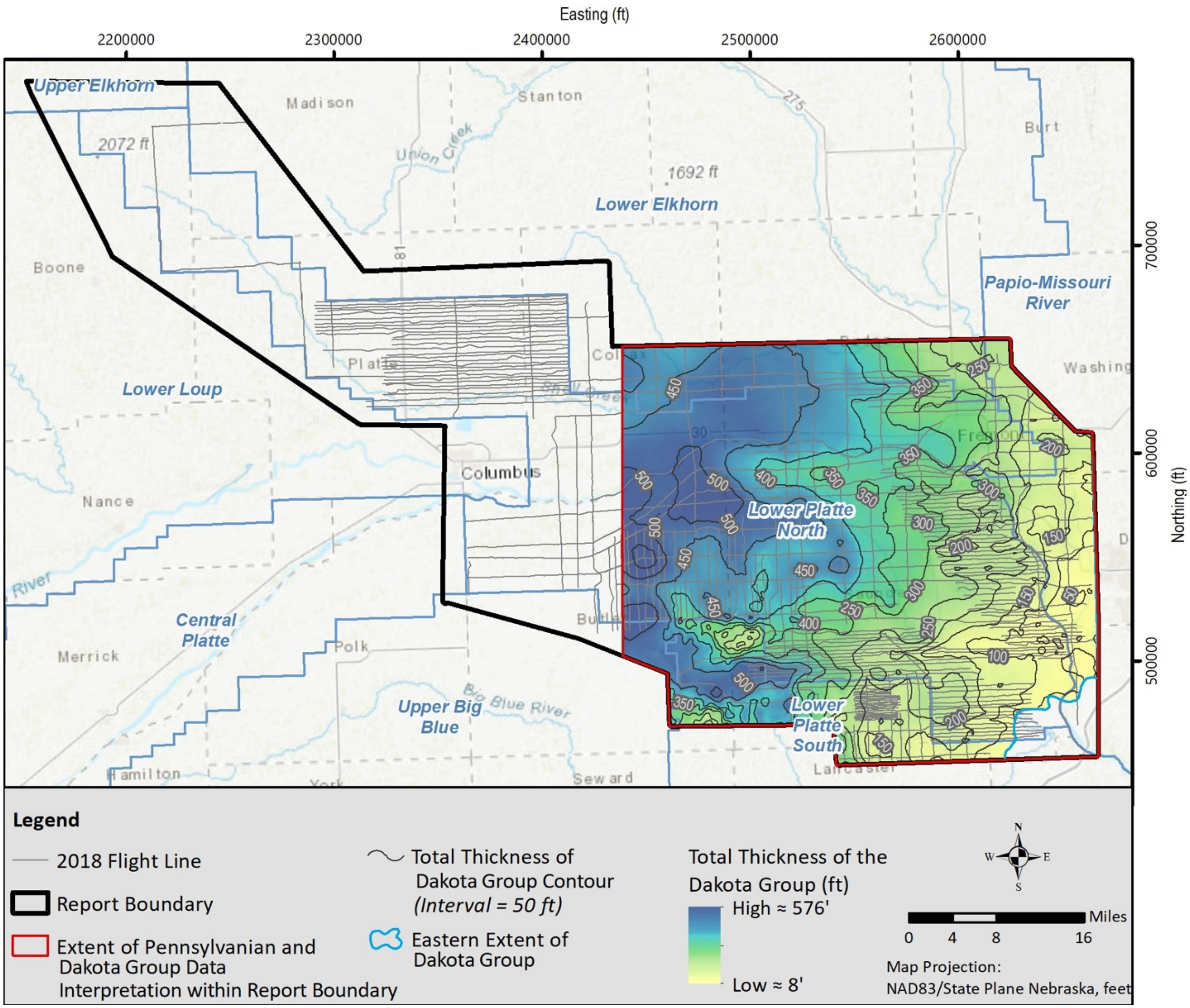


Figure 3-90. Map of the thickness of the Cretaceous Dakota Group (*Kd*) within the 2018 LPNNRD AEM survey area. Flight lines are indicated by the grey lines. The thickness varies from 8-576 feet from east to west. Note the channels north of David City, Nebraska.

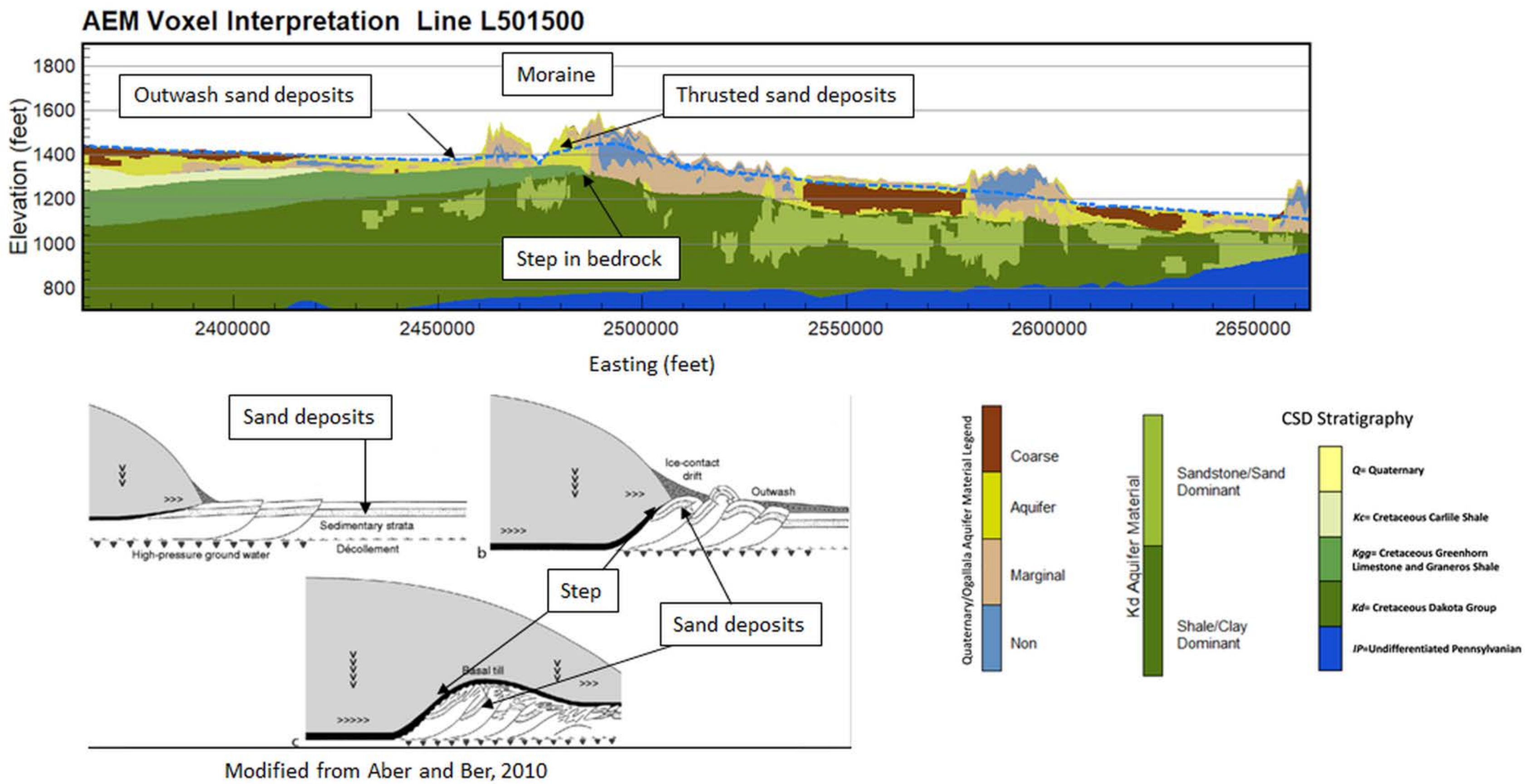


Figure 3-91. Profile of the AEM voxel interpretation from L501500 showing the glaciotectonic features along that line and a diagram from Aber and Ber (2011). Horizontal datum NAD83 State Plane Nebraska (feet).

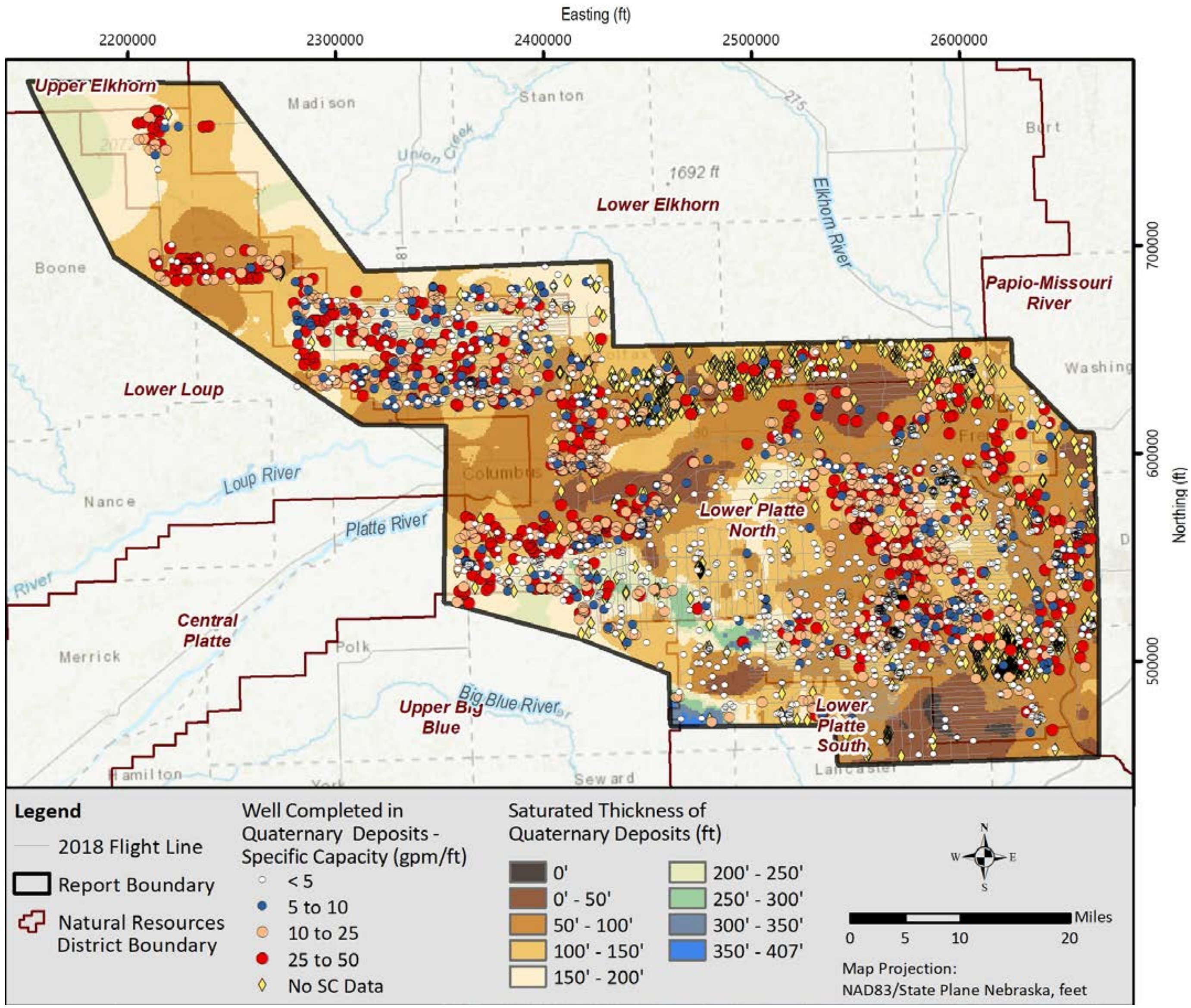


Figure 3-92. Map of the saturated Quaternary thickness for the LPNNRD 2018 AEM survey area plus the specific capacity of wells screened within the Quaternary from the NE-DNR registered well database.

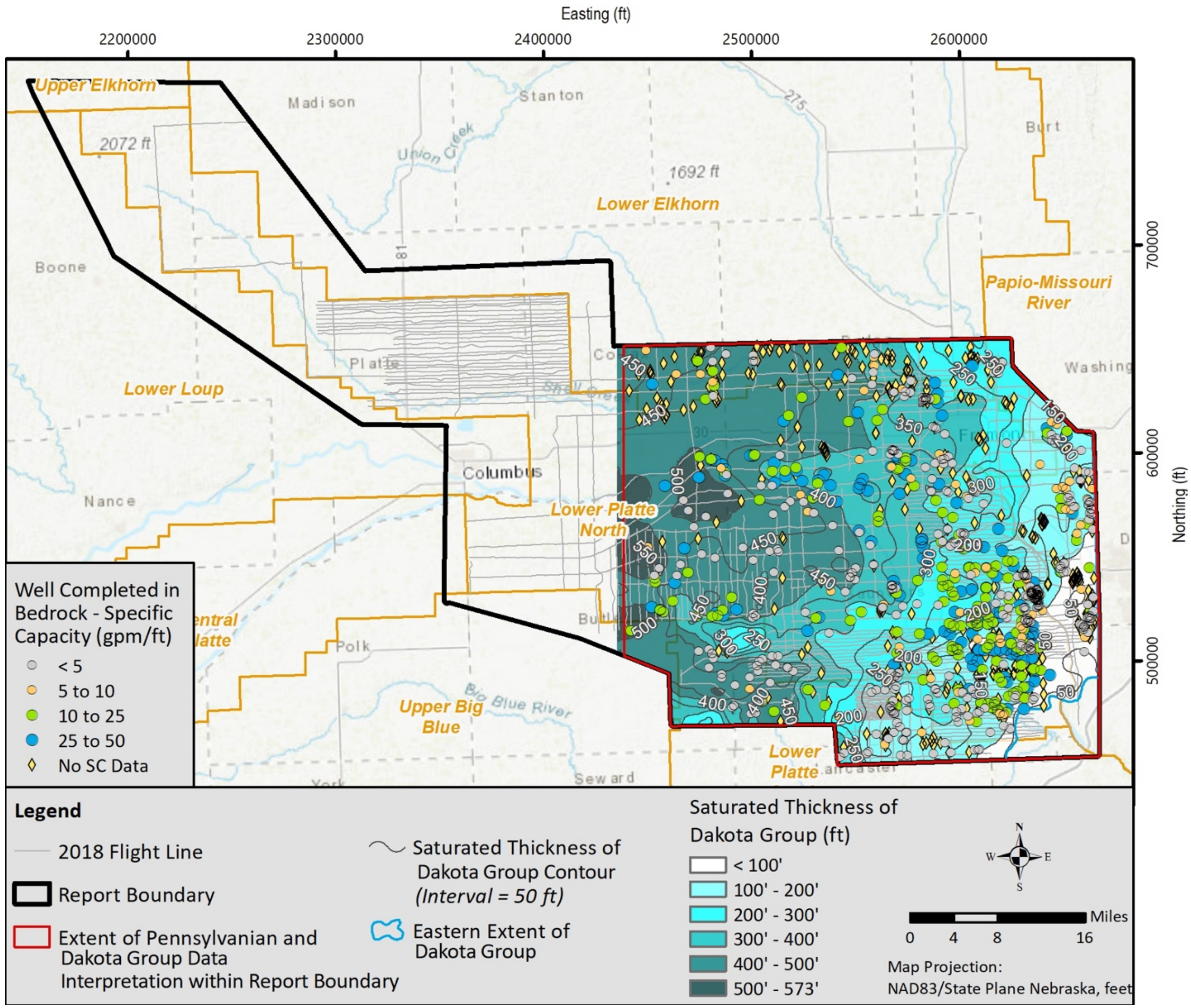


Figure 3-93. Map of the thickness of saturated Cretaceous Dakota Group for the LPNNRD 2018 AEM survey area plus the specific capacity of wells screened within the Cretaceous Dakota Group from the NE-DNR registered well database.

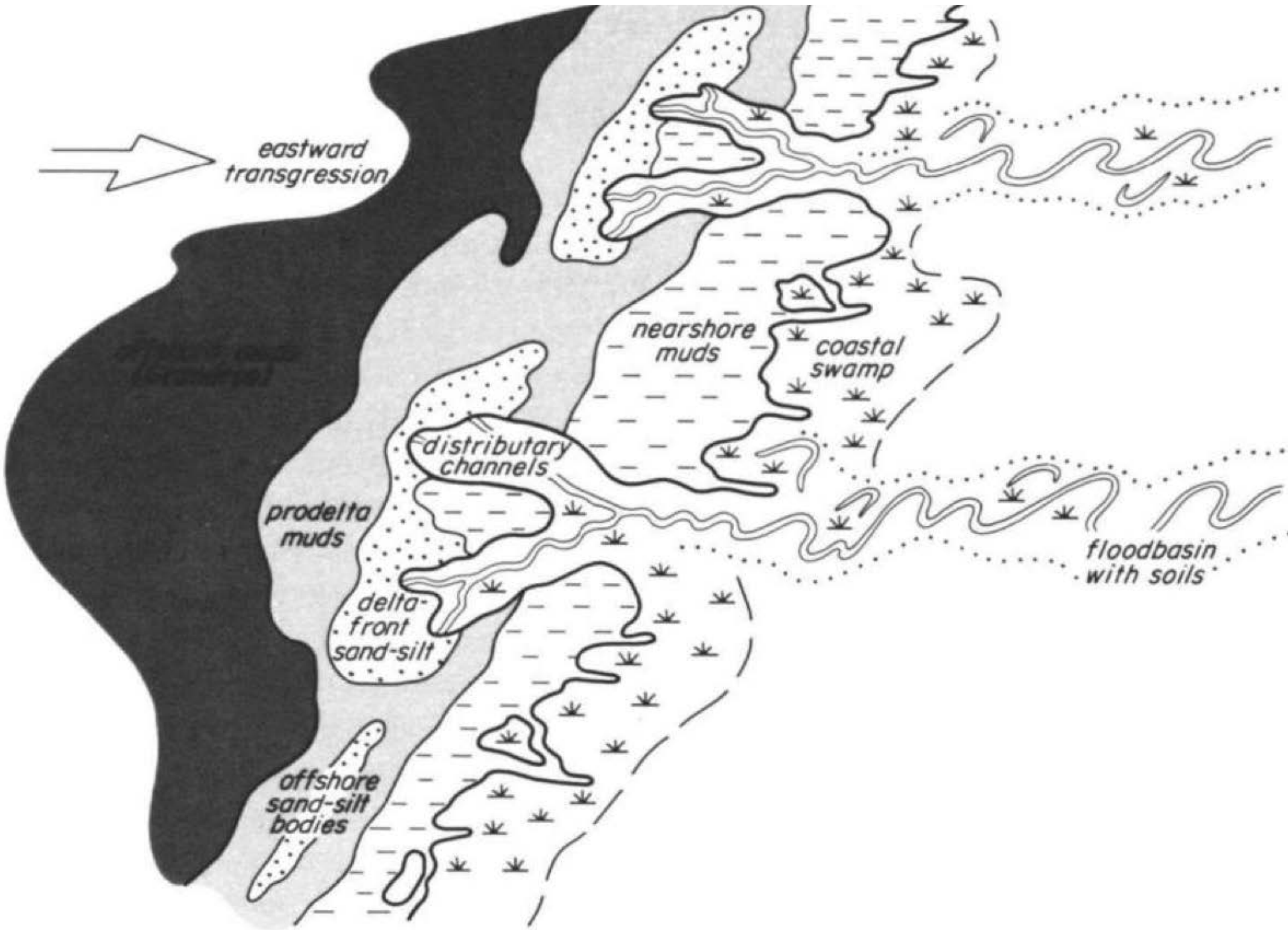


Figure 3-94. Depositional environment of the Dakota Group sediments during the Cretaceous period in eastern Nebraska and western Iowa (Witzke and Ludvigson, 1994).

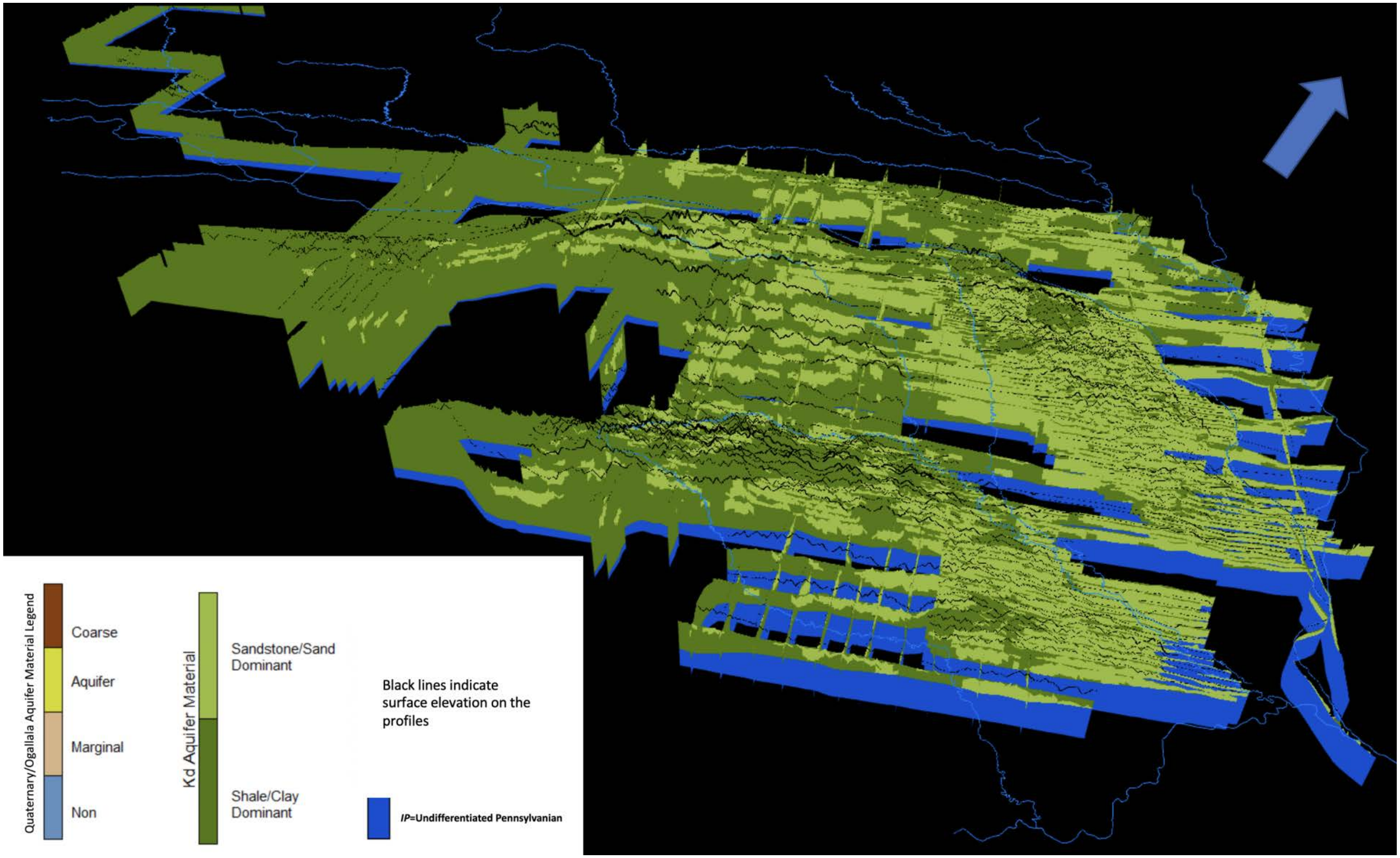


Figure 3-95. 3D fence diagram of only the Cretaceous Dakota Group (*Kd*) including the Sandstone/Sand Dominant and the Shale/Clay Dominant portions sitting on the undifferentiated Pennsylvanian (*IP*). Looking to the northeast. Major streams are indicated as blue lines for special reference.

The image clearly shows the areas of the Sandstone/Sand Dominant ***Kd*** that overlaps well with the specific capacity data presented in Figure 3-93.

3.2.2 Hydrogeologic Framework of the Leshara Uplands, SQS1, SQS2 and WAANN Block AEM Survey Areas

3.2.2.1 Hydrogeologic Framework of the Leshara Uplands Block AEM Survey Area

The AEM provided insight into the geographic distribution and extent of the unconsolidated material in the Leshara Uplands Block AEM survey area. The ***Q*** materials within the Leshara Uplands Block are composed of unconsolidated alluvial silt, sand, and gravel as well as loess and glacial till that overlie the consolidated or semi-consolidated ***Kd*** bedrock which is divided into Sandstone/Sand Dominant and Shale/Clay Dominant units. The ***Q*** material in the Leshara 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. Generally, the flight block is bounded near Silver Creek in the west and Platte River in the north and east and an east-west line, parallel to County Road G, to the south (Figure 3-96). Figure 3-97 displays a 3D fence diagram of the Leshara Uplands 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 ***Kd*** which contains a mix of Shale/Clay Dominant and Sandstone/Sand Dominant aquifer materials. The boreholes in the area indicate a mix of silty clay and sandy clay in much of the Rolling Uplands with fluvial sand and sand and gravel in the Todd Valley and Platte River valley areas above the ***Kd*** bedrock. Figure 3-98 presents 2D profile L501500, located south of the town of Woodcliff and extending west into the Todd Valley. The figure shows a blow up of the profile from approximately 2570000 East to approximately 2580000 East. This is done to show the good comparison between the AEM earth-model resistivities to the borehole lithology and stratigraphy descriptions. The CSD 1995 water table is also on the profile and shows the change in water table elevation from the Todd Valley in the west to the Platte River Valley in the east. This elevation change is a result of the aquifer materials and the land surface elevation.

The total thickness of the ***Q*** material in the Leshara Block AEM survey area (Figure 3-99) was gridded by subtracting the bedrock elevation from the ground surface elevation. The greatest thickness is on the high ground along the Leshara Upland with the thin sections along the Platte River valley. The ***Q*** material varies in thickness from 8 to 318 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 ***Kd*** and the surface water of the area. The aquifer and coarse aquifer materials provide the greatest connection for water movement through all of the ***Q*** 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 gridded 1995 CSD water table surface elevation (NE-CSD, 1995) to obtain the total saturated thickness of ***Q*** material. By separating the various aquifer materials into their components and then combining just the aquifer and coarse aquifer material values of thickness into a group, the thickness of aquifer and coarse aquifer materials can be shown for the Leshara Uplands Block (Figure 3-100). The thickness of these materials varies between 0, where there is no aquifer and coarse aquifer material and the greatest thickness at 184 feet along the east side of Todd Valley with the thin areas found mostly north and east of Rolling Uplands.

Figure 3-101 shows, underlying the ***Q***, the ***Kd*** surface elevation which is generally highest at 1,324 feet in the northwest and west areas and lowest at 975 feet in the northeast and southeast areas of the survey. The ***Kd*** lows near the towns of Arlington and Mead, Nebraska are separated by a gently sloping bedrock high that extends west to east near the town of Leshara, Nebraska. These high and low elevations correlate with the thickness map of the ***Kd*** (Figure 3-102). An area with a thin ***Kd*** material thickness of 50-100 feet is located near the town of Mead, Nebraska and extends southeast into the Platte River Valley. The saturated thickness of the ***Kd*** varies from 5 feet to 463 feet with the thickest section west-northwest of the area near the towns of Cedar Bluffs and Wahoo, Nebraska.

Figure 3-103 shows the interpreted 2D profile L502701 which is an east-west profile across the Todd Valley through the Leshara Uplands and down into the Platte River Valley. The Todd Valley is a paleochannel of the ancestral Platte River containing many of the groundwater irrigated acres in the area. The Rolling Upland of the Leshara Upland AEM area stretches north to south between the Todd Valley and Platte River Valley and is a cap of glacial till/loess made up of mostly marginal aquifer and non-aquifer material. Beneath the glacial cap is a basal unit of mostly aquifer materials approximately 100 feet thick lying on the upper surface of the ***Kd***. The basal unit of the Leshara Upland is hydrologically connected to the alluvial fill of the Todd Valley and to the Platte River alluvium along this profile. However, the hydrologic connection along the individual Profiles that make up the block can be intermittent through-out the area.

Figure 3-104 is 2D profile L502301 which is an east-west profile in the Leshara AEM Block area that starts in the Todd Valley, crosses the Rolling Upland, and then goes down into the Platte River Valley showing a complex mix of ***Q*** and ***Kd*** materials across the profile. The zone highlighted with a red box is an example where there is poor hydrologic connection between the Todd Valley and the Platte River Valley under the Rolling Upland in both the ***Q*** and ***Kd,*** units. This correlates to an area near Cedar Bluffs and Fremont, Nebraska where a thin 0-50 ft saturated ***Q*** thickness exists in the northern part of the Leshara Uplands Block AEM survey area (Figure 3-100).

Note that the area in and around Cedar Bluffs and Fremont is an important area for understanding the hydrogeologic framework for management purpose in the LPNNRD. The areas of poor hydrologic connection between the Todd Valley and the Platte River contributes to the shape of the water table in this area as seen on Figure 3-104. An exploded view of the voxel model showing the ***Q***, both saturated and unsaturated, the ***Kd***, and the ***IP*** formations is presented in Figure 3-105. The ***Q*** materials show the prevalent heterogeneity seen across the LPNNRD amongst the coarse aquifer, aquifer, marginal aquifer, and non-aquifer materials. There is a change in the composition of the aquifer and coarse aquifer materials as you move across the Todd Valley which has a strong coarse aquifer package to the Rolling Upland which is all aquifer material and into the Platte River Valley, which contains a mix of aquifer and coarse aquifer material. This shows different environments of deposition with Todd Valley and Platte Valley ***Q*** materials having a large amount of coarse aquifer material because they are fluvial in nature while the aquifer material beneath the Rolling Upland area is aquifer material originating from glacial processes.

The unsaturated ***Q*** materials shown above the water table in Figure 3-106 has potential to be used as Managed Aquifer Recharge (MAR) sites. This requires careful evaluation of the locations where the aquifer and coarse aquifer materials are present that have the volume available that would make building a MAR site beneficial. Any site selected should be located up gradient along the water table that has continuous marginal aquifer and non-aquifer material deposits which can act as a barrier to groundwater flow. These barriers should be located between Todd Valley and the Platte River valley.

The map of saturated thickness for ***Q*** deposits and specific capacity of wells in the ***Q*** (Figure 3-107) shows the relationship between specific capacity in gpm/ft and the saturated thickness. Careful evaluation of the map (black dashed box) shows a trend of 10-50 gpm/ft that follows the Todd Valley where there are 75 to 175 ft thick ***Q*** deposits. The ~ 100-foot-thick coarse aquifer material in the fluvial deposits contributes to this relationship. There is a similar situation with the Platte River Valley in the east (blue dashed box).

Figure 3-108 presents a map of the saturated thickness for ***Kd*** Sandstone/Sand Dominant deposits. Figure 3-109 shows the relationship between the data presented in Figure 3-108 and the specific capacities, in gpm/ft, for wells completed in the bedrock. Careful evaluation of the wells in Figure 3-109 shows a trend from north to south from Cedar Bluffs to southeast of Mead, Nebraska that has a higher population of wells with a specific capacity 10-50 gpm/ft range following the 50 to 400 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***.

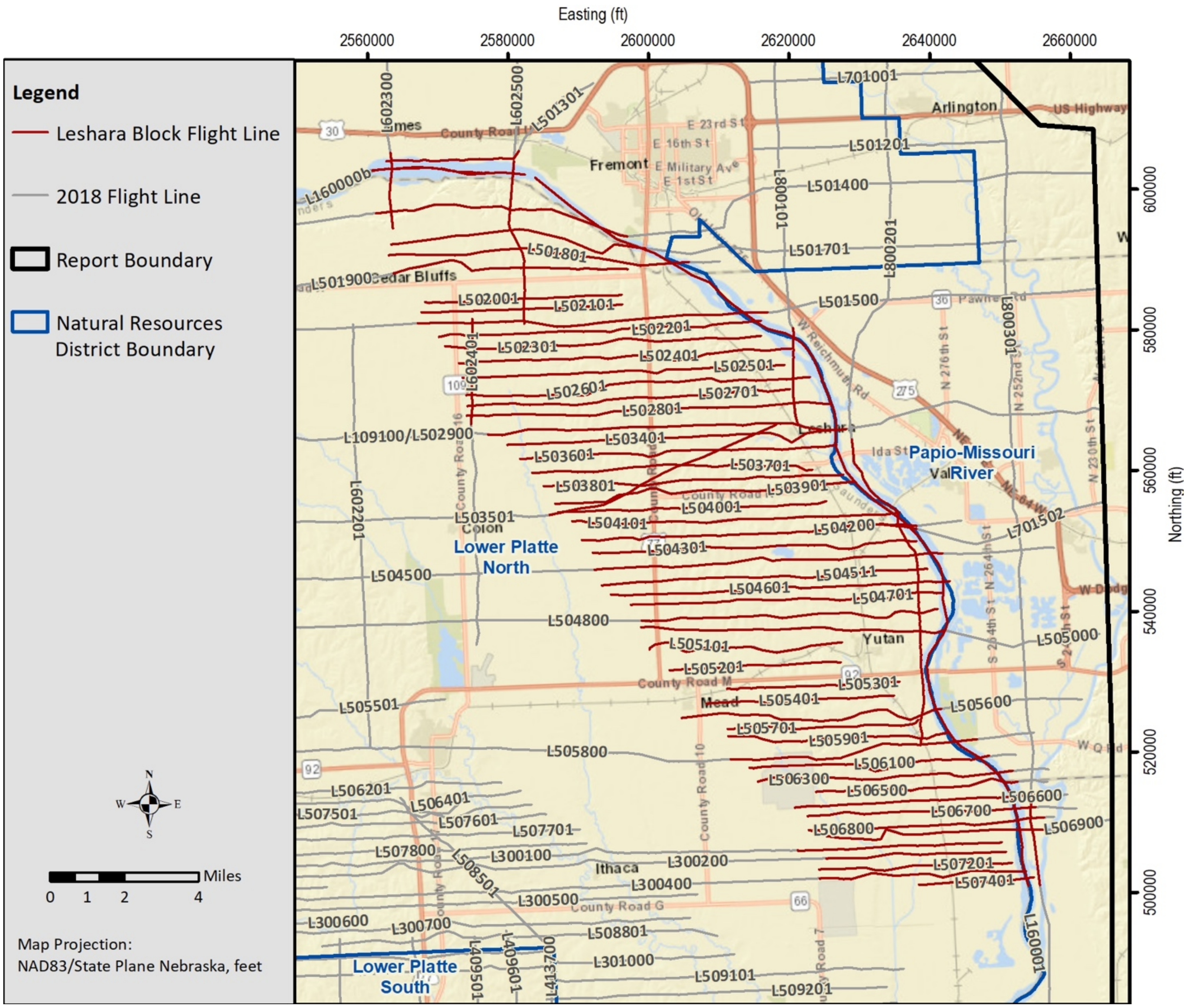


Figure 3-96. Map location of the Leshara Uplands Block indicating AEM flight lines, local roads, and streams.

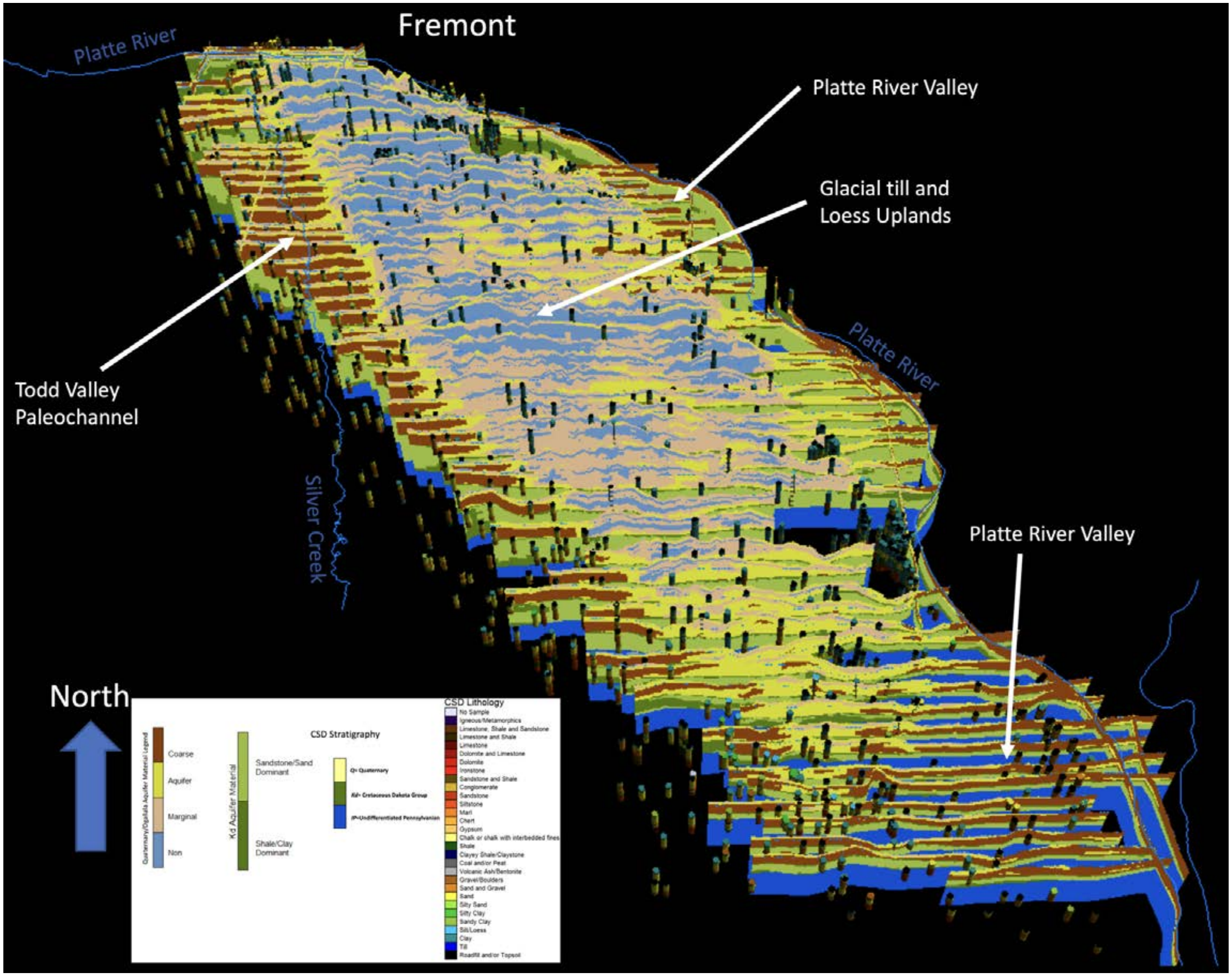


Figure 3-97. 3D fence diagram of interpreted AEM hydrostratigraphic profiles within the 2018 Leshara Uplands Block AEM survey area. VE = 15x.

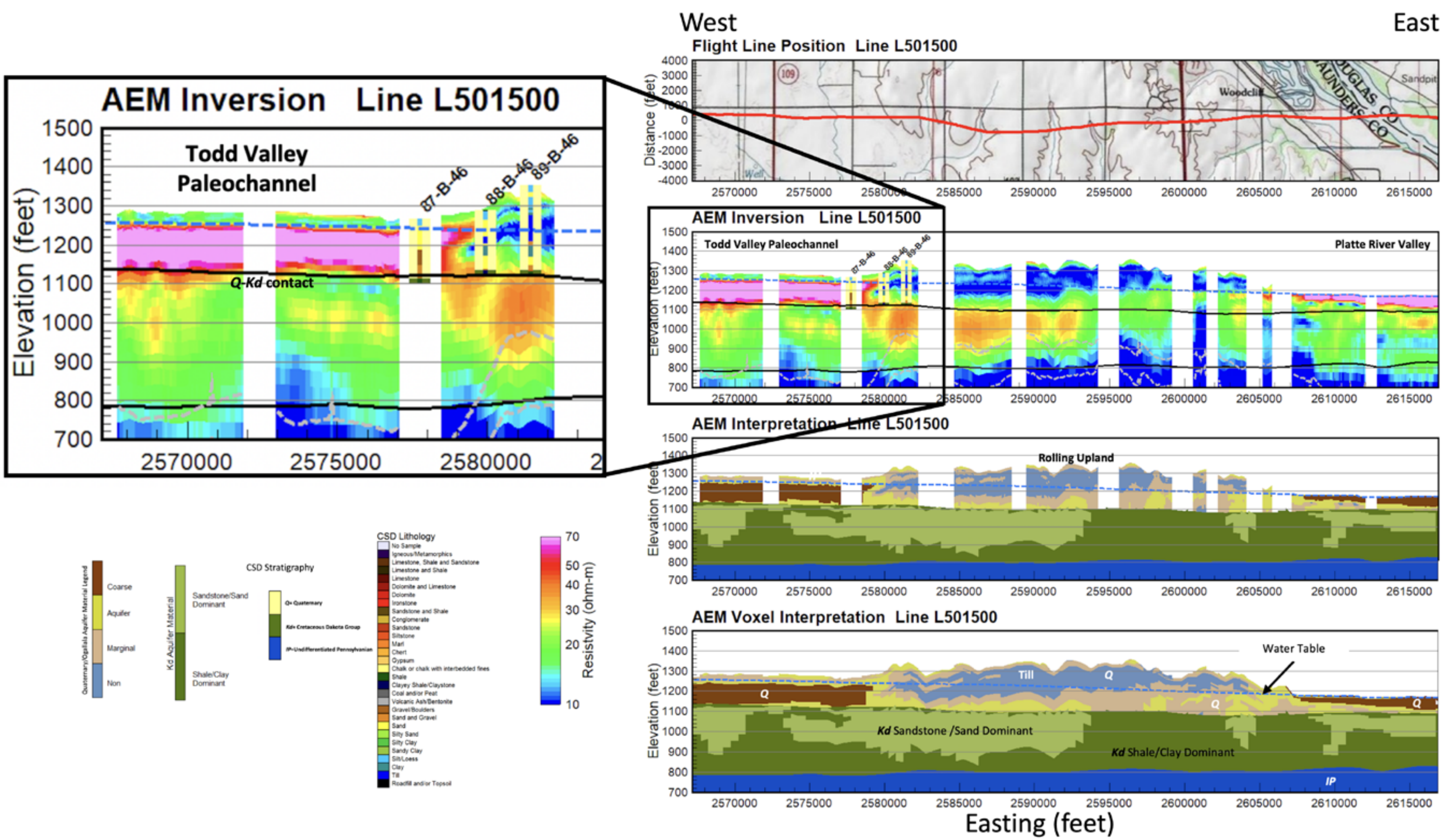


Figure 3-98. Profile of the east-west line L501500 showing the relationship of the AEM resistivity and interpretations to the CSD lithology and stratigraphy logs. The CSD 1995 water table is indicated as a dashed blue line on the profiles.

