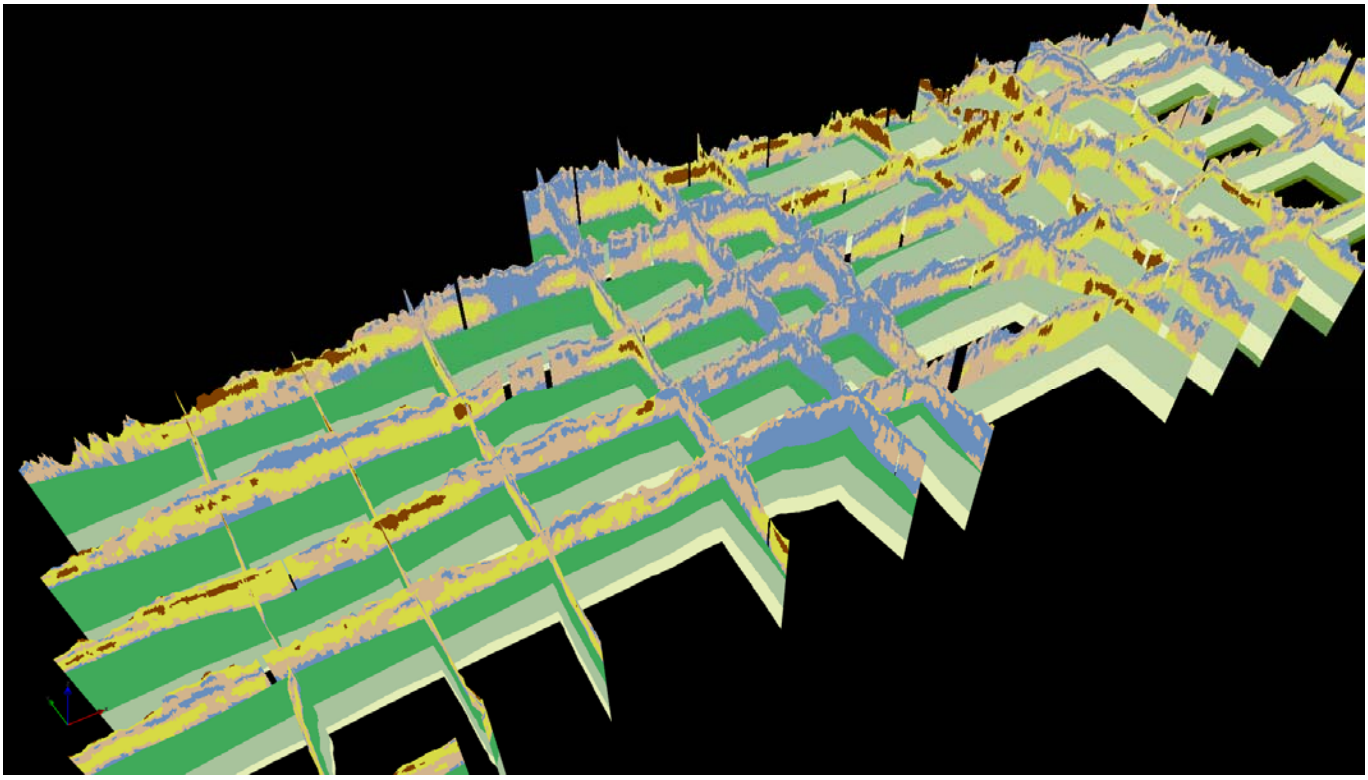
Hydrogeologic Framework of Selected Areas in the Lower Elkhorn Natural Resources District, Nebraska



***Prepared for*:**

Lower Elkhorn Natural Resources District

601 E. Benjamin Avenue
Norfolk, Nebraska, 68701

May 15, 2017

Aqua Geo Frameworks, LLC.

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Executive Summary

Aqua Geo Frameworks, LLC. (AGF) is pleased to submit this report titled "*Hydrogeologic Framework of Selected Areas in the Lower Elkhorn 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 Lower Elkhorn Natural Resources District (LENRD) to collect, process, and interpret airborne electromagnetic (AEM) data, in conjunction with other available background information, to develop a 3D hydrogeologic framework of the LENRD 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 LENRD project area. These flights have been provided as preliminary AEM inversions on July 19-27, 2016 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 the parties. This work included flight plans, database development, and review of hydrogeologic and geologic work for the area. The LENRD assisted in providing information such as power line maps, test hole databases, and related aquifer characteristic studies.

Upon conclusion of the design process the LENRD reconnaissance flight lines were approximately 55 miles in length at their longest in the east-west direction and about 48 miles at their longest in the north-south direction and were separated by approximately 3.1 miles in both east-west and north-south directions. In the area southwest of Wayne, the reconnaissance flight lines oriented southwest to northeast away from Wayne were approximately 14.2 miles in length and those that ran northwest to southeast closer to Wayne were approximately 17.3 miles in length. These reconnaissance flight lines were separated approximately 1 mile apart.

1.4 AGF acquired AEM data over the LENRD, commencing 18 July 2016 and finishing on 26 July 2016, to support development of the hydrogeological framework. Approximately 1016.5 line-miles (1,646.8 line-kilometers) were acquired over the LENRD AEM survey area. Status reports of the flying were provided to the Contract Representative of LENRD 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 19-27, 2016.

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

1.7 AGF is providing a hydrogeologic framework report that includes maps of aquifer(s), maps of aquifer materials relationships to current test holes and production groundwater wells, 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. These included CSD (Within the LENRD, 207 CSD holes contained lithology information, 151 holes contained stratigraphic information, and 63 holes contained geophysical information) and NE-DNR (A total of 4,223 registered wells contained usable lithology information) boreholes. Five NOGCC wells contained stratigraphy and lithology information.

2.2 **Digitizing Interpreted Geological Contacts** - Characterization and interpretation of the subsurface was performed in cross-section and derived surface grid formats. Contacts between the geologic units were digitized in 2D including: Quaternary (***Q***), Tertiary Ogallala Group (***To***), Cretaceous Pierre Shale (***Kp***), Niobrara Formation (***Kn***), Carlile Shale (***Kc***), Greenhorn Limestone and Graneros Shale (***Kgg***), and Dakota Group (***Kd***). The interpretive process benefited from the use of CSD and NE-DNR borehole logs. Surface grids of the interpreted geologic formations were then produced. Each flight line profile with interpretation including the Quaternary/Tertiary aquifer material mapping are included in the appendices as well as interpretative surface grids.

2.3 **Resistivity/Lithology Relationship** - Assessment of the sediment character in both the Quaternary/Tertiary Ogallala 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 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 LENRD** - The 2016 AEM survey reveals variability in the Quaternary (***Q***) deposits across the LENRD AEM survey area. When combined with the ***To***, they represent the aquifer materials in the AEM survey area, where saturated. The ***To*** is generally thick in the west and is thin to absent in the eastern regions of the AEM survey area. The ***Q*** and ***To*** make up the aquifer materials overlying the Cretaceous bedrock units. In the eastern and southern parts of the AEM survey area, the aquifer materials are predominantly marginal to non-aquifer materials which are glacial till and loess and which can be more than 200 feet thick. ***Q*** sediments found predominately on the west side are often associated with prevalent alluvial and coarse aquifer material deposits The ***Q*** and ***To*** (where present) materials are sitting on the ***Kp***, ***Kn***, ***Kc***, and ***Kgg*** which are the bedrock aquicludes for the area.

2.5 **Potential Recharge Zones within the LENRD AEM Survey Area** - The use of widely-spaced reconnaissance lines (approximately 3 miles apart) illustrates patterns or areas where the potential for recharge can be high and low. Locations where the flight lines intersect and both lines show either aquifer or coarse aquifer material should be considered as higher likelihood for recharge because of the 2D spatial nature of the aquifer material distribution. The opposite is also true where two flight lines intersect and both lines show non-aquifer or marginal material, those areas will likely not be optimal recharge locations. The area on the eastern side of the AEM survey area has potential recharge that is less than the rest of the survey area. The area on the western side of the AEM survey area has the highest potential recharge capability. There are

other discontinuous zones of potentially lower and higher recharge scattered throughout survey area.

3. Recommendations

Recommendations provided to the LENRD 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 LENRD about their management challenges.

3.1 **Additional AEM Mapping** - The hydrogeologic maps provided in this report represent the detailed framework developed for the LENRD at a reconnaissance level. LENRD is in the middle of a 5-year plan to gather AEM data that will be used to develop a hydrogeologic framework across the entire District. Beginning in 2014, the District has been collecting AEM data at approximately 3-mile grid spacing, as financial resources have allowed. The interpretations match well with the CSD and NE-DNR test holes. Reconnaissance lines collected from 2014 through 2016 in the northern and western parts of the district, with a few approximately 20 miles apart spaced lines in the east and south. New AEM reconnaissance flight lines, proposed to be collected next in the District's 5-year plan, are located in the southeast areas of the LENRD on a 3-mile grid. The existing AEM lines match each other with high fidelity and can be used to provide detail for voluntary groundwater management activities for water quantity, water quality, and integrated water management. Areas of higher interest can be mapped by AEM block flights to provide more detailed information on the hydrogeologic framework and the recharge areas. It is recommended that the 5-year plan be completed. Upon completion of the reconnaissance line surveys of the complete district, it is recommended that all data from the various surveys be integrated into one database and final continuous surface maps be developed and published for the LENRD.

3.2 **Update the Water Table map** - The groundwater data used in the analyses presented in this report utilized the 1995 CSD water table map. Additional water level measurement locations would improve the water table map where groundwater conditions are unconfined. This is especially true on the west side of LENRD in Pierce and Madison Counties. The areas of glacial till and loess covering the eastern side 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.

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

3.4 **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. The few test holes with geophysical logs in the LENRD AEM survey area were inadequate given the size of the area. None were calibrated and several had apparent hardware malfunctions. The borehole geophysical logs used in this investigation demonstrate that additional calibrated and verified geophysical logs are required in the LENRD.

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 **Recharge Zones** - The LENRD 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 additional AEM data be collected and interpreted utilizing closely-spaced flight lines using an AEM system that has good near-surface resolution in areas identified by the LENRD that are of priority importance for management purposes. It is further recommended that future work integrate new soils maps with the results of this study to provide details on soil permeability, slope, and water retention to provide a more complete understanding of the transport of water from the land surface to the groundwater aquifer.

3.6 **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 LENRD exist and what additional information would be required for final selections of MAR sites. Additional AEM mapping along the streams in the LENRD would also be beneficial in locating potential MAR locations. A detailed plan for locating and developing MAR sites would be beneficial to the LENRD for providing storage and release of water for stream flow and other uses.

4. Deliverables

In summary, the following are included as deliverables:

- Raw EM Mag data Geosoft database and ASCII *.xyz
- SCI inversion Geosoft database and ASCII *.xyz
- Borehole Geosoft databases and ASCII *.xyz
- Interpretations Geosoft database and ASCII *.xyz
- Raw Data Files - SkyTEM files *.geo, *skb, *.lin
- ESRI ArcView and Geosoft grid files – surface, topo, *.flt, *.grd, etc
- 3D fence diagrams of the AEM survey lines as *.png

Google Earth KMZs for LENRD AEM flight lines

Profile Analyst session for the Profiles and 3D maps for the LENRD data analysis

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List of Abbreviations

2D	Two-dimensional
3D	Three-dimensional
$A*m^2$	Ampere meter squared
AEM	Airborne Electromagnetic
AGF	Aqua Geo Frameworks, LLC
Bgl/Bgs	Below Ground Level/Below Ground Surface
BGMA	Bazile Groundwater Management Area
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	Feet
ft^2	Feet squared
ft^2/d	Feet squared per day
Fm	Formation
GIS	Geographic Information System
gpd	Gallons per day
gpd/ft	(Gallons per day) per foot
gpm	Gallons per minute
HEM	Helicopter Electromagnetic
Hz	Hertz (cycles per second)
IGRF	International Geomagnetic Reference Field
Km/km	Kilometers
KMZ/kmz	Keyhole Markup language Zipped file
Kc	Cretaceous Carlile Shale
Kd	Cretaceous Dakota Group
Kgg	Cretaceous Greenhorn Limestone and Graneros Shale
Kn	Cretaceous Niobrara Formation
Kp	Cretaceous Pierre Shale
LENRD	Lower Elkhorn Natural Resources District
MAG	Magnetic (data); Magnetometer (instrument)
MCG	Minimum curvature gridding
m	Meters
mi^2	Miles squared
mg/L	Milligrams per liter
NAD83	North American Datum of 1983
NAVD88	North American Vertical Datum of 1988
NE	Nebraska
NE-DEQ	Nebraska Department of Environmental Quality
NE-DNR	Nebraska Department of Natural Resources
NMR	Nuclear Magnetic Resonance
NOGCC	Nebraska Oil and Gas Conservation Commission

NRD	Natural Resources Districts
NWIS	National Water Information System
OM	Geosoft Oasis montaj
PFC	Primary Field Compensation
PLNI	Power Line Noise Intensity
Q	Quaternary
Rx	Receiver
recon	Reconnaissance
SCI	Spatially-Constrained Inversion
STD	Standard Deviation
To	Tertiary Ogallala Group
TEM	Transient Electromagnetic
TDEM	Time-Domain Electromagnetic
Tx	Transmitter
UNL	University of Nebraska Lincoln
USGS	United States Geological Survey
UTM	Universal Transverse Mercator
V/m^2	Volts per meter squared
XRI	Exploration Resources International

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 the persistent threat of drought.

To ensure that demands for both new and existing uses of water are met, additional technical information on the aquifer systems that support the groundwater resource is necessary for refining management plans. This effort will also provide information and support to the Lower Elkhorn Natural Resources District's (LENRD) commitment to develop a Voluntary Integrated Management Plan for the District, in addition to cooperation in achieving the goals of the Lower Platte River Basin Coalition management plan. These factors are compounded by the fact that there is significant geologic variability in the LENRD, which necessitates the accumulation of Airborne Electromagnetic (AEM) information, which will complement the existing hydrogeologic data set.

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.

In response to these needs the LENRD is in the middle of a 5-year plan to gather AEM data that will be used to develop a hydrogeologic framework across the entire District. Beginning in 2014, the District has been collecting AEM data at approximately 3-mile grid spacing, as financial resources have allowed. This report is for the portion of this framework that was collected in 2016.

This report describes the general hydrogeologic conditions, assessed using data collected from previous AEM surveys. 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 (NEOGCC), 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 3 miles apart in the larger area surrounding Norfolk (Figure 1-1). An AEM survey was selected to assist in the development of a 3D hydrogeologic framework of these project areas and recommend future work to enhance groundwater management activities. A location map showing the LENRD survey flight areas

and flight lines is presented in Figure 1-2. A Google Earth Keyhole Markup language Zipped file (kmz) of the "as-flown" flight lines are included in Appendix 3_Deliverables\KMZ.

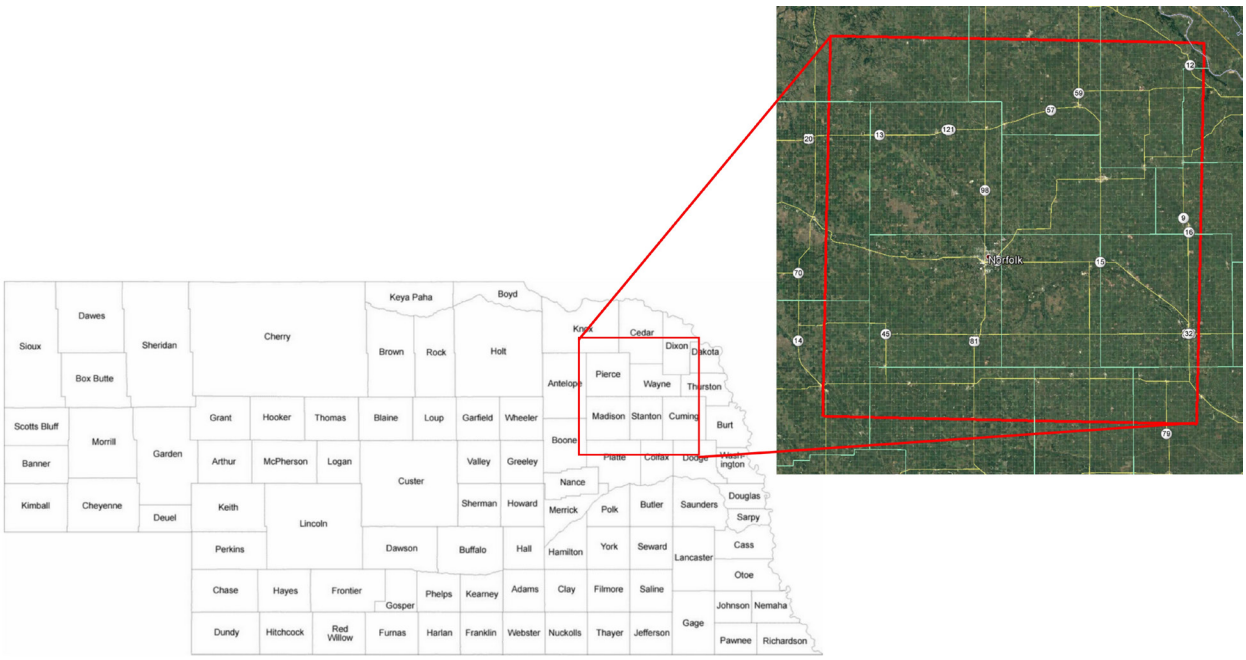


Figure 1-1. Map of Nebraska counties, indicating the location of the Lower Elkhorn Natural Resources District (LENRD) airborne electromagnetic (AEM) survey with an inset of the project area.

It is important to note that the Data collected for the 2016 AEM survey was used as part of the Bazile Groundwater Management Area (BGMA) interpretation and report. Figure 1-3 shows the overlap area for the two projects.

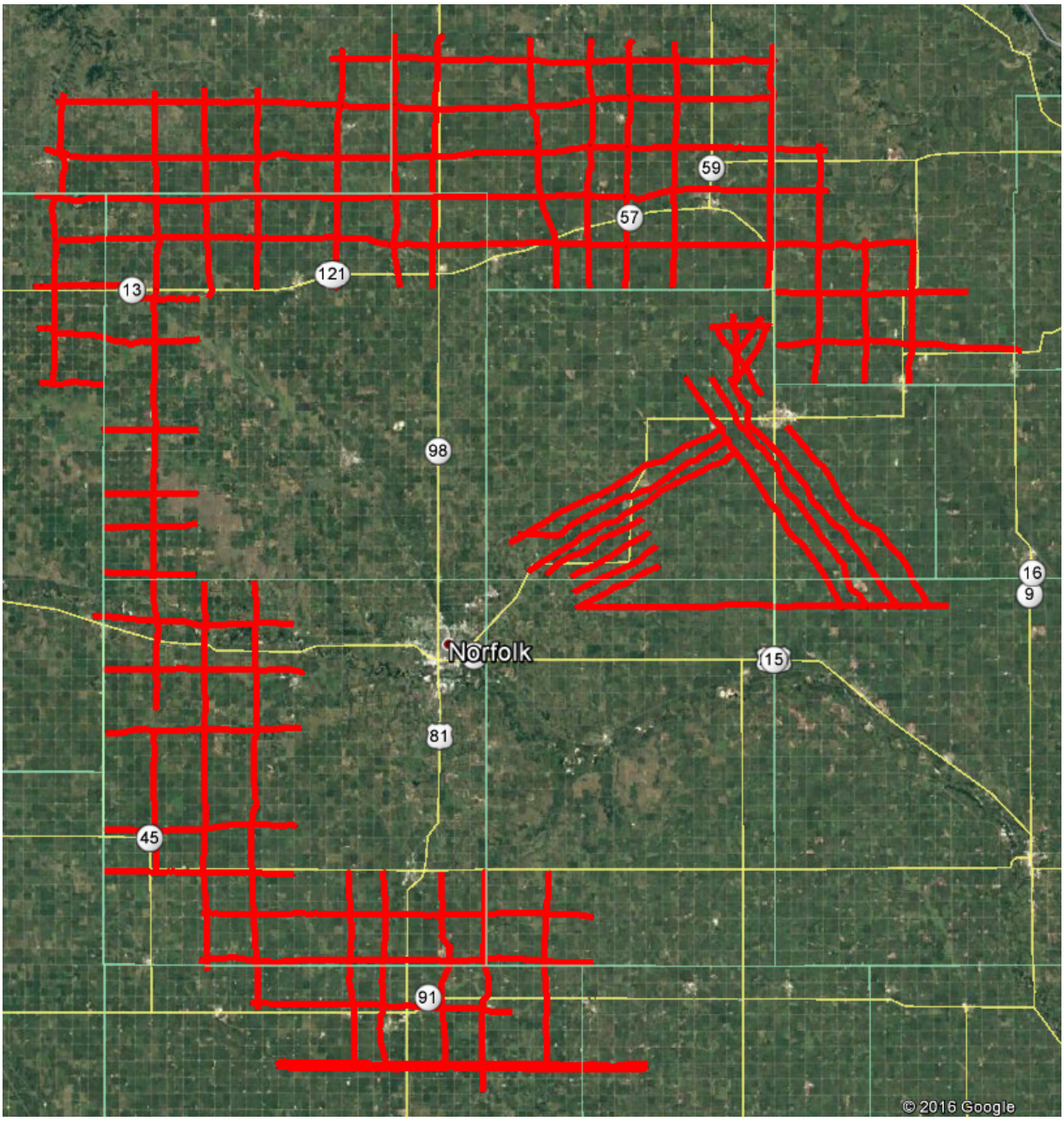


Figure 1-2. The LENRD AEM reconnaissance survey area including county lines and major roads (NE 98, 81, 91, 13, 45, 121 15, 59, 57) surrounding the city of Norfolk.

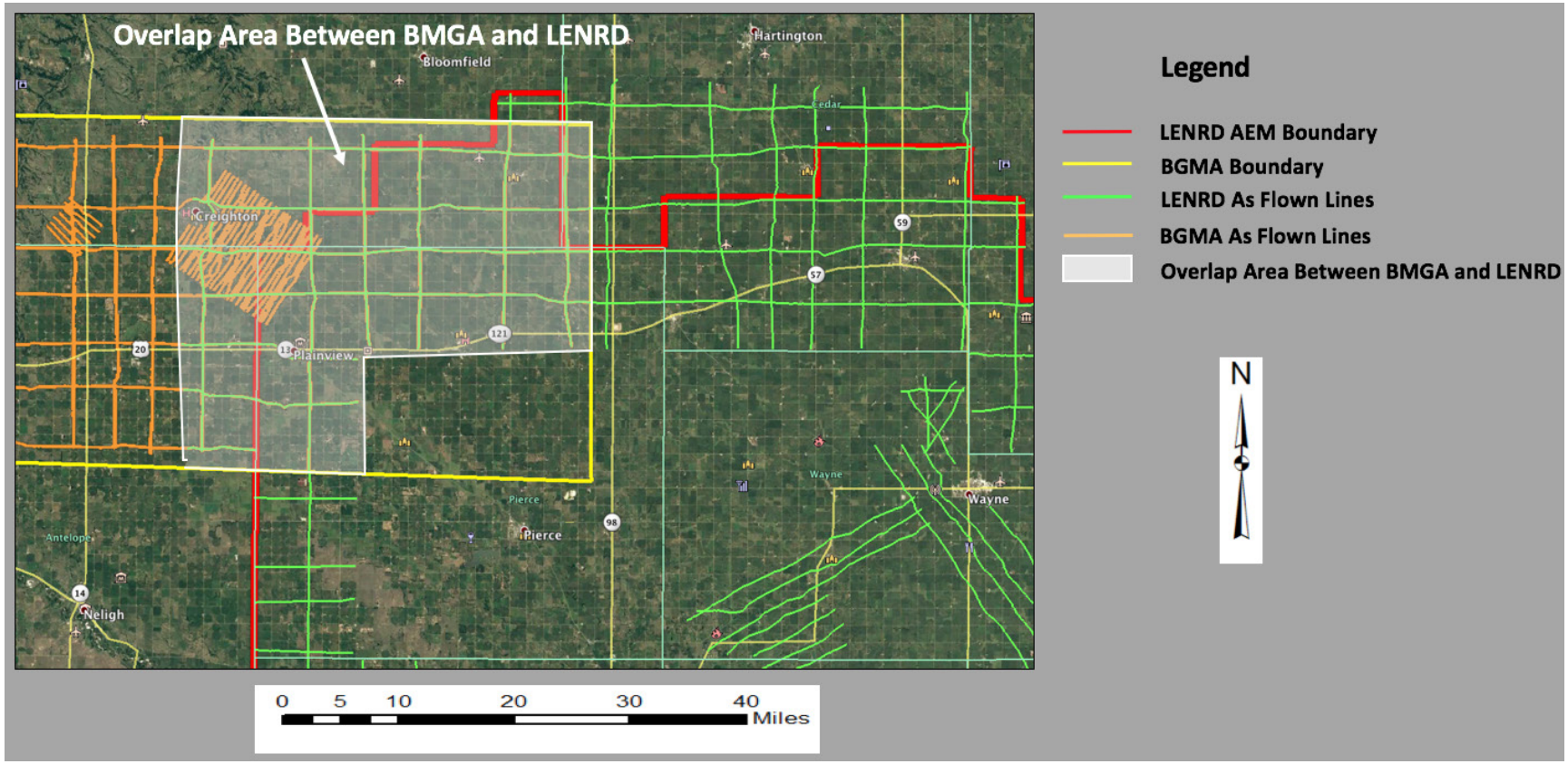


Figure 1-3. The LENRD AEM reconnaissance survey area boundary with the BGMA boundary showing the overlap and the shared flight lines for each project.

1.2 Background

In January of 1997, with the approval of the LENRD Groundwater Management Plan, the LENRD established a districtwide Groundwater Management Area, which contained information and trigger levels for purposes of managing groundwater quality and quantity. The initial Groundwater Management Plan established different Phase (or Action) Levels: Phase 1, Phase 2 and Phase 3, each containing elevated levels of requirements to address a specific level of groundwater condition. The Groundwater Management Plan has subsequently undergone some additions or revisions, most recently to require the installation of flow meters on all high capacity wells (regardless of use) in the District, and to modify and include a set of controls for a Phase 4 Area, which (if implemented) contains an ambitious set of action items meant to remediate acute groundwater contamination issues

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.

Use of AEM technology to map and evaluate groundwater resources has gained momentum over the last 20 years in the United States and abroad. The state of Nebraska has been on the forefront of implementing AEM for water resources management, over the last decade, with projects across the state in a variety of geologic settings. In recent years, the Eastern Nebraska Water Resources Assessment (ENWRA) has coordinated efforts between area Natural Resources Districts (NRDs), Conservation and Survey Division (CSD), the U.S. Geological Survey (USGS), and Aqua Geo Frameworks, LLC (AGF) in support of several projects designed to characterize the hydrogeology across the state. For purposes of this project, LENRD, ENWRA, and CSD are cooperating with AGF because of the shared aquifer boundaries and similar groundwater management efforts between these NRDs.

The ENWRA project was formed in 2006 with sponsors from six NRDs (Lewis and Clark, Lower Elkhorn, Papio-Missouri River, Lower Platte North, Lower Platte South, and Nemaha) and cooperating agencies including the CSD and the USGS. The long-term goal of the project is to develop a geologic framework and water budget for the glaciated portion of eastern Nebraska. 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 (Abraham et al., 2011; Hanson et al., 2012; Korus et al., 2013). In the following years, individual reports utilizing the AEM data collected in 2007 were released by the USGS and CSD. In 2009, a multi-faceted investigation incorporating the 2007 AEM data and 2009 ground-based geophysical techniques was conducted by the USGS to characterize the hydrogeologic setting near Oakland, Nebraska (Abraham et al., 2011). In 2009, the Lower Platte North NRD funded the USGS for the development of a 3D hydrostratigraphic framework of the subsurface near Swedeburg, Nebraska based on an AEM survey (Smith et al., 2009; Divine and Korus, 2013). Also in 2009, the Lower Platte South NRD funded the USGS and CSD for a similar investigation of the hydrostratigraphy near Sprague, Nebraska (Smith et al., 2009; Divine and Korus, 2012). In 2013, the Lower Elkhorn NRD funded Exploration

Resources International, LLC (XRI) to conduct an AEM survey near the towns of Clarkson and Howells, Nebraska to characterize the extent of the Quaternary aquifer beneath the area following the drought of 2012 (Abraham et al., 2013). At the same time the City of Madison also funded XRI for a small scale AEM study in and around the City of Madison (Carney et al., 2014a). Also in 2013, XRI completed an AEM survey covering over 800 line-miles in Butler and Saunders counties northwest of the city of Lincoln, Nebraska (Carney et al., 2014b). This survey, funded by the LPSNRD, revealed extensive, buried paleovalley aquifers beneath thick sequences of till. Additionally, intervals of Cretaceous bedrock units were revealed in the survey. The LENRD began to map their district with three-mile AEM grids in the fall of 2014 (Carney et al., 2015c). In 2014-2015 the ENWRA funded XRI for a large-scale reconnaissance AEM survey over the glaciated portion of Nebraska, approximately 2,200 line-km of approximately 32 km spaced lines (Abraham et al., 2015; Carney et al., 2015a; Carney et al., 2015b). In 2016, a study led by the CSD showed that the details gained from the AEM survey in around the Firth and Sprague area provided unique details that assisted in the management of the groundwater resources (Korus et al., 2016). In 2017, a study led by AGF provided information to improve the understanding of the hydrogeologic framework including areas of recharge to the aquifer and details for well head protection areas in the Bazile Creek Groundwater Management area (AGF, 2017a). Additionally, in 2017 another study led by AGF provided detailed 3D hydrogeologic framework for the western portions of Sarpy County characterized by eroded Dakota Sandstone aquifers overlain with glacial deposits (AGF, 2017b). A third study completed for the Lower Loup NRD was completed in 2017 and reported on the mix of glacial and non-glacial deposits near Columbus (AGF, 2017c). Thus, AEM surveys of the glacial terrain of Nebraska have followed a progressive, long-term plan spanning nearly 10 years. This body of work shows continuing advancements in the science and application of AEM to support groundwater management.

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

1.3 Description of the LENRD AEM Project Area

The LENRD spans approximately 4,050 square miles (mi^2) in northeast Nebraska. The elevation of the area ranges from 835 ft to 2235 ft above sea level**.** It is underlain by parts of six of Nebraska's eight topographic regions— Bluffs and Escarpments, Dissected Plains, Plains, Rolling Hills, Sand Hills and Valleys (Elder et al., 1951). This area stretches from the rolling, loess-mantled, glacially-derived landscape (Gosselin et al., 1996) on the east to the Holocene, sand-covered, non-glaciated areas on the west.

Principal cities within the project area, based on 2010 population estimates, include (largest to smallest) Norfolk (24,210), Wayne (5,660), Madison (2,438), Pierce (1,767), Stanton (1,577), and Wisner (1,170) (U.S. Census Bureau, 2013).

2 Project Area Hydrogeology

2.1 Geologic Setting

The geology and hydrogeology of the LENRD AEM survey area and surrounding areas have been studied extensively for over a century with the most recent studies focusing on understanding the hydrogeology of the area related to understanding the groundwater system and its relationship to surface water. The LENRD has adopted the use of AEM surveys to map the subsurface and this report is part of a multi-year plan to collect data on an approximate 3-mile spacing across the District. The object of the survey is to map the geology and related hydrogeology of the Quaternary (***Q***) and Tertiary Ogallala (***To***) sediments and bedrock surface. Much of the background geology and hydrogeology is presented in Carney et al. (2015c) and will not be repeated here in detail. The following sections will include only a brief overview of the geology and hydrogeology of the project area pertinent to the AEM investigation and interpretation analysis. For a more detailed review, the reader is encouraged to explore the background of the region using the references listed. The following narrative is based primarily on the findings from these reports.

2.1.1 Physiography and Regional Geologic Setting

The project area is in eastern Nebraska near the towns of Norfolk and Wayne within the Bluffs and Escarpments, Dissected Plains, Plains, Rolling Hills, and Sand Hills and Valleys topographic regions of Nebraska, Figure 2-1 (Elder et al., 1951). Bedrock geology in the project area is comprised of Cretaceous consolidated marine and consolidated to unconsolidated non-marine sedimentary rocks as presented in Figure 2-2 (from Burchett, 1986). These deposits are not deformed by folding and faulting. The Quaternary (***Q***) sediments are made up alluvial materials, loess and glacial deposits.

2.1.2 Surficial Geology

The complex Pleistocene and Holocene Quaternary geology in east-central Nebraska consists of sequences of clay, silt, till, sand, and gravel overlying bedrock units. These materials are capped by loess deposits in many locations. Figure 2-3 is a map of till coverage and thickness for the project area (CSD, 2017). Figure 2-4 displays the geologic time scale with CSD's lithostratigraphic sequence that underlies the state of Nebraska (Korus and Joeckel, 2011). The surficial geology of the project area is typical of western mid-continental glaciated areas of North America where buried Quaternary sand and gravel glacial outwash deposits or paleovalleys, comprised of unconsolidated Plio-Pleistocene sand and gravel units, underlie extensive areas of glacial till. In much of northeast Nebraska, glacial till often underlies loess units (e.g., Peoria, Gillman Canyon Formation, and Loveland Loess deposits). Present day surface water systems have incised the loess and till to wide stream valleys in some locations (e.g., Platte River Valley).

CSD test holes and drillers logs obtained from NE-DNR and the glacial till map in Figure 2-3 indicates glacial till units are present in most of the project area. Beneath much of the LENRD AEM survey area the surficial deposits consist of ***Q*** deposits of inter-bedded gravel, sand, silt, and clay.

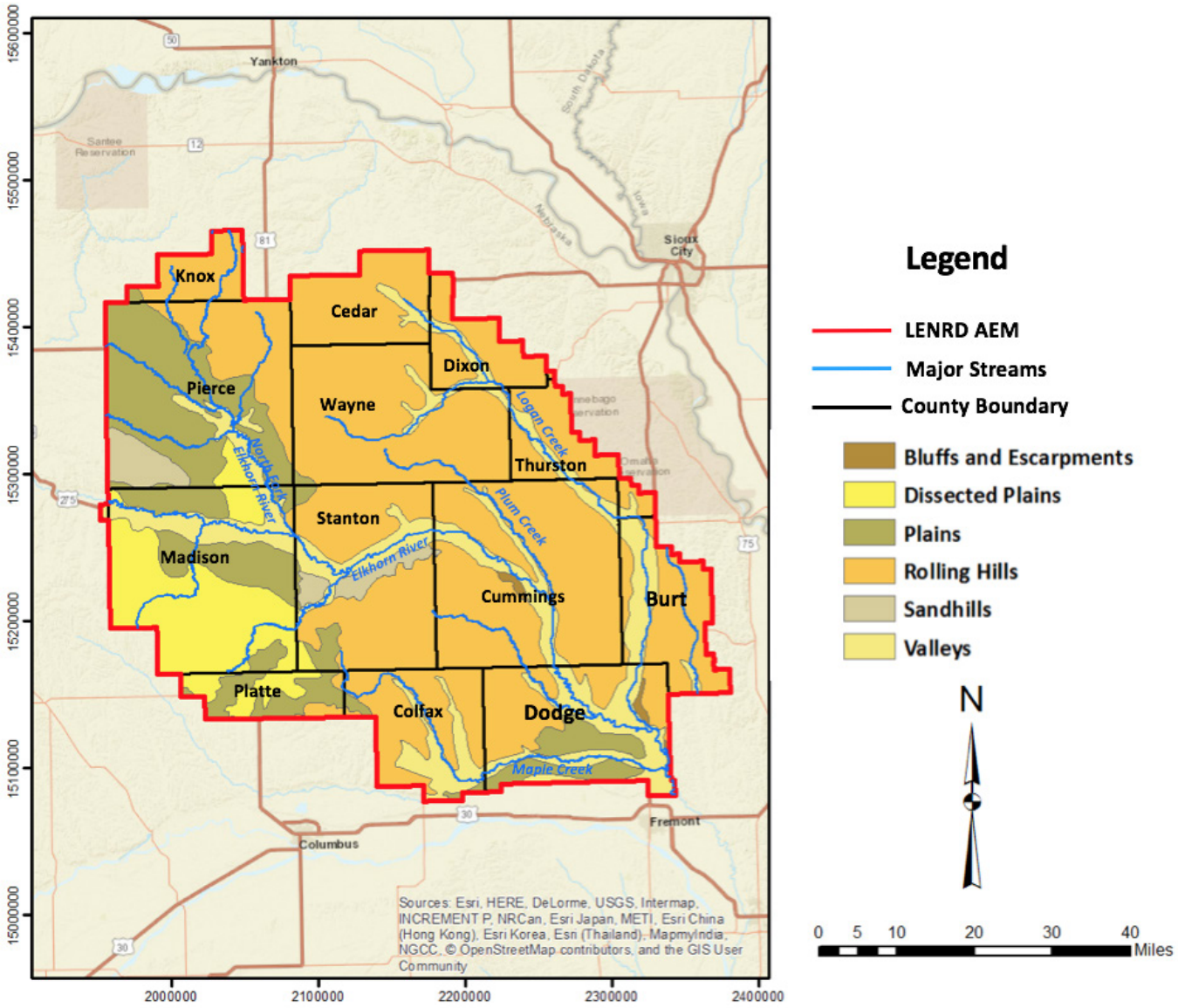


Figure 2-1. Topographic regions map of Project area. Most of the area is in the Rolling Hills section modified from Elder et al. (1951). Map projection is NAD83, UTM Zone 14N, Feet.

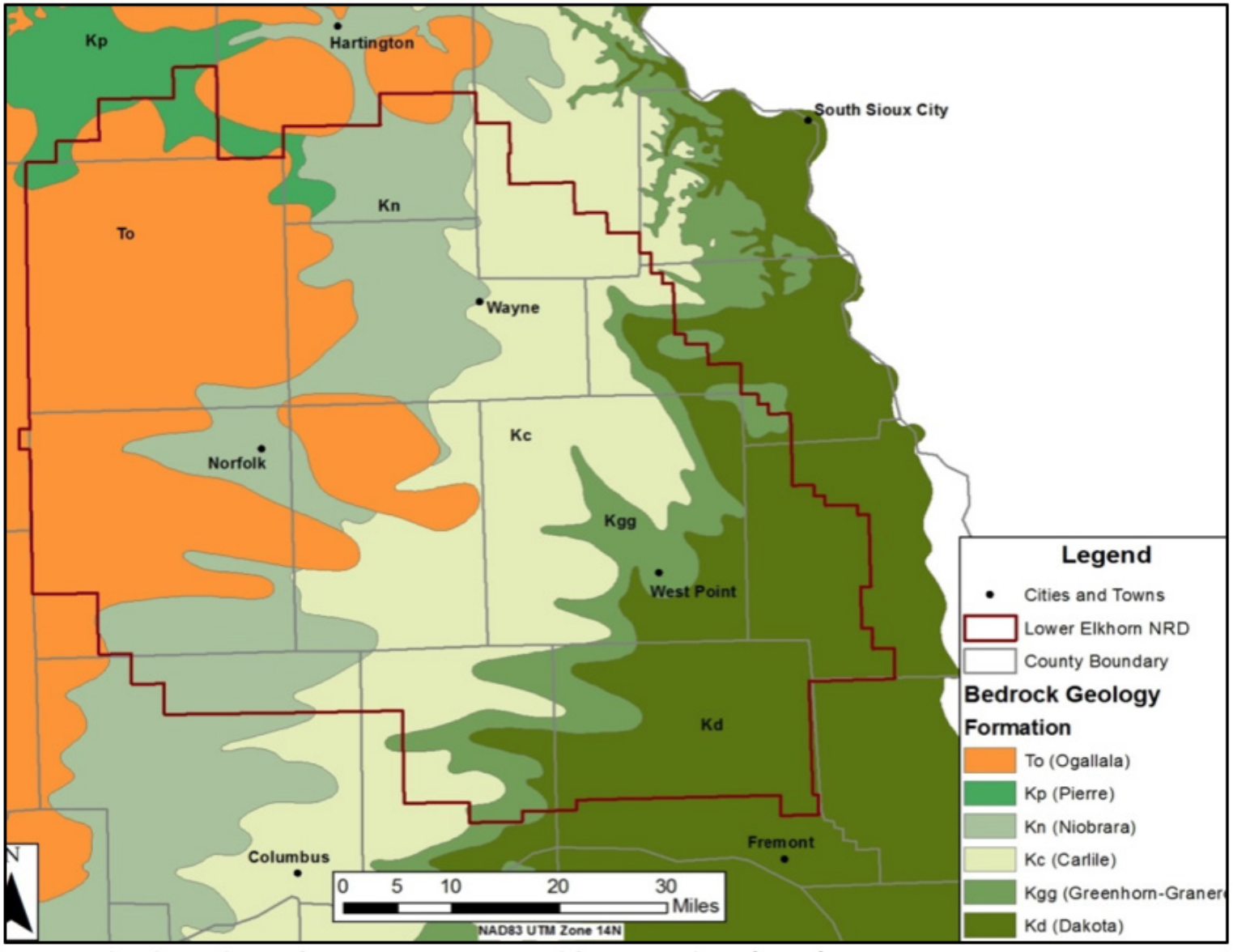


Figure 2-2. Bedrock map of the project area, modified from Burchett (1986).

