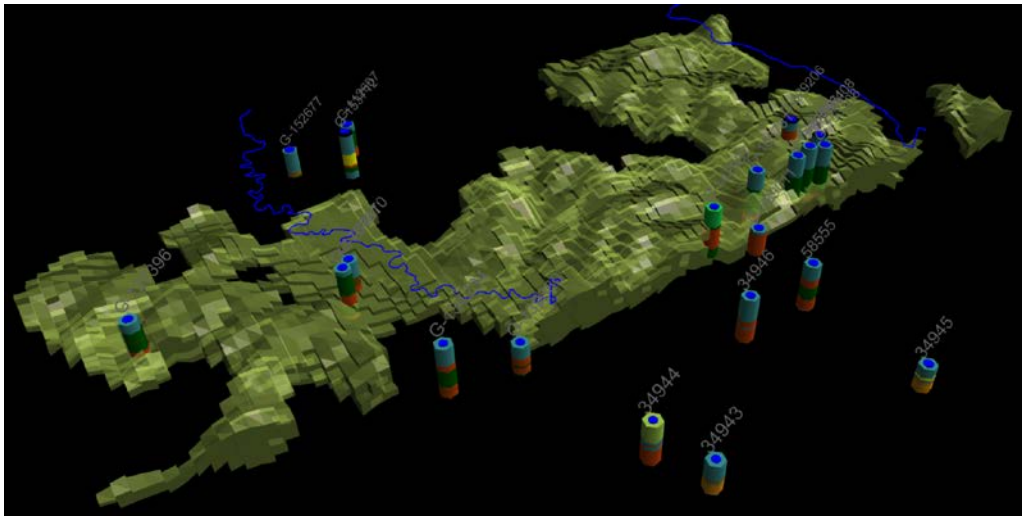
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"Airborne Electromagnetic Mapping and Hydrogeologic Framework of Selected Regions of the Eastern Nebraska Water Resources Assessment Area" Chapter on the Papio-Missouri River Natural Resources District



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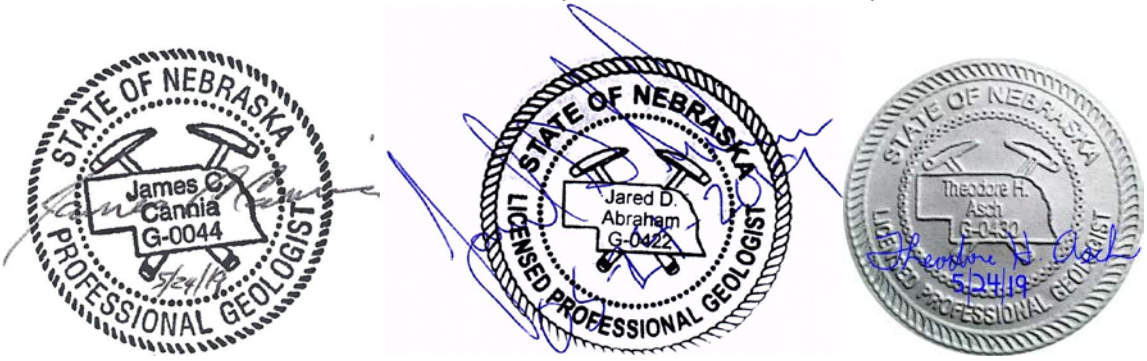
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Executive Summary

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

An understanding of the hydrogeological framework in the survey area is desired to assist in resource management. AGF entered into an agreement with the Eastern Nebraska Water Resources Assessment (ENWRA) to collect, process, and interpret airborne electromagnetic (AEM) data, in conjunction with other available background information, to develop a 3D hydrogeologic framework of the Papio-Missouri River Natural Resources District (P-MRNRD) project area and to recommend future work to enhance groundwater management activities.

The scope of work for this project was as follows:

1. SCOPE OF WORK

1.1 An AEM survey utilizing the SkyTEM304M system was flown over the P-MRNRD project area. These flights have been provided as preliminary AEM inversions and the final AEM data and inversions are included as a product attached to this data report.

1.2 AGF began project planning upon signing of the project between AGF and the ENWRA. This work included flight plans, database development, and review of hydrogeologic and geologic work for the area. The P-MRNRD assisted in providing information such as power line maps, test hole databases, and related aquifer characteristic studies, if available.

Upon conclusion of the design process the P-MRNRD reconnaissance flight lines had a maximum of approximately 33 miles (54 km) in length in the north-south direction and about 25 miles (41 km) at their longest in the east-west direction and were separated by approximately 3 miles (5 km) in both east-west and north-south directions. The Tekamah Block, in the north east region of the investigation area, had north-south lines about 3 miles (5 km) long separated by about 0.15 miles (250 m).

1.4 AGF acquired AEM data over the P-MRNRD, commencing 01 July 2018 and finishing on 20 July 2018, to support development of the hydrogeological framework. During this time frame data were collected in other adjacent NRD's surrounding P-MRNRD. Approximately 608 line-miles (985 line-kilometers) were acquired over the P-MRNRD AEM survey area. Status reports of the flying were provided to the Contract Representative of ENWRA and P-MRNRD daily, including the areas flown, production rates, and flight plan for the following day.

1.5 AGF processed and conducted quality assurance and quality control (QA/QC) procedures on all data collected from the acquisition system. AGF delivered preliminary data and inversions on July 5 – July 21, 2018. Approximately 424-line-miles (687-line kilometers) were retained for inversion amounting to a retention rate of 69.7%. This high rate is the result of careful flight line planning and design given the infrastructure that was encountered during the acquisition.

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

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

2. KEY FINDINGS

2.1 Boreholes - Information from boreholes was used to analyze the AEM inversion results and was important for all areas in the P-MRNRD. The top of the undifferentiated Pennsylvanian (***IP***) was a challenging unit to interpret due to the highly variable resistivity of the ***IP.*** Top of the bedrock for the area was developed by inspection of the borehole logs that included consolidated geologic units and CSD (Nebraska Conservation and Survey Division) bedrock contacts. The Cretaceous Carlile (***Kc***) and the Cretaceous Greenhorn Limestone and Graneros Shale ***(Kgg)*** only occurred in the northern reconnaissance lines. The CSD stratigraphic control was utilized to distinguish the ***Q*** from the underlying ***Kc*** and ***Kgg***. Contacts between the Quaternary (***Q***) and Cretaceous Dakota Group (***Kd***) often had limited or no contrast in the electrical resistivity between the different geologic formations. Use of CSD stratigraphy calls and the presence of sandstone and shale in the NE- DNR (Nebraska Department of Natural Resources) registered wells were used to pick the **Q/Kd** contact when no resistivity contrast was present. The dependence on just boreholes for geologic interpretation also has its limitations because sometimes the boreholes are wrong, improperly located, have improper stratigraphic/lithology picks, and/or other errors. These errors in the boreholes are usually encountered in the NE-DNR registered wells. Very rarely inconsistencies are encountered in the oldest of the NE- CSD wells. The limited errors in the CSD wells may very well be due to poor positioning from a time before GPS and modern survey methods. As a guide in the interpretation of the AEM a bedrock surface was prepared using the of CSD and NE-DNR borehole logs. This work was conducted by Mike Plante and Roscoe Sopiwnik of WSP. As in all surveys of this nature the use of boreholes with AEM needs to be approached in a thoughtful and considered manner as to the value of information from an individual borehole.

2.2 Digitizing Interpreted Geological Contacts - Characterization and interpretation of the subsurface was performed in cross-section and derived surface grid formats. Contacts between the geologic units were digitized in 2D including: Quaternary (***Q),*** Cretaceous Dakota Group (***Kd***), and undifferentiated Pennsylvanian (***IP***). For the three northernmost flight lines the Cretaceous Carlile (***Kc***) and the Cretaceous Greenhorn Limestone and Graneros Shale ***(Kgg)*** were picked in a similar manner. The interpretive process benefited from the use of CSD, Nebraska Oil and Gas Conservation Commission (NEOGCC), and NE-DNR borehole logs. Surface grids of the interpreted geologic formations were then produced. Each flight line profile with interpretation including the Quaternary aquifer material mapping are included in the appendices as well as interpretative surface grids. Given the known differences between the parameters of the 2015 and 2018 AEM surveys, it has become apparent that there needs to be integration work done to bring the results of all the years together in one package using the same parameters such as projection, model layer parameters, and lithologic nomenclature.

2.3 Resistivity/Lithology Relationship - Assessment of the sediment character in the Quaternary aquifer system and the bedrock strata was conducted to determine the overall composition of the major categories used to define the aquifer and aquitards in eastern Nebraska. A

numerically robust assessment of the resistivity thresholds was used to characterize non-aquifer (<12 ohm-m), marginal (12-20 ohm-m), and aquifer (20-50 ohm-m), including coarse sand-rich intervals (>50 ohm-m) was determined. This allowed for the characterization of the ranges of resistivities present in the major geologic units described in this report.

2.4 Hydrogeological Framework of the P-MRNRD - The 2018 P-MRNRD AEM survey reveals variability in the Quaternary (***Q***) and Cretaceous Dakota Group (***Kd***) deposits across the P-MRNRD AEM survey area that make up the aquifer materials. The ***Q*** make up the aquifer materials overlying the ***Kd*** bedrock units of which the ***Kd*** sandstone/sand dominant material are aquifers. In the north and south parts of the AEM survey area, the aquifer material and coarse aquifer material exist in paleochannels that are separated by ***Q*** deposits which consist of predominantly marginal to non-aquifer materials that are glacial till and loess and that can be more than 400 ft thick. ***Q*** aquifer and coarse aquifer materials are thick in the western part of the survey area near the Platte and Elkhorn Rivers. The Tekamah Block AEM flight area has very little ***Q*** aquifer and coarse aquifer material. Estimates of the groundwater in storage within the ***Q***-portion of the Tekamah Block of aquifer material below the 1995 CSD water table elevation is 3,428 acre-ft. The amount of extractable groundwater from aquifer material is 343 acre-ft. The main aquifer material type in the Tekamah Block is ***Kd*** sandstone/sand dominant material. While these materials will produce water, the yields and specific capacity will be reduced. The total estimate of the groundwater in storage for all materials for the ***Q*** and ***Kd*** below the 1995 water table is 69,571 acre-ft with 3,863 acre-ft extractable, demonstrating the impact of the fine-grained materials on the overall extractable groundwater.

2.5 Potential Recharge Zones within the P-MRNRD AEM Survey Area - The use of block flights in Tekamah area illustrates the preferred method of using AEM to identify areas where the potential for recharge to the aquifer can be high and low. Locations where the flight lines are closely spaced showing either aquifer or coarse aquifer material at the land surface should be considered as locations for higher likelihood for recharge because of the 2D and 3D spatial nature of the aquifer material distribution. The opposite is also true where AEM data analysis shows non-aquifer or marginal aquifer material; Those areas will likely not be optimal recharge locations. The area throughout the Tekamah Block has potential recharge that is limited in extent due to depth. The layers below layer about 31 ft are mostly poor aquifer materials for recharge transmission downward.

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

3. RECOMMENDATIONS

Recommendations provided to the P-MRNRD 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 P-MRNRD about their management challenges.

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

3.2 **Additional AEM Mapping** - The hydrogeologic maps provided in this report represent the completed hydrogeologic framework developed for the P-MRNRD at reconnaissance level with approximately 3-mile spacing between flight lines. The Tekamah Block flight area is the only exception to this flight line spacing which is about 700-800 feet. The first AEM project for the District was done in 2007 in the Ashland Block that was collected with dense flight lines over a limited area. In 2015 AEM data was collected at an approximately 20-mile grid spacing. The interpretations match well with the CSD and NE-DNR test holes. The 2016 AEM project was a combination of reconnaissance lines near Gretna, NE and a block flight around Springfield, NE. The 2018 AEM project for P-MRNRD selected areas for a hydrogeologic framework map to support groundwater models, selection of rural water supply well locations, locating water quality monitoring wells, determining the potential for areas make decisions about irrigation development and management policy, and selecting MAR or ASR locations. It is highly recommended that additional AEM data be collected and analyzed within the area of the Platte and Elkhorn River basins near the town of Fremont, NE and additional block flight lines near Tekamah and the surrounding area for water quality efforts by further defining recharge and internal features of the Quaternary (***Q)*** sediments and Cretaceous Dakota Group (***Kd)***. Additional analysis of the ***Kd*** and ***Q*** internal features will shed important light on groundwater movement and groundwater in storage with delineation of flow paths related to water quality. This information will strengthen the knowledge base of the important aquifer areas of the district. Most importantly it will provide information including the geographic distribution of amount of groundwater in storage, recharge areas, susceptibility to groundwater contamination, and hydrologic connection to the streams in the block flight areas within the P-MRNRD that can be selected for current and future water development impacts.

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

semiconfined nature of the area. Use of the data collected in this survey and future surveys will provide the best possible water table and conditions map for the district.

3.4 **Siting new test holes and production wells** – The AEM hydrogeological framework profiles, maps, and surfaces provided in this report provide great insight in 3D on the relationship between current test holes and production groundwater wells. At the time of this report, the currently available lithology data for the P-MRNRD area was used in building the framework maps and profiles. Additional information from previous groundwater reports were helpful in this work. It is recommended that the results from this report be used to site new test holes and monitoring wells. Often test holes are sited based on previous work that is regional in nature. By utilizing the maps in this report new drilling locations can be sited in more optimal locations. The location of new water supply wells for communities can also use the results in this report to guide development of new water supply wells. Planners should locate wells in areas of greatest saturated thickness with the least potential for non-point source pollution. A good example of this would be confined aquifers with large volumes of coarse aquifer and aquifer material with minimal sedimentary boundary conditions. The previous AEM studies have already found use by CSD and local well drillers to locate test wells and production wells within the P-MRNRD.

3.5 **Aquifer testing and borehole logging** - Aquifer tests are recommended to improve estimates of aquifer characteristics. Limited aquifer properties from previous reports were available outside the larger cities in the survey area. A robust aquifer characterization program is highly recommended at the state, regional (NRD's), and smaller municipal levels. Aquifer tests can be designed based on the results of AEM surveys and existing production wells could be used in conjunction with three or more installed water level observation wells.

Additional test holes with detailed, functional, and well calibrated geophysical logging for aquifer characteristics are highly recommended. Examples of additional logging would be flow meter logs and geophysical logs including gamma, neutron, electrical, and induction logs. Detailing aquifer characteristics can be accomplished with nuclear magnetic resonance logging (NMR) at a reduced cost when compared to traditional aquifer tests. This is a quick and effective way to characterize porosity and water content, estimates of permeability, mobile/bound water fraction, and pore-size distributions with depth.

3.6 **Recharge Zones** - The P-MRNRD hydrogeologic framework in this report provides areas of recharge from the ground surface to the groundwater aquifer in Tekamah Block. This area has water quality concerns, but not enough AEM data around Tekamah was acquired nor a detailed analysis of the ***Kd*** and the ***Q*** sediments was conducted to be definitive in this report and thus additional work in this area is recommended. 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 similar to the Tekamah Block which utilized closely-spaced flight lines using an AEM system that has good near-surface resolution in areas identified by the P-MRNRD that are of priority importance for management purposes. It is further recommended that future work integrate new soils and land use maps with the results of this study to provide details on soil permeability, slope, and water retention to provide a more complete understanding of the transport of water from the land surface to the groundwater aquifer. A potential solution to water quality, quantity, and stream depletions is adding additional fresh surface water as recharge to select areas of rangeland or other areas. Additional work can be done to identify where the best locations are for these type

of management efforts. This information can and has been used in Nebraska to improve Well Head Protection Areas by refining the estimated travel time estimates and the boundary areas.

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

3.8 **Updating previous groundwater reports and Groundwater Management Plans** - The groundwater reports and management plans should be updated with the AEM information which make it more comprehensive publications. Should future AEM work be completed the results from that effort will help guide the future groundwater management plans for the district. The addition of estimates of groundwater in storage, recharge areas, hydrologic connection to streams and consideration of managed aquifer recharge sites will greatly improve and groundwater management plan.

4. DELIVERABLES

In summary, the following are included as deliverables:

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

Google Earth KMZs for P-MRNRD AEM flight lines

Table of Contents

1 Introduction 1
1.1 Purpose of Current Project 1
1.2 Background 4
1.3 Description of the P-MRNRD 2018 AEM Project Area 4
2 Geophysical Methodology, Acquisition and Processing 6
2.1 Geophysical Methodology 6
2.2 Flight Planning/Utility Mapping 7
2.3 AEM Survey Instrumentation 8
2.4 Data Acquisition 10
2.4.1 Primary Field Compensation 12
2.4.2 Automatic Processing 12
2.4.3 Manual Processing and Laterally-Constrained Inversions 12
2.4.4 Power Line Noise Intensity (PLNI) 15
2.4.5 Magnetic Field Data 18
2.5 Spatially-Constrained Inversion 19
2.6 Merge AEM Databases from Different Flights and Inversions 24
3 AEM Results and Interpretation 27
3.1 Interpretive Process 27
3.1.1 Construct the Project Digital Elevation Model 27
3.1.2 Create Interpretative 2D Profiles 30
3.1.3 Create Interpretative Surface Grids 38
3.1.4 Resistivity/Lithology Relationship in the Quaternary Aquifer System 55
3.1.5 Resistivity/Lithology Relationship in the Bedrock 56
3.1.6 Create 3D Interpretative Voxel Grids 56
3.1.7 Comparison of Borehole Resistivity Logs to Inverted AEM Resistivity Soundings 58
3.2 Hydrogeological Framework of the P-MRNRD 2018 AEM Survey Area 63
3.2.1 The Hydrogeologic Framework of the P-MRNRD Reconnaissance Survey Area 63
3.2.2 Hydrogeologic Framework of the Tekamah Block Survey Area 83
3.3 Recharge Areas in the P-MRNRD AEM Survey Area 102
3.4 Key AEM Findings 109
3.4.1 Boreholes 109

3.4.2 Digitizing Interpreted Geological Contacts 109
3.4.3 Resistivity/Lithology Relationship 110
3.4.4 Hydrogeological Framework of the P-MRNRD 110
3.4.5 Potential Recharge Zones within the P-MRNRD AEM Survey Area 110
3.5 Recommendations 111
3.5.1 Integration of 2007-2018 AEM Hydrogeological Investigations 111
3.5.2 Additional AEM Mapping 111
3.5.3 Update the Water Table map 112
3.5.4 Siting new test holes and production wells 112
3.5.5 Aquifer testing and borehole logging 113
3.5.6 Recharge Zones 113
3.5.7 Managed Aquifer Recharge 113
3.5.8 Updating previous groundwater reports and Groundwater Management Plans 114
4 Description of Data Delivered 115
4.1 Tables Describing Included Data Files 115
4.2 Description of Included Google Earth KMZ Data and Profiles 122
4.2.1 Included README for the P-MRNRD Interpretation KMZ's 122
5 References 126
Appendix 1. P-MRNRD AEM Flight Line 2D Profiles and Surfaces A1-1
Appendix 2. P-MRNRD 3D Images A2-1
Appendix 3. Data Deliverables A3-1

List of Figures

Figure 1-1. Map of the P-MRNRD in eastern Nebraska 2
Figure 1-2. The P-MRNRD 2018 AEM survey area including county lines and major roads 3
Figure 1-3. Map of the P-MRNRD groundwater management areas 5
Figure 2-1. Schematic of an airborne electromagnetic survey 6
Figure 2-2. A) Example of a dB/dt sounding curve. B) Corresponding inverted model values. C) Corresponding resistivity earth model. 7
Figure 2-3. SkyTEM304M frame, including instrumentation locations and X and Y axes. Distances are in meters. Instrumentation locations listed in Table 2-1 9
Figure 2-4. Photo of the SkyTEM304M system in suspension beneath the helicopter 9

Figure 2-5. P-MRNRD 2018 AEM flight lines grouped by acquisition date 11

Figure 2-6. Example locations of electromagnetic coupling with pipelines or power lines. 13

Figure 2-7. A) Example of AEM data from the P-MRNRD 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. 14

Figure 2-8. A) Example of Laterally-Constrained inversion results where AEM data affected by coupling with pipelines and power lines were not removed. B) Inversion results where AEM data affected by coupling were removed. 15

Figure 2-9. Power Line Noise Intensity (PLNI) map of the P-MRNRD 2018 project area. 16

Figure 2-10. Locations of inverted data along the AEM flight lines in the P-MRNRD 2018 AEM survey area. 17

Figure 2-11. Residual magnetic Total Field intensity data for the P-MRNRD 2018 survey area corrected for diurnal drift, with the International Geomagnetic Reference Field (IGRF) removed 18

Figure 2-12. An example of an AEM profile illustrating increasing model layer thicknesses with depth. . 19

Figure 2-13. SCI inversion groups for the P-MRNRD, LPNNRD, and LPSNRD AEM data. 21

Figure 2-14. Data/model residual histogram for the P-MRNRD SCI inversion results 22

Figure 2-15. Map of data residuals for the P-MRNRD 2018 SCI inversion results 23

Figure 3-1. Map of the Digital Elevation Model for the P-MRNRD study area 28

Figure 3-2. Map of the Digital Elevation Model for the Tekamah Block AEM survey area 29

Figure 3-3. 32-mile line L160001 that is along the Platte River from approximately Fremont to the I-80 Platte River bridge at Ashland, Nebraska 33

Figure 3-4. 25-mile-long east-west line L501500 34

Figure 3-5. 33-mile-long north-south line L800301 35

Figure 3-6. 24.75-mile-long east-west line L700500 36

Figure 3-7. 17-mile-long east-west line L700300 37

Figure 3-8. Map of the elevation of the top of the Cretaceous Dakota Group (***Kd***) within the southern reconnaissance AEM survey area 40

Figure 3-9. Map of the elevation of the top of the Undifferentiated Pennsylvanian (***IP***) within the southern reconnaissance AEM survey area 41

Figure 3-10. Map of the elevation of the top of the Cretaceous Dakota Group (***Kd***) within the Tekamah Block AEM survey area 42

Figure 3-11. Map of elevation of the top of the Undifferentiated Pennsylvanian (***IP***) within the Tekamah Block AEM survey area 43

Figure 3-12. Map of the elevation of the top of the bedrock within the southern reconnaissance AEM survey area 44

Figure 3-13. Map of the thickness (in feet) of Quaternary (***Q***) deposits within the southern reconnaissance AEM survey area 45

Figure 3-14. Map of the thickness of the Cretaceous Dakota Group (***Kd***) within the southern reconnaissance AEM survey area 46

Figure 3-15. Map of the thickness of the Quaternary (***Q***) deposits within the Tekamah Block AEM survey area 47

Figure 3-16. Map of the thickness of the Cretaceous Dakota Group (***Kd***) within the Tekamah Block AEM survey area 48

Figure 3-17. Map of the elevation of the 1995 CSD water table within the southern reconnaissance AEM survey area 49

Figure 3-18. Map of the elevation of the 1995 CSD water table within the Tekamah Block AEM survey area. 50

Figure 3-19. Map of the saturated thickness of the Quaternary (***Q***) deposits within the southern reconnaissance AEM survey area 51

Figure 3-20. Map of the saturated thickness of the Cretaceous Dakota Group (***Kd***) within the southern reconnaissance AEM survey area 52

Figure 3-21. Map of the saturated thickness of the Quaternary (***Q***) deposits within the Tekamah Block AEM survey area 53

Figure 3-22. Map of the saturated thickness of the Cretaceous Dakota Group (***Kd***) within the Tekamah Block AEM survey area 54

Figure 3-23. Plot displaying the resistivities by major aquifer material color categories: blue- non-aquifer materials, tan- marginal aquifer materials, yellow- aquifer materials, brown- coarse aquifer materials . 55

Figure 3-24. Voxel model of the aquifer material types for the Tekamah Block consisting of Quaternary (***Q***) sediments, separated from the two types of Cretaceous Dakota Group (***Kd***) (sandstone/sand and shale/clay) separated from the Undifferentiated Pennsylvanian (***IP***) 57

Figure 3-25. Graph of the *01-PMR-14* 16-inch normal resistivity log values and the inverted airborne electromagnetic resistivity values for flight line L701001 and flight line L800201 59

Figure 3-26. Graph of the *02-PMR-14* 16-inch short normal and 64-inch long normal resistivity log values and the inverted airborne electromagnetic resistivity values for flight line L800201 60

Figure 3-27. Inverted AEM resistivities for flight line L701001 with borehole *01-PMR-14* overlaid on the left 61

Figure 3-28. Inverted AEM resistivities for flight line L800201 with borehole *01-PMR-14* overlaid on the right 61

Figure 3-29. Inverted AEM resistivities for flight line L700101 with borehole *02-PMR-14* overlaid in the center 62

Figure 3-30. 3D fence diagram of the southern AEM reconnaissance lines, looking north, showing Quaternary (***Q***) aquifer materials 64

Figure 3-31. Map of the total thickness of Quaternary (***Q***) units in the southern reconnaissance AEM survey area 65

Figure 3-32. Map of the total thickness of the Cretaceous Dakota Group (***Kd***) including the shale/clay dominant and sandstone/sand dominant units 66

Figure 3-33. 3D fence diagram of the southern reconnaissance lines and borehole lithology looking to the east 68

Figure 3-33. 3D fence diagram of the southern reconnaissance lines and borehole lithology looking to the east 68

Figure 3-34. Zoom in on 3D fence diagram looking northeast across the Platte River showing the extent of the coarse ***Q*** material in the Platte River floodplain and the location of the paleochannel to the east of Fremont 69

Figure 3-35. Zoom in on 3D fence diagram looking southeast from Fremont along the Platte River showing the ***Q*** coarse aquifer material in the Platte River floodplain 70

Figure 3-36. Zoom in on 3D fence diagram looking southeast from Fremont between the Platte and Elkhorn rivers showing the extent of the coarse ***Q*** material in the Platte River floodplain and the paleochannel area 71

Figure 3-37. North-south flight line L800201 72

Figure 3-38. East-west flight line L501500 73

Figure 3-39. East-west Line L700700 74

Figure 3-40. East-west Line L700500 75

Figure 3-41. Map of the total thickness of Quaternary (***Q***) aquifer material within the 2018 southern reconnaissance AEM survey area 77

Figure 3-42. Map of the saturated thickness of Quaternary (***Q***) aquifer materials within the 2018 southern reconnaissance AEM survey area 78

Figure 3-43. Map of the saturated thickness of the Quaternary (***Q***) aquifer material and an estimate of the specific capacity within the 2018 southern reconnaissance AEM survey area 79

Figure 3-44. Map of the total thickness of Cretaceous Dakota Group (***Kd***) within the 2018 southern reconnaissance AEM survey area 80

Figure 3-45. Map the saturated thickness of the Cretaceous Dakota Group (***Kd***) within the 2018 southern reconnaissance AEM survey area 81

Figure 3-46. Map the saturated thickness of the Cretaceous Dakota Group (***Kd***) and an estimate of specific capacity in the southern reconnaissance AEM survey area 82

Figure 3-47. 3D fence diagram of interpreted AEM hydrostratigraphic profiles within the 2018 Tekamah Block AEM survey area 84

Figure 3-48. Map of the total thickness of the Quaternary (***Q***) deposits within the 2018 Tekamah Block 85

Figure 3-49. Map of the elevation of the top of the Cretaceous Dakota Group (***Kd***) within the P-MRNRD Tekamah Block from the 2018 survey 86

Figure 3-50. Map of the saturated thickness of Quaternary deposits (***Q***) within the 2018 Tekamah Block AEM survey area 87

Figure 3-51. Map of the total thickness of the Cretaceous Dakota Group (***Kd***) deposits within the 2018 Tekamah Block 88

Figure 3-52. Map of the saturated thickness of the Cretaceous Dakota Group (***Kd***) deposits within the 2018 Tekamah Block 89

Figure 3-53. East-west Line L700500 located just north of the town of Tekamah and the Tekamah Block AEM survey area and west of the Missouri River. Same as Figure 3-37 with the addition of the location maps showing the line's relation to the town of Tekamah and the Tekamah Block AEM flight area..... 90

Figure 3-54. 3D voxel of the Tekamah Block, looking to the west, with DNR borehole lithology logs 92

Figure 3-55. 3D voxel of the Tekamah Block, looking to the east, with DNR borehole lithology logs 93

Figure 3-56. 3D voxel with "chair clip" of the Tekamah Block, looking to the west, with DNR borehole lithology logs. In the clipped area, the ***Q*** and ***Kd*** have been removed..... 94

Figure 3-57. 3D voxel with "chair clip" of the Tekamah Block, looking to the west, with DNR borehole lithology logs. In the clipped area, the ***Q*** has been removed and only the ***Kd*** > 40 ohm-m is present..... 95

Figure 3-58. 3D voxel with of the Tekamah Block, looking to the west, with DNR borehole lithology logs, with all ***Q*** materials removed, and with only the ***Kd*** > 40 ohm-m present 96

Figure 3-59. 3D voxel with of the Tekamah Block, looking to the west, with DNR borehole lithology logs, with all ***Q*** materials, the water table surface, and the ***IP*** removed, and with only the ***Kd*** > 40 ohm-m present 97

Figure 3-60. Depositional environment of the Dakota Group sediments during the Cretaceous Period in eastern Nebraska and western Iowa 98

Figure 3-61. 3D voxel with of the Tekamah Block, looking to the west, with CSD borehole lithology logs, without the ***Q*** materials and the water table surface, and with all the ***Kd*** and ***IP*** 99

Figure 3-62. Google Earth image of potential recharge for the range 0-3 ft (AEM inversion model layer 1) for aquifer and coarse aquifer materials (resistivities greater than 20 ohm-m) within the 2018 Tekamah Block AEM flight area 103

Figure 3-63. Google Earth image of potential recharge for the range 7-11 ft (AEM inversion model layer 3) for aquifer and coarse aquifer materials (resistivities greater than 20 ohm-m) within the 2018 Tekamah Block AEM flight area 104

Figure 3-64. Google Earth image of potential recharge for the range 15-20 ft (AEM inversion model layer 5) for aquifer and coarse aquifer materials (resistivities greater than 20 ohm-m) within the 2018 Tekamah Block AEM flight area 105

Figure 3-65. Google Earth image of potential recharge for the range 25-31 ft (AEM inversion model layer 7) for aquifer and coarse aquifer materials (resistivities greater than 20 ohm-m) within the 2018 Tekamah Block AEM flight area 106

Figure 3-66. Google Earth image of potential recharge for the range 0-3 ft (AEM inversion model layer 1) for aquifer and coarse aquifer materials (resistivities greater than 20 ohm-m) along the reconnaissance flight lines within the 2018 P-MRNRD AEM flight area 107

Figure 3-67. Google Earth image of potential recharge for the range 25-31 ft (AEM inversion model layer 7) for aquifer and coarse aquifer materials (resistivities greater than 20 ohm-m) along the reconnaissance flight lines within the 2018 P-MRNRD AEM flight area 108

Figure 4-1. Example Google Earth image for the 2018 P-MRNRD Interpretation kmz 124

Figure 4-2. Example Google Earth image for the 2018 P-MRNRD Interpretation kmz showing location attributes 125

List of Tables

Table 2-1. Positions of instruments on the SkyTEM304M frame, using the center of the frame as the origin, in feet 10

Table 2-2. Positions of corners of the SkyTEM304M transmitter coil, using the center of the frame as the origin in feet 10

Table 2-3. 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 20

Table 2-4. AEM flights included in each of the SCI inversion groups 20

Table 2-5. Combination of flight lines within the inversion areas 24

Table 3-1. Fully saturated Quaternary (*Q*) aquifer materials within the Tekamah Block area 101

Table 3-2. Fully saturated Cretaceous Dakota Group (*Kd*) aquifer materials within the Tekamah Block area 101

Table 4-1. Raw SkyTEM data files 116

Table 4-2. Channel name, description, and units for PMRNRD2018_EM_MAG_AUX.xyz with DEM, magnetic, DGPS, Inclinometer, altitude, and associated data 116

Table 4-3. Channel name, description, and units for PMRNRD2018_AEM_SCI_INV_v1.xyz with EM inversion results 117

Table 4-4. Channel name description and units for the interpretation results files PMRNRD2018_InterpSurfaces.xyz 118

Table 4-5. P-MRNRD Inverted Model Structure with DEM and Layer Top-, Bottom-, and Mid-points in Depth and Elevation plus Inverted Cell Resistivities (*PMRNRD_XYDEM_Dep_Elev_Rho.xyz)*..... 119

Table 4-6. Files containing ESRI ArcView Binary Grids *.flt (Nebraska State Plane, NAD83, feet)..... 120

Table 4-7. Channel name, description, and units for VoxelTekamah.xyz..... 121

List of Abbreviations

2D	Two-dimensional
3D	Three-dimensional
A*m^2	Ampere meter squared
AEM	Airborne Electromagnetic
AGF	Aqua Geo Frameworks, LLC
ASR	Aquifer Storage and Recovery
dB/dt	Change in amplitude of magnetic field with time
BMP	Best management plan
CSD	Conservation and Survey Division
DEM	Digital Elevation Model
DOI	Depth of Investigation
DGPS	Differential global positioning system
em, EM	Electromagnetic
ENWRA	Eastern Nebraska Water Resources Assessment
FT	Fourier Transform
FT, ft	Feet
ft^3	cubic feet
Fm	Formation
GIS	Geographic Information System
Hr, hr	hours
Hz	Hertz (cycles per second)
IGRF	International Geomagnetic Reference Field
IP	undifferentiated Pennsylvanian units
Km, km	Kilometers
KMZ, kmz	Keyhole Markup language Zipped file
LCI	Laterally-constrained Inversions
LENRD	Lower Elkhorn Natural Resources District
LPNNRD	Lower Platte North Natural Resources District
LPSNRD	Lower Platte South Natural Resources District
MAG	Magnetic (data); Magnetometer (instrument)
MCG	Minimum curvature gridding
M, m	Meters
mi^2	Miles squared
NAD83	North American Datum of 1983
MAR	Managed Aquifer Recharge
NAVD88	North American Vertical Datum of 1988
NE	Nebraska
NED	National Elevation Dataset
NE-DNR	Nebraska Department of Natural Resources

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

1 Introduction

1.1 Purpose of Current Project

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

The combination of these stresses on water resources has increased the need for detailed hydrogeologic frameworks of the subsurface. Groundwater management strategies and policies implemented to address water quality concerns is another effort that can be improved with better understanding of recharge, and its relationship with the underlying aquifers. The mapping of the subsurface related to groundwater flow and hydrologic connection between different aquifers and streams is also important in understanding water quality. Geographic regions that are identified as major contributors to recharge could be areas targeted for enhanced promotion of best management practices (BMP) to reduce or eliminate future contamination events. This is best accomplished by block flights similar to Tekamah in Burt County. Additional uses of this survey will be to determine potential areas of Managed Aquifer Recharge (MAR) for addition to current supplies of groundwater in areas if need to replace depletions from development or supply future development. This data can be used to enhance the hydrogeologic framework for groundwater modeling for testing management scenarios at a regional level where boreholes are not sufficient or are of limited use. Where AEM block flights exist, this dense flight line data would be excellent for local groundwater models by having high resolution framework to build the model.

This report describes the general hydrogeologic conditions, assessed using data collected from this AEM survey. In addition to the AEM data, reports from previous studies, analysis of historic groundwater levels, and geologic descriptions from University of Nebraska-Lincoln Conservation and Survey Division (CSD) test holes, Nebraska Oil and Gas Conservation Commission (NOGCC), and drillers logs obtained from registered wells at the Nebraska Department of Natural Resources (NE-DNR) were used. The AEM survey data were collected along reconnaissance (recon) lines spaced approximately 3 miles apart and the Tekamah Block Flight with lines separated by about 800 ft (250 m). This AEM survey was planned and selected by P-MRNRD and AGF with assistance from scientists from CSD to assist in the development of a 3D hydrogeologic framework of this project area and recommend future work to enhance groundwater management activities. This work was supported by the Natural Resources Commission Water Sustainability Fund, the P-MRNRD, and in-kind service from CSD.

A location map showing the P-MRNRD is presented in Figure 1-1. A Google Earth image of the "As-Flown" flight lines are presented in Figure 1-2 and also included as a kmz in Appendix 3-Deliverables \KMZ\FlightLines. These are discussed in detail in Section 2. The main AEM flight area was between Fremont, NE and Omaha, NE and continued north to just south of Sioux City, Iowa.

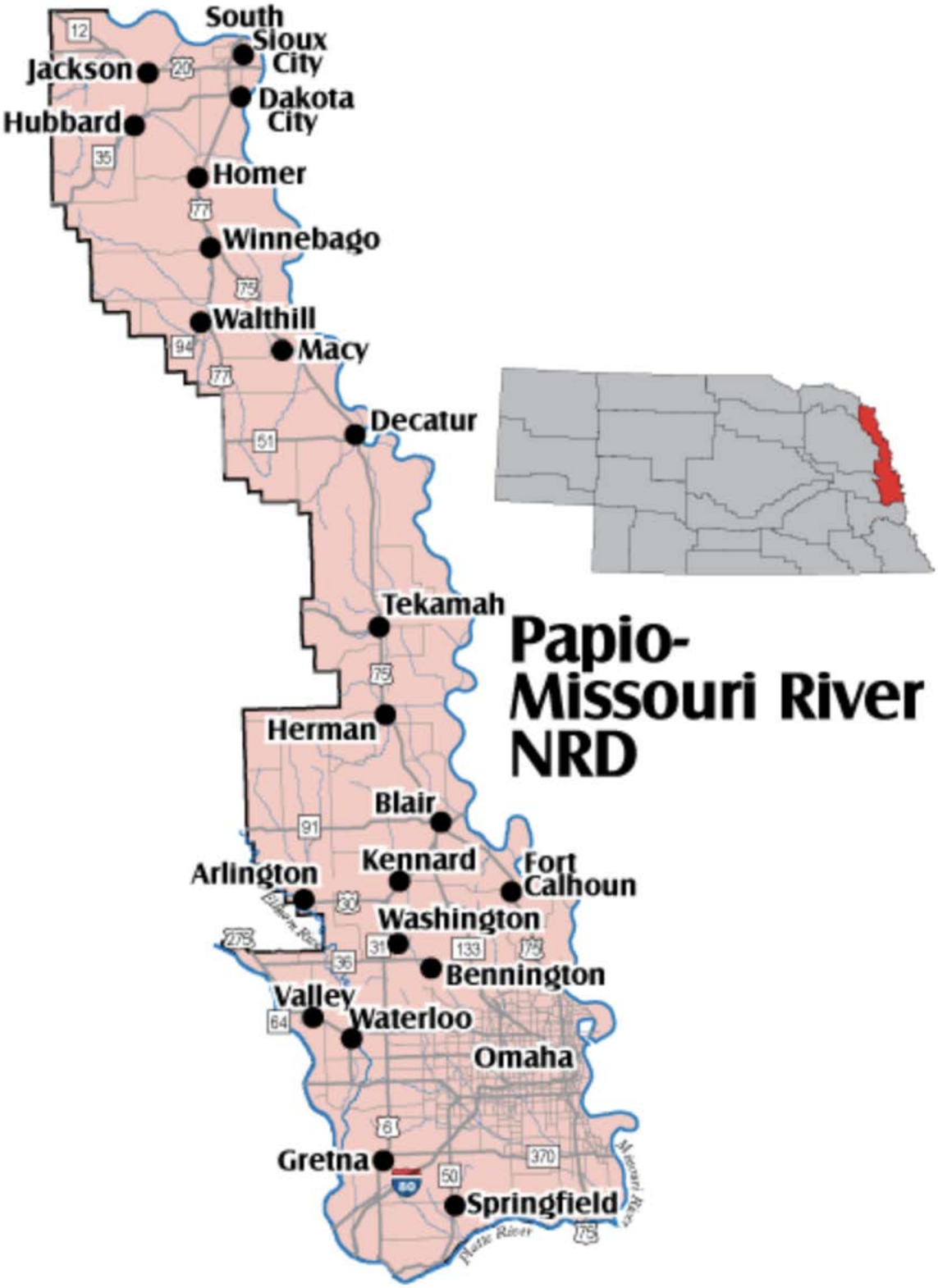


Figure 1-1. Map of the P-MRNRD in eastern Nebraska (modified from https://www.papionrd.org/).

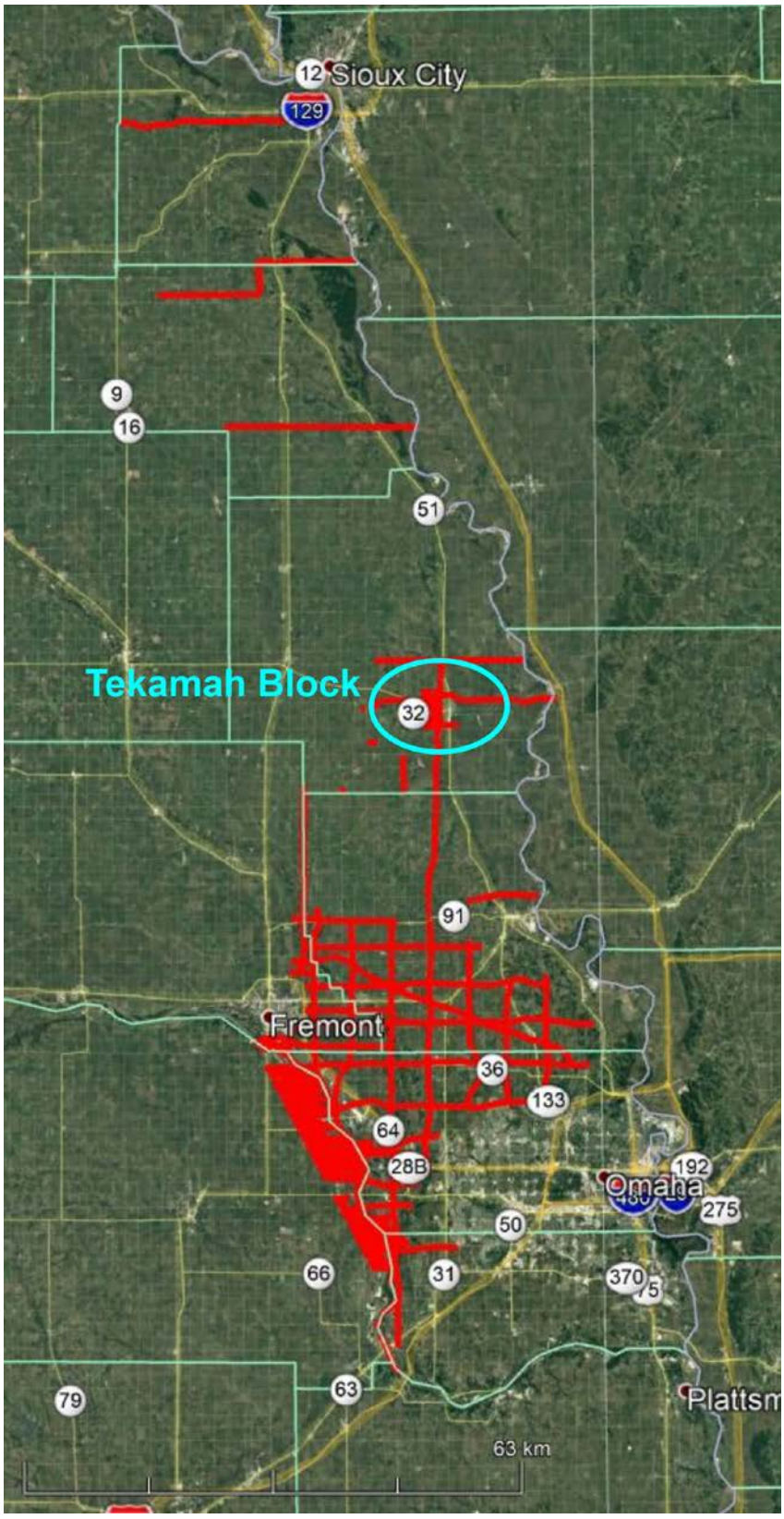


Figure 1-2. The P-MRNRD 2018 AEM survey area including county lines and major roads. The Tekamah Block AEM flight area is indicated by the blue circle.

1.2 Background

Under the current P-MRNRD Groundwater Management Plan, the P-MRNRD established a districtwide Groundwater Management Area, for purposes of managing groundwater quality and quantity. Figure 1-3 shows the Water Quality Phase I and Water Quantity Level I areas along with two smaller Water Quality Phase II areas near the towns of Springfield and Tekamah (modified from https://www.papionrd.org/).

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

The District was also interested in understanding the framework of the paleochannels near the town of Fremont along with the hydrologic connection in the areas of the Platte and Elkhorn Rivers in the same area. Additional areas of interest include the hydrologic connection to all streams and rivers along the flight lines and the framework and recharge potential of the Tekamah Block flight area is of interest for understanding water quality.

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 and more, 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, the P-MRNRD, ENWRA, and CSD are cooperating with AGF because of the shared aquifer boundaries and similar groundwater management efforts between these neighboring NRDs.

1.3 Description of the P-MRNRD 2018 AEM Project Area

The P-MRNRD spans approximately 1,790 square miles (mi^2) in eastern Nebraska. The elevation of the area ranges from 950 ft to 1520 ft above sea level**.** It is underlain by parts of two of Nebraska's eight topographic regions—Rolling Hills and Valleys (Elder et al., 1951).

Principal cities within the project area, based on 2010 population estimates, include (alphabetically) Blair (8,091), Decatur (467), Omaha (466,893), Papillion (19,539), South Sioux City (12,911), Springfield, (1,603), Tekamah (1,723), and Valley (2,271) (U.S. Census Bureau, 2013).