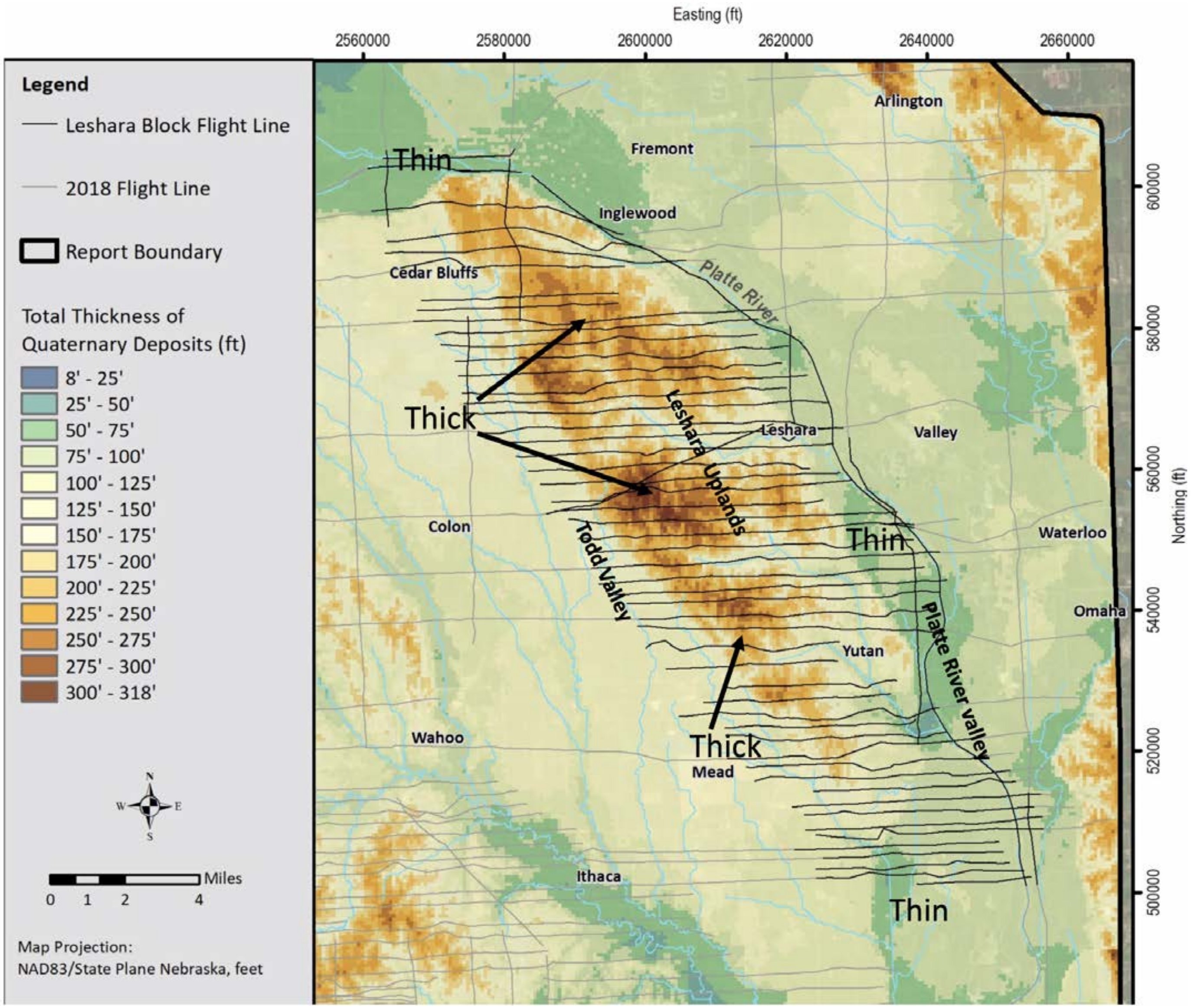


Figure 3-99. Map of the total thickness of the Quaternary (*Q*) deposits within the 2018 Leshara Uplands Block. Block flight lines are indicated by black lines.

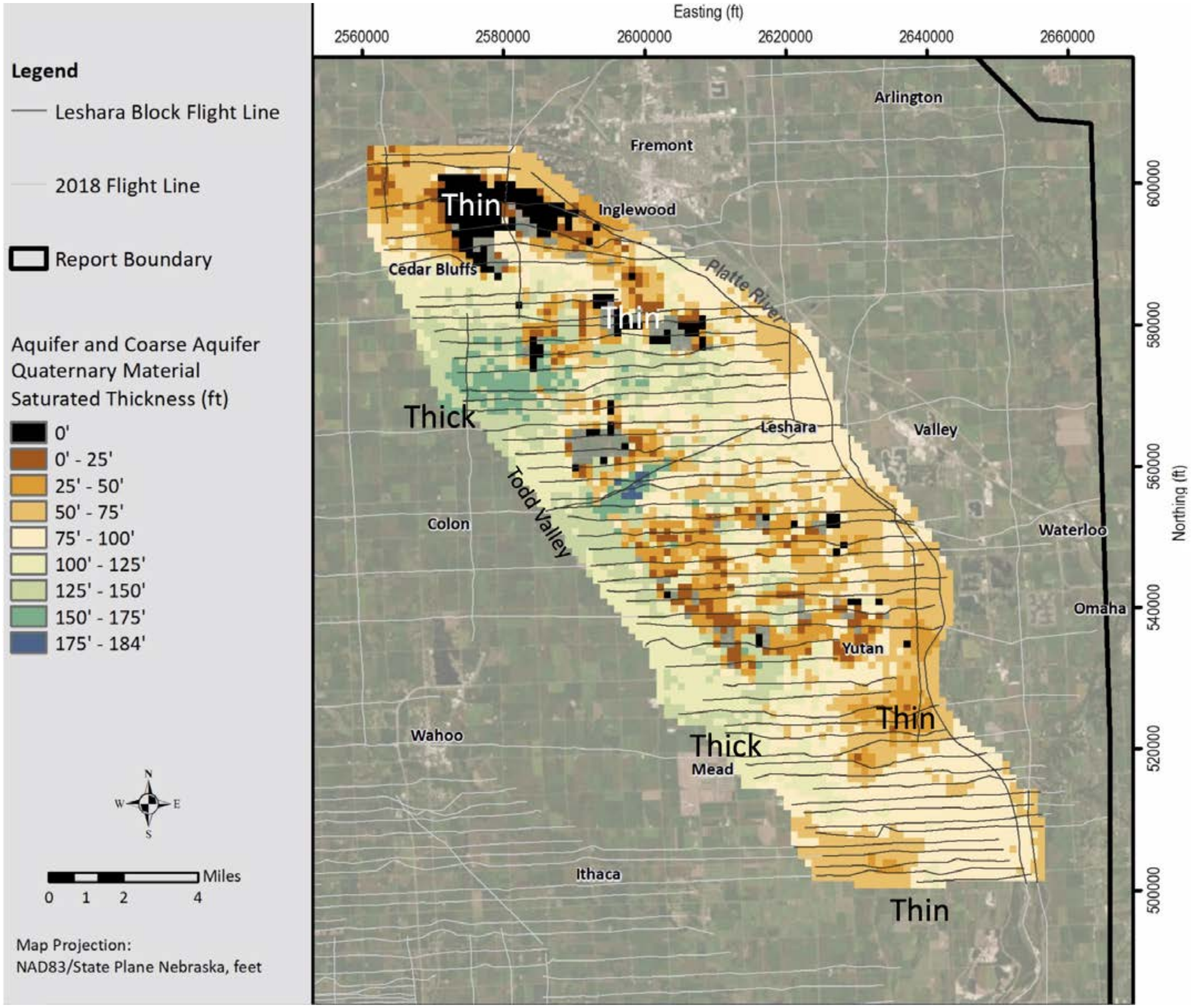


Figure 3-100. Map of the thickness of the Quaternary (*Q*) saturated aquifer and coarse aquifer materials within the 2018 Leshara Uplands Block. Block flight lines are indicated by black lines.

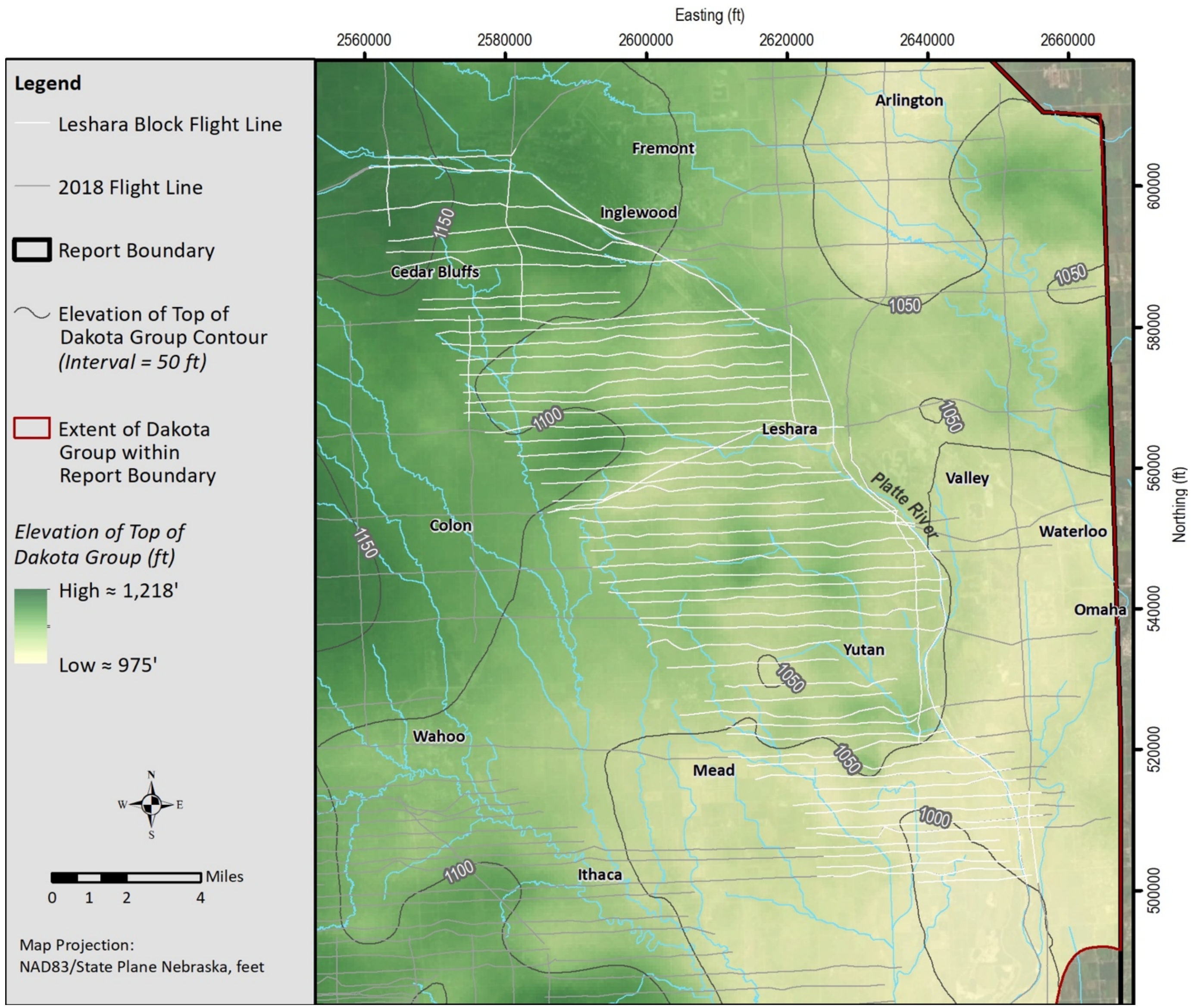


Figure 3-101. Map of the elevation of the top of the Cretaceous Dakota Group (*Kd*) within the Leshara Uplands Block from the 2018 AEM survey. Block flight lines are indicated by the white lines.

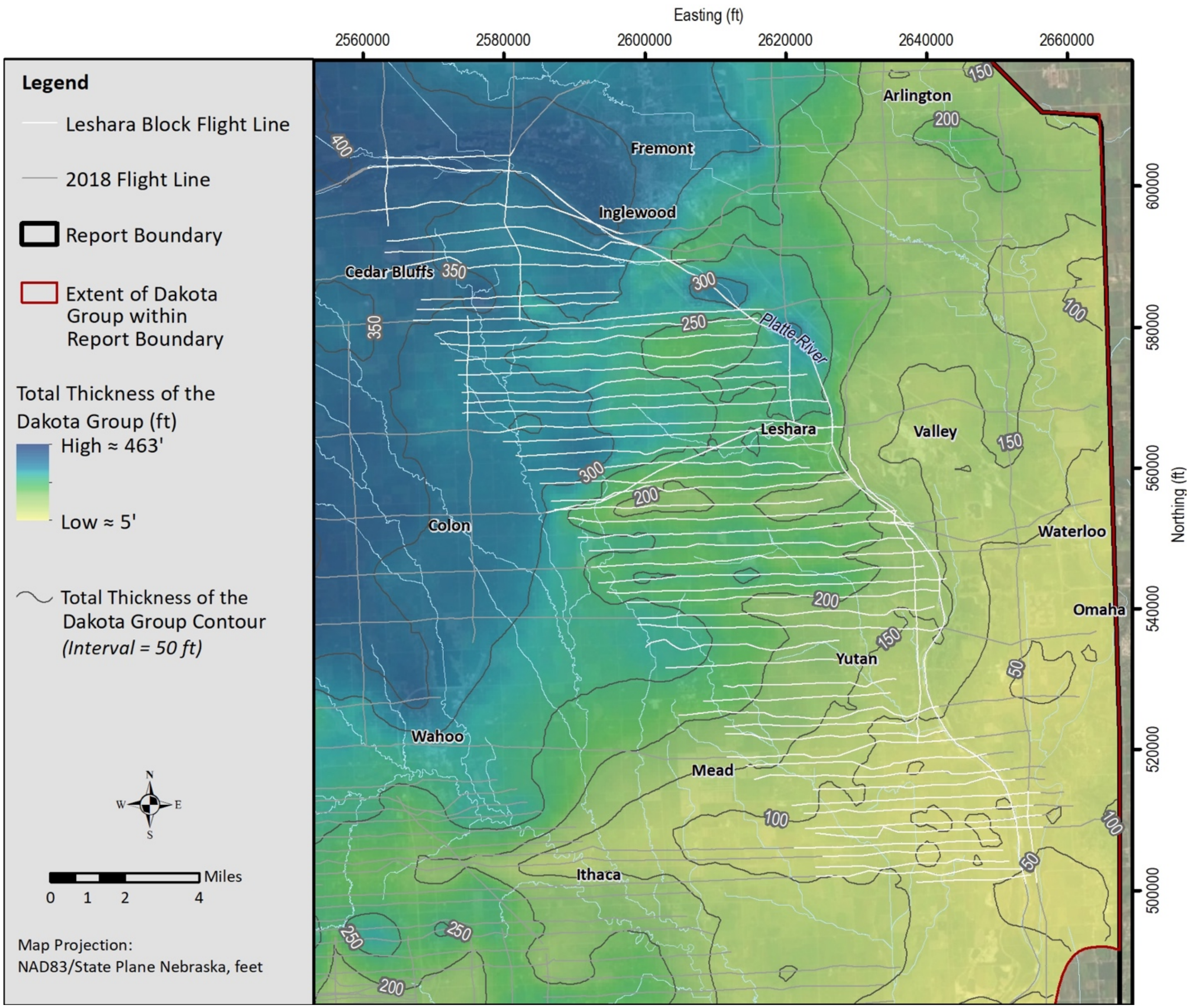


Figure 3-102. Map of the thickness of the Cretaceous Dakota Group (*Kd*) within the Leshara Uplands Block from the 2018 survey. Block flight lines are indicated by the white lines.

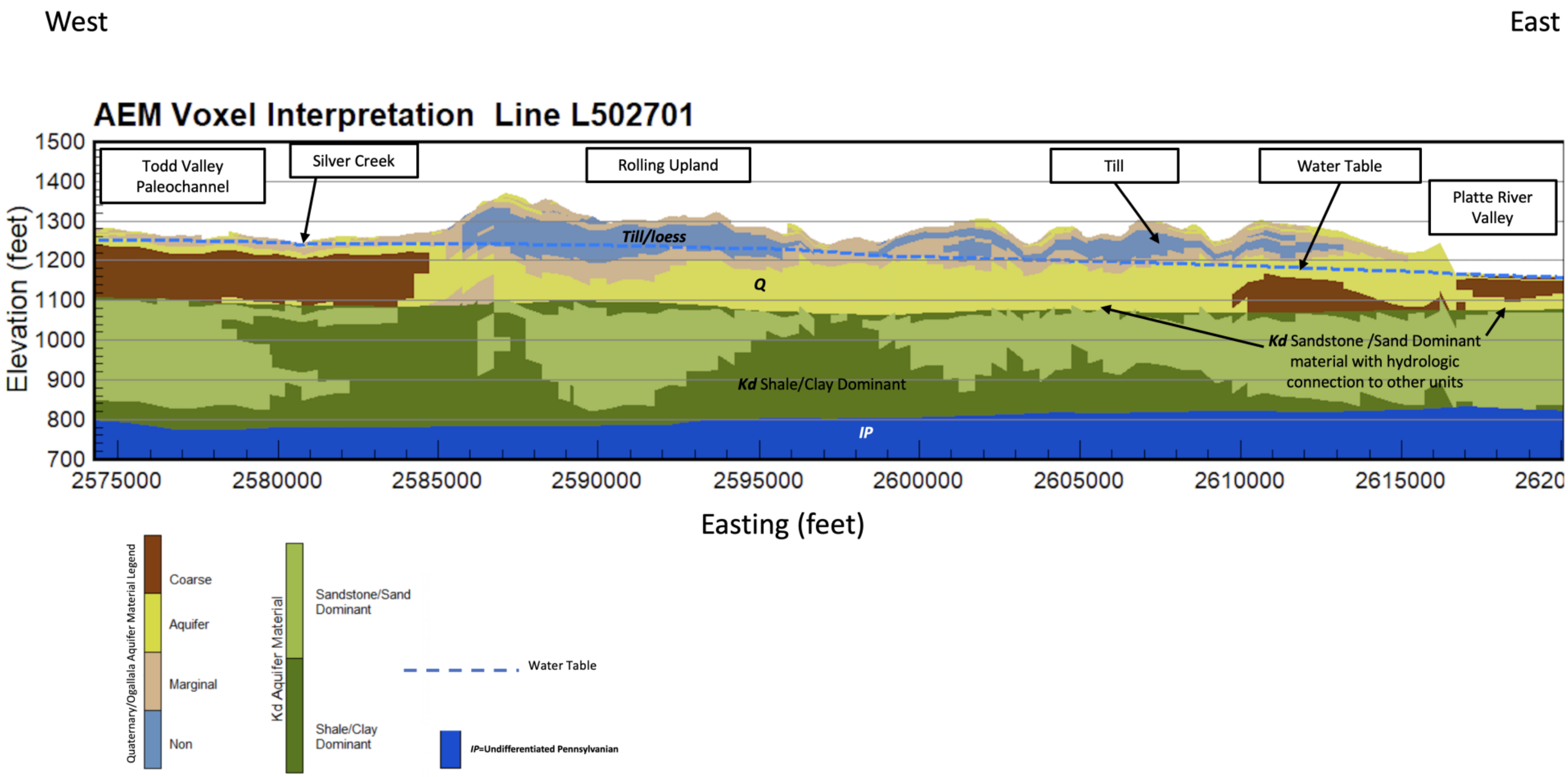


Figure 3-103. Interpreted profile of the east-west line L502701 showing the relationship of the AEM interpretations across the Leshara Upland. The CSD 1995 water table is indicated as a dashed blue line on the profiles. Horizontal datum is NAD83 State Plane Nebraska (feet).

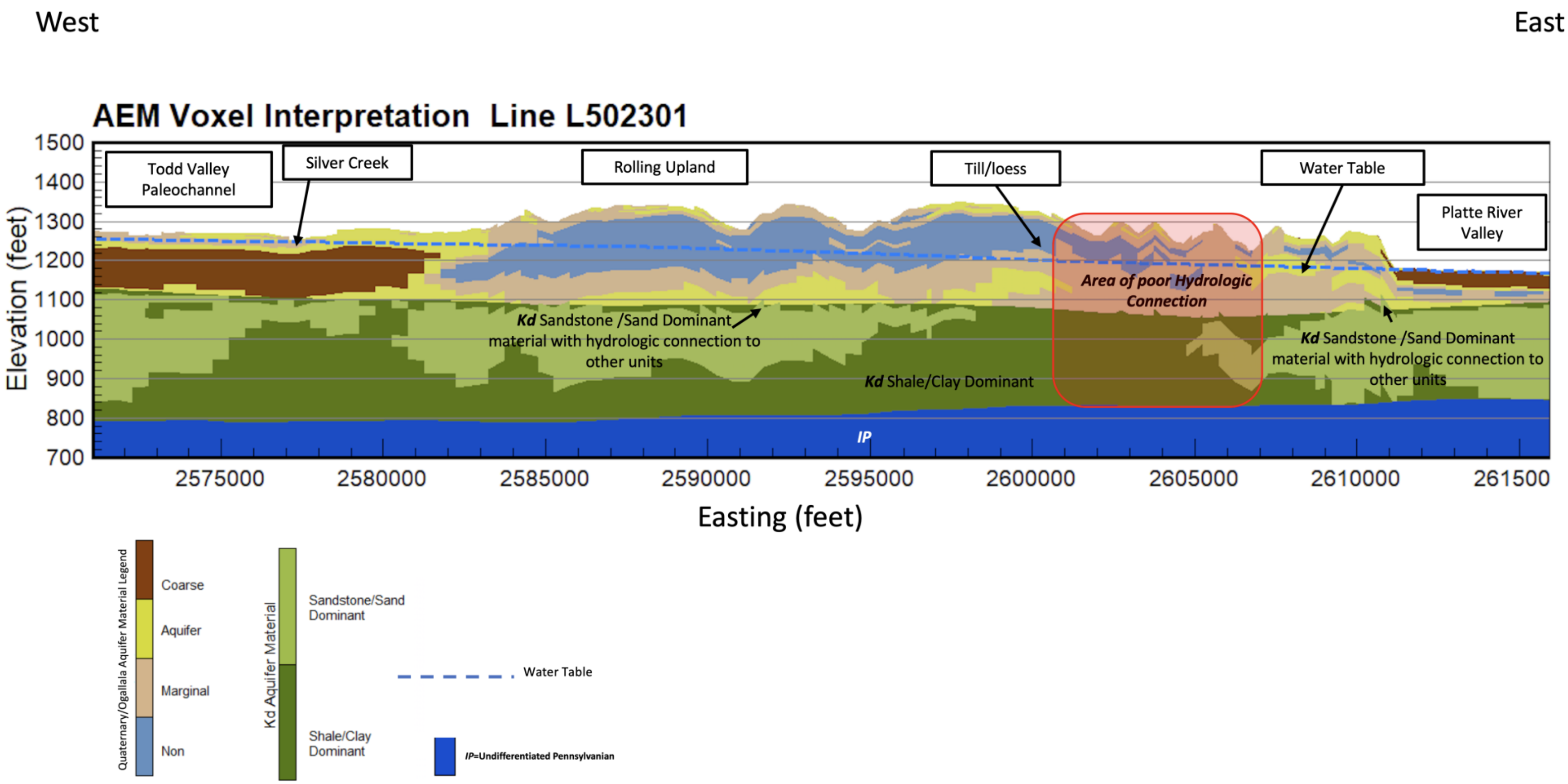


Figure 3-104. Interpreted profile of the east-west line L502301 showing the relationship of the AEM interpretations across the Leshara Upland. The CSD 1995 water table is indicated as a dashed blue line on the profiles. Horizontal datum is NAD83 State Plane Nebraska (feet).

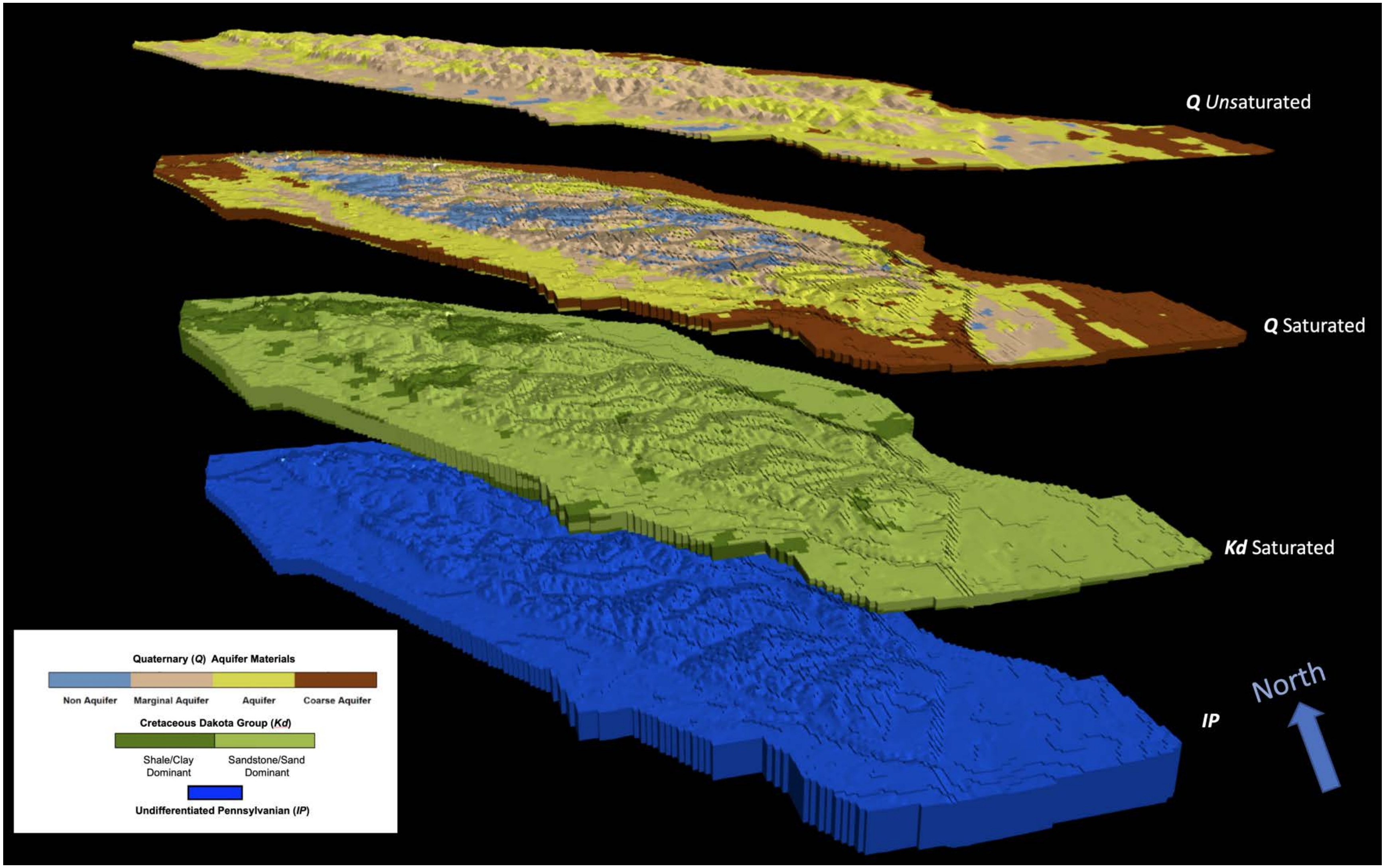


Figure 3-105. 3D exploded voxel model of the Leshara Upland Block showing unsaturated *Q*, saturated *Q*, saturated *Kd*, and *IP* units. V.E. = 10x. *Note that the image is not to scale.*

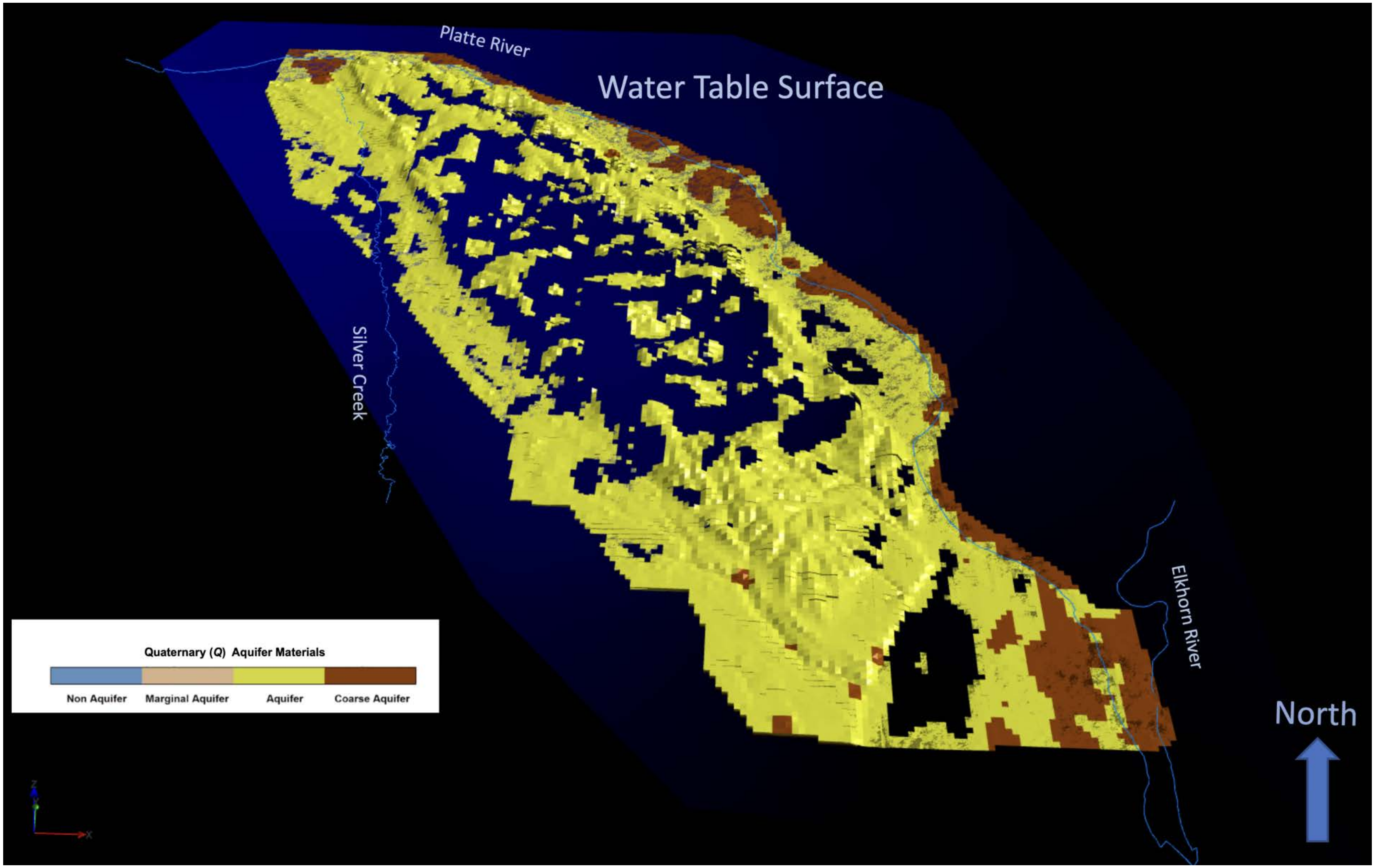


Figure 3-106. 3D voxel plot of the unsaturated Quaternary (Q) aquifer and coarse aquifer materials for the Leshara Uplands Block, looking to the north. The CSD 1995 water table is indicated as a blueish surface. Vertical scale is 10x.

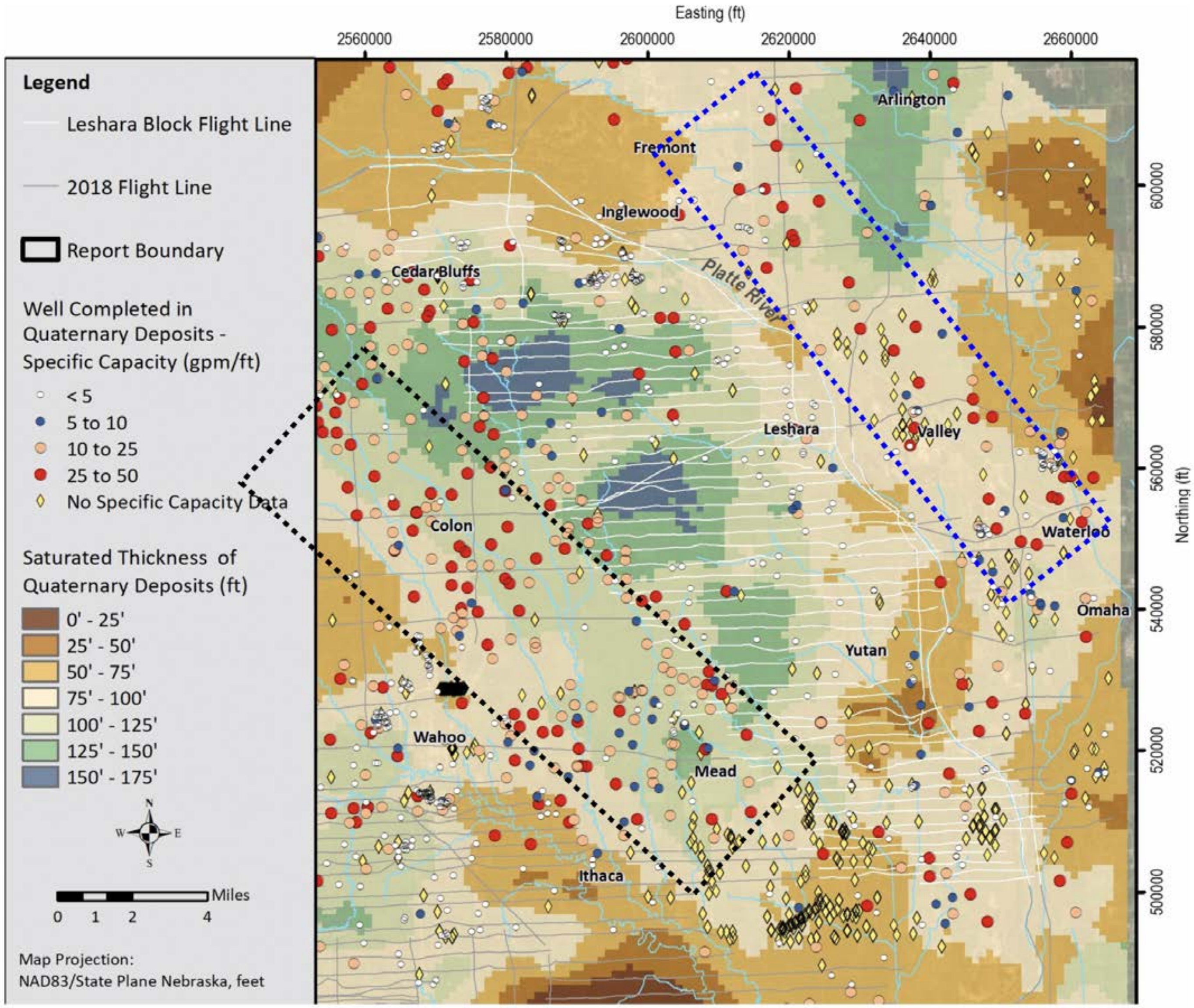


Figure 3-107. Map of saturated thickness of Quaternary (*Q*) deposits and the specific capacity measured in wells completed in the Quaternary (*Q*) deposits.

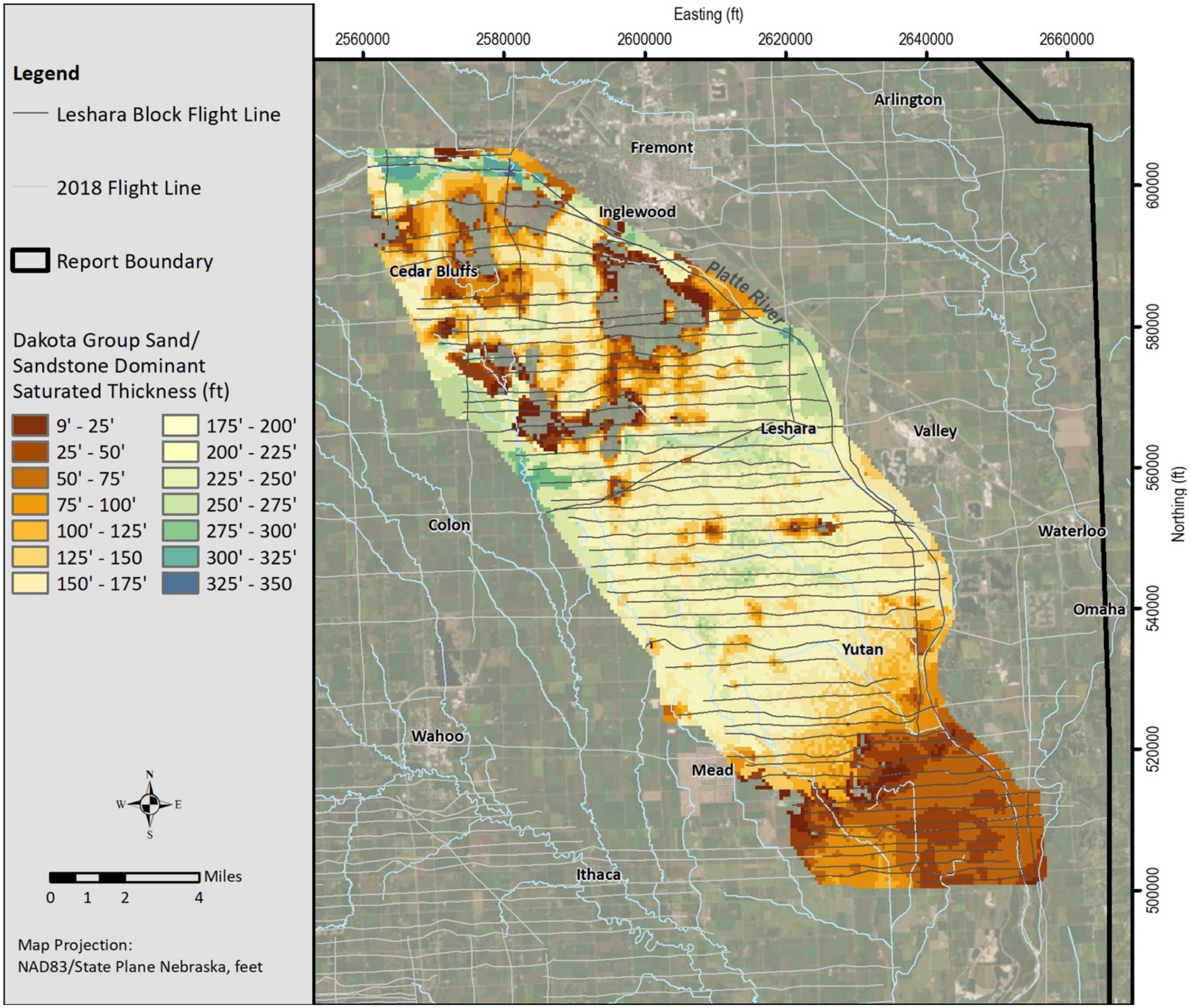


Figure 3-108. Map of the saturated thickness of the Sandstone/Sand Dominant portion of the Cretaceous Dakota Group (*Kd*) in the Leshara Block AEM survey area.

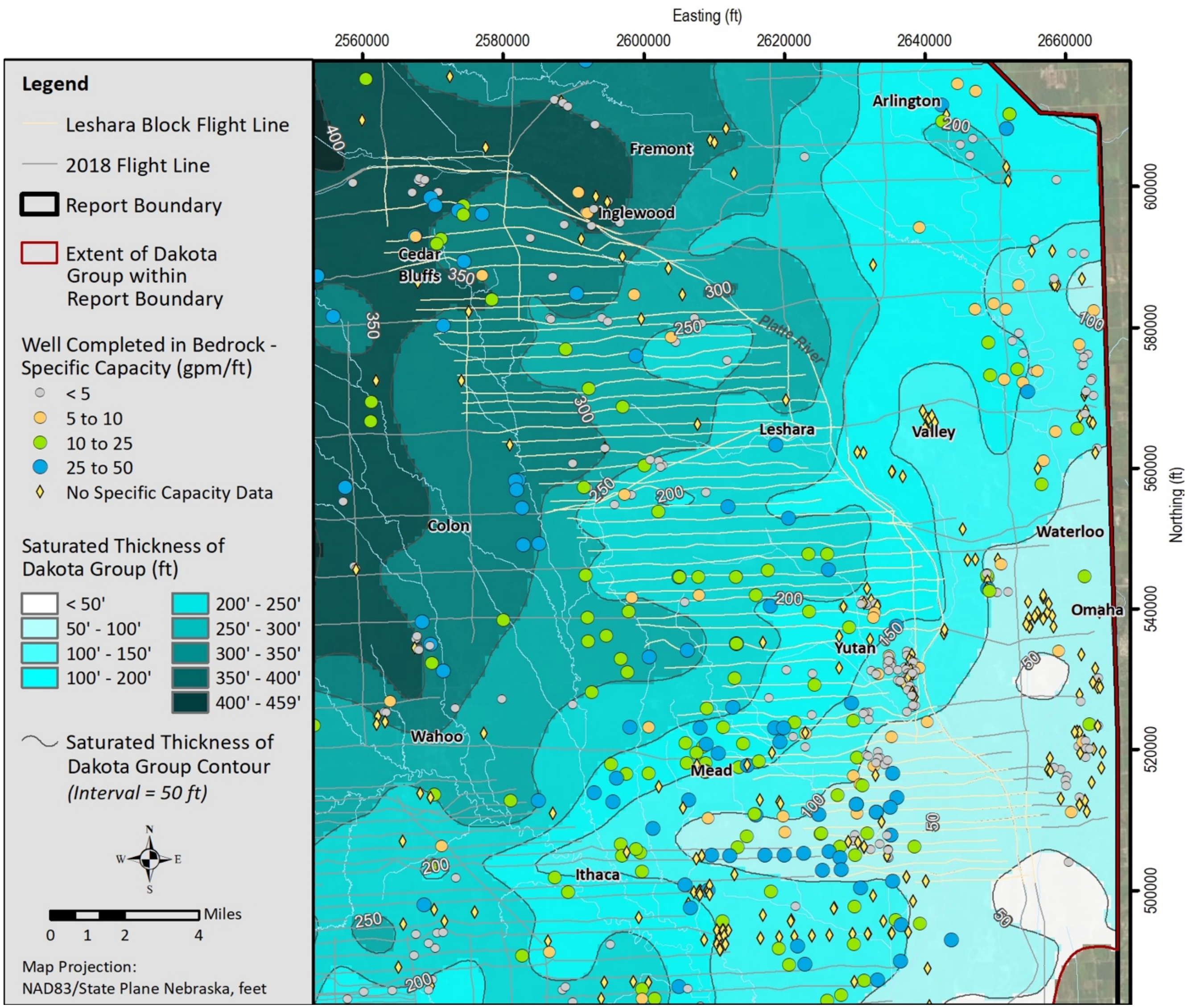


Figure 3-109. Map of the saturated thickness of the Cretaceous Dakota Group (Kd) Sandstone/Sand Dominant material in the Leshara Uplands with specific capacity indicated in wells completed in the bedrock. The wells yielding 10-50 gpm/ft follow a trend along the western side of the Leshara Uplands and the eastern edge of the Todd Valley.

