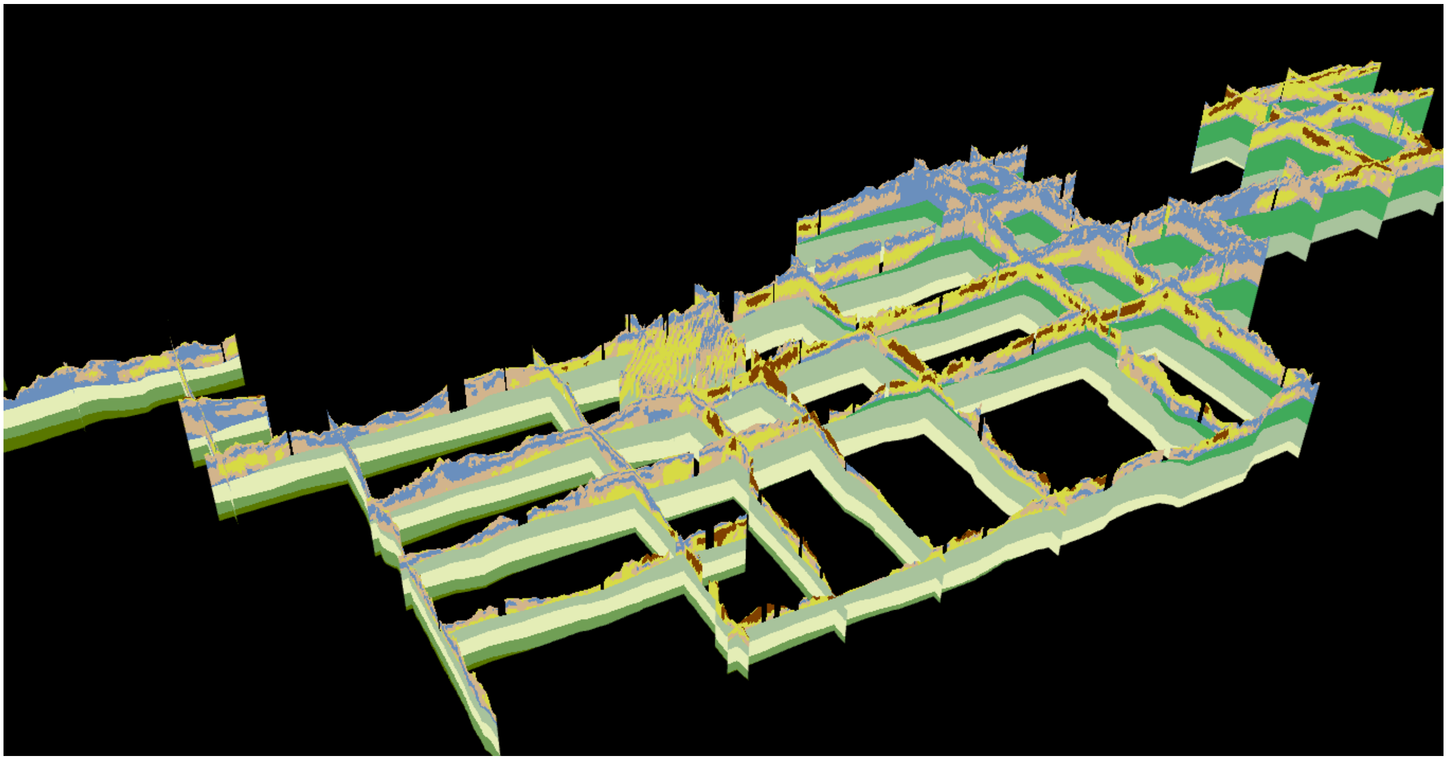
Hydrogeologic Framework of Selected Areas in the Lewis & Clark Natural Resources District, Nebraska



***Prepared for*:**

Lewis & Clark Natural Resources District

PO Box 518
Hartington, Nebraska, 68739

May 26, 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 Lewis & Clark Natural Resources District*". An understanding of the hydrogeological framework in the survey area is desired in order to assist in resource management. AGF entered into an agreement with the Lewis & Clark Natural Resources District (LCNRD) to collect, process, and interpret airborne electromagnetic (AEM) data, in conjunction with other available background information, to develop a 3D hydrogeologic framework of the LCNRD survey 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 LCNRD Area including, in detail, around Coleridge. These flights have been provided as preliminary AEM inversions on July 23-26, 2016 and the final AEM data and inversions are included as a product attached to this 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 LCNRD assisted in providing information such as power line maps, a test hole database, and related aquifer characteristic studies to AGF.

Upon conclusion of the design process, the LCNRD reconnaissance flight lines were approximately 46 miles in length at their longest in the east-west direction and about 16 miles at their longest in the north-south direction and were separated by approximately 3 miles in both east-west and north-south directions. In the Coleridge area a dense flight block was developed running from southwest to northeast with the longest flight line being approximately 3 miles in length. The Coleridge AEM flight lines are separated by approximately 0.15 miles or 800 feet.

1.4 AGF acquired AEM data over the LCNRD, commencing 23 July 2016 and finishing on 26 July 2016, to support development of the hydrogeological framework. Approximately 353.9 line-miles (573.2 line-kilometers) were acquired over the LCNRD AEM survey area on July 23-26, 2016. Of this total, approximately 66.2 line-miles (107.2 line km) were flown in a dense block around Coleridge. Status reports of the flying were provided to the Contract Representative of LCNRD on a daily basis, including the areas flown, production rates, and flight plan for the following day.

1.5 AGF processed and conducted quality assurance and quality control (QA/QC) procedures on all data collected from the acquisition system. AGF delivered preliminary data and inversions on July 28, 2016.

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

1.7 AGF is providing a hydrogeologic framework report that includes maps of aquifer(s), maps of aquifer materials relationships to current test holes and production groundwater wells, estimates of water storage capacity, and maps of estimated potential recharge areas. 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 **AEM Data Acquired, Processed, and Inverted** – Of the total of 353.9 line-miles (573.2 line-kilometers) of AEM data that were acquired for the LCNRD survey and of which approximately 66.2 line-miles (107.2 line km) were flown in a dense block around Coleridge, after final processing, 336.7 line-miles (545.5 line-km) of data were retained for the final inversions. This amounts to a data retention of 95%. This high rate is the result of careful flight line planning and design.

2.2 **Boreholes** - Information from boreholes was used to analyze the AEM inversion results. Of the total of 127 CSD holes utilized in this investigation, 36 contained geophysical logging information including resistivity, gamma-gamma, temperature, calibration, etc., 66 holes contained lithology information, and 25 holes contained stratigraphic information. A total of 1,408 NE-DNR registered wells contained usable lithology and/or stratigraphy information. Of the 5 NOGCC wells used in this study, 4 contained both lithology and stratigraphy information and 1 hole contained only lithology information.

2.3 **Comparison 2014 and 2016 AEM Databases** - 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. The portion of the BGMA within the LCNRD is included within this report. 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. No issues with the calibration or bias removal were indicated within the datasets.

2.4 **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 (***To***), and Cretaceous Pierre (***Kp***), Niobrara (***Kn***), Carlile (***Kc***), Greenhorn limestone and Graneros shale (***Kgg***), and Dakota (***Kd***). The interpretive process benefited from the use of CSD, NE-DNR, and NGOCC 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.

2.5 **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.

2.6 Hydrogeological Framework of the LCNRD - The 2016 AEM survey reveals variability in the Quaternary (***Q***) deposits across the LCNRD survey area. When combined with the ***To***, they represent the aquifer materials in the survey area, where saturated. The ***To*** is generally thick in the west and is thin, discontinuous to absent in the eastern regions of the 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 across most of the survey area and ***Q*** and ***To*** coarse aquifer and aquifer materials found predominately on the west side often associated with alluvial deposits. ***To*** is in the center of the AEM survey area and the pinches out to the east and west with ***Q*** sediments covering all other units. The ***Q*** and ***To*** make up the aquifer materials overlying the Cretaceous bedrock units.

2.7 Hydrogeological Framework of the Coleridge Block AEM Survey Area - The Coleridge Block AEM flight area is within the Quaternary Aquifer system. The area is composed of ***Q*** aquifer materials lying on the ***Kn*** bedrock surface. The bedrock is eroded and has a channel-like expression. The channel trends from west to east in the center of the block. The channels are flanked by bedrock highs that are in the AEM block area that have an increased relief of up to 100 feet in elevation. The thickness of the Quaternary material within the Coleridge Block ranges from 80 to 340 feet thick. The area is dominated by a mix of aquifer materials and coarse aquifer materials and a low-relief water table. The thicker sequences of aquifer material lie to the southeast and center of the block with marginal and non-aquifer materials creating an aquifer boundary across the area from southwest to northeast. The aquifer and coarse aquifer materials are the most productive of the Q aquifer and have the greatest amount of groundwater flow.

2.8 Estimation of Aquifer Volume and Water in Storage in the Coleridge Block - The non-aquifer material has an estimated volume of 157,651 acre-ft and contains 63,060 acre-ft of groundwater in storage. The marginal aquifer material has an estimated volume of 638,560 acre-ft and contains 223,496 acre-ft of groundwater in storage. The aquifer material has an estimated volume of 975,523 acre-ft and contains an estimated volume of 195,104 acre-ft of groundwater in storage. The coarse aquifer material contains an estimated volume of 79,784 acre-ft for a total of 19,946 acre-ft of groundwater in storage. The amount of groundwater in storage for all material groups is 501,606 acre-ft. The estimate of extractable volume of water is calculated by taking the amount of groundwater in storage times the specific yield. Non-aquifer materials in the Coleridge Block AEM survey area will yield approximately 1,261 acre-ft, marginal aquifer materials will yield approximately 11,175 acre-ft, aquifer materials will yield 29,266 acre-ft, and the coarse aquifer material will yield approximately 2,992 acre-ft. A total of 44,694 acre-ft is available from the combined non-aquifer, marginal aquifer, aquifer, and coarse aquifer materials.

2.9 Potential Recharge Zones within the LCNRD AEM Survey Area - Areas of more potential recharge in the LCNRD AEM survey area are located north of Coleridge and areas with less potential for recharge are located on the western side of the AEM survey area. There are other discontinuous zones of potentially lower and higher recharge scattered throughout survey area. To map their extent, additional flight lines are required. Potential recharge around the Coleridge Block area is greatest in the center of the block along a north-south oriented band with areas of lesser recharge potential located on the western and eastern sides of the survey block.

3. Recommendations

Recommendations provided to the LCNRD in this section are based on the interpretation and understanding gained from the addition of the AEM data to existing information and from discussions with the LCNRD about their management challenges.

3.1 **Additional AEM Mapping** - The hydrogeologic maps provided in this report represent the detailed framework developed for the LCNRD at a reconnaissance level and the Coleridge Block area. LCNRD is in the middle of a 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 20-mile spacing and in 2016 a 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 5-40 shows the reconnaissance lines collected from 2014 through 2016. As seen these lines were collected in the central and west parts of the district with a few approximately 20-mile spaced lines across the district. The red lines are the proposed locations of the 3-mile grid reconnaissance lines to be collected next in the 2017 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 in detail by block flights to provide information on the hydrogeologic framework and the recharge areas. It is recommended that the plan to continue AEM mapping be completed as planned. Upon completion of the reconnaissance line surveys it is recommended that all data be from the various surveys be brought together in one database and final continuous surface maps be developed and published for the LCNRD.

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. The areas of glacial till and loess covering the most 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. This is especially true in the glacial till area of LCNRD.

3.3 **Siting new test holes and production wells** – The AEM framework maps and profiles provided in this report provide insight into the 3D relationship between current test holes and production groundwater wells. At the time of this report, the currently available lithology data for the LCNRD area was used in building the framework maps and profiles. 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. Also these maps will help in refining the well head protection areas around the public supply wells.

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 LCNRD 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 LCNRD.

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 LCNRD hydrogeologic framework in this report provides areas of recharge from the ground surface to the groundwater aquifer. Reconnaissance level AEM investigations provide limited detailed information between the lines for understanding recharge throughout the survey area. It is recommended that 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 LCNRD that are of priority 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 **Integration of 2014 and 2016 AEM Databases and Interpretation** - 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 examined as part of the BGMA AEM survey of which LCNRD is a participant. Several other comparisons can be made within the LCNRD due to the continuation of the AEM data collection within the District from 2014 to 2016. It is recommended that, at the completion of the AEM reconnaissance lines in LCNRD, all existing AEM survey results be integrated to produce a single coherent interpretation of the hydrogeological framework within the LCNRD. Any future AEM data acquisition should also then be integrated in the unified interpretation.

4. Deliverables

In summary, the following are included as deliverables:

- Raw EM Mag data Geosoft database and ASCII *.xyz
- SCI inversion Geosoft database and ASCII *.xyz
- Borehole Geosoft databases and ASCII *.xyz
- Interpretations Geosoft database and ASCII *.xyz
- Raw Data Files - SkyTEM files *.geo, *skb, *.lin
- ESRI ArcView and Geosoft grid files – surface, topo, etc.
- 3D fence diagrams of the LCNRD AEM survey lines
- 3D voxel models as ASCII *.xyz and *.gdb for the Coleridge flight block
  KMZs for LCNRD flight lines and Profile Analyst sessions for the Profiles and 3D grids for the Coleridge Block 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
dB/dt	Change in amplitude of magnetic field with time
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
Fm	Formation
gpd	Gallons per day
gpd/ft	Gallons per day per foot
GIS	Geographic Information System
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
LCNRD	Lewis & Clark Natural Resources District
LENRD	Lower Elkhorn Natural Resources District
LLNRD	Lower Loup Natural Resources District
MAG	Magnetic (data); Magnetometer (instrument)
MCG	Minimum curvature gridding
m	Meters
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
recon	Reconnaissance
Rx	Receiver
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

The Lewis & Clark Natural Resources District (LCNRD) desired an improved understanding of the hydrogeologic framework in the LCNRD in the larger area between Creighton and east of Coleridge (Figure 1-1). An Airborne Electromagnetic (AEM) survey was selected to assist in the development of a 3D hydrogeologic framework of these project areas and recommend future work to enhance groundwater management activities (Figure 1-2).

Figure 1-1. Map of Nebraska counties, indicating the location of the Lewis & Clark Natural Resources District (LCNRD) airborne electromagnetic (AEM) survey with an inset of the project area.

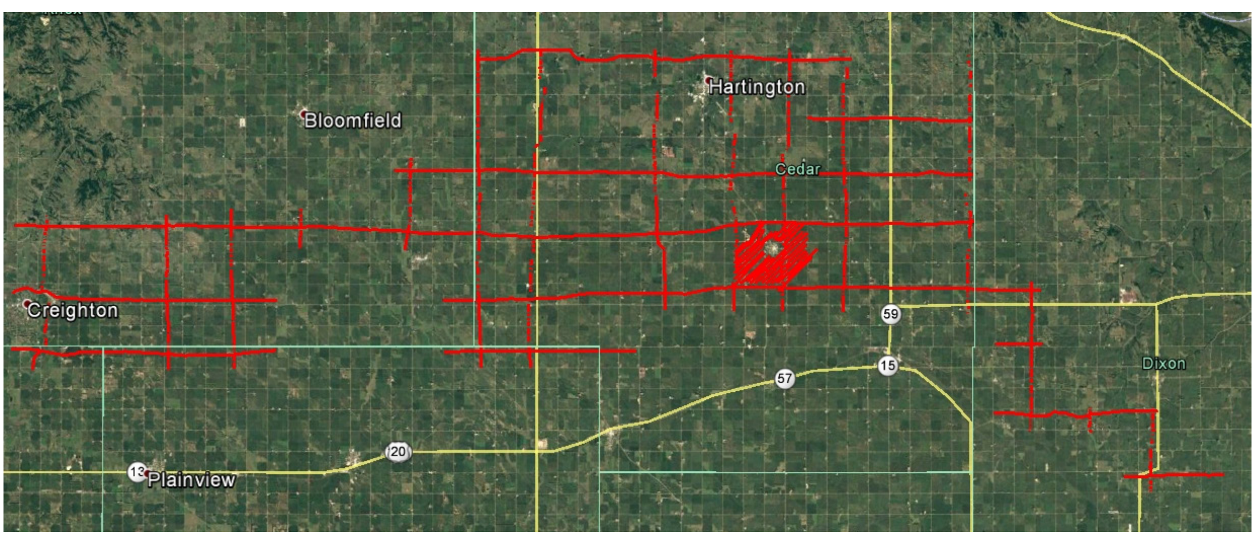

Figure 1-2. The LCNRD AEM reconnaissance and block survey areas including county lines and major roads (NE 121, 20, 81, 57, 15, 59) between Creighton and Coleridge.

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1.2 Background

On February 1, 2015, the LCNRD declared the entire District a Level I Groundwater Quantity Management Area. This includes the Niobrara Chalk Bedrock Reservoir, Dakota Sandstone Bedrock Reservoir, Area of Limited Aquifer Development Potential, Remaining Areas, Missouri River Groundwater Reservoir, and the Community Water System Protection Areas (LCNRD, 2017). There are three possible phases of management in the plan based on water use, changes in water supply, and aquifer characteristics. In addition, the LCNRD has a water quality management area for nitrogen management in portions of the Bazile Groundwater Management Area (BGMA). The boundary of the overlap area is presented in Figure 1-3 (LCNRD, 2017). This determination was based on studies by the LCNRD and the Nebraska Department of Environmental Quality (NE-DEQ) and others. The conclusions from these studies indicated that the aquifers appeared to be contaminated due to varying degrees with nitrate/nitrogen and the causes were likely related to fertilizer application and irrigation practices. The report also concluded that the most affected region, with some of the highest nitrate/nitrogen concentrations in the groundwater, occur in the Creighton area of the district. Based on this information, BGMA was declared a Phase III water quality area.

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

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

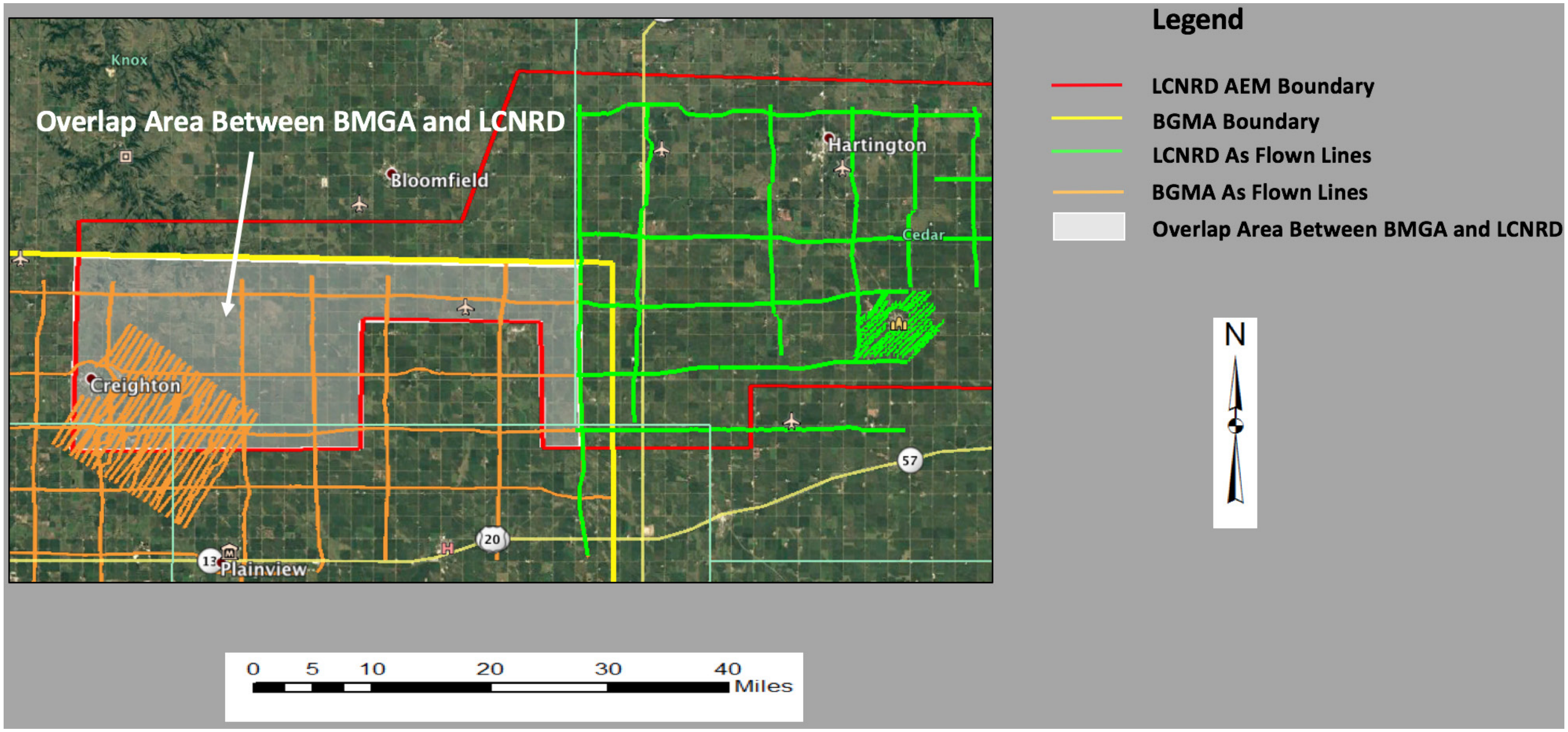

Figure 1-3. Map of AEM overlap area between the LCNRD and the BGMA. The area of overlap is shaded in white.

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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 in order 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 (Exploration Resources International, 2015). 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 other studies led by AGF provided detailed 3D hydrogeologic framework for the western portions of Sarpy County (AGF, 2017b) and for the Lower Loup Natural Resources District (AGF, 2017c), and the Lower Elkhorn Natural Resources District (LENRD) (AGF, 2017d). These studies included characterization of Quaternary and Tertiary aquifer materials and the underlying bedrock materials such as the Dakota Sandstone aquifers overlain, in places, with glacial deposits. The LENRD study continued the plan of mapping the entire district with a 3-mile grid. 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. 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. Portions of the LENRD 2016 survey are also included in this report to facilitate the understanding of the margins of the LCNRD.

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 LCNRD AEM Project Area

In the LCNRD AEM project area, the Coleridge block and the Reconnaissance flight lines are located in east-central Nebraska and encompass approximately 21 and 650 square miles, respectively (Figure 1-2). These areas lie within parts of three counties: Cedar. Dixon, and Knox. Precipitation and irrigation runoff within the survey area and Coleridge block feed into two major river basins (NEDNR, 2016a): the Elkhorn and Missouri Tributaries (Figure 1-4) and the area sits in distinct groundwater regions; namely, the Nebraska Glacial Drift and the North Central Table Land (Pederson et al., 1986). The towns of Coleridge, Hartington, Creighton and Allen lie within the LCNRD AEM survey area.

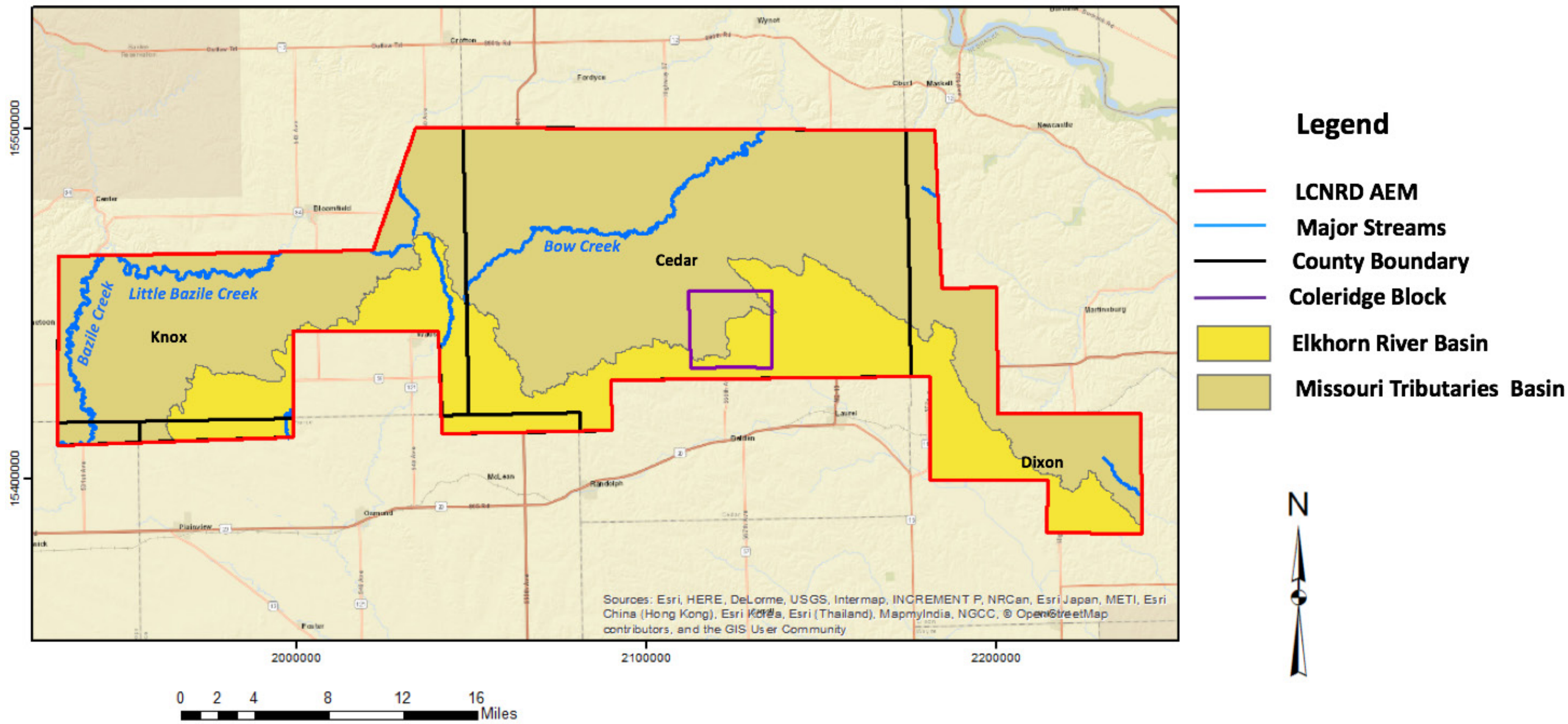


Figure 1-4: Map of major river basins within the LCNRD AEM survey area (NE-DNR, 2016a).

2 Project Area Hydrogeology

2.1 Geologic Setting

As just discussed, in the LCNRD survey, AEM data were collected over the Reconnaissance and Coleridge Block areas. The object of the survey was to map the geology and related hydrogeology of the Quaternary (***Q***) and Tertiary Ogallala (***To***) sediments and the underlying bedrock surface. Much of the background geology and hydrogeology is discussed in more detail in Carney et al. (2015a) 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 LCNRD survey area is in east-central Nebraska near the towns of Creighton and Coleridge and within the Valleys, Dissected Plains, Plains, and Rolling Hills topographic regions of Nebraska (Elder et al., 1951). Bedrock geology in the survey area is comprised of consolidated marine and consolidated to unconsolidated non-marine sedimentary rocks as presented in Figure 2-1 (from Burchett, 1986). These deposits are not deformed by folding and faulting. The Quaternary (***Q***) sediments are made up of alluvial materials in the west and glacial deposits containing aquifer materials, located in the northeast.

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 2-2 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 stream valleys in some locations (e.g., Missouri Tributaries).

CSD test holes and drillers logs obtained from NE-DNR indicate glacial till units are present in most of the project area (Figure 2-3). Beneath much of the LCNRD survey area the surficial deposits consist of Quaternary glacial deposits composed of till, loess, inter-bedded gravel, sand, and silt.

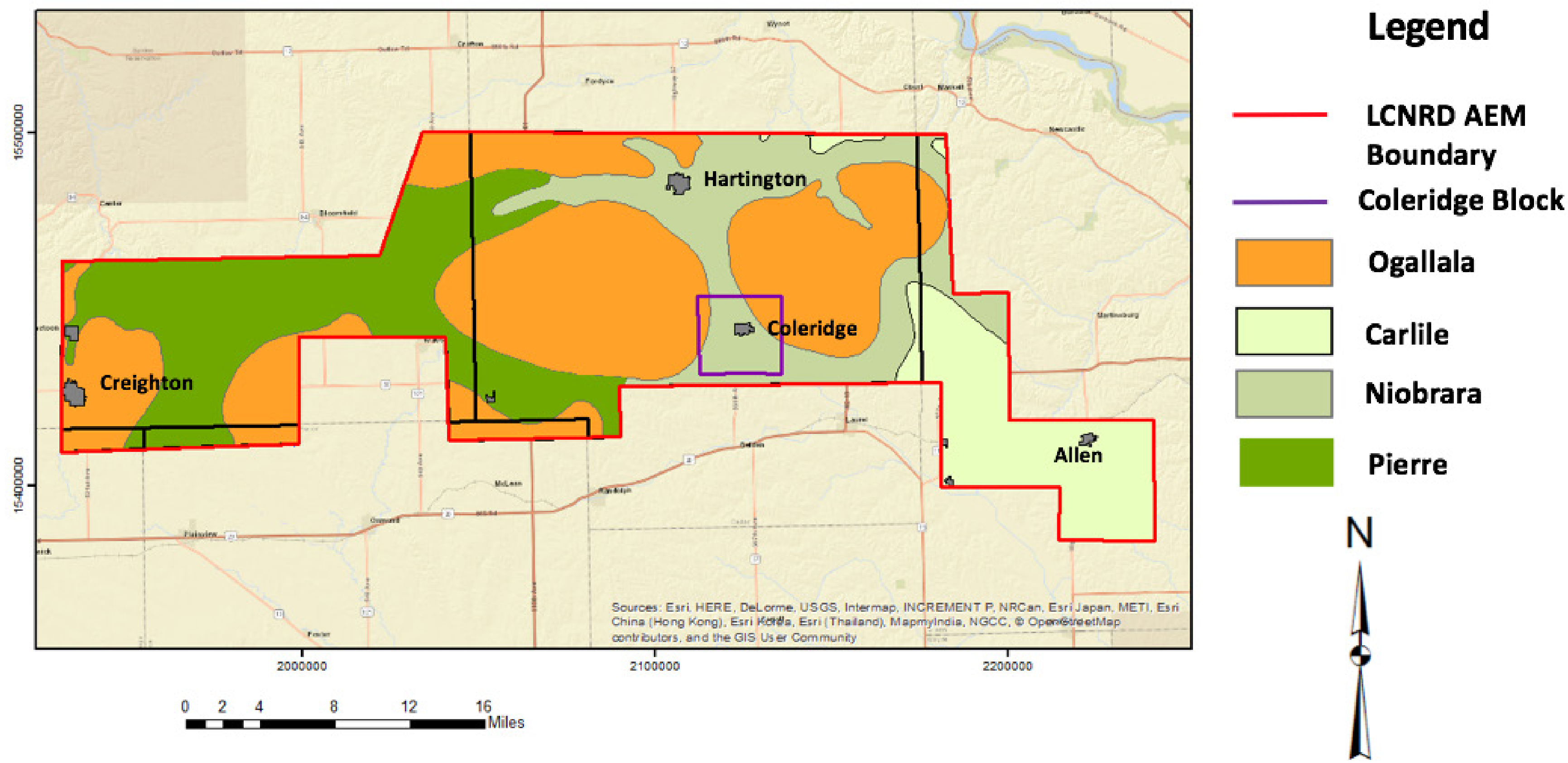


Figure 2-1. Bedrock map of the LCNRD survey area, modified from Burchett (1986). Map projection is NAD 83, UTM Zone 14 North, feet.

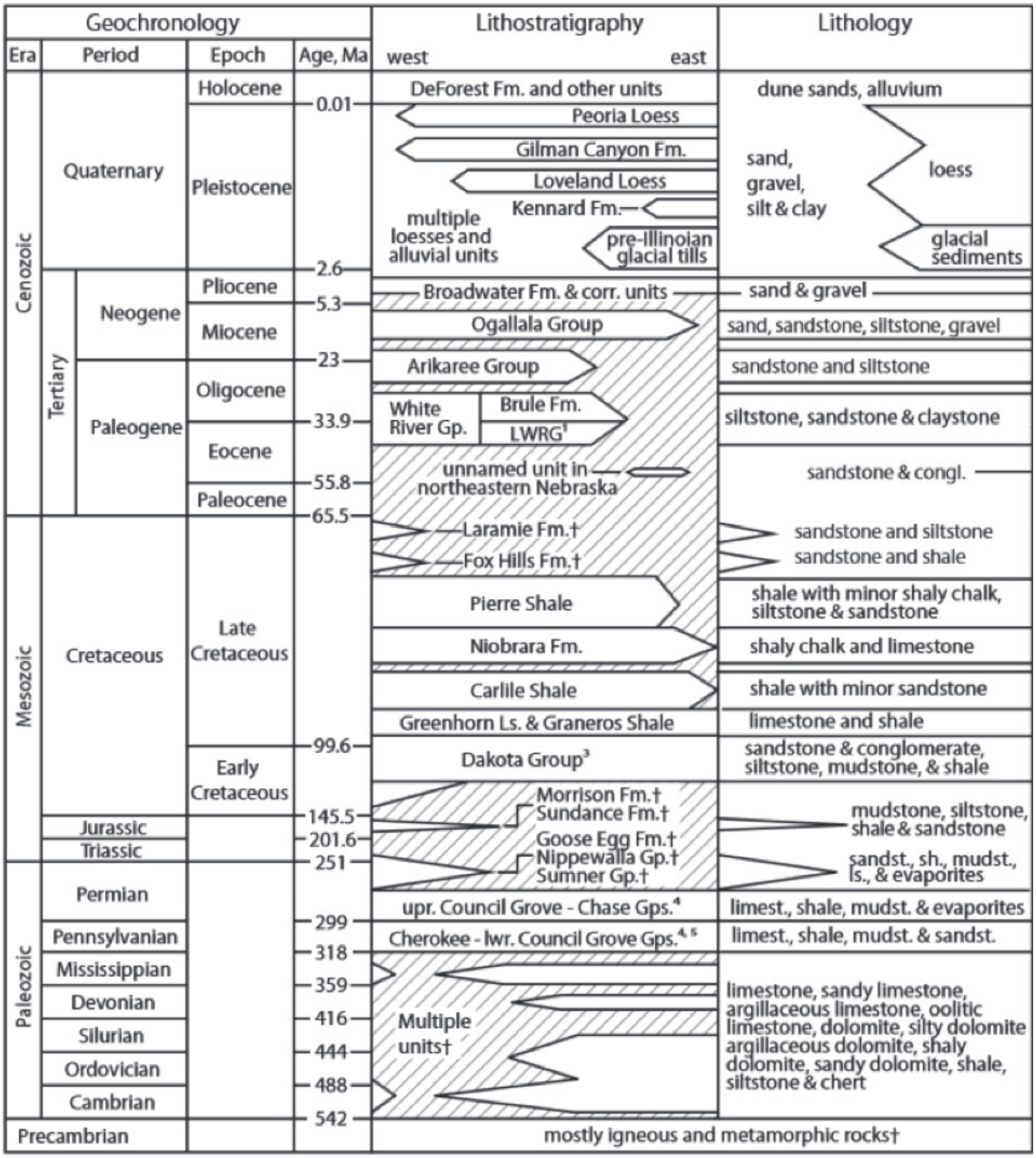


Figure 2-2. Geologic time scale with lithostratigraphic sequence underlying Nebraska, modified from Korus and Joeckel (2011).

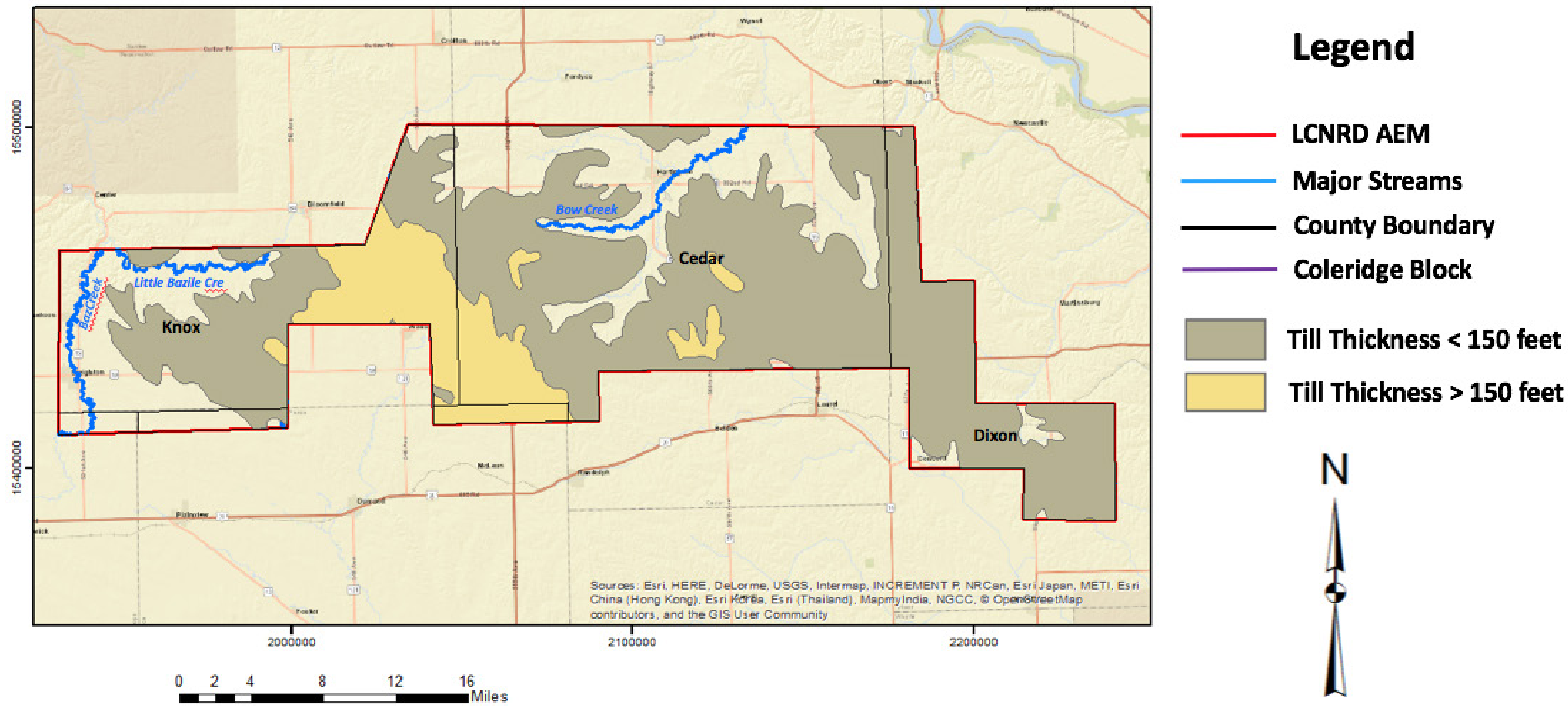


Figure 2-3. Till coverage map of the project area, modified from CSD (2017). Projection is NAD83, UTM 14 North (feet).

2.1.3 Tertiary Geology

The Tertiary deposits near the west-central part of the survey area are Miocene Ogallala Group (***To***). The ***To*** is predominantly fluvial material comprised of unconsolidated to consolidated, irregularly distributed beds of silt, clay, sand, and gravel (Burchett et al., 1988). Some members of the ***To*** contain partially cemented friable sands or sandstone (Condra and Reed, 1959). The ***To*** primarily consists of erosional remnants that exist in Knox and Cedar counties. The ***To*** rests unconformably on underlying Cretaceous strata (Burchett, 1986). Where present, the ***To*** is variable in thickness and discontinuous (Figure 2-1). The ***To*** can serve as an aquifer where it is saturated.

2.1.4 Cretaceous Geology

There are deposits within the survey area from both the Upper and Lower Cretaceous. The Upper Cretaceous bedrock formations are the Pierre Shale (***Kp***), Niobrara Formation (***Kn***), Carlile Shale (***Kc***), and Greenhorn Limestone and Graneros Shale (***Kgg***). Together these formations are comprised of shales, interbedded sandy shales, indurated shaly chalks, and 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*** and ***To*** 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 LCNRD survey area, this report will focus on the ***Kp***, ***Kn***, and ***Kc*** as they directly underlie the Quaternary and Tertiary aquifers. The Cretaceous is underlain by Paleozoic and Precambrian units. These units will not be discussed in this report.

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

A map showing the major streams and rivers with the associated basin areas within the LCNRD survey area is presented in Figure 2-4 (NE-DNR, 2016a). The largest surface-water systems in the project area are the Bazile Creek, Little Bazile Creek, and Bow Creek (U.S. Geological Survey, 2015) which flow north into the Missouri River.

The overall elevation of the water table within the AEM Reconnaissance survey area is presented in Figure 2-5 and for the Coleridge Block area 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 at 50-foot contours. Actual water levels will likely be different.

Regional groundwater-flow direction for the LCNRD AEM survey area is predominately from south to north near the town of Creighton and from southwest to northeast in the central part of the survey area including the Coleridge Block area (Figure 2-5 and Figure 2-6). The direction is similar to the course of the major streams and rivers. Groundwater is locally hydrologically connected to surface water 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.

Groundwater can be confined in aquifers near or beneath glacial till (Olafsen-Lackey et al., 2005a) (Figure 2-7), and typically exhibits more drawdown than groundwater in unconfined systems that are present in alluvial settings. The groundwater system for the LCNRD survey area is generally under confined to semi-confined conditions due to the extensive glaciated cover.

Potentiometric gradients show groundwater movement from upland areas toward stream valleys. Hilly topography and complex heterogeneity within the glacial-drift terrain can create local flow systems (Gates et al., 2014). Contrasts of hydraulic conductivity within the principal aquifers of eastern Nebraska, can commonly cause significant vertical groundwater flow gradients.

The principal hydrogeologic units within the LCNRD survey area is ***Q*** and the ***To***. The ***Q*** materials are made up of two parts. 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 the survey area. Saturated ***Q*** deposits in east-central Nebraska are a complex mixture of unconsolidated, saturated sand, and gravel deposits.