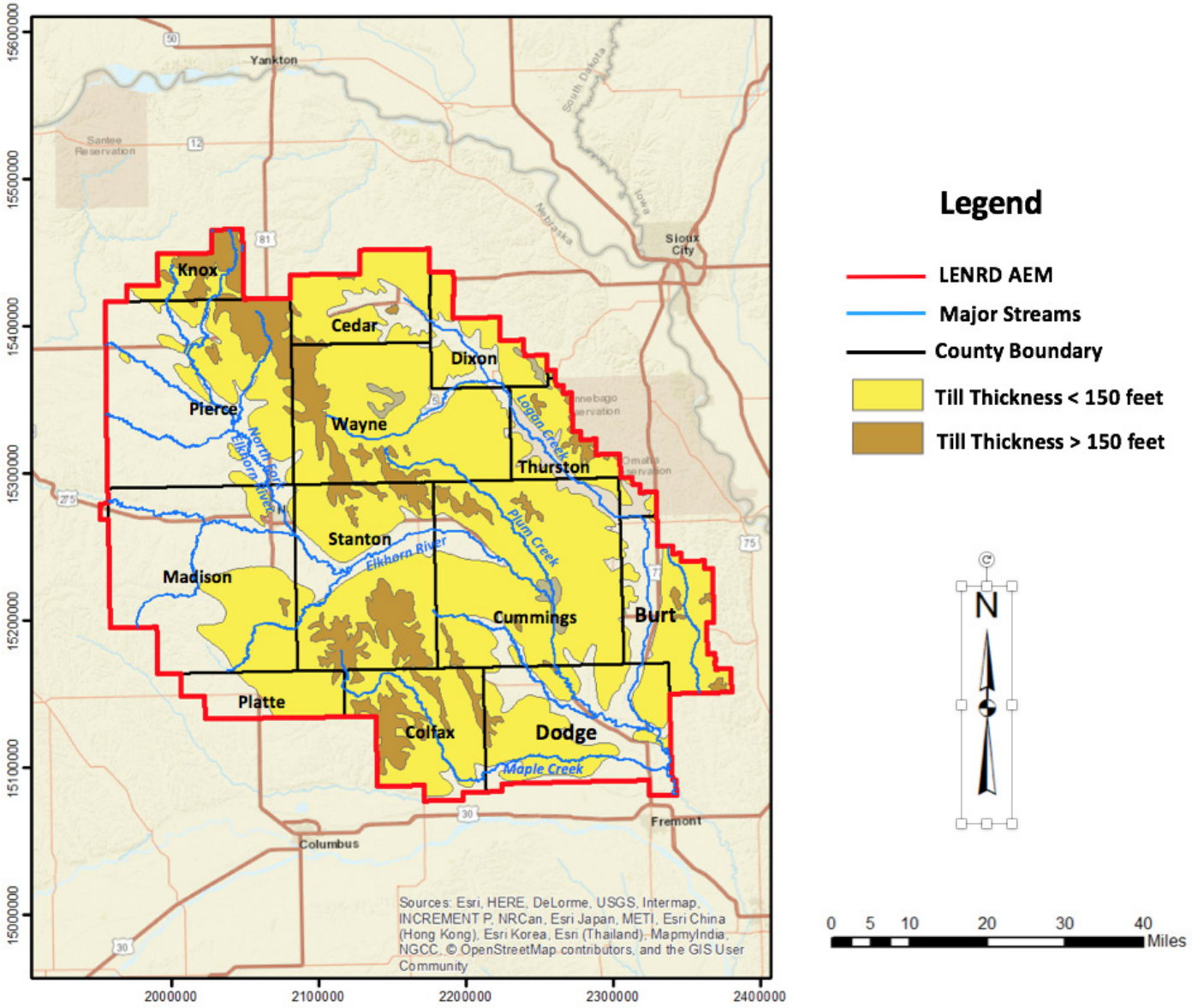


Figure 2-3. Till coverage map of the project area, modified from CSD (2017). Projection is NAD83, UTM 14 North (feet).

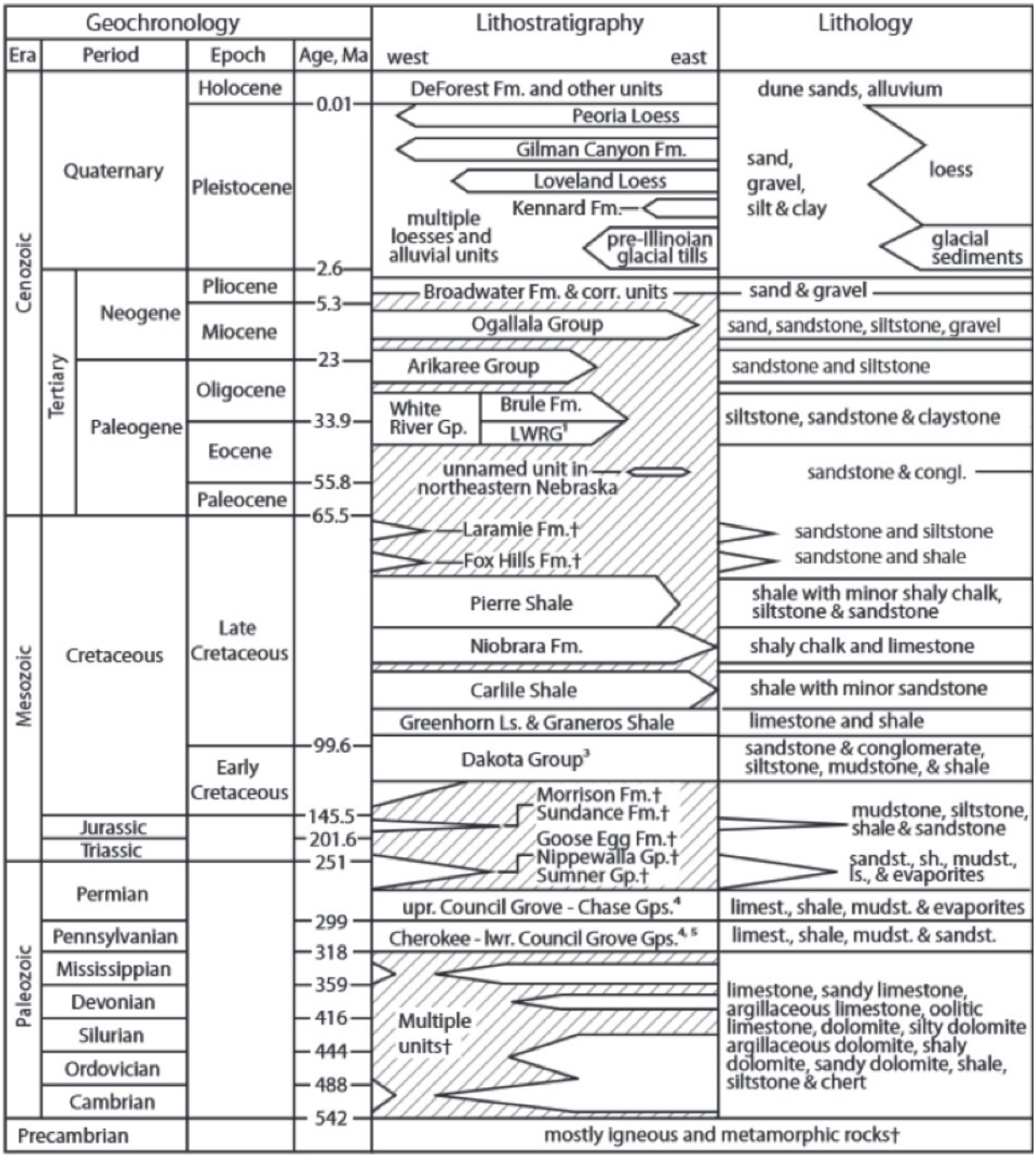


Figure 2-4. Geologic Time Scale for Nebraska from Korus and Joeckel (2011).

2.1.3 Tertiary Geology

The Tertiary deposits near the northwest-west part of AEM project area are Miocene Ogallala Group (***To***). The ***To*** is predominantly fluvial material comprised of unconsolidated to semi-consolidated, irregularly distributed beds of silt, clay, sand, and gravel (Souders, 2000). Some members of the ***To*** contain partially cemented friable sands or sandstone (Condra and Reed, 1959). The ***To*** thins and pinches out near the town of Norfolk and rests unconformably on underlying Cretaceous strata (Burchett, 1986). Along the eastern edge of the ***To*** there can be erosional remnants like the area east of Norfolk. Where present, the ***To*** is thick in the west and thins to the east. The ***To*** can serve as an aquifer where it is saturated.

2.1.4 Cretaceous Geology

There are deposits within the area from both the Upper and Lower Cretaceous. The Upper Cretaceous bedrock formations are the Niobrara Formation (***Kn***), the Carlile Shale (***Kc***), and the Greenhorn Limestone and Graneros Shale (***Kgg***). Together these formations are comprised of interbedded sandy shales, shales, indurated shaly chalks, thin layers of bentonite, and limestones (Condra and Reed, 1959; Gutentag et al., 1984). These formations thin and pinch out to the east (Divine, 2012), but, where present, they act as a lower confining unit to saturated ***Q*** deposits. None of the Upper Cretaceous formations yield beneficial amounts of potable groundwater within the project boundaries. However, in some areas of eastern Nebraska, the ***Kn***, where fractured, is known to yield water for irrigation purposes (Gutentag et al., 1984; Miller and Appel, 1997).

Underlying the Upper Cretaceous formations is the regionally extensive Lower Cretaceous Dakota Group (***Kd***). The ***Kd*** is comprised primarily of massive to interbedded sandstone with ironstone and shale, some argillaceous to slightly sandy (Condra and Reed, 1959). The sandstone in the Dakota Group typically has low permeability and storage compared to the unconsolidated units overlying it. While all the Cretaceous units discussed above occur within the LENRD AEM survey area, this report will focus on the ***Kn*** and ***Kc*** as they directly underlie the Quaternary and Tertiary aquifers. The Cretaceous is underlain by Paleozoic and Precambrian units that will not be discussed in this report.

2.2 LENRD AEM Survey Area Hydrogeologic Characteristics in the Quaternary and Tertiary Ogallala System

The ***Q*** and the ***To*** make up the aquifer materials within the project area. Maps showing the major streams and rivers with the associated basin areas within the LENRD AEM survey area are presented in Figure 2-5. Most the project area streams lie within the Elkhorn River basin. The edges of the project area may lie within the Lower Platte River and Missouri Tributaries basins (NE-DNR, 2016c). The largest surface-water systems in the project area are the Elkhorn River, North Fork of the Elkhorn River, Maple Creek, and Logan Creek (U.S. Geological Survey, 2015) which generally flow west to east. These streams join the Platte River near Ashland, Nebraska.

The overall elevation of the water table within the project area is shown in Figure 2-6. The water table maps are from the CSD 1995 water table map (Nebraska CSD, 1995) and represent the general shape of the water table as 50 foot contours of elevation; actual water levels will likely be somewhat different.

2.2.1 Aquifer Characteristics

Overall specific yield in the project area ranges from 0.05 to 0.20, with 0.15 to 0.20 in alluvium and unconfined systems in and adjacent to the Elkhorn and the North Fork of the Elkhorn River and 0.05 to 0.10 in confined areas underlying the till (Figure 2-7). Locally the specific yield is 0.20 in larger areas west and northwest of Wayne, NE. Conditions in the ***To*** generally range from 0.10 to 0.20 (Olafsen-Lackey, 2005a; Olafsen-Lackey and Summerside, 2005)

Figure 2-8 shows the lower and upper transmissivity values which range from 20,000 gpd/ft (2,700 ft^2/d) to 150,000 gpd/ft (20,000 ft^2/d). Transmissivity values are predominantly 50,000 gpd/ft in alluvium and unconfined systems with local areas of 20,000 or 100,000 gpd/ft. One area along the Elkhorn River west of Norfolk, NE shows a transmissivity of 150,000 gpd/ft. Confined systems are predominantly 20,000 gpd/ft with local areas of 50,000 gpd/ft found northwest of Wayne (Olafsen-Lackey, 2005b; Olafsen-Lackey and Summerside, 2005).

Figure 2-9 shows the CSD hydrogeology areas for the project area (Olafsen-Lackey, 2005b; Olafsen-Lackey and Summerside, 2005). Most of the project area is identified as being in the glaciated section with the remainder being made up of the Confined, Alluvial Aquifer and Non-Glaciated sections.

Regional groundwater-flow direction for the project area is predominately from northwest to southeast (Figure 2-6). The groundwater-flow direction generally follows the course of the major streams and rivers. Groundwater locally is hydrologically connected to surface water in the areas not covered by glacial till and groundwater levels are located at shallower depths in the alluvial valleys and at deeper depths below the uplands. Water levels change with the seasons and typically reach maximum depths from extensive groundwater pumping and usage during the crop growing months. Groundwater levels typically return to shallower, pre-stress levels in the March to June timeframe. Annual depths of drawdown and recharge of aquifers highly depend on the type of aquifer (e.g. confined or unconfined), proximity of the aquifer to the land surface, and the magnitude of stress exhibited on the system during the pumping season, combined with the amount of recharge available to the aquifer.

The principal hydrogeologic unit within the LENRD AEM survey area is ***Q*** alluvial materials and the ***To***. The first are saturated alluvial materials that make up the stream-valley (valley fill) and table land aquifers. The second are ***Q*** glacial-drift aquifers which are outwash alluvial and paleo-alluvial or paleo-glacial deposits of Plio-Pleistocene age that underlie till and loess deposits in the uplands in most of the AEM project area. Saturated ***Q*** deposits in east-central Nebraska are a complex mixture of unconsolidated, saturated sand, and gravel deposits. These saturated deposits can be confined to unconfined, deep to shallow, and/or regional and local, and, in places, interbedded with glacial till (Miller and Appel, 1997; Flowerday et al, 1998; Stanton et al., 2007). Stream-valley and glacial-drift systems locally can be hydraulically connected with each other.

The ***To*** is generally thick in the west and thin to absent in the eastern regions of the project area.

Table 2-1 contains summary information for each known aquifer units (***Q*** through ***To***) within the area. Included in this table are the geologic system hosting the aquifer, aquifer thickness, and a general discussion regarding the aquifer framework, groundwater flow system characteristics, and aquifer parameters.

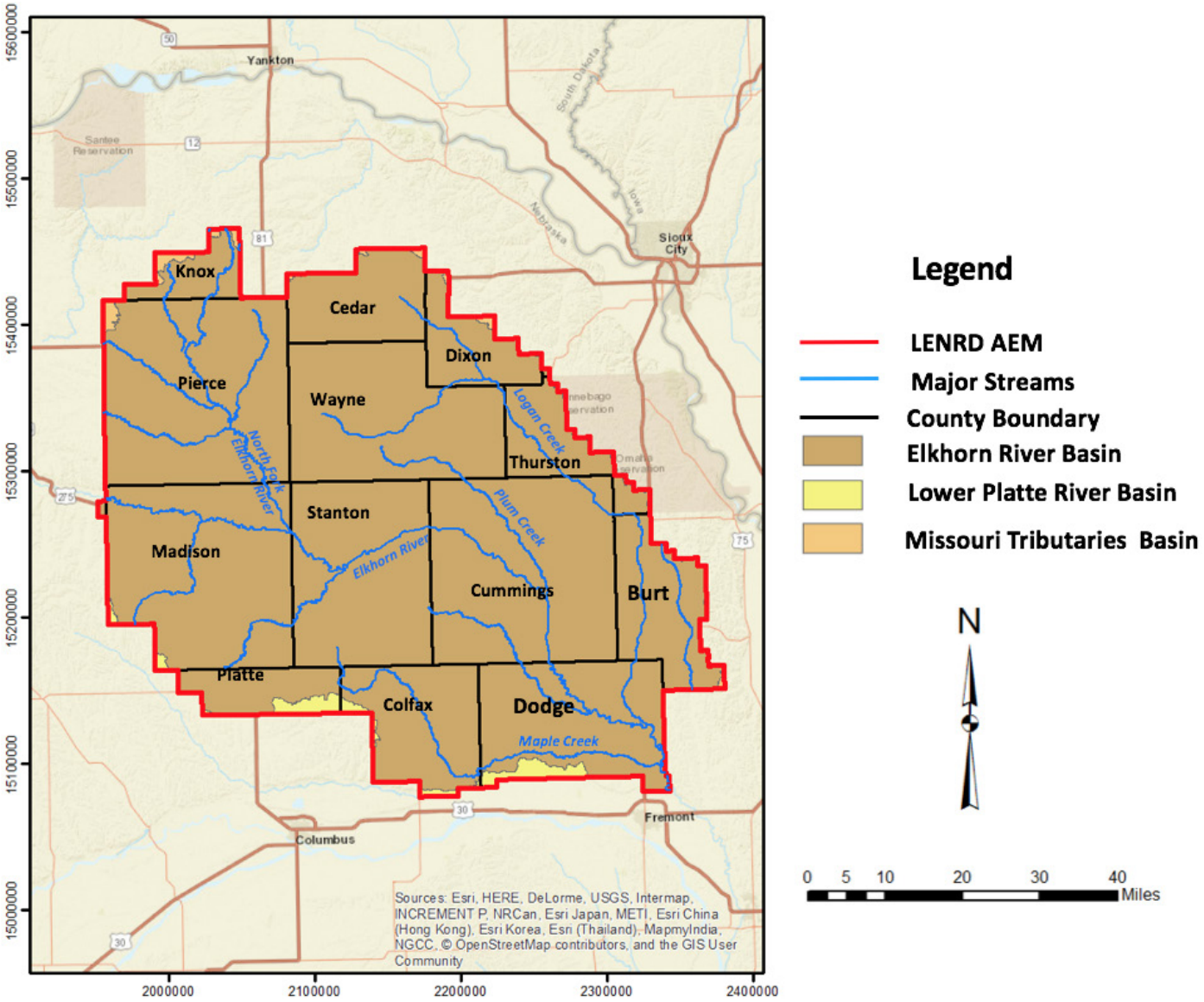


Figure 2-5. Map displaying the major streams, rivers and basins within the LENRD AEM survey area (NE-DNR, 2016c). Projection is NAD83, UTM 14 North (feet).

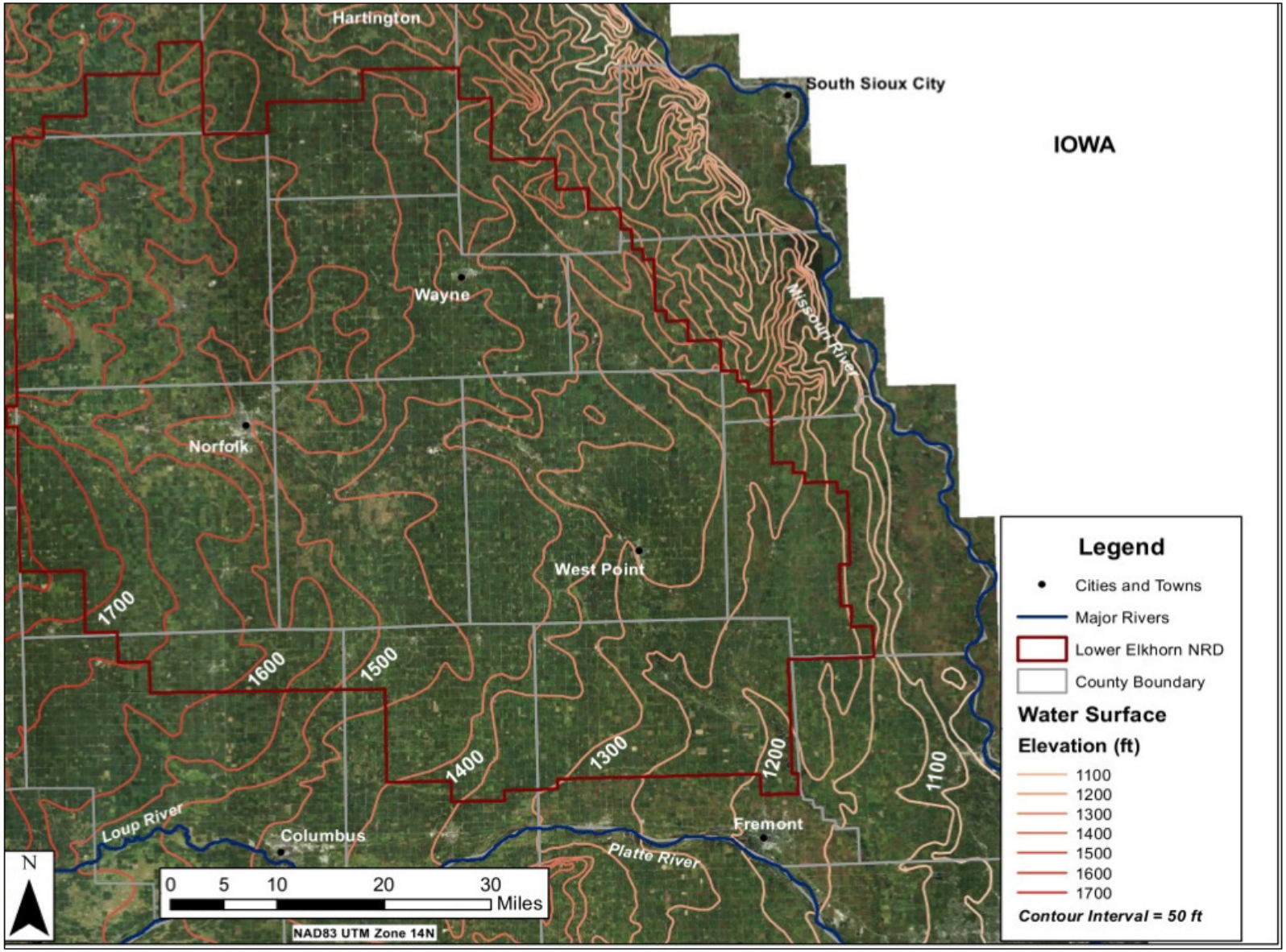


Figure 2-6. Map displaying elevation of the water table within the project area (NE-CSD, 1995). Elevation contours are in intervals of 50 feet.

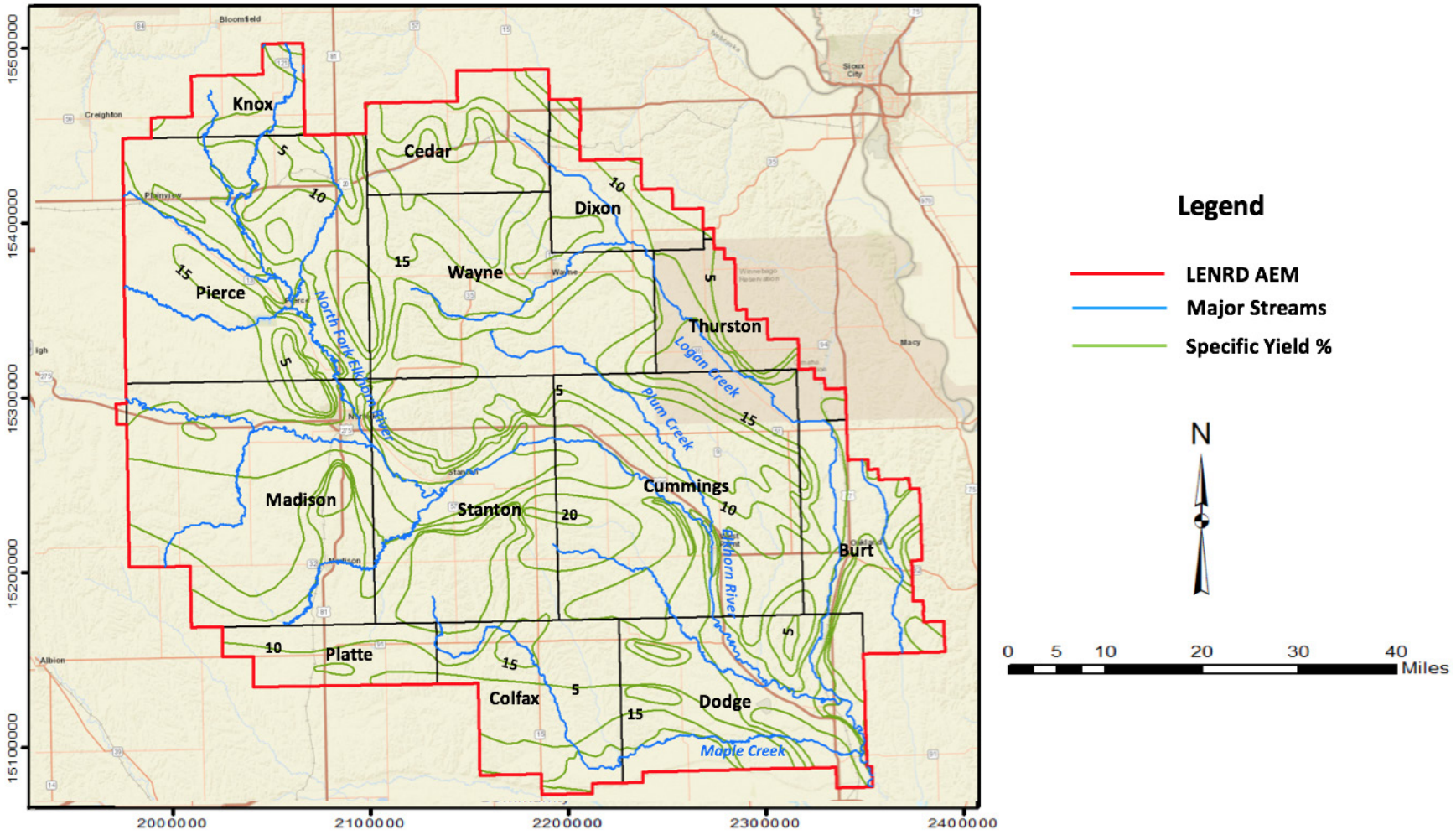


Figure 2-7. Map displaying the specific yield (percent) across the project area. The values range from 0.05 to 20 percent (Olafsen-Lackey, 2005a). Projection is NAD83, UTM 14 North (feet).

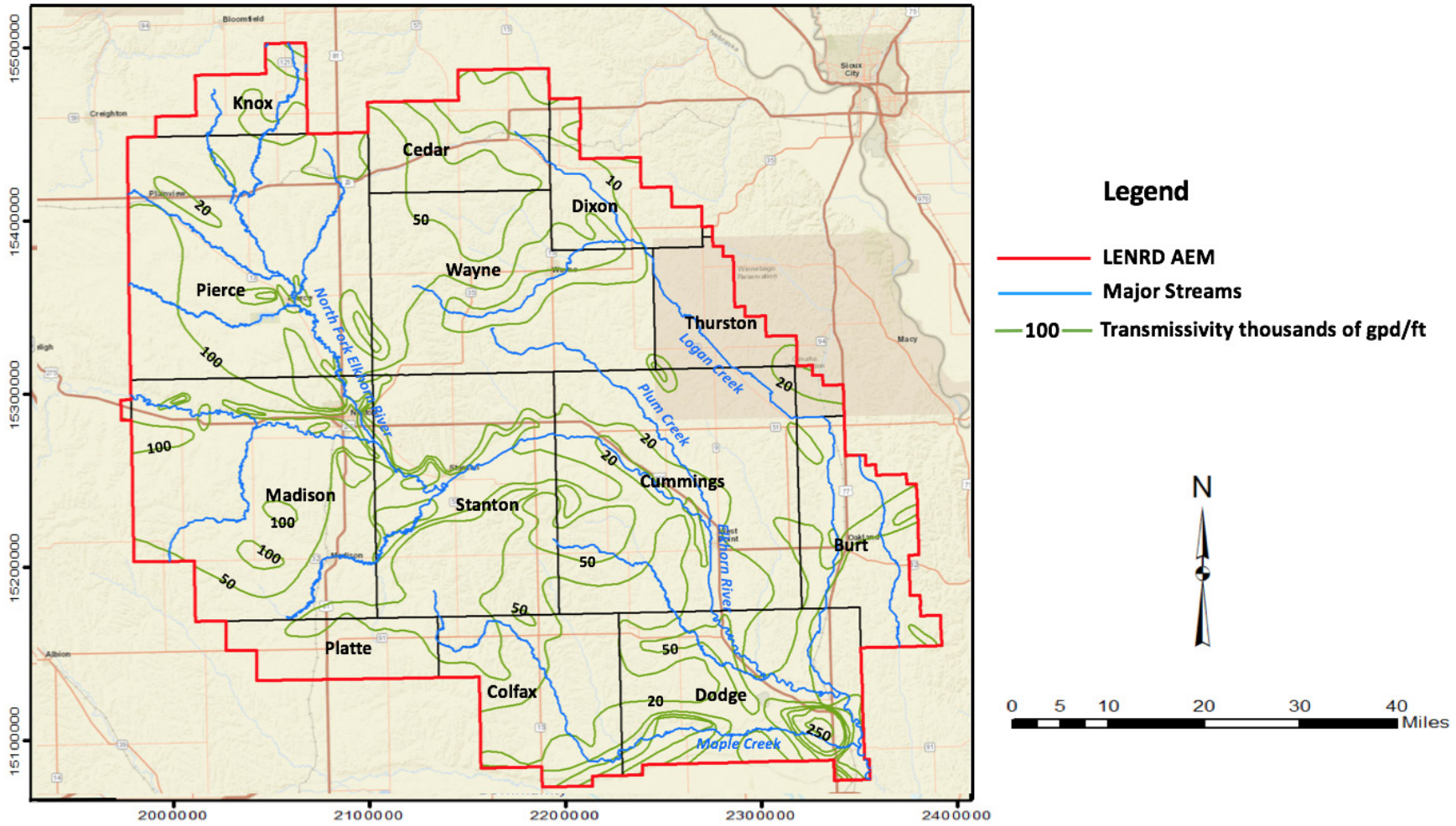


Figure 2-8. Map shows the lower and upper transmissivity values across the project area which range from 20,000 gpd/ft (2,700 ft^2/d) to 150,000 gpd/ft (Olafsen-Lackey, 2005b). Projection is NAD83, UTM 14 North (feet).

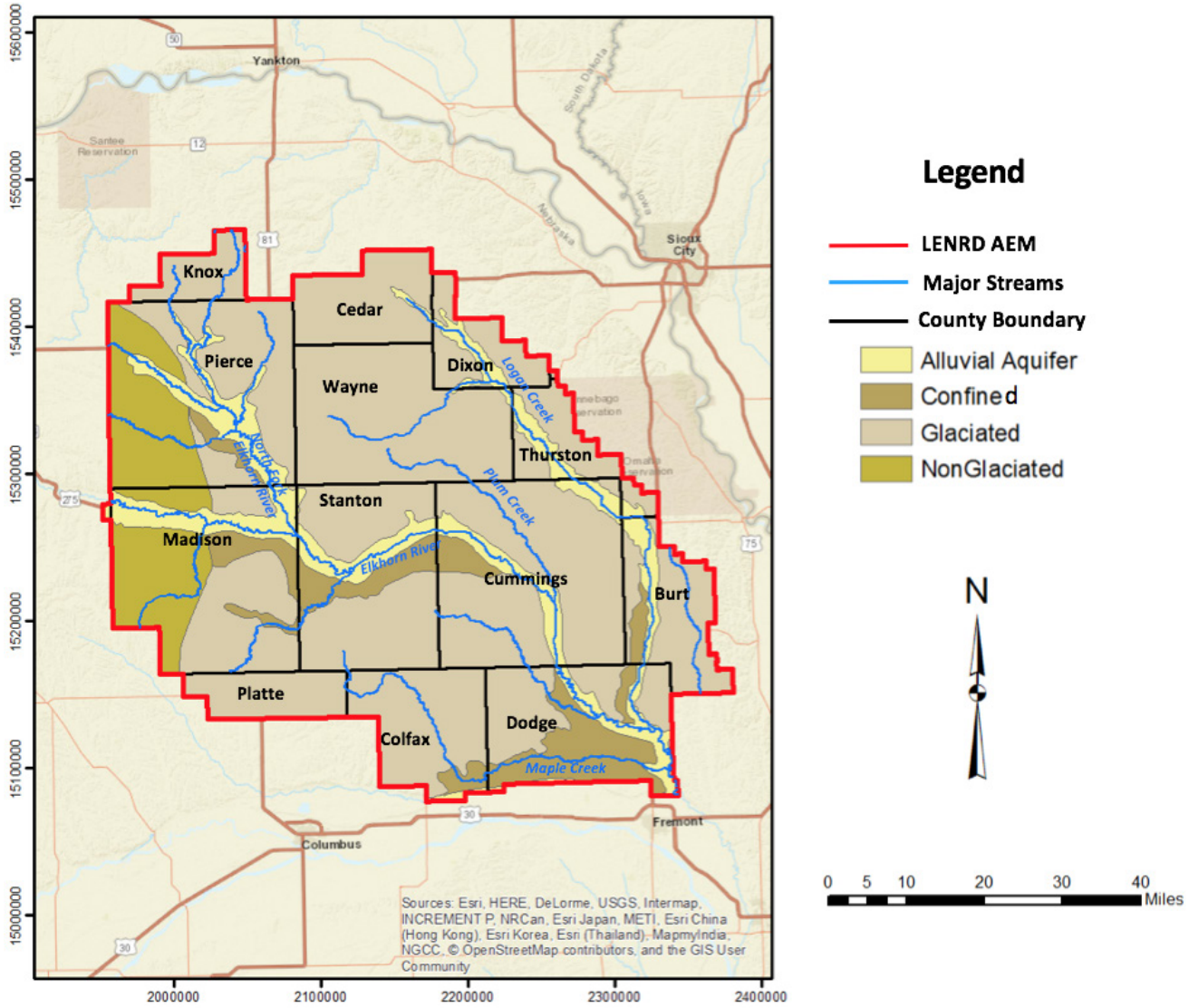


Figure 2-9. Map shows the CSD hydrogeology areas for the project area. Most the area is glaciated with the remainder being made up of the Confined, Alluvial Aquifer and Non-Glaciated sections (Olafsen-Lackey, 2005b; Olafsen-Lackey and Summerside, 2005). Projection is NAD83, UTM 14 North (feet).

Table 2-1. Aquifers in Quaternary and Tertiary Age stratigraphic units (Carney et al., 2015c).

System	Series	Hydrologic unit	Maximum thickness, ft.
Quaternary	Holocene, Pleistocene	Aquifer in undifferentiated alluvial deposits	Generally, less than 100 ft
Undifferentiated sand and gravel units in stream-valley systems. Stream-aquifer systems can be intermixed with older glacial sand and gravel making the deposits difficult to distinguish from older glacial outwash. Hydraulic head is typically unconfined. Recharge is principally from local precipitation and rapid if the source area is primarily sand and gravel. Wells capable of yielding up to several thousand gallons per minute.			
Quaternary	Holocene, Pleistocene	Aquifer in undifferentiated glacial-drift deposits	Up to 300 ft
Undifferentiated sand and gravel units in glacial-drift aquifers. Hydraulic head generally under confined conditions, but can be under unconfined conditions elsewhere. Thickness of glacial-drift aquifers vary greatly. Comprised largely of sand and gravel from ancestral river channels or glacial outwash that became capped by till or loess. Some paleovalleys several miles wide and tens of miles long. Recharge mostly from precipitation infiltration or inflow from adjacent hydraulically connected aquifers. Wells yields are highly variable; some capable of up to several thousand gallons per minute but vary greatly by location. Isolated aquifers capable of sustaining good quality water only for domestic or stock purposes only.			
Tertiary	Miocene	Aquifer in Ogallala Group	Up to 300 ft, typically 100 ft or less, thins west to east
Generally unconsolidated to semi-consolidated sand, gravel, silt, and clay, underlying saturated Quaternary deposits. Serves as principal hydrogeologic unit of the eastern part of project area and of the High Plains aquifer. Hydraulic head unconfined to confined. Recharge largely from local precipitation or inflow from adjacent hydraulically connected aquifers. Irrigation wells capable of producing yielding several thousand gallons per minute.			
Cretaceous	Upper	Confining units of the Pierre, Niobrara, Carlile, or Greenhorn–Graneros Formations	Variable Thickness
Where present, largely serve as regional confining units. Niobrara Formation may produce water where secondary fracturing occurs.			
Cretaceous	Lower	Aquifer in Dakota Sandstone	Total thickness variable. Up to 600 ft in the project area (Miller and Appel, 1997).
Locally the Dakota can serve as an aquifer or as a confining unit. Aquifer generally located in loosely- cemented, medium- to fine-grained sandstone. Hydraulic head typically confined with local unconfined conditions encountered. Groundwater more potable in eastern part of state where Dakota underlies hydraulically connected with overlying saturated Quaternary deposits. Westerly, the Dakota becomes more mineralized and is found deeper beneath the subsurface. Where Dakota units lie near the land surface, recharge is primarily from local precipitation, otherwise largely from inflow from adjacent hydraulically-connected aquifers. Sandstones capable of producing potable water to irrigation and municipal wells. Yields can be as much as 1,000 gallons per minutes locally (Miller and Appel, 1997).			

2.2.2 Soil Characteristics in the LENRD AEM Survey Area

Recharge to stream-valley aquifers is largely from local precipitation, although additional sources of recharge can occur from downward percolation of irrigation waters or inflow from underlying permeable aquifers (Carney et al., 2015c). Estimated regional mean annual recharge rates for stream valleys within the project area range from about 3.7 to 5.5 inches per year (in/year) with local annual recharge rates up to 6.4 in/year. In the uplands beyond the stream valleys, regional estimated annual recharge rates generally range from 2.4 to 5.5 in/year (Szilagyi et al., 2005). An analysis of statewide data determined that the total recharge for the Nebraska glaciated region averaged about 2.2 in/year (56 mm/year) (Szilagyi and Jozsa, 2013; Gates et al., 2014) and was similar to rates determined using other methods (Nolan et al., 2007; Gates et al., 2014).

Carney et al. (2015c) interprets the resistive sediments that are greater than 50 ohm-m provide the potential for high recharge rates where these sediments extend from the land surface to the aquifer. In this area, aquifer material with resistivities exceeding 50 ohm-m range from less than 10 ft to approximately 150 ft in thickness and are present at shallow depths in the subsurface, indicating the potential for high recharge rates to the aquifer. Resistive intervals of 50 ohm-m or greater are present along the North Fork of the Elkhorn River near the northern project area boundary as well as in an apparent northwest trending body of coarse material with characteristics of an ancestral fluvial system. Where these conditions exist, recharge from precipitation to the groundwater system provides the ability to replenish and potentially add to groundwater storage

2.2.3 Connectivity to Surface Water and to Other Aquifers

Groundwater flow connectivity to surface water features is largely undocumented in the glaciated areas of eastern Nebraska. However, Peterson and Strauch (2007) report streamflow measurements at 531 sites conducted in November 2006 in the Elkhorn and Loup River basins and selected streams in the Niobrara and Platte River basins in north-central Nebraska. Most of these sites were located throughout the Elkhorn and Loup River basins, while 49 were located within the project area. Results at these 49 sites showed streamflow increasing in a downstream direction, indicating surface-water baseflow increasing downstream in these areas. Streamflow measurements were not collected in the thick glaciated zones of the project area.

Springs are common along several tributaries of the Elkhorn River. Logan Creek and Maple Creek basins experience spring flow and locally have drains installed to keep groundwater levels from flooding local farmland. Many of the springs flow primarily during early- to mid-growing season in smaller tributaries; whereas they flow perennially in the major tributaries (Fredrick et al., 2006).

Aquifers in the project area can be hydrologically connected or isolated from each other. In the western counties, many of the aquifers are hydrologically connected (Carney et al., 2015c). The aquifers that are under or part of the glacial till can be connected or isolated from other aquifers. Generally, the aquifers within the glacial till are small in geographic extent and contain small amounts of groundwater in comparison to the unconfined aquifers of the western part of the project area (Carney et al., 2015c).