3.2.2.2 Hydrogeologic Framework of the SQS1 Block AEM Survey Area

The AEM provided insight into the geographic distribution and extent of the unconsolidated material in the SQS1 Block AEM survey area. Much of the discussion of the SQS1 block can be found in AGF (2017). The ***Q*** materials within the SQS1 Block are composed of unconsolidated alluvial silt, sand, and gravel generally in the form of loess and glacial till that overlie the ***Kgg*** in the north and west. The ***Q*** also overlies consolidated or semi-consolidated ***Kd*** bedrock which is divided into Sandstone/Sand Dominant and Shale/Clay Dominant units. Where the ***Kgg*** is present, it lies directly upon the ***Kd*** which exists in the entire area and lies upon the ***IP*** which also exists across the entire block area. The ***Q*** material in the SQS1 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 3.1.5. Generally, the flight block (Figure 3-110) is bounded in the west by Highway 15, just east of Highway 79 in the east, Highway 92 in the south, and an east west line near Octavia, Nebraska. Figure 3-111 shows the year the individual flight lines were flown. The 2018 SQS1 Block includes all flight lines available from all years of acquisition (2014, 2015, 2016, and 2018) for the interpretation. It is important to note that only 17 lines (blue in Figure 3-111) from the total used were flown in 2018 and they are mostly at the east and west ends of the block.

Figure 3-112 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*** aquifer-type materials lying upon the ***Kgg***, where it exists, and the ***Kd*** which contains a mix of Shale/Clay Dominant and Sandstone/Sand Dominant aquifer materials. The boreholes in the area indicate a mix of silty clay, sandy clay, and sand and gravel in the block area. More discussion on SQS1 can be found in the 2017 AGF report (AGF, 2017). As can be seen on Figure 3-112, 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 areas of glacial out wash and fluvial deposits made up of mostly aquifer material and minor amounts coarse aquifer material in the southeast and northwest corners of the block.

Figure 3-113 presents profile L501500, located south of the town of Bruno, Nebraska and extending west to east across the block. The CSD 1995 water table (NE-CSD, 1995) is on the profile and shows the change in water table elevation from the west to the east. From Bruno west the water table is approximately 180 feet deep and has a shallow slope to the east. As you go past Bruno to the east, the water table is only 80-100 feet deep and there is a change in its slope that becomes much steeper matching a similar 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.

Figure 3-114 is a map of the top of the bedrock, composed of both ***Kgg*** and ***Kd***, that indicates a paleovalley that slopes from David City to near Weston, Nebraska. This paleovalley is filled with ***Q*** aquifer material at its base and covered in ***Q*** marginal and non-aquifer material. The total thickness of the ***Q*** material in the SQS1 AEM block area (Figure 3-115) was calculated by subtracting the bedrock elevation from the ground surface elevation. The greatest thickness is in the paleovalley indicated in

Figure 3-114, with the thinner sections above the bedrock highs near the towns of Abie and Prague, Nebraska. The ***Q*** varies in thickness from 18 to 544 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 and the bedrock (***Kd***). 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. This means many of the ***Q*** aquifer and coarse aquifer material deposits are isolated from the ***Kd*** and surface water. 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 thickness of those units (Figure 3-116) is indicated to vary between 0, where there is no aquifer and coarse aquifer material, to a maximum thickness of about 285 feet near the discussed paleovalley. Figure 3-117 is another view of the aquifer and coarse aquifer material thickness, this time as a 3D voxel model showing the aquifer can coarse aquifer material volume in the SQS1 Block.

Figure 3-118 shows the ***Kgg*** surface elevation which is generally highest at 1,390 feet in elevation near the towns of Abie, Bruno, and Brainard, Nebraska. It is lowest at 1,225 feet in elevation in the paleovalley that extends from David City east. Figure 3-119 shows the ***Kd*** surface elevation underlying the ***Q*** where the ***Kgg*** is absent. The ***Kd*** reaches a maximum height of 1,328 feet in elevation near the town of Brainard, Nebraska. It is lowest in elevation (1,012 feet) in the paleovalley east of Weston, Nebraska. There is ridge of ***Kd*** that extends north to south east of Abie and Bruno, a ***Kd*** hill just south of Octavia, and an east-west ridge near Brainard, Nebraska. These high and low elevations correlate with the thickness map of the ***Kd*** (Figure 3-120). The total thickness of the ***Kd*** varies from 161 feet to 576 feet with the thickest section north of the paleovalley near David City. The ***Kd*** thins in the vicinity of the paleovalley east of Brainard. The saturated thickness of the ***Kd*** Sandstone/Sand dominant material is shown on Figure 3-121 with the thickest part on the east side of the SQS1 Block (338 ft) and rapidly decreases in extent and thickness west of the town of Bruno (15 ft).

Figure 3-122 presents interpreted Profile L138600, a north-south line near Bruno that extends through the SQS1 Block. It is mostly glacial till/loess made up of marginal aquifer material and non-aquifer material. However, there is a deposit of aquifer material near Bruno. On the west end of the profile is a small area of saturated aquifer material that is part of the paleovalley fill and is capped by till/loess.

Figure 3-123 shows an exploded view voxel showing the volumes of material for ***Q***, ***Kgg***, ***Kd*** and ***IP*** across the entire SQS1 AEM block**.** The ***Q*** aquifer and coarse aquifer materials being the main aquifers of the Block with ***Kd*** Sandstone/Sand Dominant material as a smaller aquifer in the area of the David City paleovalley. The ***Q*** marginal aquifer and non-aquifer materials along with the ***Kgg***, ***Kd*** Shale/Clay Dominant material, and ***IP*** are poor to non-aquifers and often they are boundaries to groundwater flow. Figure 3-124 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 paleovalley area most of the SQS1 Block has a very small number of ***Q*** wells with high specific capacity. The ***Kd*** Sandstone/Sand Dominant material (Figure 3-125) has a limited number of NE-DNR registered wells screened within the ***Kd*** with a high specific capacity within the SQS1 AEM block (indicated on the figure).

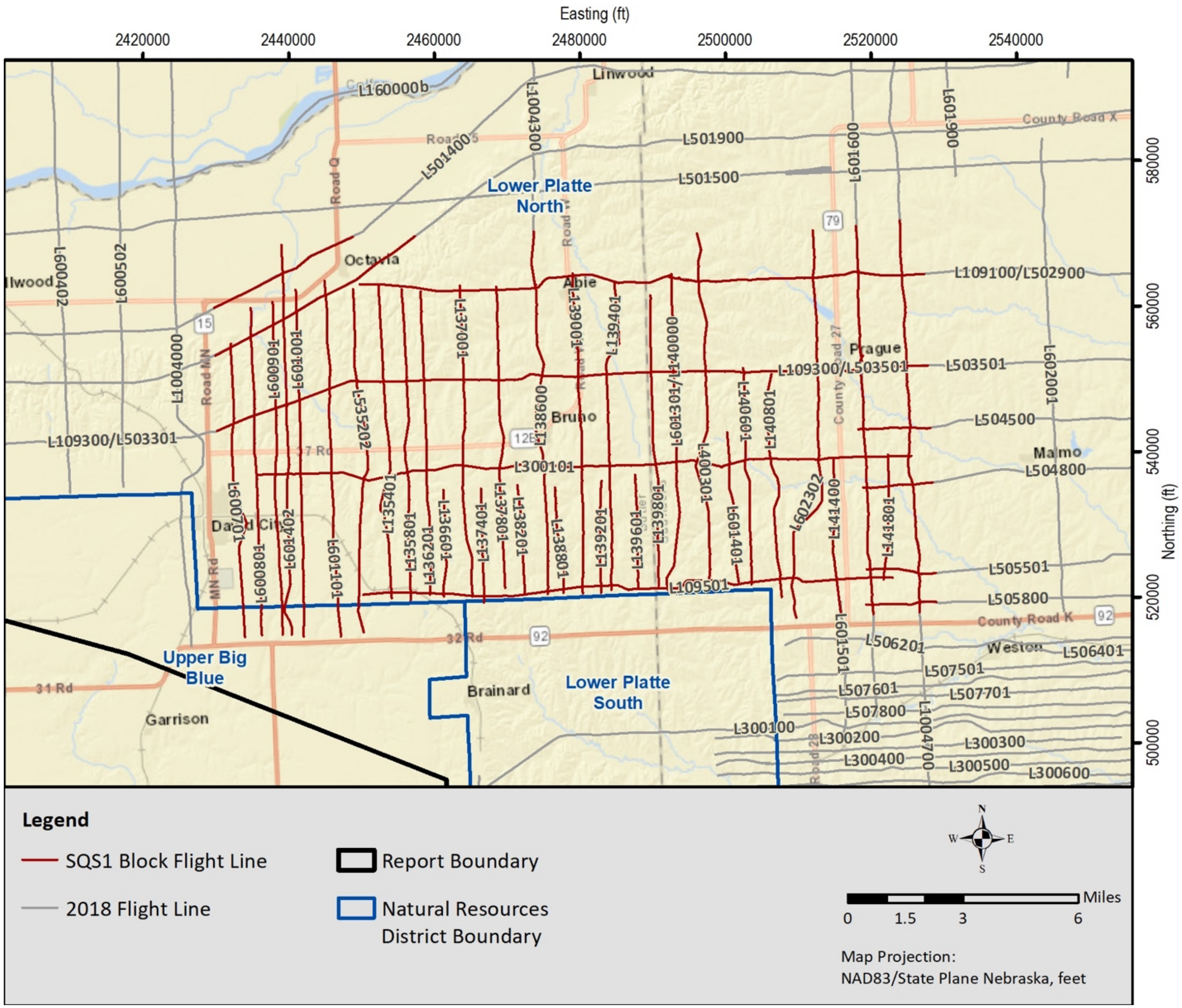


Figure 3-110. Map location of the SQS1 Block indicating AEM flight lines local roads and streams.

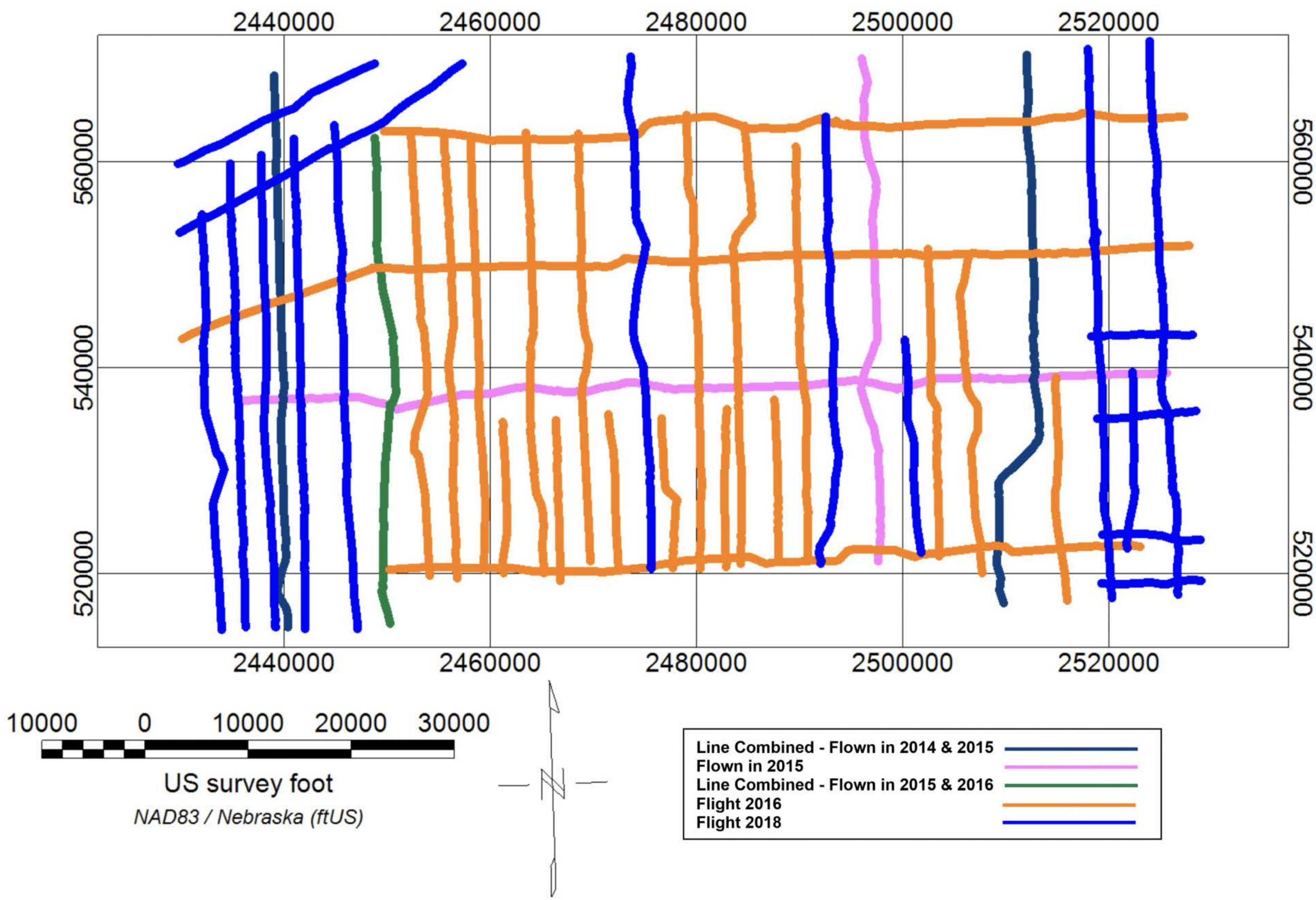


Figure 3-111. Map location of the SQS1 Block indicating the year the AEM flight lines took place. Note that most of the 2018 flight lines were on the west and east sides of the block.

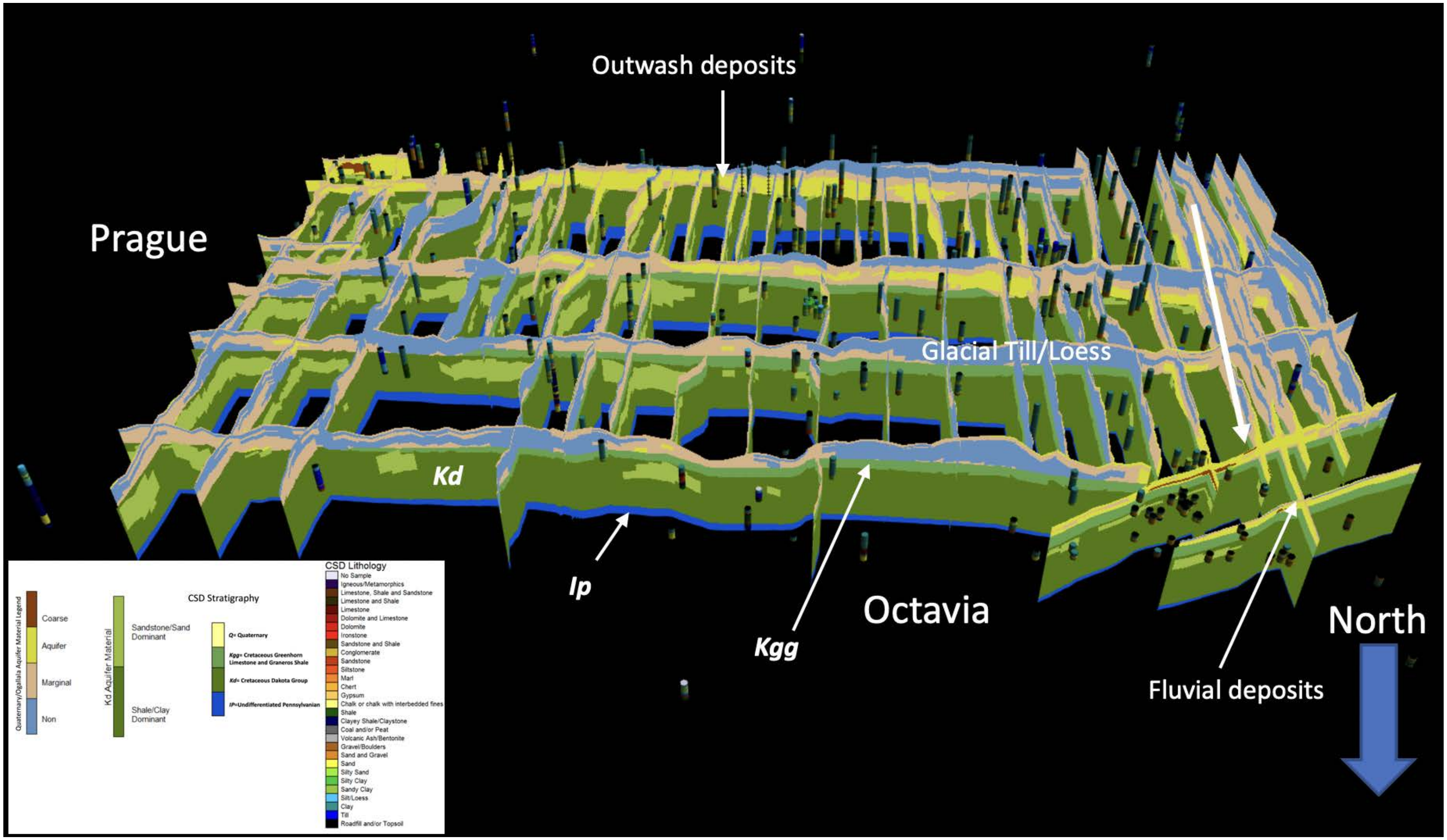


Figure 3-112. 3D fence diagram of interpreted AEM hydrostratigraphic profiles within the SQS1 Block AEM survey area. Note the majority of the area is covered in marginal to non-aquifer materials. CSD test holes and NE-DNR registered wells are indicated on the plot. V.E. = 10x.

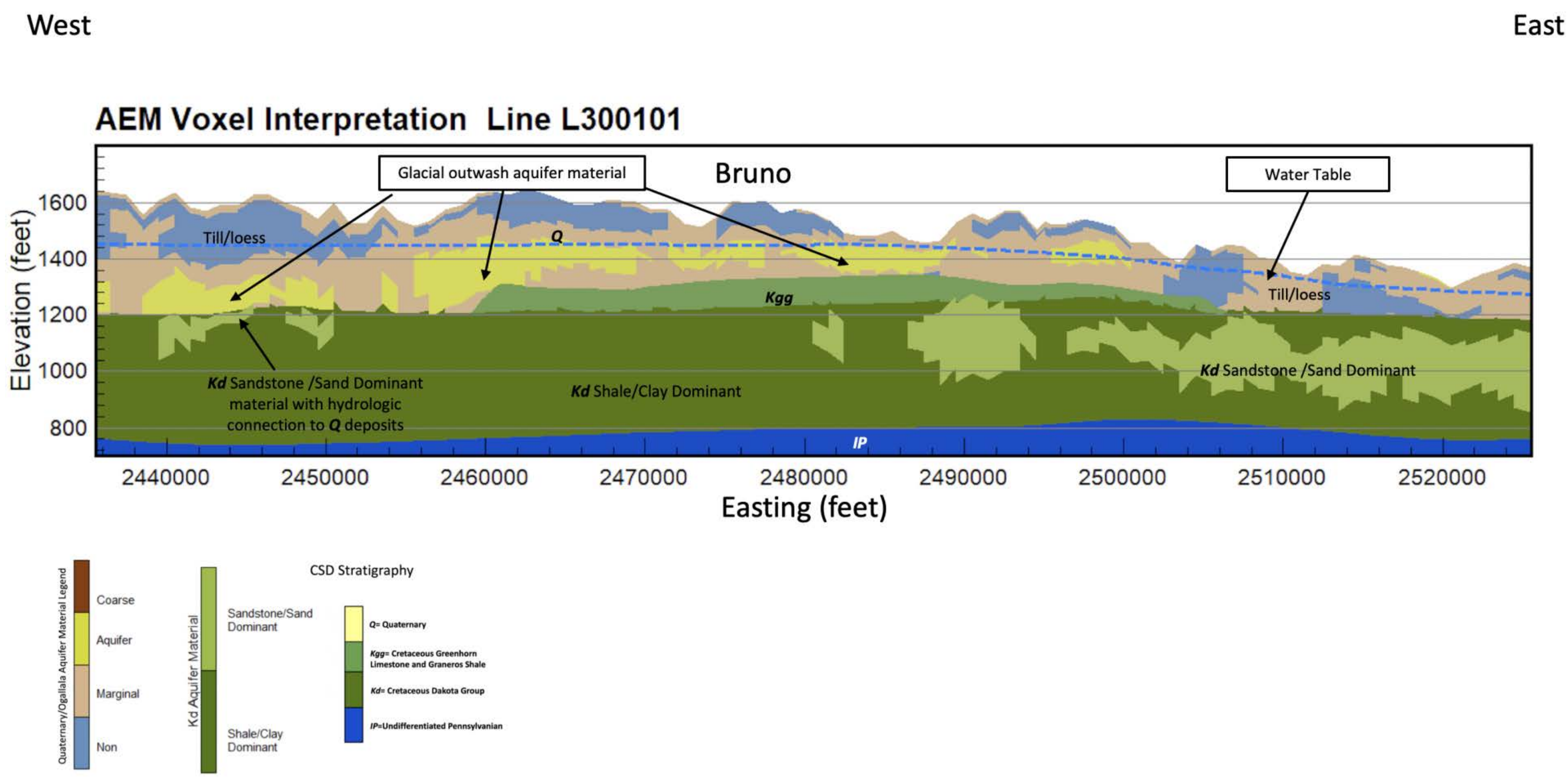


Figure 3-113. Profile of the east-west line L300101 showing the AEM interpretation. The CSD 1995 water table is indicated as a dashed blue line on the profiles. Note the isolated nature of the Quaternary (*Q*) aquifer materials. Horizontal datum is NAD83 State Plane Nebraska (feet).

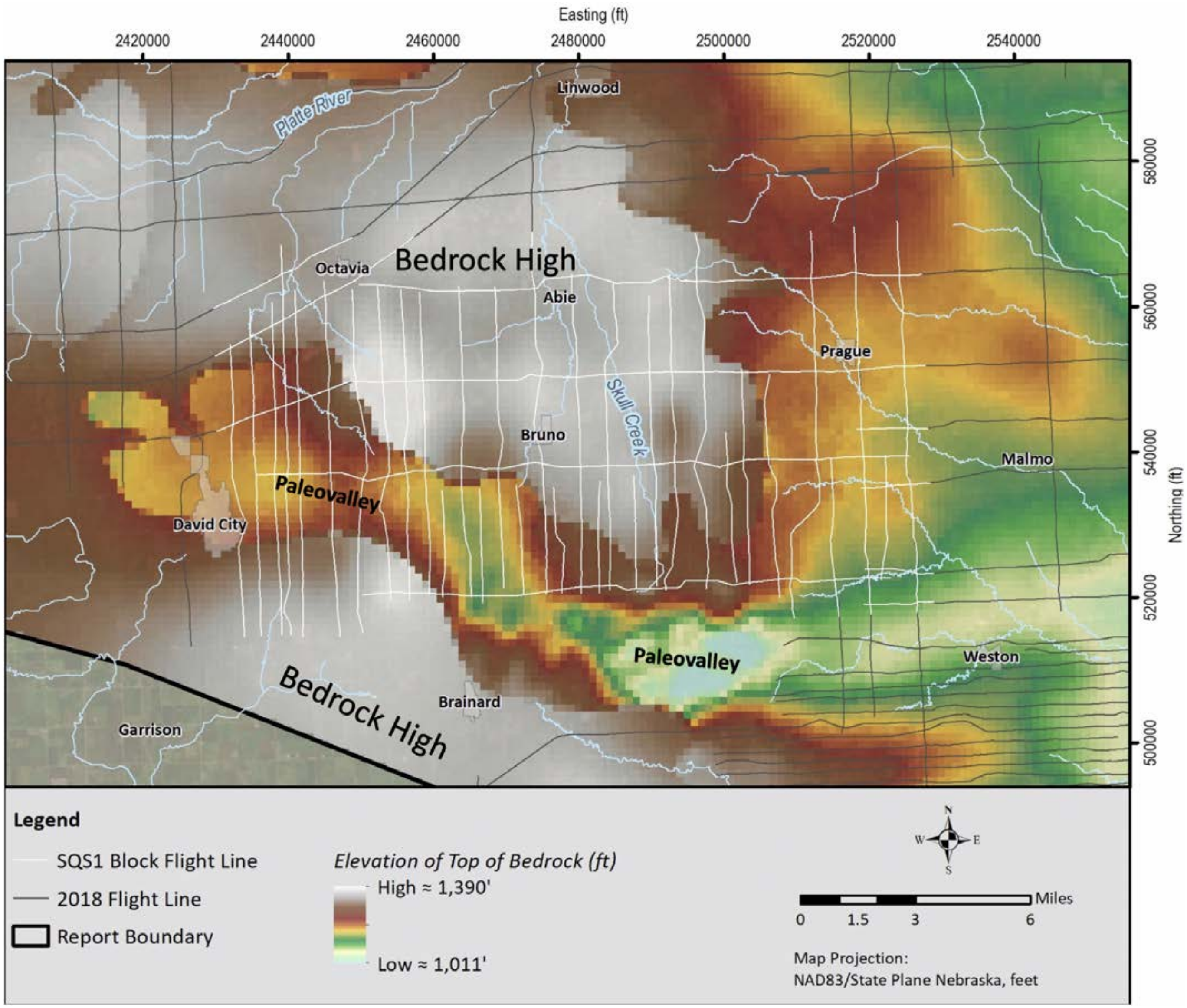


Figure 3-114. Map of the bedrock surface elevation within the SQS1 Block. Block flight lines are indicated by white lines. Note the paleovalley by David City, Nebraska and the bedrock high to each side.

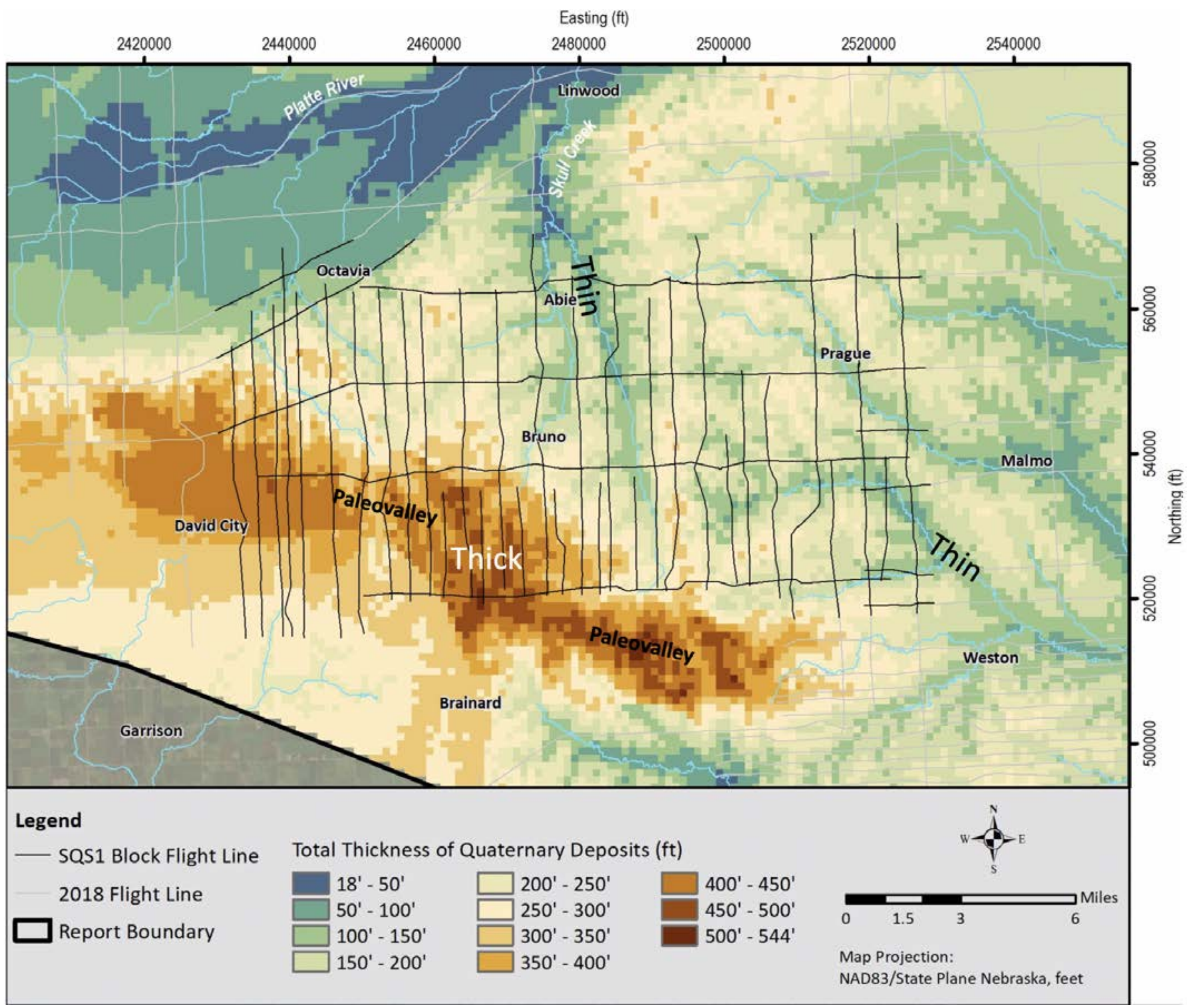


Figure 3-115. Map of the thickness of the Quaternary (*Q*) saturated aquifer and coarse aquifer materials within the SQS1 Block AEM survey area. Block flight lines are indicated by black lines. Note the thick deposits centered on the paleovalley near David city, Nebraska.

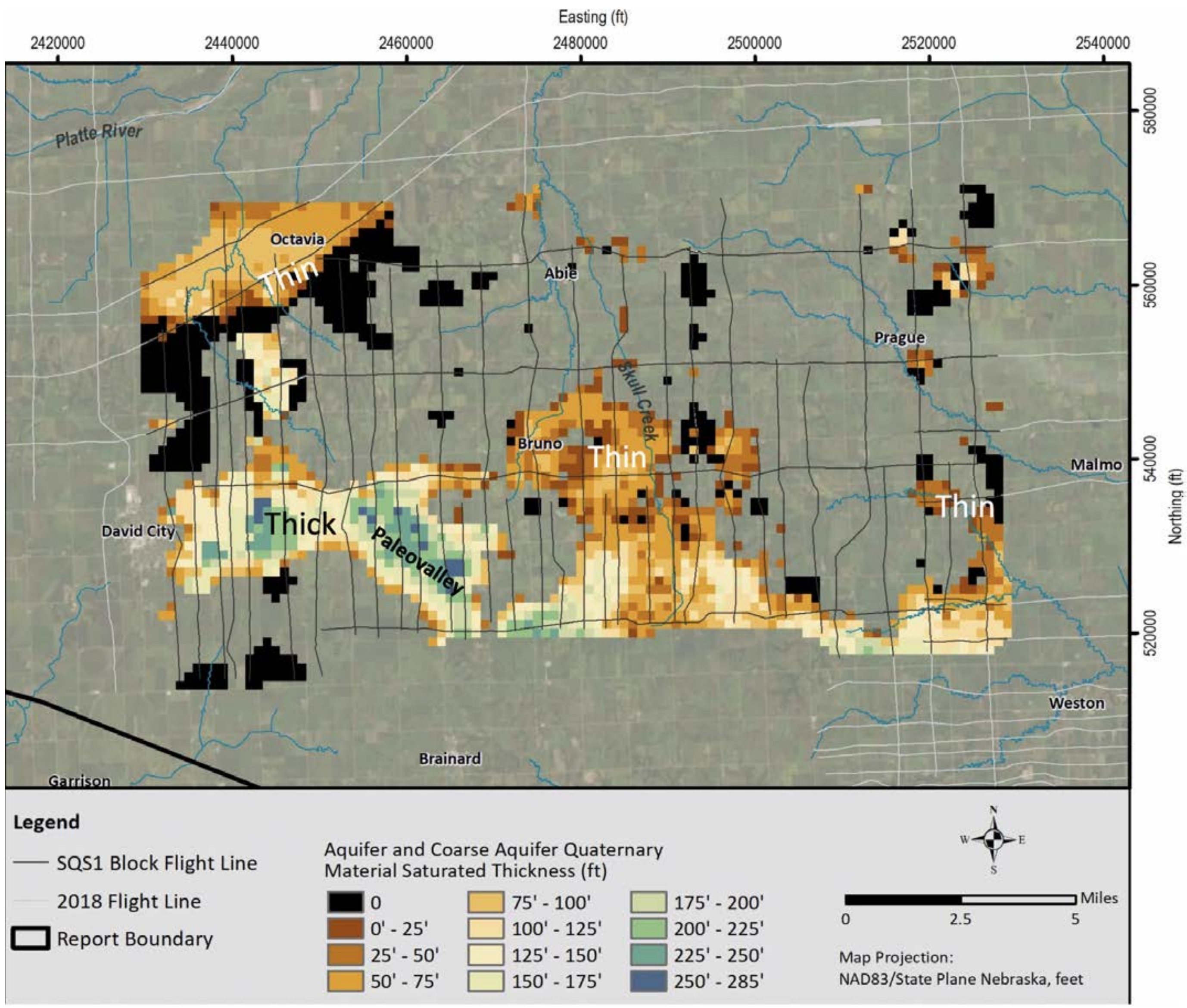


Figure 3-116. Map of the saturated thickness of the Quaternary (*Q*) aquifer and coarse aquifer materials within the SQS1 Block AEM survey area. Block flight lines are indicated by the black lines. Note the thick areas of these materials is in the paleovalley near David City, Nebraska.

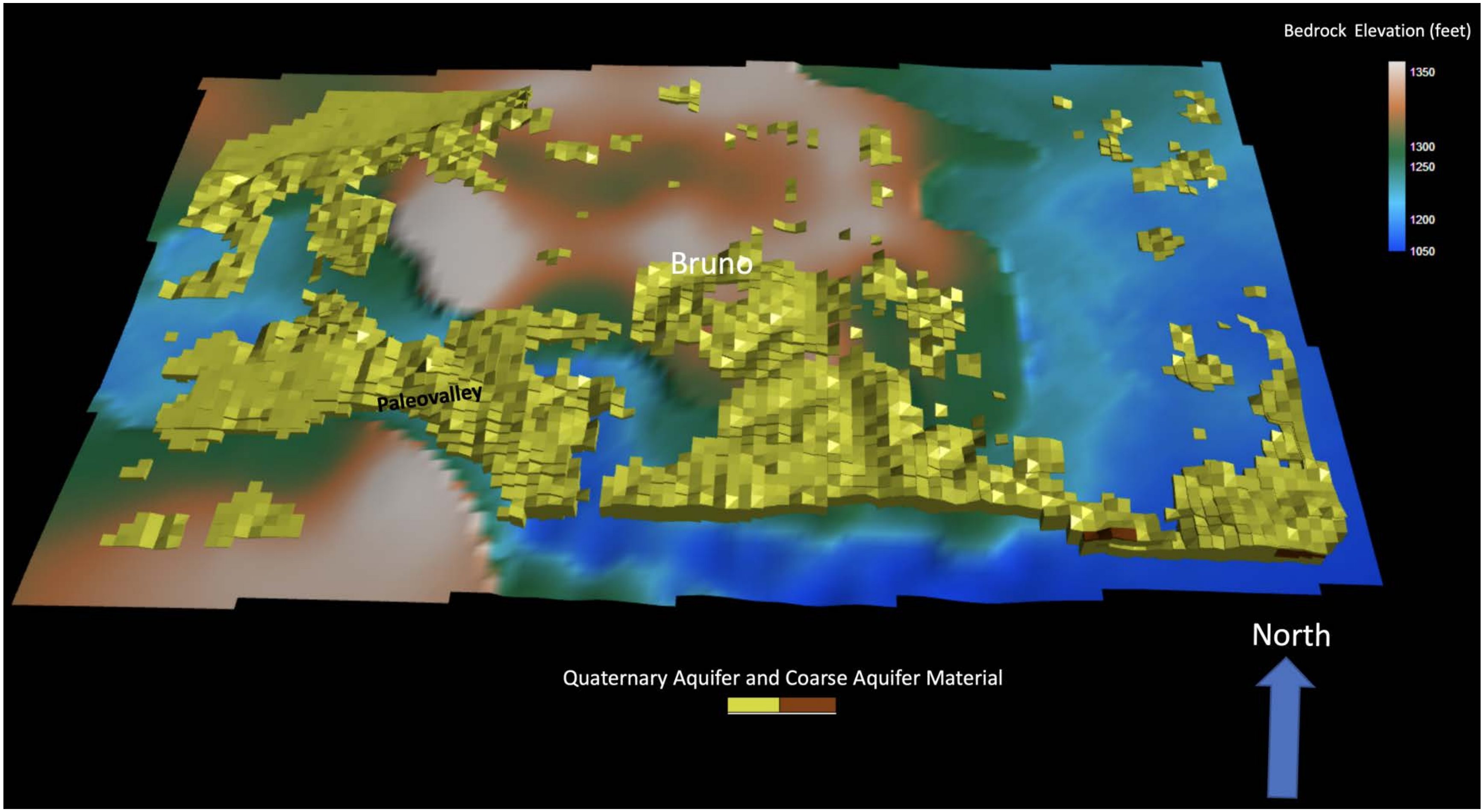


Figure 3-117. 3D voxel plot of the unsaturated Quaternary (*Q*) aquifer materials. Note the discontinuous nature of this unit. V.E. = 10x.

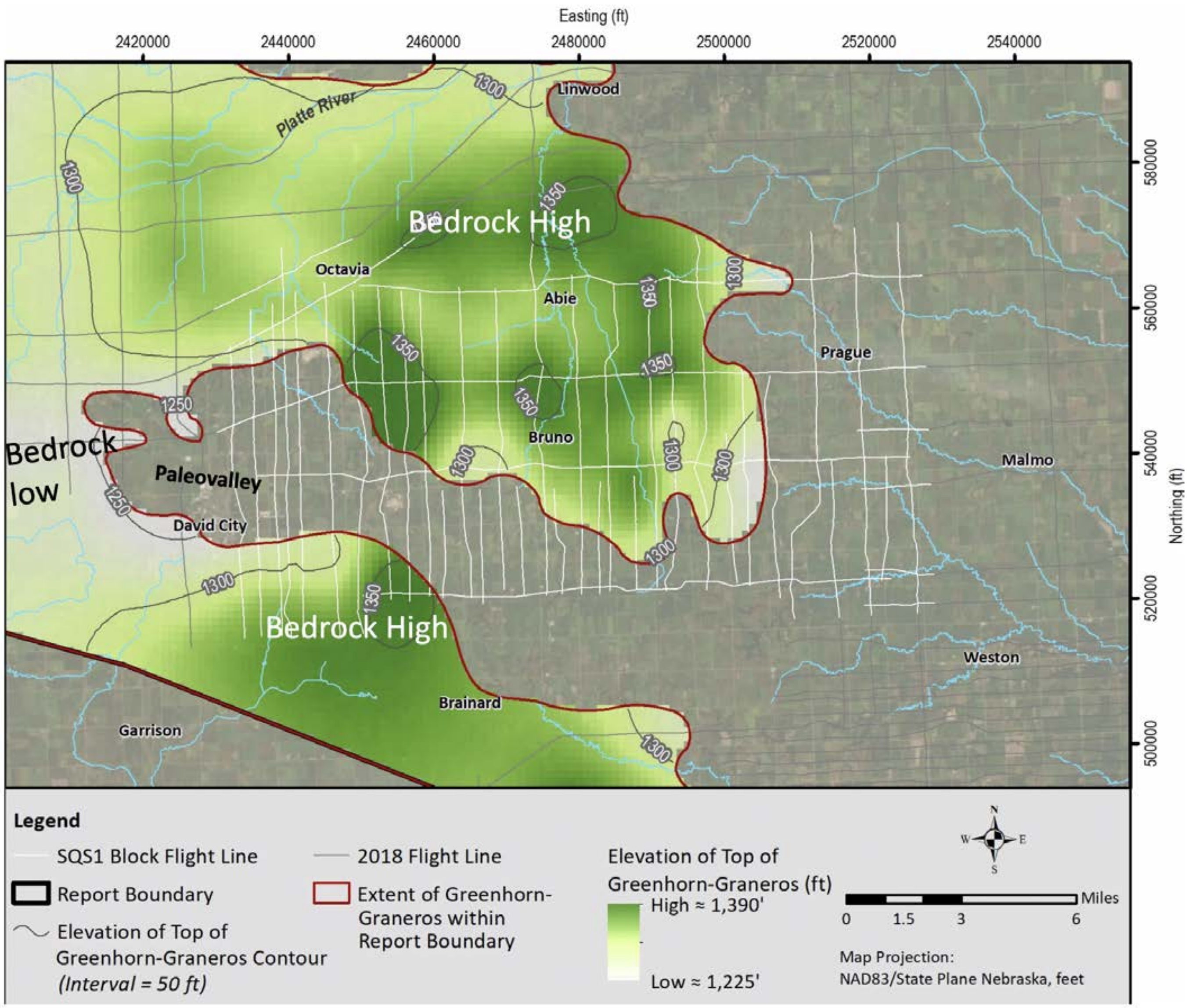


Figure 3-118. Map of the Cretaceous Greenhorn-Graneros FM (*Kgg*) surface elevation within the SQS1 Block AEM survey area. Block flight lines are indicated by white lines. Note the paleovalley by David City, Nebraska and the bedrock high to each side.