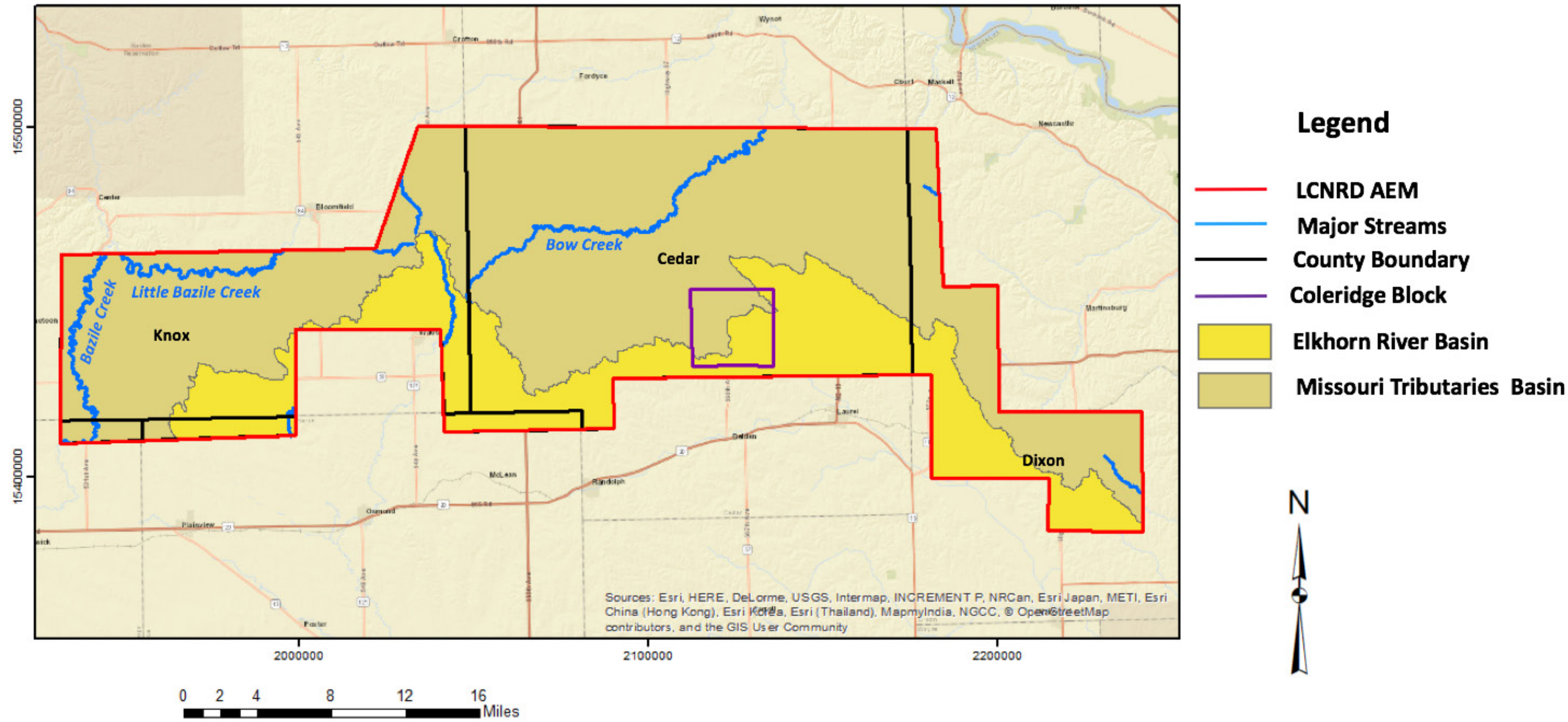


Figure 2-4. Map displaying the major streams and rivers within the LCNRD survey area (NE-DNR, 2016a). The surface water divide is also shown separating drainages flowing to the Missouri and Elkhorn Rivers. Map projection is NAD 83, UTM Zone 14 North, feet.

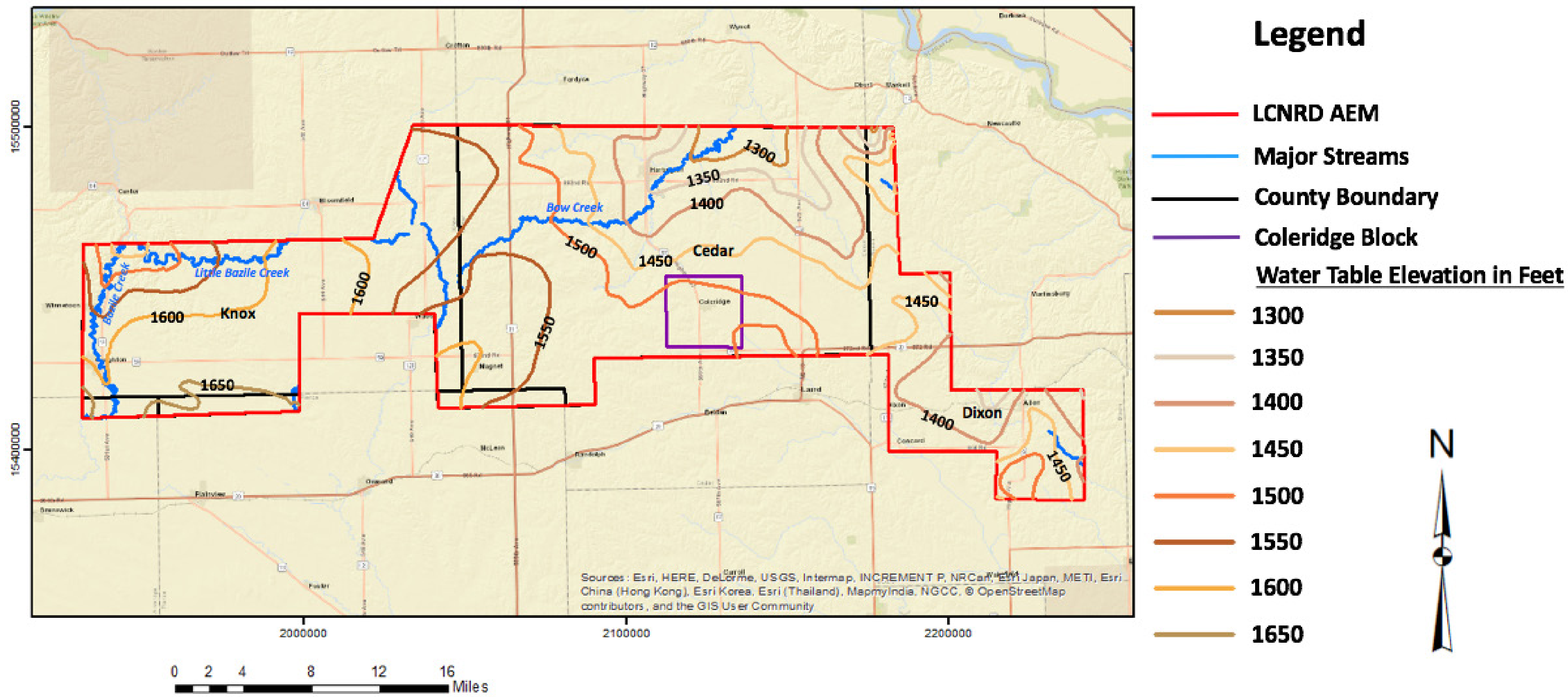


Figure 2-5. Elevation of ground water surface in survey area (NE-CSD, 1995). Map projection is NAD 83, UTM Zone 14 North, feet.

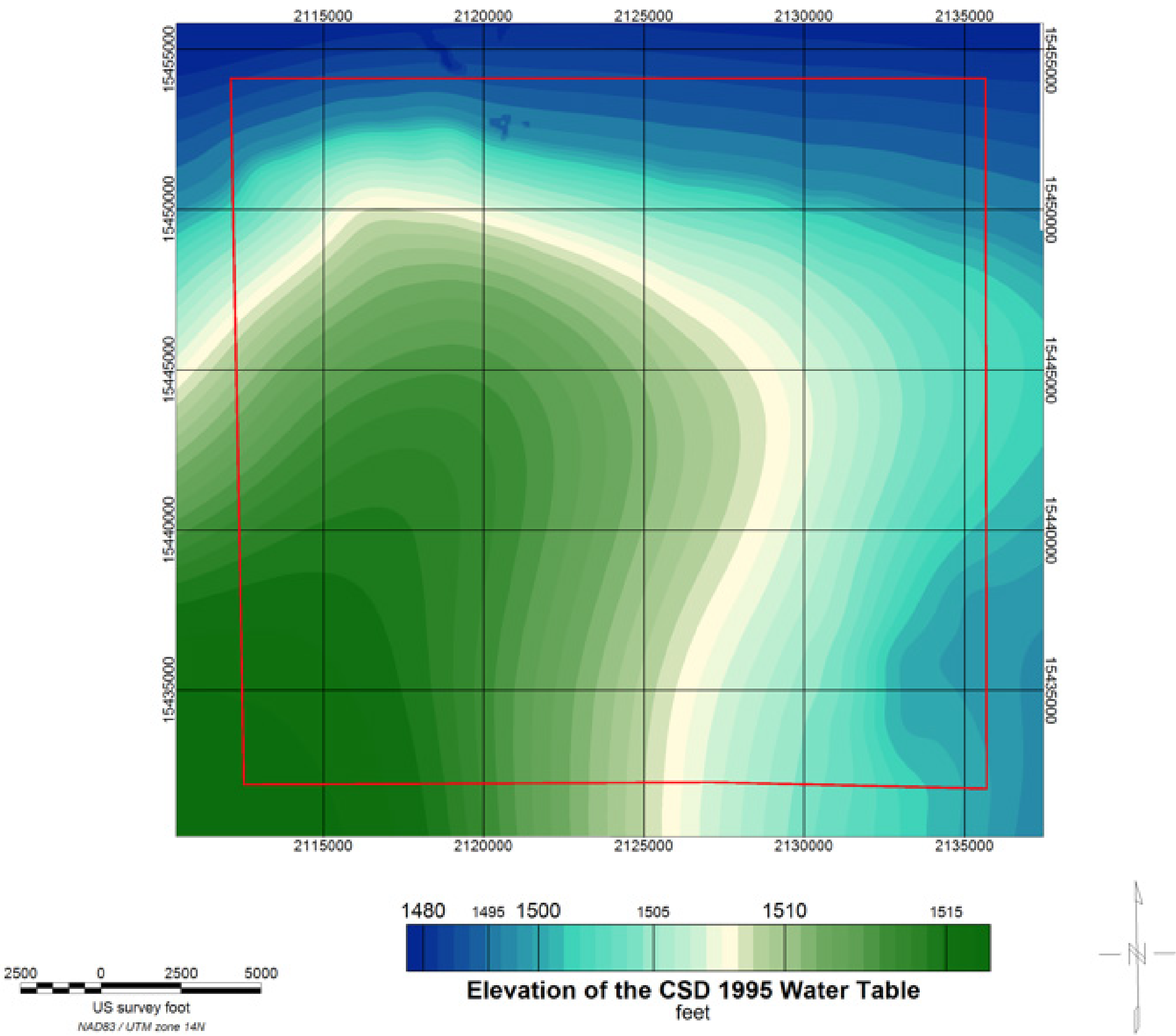


Figure 2-6. Elevation of ground water surface in the Coleridge Block survey area (NE-CSD, 1995). Map projection is NAD 83, UTM Zone 14 North, feet.

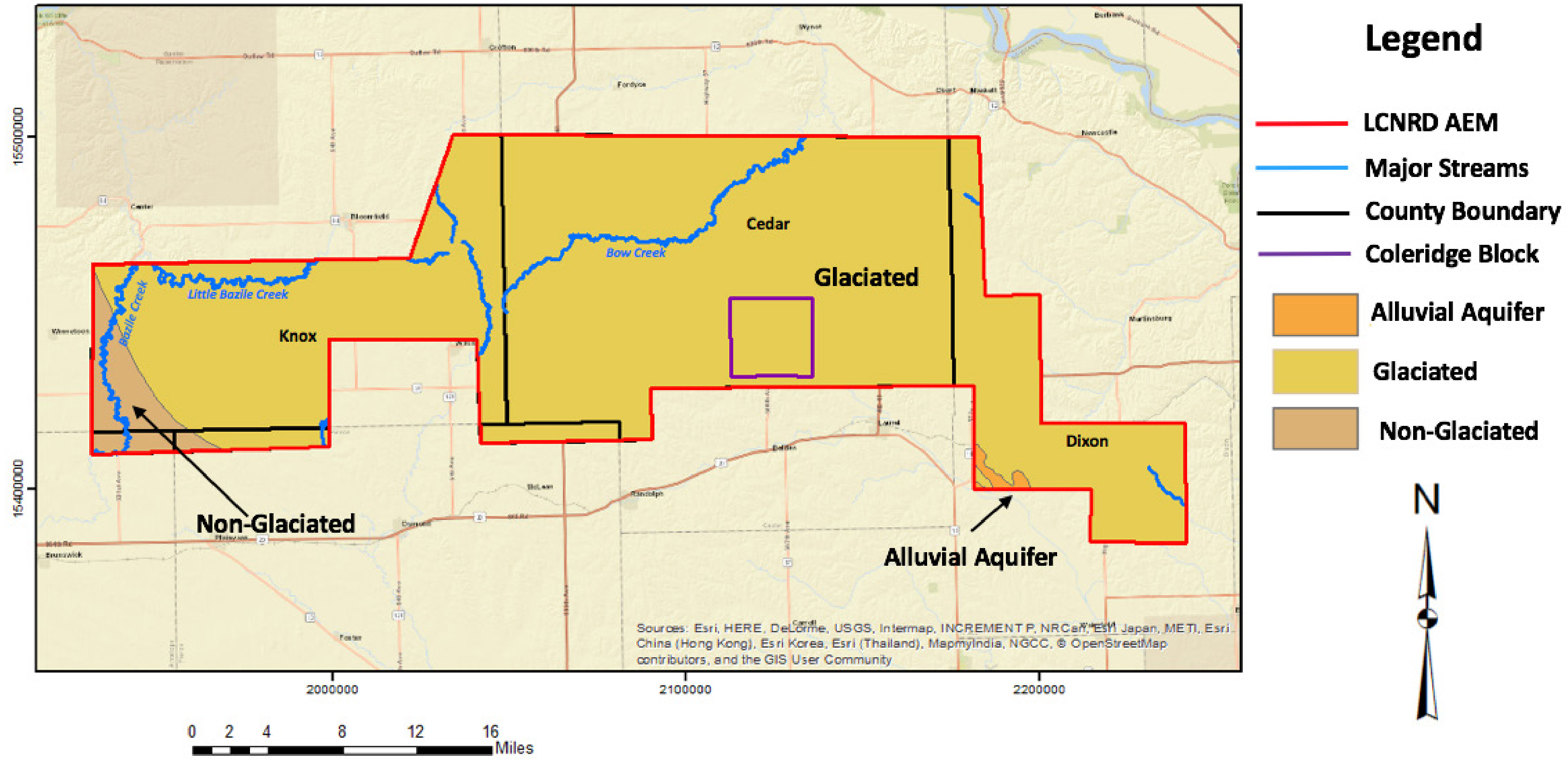


Figure 2-7. Generalized hydrogeologic connections to the streams and rivers within the LCNRD AEM survey area. Most of the area is glaciated with the remainder being made up of alluvial aquifer and non-glaciated sections (Olafsen-Lackey, 2005a). Map projection is NAD 83, UTM Zone 14 North, feet.

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*** aquifer material are composed of alluvial deposits. The ***To*** is present as erosional remnants that exist in Knox and Cedar counties.

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.

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

System	Series	Hydrologic unit	Maximum thickness, ft.
Quaternary	Holocene, Pleistocene	Aquifer in undifferentiated alluvial deposits	Generally, less than 150 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 surface water canals which can be 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 ~50 ft
Undifferentiated sand and gravel units in glacial-drift aquifers. Hydraulic head generally under confined conditions, but can be under unconfined conditions elsewhere. Thicknesses 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	Less than 50 ft
Generally unconsolidated to semi-consolidated sand, gravel, silt, and clay, underlying saturated Quaternary deposits. Limited extent near the northeast-west 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.			

2.2.1 Soil Characteristics in the LCNRD 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., 2015a). Estimated regional mean annual recharge rates for stream valleys within the survey 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 near Creighton, 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).

2.2.2 Aquifer Characteristics

Historic specific yield values within the survey area for the High Plains aquifer materials ranges from 0.5 to 0.20 based on Figure 2-8 from Olafsen-Lackey et al. (2005b). Specific yields are approximately 0.10 where the aquifer materials are made of mostly silt size particles. Aquifer materials made up of sand and gravel size particles range from approximately 0.10 to 0.25. This work is regional in nature and can change with the addition of aquifer tests to determine aquifer characteristics. Specific Yield is an estimate of the percentage of water in an aquifer that will drain under gravity (Heath, 1983).

Historic transmissivity values within the survey area for the High Plains aquifer materials range from 20,000 to 50,000 gpd/ft based on Figure 2-9 from Olafsen-Lackey et al. (2005c). This work is regional in nature and can change with the addition of aquifer tests to determine aquifer characteristics. Transmissivity is the capacity of an aquifer to transmit water and is a function of the hydraulic conductivity times the aquifer thickness (Heath, 1983).

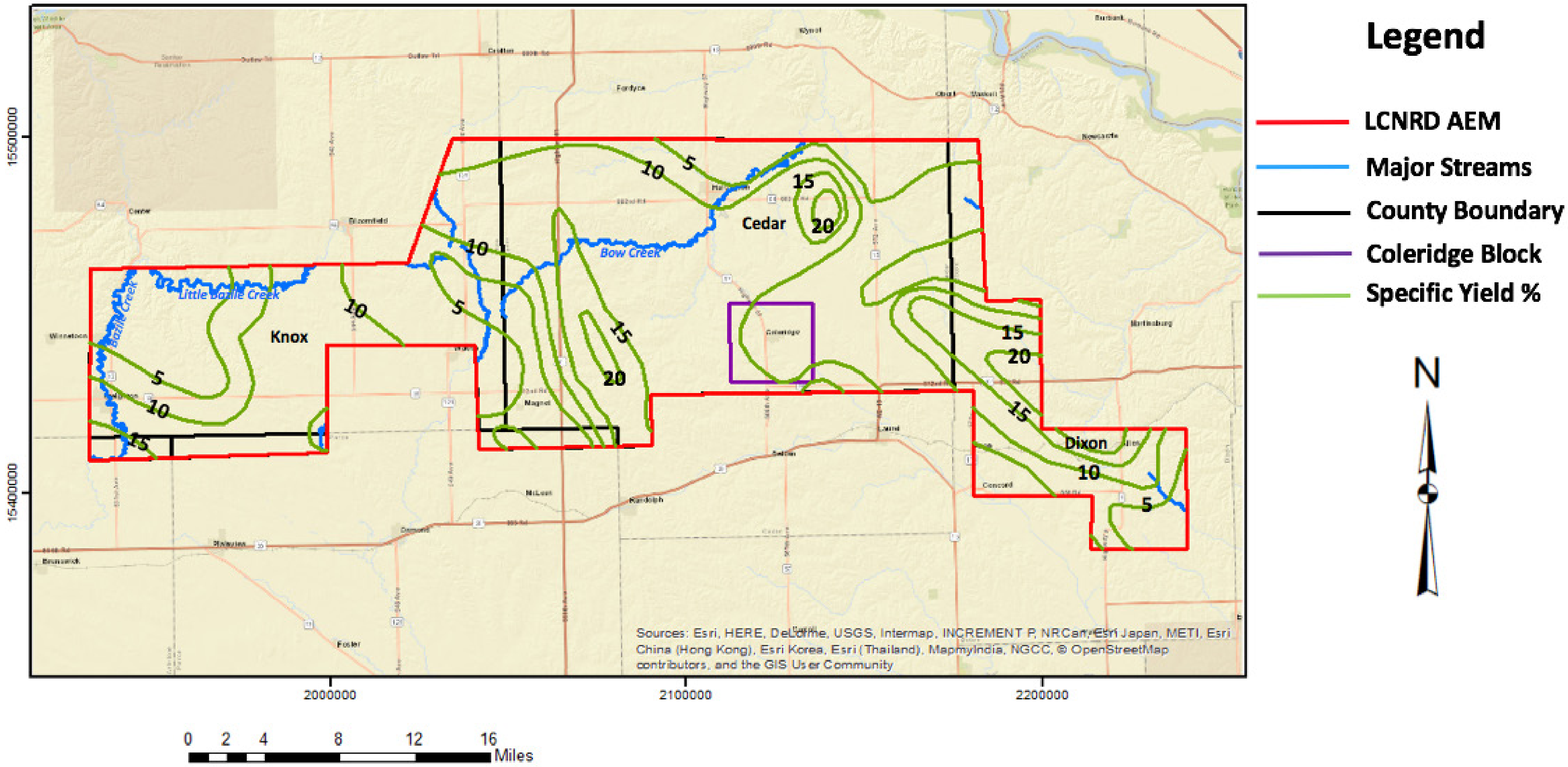


Figure 2-8. Specific yield values within the Reconnaissance and Coleridge Block AEM survey areas ([Olafsen-Lackey et al., 2005b](#)). Map projection is NAD 83, UTM Zone 14 North, feet.

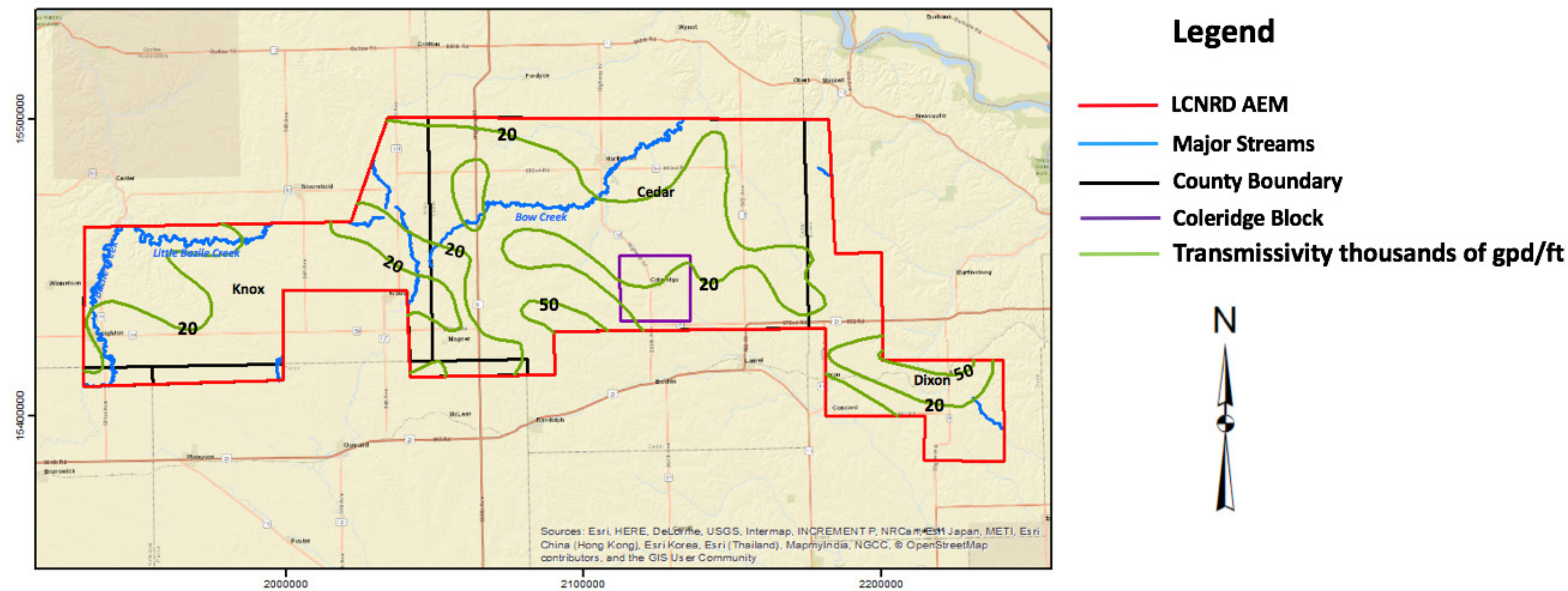


Figure 2-9. Transmissivity values within the reconnaissance and Coleridge Block areas (Olafsen-Lackey et al., 2005c). Map projection is NAD 83, UTM Zone 14 North, feet.

2.2.3 Connectivity to Surface Water and to Other Aquifers

In the Creighton area and locally elsewhere in the survey area, ***Q*** and ***To*** deposits are hydraulically connected to shallower aquifers and streams (Gosselin, 1991). The deeper aquifers can discharge into the shallow groundwater system or into the streams. The reverse is also true. Detailed studies are not available for precise estimates of groundwater-surface water relationships or where they occur. It is thought that temporal communication changes with increased pumping during the irrigation season (June to September). During this time groundwater gradients change and communication between the two systems can be enhanced. Areal communication is variable as it is possible that a glacial-drift aquifer (such as a paleovalley aquifer) could be in communication with an aquifer or stream at one location and not another. There is limited connection from the glacial aquifers to the streams.

2.2.4 Water Quality

Within the historical work for ENWRA in Northeast Nebraska, 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 survey 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. (2015a and 2015b).

Most groundwater in the area appears fresh. In some locations, larger specific conductivity, sulfate, and total dissolved solids concentrations were observed. In Cedar, Knox, and Dixon counties the average concentration of total dissolved solids (TDS) ranges from 251 to 750 mg/l (from Engberg, 1984, Figure 11). A small area that straddles the southern Knox-Cedar county line has a range of 751 to 2250 (Engberg, 1984). The quality of the groundwater in the survey 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 LCNRD AEM survey area are indicated in Figure 3-1 and Figure 3-2. Of the total of 127 CSD holes utilized in this investigation, 36 contained geophysical logging information including resistivity, gamma-gamma, temperature, calibration, etc., 66 holes contained lithology information, and 25 holes contained stratigraphic information. The six-pointed stars in Figure 3-2 contain both lithology and stratigraphy. The locations of the NE-DNR registered wells used in the LCNRD AEM survey are indicated in Figure 3-3. A total of 1,408 registered wells contained usable lithology and/or stratigraphy information. The locations of the 5 NOGCC wells used in the LCNRD AEM survey are indicated in Figure 3-4. Four NOGCC wells contained both lithology and stratigraphy information and one hole contained only lithology information (upright triangles in Figure 3-4). The six-pointed stars in Figure 3-4 contain both lithology and stratigraphy.

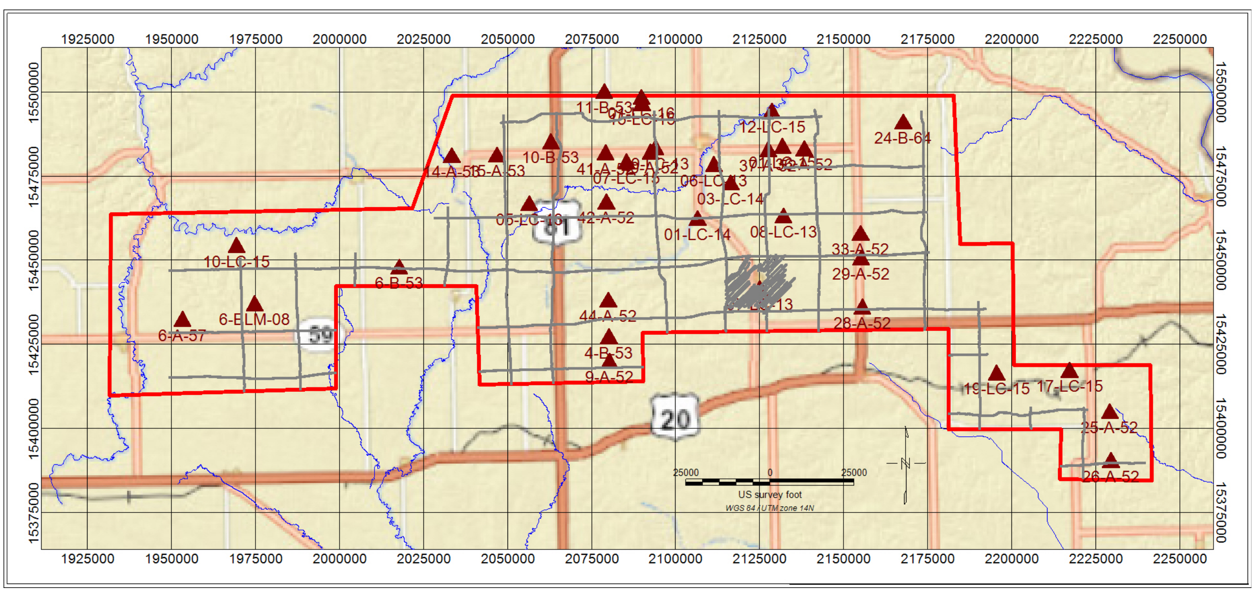


Figure 3-1. Locations of the Conservation Survey Division (CSD) boreholes (brown triangles) containing geophysical log information and the airborne electromagnetic flight lines (grey lines) in the LCNRD AEM survey area. Projection is NAD83, UTM 14 North (feet).

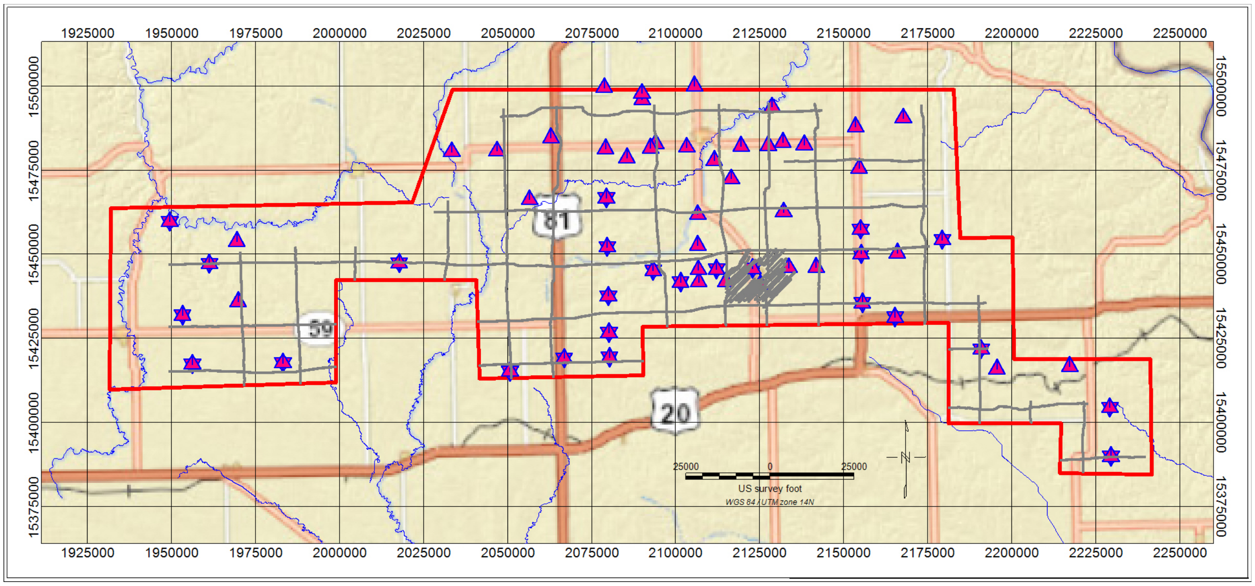


Figure 3-2. Within the LCNRD AEM survey area, locations of the Conservation Survey Division (CSD) boreholes containing lithology information (upright pink triangles) and stratigraphy information (inverted pink triangles). Locations with both lithology and stratigraphy appear as six-pointed pink stars.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

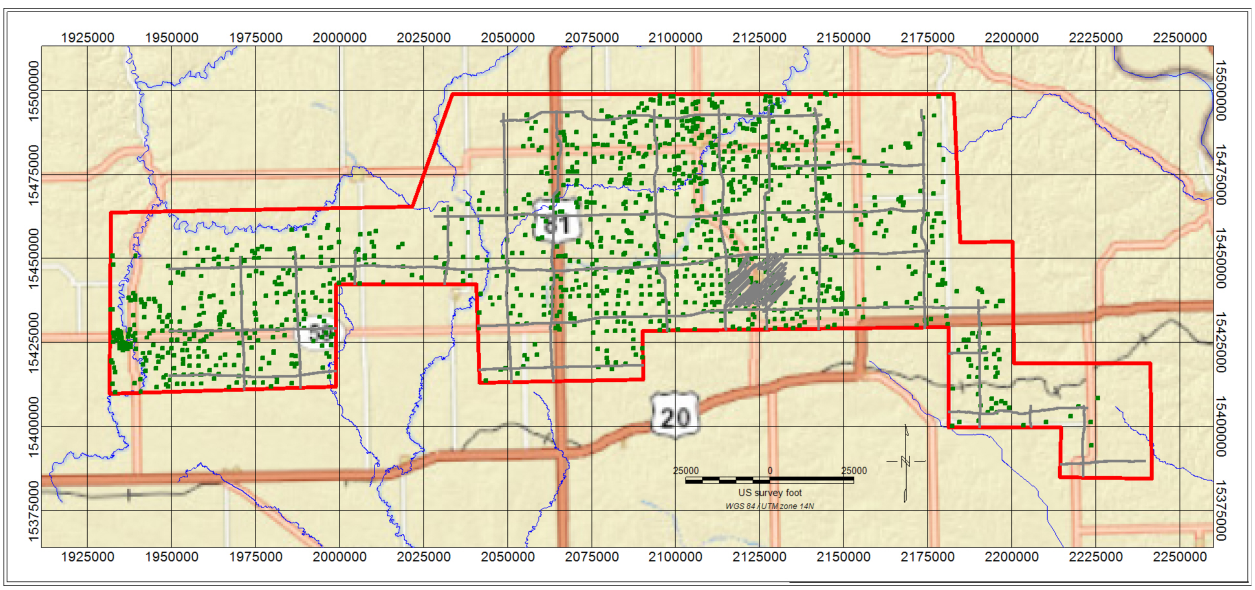


Figure 3-3. Locations of the Nebraska Division of Natural Resources Registered wells (green dots) and the airborne electromagnetic flight lines (grey lines) in the LCNRD AEM survey area. Projection is NAD83, UTM 14 North (feet).

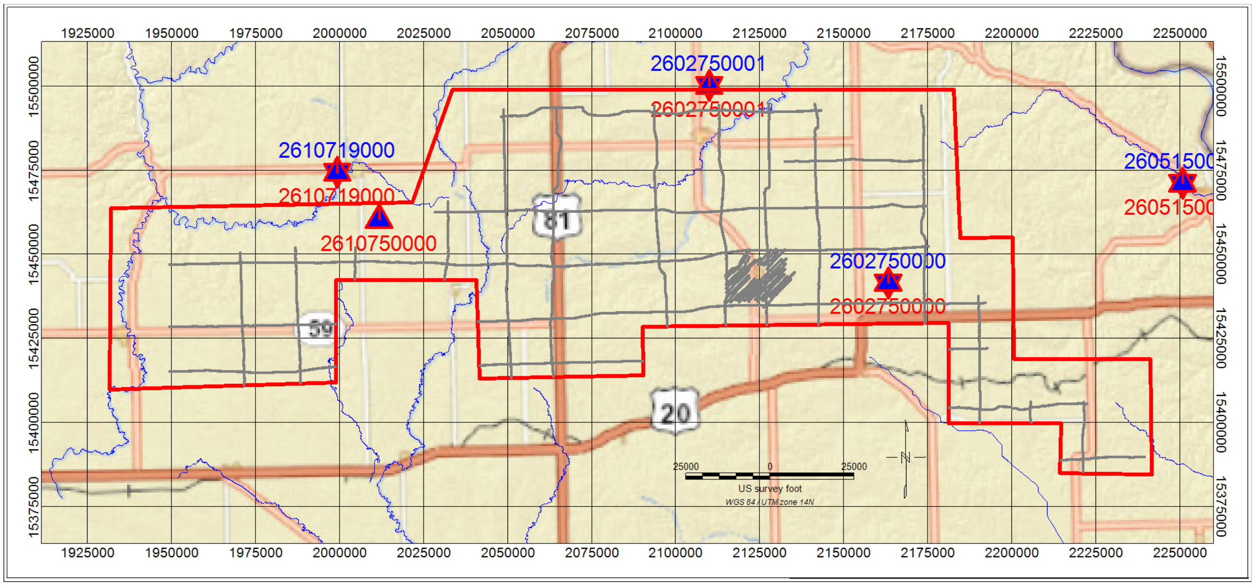


Figure 3-4. Locations of Nebraska Oil and Gas Conservation Commission wells with lithology (upright blue triangles with red edges and red labels) and stratigraphy (inverted blue triangles with blue labels) and the AEM flight lines (grey lines) in the LCNRD AEM survey area. Projection is NAD83, UTM 14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

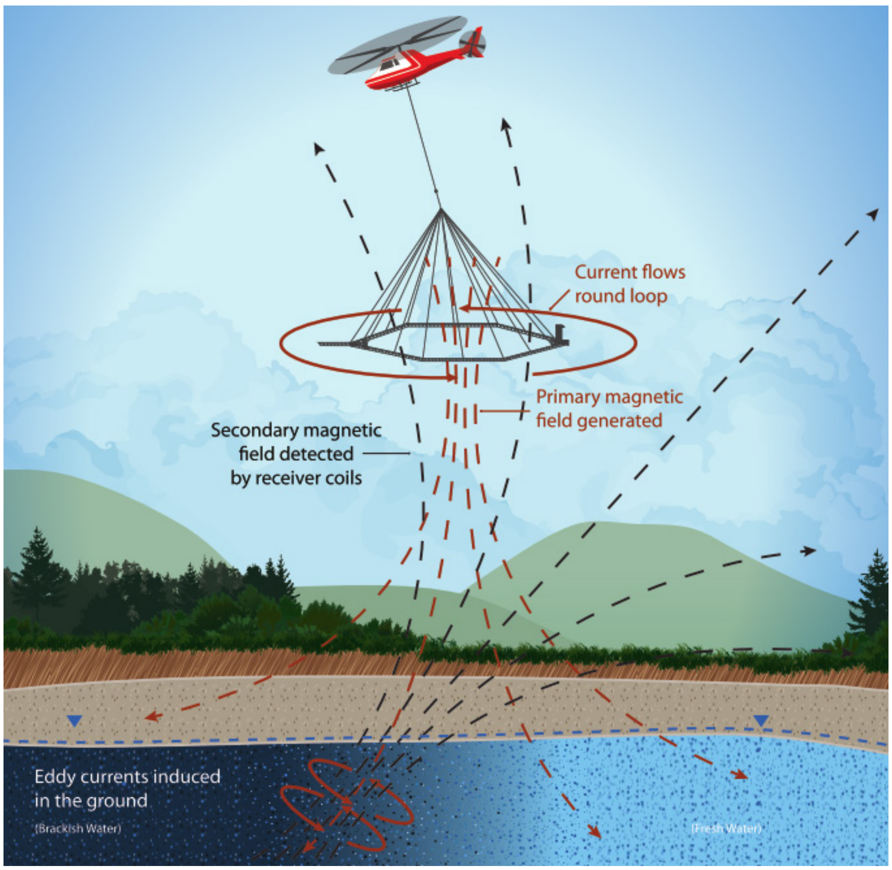
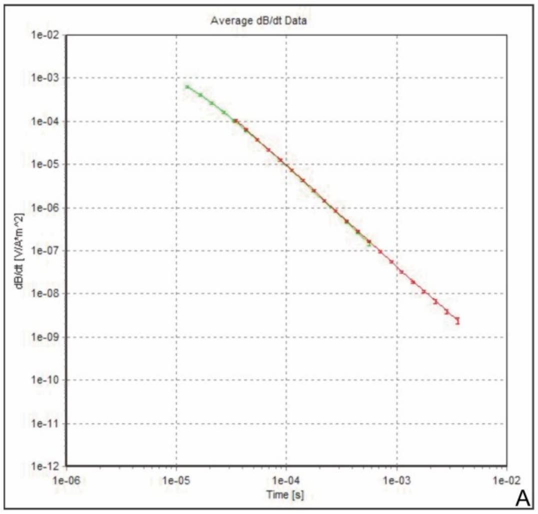


Figure 4-1: Schematic of an airborne electromagnetic survey, modified from Carney et al. (2015a).

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				

B

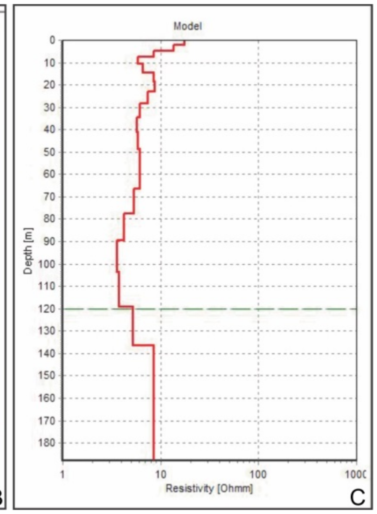


Figure 4-2: A) Example of a dB/dt sounding curve. B) Corresponding inverted model values. C) Corresponding resistivity earth model.

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 LCNRD, three types of utilities (pipelines, railroads, and power lines) were located. Various public power districts in Eastern Nebraska provided power line locations in Google Earth “kmz” format that were then converted to a Geographic Information Systems (GIS) Arc shapefile format. Some areas did not have coverage available for power line locations and were mapped by inspection from Google Earth imagery. Public power entities that provided power line location data included: North Central Public Power District, Cedar-Knox Public Power District, and the Nebraska 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 in order to avoid electromagnetic coupling with the previously mentioned utilities. This was done by moving along each flight line in Google Earth to inspect the path for visible power lines, radio towers, railroads, highways and roads, confined feeding operations and buildings, and any other obstructions that needed to be avoided during flight.

At the conclusion of the design process the LCNRD reconnaissance flight lines were approximately 46 miles in length at their longest in the east-west direction and about 16 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 Coleridge area a dense flight block was developed running from southwest to northeast with the longest flight line being approximately 2.9 miles in length. The Coleridge AEM flight lines are separated by approximately 0.15 miles.

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.

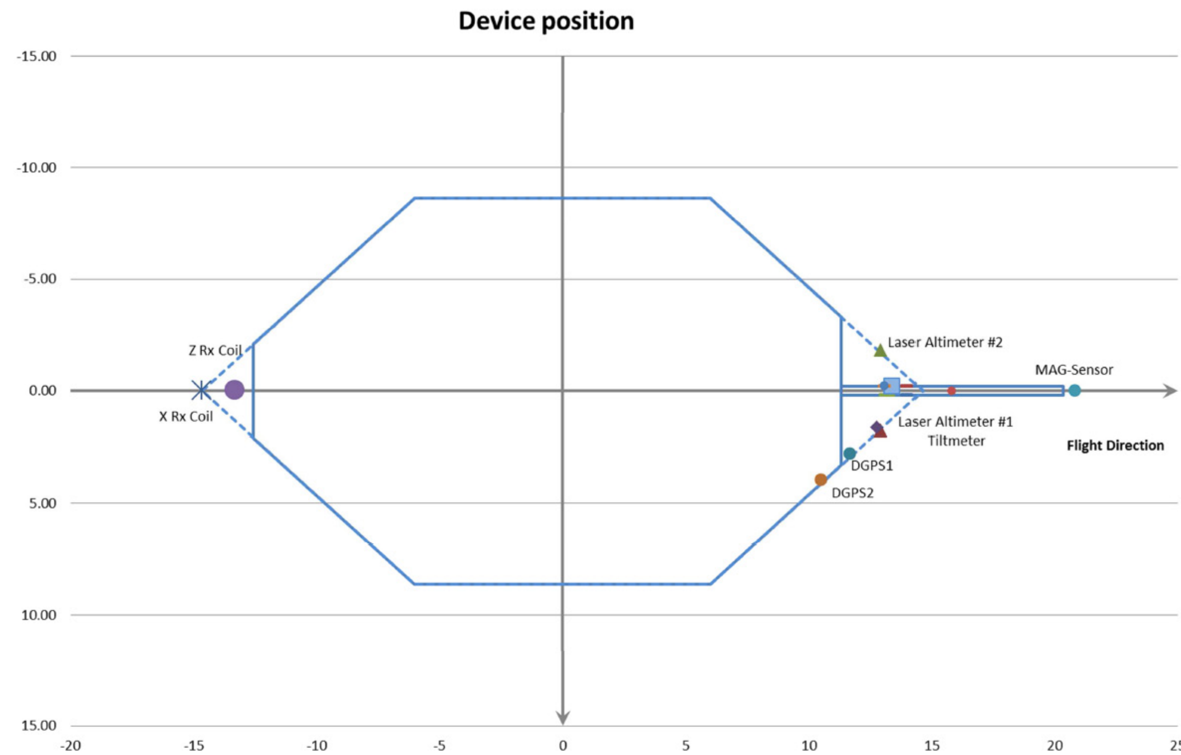


Figure 4-3: SkyTEM304M frame, including instrumentation locations and X and Y axes. Distances are in meters. Instrumentation locations listed in Table 4-1.