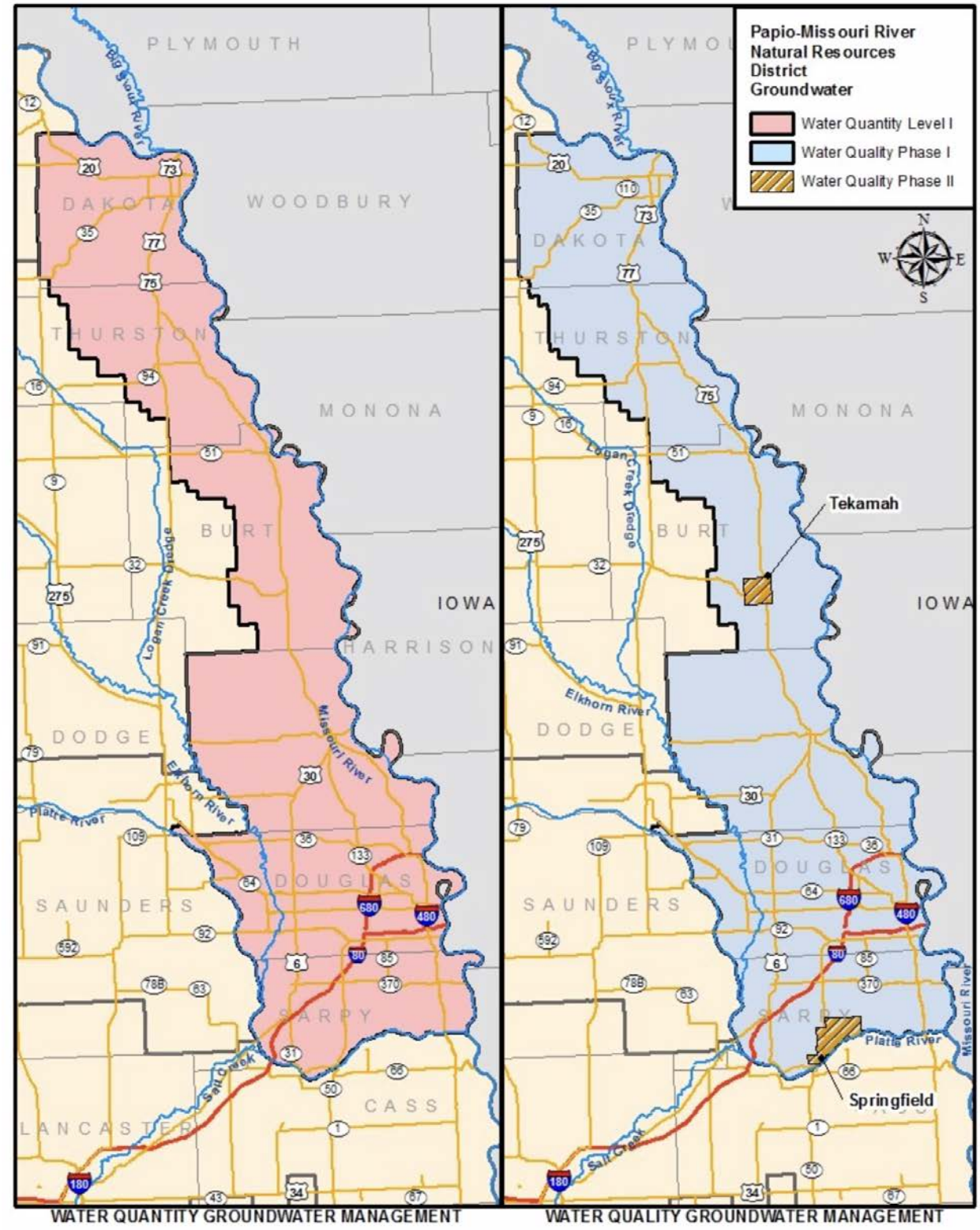


Figure 1-3. Map of the P-MRNRD groundwater management areas. The red shaded area on the left is the groundwater Quantity management area and the blue shaded area on the right along with small hatched zones are for groundwater water Quality within the boundary of the P-MRNRD (modified from https://www.papionrd.org/).

2 Geophysical Methodology, Acquisition and Processing

2.1 Geophysical Methodology

Airborne Transient Electromagnetic (TEM) or airborne Time-Domain Electromagnetic (TDEM), or generally AEM, investigations provide characterization of electrical properties of earth materials from the land surface downward using electromagnetic induction. Figure 2-1 gives a conceptual illustration of the airborne TEM method.

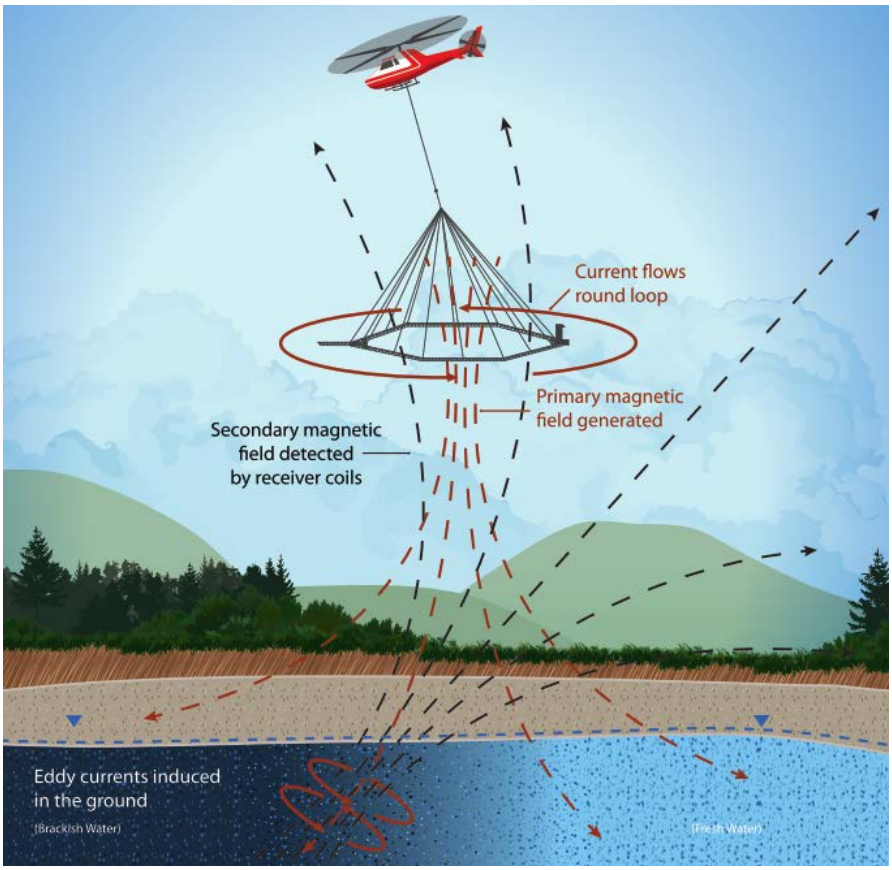
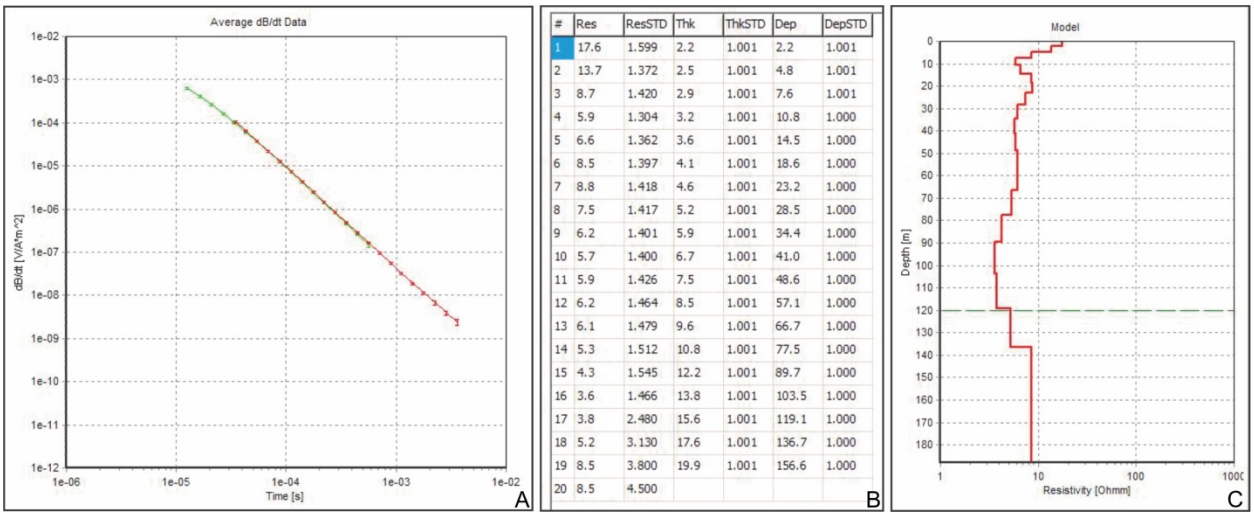


Figure 2-1: Schematic of an airborne electromagnetic survey, modified from Carney et al. (2015a).

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

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

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



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

B

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

2.2 Flight Planning/Utility Mapping

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

Public power entities that provided power line location data to ENWRA included: Burt County Power District, City of Fremont, Lincoln Electric Systems, Nebraska Public Power District, and the Omaha Public Power District.

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

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

Upon conclusion of the design process the P-MRNRD reconnaissance flight lines had a maximum of approximately 33 miles (54 km) in length in the north-south direction and about 25 miles (41 km) at their longest in the east-west direction and were separated by approximately 3 miles (5 km) in both east-west and north-south directions. The Tekamah Block, in the north east region of the investigation area, had north-south lines about 3 miles (5 km) long separated by about 0.15 miles (250 m).

2.3 AEM Survey Instrumentation

AEM data were acquired using the SkyTEM304M (304M) airborne electromagnetic system (SkyTem Airborne Surveys Worldwide, 2018). The 304M is a rigid frame, dual-magnetic moment (Low and High) TEM system. The area of the 304M Tx coil is 342 m^2 and the coil contains four (4) turns of wire. A peak current of nine (9) amps is passed through one turn of wire in the Tx for Low Moment measurements and a peak current of about 110 amps is passed through the four turns of wire for High Moment measurements. This results in peak Tx Low and High magnetic moments of ~3,000 Ampere-meter-squared ($A*m^2$) and ~150,000 $A*m^2$, respectively.

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

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

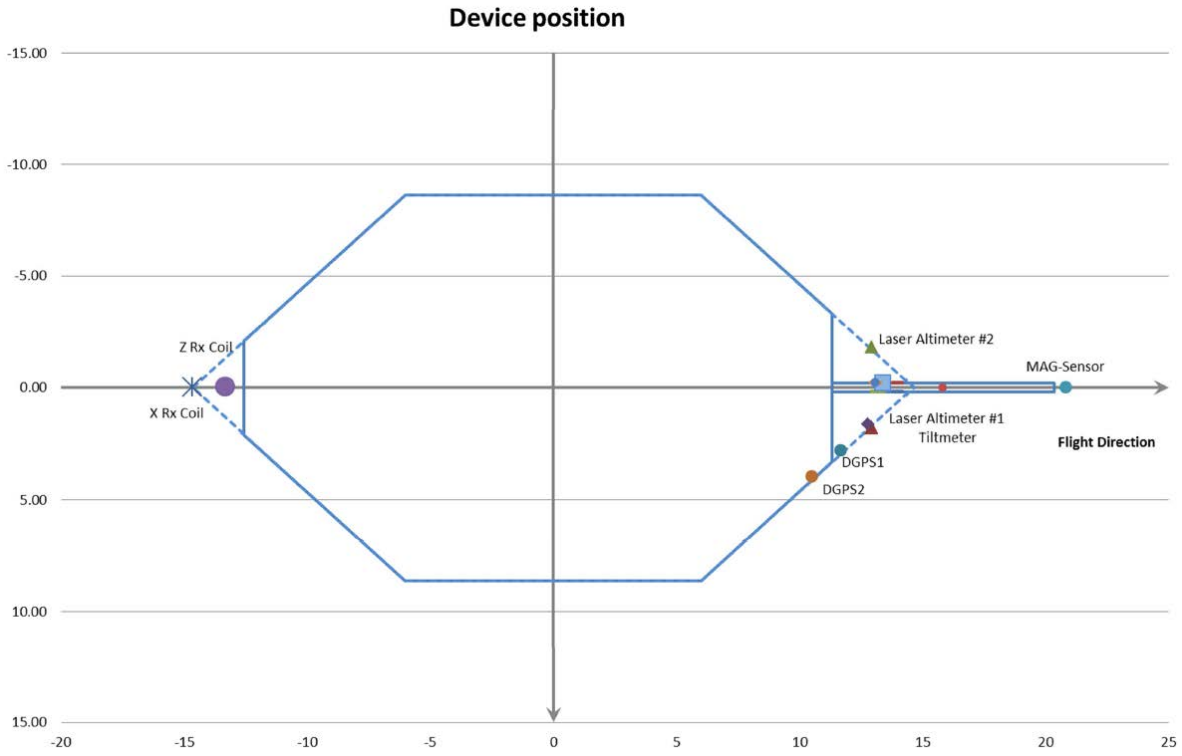


Figure 2-3: SkyTEM304M frame, including instrumentation locations and X and Y axes. Distances are in meters. Instrumentation locations listed in Table 2-1.



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

For this project, the 304M was flown at an average speed of 48 mi/hr (78.0 kilometers/hr) at an average flight height of 135.8 ft (41.4 m) above land surface, using the sling-load cargo system of a Eurocopter AS350 helicopter. Figure 2-4 displays a couple of images of the 304M in operation.

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

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

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

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

2.4 Data Acquisition

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

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

Approximately 608 line-miles (985 line-kilometers) were acquired over the P-MRNRD AEM survey area between 01 July 2018 and finishing on 20 July 2018. A data acquisition map is presented in Figure 2-5 with the flight lines grouped by acquisition date.

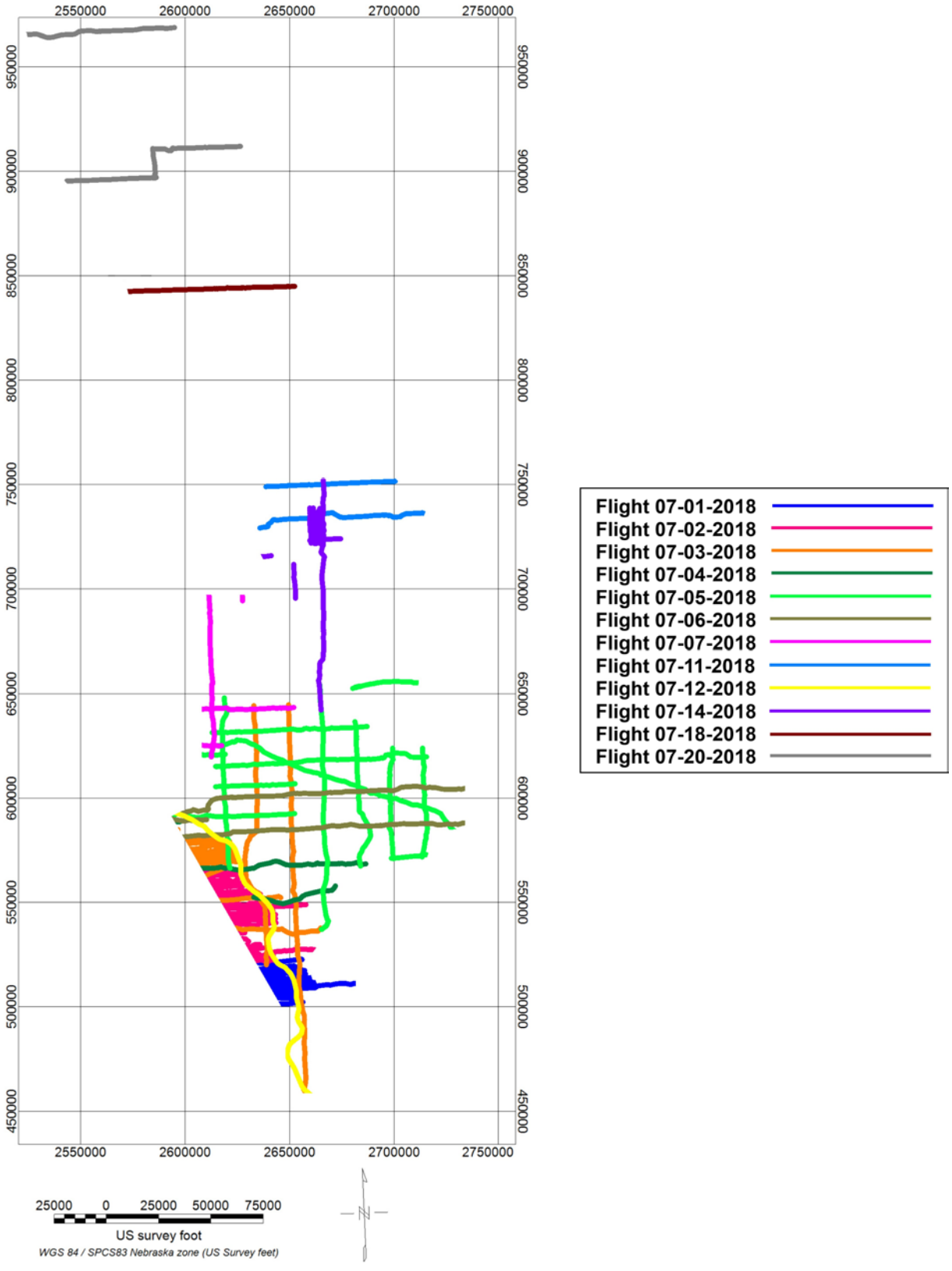


Figure 2-5: P-MRNRD 2018 AEM flight lines grouped by acquisition date. Projection is Nebraska State Plane NAD83, feet.

2.4.1 Primary Field Compensation

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

2.4.2 Automatic Processing

The AEM data collected by the 304M were processed using Aarhus Workbench version 5.8.3.0 (Aarhus Geosoftware (http://www.aarhusgeosoftware.dk/aarhus-workbench-ib3ao) described in HydroGeophysics Group, Aarhus University (2011).

Automatic processing algorithms provided within the Workbench program are initially applied to the AEM data. DGPS locations were filtered using a stepwise, second-order polynomial filter of nine seconds with a beat time of 0.5 seconds, based on flight acquisition parameters. The AEM data are corrected for tilt deviations from level and so filters were also applied to both tilt meter readings with a median filter of three seconds and an average filter of two seconds. The altitude data were corrected using a series of two polynomial filters. The lengths of both eighth-order polynomial filters were set to 15 seconds with shift lengths of twelve (12) seconds. The lower and upper thresholds were 1 and 100 meters, respectively.

Trapezoidal spatial averaging filters were next applied to the AEM data. The times used to define the trapezoidal filters for the Low Moment were $1.0x10^{-5}$ sec, $1.0x10^{-4}$ sec, and $1.0x10^{-3}$ sec with widths of 4, 7, and 18 seconds. The times used to define the trapezoid for the High Moment were $1.0x10^{-4}$ sec, $1.0x10^{-3}$ sec, and $1.0x10^{-2}$ sec with widths of 10, 20, and 36 seconds. The trapezoid sounding distance was set to 1.0 seconds and the left/right setting, which requires the trapezoid to be complete on both sides, was turned on. The spike factor and minimum number of gates were both set to 20 percent for both soundings. Lastly, the locations of the averaged soundings were synchronized between the two moments.

2.4.3 Manual Processing and Laterally-Constrained Inversions

After the implementation of the automatic filtering, the AEM data were manually examined using a sliding two-minute time window. The data were examined for possible electromagnetic coupling with surface and buried utilities and metal, as well as for late time-gate noise. Data affected by these were removed. Examples of locating areas of EM coupling with pipelines or power lines and recognizing and removing coupled AEM data in Aarhus Workbench are shown in Figure 2-6 and Figure 2-7, respectively. Examples of two inversions, one without EM coupling and the other with EM coupling, are shown in Figure 2-8. Areas were also cut out where the system height was flown greater than 213 feet (65 m) above the ground surface which caused a decrease in the signal level. This problem was encountered at several locations along the major rivers and streams due to the tall cottonwood trees.

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

After final processing, 424-line-miles (687-line kilometers) were retained for inversion amounting to a retention rate of 69.7%. This high rate is the result of careful flight line planning and design given the infrastructure that was encountered during the acquisition

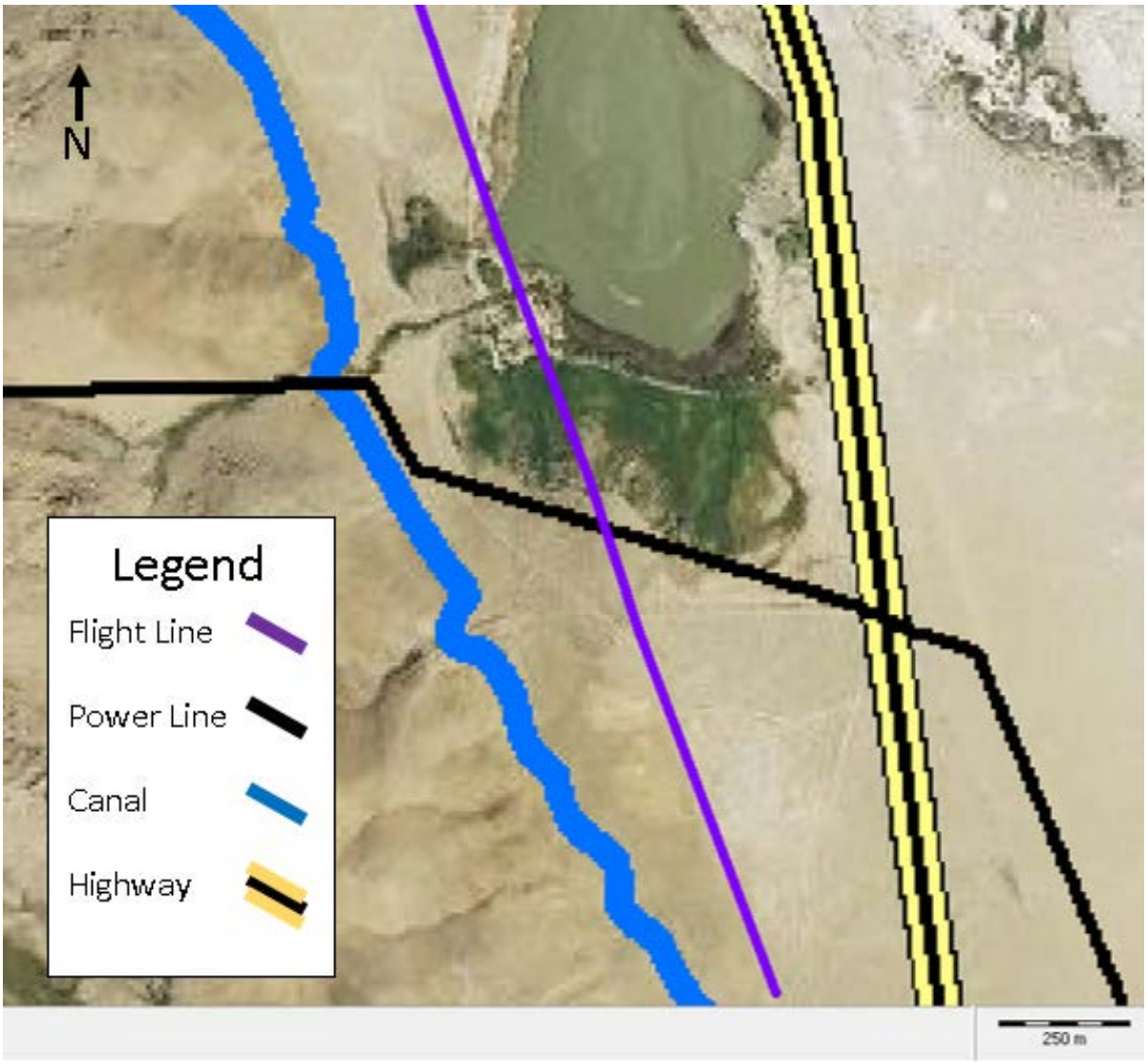


Figure 2-6: Example locations of electromagnetic coupling with pipelines or power lines.

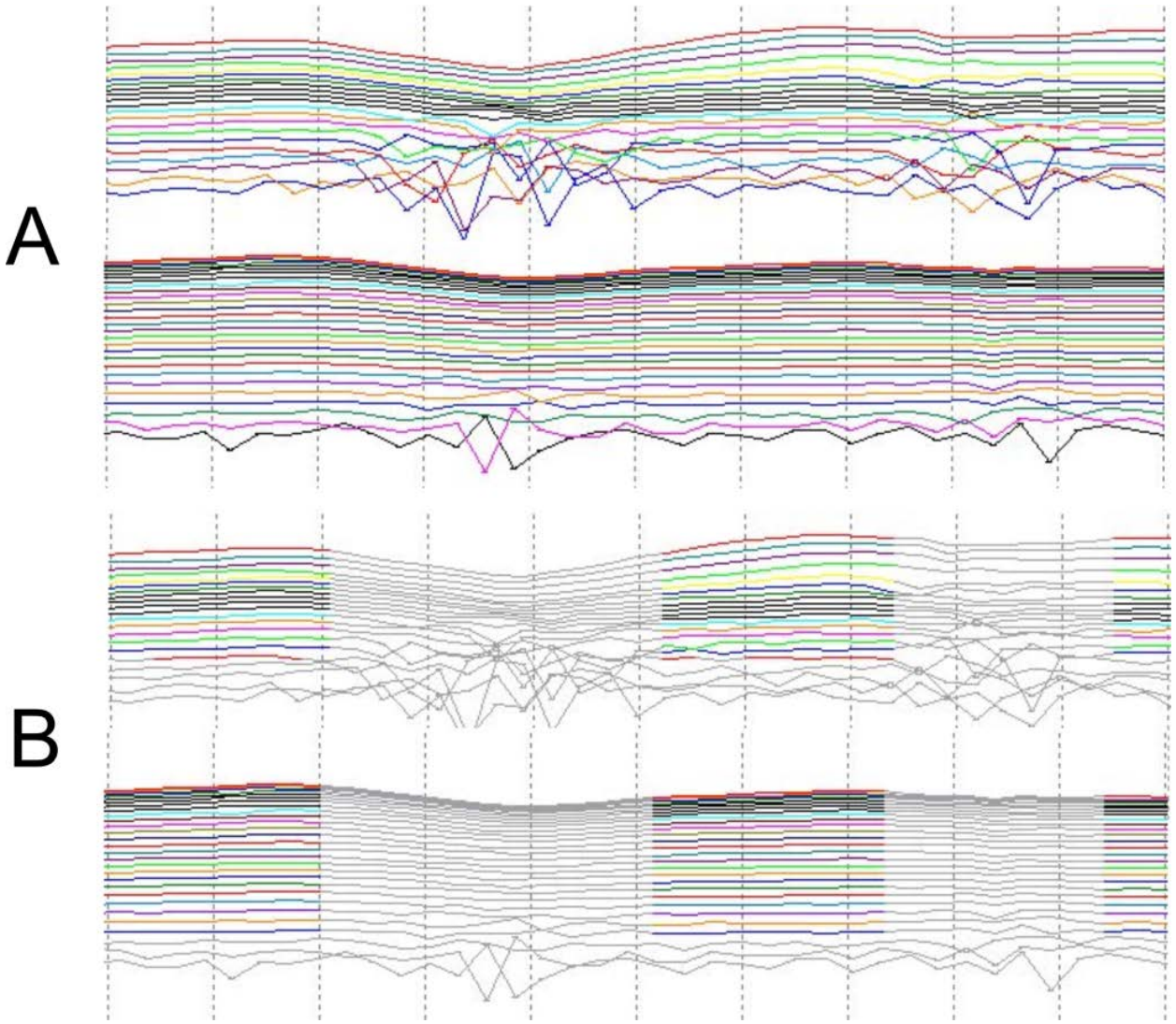


Figure 2-7: A) Example of AEM data affected by electromagnetic coupling as presented in the Aarhus Workbench editor. The top group of lines is the unedited data with the Low Moment on top and the High Moment on the bottom. The bottom group shows the same data after editing.

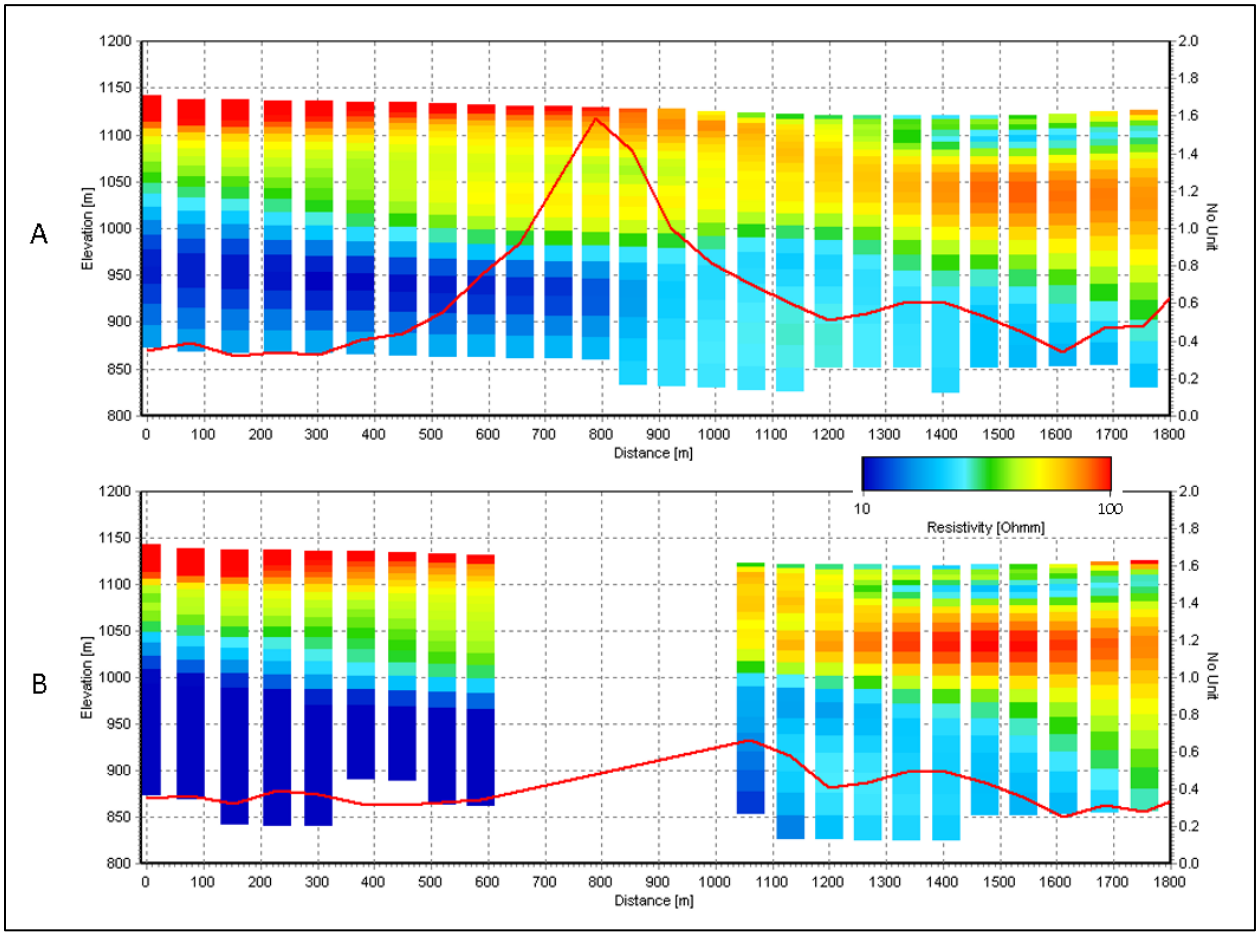


Figure 2-8: A) Example of Laterally-Constrained inversion results where AEM data affected by coupling with pipelines and power lines were not removed. B) Inversion results where AEM data affected by coupling were removed.

2.4.4 Power Line Noise Intensity (PLNI)

The Power Line Noise Intensity (PLNI) channel assists in identifying possible sources of noise from power lines. Pipelines, unless they are cathodically-protected, are not mapped by the PLNI. The PLNI is produced by performing a spectral frequency content analysis on the raw received Z-component SkyTEM data. For every Low Moment data block, a Fourier Transform (FT) is performed on the latest usable time gate data. The FT is evaluated at the local power line transmission frequency (60 Hz) yielding the amplitude spectral density of the local power line noise. The PLNI data for the P-MRNRD 2018 AEM survey are presented in Figure 2-9. The P-MRNRD-flight lines with blue colors representing the 69.7% of data retained for inversion and red lines representing data removed due to infrastructure and late time noise are presented in Figure 2-10.

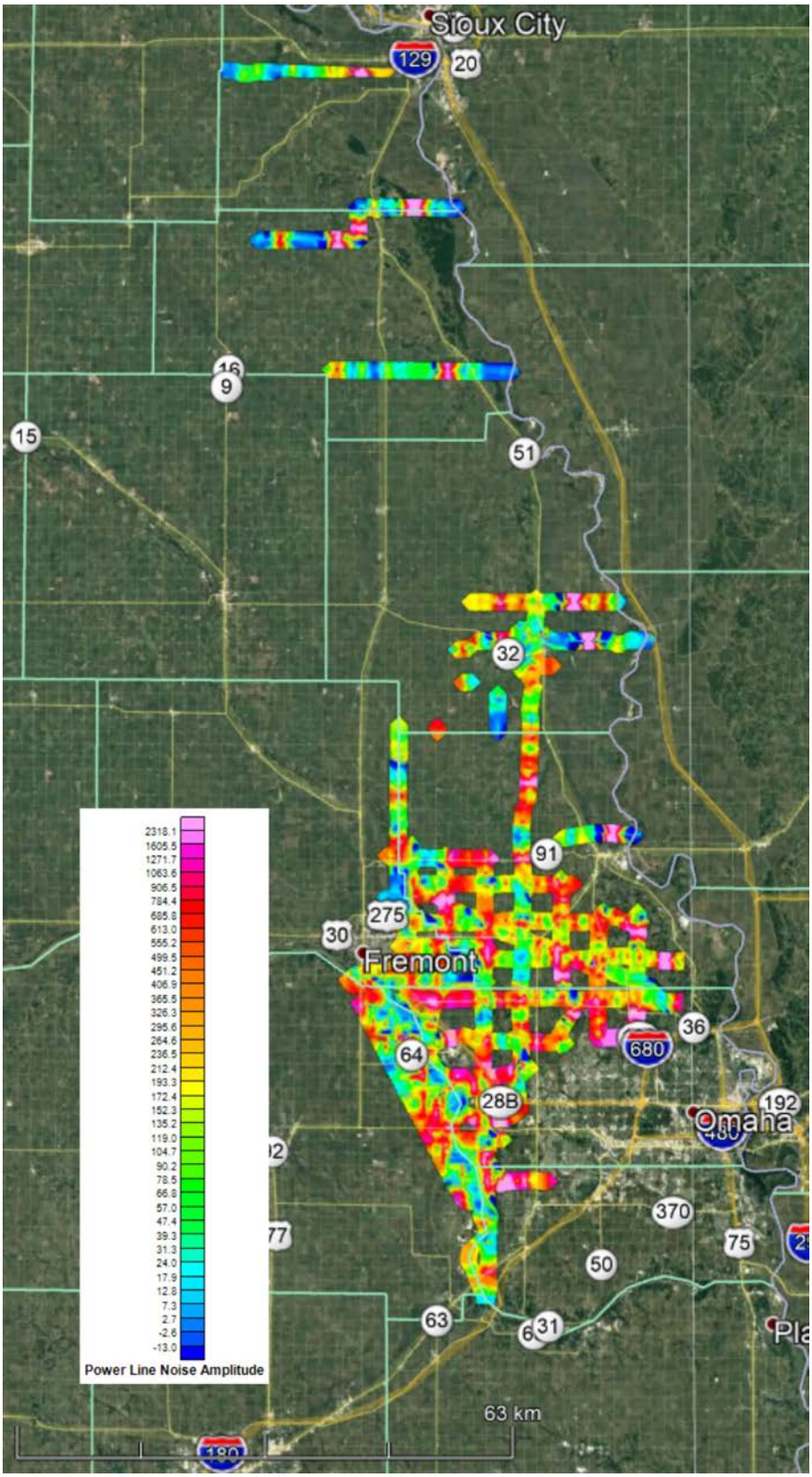


Figure 2-9: Power Line Noise Intensity (PLNI) map of the P-MRNRD 2018 project area.

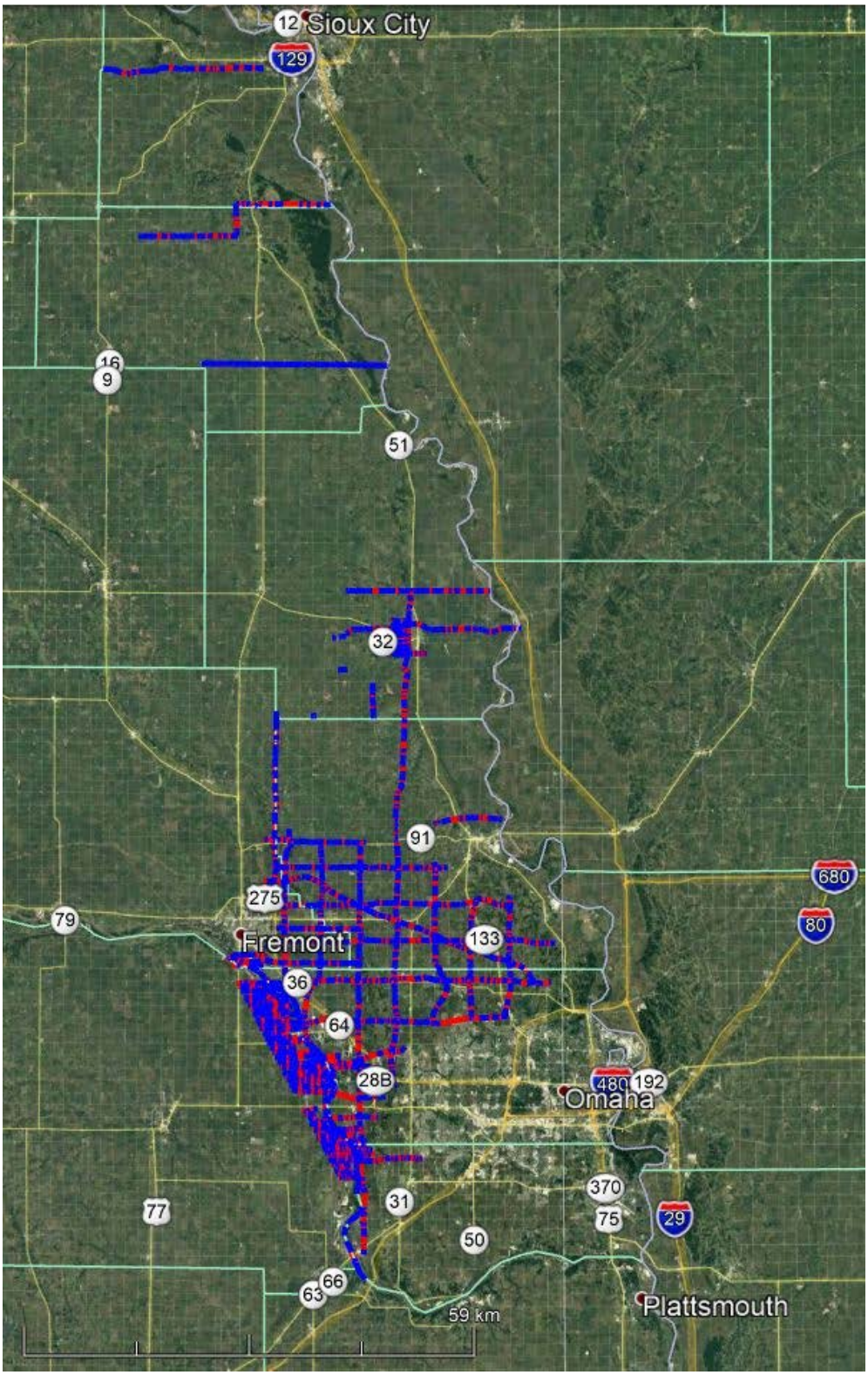


Figure 2-10: Locations of inverted data (blue lines) along the AEM flight lines (red lines) in the P-MRNRD 2018 AEM survey area. Where blue lines are not present indicates decoupled (removed) data. 69.7% of the acquired data was retained for inversion and interpretation. Google Earth kmz's of the inverted data locations as well as the "as-flown" flight lines are included in Appendix 3\KMZ.

2.4.5 Magnetic Field Data

As discussed above, the SkyTEM 304M includes a Total Field magnetometer. The magnetic Total Field data can yield information about infrastructure as well as geology. Figure 2-11 shows the residual magnetic Total Field intensity data for the P-MRNRD AEM survey area after correcting for diurnal drift and removing the International Geomagnetic Reference Field (IGRF). This data is used in decoupling efforts.

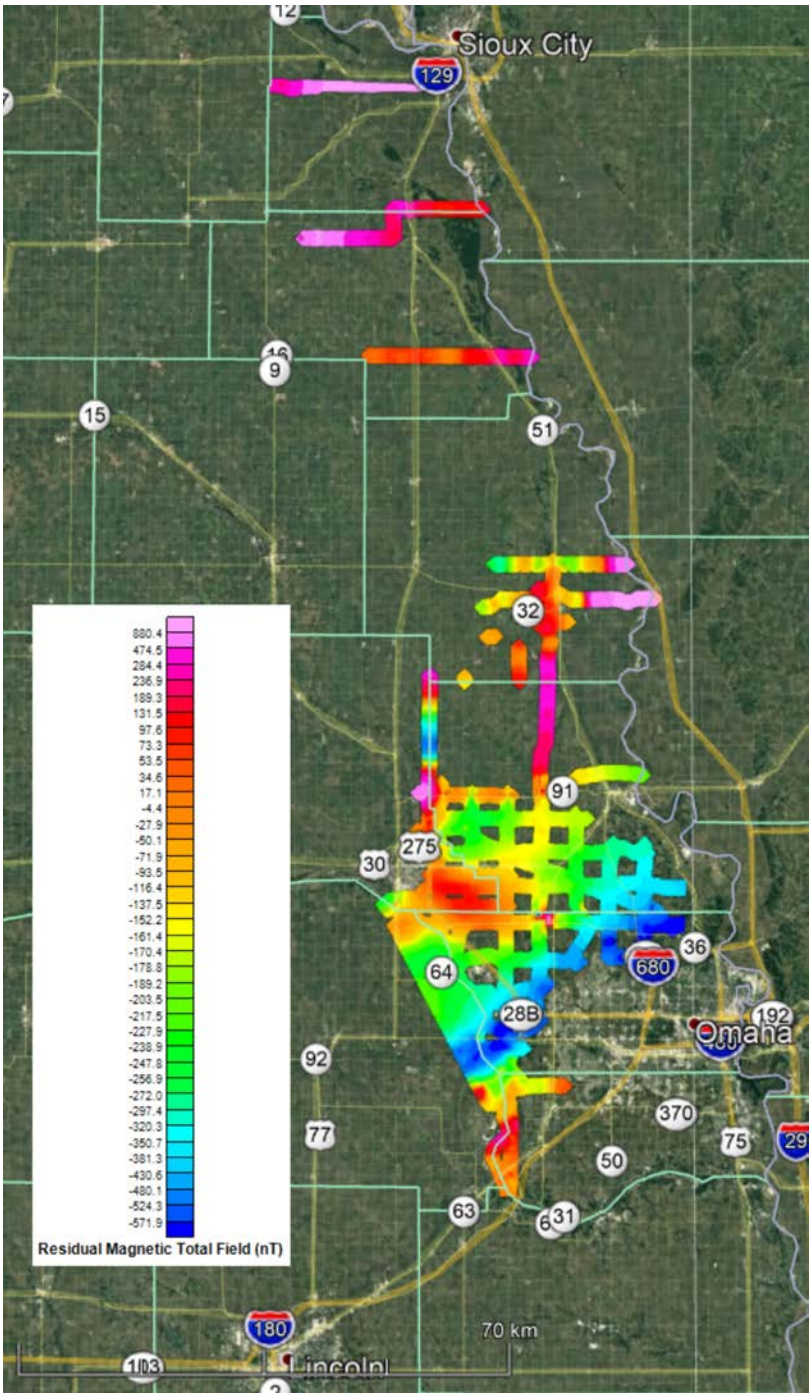


Figure 2-11: Residual magnetic Total Field intensity data for the P-MRNRD 2018 survey area corrected for diurnal drift, with the International Geomagnetic Reference Field (IGRF) removed.

2.5 Spatially-Constrained Inversion

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

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

The areas that were flown for the P-MRNRD, LPNNRD, and LPSNRD districts were inverted together with some areas of LENRD along the borders of the other NRD's. Seven groups of inversions, with about 10-15 flights each, were required to invert the AEM data. This process provided adequate overlap and allowed for full advantage to be taken with the SCI. Table 2-4 lists the SCI inversion groups and the flights that were included in each group and Figure 2-13 presents Google Earth images of the different inversion groups.

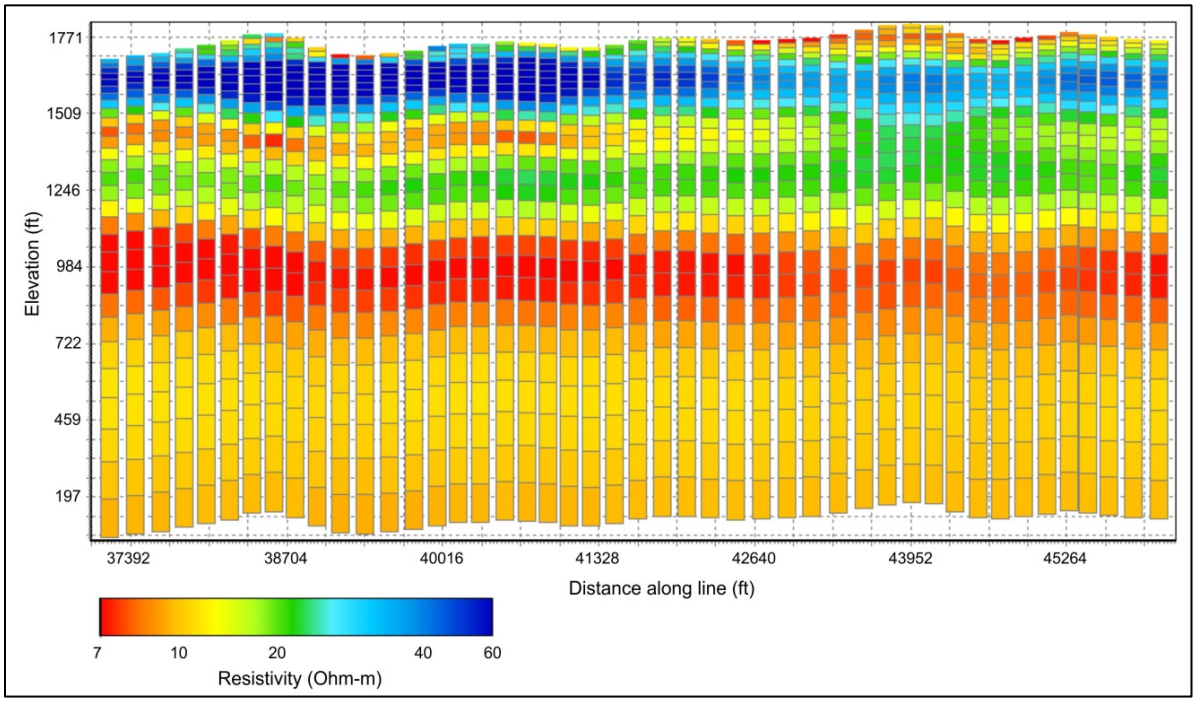


Figure 2-12: An example of an AEM profile illustrating increasing model layer thicknesses with depth.