2.2.4 Water Quality

A total of 740 historic water quality samples were analyzed from the USGS National Water Information System (NWIS) to determine water chemistry characteristics of the project area — 423 water samples from 184 stream-valley or alluvial wells, 192 water samples from 62 glacial-fill wells, 32 water samples from 31 High Plains wells, and 93 water samples from 29 wells tapping Cretaceous strata (most likely *Kd*). The water-quality samples from the High Plains wells likely were collected from wells screened in or open to the *To*. The High Plains aquifer also includes Quaternary deposits. Additional detailed information on Water Quality can be found in Carney et al. (2015c).

Most groundwater in the area appears fresh. In some locations, larger specific conductivity, sulfate, and total dissolved solids concentrations were observed. The quality of the groundwater in the AEM project area should pose no interference for interpretation of AEM data.

3 Additional Background Information

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

3.1 Borehole Data

Borehole data for this project consisted of a combination of lithologic, stratigraphic, and downhole geophysical logs. The borehole information was gathered from three sources: 1) CSD Nebraska Statewide Test Hole Database (UNL, 2016) accessed January 28, 2017, which contains information from boreholes drilled between 1930 and 2016 by the CSD and other cooperating agencies.; 2) NE-DNR (Nebraska Department of Natural Resources, 2016b) accessed September 22, 2016; and 3) Nebraska Oil and Gas Conservation Commission (NOGCC, 2017)

The locations of the CSD boreholes utilized in the LENRD AEM survey area are indicated in Figure 3-1 and Figure 3-2. Of the total of 241 CSD holes utilized in this investigation, 63 contained geophysical logging information including resistivity, gamma-gamma, temperature, calibration, etc., 207 holes contained lithology information, and 151 holes contained stratigraphic information. The locations of the NE-DNR registered wells used in the LENRD AEM survey are indicated in Figure 3-3. A total of 4,223 registered wells contained usable lithology and/or stratigraphy information.

The locations of the NOGCC wells used in the LENRD AEM survey are indicated in Figure 3-4. Five NOGCC wells contained stratigraphy (inverted triangles in Figure 3-4) and five wells contained lithology information (upright triangles in Figure 3-4). Four of the NOGCC wells contained both stratigraphy and lithology (six-pointed star symbols in Figure 3-4).

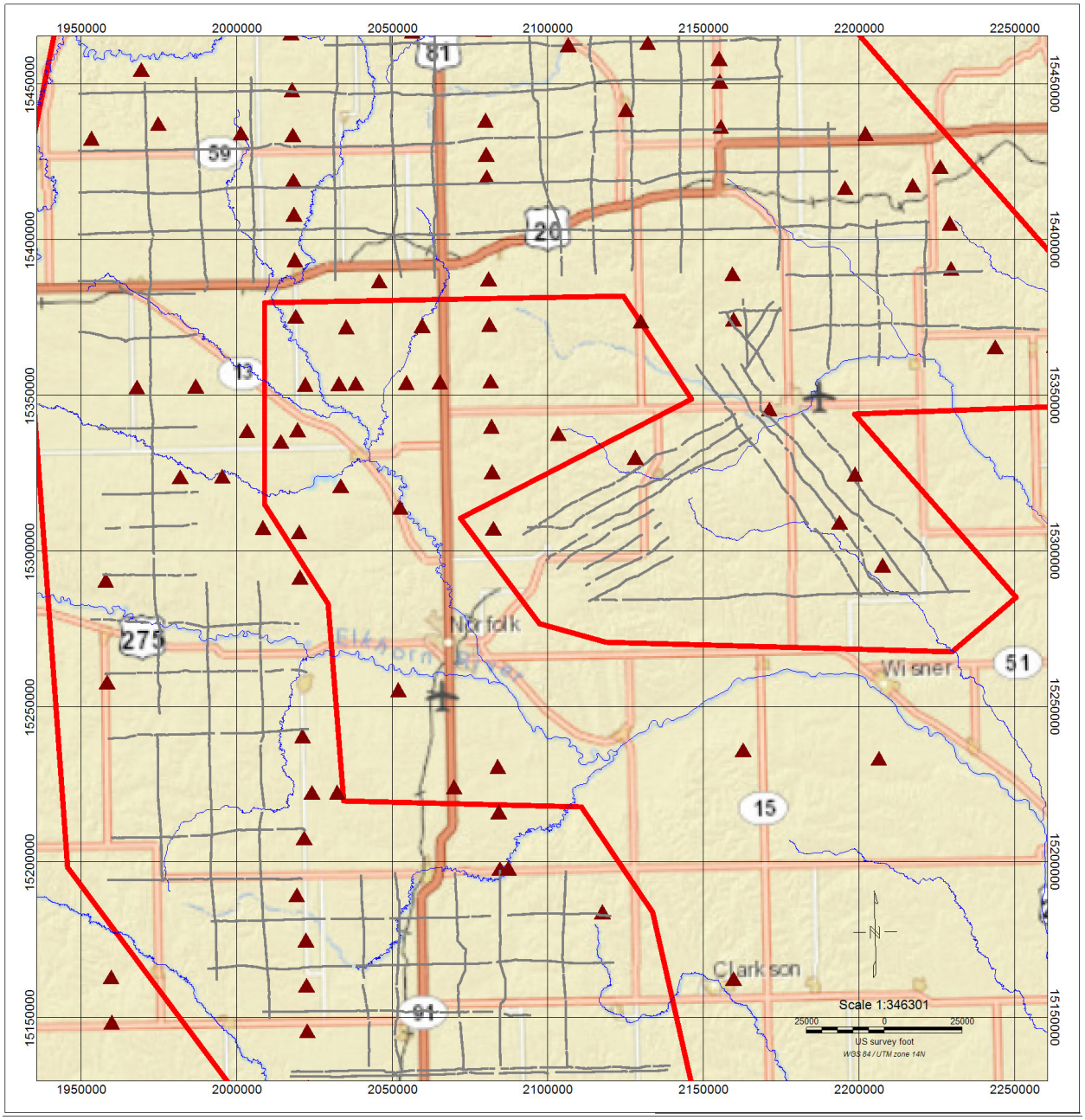


Figure 3-1. Locations of the Conservation Survey Division (CSD) boreholes (brown triangles) containing geophysical log information and the airborne electromagnetic flight lines (grey lines) in the LENRD AEM survey area (red line). Projection is NAD83, UTM 14 North (feet).

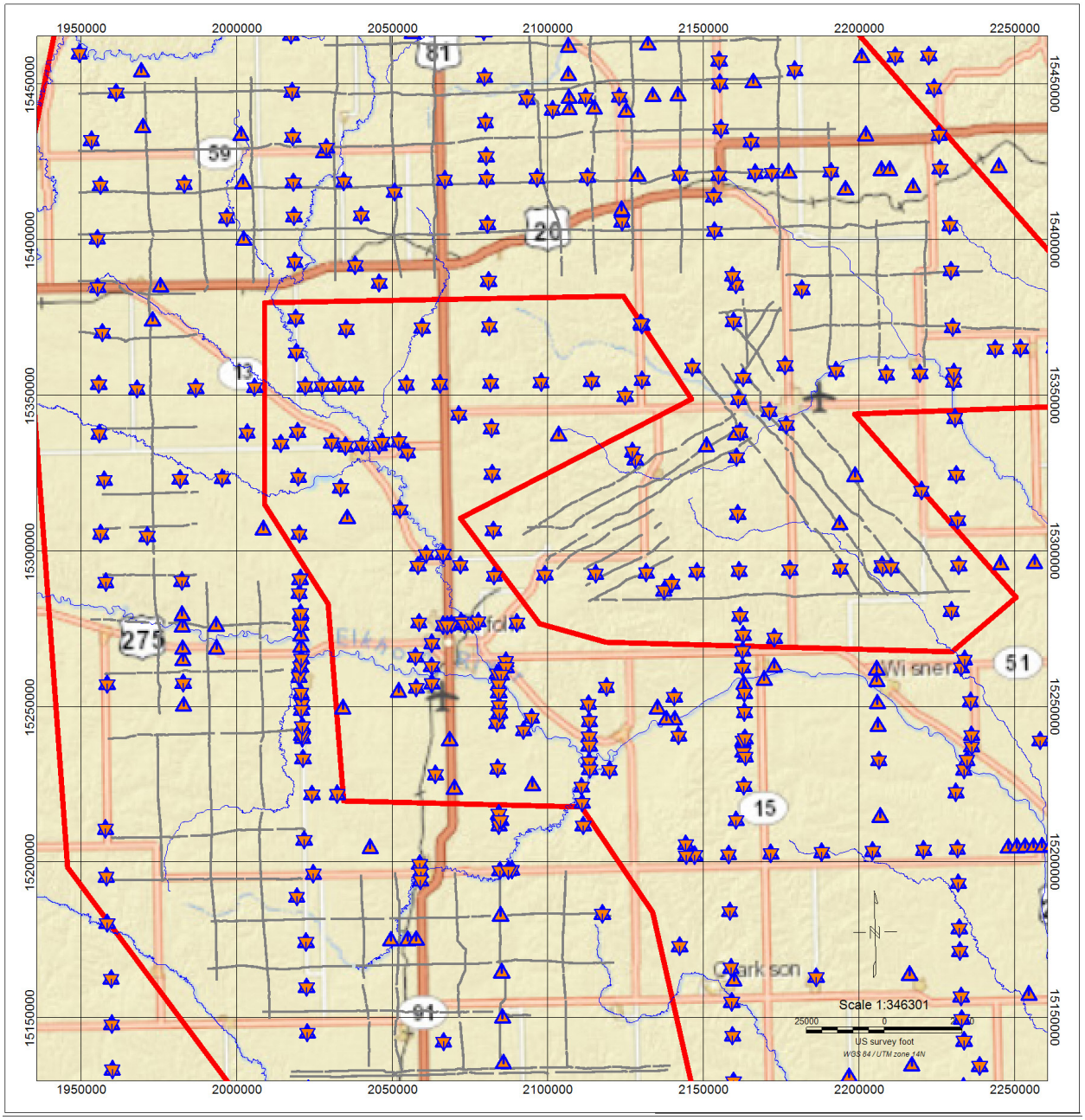


Figure 3-2. Within the LENRD AEM survey area (red line), locations of the Conservation Survey Division (CSD) boreholes containing lithology information (upright pink triangles) and stratigraphy information (inverted pink triangles). Locations with both lithology and stratigraphy appear as six-pointed pink stars. The AEM flight lines are in grey. Projection is NAD83, UTM 14 North (feet).

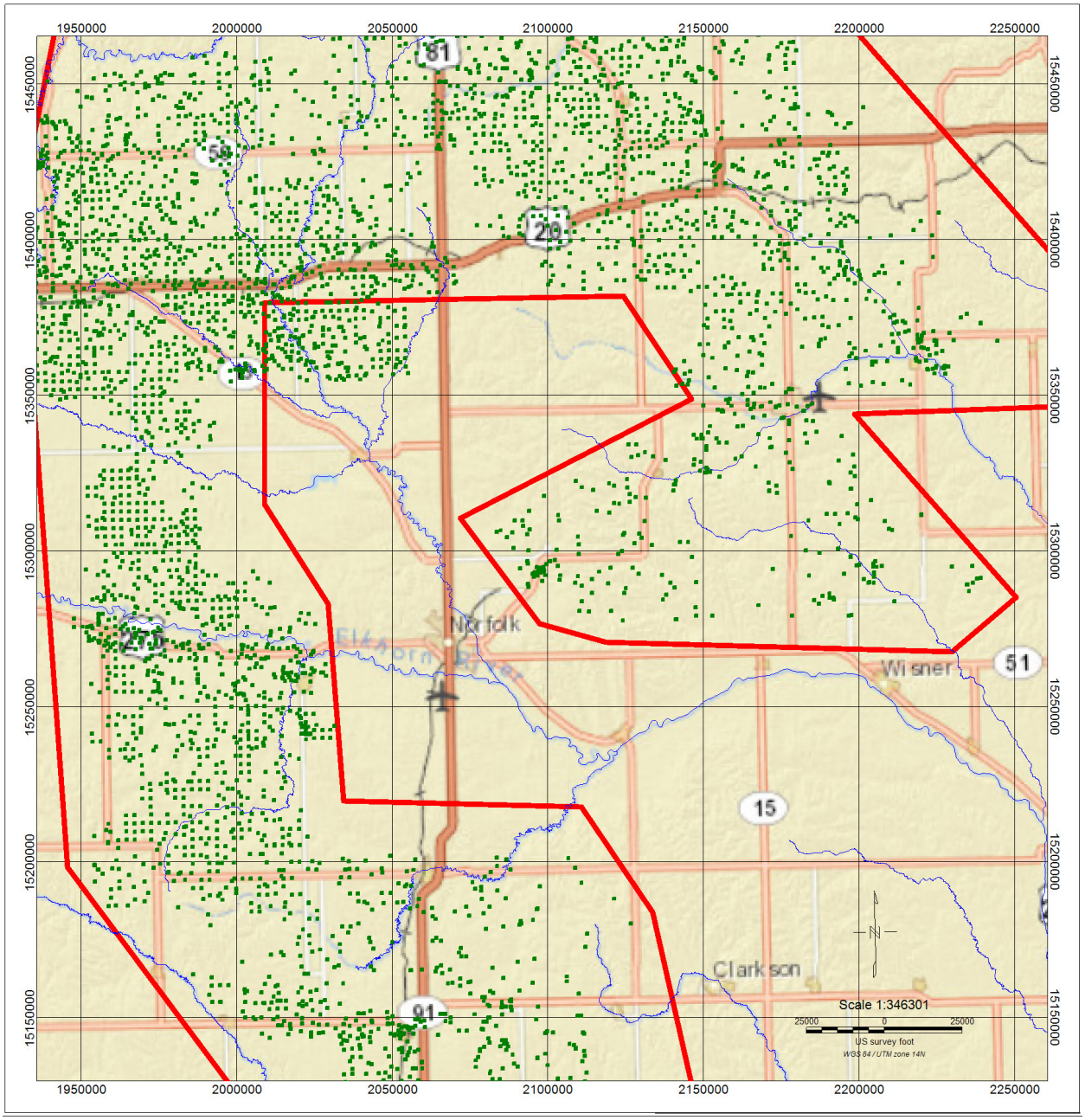


Figure 3-3. Locations of the Nebraska Division of Natural Resources Registered wells (green dots) and the airborne electromagnetic flight lines (grey lines) in the LENRD AEM survey area (red line). Projection is NAD83, UTM 14 North (feet).

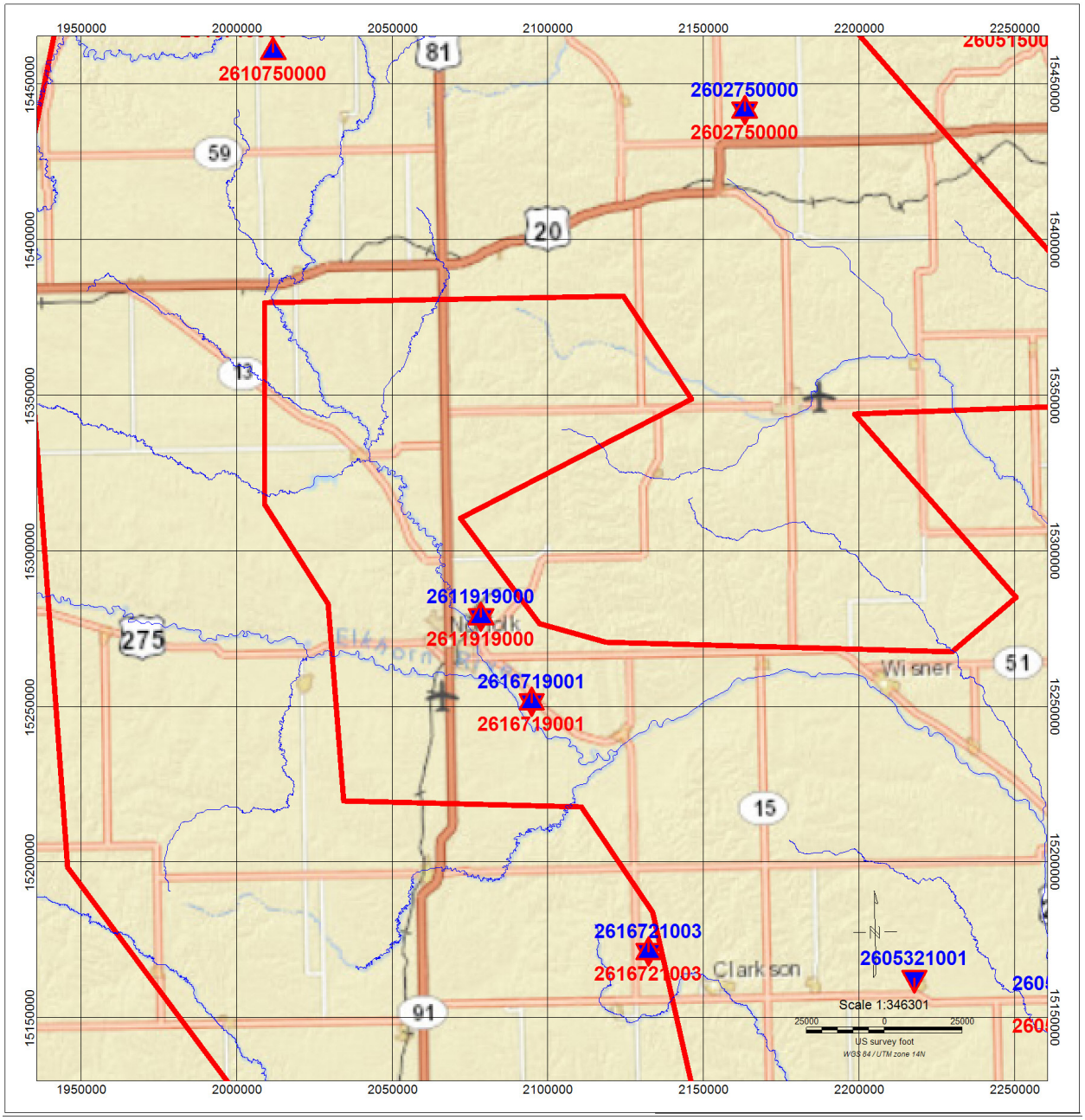


Figure 3-4. Locations of Nebraska Oil and Gas Conservation Commission wells with lithology (upright blue triangles with red edges and red labels) and stratigraphy (inverted blue triangles with blue labels) and the AEM flight lines (grey lines) in the LENRD AEM survey area (red line). Projection is NAD83, UTM 14 North (feet).

4 Geophysical Methodology, Acquisition and Processing

4.1 Geophysical Methodology

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

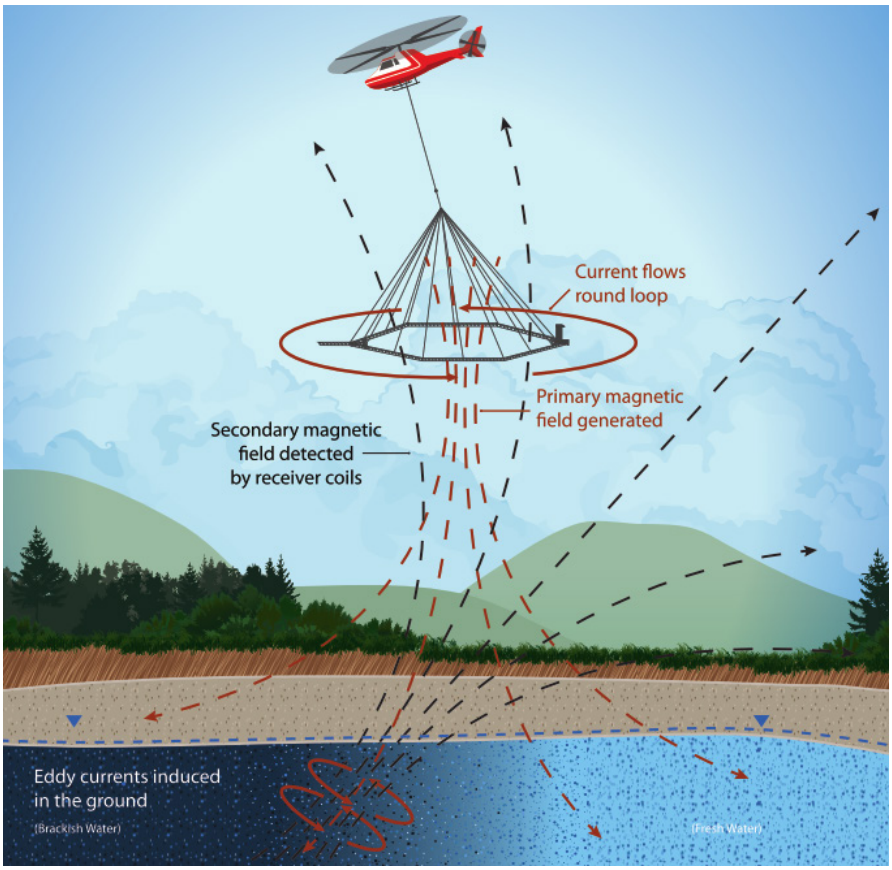
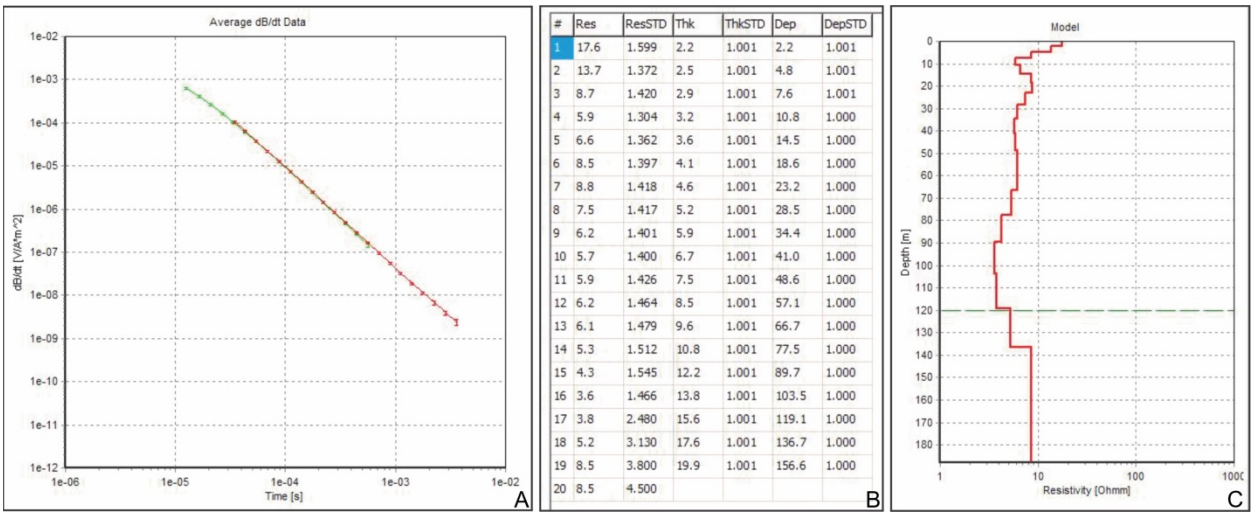


Figure 4-1: Schematic of an airborne electromagnetic survey, modified from Carney et al. (2015a).

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

these measurements constitute a "sounding" at that location. Each TEM measurement produces an EM sounding at one point on the surface.

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



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

4.2 Flight Planning/Utility Mapping

The primary source of noise in geophysical electromagnetic surveys are other electromagnetic devices that are part of typical municipal utility infrastructure. These include, for example, power lines, railroads, pipelines, and water pumps. Prior to AEM data acquisition in the LENRD, 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.

Public power entities that provided power line location data to ENWRA included: Auburn Board of Public Works, Burt County Power District, Butler County Power District, Cedar-Knox Power District, City of Freemont, Cornhusker Public Power District, Cuming County Power District, Elkhorn Rural Public Power District, Lincoln Electric Systems, Loup Power District, Nebraska Public Power District, Nemaha-Marshall Electric Cooperative, Norris Public Power District, North Central Public Power District, Northeast Nebraska Public Power District, Omaha Public Power District, Polk County Rural Public Power District, Seward County Public Power District, and the Stanton County Public Power District.

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.

At the conclusion of the design process the LENRD reconnaissance flight lines were approximately 55 miles in length at their longest in the east-west direction and about 48 miles at their longest in the north-south direction and were separated by approximately 3.1 miles in both east-west and north-south directions (Figure 1-2 and Figure 4-5). In the area southwest of Wayne the reconnaissance flight lines oriented southwest to northeast away from Wayne were approximately 14.2 miles in length and those that ran northwest to southeast closer to Wayne were approximately 17.3 miles in length. These reconnaissance flight lines were separated approximately 1 mile apart.

4.3 AEM Survey Instrumentation

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

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

The coordinate system used by the 304M defines the +x direction as the direction of flight, the +y direction is defined 90 degrees to the right and the +z direction is downward. The center of the

transmitter loop, mounted to the octagonal SkyTEM frame is used as the origin in reference to instrumentation positions. Table 4-1 lists the positions of the instruments (in feet) and Table 4-2 lists the corners of the transmitter loop in feet (whereas units of meters are presented in Figure 4-3).

The DGPS and magnetometer mounted on the frame of the SkyTEM304M require the use of base stations, which are located on the ground and are positioned in an area with low cultural noise. Data from the magnetometer and DGPS base stations were downloaded each day after the end of the day's AEM flights. The DGPS and magnetometer base stations were placed at the Universal Transverse Mercator (UTM) coordinate system location listed in Table 4-3. The horizontal geodetic reference used is North American Datum of 1983 (NAD83 in feet). All elevations are from USGS's National Elevation Dataset, referenced to the North American Vertical Datum of 1988; with feet as the unit of measurement.

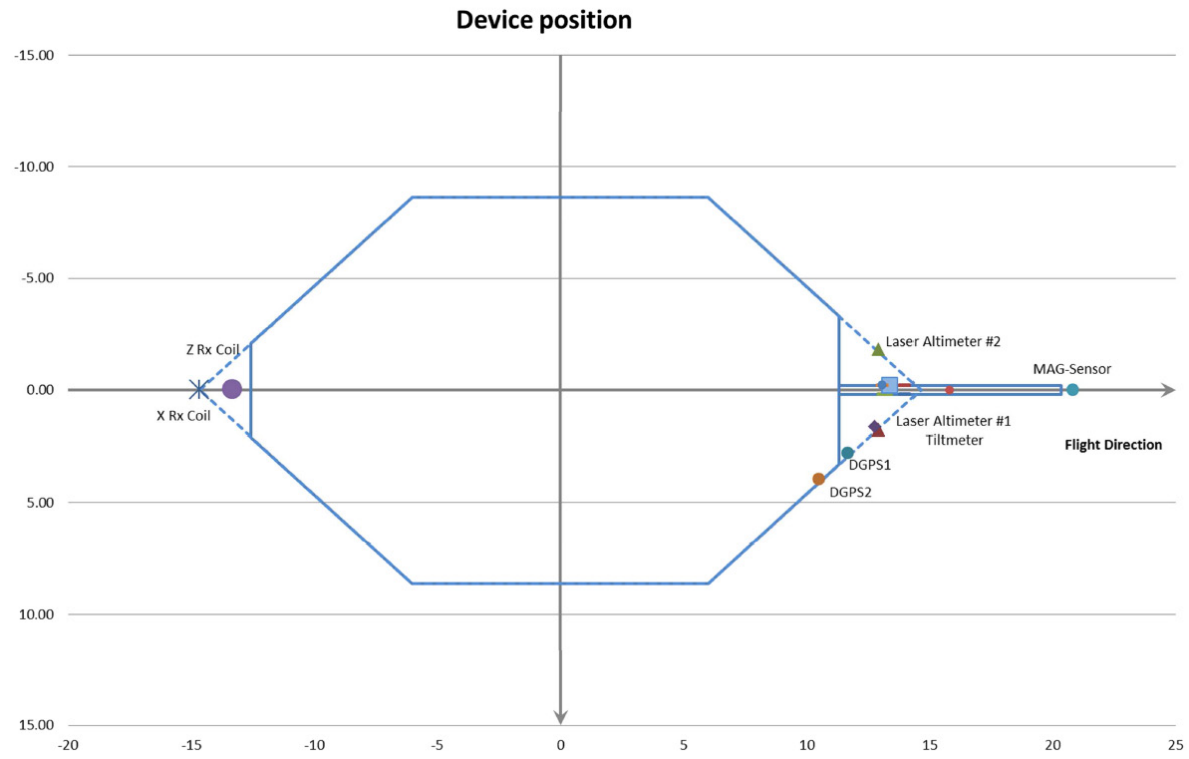


Figure 4-3: SkyTEM304M frame, including instrumentation locations and X and Y axes. Distances are in meters. Instrumentation locations listed in Table 4-1.



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

For this project, the 304M was flown at an average speed of 62 mi/hr (100.5 kilometers/hr) at an average flight height of 36.4 m above land surface, using the sling-load cargo system of a Eurocopter AS350BA FX2 helicopter. Figure 4-4 displays a couple of images of the 304M in operation.

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

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

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

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

Table 4-3: Location of DGPS and magnetic field base station instruments was the Genoa Airport.

Instrument	Easting (ft)	Northing (ft)	UTM Zone
Magnetometer Base Station (Genoa Airport)	1861536	15142856	14 N
Magnetometer Base Station (Norfolk Airport)	1980432	15497198	14 N
DGPS Base Station (NEHO)	1472667	14796700	14 N
DGPS Base Station (NEHO)	1472667	14796700	14 N
DGPS Base Station (NENF)	1997119	15283124	14 N
DGPS Base Station (NEHA)	2049281	15631409	14 N

4.4 Data Acquisition

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

For these surveys, installation of the navigational instruments in the helicopter and assembly of the SkyTEM304M system commenced at the beginning of the project. The helicopter and the SkyTEM304M system were located at the Norfolk, 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 1016.5 line-miles (1,646.8 line-kilometers) were acquired over the LENRD AEM survey area on July 18-26, 2016. The Columbus, Norfolk, David City, Creighton, Hartington, and Wayne airports were used for landing and refueling between production flights. A data acquisition map is presented in Figure 4-5 with the flight lines grouped by acquisition date.

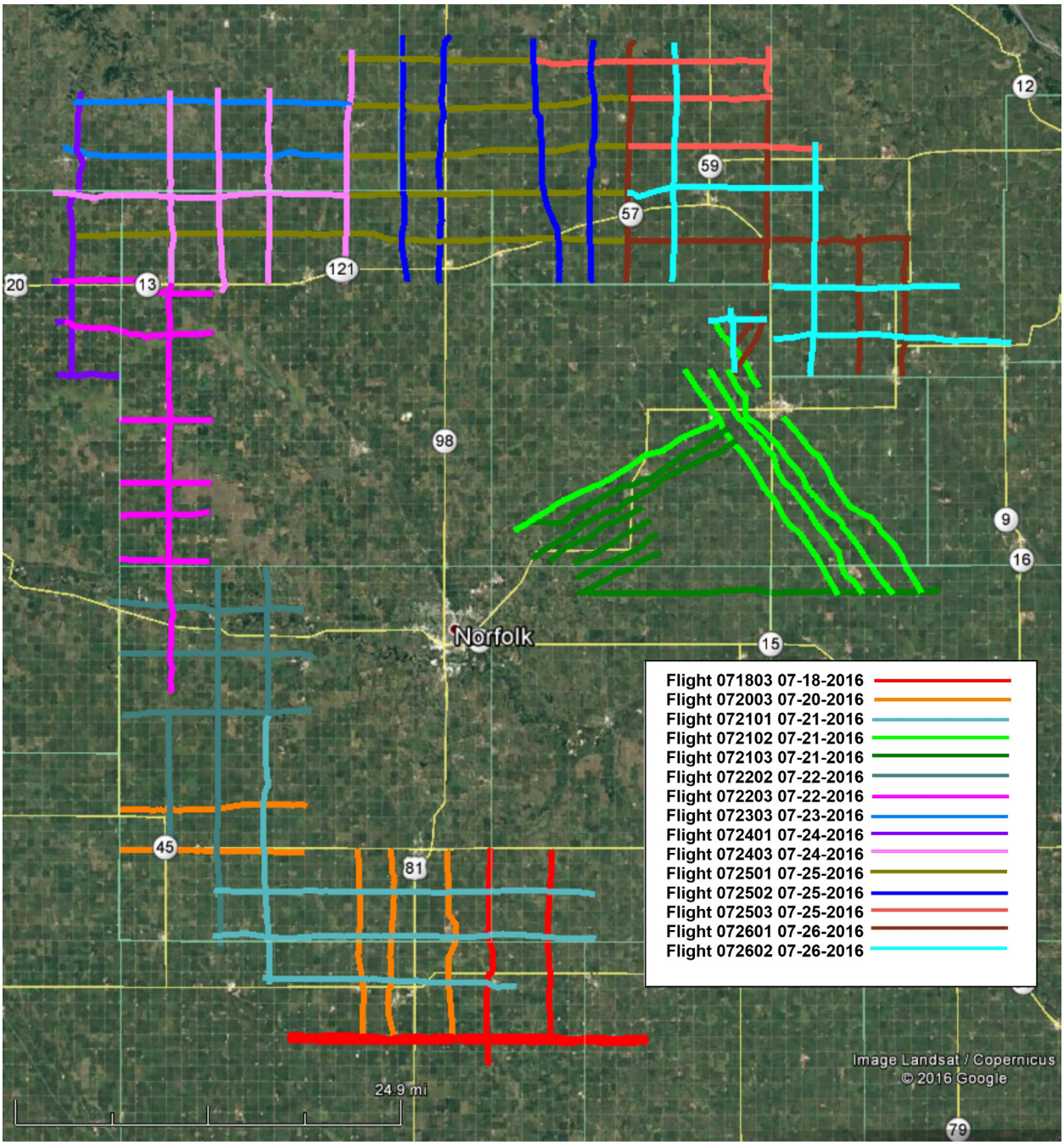


Figure 4-5: LENRD AEM flight lines grouped by acquisition date.

4.4.1 Primary Field Compensation

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

4.4.2 Automatic Processing

The AEM data collected by the 304M were processed using Aarhus Workbench version 5.1.1.0 (at Aarhus Geosoftware (http://www.aarhusgeosoftware.dk/aarhus-workbench-ib3ao) described in HydroGeophysics Group, Aarhus University (2011).

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

Trapezoidal spatial averaging filters were next applied to the AEM data. The times used to define the trapezoidal filters for the Low Moment were $1.0x10^{-5}$ sec, $1.0x10^{-4}$ sec, and $1.0x10^{-3}$ sec with widths of 8, 10, and 12 seconds. The times used to define the trapezoid for the High Moment were $1.0x10^{-4}$ sec, $1.0x10^{-3}$ sec, and $1.0x10^{-2}$ sec with widths of 10, 12, and 20 seconds. The trapezoid sounding distance was set to 2.5 seconds and the left/right setting, which requires the trapezoid to be complete on both sides, was turned on. The spike factor and minimum number of gates were both set to 25 percent for both soundings. Lastly, the locations of the averaged soundings were synchronized between the two moments.

4.4.3 Manual Processing and Laterally-Constrained Inversions

After the implementation of the automatic filtering, the AEM data were manually examined using a sliding two-minute time window. The data were examined for possible electromagnetic coupling with surface and buried utilities and metal, as well as for late time-gate noise. Data affected by these were removed. Examples of locating areas of EM coupling with pipelines or power lines and recognizing and removing coupled AEM data in Aarhus Workbench are shown in Figure 4-6 and Figure 4-7, respectively. Examples of two inversions, one without EM coupling and the other with EM coupling, are shown in Figure 4-8. Areas were also cut out where the system height was flown greater than 200 feet above the ground surface which caused a decrease in the signal level. This problem was encountered at several locations along the Loup River due to the tall cottonwood trees.

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

After final processing, 935.5line-miles (1,515.5 line-km) of data were retained for the final inversions for the LENRD AEM reconnaissance survey. This amounts to a data retention of 92%. This high rate is the result of careful flight line planning and design.

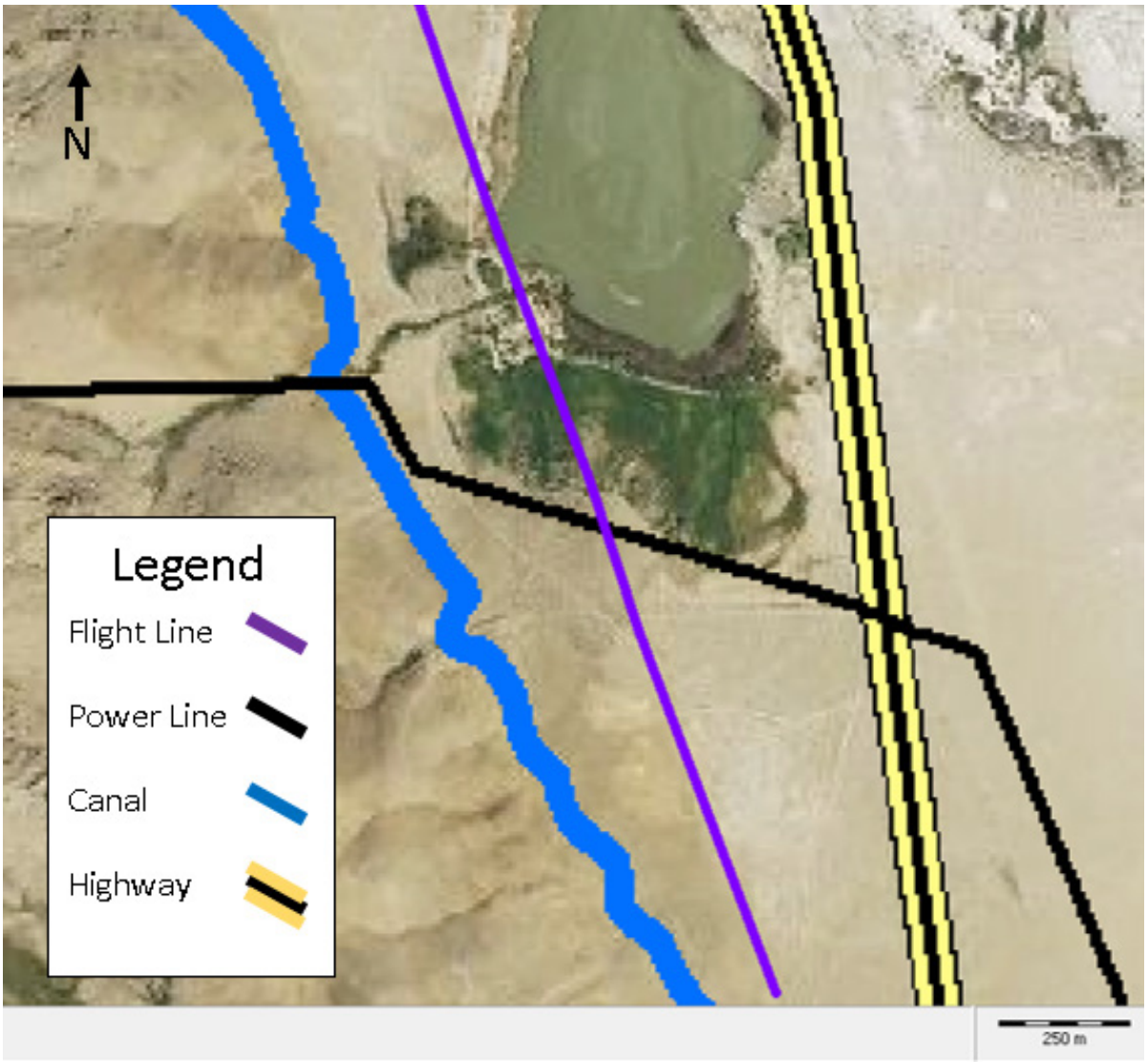


Figure 4-6: Example locations of electromagnetic coupling with pipelines or power lines.