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.

Instrument	Easting (ft)	Northing (ft)	UTM Zone
Magnetometer Base Station (Norfolk Airport)	1980432	15497198	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 Genoa 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 353.9 line-miles (573.2 line-kilometers) were acquired over the LCNRD AEM survey area on July 23-26, 2016. Of this total, approximately 66.2 line-miles (107.2 line km) were flown in a dense block around Coleridge. The Creighton, Hartington, and Wayne airports was 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.

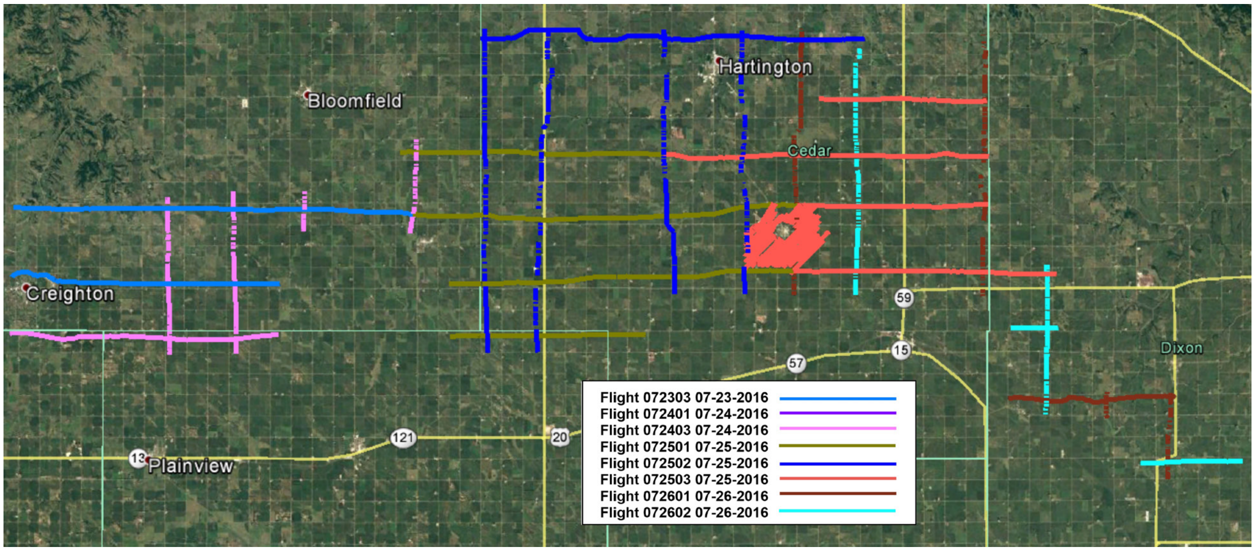


Figure 4-5: LCNRD AEM flight lines grouped by acquisition date.

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 of the tilt meter readings with a median filter of three seconds and an average filter of two seconds. The altitude data were corrected using a series of two polynomial filters. The lengths of both eighth-order polynomial filters were set to 30 seconds with shift lengths of six (6) seconds. The lower and upper thresholds were 1 and 100 meters, respectively.

Trapezoidal spatial averaging filters were next applied to the AEM data. The times used to define the trapezoidal filters for the Low Moment were $1.0x10^{-5}$ sec, $1.0x10^{-4}$ sec, and $1.0x10^{-3}$ sec with widths of 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, 336.7 line-miles (545.5 line-km) of data were retained for the final inversions for the LCNRD AEM reconnaissance and block surveys. This amounts to a data retention of 95%. This high rate is the result of careful flight line planning and design.

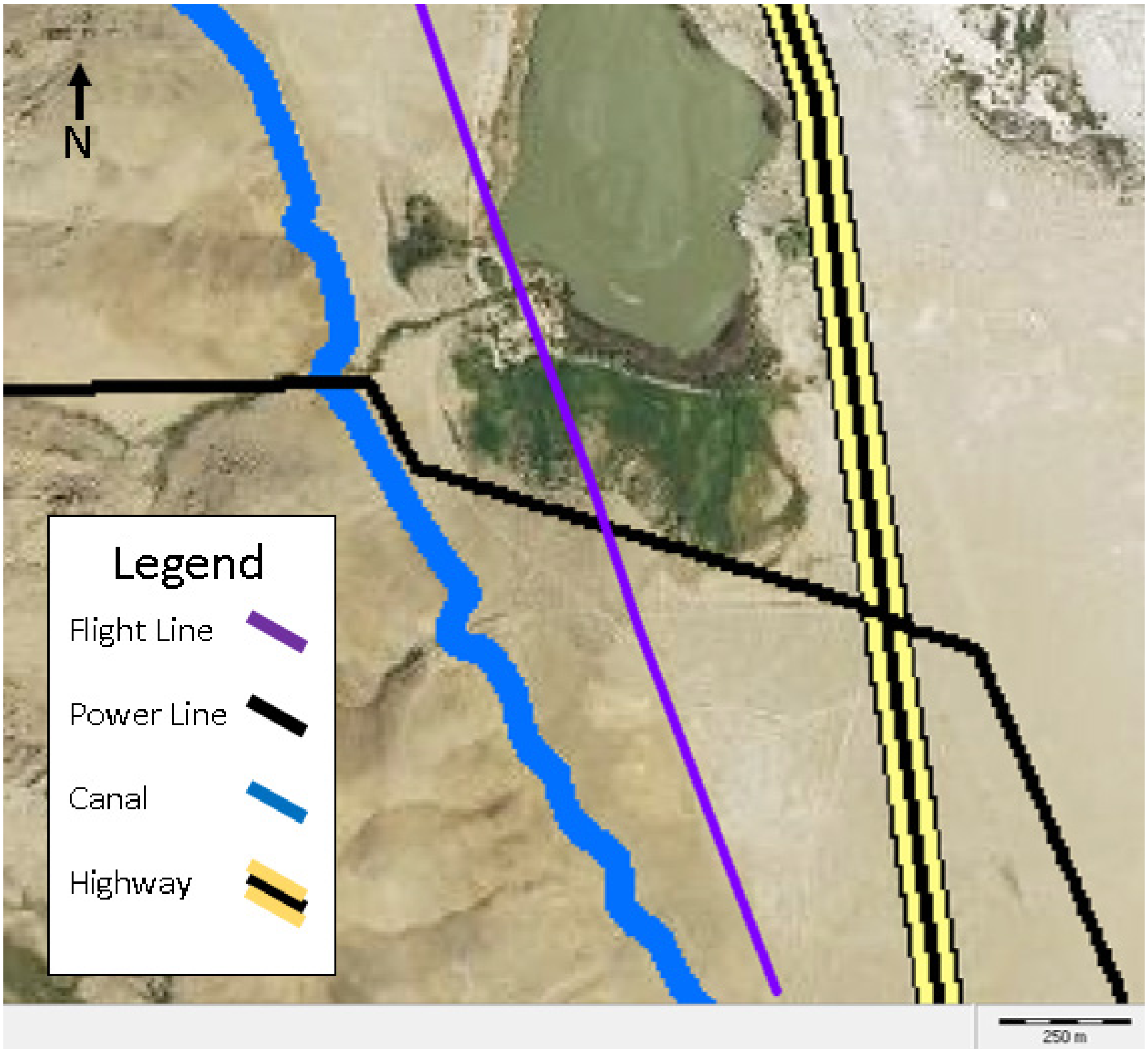


Figure 4-6: Example locations of electromagnetic coupling with pipelines or power lines.

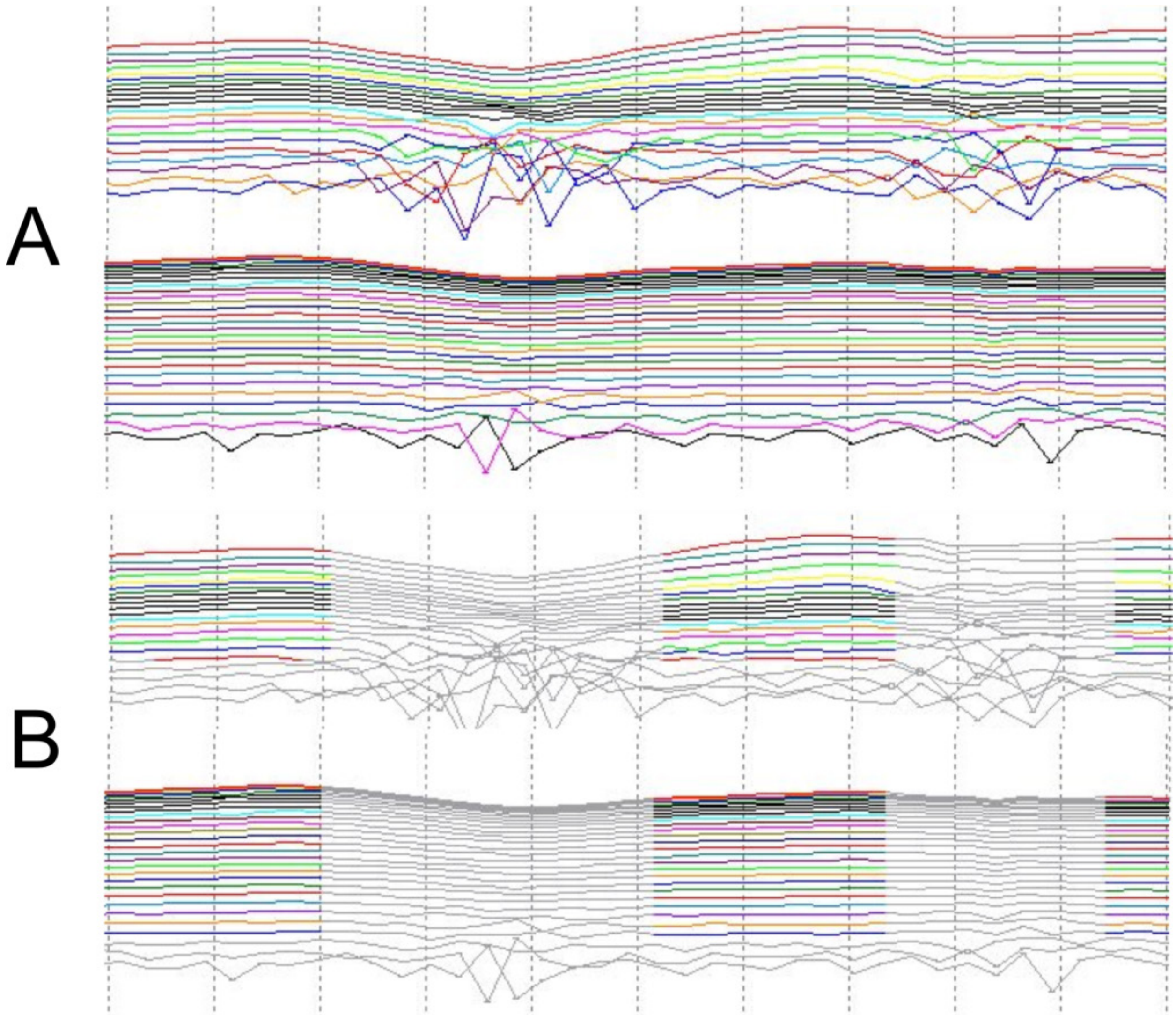


Figure 4-7: A) Example of AEM data from the LCNRD AEM survey affected by electromagnetic coupling in the Aarhus Workbench editor. The top group of lines is the unedited data with the Low Moment on top and the High Moment on the bottom. The bottom group shows the same data after editing.

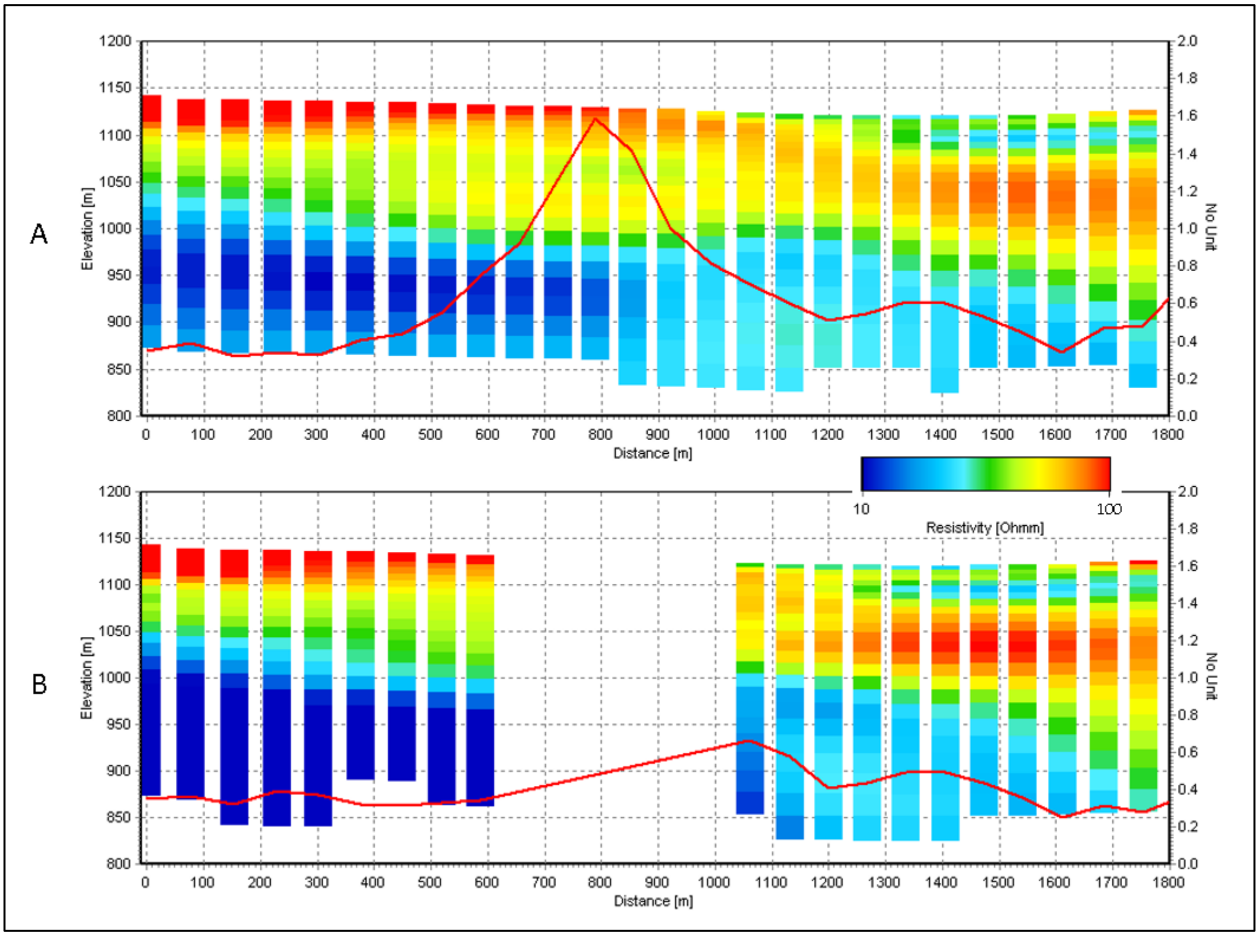


Figure 4-8: A) Example of Laterally-Constrained inversion results where AEM data affected by coupling with pipelines and power lines were not removed. B) Inversion results where AEM data affected by coupling were removed.

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 High Moment data block, a Fourier Transform (FT) is performed on the latest usable time gate data. The FT is evaluated at the local power line transmission frequency (60 Hz) yielding the amplitude spectral density of the local power line noise. The PLNI data for the LCNRD AEM survey are presented in Figure 4-9. The LCNRD-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.

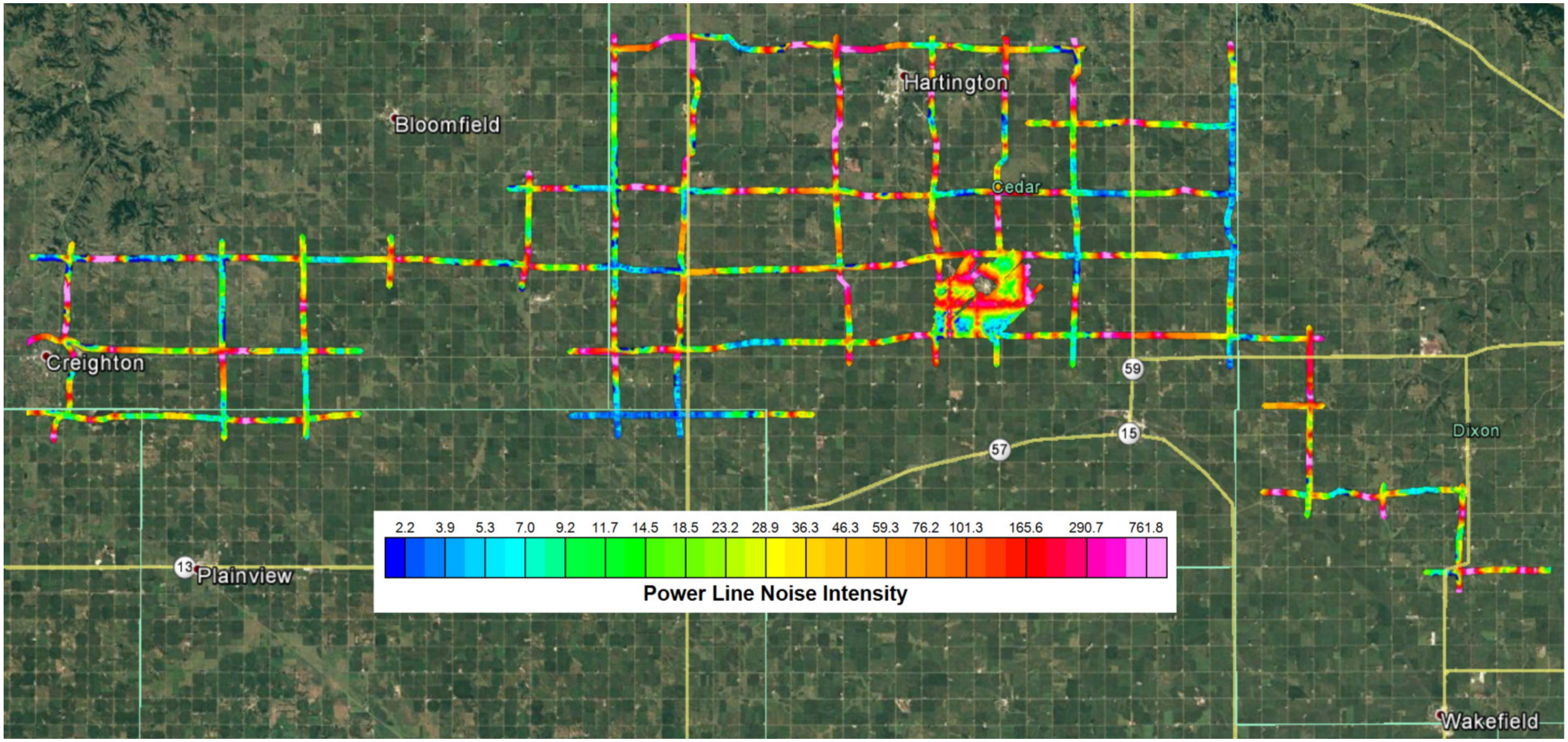


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Figure 4-9: Power Line Noise Intensity (PLNI) map of the LCNRD project area.

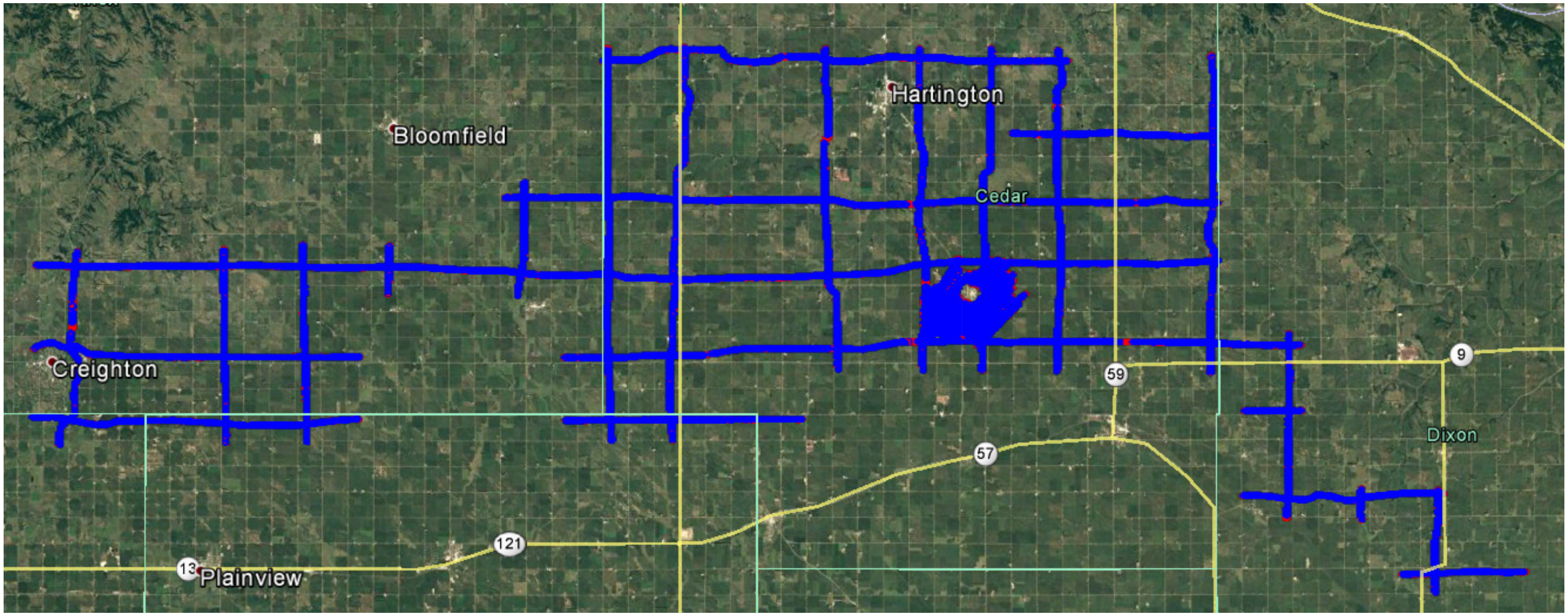

Figure 4-10: Locations of inverted data (blue lines) along the AEM flight lines (red lines) in the LCNRD AEM survey area. Where blue lines are not present indicates decoupled (removed) data. Google Earth kmz's of the inverted data locations as well as the flight lines are included in *Appendix 3-Deliverables\KMZ*.

4.4.5 Magnetic Field Data

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

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 LCNRD 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 anomalies that can be observed to the north of Coleridge and in the western portions of the LCNRD reconnaissance survey area.

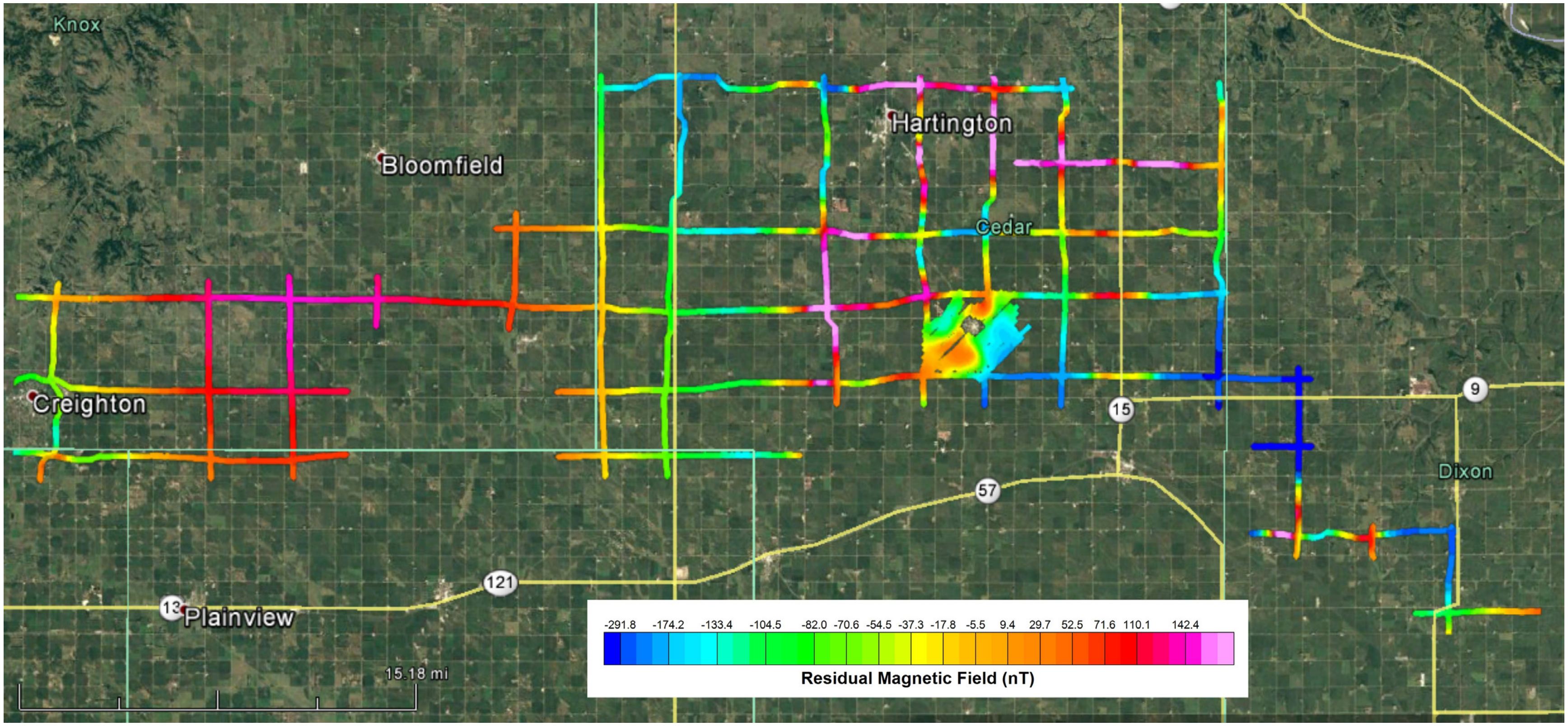

Figure 4-11: Magnetic Total Field intensity data for the LCNRD AEM survey area corrected for diurnal drift, with the International Geomagnetic Reference Field (IGRF) removed.

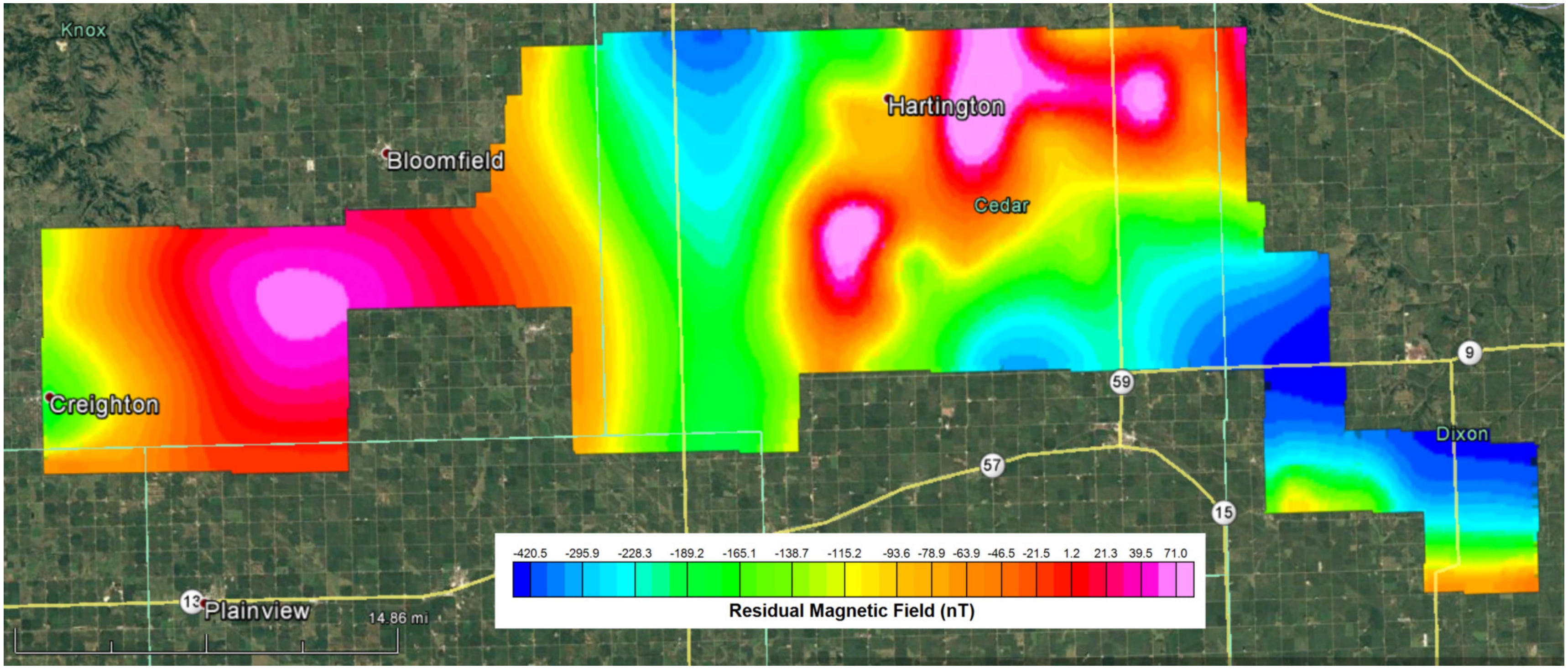

Figure 4-12: USGS magnetic Total Field intensity residual data for the LCNRD survey area corrected for diurnal drift, with IGRF removed (Sweeney and Hill, 2005). The data was collected on an approximately 5 mile line spacing and upward continued to a reference elevation of 1000 ft.

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 LCNRD 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			

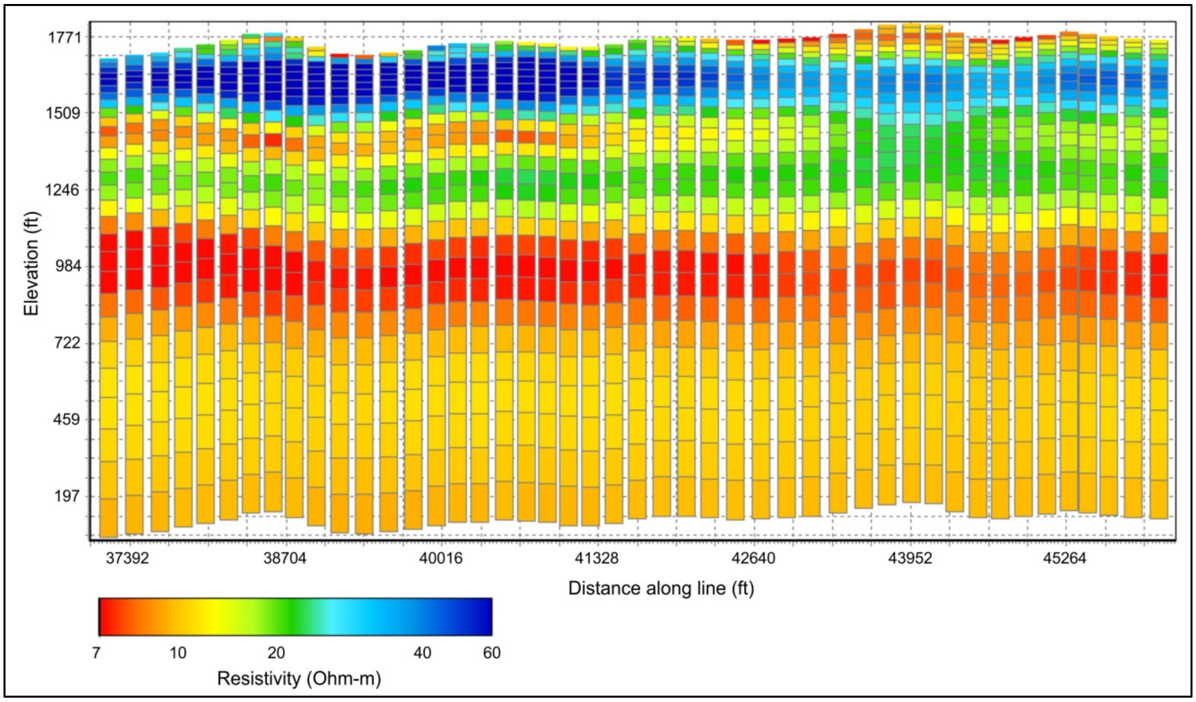

Figure 4-13: An example of an AEM profile illustrating increasing model layer thicknesses with depth.

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

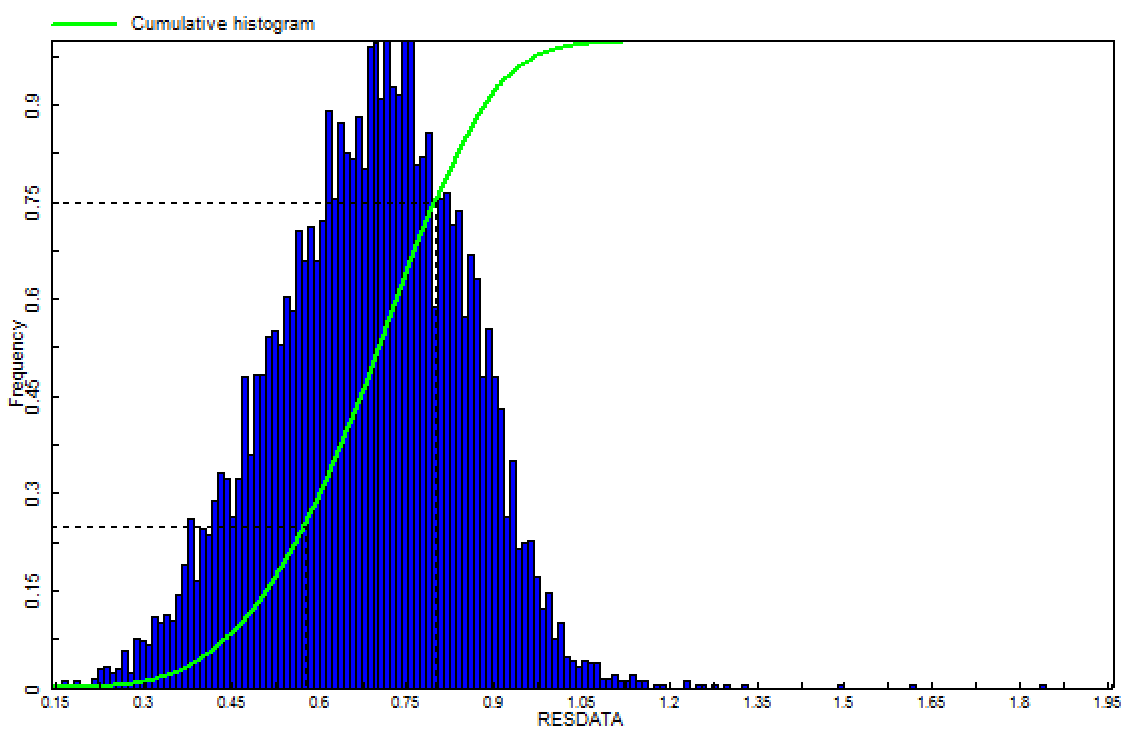

Figure 4-14: Data/model residual histogram for the LCNRD SCI inversion results.

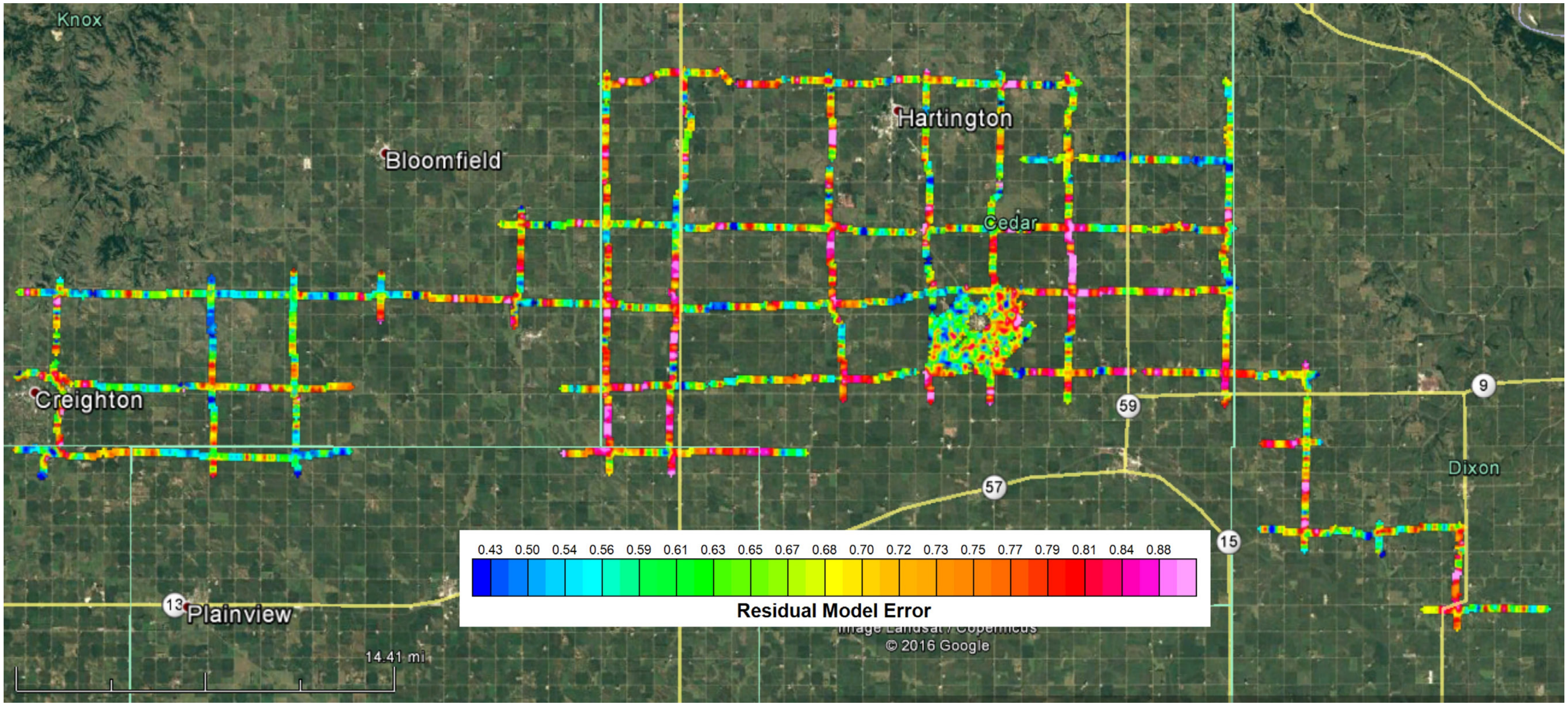

Figure 4-15. Map of data residuals for the LCNRD SCI inversion results.

5 AEM Results and Interpretation

This section provides the details on the process involved in the interpretation of the LCNRD 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 survey area. This included lines that composed the 3-mile reconnaissance grid and closely spaced approximately 800 ft detailed lines around Coleridge, Nebraska. 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.

Table 5-1. Combination of flight lines within the LCNRD 2016 AEM 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
L134101, and L134102	Coleridge Block Southwest-Northeast	L268203
L134301, and L134302	Coleridge Block Southwest-Northeast	L268603
L135101, and L135301	Coleridge Block Southwest-Northeast	L270402
L135501, and L135701	Coleridge Block Southwest-Northeast	L271202
L135901, and L136101	Coleridge Block Southwest-Northeast	L272002
L136301, and L136501	Coleridge Block Southwest-Northeast	L272802

A portion of the LCNRD has had AEM data collection before that is summarized in Carney et al. (2015a), and AGF (2017a). 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 examined in AGF (2017a) as part of the BGMA AEM survey of which LCNRD is a participant. As discussed above, the portion of the BGMA within the LCNRD is included within this report. Also, a small portion of the LENRD is included within this report to facilitate the mapping of the margins of the LCNRD. 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. No issues were observed within the AEM data within the LCNRD survey. Several other comparisons can be made within the LCNRD due to 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 LCNRD 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 5-1 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.