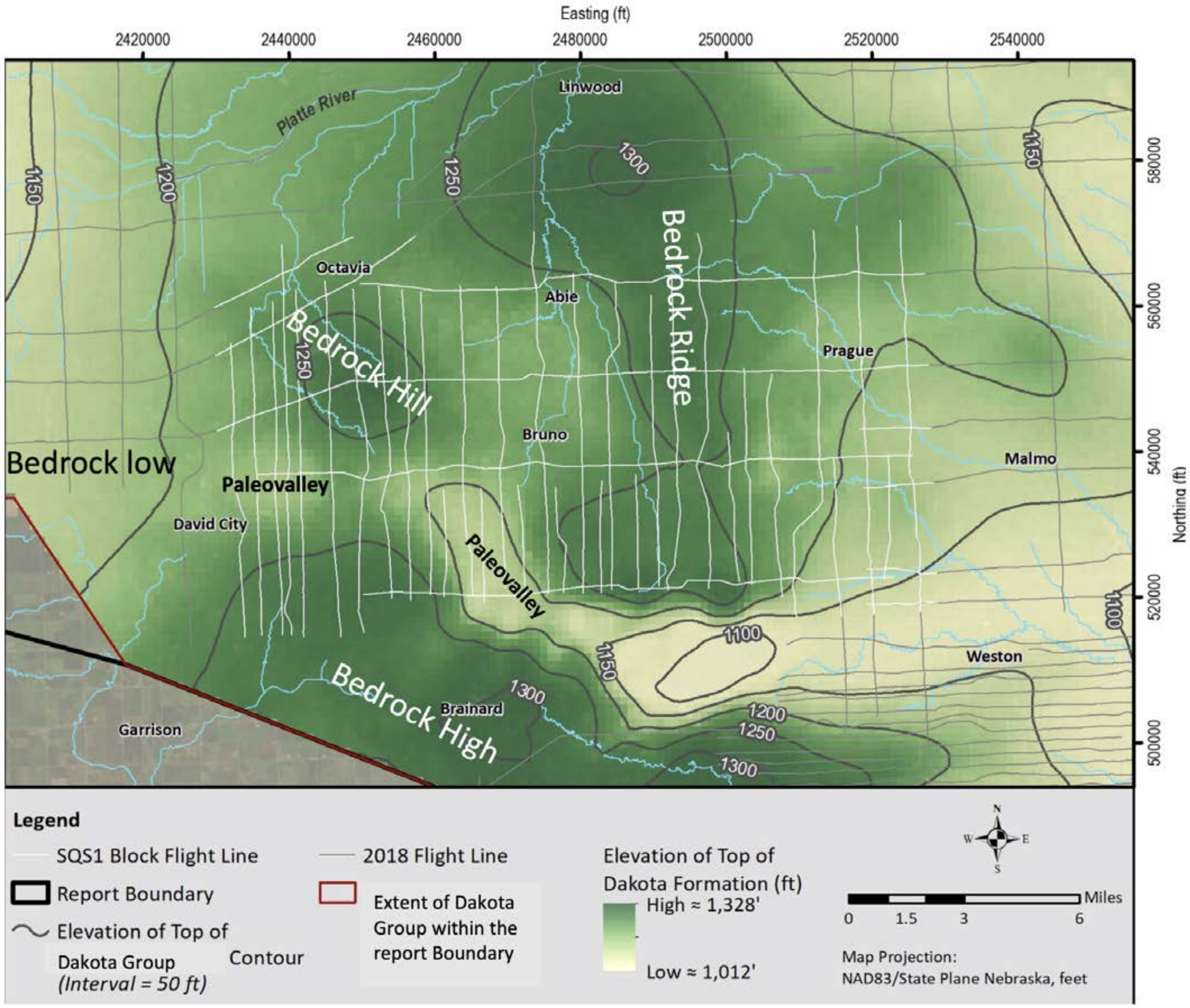


Figure 3-119. Map of the surface elevation of the Cretaceous Dakota Group (*Kd*) within the SQS1 Block AEM survey area. Block flight lines are indicated by white lines. Note the bedrock highs centered on Bruno, Nebraska.

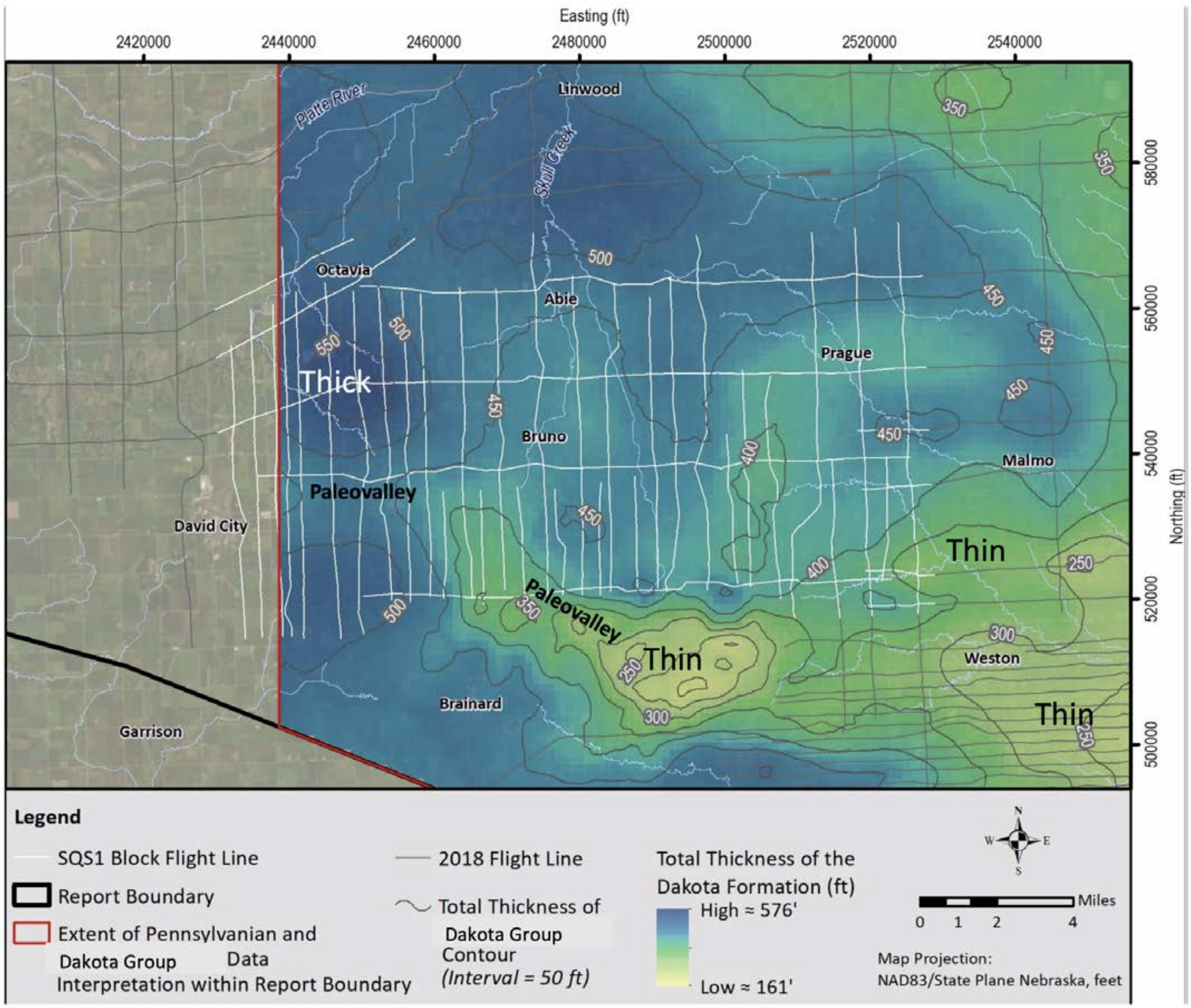


Figure 3-120. Map of the thickness of the Cretaceous Dakota Group (*Kd*) within the SQS1 Block AEM survey area. Block flight lines are indicated by white lines. Note the thin deposits centered on the paleovalley near David city, Nebraska.

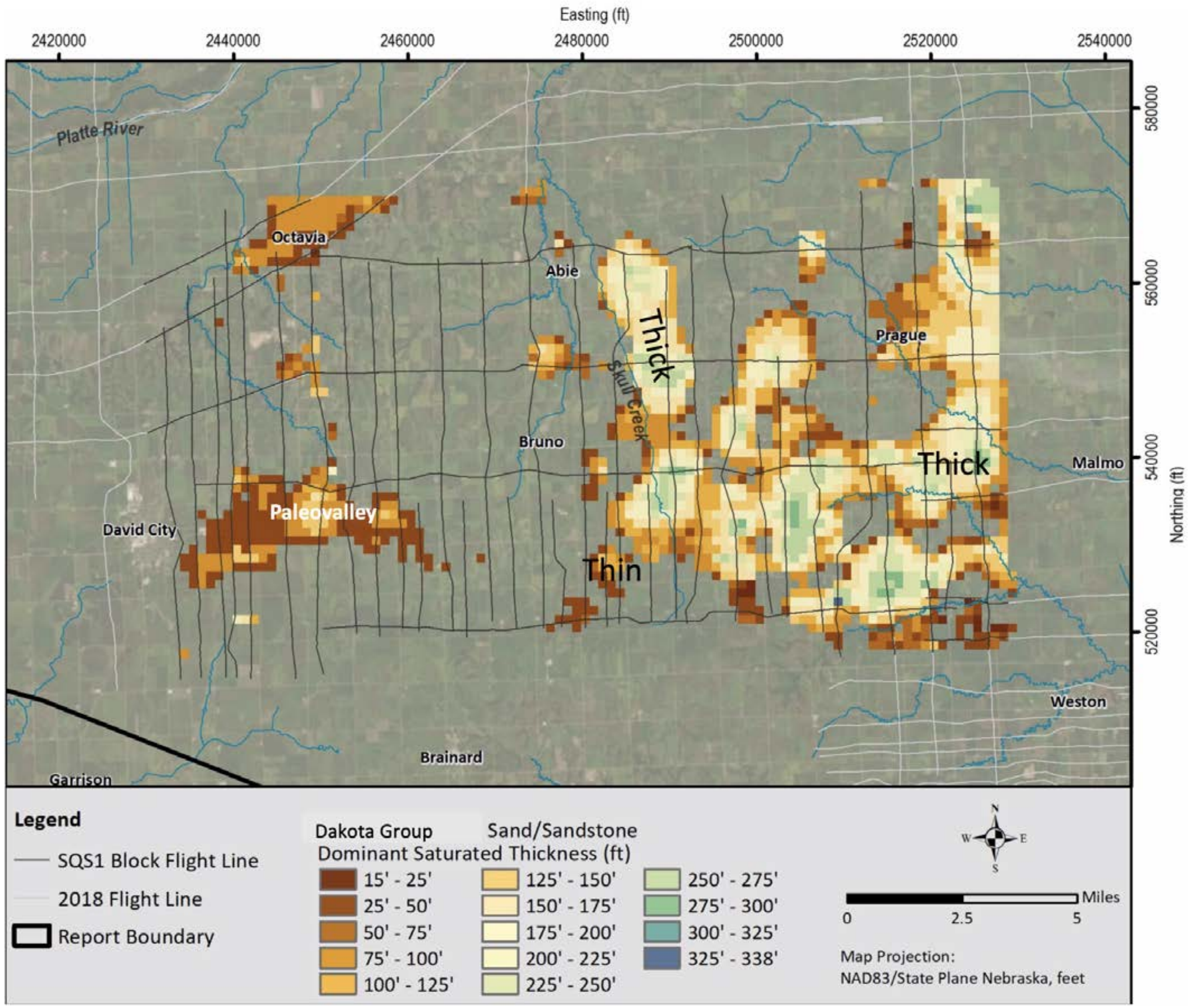


Figure 3-121. Map of the saturated thickness of the Cretaceous Dakota Group (*Kd*) Sandstone/Sand Dominant material within the SQS1 Block AEM survey area. Block flight lines are indicated by the black lines. Note the thick areas of these materials on the east side of the block area.

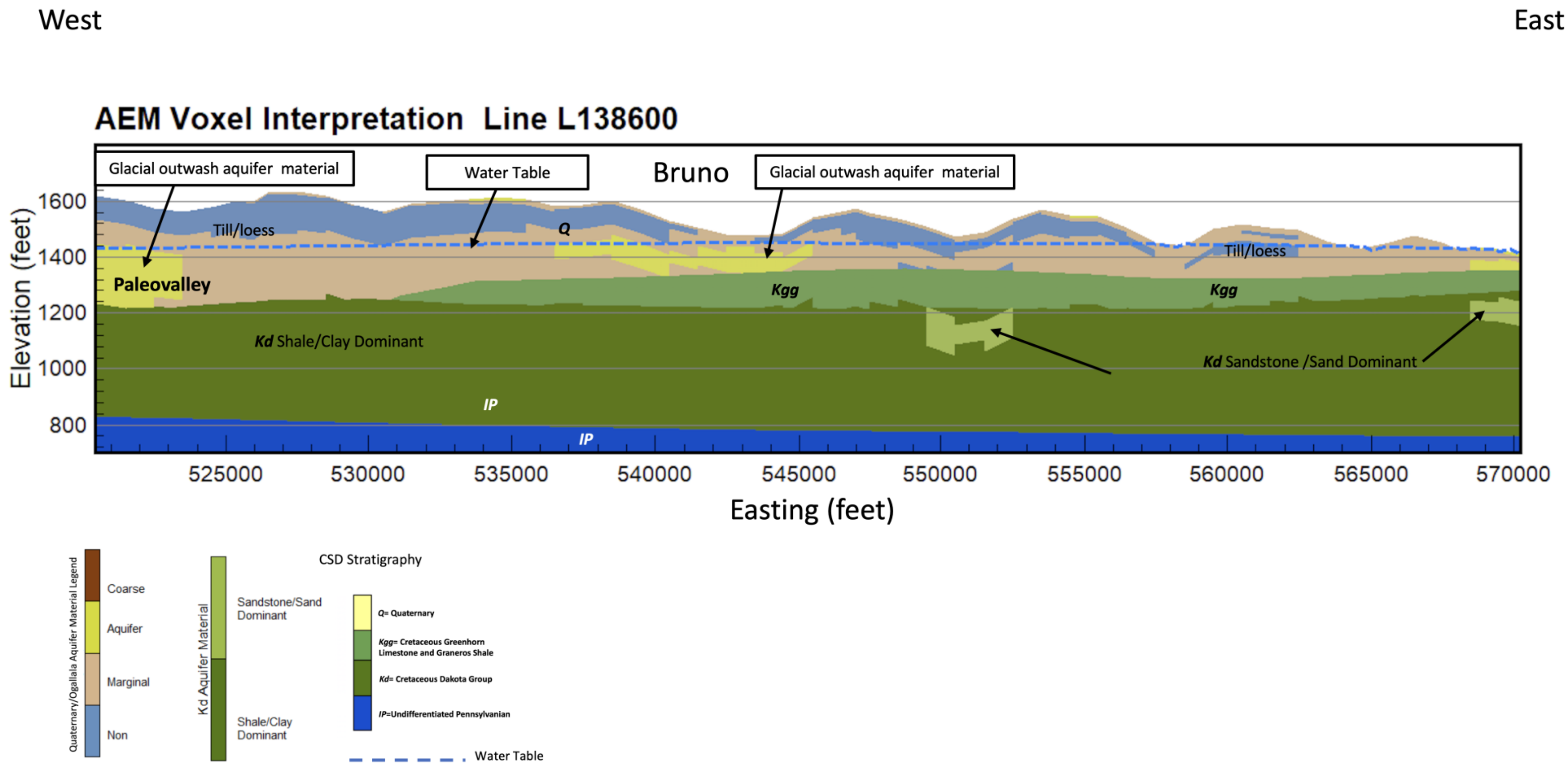


Figure 3-122. Profile of the east-west line L138600 showing the AEM interpretation. The CSD 1995 water table is indicated as a dashed blue line. Note the isolated nature of the Quaternary (*Q*) aquifer materials. Horizontal datum is NAD83 State Plane Nebraska (feet).

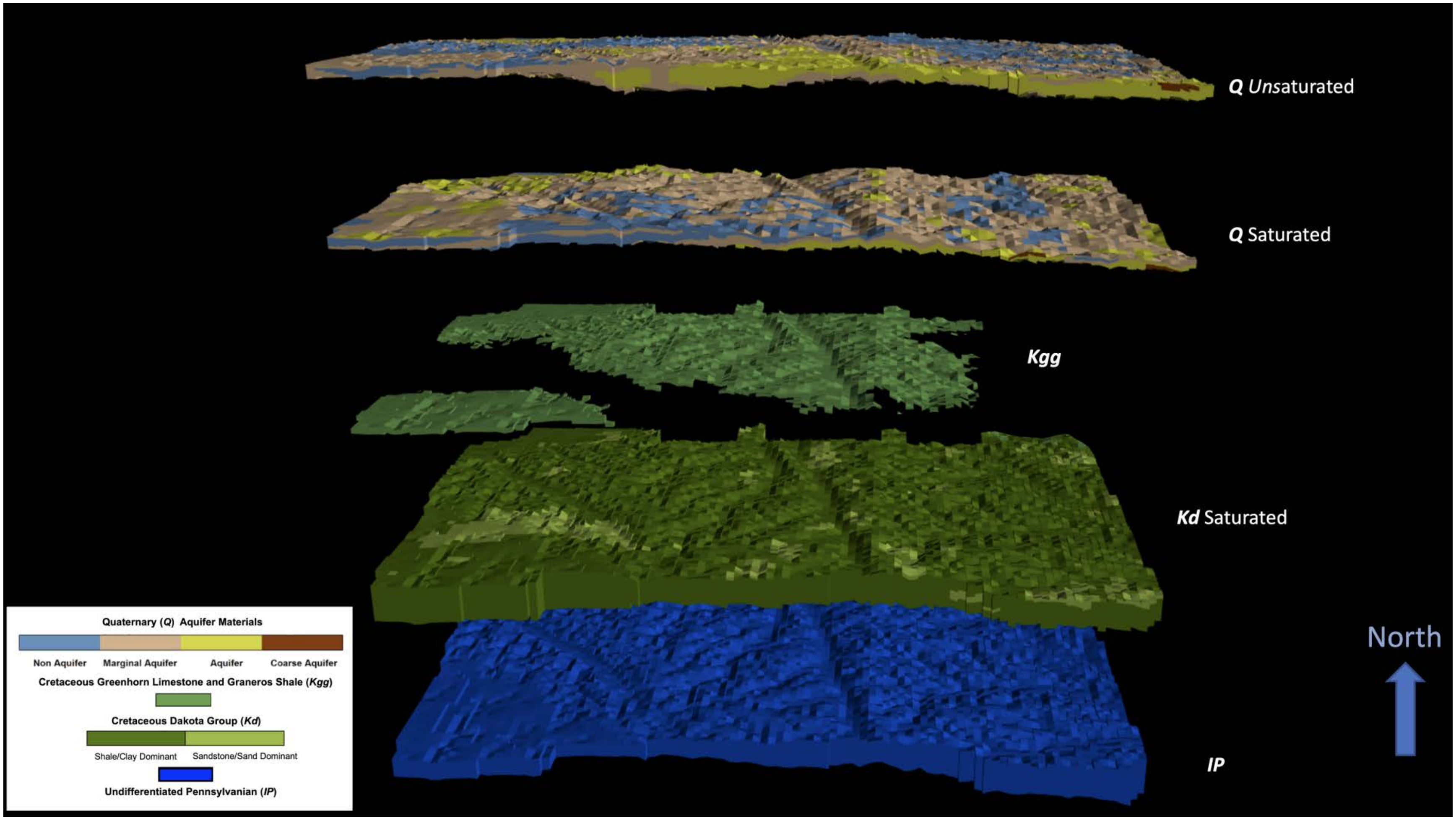


Figure 3-123. 3D 'exploded' voxel model of the SQS1 Block AEM survey area showing unsaturated *Q*, saturated *Q*, the *Kgg*, saturated *Kd*, and the *IP.* V.E. =10x, but the image is not to scale.

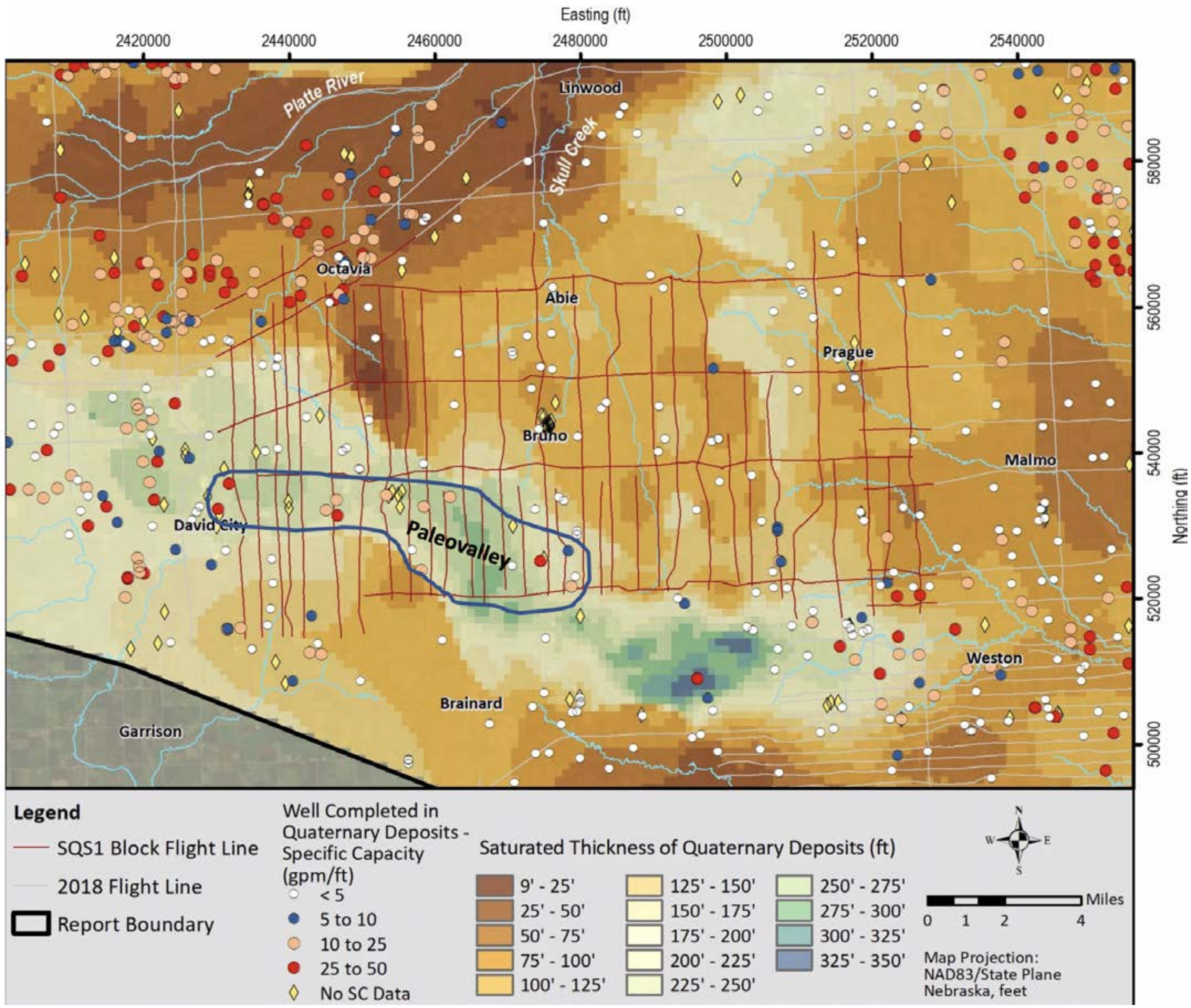


Figure 3-124. Map of the saturated thickness of the Quaternary (*Q*) deposits related to the specific capacity of the wells screened within the *Q*. Block flight lines are indicated by the red lines. Note the thick areas of these materials is in the paleovalley near David City, Nebraska.

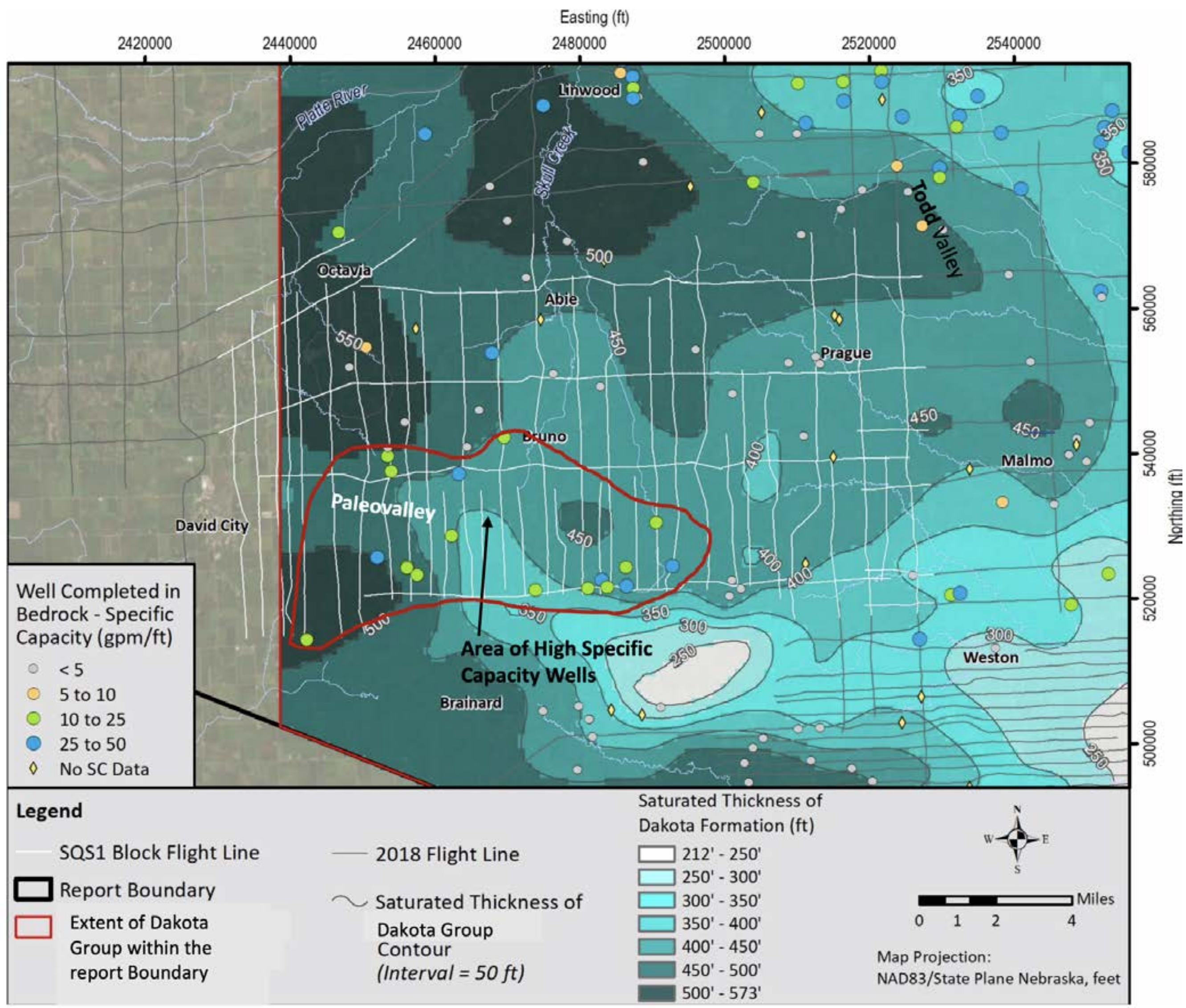


Figure 3-125. Map of the saturated thickness of the Cretaceous Dakota Group (*Kd*) material compared to the specific capacity of the NE-DNR wells screened within the *Kd*. Block flight lines are indicated by the black lines. Note high capacity wells in the area around the paleovalley near David City, Nebraska.

3.2.2.3 Hydrogeologic Framework of the SQS2 Block AEM Survey Area

In 2016 an AEM survey was flown over the majority of the area of SQS2 (AGF, 2017). The AEM survey provided insight into the geographic distribution and extent of the unconsolidated material in the SQS2 Block AEM survey area, as well as the Cretaceous bedrock configuration. The bedrock in the SQS2 Block is composed of ***Kn***, ***Kc***, and ***Kgg***. In much of the area the AEM system did not have the depth of investigation to fully image the ***Kd*** nor the ***IP***. The ***Q*** materials within the SQS2 Block are composed of unconsolidated alluvial silt, sand, and gravel as well as glacial derived outwash and till. The area is generally overlain with loess (AFG, 2017). The flight block is on the western edge of the LPNNRD near the LLNRD and the LENRD in the area that is bounded on the north and east by the LENRD and partially on the south and east by the LLNRD. The SQS2 Block is located north of Columbus, Nebraska and is south of the LENRD boundary. The eastern edge of the block is east of the Platte/Colfax county line and encompasses a north-south line east within the LENRD boundary Figure 3-126. The 2018 flight block is 93% of the size of the 2016 SQS2 flight Block. The Block was reduced due to an error in the interpolation between reconnaissance lines. Figure 3-127 shows the year the individual flight lines were flown including: 2014, 2016, and 2018. The 2018 SQS2 Block uses all of the available data for the interpretation, but it is important to note that only seven lines (blue on map) from the total used were flown in 2018 and they are mostly at the southern ends of the block. This section will build on the 2017 AGF LPNNRD report (AGF, 2017).

Figure 3-128 displays a 3D fence diagram looking to the north of the interpreted hydrostratigraphic profiles with CSD and NE-DNR borehole lithology data for the SQS2 Block AEM survey area. The area generally contains a mix of all ***Q*** aquifer materials lying upon the ***Kn***, ***Kc***, and ***Kgg***. The boreholes in the area indicate a mix of silty clay, sandy clay, and sand in the block area. The area to the south along Shale Creek has aquifer and coarse aquifer material. As can be seen on Figure 3-128, 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 much of the area because the permeability of these materials is low limiting the amount of infiltration. The main aquifer material is areas of glacial outwash and fluvial deposits made up of mostly aquifer material and minor amounts coarse aquifer material in the south. Figure 3-129 is a 2D profile of flight line L500601, one of the 2018 east-west flight lines along Shale Creek that is dominated by aquifer and coarse aquifer material. The bedrock shows the Cretaceous units dipping to the west and the younger units eroded off toward the east.

Figure 3-130 is a map of the top of the Cretaceous bedrock for the SQS2 block area with a paleovalley cut ~250 feet deep that trends east from Tarnov, Nebraska. The total thickness of the ***Q*** material in the SQS2 Block AEM area (Figure 3-131) was calculated by subtracting the bedrock elevation from the ground surface elevation. The ***Q*** varies in thickness from 54 to 429 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.

Not all of the ***Q*** is saturated as indicated in Figure 3-132, a map of the saturated ***Q*** thickness. The greatest saturated thickness is in the area of the paleochannel from Figure 3-130. 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. The saturated aquifer and coarse aquifer material for SQS2 is shown in Figure 3-133. As can been seen from this iteration of the SQS2 block interpretation as well as the 2016 version (AGF, 2017) much of the area has deposits of saturated aquifer materials. The thickness of these materials varies between 0, where there is no aquifer and coarse aquifer material to the maximum thickness of 230 feet with an average thickness of 75 feet.

Examining the specific capacity of the NE-DNR registered wells screened within the ***Q*** can provide insight into the quality of the aquifer that is indicated in Figure 3-133. A map of the saturated thickness of the ***Q*** deposits with the specific capacity of the NE-DNR registered wells screened within the ***Q*** plotted is presented in Figure 3-134. The areas indicate an even distribution of wells that are for 10 to 50 gpm/ft.

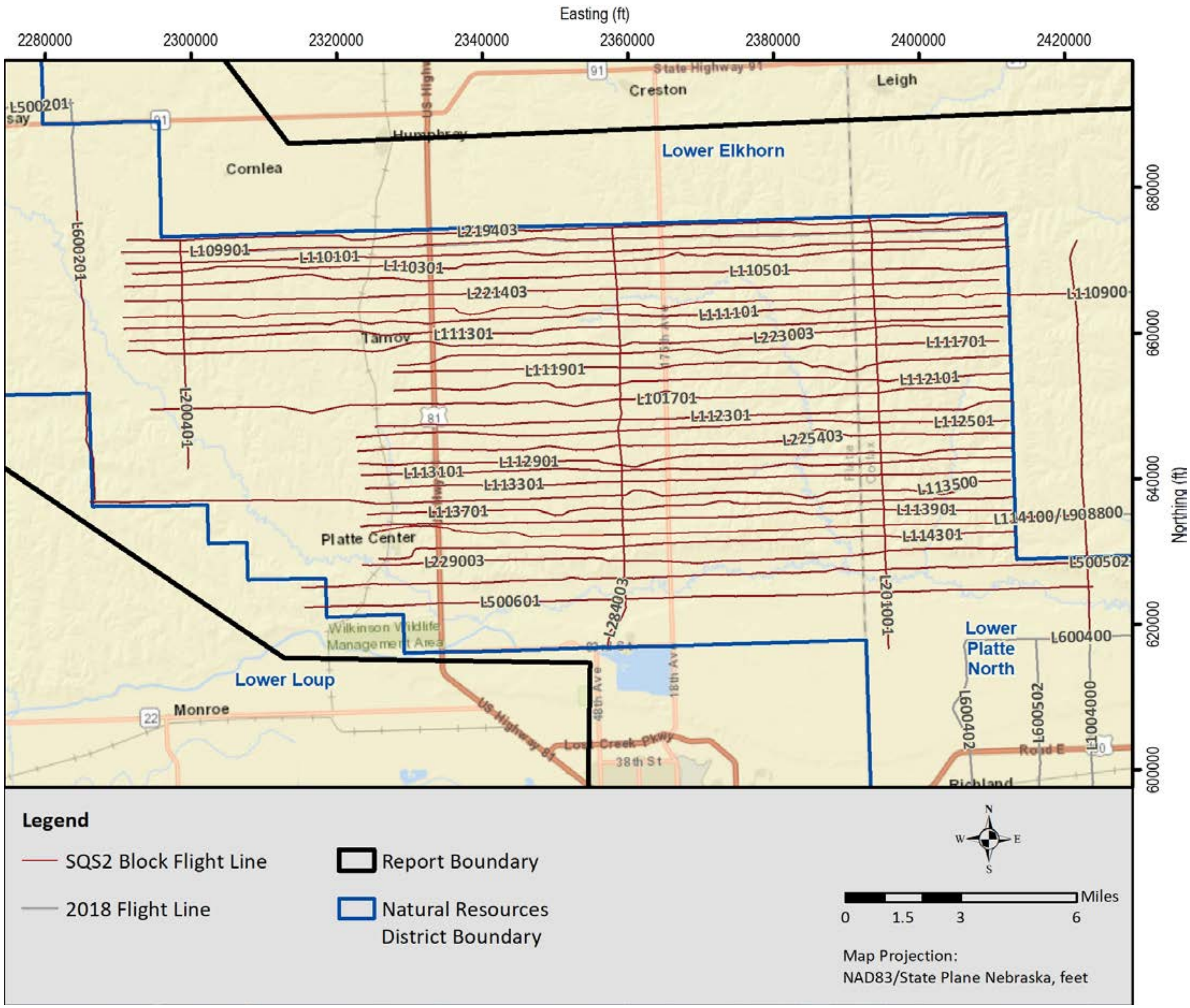


Figure 3-126. Map location of the SQS2 Block indicating AEM flight lines, local roads, and streams.

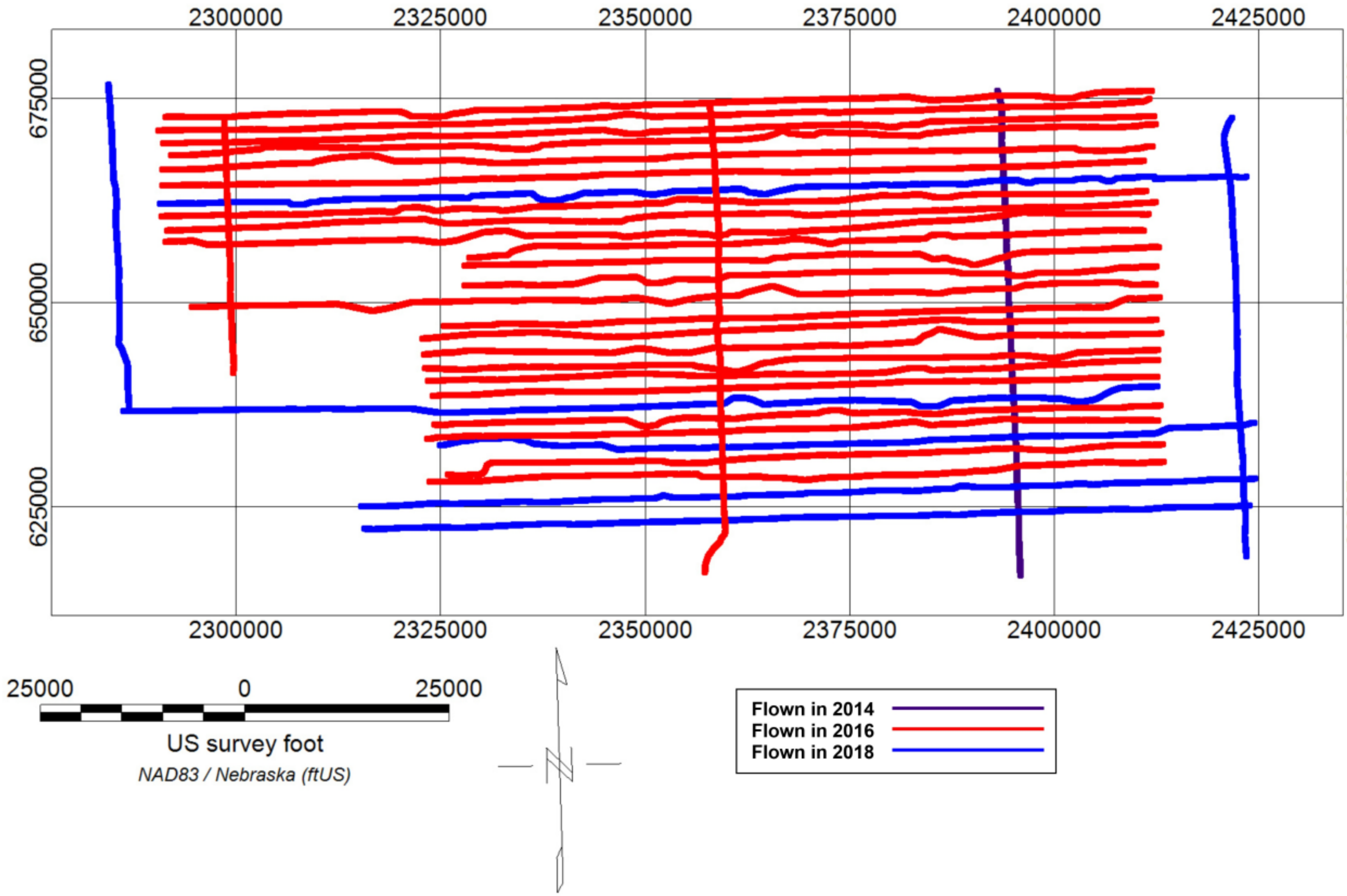


Figure 3-127. Map location of the SQS2 Block indicating the year the AEM flight lines took place. Note that only a few lines were flown in 2018.

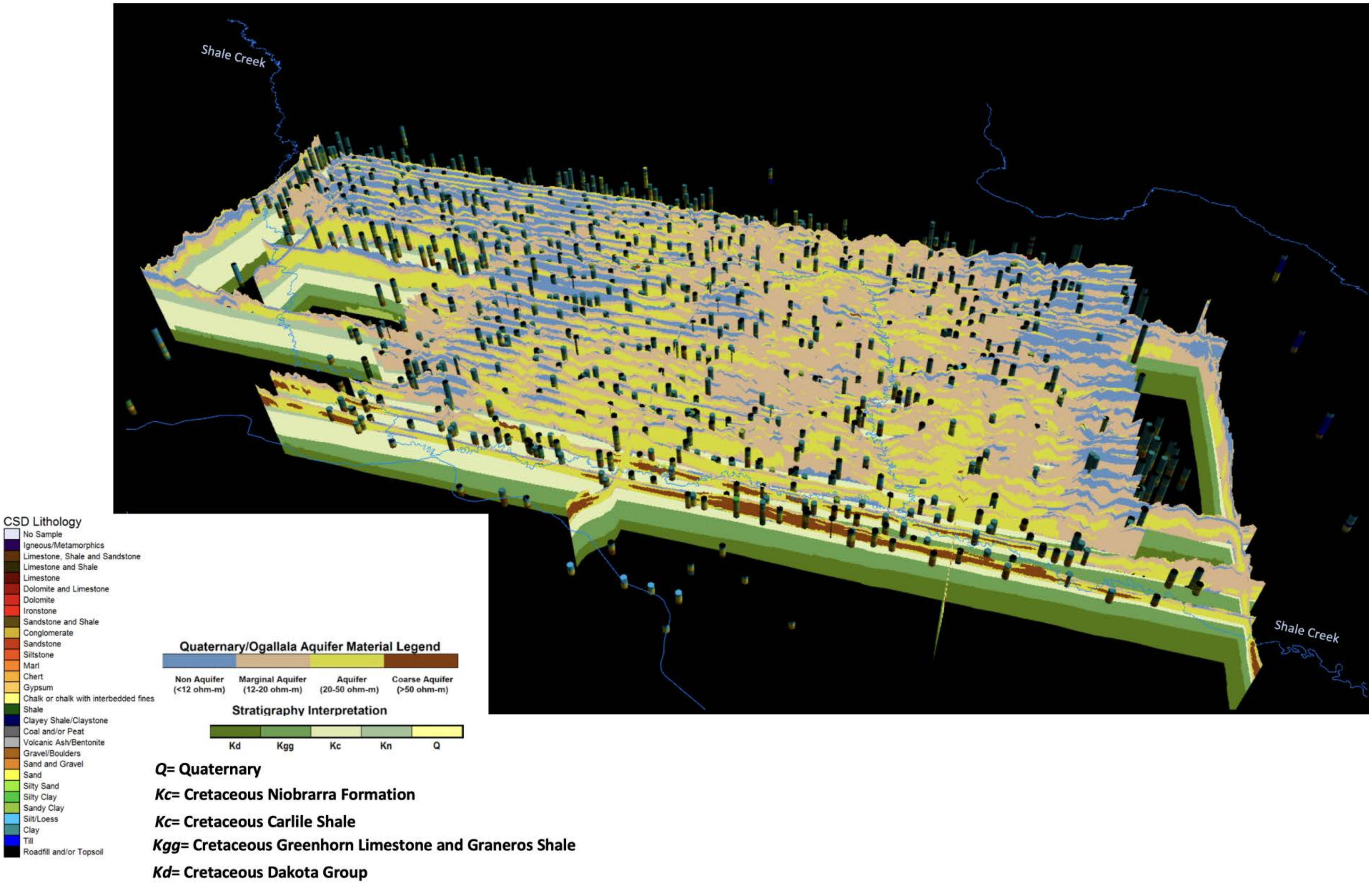


Figure 3-128. 3D fence diagram of interpreted AEM hydrostratigraphic profiles within the 2018 SQS2 Block AEM survey area. Note the majority of the area is covered in marginal to non-aquifer materials, with the exception of the area along Shale Creek. V.E. = 10x.