In addition to the recovered resistivity models the SCIs also produce data residual error values (single sounding error residuals) and Depth of Investigation (DOI) estimates. The data residuals compare the

measured data with the response of the individual inverted models (Christensen et al., 2009). The DOI provides a general estimate of the depth to which the AEM data are sensitive to changes in the resistivity distribution at depth (Christiansen and Auken, 2012). Two DOI's are calculated: an "Upper" DOI at a cumulative sensitivity of 1.2 and a "Lower" DOI set at a cumulative sensitivity of 0.6. A more detailed discussion on the DOI can be found in Asch et al. (2015).

Table 2-3: Thickness and depth to bottom for each layer in the Spatially Constrained Inversion (SCI) AEM earth models. The thickness of the model layers increase with depth as the resolution of the AEM technique decreases.

Layer	Depth to Bottom (ft)	Thickness (ft)	Depth to Bottom (m)	Thickness (m)	Layer	Depth to Bottom (ft)	Thickness (ft)	Depth to Bottom (m)	Thickness (m)
1	3.3	3.3	1.0	1.0	21	197.8	20.0	60.3	6.1
2	6.9	3.6	2.1	1.1	22	219.8	22.0	67.0	6.7
3	10.8	3.9	3.3	1.2	23	243.7	23.9	74.3	7.3
4	15.1	4.3	4.6	1.3	24	269.9	26.2	82.3	8.0
5	19.7	4.6	6.0	1.4	25	298.8	28.9	91.1	8.8
6	24.9	5.2	7.6	1.6	26	330.3	31.5	100.7	9.6
7	30.5	5.6	9.3	1.7	27	364.7	34.4	111.2	10.5
8	36.7	6.2	11.2	1.9	28	402.5	37.7	122.7	11.5
9	43.6	6.9	13.3	2.1	29	443.8	41.3	135.3	12.6
10	51.2	7.5	15.6	2.3	30	489.0	45.3	149.0	13.8
11	59.4	8.2	18.1	2.5	31	538.6	49.5	164.2	15.1
12	68.2	8.9	20.8	2.7	32	593.0	54.4	180.7	16.6
13	78.1	9.8	23.8	3.0	33	652.4	59.4	198.8	18.1
14	88.6	10.5	27.0	3.2	34	717.3	64.9	218.6	19.8
15	100.4	11.8	30.6	3.6	35	788.5	71.2	240.3	21.7
16	113.2	12.8	34.5	3.9	36	866.6	78.1	264.1	23.8
17	127.3	14.1	38.8	4.3	37	951.9	85.3	290.1	26.0
18	142.7	15.4	43.5	4.7	38	1045.3	93.5	318.6	28.5
19	159.4	16.7	48.6	5.1	39	1147.7	102.3	349.8	31.2
20	177.8	18.4	54.2	5.6					

Table 2-4. AEM flights included in each of the SCI inversion groups.

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

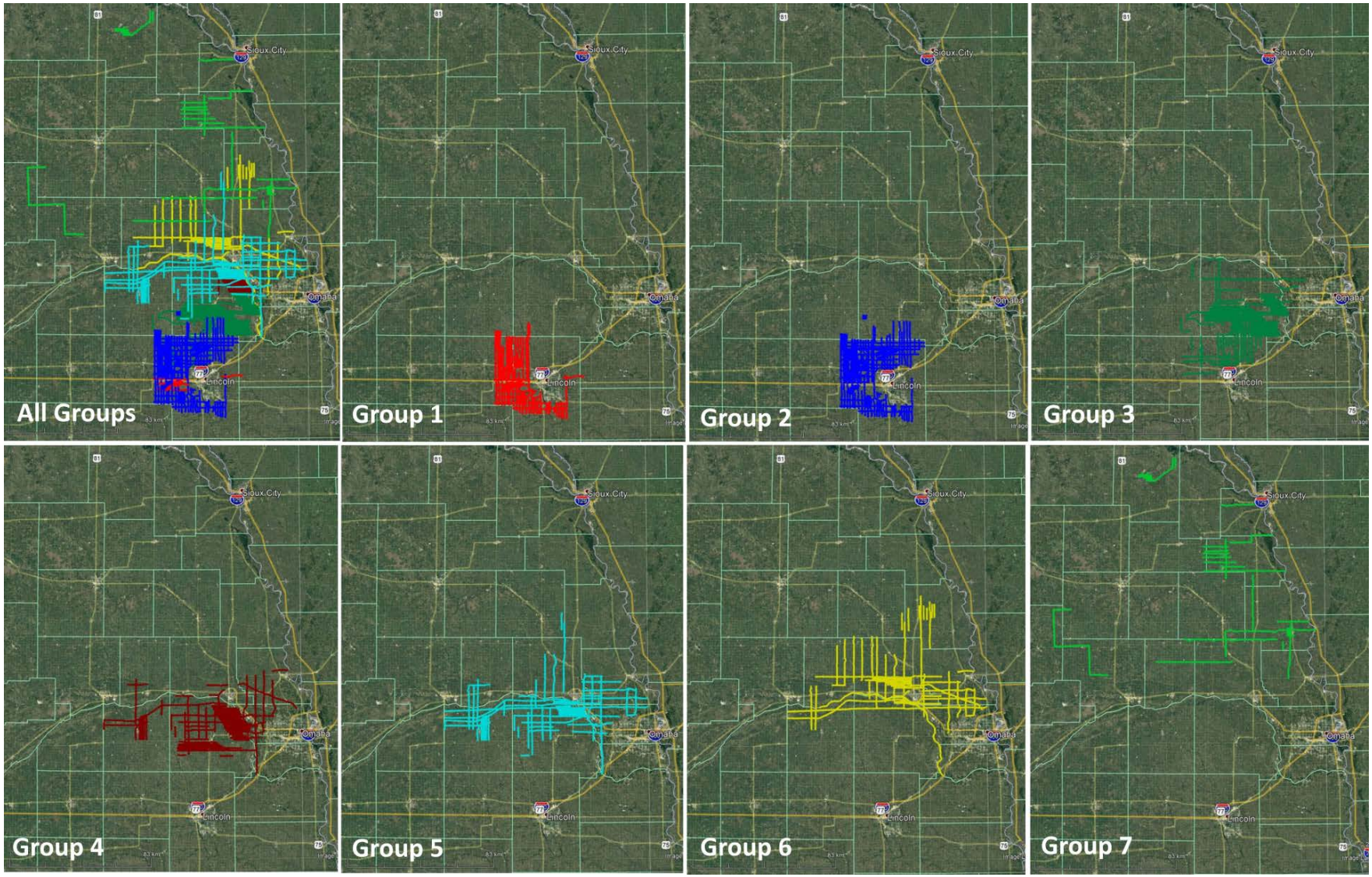


Figure 2-13. SCI inversion groups for the P-MRNRD, LPNNRD, and LPSNRD AEM data.

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

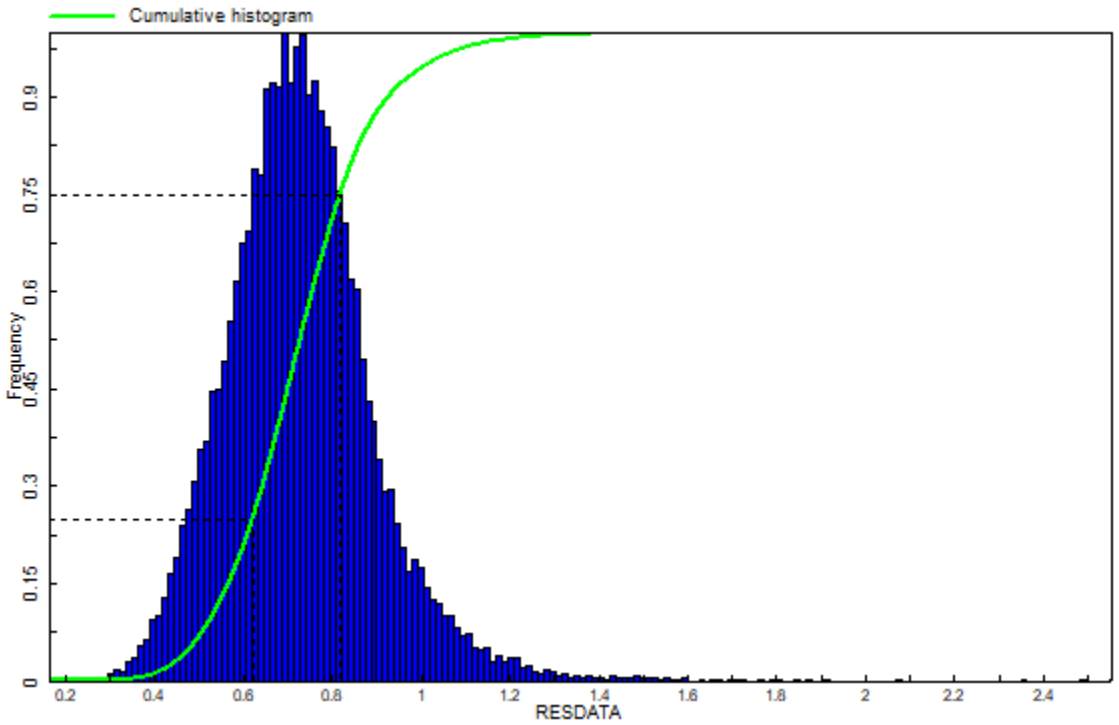


Figure 2-14: Data/model residual histogram for the P-MRNRD 2018 SCI inversion results.

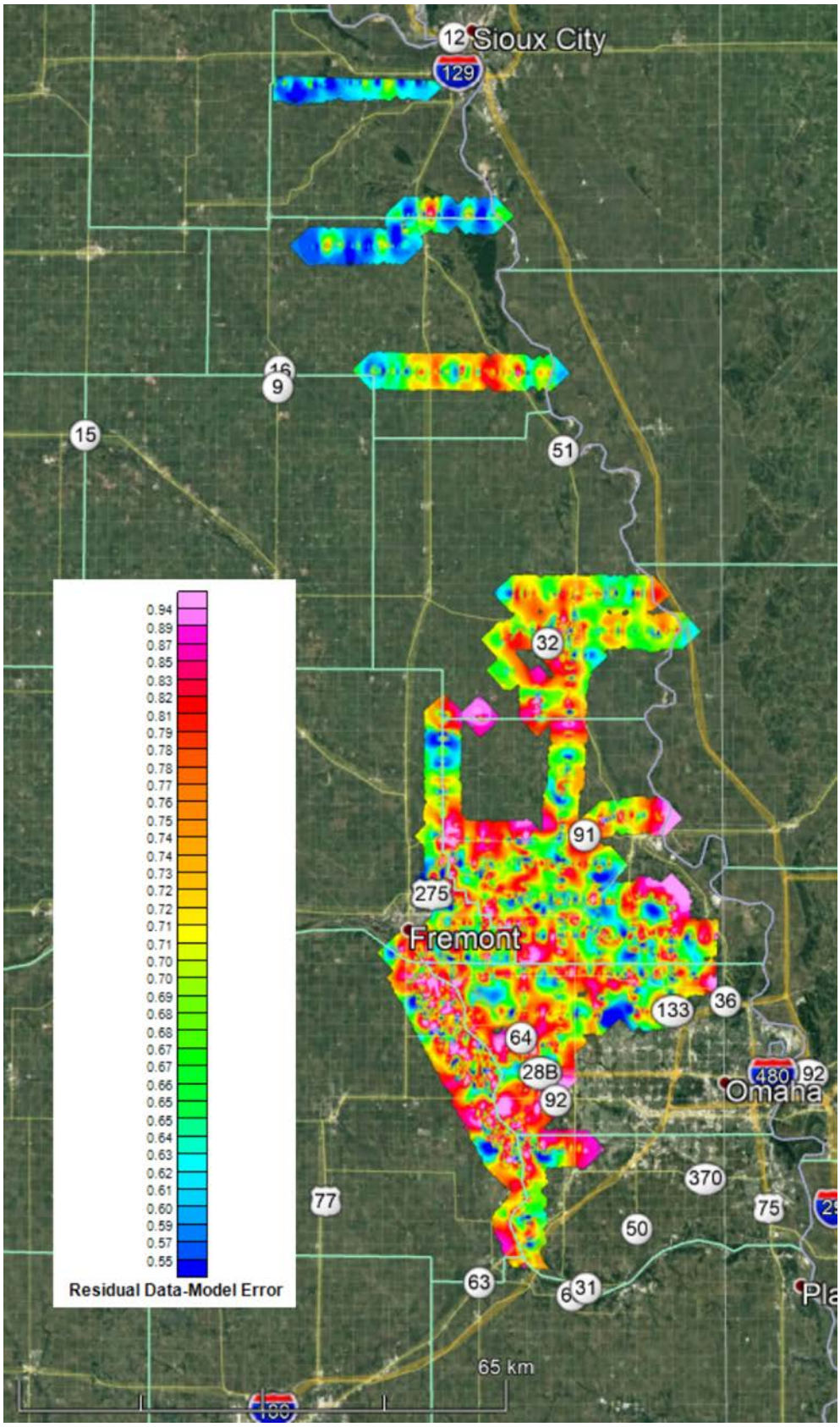


Figure 2-15. Map of data-inversion model residuals for the P-MRNRD 2018 SCI inversion results.

2.6 Merge AEM Databases from Different Flights and Inversions

After the inversion process several lines segments were combined to form continuous lines within the survey area. This included lines that composed the block flights and reconnaissance grid lines. These continuous lines allow for improved viewing and interpretation of the AEM inversions results. As just discussed above, the areas that were flown for the P-MRNRD, LPNNRD, and LPSNRD AEM survey were inverted together with some areas of the LENRD. A consequence of this inversion procedure resulted in/provided multiple inversions of many lines. The lines that had multiple inversions were compared and the line-inversion with the lowest data-model residual was retained, and the other repeat line-inversions were deleted from the data base. At that point the segmented lines were merged to form continuous lines. Table 2-5 lists the original flown lines and the new combined lines.

Table 2-5. Combination of flight lines within the inversion areas.

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

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

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

3 AEM Results and Interpretation

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

3.1 Interpretive Process

3.1.1 Construct the Project Digital Elevation Model

To ensure that the elevation used in the project is constant for all the data sources (i.e. boreholes and AEM), a Digital Elevation Model (DEM) was constructed for the ENWRA area. The data was downloaded from the National Elevation dataset (NED) located at the National Map Website (U.S. Geological Survey, 2018) at a resolution of 1 arc-second or approximately 100 ft. The geographic coordinates are North American Datum of 1983 (NAD 83) and the elevation values are referenced to the North American Vertical Datum of 1988 (NAVD 88). The 100 ft grid cell size was used throughout the project and resulting products. Figure 3-1 is a map of the DEM for the P-MRNRD survey area having a vertical relief of 800 ft with a minimum elevation of 900 ft and a maximum elevation of 1,700 ft. This DEM was used to reference all elevations within the AEM and borehole datasets. Figure 3-2 is a DEM of the Tekamah Block and has a vertical relief of 310 ft with a minimum elevation of 1,015ft and a maximum elevation of 1,325 ft.

3.1.1 Borehole Derived Bedrock Surface

As a guide in the interpretation of the AEM, a bedrock surface was prepared using CSD and NE-DNR borehole logs. This work was conducted by Mike Plante and Roscoe Sopiwnik of WSP. The process included the following steps:

1) The lithology databases for the CSD and NE-DNR wells were inspected for bedrock consolidated units (i.e. limestone, shale, sandstone, mudstone). These locations were flagged as “B-rock”. CSD holes with identified bedrock contacts were also utilized. The databases were inspected for areas where unconsolidated units (i.e. sand, gravel, clay) were logged below consolidated units. These areas were flagged and inspected utilizing the CSD holes.
2) The Project DEM was used to sample the elevation for the hole. The depth of the “B-rock” pick was subtracted to provide the elevation of the Bedrock.
3) An initial bedrock surface was developed using natural neighbor interpolation in ArcGIS and known bedrock elevations from the lithology database.
4) The initial interpolated bedrock surface was compared to the input data to determine how well the interpolation simulated the input data and to identify locations where a borehole was intersected by the bedrock surface, yet bedrock was not encountered in the borehole. In the latter example, the bottom elevation of the borehole was used to force the second natural neighbor interpolation surface under the borehole. The initial and forced bedrock surfaces were compared against the DEM to identify areas where the interpolated surface was above the DEM. A conditional statement was used to restrict the top of bedrock surface to be no higher than the ground elevation. Input data was compared against the interpolated results to determine how many locations had differentials greater than 10 feet. A differential of 10 feet was chosen since it approximates the lower end of AEM layer thickness. Analysis of the data

found that 47 out of 1,992 locations from the initial surface had differentials greater than 10 feet. Similar analysis of the data from the forced surface found that 77 out of 2,642 locations had differentials greater than 10 feet. The discrepancy is attributed to an unknown number of borings that were likely drilled into the ***Kd***, but the geologic contact was not identified.

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

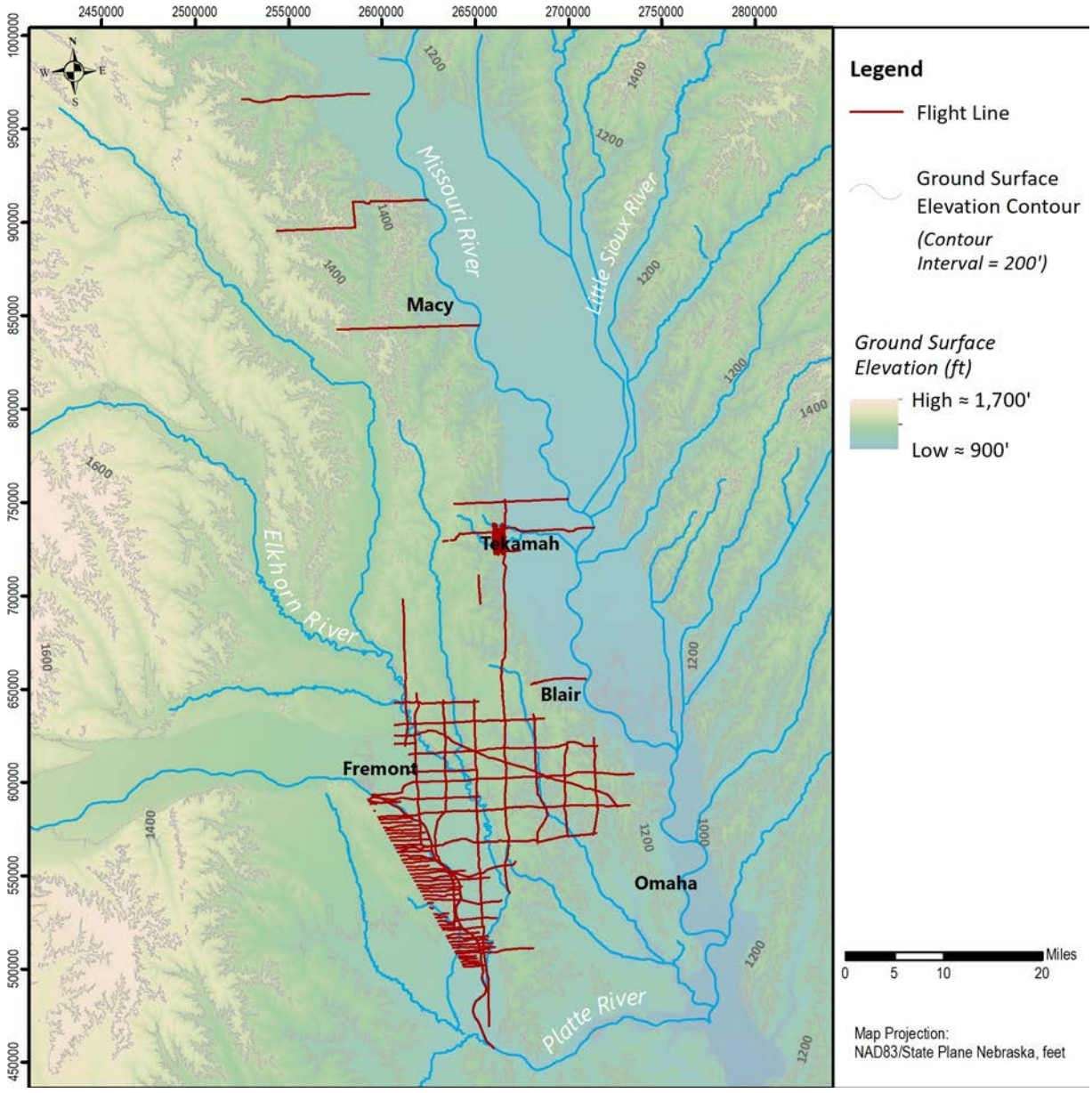


Figure 3-1. Map of the Digital Elevation Model for the P-MRNRD study area. Flight lines are indicated with maroon lines. Data source is the one (1) arc-second National Elevation Dataset (U.S. Geological Survey, 2018). North American Datum of 1983 (NAD 83) State Plane Nebraska (feet) and the elevation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

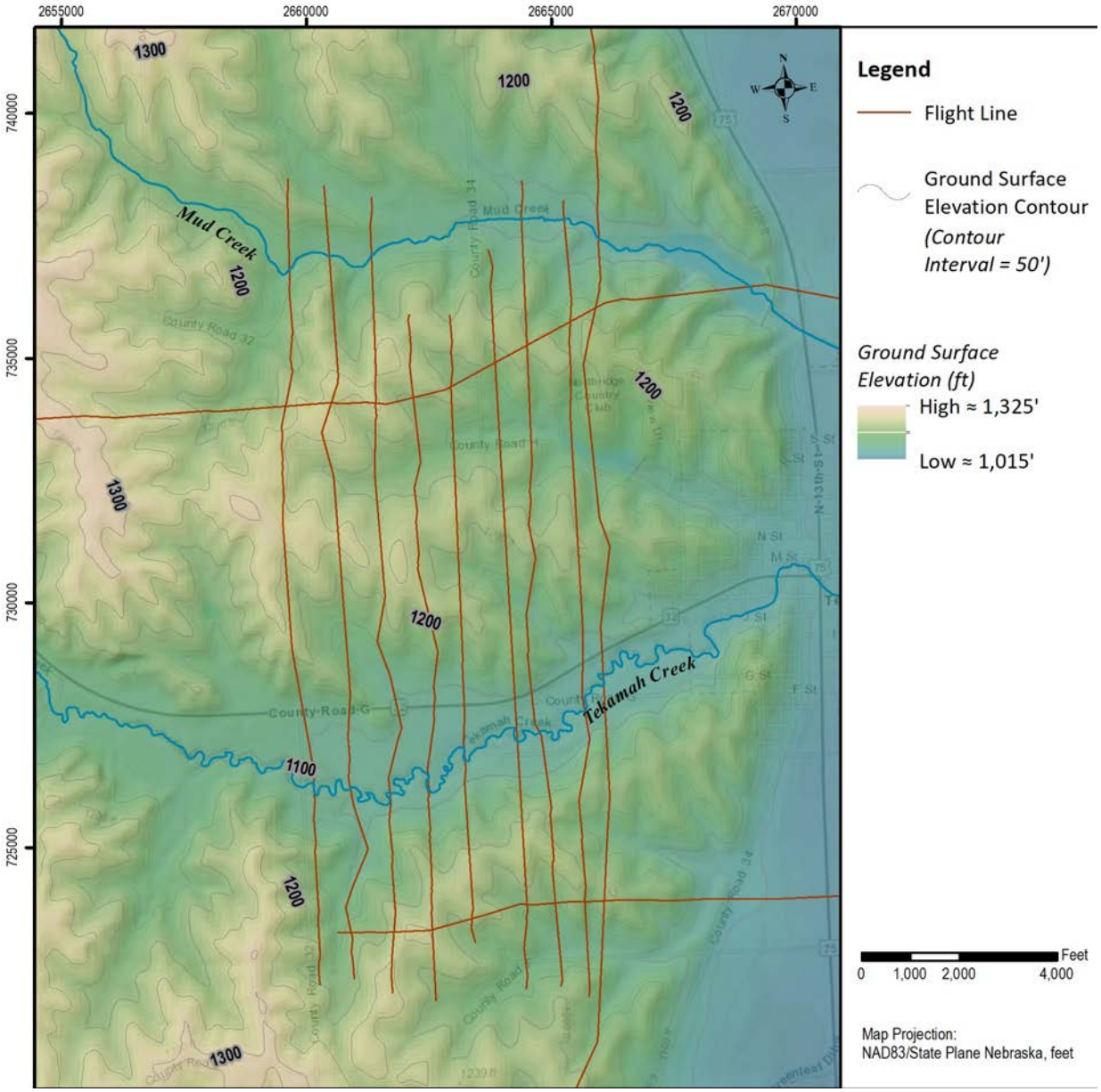


Figure 3-2. Map of the Digital Elevation Model for the Tekamah Block AEM survey area. Data source is the one (1) arc-second National Elevation Dataset (U.S. Geological Survey, 2018). Flight lines are indicated by brown lines. North American Datum of 1983 (NAD 83) State Plane Nebraska (feet) and the elevation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

3.1.2 Create Interpretative 2D Profiles

After final combination of the AEM data (described above in Section 2.6), characterization of the subsurface was performed in cross-section format using Datamine Discover Profile Analyst (PA) (Datamine Discover, 2019). During interpretation, the horizontal and vertical scales of the profiles were adjusted to facilitate viewing. The color scale of the resistivity data was also adjusted to illuminate subtle differences in the resistivity structure within the inverted AEM resistivity data related to the area being interpreted. The first step in the interpretation is digitizing the contacts between the geologic units including: Quaternary (***Q***), Cretaceous Carlile Formation (***Kc***), Cretaceous Greenhorn Limestone and Graneros Shale (***Kgg***), Cretaceous Dakota Group (***Kd***), and the undifferentiated Pennsylvanian (***IP***). The interpretive process benefited from the use of CSD, NE-DNR, and NEOGCC borehole logs, which provided lithologic, stratigraphic, and geophysical information. The interpretations were simultaneously checked against the CSD's Nebraska bedrock geology map (Burchett, 1986), but may differ due to the final interpretation. Additionally, the bedrock surface, as developed by WSP (Personal communication Mike Plante, Supervising Hydrologist, WSP, April 2019), was used as a guide for the interpretation of the ***Kd*** and ***IP*** in areas of low electrical resistivity contrast and no boreholes.

The ***Kc*** and the ***Kgg*** only occurred along the northern reconnaissance lines. The CSD stratigraphic control was utilized to distinguish the ***Q*** from the underlying ***Kc*** and ***Kgg***. The ***Kc*** is a marine shale and is distinguished by its electrically conductive nature. The ***Kgg*** is typically observed as an electrical resistor from the inclusion of the Greenhorn Limestone, but is masked in many locations by the Graneros Shale which is a low resistivity unit.

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

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

Figure 3-3 is an approximately 32-mile-long line, L160001, that is flown along the Platte River from approximately Fremont to the I-80 Platte River bridge at Ashland Nebraska. The line is down the border of the P-MRNRD and LPNNRD districts. Several CSD test holes are projected onto the line that are within one mile. The ***Q*** sediments are composed almost entirely of Platte River alluvium overlying the ***Kd*** that is heavily eroded. On the southern end of the line, the Platte River alluvium is directly in contact with the ***IP***. The color scale is set to a range that shows the resistive material within the ***Kd*** that is in direct contact with the resistive materials within the ***Q***. There is an excellent match of the resistivities with the lithologies in the CSD wells. Many NE-DNR wells are within this stretch of the river but are too numerous to show on this scale of a plot.

Figure 3-4 is an approximately 25-mile-long east-west line, L501500, that is south of the towns of Fremont and Washington and north of Bennington. The line crosses the Platte River, the Elkhorn River, and Papillion Creek. Several CSD test holes and many NE-DNR wells penetrate the ***Kd*** and/or stop at the top of the ***IP***. Line L501500 is dominated by the resistive Platte River alluvium in the west that abruptly changes into glacial till to the east of the Elkhorn River. Several NE-DNR registered wells confirm the presence of sands and sand and gravel in the ***Q*** alluvium as well as the sand and sandstone in the ***Kd***. The water table is close to the surface in the areas of the Platte and Elkhorn rivers and is deeper under the glacial till.

Figure 3-5 is an approximately 33-mile-long north-south line, L800301, that is east of the town of Valley, Nebraska and west of Waterloo, Nebraska. The line crosses the Elkhorn River in the north and bisects the area between the Platte River and the Elkhorn River and crosses the confluence of the two rivers and continues south on the east side of the Platte River. Several CSD test holes penetrate the ***Kd*** and/or stop at the top of the ***IP***. This line is dominated by high resistivity materials in the southern portion of the line associated with the Platte River alluvium. Several areas in the ***Kd*** show the change in resistivity associated with sandtone/sand versus the clay/shale. On the northern portion of the line there are resistive materials associated with the ***Q*** sands under the till.

Figure 3-6 is an approximately 24.75-mile-long east-west line, L700500, that is north of the town of Tekamah. The line crosses the Missouri River on the far eastern end. Several NE-DNR registered wells penetrate the ***Kd*** and/or stop at the top of the ***IP***. The Tekamah area displays ***Q*** materials with a generally lower electrical resistivity overlying resistive areas within the ***Kd***. The water table is generally indicating a regional trend from the highlands in the west towards the Missouri River. Much of the ***Q*** west of the town of Tekamah is unsaturated. To the east of the ***Kd*** bench, the ***Q*** materials are resistive Missouri River alluvial sediments that are saturated overlying the ***IP***. There is a zone of low resistivity materials just east of the town of Tekamah, that extends from NE-DNR well *G089745* towards the east to borehole *G-126292*, that is indicated as clay in several registered wells that match the resistivity indicated by the AEM.

Figure 3-7 is an approximately 17-mile-long east-west line, L700300, that is on the north end of the P-MRNRD AEM survey area. This is one of the three reconnaissance lines to the north of the main survey area. The line presented, L700300, is south of the town of Macy, Nebraska and crosses the Missouri River on the far eastern end. Several CSD test holes and many NE-DNR wells penetrate the ***Kgg*** and the

Kd. There are unsaturated resistive ***Q*** materials on the eastern end of the survey line just before dropping into the Missouri River floodplain. The western end of the line indicates low resistivity tills with the ***Q***. There is a high resistivity zone in the center of the profile that indicates sandstone within the ***Kd*** and correlates with CSD test hole *17-B-53*. The NE-DNR registered wells indicate a majority of the material is sand within the Missouri River alluvium.

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

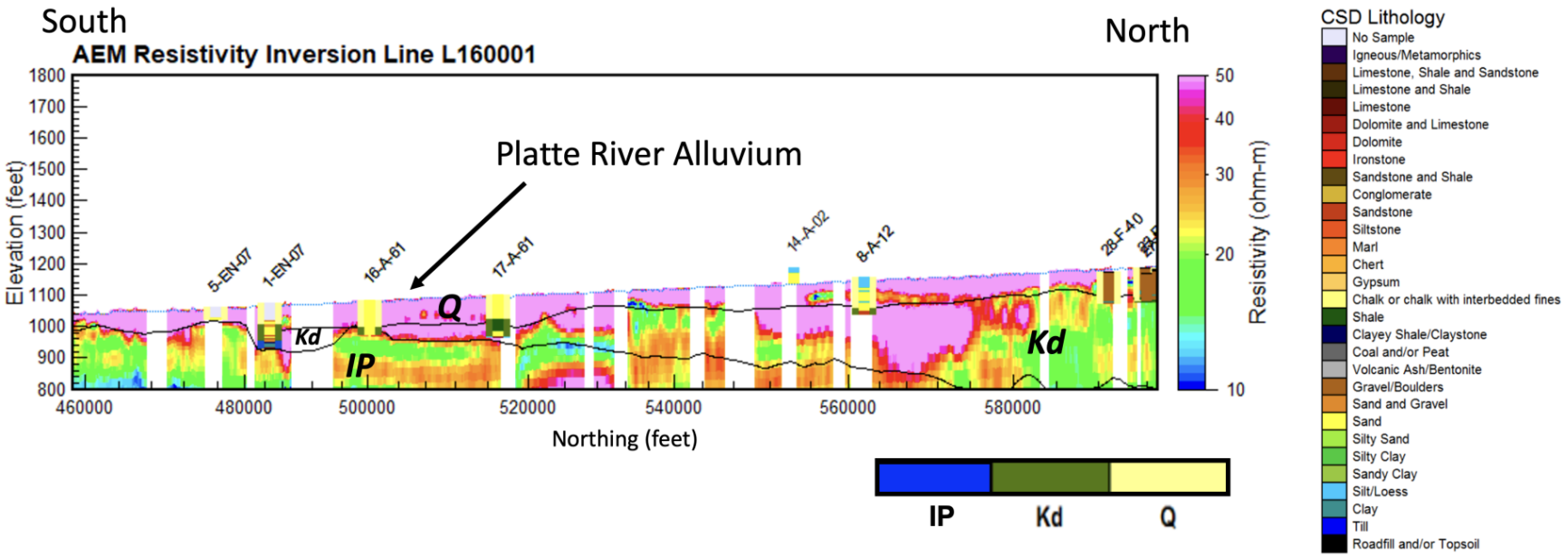


Figure 3-3. 32-mile line L160001 that is along the Platte River from approximately Fremont to the I-80 Platte River bridge at Ashland, Nebraska. CSD and borehole lithology and stratigraphy logs are indicated on the AEM inverted earth models if they are within one mile of the flight line. Interpretations of the top of the Cretaceous Dakota Group (*Kd*) and undifferentiated Pennsylvanian (*IP*) are indicated by the black lines. The Quaternary (*Q*) material is predominantly Platte River alluvium. Gaps indicate areas removed due to coupling. The CSD 1995 water table is indicated with a dashed blue line and is at the surface due to the line occurring along the river.

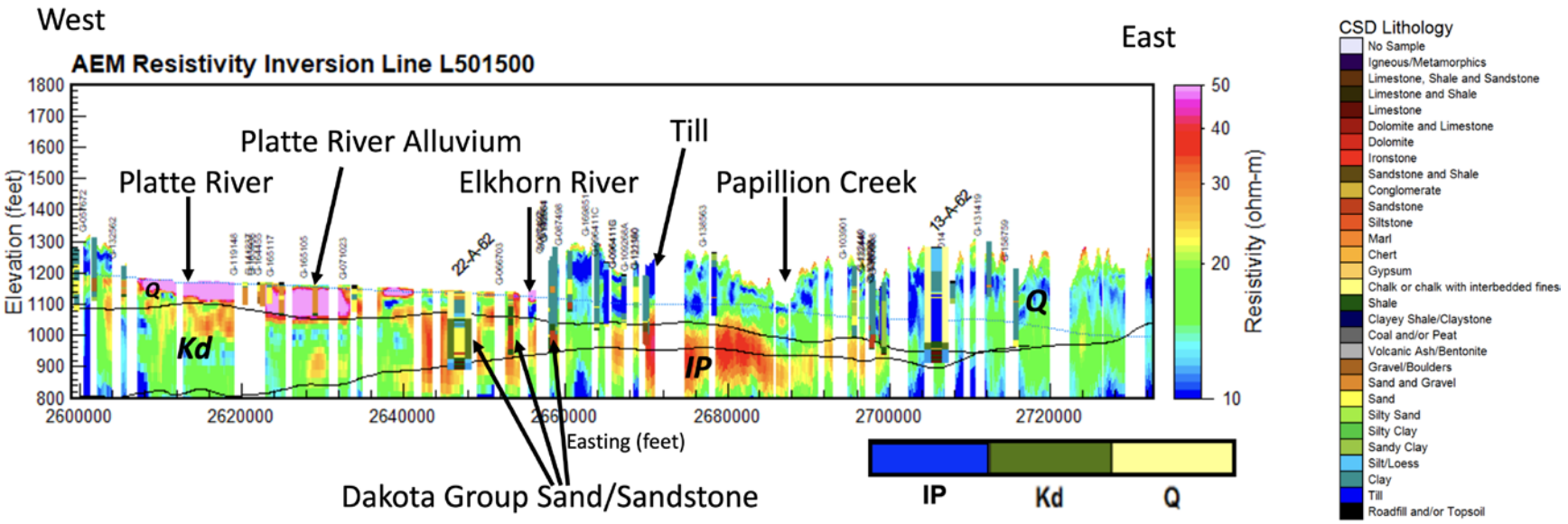


Figure 3-4. 25-mile-long east-west line L501500. CSD (within one mile) and Nebraska DNR (within ¼ mile) boreholes lithology and stratigraphy logs are indicated on the AEM inverted earth model. Interpretations of the top of the Cretaceous Dakota Group (*Kd*) and undifferentiated Pennsylvanian (*IP*) are indicated by the black lines. The Quaternary (*Q*) material is predominantly Platte River alluvium in the west. Gaps indicate areas removed due to coupling. The CSD 1995 water table is indicated with a dashed blue line and is at the surface near the Platte and Elkhorn Rivers.

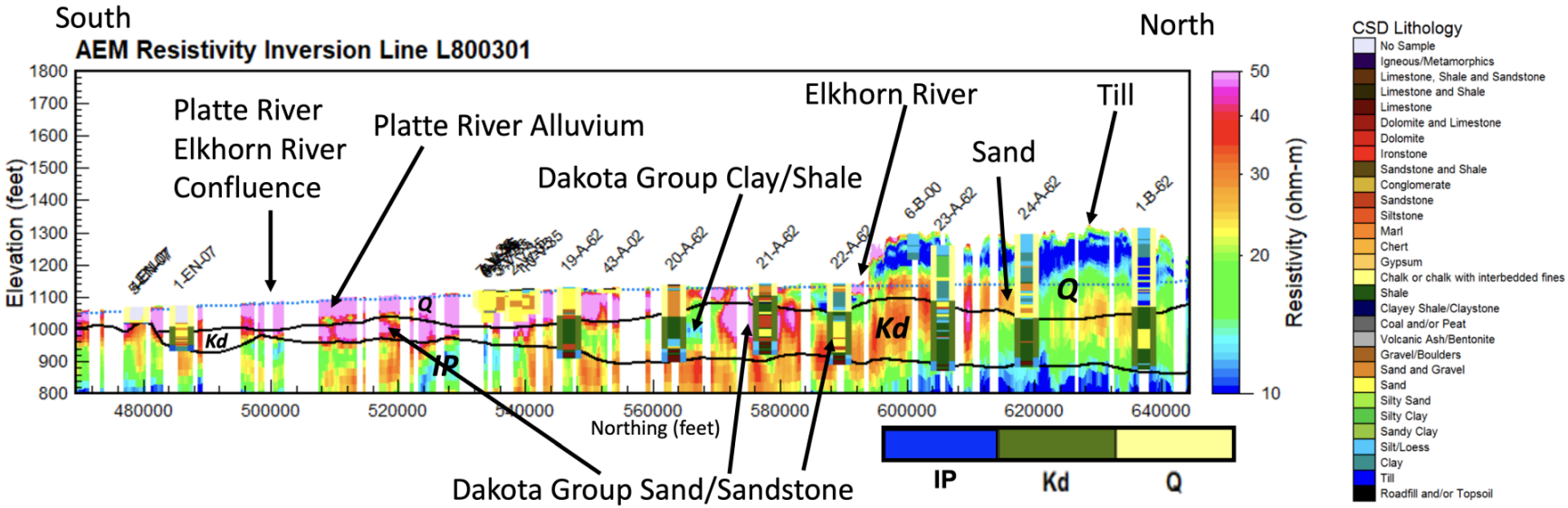


Figure 3-5. 33-mile-long north-south line L800301. CSD borehole lithology and stratigraphy logs are indicated on the AEM inverted earth models if they are within one mile of the flight line. Interpretations of the top of the Cretaceous Dakota Group (*Kd*) and undifferentiated Pennsylvanian (*IP*) are indicated by the black lines. The Quaternary (*Q*) material is predominantly Platte River alluvium in the south. Gaps indicate areas removed due to coupling. The CSD 1995 water table is indicated with a dashed blue line and is at the surface near the Platte and Elkhorn Rivers.

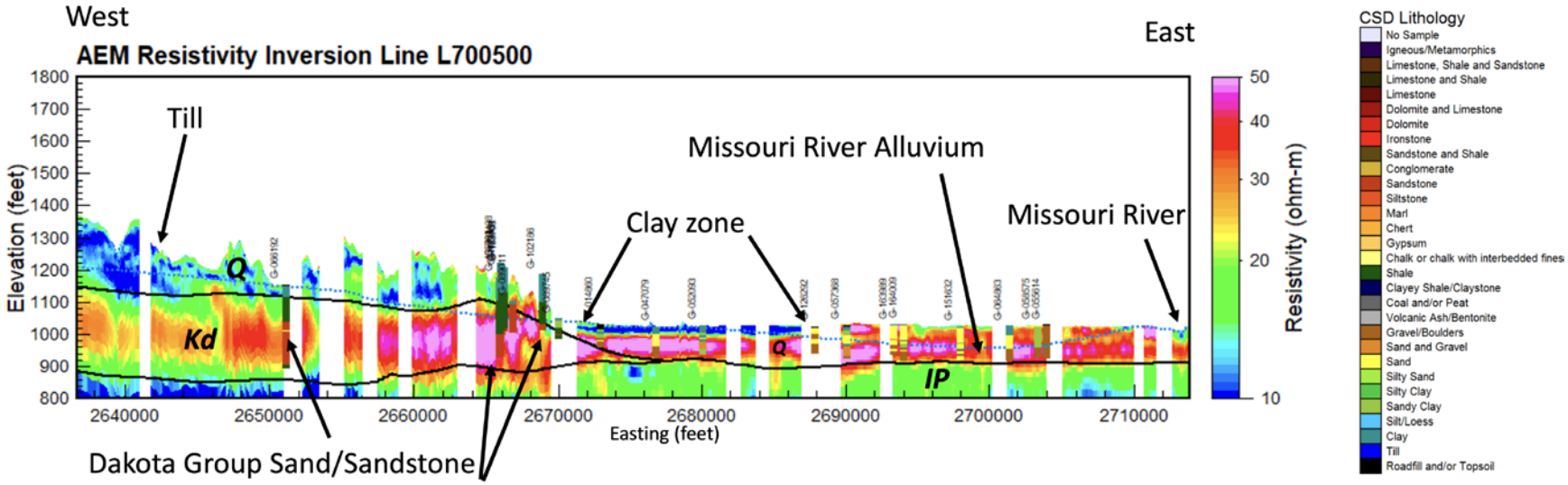


Figure 3-6. 24.75-mile-long east-west line L700500. Nebraska DNR borehole lithology and stratigraphy logs are indicated on the AEM inverted earth models if they are within ¼ mile of the flight line. Interpretations of the top of the Cretaceous Dakota Group (*Kd*) and undifferentiated Pennsylvanian (*IP*) are indicated by the black lines. The Quaternary (*Q*) material is predominantly till in the west and Missouri River alluvium in the east. Gaps indicate areas removed due to coupling. The CSD 1995 water table is indicated with a dashed blue line.

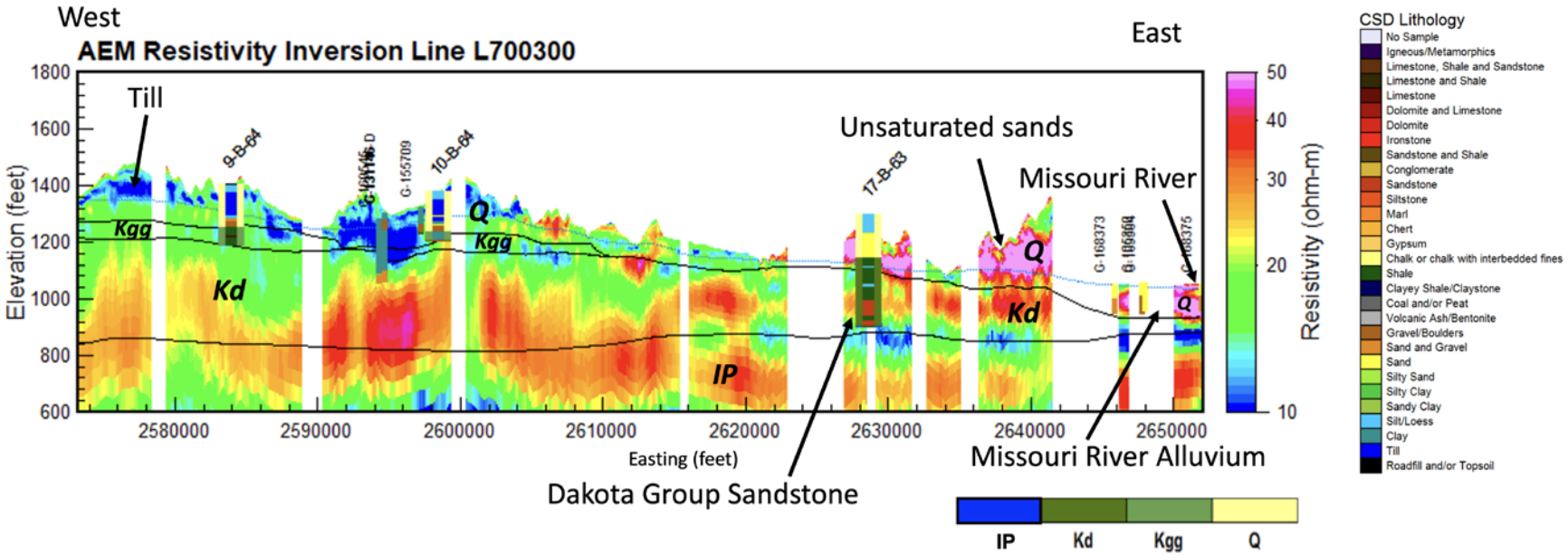


Figure 3-7. 17-mile-long east-west line L700300. CSD and Nebraska DNR borehole lithology and stratigraphy logs are indicated on the AEM inverted earth models if they are within one mile of the flight line. Interpretations of the top of the Cretaceous Greenhorn Limestone and Graneros Shale (*Kgg*), Cretaceous Dakota Group (*Kd*), and undifferentiated Pennsylvanian (*IP*) are indicated by the black lines. The Quaternary (*Q*) material is predominantly till in the west and Missouri River alluvium in the east with a large sand body on the ridge before dropping off into the Missouri River floodplain. Gaps indicate areas removed due to coupling. The CSD 1995 water table is indicated with a dashed blue line.