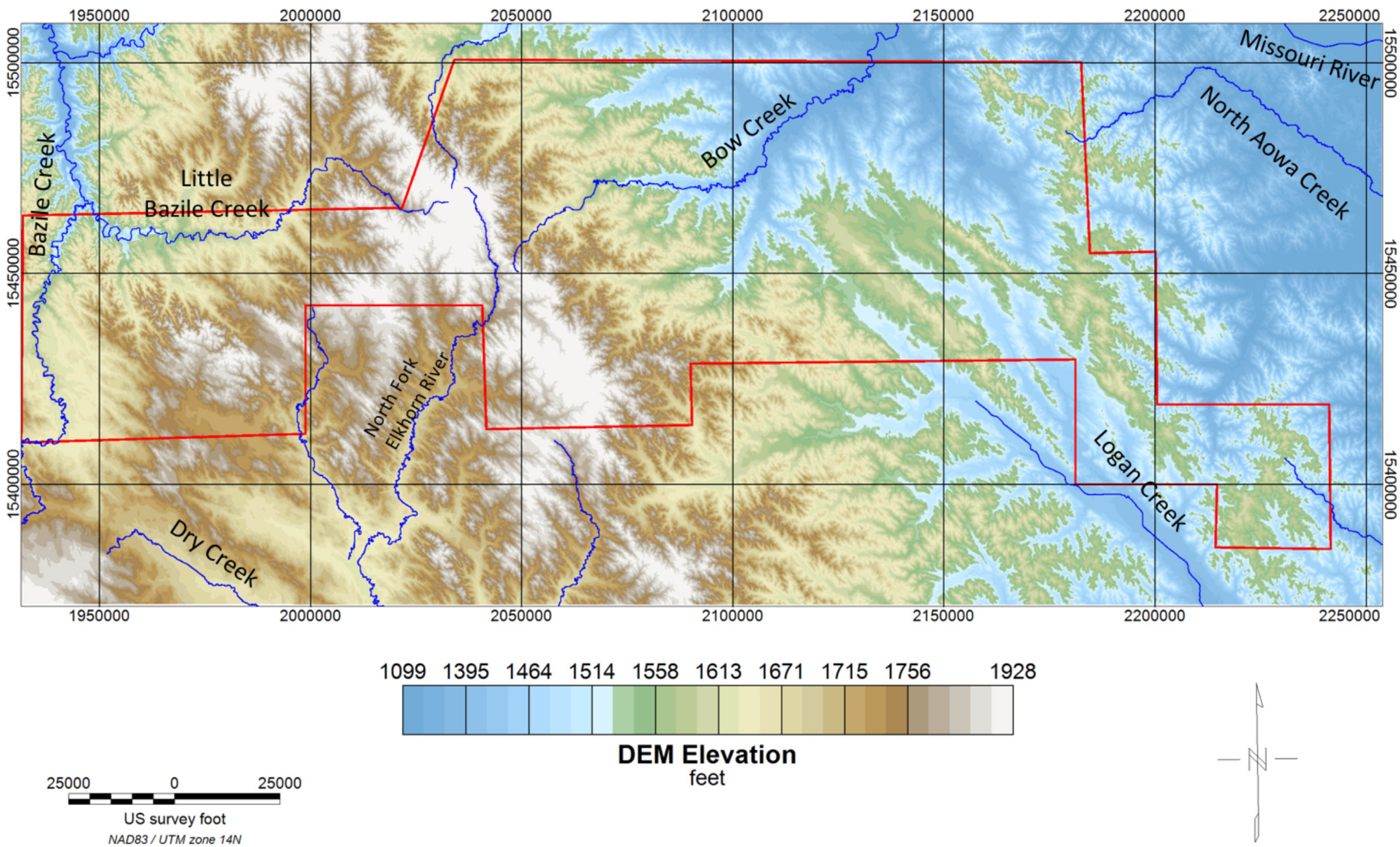

Figure 5-1. Map of the Digital Elevation Model for the LCNRD AEM survey area. Data source is the one (1) arc-second National Elevation Dataset (U.S. Geological Survey, 2016). North American Datum of 1983 (NAD 83) and the elevation values are referenced to the North American Vertical Datum of 1988 (NAVD 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 geologic units including: Quaternary (***Q***), Tertiary Ogallala Group (***To***), Cretaceous Pierre Shale (***Kp***), Cretaceous Niobrara (***Kn***), Cretaceous Carlile Shale (***Kc***), Cretaceous Greenhorn Limestone and Cretaceous Graneros Shale (***Kgg***), and Cretaceous Dakota Group (***Kd***). The interpreted geological units included the ***Q***, ***To***, ***Kp***, ***Kn***, ***Kc***, ***Kgg***, and ***Kd*** from the upper ground surface 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*** contact and then the ***Kc, Kn***, ***Kgg, Kd*** contacts and then finally the ***To*** interface. The process was iterative around the eroded ***Kp*** overlying the ***Kn*** and the eroded ***Kn*** overlaying the ***Kc*** due to the irregular boundary.

The interpretation of the ***To*** included examination of the CSD and NE-DNR boreholes and comparison with the AEM resistivities. Unlike the ***Kp/To*** and ***Kp/Q*** surfaces, there is not a strong resistivity contrast between the ***Q*** and the ***To***. Thus, 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 low electrical resistivity layer that was also indicated in the borehole logs as the base of aquifer. Many of the CSD as well as the NE-DNR borehole logs stop at the ***Kp*** due to that stratigraphic unit not being considered aquifer material since it is composed predominantly of shale, containing clay minerals. Many of the CSD boreholes have stratigraphic calls that assist in the location of the ***Kp***. For the profiles, the clipping distance from the flight line was set independently for the CSD boreholes and the NE-DNR boreholes. Typically, the CSD clipping distance was set to one mile or 5,280 ft; the NOGCC wells were set to 2.84 miles or 15,000 ft; and the NE-DNR boreholes was set to a quarter mile or 1,320 ft. The inversion DOI was also inspected during interpretation of the profiles, but was almost always below the top of the ***Kp*** in the LCNRD 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 an electrically resistive unit to a conductive unit based on the presence of the clay minerals within the shale, chalk, and limestone lithologies. The best way to interpret the 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 more 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 on top of the ***Kn***.

The ***Kc*** unit is identified as a low resistivity unit in the LCNRD. As the ***Kc*** is composed of shale containing clay minerals, the conductive nature of the unit is easily identified and interpreted. Additionally, CSD and NE-DNR wells can 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 is interrupted beneath the ***Kc***. The interpretation of the bottom of the ***Kgg*** is more challenging due to the variably resistivity of the ***Kd*** immediately below the conductive Graneros Shale. When the ***Kd*** contains resistive sands and sandstone, the lower contact of the ***Kgg*** and the top of the ***Kd*** are 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 and 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 5-2 is a 43-mile-long east-west line L618909 in the middle of the LCNRD survey area. This line encompasses all the geological units mapped within the LCNRD and 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 central 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 indicated above, the top of the ***Kn*** is detectable when it is overlain by the ***Kp.*** Otherwise the top is interpreted by the use of 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 with the ***Q*** materials with the exception of when the ***Q*** material contains large areas of conductive clays. 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 NOGCC well that penetrates the sandstone of the ***Kd***.

The regional nature of the long reconnaissance lines within the LCNRD is illustrated in Figure 5-2 which also illuminates the Cretaceous units and their structural attitude. After completing the interpretation of the Cretaceous bedrock units, the Q materials can be inspected. Along Line L618909 many positive correlations of the AEM resistivity and the lithology can be observed in the CSD and the NE-DNR wells.

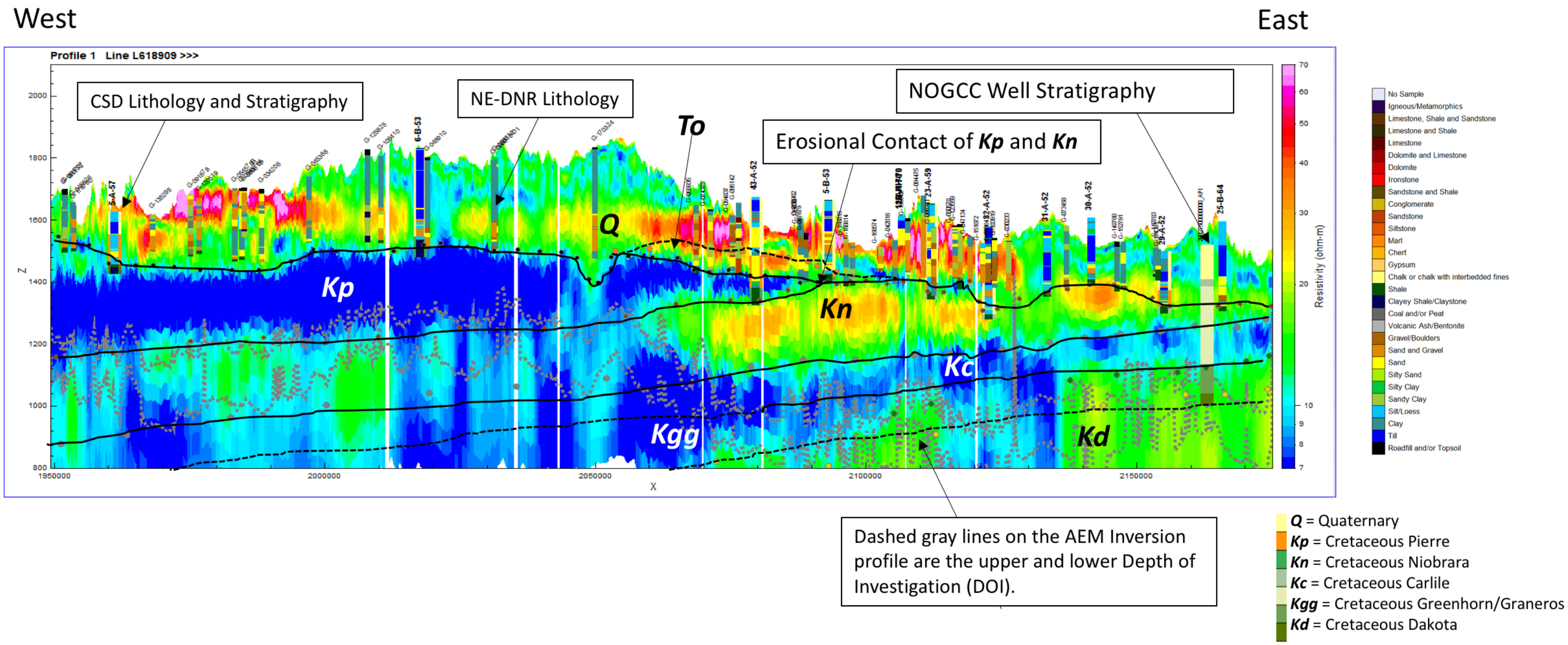

Figure 5-2. Example 2D Profile- 43-mile east-west AEM flight line L618909 in the middle of the LCNRD survey area. CSD and Nebraska DNR borehole lithology and stratigraphy logs are indicated on the AEM inverted earth models. A single NOGCC well is indicated on the eastern end of the line. Interpretations are indicated by lines labeled with stratigraphic names.

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Line L294602, a 15-mile-long north-south line on the western end of the LCNRD survey area, is presented in Figure 5-3. Many of the geological units within the LCNRD can be seen along this line. The ***To*** is interpreted as a thin deposit in the center of the line overlying the ***Kp*** as well as the southern section of the line***.*** The interpretation of the ***Kp*** is easily accomplished including two parts overlying the ***Kn.*** The top of the ***Kn*** is exposed in the area where the ***Kp*** is eroded. Below the ***Kn***, the ***Kc*** is detectable as a conductor, but is masked by the DOI on the southern end due to the depth and the 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*** are drastic in some areas and is reflected by the resistivity distribution, especially in the area of the thick, low resistivity ***Q*** deposits.

Line L136701, a 3.4-mile-long northeast-southwest line located within the Coleridge block, is presented in Figure 5-4. In this location, the ***To*** and the ***Kp*** are not present and the ***Kn*** is the bedrock unit. The interpretation of the top of the ***Kn*** is complicated in this area but is facilitated by the presence of CSD test holes and 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***. Within the ***Q*** section, discrete bodies of sand are indicated by their resistivities and by the lithology data from nearby NE-DNR wells that show zones of low resistivity identified as till, clay, and silt.

The above examples illustrate the interpretive process that was used on the profiles provided within this report. Each flight line with the resistivity and interpretation including the Quaternary/Tertiary Aquifer material mapping (Section 5.2.1) are included in *Appendix 1* (2D profiles) and *Appendix 2* (3D fence diagrams).

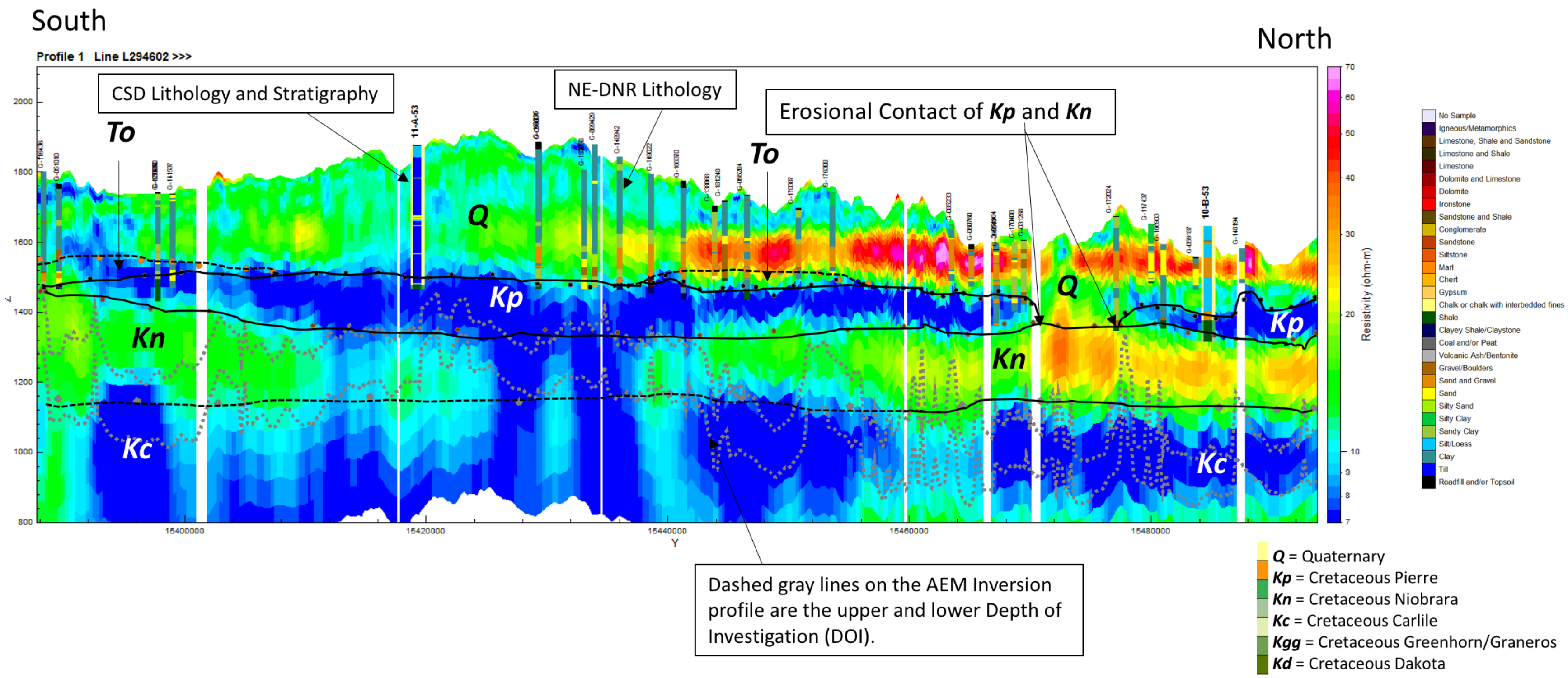


Figure 5-3. Example 2D Profile - 15-mile north-south line L294602 on the western end of the LCNRD survey area. CSD and Nebraska DNR borehole lithology and stratigraphy logs are indicated on the AEM inverted earth models. Interpretations are indicated by lines labeled with stratigraphic names.

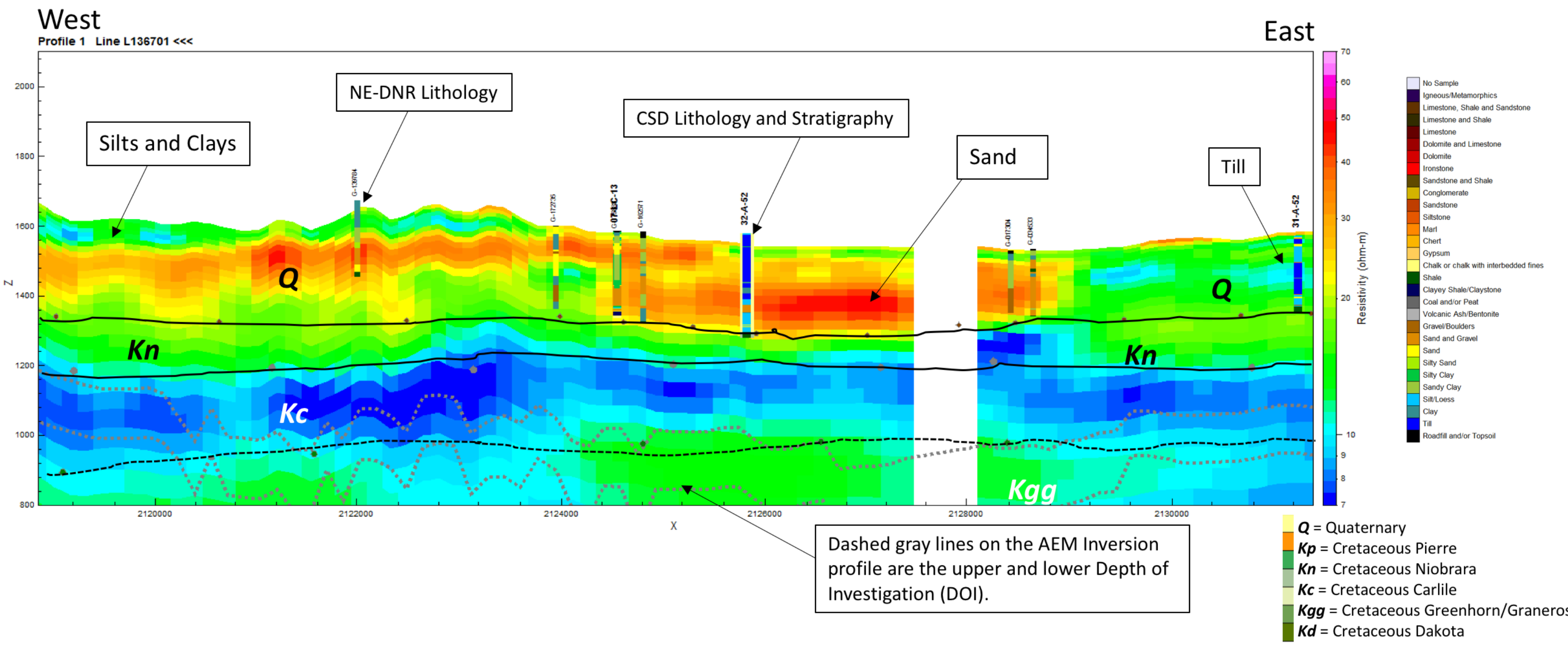


Figure 5-4. Example 2D Profile - 25-mile east-west line L136701 within the Coleridge block. CSD and Nebraska DNR borehole lithology and stratigraphy logs are indicated on the AEM inverted earth models. Interpretations are indicated by lines labeled with stratigraphic names.

5.1.4 Create Interpretative Surface Grids

LCNRD AEM survey area surface grids of geologic formations were also produced. To create these grids, the elevations of the AEM interpreted top of the formation 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, 3,333 points were used in the grid including points from BGMA (AGF, 2017a) and the LENRD (AGF, 2017d). An original cell size of 1,000 feet was used 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. While the MCG routine performs reasonably well with honoring the data, in areas where the spatial density of data points is low, the MCG routine may trend towards an overall average data value. The ***Kp*** surface was then regridded at a 100 ft cell size and compared with the surface DEM which was also at 100 ft cell size. Where the ***Kp*** surface was higher in elevation then the DEM the KP surface as set to the DEM minus three feet. This process was required due to the outcrop of the ***Kp*** in the northwestern area of the LCNRD. The AEM and the boreholes did not have the spatial resolution to properly represent the ***Kp*** outcrop and the original ***Kp*** surface did not reflect the complexity of the outcropping ***Kp***. The grid was then clipped to the interpreted erosional contact and then clipped again to the LCNRD survey area. On the margins of the survey area some areas are blank due to lack of data. Figure 5-5 is a map of the elevation of the top of the ***Kp*** within the LCNRD survey area. The area of the Coleridge block did not contain any ***Kp*** material.

For the ***Kn*** top surface, 1,642 points were used in the grid including points from BGMA (AGF, 2017a) and the LENRD (AGF, 2017d). A cell size of 1,000 feet was used 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. While the MCG routine performs reasonably well with honoring the data, in areas where the spatial density of data points is low, the MCG routine may trend towards an overall average data value. The grid was then clipped to the interpreted erosional contact and then clipped again to the LCNRD survey area. On the margins of the survey area some areas are blank due to a lack of data. Figure 5-6 is a map of the elevation of the top of the ***Kn*** within the LCNRD survey area. The Coleridge ***Kn*** grid was gridded at 250 feet (Figure 5-7).

For the ***Kc*** top surface, 1,518 AEM picks were used in the grid including picks from the LENRD (AGF, 2017d). A cell size of approximately 2,144 feet was used 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 LCNRD survey area. On the margins of the survey area some areas are blank due to a lack of data. Figure 5-8 is a map of the elevation of the top of the ***Kc*** within the LCNRD AEM survey area. The Coleridge ***Kc*** was gridded at 250 feet (Figure 5-9).

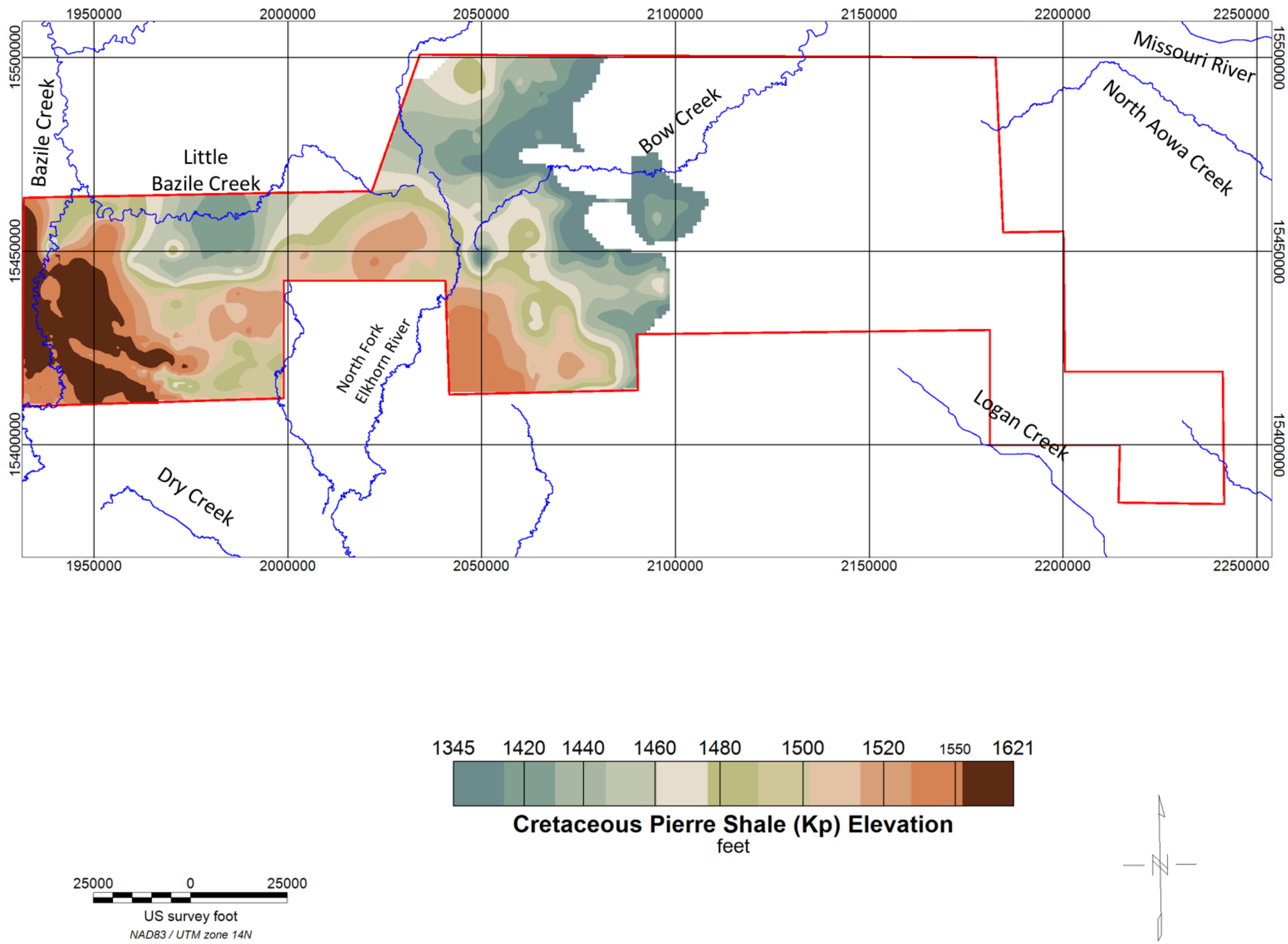


Figure 5-5. Map of the elevation of the top of the Cretaceous Pierre Shale (*Kp*) within the LCNRD AEM survey area (red line). Major streams are indicated for reference. The projection is NAD83 UTM Zone 14 North and the elevation values are referenced to NAVD 88.

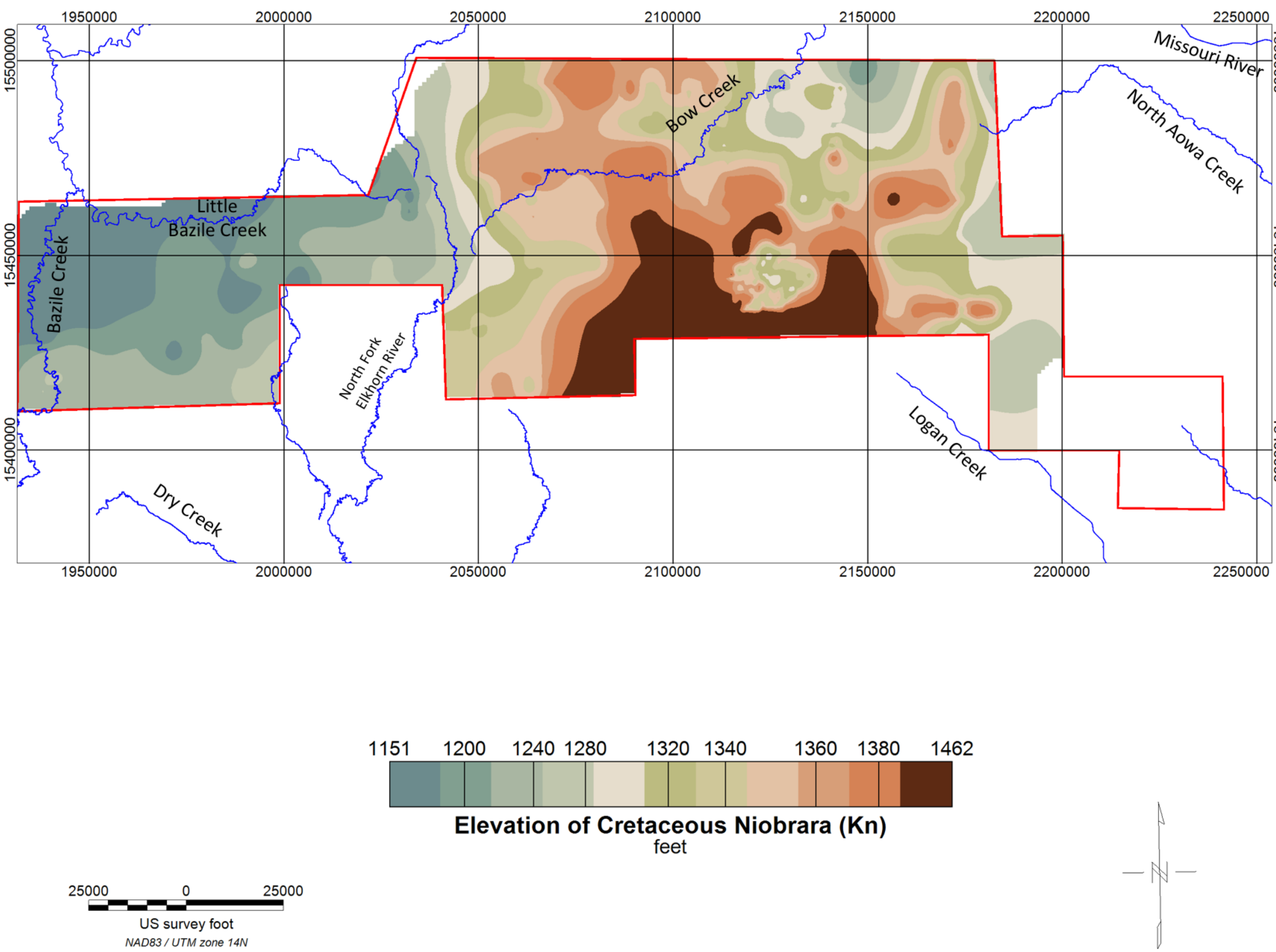


Figure 5-6. Map of the elevation of the top of the Cretaceous Niobrara (*Kn*) within the LCNRD AEM survey area (red line). Major streams are indicated for reference. The projection is NAD83 UTM Zone 14 North and the elevation values are referenced to NAVD 88.

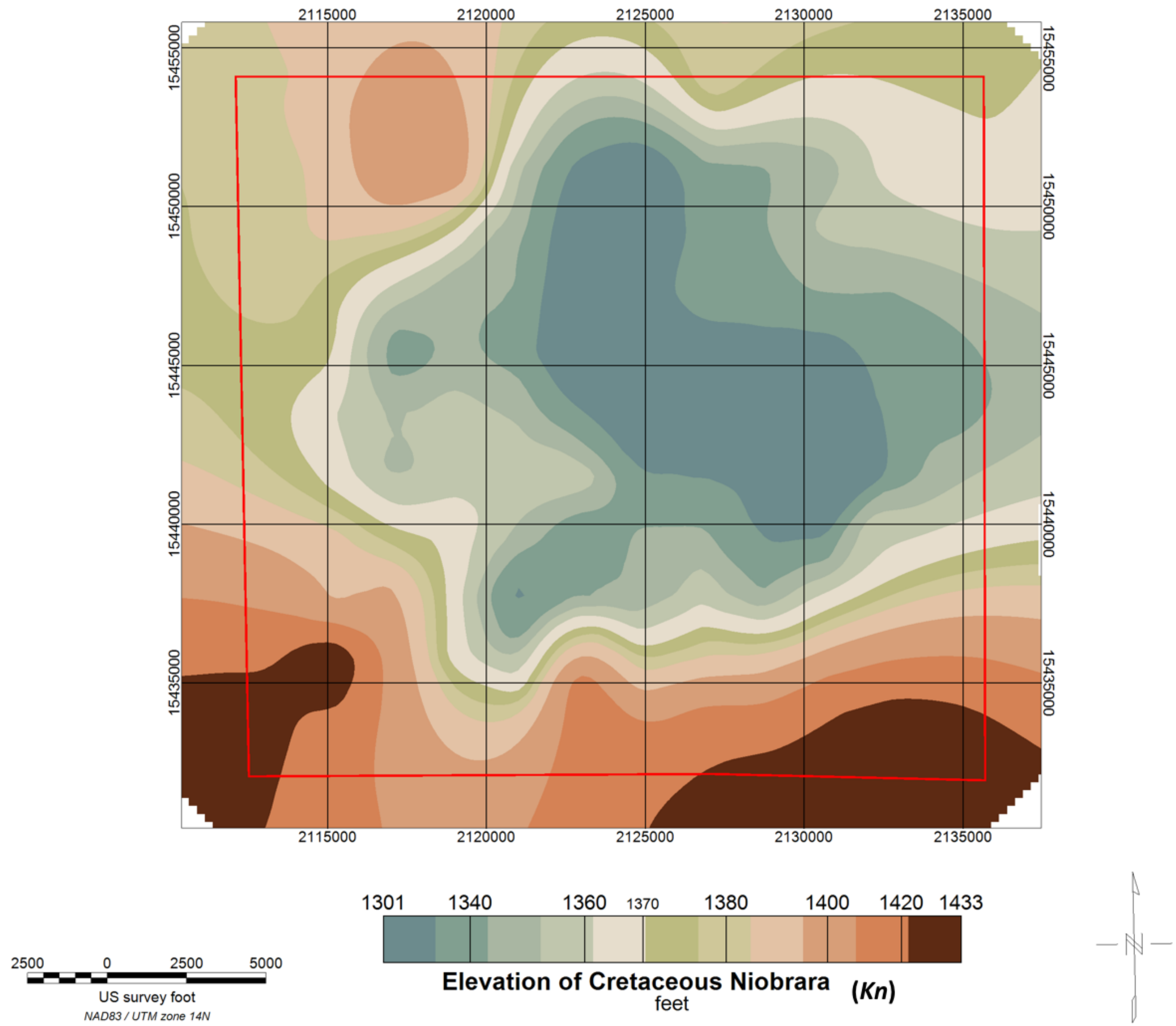


Figure 5-7. Map of the elevation of the top of the Cretaceous Niobrara (*Kn*) within the Coleridge AEM survey block (red line). The projection is NAD83 UTM Zone 14 North and the elevation values are referenced to NAVD 88.

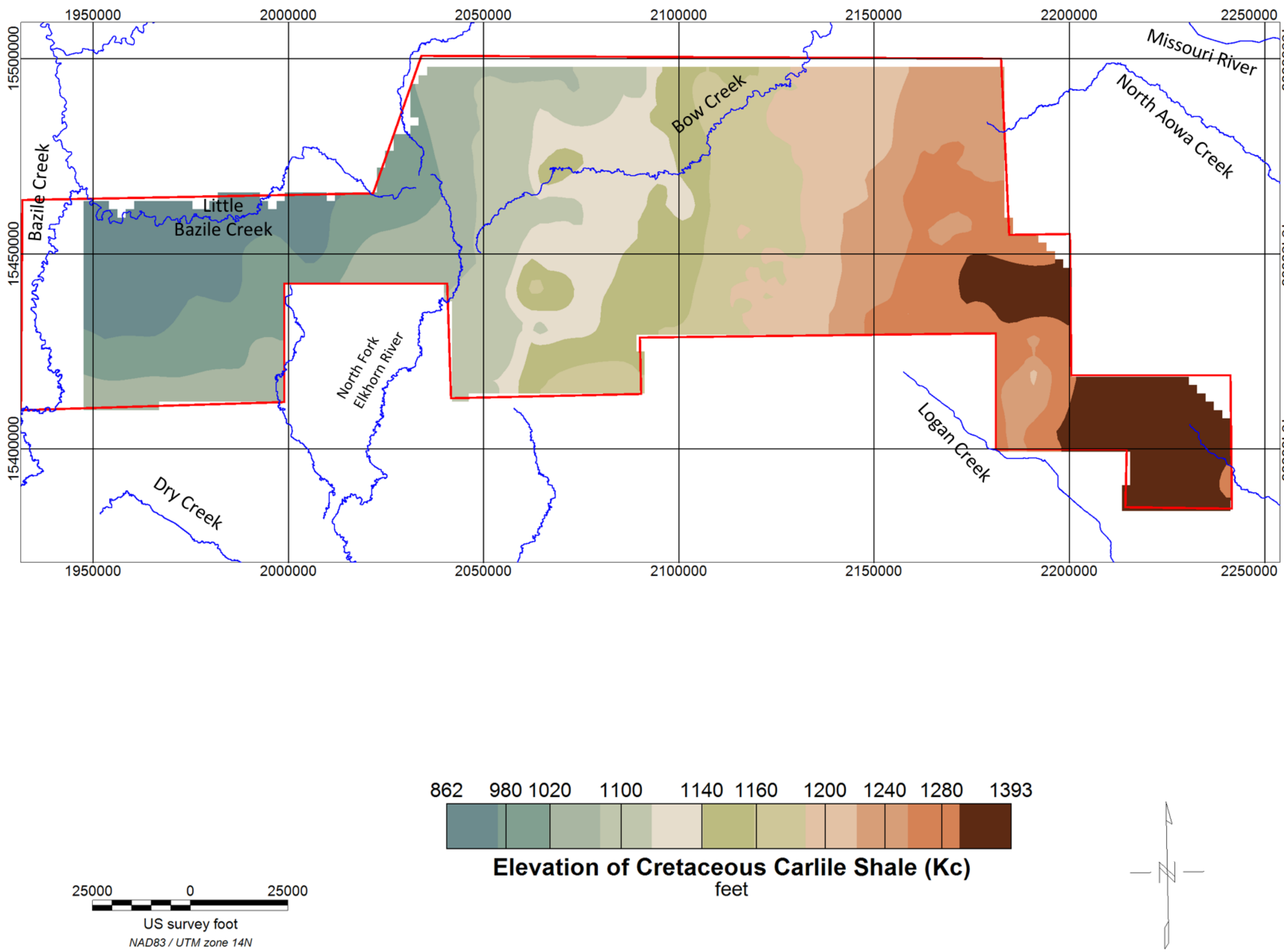


Figure 5-8. Map of the elevation of the top of the Cretaceous Carlile Shale (*Kc*) within the LCNRD AEM survey area (red line). Major streams are indicated for reference. The projection is NAD83 UTM Zone 14 North and the elevation values are referenced to NAVD 88.

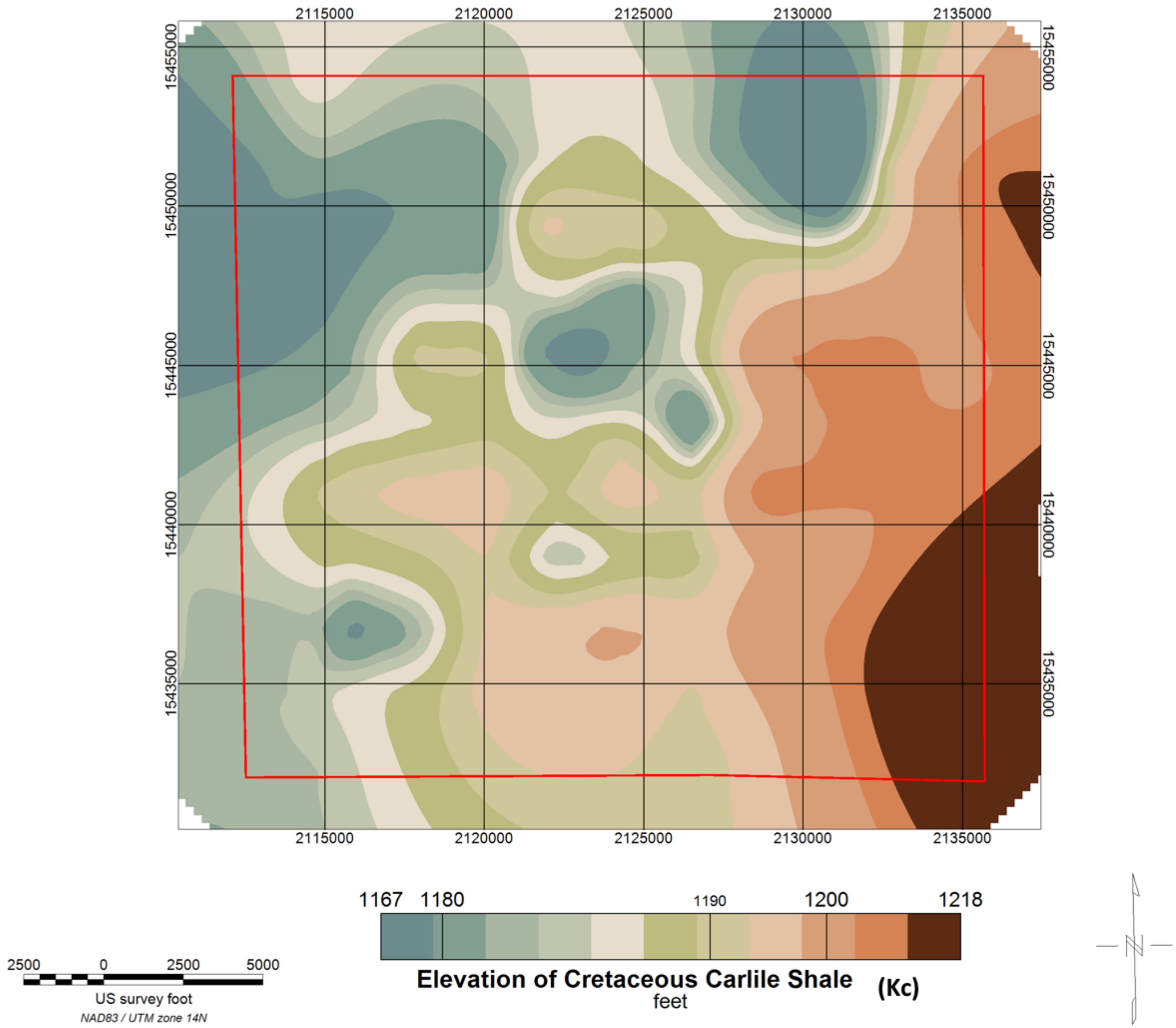


Figure 5-9. Map of the elevation of the top of the Cretaceous Carlile Shale (*Kc*) within the Coleridge AEM survey block (red line). The projection is NAD83 UTM Zone 14 North and the elevation values are referenced to NAVD 88.

For the ***Kgg*** top surface, 570 AEM picks were used in the grid including picks from the LENRD (AGF, 2017d). A cell size of approximately 3,201 feet was used 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 LCNRD survey area. In the western portion of the LCNRD 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 LCNRD survey area. The Coleridge ***Kgg*** grid was clipped from the LCNRD ***Kg*** grid and is presented in Figure 5-11.

For the ***Kd*** top surface, 311 AEM picks were used in the grid including picks from the LENRD (AGF, 2017d). A cell size of approximately 4,376 feet was used 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 LCNRD survey area. In the western portion of the LCNRD 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 lack of data. Figure 5-12 is a map of the elevation of the top of the ***Kgg*** within the LCNRD survey area. The Coleridge ***Kd*** grid was clipped from the LCNRD ***Kd*** grid and is presented in Figure 5-13.

The Cretaceous bedrock or the base of the Quaternary (***Q***) and Tertiary Ogallala (***To***) aquifer throughout the LCNRD is a combination of the ***Kp, Kn,*** and ***Kc*** surfaces. The ***Kp*** is eroded away over much of the LCNRD survey area (Figure 5-5). Over much of the LCNRD survey area, the ***Kn*** is the bedrock unit (Figure 5-6) and the ***Kn*** surface represents the base of aquifer. As indicated above in Section 2.1.4, 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 in the eastern sections of the LCNRD survey area, the ***Kc*** is the bedrock unit (Figure 5-8). To construct the top of bedrock or the base of the aquifer system, the four surfaces were combined into one surface at 1,000 ft cell size. The grid was then regridded 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 LCNRD survey area. The Coleridge Cretaceous bedrock grid (Figure 5-14) is equivalent to the Coleridge ***Kn*** grid (Figure 5-7) in the vicinity of the Coleridge area.