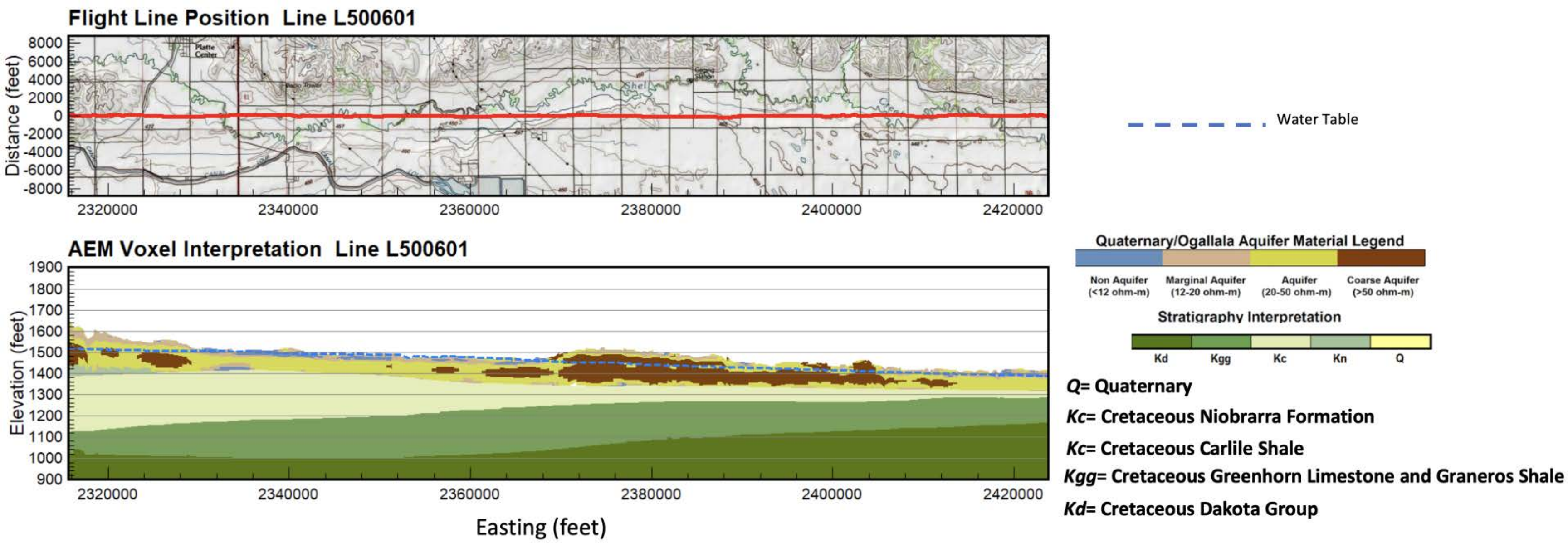


Figure 3-129. Profile of the 2018 east-west line L500601 showing the relationship of the AEM interpretation to a line along Shale Creek. The CSD 1995 water table is indicated as a dashed blue line on the profiles. Note the Cretaceous units dipping to the west. Horizontal datum is NAD83 State Plane Nebraska (feet).

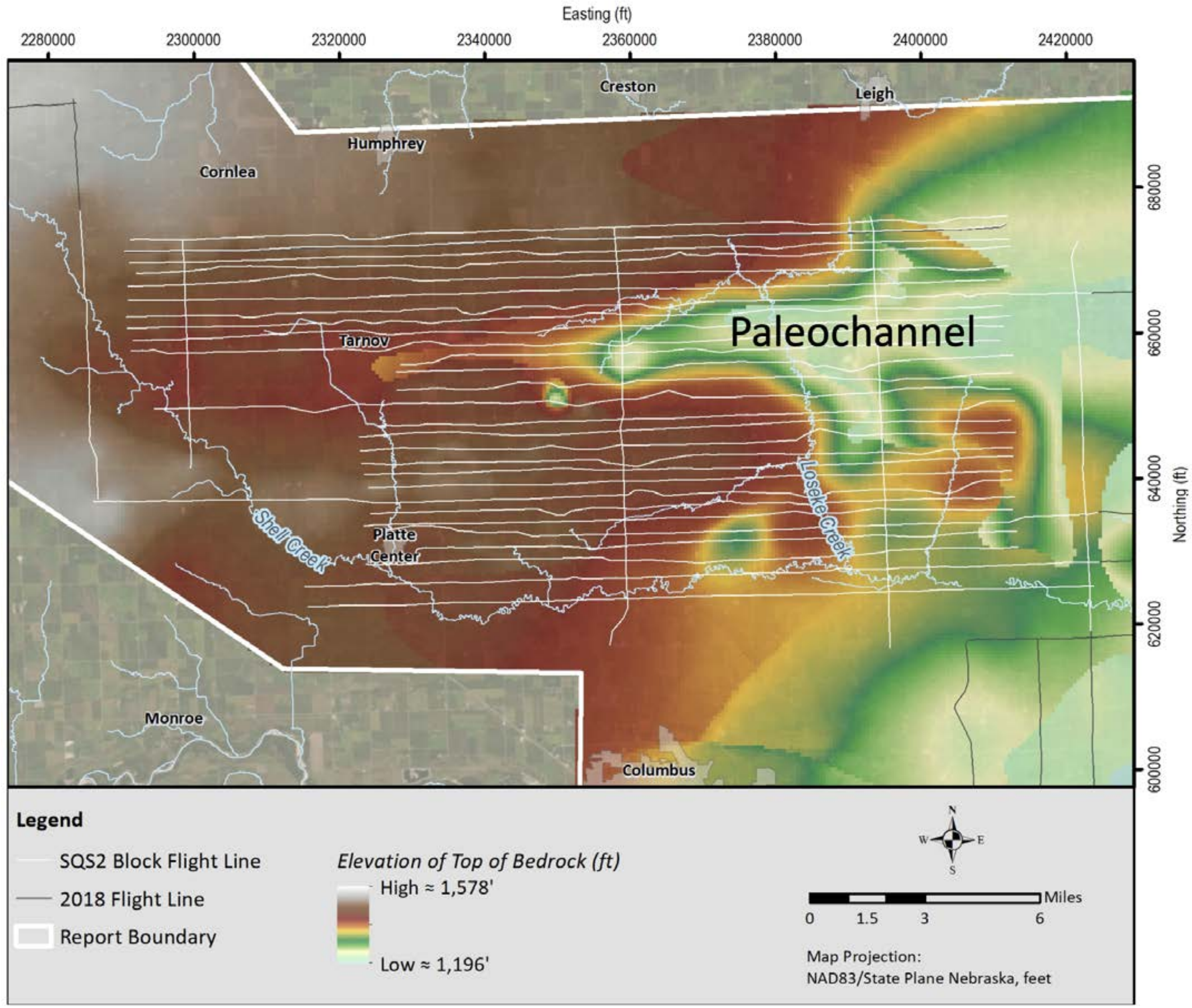


Figure 3-130. Map of the bedrock surface elevation within the SQS2 Block. Block flight lines are indicated by white lines. Note the paleovalley east of Tarnov, Nebraska and the bedrock high to each side.

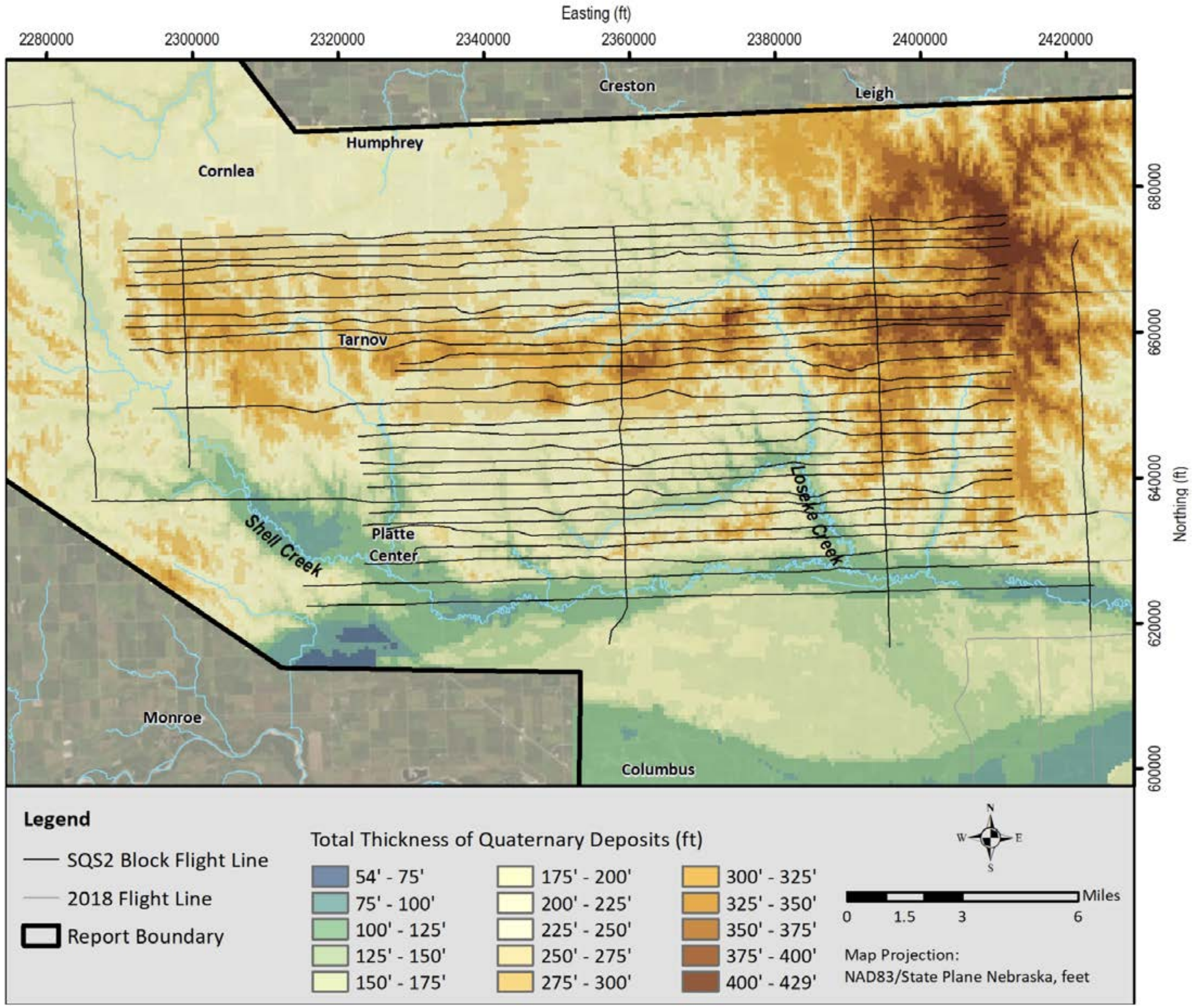


Figure 3-131. Map of the thickness of the Quaternary (*Q*) material within the SQS2 Block. Block flight lines are indicated by the black lines.

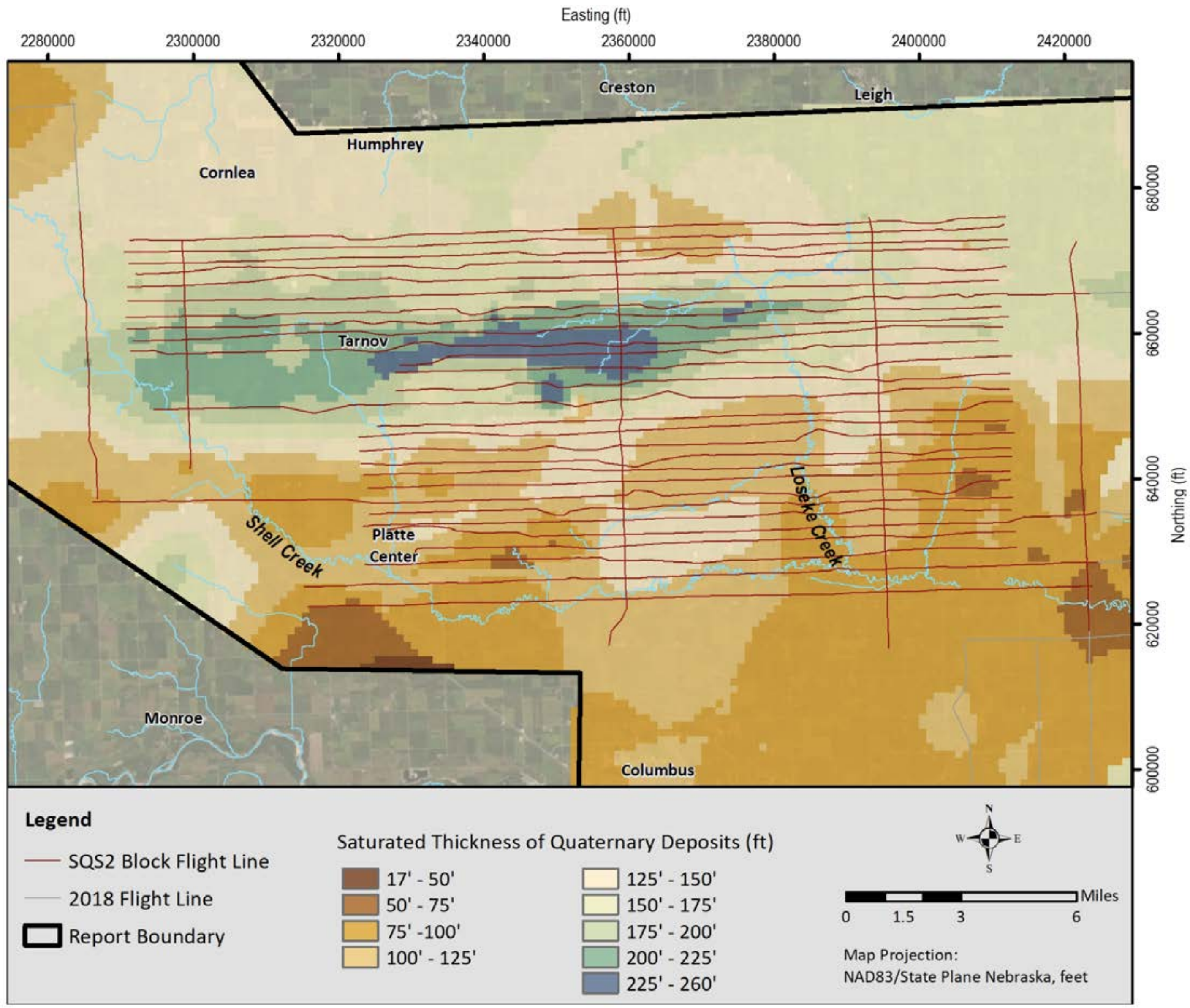


Figure 3-132. Map of the saturated thickness of the Quaternary (*Q*) within the SQS2 Block. Block flight lines are indicated by the red lines.

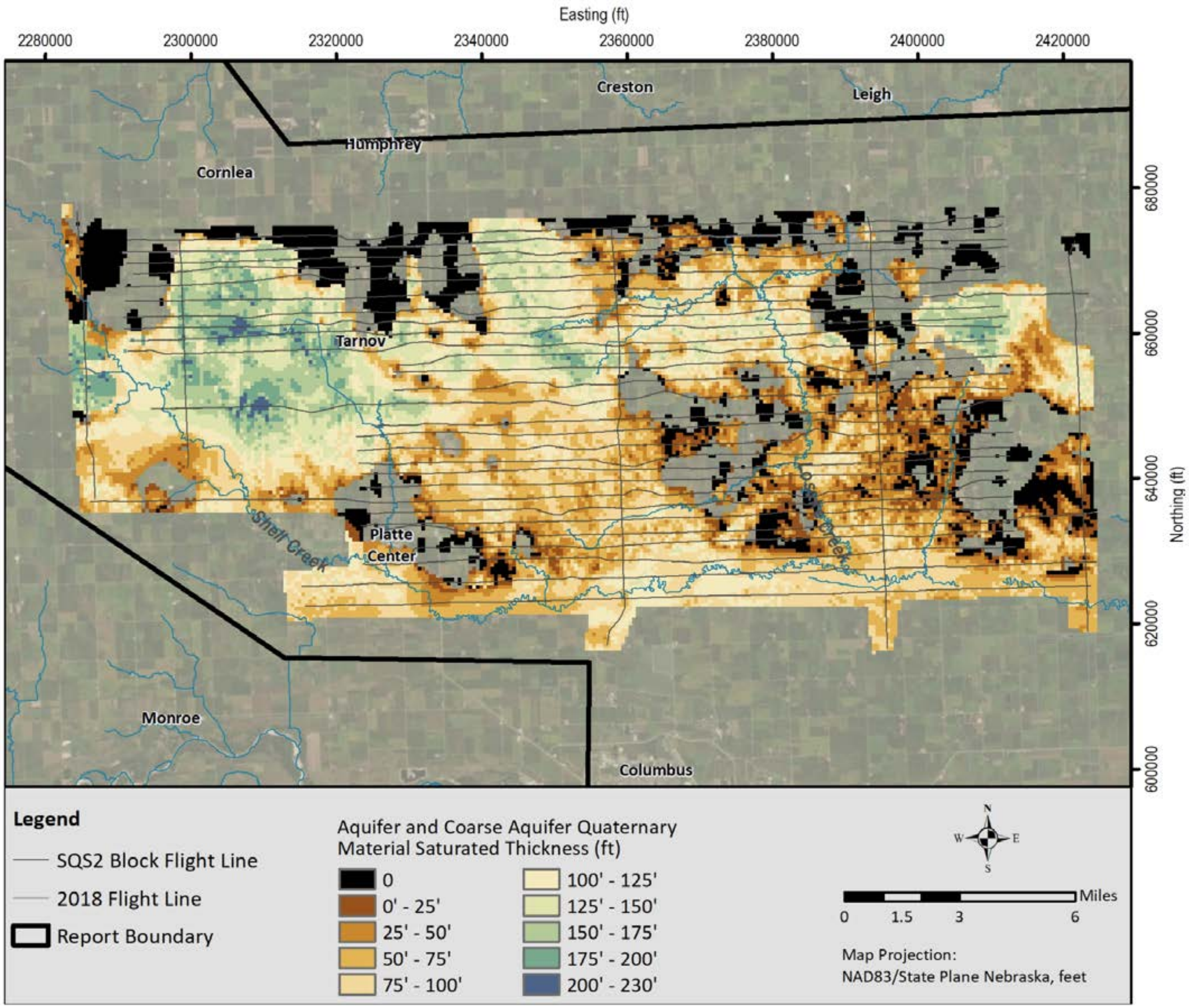


Figure 3-133. Map of the thickness of the saturated Quaternary (*Q*) aquifer and coarse aquifer materials within the SQS2 Block. Flight lines are indicated by black lines.

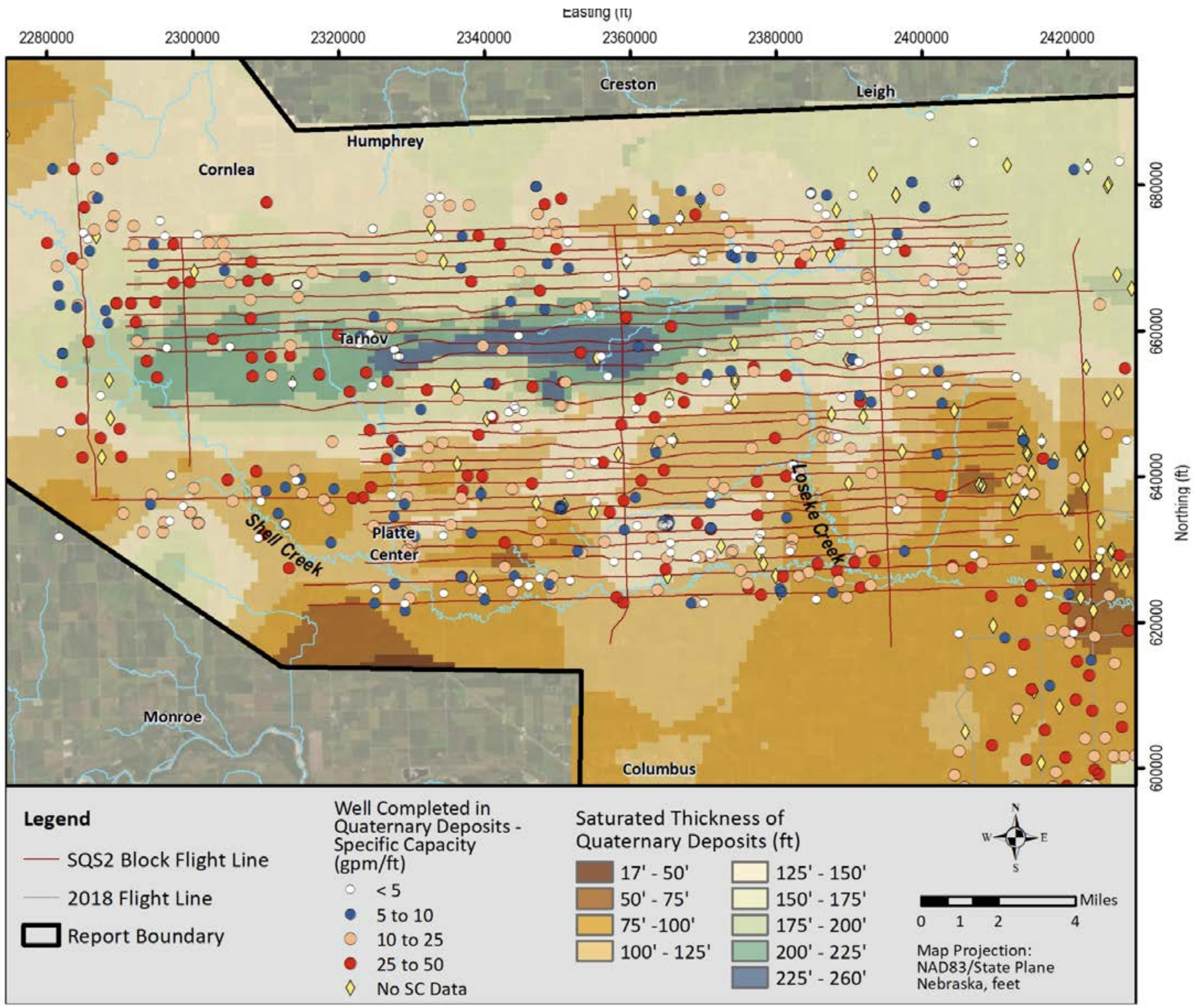


Figure 3-134. Map of the saturated thickness of the Quaternary (*Q*) deposits related to the specific capacity of the wells screened within the *Q*. Block flight lines are indicated by the black lines.

3.2.2.4 Hydrogeologic Framework of the Waann Block Survey Area

The AEM provided insight into the geographic distribution and extent of the unconsolidated ***Q*** and consolidated to semi-consolidated ***Kd*** material in the Waann Block AEM survey area. The ***Q*** materials within the Waann Block are composed of unconsolidated alluvial silt, sand, and gravel as well as loess and glacial till that overlie the consolidated or semi-consolidated ***Kd*** bedrock which is divided into Sandstone/Sand Dominant and Shale/Clay Dominant units. The ***Q*** material in the Waann 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 3.1.5. Generally, the flight block is bounded on the east by the Todd Valley and in the west along a north-south line approximately 3 miles west of Highway 28 (Figure 3-135).

Figure 3-136 displays a 3D fence diagram looking to the north of the Waann flight lines and the interpreted hydrostratigraphic profiles with CSD and NE-DNR borehole lithology data. The area generally contains a mix of all ***Q*** aquifer materials lying upon the ***Kd*** which contains a mix of Shale/Clay Dominant and Sandstone/Sand Dominant aquifer materials. An exception is an area near Ashland that has an ***IP*** subcrop due to the erosion of the ***Kd***. The boreholes in the area indicate a mix of sand, silty clay, and sandy clay in much of the uplands west of the Todd Valley. There are fluvial sand and sand and gravel in the Todd Valley and Platte River Valley areas above the ***Kd*** bedrock.

Figure 3-137 presents east-west Profile L506201 south of the town of Wahoo. It is the northern-most profile in the Block and starts at the west end of the block and extends east into Todd Valley. The CSD 1995 water table is also on the profile and shows the change in water table elevation from the (high) western end of the block to Todd Valley in the east (low). This elevation change is a result of the aquifer materials and the land surface elevation which is generally similar to the water table. The ***Q*** thickness thins near the east end of the profile where there is more marginal aquifer and non-aquifer material in direct contact with ***Kd*** Shale/Clay Dominant material. There is also thin marginal aquifer and non-aquifer material layer just below the surface that starts near 2530000 East and continues to near the western edge of Todd Valley. This layer has an impact on the hydrology of the system because the water table elevation is above the layer creating a confining condition for the aquifer below it. It also has an impact on recharge because it reduces the rate of infiltration down into the aquifer material.

The total thickness of the ***Q*** material in the Waann AEM Block area (Figure 3-138) was gridded by subtracting the bedrock elevation from the ground surface elevation. The greatest ***Q*** material thickness is on the high ground along the northwest corner and with thin areas along the west side of Todd Valley and Platte River Valley. The ***Q*** material varies in thickness from 0 to 542 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 ***Kd*** and the surface water of the area. The aquifer and coarse aquifer materials provide the greatest connection for water movement among all of the ***Q*** aquifer materials present in the area.

Of equal importance is the saturated thickness of the ***Q*** materials which was calculated by the bedrock elevation subtracted from the gridded 1995 CSD water table surface elevation (NE-CSD, 1995) to obtain a total saturated thickness of ***Q*** material. By separating the various aquifer materials into their components and then combining just the aquifer and coarse aquifer material values of thickness into a group, the sum of aquifer and coarse aquifer materials thickness is shown on Figure 3-139 for the Waann Block AEM survey area. The thickness of these materials varies between 0, where there is no aquifer and coarse aquifer material, to 270 feet. The greatest thickness of 270 feet is near the northwest corner of the Block.

Figure 3-140 shows the ***Kd*** surface elevation underlying the ***Q*** which is generally highest in elevation at 1,329 feet in the northwest and west areas and lowest at 975 feet in elevation in the northeast and southeast areas of the survey area. The ***Kd*** lows are just west of Weston and near Memphis, Nebraska. There is a paleovalley cut into the ***Kd*** surface that runs from west to east past the town of Wahoo and then bends southeast down Todd Valley. There are bedrock highs to the north and south sides of the paleovalley. These high and low elevations correlate with the thickness map of the ***Kd*** (Figure 3-141) including the thin areas along the ***Kd*** paleovalley. An area with a thin ***Kd*** material thickness of 50-100 feet is located near the town of Memphis, Nebraska and thins southeast towards the subcrop of ***IP*** near Ashland, Nebraska. The saturated thickness of the ***Kd*** varies from 5 feet to 538 feet with the thickest section to west-northwest of the area.

Figure 3-142 presents the interpreted profile L30370 which is an east-west profile across the western upland and moves east down into Todd Valley which is a paleochannel, or even meander cut-off, of the ancestral Platte River and many of the groundwater irrigated acres in the area. The ***Q*** material in this area is all glacial material until it intersects Todd Valley where it becomes fluvial material filling the paleochannel. The west end of the profile has deposits of ***Q*** marginal aquifer material with some non-aquifer material. There are minor aquifer material deposits in this area that are hydrologically isolated. Beginning at location 2610000 East, there is a near continuous deposit of glacial outwash aquifer and some coarse aquifer material that can be up to 100 feet thick lying on the upper surface of the ***Kd***. There is a cap of marginal aquifer material near the land surface that limits recharge. On the east end of the profile there is a hydrologic constriction near the contact with Todd Valley fluvial deposits. Near the contact between the ***Q*** and ***Kd*** formations there is a near continuous thin layer of ***Kd*** Shale/Clay Dominant material that limits hydrologic connection with the ***Q*** aquifer materials above and the ***Kd*** Sandstone/Sand Dominant material immediately below.

Figure 3-143 is an exploded view of the voxel model showing both saturated and unsaturated ***Q*** and ***Kd*** underlain by ***IP***. The ***Q*** materials show the prevalent heterogeneity seen across the LPNNRD including the coarse aquifer, aquifer, marginal aquifer, and non-aquifer materials. As seen in Figure 3-139 above there is a change in the ***Q*** coarse aquifer materials as you move across the Waann Block AEM survey area from west to east. There are many areas that have no coarse material in them but do have aquifer material which is mostly due to the outwash nature of the glacial deposition.

The saturated thicknesses of ***Q*** deposits and ND-DNR registered wells with specific capacity measurements (in gpm/ft) are presented in Figure 3-144. Careful evaluation of the map shows a trend from west to east near the ***Kd*** paleochannel that has a higher population of wells with a specific capacity in the 10-50 gpm/ft range that follows the 100 to 350 ft thick ***Q*** deposits filling the paleochannel identified in Figure 3-140. Todd Valley also has many similar wells due to the approximately 100-foot thick coarse aquifer material of the fluvial deposits.

The saturated thickness for ***Kd*** deposits and the specific capacities (in gpm/ft) for DNR boreholes in the Waann AEM survey area are presented in Figure 3-145. Evaluation of the map shows a trend from north to south from Wahoo to Memphis, Nebraska and a narrow band of wells from Weston, Nebraska west to the block boundary that has a higher population of wells with a specific capacity 10-50 gpm/ft range that follows the 100 to 400 ft thick ***Kd*** deposits.

Figure 3-146 shows the ***Kd*** Sandstone/Sand Dominant total thickness from the voxel model which when compared to Figure 3-145 shows the most likely areas for well development in the ***Kd*** are in the Sandstone/Sand Dominant materials.

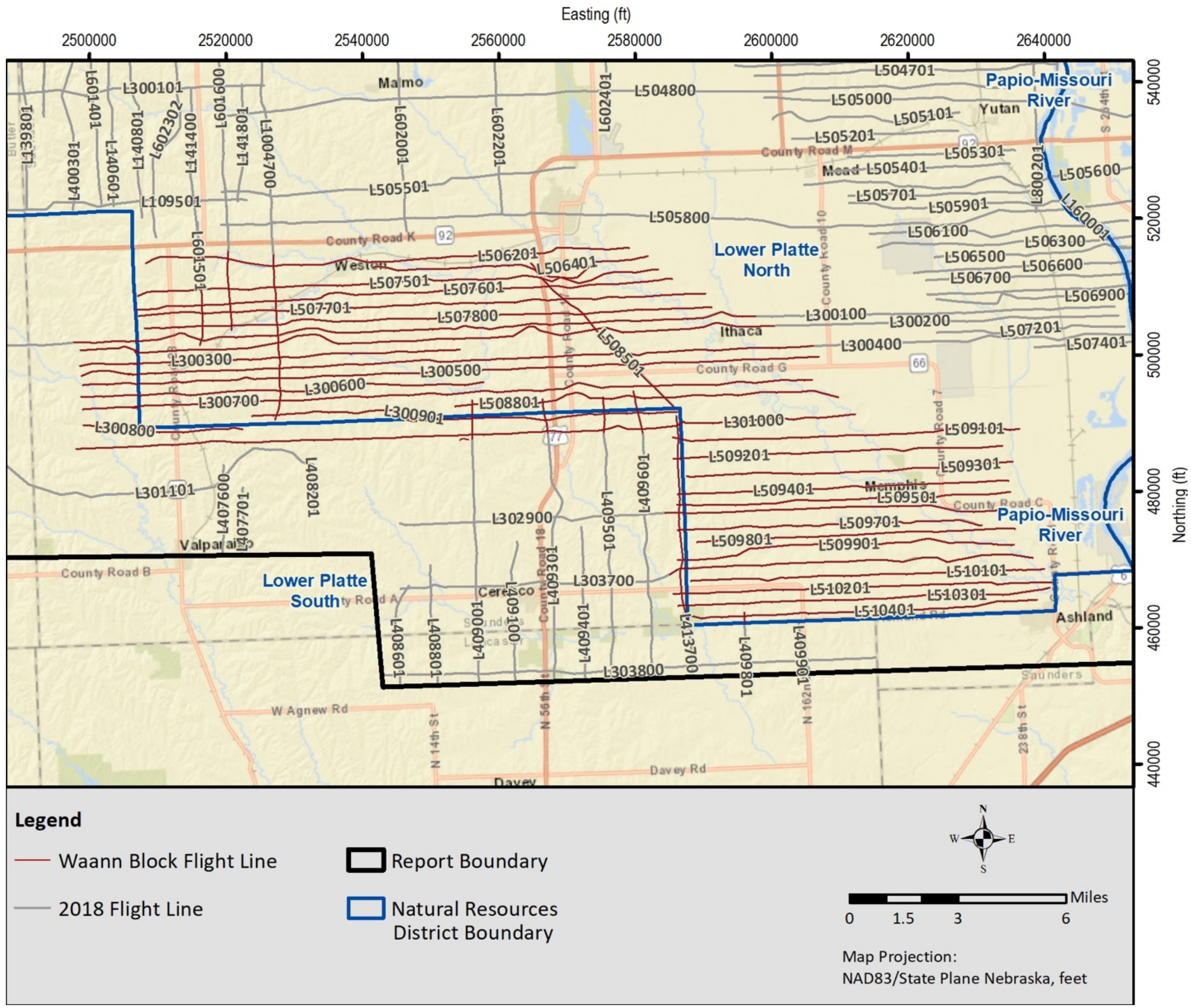


Figure 3-135. Map location of the Waann Block indicating AEM flight lines local roads and streams.

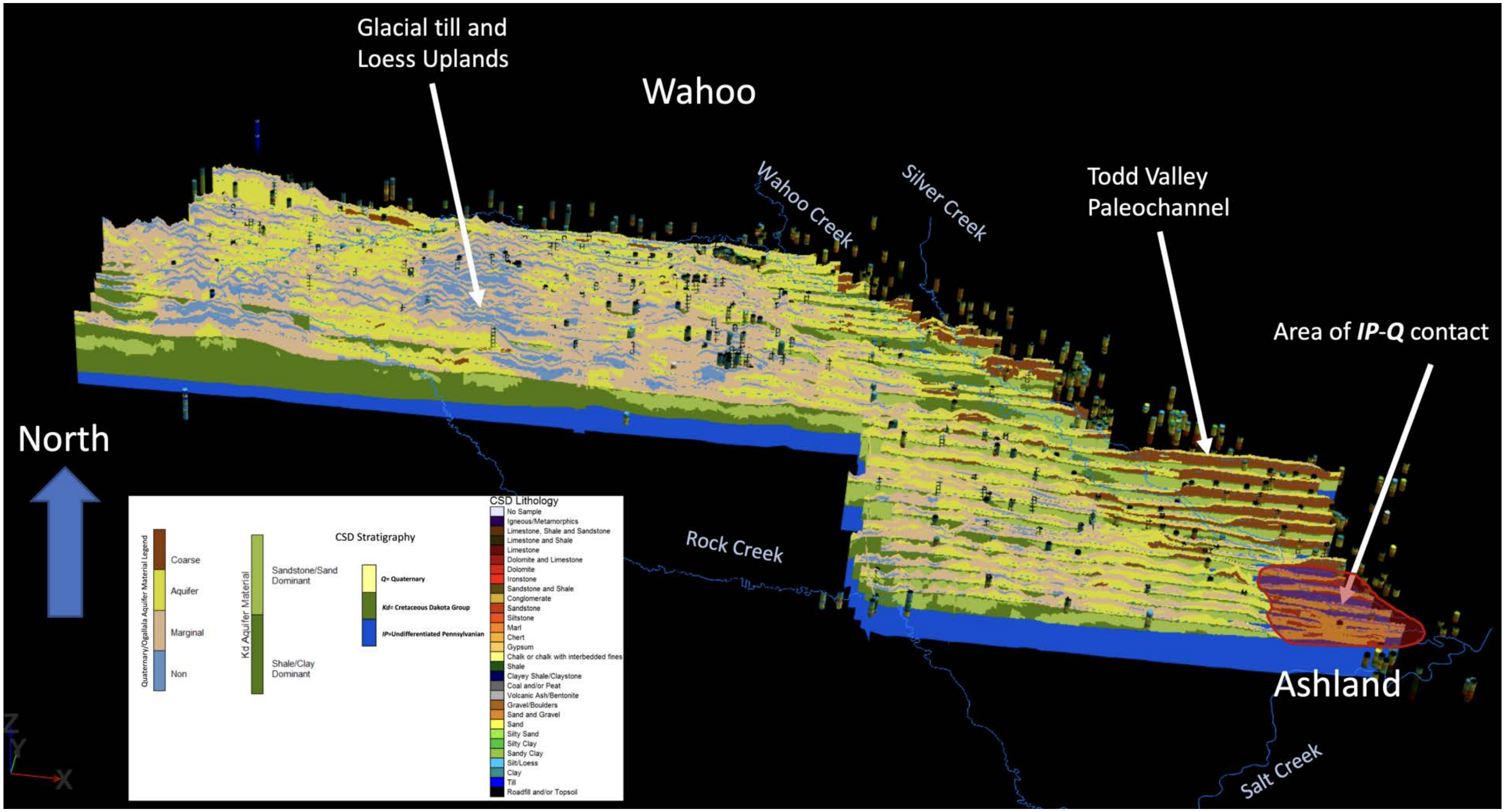


Figure 3-136. 3D fence diagram of interpreted AEM hydrostratigraphic profiles within the 2018 Waann Block AEM survey area. CSD and NE-DNR test holes and wells lithology are indicated. V.E. = 15x.

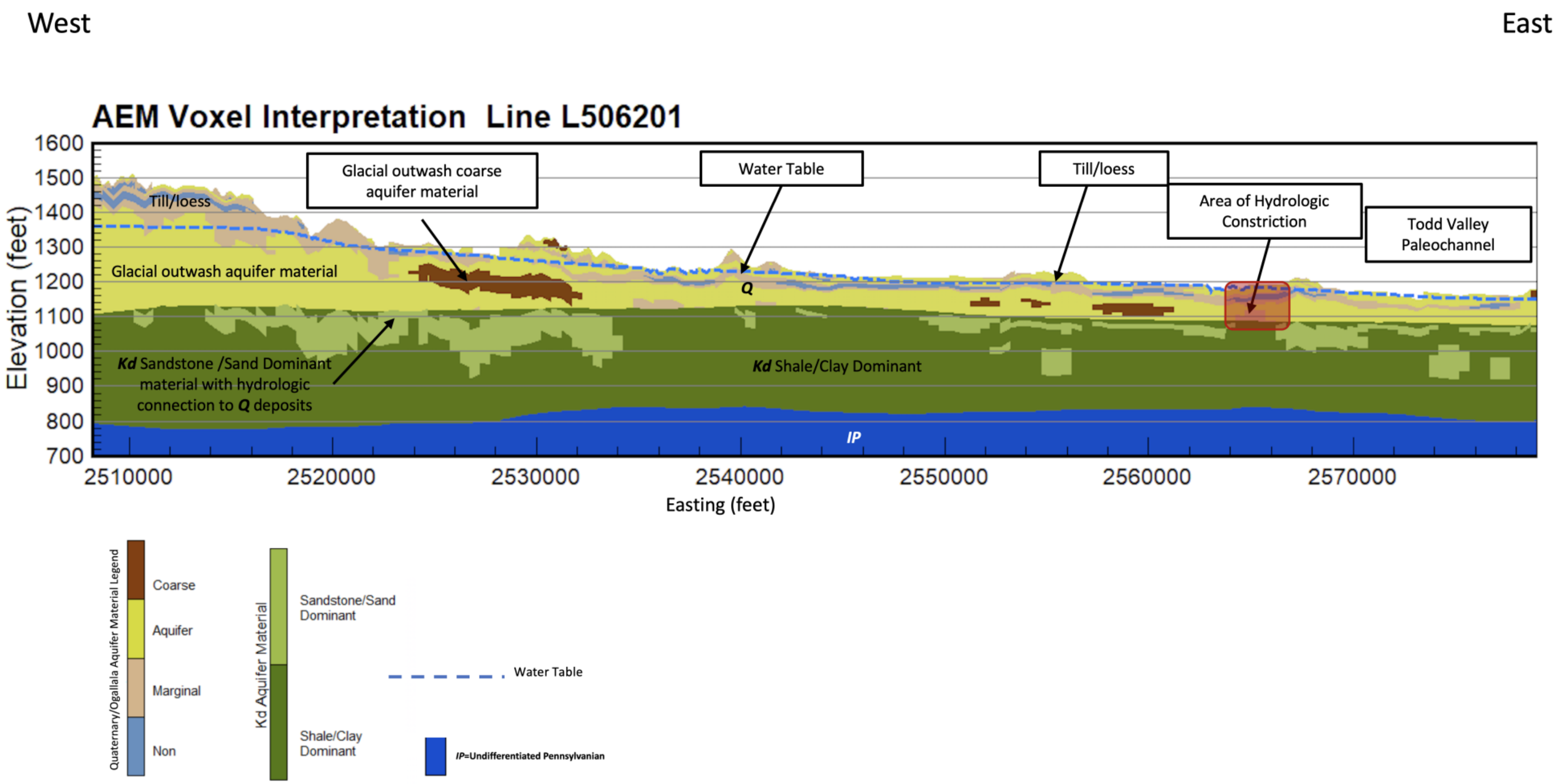


Figure 3-137. Profile of the east-west line L506201 showing interpretation of the Quaternary (*Q*) and Cretaceous Dakota (*Kd*) materials. The CSD 1995 water table is indicated as a dashed blue line on the profiles and is used to show an area of hydrologic constriction near the western edge of the Todd Valley. Horizontal datum is NAD83 State Plane Nebraska (feet).