3.1.3 Create Interpretative Surface Grids

Due to the large distance of the three northern reconnaissance lines from the Tekamah Block and the southern reconnaissance survey, the interpretative surface grids presented here encompass the area from the Tekamah Block south. Grids for the southern reconnaissance area and the Tekamah Block surface elevation, thickness, and saturated thickness were have been developed. To create these grids, data such as a ground surface digital elevation model (DEM), water table elevation, borehole data from the WSP borehole-only bedrock interpretation, and AEM-interpreted point data of the survey area were imported and processed in ESRI's ArcMap along with the Spatial and Geostatistical Analyst extensions.

The elevation of the top of the Cretaceous Dakota Group (***Kd***) and undifferentiated Pennsylvanian (***IP***) raster grids for the southern reconnaissance AEM survey area were produced. To create the grids, over 6,500 data points with top elevation values were extracted from the AEM interpretation. Additionally, ~1,000 borehole data points used in in borehole-only bedrock surface interpretation were utilized. Then, the total ~7,500 data points were input into ArcMap. The elevation point data were interpolated into a continuous surface using a kriging geostatistical model and exported to a 1,000 ft cell size grid. Grids that were created for the Tekamah Block AEM survey area were developed by a similar method, except that parameters input into the kriging model varied slightly from the model used to create the southern reconnaissance AEM survey area grids due to the consistently closer line-spacing in the Tekamah Block AEM survey area. The Tekamah Block grids were exported to a 200 ft cell size based on the approximate 500-1,000 ft spacing across line and 200-250 ft spacing down line. Figure 3-8, Figure 3-9, Figure 3-10, and Figure 3-11 are maps of the elevation of the top of the ***Kd*** and ***IP*** within the southern reconnaissance AEM survey area and top elevation of ***Kd*** and ***IP*** within the Tekamah Block survey area, respectively.

A raster grid of the elevation of the top of bedrock was produced for the southern reconnaissance AEM survey area by first subtracting the grid of the elevation of the top of the ***IP*** from the grid of the elevation of the top of the ***Kd*** to determine approximately where the surface contact between ***Kd*** and ***IP*** exists. Next, a comparison was made between the ***Kd***/***IP*** contact interpreted on the geologic map (Burchett, 1986), and where the AEM data show the contact to exist. Small adjustments were made to the mapped contact based on this comparison. Finally, the grids of the elevations of the tops of the ***IP*** and ***Kd*** were mosaicked in ArcMap to create one continuous top of bedrock elevation grid. The adjusted ***Kd***/***IP*** contact line was then used to mask all ***Kd*** raster grids that were produced. Figure 3-12 is a map of the elevation of the top of the bedrock surface within the southern reconnaissance AEM survey area.

Quaternary deposits (***Q***) and ***Kd*** thicknesses were calculated using existing grids for both the southern reconnaissance and Tekamah Block AEM survey areas using ArcMap's raster calculator. For the ***Q*** thickness grid, the elevation of the top of bedrock was subtracted from the project DEM. For the ***Kd*** thickness grid, the elevation of the top of the ***IP*** was subtracted from the elevation of the top of the ***Kd***, and then the resultant grid was masked with the ***Kd***/***IP*** contact line polygon. Figure 3-13, Figure 3-14, Figure 3-15, and Figure 3-16 are maps of ***Q*** and ***Kd*** thickness within the southern reconnaissance AEM survey area and within the Tekamah Block AEM survey area, respectively.

To assist in the approximation of the saturated materials along the surveyed AEM flight lines, the 1995 CSD statewide water table (Nebraska CSD, 1995) was utilized. It should be noted that this inclusion provides only a generalized characterization of the saturated thickness of the aquifer as the CSD's dataset is two decades old at the time of the 2018 P-MRNRD AEM survey and local conditions likely deviate in areas with variable topography. The water table in the P-MRNRD area is close to the surface in some of the areas. To this end a topographic correction was required to ensure that the water table height was below the surface topography. The original water table contour lines were gridded at a 1,000 ft cell size using the Oasis Montaj Minimum Curvature Grid and a blanking distance of 5,000 ft. The cells were set 'to extend beyond' to 50. The resulting grid was then re-gridded at a 100 ft cell size and compared with the DEM (Figure 3-1) of the P-MRNRD AEM survey area. In areas where the water table was greater than the topography, the water table was set to an elevation of the topography minus three feet. The grid was then clipped to the southern reconnaissance AEM survey area. The result is presented in Figure 3-17. A water table was also prepared for the Tekamah Block AEM survey area (Figure 3-18).

Saturated thicknesses of ***Q*** and ***Kd*** were calculated for both the southern reconnaissance and Tekamah Block AEM survey areas with existing grids using ArcMap's raster calculator. For the ***Q*** saturated thickness grid, the elevations of the top of bedrock was subtracted from the 1995 water table for both of the southern reconnaissance and the Tekamah Block AEM survey areas. For the ***Kd*** saturated thickness grid, the elevation of the top of the ***IP*** was subtracted from the 1995 water table. Then the ***Q*** saturated thickness was subtracted from the resultant grid. Finally, the resultant grid was masked with the ***Kd***/***IP*** contact line polygon. Figure 3-19, Figure 3-20, Figure 3-21, and Figure 3-22 are maps of ***Q*** and ***Kd*** saturated thickness within the southern reconnaissance AEM survey area and within the Tekamah Block AEM survey areas, respectively.

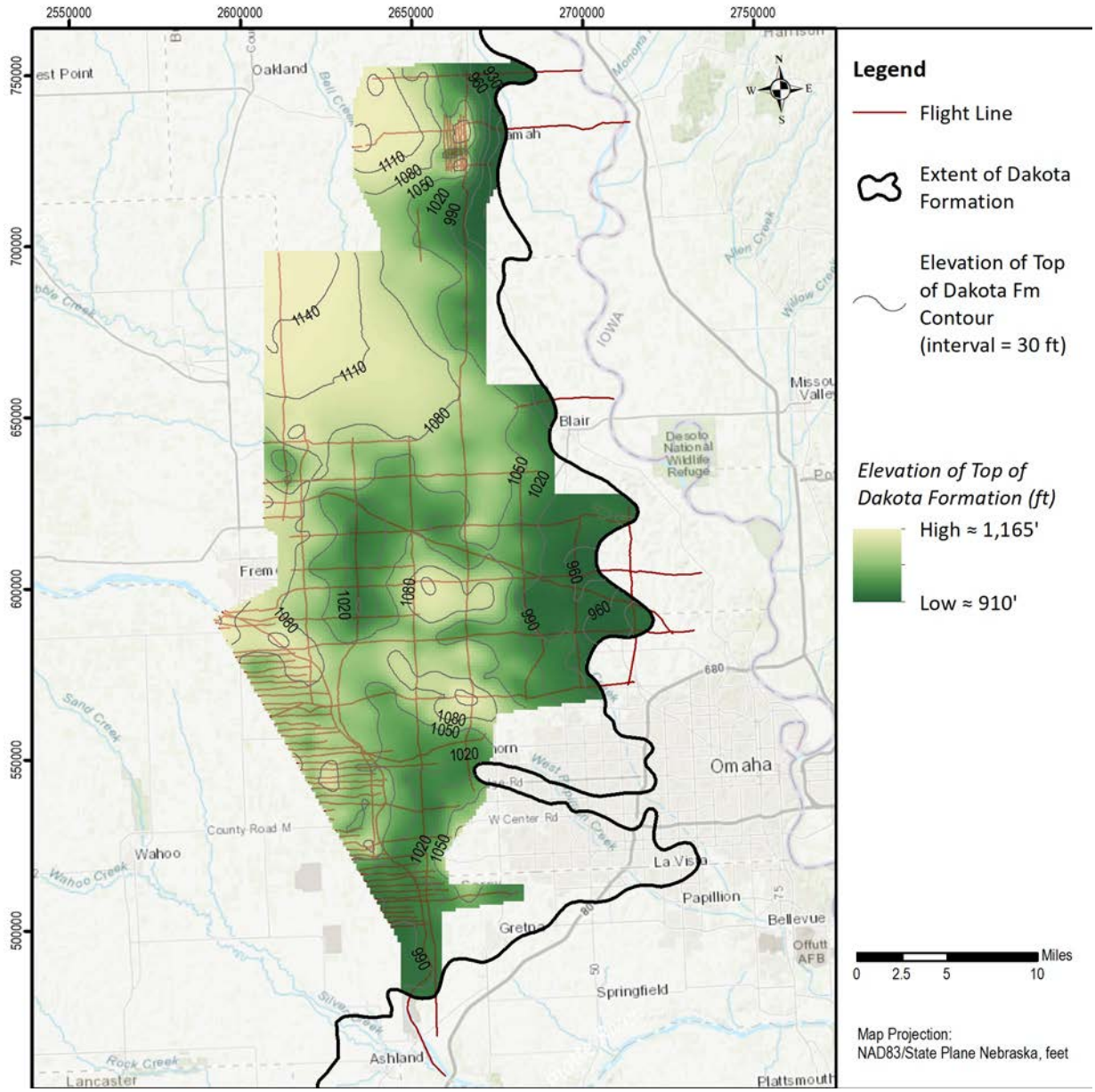


Figure 3-8. Map of the elevation of the top of the Cretaceous Dakota Group (*Kd*) within the southern reconnaissance AEM survey area. The projection is NAD83 State Plane Nebraska (feet) and the elevation values are referenced to NAVD 88 (feet).

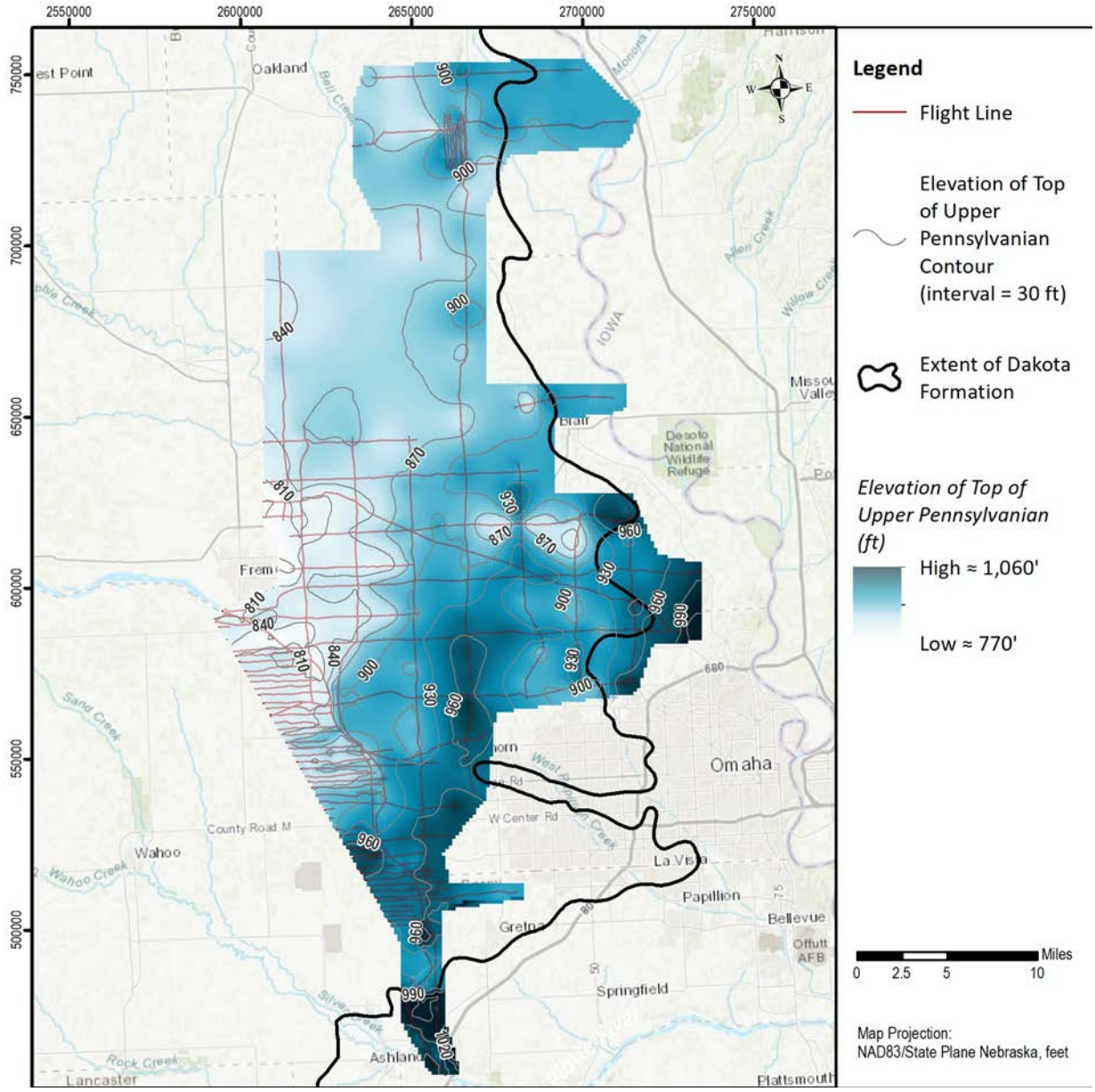


Figure 3-9. Map of the elevation of the top of the Undifferentiated Pennsylvanian (*IP*) within the southern reconnaissance AEM survey area. The projection is NAD83 State Plane Nebraska (feet) and the elevation values are referenced to NAVD 88 (feet).

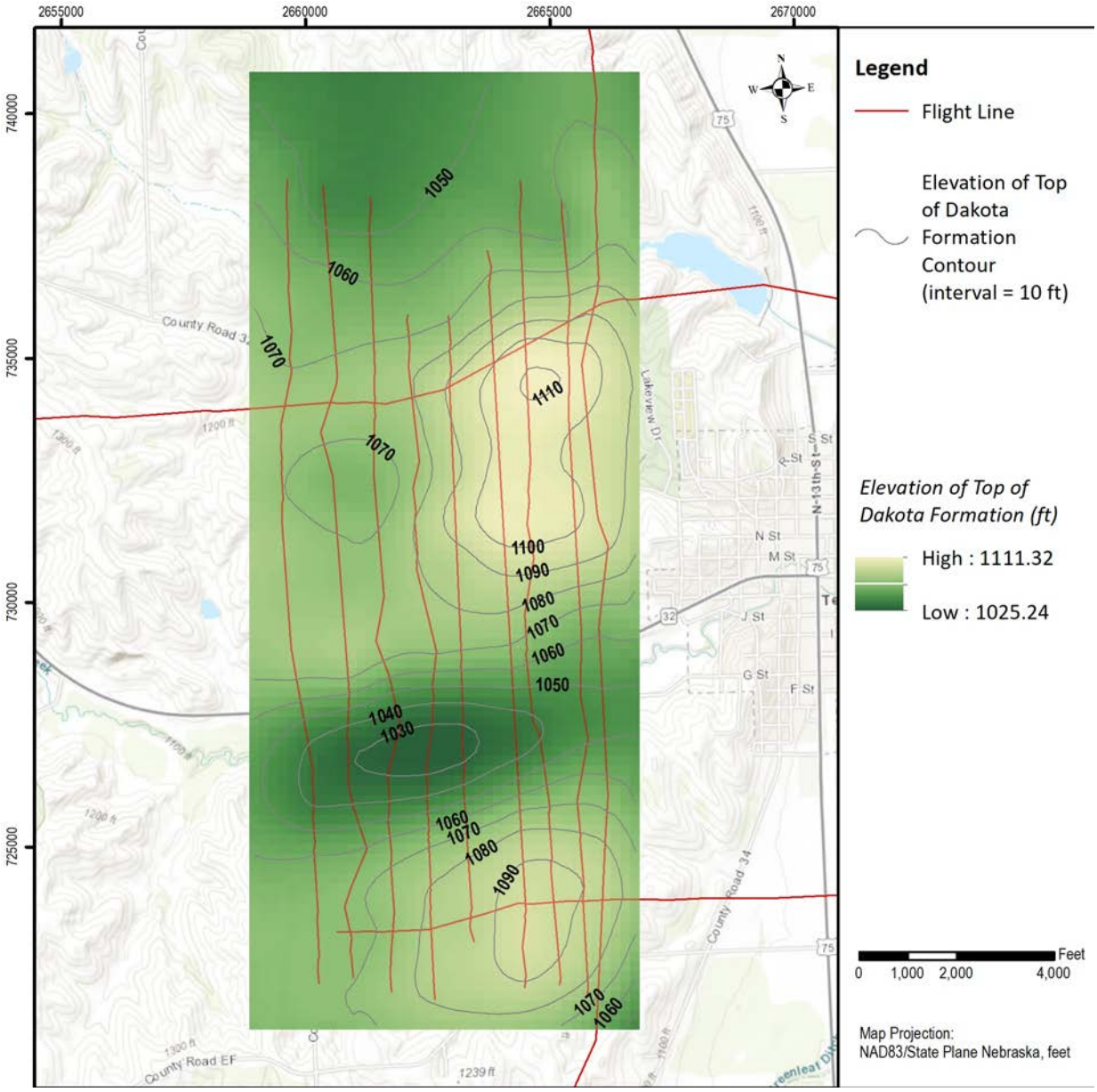


Figure 3-10. Map of the elevation of the top of the Cretaceous Dakota Group (*Kd*) within the Tekamah Block AEM survey area. The projection is NAD83 State Plane Nebraska (feet) and the elevation values are referenced to NAVD 88 (feet).

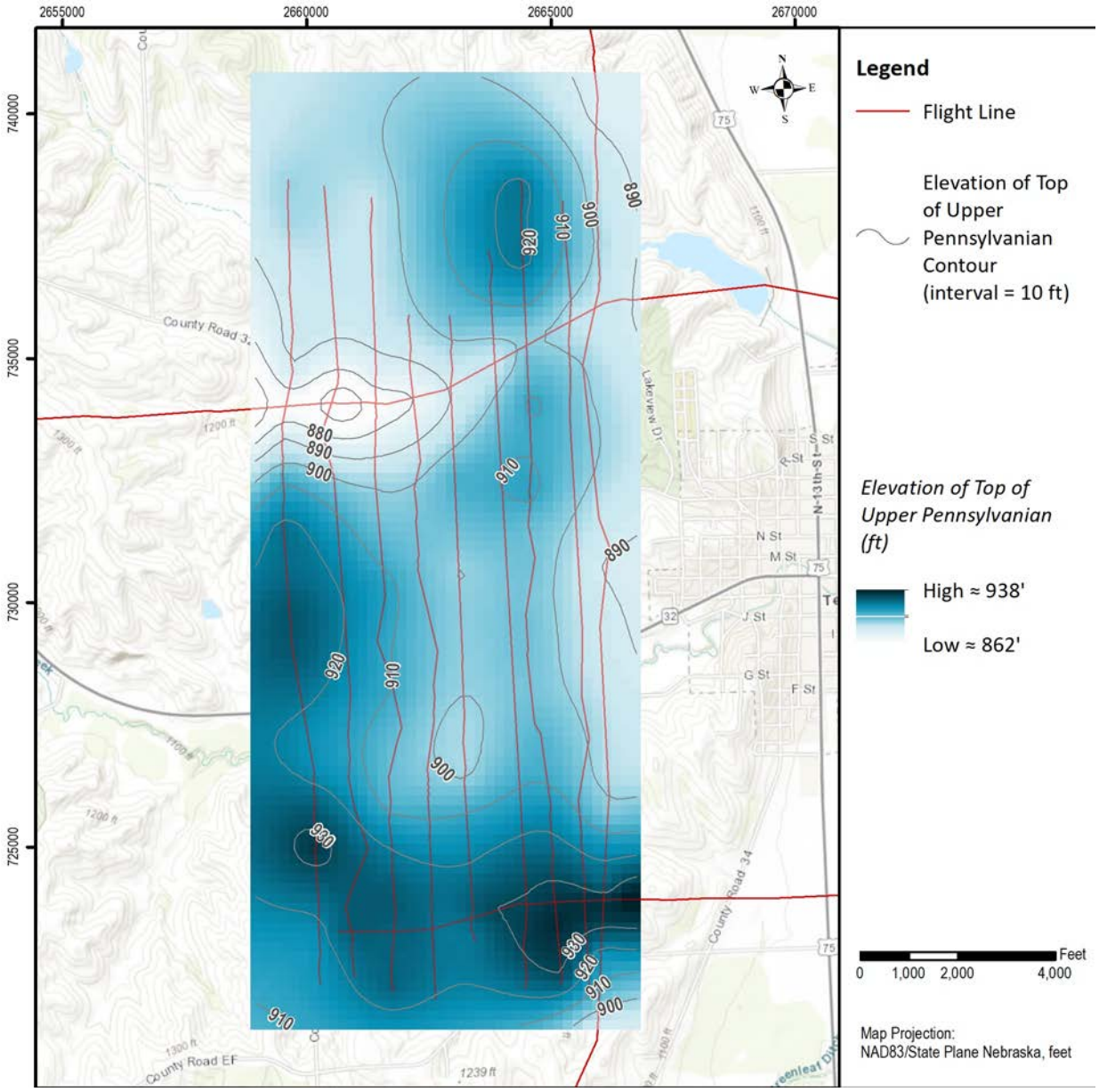


Figure 3-11. Map of elevation of the top of the Undifferentiated Pennsylvanian (*IP*) within the Tekamah Block AEM survey area. The projection is NAD83 State Plane Nebraska (feet) and the elevation values are referenced to NAVD 88 (feet).

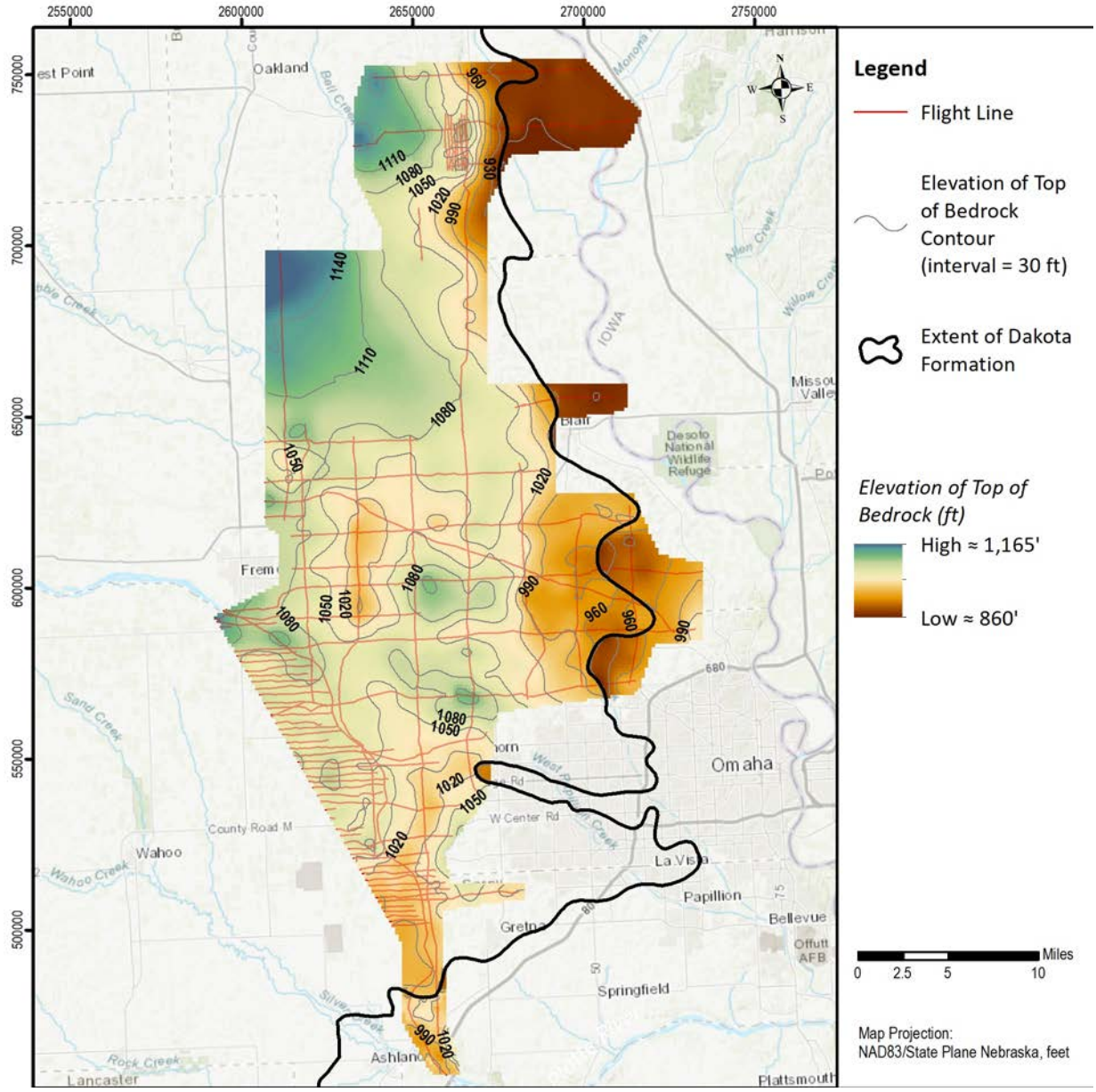


Figure 3-12. Map of the elevation of the top of the bedrock within the southern reconnaissance AEM survey area. The projection is NAD83 State Plane Nebraska (feet) and the elevation values are referenced to NAVD 88 (feet).

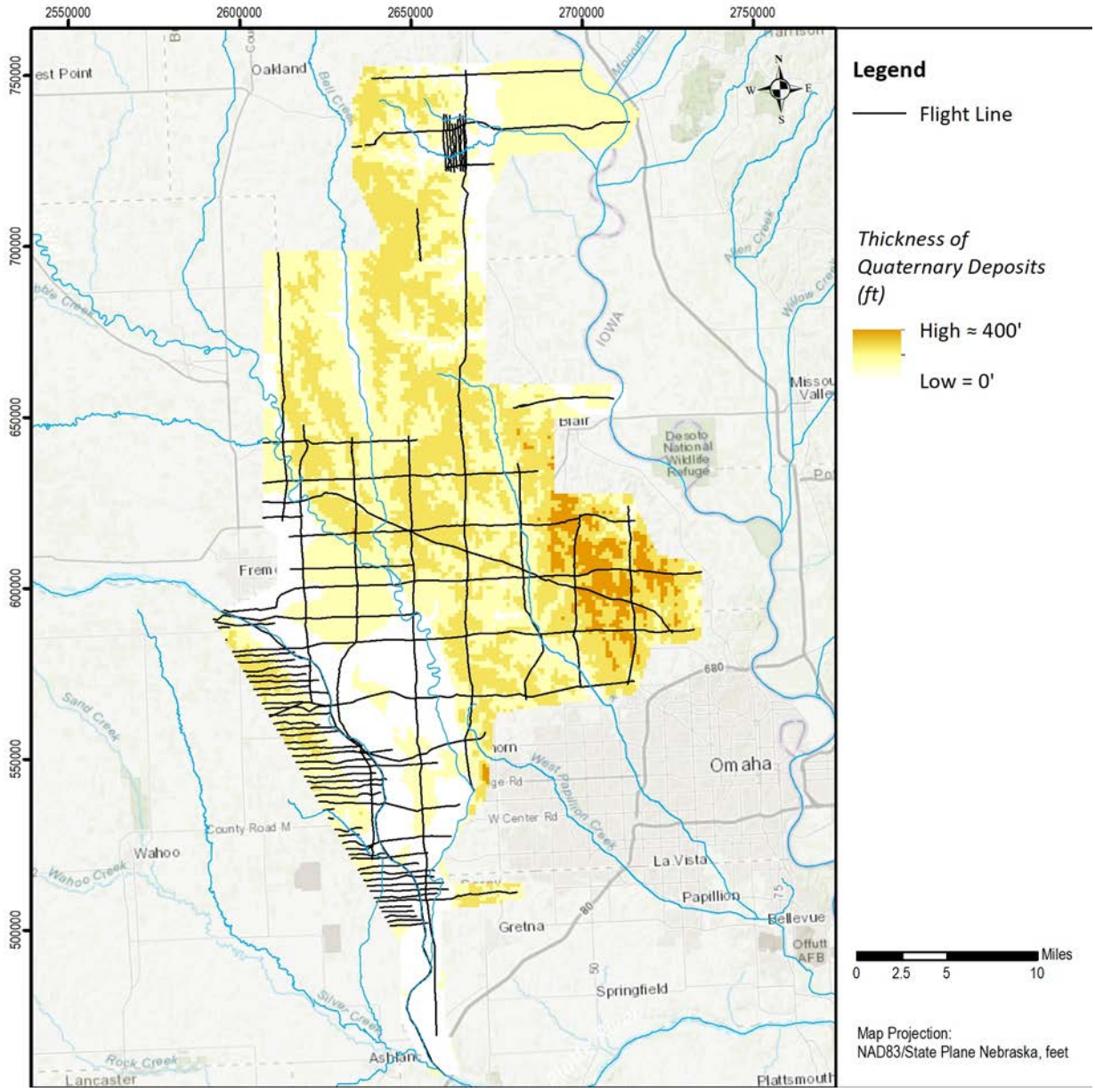


Figure 3-13. Map of the thickness (in feet) of Quaternary (*Q*) deposits within the southern reconnaissance AEM survey area. The projection is NAD83 State Plane Nebraska (feet).

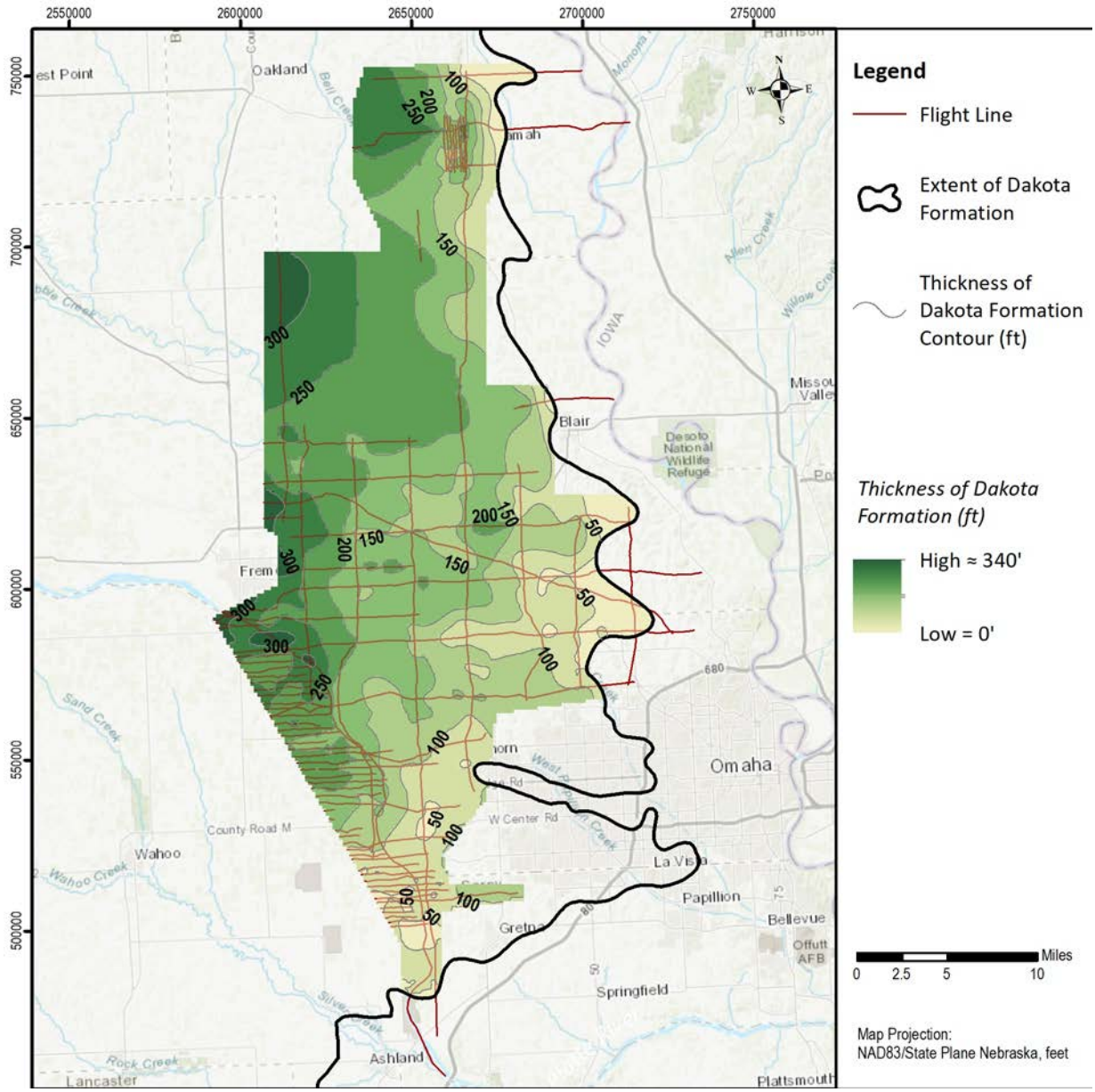


Figure 3-14. Map of the thickness (in feet) of the Cretaceous Dakota Group (*Kd*) within the southern reconnaissance AEM survey area. The projection is NAD83 State Plane Nebraska (feet).

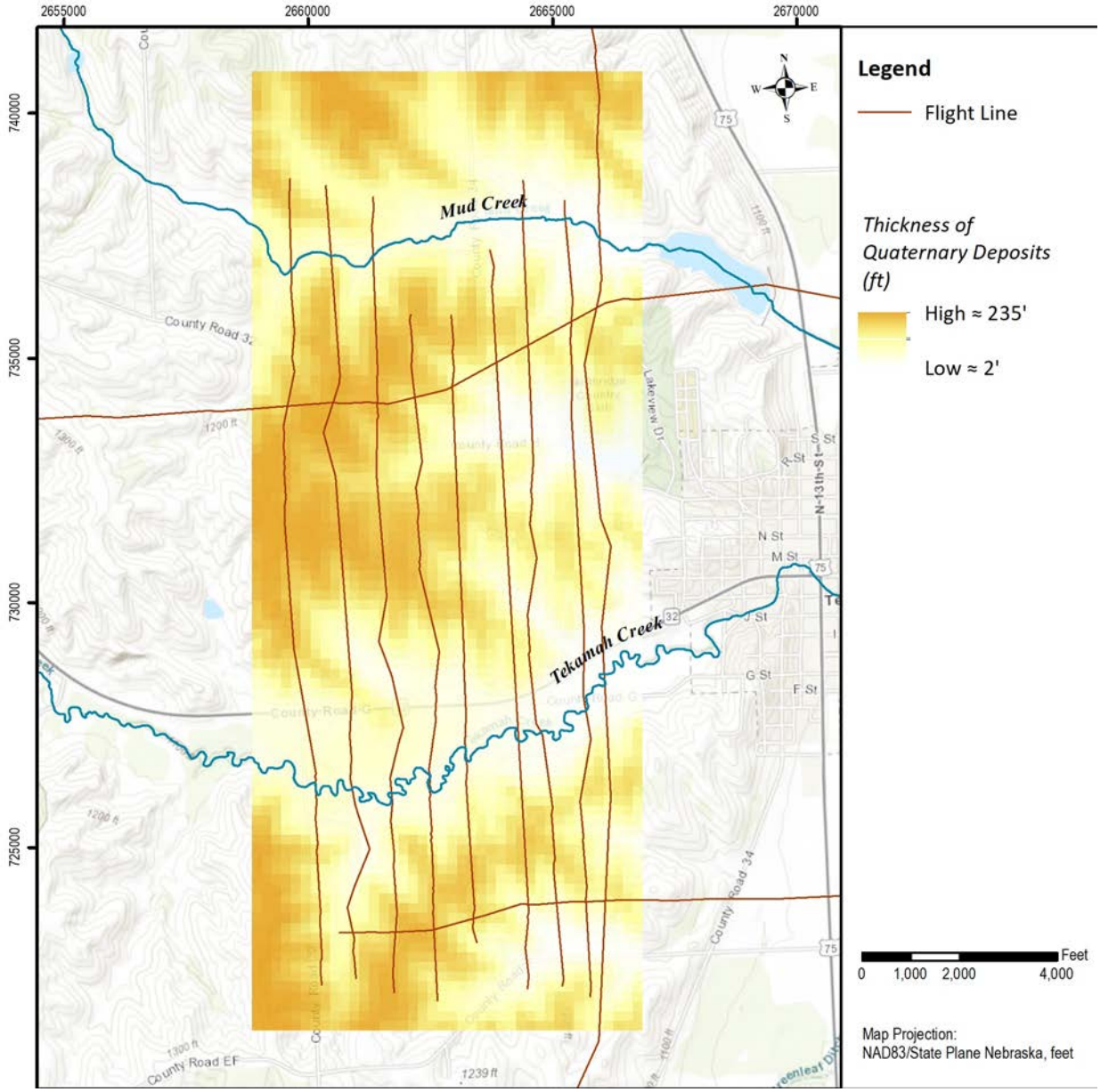


Figure 3-15. Map of the thickness (in feet) of the Quaternary (*Q*) deposits within the Tekamah Block AEM survey area. The projection is NAD83 State Plane Nebraska (feet).

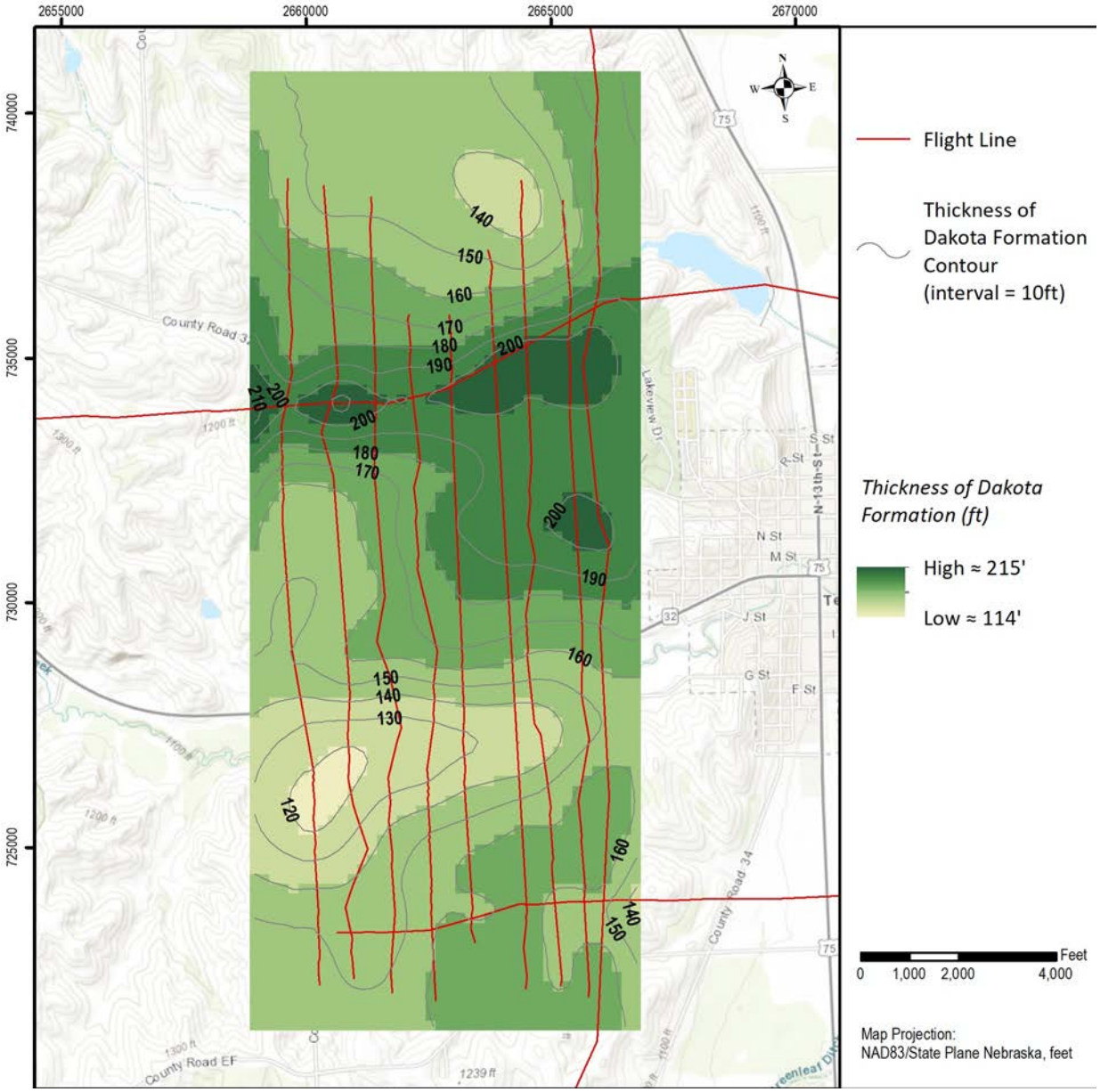


Figure 3-16. Map of the thickness (in feet) of the Cretaceous Dakota Group (*Kd*) within the Tekamah Block AEM survey area. The projection is NAD83 State Plane Nebraska (feet).

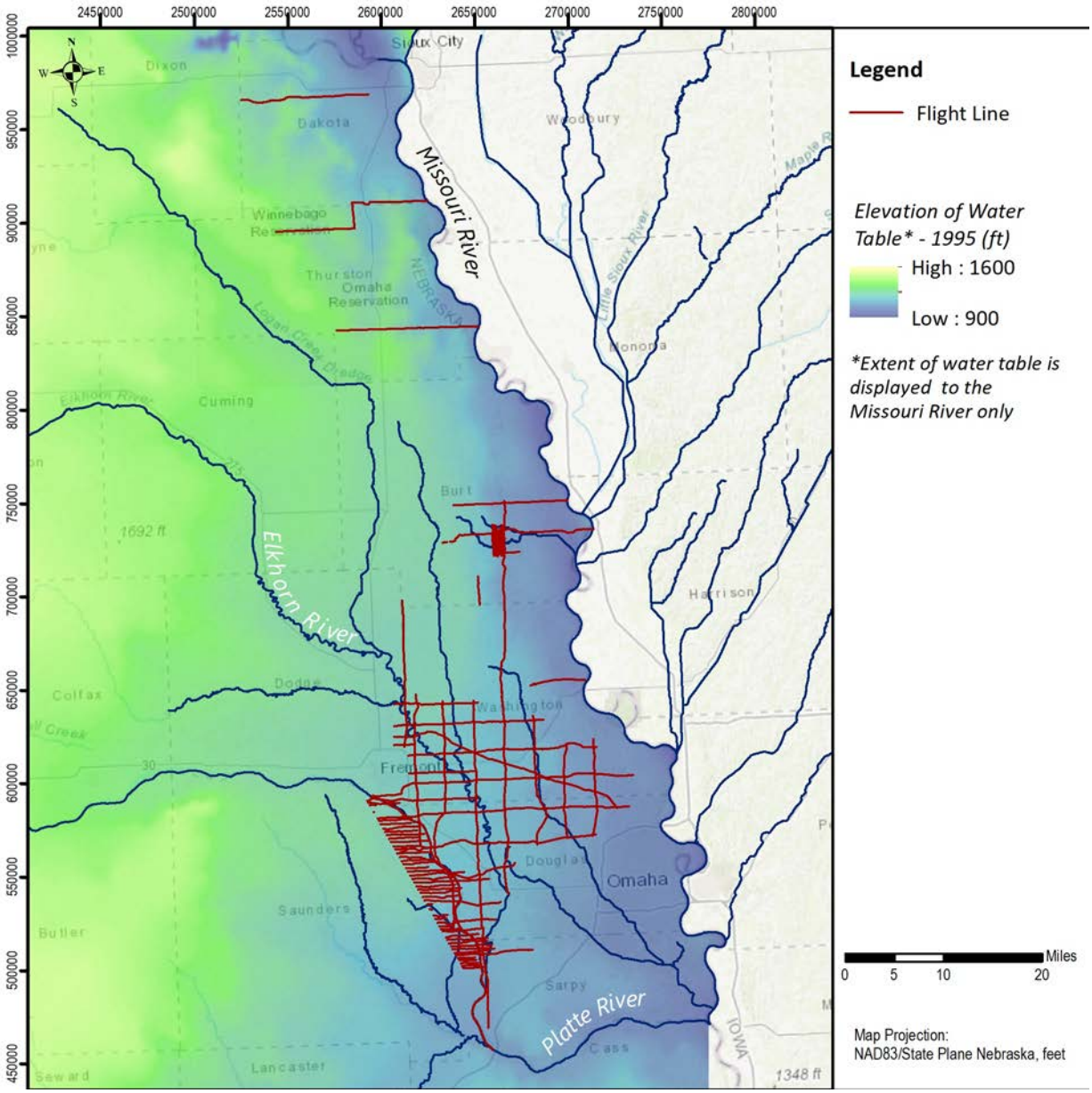


Figure 3-17. Map of the elevation (in feet) of the 1995 CSD water table within the southern reconnaissance AEM survey area. The projection is NAD83 State Plane Nebraska (feet).