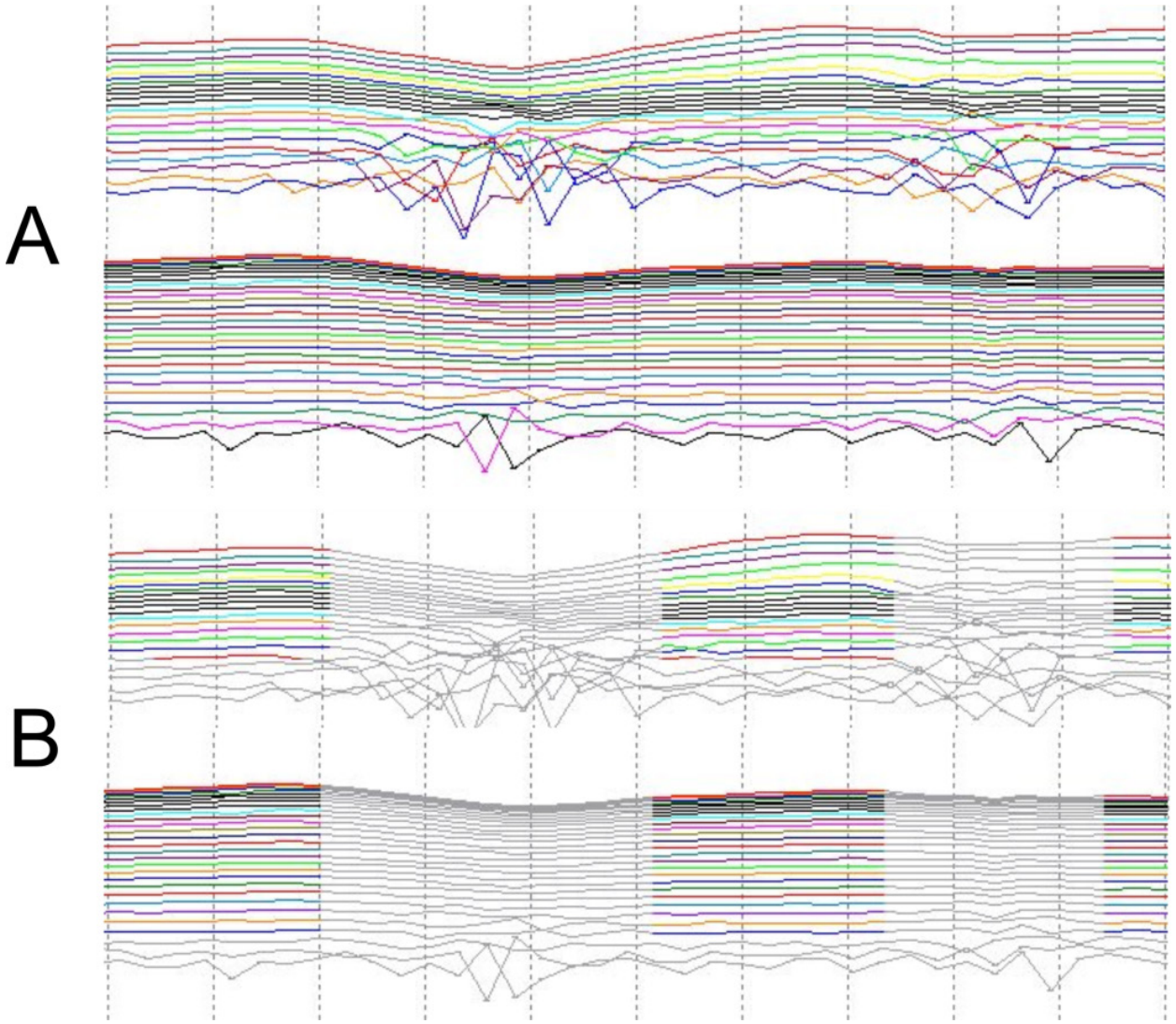


Figure 4-7: A) Example of AEM data from the LENRD AEM survey affected by electromagnetic coupling in the Aarhus Workbench editor. The top group of lines is the unedited data with the Low Moment on top and the High Moment on the bottom. The bottom group shows the same data after editing.

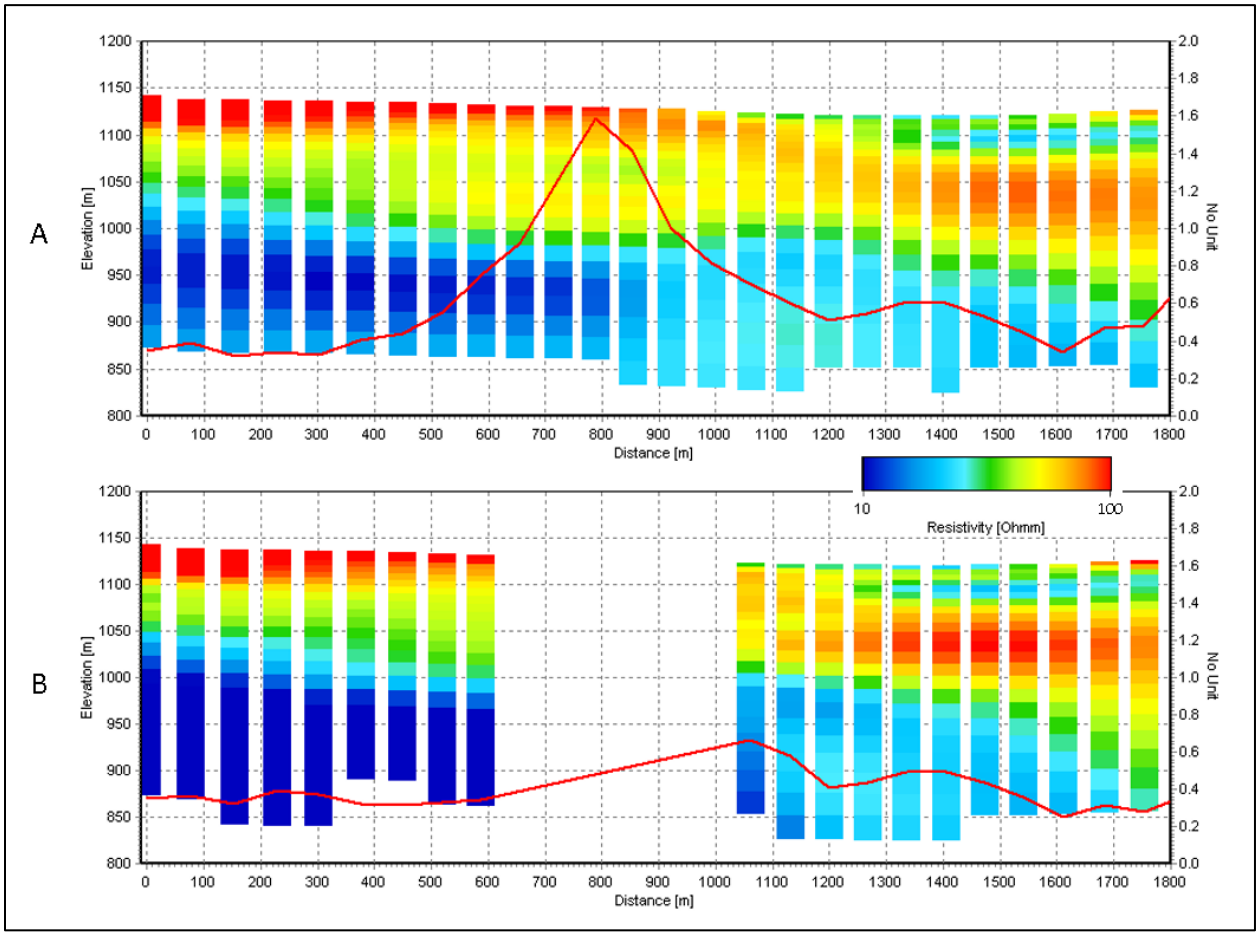


Figure 4-8: A) Example of Laterally-Constrained inversion results where AEM data affected by coupling with pipelines and power lines were not removed. B) Inversion results where AEM data affected by coupling were removed.

4.4.4 Power Line Noise Intensity (PLNI)

The Power Line Noise Intensity (PLNI) channel assists in identifying possible sources of noise from power lines. Pipelines, unless they are cathodically-protected, are not mapped by the PLNI. The PLNI is produced by performing a spectral frequency content analysis on the raw received Z-component SkyTEM data. For every Low Moment data block, a Fourier Transform (FT) is performed on the latest usable time gate data. The FT is evaluated at the local power line transmission frequency (60 Hz) yielding the amplitude spectral density of the local power line noise. The PLNI data for the LENRD AEM survey are presented in Figure 4-9. The LENRD-flight lines with blue colors representing data retained for inversion and red lines representing data removed due to infrastructure and late time noise are presented in Figure 4-10.

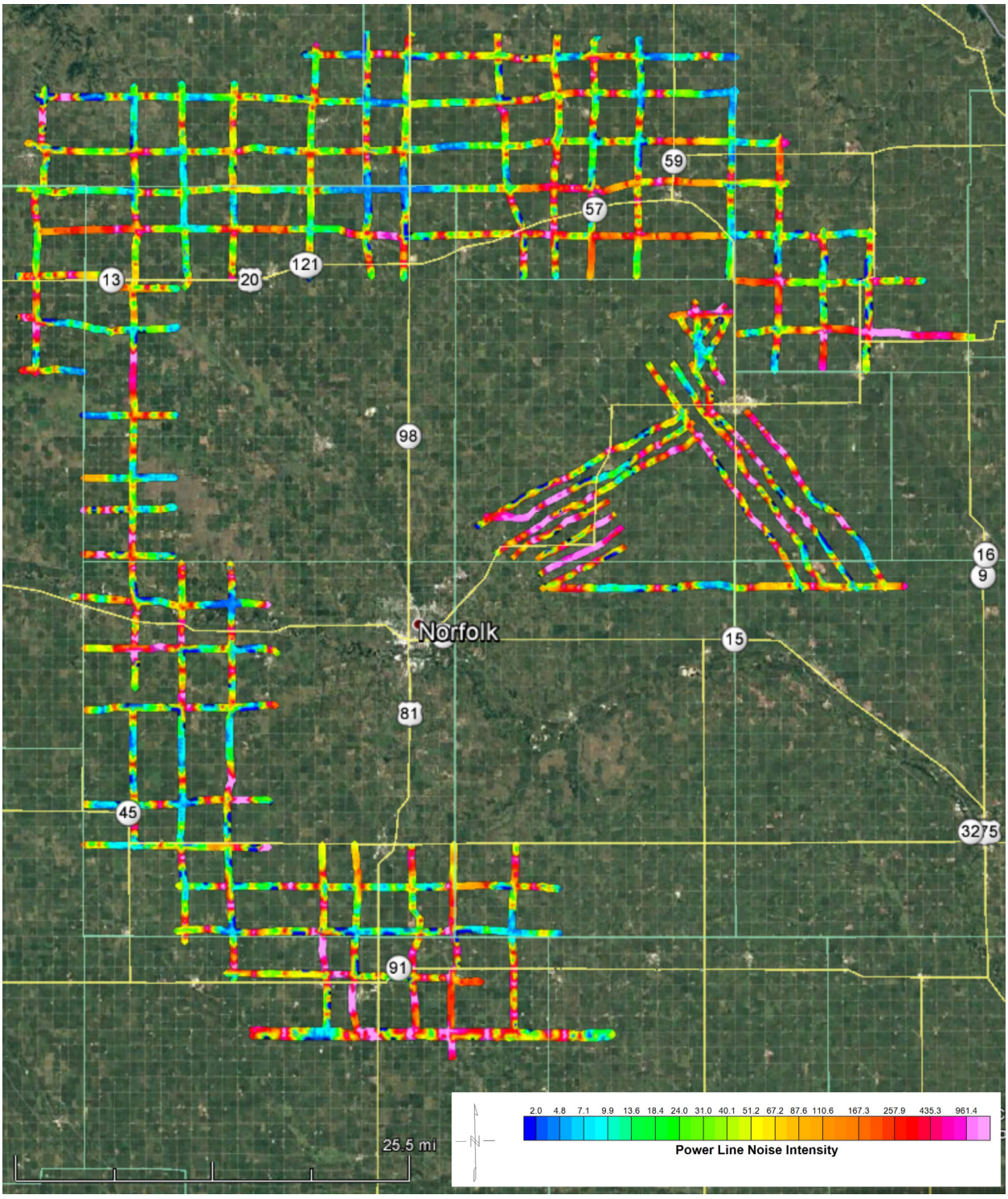


Figure 4-9: Power Line Noise Intensity (PLNI) map of the LENRD project area.

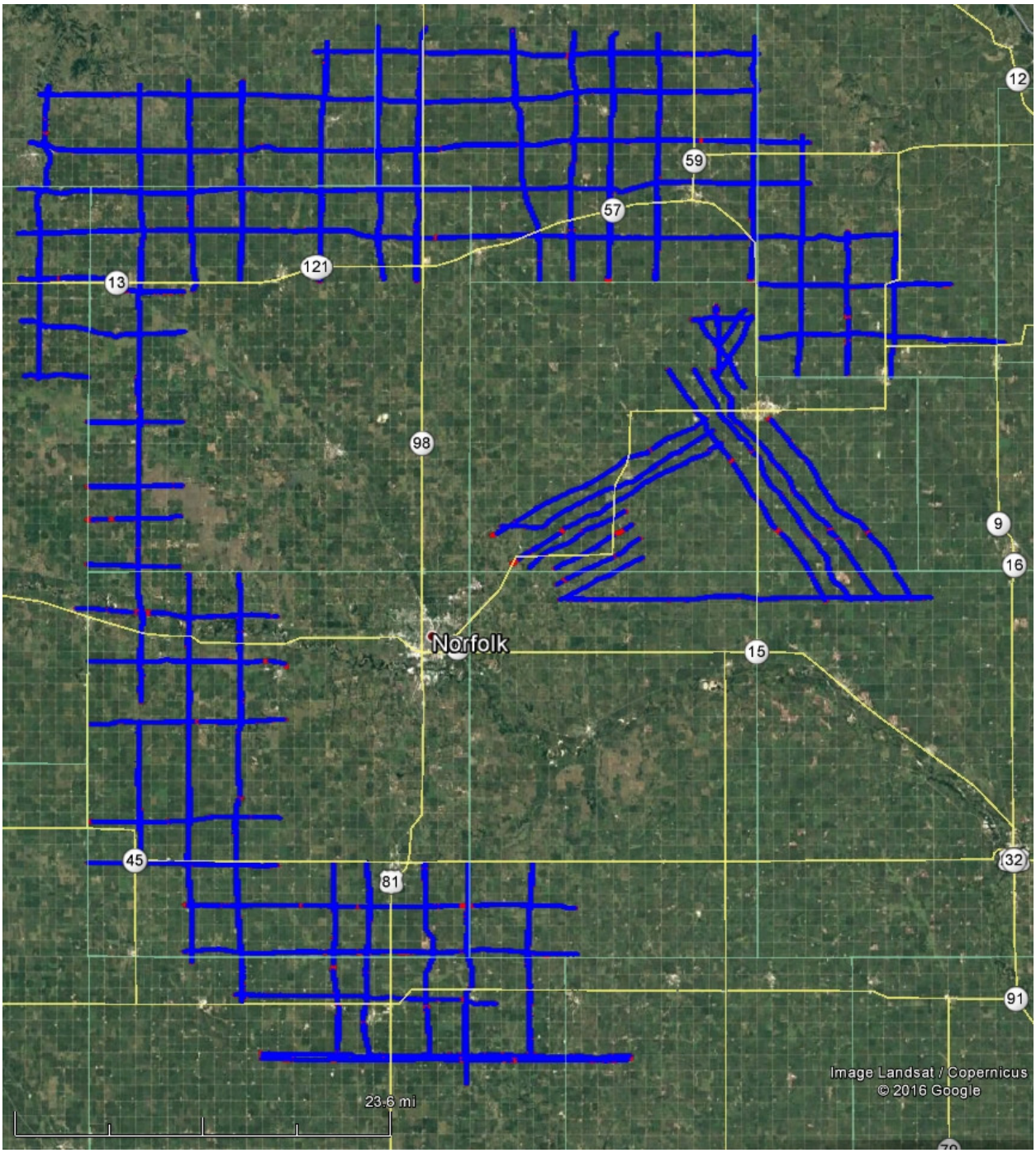


Figure 4-10: Locations of inverted data (blue lines) along the AEM flight lines (red lines) in the LENRD AEM survey area. Where blue lines are not present indicates decoupled (removed) data. Google Earth kmz's of the inverted data locations as well as the flight lines are included in Appendix 3\KMZ.

4.4.5 Magnetic Field Data

As discussed above, the SkyTEM 304M includes a Total Field magnetometer. The magnetic Total Field data can yield information about infrastructure as well as geology. Figure 4-11 shows the magnetic Total Field intensity data for the LENRD AEM survey area after correcting for diurnal drift and removing the International Geomagnetic Reference Field (IGRF). This data is used in decoupling efforts.

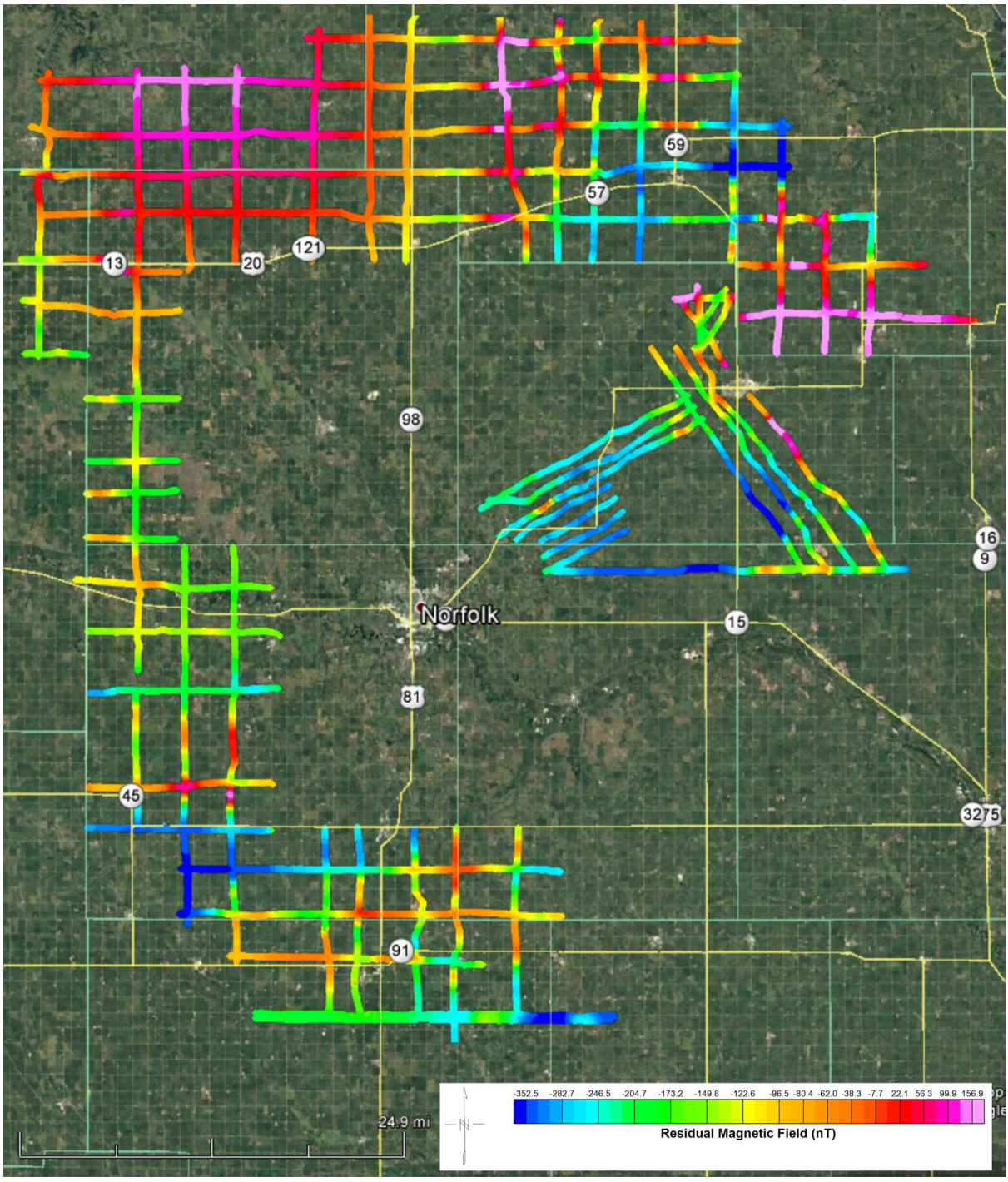


Figure 4-11: Magnetic Total Field intensity data for the LENRD survey area corrected for diurnal drift, with the International Geomagnetic Reference Field (IGRF) removed.

For comparison purposes, an image of magnetic Total Field data collected by the USGS (Sweeney and Hill, 2005) are presented in Figure 4-12. The USGS data were collected over a much larger reconnaissance grid spacing (5-mile line separation) than was collected in the present survey over the LENRD and then the USGS data were "upward continued" to a 1000 ft elevation. Even so the comparison between the two data sets is quite good – especially the large high amplitude anomaly in the northwestern region of the survey area and the smaller high amplitude anomaly near Wayne.

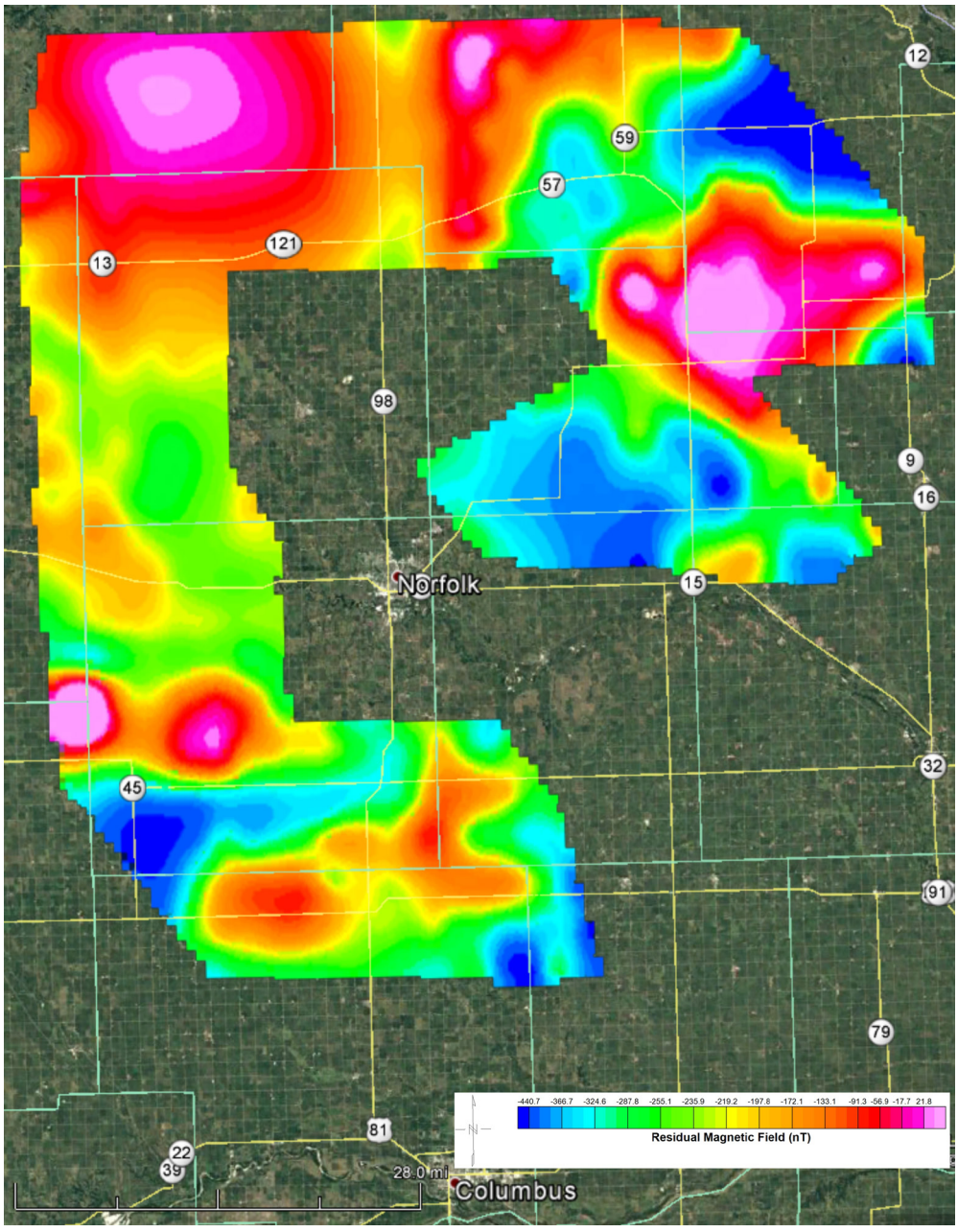


Figure 4-12: USGS magnetic Total Field intensity residual data for the LENRD survey area corrected for diurnal drift, with IGRF removed (Sweeney and Hill, 2005). The data was collected on an approximately 5-mile line spacing and upward continued to a reference elevation of 1000 ft.

4.5 Spatially-Constrained Inversion

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

The LENRD AEM data were inverted using SCI smooth models with 29 layers, each with a starting resistivity of 10 Ohm-m (equivalent to a 10 ohm-m halfspace). The thicknesses of the first layers of the models were about 10 ft with the thicknesses of the consecutive layers increasing by a factor of 1.08. The depths to the bottoms of the 28th layers were set to 1,023 ft, with thicknesses up to about 85 ft. The thicknesses of the layers increase with depth (Table 4-4 and Figure 4-13) as the resolution of the technique decreases. The spatial reference distance, ***s***, for the constraints were set to 98 ft with power laws of 0.5. The vertical and lateral constraints, ***ResVerSTD*** and ***ResLatStD***, were set to 2.7 and 1.6, respectively, for all layers.

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

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

Layer	Depth to Bottom (ft)	Thickness (ft)	Layer	Depth to Bottom (ft)	Thickness (ft)
1	9.8	9.8	16	298.4	31.2
2	20.5	10.6	17	332.1	33.7
3	31.9	11.5	18	368.5	36.4
4	44.3	12.4	19	407.8	39.3
5	57.7	13.4	20	450.3	42.5
6	72.2	14.5	21	496.2	45.9
7	87.8	15.6	22	545.7	49.5
8	104.7	16.9	23	599.2	53.5
9	122.9	18.2	24	657.0	57.8
10	142.5	19.7	25	719.4	62.4
11	163.8	21.2	26	786.8	67.4
12	186.7	22.9	27	859.5	72.8
13	211.5	24.8	28	938.1	78.6
14	238.3	26.8	29	1023.0	84.9
15	267.2	28.9			

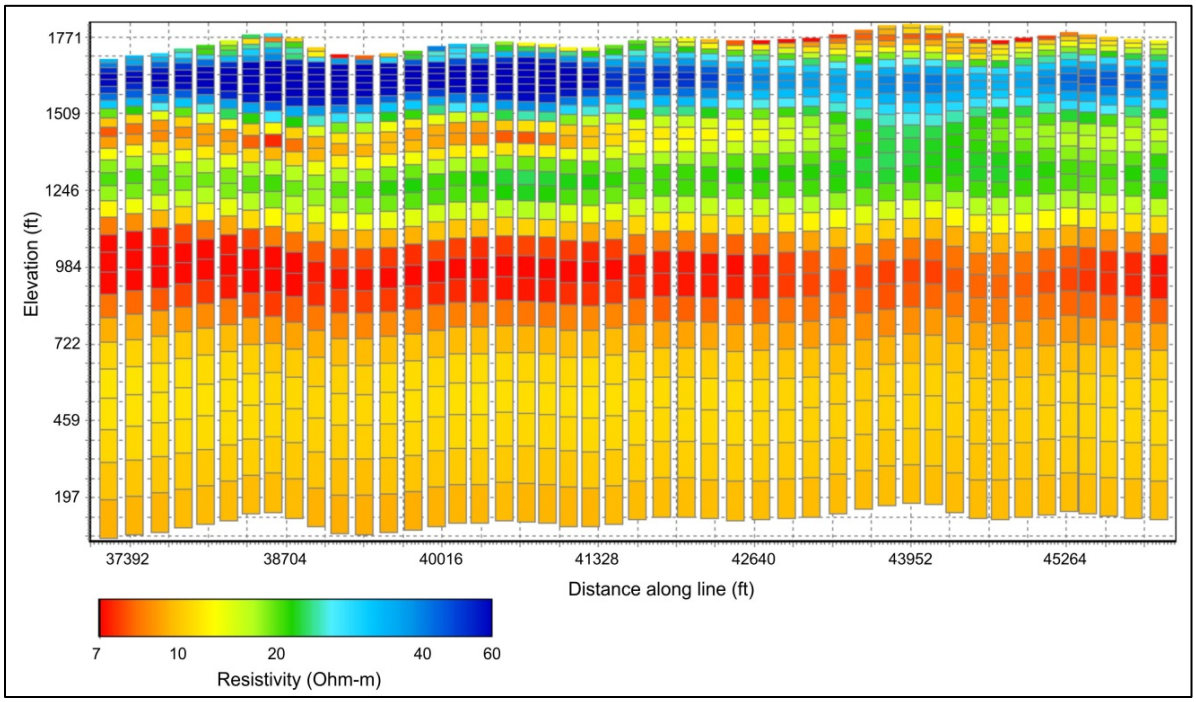


Figure 4-13: An example of an AEM profile illustrating increasing model layer thicknesses with depth.

Figure 4-14 presents a histogram of the LENRD SCI inversion data/model residuals. A map of data residuals for the LENRD AEM study area is presented in Figure 4-15.

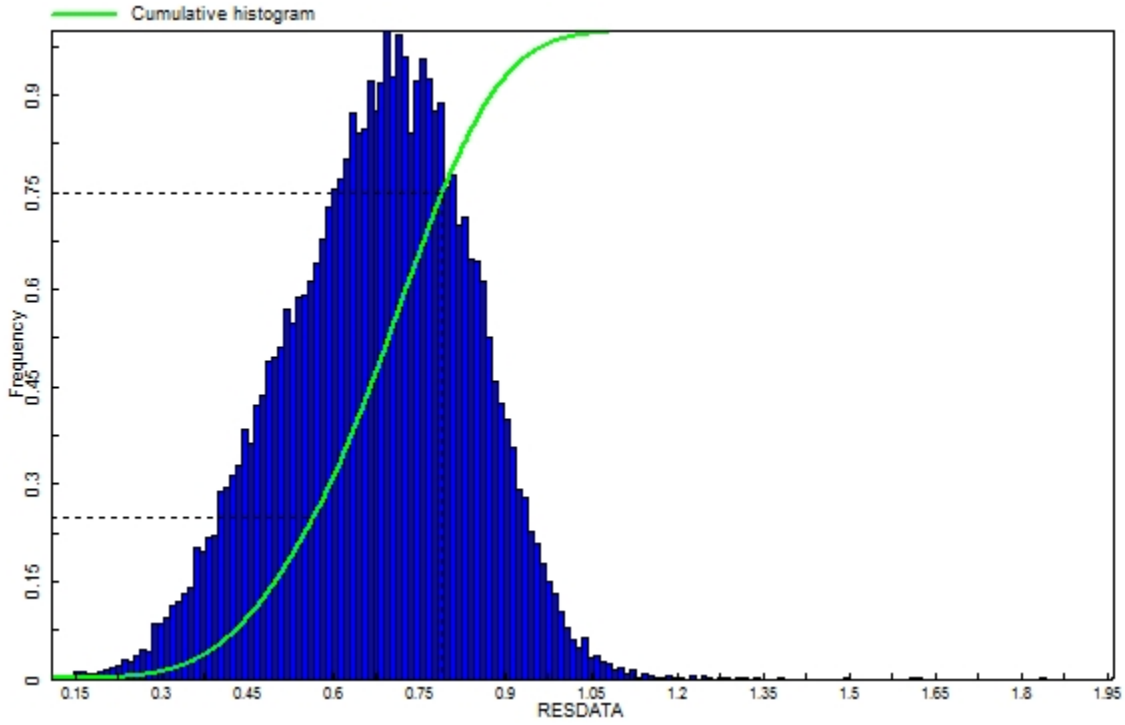


Figure 4-14: Data/model residual histogram for the LENRD SCI inversion results.

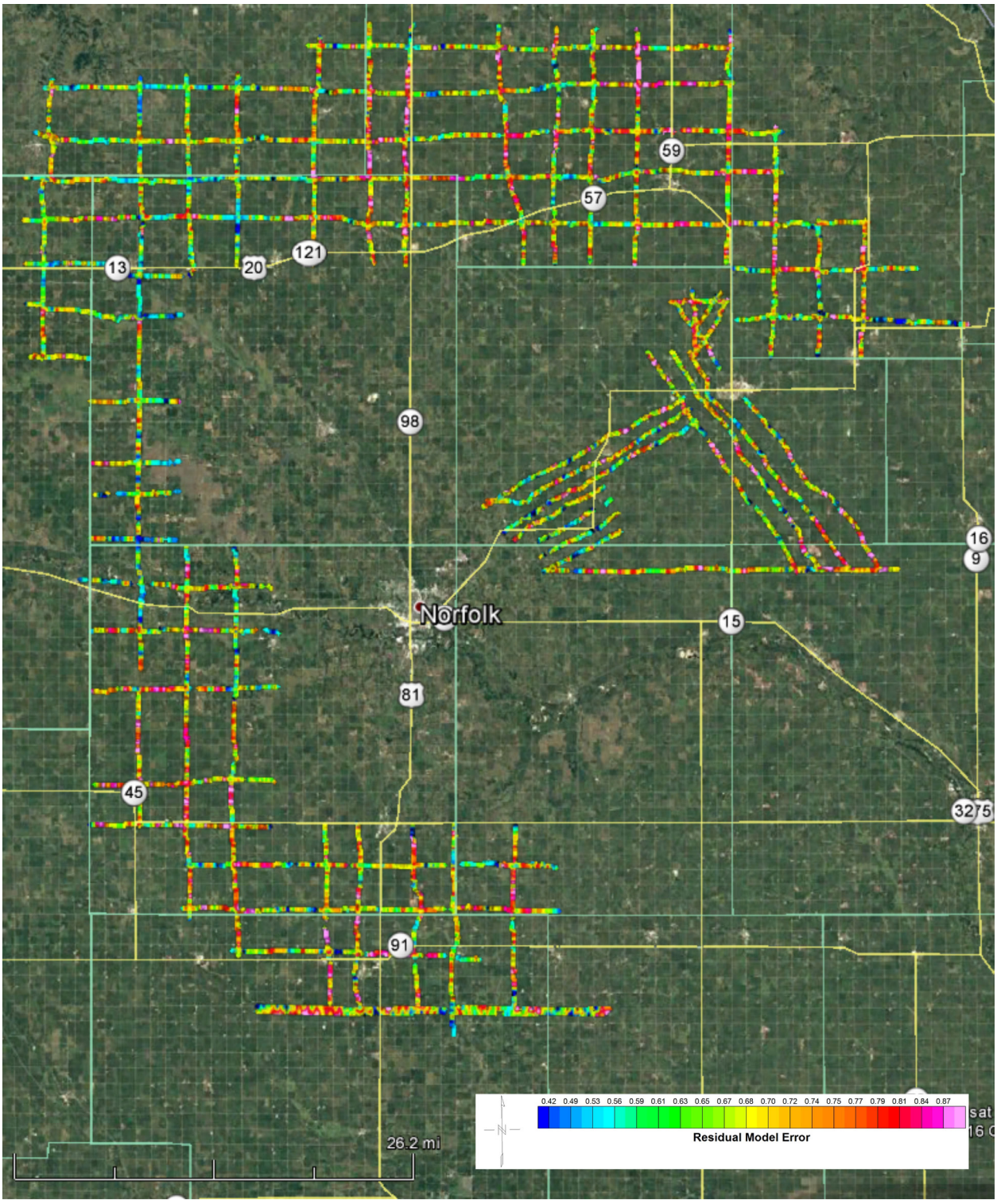


Figure 4-15. Map of data residuals for the LENRD SCI inversion results.

5 AEM Results and Interpretation

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

5.1 Interpretive Process

5.1.1 Merge AEM Databases from Different Flights

After the inversion process several short lines were combined to form continuous lines within the AEM survey area. This included lines that composed the 3-mile reconnaissance grid lines. These continuous lines allow for improved viewing and interpretation of the AEM inversions results. Table 5-1 lists the original flown lines and the new combined lines. One line required splitting in the survey area Table 5-2 due to the line wrapping around from one north-south line to another.

Table 5-1. Combination of flight lines within the LENRD 2016 survey.

Original Source Lines	Direction	New Line
L143401 and L143402	North-South	L286803
L144801 and L149801	North-South	L294602
L144601 and L149201	North-South	L294802
L145001 and L150001	North-South	L295002
L145201 and L150201	North-South	L295402
L145401 and L150401	North-South	L295802
L145601 and L150601	North-South	L296202
L145801 and L150801	North-South	L296602
L149401 and L149601	North-South	L299002
L143001, L143002, L148601, and L148602	North-South	L683206
L109701 and L109702	East-West	L219403
L118501, L118502, and L125302	East-West	L362305
L117701, L133501, and L133502	East-West	L384704
L118301, L118302, L125102, and L125103	East-West	L486808
L118101, L118102, L124902, L124904, and L133901	East-West	L609310
L117901, L117902, L124702, L124703, and L133701	East-West	L618909

Table 5-2. Splitting of flight lines within the LENRD 2016 survey

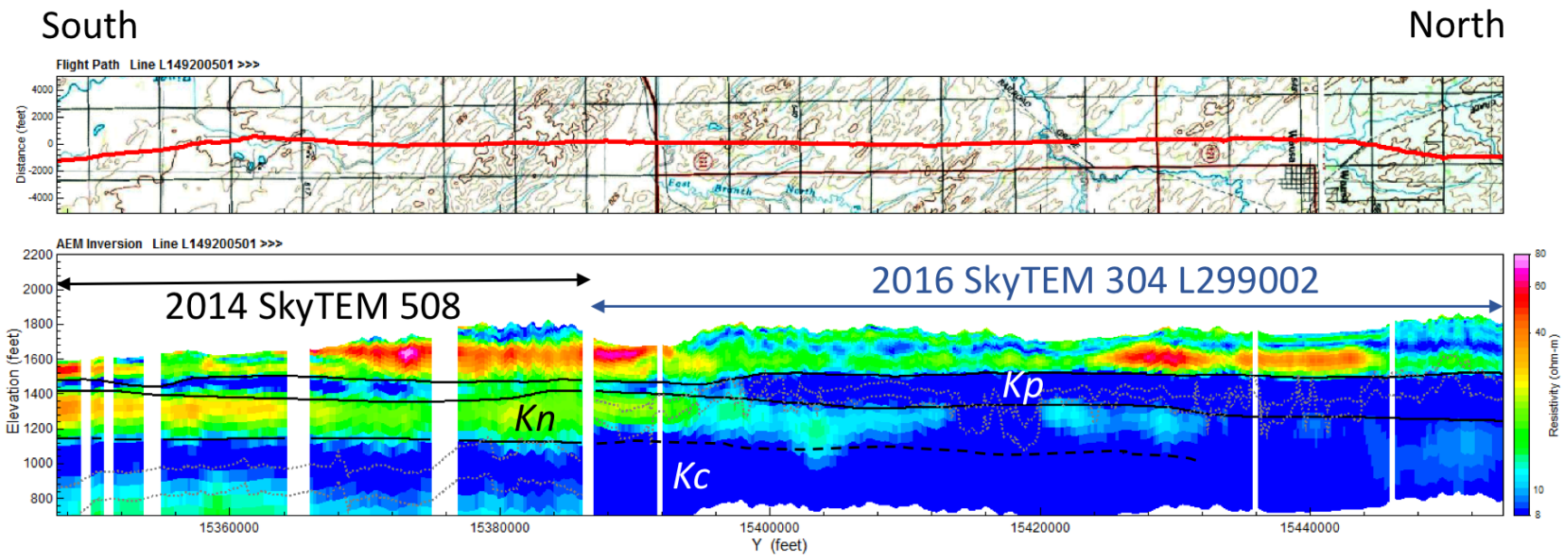
Original Line	New Line
L144001	L144001a
	L144001b

A substantial portion of the LENRD has had AEM data collection before that is summarized in Carney et al (2015c). A comparison of the data collected in 2014 and 2016 can indicate the stability of the system and the ability of the data to be integrated together. This comparison was also examined in AGF (2017a) as part of the BGMA AEM survey of which the LENRD is a participant. As indicated above, the portion of the BGMA within the LENRD is included within this report. When examining the combination of the two

separate data sets that were collected by different systems at different times and inverted separately, it is important to note that both data sets were properly calibrated and any system bias was removed prior to inversion. Inspection of the profiles created from the combined lines displaying inverted resistivity at the same color scale can indicate an issue with calibration and incomplete bias removal. Figure 5-1 is a north-south line that was combined from the 2016 LENRD SkyTEM 304M AEM inversions (north end) and the 2014 SkyTEM 508 AEM inversions (south end). Inspection of Figure 5-1 shows a small break in the data coverage at the meeting point of the two datasets. However, the resistivity values continue along the line until the top of the ***Kc*** is encountered in the 2016 SkyTEM304M inversions. This is due to the differences of the depths of investigation (DOI) of the SkyTEM304M and the SkyTEM 508. The combination of the two datasets indicates that there is no observable bias that was not removed from the data prior to inversion. Several other comparisons can be made within the LENRD showing the continuation of the AEM data collection within the district from 2014 to 2016. However, that is beyond the scope of this report as there is no indication of any problem with the AEM inversions.