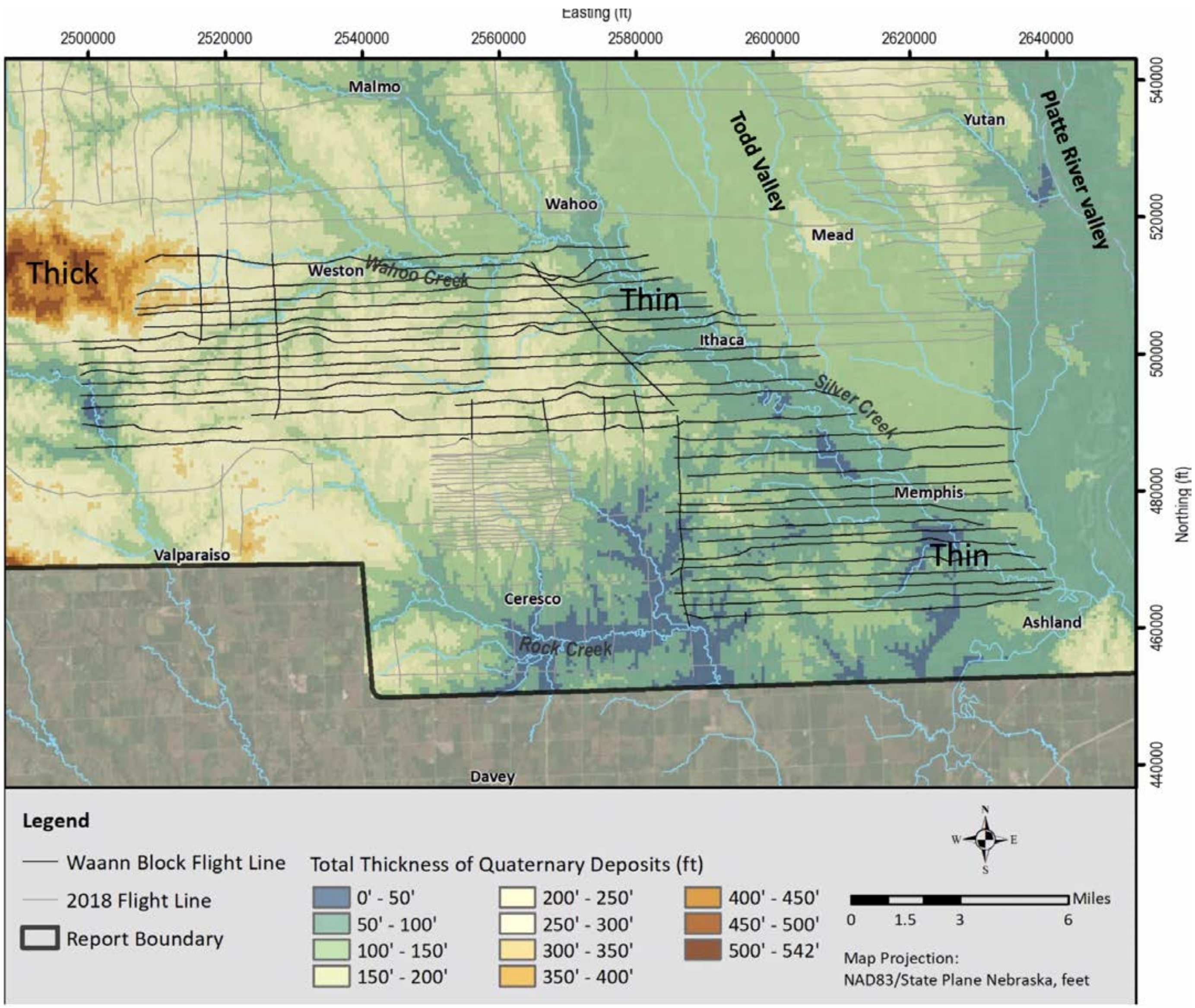


Figure 3-138. Map of the total thickness of the Quaternary (*Q*) deposits within the Waann Block. Block flight lines are indicated by black lines. The thick areas are in the west and the thin areas are in the near the Todd Valley.

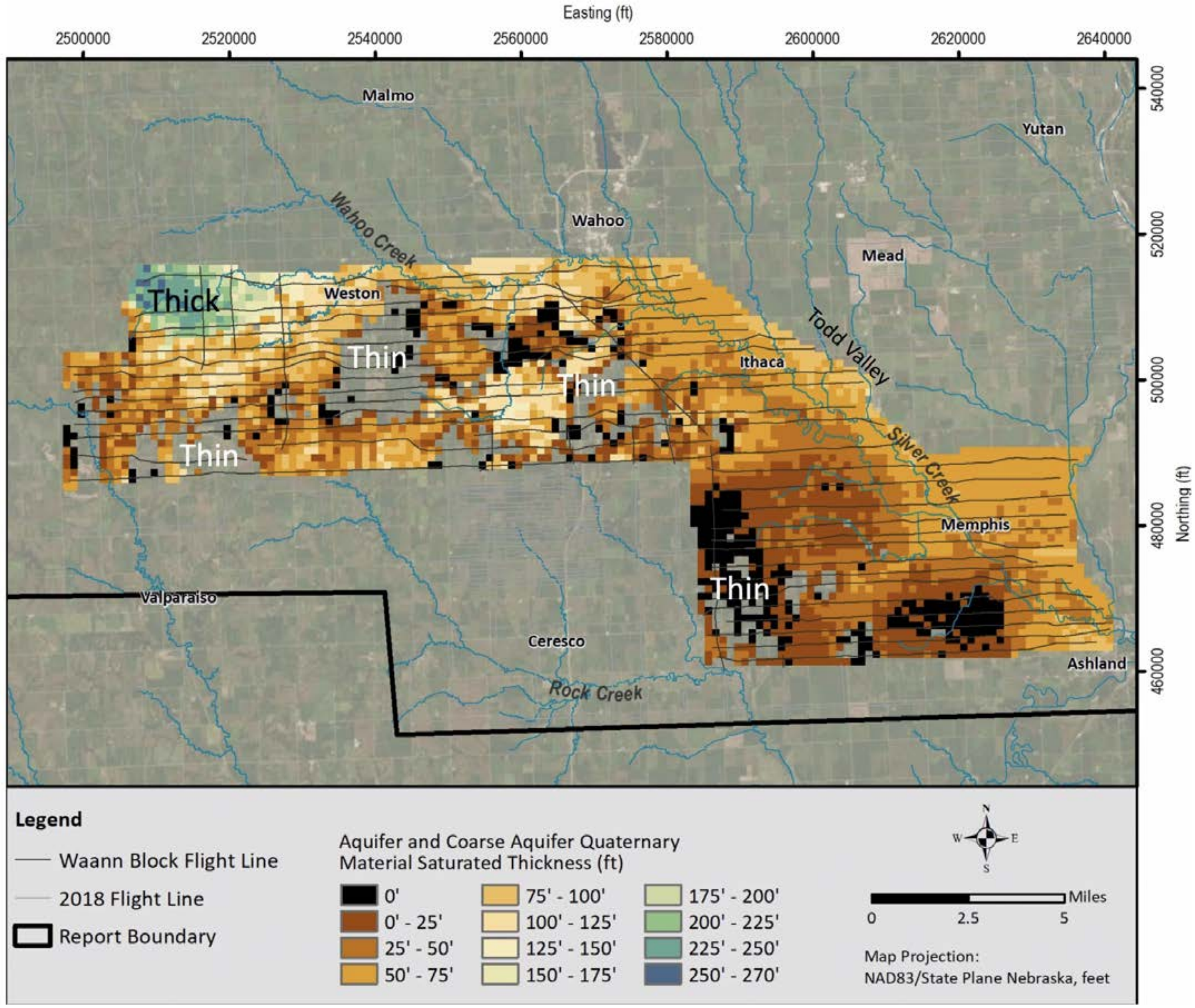


Figure 3-139. Map of the thickness of the Quaternary (*Q*) saturated coarse aquifer materials within the Waann Block. Block flight lines are indicated by black lines. Note the areas of thin to no coarse aquifer material.

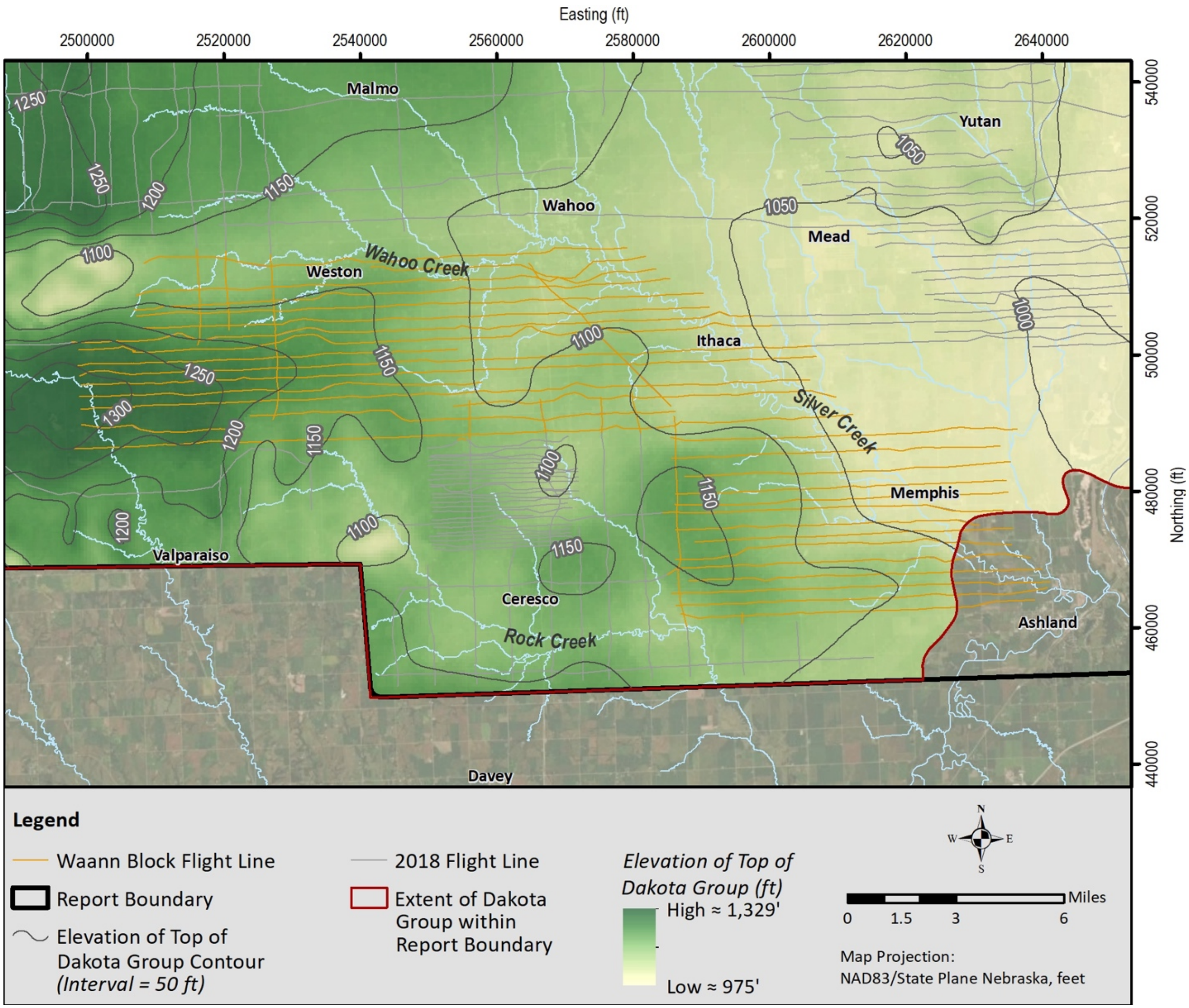


Figure 3-140. Map of the elevation of the top of the Cretaceous Dakota Group (*Kd*) within the Waann Block. Block flight lines are indicated by the yellow lines. Note the paleochannel (bedrock low) cut into the *Kd* near Weston, Nebraska.

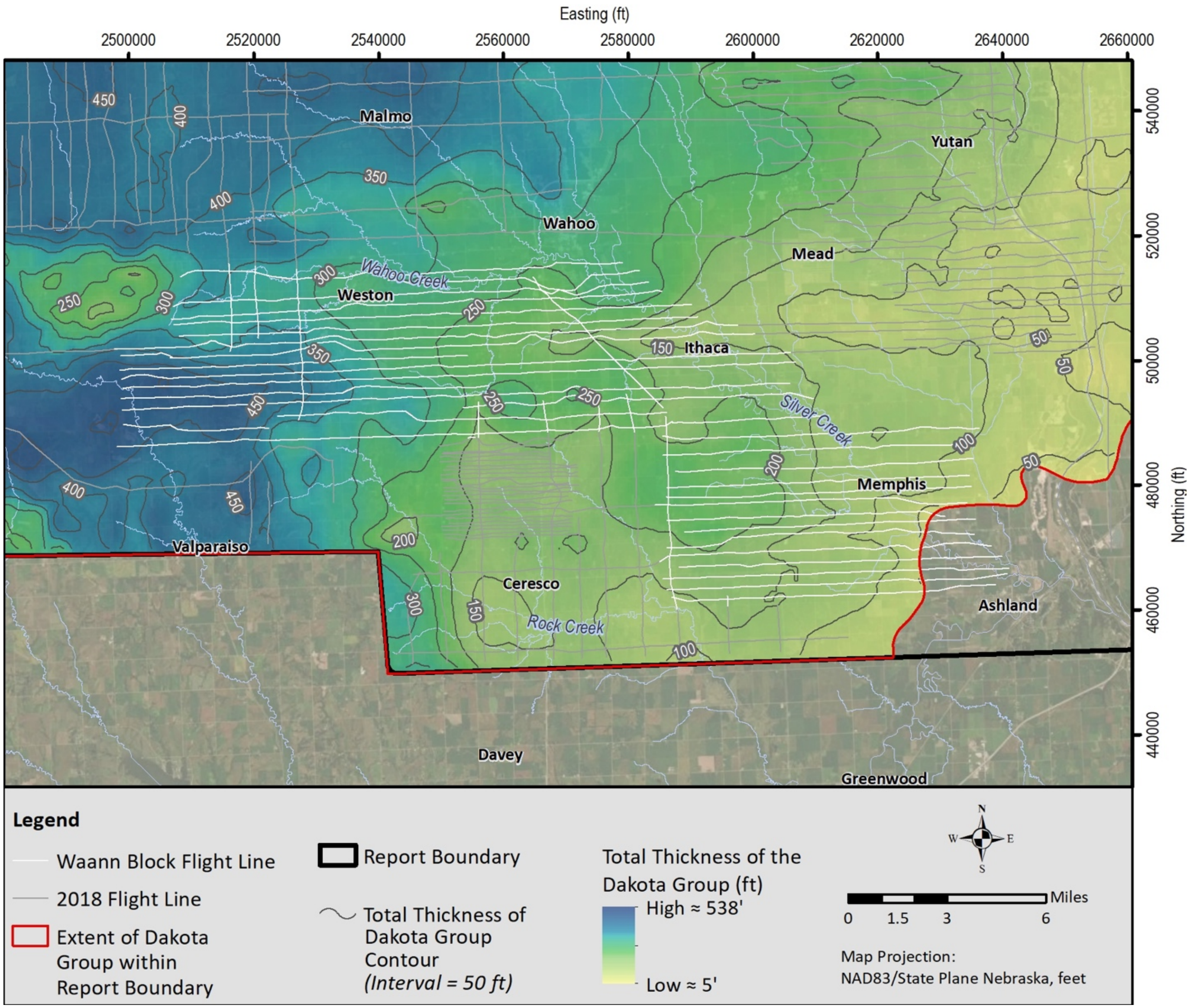


Figure 3-141. Map of the thickness of the Cretaceous Dakota Group (*Kd*) within the Waann Block. Block flight lines are indicated by the white lines. Note the thin areas follow the trend of the paleochannel and the topography of the land surface.

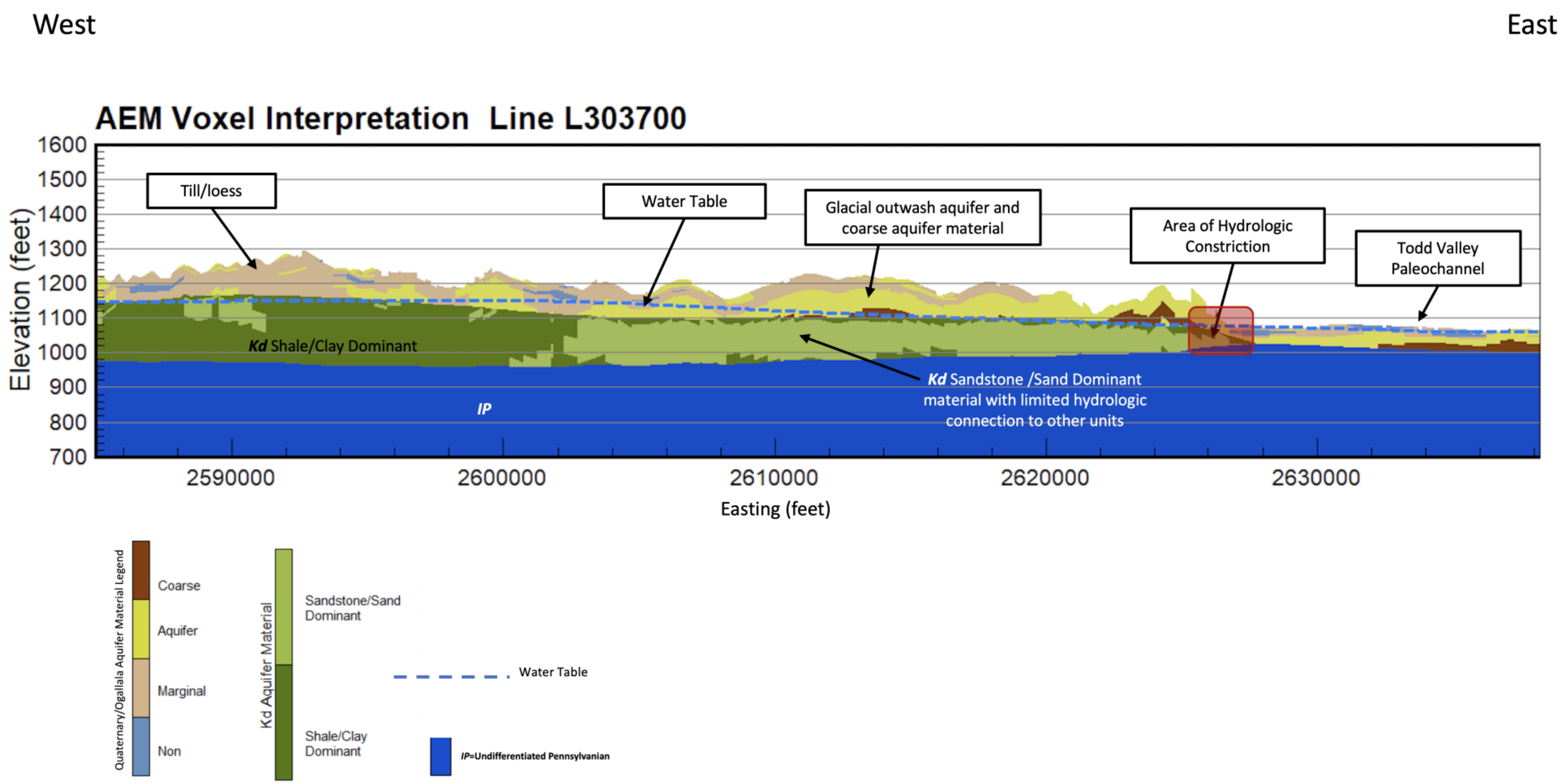


Figure 3-142. Interpreted profile of east-west line L303700 near Ashland, Nebraska showing the contact between the Quaternary (*Q*) deposits and the Undifferentiated Pennsylvanian (*IP*) on the eastern end. The CSD 1995 water table is indicated as a dashed blue line on the profiles and is used to show an area of hydrologic constriction near the west edge of the Todd Valley. Horizontal datum is NAD83 State Plane Nebraska (feet).

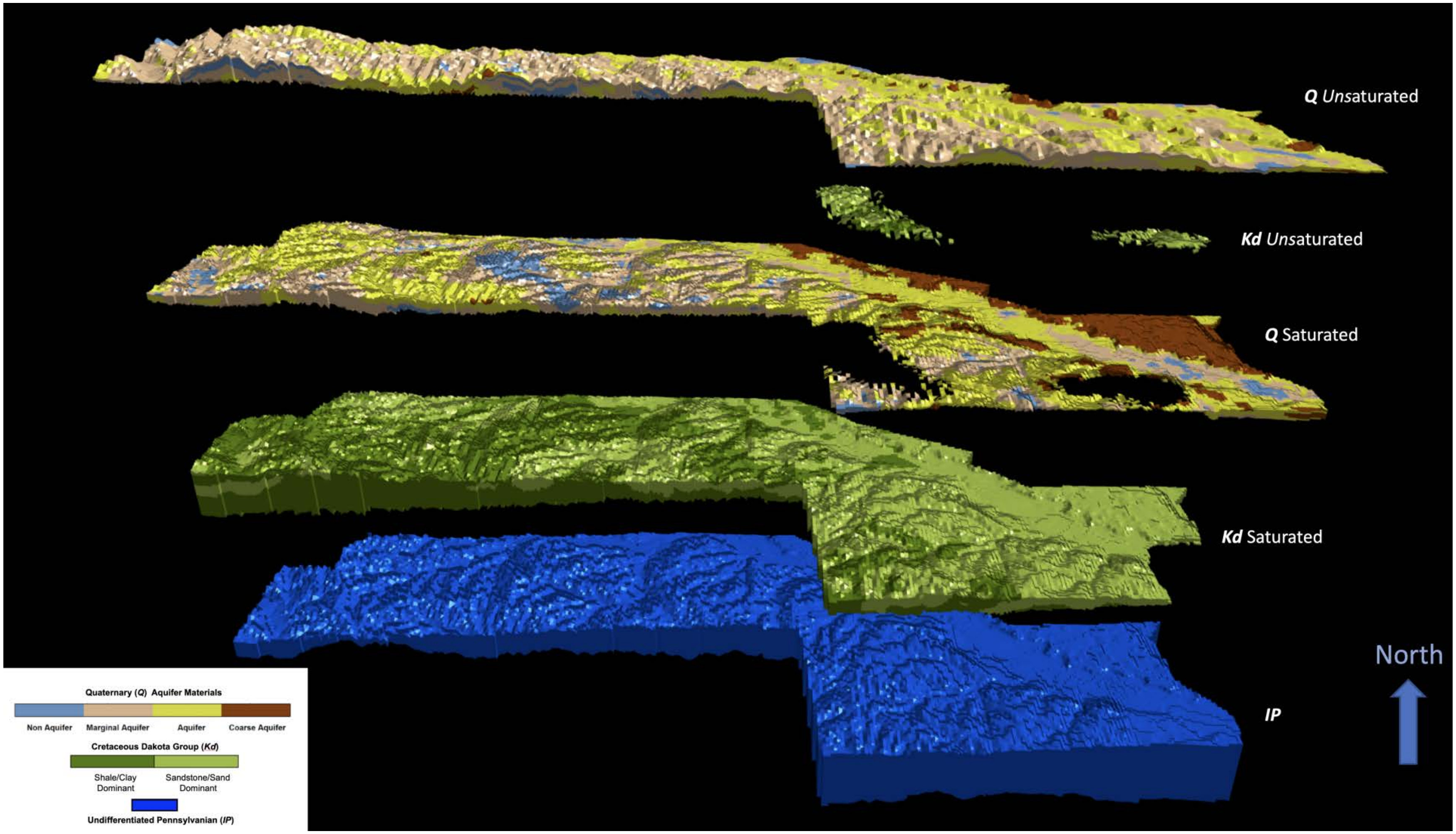


Figure 3-143. 3D exploded voxel solid model of the Waann block. With the model broken up into the unsaturated Quaternary (*Q*), unsaturated Cretaceous Dakota Group (*Kd*), saturated *Q*, saturated *Kd*, and the Undifferentiated Pennsylvanian (*IP*). V.E. = 10x, but the image is not to scale.

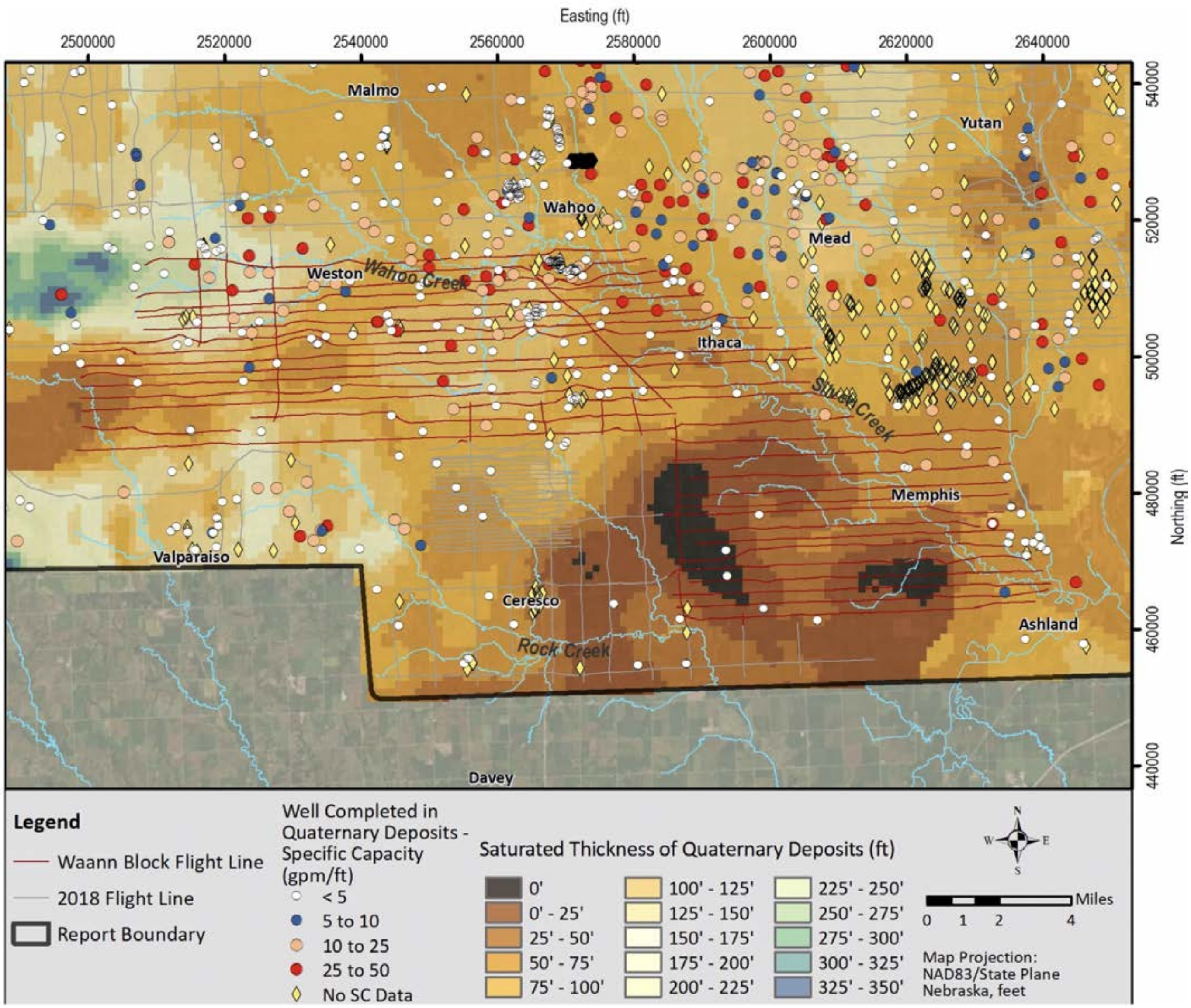


Figure 3-144. Map of the Quaternary (*Q*) saturated thickness with well locations showing specific capacity. The wells yielding 10-50 gpm follow a trend similar to the Cretaceous Dakota Group (*Kd*) paleovalley.

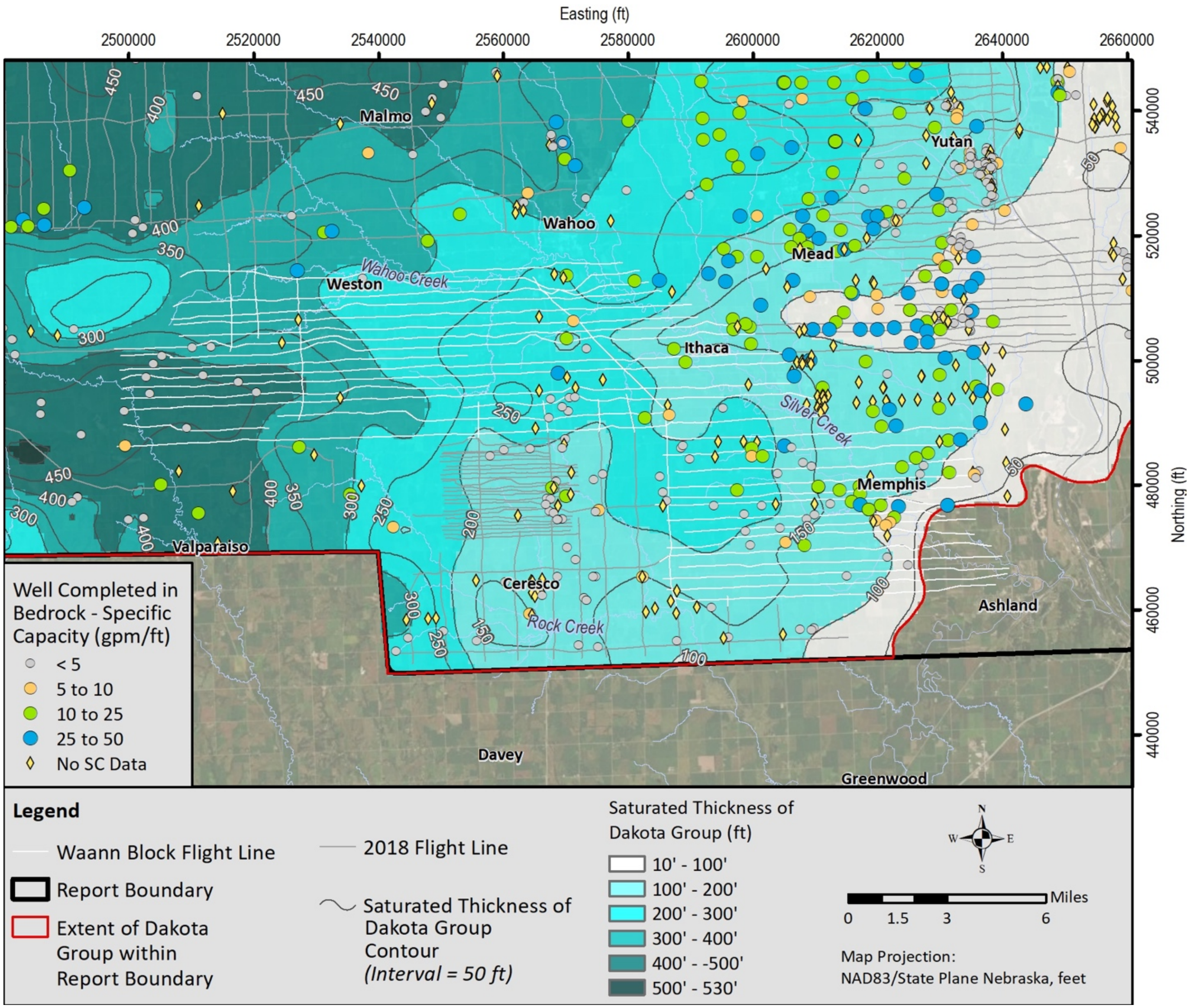


Figure 3-145. Map of the Cretaceous Dakota Group (*Kd*) saturated thickness with well locations showing specific capacity. The wells yielding 10-50 gpm follow a trend similar to the Cretaceous Dakota Group (*Kd*) paleovalley.

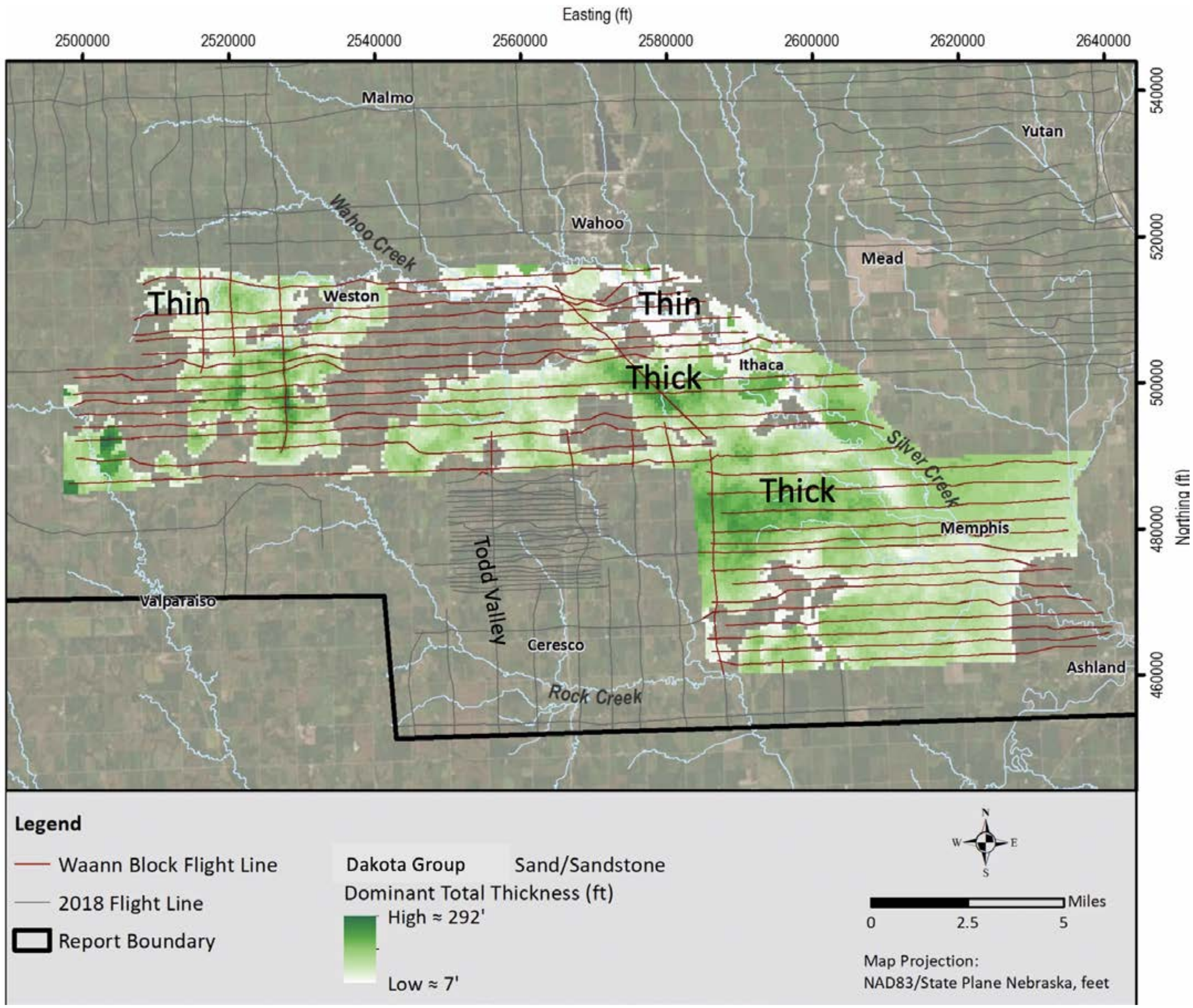


Figure 3-146. Map of the thickness of the Cretaceous Dakota Group (*Kd*) sand/Sandstone Dominant thickness from the voxel model of the AEM.

3.2.3 Estimation of Aquifer Volume and Water in Storage for the LPNNRD Leshara Upland, SQS1, SQS2, and WAANN AEM Block Areas

The 3D voxel representation of the subsurface resulting from the AEM dense block investigation method provides users the ability to more accurately estimate total unsaturated and saturated aquifer volume and the amount of extractable water present. The Leshara Upland, SQS1, SQS2, and Wann AEM block areas were mapped at high resolution for this purpose. The Leshara Upland area covers approximately 166.4 mi^2. or 106,496 acres, the SQS1 area covers approximately 257.4 mi^2 or 111,104 acres, the SQS2 approximately 257.4 mi^2 or 164,136 acres, and the Wann area covers approximately 157.1 mi^2 or 100,544 acres (Figure 3-147). It should be noted that any comparison of results in volumes of material between the 2016 (AGF, 2017) and 2018 for blocks SQS1 and SQS2 needs to take into account the change in geographic size which was requested by the LPNNRD. SQS1 is 87% larger in 2018 than in 2016 and SQS2 is 108% larger in 2016 than 2018. The grid spacing was also changed which affected the volume calculations from the voxels (discussed in Section 3.1.7). In 2018 the Leshara Upland, SQS2, and Waann blocks used a 500 ft grid size and SQS1 used a 1,000 ft grid cell size. In 2016 grids for SQS1 and SQS2 used a 250 ft grid size for the voxel calculations (AGF, 2017). These changes were made after discussions with LPNRD staff regarding interpolation of results across the widely spaced lines.

The criteria for determining the basis for the range of resistivity values used in calculating the volumes of interpreted aquifer material are provided in Section 3.1.5 AEM. The resistivity ranges for interpreted aquifer materials are Non-aquifer material: <12 ohm-m), Marginal aquifer material: 12-20 ohm-m, Aquifer material: 20-50 ohm-m, and Coarse Aquifer material: >50 ohm-m. The ***Kd*** Sandstone/Sand Dominant material has a resistivity cutoff of >20 ohm-m and the Shale/Clay Dominant is < 20 ohm-m.

In the current section, information is provided on unsaturated and saturated volumes of the Quaternary non-aquifer, marginal aquifer, aquifer, and coarse aquifer materials; as well as, the unsaturated and saturated volumes of the ***Kd*** Sandstone/Sand Dominant and the Shale/Clay Dominant material. There is no ***Kd*** volume calculated for SQS2 due to no data interpretation of the ***Kd*** due to the depth of investigation (DOI) in that area.

As discussed in Section 3.1.7, the voxels for the ***Q*** and ***Kd*** can be further divided using the water table. Figure 3-148 is a 3D exploded solid voxel model of the Leshara Upland Block AEM area showing unsaturated ***Q***, saturated ***Q***, saturated ***Kd***, and ***IP*** units. Figure 3-149 is an exploded voxel model of the SQS1 Block showing unsaturated ***Q***, saturated ***Q***, ***Kgg***, saturated ***Kd***, and ***IP*** units. As noted above, the ***Kgg*** may be saturated but is not considered an aquifer. Figure 3-150 is an exploded voxel model of the SQS2 Block showing unsaturated ***Q***, saturated ***Q***, and undifferentiated Cretaceous bedrock (***K***) units. As indicated above the bedrock within the SQS block is made up of the ***Kn***, ***Kc***, and ***Kgg***. In the SQS2 survey area, the ***Kd*** is below the DOI and is not modeled. Figure 3-151 is a 3D exploded solid voxel model of the Waann AEM Block area showing unsaturated ***Q***, unsaturated ***Kd*** (due to topography)**,** saturated ***Q***, saturated ***Kd***, and ***IP*** units. These figures show the variability in each area as well as the voxels that were used in the determination of aquifer volume. Volumes of ***Q*** and ***Kd*** aquifer materials are calculated for each block and are used in the aquifer volume calculation which are given in units of cubic feet (ft^3) NS acre-ft, groundwater in storage volume given in acre-ft, and extractable water volume also given in units of acre-ft.

The complete volumes of both saturated and unsaturated materials are used for the calculations. The unsaturated calculation is used as a way of determining the potential storage and recovery in the unsaturated materials, assuming 100% saturation. All ***Q*** 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 areas. Both the ***Kd*** Sandstone/Sand Dominant and the Shale/Clay Dominant material were used in the calculating the groundwater in storage volume and the extractable water volumes. 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 are used in these calculations within the survey area. They 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 Leshara Upland, SQS1, SQS2, and Waann AEM block areas were selected by estimating values provided by CSD (Personal Communication, Susan Olafsen Lackey, CSD Hydrologist, 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 chosen at 0.02, for marginal aquifer materials (12-20 ohm-m) a value of 0.05 was selected (Heath, 1983). The aquifer material (20-50 ohm-m) ranges from 0.1 to 0.2 with an average of 0.15. 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 values for sandstone for porosity is 0.11 of volume and specific yield is 0.06. The ***Kd*** Shale/Clay Dominant materials have values 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 including non-aquifer, marginal aquifer, aquifer, and coarse aquifer that are in both saturated and unsaturated condition using the CSD 1995 water table: Leshara Upland – Table 3-1, Table 3-2; SQS1 – Table 3-4, Table 3-5), SQS2 – Table 3-7, Table 3-8; and Waann – Table 3-9, Table 3-10. Tables have also been created describing the volumes of ***Kd*** aquifer materials including Shale/Clay Dominant and Sandstone/Sand Dominant materials for both saturated and unsaturated conditions (except for SQS2 where no ***Kd*** is present): Leshara Upland – Table 3-3; SQS1 – Table 3-6; Waann – Table 3-11, Table 3-12.

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 of the AEM block areas 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.