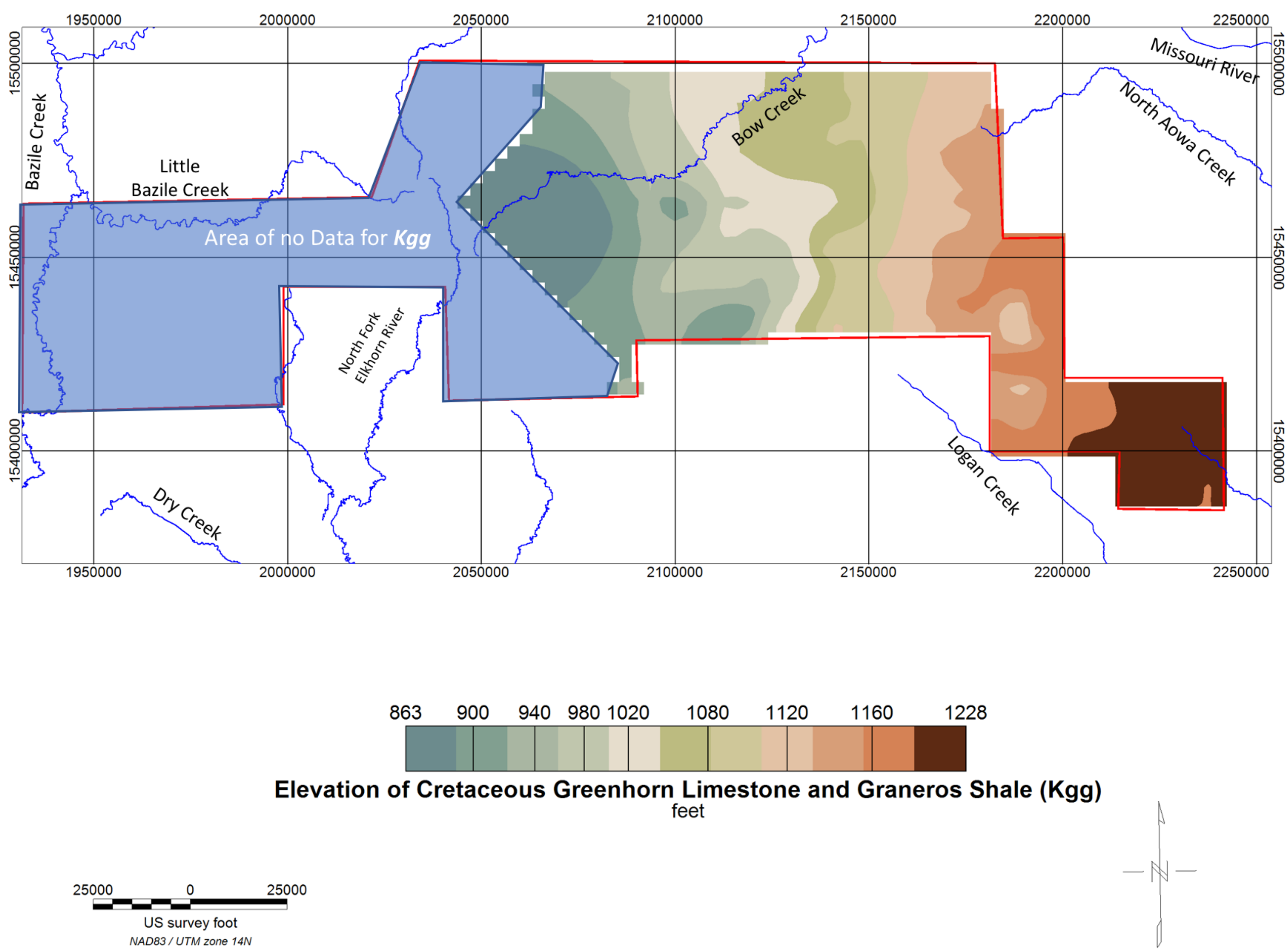


Figure 5-10. Map of the elevation of the top of the Cretaceous Greenhorn Limestone and Graneros Shale (*Kgg*) within the LCNRD AEM survey area (redline). Major streams are indicated for reference. The projection is NAD83 UTM Zone 14 North and the elevation values are referenced to NAVD 88.

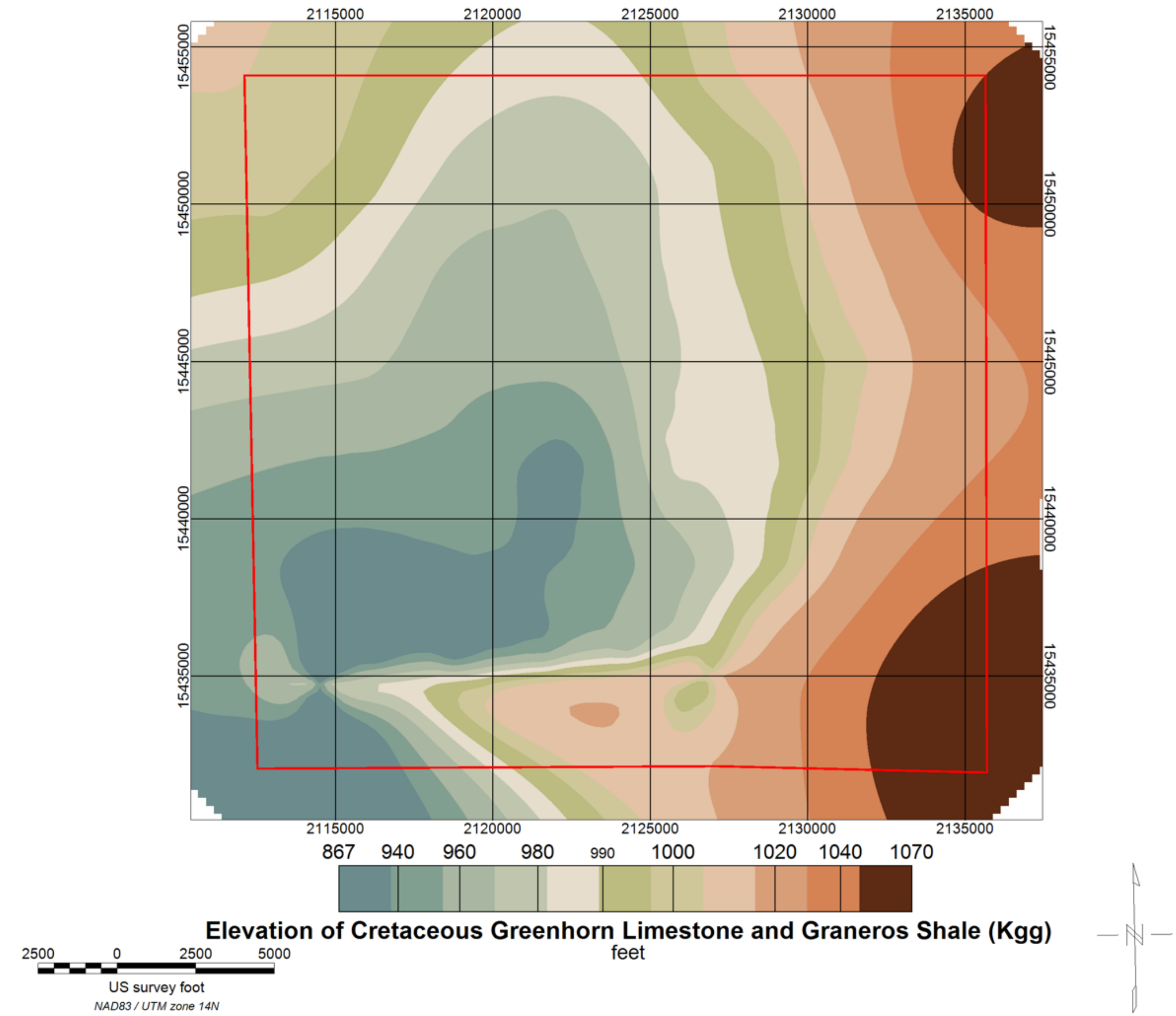


Figure 5-11. Map of the elevation of the top of the Cretaceous Greenhorn Limestone and Graneros Shale (*Kgg*) within the Coleridge AEM survey block (red line). The projection is NAD83 UTM Zone 14 North and the elevation values are referenced to NAVD 88.

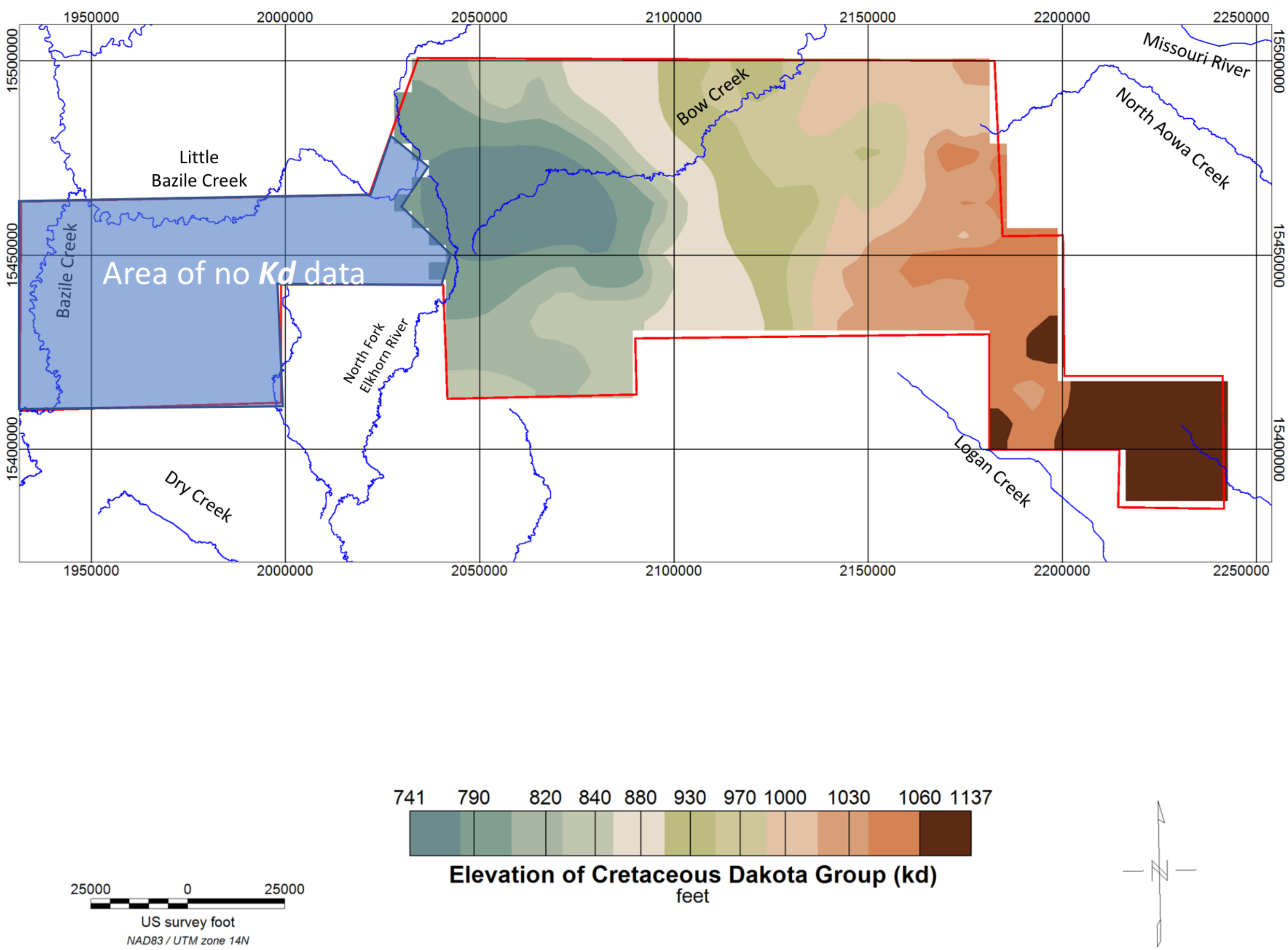


Figure 5-12. Map of the elevation of the top of the Cretaceous Dakota Group (*Kd*) within the LCNRD AEM survey area (red line). Major streams are indicated for reference. The projection is NAD83 UTM Zone 14 North and the elevation values are referenced to NAVD 88.

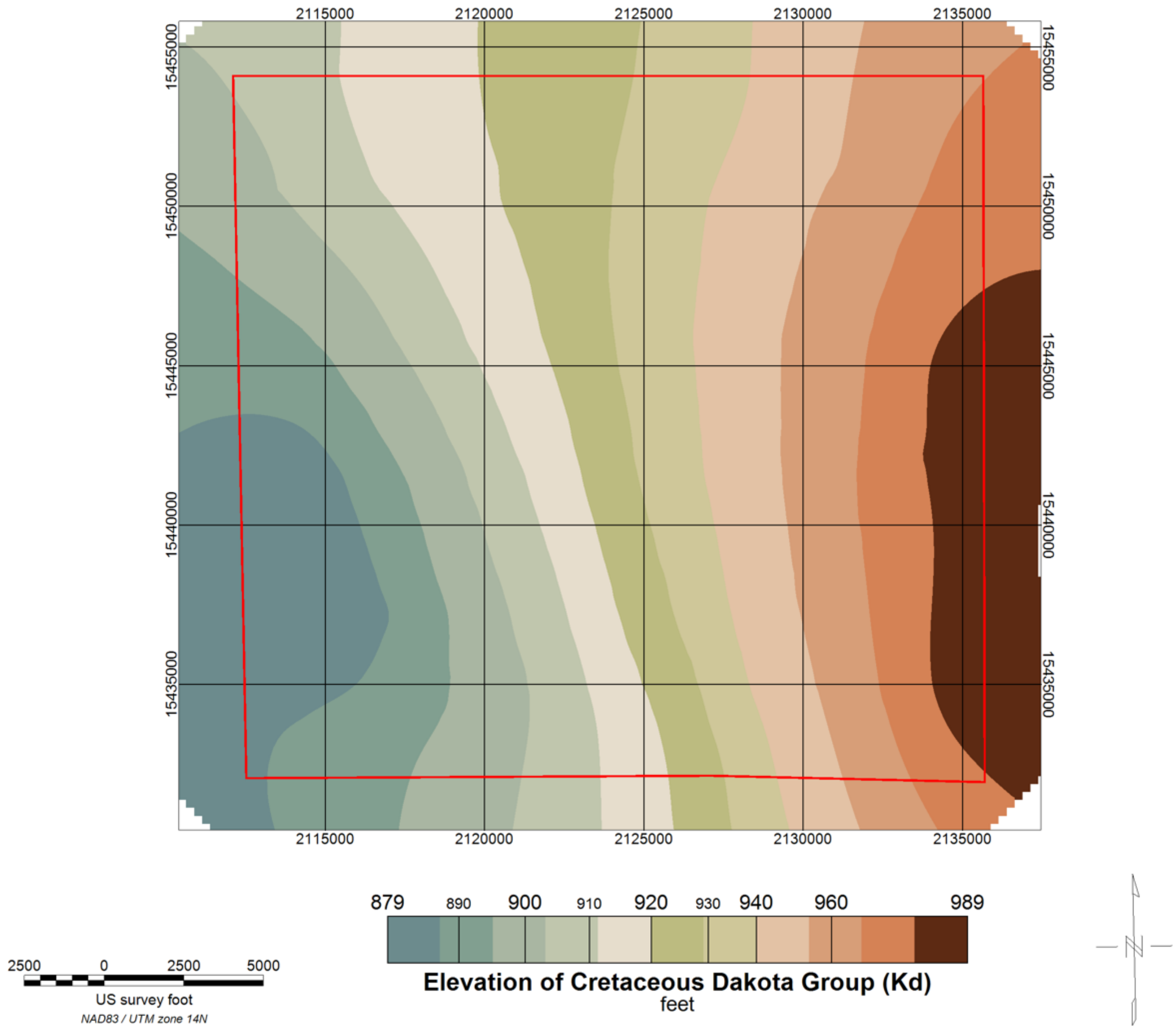


Figure 5-13. Map of the elevation of the top of the Cretaceous Dakota Group (*Kd*) within the Coleridge AEM survey block (red line). The projection is NAD83 UTM Zone 14 North and the elevation values are referenced to NAVD 88.

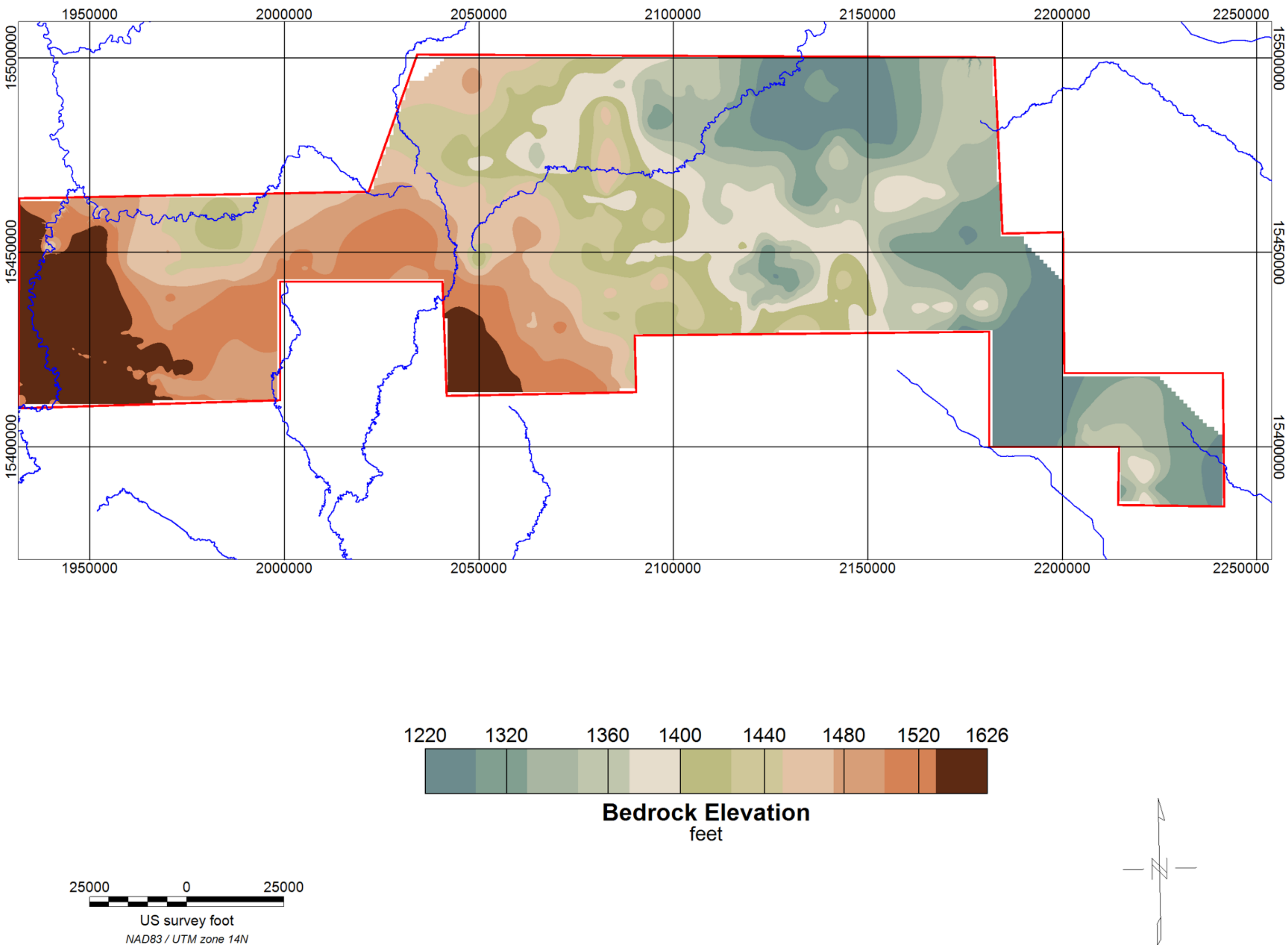


Figure 5-14. Map of the elevation of the top of the Cretaceous bedrock within the LCNRD AEM survey area (red line). Major streams are indicated for reference. The projection is NAD83 UTM Zone 14 North and the elevation values are referenced to NAVD 88.

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 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. (2015a)). Results of these interpretations can be found in Appendix 1-2D Profiles for both the Reconnaissance and Coleridge Block flight lines.

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 LCNRD AEM survey and local conditions likely deviate in areas with variable topography. The water table in the LCNRD 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 set to extend beyond” was set to 50. The resulting grid was then regridded at a 100 ft cell size and compared with the DEM of the LCNRD 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 LCNRD survey area. The result is presented in Figure 5-15. The Coleridge 1995 water table grid was clipped from the LCNRD 1995 water table grid and is presented in Figure 5-16.

A voxel grid was completed for the Coleridge dense flight block. A voxel grid was not completed for the reconnaissance flight lines due to the large distance (approximately three miles) between lines and the variable aquifer material within that spacing. The voxel grids were made using a 250 ft grid cell size and the model layer thickness (Table 4-4 in the previous section). A minimum curvature method was used within Encom PA (pbEncom, 2016). All layers were referenced to their depth from the surface. After the grid was calculated for the Coleridge block, the bedrock/base of aquifer system was then truncated/clipped from the voxel grid using the bedrock/base of aquifer grid explained above.

The resulting grids are from the surface down to the bedrock/base of the ***Q*** aquifer system. This grid can be used to explore the distribution of the aquifer materials within the area in 3D. Specifically, this grids can allow for the calculation of the volume of materials above the bedrock as well as be used to illustrate the distribution of surface materials. The grid can be found in Appendix 3-Deliverables\Voxel. In order to calculate the material that is saturated another surface needs to be clipped from the voxel grid. Using the 1995 water table surface, the voxel grid was clipped again from the water table to the surface. This subset voxel grid represents the area from the bedrock/ base of aquifer system up to the 1995 water table. This subset grid is also located in Appendix 3-Deliverables\Voxel.

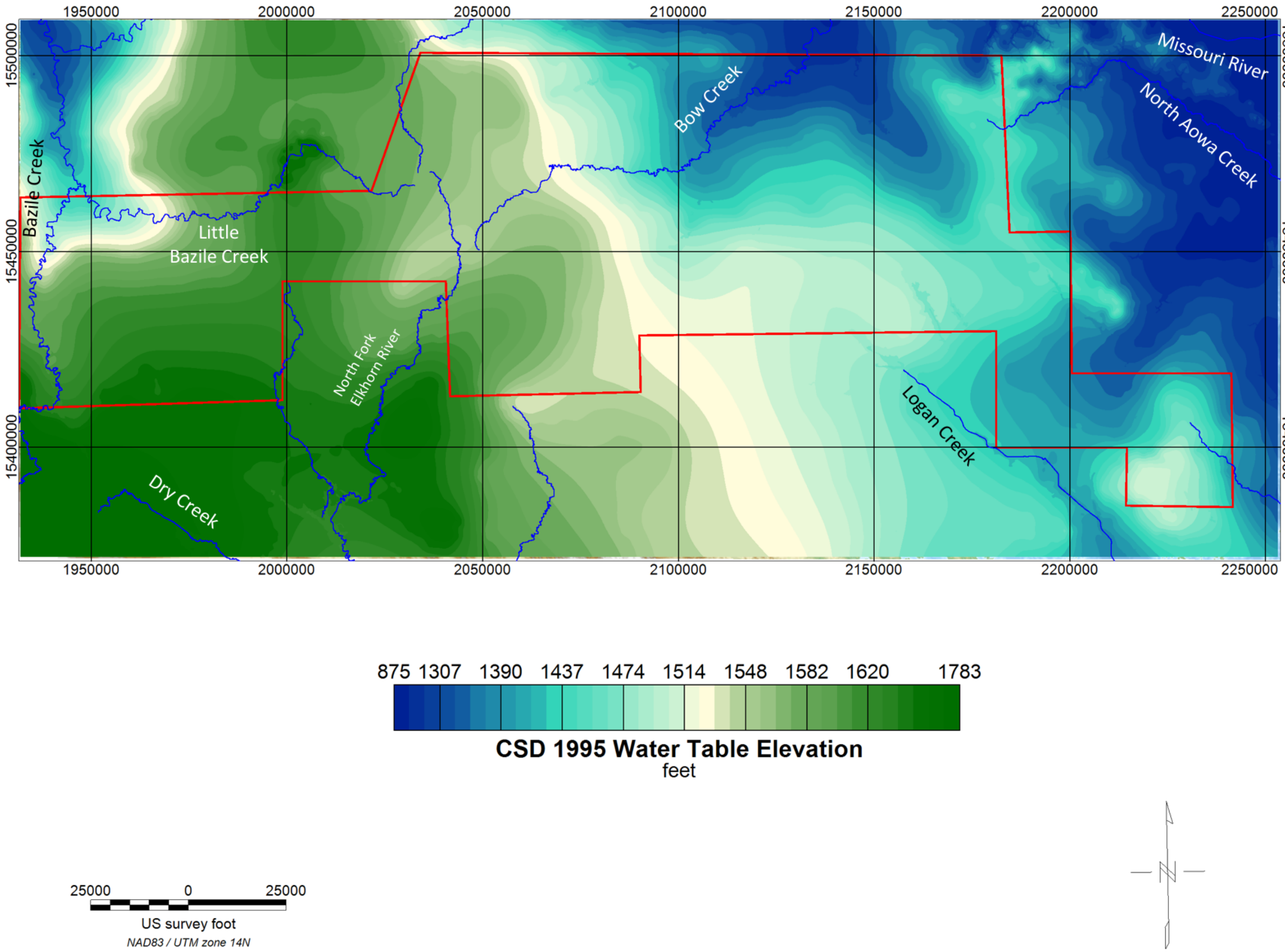


Figure 5-15. Map of the elevation of the 1995 CSD water table within the LCNRD AEM survey area (red line). Major streams are indicated for reference. The projection is NAD83 UTM Zone 14 North and the elevation values are referenced to NAVD 88.

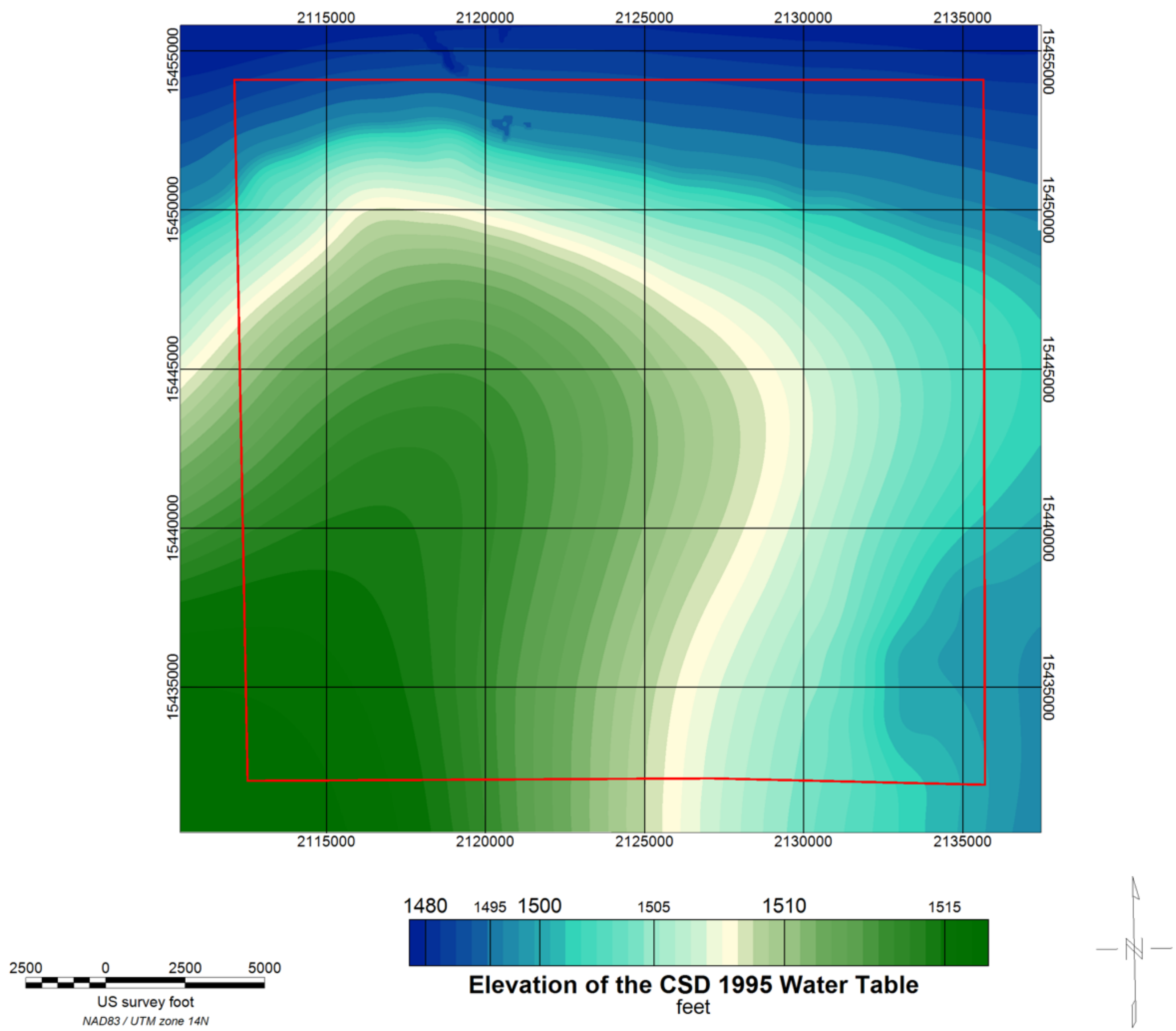


Figure 5-16. Map of the elevation of the 1995 CSD water table (NE CSD, 1995) within the Coleridge AEM survey block (red line). Major streams are indicated for reference. The projection is NAD83 UTM Zone 14 North and the elevation values are referenced to NAVD 88.

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. In regards to the LCNRD 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 systems and bedrock data from both of the ENWRA project areas (Carney et al., 2015a). The original analysis that was completed as part of Carney et al. (2015a) included the overall area of the LCNRD. 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., 2015a). The relationship between resistivity and lithology type was assessed by performing an association function that linked nine lithologic descriptor codes for ***Q***/***To*** sediments used in the CSD test hole lithologic characterization with the resistivity values across that depth interval as indicated in the 58 high-graded resistivity logs applied in the AEM data inversion (25 from the southern area, 33 from the northern area). With this approach, several thousand points became available for each lithologic description in the test holes used in this analysis. From this list of associated resistivity levels and pre-categorized lithologies, statistical analyses were performed to aide in defining the various thresholds used to determine the aquifer material type in the project area subsurface. Details of the analysis can be found in Carney et al. (2015a). A summary of the resistivities and the color scale is shown in Figure 5-17.

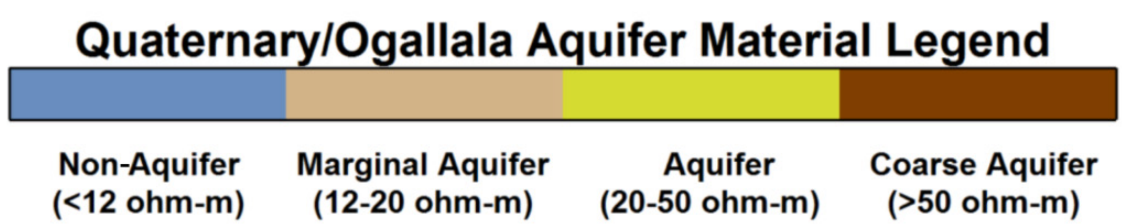


Figure 5-17. Plot displaying the resistivities by major aquifer material color categories (blue- non-aquifer material, tan- marginal aquifer, yellow- aquifer, brown- sand-rich, coarse intervals of the aquifer material).

5.2.2 Bedrock Resistivity Thresholds

The bedrock in the LCNRD analyzed in this study includes the ***Kp, Kn, Kc, Kgg,*** and ***Kd.*** These were included to demonstrate the overall distribution in resistivity of bedrock materials across the entire LCNRD. The median resistivity values for each unit are 9 ohm-m for the ***Kp***, 38 ohm-m for the ***Kn,*** 16 ohm-m for the ***Kc*** and the ***Kgg*** lumped together, and 35 ohm-m for the ***Kd*** (Carney et al., 2015a). For the ENWRA study the ***Kc*** and the ***Kgg*** were interpreted together. For this 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 LCNRD displayed some low resistivity 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 LCNRD.

5.2.3 Comparison of AEM Inversion Resistivity to Borehole Geophysical Resistivity Logs

Three CSD borehole geophysical resistivity logs were selected from the LCNRD survey area for comparison with the AEM inversions: Test holes *05-LC-13*, *01-LC-14*, and *03-LC-14*. 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 truths when comparing to AEM inversions that are well calibrated using modern techniques. Throughout much of the geophysical logging at the time it was acquired, the relative deflections of the resistivity measurements were all that was required or expected from a geophysical log. Operators were seldom trained in 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 5-18 is a plot of *05-LC-13*, a 16-inch normal resistivity log plotted with the inverted AEM resistivity for line L384704. *05-LC-13* is located 3,098 feet from line L384704 and the AEM sounding displayed is selected from the closest point to the borehole geophysical log. The agreement in the resistivity is good given the distance between the test hole and the AEM sounding. The shape of the curves show a shift in the general location of the relatively resistive body and a slight decrease in the resistivity indicated by the AEM. The AEM is indicating the aquifer material similar to that indicated by the lithology log. The vertical shift between the AEM and the resistivity log would indicate that the lithology has changed over the distance of the borehole compared with the AEM.

Figure 5-19 is a plot of *01-LC-14*, a 16-inch normal resistivity log plotted with the inverted AEM resistivity for line L384704. *01-LC-14* is located 680 feet from line L384704 and the AEM sounding is selected from the closest point to the borehole geophysical log. The agreement in the resistivity is good with the AEM matching the resistivity log over the portion of the subsurface that the log was collected. Unique about this log is that it is much deeper them any of the CSD logs within the database and penetrates the Cretaceous units. However, the resistivity log unfortunately does not contain data over the length of the test hole. Figure 5-19 contains the interpreted stratigraphic contacts from the AEM data. At the time of the download of the database, CSD had not included the stratigraphic contacts.

Figure 5-20 is a plot of *03-LC-14*, a 16-inch normal resistivity log plotted with the inverted AEM resistivity for line L295402. *03-LC-14* is located 2,248 feet from line L295402 and the AEM sounding displayed is selected from the closest point to the borehole geophysical log. The agreement in the log resistivity is relatively good with the AEM resistivity given the distance between the two points. The AEM shows a lower average resistivity for the sand layers but at relatively the same upper depth. The AEM also indicates that the body is deeper than the log from *03-LC-14*. 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 *03-LC-14*. The interpretation of Line L295402 indicates that the ***Kn*** is the bedrock unit in the area.

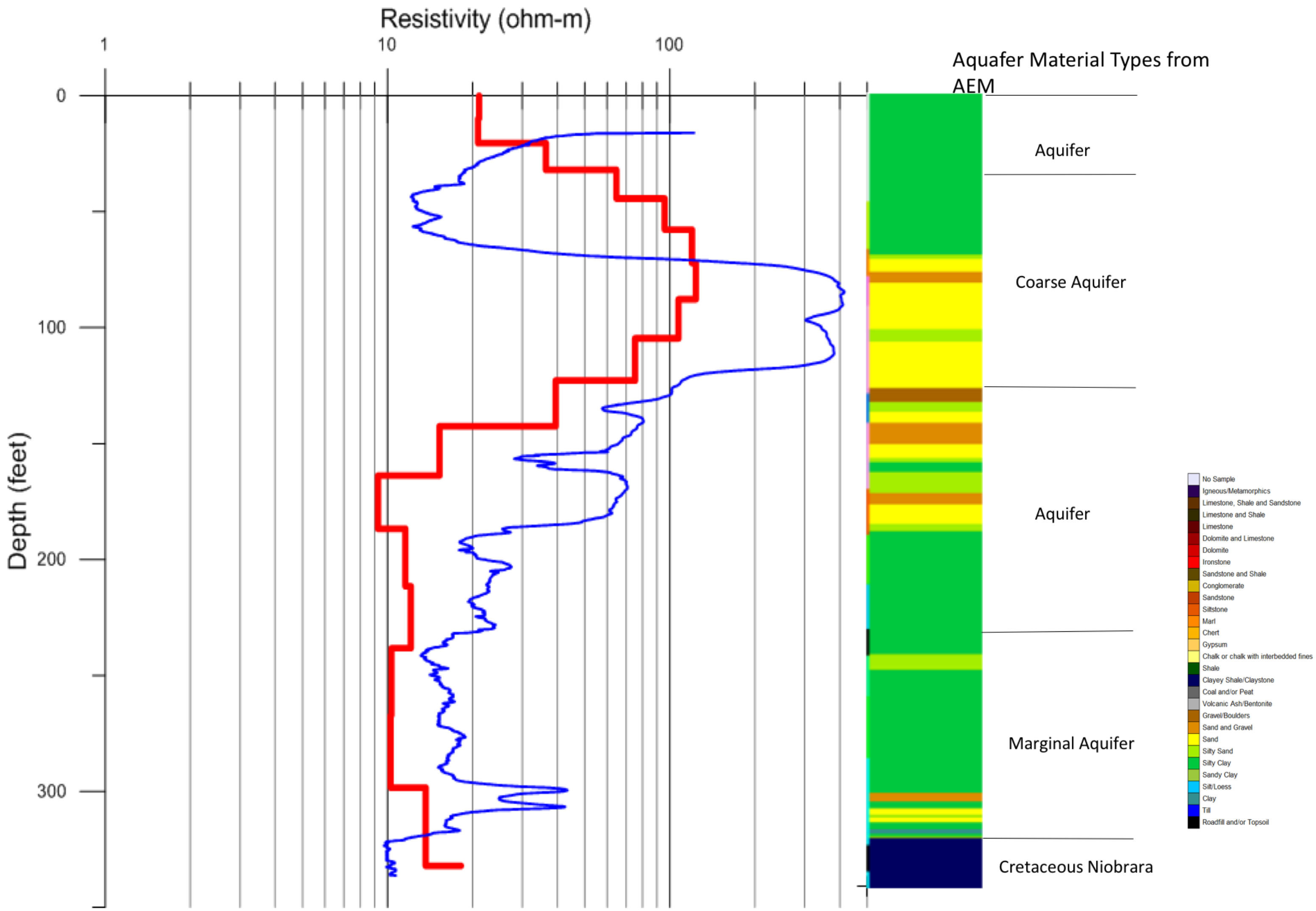


Figure 5-18. Graph of the *05-LC-13* 16-inch normal resistivity log values (blue line) and the inverted airborne electromagnetic resistivity values (red line). Also indicated is the lithology log from *05-LC-13* as well as the aquifer material categories and the interpreted stratigraphy from the AEM inversion.

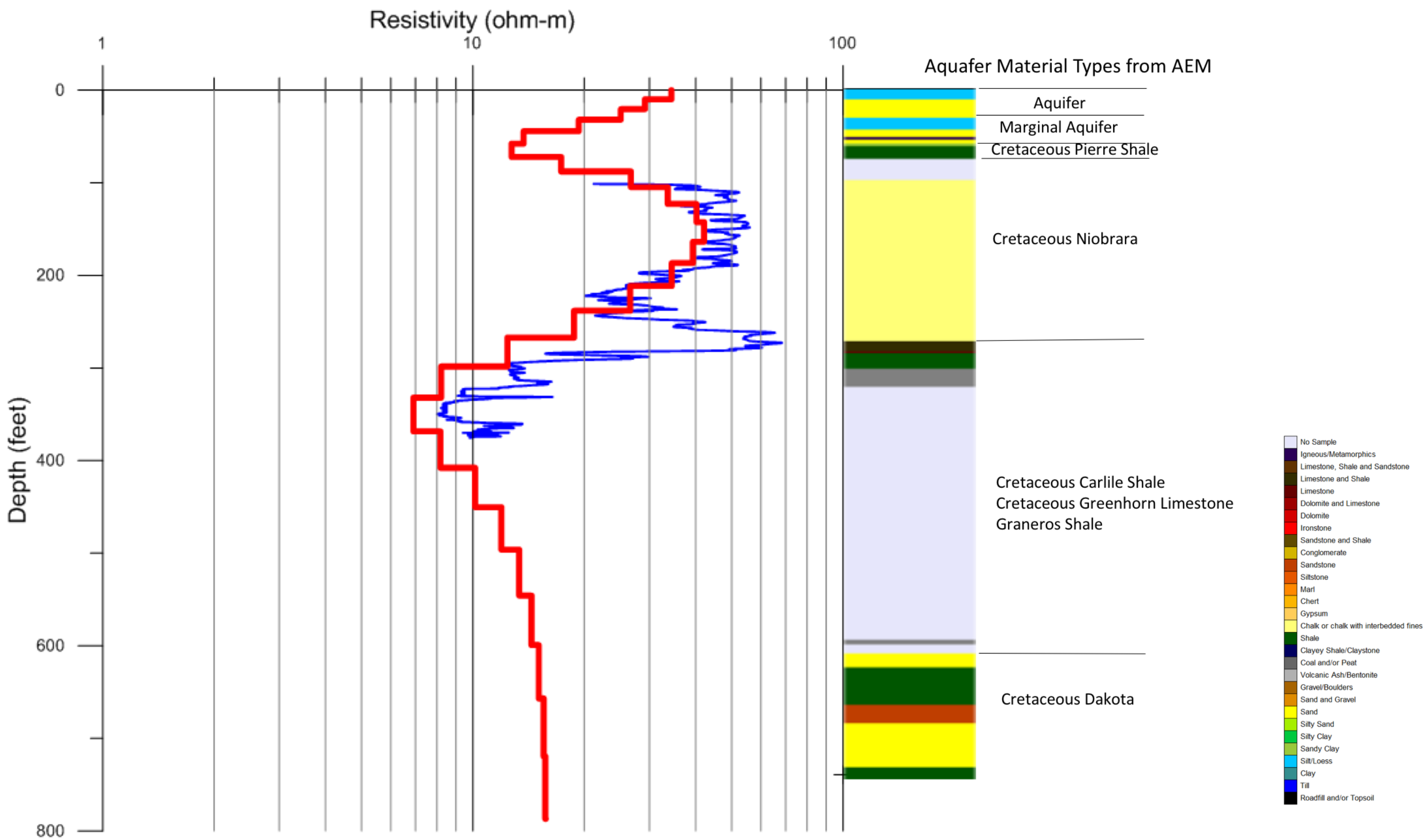


Figure 5-19. Graph of the *01-LC-14* 16-inch normal resistivity log values (blue line) and the inverted airborne electromagnetic resistivity values (red line). Also indicated is the lithology log from *01-LC-14* as well as the aquifer material categories from the AEM inversion and interpreted stratigraphic contacts.

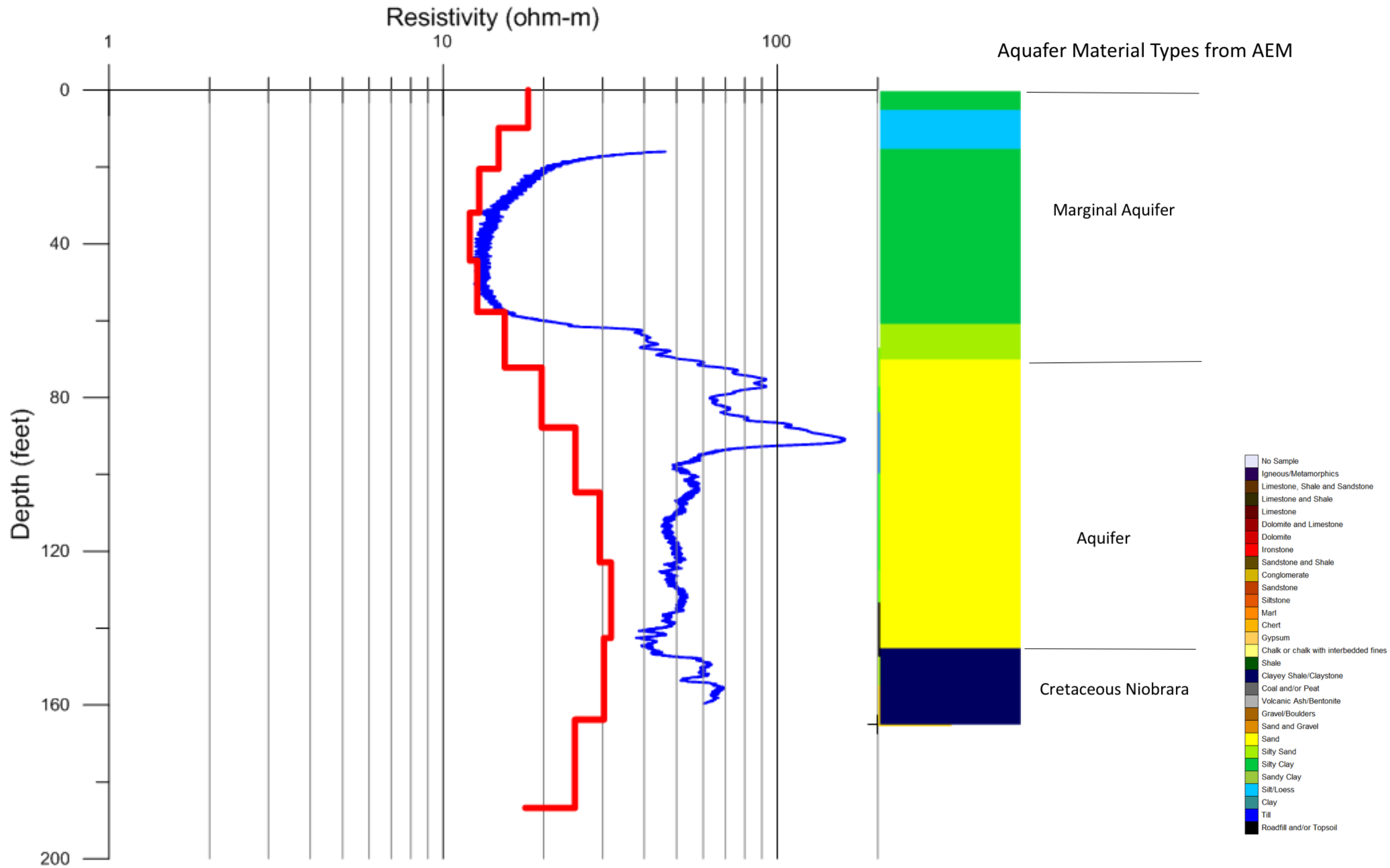


Figure 5-20. Graph of the *03-LC-14* 16-inch normal resistivity log values (blue line) and the inverted airborne electromagnetic resistivity values (red line). Also indicated is the lithology log from *03-LC-14* as well as the aquifer material categories and bedrock interpretation from the AEM inversion.