5.1.2 Construct the Project Digital Elevation Model

To ensure that the elevation used in the project is constant for all the data sources (i.e. boreholes and AEM) a Digital Elevation Model (DEM) was constructed for the LENRD survey. The data was downloaded from the National Elevation dataset (NED) located at the National Map Website (U.S. Geological Survey, 2016) at a resolution of 1 arc-second or approximately 100 ft. The geographic coordinates are North American Datum of 1983 (NAD 83) and the elevation values are referenced to the North American Vertical Datum of 1988 (NAVD 88). The 100 ft grid cell size was used throughout the project and resulting products. Figure 5-2 is a map of the DEM showing a vertical relief of 852 ft with a minimum elevation of 1,132 ft and a maximum elevation of 1,984 ft. This DEM was used to reference all elevations within the AEM and borehole datasets.



Dashed gray lines on the AEM Inversion profile are the upper and lower Depth of Investigation (DOI).

Kp = Cretaceous Pierre
Kn = Cretaceous Niobrara
Kc = Cretaceous Carlile

Figure 5-1. Example of a map and profile view of a north-south flight line L149200501, part of the BGMA that was combined from the 2014 LENRD AEM and the 2016 LENRD AEM. The 2016 portion is labeled as L299002 within the LENRD. The top map is a flight line positioned on the U.S. Geological Survey 100K topography at the same horizontal scale as the AEM inversions profile. The bottom profile displays the resistivity values of the 2014 ENWRA SkyTEM 508 and the 2016 LENRD SkyTEM 304 inversions. Geological interpretations on the profile include the Cretaceous Pierre (*Kp*), Niobrara (*Kn*), and Carlile (*Kc*). The dashed black line shows the inferred location of the *Kn* and *Kc* contact in the SkyTEM304M inversions. The dotted gray lines represent the upper and lower depths of investigation from the inversions.

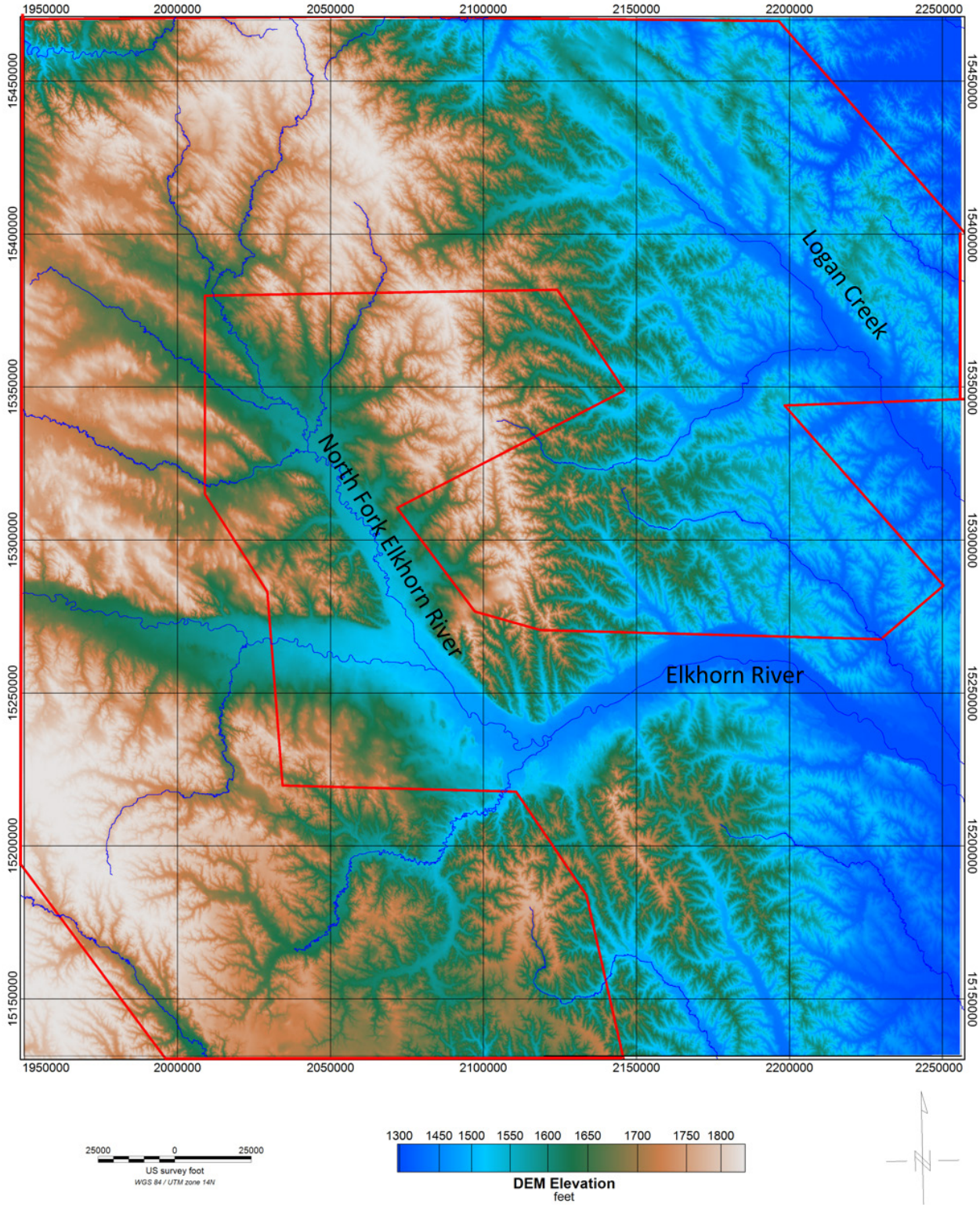


Figure 5-2. Map of the Digital Elevation Model for the LENRD Study area (red line). Data source is the one (1) arc-second National Elevation Dataset (U.S. Geological Survey, 2016). North American Datum of 1983 (NAD 83) and the elevation values are referenced to the North American Vertical Datum of 1988 (NAVD 88).

5.1.3 Create Interpretative 2D Profiles

After final combination of the AEM data, characterization of the subsurface was performed in cross-section format using Encom PA (**pbEncom, 2016**). During interpretation, the horizontal and vertical scale of the profiles were adjusted to facilitate viewing. The color scale of the resistivity data was also adjusted to illuminate subtle differences in the resistivity structure within the inverted AEM resistivity data related to the area being interpreted. The first step in the interpretation is digitizing the contacts between the geological units including: Quaternary (***Q***), the Tertiary Ogallala Group (***To***), the Cretaceous Pierre Shale (***Kp***), the Cretaceous Niobrara Formation (***Kn***), the Cretaceous Carlile Shale (***Kc***), the Cretaceous Greenhorn Limestone and Cretaceous Graneros Shale (***Kgg***), and the Cretaceous Dakota Group (***Kd***). The interpreted geological units included the ***Q***, ***To***, ***Kp***, ***Kn***, ***Kc***, ***Kgg***, and ***Kd*** from the upper surface of the model to the DOI. The interpretive process benefited from the use of CSD, NE-DNR, and NOGCC borehole logs, which provided lithologic, stratigraphic, and geophysical information. The interpretations were simultaneously checked against the CSD's Nebraska bedrock geology map (**Burchett, 1986**).

The interpretation began with picking the ***Kp***, ***Kc***, ***Kn***, ***Kgg***, and ***Kd*** contacts and then finally the ***To*** interface. The process was iterative around the eroded ***Kp*** overlaying the ***Kn*** and the eroded ***Kn*** overlaying the ***Kc*** due to the irregular nature of the boundary.

The interpretation of the ***To*** included examination of the CSD and NE-DNR boreholes and comparison with the AEM resistivities. Unlike the ***Kp/To*** and ***Kp/Q*** surfaces there is not a strong resistivity contrast between the ***Q*** and the ***To***. The borehole information is critical in the determination of an estimated top of the ***To***.

The following characteristics were used to locate the ***To*** top: 1) ***To*** indicated on the CSD borehole stratigraphic logs; 2) indication of sandstone in the CSD borehole lithology logs; 3) indication of sandstone in the NE-DNR lithology logs; and 4) a generally lower electrical resistivity than the overlying ***Q*** alluvial deposits. Patterns in the resistivity were also used to match the differences in the ***Q*** and the ***To***.

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

The top of the ***Kn*** was a much more challenging unit to interpret when the ***Kp*** is eroded off the ***Kn***. This is due to the highly variable resistivity of the ***Kn***. The unit goes from a resistive unit to a conductive unit

based on the presence of clay minerals that are within the shale, chalk, and limestone lithologies. The best way to interpret the ***Kn*** unit is to use the boreholes in the area and use the underlining ***Kc*** as a guide to the dip of the ***Kn***. Several of the CSD and the NE-DNR holes have shale, chalk, or limestone indicated at the bottom. This provides a clear indication of the ***Kn***. When the CSD holes contain stratigraphic information, that boundary can be confidently interpreted. In some instances, there are no indications of the ***Kn*** at the bottom of the holes. Inspecting the area for the average depth of the NE-DNR holes provides another clue to the positon of the ***Kn*** as many wells stop at the top of the ***Kn***.

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

The ***Kgg*** can be difficult to detect depending on the depth. The ***Kgg*** is generally a thin unit composed of resistive limestone and conductive shale. When detectable, the resistive limestone of the Greenhorn Limestone is interrupted beneath the ***Kc***. The interpretation of the bottom of the ***Kgg*** is more challenging due to the variable resistivity of the ***Kd*** immediately below the conductive Graneros Shale. When the ***Kd*** contains resistive sands/sandstone, the lower contact of the ***Kgg*** and the top of the ***Kd*** is identifiable. Deep CSD test holes and very rare deep NE-DNR wells can assist in the verification of the position of the ***Kgg*** and ***Kd***. The ***Kd*** general location is detectable when there are resistive sands/sandstones. Use of general thickness constraints can also assist in the interpretation of the ***Kd*** location. NOGCC wells in the area also provide general stratigraphic control assisting in the location of the geologic units.

Figure 5-3 is a 52-mile-long east-west line L362305 on the northern end of the LENRD. This line encompasses all the geological units mapped within the LENRD. This line illustrates the regional dip of the Cretaceous units toward the west and how those units are eroded off toward the east. A thin layer of ***To*** is interpreted by using the stratigraphic control of the CSD test holes and the lithology of both the CSD and the NE-DNR wells. The ***To*** is only present in the western portion of the line. The ***Kp*** is present on the western end of the line and is easy to identify as a low resistivity unit. Several CSD test holes and many NE-DNR wells penetrate or stop at the top of the ***Kp***. The eastern extent of the ***Kp*** is easily detected. As discussed above, the top of the ***Kn*** is detectable when it is overlain by the ***Kp.*** Otherwise the top is interpreted by using the test holes and the wells. The top of the ***Kc*** is also detectable when above the DOI due to the higher resistivity of the ***Kn***. The eastern extent of the ***Kn*** is easily detected due to the conductive nature of the ***Kc***. When the ***Kc*** is the bedrock in the area, it is also detectable as compared to the ***Q*** materials with the exception when the ***Q*** material contains large areas of conductive clays with the glacial tills. On the eastern end of this line, the presence of the ***Kgg*** is detectable. The location of the top of the ***Kd*** is estimated from the thickness of the ***Kgg*** and a single deep NE-DNR well, *G-096784*, that penetrates the sandstone of the ***Kd***. Figure 5-3 illustrates the regional nature of the long reconnaissance lines within the LENRD and illuminates the Cretaceous units and their structural attitude. After the completion of the interpretation of the Cretaceous bedrock units the ***Q*** materials can be inspected. Along Line 362305 many positive correlations of the AEM resistivity and the lithology can be observed in the CSD and the NE-DNR wells.

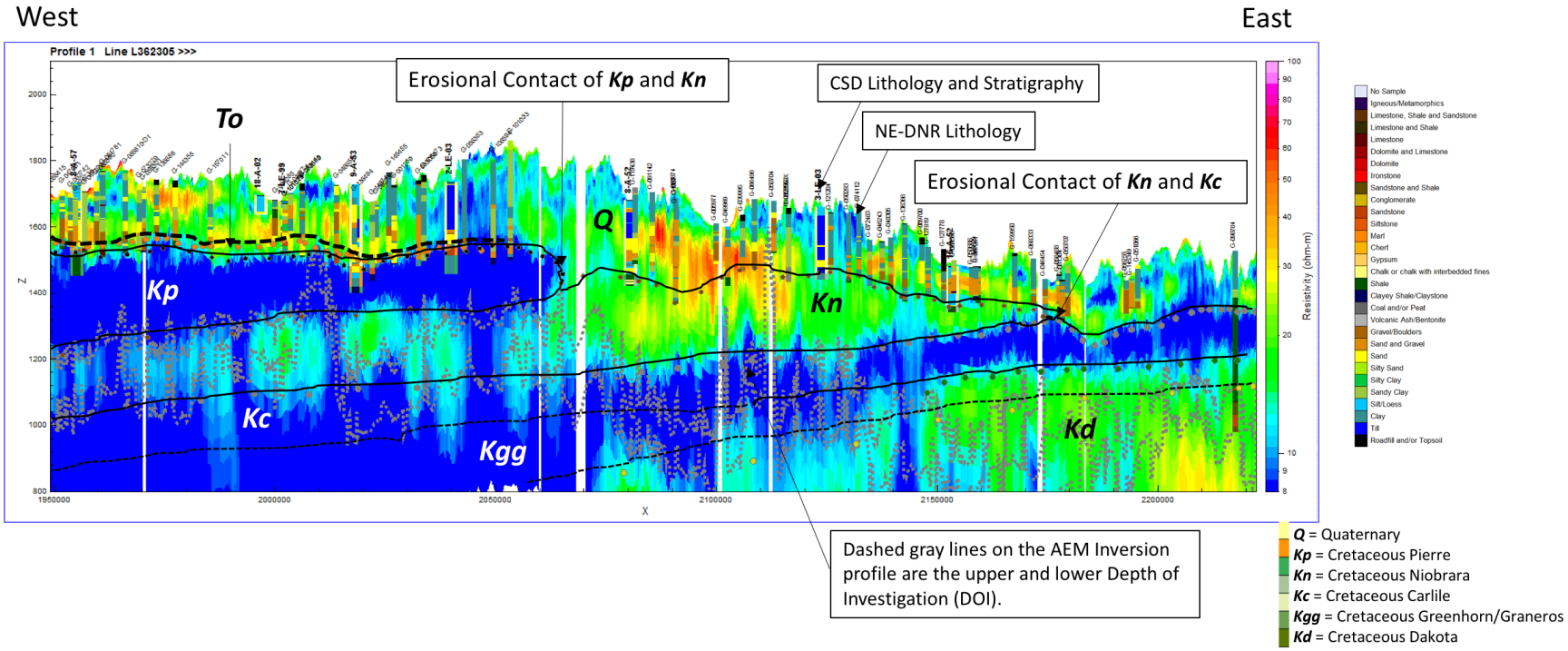


Figure 5-3. 52-mile long east-west line L362305 on the northern end of the LENRD AEM survey area. CSD and Nebraska DNR borehole lithology and stratigraphy logs are indicated on the AEM inverted earth models. Interpretations are indicated by lines labeled with stratigraphic names.

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Figure 5-4 is Line L683200, a 48-mile-long north-south line on the western edge of the LENRD survey area. Similarly, as observed in Figure 5-3, all the geological units mapped within the LENRD are present along this line. The ***To*** is interpreted as thinning to the north and overlying both the ***Kn*** to the south and the ***Kp*** to the north. Abundant indications of sandstone in the CSD and NE-DNR test holes and wells provide a confident estimation of the top of the ***To***.

The detection of the ***Kp*** is easily accomplished by its conductive nature and includes two erosional remnants overlying the ***Kn*** (Figure 5-4)**.** The top of the ***Kn*** is difficult to interpret when the ***To*** is overlying it, but is easily interpreted when overlain by the ***Kp***. On the southern end of the line, the ***Kn*** bedrock is interpreted by utilizing the NE-DNR wells. Below the ***Kn***, the ***Kc*** is detectable on the southern end as a conductor, but is masked by the DOI on the northern end due to the thick layer of ***Kp***. Within the ***Q*** deposits many positive correlations with the test holes and wells can be observed. Changes in the lithology within the ***Q*** is drastic in some areas and is reflected by the AEM electrical resistivity.

Figure 5-5 is Line L121101, a 25-mile-long east-west line located on the south-western end of the LENRD AEM survey area. In this location, the ***To*** and the ***Kp*** are not present and the ***Kn*** and ***Kc*** are the bedrock units. Similar to that observed Figure 5-3, the Cretaceous units dip toward the west and are eroded off the eastern end. The interpretation of the top of the ***Kn*** is complicated in this area but is facilitated by the presence of some NE-DNR wells. The top of the ***Kc*** is easily interpreted along this line. The interpretation of the top of the ***Kgg*** is also confidently interpreted due to the conductive nature of the ***Kc***. However, the top of the ***Kd*** is only estimated from the thickness of the ***Kgg***, due to the low resolution below and close to the DOI. Within the ***Q*** section of this line, two discrete bodies of sand are indicated by the resistivity and by the NE-DNR wells.

Figure 5-6 is Line 121501, an east-west line, 23-miles long on the eastern side of the LENRD AEM survey area north of the town of Pilger, Nebraska. As in Figure 5-5, the ***To*** and the ***Kp*** are not present along this line. Only a very thin layer of ***Kn*** is detectable on the western end of this line overlaying the ***Kc***. As noted above, the ***Kc*** is easily detectable and interpreted. The ***Kgg*** can also be interpreted in this area. The ***Kd*** is masked by the DOI but can be estimated based on the thickness of the ***Kgg***. Within the ***Q*** along this line, most of the lithologic materials exhibit electrically conductive properties associated with mineralogical clays. There are three NE-DNR wells that indicate a discrete sand body in, approximately, the center of the line.

The above examples illustrate the interpretive process that was used on the profiles provided within this report. Each flight line with interpretation including the Quaternary/Tertiary Aquifer material mapping (Section 5.2.1) are included in Appendix 1.

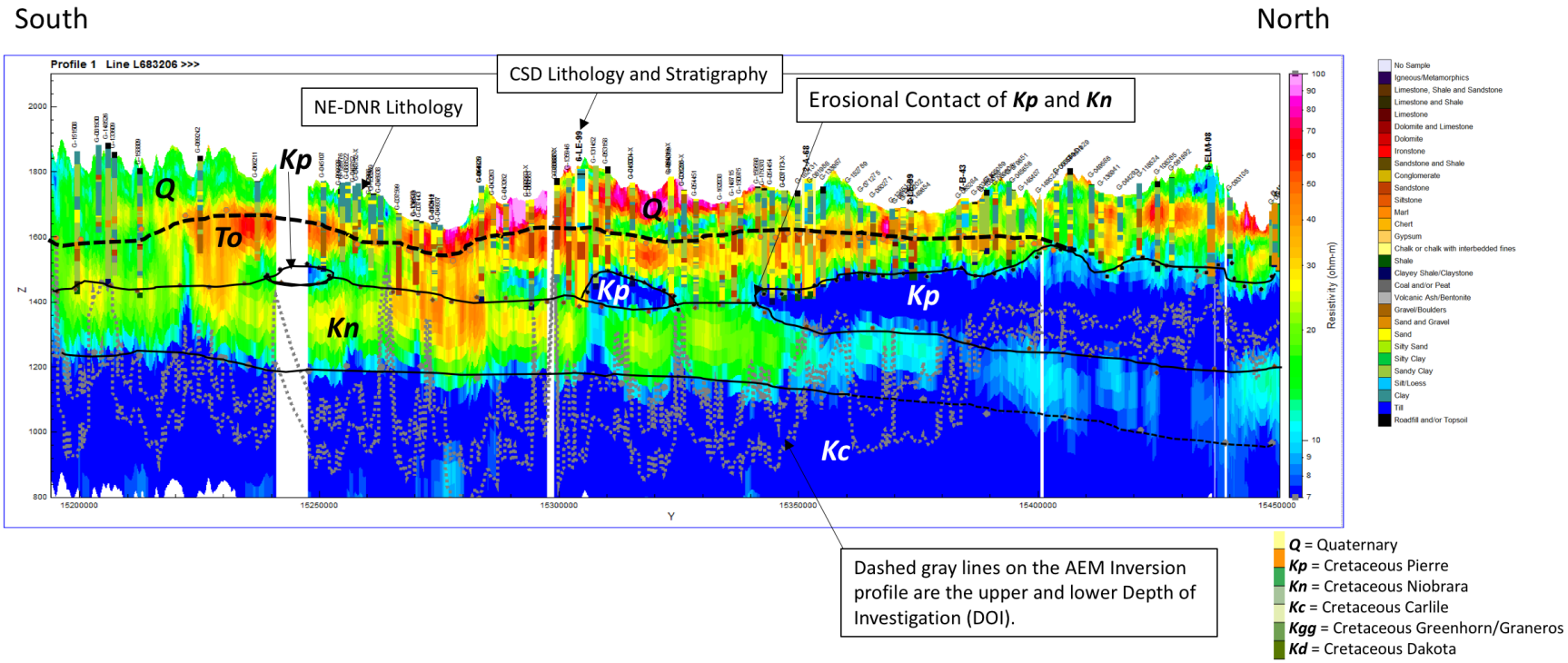


Figure 5-4. 48-mile long north-south line L683200 on the western edge of the LENRD survey area. CSD and Nebraska DNR borehole lithology and stratigraphy logs are indicated on the AEM inverted earth models. Interpretations are indicated by lines labeled with stratigraphic names.

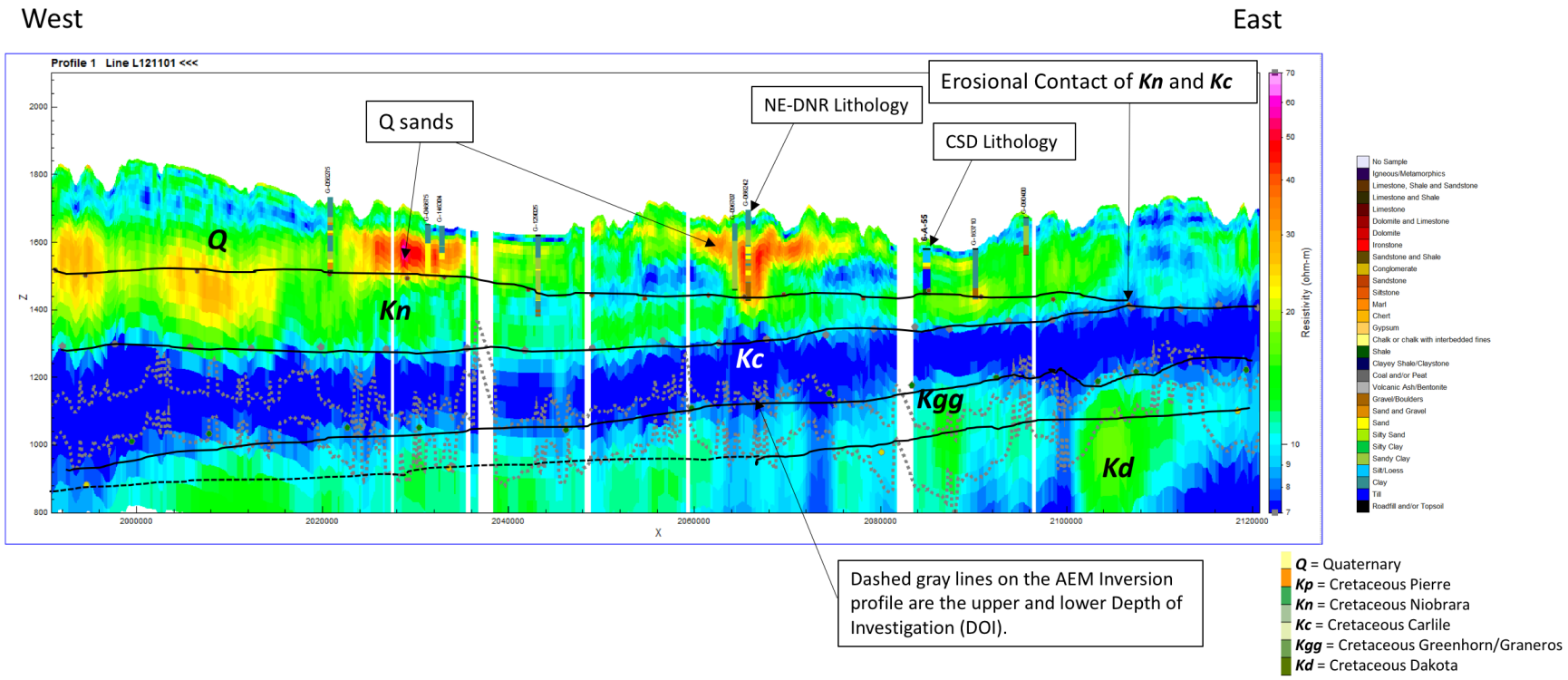


Figure 5-5. 25-mile long east-west line L121101 on the south-western end of the LENRD survey area. CSD and Nebraska DNR borehole lithology and stratigraphy logs are indicated on the AEM inverted earth models. Interpretations are indicated by lines labeled with stratigraphic names.

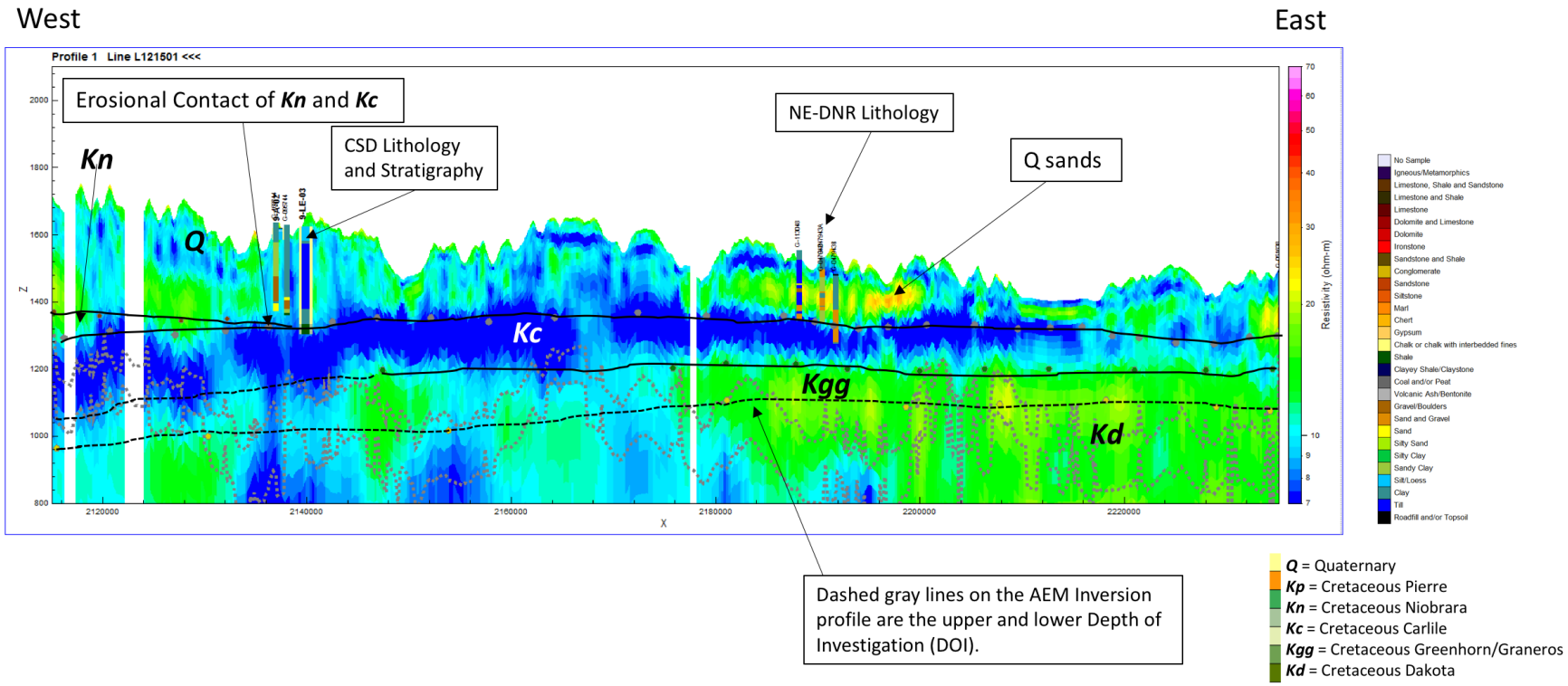


Figure 5-6. 23-milelong east-west line L121501 north of Pilger, Nebraska. CSD and Nebraska DNR borehole lithology and stratigraphy logs are indicated on the AEM inverted earth models. Interpretations are indicated by lines labeled with stratigraphic names.

5.1.4 Create Interpretative Surface Grids

LENRD AEM survey area surface grids of geologic formations were also produced. To create these grids, the elevations of the AEM-interpreted top of the formations were imported to a Geosoft Oasis montaj (OM) database. The interpreted elevation data were then gridded for each formation independently using the OM minimum curvature gridding (MCG) algorithm.

For the ***Kp*** top surface, 789 AEM picks were used in the grid using a cell size of approximately 1,907 feet and the "*cells to extend beyond*" was set to 10. All other parameters were either set to the default or left blank. The large extended area was required to fill in between the broadly spaced reconnaissance lines, where three miles or more separated adjacent flight lines. The grid was then clipped to the interpreted erosional contact and then clipped again to the LENRD survey area. On the margins of the survey area some areas are blank due to lack of data. Figure 5-7 is a map of the elevation of the top of the ***Kp*** within the LENRD AEM survey area.

For the ***Kn*** top surface 1,620 AEM picks were used in the grid with a cell size of approximately 1,937 feet and the "*cells to extend beyond*" set to 10. All other parameters were either left as the default or blank. The large extended area was required to fill in between the broadly spaced reconnaissance lines, where three miles or more separated adjacent flight lines. The grid was then clipped to the interpreted erosional contact and then clipped again to the LENRD survey area. On the margins of the survey area some areas are blank due to lack of data. Figure 5-8 is a map of the elevation of the top of the ***Kn*** within the LENRD survey area.

For the ***Kc*** top surface 1,518 AEM picks were used in the grid with a cell size of approximately 2,144 feet and the "*cells to extend beyond*" set to 10. All other parameters were either left as the default or blank. The large extended area was required to fill in between the broadly spaced reconnaissance lines, where three miles or more separated adjacent flight lines. The grid was then clipped to the LENRD survey area. One area within the survey area indicated an erosional window into the ***Kgg***. On the margins of the survey area some areas are blank due to lack of data. Figure 5-9 is a map of the elevation of the top of the ***Kc*** within the LENRD survey area.

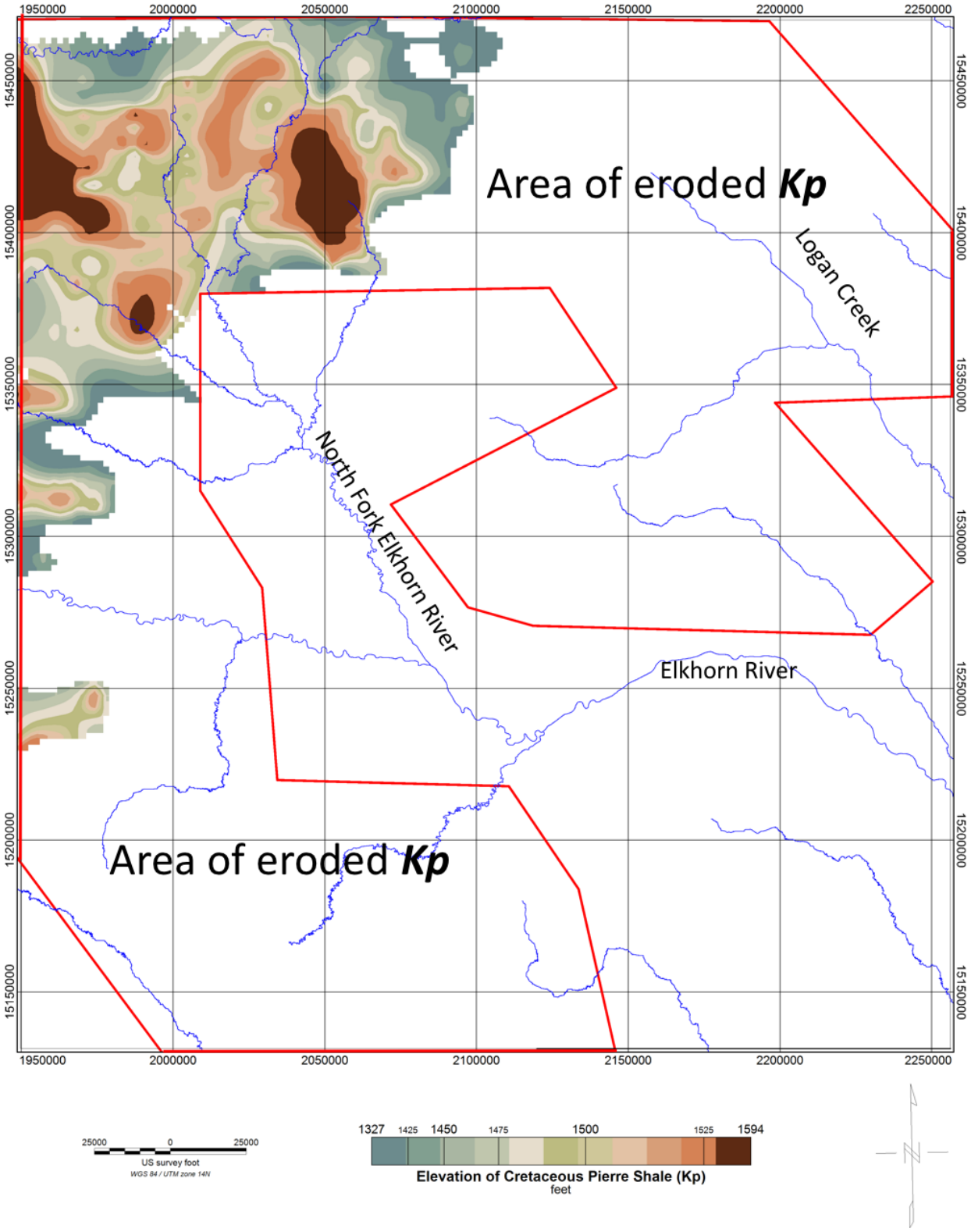


Figure 5-7. Map of the elevation of the top of the Cretaceous Pierre Shale (*Kp*) within the LENRD AEM survey area (red line). Major streams are indicated for reference. The projection is NAD83 UTM Zone 14 North and the elevation values are referenced to NAVD 88.

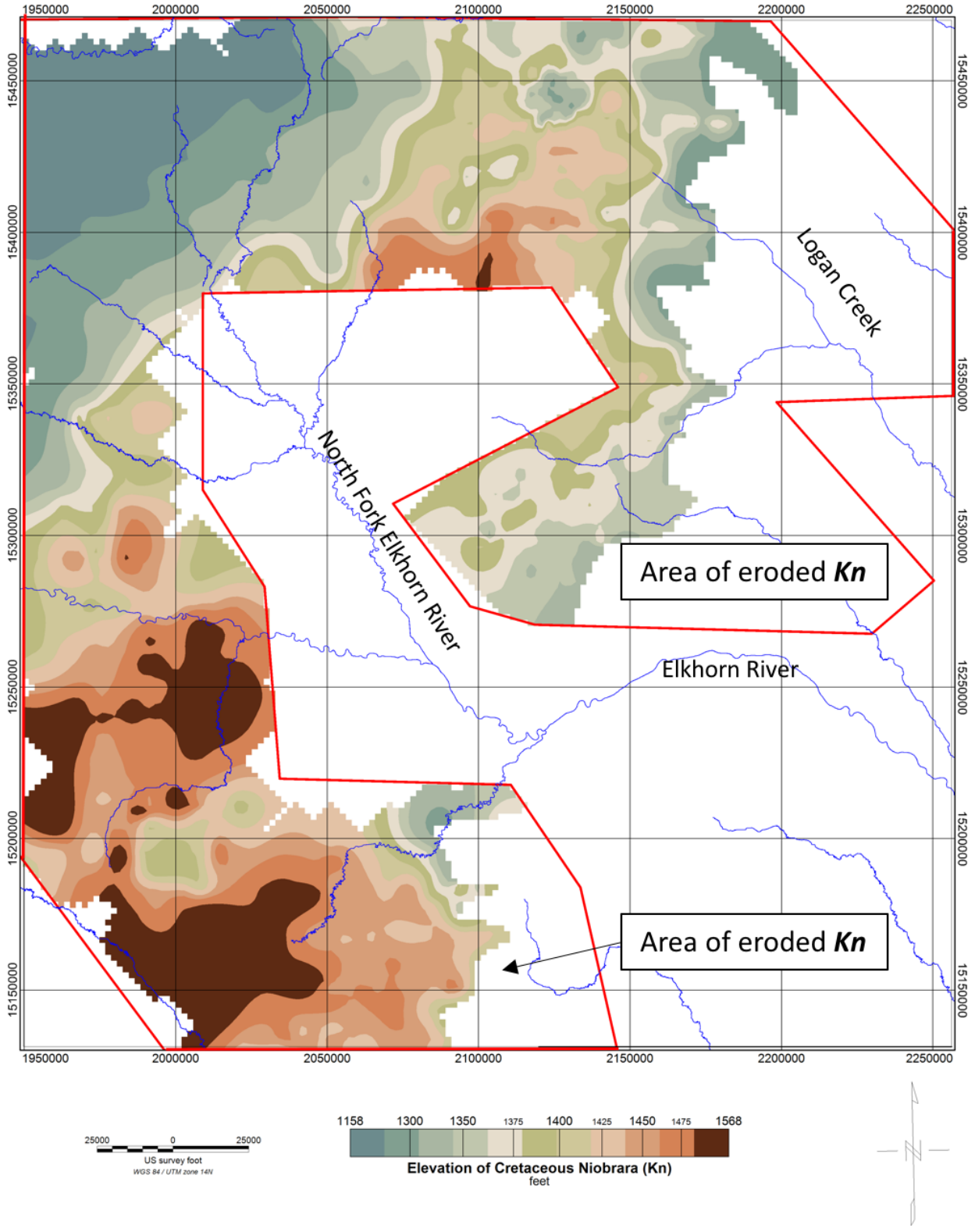


Figure 5-8. Map of the elevation of the top of the Cretaceous Niobrara (*Kn*) within the LENRD AEM survey area (red line). Major streams are indicated for reference. The projection is NAD83 UTM Zone 14 North and the elevation values are referenced to NAVD 88.