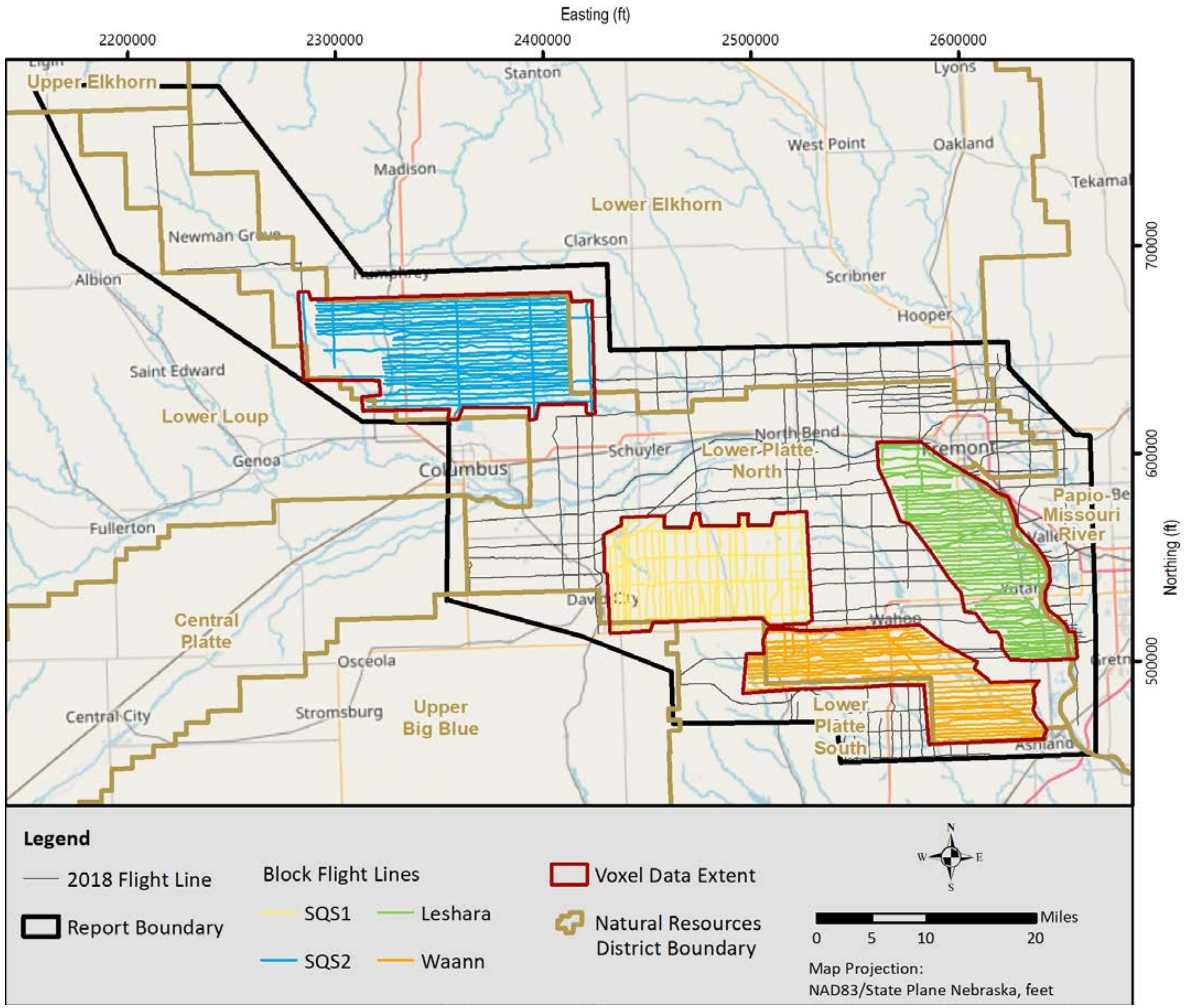


Figure 3-147. Map of the Leshara Upland, SQS1, SQS2 and WAANN block locations. Flight lines included in each block are indicated by color for each separate block.

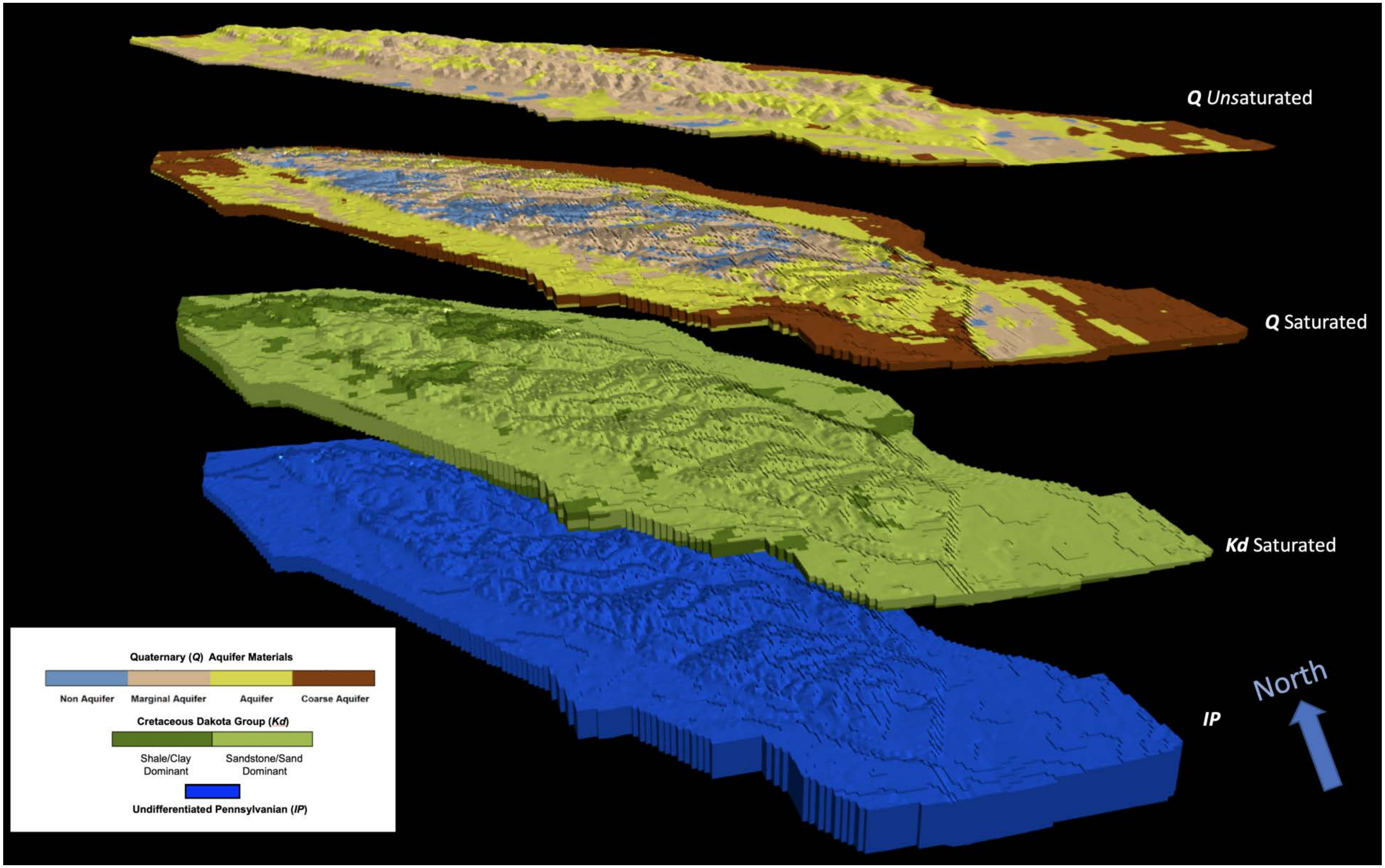


Figure 3-148. 3D exploded voxel model of the Leshara Upland Block broken up into unsaturated *Q*, saturated *Q*, saturated *Kd*, and *IP* units. VE = 10x, but is not to scale..

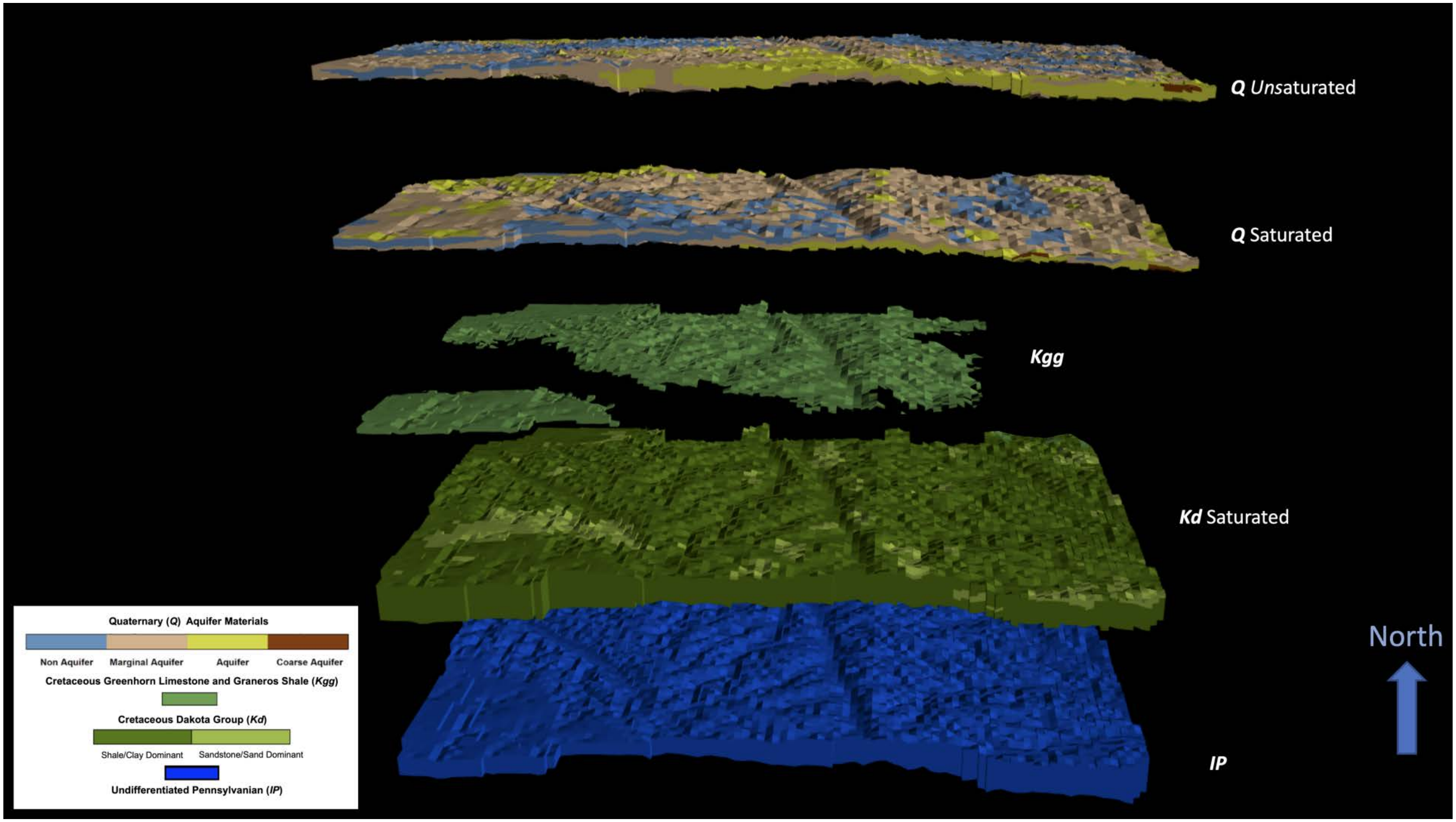


Figure 3-149. 3D exploded voxel solid model of the SQS1 Block broken up into unsaturated *Q*, saturated *Q*, *Kgg*, saturated *Kd*, and *IP* units. VE = 10x, but is not to scale.

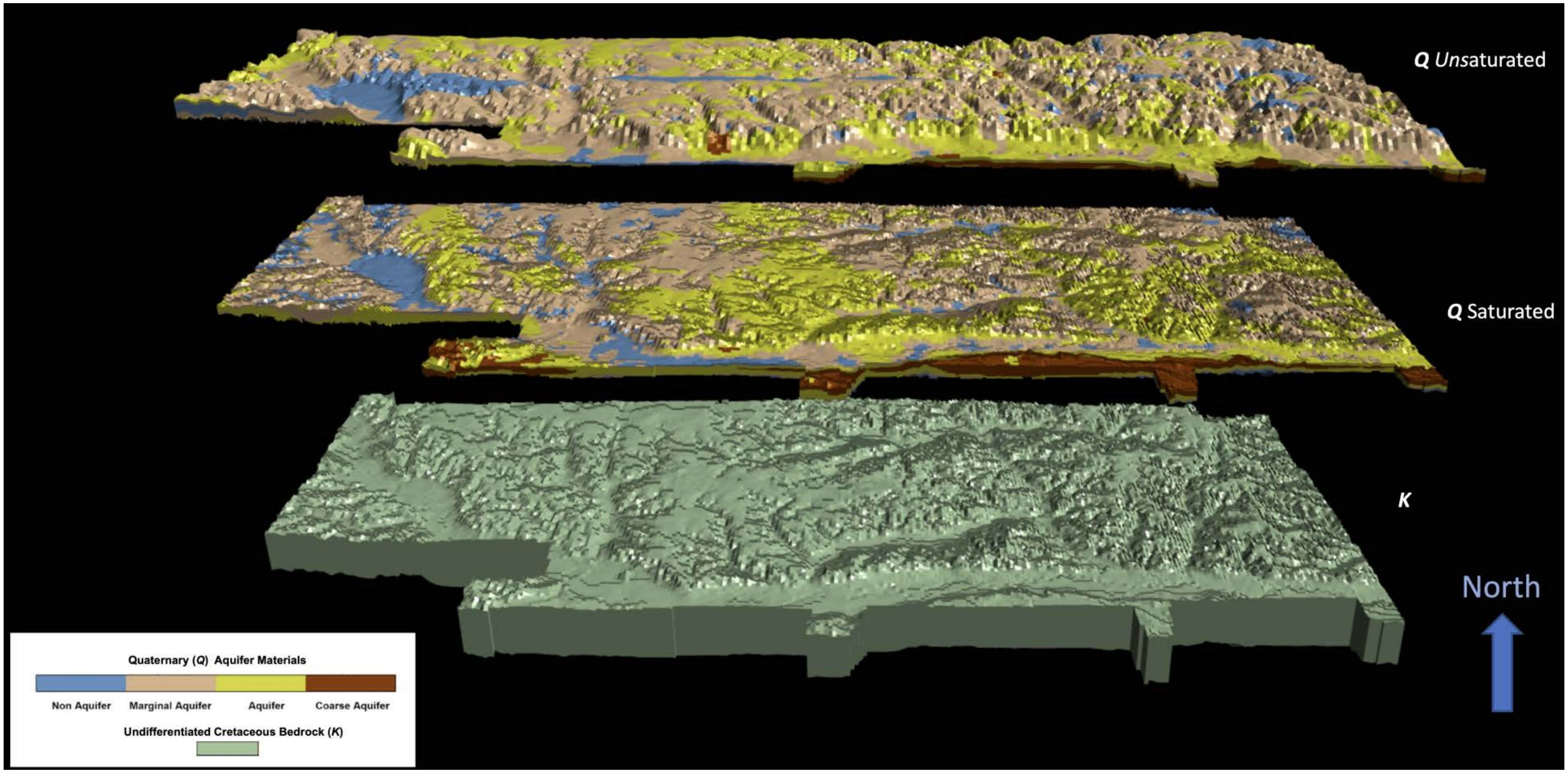


Figure 3-150. 3D exploded voxel solid model of the SQS2 Block broken up into unsaturated *Q*, saturated *Q*, and undifferentiated Cretaceous (*K*) units. VE = 10x, but is not to scale.

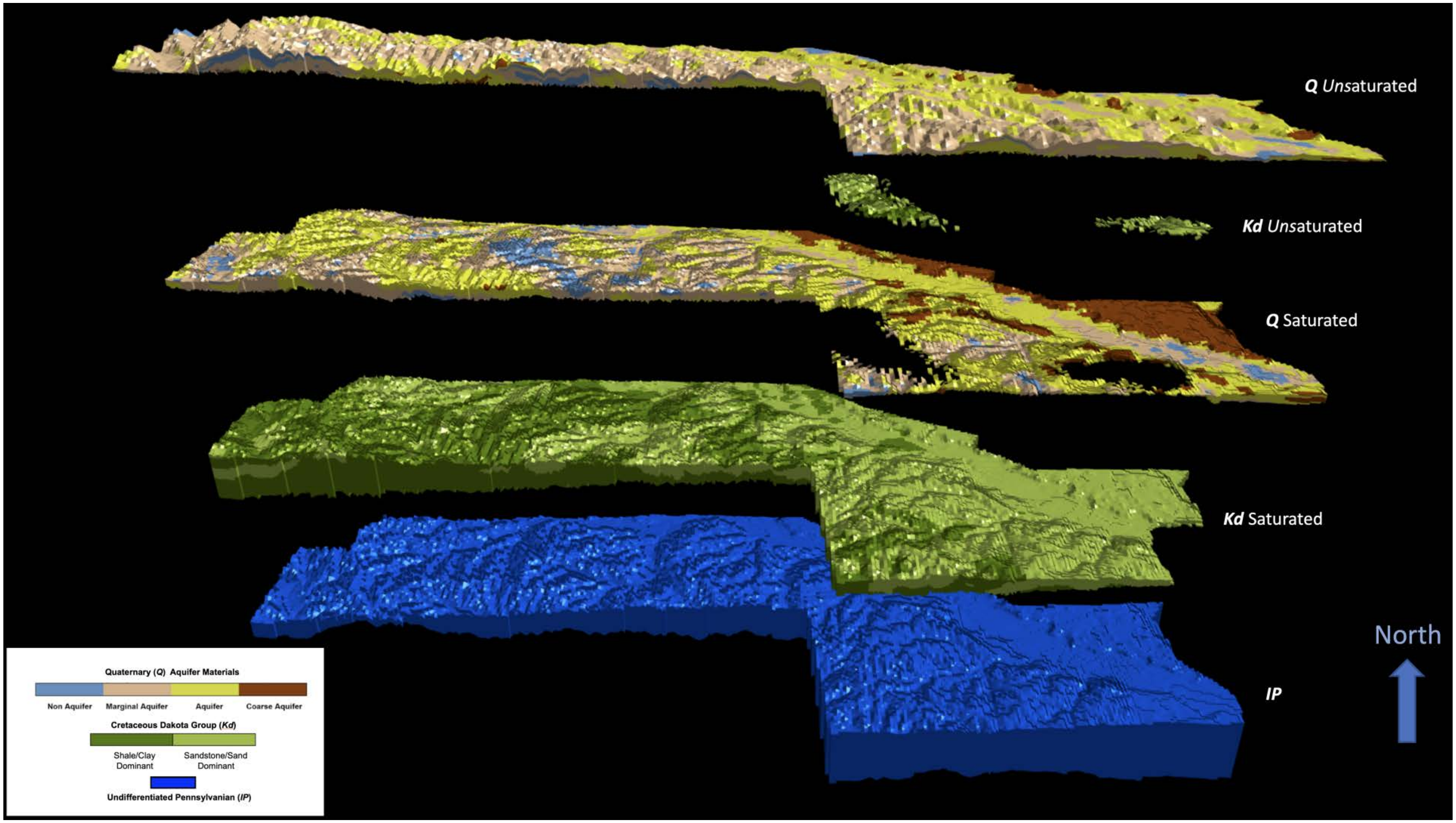


Figure 3-151. 3D exploded voxel solid model of the Waann Block broken up into unsaturated *Q*, unsaturated *Kd*, saturated *Q*, saturated *Kd*, and *IP* units. V.E. = 10x, but is not to scale.

3.2.3.1 *Leshara AEM Block Area*

Table 3-1. Unsaturated Q aquifer materials underlying the Leshara 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)
Non-Aquifer	8,960,015,723	205,693	0.40	82,277	0.02	1,645
Marginal	49,031,915,420	1,125,619	0.35	393,966	0.05	19,698
Aquifer	97,805,136,845	2,245,300	0.20	449,060	0.10	44,906
Coarse Aquifer	80,296,461,490	1,843,355	0.25	460,838	0.15	69,125
TOTAL	236,093,529,478	5,419,969		1,386,141		135,374

Table 3-2. Saturated *Q* aquifer materials underlying the Leshara 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)
Non-Aquifer	133,079,051,330	3,055,079	0.40	1,222,031	0.02	24,440
Marginal	200,526,101,528	4,603,452	0.35	1,611,208	0.05	80,560
Aquifer	112,381,180,318	2,579,920	0.20	515,984	0.10	51,598
Coarse	24,094,461,723	553,133	0.25	138,283	0.15	20,742
TOTAL	470,080,794,898	10,791,586		3,487506		177,340

Table 3-3. Saturated *Kd* aquifer materials underlying the Leshara 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)
Shale/clay	635,131,776,333	14,580,641	0.11	1,603,870	0.02	32,077
Sandstone/ sand	414,262,708,785	9,510,177	0.40	3,804,070	0.06	228,244
TOTAL	1,049,394,485,118	24,090,818		5,407,940		260,321

3.2.3.2 SQS1 AEM Block Area

Table 3-4. Unsaturated *Q* aquifer materials underlying the SQS1 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)
Non-Aquifer	574,460,000	13,187	0.40	5,274	0.02	1,054
Marginal	35,515,350,000	815,321	0.35	285,362	0.05	14,268
Aquifer	222,908,195,000	5,117,275	0.20	1,023,455	0.10	102,345
Coarse	260,553,590,000	5,981,496	0.25	1,495,374	0.15	224,306
TOTAL	519,551,595,000	11,927,281		2,809,465		341,973

Table 3-5. Saturated *Q* aquifer materials underlying the SQS1 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)
Non-Aquifer	1,184,205,000	27,185	0.40	10,874	0.02	217
Marginal	143,283,515,000	3,289,341	0.35	1,151,269	0.05	57,563
Aquifer	366,064,250,000	8,403,691	0.20	1,680,738	0.10	168,073
Coarse	136,395,410,000	3,131,212	0.25	782,803	0.15	117,420
TOTAL	646,927,380,000	14,851,431		3,625,684		343,273

Table 3-6. Saturated *Kd* aquifer materials underlying the SQS1 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)
Shale/clay	221,860,480,000	5,093,223	0.11	560,254	0.02	11,205
Sandstone/ sand	1,981,681,670,000	45,493,219	0.40	18,197,287	0.06	1,091,837
TOTAL	2,203,542,150,000	50,586,442		18,757,541		1,103,042

3.2.3.3 SQS2 AEM Block Area

Table 3-7. Unsaturated *Q* aquifer materials underlying the SQS2 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)
Non-Aquifer	5,236,108,750	120,204	0.40	48,081	0.02	961
Marginal	116,780,637,500	2,680,918	0.35	938,321	0.05	46,916
Aquifer	414,382,140,000	9,512,919	0.20	1,902,583	0.10	190,258
Coarse	164,718,308,750	3,781,417	0.25	475,645	0.15	71,346
TOTAL	701,117,195,000	16,095,460		3,364,630		309,481

Table 3-8. Saturated *Q* aquifer materials underlying the SQS2 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)
Non-Aquifer	19,400,856,250	445,383	0.40	178,153	0.02	3,563
Marginal	417,285,216,250	9,579,564	0.35	3,352,847	0.05	167,642
Aquifer	462,342,957,500	10,613,949	0.20	2,122,789	0.10	212,278
Coarse	100,534,303,750	2,307,953	0.25	530,697	0.15	79,604
TOTAL	999,563,333,750	22,946,850		6,184,486		463,087

3.2.3.4 WAANN AEM Block Area

Table 3-9. Unsaturated *Q* aquifer materials underlying the Waann 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)
Non-Aquifer	13,404,325,758	307,721	0.40	123,088	0.02	2,461
Marginal	95,935,519,453	2,202,379	0.35	770,832	0.05	38,541
Aquifer	131,773,732,495	3,025,113	0.20	605,022	0.10	60,502
Coarse	33,898,060,248	778,193	0.25	194,548	0.15	29,182
TOTAL	275,011,637,953	6,313,407		1,693,490		130,686

Table 3-10. Saturated *Q* aquifer materials underlying the Waann 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)
Non-Aquifer	35,429,689,755	813,354	0.40	325,341	0.02	6,506
Marginal	158,202,289,668	3,631,830	0.35	1,271,140	0.05	63,557
Aquifer	117,699,632,003	2,702,015	0.20	540,403	0.10	54,040
Coarse	13,276,948,798	304,797	0.25	76,199	0.15	11,429
TOTAL	324,608,560,223	7,451,998		2,213,083		135,532

Table 3-11. Unsaturated *Kd* aquifer materials underlying the Waann 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)
Shale/clay	1,765,750,100	40,536	0.11	4,458	0.02	89
Sandstone/ sand	337,393,780	7,745	0.40	3,098	0.06	185
TOTAL	2,103,143,880	48,281		7,556		274

Table 3-12. Saturated *Kd* aquifer materials underlying the Waann 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)
Shale/clay	287,240,056,163	6,594,134	0.11	725,354	0.02	14,507
Sandstone/ sand	731,466,750,595	16,792,191	0.40	6,716,876	0.06	403,012
TOTAL	1,018,706,806,758	23,386,325		7,442,230		417,519

3.3 Recharge Areas in the LPNNRD 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 Leshara Upland, Waann, SQS1, and SQS2 Block AEM flight areas that present the resistivity to lithology relationship described in Section 3.1.5 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 2-4, 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 surface ***Q*** sediments presented as aquifer material types for the 2018 LPNNRD AEM survey area and the Block flight areas are presented in Figure 3-152 – 2018 LPNNRD flight lines, Figure 3-153 – the Leshara Upland Block area, Figure 3-154 – the SQS1 Block flight area, Figure 3-155 – the SQS2 Block AEM survey area, and Figure 3-156 –the Waann Block AEM survey area.

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 LPNNRD AEM survey areas are the alluvial valley floor in Todd Valley and the Platte River Valley as well as the creek beds that have aquifer and coarse aquifer materials near the land surface. On the table lands, the best possible locations for recharge would be where there is a combination of aquifer and coarse aquifer materials at the land surface on the uplands with little relief in elevation with a pathway of similar materials down to the saturated aquifer at depth. A more in-depth recharge analysis could be performed using slope and run-off analysis combined with detailed soils maps with the additions of the AEM.

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

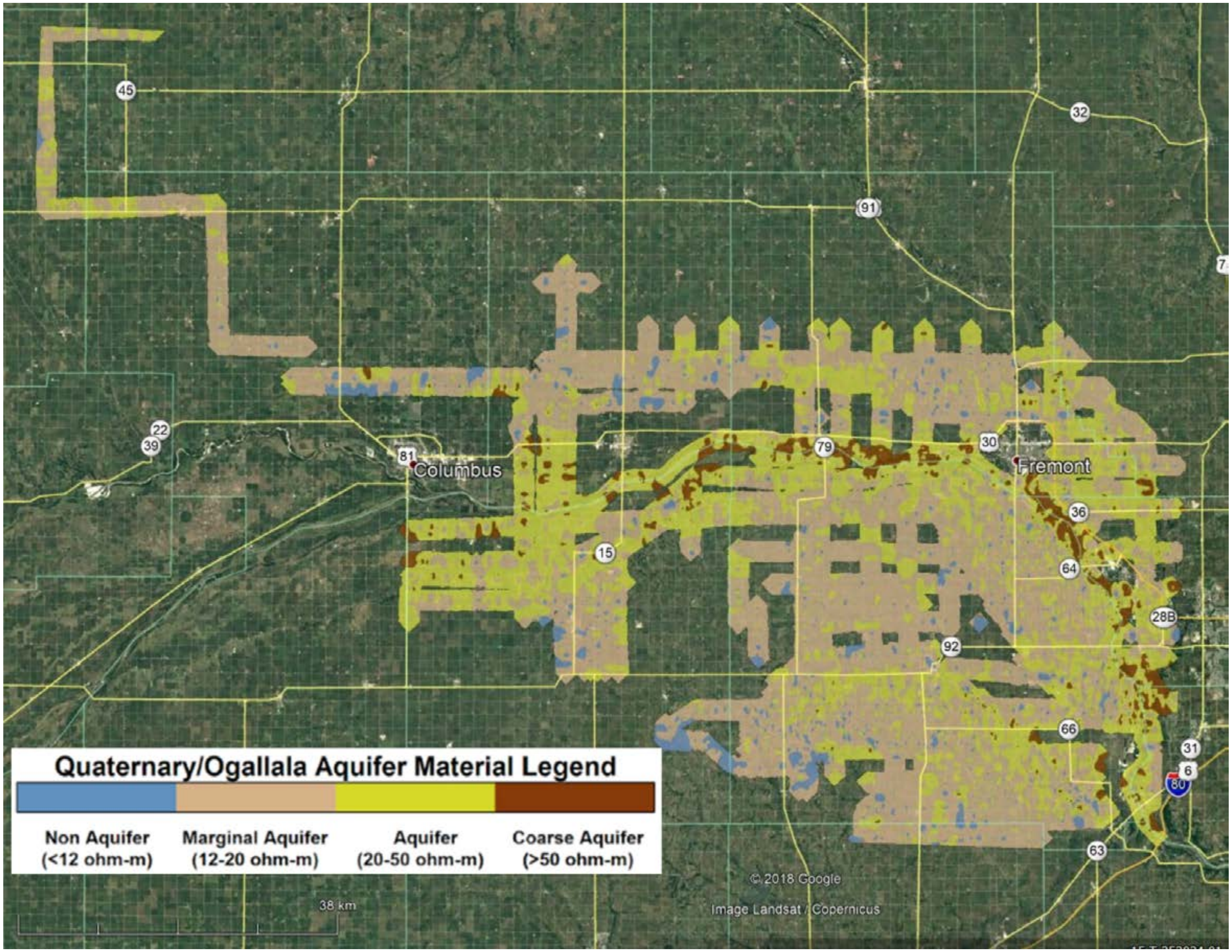


Figure 3-152. Map of near-surface aquifer materials in the 2018 LPNNRD AEM survey area. Note the presence of aquifer and coarse aquifer material along the Platte River Valley.

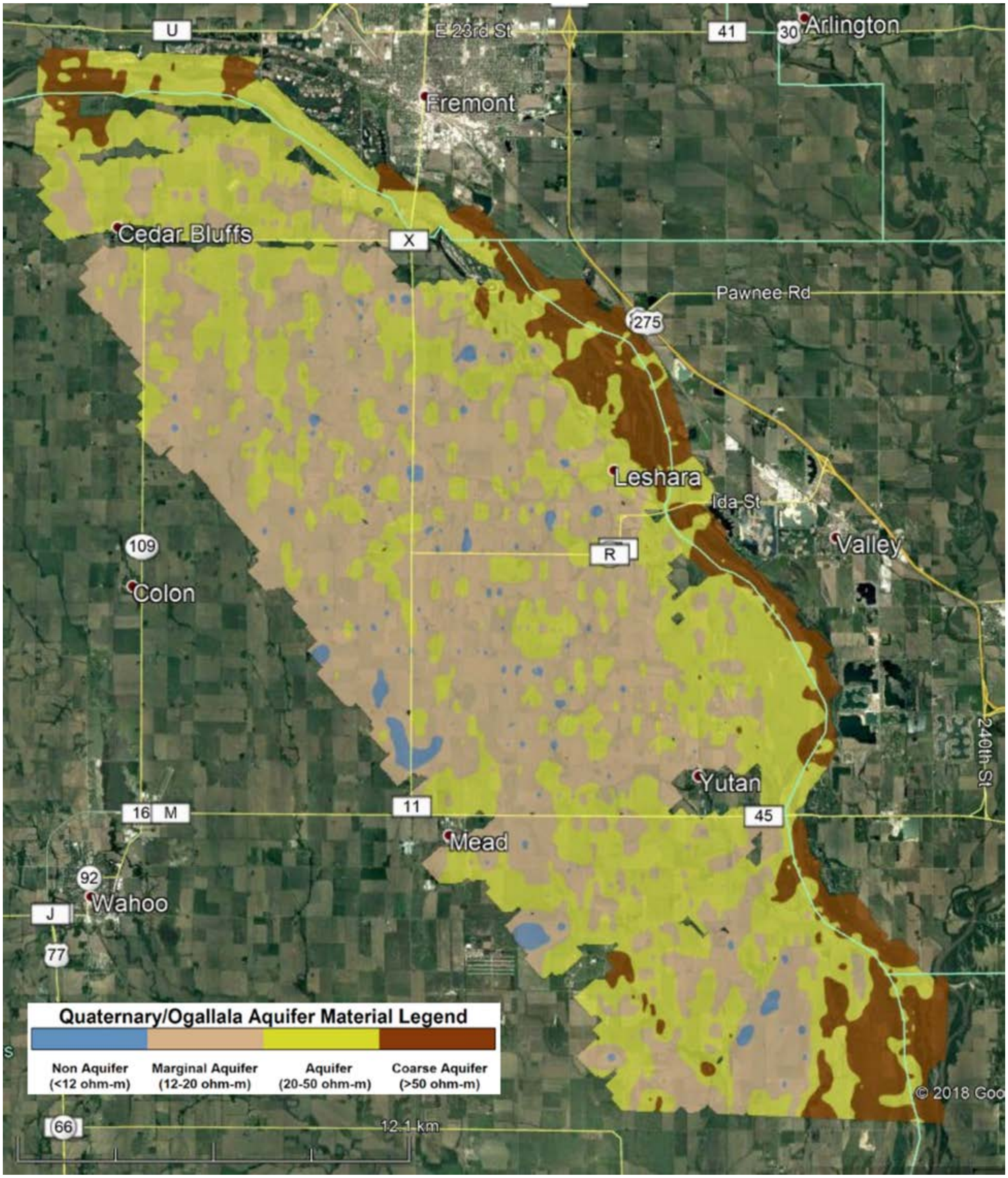


Figure 3-153. Map of near-surface aquifer materials in the Leshara Upland Block AEM survey area. Note the presence of aquifer and coarse aquifer material along the Platte River Valley.

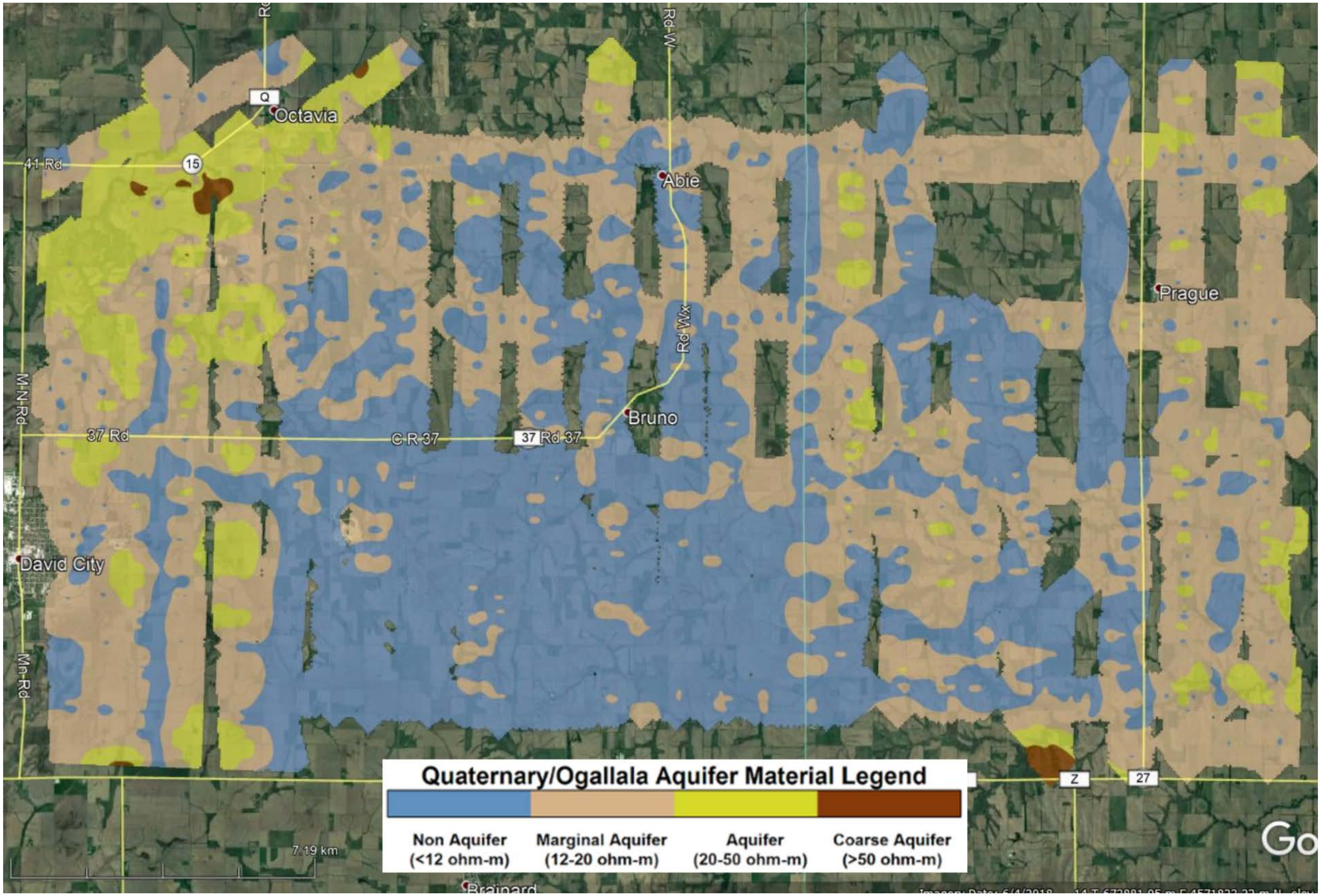


Figure 3-154. Map of near-surface aquifer materials in the SQS1 Block AEM survey area. The majority of the material in SQS1 is non-aquifer (blue) and marginal aquifer (tan) material. In the northwest corner there is aquifer material (yellow color).

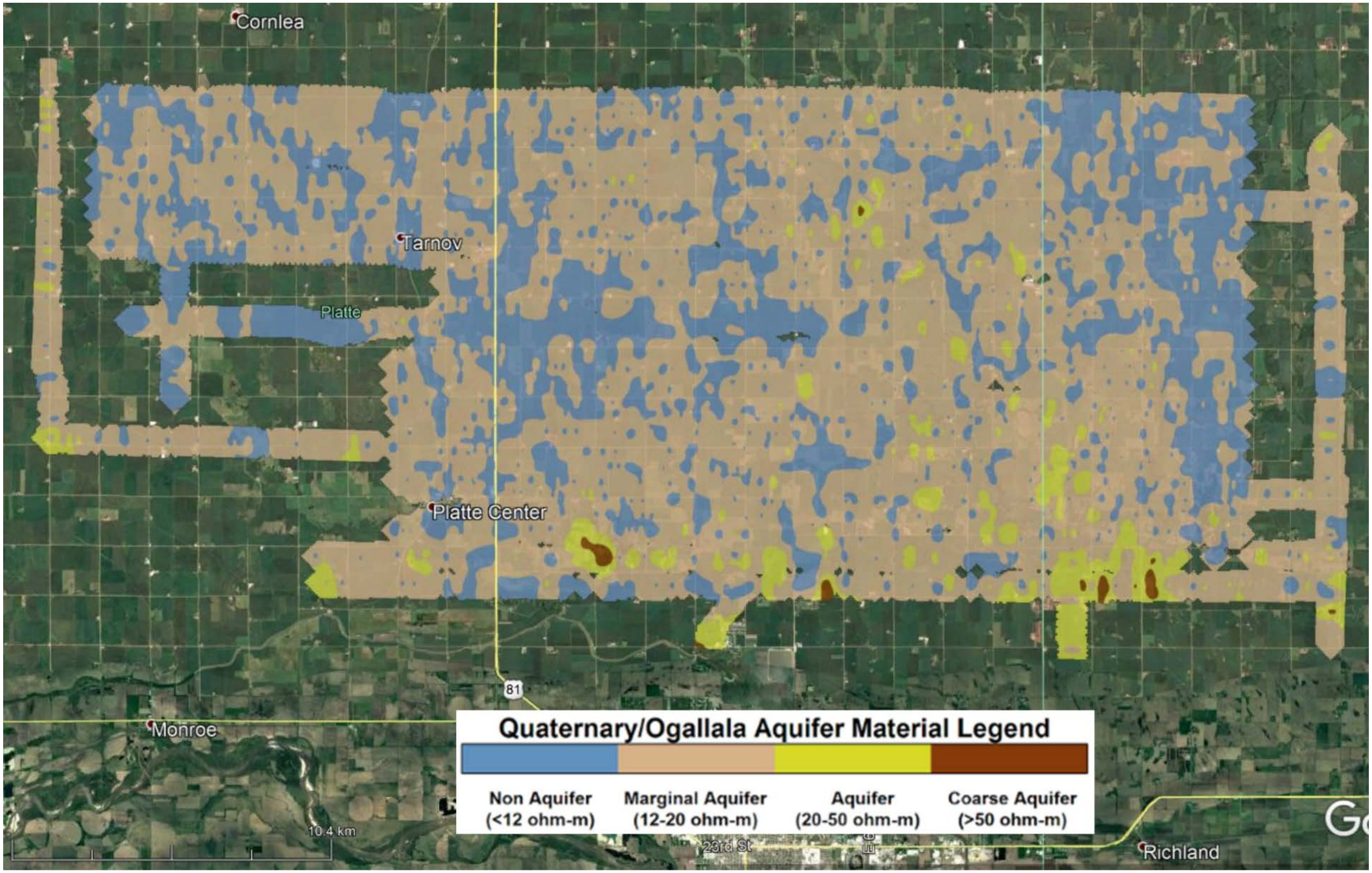


Figure 3-155. Map of near-surface aquifer materials in the SQS2 Block AEM survey area. The majority of the material in SQS2 is non-aquifer (blue) and marginal aquifer (yellow) material with small sub-areas of aquifer material (yellow) and coarse aquifer material (brown).