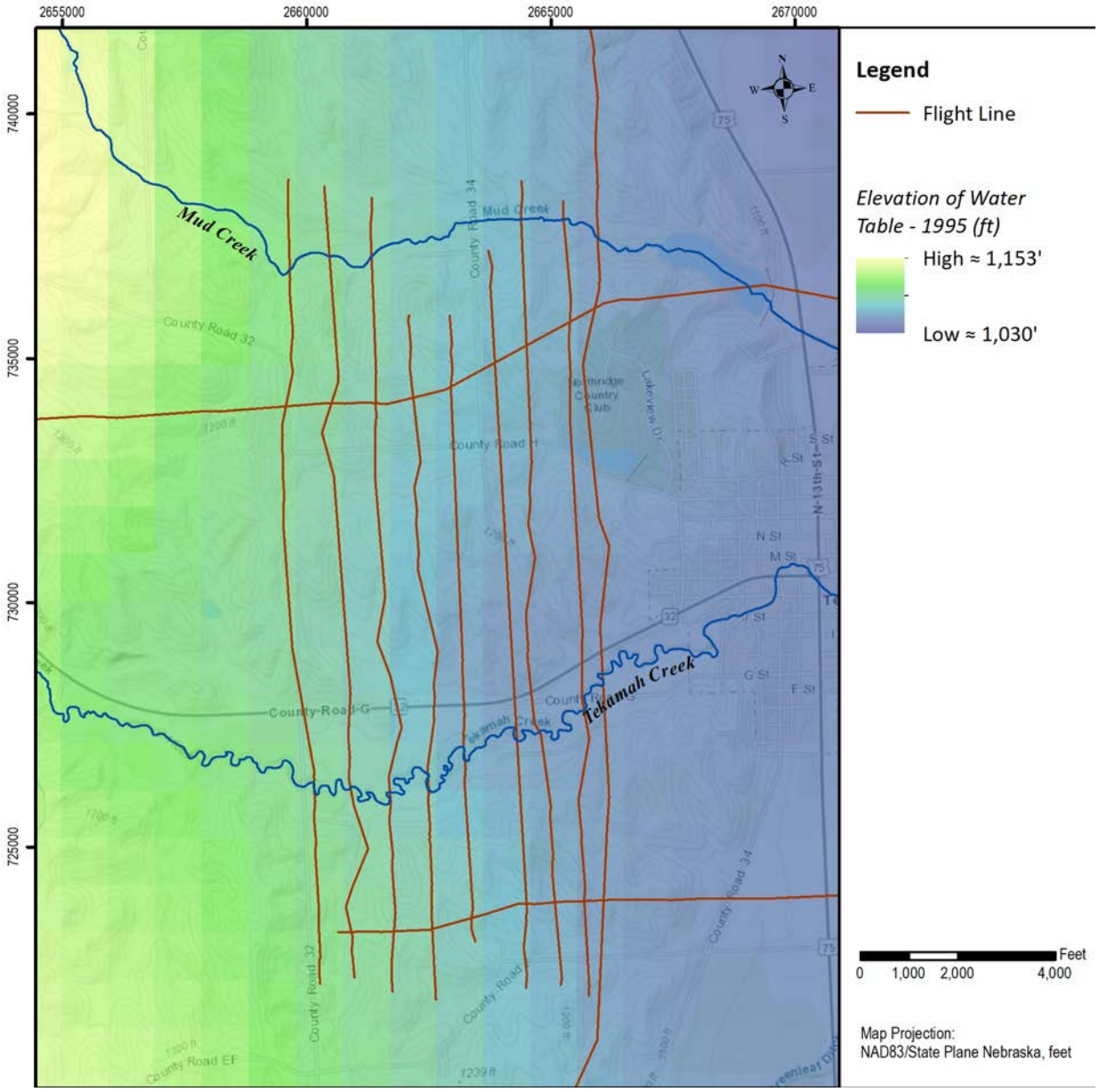


Figure 3-18. Map of the elevation (in feet) of the 1995 CSD water table within the Tekamah Block AEM survey area. The projection is NAD83 State Plane Nebraska (feet).

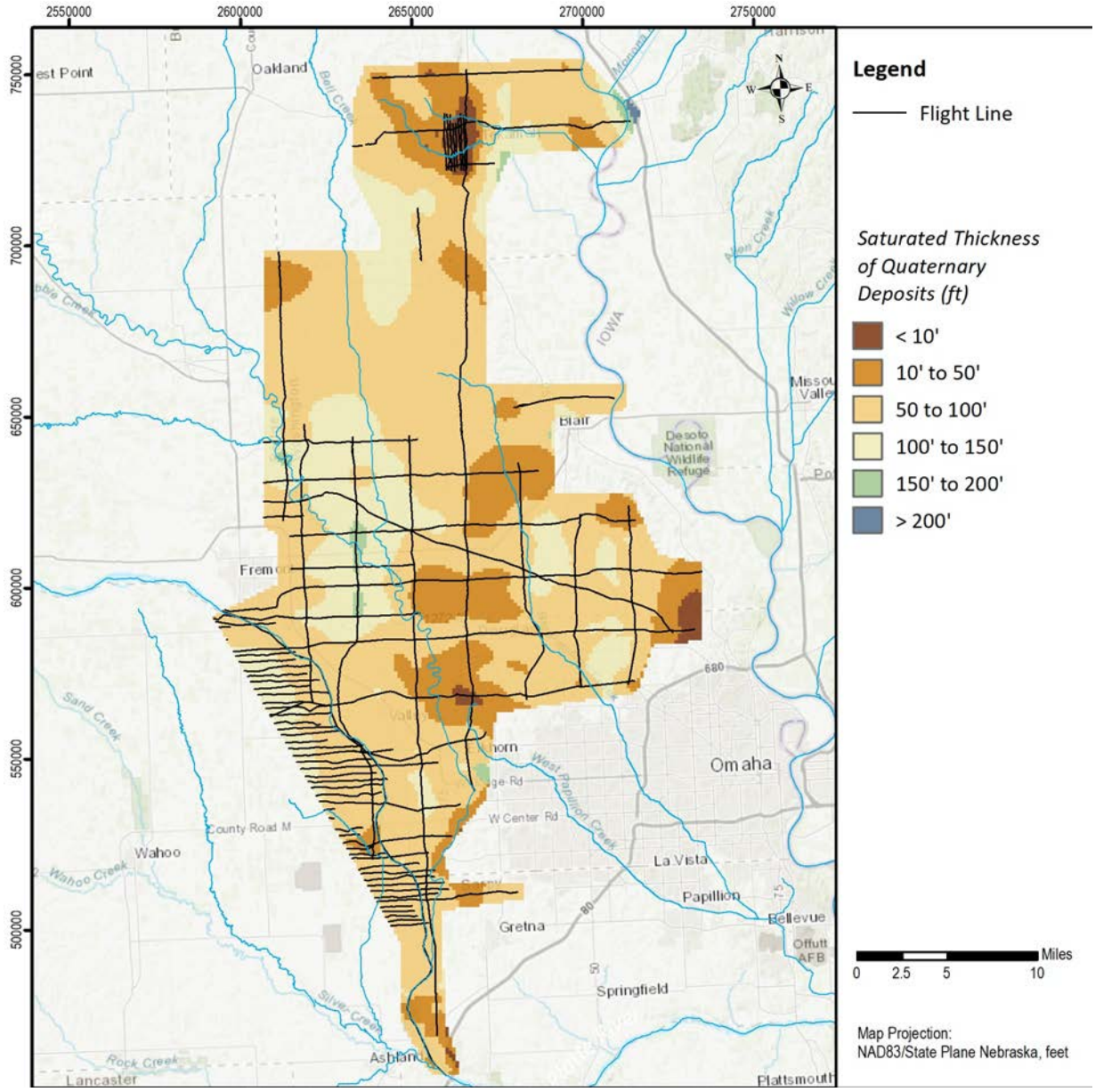


Figure 3-19. Map of the saturated thickness (in feet) of the Quaternary (*Q*) deposits within the southern reconnaissance AEM survey area. The projection is NAD83 State Plane Nebraska (feet).

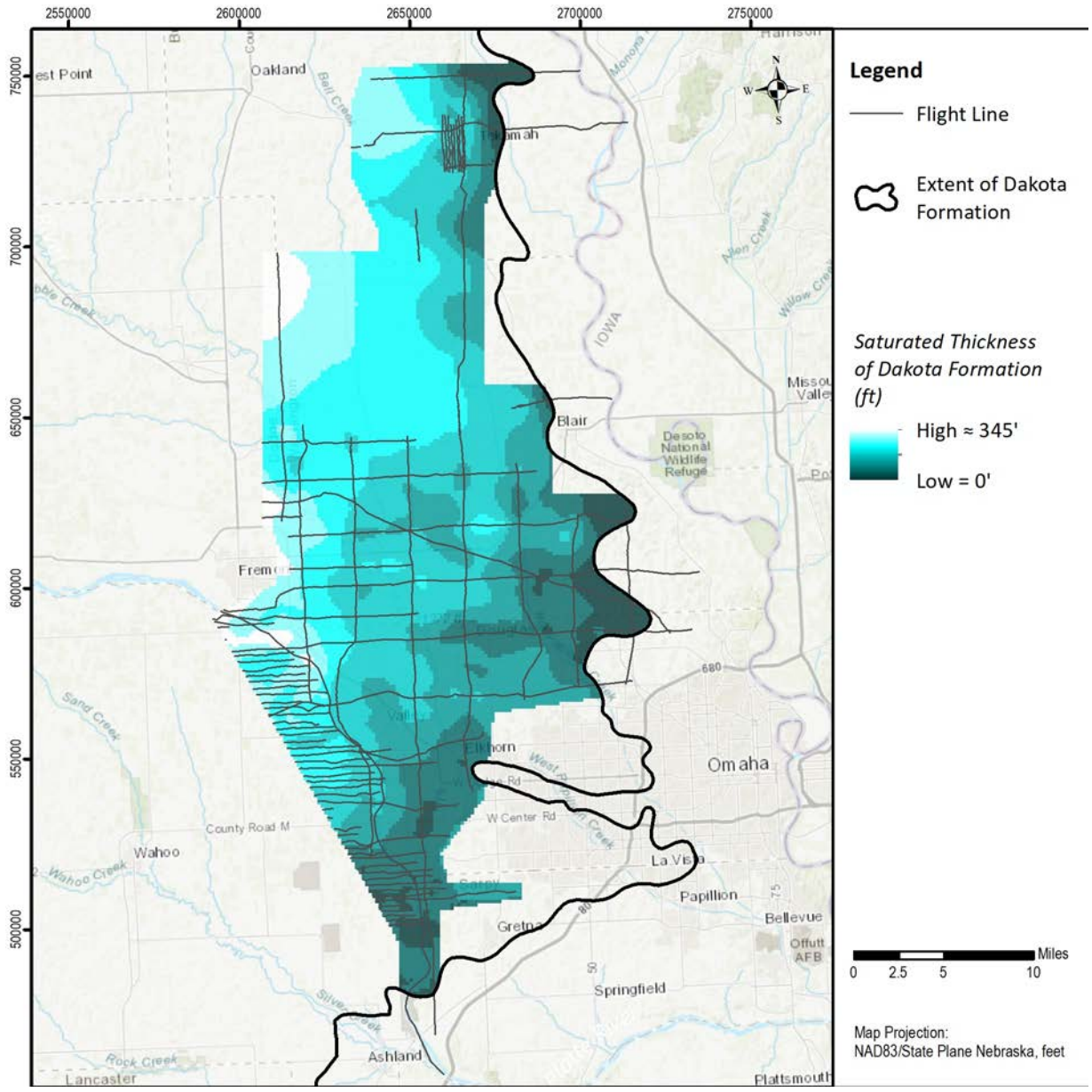


Figure 3-20. Map of the saturated thickness (in feet) of the Cretaceous Dakota Group (*Kd*) within the southern reconnaissance AEM survey area. The projection is NAD83 State Plane Nebraska (feet).

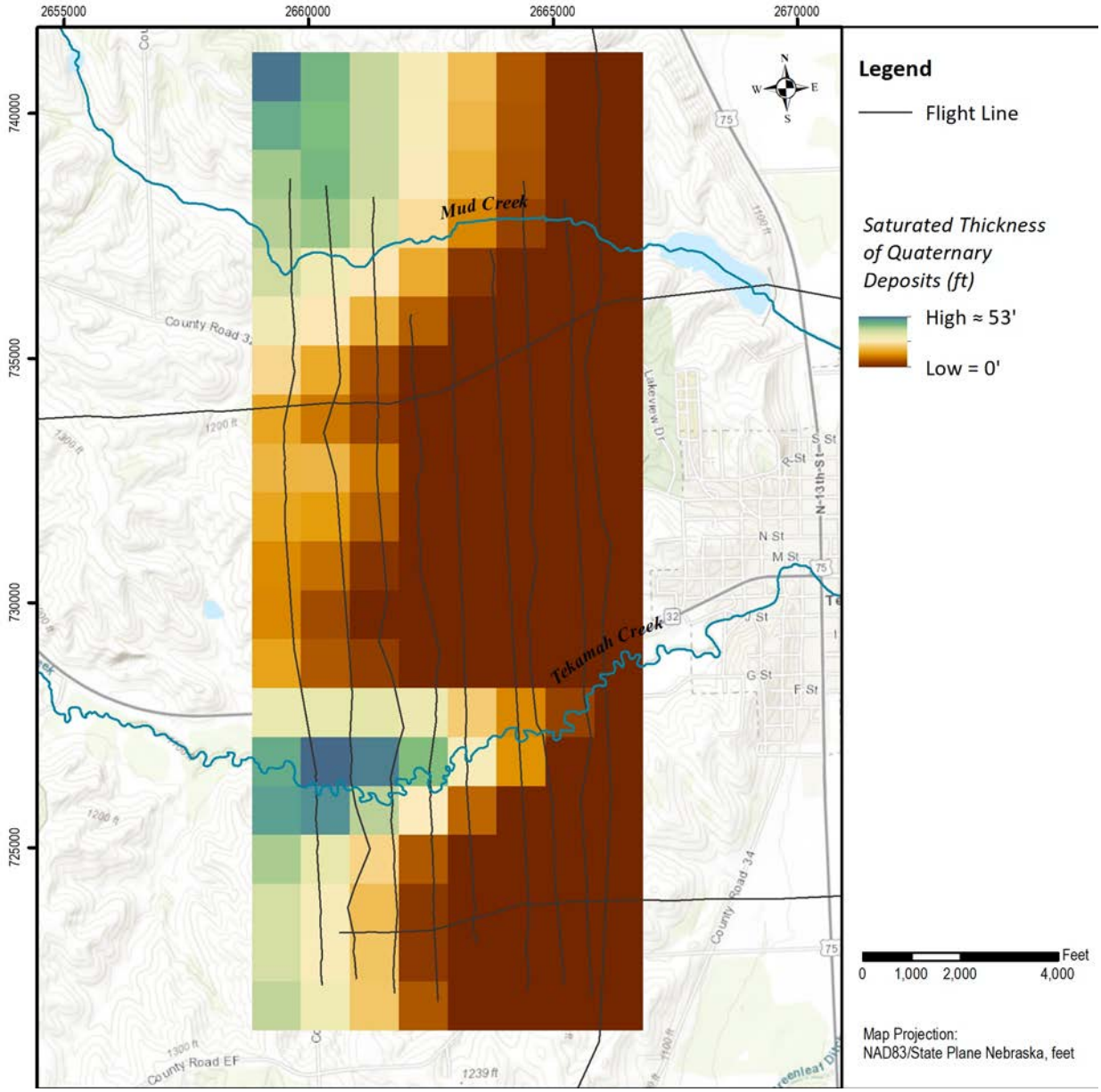


Figure 3-21. Map of the saturated thickness (in feet) of the Quaternary (*Q*) deposits within the Tekamah Block AEM survey area. The projection is NAD83 State Plane Nebraska (feet).

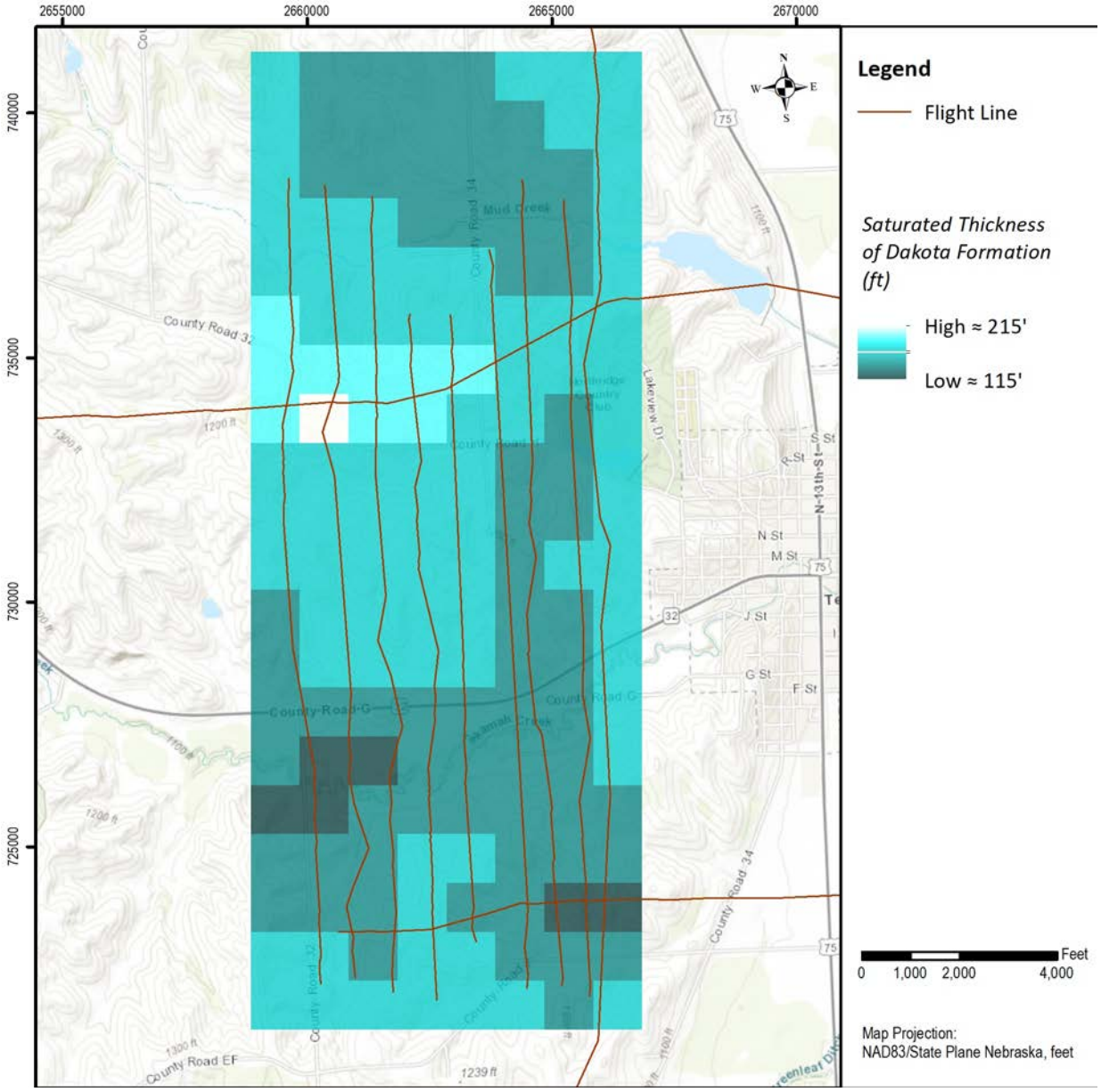


Figure 3-22. Map of the saturated thickness (in feet) of the Cretaceous Dakota Group (*Kd*) within the Tekamah Block AEM survey area. The projection is NAD83 State Plane Nebraska (feet).

3.1.4 Resistivity/Lithology Relationship in the Quaternary Aquifer System

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

Data for this analysis was utilized from locations across the ENWRA reconnaissance line area (Carney et al., 2015a, 2015b). The relationship between resistivity and lithology type was assessed by performing an association function that linked nine lithologic descriptor codes for ***Q/To*** sediments used in the CSD test hole lithologic characterization with the resistivity values across that depth interval as indicated in the 58 high-graded resistivity logs applied in the AEM data inversion (25 from the southern area, 33 from the northern area). With this approach, several thousand points became available for each lithologic description in the test holes used in this analysis. From this list of associated resistivity levels and pre-categorized lithologies, statistical analyses were performed to aide in defining the various thresholds used to determine the aquifer material type in the project area subsurface. Details of the analysis can be found in Carney et al. (2015a, 2015b). A summary of the resistivities and the color scale is shown in Figure 3-23.

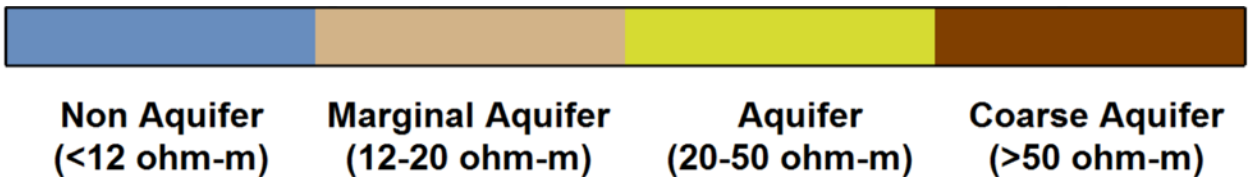


Figure 3-23. Plot displaying the resistivities by major aquifer material color categories: blue- non-aquifer materials, tan- marginal aquifer materials, yellow- aquifer materials, brown- coarse aquifer materials (Carney et al., 2015b).

3.1.5 Resistivity/Lithology Relationship in the Bedrock

The bedrock in the P-MRNRD analyzed in this study includes the ***Kc, Kgg, Kd,*** and ***IP.*** These were included to demonstrate the overall distribution in resistivity of bedrock materials across the entire P-MRNRD. The median resistivity values for each unit are 16 ohm-m for the ***Kc*** and the ***Kgg*** lumped together, the mean for the ***Kd*** is 35 ohm-m, and the mean for the ***IP*** is 16 ohm-m (Carney et al., 2015a, 2015b). ***IP*** units show the widest range in detected resistivities, which should not be unexpected as this sequence contains resistive limestone and conductive shale units. For the ENWRA study, the ***Kc*** and the ***Kgg*** were interpreted together. For this current study, the proximity of the ***Kgg*** to the surface allows for a more accurate interpretation. The low resistivity character of 3 to 9 ohm-m for the ***Kc*** made the interpretation of the ***Kc*** relatively straight forward. The ***Kgg*** showed a more resistive character on the order of 15 ohm-m. The ***Kd*** within the LENRD displayed some low resistivity on the order of 9 to 13 ohm-m indicating either clay/shale dominant lithology.

3.1.6 Create 3D Interpretative Voxel Grids

A voxel grid was completed for the Tekamah Block. The voxel grids were made using a 200 feet grid cell size and the model layer thickness (Table 2-3 in the Section 2.5). A minimum curvature method was used within Datamine Discover PA (Datamine Discover, 2019). All layers were referenced to their depth from the surface and then projected on the area DEM. After the grid was calculated, the grid was split at the top of the Cretaceous Dakota Group (***Kd***) and the undifferentiated Pennsylvanian (***IP***). The units were also split at the 1995 CSD water table. These resulting voxel grids can be used to explore the distribution of the aquifer materials within the area in 3D. Specifically, these grids can allow for visual inspection of the volume of materials above the ***IP*** bedrock including the ***Kd*** and the ***Q*** materials. The ***Q*** and ***Kd*** materials can be separated by the thresholds developed above for the four lithology classes. Utilizing the voxel grids from the ***Q*** analysis, volumes of the different materials within the section can be estimated. Additionally, the ***Kd*** can be divided into Sandstone/Sand-dominant versus Shale/Clay-dominant portions. Within the ***Kd*** Sandstone/Sand-dominant zones, higher resistivities can be illustrated that are greater than 40 ohm-m. Figure 3-24 is a plot of the ***Q*** material separated from the ***Kd*** above the ***IP*** bedrock, looking to the north. The Tekamah Block voxel grid can be found in *Appendix 3-Deliverables\Voxel*.

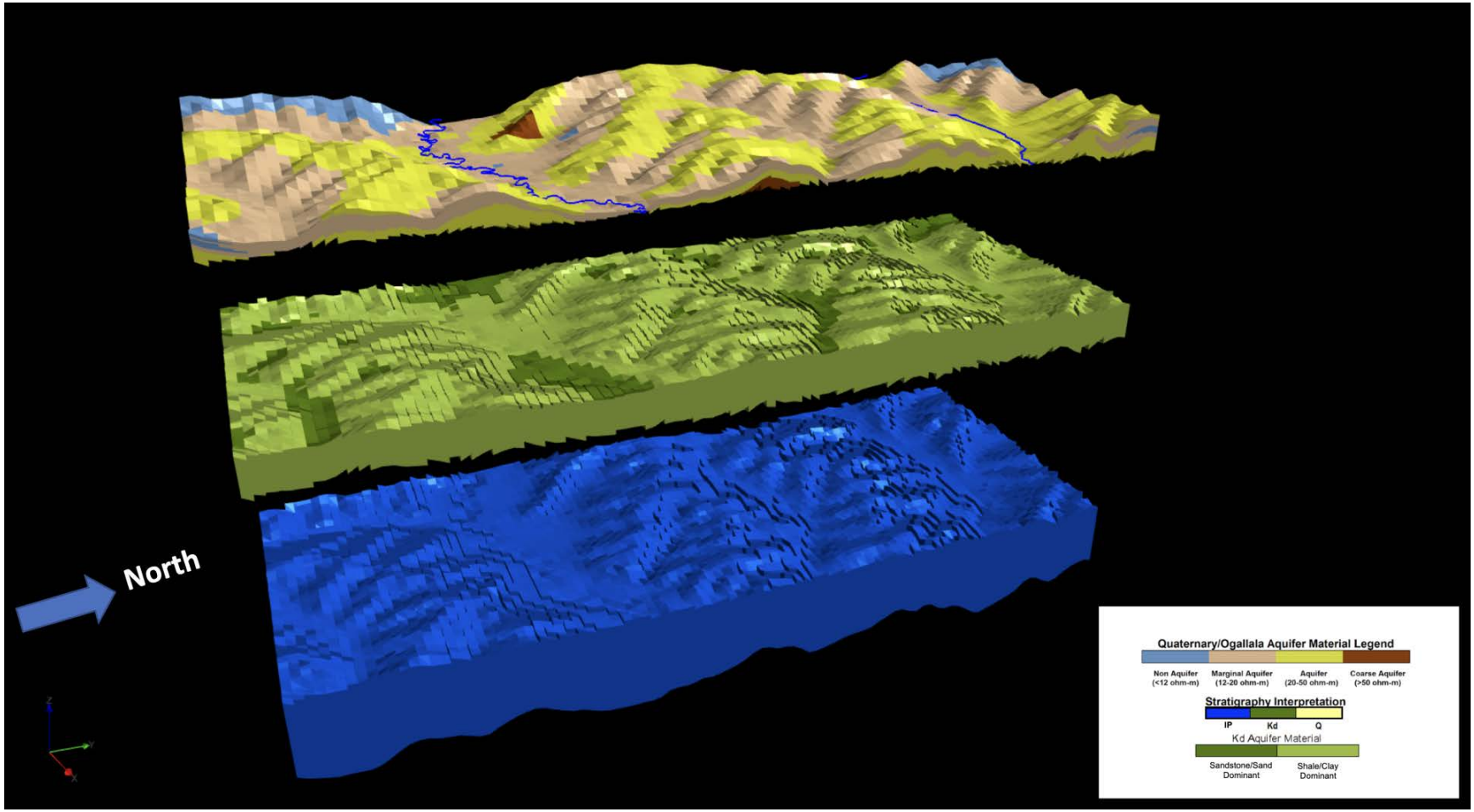


Figure 3-24. Voxel model of the aquifer material types for the Tekamah Block consisting of Quaternary (*Q*) sediments, separated from the two types of Cretaceous Dakota Group (*Kd*) (sandstone/sand and shale/clay) separated from the Undifferentiated Pennsylvanian (*IP*). Not to scale. Streams are indicated by blue lines.

3.1.7 Comparison of Borehole Resistivity Logs to Inverted AEM Resistivity Soundings

Two recent CSD borehole geophysical resistivity logs were selected from the P-MRNRD AEM survey area for comparison with the AEM inversions: CSD test holes *01-PMR-14* and *02-PMR-14*.

Figure 3-25 is a plot of the *01-PMR-14* 16-inch short normal resistivity log plotted with the inverted AEM resistivities for flight line L701001, which is 479 feet away, and flight line L800201, which is 920 feet away. The AEM soundings selected are from the closest points to the location of the borehole geophysical log. The agreement in the resistivity is generally good. The higher resistivity peaks in the 16-inch log at ~110 ft depth and at ~160 feet depth are not well imaged by the AEM which presents a rather broad increase in the resistivity from ~100 to ~320 feet. This encompasses the zones of the sand and silty sand in the ***Q*** sections as well as the sands and sandstone in the ***Kd***. The sand zone at ~110 feet is about 10 feet thick and would be in AEM inversion model layer 16 which runs from depths of 100.4 ft to 113.2 ft (Table 2-3). The next model layer is 14.2 ft thick. So there is likely some averaging happening.

Figure 3-26 presents borehole *02-PMR-14* 16-inch short normal and 64-inch long normal resistivity logs plotted with the inverted AEM resistivity for flight line L800201 which is located 535 feet from *02-PMR-14* at its closest point. The agreement in the resistivity is generally fair. The AEM indicates a low resistivity zone at approximately 50 feet. The nature of the resistivity logs indicate that they are contaminated from issues of the airfield anulus at the top of the hole. The 16-inch log has a low resistivity zone centered around 75 feet. The 64-inch log indicates a much higher resistivity then both the AEM and the 16-inch. This may be indicating an issue with the 64-inch log in the upper 100 feet as all logs track each other beginning at ~ 100 feet. The high resistivity zone in the 16-inch and 64-inch logs at ~145 feet and ~155 feet are not well imaged by the AEM. The 16-inch and 64-inch logs indicate an increase in resistivity from ~175 to ~275 including sand and silty sand zones in the ***Kd.*** This zone is also indicated in the AEM as a broad zone from ~150 to ~300 feet. Below 300 feet both the 16-inch and the 64-inch logs oscillate between 30 and 60 ohm-m. The AEM indicates a lower resistivity of ~ 30 ohm-m throughout the zone.

The 16-inch short normal log from borehole *01-PMR-14* is presented in situ on the 2D inverted AEM resistivity profile sections for flight lines L701001 and L800201 in Figure 3-27 and Figure 3-28, respectively. Again, the resistivity comparison between *01-PMR-14* and the AEM is generally pretty good.

Similarly, Figure 3-29 presents inverted AEM resistivities on a 2D profile of flight line L700101 with borehole *02-PMR-14* displaying the 16-inch short normal log overlaid in the center. They compare well.

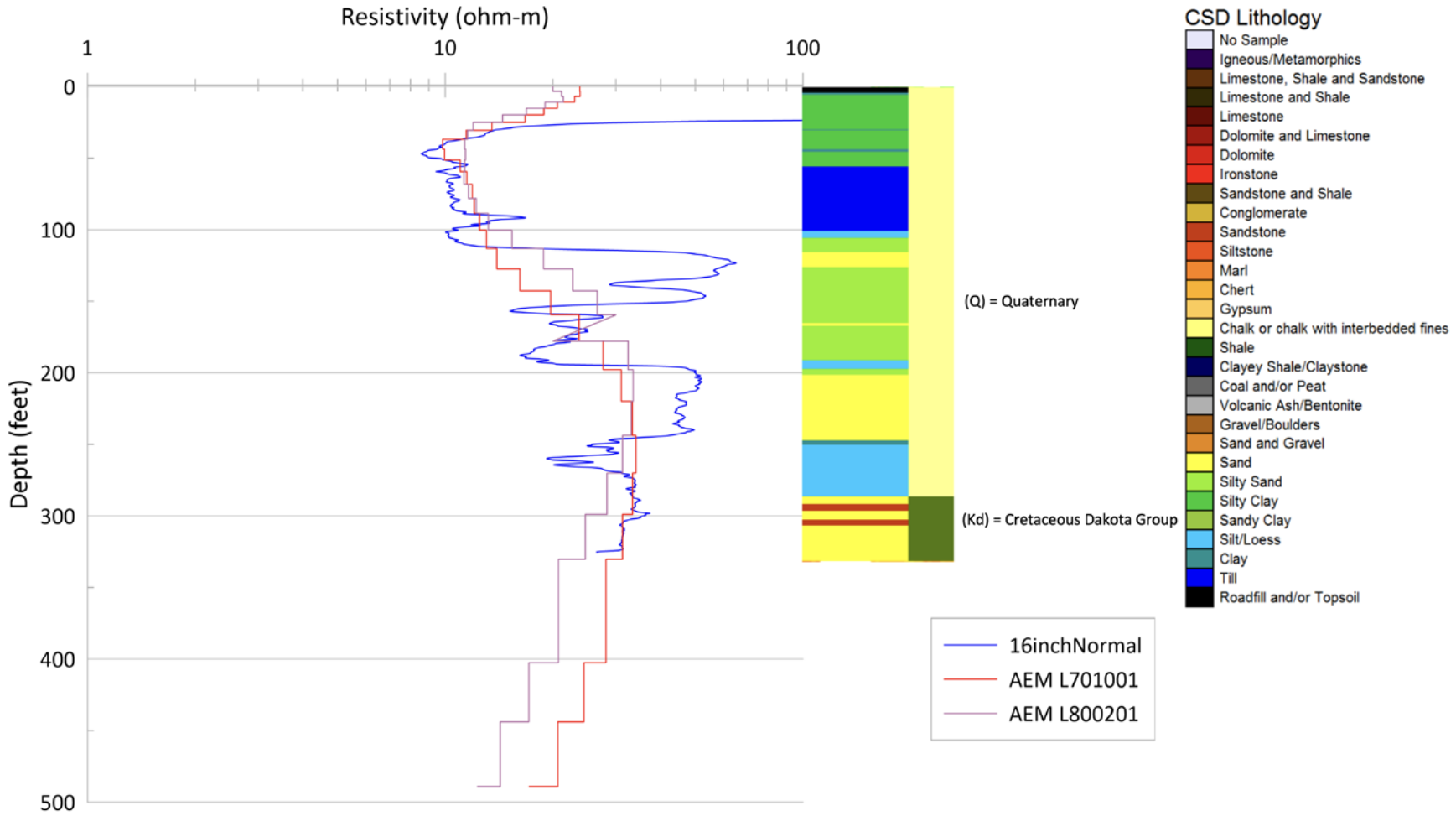


Figure 3-25. Graph of the *01-PMR-14* 16-inch normal (blue line) resistivity log values and the inverted airborne electromagnetic resistivity values for flight line L701001(red line) and flight line L800201 (purple line). Also included are the lithology and stratigraphy logs from *01-PMR-14*.

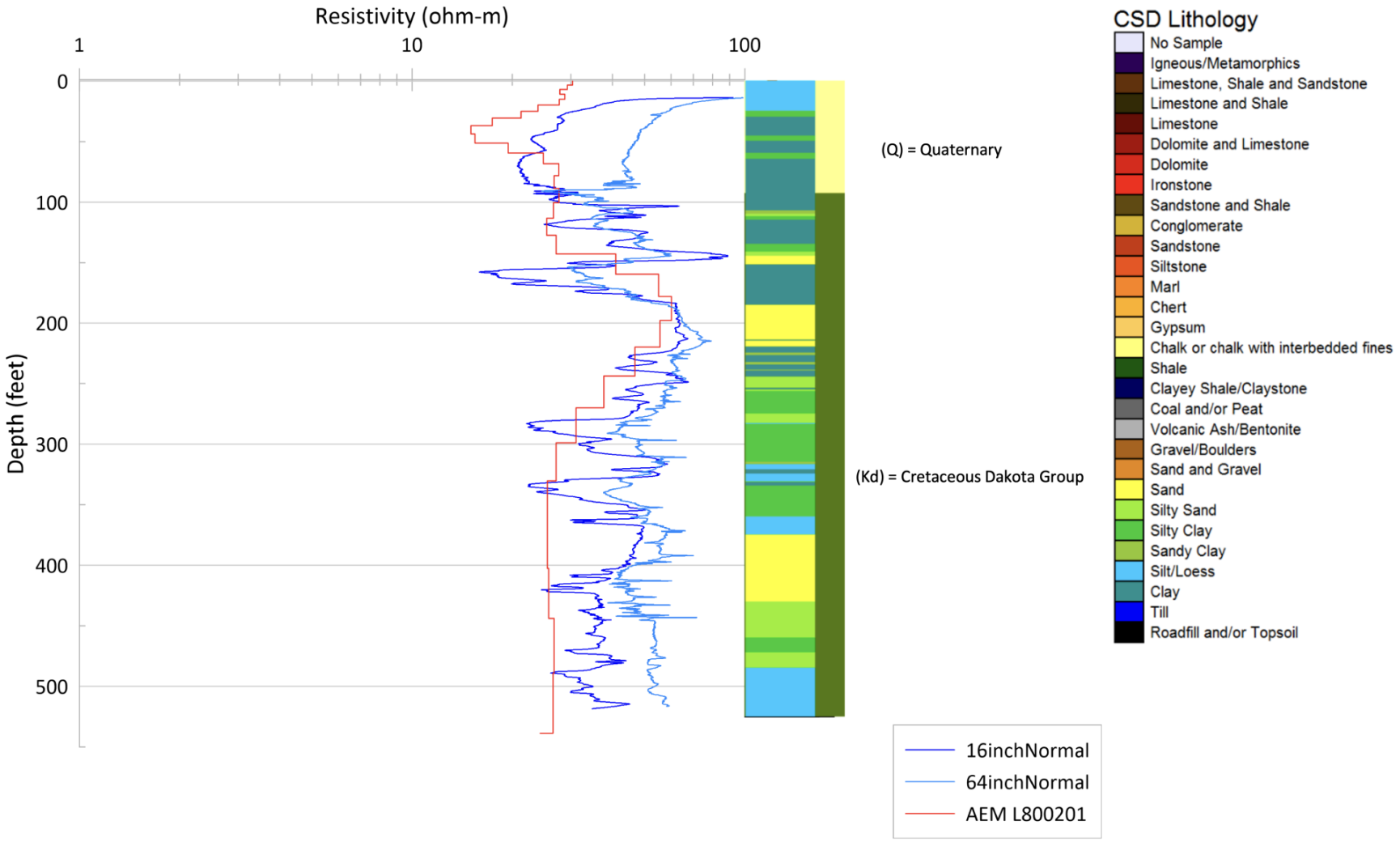


Figure 3-26. Graph of the *02-PMR-14* 16-inch short normal (dark blue line) and 64-inch long normal (light blue line) resistivity log values and the inverted airborne electromagnetic resistivity values for flight line L800201 (red line). Also included are the lithology and stratigraphy logs from *02-PMR-14*.

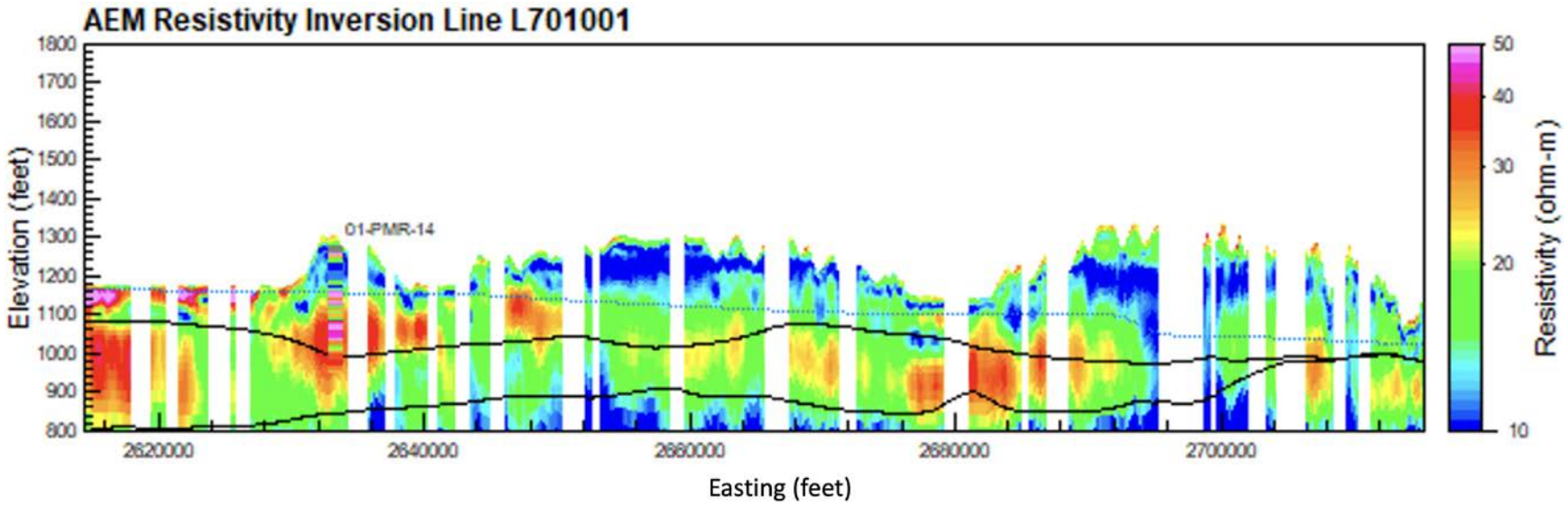


Figure 3-27. Inverted AEM resistivities for flight line L701001 with borehole *01-PMR-14* overlaid on the left. They compare well.

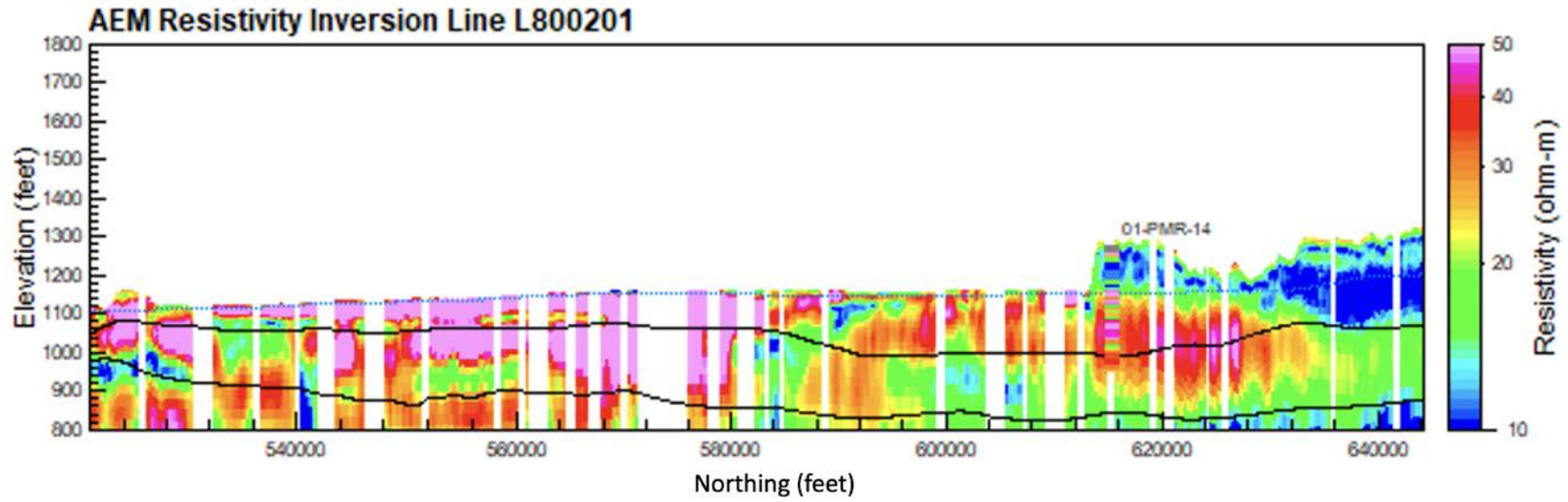


Figure 3-28. Inverted AEM resistivities for flight line L800201 with borehole *01-PMR-14* overlaid on the right. They compare well.

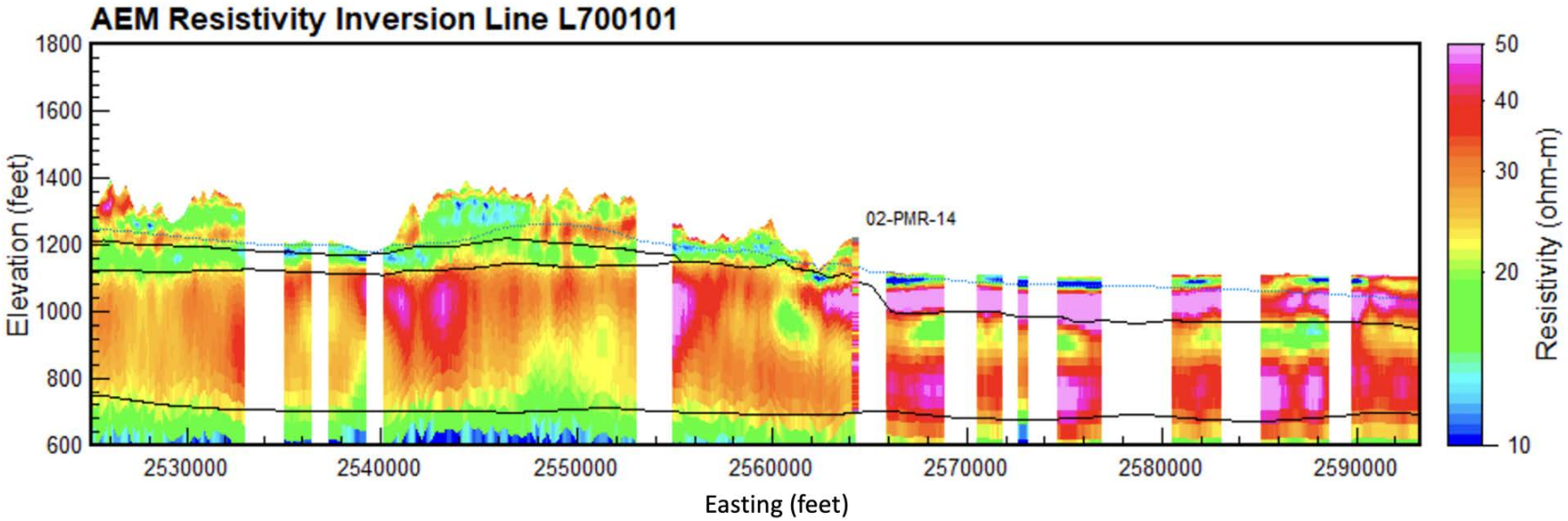


Figure 3-29. Inverted AEM resistivities for flight line L700101 with borehole *02-PMR-14* overlaid in the center. They compare well.

3.2 Hydrogeological Framework of the P-MRNRD 2018 AEM Survey Area

The 2018 survey continues to build upon the previous AEM survey efforts within P-MRNRD beginning in 2007 with the Ashland survey (Smith et al., 2008), the 2015 reconnaissance lines (Carney et al., 2015b) , and the Sarpy County survey (AGF, 2017). These AEM-derived results provide new information on the hydrogeology in areas that was previously unknown to the P-MRNRD or were only known to a limited extent from just the borehole information. The survey completed in 2018 by AGF provides the basis for this section of the report. The following highlights the additions to the current multi-year project being conducted by the P-MRNRD and ENWRA.