5.3 Hydrogeological Framework of the LCNRD Reconnaissance 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 LCNRD or was only known to a limited extent with just the borehole information. The survey completed in 2014 by Carney et al. (2015a) provides a basis for this section of the report.

The 2016 AEM survey reveals variability in the Quaternary (***Q***) deposits across the LCNRD survey area. When combined with the ***To***, they represent the aquifer materials in the survey area, where saturated. The ***To*** is generally thicker in the west and is thin, discontinuous to absent in the eastern regions of the survey area. The ***Q*** and ***To*** make up the aquifer materials overlying the Cretaceous bedrock units. 3D fence diagrams in Figure 5-21, looking north, and Figure 5-22, looking west, display the overall distribution of ***Q*** and ***To*** materials across the LCNRD 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 across most of the survey area and ***Q*** and ***To*** coarse aquifer and aquifer materials found predominately on the west side often associated with alluvial deposits. A mix of both can be seen near the Creighton area near the west side of the survey boundary. The ***Kp***, ***Kn*,** **Kc**, **Kgg**, and ***Kd*** bedrock units are displayed in 3D in Figure 5-23. A profile of AEM flight line L609310 (Figure 5-24) shows all the different geologic units in the survey area including the ***Q***, ***To***, ***Kp***, ***Kn***, ***Kc***, ***Kgg***, and ***Kd***. The youngest Cretaceous units are in the west and the oldest are in the east. ***To*** is in the center and the pinches out to the east and west with ***Q*** sediments covering all units.

5.3.1 The Quaternary and Tertiary Aquifers

The ***Q*** and ***To*** aquifer of the LCNRD AEM survey area is predominantly composed of unconsolidated aquifer material (yellow color in figures) and coarse aquifer material (brown color in figures) composed of alluvial sediments in the western and central parts of the survey area. In the eastern central part 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. This sequence of marginal to non-aquifer material is continuous from the south border of the survey area to the north border and acts as a boundary condition for groundwater flow from east to west (for example, the shaded area in Figure 5-25). The ***Q*** and ***To*** materials (where present) are sitting on the ***Kp***, ***Kn***, ***Kc***, and ***Kgg*** which are the bedrock aquicludes for the area. A map showing the elevation of the bedrock based on the combined tops of the ***Kp***, ***Kn***, ***Kc***, and ***Kgg*** is presented in Figure 5-26. A detailed description of the bedrock units is given in Section 2.1.4. The thickness of the ***Q*** and ***To*** materials within the LCNRD AEM survey area range from 0 to greater than 450 feet thick (Figure 5-27). The thicknesses of the ***Q*** *and* ***To*** materials increase toward the west. 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*** is thin and then thickens and again thins to the east. There is small thick area of till southeast of Coleridge. Near the western survey boundary near Creighton, the mix of ***Q*** and ***To*** aquifer and coarse aquifer materials act as a groundwater supply route that is hydrologically connected to the surface water system.

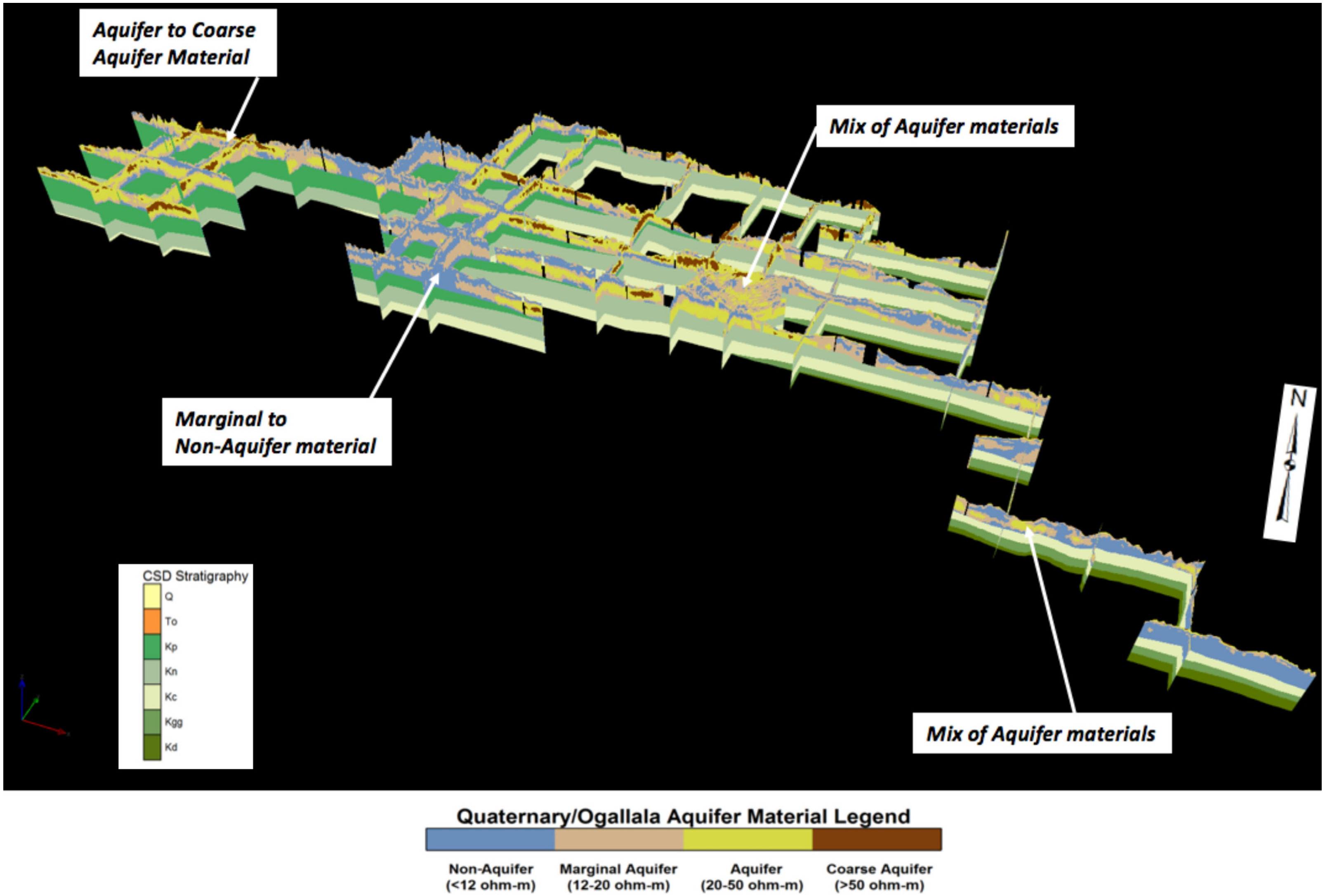


Figure 5-21. 3D fence diagram map looking to the north of the interpreted distributions of aquifer materials within the LCNRD AEM survey area. Brown is coarse aquifer, yellow is aquifer, tan is marginal, and blue is non-aquifer material. Vertical exaggeration is 20x. Bedrock units consist of Cretaceous Pierre Shale=*Kp*, Cretaceous Niobrara Formation=*Kn*, Cretaceous Carlile Shale=*Kc*, Cretaceous Greenhorn Limestone and Graneros Shale=*Kgg*, and Cretaceous Dakota Group=*Kd*. The image projection is NAD 83, UTM Zone 14 North.

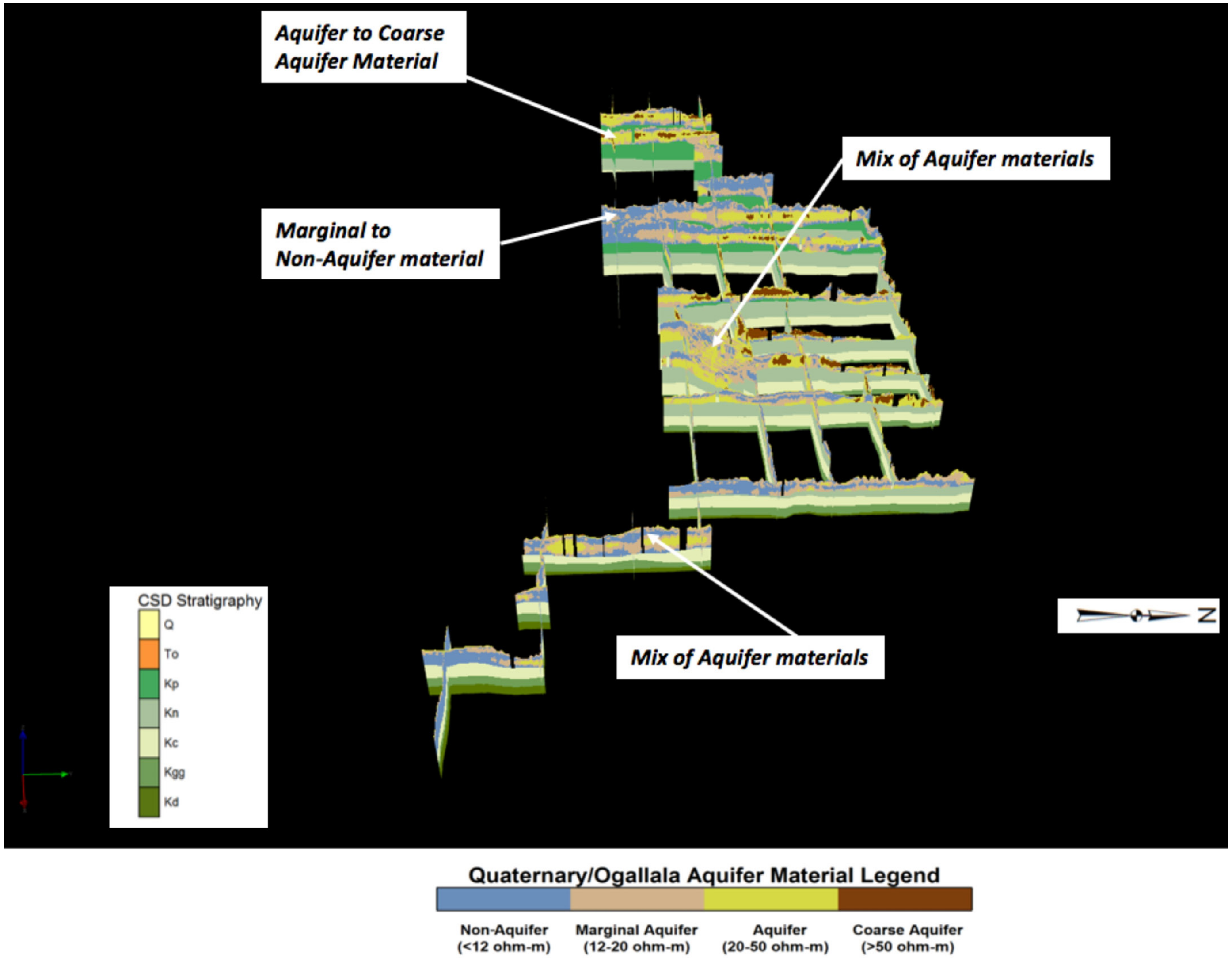


Figure 5-22. 3D fence diagram map looking to the west of the interpreted distributions of aquifer materials within the LCNRD AEM survey area. Brown is coarse aquifer, yellow is aquifer, tan is marginal and blue is non-aquifer material. Bedrock units consist of Cretaceous Pierre Shale=*Kp*, Cretaceous Niobrara Formation=*Kn*, Cretaceous Carlile Shale=*Kc*, Cretaceous Greenhorn Limestone and Graneros Shale=*Kgg*, and Cretaceous Dakota Group=*Kd*. Vertical exaggeration is 20x. The image projection is NAD 83, UTM Zone 14 North.

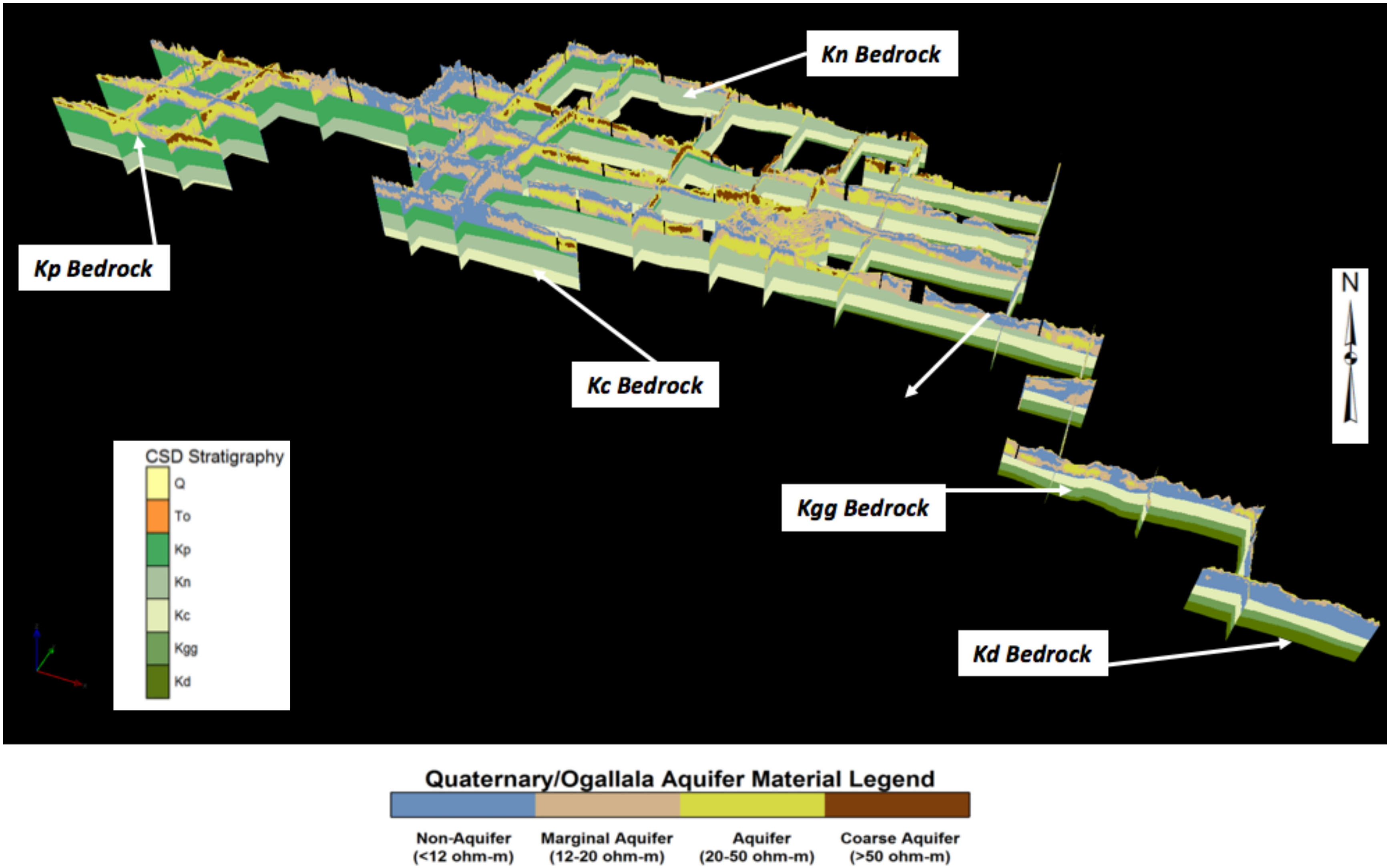


Figure 5-23. 3D fence diagram map looking to the west of the geologic interpretations of bedrock within the LCNRD AEM survey area. The bedrock units are from west to east Cretaceous Pierre Shale=*Kp*, Cretaceous Niobrara Formation=*Kn*, Cretaceous Carlile Shale=*Kc*, Cretaceous Greenhorn Limestone and Graneros Shale=*Kgg*, and Cretaceous Dakota Group=*Kd*. Vertical exaggeration is 20x. The image projection is NAD 83, UTM Zone 14 North.

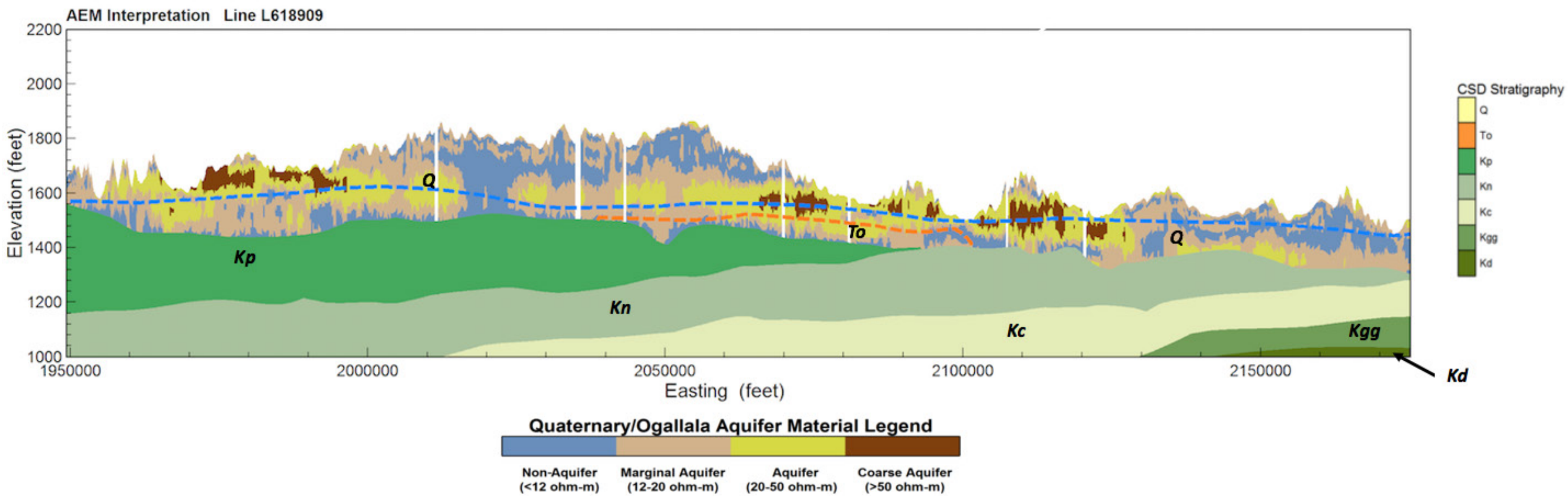


Figure 5-24. Profile view of AEM flight line L618909 from west-east. All the Quaternary=*Q* and Tertiary Ogallala Group=*To* aquifer materials are resting on the bedrock which from west to east are Cretaceous Pierre Shale=*Kp*, Cretaceous Niobrara Formation=*Kn*, Cretaceous Carlile Shale=*Kc*, Cretaceous Greenhorn Limestone and Graneros Shale=*Kgg*, and Cretaceous Dakota Group=*Kd*. Note the discontinuous thin nature of the *To* in the center of the profile. The image projection is NAD 83, UTM Zone 14 North, feet.

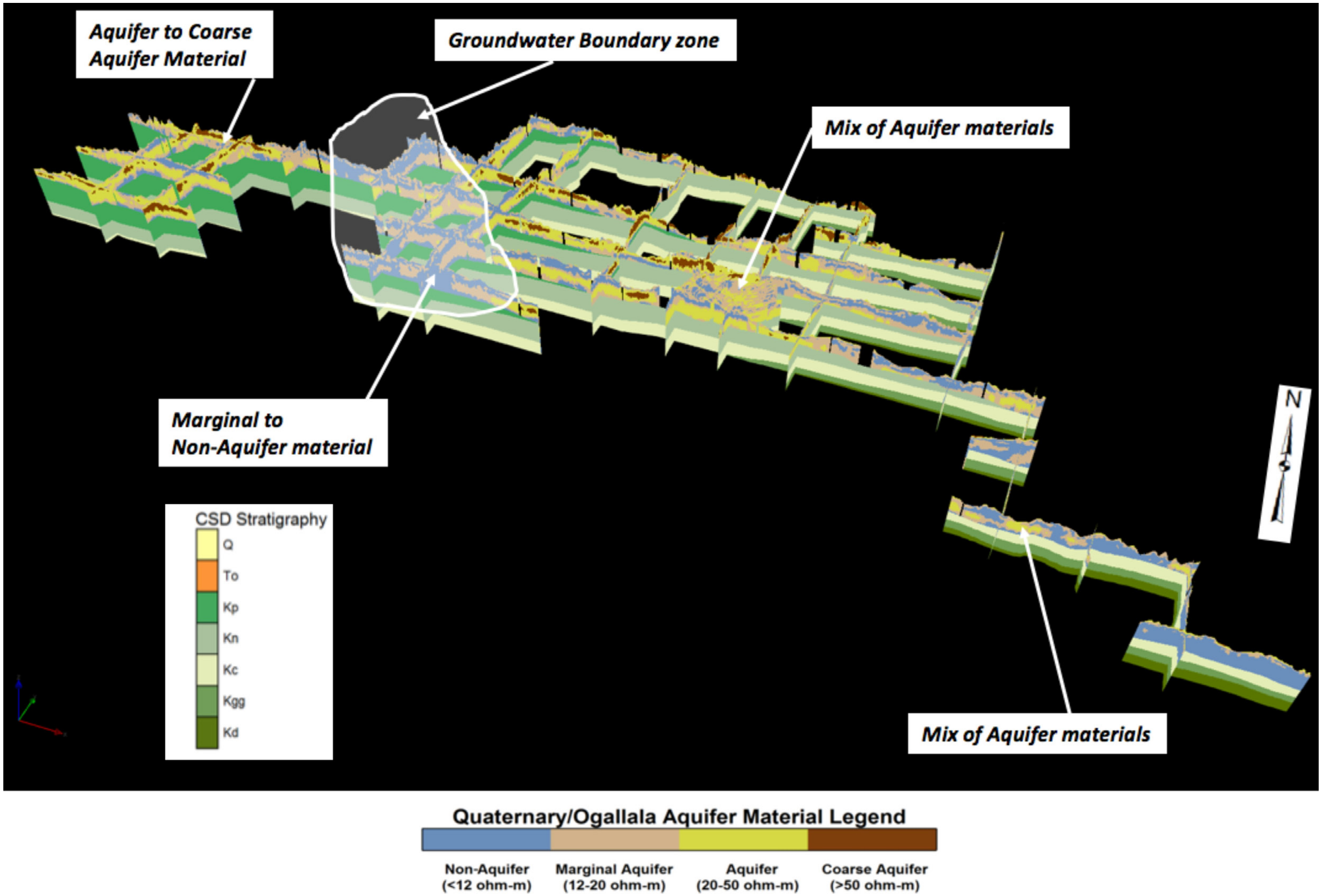


Figure 5-25. 3D fence diagram map looking to the north showing the continuous nature of the marginal aquifer and non-aquifer materials which act as a groundwater flow boundary. Bedrock units consist of Cretaceous Pierre Shale=*Kp*, Cretaceous Niobrara Formation=*Kn*, Cretaceous Carlile Shale=*Kc*, Cretaceous Greenhorn Limestone and Graneros Shale=*Kgg*, and Cretaceous Dakota Group=*Kd*. Vertical exaggeration is 20x. The image projection is NAD 83, UTM Zone 14 North.

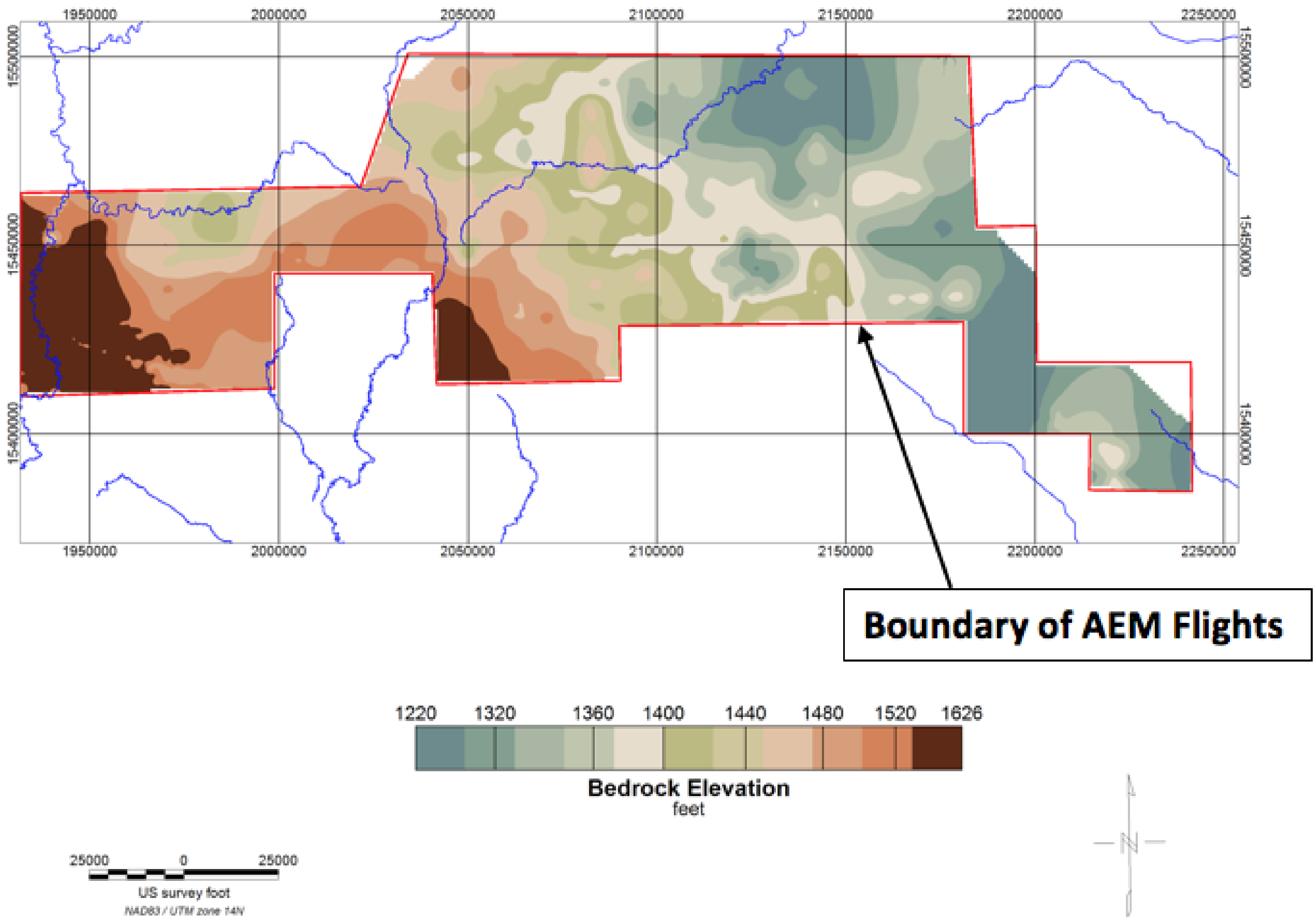


Figure 5-26. 2D map of the elevation of the top of the Cretaceous bedrock. The bedrock slopes from west to east across the project area. The image projection is NAD 83, UTM Zone 14 North, feet.

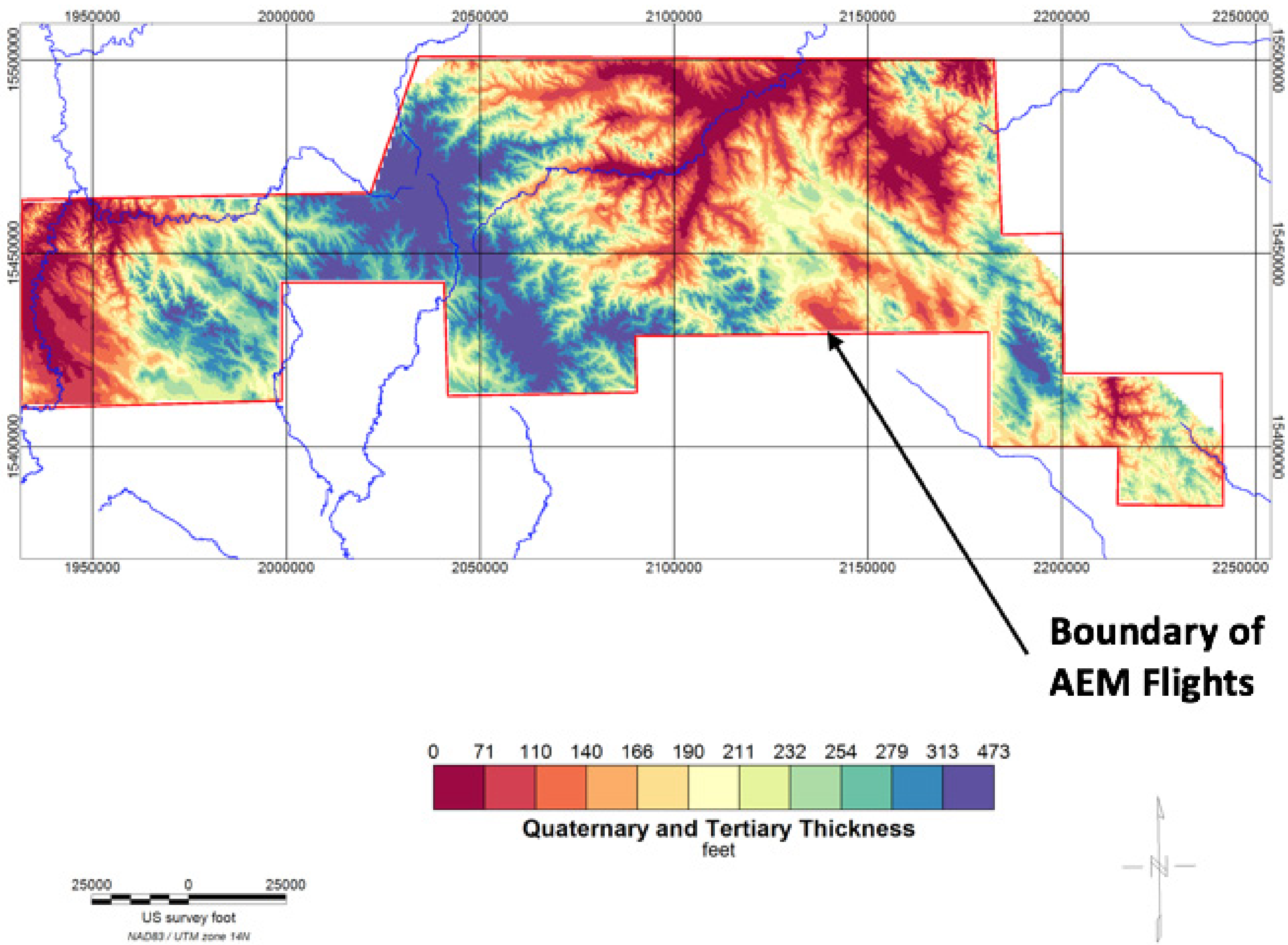


Figure 5-27. 2D map presenting the thickness of the Quaternary=*Q* and Tertiary Ogallala Group=*To* materials within the LCNRD AEM survey area. Thicknesses range from 0 to over 450 feet thick. The image projection is NAD 83, UTM Zone 14 North.

The saturated thicknesses of the ***Q*** and ***To*** aquifer materials are presented in Figure 5-28. They range in thickness from 0 to greater than 200 feet. The coarse aquifer and aquifer materials are the best producing zones for groundwater wells where saturated. Even though the marginal and non-aquifer materials are saturated they make poor to marginal groundwater wells. Figure 5-29 presents an example of a profile illustrating areas of good aquifer and poor aquifer material within the LCNRD overlain with the water table elevation and the bedrock contact.

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.

A disadvantage of widely separated reconnaissance lines is that they only identify aquifer and coarse aquifer material deposits along the actual AEM acquisition flight lines and not in between the flight lines due to the line separation involved. Thus, the complete extent of these deposits cannot be determined expediently without further AEM acquisition or exhaustive interpretation from added boreholes.

Appendix 1-2D Profiles contains interpreted resistivity profiles that illustrate the details of the Quaternary in the LCNRD AEM survey area. Appendix 2-3D Images contains 3D images of the LCNRD 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 5-23). 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 LCNRD, there is a limited amount of knowledge of the 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. Overall, the elevation decreases from west to east (Figure 5-26).

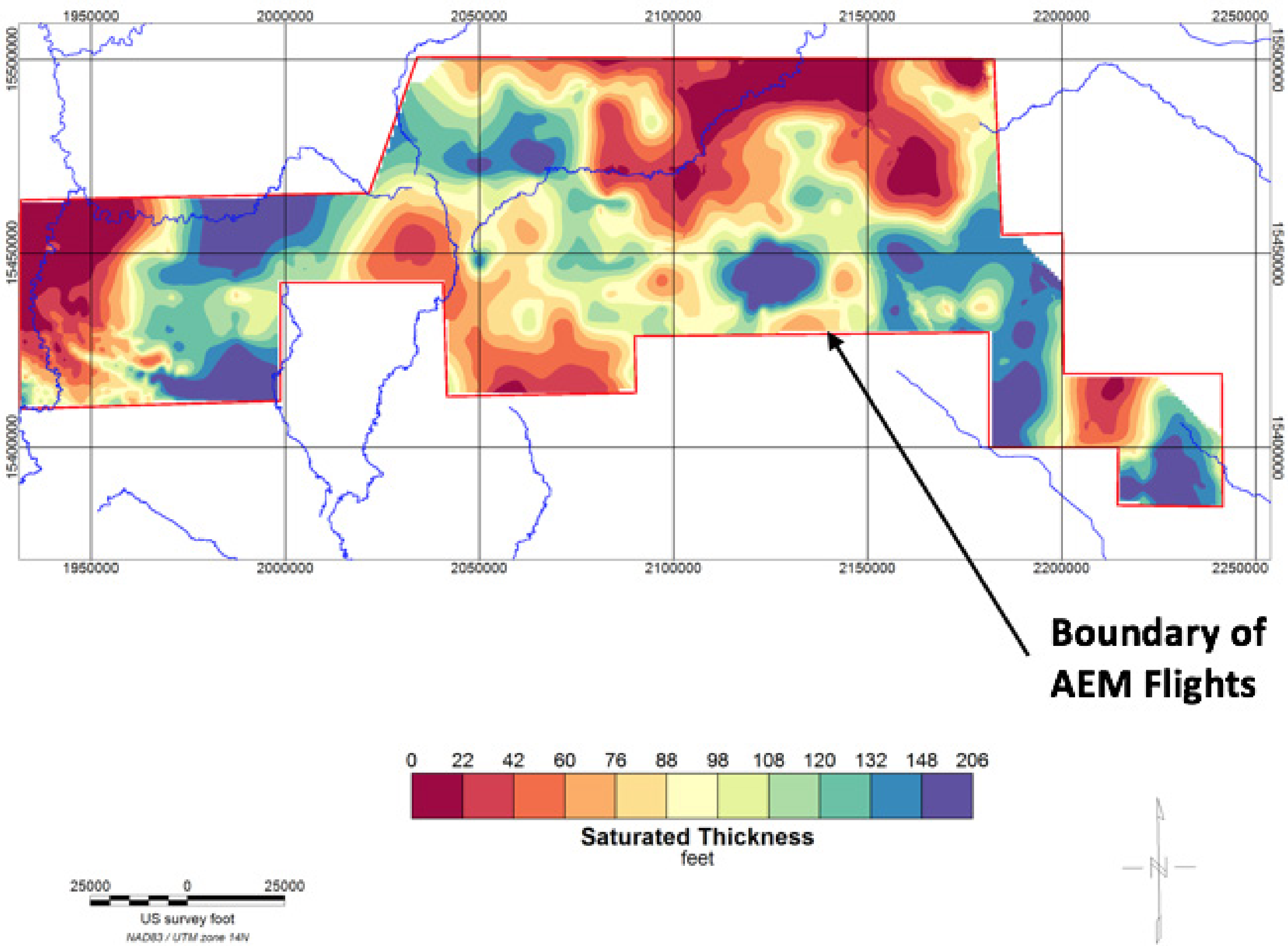


Figure 5-28. 2D map of saturated thickness of the Quaternary=*Q* and Tertiary Ogallala Group=*To* aquifer materials. They range in thickness from 0 to over 200 feet. The image projection is NAD 83, UTM Zone 14 North.

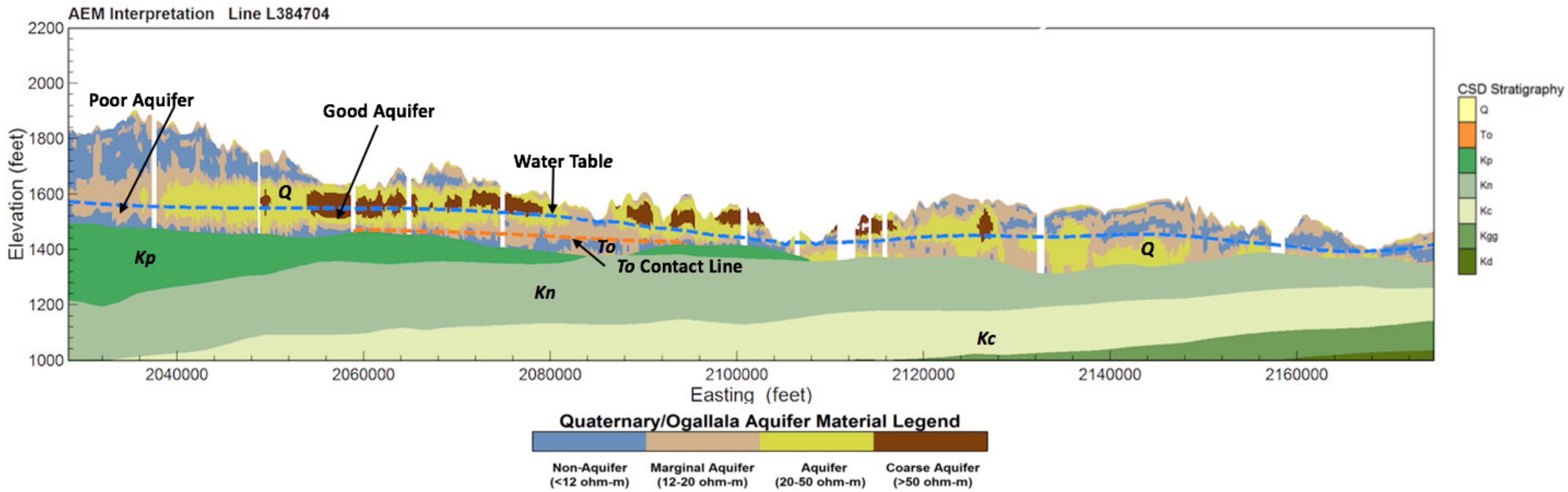


Figure 5-29. Example profile L384704 showing the areas of good aquifer and poor aquifer with water table elevation and bedrock contact. Best zones for groundwater wells are in the coarse aquifer (brown) and aquifer materials (yellow). Bedrock units consist of Cretaceous Pierre Shale=*Kp*, Cretaceous Niobrara Formation=*Kn*, Cretaceous Carlile Shale=*Kc*, Cretaceous Greenhorn Limestone and Graneros Shale=*Kgg*, and Cretaceous Dakota Group=*Kd*. The image projection is NAD 83, UTM Zone 14 North.

5.4 Hydrogeological Framework of the Coleridge Block AEM Survey Area

The Coleridge Block AEM flight area is within the Quaternary and Tertiary Aquifer system defined above (Section 5.3.1). Figure 5-30 is a map showing the AEM survey lines included within the Coleridge Block AEM survey area. The area is composed of ***Q*** aquifer materials lying on the ***Kn*** bedrock surface. The bedrock is eroded and has a channel-like expression. The channel trends from west to east in the center of the block (Figure 5-31). The channels are flanked by bedrock highs that are in the AEM block area that have an increased relief of up to 100 feet in elevation.

The thickness of the Quaternary material within the Coleridge Block ranges from 80 to 340 feet thick (Figure 5-32). The area is dominated by a mix of aquifer materials and coarse aquifer materials and a variable water table with good aquifer properties. Figure 5-33 shows a 3D fence diagram with the bedrock surface in grey showing a large amount of aquifer (yellow) and a small amount coarse aquifer (brown) material in the block. The thicker sequences of aquifer material lie to the southeast and center of the block with marginal and non-aquifer materials creating an aquifer boundary across the area from southwest to northeast. A voxel model (Figure 5-34) showing continuous volumes of saturated aquifer and coarse aquifer material along with the fence diagram of the marginal and Non-aquifer materials illustrates the near continuous nature of the groundwater boundary. The aquifer and coarse aquifer materials are the most productive of the ***Q*** aquifer and have the greatest amount of groundwater flow. Figure 5-35 presents the earth model for north-south flight profile L136701 showing the cross section of the Coleridge Block area east of Coleridge including the features discussed above.

Individual profiles for the interpreted resistivity sections can be found in *Appendix 1* (2D profiles) and *Appendix 2* (3D images)..