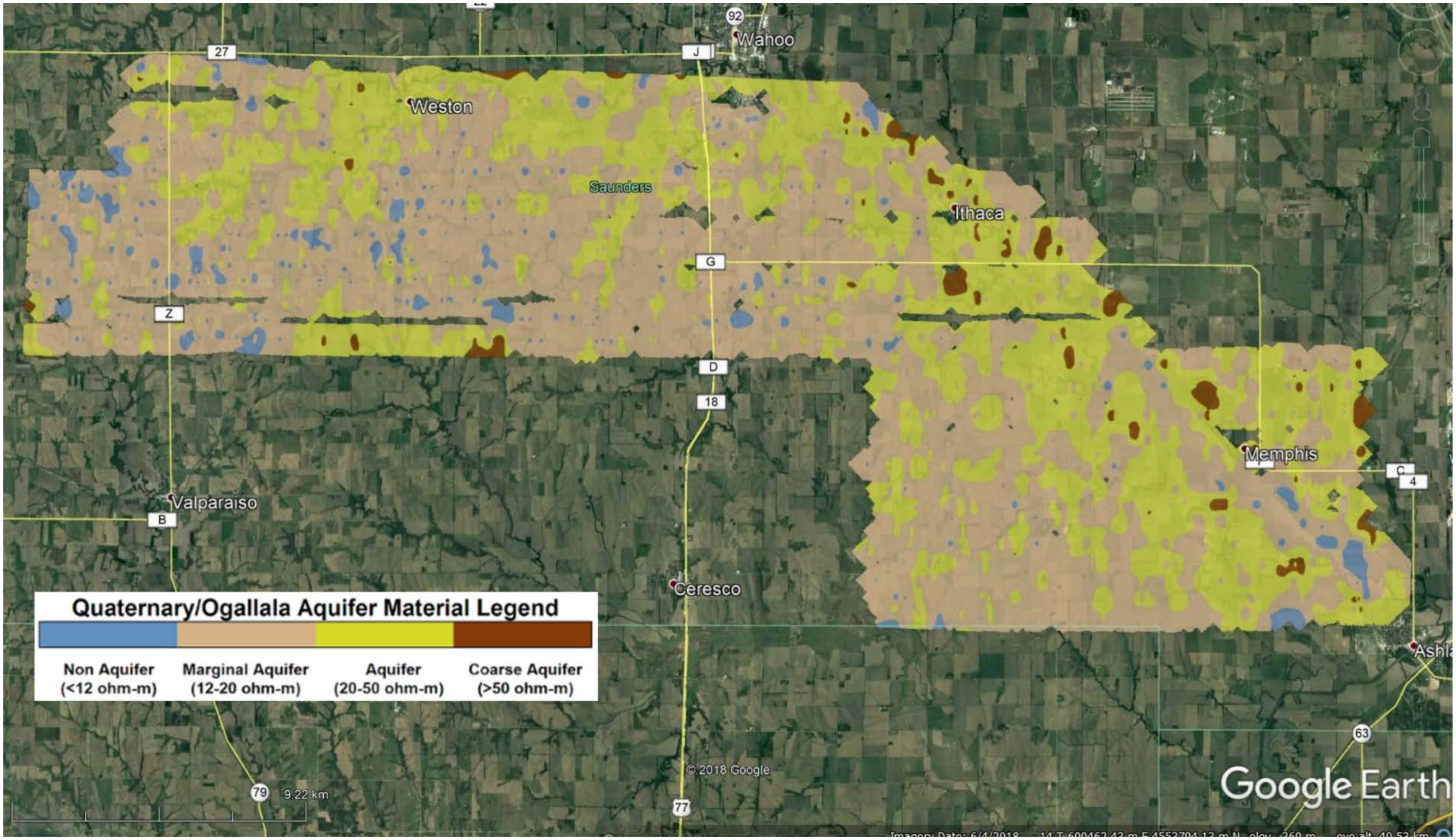


Figure 3-156. Map of near-surface aquifer materials in the Waann Block AEM survey area.

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 LPNNRD. The top of the undifferentiated Pennsylvanian (***IP***) was a challenging unit to interpret due to the highly variable resistivity of the IP. Top of the bedrock for the area was developed by inspection of the borehole logs that included consolidated geologic units and CSD (Nebraska Conservation and Survey Division) bedrock contacts. The CSD stratigraphic control was utilized to distinguish the ***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 ***Q***/***Kd*** contact when no resistivity contrast was present. The dependence on just boreholes for geologic interpretation also has its limitations because sometimes the boreholes 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. Very rarely 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. 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 (***To***), Cretaceous Niobrara (***Kn***), Cretaceous Carlile (***Kc***), Cretaceous Greenhorn Graneros (***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. 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. Given the known differences between the parameters of the 2014, 2015, 2016, and 2018 AEM surveys, it has become apparent that there needs to be integration work done to bring the results of all the years together in one package using the same parameters such as projection, model layer parameters, and lithologic nomenclature.

3.4.3 Resistivity/Lithology Relationship

Assessment of the sediment character in the Quaternary (***Q***) 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 numerically robust 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. 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 LPNNRD

The 2018 LPNNRD AEM survey reveals variability in the Quaternary (***Q***) and Cretaceous Dakota Group (***Kd***) deposits across the LPNNRD AEM survey area that make up the aquifer materials. The ***Q*** make up the aquifer materials overlying the Cretaceous bedrock units of which the ***Kd*** Sandstone/Sand Dominant material are aquifers. 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 SQS1, SQS2, and Todd Valley areas.

Estimates of the groundwater in storage within the ***Q***-portion of the Leshara AEM Block of aquifer material below the 1995 CSD water table elevation is 3,487,506 acre-ft. The amount of extractable groundwater from aquifer material is 51,598 acre-ft and coarse aquifer material is 20,742. The amount of extractable groundwater from ***Kd*** Sandstone/Sand Dominant material is 228,244.

Estimates of the groundwater in storage within the ***Q***-portion of the SQS1 AEM Block of aquifer material below the 1995 CSD water table elevation is 3,625,684 acre-ft. The amount of extractable groundwater from aquifer material is 168,073 acre-ft and coarse aquifer material is 117,420. The amount of extractable groundwater from ***Kd*** Sandstone/Sand Dominant material is 1,091,837.

Estimates of the groundwater in storage within the ***Q***-portion of the SQS2 AEM Block of aquifer material below the 1995 CSD water table elevation is 6,184,486 acre-ft. The amount of extractable groundwater from aquifer material is 212,278 acre-ft and coarse aquifer material is 79,604. 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 Waann AEM Block of aquifer material below the 1995 CSD water table elevation is 7,451,998 acre-ft. The amount of extractable groundwater from aquifer material is 54,040 acre-ft and coarse aquifer material is 11,429. The amount of extractable groundwater from ***Kd*** Sandstone/Sand Dominant material is

403,012.

3.4.5 Potential Recharge Zones within the LPNNRD AEM Survey Area

The use of block flights for Leshara, Waann, SQS1 and SQS2 AEM Blocks illustrates 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 area throughout the Leshara Block has potential recharge that is limited in extent due to the ***Q*** aquifer materials (marginal and non-aquifer) at the land surface. The exception is along the Platte River Valley and the south end of the Todd Valley. The area throughout the SQS1 Block has potential recharge that is limited in extent due to the ***Q*** aquifer materials at the land surface. The exception is near Octavia along the Platte River Valley. The area throughout the SQS2 Block has potential recharge that is limited in extent due to the ***Q*** aquifer materials at the land surface. The exception is the southern end of the SQS2 Block that is near the town of Columbus. The area throughout the Waann Block has potential recharge that is limited in extent due to the ***Q*** aquifer materials (marginal and non-aquifer) at the land surface. The exception is near the town of Ithaca and the south end of the Todd Valley.

Within the reconnaissance AEM flight area of the LPNNRD, 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.

3.4.6 Hydrologic connection between groundwater and surface water in the LPNNRD AEM Survey Area

The AEM data and interpretation provides detailed empirical data for determining earth materials at depth which 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 LPNNRD 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 LPNNRD about their management challenges.

3.5.1 Integration of 2007-2018 AEM Hydrogeological Investigations

The LPNNRD has acquired AEM data from 2007, 2014, 2015, 2016 and 2018 with several different AEM systems and contractors performing the work including USGS, XRI Geophysics and AGF with oversight from the ENWRA and the LPNNRD. With the completion of this current study there needs to be additional work done to bring all the work from previous years together in one seamless package using the same parameters such as the three different geographic projections NAD83 Zone 14N (meters), NAD83 Zone 14N (feet), and NAD83 Nebraska State Plane (feet), model layering structure, and hydrologic nomenclature. Recent communication with consultants and the NE-DNR has also brought to light that additional effort is needed to quantify the NE-DNR boreholes relationship to the aquifer materials that the AEM has mapped. There apparently exists confusion on the use of “principal aquifer material” versus “aquifer material” versus “Principal Aquifer” as determined by NE-DNR. While these are apparently minor additions and changes, they can add to the overall usability and portability of the AEM analysis results within the LPNNRD.

3.5.2 Additional AEM Mapping

The AEM coverage of the district is nearly complete. At this time the only reason to gather additional AEM is to better understand the details of a specific area. Examples of those areas could be the Bellwood and Richland-Schuyler control areas.

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 LPNNRD 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 sedimentary 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 LPNNRD.

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 LPNNRD 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 LPNNRD exist and what additional information would be required for final selections of MAR sites. A detailed plan for locating and developing MAR sites would be beneficial to the LPNNRD 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 LPNNRD 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, thirty-two (32) flights were required to acquire the LPNNRD 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 file LPNNRD2018_EM_MAG_AUX.xyz. This file contains the electromagnetic data, plus the magnetic and navigational data, as supplied directly from SkyTEM. The result of the SCI is included in LPNNRD2018_AEM_SCI_INV_v1.xyz and the data columns of these databases are described in Table 4-3.

The interpretation results are included in the data files 2018 LPNNRD Interpretation.xyz., 2018 Leshara Block Interpretation.xyz, 2018 SQS1 Block Interpretation.xyz, 2018 SQS2 Block Interpretation.xyz, and 2018 Waann Block Interpretation.xyz in ASCII format. Table 4-4 describes the data columns of those 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. The file is LPNNRD2018_XYDEM_Dep_Elev_Rho.xyz.

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 Leshara, SQS1, SQS2, and Waann blocks are described in Table 4-7. The voxel grid is presented as an xyz file.

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 of the flight blocks *.xyz
- 2D profiles and 3D fence diagrams of the AEM survey inversion results

KMZs for LPNNRD AEM flight lines and Block areas (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
Geo	20180823_304_DualWaveform_60Hz_skb.gex 20181002_304_446_Nebraska_skb_SR2.gex 20181002_304_446_Nebraska_skb_SR2.sr2	304M System Description
Mask	20180613_446_NE304_LPNNRD.lin	Production file listing dates, flights, and assigned line numbers

Table 4-2: Channel name, description, and units for LPNNRD2018_EM_MAG_AUX.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 LPNNRD2018_AEM_SCI_INV_v1.xyz 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 2018 LPNNRD Interpretation.xyz., 2018 Leshara Block Interpretation.xyz, 2018 SQS1 Block Interpretation.xyz, 2018 SQS2 Block Interpretation.xyz, and 2018 Waann Block Interpretation.xyz. 9999 = Dummy value.

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	Feet [ft]
DEP_BOT_FT [0] through DEP_BOT_FT [38]	Depth to the bottom of 39 individual layers	Feet [ft]
DOI_UPPER_FT	More conservative estimate of DOI from Workbench	Feet [ft]
DOI_LOWER_FT	Less conservative estimate of DOI from Workbench	Feet [ft]
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. LPNNRD Inverted Model Structure with DEM and Layer Top-, Bottom-, and Mid-points in Depth and Elevation plus Inverted Cell Resistivities (LPNNRD2018_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)
LPNNRD_DEM_ft	Digital Elevation Model (ground surface elevation) (NAVD88 feet) of the 2018 LPNNRD survey area, NAD83/State Plane Nebraska, feet	100
LPNNRD_WT_1995	Elevation (NAVD88 feet) of water table (1995) for the 2018 LPNNRD survey area, NAD83/State Plane Nebraska, feet	100
LPNNRD_Top_Bedrock	Elevation (NAVD88 feet) of top of bedrock for the 2018 LPNNRD survey area, NAD83/State Plane Nebraska, feet	1000
LPNNRD_Top_To	Elevation (NAVD88 feet) of top of Ogallala Group for the 2018 LPNNRD survey area, NAD83/State Plane Nebraska, feet	1000
LPNNRD_Top_Kn	Elevation (NAVD88 feet) of top of Niobrara Formation for the 2018 LPNNRD survey area, NAD83/State Plane Nebraska, feet	1000
LPNNRD_Top_Kc	Elevation (NAVD88 feet) of top of Carlile Shale for the 2018 LPNNRD survey area, NAD83/State Plane Nebraska, feet	1000
LPNNRD_Top_Kgg	Elevation (NAVD88 feet) of top of Greenhorn-Graneros for the 2018 LPNNRD survey area, NAD83/State Plane Nebraska, feet	1000
LPNNRD_Top_Kd	Elevation (NAVD88 feet) of top of Dakota Group for the 2018 LPNNRD survey area, NAD83/State Plane Nebraska, feet	1000
LPNNRD_Top_IP	Elevation (NAVD88 feet) of top of Undifferentiated Pennsylvanian for the 2018 LPNNRD survey area, NAD83/State Plane Nebraska, feet	1000
LPNNRD_Thickness_Q	Thickness (feet) of Quaternary Deposits for the 2018 LPNNRD survey area, NAD83/State Plane Nebraska, feet	1000
LPNNRD_Thickness_To	Thickness (feet) of Ogallala Group for the 2018 LPNNRD survey area, NAD83/State Plane Nebraska, feet	1000
LPNNRD_Thickness_Kn	Thickness (feet) of Niobrara Formation for the 2018 LPNNRD survey area, NAD83/State Plane Nebraska, feet	1000
LPNNRD_Thickness_Kc	Thickness (feet) of Carlile Shale for the 2018 LPNNRD survey area, NAD83/State Plane Nebraska, feet	1000
LPNNRD_Thickness_Kgg	Thickness (feet) of Greenhorn-Graneros for the 2018 LPNNRD survey area, NAD83/State Plane Nebraska, feet	1000
LPNNRD_Thickness_Kd	Thickness (feet) of Dakota Group for the 2018 LPNNRD survey area, NAD83/State Plane Nebraska, feet	1000
LPNNRD_SatThick_Q	Saturated thickness (feet) of Quaternary Deposits for the 2018 LPNNRD survey area, NAD83/State Plane Nebraska, feet	1000
LPNNRD_SatThick_Kd	Saturated thickness (feet) of Dakota Group for the 2018 LPNNRD survey area, NAD83/State Plane Nebraska, feet	1000
Leshara_Top_Bedrock	Elevation (NAVD88 feet) of top of bedrock for the Leshara Block survey area, NAD83/State Plane Nebraska, feet	500
Leshara_Top_Kd	Elevation (NAVD88 feet) of top of Dakota Group for the Leshara Block survey area, NAD83/State Plane Nebraska, feet	500

Leshara_Top_IP	Elevation (NAVD88 feet) of top of Undifferentiated Pennsylvanian for the Leshara Block survey area, NAD83/State Plane Nebraska, feet	500
Leshara_Thickness_Q	Thickness (feet) of Quaternary Deposits for the Leshara Block survey area, NAD83/State Plane Nebraska, feet	500
Leshara_Thickness_Kd	Thickness (feet) of Dakota Group for the Leshara Block survey area, NAD83/State Plane Nebraska, feet	500
Leshara_SatThick_Q	Saturated thickness (feet) of Quaternary Deposits for the Leshara Block survey area, NAD83/State Plane Nebraska, feet	500
Leshara_SatThick_Kd	Saturated thickness (feet) of Dakota Group for the Leshara Block survey area, NAD83/State Plane Nebraska, feet	500
Waann_Top_Bedrock	Elevation (NAVD88 feet) of top of bedrock for the Waann Block survey area, NAD83/State Plane Nebraska, feet	500
Waann_Top_Kd	Elevation (NAVD88 feet) of top of Dakota Group for the Waann Block survey area, NAD83/State Plane Nebraska, feet	500
Waann_Top_IP	Elevation (NAVD88 feet) of top of Undifferentiated Pennsylvanian for the Waann Block survey area, NAD83/State Plane Nebraska, feet	500
Waann_Thickness_Q	Thickness (feet) of Quaternary Deposits for the Waann Block survey area, NAD83/State Plane Nebraska, feet	500
Waann_Thickness_Kd	Thickness (feet) of Dakota Group for the Waann Block survey area, NAD83/State Plane Nebraska, feet	500
Waann_SatThick_Q	Saturated thickness (feet) of Quaternary Deposits for the Waann Block survey area, NAD83/State Plane Nebraska, feet	500
Waann_SatThick_Kd	Saturated thickness (feet) of Dakota Group for the Waann Block survey area, NAD83/State Plane Nebraska, feet	500
SQS1_Top_Bedrock	Elevation (NAVD88 feet) of top of bedrock for the SQS1 Block survey area, NAD83/State Plane Nebraska, feet	1000
SQS1_Top_Kgg	Elevation (NAVD88 feet) of top of Greenhorn-Graneros (Kgg) for the SQS1 Block survey area, NAD83/State Plane Nebraska, feet	1000
SQS1_Top_Kd	Elevation (NAVD88 feet) of top of Dakota Group for the SQS1 Block survey area, NAD83/State Plane Nebraska, feet	1000
SQS1_Top_IP	Elevation (NAVD88 feet) of top of Undifferentiated Pennsylvanian for the SQS1 Block survey area, NAD83/State Plane Nebraska, feet	1000
SQS1_Thickness_Q	Thickness (feet) of Quaternary Deposits for the SQS1 Block survey area, NAD83/State Plane Nebraska, feet	1000
SQS1_Thickness_Kgg	Thickness (feet) of Greenhorn-Graneros for the SQS1 Block survey area, NAD83/State Plane Nebraska, feet	1000
SQS1_Thickness_Kd	Thickness (feet) of Dakota Group for the SQS1 Block survey area, NAD83/State Plane Nebraska, feet	1000
SQS1_SatThick_Q	Saturated thickness (feet) of Quaternary Deposits for the SQS1 Block survey area, NAD83/State Plane Nebraska, feet	1000

SQS1_SatThick_Kd	Saturated thickness (feet) of Dakota Group for the SQS1 Block survey area, NAD83/State Plane Nebraska, feet	1000
SQS2_Top_Bedrock	Elevation (NAVD88 feet) of top of bedrock for the SQS2 Block survey area, NAD83/State Plane Nebraska, feet	500
SQS2_Top_Kn	Elevation (NAVD88 feet) of top of Niobrara Formation for the SQS2 Block survey area, NAD83/State Plane Nebraska, feet	500
SQS2_Top_Kc	Elevation (NAVD88 feet) of top of Carlile Shale for the SQS2 Block survey area, NAD83/State Plane Nebraska, feet	500
SQS2_Top_Kgg	Elevation (NAVD88 feet) of top of Greenhorn-Graneros for the SQS2 Block survey area, NAD83/State Plane Nebraska, feet	500
SQS2_Top_Kd	Elevation (NAVD88 feet) of top of Dakota Group for the SQS2 Block survey area, NAD83/State Plane Nebraska, feet	500
SQS2_Thickness_Q	Thickness (feet) of Quaternary Deposits for the SQS2 Block survey area, NAD83/State Plane Nebraska, feet	500
SQS2_Thickness_Kn	Thickness (feet) of Niobrara Formation for the SQS2 Block survey area, NAD83/State Plane Nebraska, feet	500
SQS2_Thickness_Kc	Thickness (feet) of Carlile Shale for the SQS2 Block survey area, NAD83/State Plane Nebraska, feet	500
SQS2_SatThick_Q	Saturated thickness (feet) of Quaternary Deposits for the SQS2 Block survey area, NAD83/State Plane Nebraska, feet	500
Leshara_Thickness_AMCA	Thickness (feet) of aquifer material and coarse aquifer Quaternary material for the Leshara Block survey area, NAD83/State Plane Nebraska, feet	500
Leshara_Thickness_NAM	Thickness (feet) of non-aquifer and marginal Quaternary material for the Leshara Block survey area, NAD83/State Plane Nebraska, feet	500
Leshara_Thickness_KdSandSandstone	Thickness (feet) of Dakota Formation sand/sandstone dominant material for the Leshara Block survey area, NAD83/State Plane Nebraska, feet	500
Leshara_Thickness_KdClayShale	Thickness (feet) of Dakota Formation clay/shale dominant material for the Leshara Block survey area, NAD83/State Plane Nebraska, feet	500
Leshara_SatThick_AMCA	Saturated thickness (feet) of aquifer material and coarse aquifer Quaternary material for the Leshara Block survey area, NAD83/State Plane Nebraska, feet	500
Leshara_SatThick_KdSandSandstone	Saturated thickness (feet) of Dakota Group sand/sandstone dominant material for the Leshara Block survey area, NAD83/State Plane Nebraska, feet	500
Waann_Thickness_AMCA	Thickness (feet) of aquifer material and coarse aquifer Quaternary material for the Waann Block survey area, NAD83/State Plane Nebraska, feet	500
Waann_Thickness_NAM	Thickness (feet) of non-aquifer and marginal Quaternary material for the Waann Block survey area, NAD83/State Plane Nebraska, feet	500
Waann_Thickness_KdSandSandstone	Thickness (feet) of Dakota Group sand/sandstone dominant material for the Waann Block survey area, NAD83/State Plane Nebraska, feet	500

Waann_Thickness_KdClayShale	Thickness (feet) of Dakota Group clay/shale dominant material for the Waann Block survey area, NAD83/State Plane Nebraska, feet	500
Waann_SatThick_AMCA	Saturated thickness (feet) of aquifer material and coarse aquifer Quaternary material for the Waann Block survey area, NAD83/State Plane Nebraska, feet	500
Waann_SatThick_KdSandSandstone	Saturated thickness (feet) of Dakota Group sand/sandstone dominant material for the Waann Block survey area, NAD83/State Plane Nebraska, feet	500
SQS1_Thickness_AMCA	Thickness (feet) of aquifer material and coarse aquifer Quaternary material for the SQS1 Block survey area, NAD83/State Plane Nebraska, feet	500
SQS1_Thickness_KdSandSandstone	Thickness (feet) of Dakota Group sand/sandstone dominant material for the SQS1 Block survey area, NAD83/State Plane Nebraska, feet	500
SQS1_SatThick_AMCA	Saturated thickness (feet) of aquifer material and coarse aquifer Quaternary material for the SQS1 Block survey area, NAD83/State Plane Nebraska, feet	500
SQS1_SatThickKdSandSandstone	Saturated thickness (feet) of Dakota Group sand/sandstone dominant material for the SQS1 Block survey area, NAD83/State Plane Nebraska, feet	500
SQS2_Thickness_AMCA	Thickness (feet) of aquifer material and coarse aquifer Quaternary material for the SQS2 Block survey area, NAD83/State Plane Nebraska, feet	1000
SQS2_SatThick_AMCA	Saturated thickness (feet) of aquifer material and coarse aquifer Quaternary material for the SQS2 Block survey area, NAD83/State Plane Nebraska, feet	1000

Table 4-7. Channel name, description, and units for *_Quat_voxel.xyz and *_Kd_voxel.xyz. This is for the Leshara, SQS1, SQS2 (Quaternary only), and Waann. Quat=Quaternary, Kd=Cretacouse Dakota Group.

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 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\LPNNRD_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 LPNNRD GoogleE_Readme.pdf file is repeated below as a convenience. The LPNNRD interpretation KMZ is presented in Figure 4-1, the Leshara Block kmz in Figure 4-2, the SQS1 Block kmz in Figure 4-3, the SQS2 Block in Figure 4-4, and the Waann Block in Figure 4-5.

4.2.1 Included README for the LPNNRD Interpretation KMZ's

README for:

2018_LPNNRD_Interpretation.kmz (in 5 parts)
2018_Leshara_Block_Interp.kmz
2018_Waann_Block_Interp.kmz
2018_SQS1_Block_Interp.kmz
2018_SQS2_Block_Interp.kmz

Data Files - Please copy the folder *LPNNRD_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 *LPNNRD_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=Aquifer or Coarse Aquifer Material on Surface; 0=Non-Aquifer or Marginal Aquifer Material on Surface.

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

Sum Thk Aq-CAq (ft) – Sum of the thicknesses of Aquifer Material and Coarse Aquifer Material at the sounding location.

Thk NAq (ft) – Sum of thicknesses of Non-Aquifer Material at the sounding location.

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

Bedrock (ft) – Elevation of Bedrock surface, 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.

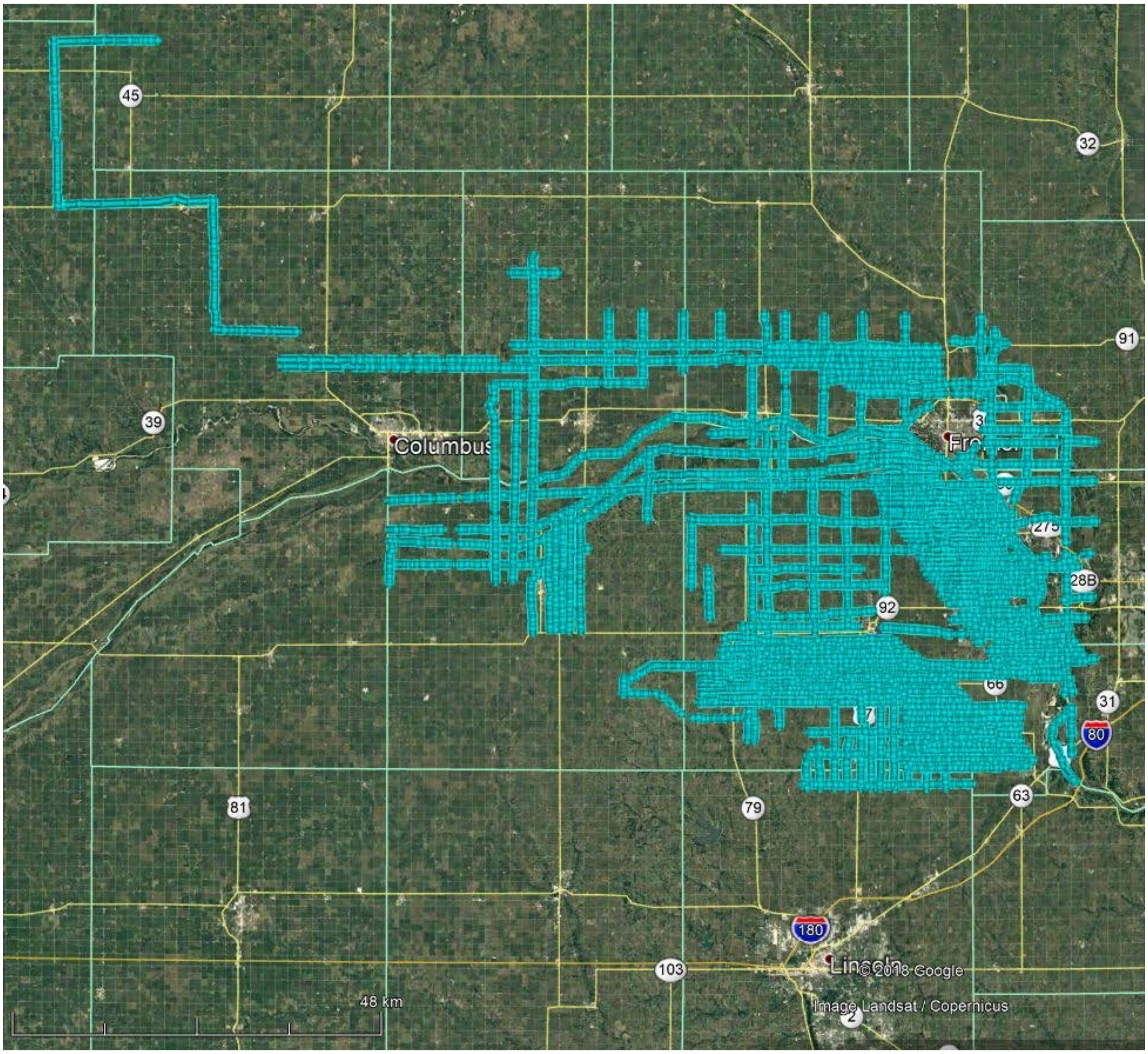


Figure 4-1. Example Google Earth image for the 2018 LPNNRD Interpretation kmz. Due to the size of the data set, this kmz has been divided into five (5) parts (Pt1, Pt2, Pt3, Pt4, and Pt5).

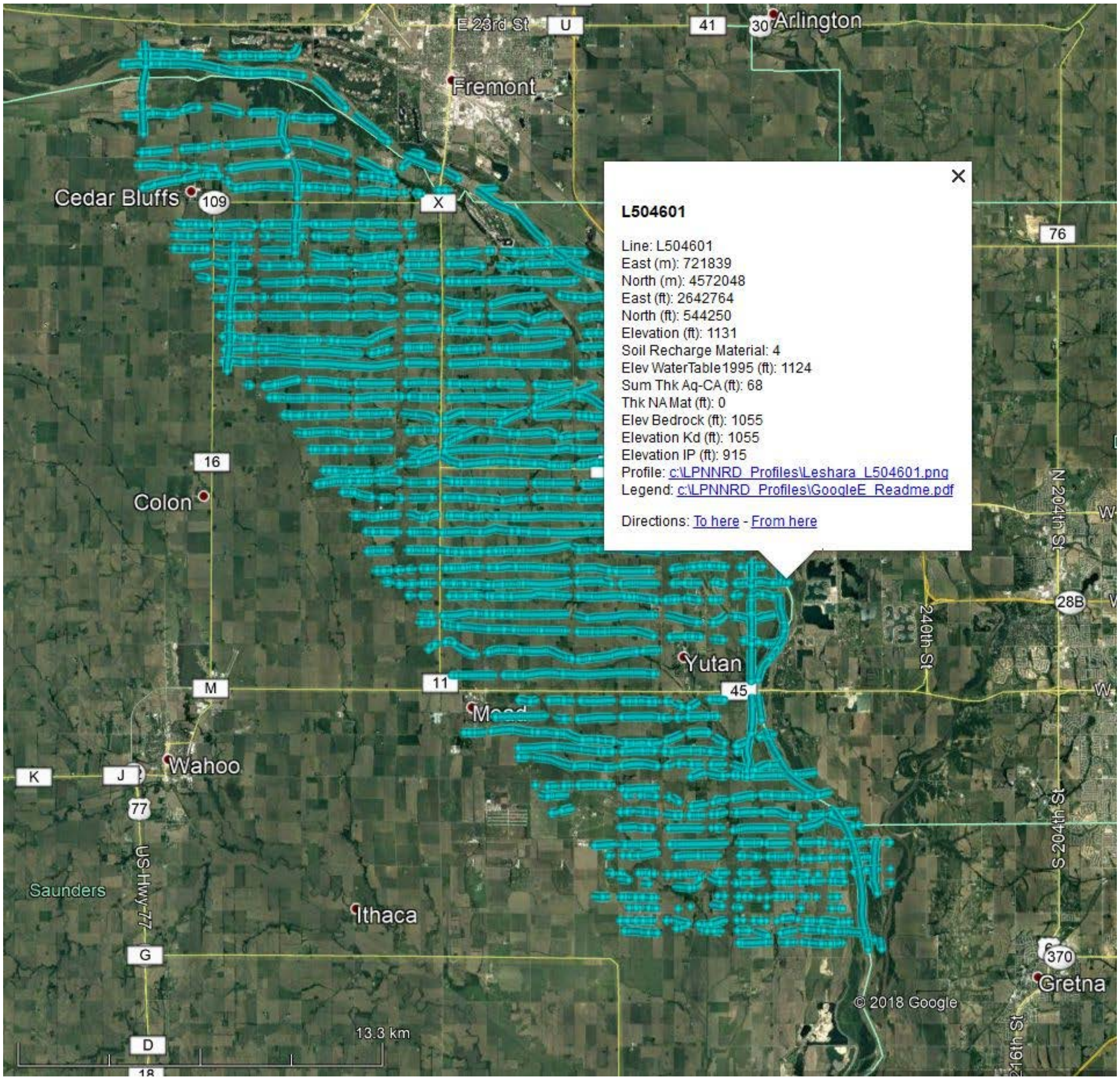


Figure 4-2. Example Google Earth image for the 2018 Leshara Block Interpretation kmz showing location attributes.

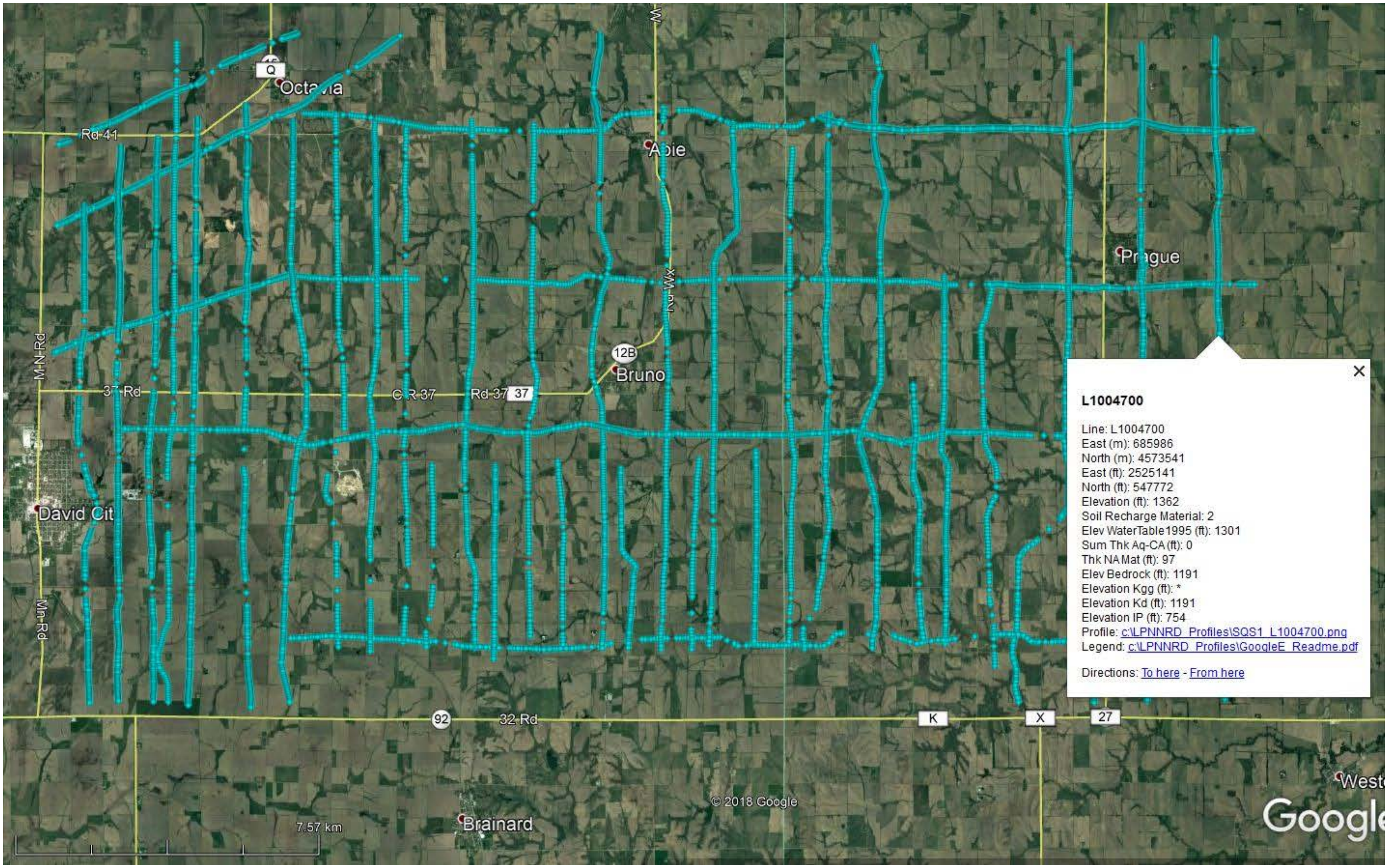


Figure 4-3. Example Google Earth image for the 2018 SQS1 Block Interpretation kmz showing location attributes.

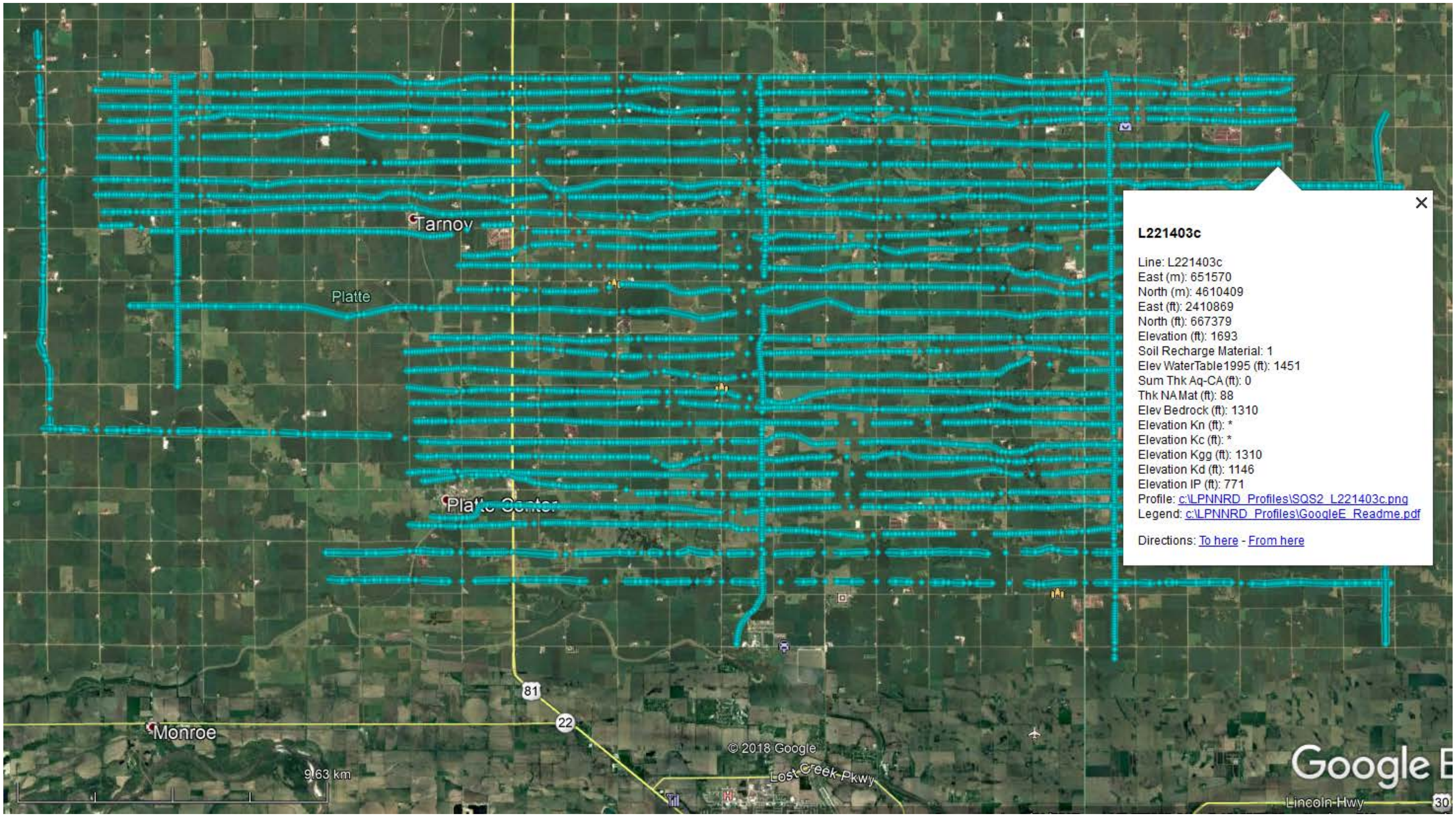


Figure 4-4. Example Google Earth image for the 2018 SQS2 Block Interpretation kmz showing location attributes.

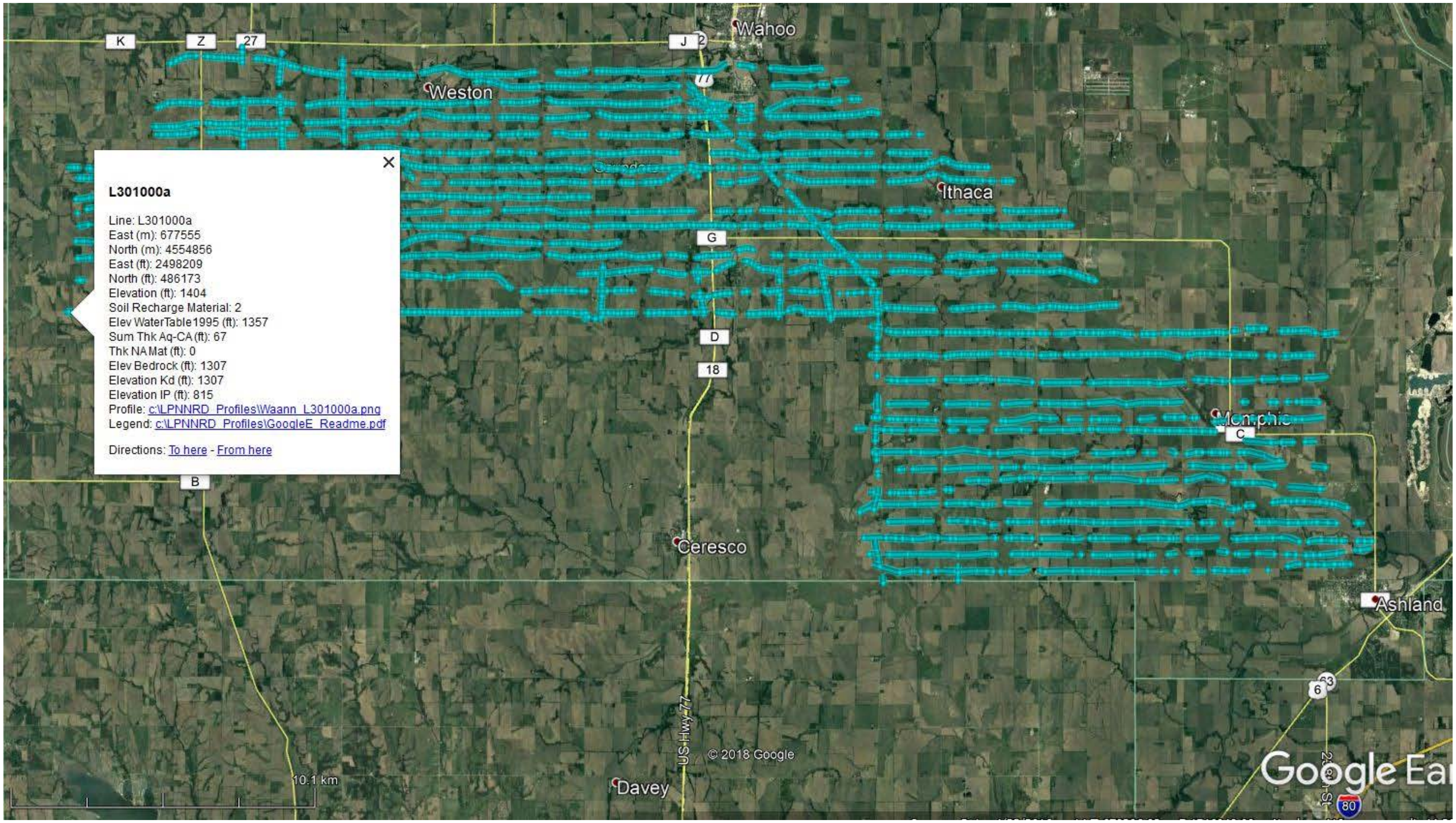


Figure 4-5. Example Google Earth image for the 2018 Waann Block Interpretation kmz showing location attributes.

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