3.2.1 The Hydrogeologic Framework of the P-MRNRD Reconnaissance Survey Area

The AEM reveals variability in the Quaternary and Cretaceous deposits which make up the aquifers across the AEM survey area. Quaternary (***Q***), Cretaceous Dakota Group ***(Kd)***, Cretacouse Greenhorn Limestone and Graneros Shale ***(Kgg)*** and Cretaceous Carlile Formation (***Kc***) are terms used to describe stratigraphic units in the interpretative section of this report to describe all unconsolidated, semi-consolidated, and consolidated materials overlying the undifferentiated Pennsylvanian (***IP)*** units; thus, including aquifer and non-aquifer material alike. It is generally accepted that the ***Kgg***, ***Kc***, and ***IP*** are not aquifers in the ENWRA. It should be noted that in the entire survey area only flight lines L700101, L700200, and 700300, which are in the very northern end of the AEM flight area, have ***Kgg*** and ***Kc*** in the subsurface. These units are not considered aquifers. For purposes of this section the ***Q*** and ***Kd*** will be discussed concurrently. The ***Q*** aquifer materials of the survey area are composed of unconsolidated non-aquifer (blue color in figures), marginal aquifer (tan color in figures), aquifer (yellow color in figures), and coarse aquifer (brown color in figures) materials. These materials are composed predominantly of glacial, pre-glacial alluvial, and alluvial deposits related to the current drainages. The dominant hydrogeologic features that are in the southern reconnaissance AEM survey area are ***Q*** alluvial deposits found in the modern drainages and paleo channels, the till deposits which are a mix of all aquifer materials, and the ***Kd*** sandtone/sand dominant deposits which are considered bedrock aquifers. Figure 3-30 is a 3D image of the AEM interpretation as a fence diagram looking to the north that shows the geologic formations across the survey area. Note that the three northernmost survey flight lines, L700101, L700200, and 700300 are not present in the figure. Figure 3-31 is the total thickness of all ***Q*** material including non-, marginal-aquifer, aquifer, and coarse aquifer materials. Figure 3-32 shows the total thickness of the ***Kd*** including the shale/clay dominant and sandstone/sand dominant materials.

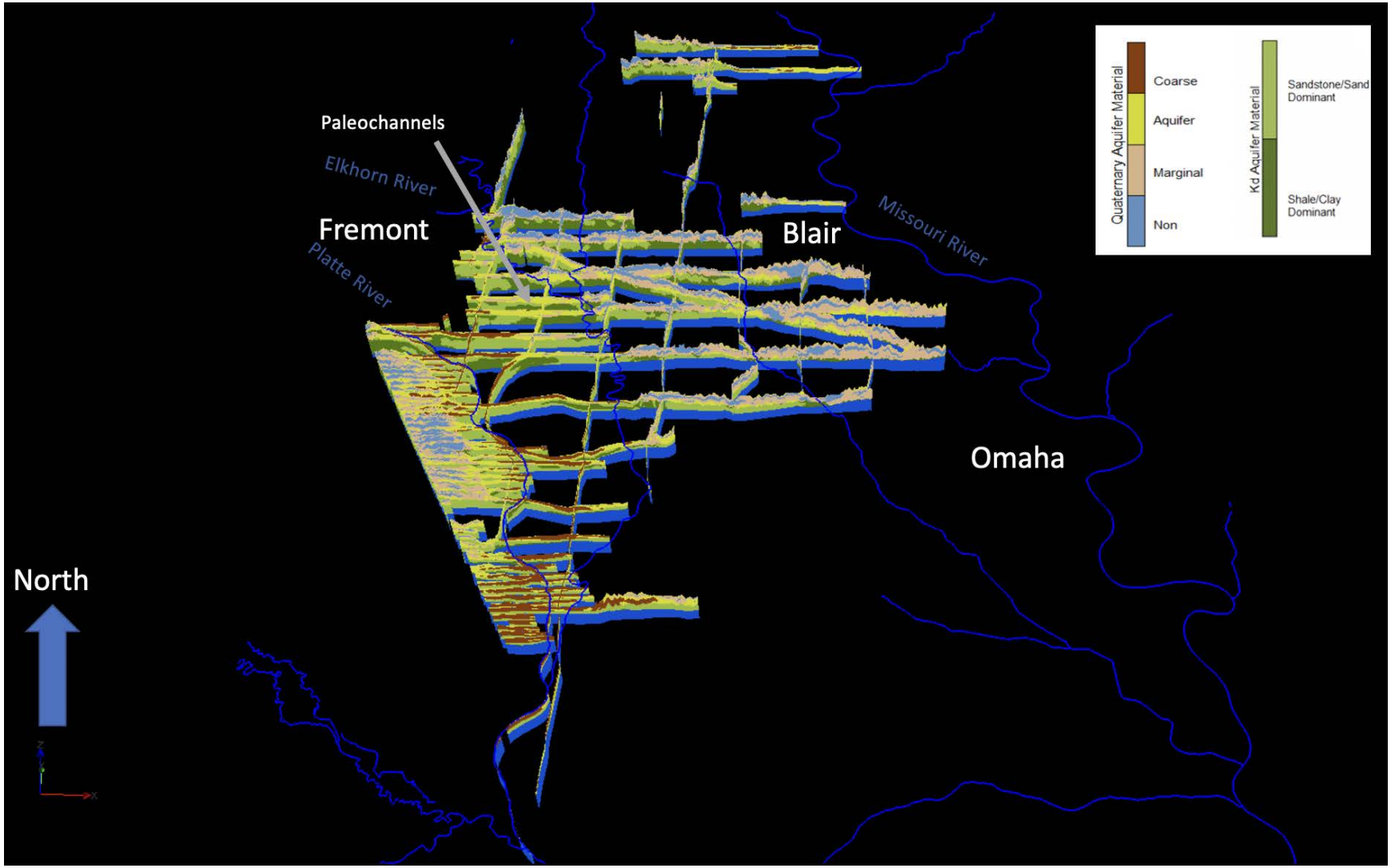


Figure 3-30. 3D fence diagram of the P-MRNRD southern AEM reconnaissance lines, looking north, showing Quaternary (*Q*) aquifer materials. In the Cretaceous Dakota Group (*Kd*) dark green is shale/clay dominant and light green is sandstone/sand dominant. Blue area at depth in the fence diagrams is the undifferentiated Pennsylvanian (*IP*). Vertical exaggeration (VE) = 15x.

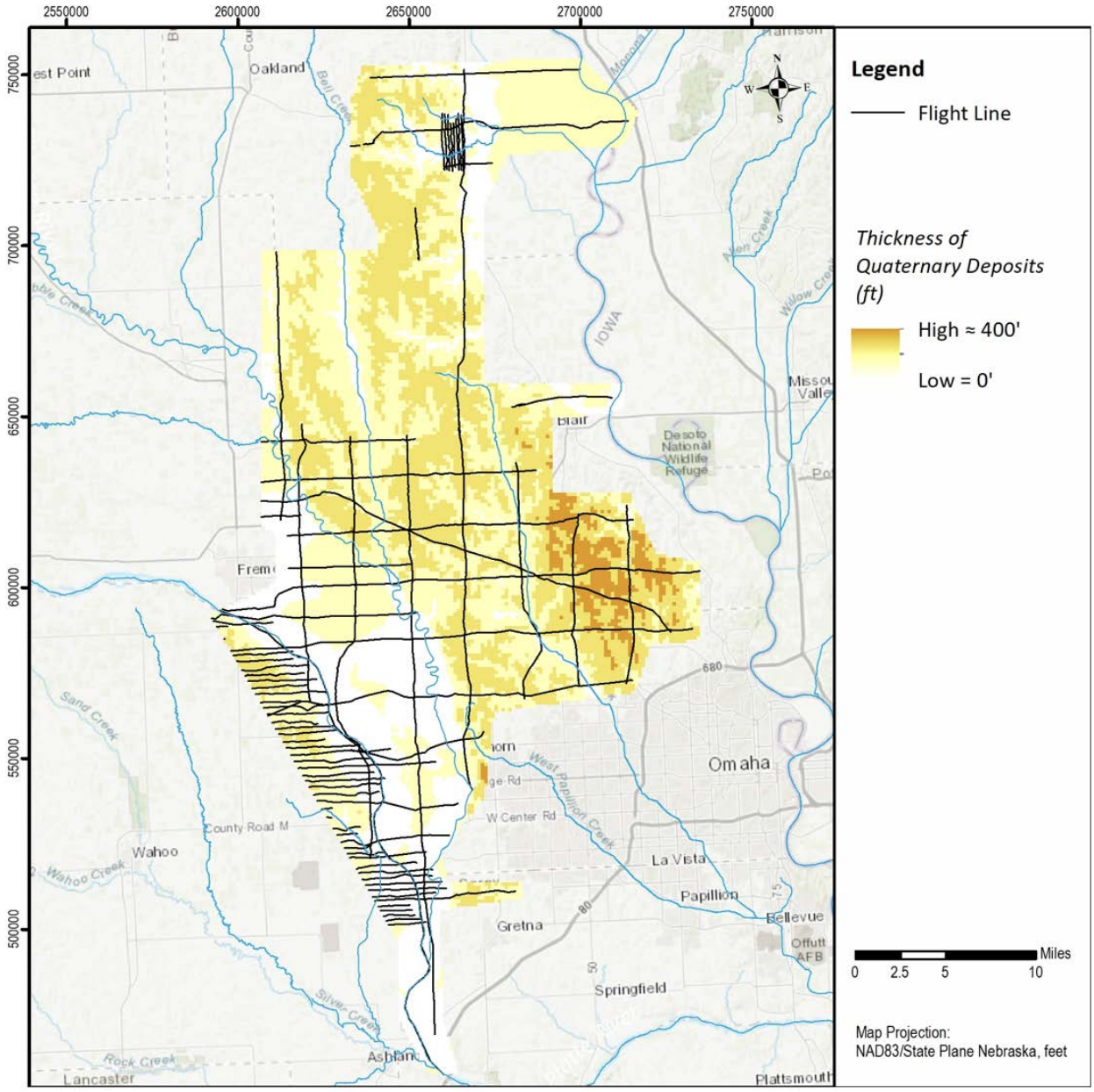


Figure 3-31. Map of the total thickness of Quaternary (*Q*) units in the southern reconnaissance AEM survey area. The projection is NAD83 State Plane Nebraska (feet).

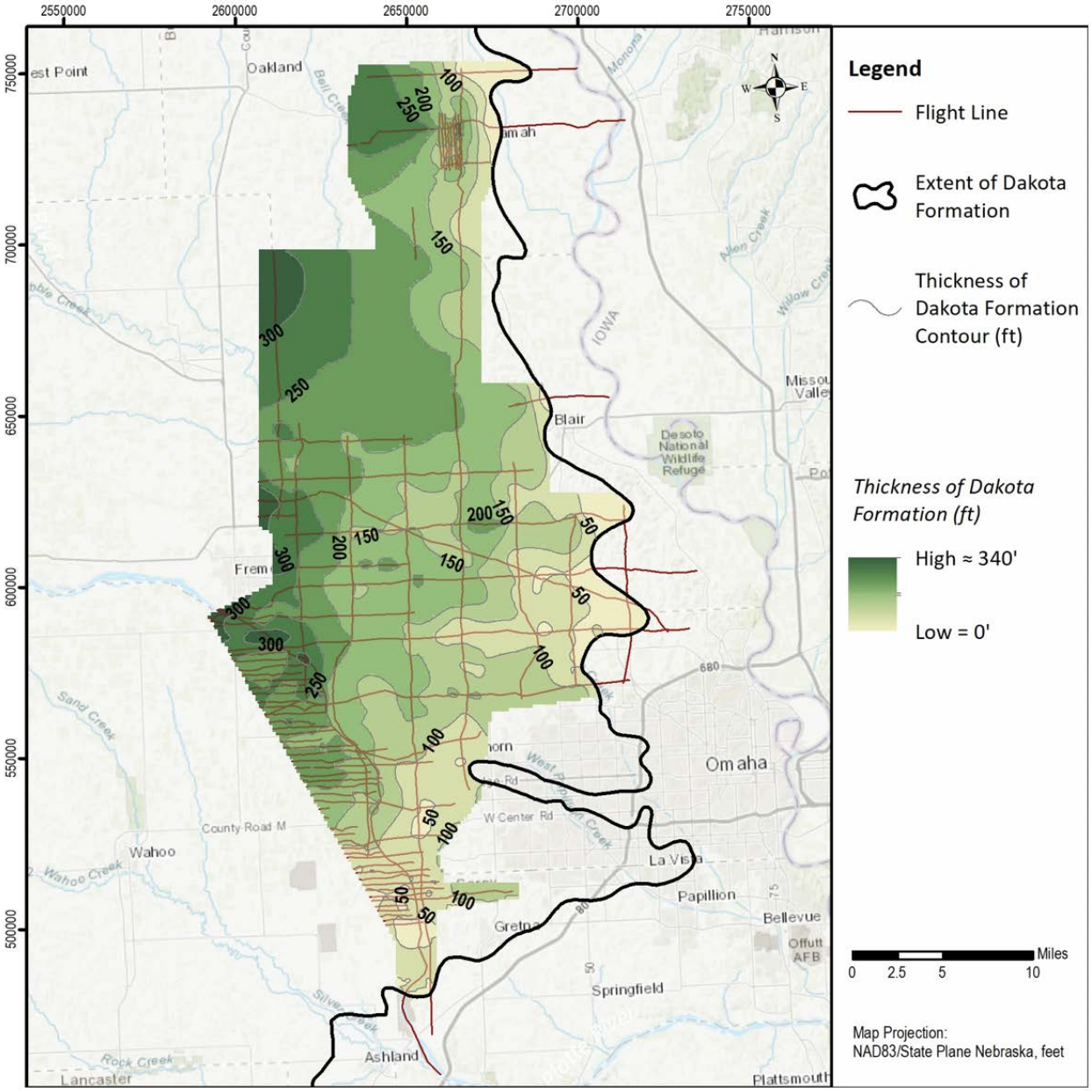


Figure 3-32. Map of the total thickness of the Cretaceous Dakota Group (*Kd*) including the shale/clay dominant and sandtone/sand dominant units. The projection is NAD83 State Plane Nebraska (feet).

Examining 3D fence diagrams provides a spatial understanding of the distribution of aquifer materials within the southern reconnaissance AEM survey area. Figure 3-33 is a 3D fence diagram, looking to the northeast, that includes the top surface of the undifferentiated Pennsylvanian as well as some of the major streams and towns. The AEM ***Q*** aquifer material classifications illuminate the areas of the main aquifers with the yellow and brown colors of the aquifer and coarse aquifer materials along with the ***Kd*** sandstone/sand dominant zones. The boreholes also provide additional evidence as the area of sand and sand and gravel are shown as yellow and orange respectively. In areas where there are no paleochannels or alluvial channels, the dominant aquifer material type is marginal (tan areas). ***Q*** non-aquifer materials and ***Kd*** shale/clay dominant materials do exist in the area. These areas have few to no

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

Zooming in on the 3D fence diagram in Figure 3-33 in the area just east of Fremont allows for examination in greater detail of the nature and extent of the Platte River floodplain, the glacial till on its borders, the Elkhorn River, and the area of the paleochannel that's been imaged with the AEM just southwest of the Elkhorn River (Figure 3-34, Figure 3-35, Figure 3-36).

In some areas of the AEM survey the paleochannels are discrete and have very sharp transitions from non-aquifer and marginal aquifer materials to aquifer and coarse aquifer materials. North-south line L800201 (Figure 3-37) is east of the town of Fremont in the western portion of the southern reconnaissance AEM survey area and illustrates the discrete nature of the paleochannel deposits. In the eastern end of Line L800201 a paleochannel is characterized by the AEM as well as by NE-DNR registered wells and CSD test holes. Note the transition from the Platte River to the Elkhorn River and then the Glacial till-covered bluffs which cover the aquifer material of the paleochannel. This aquifer geometry provides for sharp flow boundaries within the aquifer system. The paleochannel and alluvial channel deposits of the Platte and Elkhorn Rivers are in direct contact with the ***Kd***. Where the ***Q*** coarse aquifer, aquifer, and marginal aquifer material overlie the ***Kd*** sandstone/sand dominant materials, you have hydrologic connection between the ***Q*** and ***Kd***. This connection includes recharge from the land surface through the ***Q*** down into the ***Kd***.

East-west line L501500 (Figure 3-38) east of the town of Fremont also displays river channel systems from the Platte and Elkhorn Rivers on the left side of the line. While the channel is not as sharp as the example from L800201, this profile exhibits discrete deposits of coarse aquifer and aquifer materials bounded by till on the east and west sides of the valley. The Elkhorn River deposits show a mix of all aquifer materials which is different from the coarse aquifer and aquifer materials on the west side related to the Platte River. This indicates a different source of materials for the two rivers.

East-west line 700700 (Figure 3-39) is north of the town of Blair and west of the Missouri River. This profile illustrates the transition from glacial till-covered hills in the west to the Missouri River flood plain in the east. Note the till lies upon ***Kd*** shale/clay dominant material which pinches out under the paleochannel near the terrace next to the west side of the flood plain. Beneath the ***Q*** fill of the flood plain lies the ***IP***. The ***Kd*** has a poor hydrologic connection to the Missouri River along this profile.

East-west line 700500 (Figure 3-40) is north of the town of Tekamah and west of the Missouri River. This profile also illustrates the transition from glacial till-covered hills in the west to the Missouri River flood plain in the east. Here, though, the till lies mostly upon ***Kd*** sandstone/sand dominant material which pinches out under the floodplain on the east. Beneath the ***Q*** fill of the flood plain lies the ***IP***. Along this profile, the ***Kd*** has a good hydrologic connection to the Missouri River.

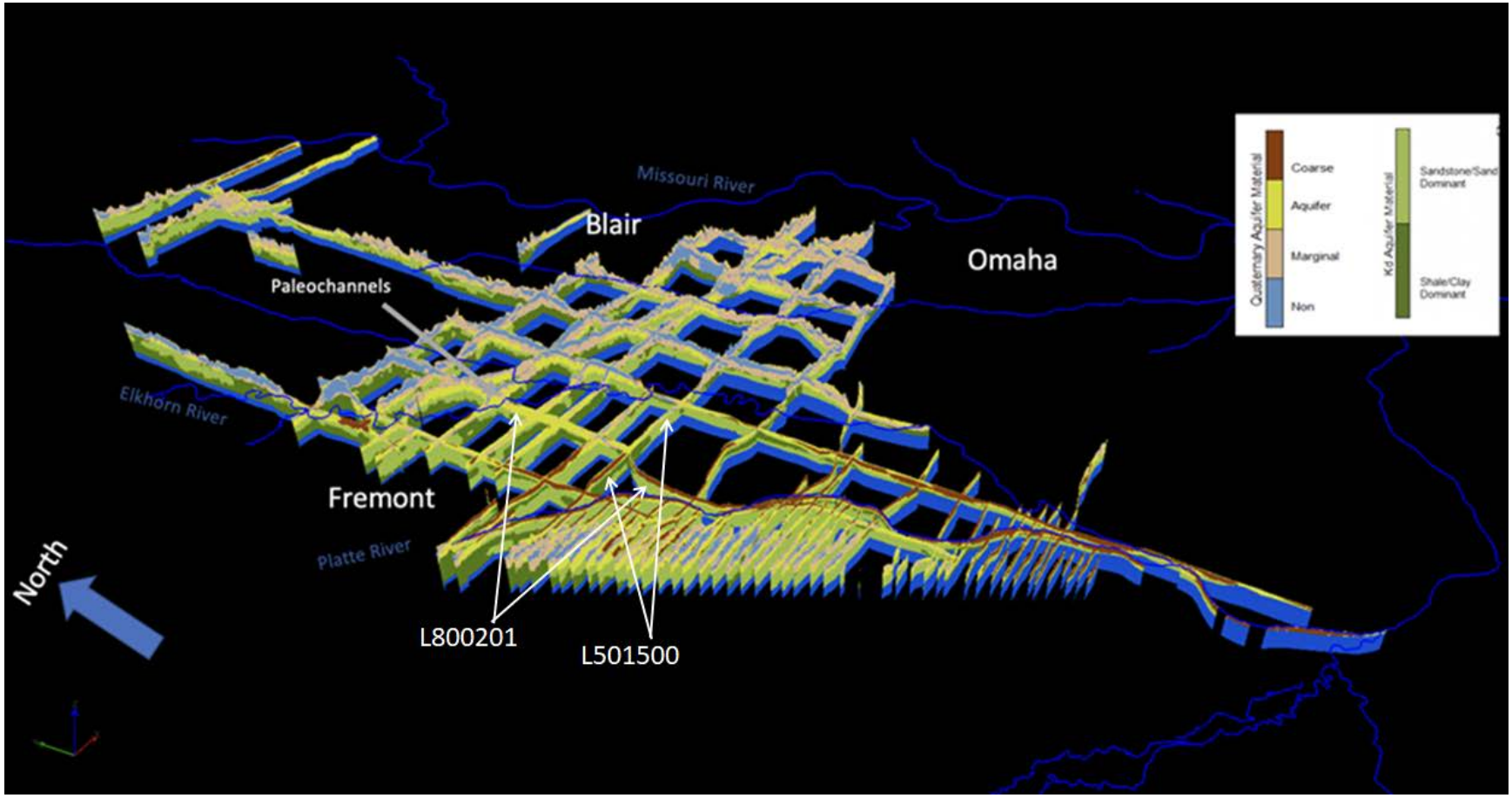


Figure 3-33. 3D fence diagram of the southern reconnaissance lines and borehole lithology looking to the east. Near the town of Fremont to the east is a paleochannel. Blue surface at depth is the undifferentiated Pennsylvanian (*IP*). VE = 15x.

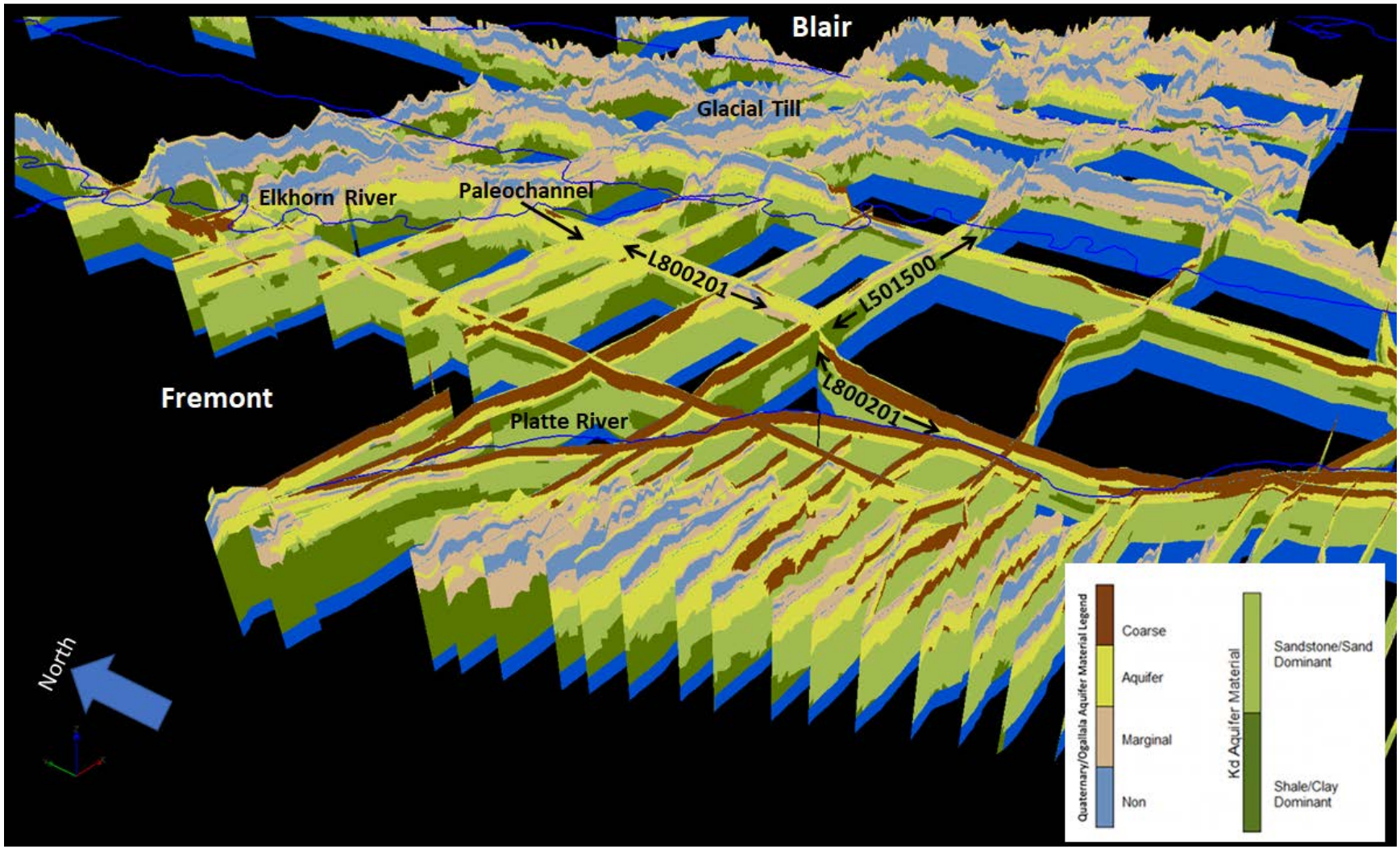


Figure 3-34. Zoom in on 3D fence diagram looking northeast across the Platte River showing the extent of the coarse *Q* material in the Platte River floodplain, the location of the paleochannel to the east of Fremont, and the locations of AEM flight lines L800201 and L501500 (shown below as 2D profile in Figure 3-37 and Figure 3-38, respectively). Interpretation of the undifferentiated Pennsylvanian (*IP*) is indicated by the blue area. VE = 15x.

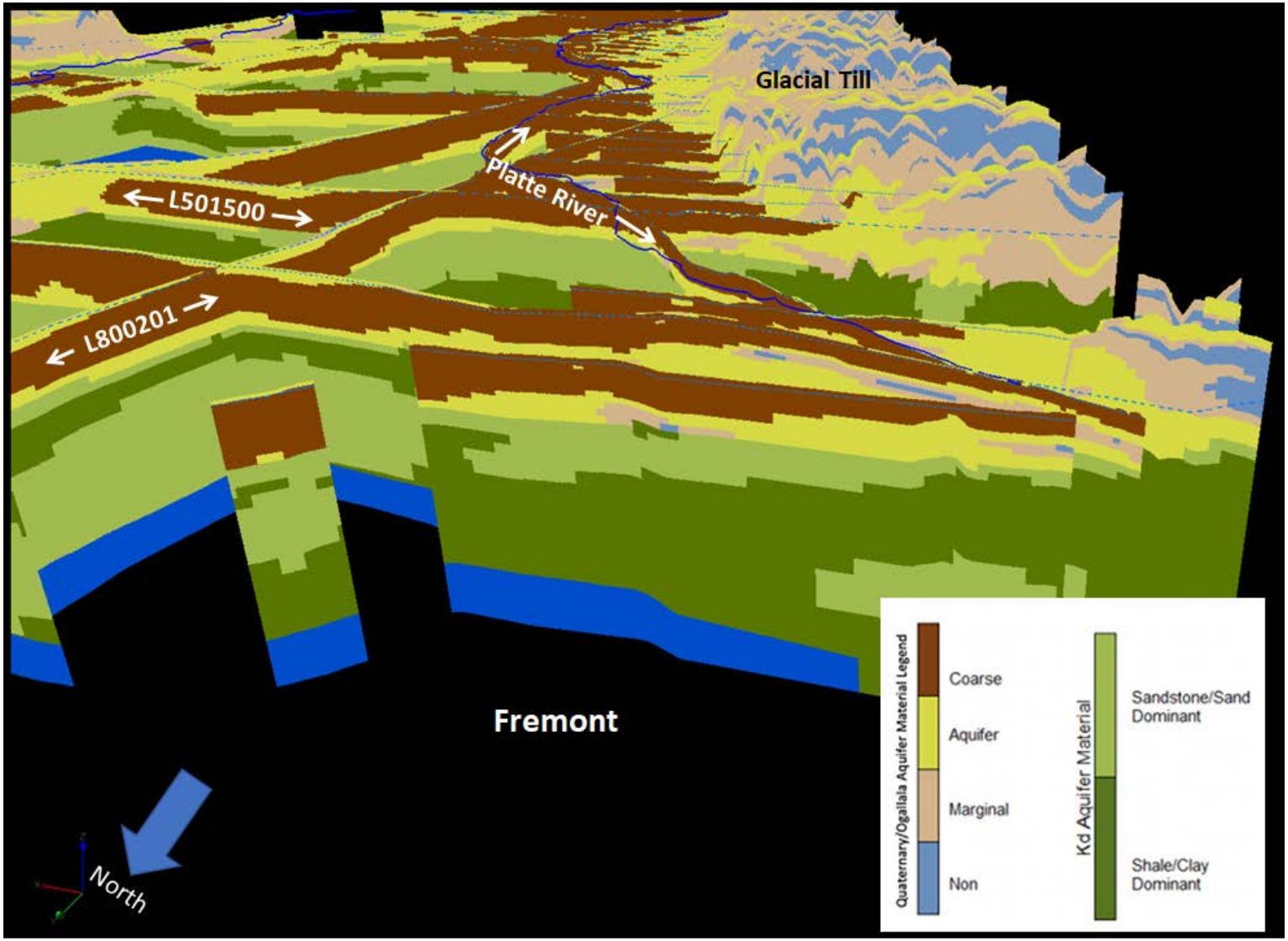


Figure 3-35. Zoom in on 3D fence diagram looking southeast from Fremont along the Platte River showing the *Q* coarse aquifer material in the Platte River floodplain and the locations of AEM flight lines L800201 and L501500. Interpretation of the undifferentiated Pennsylvanian (*IP*) is indicated by the blue area. VE = 15x.

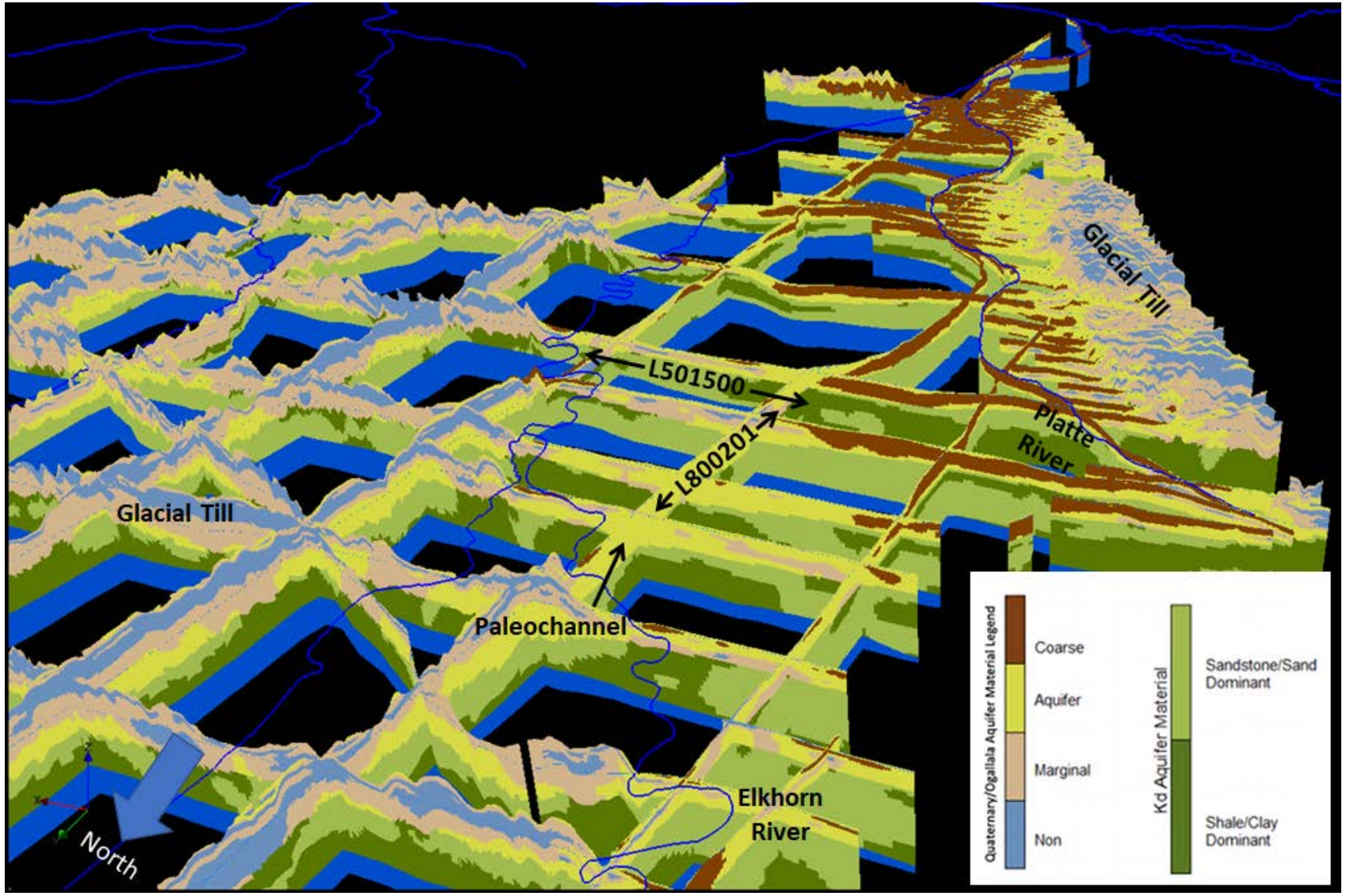


Figure 3-36. Zoom in on 3D fence diagram looking southeast from Fremont between the Platte and Elkhorn rivers showing the extent of the coarse *Q* material in the Platte River floodplain, the paleochannel area, and the locations of AEM flight lines L800201 and L501500. Interpretation of the undifferentiated Pennsylvanian (*IP*) is indicated by the blue area. VE = 15x.

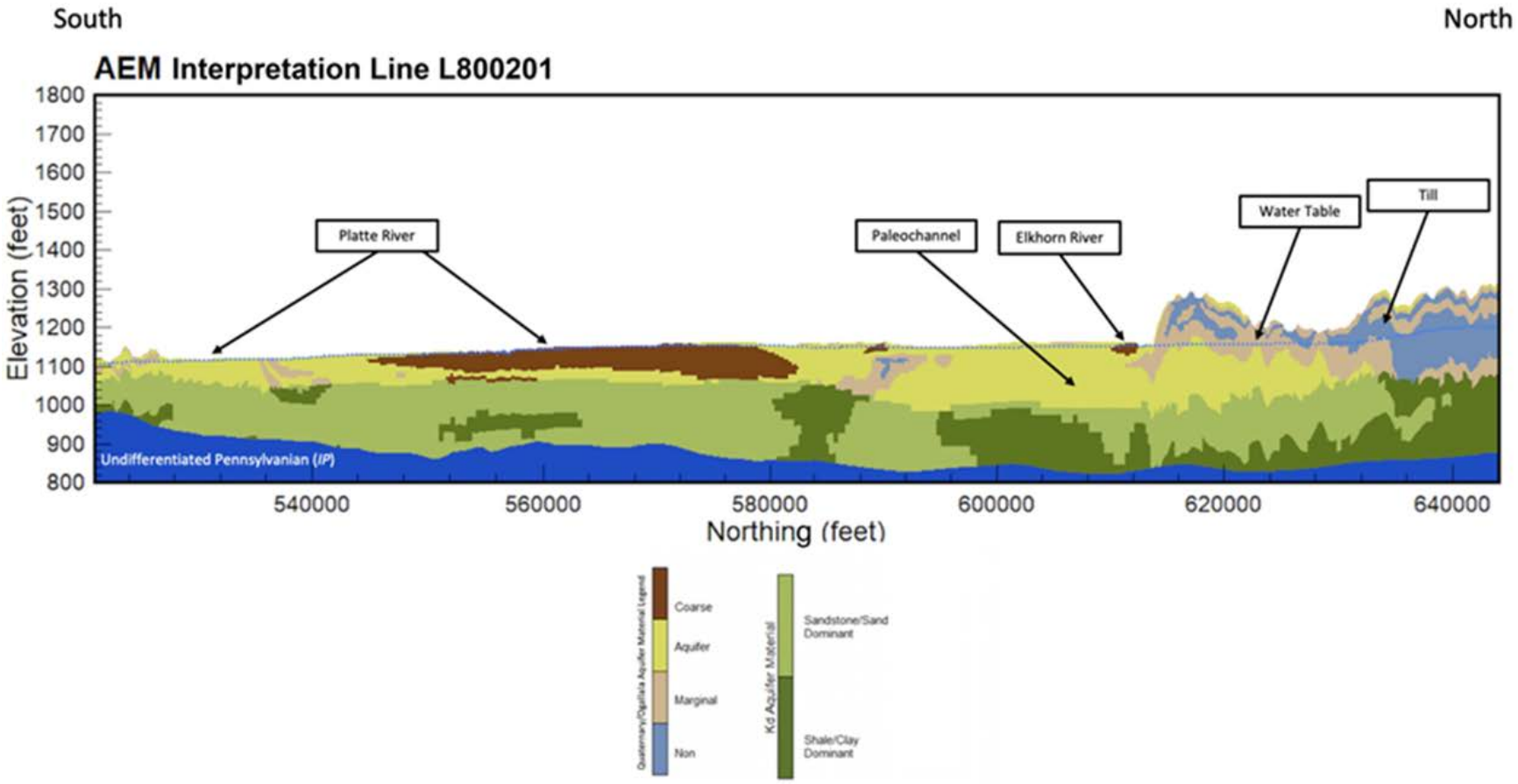


Figure 3-37. North-south flight line L800201. On the eastern end of the line there is a paleochannel that is detected by the AEM as well as by NE-DNR registered wells and CSD test holes. Interpretation of the undifferentiated Pennsylvanian (*IP*) is indicated by the blue area. The CSD 1995 water table is indicated with a dashed blue line.

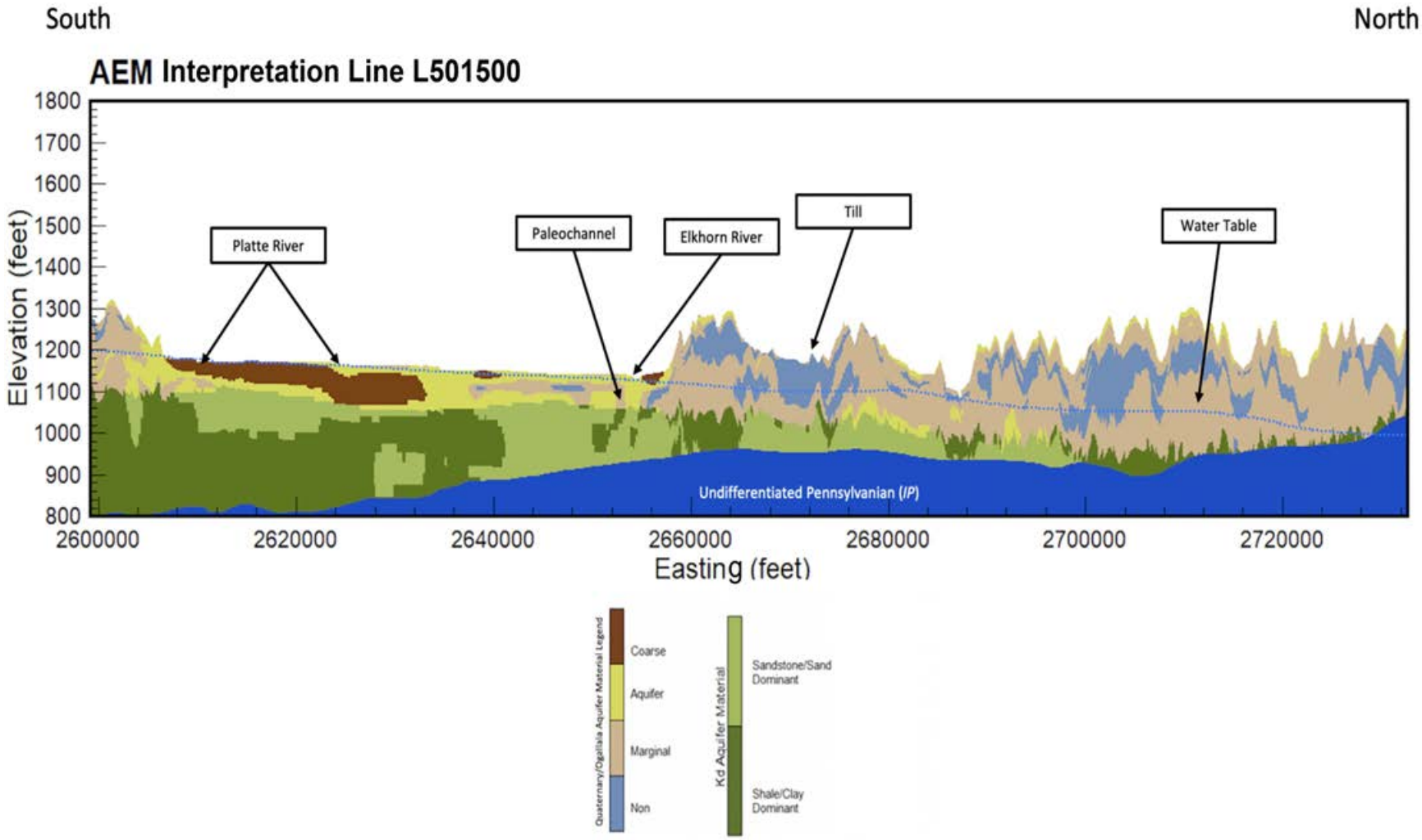


Figure 3-38. East-west flight line L501500. East of the town of Fremont also displays river channel system from the Platte and Elkhorn Rivers that lies upon the Cretaceous Dakota which is bounded by glacial till to the west and east. Interpretation of the undifferentiated Pennsylvanian (*IP*) is indicated by the blue area. The CSD 1995 water table is indicated with a dashed blue line.

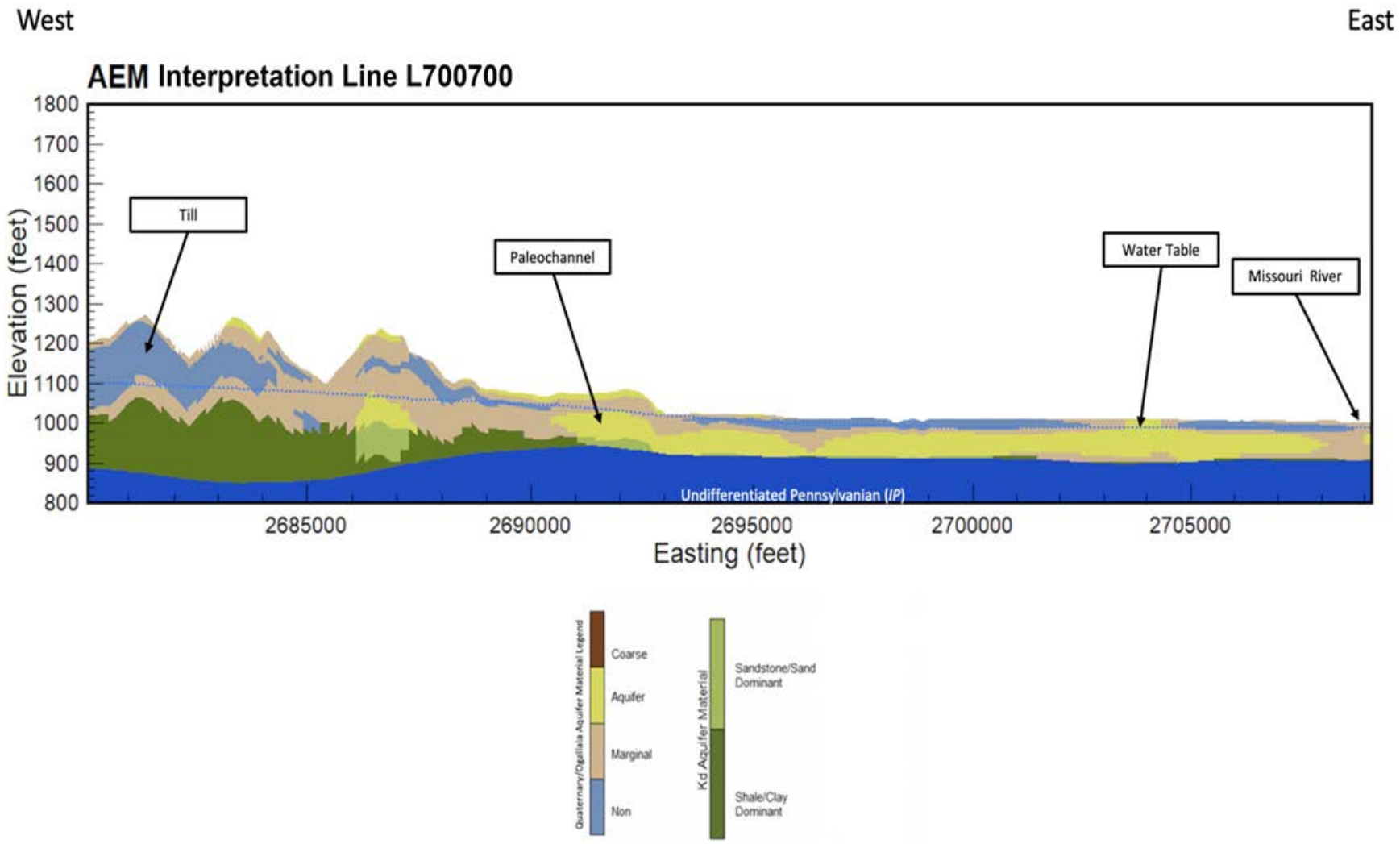


Figure 3-39. East-west Line L700700. North of the town of Blair and west of the Missouri River illustrates the transition from glacial till covered hills in the west to the Missouri River flood plain in the east. Note the paleochannel on the terrace west of the Missouri River flood plain. There is poor hydrologic connection between the cretaceous Dakota and the Missouri River Quaternary deposits. Interpretation of the undifferentiated Pennsylvanian (*IP*) is indicated by the blue area. The CSD 1995 water table is indicated with a dashed blue line.