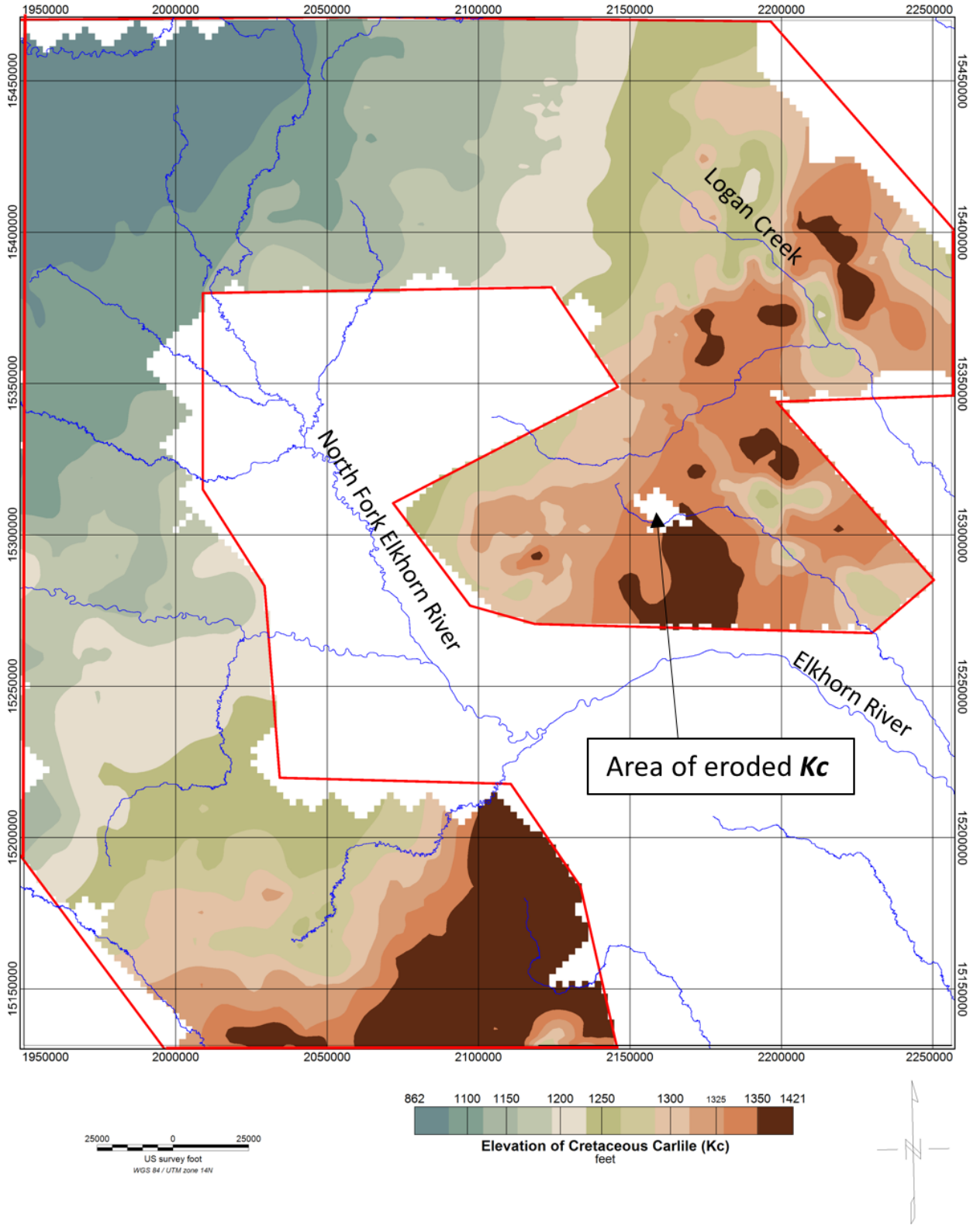


Figure 5-9. Map of the elevation of the top of the Cretaceous Carlile Shale (*Kc*) within the LENRD AEM survey area (red line). Major streams are indicated for reference. The projection is NAD83 UTM Zone 14 North and the elevation values are referenced to NAVD 88.

For the ***Kgg*** top surface 570 AEM picks were used in the grid with a cell size of approximately 3,201 feet and the "*cells to extend beyond*" set to 10. All other parameters were either left as the default or blank. The large extended area was required to fill in between the broadly spaced reconnaissance lines, where three miles or more separated adjacent flight lines. The grid was then clipped to the LENRD AEM survey area. In the western portion of the LENRD AEM survey area, the ***Kgg*** was below the DOI and no data were included in the gridding. On the margins of the survey area some areas are blank due to lack of data. Figure 5-10 is a map of the elevation of the top of the ***Kgg*** within the LENRD survey area.

For the ***Kd*** top surface 311 AEM picks were used in the grid with a cell size of approximately 4,376 feet and the "*cells to extend beyond*" set to 10. All other parameters were either left as the default or blank. The large extended area was required to fill in between the broadly spaced reconnaissance lines, where three miles or more separated adjacent flight lines. The grid was then clipped to the LENRD AEM survey area. In the western portion of the LENRD survey area the ***Kd*** was below the DOI and no data were included in the gridding. On the margins of the survey area some areas are blank due to a lack of data. Figure 5-11 is a map of the elevation of the top of the ***Kgg*** within the LENRD AEM survey area.

The Cretaceous bedrock or the base of the Quaternary (***Q***) and Tertiary Ogallala (***To***) aquifer throughout the LENRD is a combination of the ***Kp, Kn, Kc***, and ***Kgg*** surfaces. The ***Kp*** is eroded away over much of the LENRD AEM survey area (Figure 5-7). The ***Kn*** is the bedrock unit (Figure 5-8) and the ***Kn*** surface represents the base of aquifer. As indicated in Carney et al. (2015c), the ***Kn*** can be a local aquifer when fractured and the fractures have connection to surface water sources. However, in this region it is assumed that the ***Kn*** is a non-aquifer and thus the base of the aquifer system in the area. Over the eastern sections of the LENRD AEM survey area, the ***Kc*** is the bedrock unit (Figure 5-9).

There is one exception with a small window to the ***Kgg*** (Figure 5-10).

To construct the top of bedrock or the base of the aquifer system, the four surfaces were combined into one surface at a 1,000 ft cell size. The grid was then re-gridded at a 100 ft grid cell size and checked against the DEM to verify no locations were above the DEM. The Cretaceous bedrock grid was then clipped to the LENRD AEM survey area (Figure 5-12).

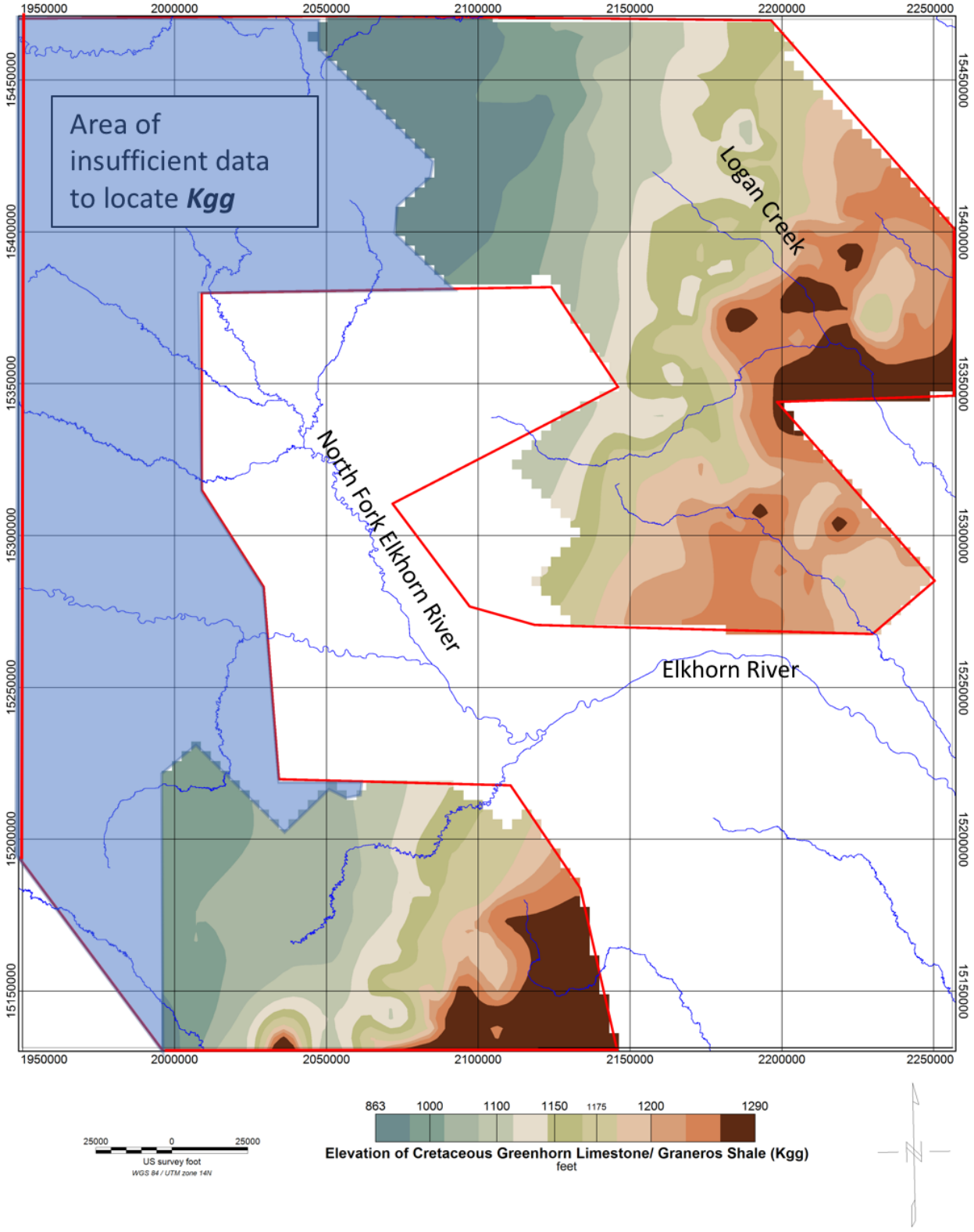


Figure 5-10. Map of the elevation of the top of the Cretaceous Greenhorn Limestone and Graneros Shale (*Kgg*) within the LENRD survey area (red line). Major streams are indicated for reference. The projection is NAD83 UTM Zone 14 North and the elevation values are referenced to NAVD 88.

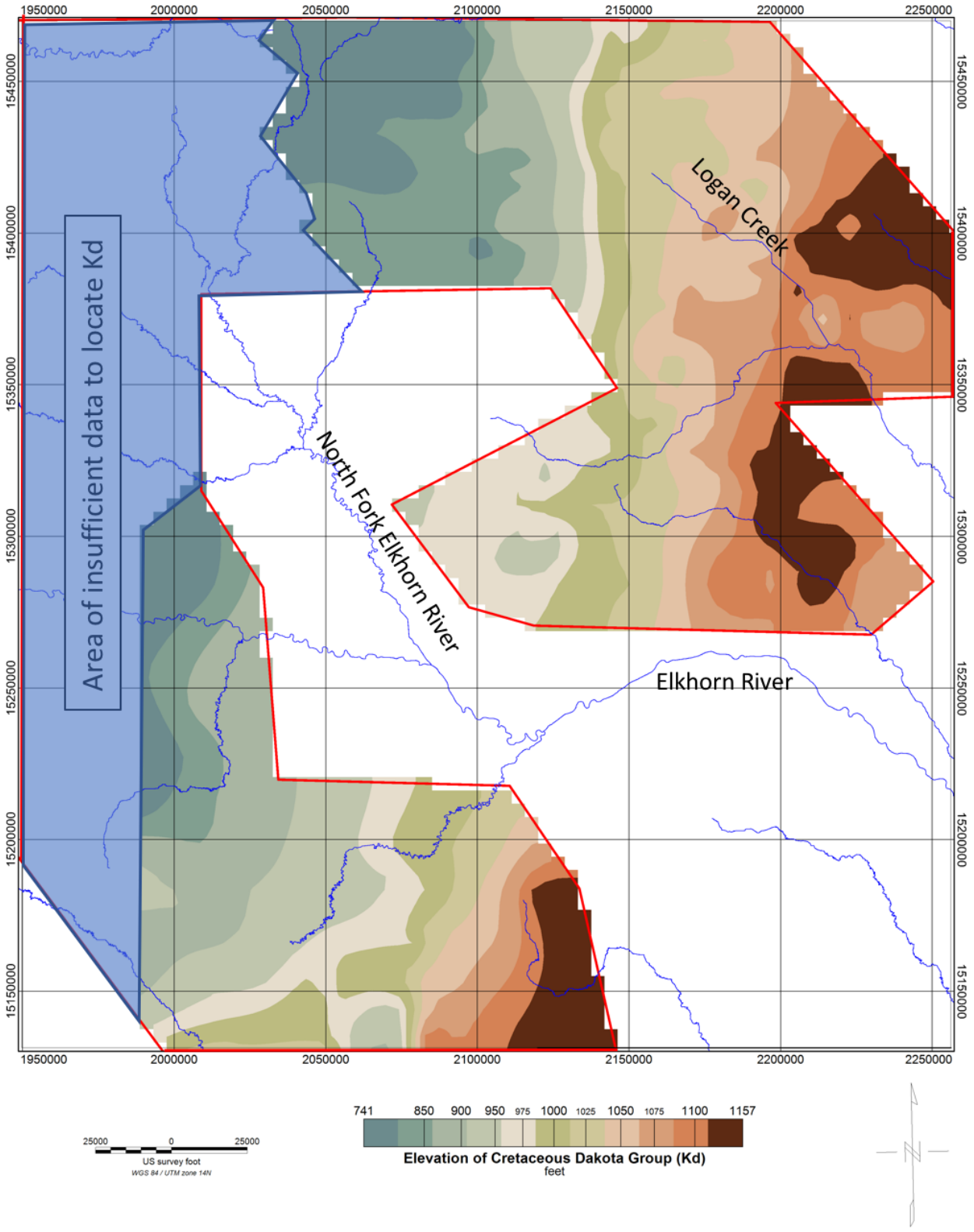


Figure 5-11. Map of the elevation of the top of the Cretaceous Dakota Group (*Kd*) within the LENRD survey area (red line). Major streams are indicated for reference. The projection is NAD83 UTM Zone 14 North and the elevation values are referenced to NAVD 88.

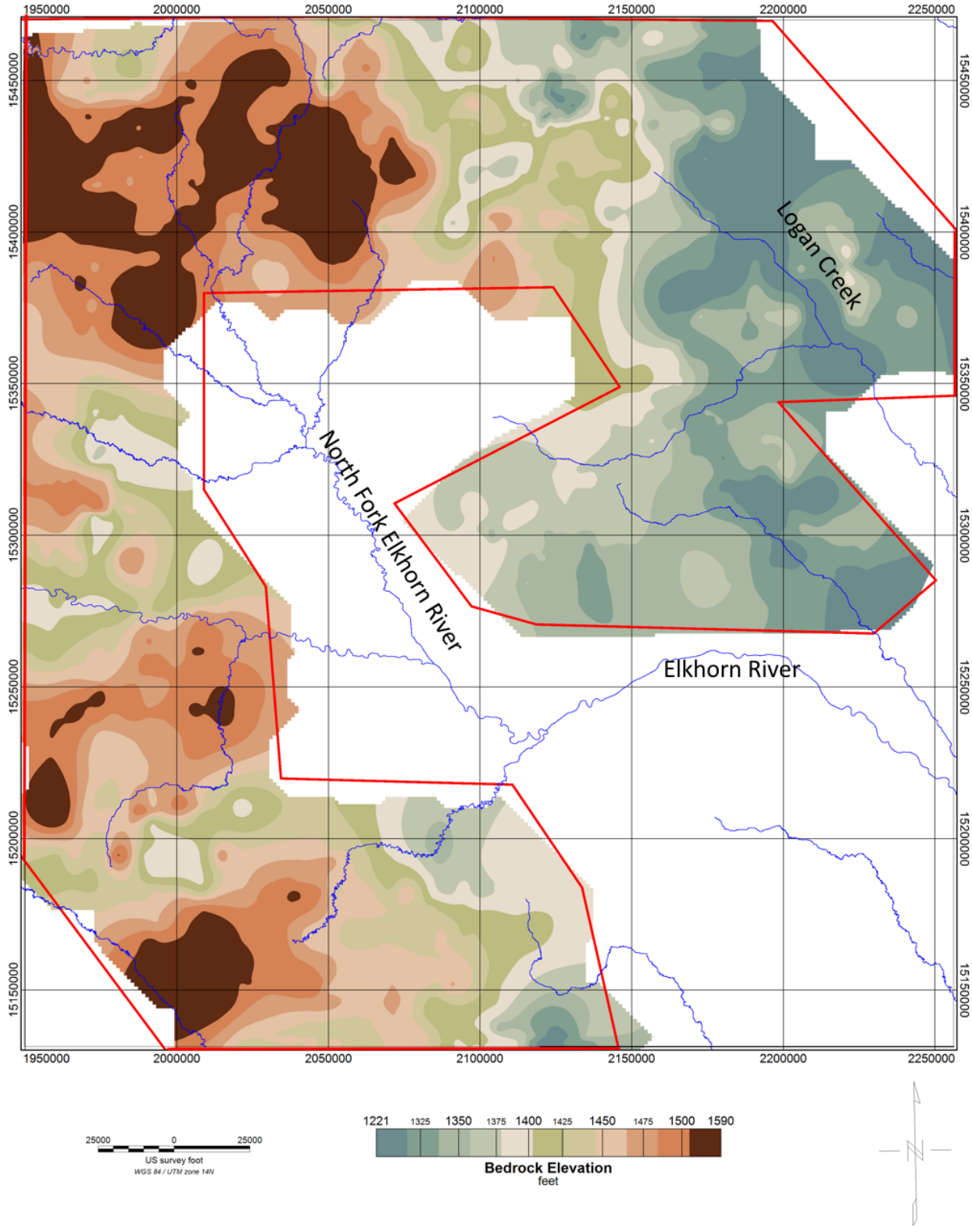


Figure 5-12. Map of the elevation of the top of the Cretaceous bedrock within the LENRD survey area (red line). Major streams are indicated for reference. The projection is NAD83 UTM Zone 14 North and the elevation values are referenced to NAVD 88.

Following construction of the Cretaceous bedrock surface, the consolidated and unconsolidated ***Q***/***To*** deposits were isolated within the AEM data. The aquifer and non-aquifer materials in the Quaternary and Tertiary system were separated by four major resistivity thresholds. These ranges include less than 12 ohm-m, representing non-aquifer materials ("aquitard"- primarily glacial till, loess), 12-20 ohm-m, representing marginal aquifer deposits with the potential for interlayered silt and clay, 20-50 ohm-m, indicating the Quaternary/Tertiary system's aquifer, and an interval of 50 ohm-m or greater, indicating the coarsest, sand-rich intervals within the aquifer (further discussion regarding the selection of these threshold ranges is provided in the following section regarding the selection of these threshold ranges and in Carney et al. (2015c)). Results of these interpretations can be found in Appendix_1-2D_Profiles.

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 mapped into the cross-sections. It should be noted that this inclusion provides only a generalized characterization of the saturated thickness of the aquifer as the CSD's dataset is two decades old at the time of the 2016 LENRD AEM survey and local conditions likely deviate in areas with variable topography. The water table in the LENRD area is close to the surface in some of the areas. To this end a topographic correction was required to adjust the water table height to be below the surface topography. The original water table contour lines were gridded at a 1,000 ft cell size using the OM MCG and a blanking distance of 5,000 ft. The cells were set "*to extend beyond*" to 50. The resulting grid was then re-gridded at a 100 ft cell size and compared with the DEM of the LENRD 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 LENRD AEM survey area. The result is presented in Figure 5-13.

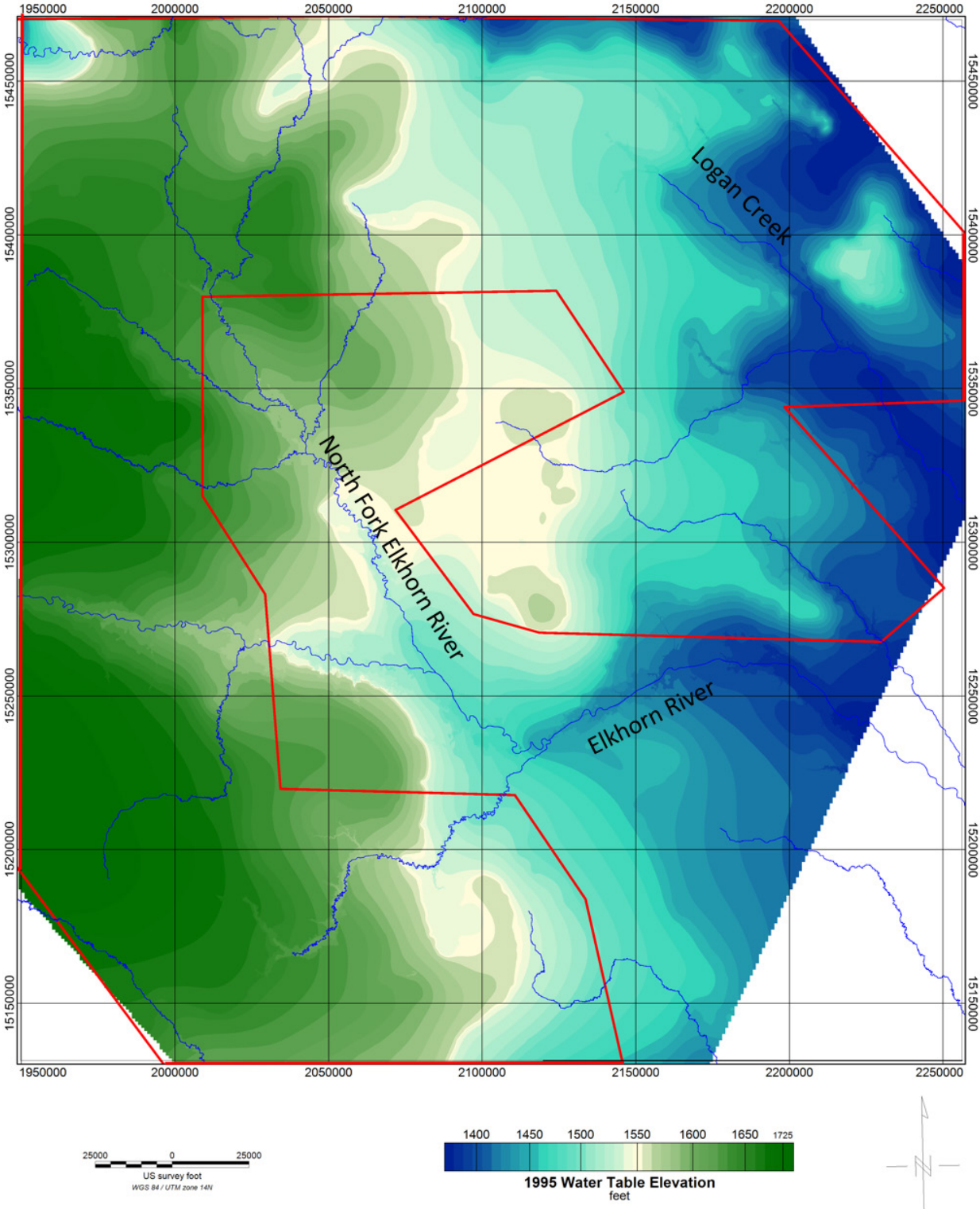


Figure 5-13. Map of the elevation of the 1995 CSD water table (NE CSD, 1995) within the LENRD AEM survey area (red line). Major streams are indicated for reference. The projection is NAD83 UTM Zone 14 North and the elevation values are referenced to NAVD 88.

5.2 Resistivity-Lithology Relationship

5.2.1 Quaternary/Tertiary Ogallala 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. Regarding the LENRD AEM survey, assessment of the sediment character in both the Quaternary/Tertiary Ogallala 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 the ENWRA project area (Carney et al., 2015c). The original analysis that was completed as part of Carney et al. (2015c) included the overall area of the LENRD. This analysis has been used in the current report for the categorization of the Quaternary/Tertiary Ogallala aquifer system.

Data for this analysis was utilized from locations across the ENWRA reconnaissance line area (Carney et al., 2015c). 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. (2015c). A summary of the resistivities and the color scale is shown in Figure 5-14.

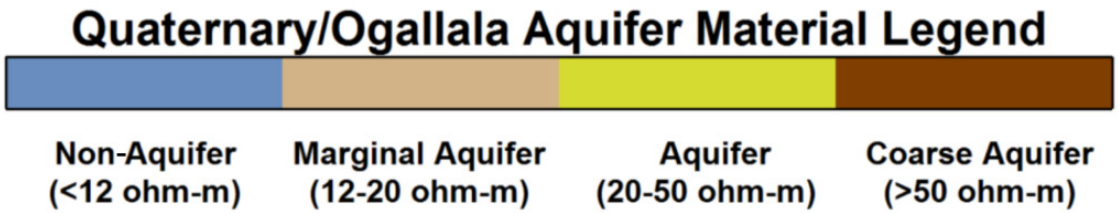


Figure 5-14. Plot displaying the resistivities by major aquifer material color categories (blue- non-aquifer material, tan- marginal aquifer, yellow- aquifer, brown- sand-rich, coarse intervals of the aquifer material).

5.2.2 Bedrock Resistivity Thresholds

The bedrock in the LENRD 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 LENRD. 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 ***Kc*** and the ***Kgg*** lumped together, and the ***Kd*** 35 ohm-m (Carney et al., 2015c). For the ENWRA study the ***Kc*** and the ***Kgg*** were interpreted together. In the present study, 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. The ***Kgg*** showed a more resistive character, on the order of 15 ohm-m. The ***Kd*** within the LENRD displayed some low resistivities on the order of 9 to 13 ohm-m indicating either clay/shale dominant lithology or the presence of saline waters, mostly in the western portions of the LENRD.

5.2.3 Comparison of AEM Inversion Resistivity to Borehole Geophysical Resistivity Logs

Three CSD borehole geophysical resistivity logs were selected from the LENRD AEM survey area for comparison with the AEM inversions: Test holes *5-GT-80*, *05-LE-13*, and *01-LE-15*. Since the resistivity logs within the CSD database are of various vintages and conducted by various staff with differing equipment, a critical examination of the absolute values of the resistivity needs to include an awareness of errors in calibration and in the proper operation of the equipment. There is a long-standing issue with using geophysical logs as ground truth when comparing to AEM inversions that are well calibrated using modern techniques. Throughout much of the geophysical logging at the time it was acquired, the relative deflections of the resistivity measurements were all that was required or expected from a geophysical log. Operators were seldom trained in the proper operation of a calibrated sonde or in the ability to recognize high contact resistance of a cable head. This has led to many geophysical logs that are uncalibrated within the CSD database. Note that these logs still have scientific merit in their ability to relatively indicate an increase or a decrease in the formation resistivity. The logs used herein are for qualitative comparison to the AEM because detailed calibration and corrections would need to be carried out for the resistivity values in the logs to be directly used as numerical constraints in the inversion of the AEM data (Ley-Copper and Davis, 2010).

Figure 5-15 is a plot of *5-GT-80* 16-inch short normal resistivity log plotted with the inverted AEM resistivity for line L123501. *5-GT-80* is located 1,676 feet from line L123501 and the AEM sounding is selected from the closest point to the borehole geophysical log. The agreement in the resistivity is not great with the AEM indicating a much lower resistivity. The shape of the curves show a shift in the general location of the relatively resistive body. The AEM is indicating the aquifer material higher in the section then the geophysical log and the lithology log. This would indicate that the lithology has changed over the distance of the borehole compared with the AEM. The AEM and *5-GT-80* both indicate the lower resistivity of the ***Kc*** but the decrease in the AEM is higher than *5-GT-80* indicates. Overall, the log and the AEM show that there is a change in the position of the Quaternary Aquifer material within the distance of 1,676 feet and the depth of the ***Kc*** is higher at the AEM sounding location.

Figure 5-16 is a plot of 05-LE-13 16-inch normal resistivity log plotted with the inverted AEM resistivity for line L123301. 05-LE-13 is located 239 feet from line L123301 and the AEM sounding is selected from the closest point to the borehole geophysical log. The agreement in the resistivity is relatively good with the AEM for the overall average resistivity. However, the AEM doesn't indicate the sands in the lower portions of the log from ~125 feet to 180 ft. The AEM is indicating a slight increase in the average resistivity that would translate into a marginal aquifer material type. The fact that the sand layers in 05-LE-13 are separated by a silt layer is causing the average resistivity to decrease at those depths within the AEM response. This is a good example of the averaging impact that the AEM has at depth regarding thin layers. The AEM also fails to indicate the thin layer of sand at ~ 50 feet. The AEM does indicate that the overall section is very conductive. The CSD log did not indicate that the shale at the bottom of the log was ***Kn***, but from the in interpretation of the AEM it is interpreted as being the ***Kn***.

Figure 5-17 is a plot of *01-LE-15 16*-inch short normal resistivity log plotted with the inverted AEM resistivity for line L149001. *01-LE-15* is located 3,338 feet from line L149001 and the AEM sounding is selected from the closest point to the borehole geophysical log. The agreement in the resistivity is relatively good with the AEM for resistivity for the distance between the two points. The AEM shows a lower average resistivity for the sand and gravel layers but in relatively the same upper depth. The AEM also shows the body is deeper than the log from *01-LE-15*. This may simply be due to the distance between the points and changes in the depositional conditions and variability within the sand and gravel layers. The important point in this comparison is that the AEM indicates the location of the aquifer materials as indicated by *01-LE-15*. Another curious issue with the resistivity log from *01-LE-15* is the sharp decrease in the resistivity at the bottom indicating a shale or clay material. The lithology log indicates a sand. The interpretation of Line L149001 indicates that the ***Kp*** is the bedrock unit in the area and would correspond to the low resistivity at the bottom of *01-LE-15*.

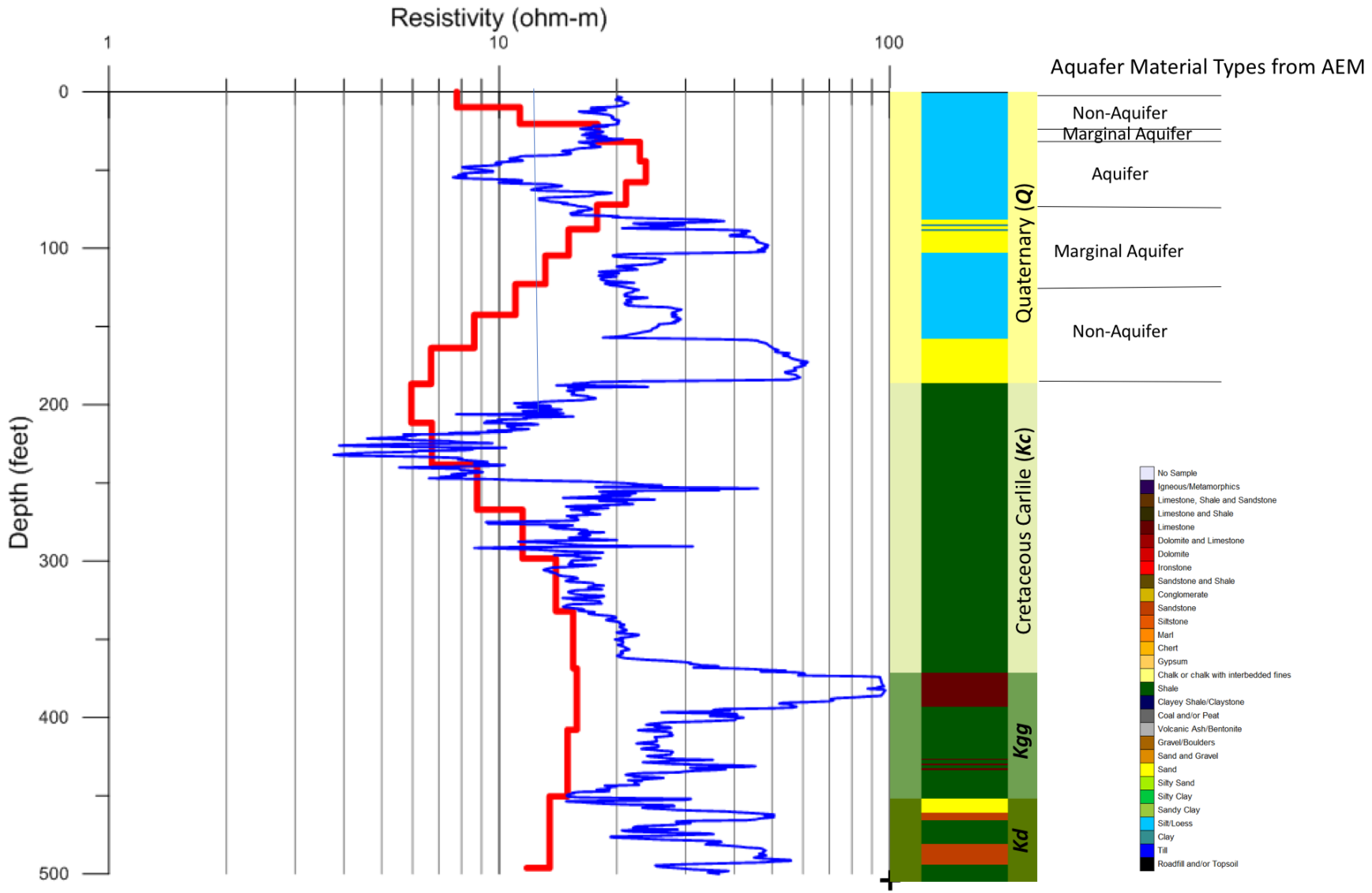


Figure 5-15. Graph of the *5-GT-80* 16-inch normal resistivity log values (blue line) and the inverted airborne electromagnetic resistivity values (red line). Also indicated is the lithology and stratigraphy log from *5-GT-80* as well as the aquifer material categories from the AEM inversion.

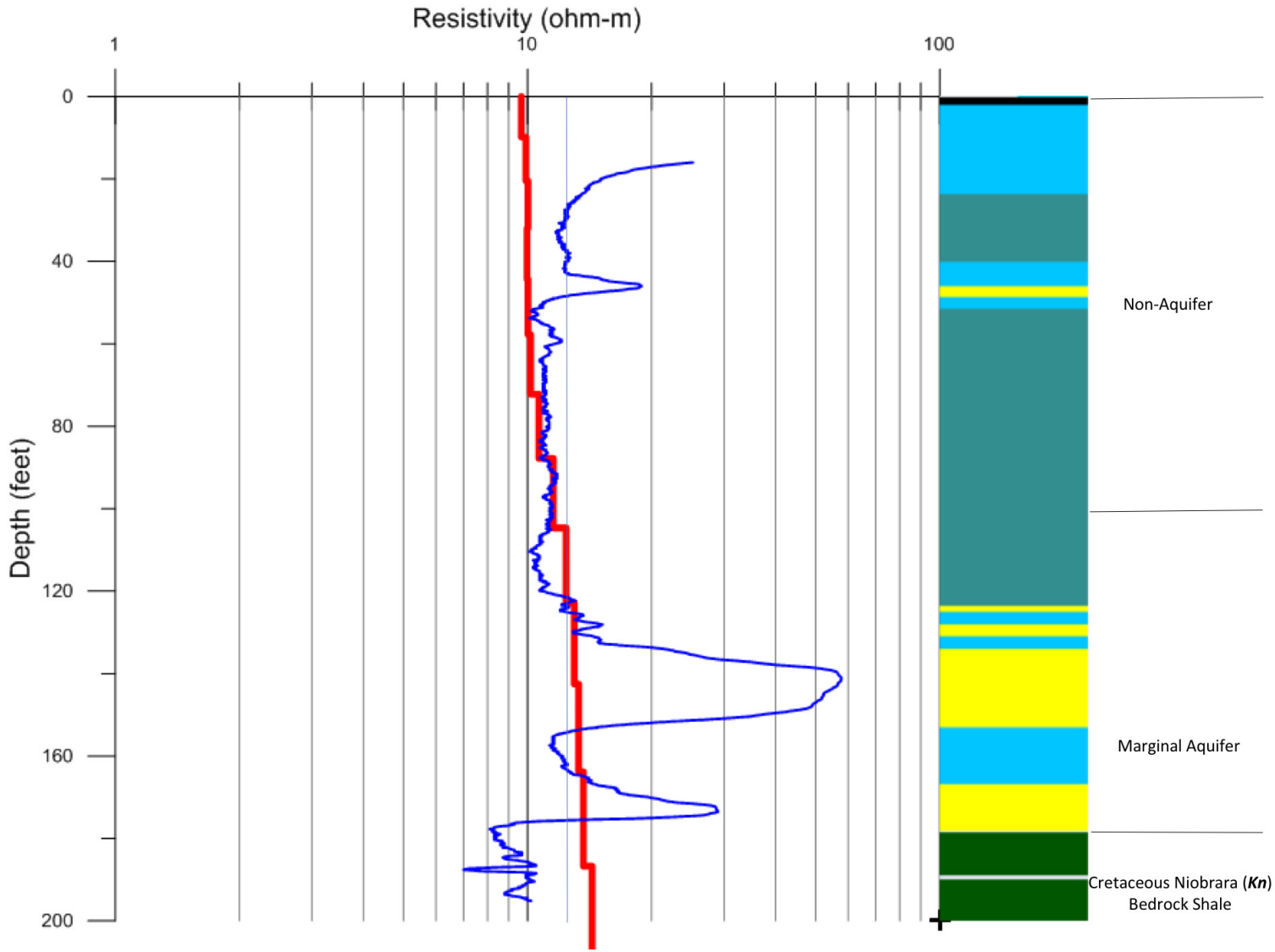


Figure 5-16. Graph of the *05-LE-13* 16-inch normal resistivity log values (blue line) and the inverted airborne electromagnetic resistivity values (red line). Also indicated is the lithology log from *05-LE-13* as well as the aquifer material categories from the AEM inversion and interpreted bedrock.

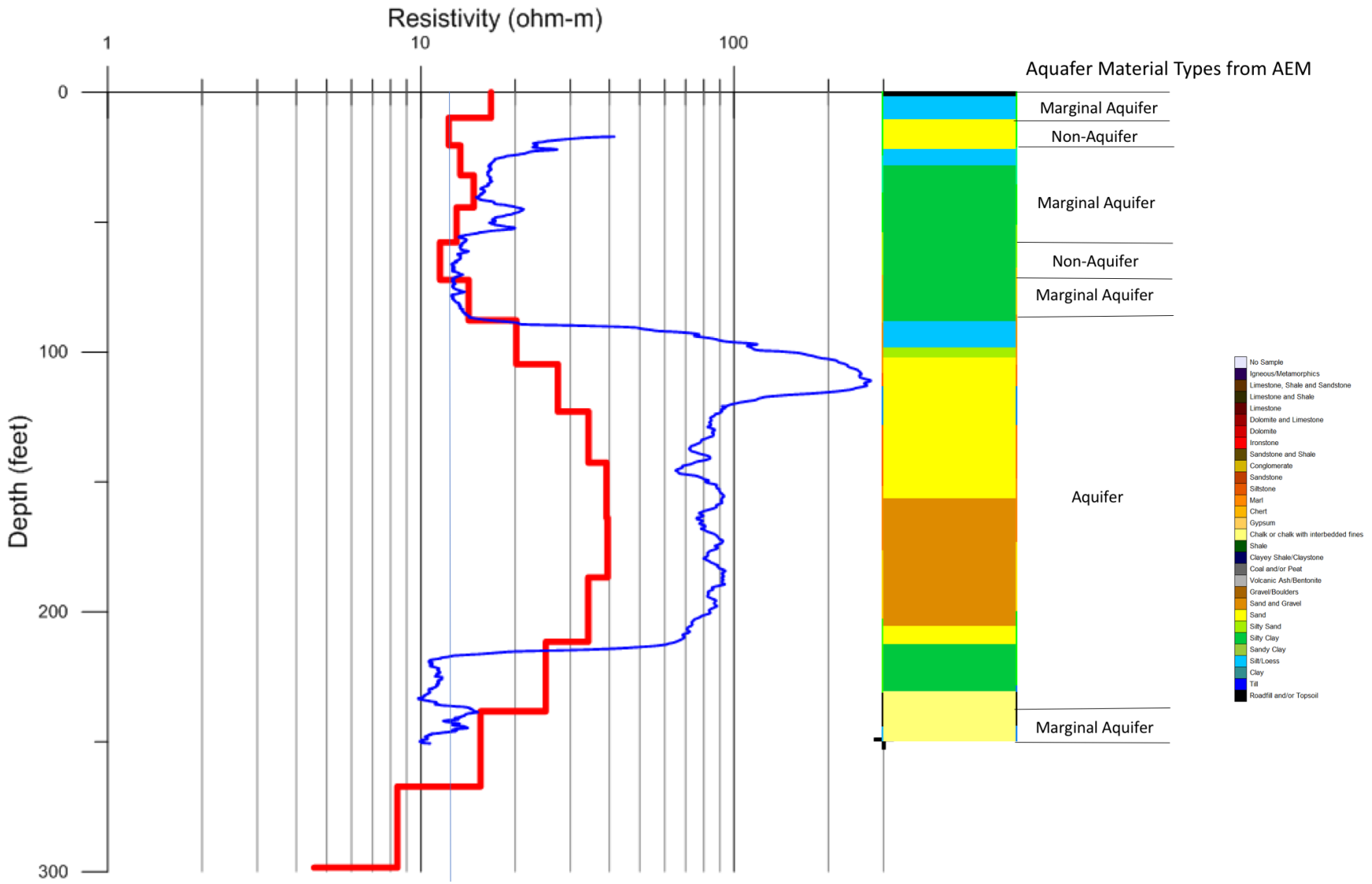


Figure 5-17. Graph of the *01-LE-15* 16-inch normal resistivity log values (blue line) and the inverted airborne electromagnetic resistivity values (red line). Also indicated is the lithology log from *01-LE-15* as well as the aquifer material categories from the AEM inversion.