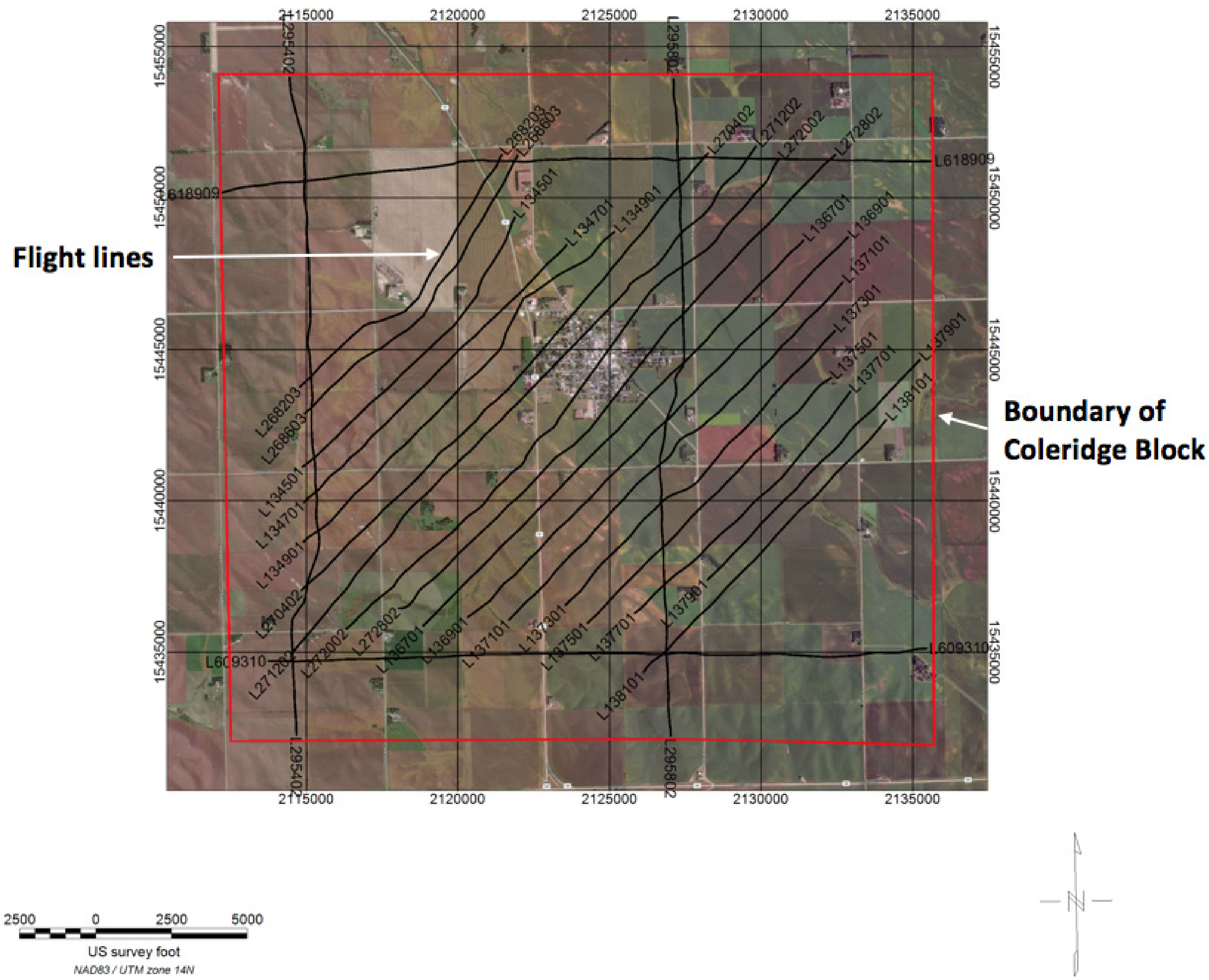


Figure 5-30. Map of the AEM flight lines within the Coleridge Block AEM survey area. The image projection is NAD 83, UTM Zone 14 North feet

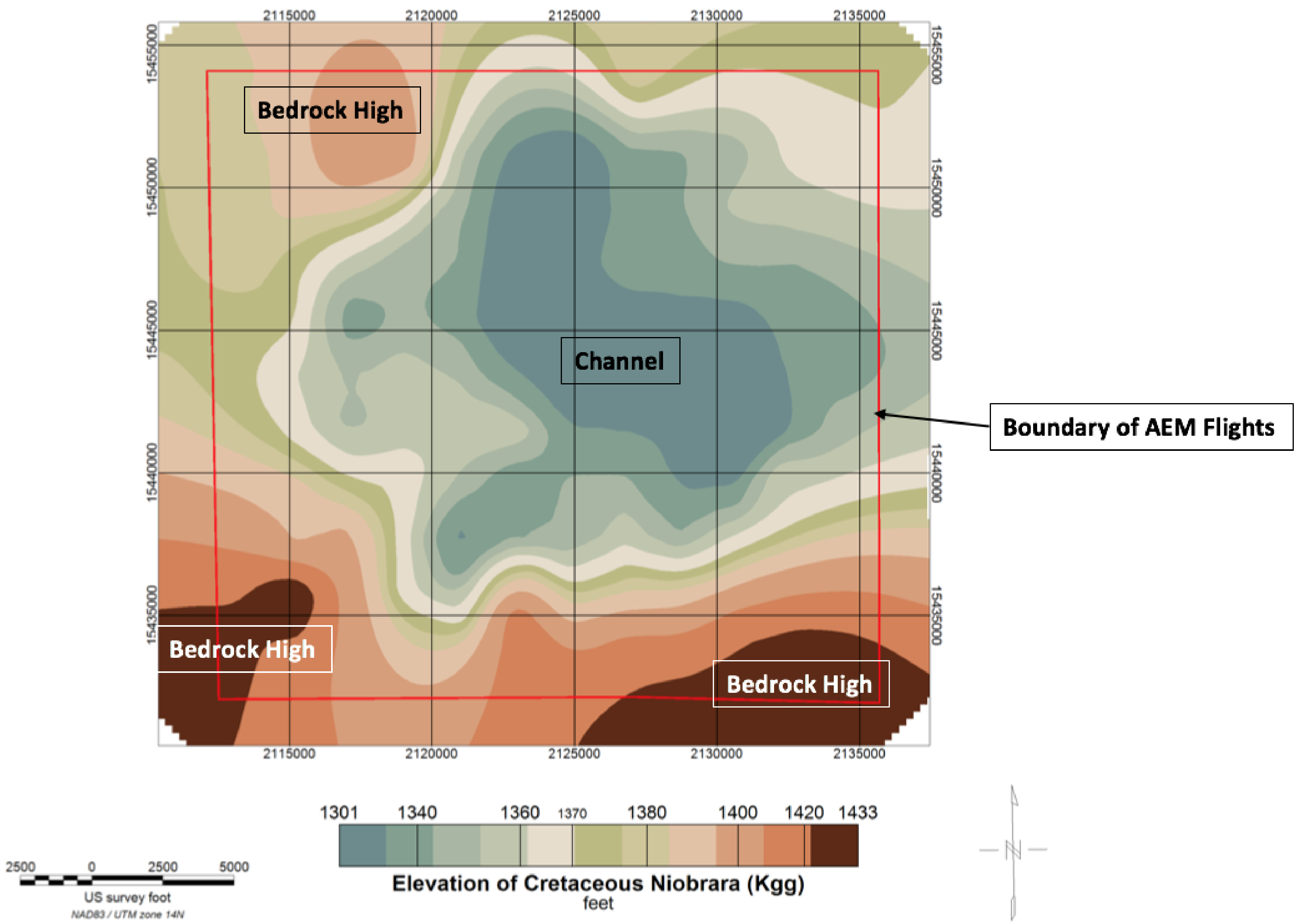


Figure 5-31. Base of the Quaternary aquifer which is the top of the bedrock. The channel-like feature that is eroded into the bedrock can be seen lying between three bedrock highs. The image projection is NAD 83, UTM Zone 14 North feet.

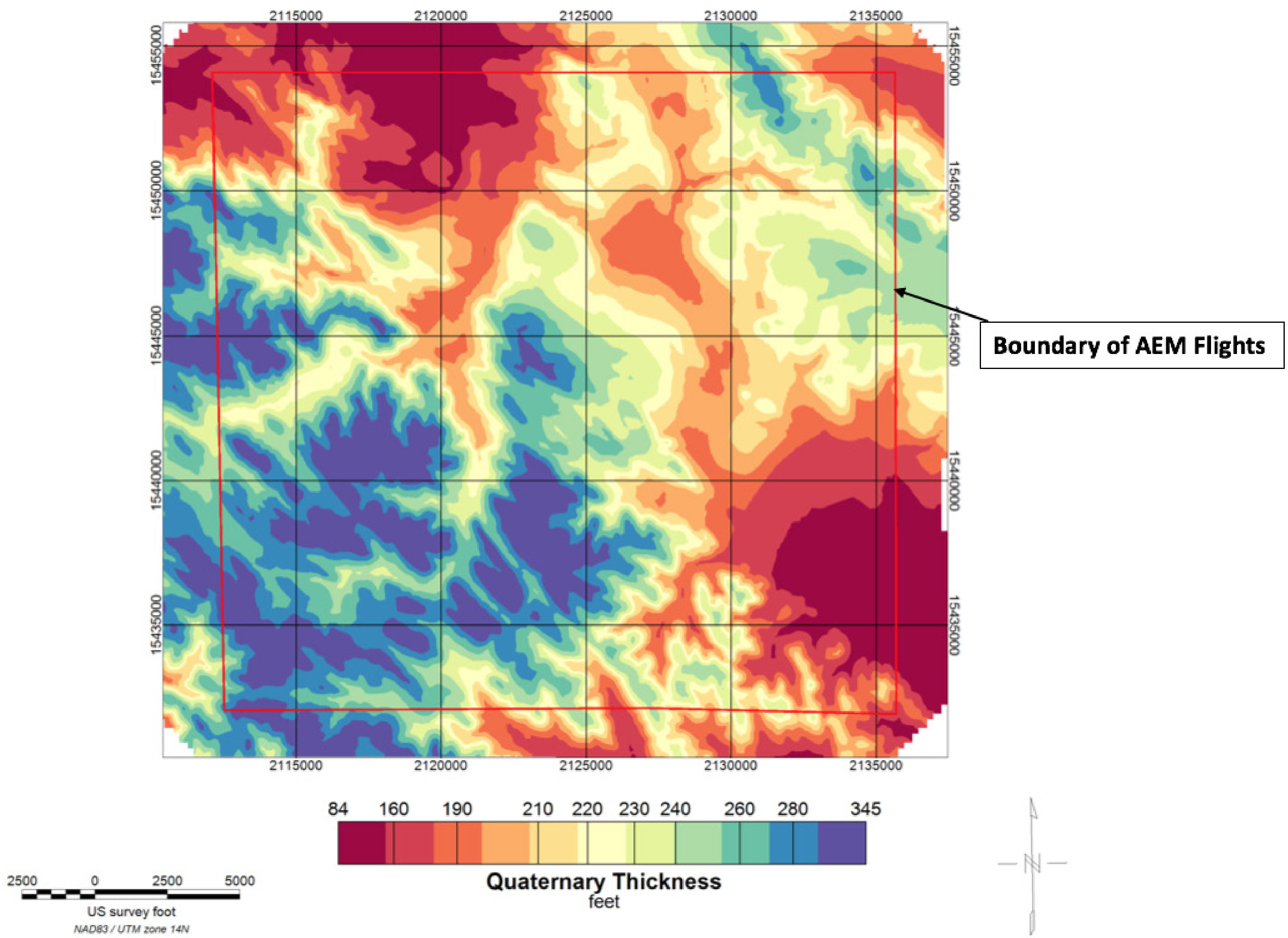


Figure 5-32. Thickness of the Quaternary (*Q*) materials within the Coleridge Block AEM survey area. The projection is NAD83 and the elevation values are referenced to NAVD 88 feet

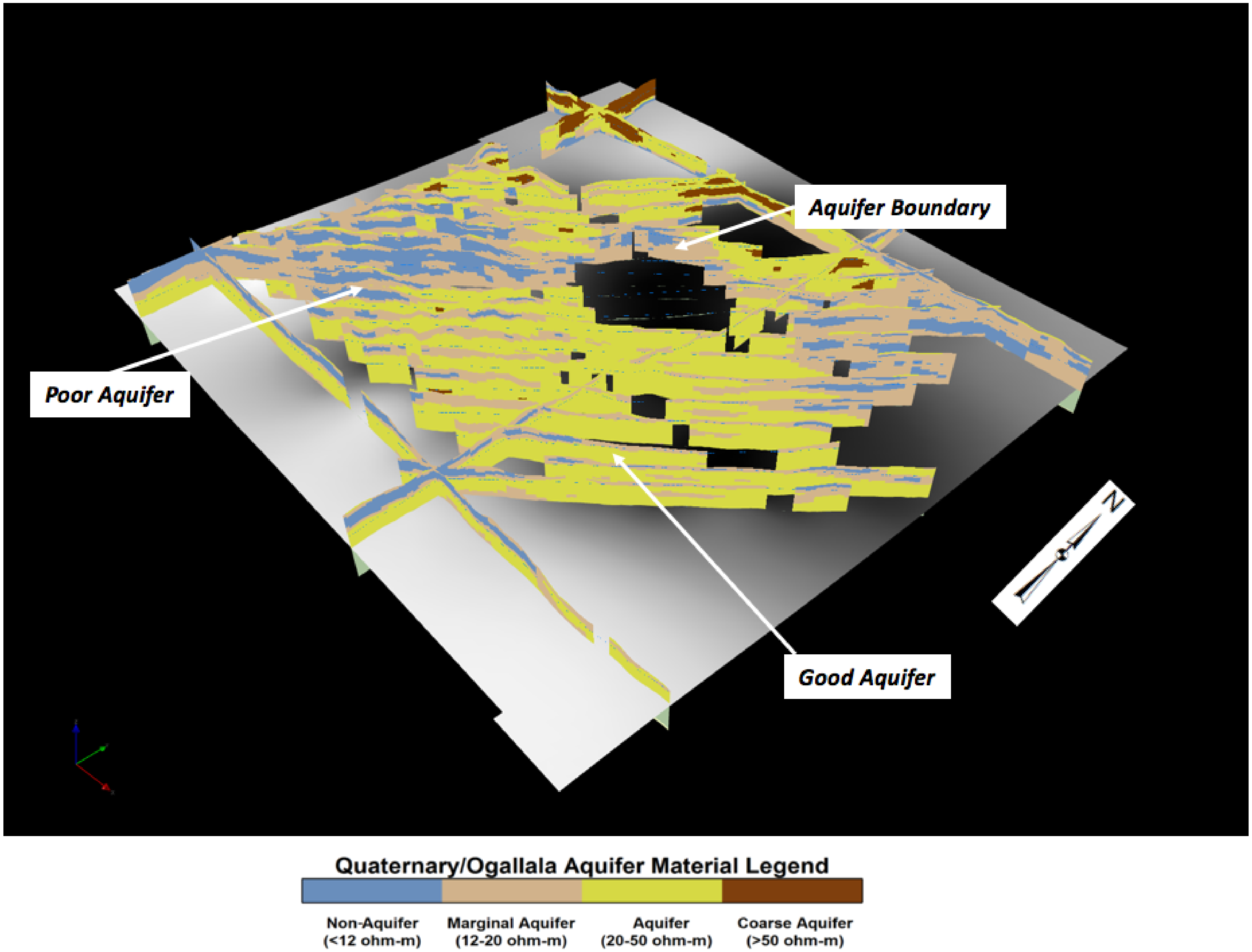


Figure 5-33. 3D fence diagram with a bedrock surface in gray showing the large amount of aquifer (yellow) and coarse aquifer (brown) material in the block. Note the marginal aquifer and non-aquifer material forming a groundwater boundary from southwest to northeast in the survey area. The map projection is NAD 83, UTM Zone 14 North, feet.

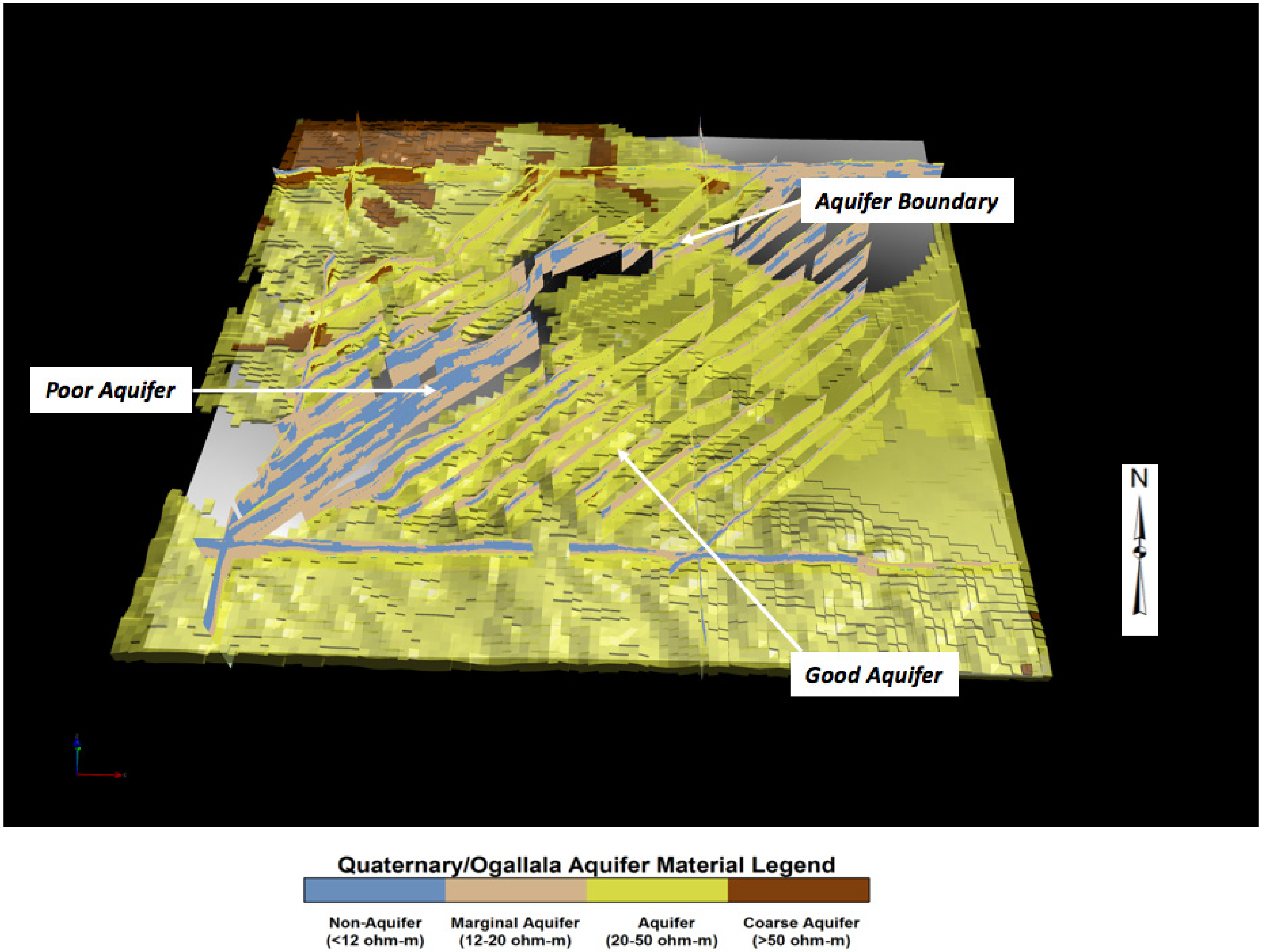


Figure 5-34. Voxel model with a view to the north, showing continuous volumes of the saturated aquifer (yellow) and coarse aquifer (brown). Note the presence of the marginal (tan) and non-aquifer (blue) material creating the groundwater boundary. The map projection is NAD 83, UTM Zone 14 North, feet.

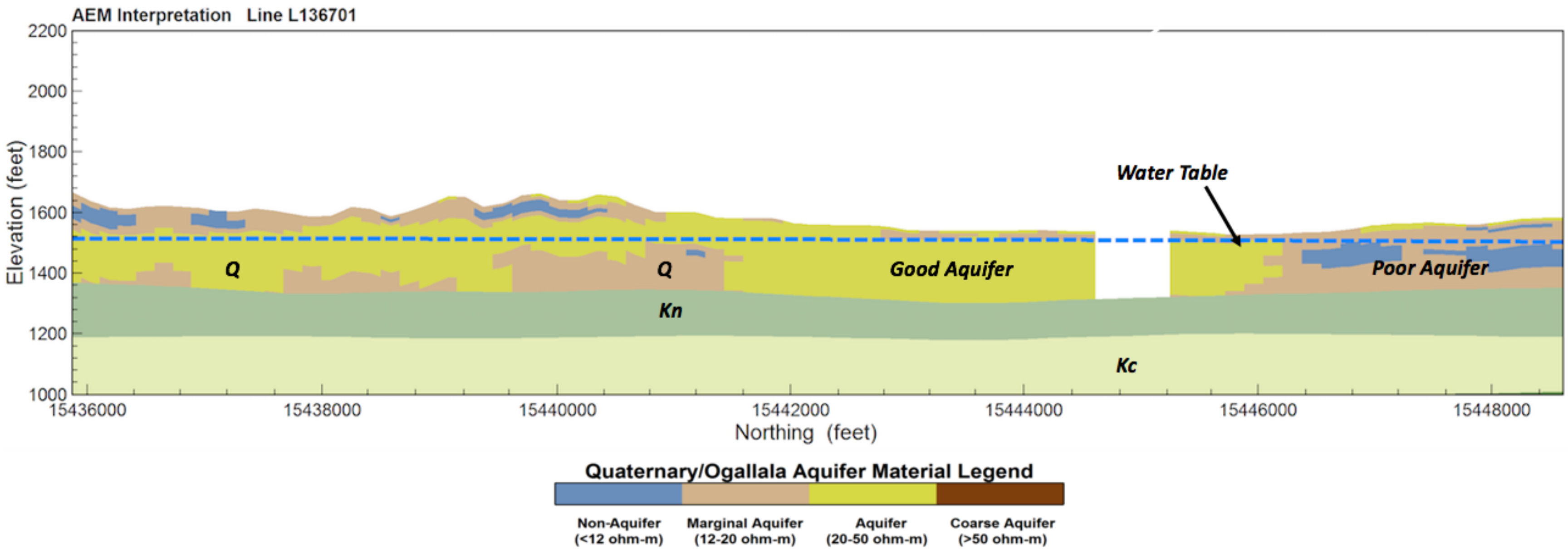


Figure 5-35. Profile L136701 showing the cross section of the Coleridge Block area east of Coleridge. Notice the thick sequence of aquifer materials in the area mixed with marginal (tan) and non-aquifer (blue) materials. (*Kn*-Cretaceous Niobrara, *Kc*-Cretaceous Carlile). The map projection is NAD 83, UTM Zone 14 North, feet.

5.5 Estimation of Aquifer Volume and Water in Storage for the Coleridge Block AEM Survey Area

The 3D digital representation of the subsurface resulting from the AEM method provides users the ability to more accurately estimate total unsaturated and saturated aquifer volume and the amount of extractable water present. The Coleridge Block AEM survey area was mapped at high resolution for this purpose. Approximately 21.1 square miles (approximately 13,500 acres) of AEM data were collected in the Coleridge area and interpreted (Figure 1-2).

The criteria for determining the basis for the range of resistivity values used in calculating the volumes of interpreted aquifer material are provided in Section 5.2. Figure 5-17 shows resistivity ranges for interpreted non-aquifer, marginal aquifer, aquifer, and coarse aquifer materials. This report provides information on unsaturated and saturated volumes of non-aquifer, marginal aquifer, aquifer, and coarse aquifer materials.

Figure 5-36 shows the distribution of the volumes of all saturated Quaternary aquifer materials, including non-aquifer, marginal aquifer, aquifer and coarse aquifer material from the water table down to bedrock showing the complex nature of the area. Understanding this complexity in the area and within the sedimentary deposits shows that estimated average values for porosity and specific yield are the best values to use in making the following calculations. Note that the images in these figures were created in pbEncom Discover PA, version 2015, Release Build 15.0.13 (pbEncom, 2016). They can be examined in greater detail by opening the PA sessions provided in *Appendix 3-Deliverables\PA_Session*.

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

Specific yield values were selected by estimating values (Figure 2-8) from Olafsen-Lackey (2005b) and personal communication (Susan Olafsen Lackey, UNL-CSD, Northeast Research and Extension Center, January 5, 2017). No aquifer test information was available for this report for the Coleridge Block AEM survey area. Estimates of specific yield were made for all aquifer materials. Specific yield for non-aquifer (<12 ohm-m) materials was chosen at 0.02, for marginal aquifer materials (12-20 ohm-m) a value of 0.05 was selected (Heath, 1983). The aquifer material (20-50 ohm-m) ranges from 0.1 to 0.2 with an average of 0.15 (Olafsen-Lackey, 2005b). Coarse aquifer materials exist as continuous deposits across 50 percent of the area. Estimates of specific yield for the coarse aquifer material (>50 ohm-m) ranges from 0.10 to 0.20 with an average of 0.15 (Olafsen-Lackey, 2005b).

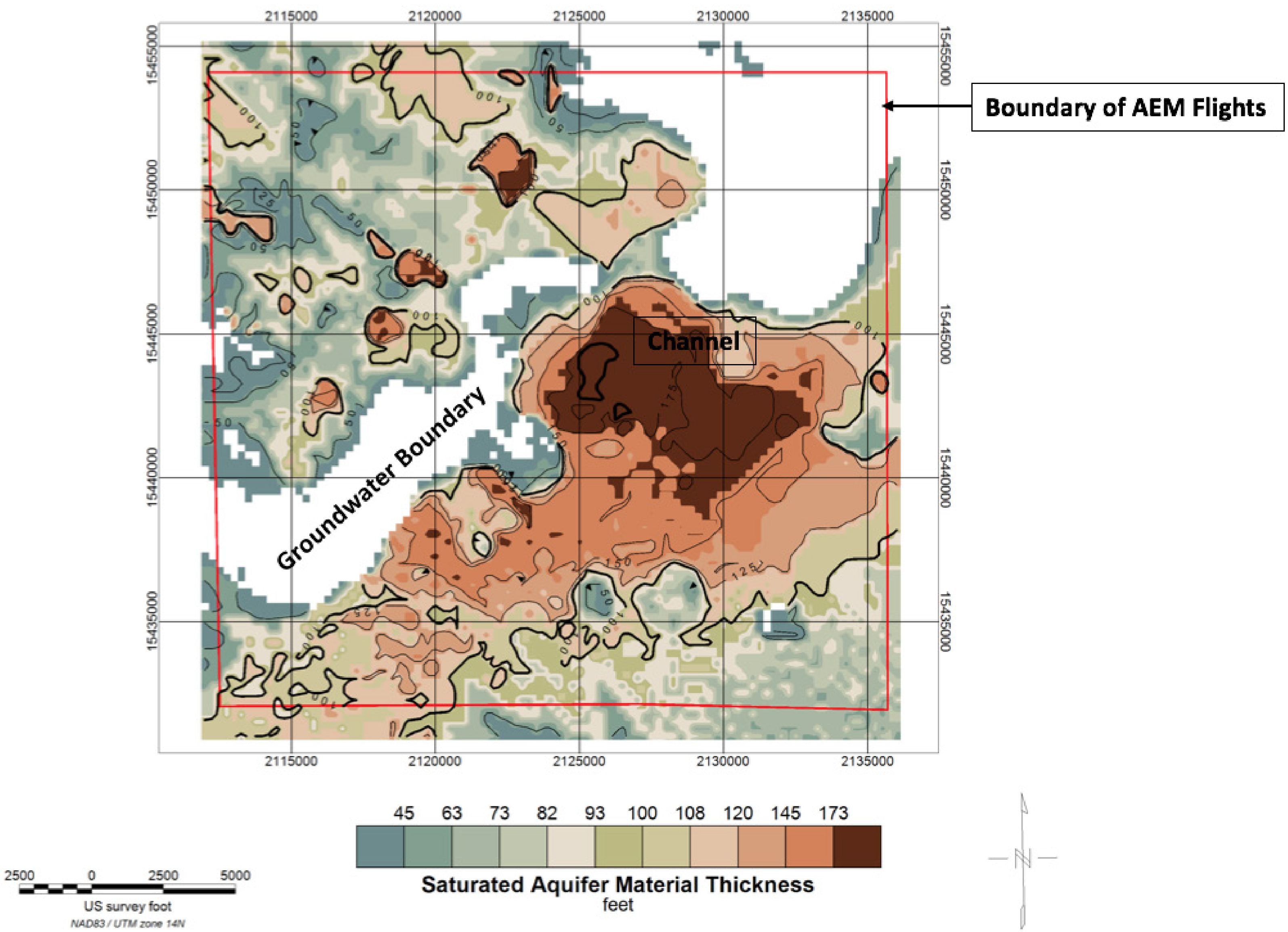


Figure 5-36. Map showing the distribution of the volumes of all saturated Quaternary aquifer materials, including non-aquifer, marginal aquifer, aquifer, and coarse aquifer material from the water table down to bedrock. The map projection is NAD 83, UTM Zone 14 North, feet.

Table 5-2 shows the results of calculations for amount of groundwater in storage calculated by volume of all aquifer materials below the water table then multiplied by the estimated porosity. The following calculation from values in the table shows the non-aquifer material has an estimated volume of 157,651 acre-ft and contains 63,060 acre-ft of groundwater in storage. The marginal aquifer material has an estimated volume of 638,560 acre-ft and contains 223,496 acre-ft of groundwater in storage. The aquifer material has an estimated volume of 975,523 acre-ft and contains an estimated volume of 195,105 acre-ft of groundwater in storage. The coarse aquifer material contains an estimated volume of 79,784 acre-ft for a total of 19,946 acre-ft of groundwater in storage. The amount of groundwater in storage for all material groups is 501,607 acre-ft.

The estimate of extractable volume of water is calculated by taking the amount of groundwater in storage times the specific yield. Non-aquifer materials in the Coleridge Block AEM survey area will yield approximately 1,261 acre-ft, marginal aquifer materials will yield approximately 11,175 acre-ft, aquifer materials will yield 29,266 acre-ft, and the coarse aquifer material will yield approximately 2,992 acre-ft. A total of 44,694 acre-ft is available from the combined non-aquifer, marginal, aquifer, and coarse aquifer materials.

These estimates are based on the CSD 1995 water table map. These values are conservative, as portions of the AEM data were removed during the inversion process due to interference from infrastructure at the land surface. Also, these volumetric estimates consider only the volume of water assumed in the pore spaces of the aquifer material defined by the resistivity threshold levels and do not account for amount of the possible “confined or semi-confined” water under pressure (head above the aquifer). This volume of water would add to the values reported in Table 5-2. However, too much uncertainty exists in developing an average level of head above the top of the aquifer across the entire project area, as well as defining a representative storativity term for the confined or semi-confined aquifers. Thus, the volumes listed in Table 5-2 are conservative estimates and the amounts released from the decline in pressure are not considered.

Table 5-2. Estimates of groundwater in storage and extractable water content in all aquifer materials underlying the Coleridge Block AEM survey area

Aquifer Material Type	Aquifer Volume (ft^3)	Aquifer Volume (acre-ft)	Average Porosity	Groundwater in Storage Volume (acre-ft)	Average Specific Yield	Extractable Water Volume (acre-ft)
Non-Aquifer	6,867,277,581	157,651	0.40	63,060	0.02	1,261
Marginal	27,815,690,738	638,560	0.35	223,496	0.05	11,175
Aquifer	42,493,792,238	975,523	0.20	195,105	0.15	29,266
Coarse	3,475,403,063	79,784	0.25	19,946	0.15	2,992
TOTAL	80,652,163,619	1,851,519		501,607		44,694

5.6 Recharge Areas within the LCNRD AEM Survey Area

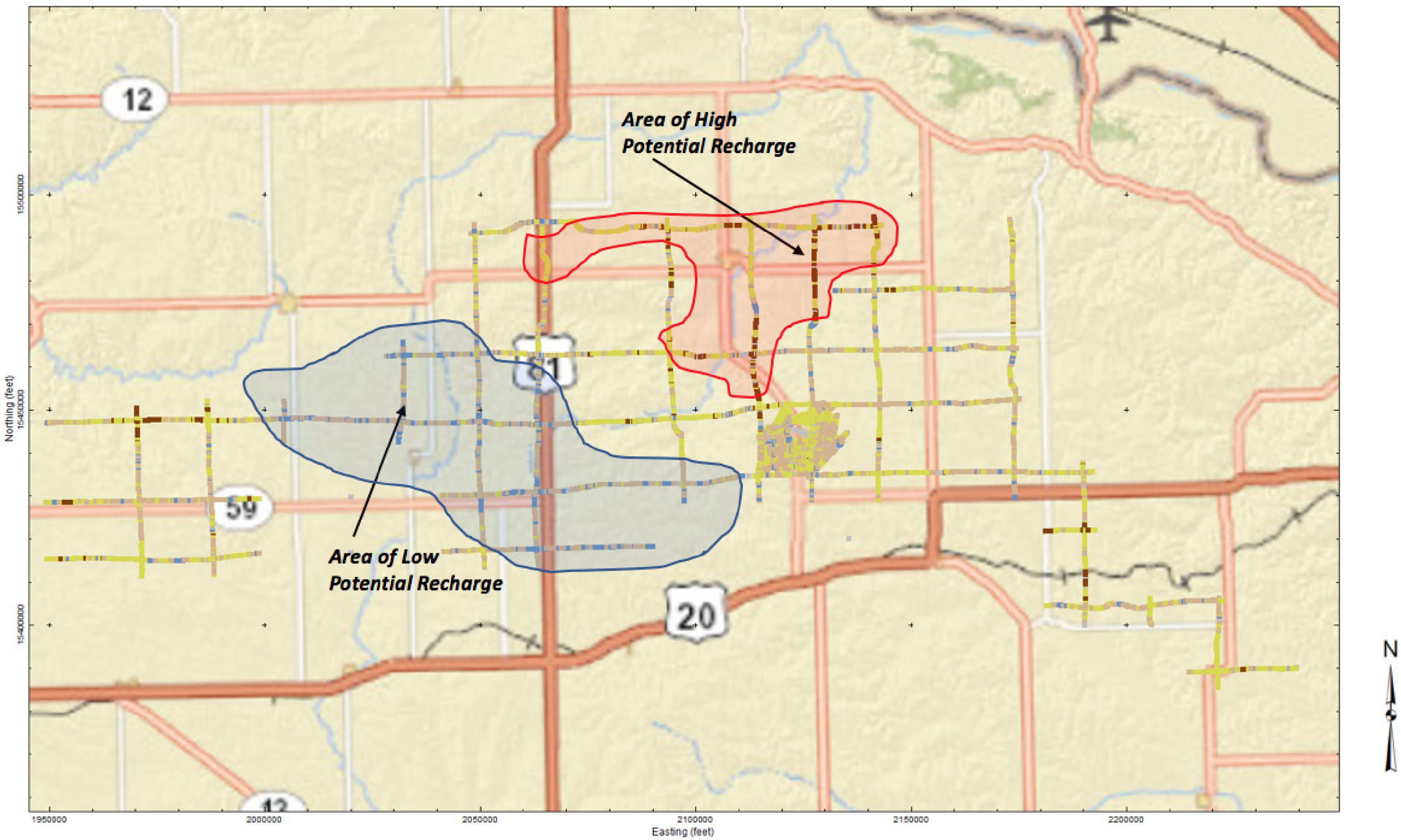
3D representations of the subsurface resulting from the AEM method illustrate areas of interpreted aquifer materials from the bedrock up to the land surface. From these maps a new series of near-surface maps, which includes the interval from 0 to10 feet, were constructed. The interval of 0-10 feet is 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 LCNRD AEM survey area are explained in detail in Section 5.3. A total of 353.9 line-miles (573.2 line-kilometers) of AEM data were acquired for the survey. Of this total, approximately 66.2 line-miles (107.2 line km) were flown in a dense block around Coleridge.

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 5-37). 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 western side of the AEM survey area in Figure 5-37 shows the area where recharge is potentially less than the rest of the survey area. The map also shows an area on the eastern 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.

The Coleridge Block area is shown in Figure 5-38 and highlights areas of high and low potential recharge. Potential recharge around the Coleridge Block area is greatest in the center of the block along a north-south oriented band with areas of lesser recharge potential located on the western and eastern sides of the survey.

A Google Earth image showing areas of high and low potential recharge based on the aquifer materials and the coarse aquifer materials noted along the flight lines in the survey area is presented in Figure 5-39. This data is included as a kmz file in *Appendix_3_Deliverables\KMZ\Recharge*.



Quaternary/Ogallala Aquifer Material Legend

Non-Aquifer (<12 ohm-m) | Marginal Aquifer (12-20 ohm-m) | Aquifer (20-50 ohm-m) | Coarse Aquifer (>50 ohm-m)

Figure 5-37. Map of LCNRD AEM reconnaissance flight lines (approximately 3 miles apart) showing patterns or areas where the potential for recharge within the first 10 feet can be high (red polygon) and low (blue polygon). The image projection is NAD 83, UTM Zone 14 North, feet.

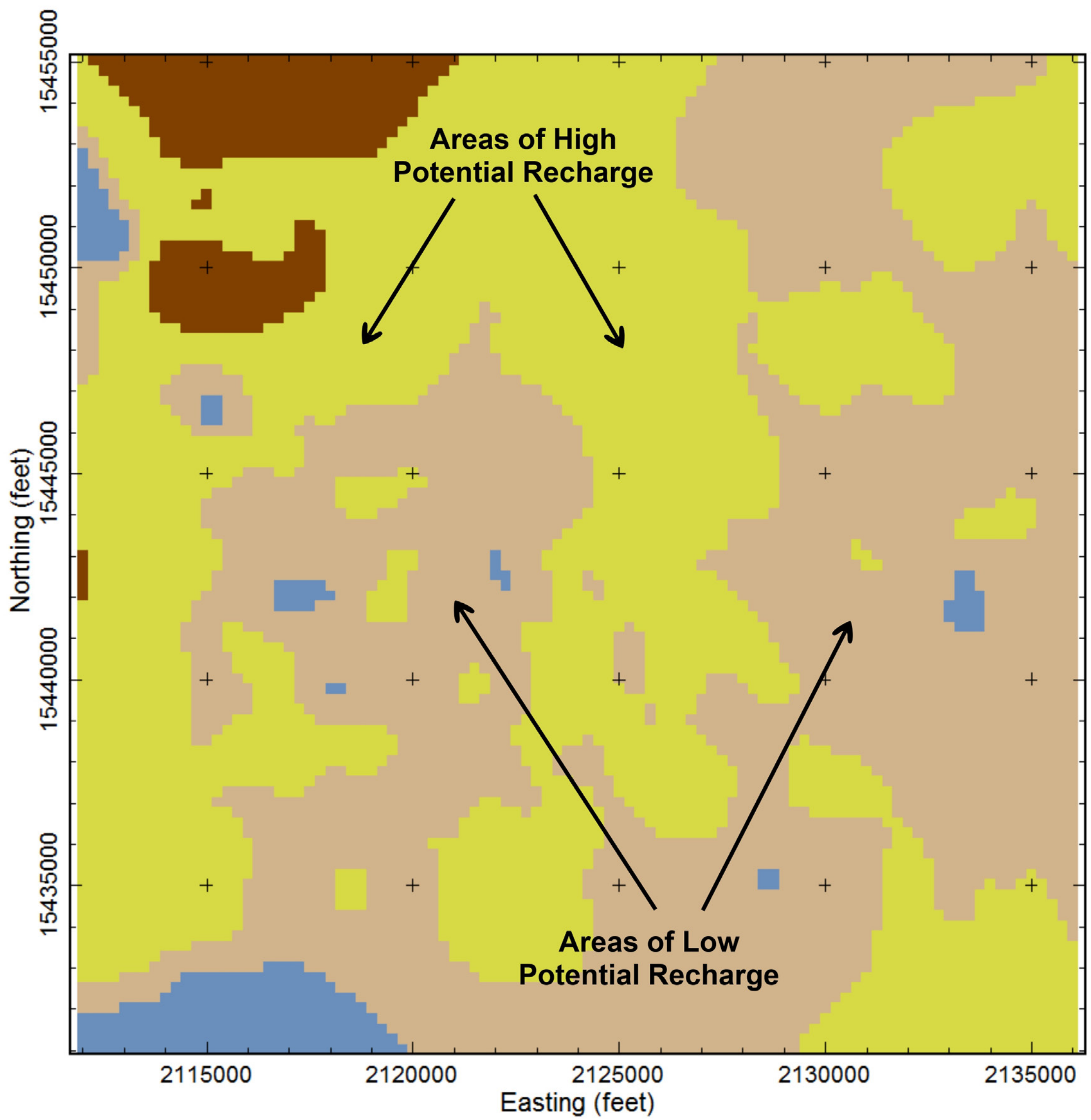


Figure 5-38. Map of Coleridge Block AEM flight lines showing patterns or areas where the potential for recharge within the first 10 feet can be high and low. The image projection is NAD 83, UTM Zone 14 North.

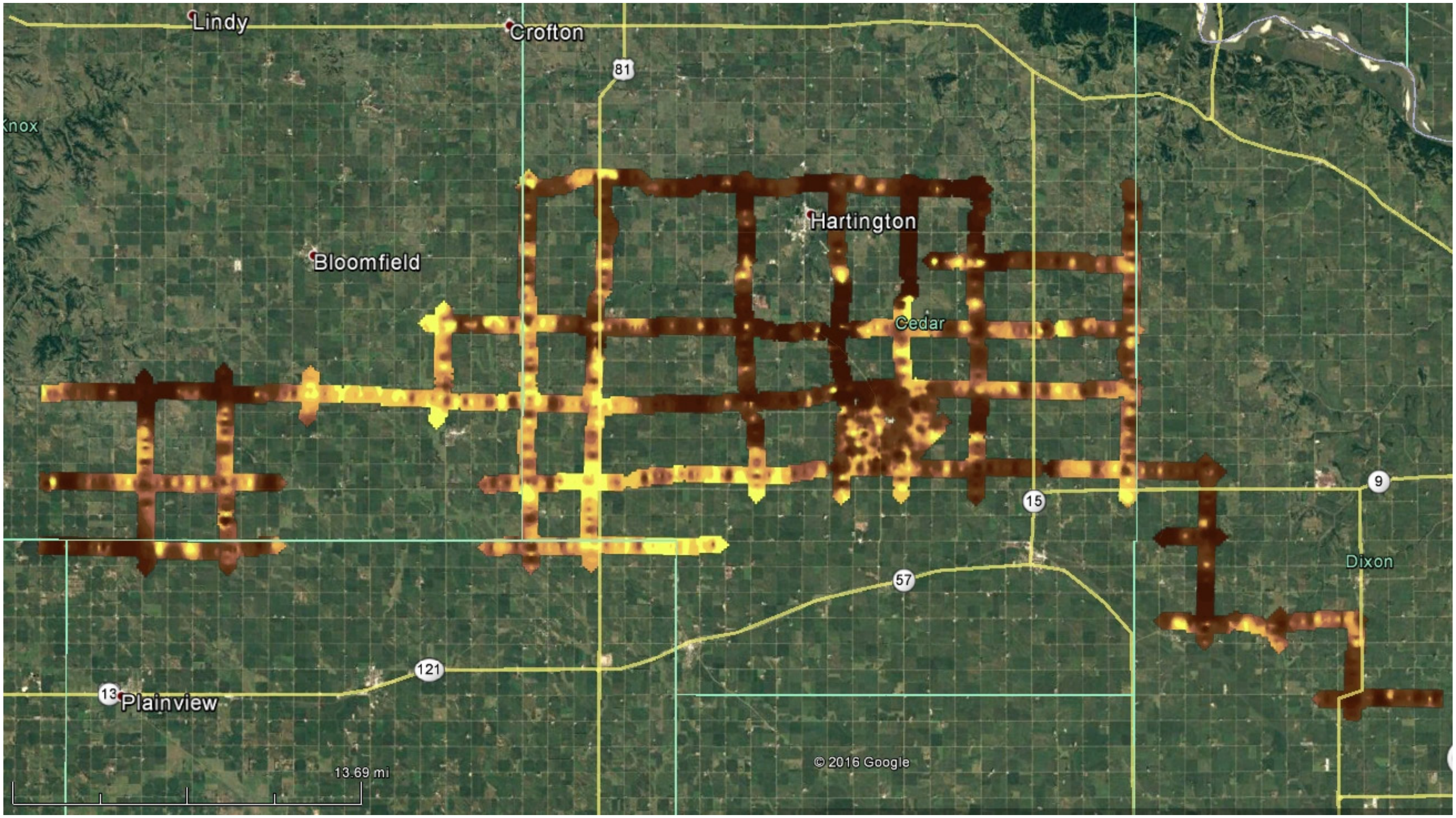


Figure 5-39. Potential aquifer and coarse material recharge zones within the LCNRD AEM survey area displayed as a kmz in Google Earth. This kmz is included as a deliverable in Appendix_3_Deliverables\KMZ\Recharge.