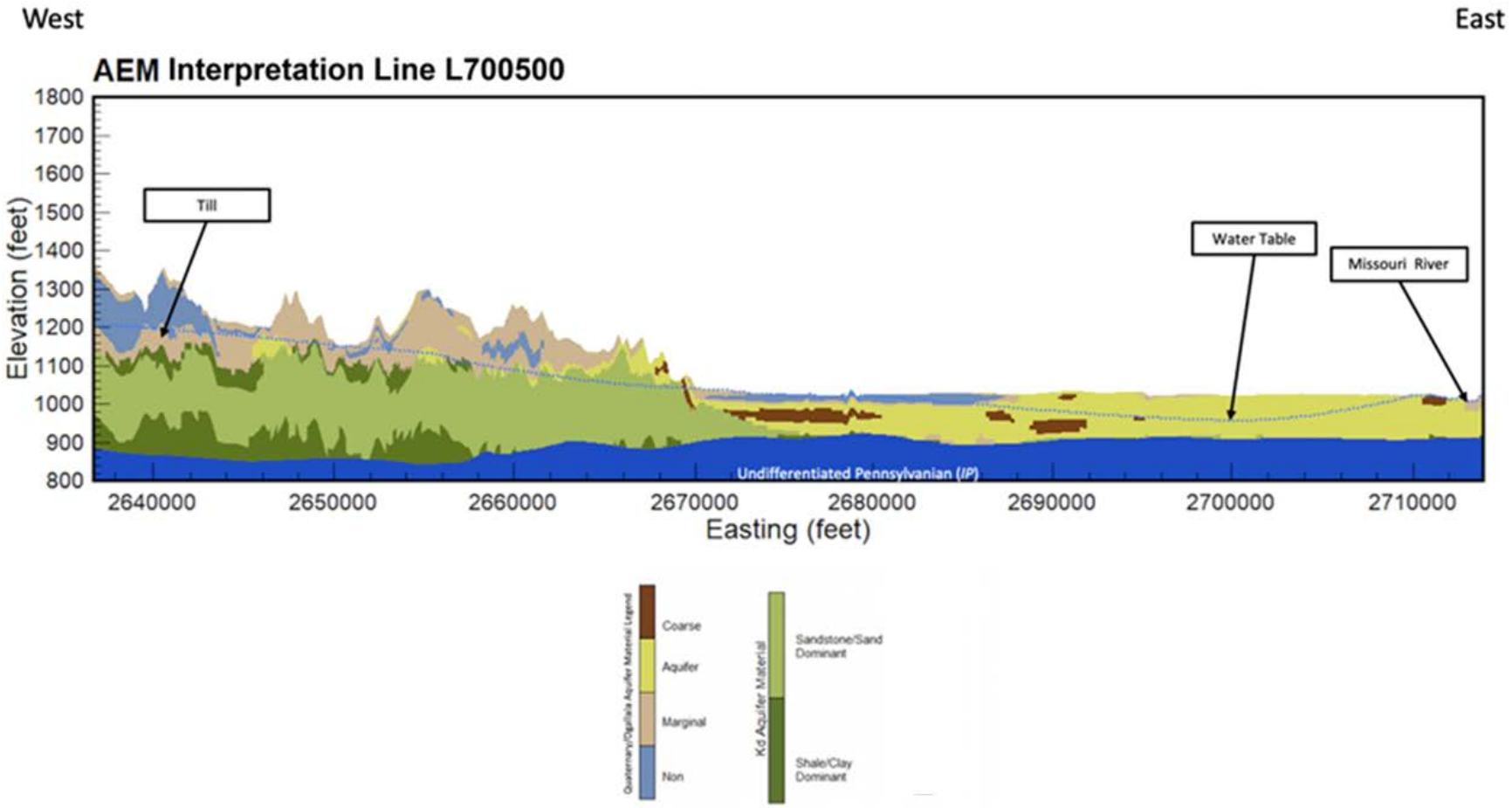


Figure 3-40. East-west Line L700500. North of the town of Tekamah and west of the Missouri River illustrates the transition from glacial till covered hills in the west to the Missouri River flood plain in the east. There is good hydrologic connection between the Cretaceous Dakota Group and the Missouri River Quaternary deposits. Interpretation of the undifferentiated Pennsylvanian (*IP*) is indicated by the blue area. The CSD 1995 water table is indicated with a dashed blue line.

Using the interpretive surfaces and grids that were produced as described above an enhanced understanding of the hydrogeological framework of the southern reconnaissance AEM survey area can be achieved. Figure 3-41 is the total thickness of all ***Q*** materials in the southern reconnaissance AEM survey area. The ***Q*** alluvial fill in the valleys tend to be thinner than the till covered hills surrounding the valleys. When the 1995 CSD water table (NE-CSD, 1995) is used to separate the total thickness of aquifer materials into saturated and unsaturated and from that calculation a thickness map is created (Figure 3-42), the paleochannel system near the town of Fremont has ~100-150 feet of thickness.

As indicated above by using the saturated thickness of the aquifer material, an estimate of the specific capacity can be developed (Figure 3-43). The coarsest and thickest areas of the saturated thickness have the highest specific capacity values. It is important to note that the values in Figure 3-43 used the thickness of the aquifer materials which varied in thickness from 0 to 265 feet. Areas within the alluvial valley floors and paleochannels have some of the highest specific capacities which vary from less than 5 to greater than 50 gpm/ft.

Figure 3-44 is the total thickness of all ***Kd*** aquifer materials. The ***Kd*** thickens from east to west and is only interpreted where the flight lines exist. It varies in thickness from 0 to 340 feet. The 1995 CSD water table (NE-CSD, 1995) is used to separate the total thickness of ***Kd*** into saturated and unsaturated and from that calculation a thickness map can be created which is presented in Figure 3-45.

As indicated above by using the saturated thickness of the ***Kd***, an estimate of the specific capacity can be developed (Figure 3-46). The coarsest and thickest areas of the saturated thickness have the highest specific capacity values. It is important to note that the values on the map in Figure 3-46 used the thickness of the aquifer materials which varied in thickness from 0 to 345 feet. The specific capacity values vary from less than 5 to greater than 50 gpm/ft.

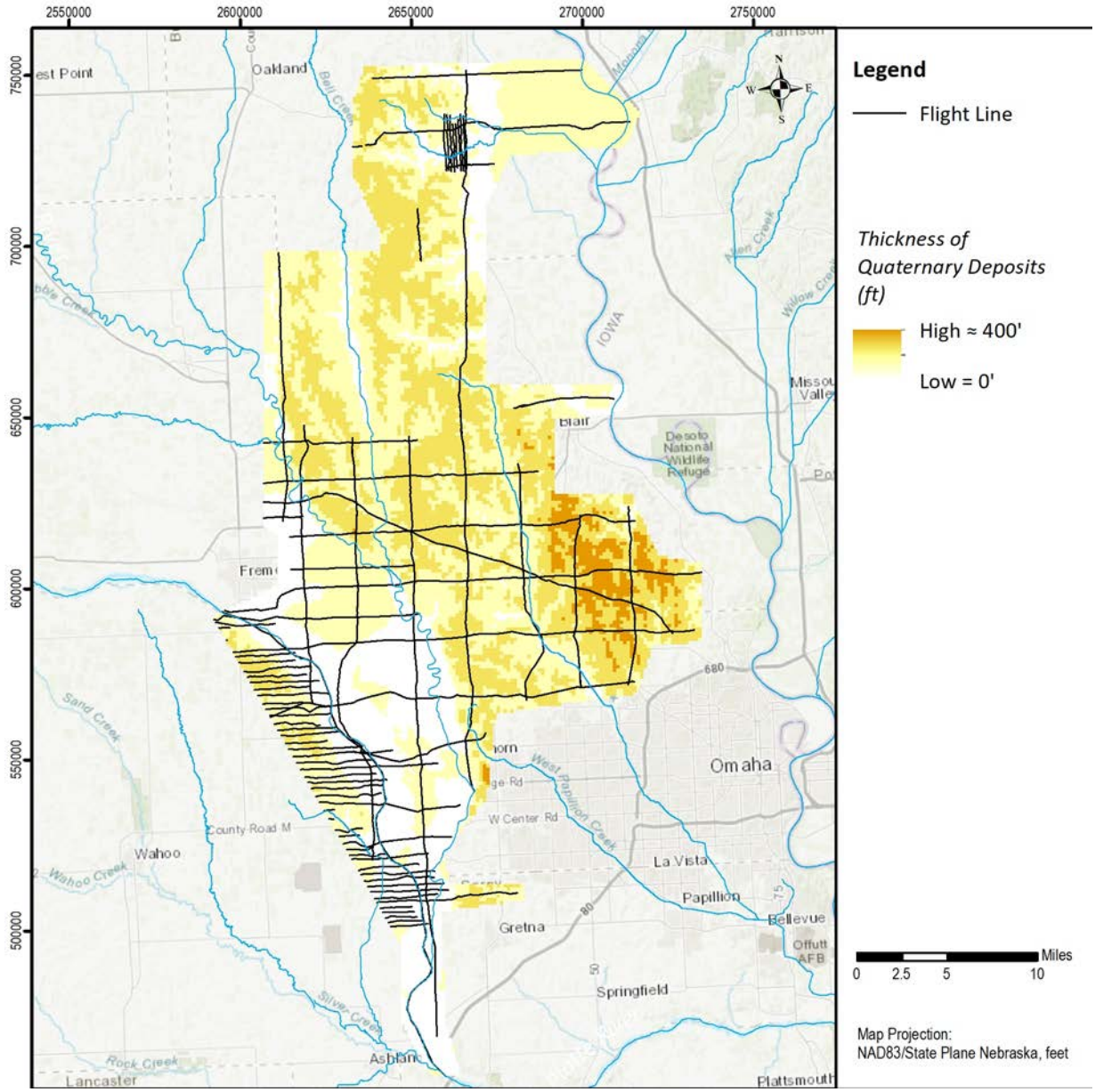


Figure 3-41. Map of the total thickness of Quaternary (*Q*) materials within the 2018 southern reconnaissance AEM survey area. Flight lines are indicated by the black lines. The projection is NAD83 State Plane Nebraska (feet).

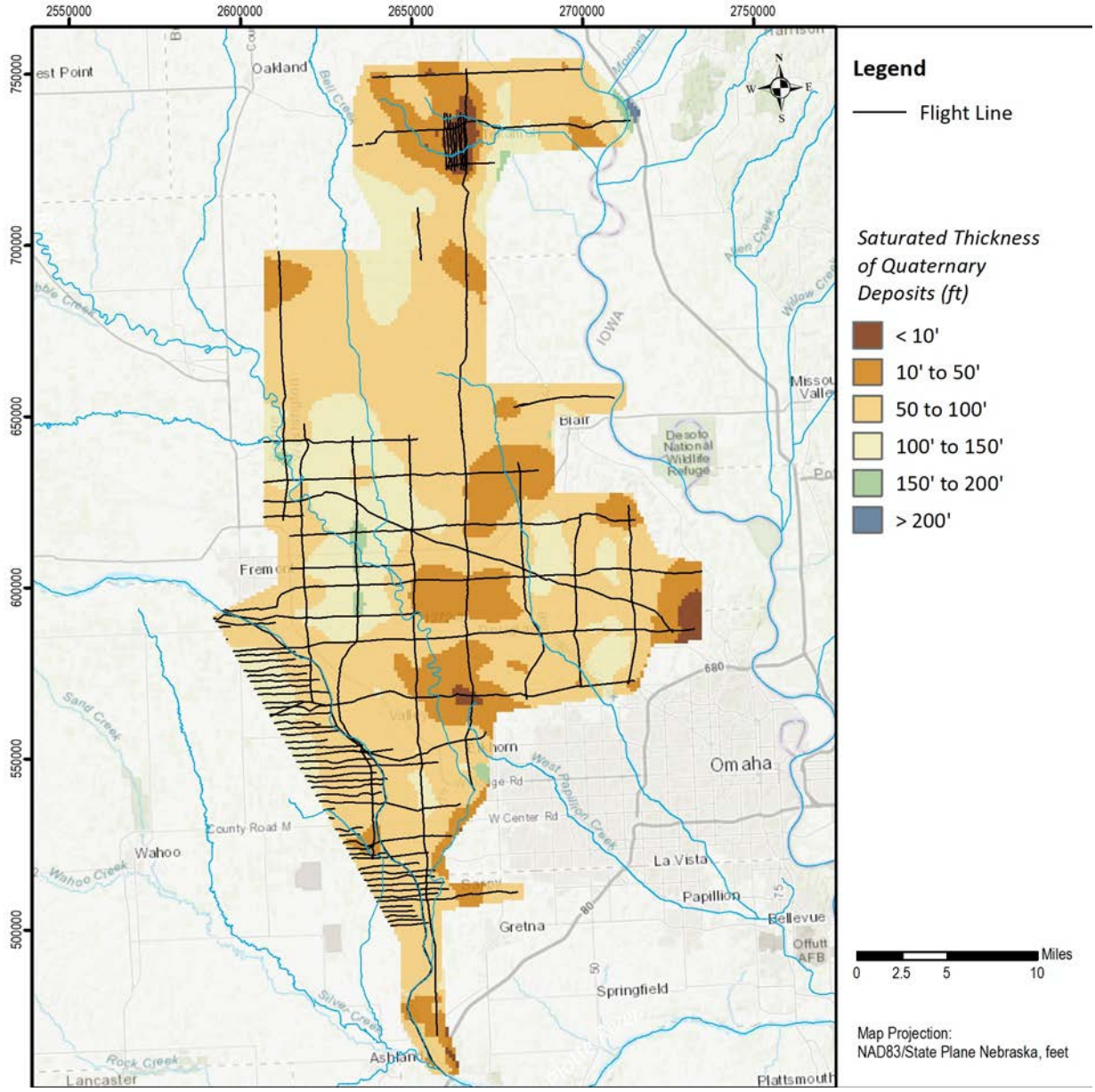


Figure 3-42. Map of the saturated thickness of Quaternary (*Q*) materials within the 2018 southern reconnaissance AEM survey area. Flight lines are indicated by the black lines. The projection is NAD83 State Plane Nebraska (feet).

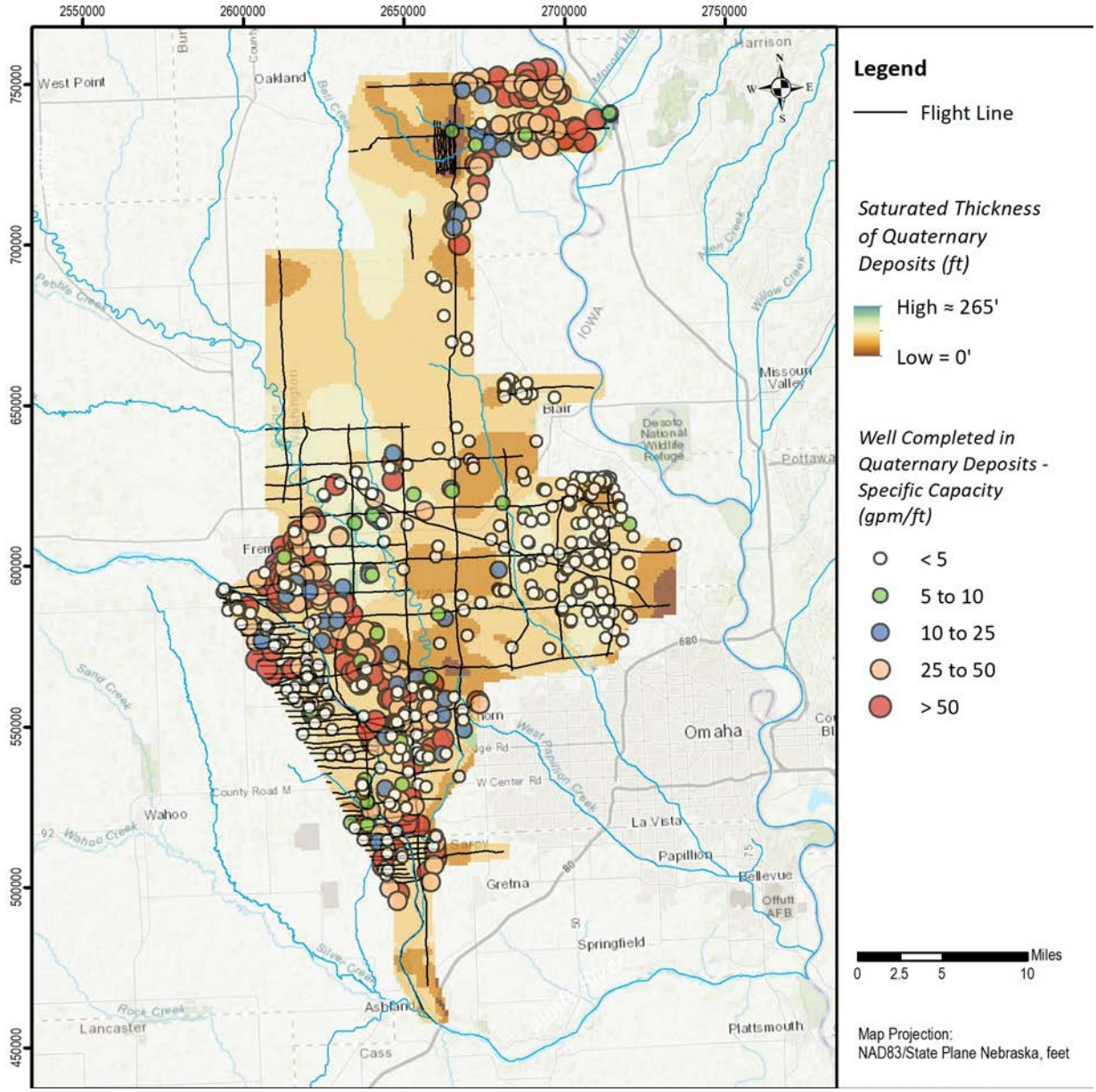


Figure 3-43. Map of the saturated thickness of the Quaternary (*Q*) materials and an estimate of the specific capacity within the 2018 southern reconnaissance AEM survey area. Flight lines are indicated by the blue lines. The projection is NAD83 State Plane Nebraska (feet).

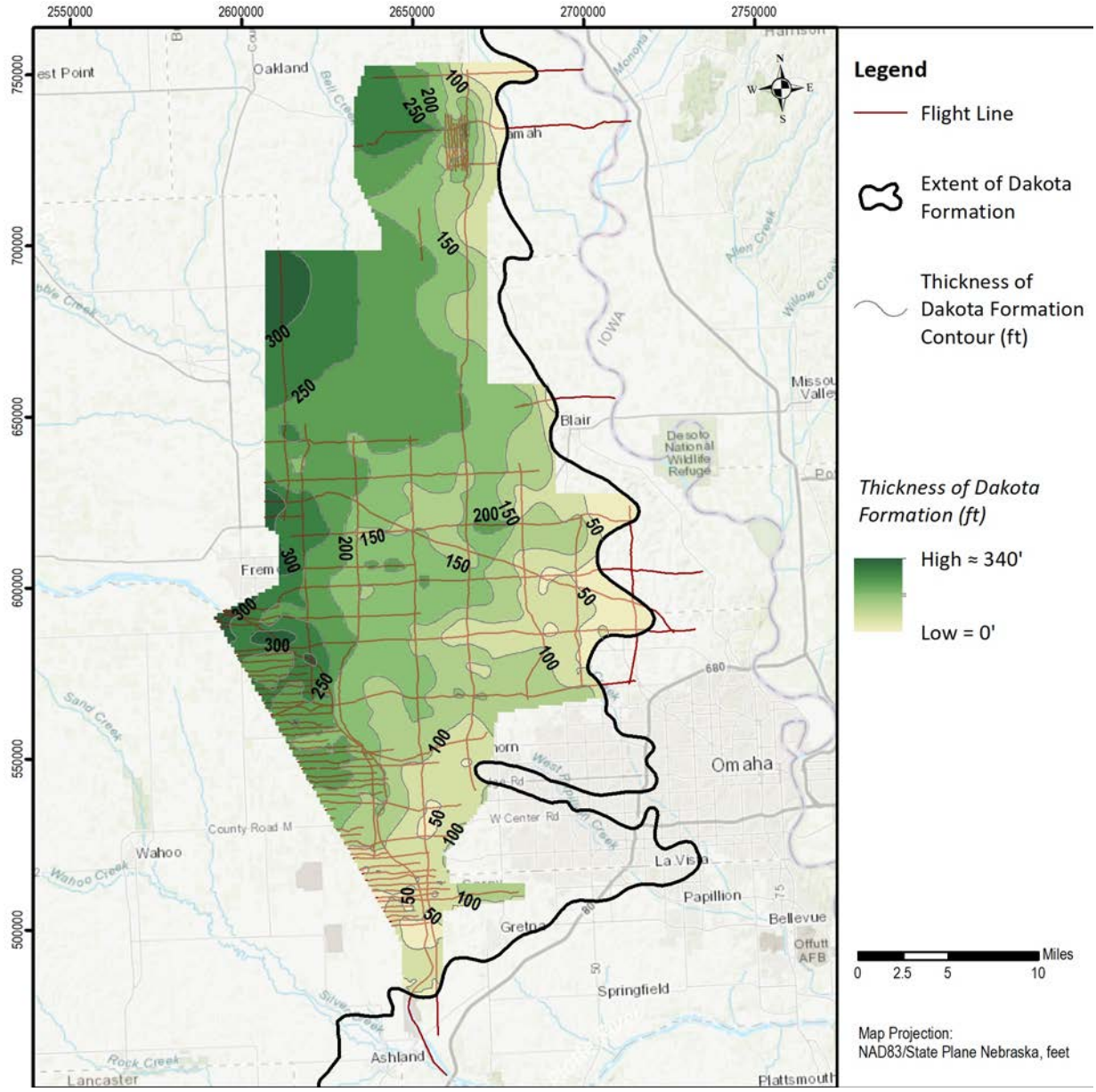


Figure 3-44. Map of the total thickness of Cretaceous Dakota Group (*Kd*) within the 2018 southern reconnaissance AEM survey area. Flight lines are indicated by the black lines. The projection is NAD83 State Plane Nebraska (feet).

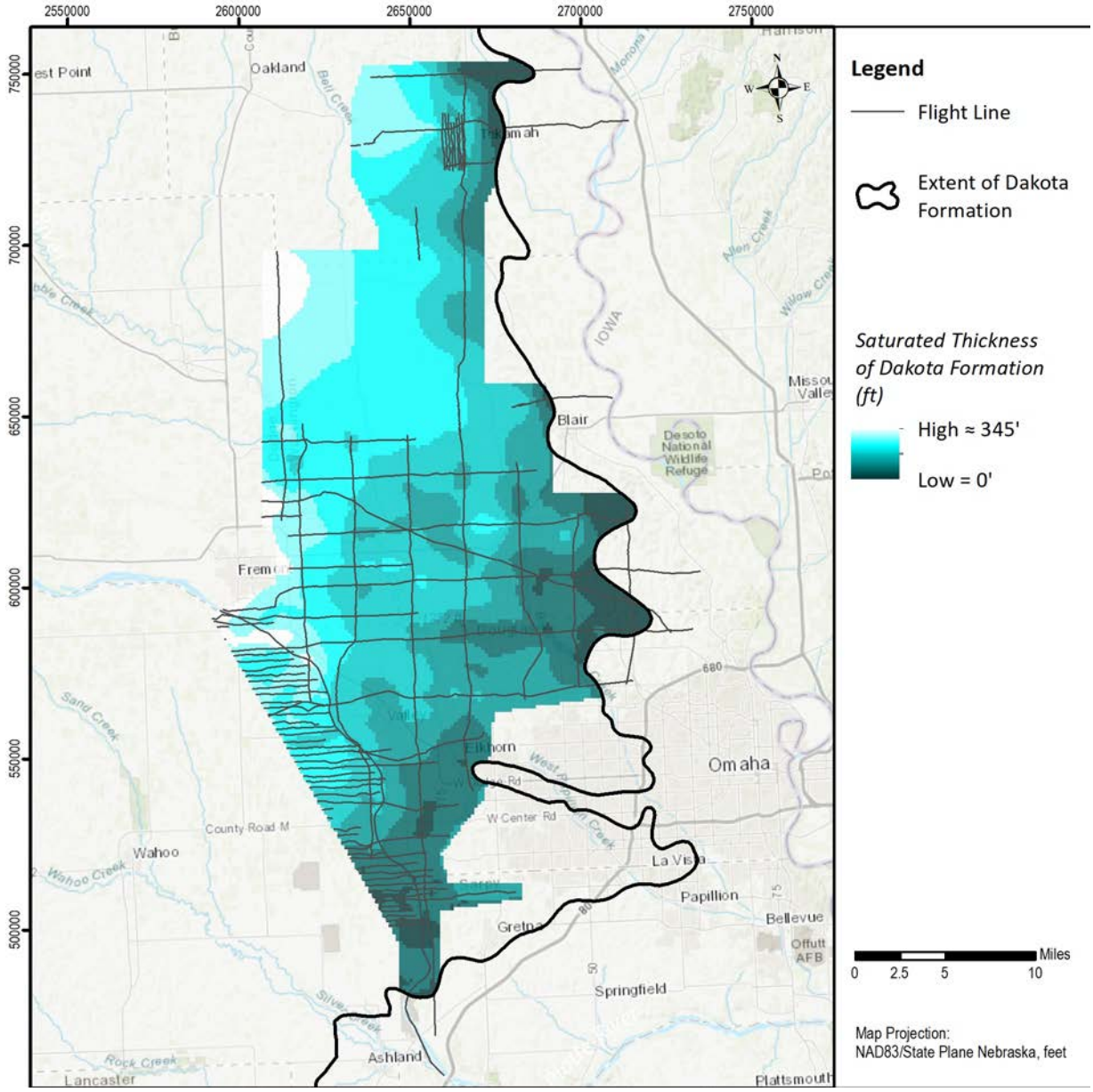


Figure 3-45. Map the saturated thickness of the Cretaceous Dakota Group (*Kd*) within the 2018 southern reconnaissance AEM survey area. Flight lines are indicated by the blue lines. The projection is NAD83 State Plane Nebraska (feet).

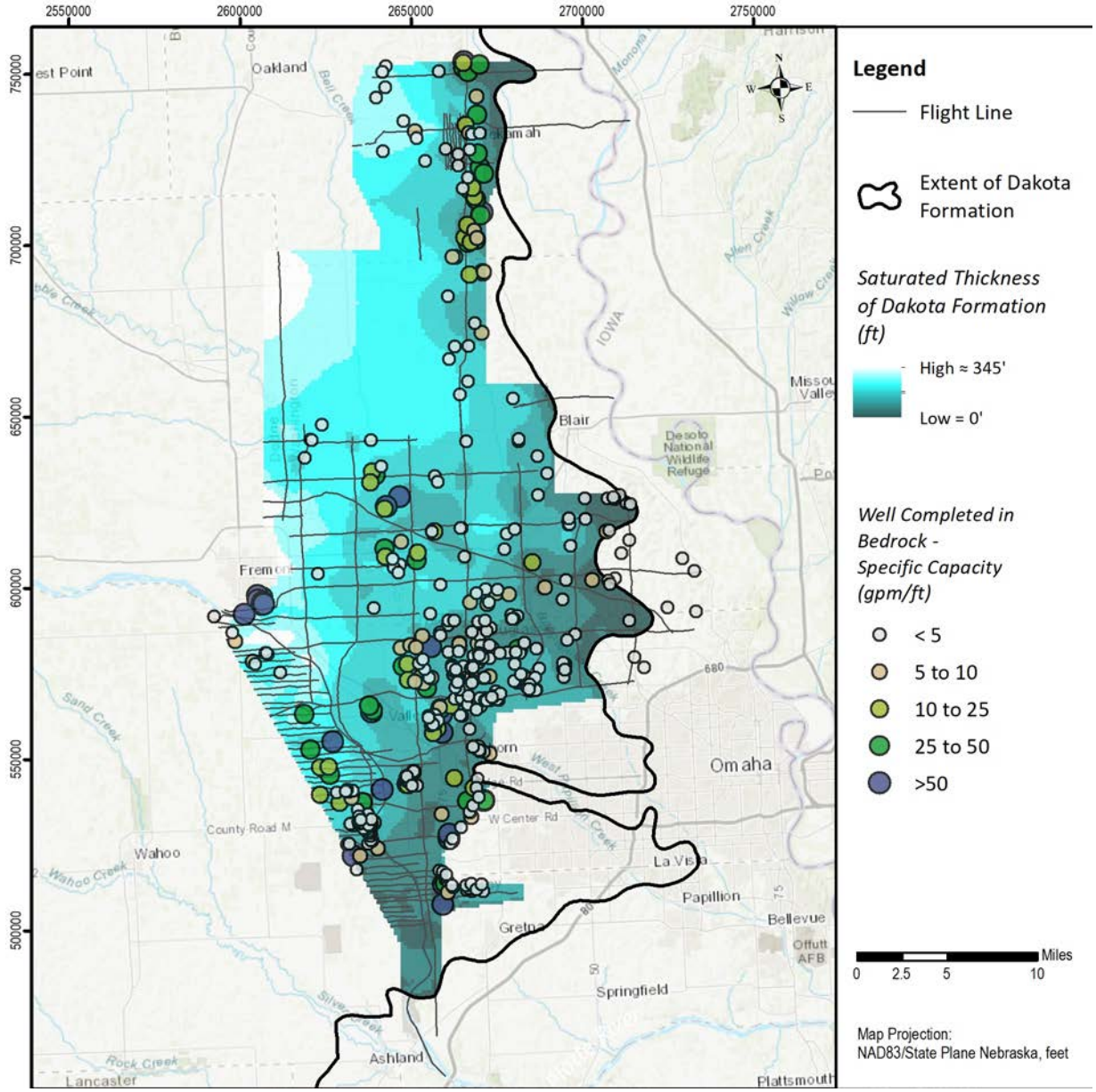


Figure 3-46. Map the saturated thickness of the Cretaceous Dakota Group (*Kd*) and an estimate of specific capacity in the southern reconnaissance AEM survey area. Flight lines are indicated by the blue lines. The projection is NAD83 State Plane Nebraska (feet).

3.2.2 Hydrogeologic Framework of the Tekamah Block Survey Area

The AEM provided insight into the geographic distribution and extent of the unconsolidated material in the Tekamah Block AEM survey area. The term "unconsolidated material" refers to the ***Q*** alluvial silt, sand, and gravel as well as loess and glacial till that overlie the ***Kd*** bedrock which is divided into sandstone/sand dominant and shale/clay dominant units. The unconsolidated material in the Tekamah Block AEM survey area is identified through interpretation of the AEM data as non-aquifer (blue), marginal aquifer (tan), aquifer material (yellow), and coarse aquifer (brown) material as discussed in Section 3.1.4. Figure 3-47 displays a 3D fence diagram of the flight lines and the interpreted hydrostratigraphic profiles of the Tekamah Block AEM survey area looking to the west. Generally, the flight block is divided by Tekamah Creek in the south and Mud Creek in the north with the northern and southern portions of the AEM survey area being a similar mix of ***Q*** aquifer materials and the ***Kd*** being mostly sandstone/sand dominant. There are no flight lines directly within the town of Tekamah due to FAA restrictions. The boreholes in the area indicate silty clay and sandy clay in much of the area with only thin layers of sand and sand and gravel in the basal areas above the bedrock. In the southern and northern portions, the material is made up of mostly marginal aquifer material with the exception of isolated bodies of coarse aquifer, aquifer, and non-aquifer materials at near surface elevations and lying on the bedrock.

As discussed above the total thickness of the ***Q*** unconsolidated material (Figure 3-48) was gridded by subtracting the bedrock elevation from the ground surface elevation. The greatest thickness is on the high ground north and south of Tekamah Creek. The ***Q*** unconsolidated material varies in thickness from 2 to 235 feet. The ***Kd*** bedrock underlying the unconsolidated material is generally highest in elevation in the southeast/east-central area and lowest in elevation in the northern part of the survey area (Figure 3-49). The bedrock lows in the southern and northern parts of the flight block underly an area of topographically lower elevation. This correlates to an area with a thin unconsolidated material thickness of about 25 ft. The 1995 CSD water table (NE-CSD, 1995) surface elevation was converted to a gridded dataset and incorporated into the interpreted AEM hydrostratigraphic profiles. Generally, the water table surface is flat across the Tekamah Block AEM flight area at a shallow depth within the drainage valleys. The bedrock elevation was subtracted from the gridded 1995 CSD water table surface elevation (NE-CSD, 1995) to obtain a total saturated thickness of ***Q*** unconsolidated material (Figure 3-50). Areas where there are low total saturated thickness values generally correlate to locations of bedrock highs. Bedrock low elevations are associated with high saturated thickness where the water level elevation may be over 50 feet above the bedrock surface as seen in the southeast and northwest corners of the survey area.

The thickness of the ***Kd*** in the Tekamah Block flight area varies from 114 to 215 feet (Figure 3-51). The thickest sections are in the center of the flight block. The saturated thickness of the ***Kd*** in the Tekamah Block varies from 115 to 215 feet (Figure 3-52). The greatest saturated thickness is in the southern portion of the block and the majority of the material making up the ***Kd*** is sandstone/sand dominant and is the important aquifer in the block. The ***Kd*** has a strong hydrologic connection to the Missouri River ***Q*** alluvium to the east of the flight block. Figure 3-53 shows this hydrologic relationship along profile L700500 which is the east-west line just north of the town of Tekamah (shown earlier as Figure 3-40).

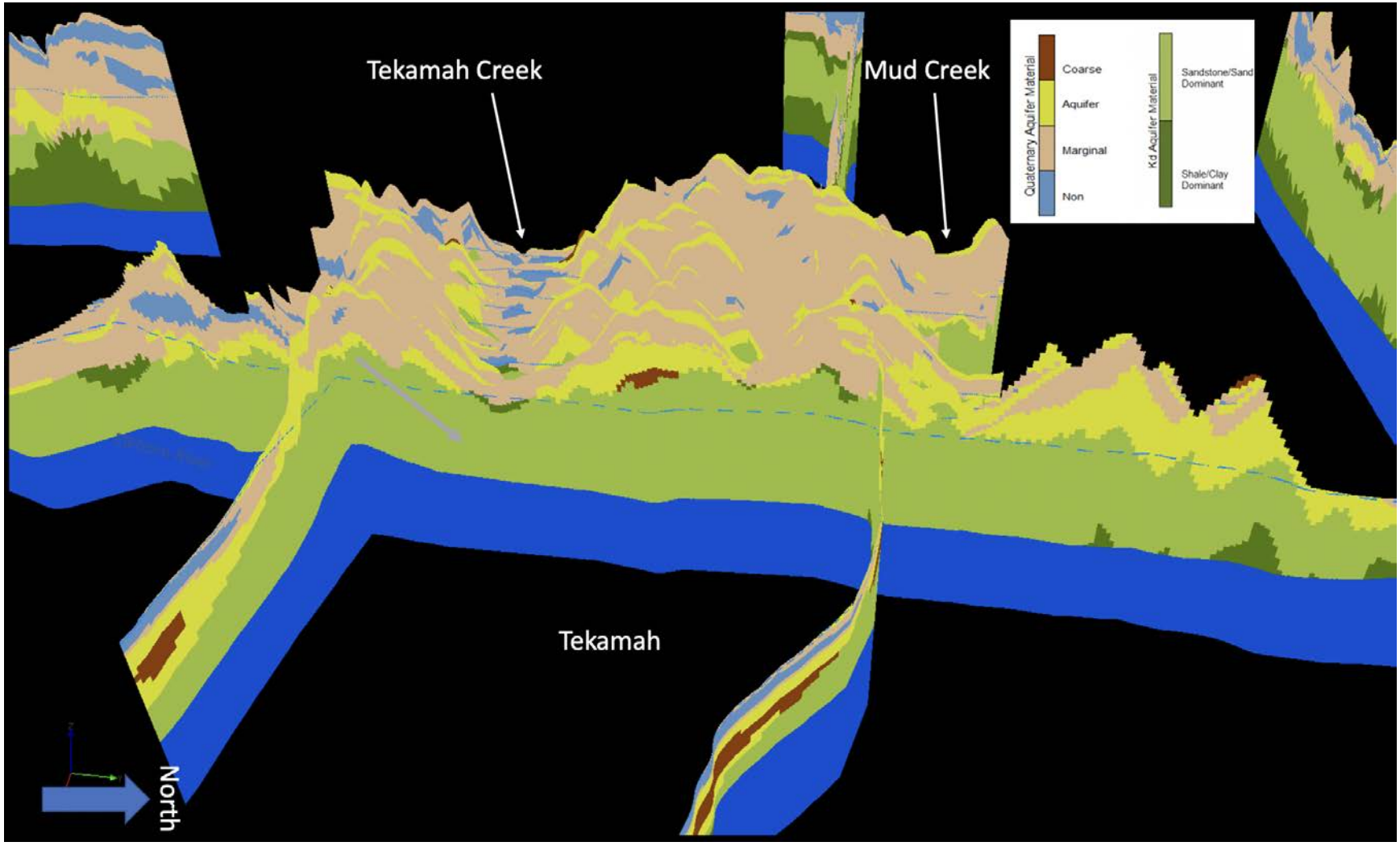


Figure 3-47. 3D fence diagram of interpreted AEM hydrostratigraphic profiles within the 2018 Tekamah Block AEM survey area. Interpretation of the undifferentiated Pennsylvanian (*IP*) is indicated by the blue area. VE = 15x.

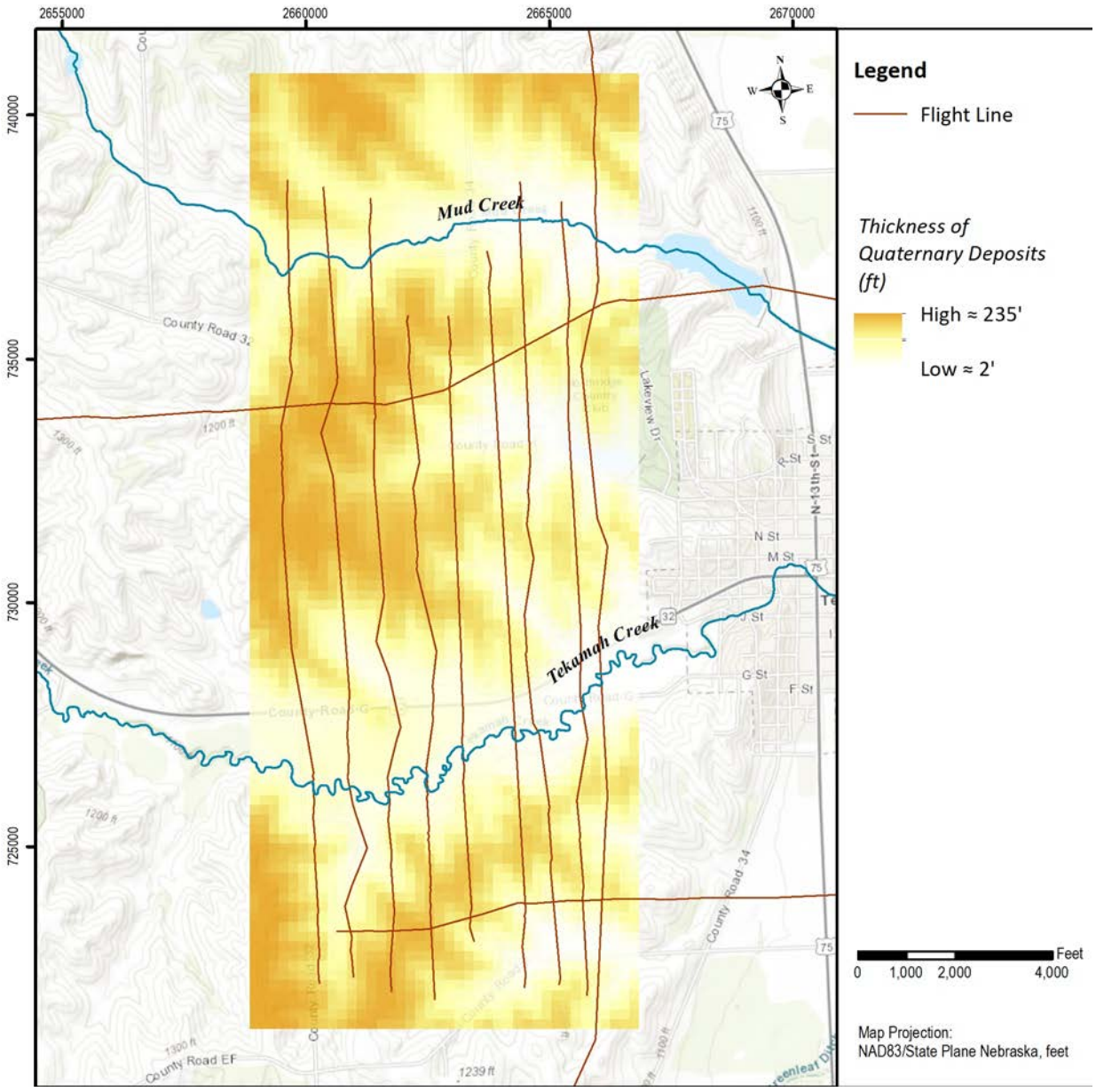


Figure 3-48. Map of the total thickness of the Quaternary (*Q*) deposits within the 2018 Tekamah Block. Flight lines are indicated by brown lines. The projection is NAD83 State Plane Nebraska (feet).

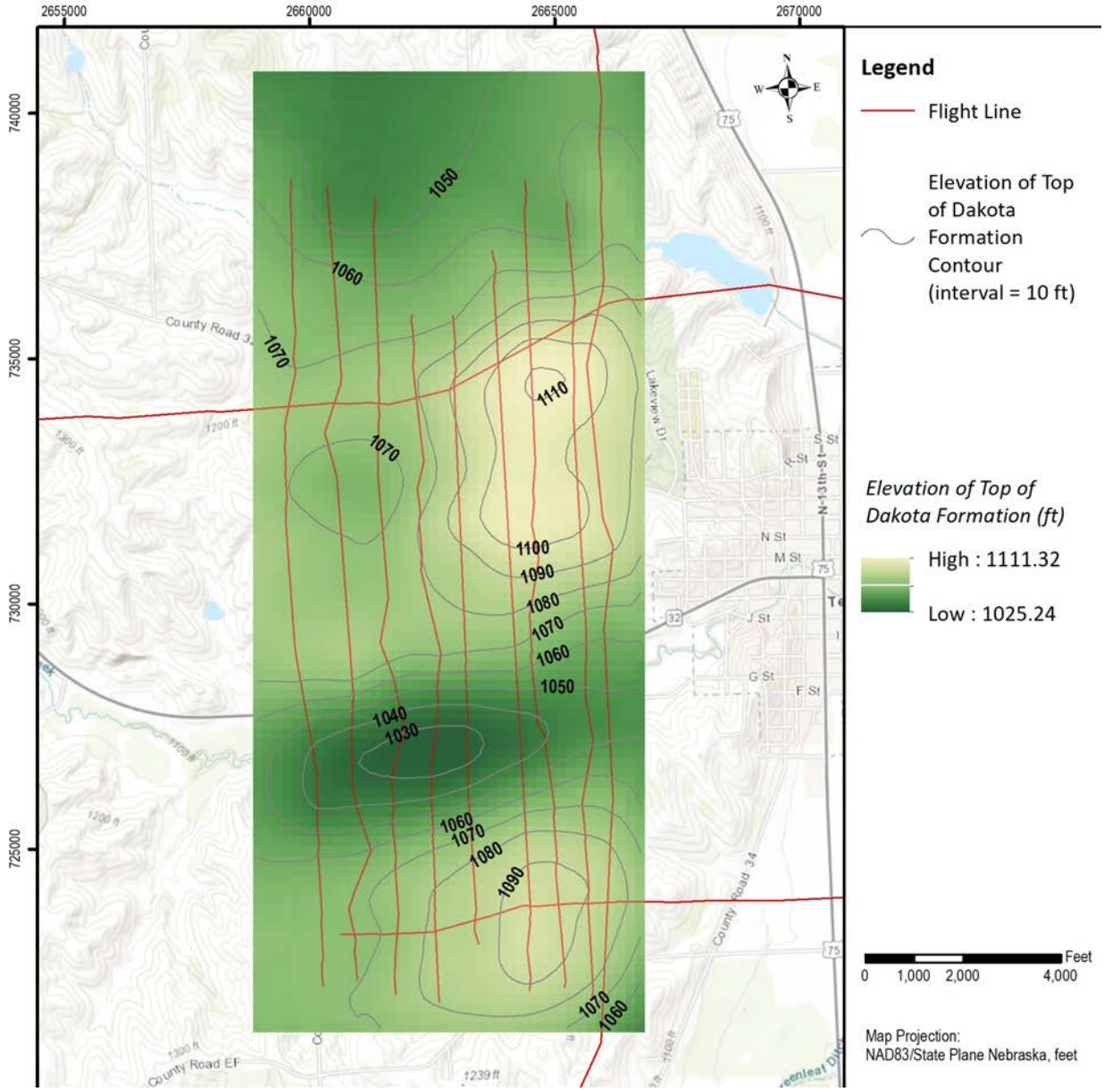


Figure 3-49. Map of the elevation of the top of the Cretaceous Dakota Group (*Kd*) within the P-MRNRD Tekamah Block from the 2018 survey. Flight lines are indicated by the brown lines. The projection is NAD83 State Plane Nebraska (feet) and the elevation values are referenced to NAVD 88 (feet).