5.3 Hydrogeological Framework of the LENRD AEM Survey Area

The 2016 survey continues and builds upon the previous AEM survey efforts over the recent past described in Section 1.2 of this report. These results provide new information on the hydrogeology in areas that was previously unknown to the LENRD or was only known to a limited extent with just the borehole information. The survey completed in 2014 by Carney et al. (2015c) provides a basis for this section of the report. The following highlights the additions to the continuing multi-year project being conducted by the LENRD that is outlined in Section 1.

The 2016 AEM survey reveals variability in the Quaternary (***Q***) deposits across the LENRD AEM survey area. When combined with the ***To***, they represent the aquifer materials in the AEM survey area, where saturated. The ***To*** is generally thick in the west and is thin to absent in the eastern regions of the AEM survey area. The ***Q*** and ***To*** make up the aquifer materials overlying the Cretaceous bedrock units. Figure 5-18, looking north, and Figure 5-19, looking west, display in 3D the overall distribution of ***Q*** and ***To*** materials across the LENRD AEM survey area. The subsurface distribution of ***Q*** materials can be generally characterized into two somewhat overlapping, but distinct, areas distributed over various locations within the AEM survey area. These areas are glacial till material that identifies as marginal aquifer and non-aquifer deposits mostly on the east side of the survey area and ***Q*** sediments found predominately on the west side often associated with prevalent alluvial deposits. A mix of both can be seen along the Elkhorn River to the south of the survey area and along the northern area of the survey boundary. The ***Kp***, ***Kn***, **Kc**, **Kgg**, and ***Kd*** bedrock units displayed in 3D are presented in Figure 5-20. A profile of flight line L609310 shows all the different geologic units in the survey area, ***Q***, ***To***, ***Kp***, ***Kn***, ***Kc***, ***Kgg***, and ***Kd*** (Figure 5-21). The youngest Cretaceous units are in the west and the oldest are in the east. ***To*** is in the west and the pinches out to the east with ***Q*** sediments covering all units.

5.3.1 The Quaternary and Tertiary Aquifer

The ***Q*** and ***To*** aquifer of the LENRD AEM survey area is predominantly composed of unconsolidated aquifer (yellow color in figures) and coarse aquifer (brown color in figures) materials composed of alluvial sediments in the western and northern parts of the AEM survey area. In the eastern and southern parts of the AEM survey area, the aquifer materials are predominantly marginal to non-aquifer materials which are glacial till and loess and which can be more than 200 feet thick. The ***Q*** and ***To*** (where present) materials are sitting on the ***Kp***, ***Kn***, ***Kc***, and ***Kgg*** which are the bedrock aquicludes for the area. The maps showing the elevations of the combined tops of the ***Kp***, ***Kn***, ***Kc***, and ***Kgg*** can be found in Figure 5-22. A detailed description of the bedrock units is given in Section 2.1.4. The thickness of the ***Q*** and ***To*** materials within the LENRD AEM survey area range from 25 to >500 feet thick (Figure 5-23). The thickness of the ***Q*** *and* ***To*** materials increase toward the west near the channel along the western border. The ***Q*** and ***To*** alluvial system can be very heterogeneous in places with a changing mix of all aquifer materials. When moving from west to east across the survey area, the ***To*** thins and is eroded off or not deposited from the central part of the AEM survey area to the eastern border. Near the western survey boundary to approximately 10-20 miles east, the mix of ***Q*** and ***To*** aquifer and coarse aquifer materials act as the groundwater supply route which is hydrologically connected to the surface water system.

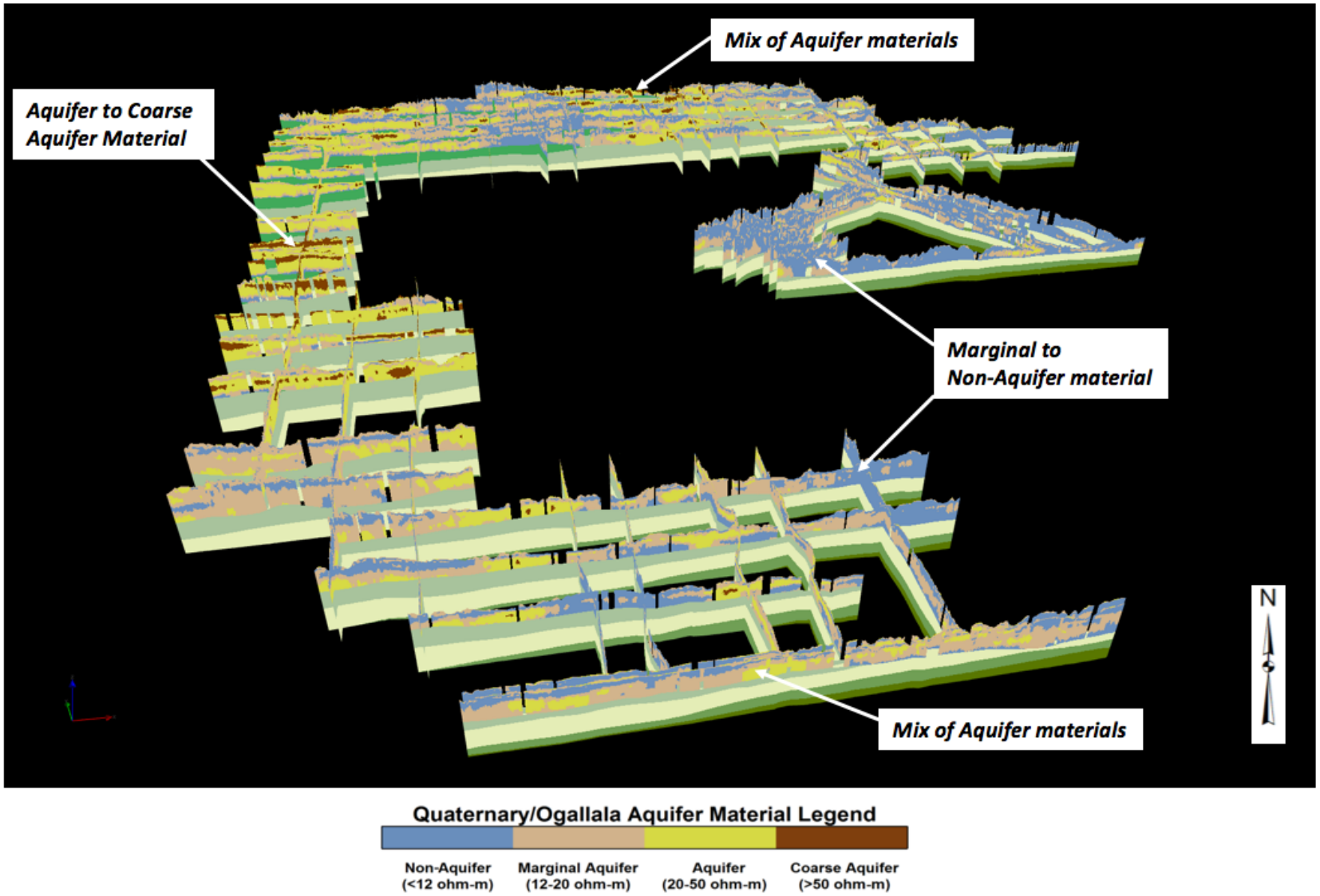


Figure 5-18. 3D map looking to the north of the interpreted distributions of aquifer materials within the survey area. Brown is coarse aquifer, yellow is aquifer, tan is marginal and blue is non-aquifer material. Vertical exaggeration is 20x. The image projection is NAD 83, UTM Zone 14 North.

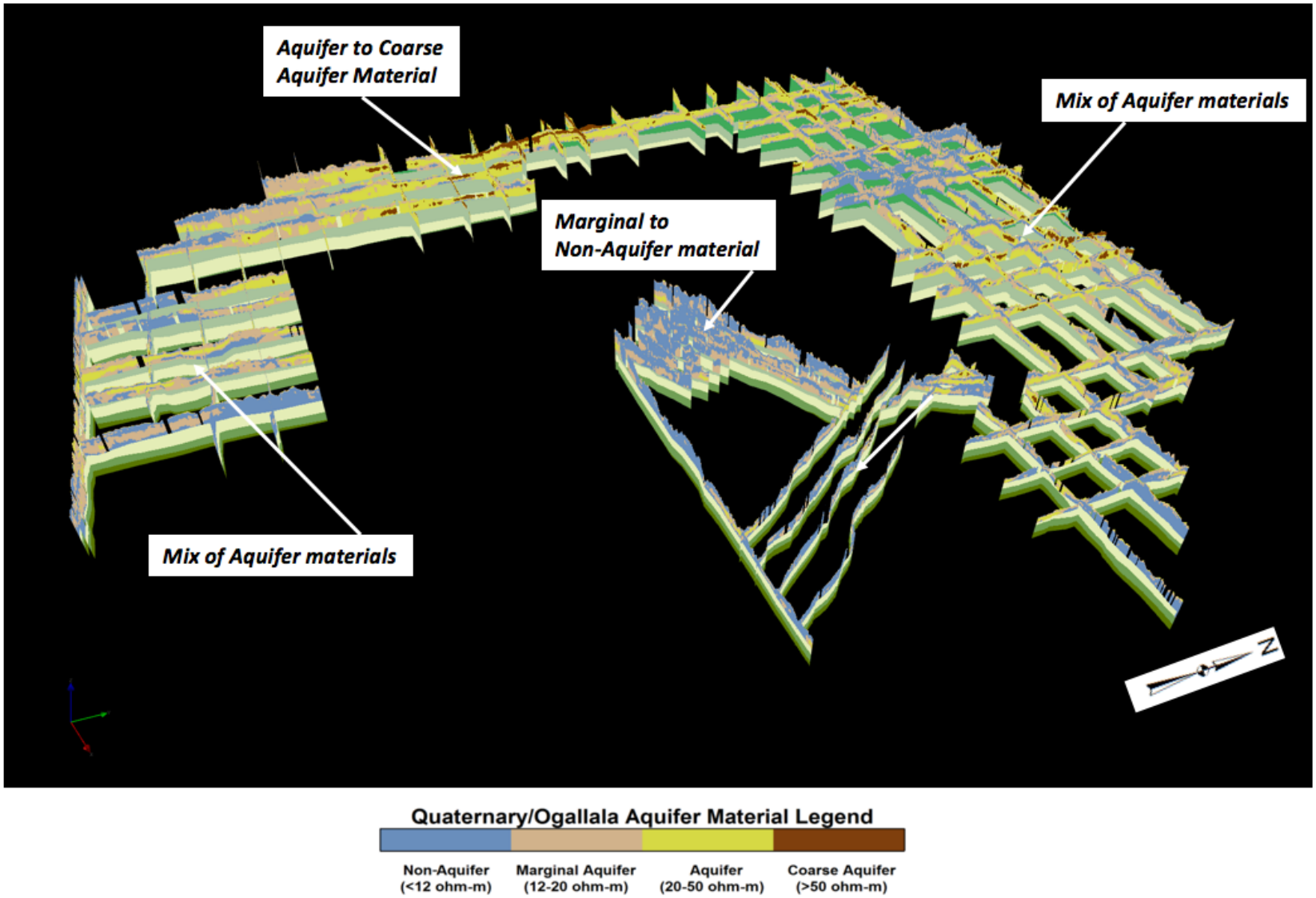


Figure 5-19. 3D map looking to the west of the interpreted distributions of aquifer materials within the survey area. Brown is coarse aquifer, yellow is aquifer, tan is marginal and blue is non-aquifer material. Vertical exaggeration is 20x. The image projection is NAD 83, UTM Zone 14 North.

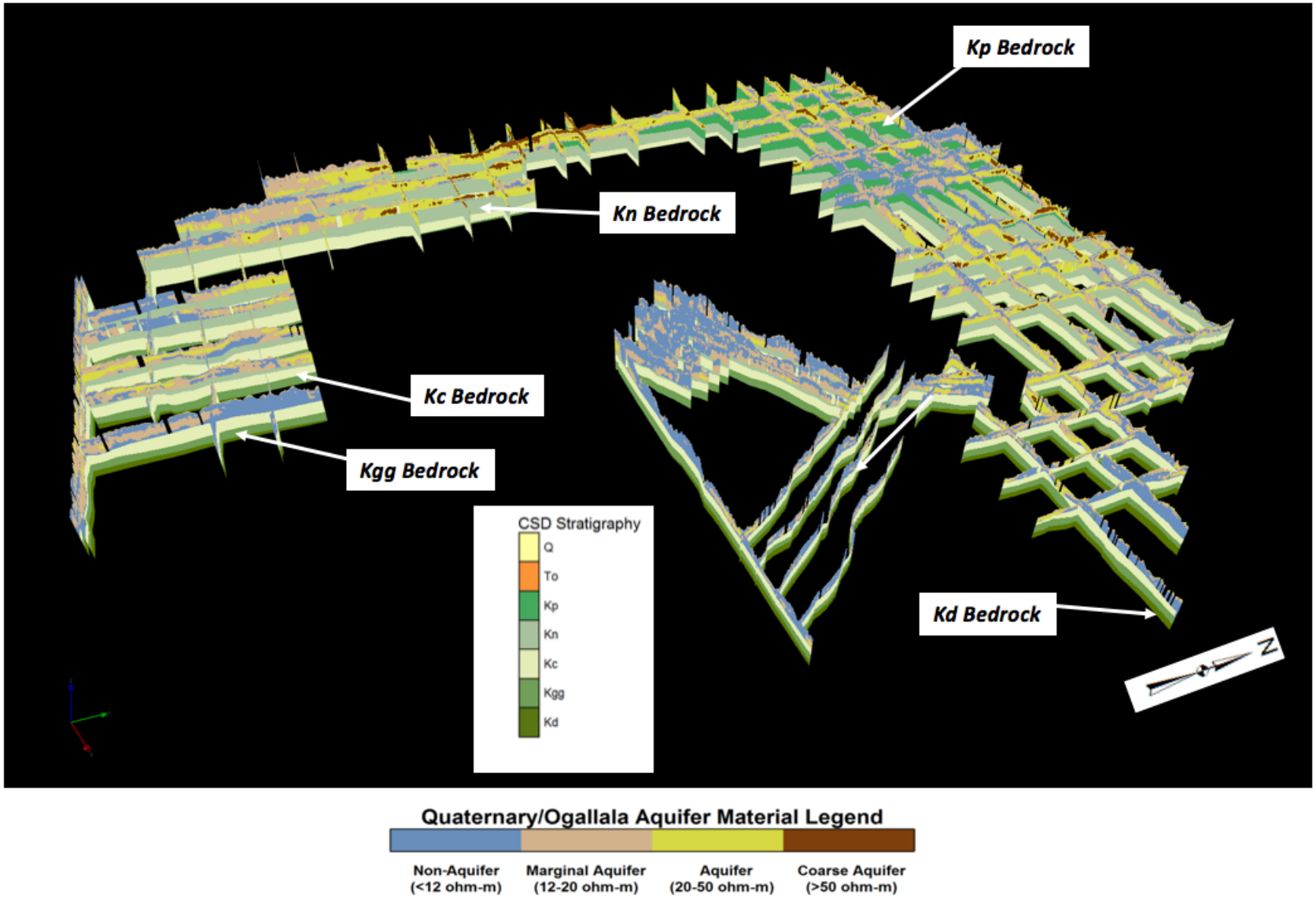


Figure 5-20. 3D map looking to the west of the geologic interpretations of bedrock within the survey area. The bedrock units are from west to east *Kp*, *Kn*, *Kc*, *Kgg* and *Kd*. Vertical exaggeration is 20x. The image projection is NAD 83, UTM Zone 14 North.

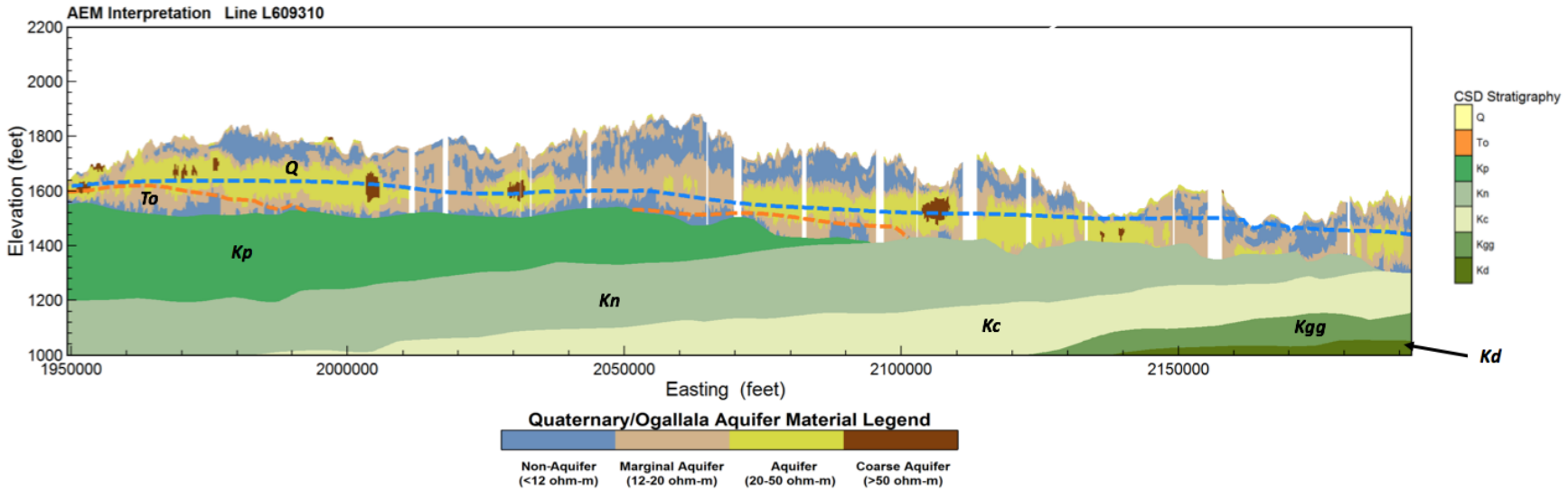


Figure 5-21. Profile view of line L609310 from west-east. All the *Q* and *To* aquifer materials are resting on the bedrock which from west to east are *Kp*, *Kn*, *Kc*, *Kgg* and *Kd*. Note the discontinuous thin nature of the *To*. The image projection is NAD 83, UTM Zone 14 North, feet.

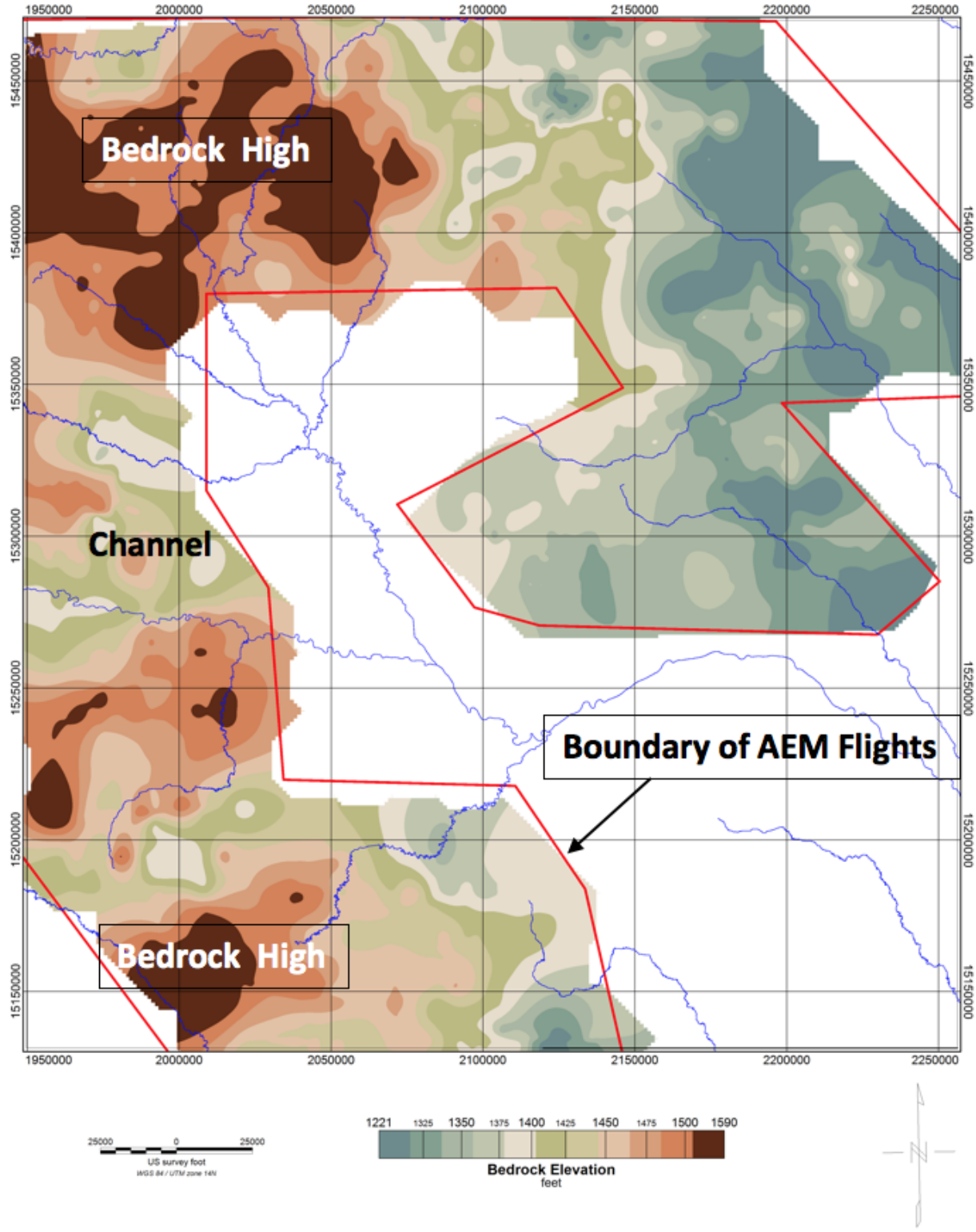


Figure 5-22. 2D map looking to the north of the bedrock elevation within the LENRD survey area (red line). Note the bedrock high to the north and south separated by a channel between them. Elevation is higher to the west and lowest in the east. Vertical exaggeration is 20x. The image projection is NAD 83, UTM Zone 14 North.

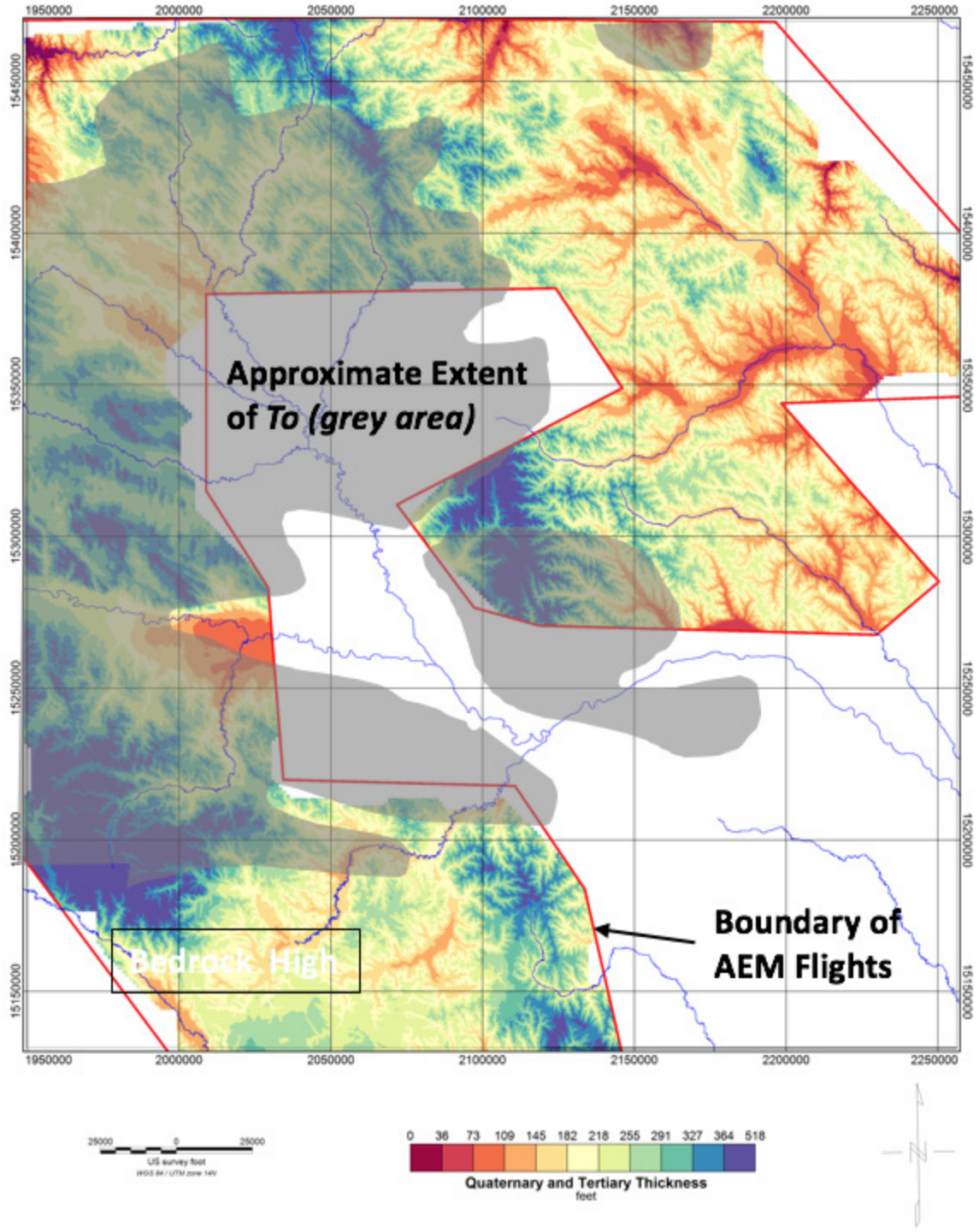


Figure 5-23. 2D map looking to the north of the *Q* and *To* aquifer materials within the LENRD survey area (red line). Note the approximate limit of *To* material in the shaded areas (adapted from Burchett, 1986). The *Q* and *To* thickness is high in the west and center-north and thins in the east. Vertical exaggeration is 20x. The image projection is NAD 83, UTM Zone 14 North.

Accompanying the aquifer and coarse aquifer materials are areas of non-aquifer and marginal aquifer materials. Where the ***To*** does not exist in the survey area, a change in the make up the aquifer materials transitions from mostly aquifer and coarse aquifer material to mostly marginal and non-aquifer materials. The marginal and non-aquifer materials are typically glacial tills and loess located proximally to near-surface loess deposits, basal silts and clays, and continuous layers of fine grained material. These layers can locally act as aquicludes and prevent or inhibit hydrologic connection to a stream, recharge areas, or serve as locally confining units.

Figure 5-24 presents an example of this displayed as a 3D image of several of these layers of marginal (tan color) and non-aquifer (blue color) materials found in the north-central part of the survey area. This is a boundary within the flow system for groundwater flow between the Elkhorn River and its tributaries and the aquifer and coarse aquifers in the eastern side of the survey area. Figure 5-25 presents a profile view of line L294602, a north-south flight line highlighted in Figure 5-24. All aquifer type materials are present along this profile with a majority of the profile indicating the positions of marginal and non-aquifer materials which impact the area hydrologically by blocking or slowing down groundwater movement to and from the surface water features. This profile also indicates the limited potential for water movement from the land surface to the aquifer as recharge. The Quaternary units of the LENRD AEM survey area contain zones of saturated thickness up to 150 ft and, in some places, more.

Figure 5-26 shows a 3D image of aquifers and bedrock aquicludes with the water table elevation downward as the blue shaded zone. Note the shallow nature of the water table near the rivers and streams and the deepest water table in the thick glacial till areas in the north and east parts of the survey area (Figure 5-27). Areas where the sediments are made up of saturated aquifer or coarse aquifer materials will be an area of good groundwater supply.

A disadvantage of the reconnaissance lines is that they have only identified these aquifer and coarse aquifer material deposits along AEM acquisition flight lines and not in between the flight lines due to the distances involved. Thus, the complete extent of these deposits cannot be determining expediently without further AEM acquisition or exhaustive interpretation from added boreholes. Appendix_1-2D_Profiles contains interpreted profiles that illustrate the details of the Quaternary in the LENRD AEM survey area. Appendix_2-3D_Images contains 3D images of the LENRD AEM survey area that have been rotated around to allow viewing of the overall distribution of materials at various angles.

5.3.2 The Cretaceous Bedrock Aquiclude

The Cretaceous bedrock is made up of the ***Kp***, ***Kn***, ***Kc***, ***Kgg*** and ***Kd*** from west to east (Figure 5-20). These units make up a continuous surface beneath the ***Q*** and ***To*** sediments that combine to act as an aquiclude restricting groundwater flow across the boundaries. In the Norfolk area, there is limited amount of fracturing in the ***Kn*** that can provide groundwater to wells (Gutentag et al., 1984; Miller and Appel, 1997). The Cretaceous bedrock has been eroded post deposition and Figure 5-22 shows the bedrock highs to the north and south with a channel in between. Overall, the elevation decreases from west to east.

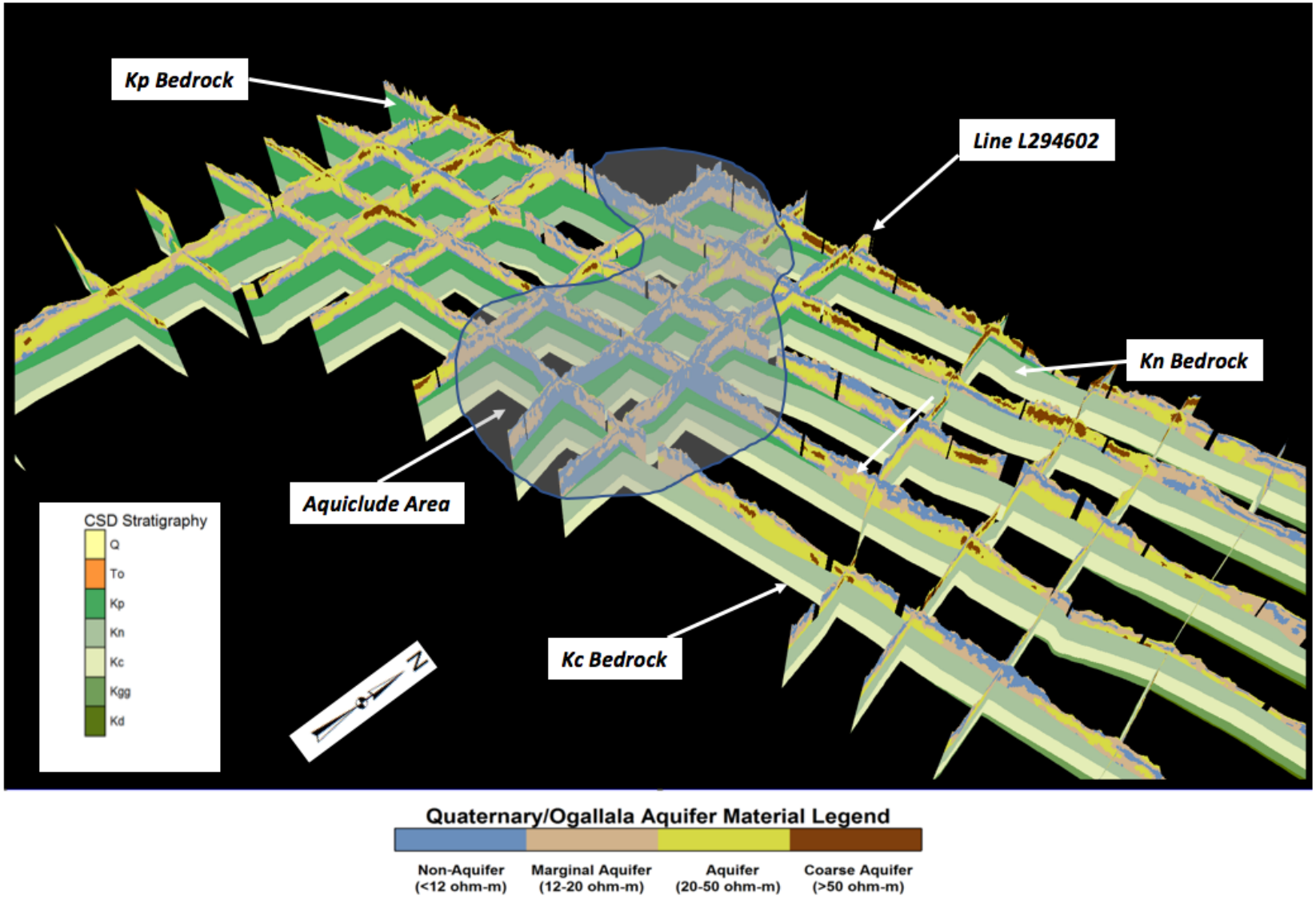


Figure 5-24. 3D map looking to the northwest of the interpreted distributions of aquifer materials within the survey area. Brown is coarse aquifer, yellow is aquifer, tan is marginal, and blue is non-aquifer material. The shaded area is a zone where local non-aquifer and marginal aquifer materials act as boundaries to groundwater flow. Vertical exaggeration is 20x. The image projection is NAD 83, UTM Zone 14 North.

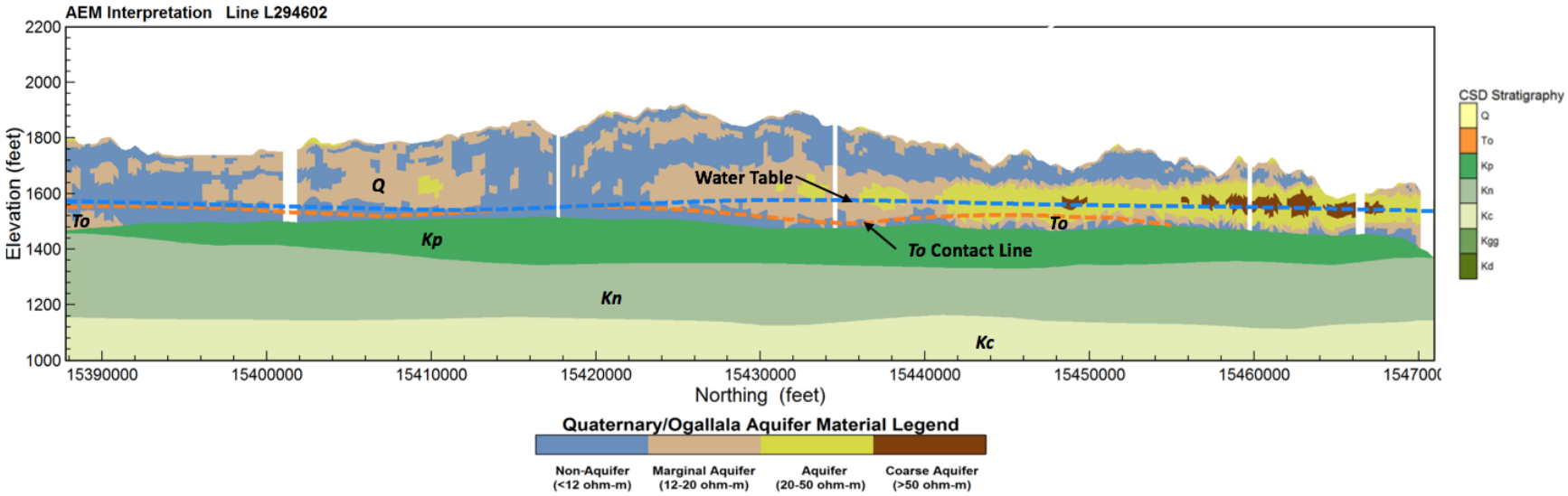


Figure 5-25. Profile view of flight line L294602 from south to north. All the *Q* and *To* aquifer materials are resting on the bedrock, which, from west to east, are *Kp*, *Kn*, *Kc*, *Kgg*, and *Kd*. Note the discontinuous thin nature of the *To*. This profile shows the dominance of non-aquifer and marginal aquifer materials which inhibit groundwater flow and act as a boundary condition. The image projection is NAD 83, UTM Zone 14 North, feet.

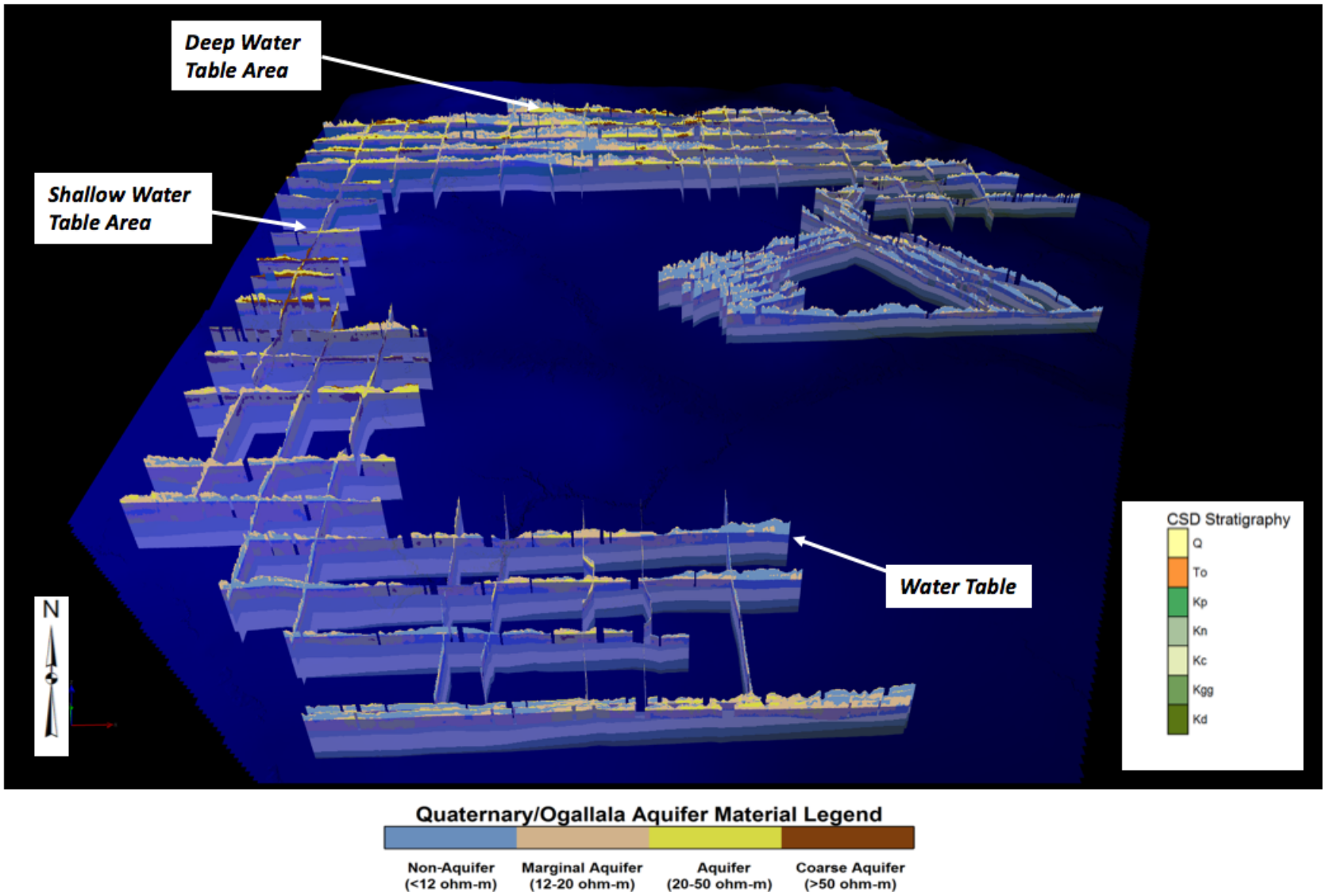


Figure 5-26. 3D map looking to the north of the interpreted distributions of aquifer materials within the survey area. Brown is coarse aquifer, yellow is aquifer, tan is marginal, and blue is non-aquifer material. The shaded area is the water table elevation. Vertical exaggeration is 20x. The image projection is NAD 83, UTM Zone 14 North.