5.7 Key AEM Findings

5.7.1 AEM Data Acquired, Processed, and Inverted

A total of 353.9 line-miles (573.2 line-kilometers) of AEM data were acquired for the LCNRD survey. Of this total, approximately 66.2 line-miles (107.2 line km) were flown in a dense block around Coleridge. After final processing, 336.7 line-miles (545.5 line-km) of data were retained for the final inversions. This amounts to a data retention of 95%. This high rate is the result of careful flight line planning and design.

5.7.2 Boreholes

Information from boreholes was used to analyze the AEM inversion results. Of the total of 127 CSD holes utilized in this investigation, 36 contained geophysical logging information including resistivity, gamma-gamma, temperature, calibration, etc., 66 holes contained lithology information, and 25 holes contained stratigraphic information. A total of 1,408 NE-DNR registered wells contained usable lithology and/or stratigraphy information. Of the 5 NOGCC wells used in this study, 4 contained both lithology and stratigraphy information and 1 hole contained only lithology information.

5.7.3 Comparison of 2014 and 2016 AEM Databases

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. The portion of the BGMA within the LCNRD is included within this report. 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. Several other comparisons can be made within the LCNRD due to 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.

5.7.4 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 (***To***), and Cretaceous Pierre (***Kp***), Niobrara (***Kn***), Carlile (***Kc***), Greenhorn limestone and Graneros shale (***Kgg***), and Dakota (***Kd***). The interpretive process benefited from the use of CSD, NE-DNR, and NGOCC 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.

5.7.5 *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.

5.7.6 *Hydrogeological Framework of the LCNRD*

The 2016 AEM survey reveals variability in the Quaternary (***Q***) deposits across the LCNRD survey area. When combined with the ***To***, they represent the aquifer materials in the survey area, where saturated. The ***To*** is generally thick in the west and is thin, discontinuous to absent in the eastern regions of the 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 across most of the survey area and ***Q*** and ***To*** coarse aquifer and aquifer materials found predominately on the west side often associated with alluvial deposits. ***To*** is in the center of the AEM survey area and the pinches out to the east and west with ***Q*** sediments covering all units. The ***Q*** and ***To*** make up the aquifer materials overlying the Cretaceous bedrock units.

5.7.7 *Hydrogeological Framework of the Coleridge Block AEM Survey Area*

The Coleridge Block AEM flight area is within the Quaternary Aquifer system. The area is composed of ***Q*** aquifer materials lying on the ***Kn*** bedrock surface. The bedrock is eroded and has a channel-like expression. The channel trends from west to east in the center of the block. The channels are flanked by bedrock highs that are in the AEM block area that have an increased relief of up to 100 feet in elevation. The thickness of the Quaternary material within the Coleridge Block ranges from 80 to 340 feet thick. The area is dominated by a mix of aquifer materials and coarse aquifer materials and a low-relief water table. The thicker sequences of aquifer material lie to the southeast and center of the block with marginal and non-aquifer materials creating an aquifer boundary across the area from southwest to northeast. The aquifer and coarse aquifer materials are the most productive of the Q aquifer and have the greatest amount of groundwater flow.

5.7.8 Estimation of Aquifer Volume and Water in Storage in the Coleridge Block

The non-aquifer material has an estimated volume of 157,651 acre-ft and contains 63,060 acre-ft of groundwater in storage. The marginal aquifer material has an estimated volume of 638,560 acre-ft and contains 223,496 acre-ft of groundwater in storage. The aquifer material has an estimated volume of 975,523 acre-ft and contains an estimated volume of 195,104 acre-ft of groundwater in storage. The coarse aquifer material contains an estimated volume of 79,784 acre-ft for a total of 19,946 acre-ft of groundwater in storage. The amount of groundwater in storage for all material groups is 501,606 acre-ft. The estimate of extractable volume of water is calculated by taking the amount of groundwater in storage times the specific yield. Non-aquifer materials in the Coleridge Block AEM survey area will yield approximately 1,261 acre-ft, marginal aquifer materials will yield approximately 11,175 acre-ft, aquifer materials will yield 29,266 acre-ft, and the coarse aquifer material will yield approximately 2,992 acre-ft. A total of 44,694 acre-ft is available from the combined non-aquifer, marginal aquifer, aquifer, and coarse aquifer materials.

5.7.9 Potential Recharge Zones within the LCNRD AEM Survey Area

Areas of more potential recharge in the LCNRD AEM survey area are located north of Coleridge and areas with less potential for recharge are located on the western side of the AEM survey area. There are other discontinuous zones of potentially lower and higher recharge scattered throughout survey area. To map their extent, additional flight lines are required. Potential recharge around the Coleridge Block area is greatest in the center of the block along a north-south oriented band with areas of lesser recharge potential located on the western and eastern sides of the survey block.

5.8 Recommendations

Recommendations provided to the LCNRD in this section are based on the interpretation and understanding gained from the addition of the AEM data to existing information and from discussions with the LCNRD about their management challenges.

5.8.1 Additional AEM Mapping

The hydrogeologic maps provided in this report represent the detailed framework developed for the LCNRD at a reconnaissance level and the Coleridge Block area. LCNRD is in the middle of a 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 20-mile spacing in 2014 and in 2016 a 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 5-40 shows the reconnaissance lines collected from 2014 through 2016. As seen these lines were collected in the central and west parts of the district with a few 20-mile spaced lines across the district. The red lines are the proposed locations of the 3-mile grid reconnaissance lines to be collected next in the 2017 plan. The previously mapped lines match each other 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 in detail by block flights to provide information on the hydrogeologic framework and the recharge areas. It is recommended that the plan to continue AEM mapping be completed (Figure 5-40). Upon completion of the reconnaissance line surveys, it is recommended that all the data from the various vintage surveys be brought together in one database and final continuous surface maps be developed for the LCNRD.

5.8.2 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. The areas of glacial till and loess covering the most 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. This is especially true in the glacial till area of LCNRD.

5.8.3 Siting new test holes and production wells

The AEM framework maps and profiles provided in this report provide insight into the 3D relationship between current test holes and production groundwater wells. At the time of this report, the currently available lithology data for the LCNRD area was used in building the framework maps and profiles. 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.

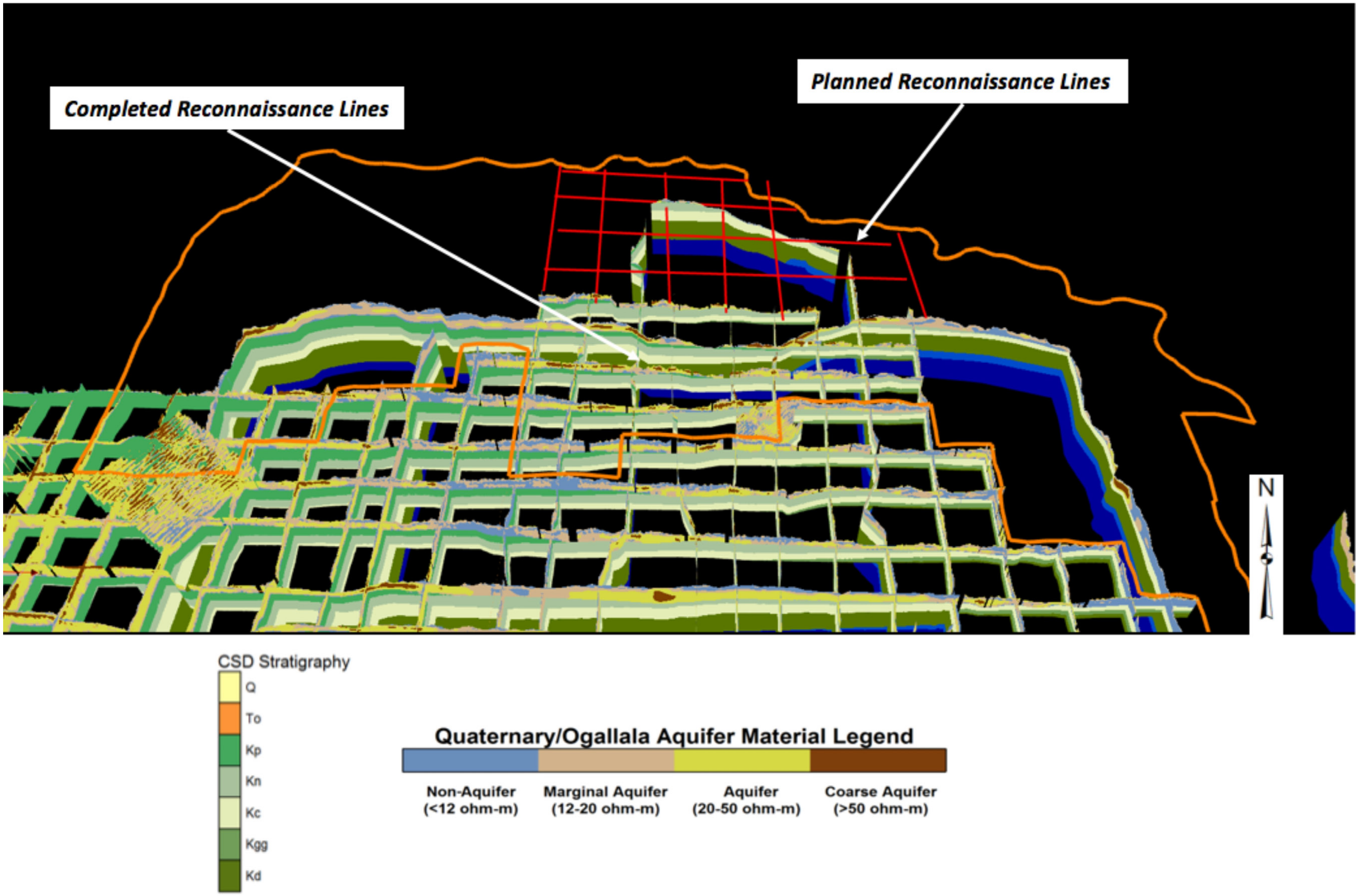


Figure 5-40. Map displaying the completed and the proposed LCNRD reconnaissance lines.

Planners should locate wells in areas of greatest saturated thickness with the least potential for non-point source pollution. Also these maps will help in refining the well head protection areas around the public supply wells.

5.8.4 Aquifer testing and borehole logging

Aquifer tests and additional test holes 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 LCNRD 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 LCNRD. 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.

5.8.5 Recharge Zones

The LCNRD hydrogeologic framework in this report provides areas of recharge from the ground surface to the groundwater aquifer. Reconnaissance level AEM investigations provide limited detailed information between the lines for understanding recharge throughout the survey area. It is recommended that 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 LCNRD 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.

5.8.6 Integration of 2014 and 2016 AEM Databases and Interpretation

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 examined in AGF (2017a) as part of the BGMA AEM survey of which LCNRD is a participant. Several other comparisons can be made within the LCNRD due to the continuation of the AEM data collection within the District from 2014 to 2016. It is recommended that, at the completion of the AEM reconnaissance lines in LCNRD, all existing AEM survey results be integrated to produce a single coherent interpretation of the hydrogeological framework within the LCNRD. Any future AEM data acquisition should also then be integrated in the unified interpretation.

6 Description of Data Delivered

6.1 Tables Describing Included Data Files

Table 6-1 describes the data columns in the ASCII *.xyz file LCNRD_EM_MAG_UTM14n_feet.xyz as well as the Geosoft database file LCNRD_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 LCNRD_AEM_SCI_INV_v1.gdb files and LCNRD_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 various interpretation results are included in data files LCNRD_InterpSurfaces_v1 in gdb and ASCII xyz formats. Table 6-6 describes the data columns of this file.

Table 6-7 describes the raw data files included in Appendix 3_Deliverables \Raw_Data. As discussed above, eight (8) flights were required to acquire the LCNRD 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.

Two voxel grids were completed for the LCNRD reconnaissance area and the Coleridge dense flight block within the LCNRD survey area. The voxel grids were made using a 250 ft grid cell size and the model layer thickness (Table 4-4). The voxel grid was clipped below the bedrock surface interpreted from the AEM and the boreholes as detailed in Section 5.1.4. The bedrock surface grid “*LCNRD_bedrock_elevation*” was used to clip the voxel, and can be found in (Table 6-8). Table 6-9 is a list of the channel names in both ASCII *.xyz and Geosoft *.gdb format for the Coleridge_Q_resistivity_voxel and the Coleridge_Saturated_resistivity_voxel.

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 LCNRD AEM survey lines
- 3D voxel models as ASCII *.xyz and *.gdb for the Coleridge flight block

KMZs for LCNRD flight lines (Discussed in Section 6.2)

Profile Analyst sessions for the Profiles and 3D grids for the Coleridge Block data analysis. (Discussed in Section 6.3)

Table 6-1: Channel name, description, and units for LCNRD_EM_MAG_UTM14n_Feet.gdb and LCNRD_EM_MAG_UTM14n_Feet.csv 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 LCNRD_AEM_SCI_Inv_v1.gdb and LCNRD_AEM_SCI_Inv_v1.xyz with EM inversion results.

Parameter	Description	Unit
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	
LINE	Line 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	Meters [m]
DOI_UPPER_FT	More conservative estimate of DOI	Meters [m]
DOI_LOWER_M	Less conservative estimate of DOI	Feet [ft]
DOI_UPPER_M	More conservative estimate of DOI	Feet [ft]
RHO_I_0 THROUGH RHO_I_28	Inverted resistivity of each later	Ohm-m
RHO_STD_0 THROUGH RHO_STD_28	Standard Deviation of inverted Rho estimates	
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 LCNRD Survey Area
BazileCreekDNRLith_Data_project.	
CSD-GP-E-logs_Collar_project.	Geophysical logs from CSD boreholes in the LCNRD Survey Area
CSD-GP-E-logs_Data_project.	
CSD-GP-GEO-logs_Collar_project.	Geophysical logs from CSD boreholes in the LCNRD Survey Area
CSD-GP-GEO-logs_Data_project.	
ENWRANorthLith_Collar_project.	Lithology logs from ENWRA-North wells within the LCNRD Survey Area
ENWRANorthLith_LITH_project.	
ENWRANorthStrat_Collar_project.	Stratigraphic logs from ENWRA-North wells within the LCNRD Survey Area
ENWRANorthStrat_Strat_project.	
LCNRDLith_Collar_project	Lithology logs from within the LCNRD Survey Area
LCNRDLith_Lith_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 LCNRD 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 LCNRD 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 LCNRD_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	LCNRD_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)
LCNRD_bedrock_elevation.	Grid of the Bedrock composed of ***Kp***, ***Kn***, ***Kc*** and ***Kgg*** which is also the base of the aquifer elevation NAVD88 (feet) LCNRD Survey Area	100
LCNRD_DEM_elevation.	Grid of the Digital Elevation Model (DEM) downloaded from the National Elevation Dataset (NED) August 2016 NAVD88 (feet)	100
LCNRD_Kp_elevation.	Grid of the top of the ***Kp*** elevation NAVD88 (feet) LCNRD Survey Area	100
LCNRD_Kn_elevation.	Grid of the top of the ***Kn*** elevation NAVD88 (feet) LCNRD Survey Area	1000
Coleridge_Kn_elevation.	Grid of the top of the ***Kn*** elevation NAVD88 (feet) Coleridge block	250
LCNRD_Kc_elevation.	Grid of the top of the ***Kc*** elevation NAVD88 (feet) LCNRD Survey Area	~2144
Coleridge_Kc_elevation.	Grid of the top of the ***Kc*** elevation NAVD88 (feet) Coleridge block	250
LCNRD_Kgg_elevation.	Grid of the top of the *Kgg* elevation NAVD88 (feet) LCNRD Survey Area	~3201
Coleridge_Kgg_elevation.	Grid of the top of the ***Kgg*** elevation NAVD88 (feet) Coleridge block	250
LCNRD_Kd_elevation.	Grid of the top of the ***Kd*** elevation NAVD88 (feet) LCNRD Survey Area	~4376
Coleridge_Kd_elevation.	Grid of the top of the ***Kd*** elevation NAVD88 (feet) Coleridge block	250
LCNRD_1995WT_elevation.	Grid of the CSD 1995 water table NAVD88 (feet)	100
LCNRD_Q_To_thickness	Grid of the thickness of the ***Q*** and ***To*** material within the LCNRD Survey Area (feet)	100
Coleridge_Q_To_thickness	Grid of the thickness of the ***Q*** material within the Coleridge block (feet)	100
LCNRD_Saturated_thickness.	Grid of thickness of the saturated ***Q*** and ***To*** from the water table to the bedrock within the LCNRD survey area NAVD88 (feet)	100

Coleridge_Saturated_ thickness.	Grid of thickness of the saturated ***Q*** and ***To*** from the water table to the bedrock within the Coleridge block NAVD88 (feet)	100

Table 6-9. Channel name, description, and units for Coleridge_Q_resistivity_voxel.* and Coleridge_Saturated_resistivity_voxel.*csv and *.gdb.

Parameter	Description	Unit
X	Easting NAD83, UTM Zone 14	Feet [ft]
Y	Northing NAD83, UTM Zone 14	Feet [ft]
Depth	Depth negative down surface at 0.0	Feet [ft]
Quaternary_ or Saturated Resistivity	Voxel cell resistivity value	Ohm-m
Elevation	Elevation NAVD 88 100 ft grid	Feet [ft]

6.2 Description of Included Google Earth KMZ Data and Profiles

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

KMZ files of the potential recharge zones in the LCNRD AEM survey area are included in the folder "*Appendix_3_Deliverables\KMZ\LCNRD_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, and the elevations of the tops of the Cretaceous Pierre, Niobrara, Carlile, Greenhorn and Graneros, and Dakota group formations. These KMZ files are located within the "*Appendix_3_Deliverables\KMZ\LCNRD_Interp\LCNRD_Prof*" folder. Also in this folder is a "*GoogleE_Readme_LCNRD.pdf*" file that provides instructions in regards to the "*Settings*" changes that need to be made in Google Earth, and how to use the KMZ files in Google Earth including a legend of what attributes are displayed when an AEM sounding location is clicked. This file is repeated below as a convenience. An example of the LCNRD KMZ is presented in Figure 6-1.

6.2.1 Included README for the LCNRD Interpretation KMZ's

README for:

LCNRD_Interpretation_v1.kmz

Data Files - Please copy the folder *LCNRD_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 *LCNRD_Interpretation_v1.kmz* file within the folder named *LCNRD_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

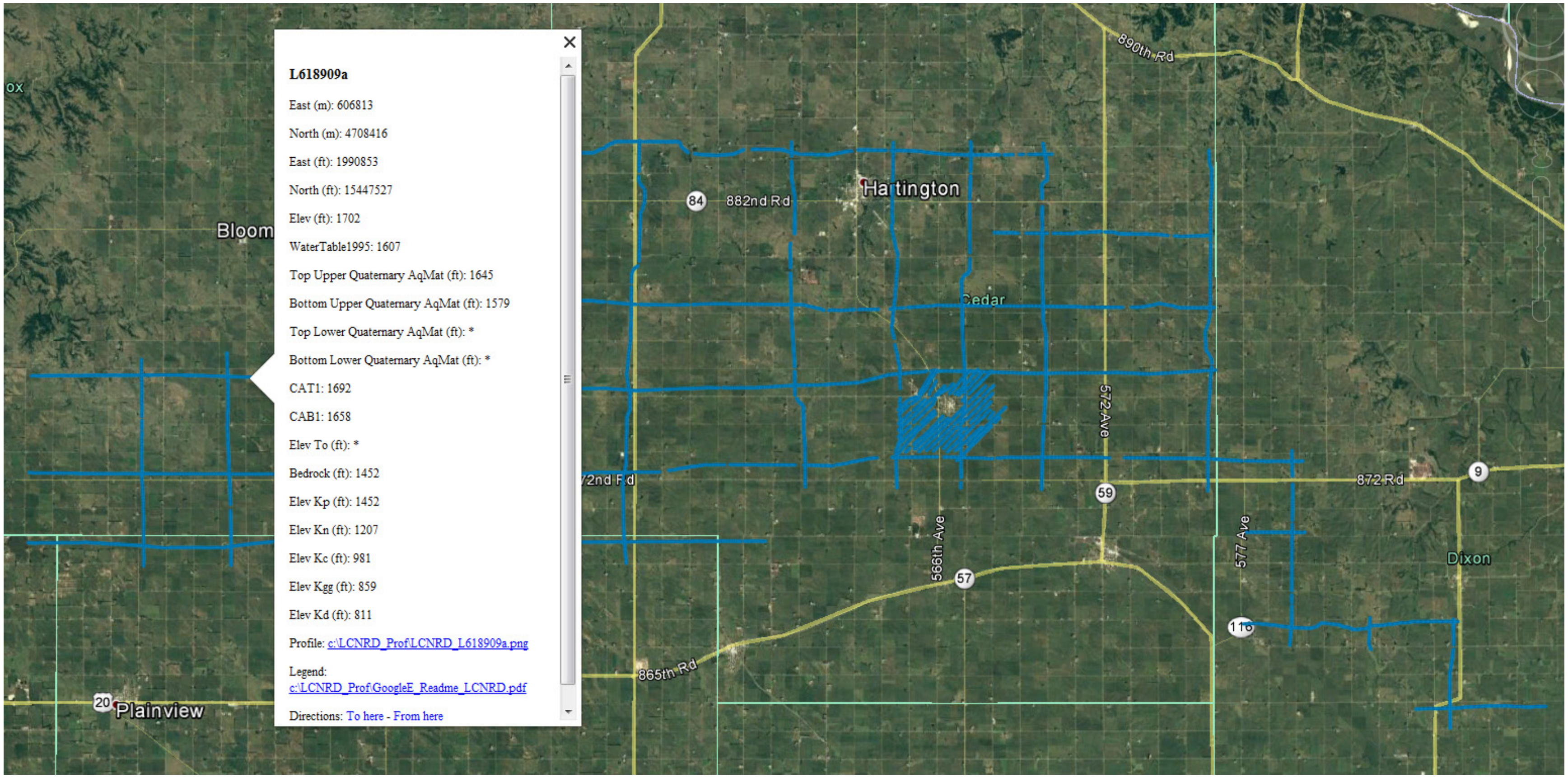


Figure 6-1. Example Google Earth image for the LCNRD Interpretation kmz.

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. In order to allow the future use of the information imported into the PA platform, PA Session Package files were created and are included within this report. A free viewer is available from the pbEncom Discover PA website: http://web2.encom.com.au/downloads/discover_3D/Discover_Viewer_2015.exe

The files located in the Appendix 3\PA_Sessions need to be unzipped and copied to a directory and then the Session file needs to be opened within Discover PA. Details on the function of Discover PA can be accessed from the pbEncom website and the help functions within Discover PA. The Session files that are included with the project deliverables are summarized in Table 6-10.

Table 6-10. pbEncom Discover PA Session Files

Area Covered	View Format	File name
Lewis & Clark 2016 Survey Area	2D	LCNRD_Profiles.egs
Coleridge Block	3D	Coleridge_Voxel3D.egs

7 References

Abraham, J. D., Bedrosian, P.A., Asch, T.H., Ball, L.B., Cannia, J. C., Phillips, J.D., and S. Olafsen-Lackey. 2011. Evaluation of Geophysical Techniques for the Detection of Paleochannels in the Oakland Area of Eastern Nebraska as Part of the Eastern Nebraska Water Resource Assessment. U.S. Geological Survey Scientific Investigations Report 2011-5228. https://pubs.usgs.gov/sir/2011/5228/ (accessed on January 9, 2017).

Abraham, J. D., Carney, C.P., and J. C. Cannia. 2013. Data Report on Mapping the Hydrogeology of the Clarkson Area within the Lower Elkhorn Natural Resources District Using an Airborne Electromagnetic Survey. Project findings report prepared for the Lower Elkhorn Natural Resources District by Exploration Resources International Geophysics LLC, Vicksburg, MS. http://www.lenrd.org/latest-news/2014/5/15/report-on-airborne-electromagnetic-aem-survey-in-the-clarkso.html (accessed on January 9, 2017).

Abraham, J.D., Cannia, J.C., Cameron, K., and Asch T.H. 2015. Watershed scale characterization of glacial and bedrock aquifers in eastern Nebraska, NovCare 2015, Lawrence, KS, May 19-21.

AGF, 2017a, Mapping the Hydrogeology of the Bazile Groundwater Management Area with Airborne Electromagnetics Surveys, Prepared for Bazile Groundwater Management Area Project (Lewis and Clark Natural Resources District, Lower Elkhorn Natural Resources District, Lower Niobrara Natural Resources District, and Upper Elkhorn Natural Resources District): by Aqua Geo Frameworks, LLC, Mitchell, Nebraska.

AGF, 2017b, Hydrogeologic Framework of Selected Area in Sarpy County, Nebraska, Prepared for the Papio-Missouri River Natural Resources District: by Aqua Geo Frameworks, LLC, Mitchell, Nebraska. http://enwra.org/aem2016.html#papio (accessed on May 25, 2017)

AGF, 2017c, Hydrogeologic Framework of Selected Area in Lower Loup Natural Resources District with Airborne Electromagnetic Surveys, Prepared for the Lower Loup Natural Resources District: by Aqua Geo Frameworks, LLC, Mitchell, Nebraska.

AGF, 2017d, Hydrogeologic Framework of Selected Area in Lower Elkhorn Natural Resources District with Airborne Electromagnetic Surveys, Prepared for the Lower Elkhorn Natural Resources District: by Aqua Geo Frameworks, LLC, Mitchell, Nebraska.

Asch, T.H., Abraham, J.D., and Irons, T., 2015, "A discussion on depth of investigation in geophysics and AEM inversion results", Presented at the Society of Exploration Geophysicists Annual Meeting, New Orleans.

Burchett, R. R., 1986, Bedrock geology of Nebraska. University of Nebraska-Lincoln, School of Natural Resources.

Burchett, R.R, Dreeszen, V.H., Souders, V.L., Prichard, G.E., Bedrock geologic map showing configuration of the bedrock surface in the Nebraska part of the Sioux City 1 degree x 2 degrees quadrangle-1988. https://ngmdb.usgs.gov/maps/mapview/ (accessed May18, 2017).

Carney, C.P, Abraham, J.D., and Cannia, J.C. 2014a. Data report on mapping the hydrogeology near the City of Madison, Nebraska using an airborne electromagnetic survey: Prepared for the City of Madison by Exploration Resources International Geophysics LLC, Vicksburg, MS.

Carney, C. P., Pierce, K.S., Abraham, J.D., Steele, G.V., Genco, A.G., and Cannia, J.C., 2014b, "Hydrogeologic Assessment and Framework Development of the Aquifers beneath the Brainard-

Valparaiso Area of the Lower Platte South Natural Resources District in Eastern Nebraska." Prepared for the Lower Platte South Natural Resources District by Exploration Resources International Geophysics LLC, Vicksburg, MS. http://www.lpsnrd.org/Programs/gwaem.htm (accessed on January 9, 2017).

Carney, C.P., Abraham, J.D., Cannia, J.C., and Steele, G.V., 2015a, Final Report on Airborne Electromagnetic Geophysical Surveys and Hydrogeologic Framework Development for the Eastern Nebraska Water Resources Assessment – Volume I, including the Lewis and Clark, Lower Elkhorn, and Papio-Missouri River Natural Resources Districts: Prepared for the Eastern Nebraska Water Resources Assessment (ENWRA) by Exploration Resources International Geophysics LLC, Vicksburg, MS., http://www.enwra.org/aem%20data%20download.html (accessed on January 9, 2017).

Carney, C.P., Abraham, J.D., Cannia, J.C., and Steele, G.V. 2015b. Final Report on Airborne Electromagnetic Geophysical Surveys and Hydrogeologic Framework Development for the Eastern Nebraska Water Resources Assessment – Volume II, including the Lower Platte North, Lower Platte South, and Nemaha Natural Resources Districts: Prepared for the Eastern Nebraska Water Resources Assessment (ENWRA) by Exploration Resources International Geophysics LLC, Vicksburg, MS. http://www.enwra.org/aem%20data%20download.html (accessed on January 9, 2017).

Christensen, N. B., J. E. Reid, and M. Halkjaer, 2009, "Fast, laterally smooth inversion of airborne time-domain electromagnetic data." *Near Surface Geophysics*, v.7, No. 5-6, p. 599-612.

Christiansen, A. V., and E. Auken, 2012, "A global measure for depth of investigation." Geophysics,v.77, No. 4, WB171-177.

Condra, G. E., and Reed, C. E., 1959. The geological section of Nebraska with current revisions by C.E. Reed: Nebraska Geological Survey Bulletin, University of Nebraska-Lincoln, Conservation and Survey Division.

Conservation and Survey Division, University of Nebraska-Lincoln, 1951, Topographic Regions of Nebraska. [Online] Available at: http://snr.unl.edu/data/geographygis/geology.aspx (accessed December 22, 2016)

CSD, Till map for Nebraska 2017a. http://snr.unl.edu/data/geographygis/geology.aspx

Divine, D. P., Ross, S., and J. Korus. 2010. Compilation of Geologic Cross Sections of Eastern Nebraska. Open-File Report 109, Lincoln, Nebraska: School of Natural Resources, University of Nebraska-Lincoln.

Divine, D. P., 2012, Geologic cross section across eastern Nebraska from Pierce County to Dakota County, Conservation and Survey Division, School of Natural Resources, Institute of Agriculture and Natural Resources, University of Nebraska-Lincoln, Correlations and Cross Sections, Issue 18.2.

Divine, D. P. and J. T. Korus, 2012, Eastern Water Resources Assessment. Three-dimensional Hydrostratigraphy of the Sprague Nebraska Area: Results from Helicopter Electromagnetic (HEM) Mapping in the Eastern Nebraska Water Resources Assessment (ENWRA), Conservation and Survey Division, School of Natural Resources, Institute of Agriculture and Natural Resources, University of Nebraska-Lincoln, http://www.enwra.org/media/2012ENWRA_Sprague_final.pdf (accessed Jan 8, 2015).

Divine, D.P. and Korus, J.T., 2013, Three-dimensional hydrostratigraphy of the Swedeburg, Nebraska Area: Results from Helicopter Electromagnetic (HEM) Mapping for the Eastern Nebraska Water Resources Assessment (ENWRA) Conservation and Survey Division, School of Natural Resources, Institute of Agriculture and Natural Resources, University of Nebraska-Lincoln. Conservation Bulletin (New Series), Link to PDF file: http://enwra.org/media/2013SwedeburgFINAL.pdf (accessed January 9, 2017)

Driscoll, F.G, 1987, "Groundwater and Wells", Published by Johnson Division, St. Paul, MN.

Engberg, R.A., 1984. Appraisal of Data for Groundwater Quality in Nebraska: U.S. Geological Survey Water Supply Paper 2245.

Elder, J. A., V. H. Dreesen, and E. C. Weakly, 1951, "University of Nebraska-Lincoln, School of Natural Resources." Topographic Regions of Nebraska. http://snr.unl.edu/data/geographygis/NebrGISgeology.asp#topography (accessed Jan 15, 2015).

Exploration Resources International (XRI), 2015, Airborne Electromagnetic Geophysical Surveys and Hydrogeologic Framework Development for Selected Sites in the Lower Elkhorn Natural Resources District. Project findings report prepared for the Lower Elkhorn Natural Resources District by Exploration Resources International Geophysics LLC, Vicksburg, MS. http://www.enwra.org/LENRD2014AEMDataDownload.html (accessed January 9, 2017)

Flowerday, C. A., R. D. Kuzelka, and D. T. Pederson, 1998, The groundwater atlas of Nebraska. Resorce Atlas No. 4A, Lincoln, Nebraska: Conservation and Survey Division, School of Natural Resoirces, Institute of Agriculture and Natural Resoruces, University of Nebraska-Lincoln.

Foged, Nikolaj, Esben Auken, Anders Vest Christiansen, and Kurt Ingvard Sorensen, 2013, "Test-site calibration and validation of airborne and ground based TEM systems." *Geophysics* 78, No.2: E95-E106.

Freeze, R.A. and J.A. Cherry, 1979, "Groundwater": Published by Prentice Hall, New Jersey, ISBN 0-13-365312-9.

Gates, J. B., G. V. Steele, P. Nasta, and J. Szilagyi, 2014, "Lithologic influenes on groundwater recharge through incised glacial till from profile to regional scales: Evidence from glaciated Eastern Nebraska." Water Resources 50, 466-481.

Gosselin, D.C., 1991. Bazile Triangle Groundwater Quality Study, Nebraska. Conservation and Survey Division, Institute of Agriculture and Natural Resources, University of Nebraska-Lincoln, Nebraska Water Survey Paper No. 68.

Gutentag, E. D., Heimes, F.J., Krothe, N.C., Luckey, R.R., and Weeks, J.B. 1984. Geohydrology of the High Plains aquifer in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming: U.S. Geological Survey Professional Paper 1400-B.

Hanson, P. R., Korus, J.T., and D. P. Divine. 2012. Three-dimensional hydrostratigraphy of the Platte River Valley near Ashland, Nebraska: Results from helicopter electromagnetic mapping in the Eastern Nebraska Water Resources Assessment. Bulletin 2, Conservation and Survey Division, School of Natural Resources, Institute of Agriculture and National Resources, University of Nebraska-Lincoln. Link to PDF file: http://enwra.org/media/Ashland_ENWRA_Bull_2_2012_small.pdf (accessed January 9, 2017).

Heath, R.C., 1983. Basic ground-water hydrology, U.S. Geological Survey Water-Supply Paper 2220, 86p, http://pubs.er.usgs.gov/publication/wsp2220 (accessed Jan 8, 2017)

HydroGeophysics Group, Aarhus University, 2010, "Validation of the SkyTEM system at the extended TEM test site." Aarhus, Denmark.

HydroGeophysics Group, Aarhus University, 2011, "Guide for processing and inversion of SkyTEM data in Aarhus Workbench, Version 2.0."

Korus, J.T., and R. M. Joeckel. 2011. Generalized geologic and hydrostratigraphic framework of Nebraska 2011, version 2. Conservation and Survey Division, School of Natural Resources, Institute of Agriculture and Natural Resources, University of Nebraska-Lincoln.

Korus, J.T., 2012, Geologic cross section across eastern Nebraska from Thurston County to Pawnee County. Conservation and Survey Division, School of Natural Resources Institute of Agriculture and Natural Resources, University of Nebraska-Lincoln.

Korus, J. T., Divine, D. P., Hanson, P.R., and J. S. Dillon, 2012, Three geologic cross sections across portions of eastern Nebraska showing Quaternary lithologic units and stratigraphy of uppermost bedrock. Correlations and Cross Sections, Conservation and Survey Division School of Natural Resources, University of Nebraska-Lincoln.

Korus, J.T., Joeckel, R.M. and Divine, D.P. 2013. Three-dimensional hydrostratigraphy of the Firth, Nebraska Area: Results from Helicopter Electromagnetic (HEM) mapping in the Eastern Nebraska Water Resources Assessment (ENWRA). Conservation and Survey Division, School of Natural Resources, Institute of Agriculture and Natural Resources, University of Nebraska-Lincoln. Conservation Bulletin 3 (New Series).

Korus, J. T., Joeckel, R. M., Divine, D. P. and Abraham, J. D. 2016. Three-dimensional architecture and hydrostratigraphy of cross-cutting buried valleys using airborne electromagnetics, glaciated Central Lowlands, Nebraska, USA. Sedimentology. doi:10.1111/sed.12314

Ley-Cooper, Y. and Davis, A., 2010. Can a borehole conductivity log discredit a whole AEM survey?: *in* Extended abstracts of the Australian Society of Exploration Geophysicists Annual meeting Aug 20-24, Sydney, Australia.

LCNRD, Lewis and Clark Natural Resources District Management Area Rules and Regulations for Groundwater Quantity Management Areas, 2015. http://www.lcnrd.org/groundwater/quantity_rules_regs/2015_quantity_rr_draft_february_revisions_wfigs.pdf, last accessed May 14, 2017.

Miller, J. A., and C. L. Appel, 1997, Ground water atlas of the United States; Segment 3 Kansas, Missouri, and Nebraska. Hydraulic Atlas 730D, U.S. Geological Survey. https://pubs.er.usgs.gov/publication/ha730D (accessed January 9, 2017). .

Nebraska Conservation and Survey Division, 1995. Configuration of the water table in 1995. Institute of Agriculture & Natural Resources, University of Nebraska-Lincoln. Online GIS data set at accessed June 10, 2015 http://csd.unl.edu/general/gis-datasets.asp.

Nebraska Department of Natural Resources, 2016a, National Hydrographic Dataset, http://www.dnr.ne.gov/surface-water-data (accessed November 29, 2016).

Nebraska Department of Natural Resources. 2016b. Registered Groundwater Wells Data Retrieval. http://dnr.ne.gov/gwr/groundwaterwelldata (accessed September 22, 2016)

NOGCC - Nebraska Oil and Gas Conservation Commission, 2017, Data and Publications website, http://www.nogcc.ne.gov/NOGCCPublications.aspx (accessed March 6, 2017).

Nolan, B. T., Healy, R. W., Taber, P. E., Perkins, K., Hitt, K. J., and Wolock, D. M., 2007, Factors influencing ground-water recharge in the eastern United States. Journal of Hydrology 332, 187-205.

Olafsen-Lackey, S, 2005a, Hydrogeology of the Sioux City Quadrangle, Nebraska: Open File Report-71, Conservation and Survey Division, School of Natural Resources, University of Nebraska-Lincoln.

Olafsen-Lackey, S, 2005b, Specific yield of principal aquifer Sioux City Quadrangle, Nebraska: Open File Report-71, Conservation and Survey Division, School of Natural Resources, University of Nebraska-Lincoln.

Olafsen-Lackey, S, 2005c, Transmissivity of principal aquifer Sioux City Quadrangle, Nebraska: Open File Report-71, Conservation and Survey Division, School of Natural Resources, University of Nebraska-Lincoln.

pbEncom, 2016, pbEncom Discover Profile Analyst, available on the world-wide web at: http://www.pitneybowes.com/pbencom/products/Geophysics/encom-pa.html

Pederson, D., Kuzelka, B., and Flowerday, C., 1986. The Groundwater Atlas of Nebraska. Conservation and Survey Division, Institute of Agriculture and Natural Resources, University of Nebraska-Lincoln. http://nlc1.nlc.state.ne.us/epubs/U2375/X001.0004-1986.pdf (accessed on February 22, 2017).

Schamper, C., Auken, E., and Sorensen, K., 2014, *Coil response inversion for very early time modelling of helicopter-borne time-domain electromagnetic data and mapping of near-surface Geologic Layers.* European Association of Geoscientistis & Engineers, Geophysical Prospecting, v. 62, Issue 3, p. 658–674.

SkyTEM Airborne Surveys Worldwide, 2012, "SkyTEM survey: Mary Creek Canada data report." Beder, Denmark.

SkyTem Airborne Surveys Worldwide, 2016, SkyTEM304M, http://skytem.com/system-specifications/ (accessed January 9, 2016)

Smith, B.D., Abraham, J.A., Cannia, J.C., Steele, G.V., and P.L. Hill. 2008. Helicopter electromagnetic and magnetic geophysical survey data, Oakland, Ashland, and Firth study areas, Eastern Nebraska, March 2007: U.S. Geological Survey Open-File Report 2008-1018. Link to PDF file: https://pubs.usgs.gov/of/2008/1018/downloads/REPORT/ofr_2008_1018_v18.pdf (accessed January 9, 2016)

Smith, B.D., Abraham, J.D., Cannia, J.C., Minsley, B.J., Ball, L.B., Steele, G.V., and Deszcz-Pan, M., 2009, Helicopter Electromagnetic Geophysical Survey Data, Swedeburg and Sprague Areas, Eastern Nebraska: U.S. Geological Survey Open-File Report 2010-1288. Link to PDF file: https://pubs.usgs.gov/of/2010/1288/downloads/REPORT/ofr_2010_1288_v1_2.pdf (accessed January 9, 2017)

Stanton, J.S., Steele, G.V., and Vogel, J.R. 2007, Occurrence of agricultural chemicals in shallow ground water and the unstaturated zone, northeast Nebraska glacial till, Scientific Investigations Report 2002-04, U.S. Geological Survey. Link to PDF file: . https://pubs.usgs.gov/sir/2007/5228/pdf/sir2007-5228.pdf (accessed January 9, 2017)

Souders, V. L., 2000. Geologic maps and cross sections showing configurations of bedrock surfaces, Broken Bow 1° x 2° quadrangle, east-central Nebraska. U.S. Geological Survey Geologic Investigations Series I–2725 https://pubs.usgs.gov/imap/i-2725/i-2725.htm (accessed January 9, 2017)

Sweeney, R. E., and Hill, P.L, 2005, Nebraska, Kansas, and Oklahoma Aeromagnetic and Gravity Maps and Data: A Web Site for Distribution of Data: U.S. geological Survey Data Series 138, 2005. https://pubs.usgs.gov/ds/2005/138/neksok.html. (accessed January 9, 2017)

Szilagyi, J., Harvey, F. E., and Ayers, J. F., 2005, "Regional estimation of total recharge to ground water in Nebraska." Ground Water 43, 63-69.

Szilagyi, J., and J. Jozsa, 2013, MODIS-Aided statewide net groundwater-recharge estimation in Nebraska. Ground Water 51, 735-744.

United States Department of Agriculture, 2014. USDA Natural Resources Conservation Service. http://www.nrcs.usda.gov/wps/portal/nrcs/detail/oh/technical/dma/gis/?cid=nrcs144p2_029531 (accessed January 9, 2017).

University of Nebraska-Lincoln (UNL) School of Natural Resources. 2016. Nebraska statewide test-hole database. http://snr.unl.edu/data/geologysoils/NebraskaTestHole/NebraskaTestHoleIntro.asp (accessed April 22, 2016).

U.S. Geological Survey (USGS). Water. https://water.usgs.gov/edu/earthgwaquifer.html (accessed January 9, 2017)

U.S. Geological Survey, 2015, USGS surface-water data for Nebraska. http://waterdata.usgs.gov/ne/nwis/sw/ (accessed January 8, 2017).

U.S. Geological Survey (USGS), 2016, The National Map, 2016, 3DEP products and services: The National Map, 3D Elevation Program Web page, http://nationalmap.gov/3DEP/3dep_prodserv.html (accessed May 26, 2016)

Viezzoli, A., A. V. Christiansen, E. Auken, and K. Sorensen, 2008, "Quasi-3D modeling of airborne TEM data by spatially constrainted inversion." *Geophysics Vol. 73 No. 3* F105-F11