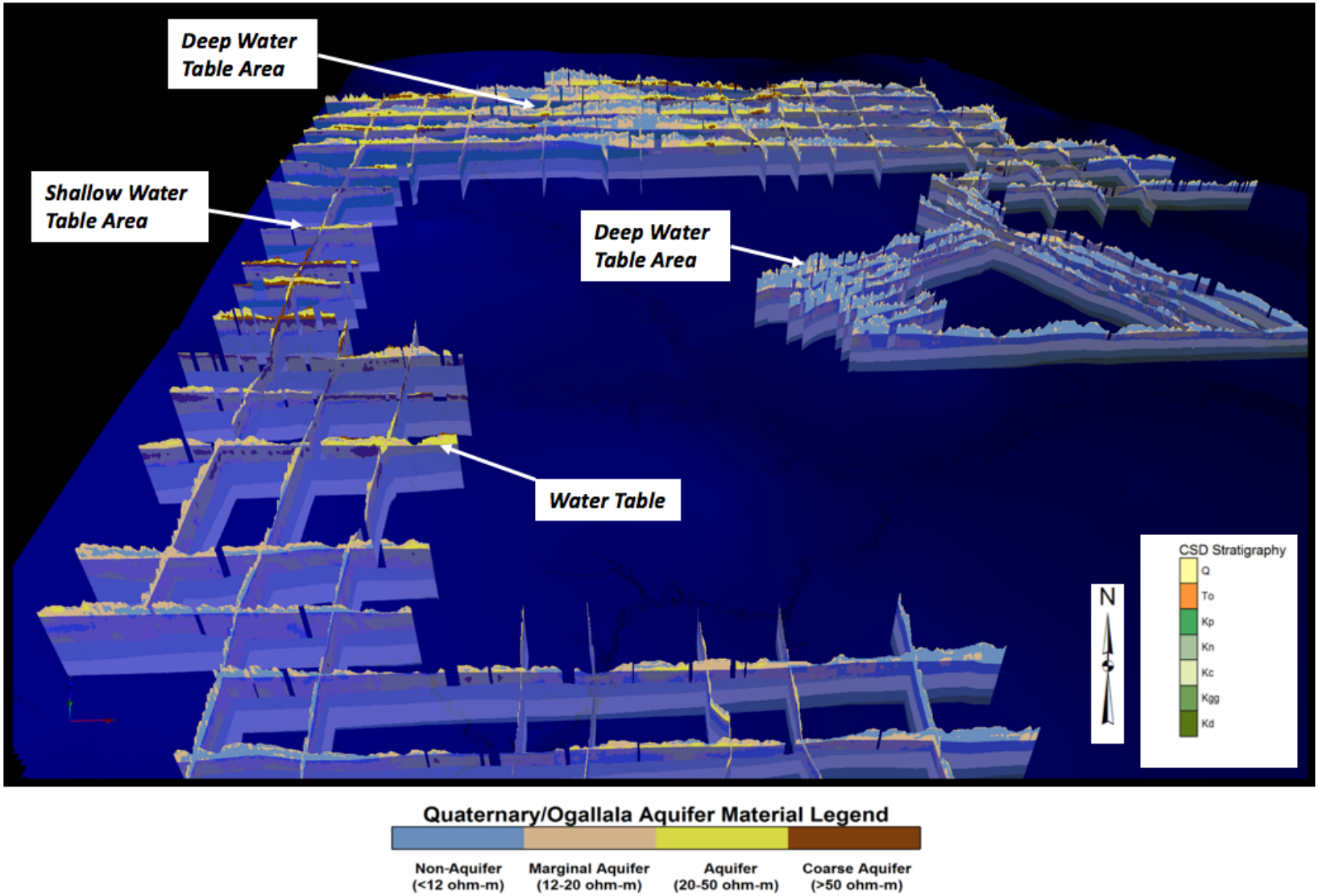


Figure 5-27. This is a close-up view of the 3D map looking to the north of the interpreted distributions of aquifer materials within the AEM survey area. Brown is coarse aquifer, yellow is aquifer, tan is marginal, and blue is non-aquifer material. The shaded area is the water table elevation. Vertical exaggeration is 20x. The image projection is NAD 83, UTM Zone 14 North.

5.4 Recharge Areas within the LENRD AEM Survey Area

3D representations of the subsurface resulting from the AEM method illustrate areas of interpreted aquifer materials from the bedrock up to the land surface. From these maps a new series of near-surface maps, which includes the interval from 0 to10 feet, were constructed. The interval of 0-10 feet is noteworthy because this is the first layer of the inverted AEM earth model. Remember from the discussion of Table 4-4 that each model layer represents an average of the earth's resistivities within the bounds of each layer, based on the physics behind the electromagnetic exploration technique. These first layer maps show all aquifer materials including non-aquifer material, marginal aquifer material, aquifer material, and coarse aquifer material. These maps indicate the areas at the land surface that can potentially transmit water to the groundwater aquifers in the area. The coarse aquifer material transmits the largest volume of water and the non-aquifer material being the least able to transmit water. The information from the interpreted aquifer materials maps and the information from Section 2.2.1 provides the basis of the information utilized in this section.

The results of the interpretation of the aquifer materials in the LENRD AEM survey area are explained in detail in Section 5.3. A total of 1016.5 line-miles (1,646.8 line-kilometers) of AEM data were acquired for the survey.

The use of widely-spaced reconnaissance lines (approximately 3 miles apart) illustrates patterns or areas where the potential for recharge can be high and low (Figure 5-28). Locations where the flight lines intersect and both lines show either aquifer or coarse aquifer material should be considered as higher likelihood for recharge because of the 2D spatial nature of the aquifer material distribution. The opposite is also true where two flight lines intersect and both lines show non-aquifer or marginal material, those areas will likely not be optimal recharge locations. The area marked with a blue polygon on the eastern side of the AEM survey area in Figure 5-28 shows the area where recharge is potentially less than the rest of the survey area. The map also shows an area on the western side of the AEM survey area that is surrounded by a red polygon where recharge is potentially the highest. There are other discontinuous zones of potentially lower and higher recharge scattered throughout survey area; to map their extent, additional flight lines are required. Figure 5-29 presents a Google Earth image showing areas of potential recharge based on the aquifer materials and the coarse aquifer materials noted along the flight lines in the survey area. This data is included as a kmz file in *Appendix_3_Deliverables\KMZ\Recharge*.

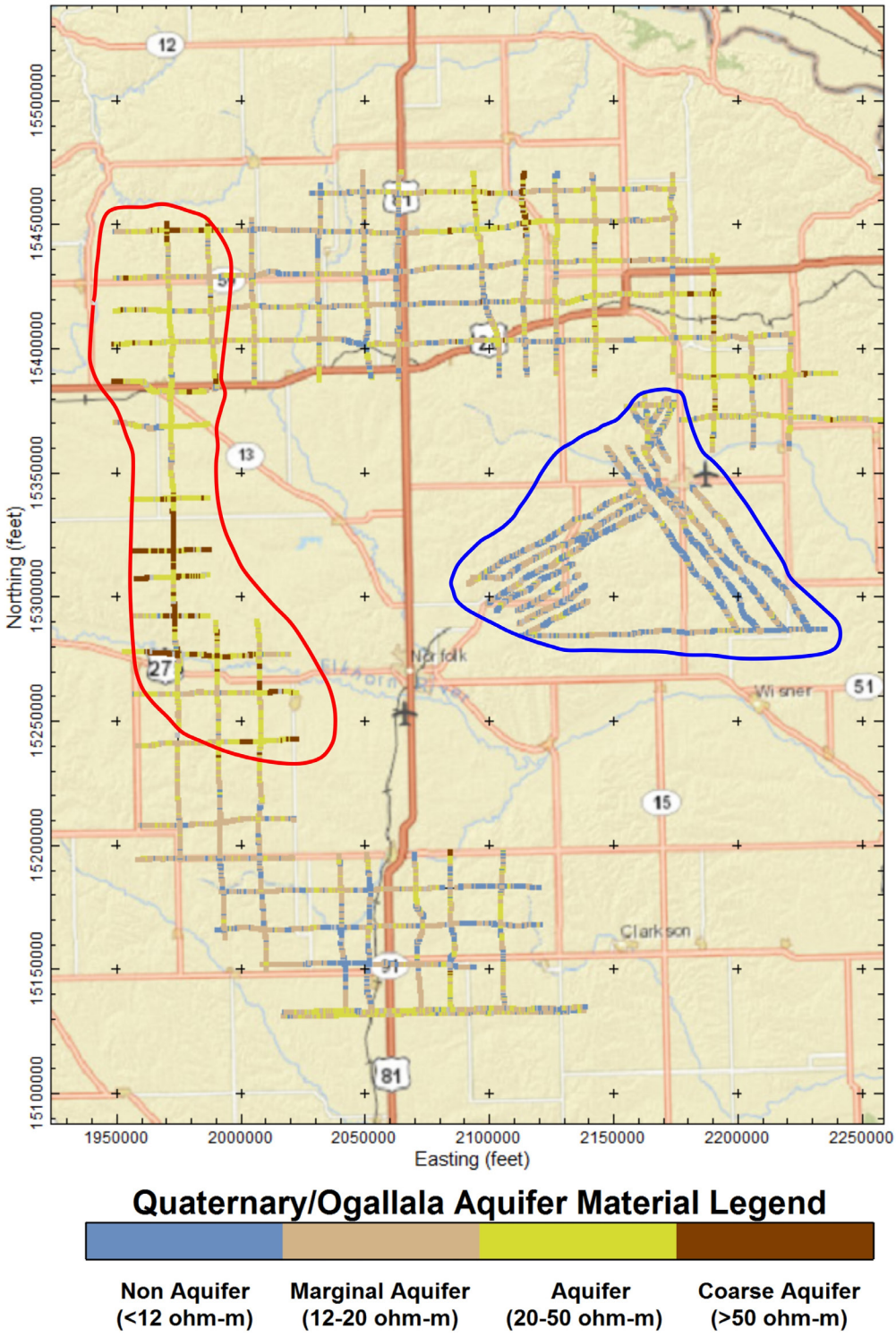


Figure 5-28. Map of aquifer materials for the first 0 to 10 feet, by flight line, displayed over the AEM survey area. Area highlighted by blue polygon shows area of least potential recharge, area highlighted by red polygon shows area of high potential recharge. The rest of the AEM survey area has a varied mix of recharge potential. This is an example of how to use the map by selecting an area where the dominant color is continuous along the flight line (s). Map projection is NAD 83, UTM Zone 14 North, feet.

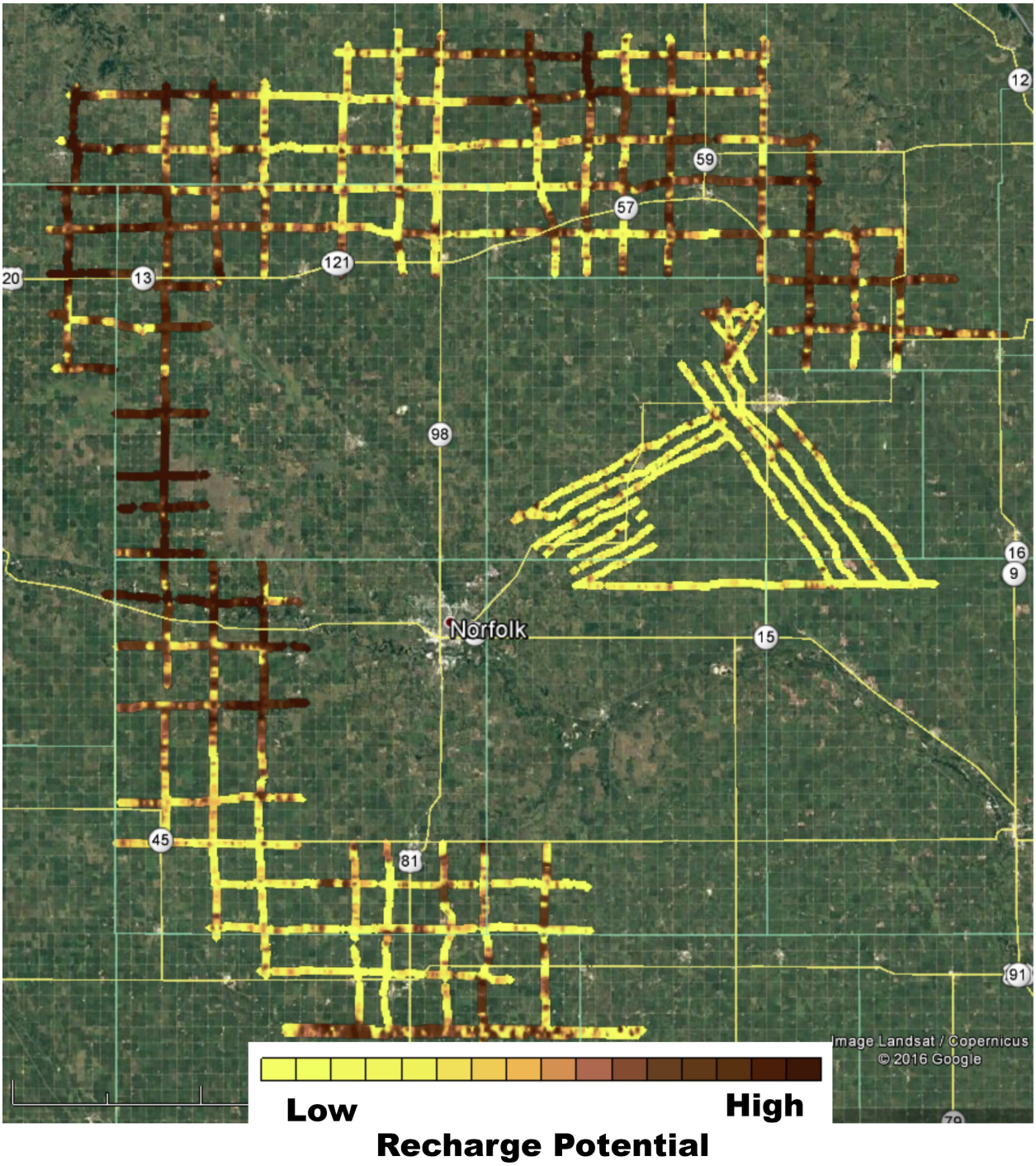


Figure 5-29. Potential aquifer and coarse material recharge zones within the LENRD AEM survey area displayed as a kmz in Google Earth. The darker colors indicate the higher potential recharge areas. This kmz is included as a deliverable in Appendix_3_Deliverables\KMZ\Recharge.

5.5 Key AEM Findings

5.5.1 Boreholes

Information from boreholes was used to analyze the AEM inversion results. These included CSD (Within the LENRD, 207 CSD holes contained lithology information, 151 holes contained stratigraphic information, and 63 holes contained geophysical information) and NE-DNR (A total of 4,223 registered wells contained usable lithology information) boreholes. Five NOGCC wells contained stratigraphy and lithology information.

5.5.2 Digitizing Interpreted Geological Contacts

Characterization and interpretation of the subsurface was performed in cross-section and derived surface grid formats. Contacts between the geologic units were digitized in 2D including: Quaternary (***Q***), Tertiary Ogallala Group (***To***), Cretaceous Pierre Shale (***Kp***), Niobrara Formation (***Kn***), Carlile Shale (***Kc***), Greenhorn Limestone and Graneros Shale (***Kgg***), and Dakota Group (***Kd***). The interpretive process benefited from the use of CSD and NE-DNR borehole logs. Surface grids of the interpreted geologic formations were then produced. Each flight line profile with interpretation including the Quaternary/Tertiary aquifer material mapping are included in the appendices as well as interpretative surface grids.

5.5.3 Resistivity/Lithology Relationship

Assessment of the sediment character in both the Quaternary/Tertiary Ogallala 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 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.

5.5.4 Hydrogeological Framework of the LENRD

The 2016 AEM survey reveals variability in the Quaternary (***Q***) deposits across the LENRD AEM survey area. When combined with the ***To***, they represent the aquifer materials in the AEM survey area, where saturated. The ***To*** is generally thick in the west and is thin to absent in the eastern regions of the AEM survey area. The ***Q*** and ***To*** make up the aquifer materials overlying the Cretaceous bedrock units. In the eastern and southern parts of the AEM survey area, the aquifer materials are predominantly marginal to non-aquifer materials which are glacial till and loess and which can be more than 200 feet thick. ***Q*** sediments found predominately on the west side are often associated with prevalent alluvial and coarse aquifer material deposits The ***Q*** and ***To*** (where present) materials are sitting on the ***Kp***, ***Kn***, ***Kc***, and ***Kgg*** which are the bedrock aquicludes for the area.

5.5.5 Potential Recharge Zones within the LENRD AEM Survey Area

The use of widely-spaced reconnaissance lines (approximately 3-miles apart) illustrates patterns or areas where the potential for recharge can be high and low. Locations where the flight lines intersect and both lines show either aquifer or coarse aquifer material should be considered as higher likelihood for recharge because of the 2D spatial nature of the aquifer material distribution. The opposite is also true where two flight lines intersect and both lines show non-aquifer or marginal material, those areas will likely not be optimal recharge locations. The area on the eastern side of the AEM survey area has potential recharge that is less than the rest of the survey area. The area on the western side of the AEM survey area has the highest potential recharge capability. There are other discontinuous zones of potentially lower and higher recharge scattered throughout survey area.

5.6 Recommendations

Recommendations provided to the LENRD 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 LENRD about their management challenges.

5.6.1 Additional AEM Mapping

The hydrogeologic maps provided in this report represent the detailed framework developed for the LENRD at a reconnaissance level. LENRD is the middle of a 5-year plan to gather AEM data that will be used to develop a hydrogeologic framework across the entire District. Beginning in 2014, the District has been collecting AEM data at approximately 3-mile grid spacing, as financial resources have allowed. The interpretations match well with the CSD and NE-DNR test holes. The 3D map in Figure 5-30 shows the reconnaissance lines collected from 2014 through 2016 in the northern and western parts of the district, with a few approximately 20 miles apart spaced lines in the east and south. The red lines in the southeast are the proposed locations of the 3-mile grid reconnaissance lines to be collected next in the 5-year plan. The already mapped lines match each other with high fidelity and can be used to provide detail for voluntary groundwater management activities for water quantity, water quality, and integrated water management. Areas of higher interest can be mapped by AEM block flights to provide more detailed information on the hydrogeologic framework and the recharge areas. It is recommended that the 5-year plan be completed as planned. Upon completion of the reconnaissance line surveys of the complete district, it is recommended that all data from the various surveys be integrated into one database and final continuous surface maps be developed and published for the LENRD.

5.6.2 Update the Water Table map

The groundwater data used in the analyses presented in this report utilized the 1995 CSD water table map. Additional water level measurement locations would improve the water table map where groundwater conditions are unconfined. This is especially true on the west side of LENRD in Pierce and Madison Counties. The areas of glacial till and loess covering the eastern side 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.

5.6.3 Siting new test holes and production wells

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

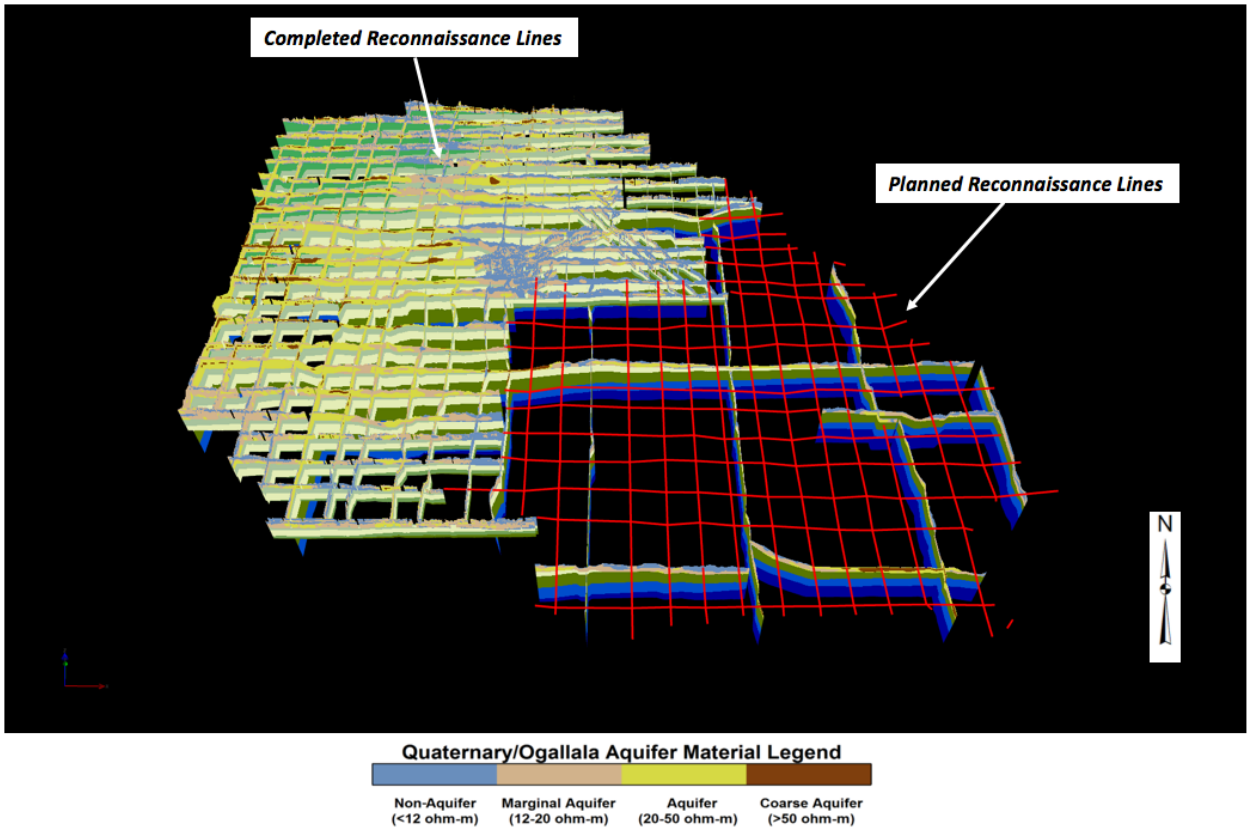


Figure 5-30. Map displaying the completed and the proposed LENRD reconnaissance lines. Map projection is NAD83, UTM Zone 14N.

5.6.4 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. The few test holes with geophysical logs in the LENRD AEM survey area were inadequate given the size of the area. None were calibrated and several had apparent hardware malfunctions. The borehole geophysical logs used in this investigation demonstrate that additional calibrated and verified geophysical logs are required in the LENRD.

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.

5.6.5 Recharge Zones

The LENRD 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 additional AEM data be collected and interpreted utilizing closely-spaced flight lines using an AEM system that has good near-surface resolution in areas identified by the LENRD that are of priority importance for management purposes. It is further recommended that future work integrate new soils maps with the results of this study to provide details on soil permeability, slope, and water retention to provide a more complete understanding of the transport of water from the land surface to the groundwater aquifer.

5.6.6 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 LENRD exist and what additional information would be required for final selections of MAR sites. Additional AEM mapping along the streams in the LENRD would also be beneficial in locating potential MAR locations. A detailed plan for locating and developing MAR sites would be beneficial to the LENRD for providing storage and release of water for stream flow and other uses.

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6 Description of Data Delivered

6.1 Tables Describing Included Data Files

Table 6-1 describes the data columns in the ASCII *.xyz file LENRD_EM_MAG_UTM14n_feet.xyz as well as the Geosoft database file LENRD_EM_MAG_UTM14n_feet.gdb. 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 LENRD_AEM_SCI_INV_v1.gdb files and LENRD_AEM_SCI_INV_v1.xyz and the data columns of these databases are described in Table 6-2.

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

The interpretation results are included in data files LENRD_InterpSurfaces_v1 in gdb and ASCII xyz formats. Table 6-6 describes the data columns of those files.

Table 6-7 describes the raw data files included in Appendix 3_Deliverables \Raw_Data. As discussed above, fifteen (15) flights were required to acquire the LENRD AEM data (Figure 4-5). 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 4.4.1). Two additional files are used for all the flights. These are the system description and specifications file (with the extension "*.gex") in the GEO subdirectory and the 'mask' file (with the extension "*.lin"), in the MASK subdirectory, which correlates the flight dates, flight numbers, and assigned line numbers.

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

In summary, the following are included as deliverables:

- Raw EM Mag data Geosoft database and ASCII *.xyz
- SCI inversion Geosoft database and ASCII *.xyz
- Borehole Geosoft databases and ASCII *.xyz
- Interpretations Geosoft database and ASCII *.xyz
- Raw Data Files - SkyTEM files *.geo, *skb, *.lin
- ESRI ArcView and Geosoft grid files – surface, topo, etc
- 3D fence diagrams of the AEM survey lines

KMZs for LENRD AEM flight lines (Discussed in Section 6.2). Profile Analyst session for the Profiles and 3D grids for the LENRD data analysis. (Discussed in Section 6.3).

Table 6-1: Channel name, description, and units for LENRD_EM_MAG_UTM14n_Feet.gdb and LENRD_EM_MAG_UTM14n_Feet.xyz with EM, magnetic, DGPS, Inclinometer, altitude, and associated data.

Parameter	Description	Unit
Fid	Unique Fiducial Number	
Line	Line Number	
Flight	Name of Flight	yyyymmdd.ff
DateTime	DateTime Format	Decimal days
Date	DateTime Format	yyyymmdd
Time	Time UTC	hhmmss.sss
AngleX	Angle (in flight direction)	Degrees
AngleY	Angle (perpendicular to flight direction)	Degrees
Height	Filtered Height Measurement	Meters [m]
Lon	Longitude, WGS84	Decimal Degrees
Lat	Latitude, WGS84	Decimal Degrees
E_UTM14N	Easting, NAD83 UTM Zone 14N	Meters [m]
N_UTM14N	Northing, NAD83 UTM Zone 14N	Meters [m]
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	$pV/(m^4*A)$
LMX_G01	Normalized (PFC-Corrected) Low Moment X-RxCoil values array	$pV/(m^4*A)$
HMX_G01	Normalized (PFC-Corrected) High Moment X-RxCoil values array	$pV/(m^4*A)$
_60Hz_Intensity	Power Line Noise Intensity monitor	V/m^2
Bmag_f	Raw Base Station Mag Data filtered	nanoTesla [nT]
Diurnal	Diurnal Mag Data	nanoTesla [nT]
MA1_orig	Raw Mag Data	nanoTesla [nT]
Mag_fil	Mag filtered	nanoTesla [nT]
Mag_CD	Mag Data Corrected for Diurnal Drift	nanoTesla [nT]
RMF	Residual Magnetic Field	nanoTesla [nT]
IGRF	International Geomagnetic Reference Field	nanoTesla [nT]
E_UTM14N_ft	Easting, NAD83 UTM Zone 14N	Feet [ft]
N_UTM14N ft	Northing, NAD83 UTM Zone 14N	Feet [ft]
Elevation_ft	Elevation, 100 ft grid of NED DEM NAVD88	Feet [ft]

Table 6-2: Channel name, description, and units for LENRD_AEM_SCI_Inv_v1.gdb and LENRD_AEM_SCI_Inv_v1.xyz with EM inversion results.

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

Table 6-3: Files containing borehole information.

Database (*.xyz, *.gdb)	Description
BazileCreekDNRLith_Collar_project.	Lithology logs from NE-DNR registered wells within the Bazile Creek Block of the LENRD Survey Area
BazileCreekDNRLith_Data_project.	
CSD-GP-E-logs_Collar_project.	Geophysical logs from CSD boreholes in the LENRD Survey Area
CSD-GP-E-logs_Data_project.	
CSD-GP-GEO-logs_Collar_project.	Geophysical logs from CSD boreholes in the LENRD Survey Area
CSD-GP-GEO-logs_Data_project.	
ENWRANorthLith_Collar_project.	Lithology logs from ENWRA-North wells within the LENRD Survey Area
ENWRANorthLith_LITH_project.	
ENWRANorthStrat_Collar_project.	Stratigraphic logs from ENWRA-North wells within the LENRD Survey Area
ENWRANorthStrat_Strat_project.	
LENRDLith_Collar_project	Lithology logs from within the LENRD Survey Area
LENRDLith_Lith_project	
OandG-wels-LITH_Collar_project	Lithology Data from wells from the Nebraska Oil and Gas Conservation Commission within the LENRD Survey Area
OandG-wels-LITH_LITH_project	
OandG-wels-STRAT_Collar_project	Stratigraphy Data from wells from the Nebraska Oil and Gas Conservation Commission within the LENRD Survey Area
OandG-wels-STRAT_STRAT_project	

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

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

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

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

Table 6-6: Channel name description and units for the interpretation results file LENRD_InterpSurfaces_v1 "gdb" and "xyz" files.

Parameter	Description	Unit
East_M	Easting NAD83, UTM Zone 14N	Meters (m)
North_M	Northing NAD83, UTM Zone 14N	Meters (m)
East_ft	Easting NAD83, UTM Zone 14	Feet [ft]
North_ft	Northing NAD83, UTM Zone 14	Feet [ft]
DEM_ft	Topography at 100ft sampling (NAVD 1988)	Feet [ft]
RHO[0] through RHO[28]	Array of Inverted model resistivities of each layer	Ohm-m
RHO_STD[0] through RHO_STD[28]	Array of inverted resistivity errors per layer	
RESDATA	Inversion model residuals of each individual sounding	
RESTOTAL	Inversion model average of all residuals	
DEP_TOP_FT[0] through DEP_TOP_FT [28]	Depth to the top of individual layers	Feet [ft]
DEP_BOT_FT [0] through DEP_BOT_FT [28]	Depth to the bottom of individual layers	Feet [ft]
DOI_LOWER_FT	Less conservative estimate of DOI from Workbench	Feet [ft]
DOI_UPPER_FT	More conservative estimate of DOI from Workbench	Feet [ft]
WaterTable_1995	Elevation of the top of the water table from the Nebraska School of Natural Resources Configuration Report, 1995.	Feet [ft]
AquiferTyp[0] through AquiferTyp[28]	Array of Aquifer Material types: 0 - Bedrock; 1 - Non-Aquifer Material; 2 - Marginal Aquifer Material; 3 - Aquifer Material; 4 - Coarse Aquifer Material	Integer Array
Top_AqMat1	Elevation of top of upper Aquifer Material (20 - 50 ohm-m)	Feet [ft]
Bot_AqMat1	Elevation of bottom of upper Aquifer Material (20 - 50 ohm-m)	Feet [ft]
Top_AqMat2	Elevation of top of lower Aquifer Material (20 - 50 ohm-m), if present	Feet [ft]
Bot_AqMat2	Elevation of bottom of lower Aquifer Material (20 - 50 ohm-m), if present	Feet [ft]
Top_Coarse_AqMat	Elevation of top of Coarse Aquifer Material (>50 ohm-m)	Feet [ft]
Bot_Coarse_AqMat	Elevation of bottom of Coarse Aquifer Material (>50 ohm-m)	Feet [ft]
To	Elevation of the top of the Tertiary Ogallala Group.	Feet [ft]
Bedrock	Elevation of interpreted bedrock surface	Feet [ft]
Kp	Elevation of the top of the Cretaceous Pierre Formation	Feet (ft)
Kn	Elevation of the top of the Cretaceous Niobrara Formation.	Feet [ft]
Kc	Elevation of the top of the Cretaceous Carlile Shale.	Feet [ft]
Kgg	Elevation of the top of the Cretaceous Greenhorn-Graneros Shale	Feet [ft]
Kd	Elevation of the top of the Cretaceous Dakota Formation.	Feet [ft]

Table 6-7: Raw SkyTEM data files

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

Table 6-8. Files containing ESRI ArcView Binary Grids *.flt and Geosoft Grids *.grd (NAD 83 UTM 14 North, feet)

Grid File Name	Description	Grid Cell Size (feet)
LENRD_bedrock_elevation.	Grid of the Bedrock composed of ***Kp***, ***Kn***, ***Kc*** and ***Kgg*** which is also the base of the aquifer elevation NAVD88 (feet) LENRD Survey Area	100
LENRD_DEM_elevation.	Grid of the Digital Elevation Model (DEM) downloaded from the National Elevation Dataset (NED) August 2016 NAVD88 (feet)	100
LENRD_Kp_elevation.	Grid of the top of the ***Kp*** elevation NAVD88 (feet) LENRD Survey Area	~1907
LENRD_Kn_elevation.	Grid of the top of the ***Kn*** elevation NAVD88 (feet) LENRD Survey Area	~1937
LENRD_Kc_elevation.	Grid of the top of the ***Kc*** elevation NAVD88 (feet) LENRD Survey Area	~2144
LENRD_Kgg_elevation.	Grid of the top of the *Kgg* elevation NAVD88 (feet) LENRD Survey Area	~3201
LENRD_Kd_elevation.	Grid of the top of the ***Kd*** elevation NAVD88 (feet) LENRD Survey Area	~4376
LENRD_1995WT_elevation.	Grid of the CSD 1995 water table NAVD88 (feet)	100
LENRD_Q_To_thickness	Grid of the thickness of the ***Q*** and ***To*** material within the LENRD Survey Area (feet)	100
LENRD_Saturated_thickness.	Grid of thickness of the saturated ***Q*** and ***To*** from the water table to the bedrock within the LENRD survey area NAVD88 (feet)	100

6.2 Description of Included Google Earth KMZ Data and Profiles

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

KMZ files of the potential recharge zones in the LENRD AEM survey area are included in the folder "*Appendix_3_Deliverables\KMZ\Recharge*"

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 plus the elevations of tops and bottoms of aquifer material and coarse aquifer material as well as bedrock, the water table (2016), and the elevations of the tops of the Cretaceous Niobrara (if present), Carlile, Greenhorn and Graneros, and Dakota formations. These KMZ files are located within the "*Appendix_3_Deliverables\KMZ\LENRD_Interp\LENRD_Prof*" folder. Also in this folder is a "*GoogleE_Readme_LENRD.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 file is repeated below as a convenience. An example of the LENRD interpretation KMZ is presented in Figure 6-1.

6.2.1 Included README for the LENRD Interpretation KMZ's

README for:

LENRD_Interpretation_v1.kmz

Data Files - Please copy the folder *LENRD_Prof* 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 *LENRD_Interpretation_v1.kmz* file within the folder named *LENRD_Prof* 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, UTM 14N, in feet

North (ft) – Northing coordinate in NAD83, UTM 14N, in feet

Elev (ft) – DEM elevation in feet

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

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

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

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

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

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

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

Elev To (ft) – Elevation of Tertiary Ogallala Group formation, in feet.

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

Elev Kp (ft) – Elevation of Cretaceous Pierre Fm, in feet.

Elev Kn (ft) – Elevation of Cretaceous Niobrara Fm, in feet

Elev Kc (ft) – Elevation of Cretaceous Carlile Fm, in feet

Elev Kgg (ft) – Elevation of Greenhorn and Graneros formations, in feet

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

Profile – Link to Interpreted AEM profile images

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

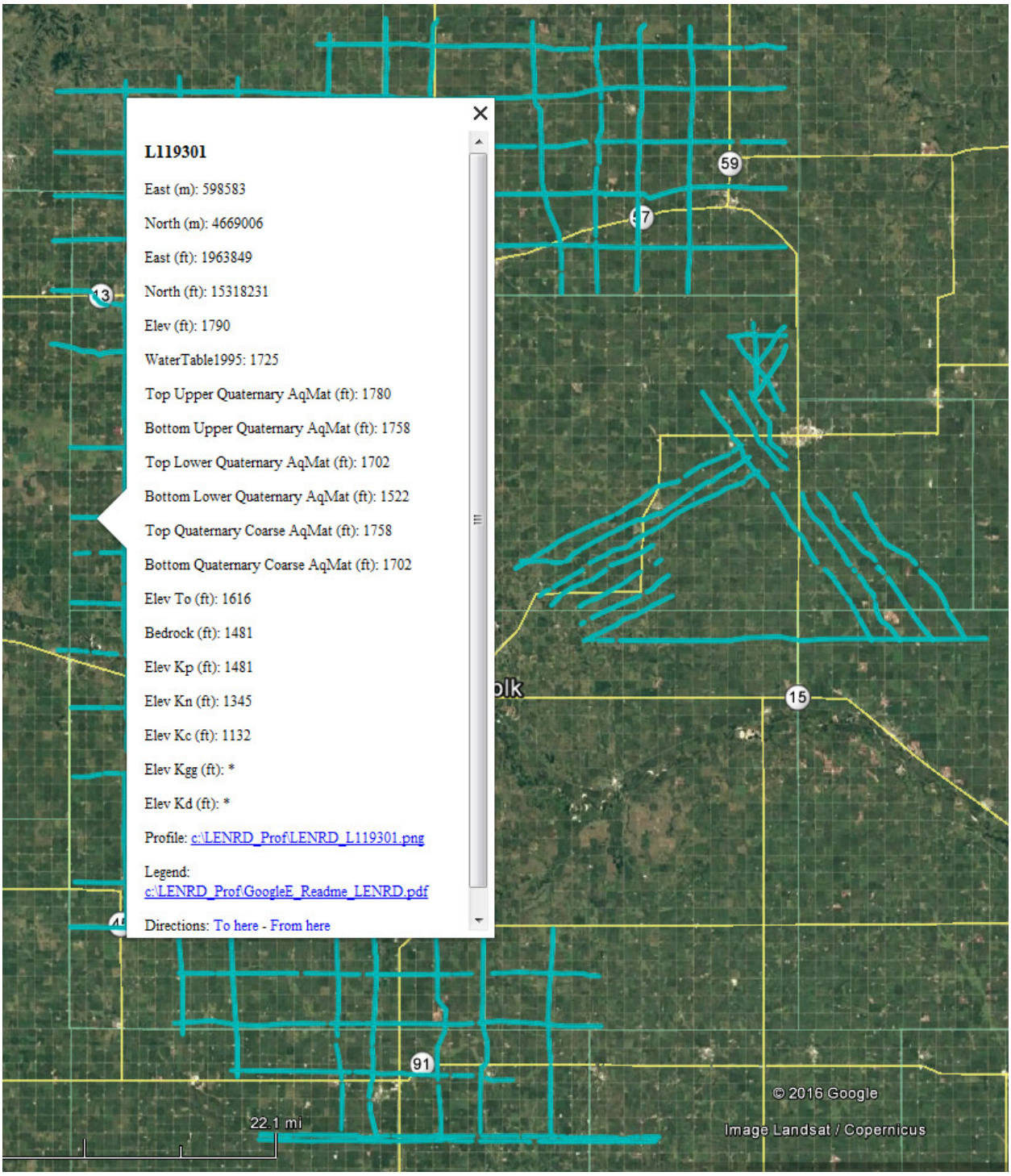


Figure 6-1. Example Google Earth image for the LENRD Interpretation kmz.

6.3 Description of Included Profile Analyst (PA) Session Material

As discussed above PitneyBowes pbEncom Discover PA Version 2015 Release Build 15.0.13 (pbEncom, 2016) was used to create the 3D volumes and the profiles used in the interpretation within this report. To allow the future use of the information imported into the PA platform, PA Session Package files were created and are included within this report. A free viewer is available from the pbEncom Discover PA website: http://web2.encom.com.au/downloads/discover_3D/Discover_Viewer_2015.exe

The files located in the Appendix_3_Deliverables\PA_Session need to be unzipped and copied to a directory and then the Session file needs to be opened within Discover PA. Details on the function of Discover PA can be accessed from the pbEncom website and the help functions within Discover PA. The session files that are included with the project deliverables are summarized in Table 6-9.

Table 6-9. pbEncom Discover PA Session Files

Area Covered	View Format	File name
LENRD Survey Area	**2D**	**LENRD_2016_profiles.egs**
LENRD Survey Area	**3D**	**LENRD_2016_Fence.egs**

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