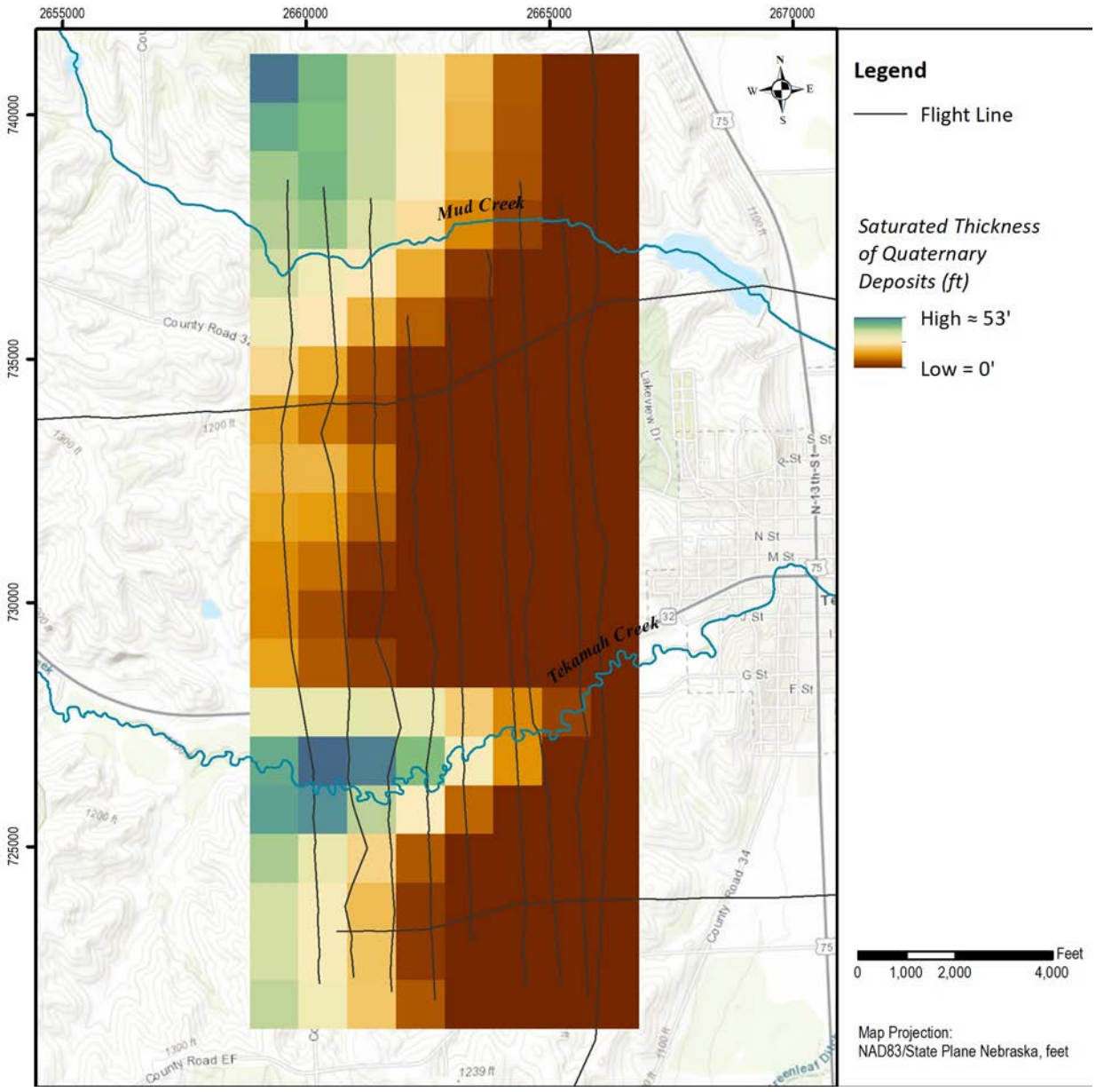


Figure 3-50. Map of the saturated thickness of Quaternary deposits (*Q*) within the 2018 Tekamah Block AEM survey area. Flight lines are indicated by black lines. The projection is NAD83 State Plane Nebraska (feet).

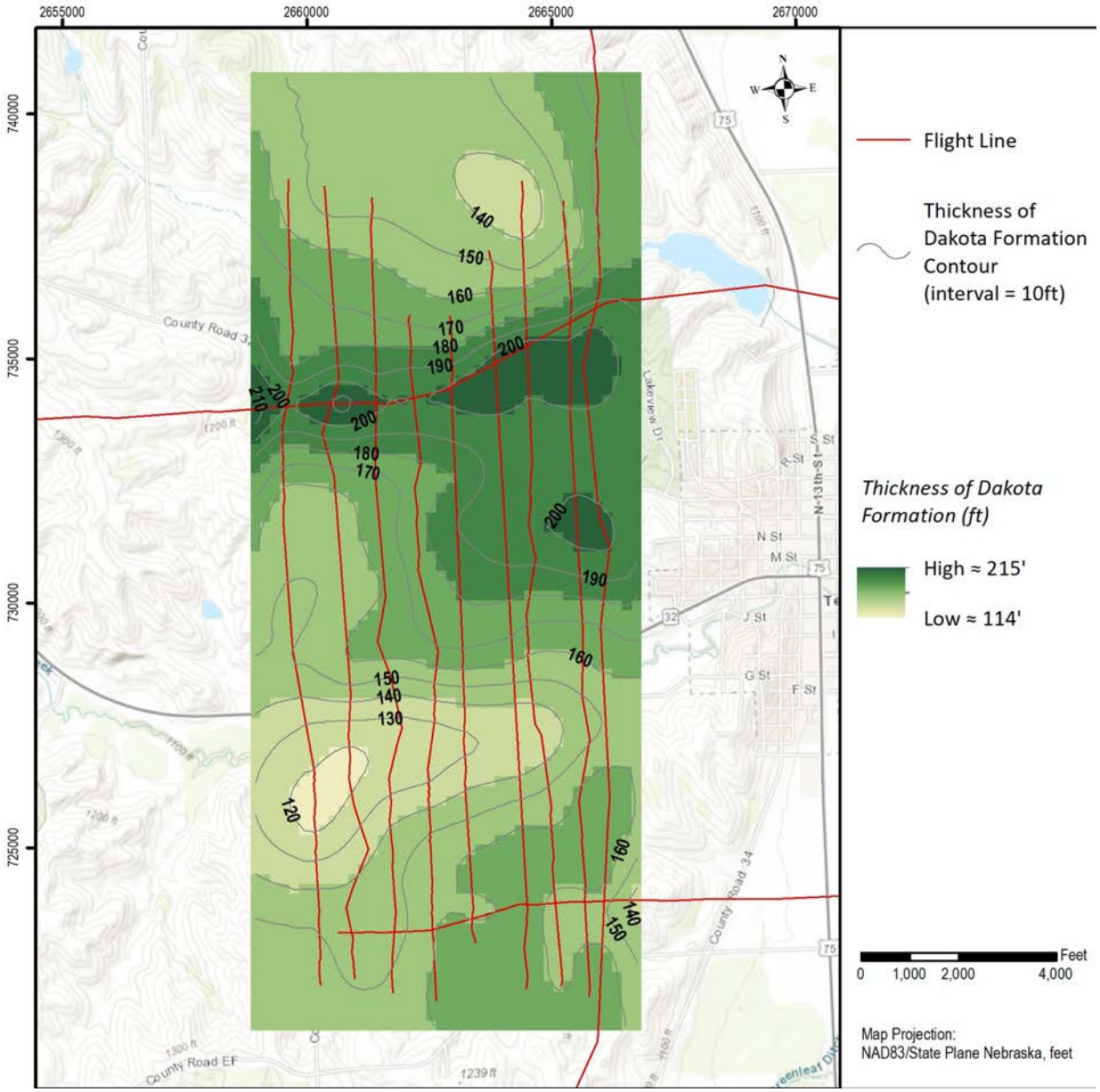


Figure 3-51. Map of the total thickness of the Cretaceous Dakota Group (*Kd*) deposits within the 2018 Tekamah Block. Flight lines are indicated by brown lines. The projection is NAD83 State Plane Nebraska (feet).

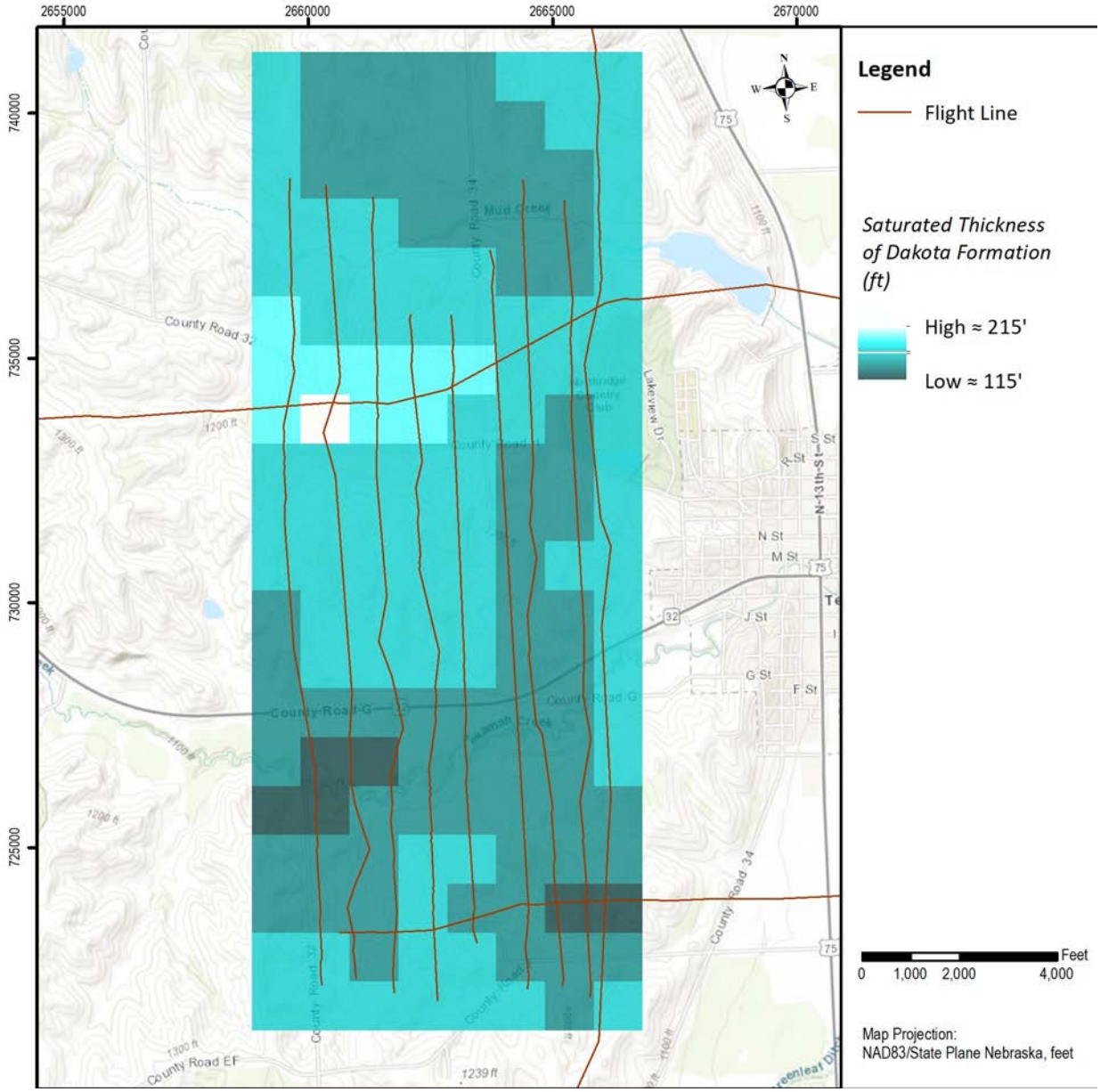


Figure 3-52. Map of the saturated thickness of the Cretaceous Dakota Group (*Kd*) deposits within the 2018 Tekamah Block. Flight lines are indicated by brown lines. The projection is NAD83 State Plane Nebraska (feet).

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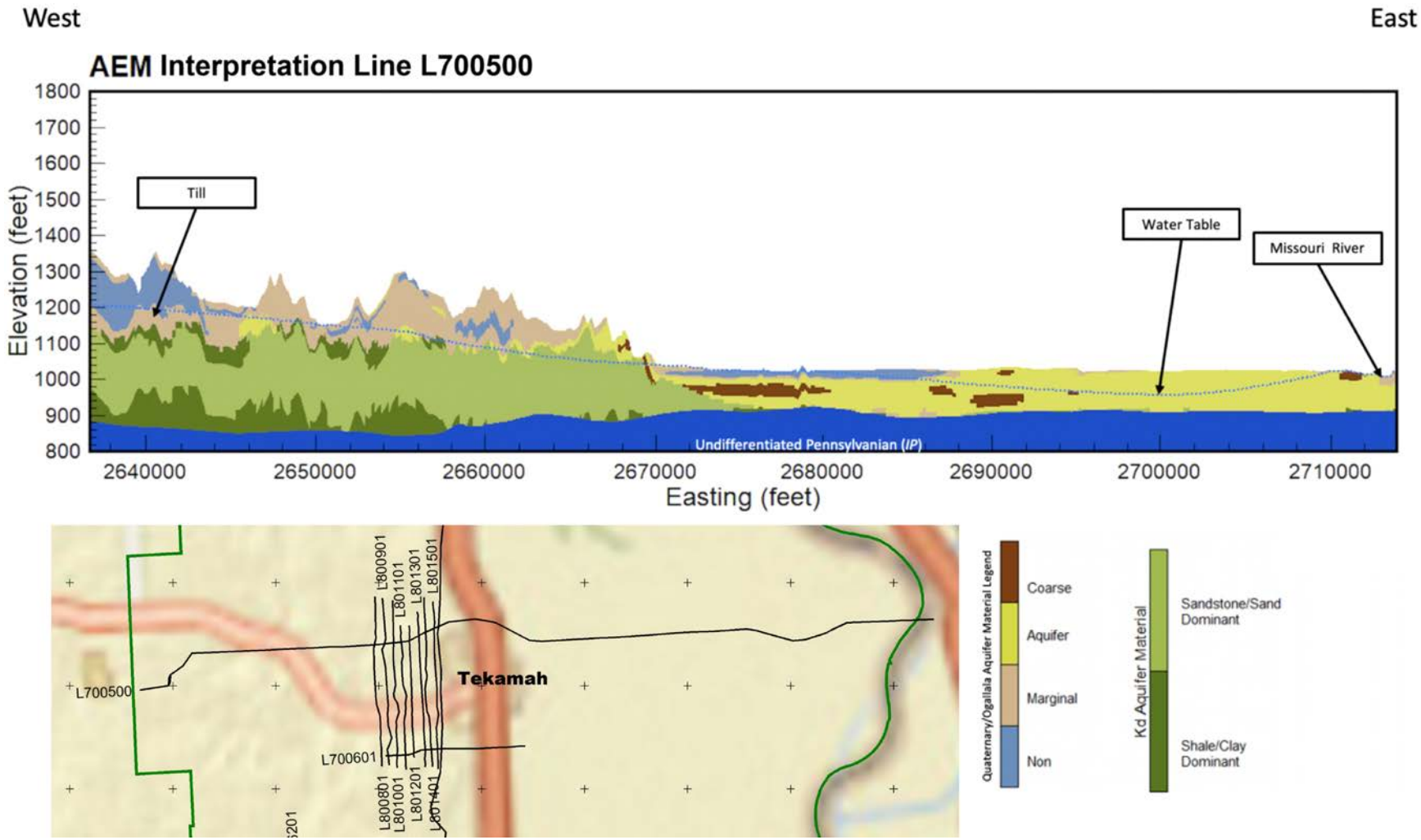


Figure 3-53. East-west Line L700500 located just north of the town of Tekamah and the Tekamah Block AEM survey area and west of the Missouri River. Same as Figure 3-40 with the addition of the location maps showing the line's relation to the town of Tekamah and the Tekamah Block AEM flight area. The profile shows good hydrologic connection between the Cretaceous Dakota Group (*Kd*) and the Missouri River Quaternary deposits. Interpretation of Undifferentiated Pennsylvanian (*IP*) is indicated by the blue area. The CSD 1995 water table is indicated with a dashed blue line.

As was discussed in Section 3.1.6, an alternate method for examination of the AEM results is as a 3D voxel in which the inversion results along the profiles are gridded and interpolated in 3D. Since the Tekamah Block AEM flight lines were designed to be only 820 ft (250 m) apart, the inversion results can be presented in high-definition as a 3D voxel.

Figure 3-54 is a view of a 3D voxel of the Tekamah Block, looking to the west, with the DNR borehole lithology logs spread across the area. All ***Q***, ***Kd***, and ***IP*** materials are present in this view. The ***Q*** materials are dominated by non- and marginal-aquifer materials in the Tekamah Block as it is apparent from this view that the aquifer materials and coarse aquifer material are quite thin across the area. Interpretation of the undifferentiated Pennsylvanian (***IP***) is indicated by the blue colored material at depth. Figure 3-55 is a similar view, but looking to the east.

Figure 3-56 is a "chair clip" view of the 3D voxel of the Tekamah Block, looking to the west, with the southeast corner of the ***Q*** and ***Kd*** material removed. The surface of the water table (NE-CSD, 1995) is now apparent as is a side-cut view of the ***Q*** materials. Note that the sandstone in the lithology logs matches the lighter green ***Kd*** sandstone/sand dominant area.

Figure 3-57 is similar "chair clip" view of the voxel as Figure 3-56 but with a difference being that the ***Kd*** > 40 ohm-m is now in view in the clipped area. The 40 ohm-m divide was an arbitrary selection of the ***Kd*** sandstone/sand dominant material that visually matched the areas of sandstone in the lithology logs. Note that ***Kd*** sandstone/sand dominant material > 40 ohm-m exists both above and below the water table surface (i.e. the lighter colored ***Kd*** material versus the darker colored ***Kd*** material).

In Figure 3-58 the 3D voxel has had all the ***Q*** materials removed. The surface of the water table is still there as are the ***Kd*** > 40 ohm-m and the ***IP***. Here it is more apparent that there is ***Kd*** sandstone/sand dominant material > 40 ohm-m both above and below the water table surface. Also note the presence of an erosional gap in the ***Kd*** just to the north of the location of Mud Creek. As interpretation of the ***IP*** is indicated by the blue-colored area, it appears that even the ***IP*** may be eroded in the identified gap area.

Now in Figure 3-59 the 3D voxel consists of only the ***Kd*** > 40 ohm-m. The erosional gap in the ***Kd*** just to the north of Mud Creek is still present. Note the character of the ***Kd*** on the west side of the Tekamah Block - There are apparent erosional features cut out on that side. The image of these apparent erosional features brings to mind a paper by Witzke and Ludvigson (1994) in which there was a cartoon depicting a prograding deltaic environment. This cartoon is presented in Figure 3-60. The pattern on the west side of the ***Kd*** > 40 ohm-m matches the depositional environment as described by Witzke and Ludvigson (1994). In particular, the similarities to the features identified in Figure 3-60 as "prodelta muds", "distributary channels", and "delta-front sand-silt". This is also discussed in O'Connor (1987).

Just for completeness sake, Figure 3-61 presents all the ***Kd*** and ***IP*** materials including both the sandstone/sand dominant and the shale/clay dominant ***Kd*** materials and without the surface of the water table.

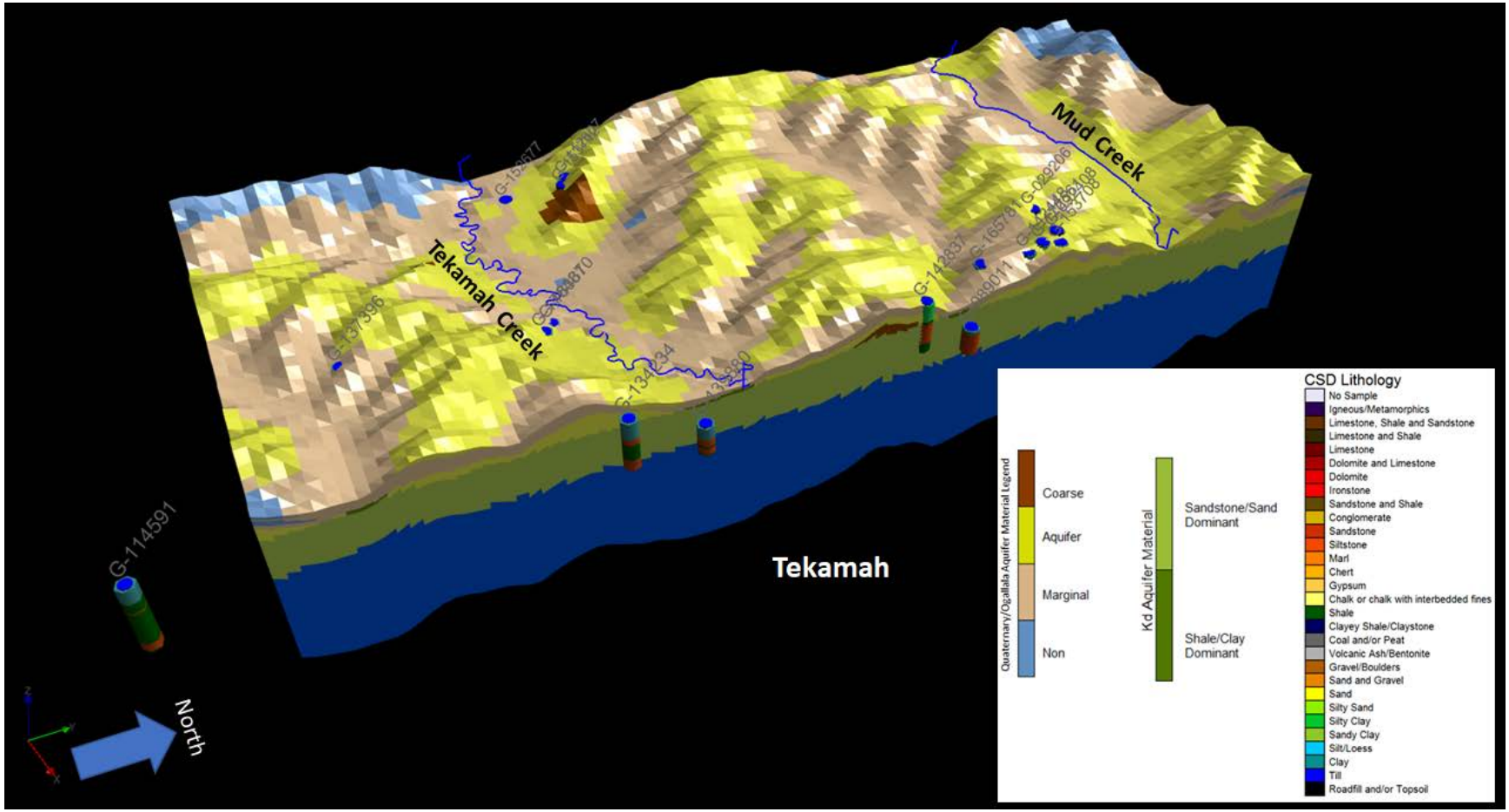


Figure 3-54. 3D voxel of the Tekamah Block, looking to the west, with DNR borehole lithology logs. The Q materials are dominated by non- and marginal-aquifer materials. Interpretation of the undifferentiated Pennsylvanian (*IP*) is indicated by the blue area. VE = 15x.

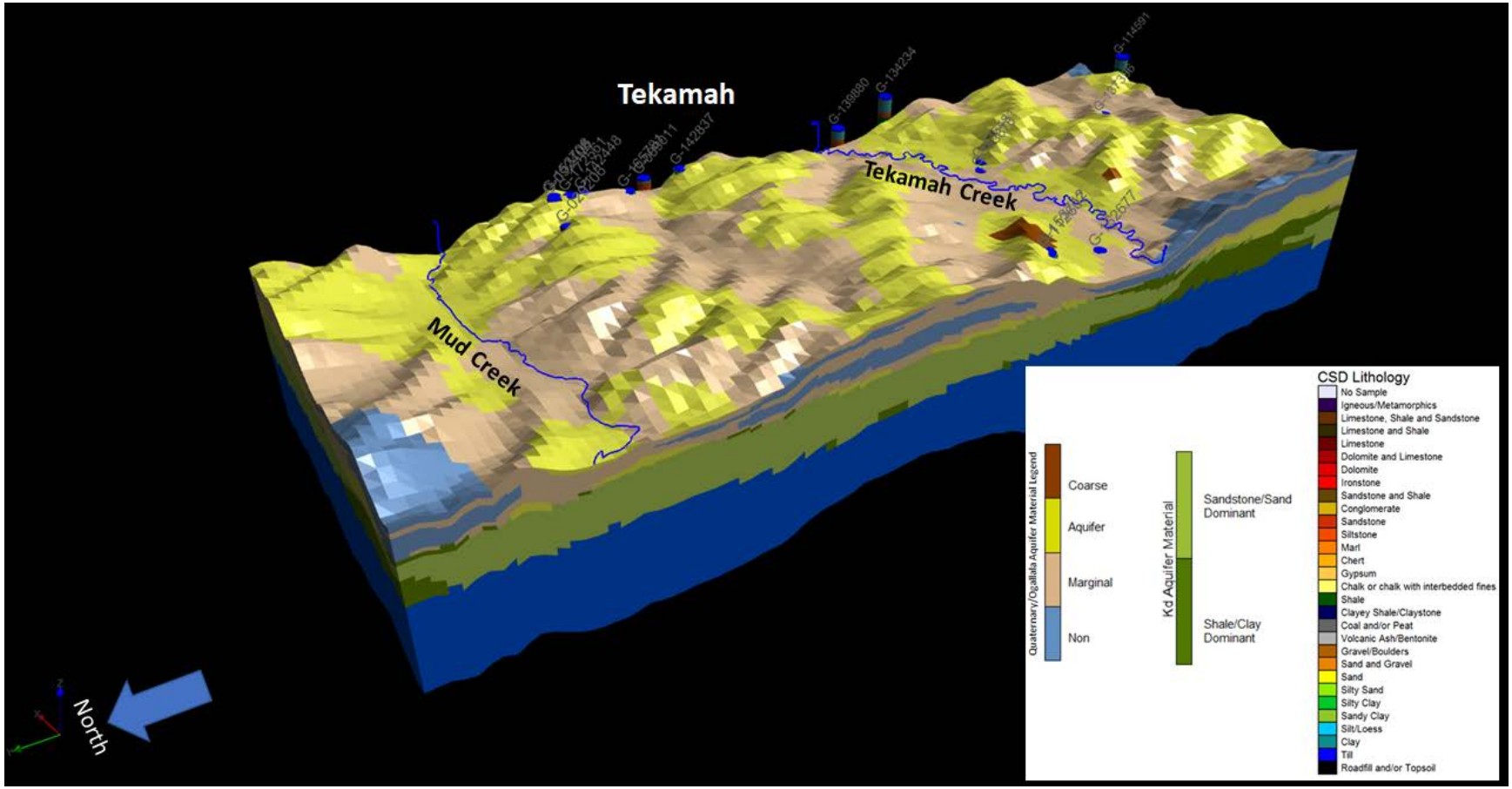


Figure 3-55. 3D voxel of the Tekamah Block, looking to the east, with DNR borehole lithology logs. The *Q* materials are dominated by non- and marginal-aquifer materials. Interpretation of the undifferentiated Pennsylvanian (*IP*) is indicated by the blue area. VE = 15x.

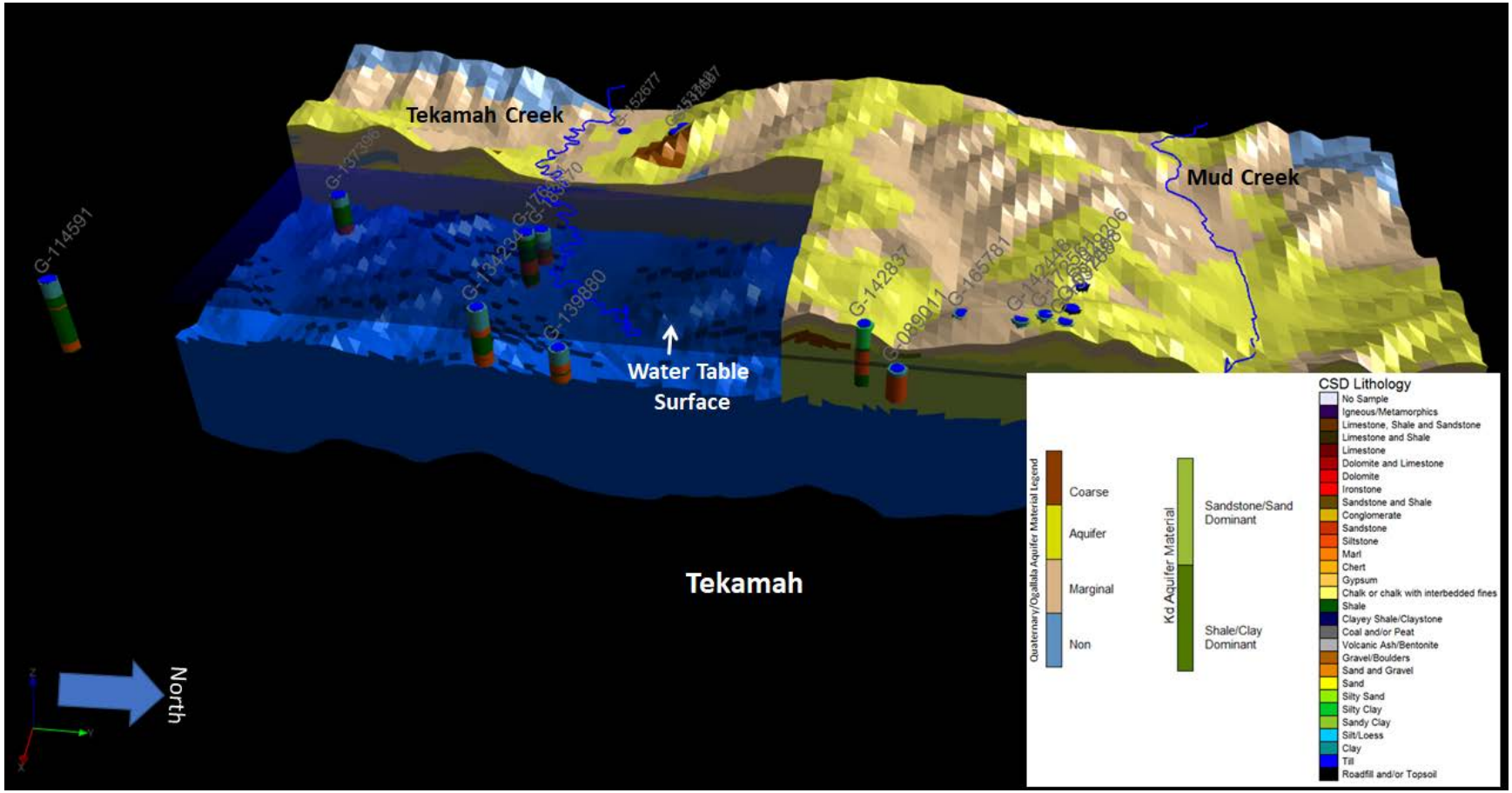


Figure 3-56. 3D voxel with "chair clip" of the Tekamah Block, looking to the west, with DNR borehole lithology logs. In the clipped area, the *Q* and *Kd* have been removed. Note that the sandstone in the logs matches the *Kd* sandstone/sand dominant area. Interpretation of the undifferentiated Pennsylvanian (*IP*) is indicated by the blue area. VE = 15x.

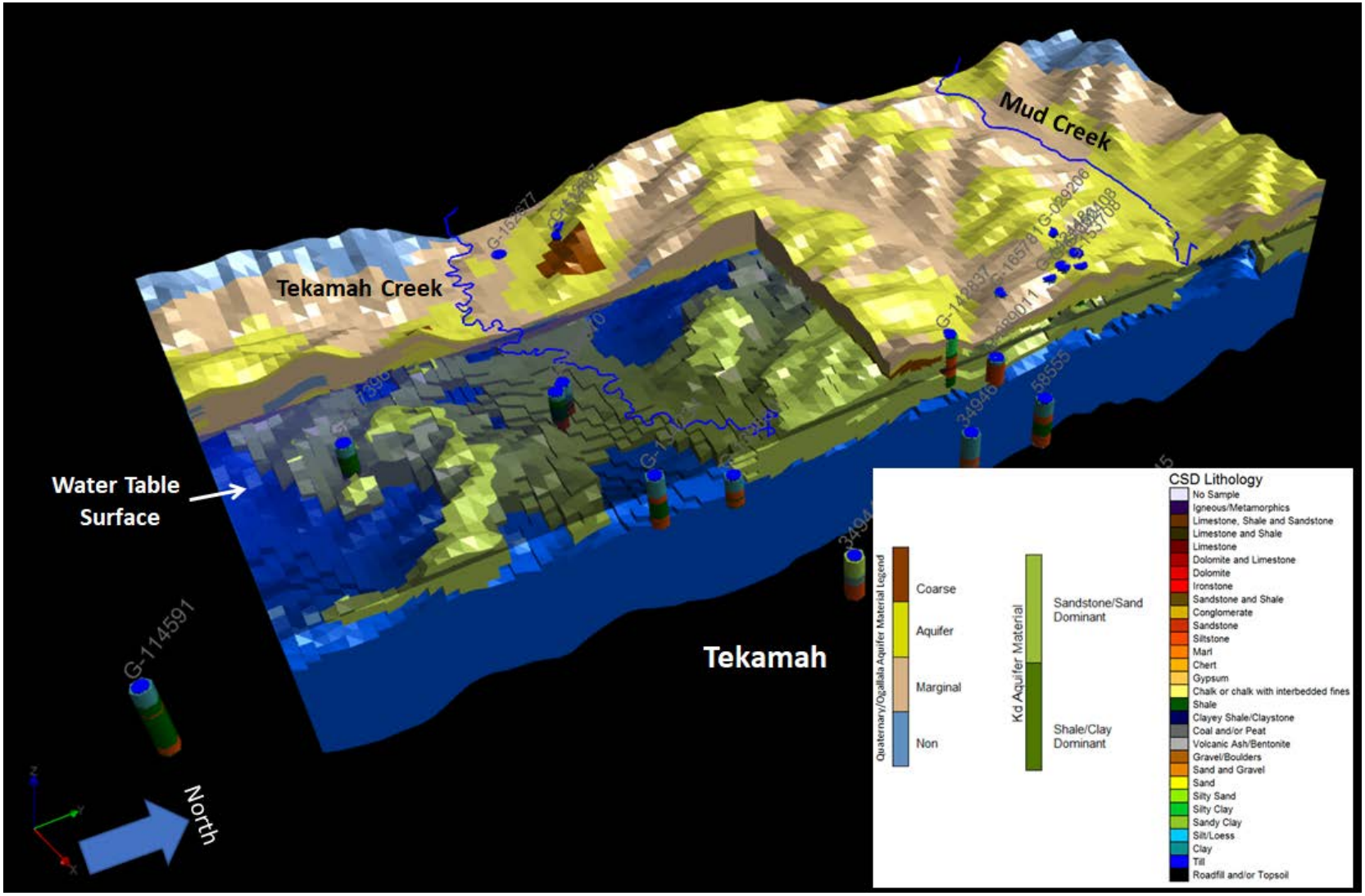


Figure 3-57. 3D voxel with "chair clip" of the Tekamah Block, looking to the west, with DNR borehole lithology logs. In the clipped area, the *Q* has been removed and only the *Kd* > 40 ohm-m is present. Note that *Kd* sandstone/sand dominant material is both above (lighter colored material) and below (darker colors) the water table surface. Interpretation of the undifferentiated Pennsylvanian (*IP*) is indicated by the blue area. VE = 15x.

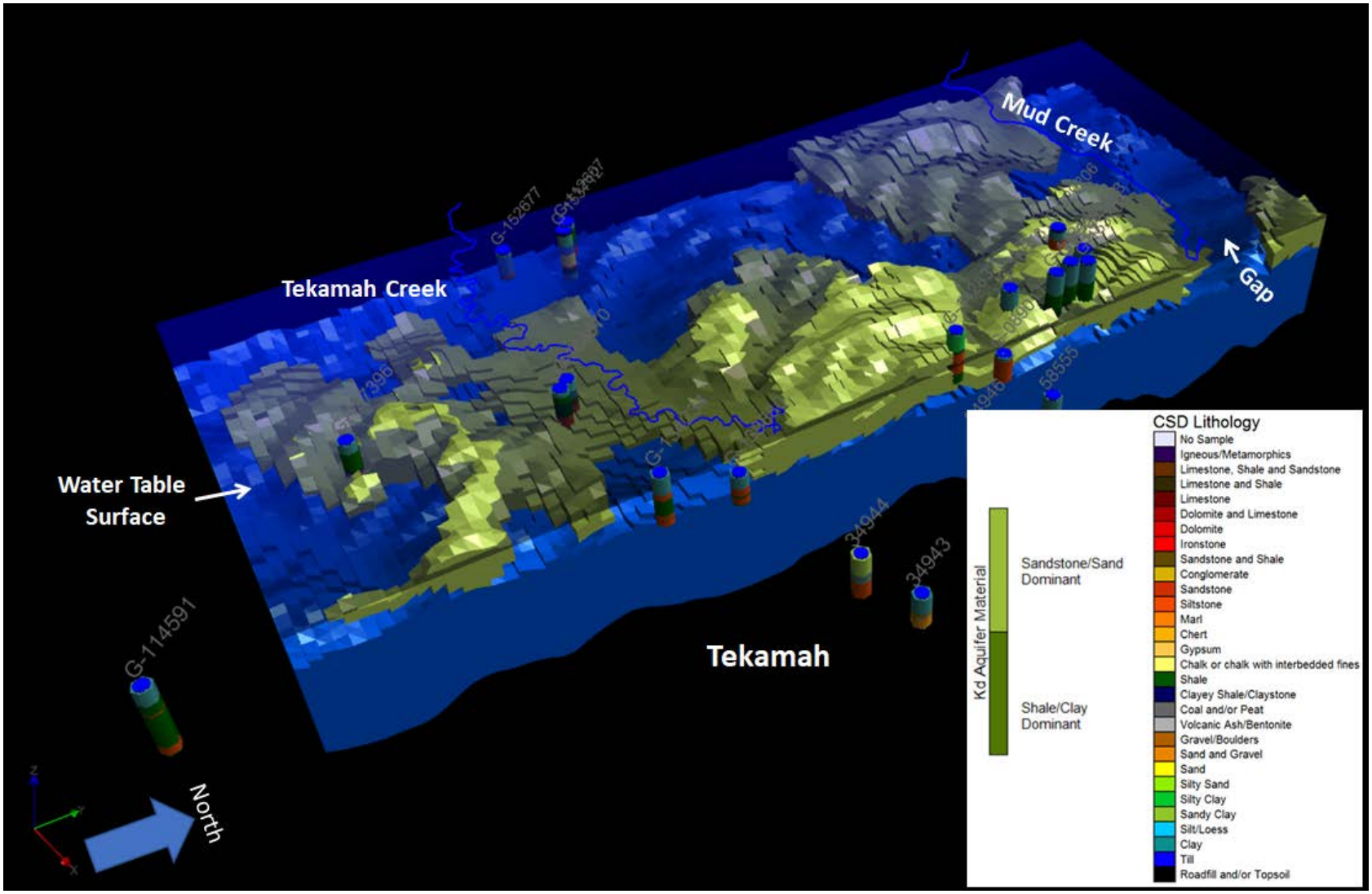


Figure 3-58. 3D voxel with of the Tekamah Block, looking to the west, with DNR borehole lithology logs, with all *Q* materials removed, and with only the *Kd* > 40 ohm-m present. Note that *Kd* sandstone/sand dominant material is both above (lighter colored material) and below (darker colors) the water table surface. Note the erosional gap in the *Kd* just to the north of Mud Creek. Interpretation of the undifferentiated Pennsylvanian (*IP*) is indicated by the blue area. It appears that even the *IP* may be eroded in the gap area. VE = 15x.

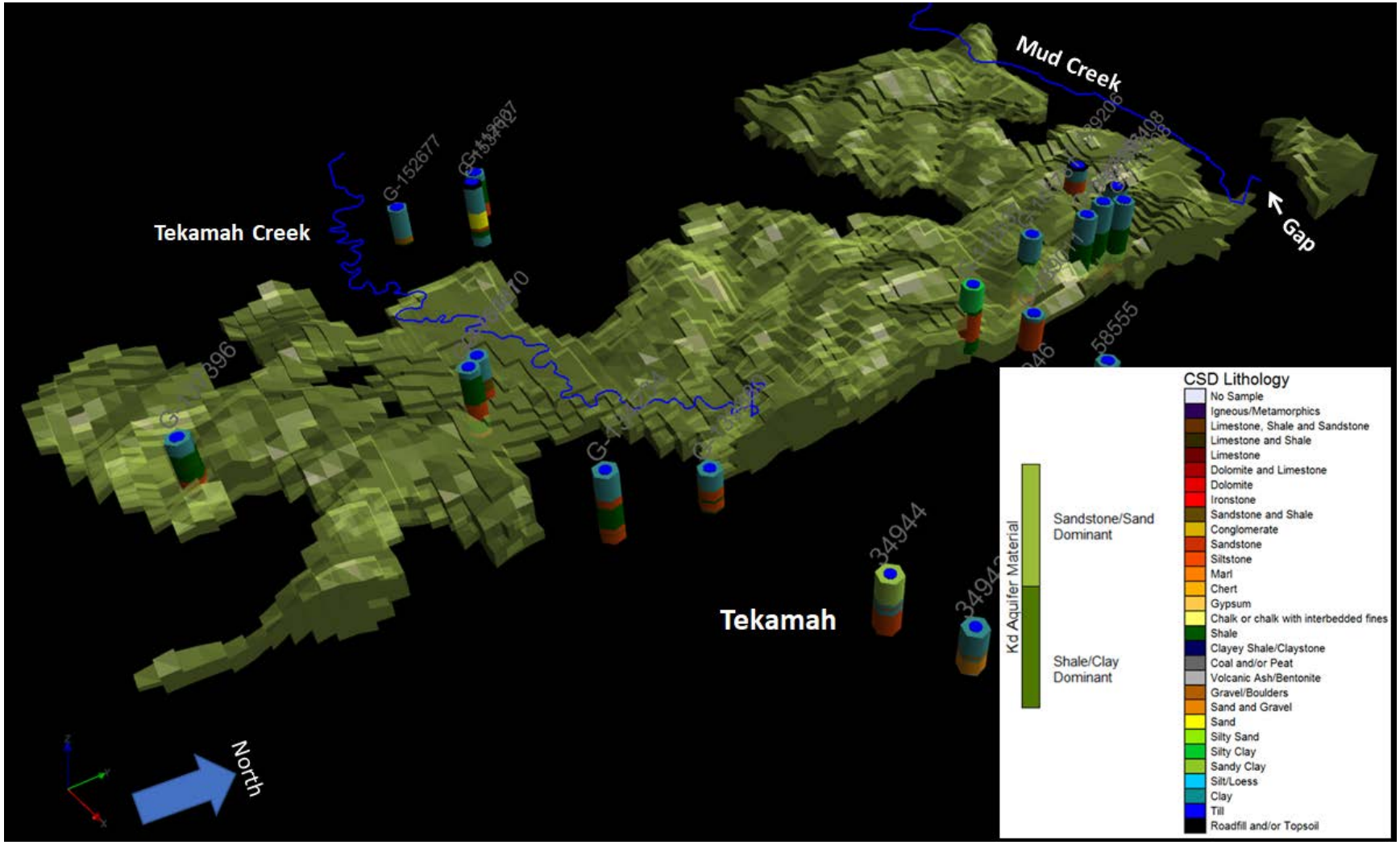


Figure 3-59. 3D voxel with of the Tekamah Block, looking to the west, with DNR borehole lithology logs, with all *Q* materials, the water table surface, and the *IP* removed, and with only the *Kd* > 40 ohm-m present. Note the erosional gap in the *Kd* just to the north of Mud Creek. VE = 15x.

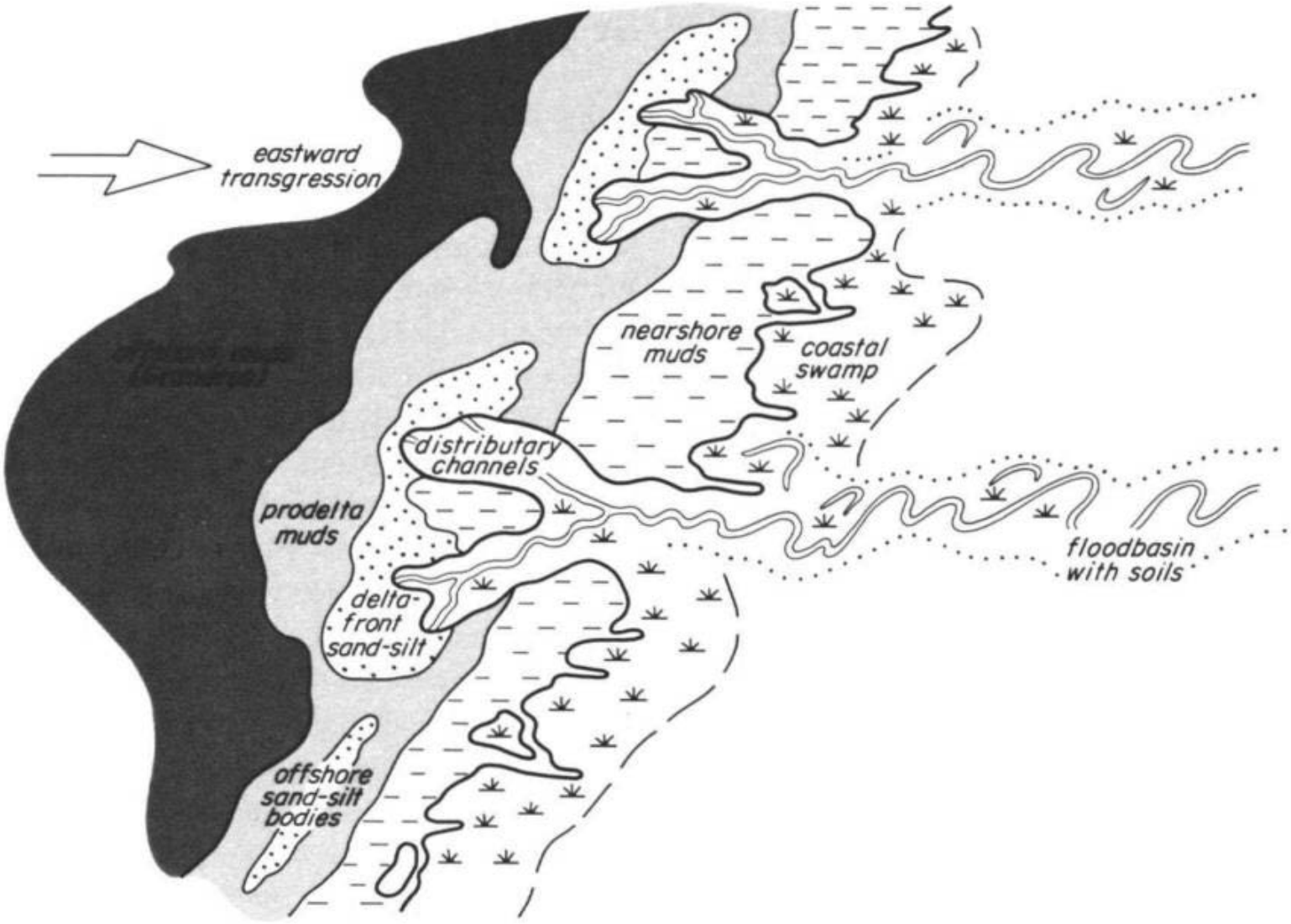


Figure 3-60. Depositional environment of the Dakota Group sediments during the Cretaceous Period in eastern Nebraska and western Iowa (Witzke and Ludvigson, 1994). Note the similarities of the features identified in this image as "prodelta muds", "distributary channels", and "delta-front sand-silt" with the shapes and character of the Kd > 40 ohm-m presented in Figure 3-59.

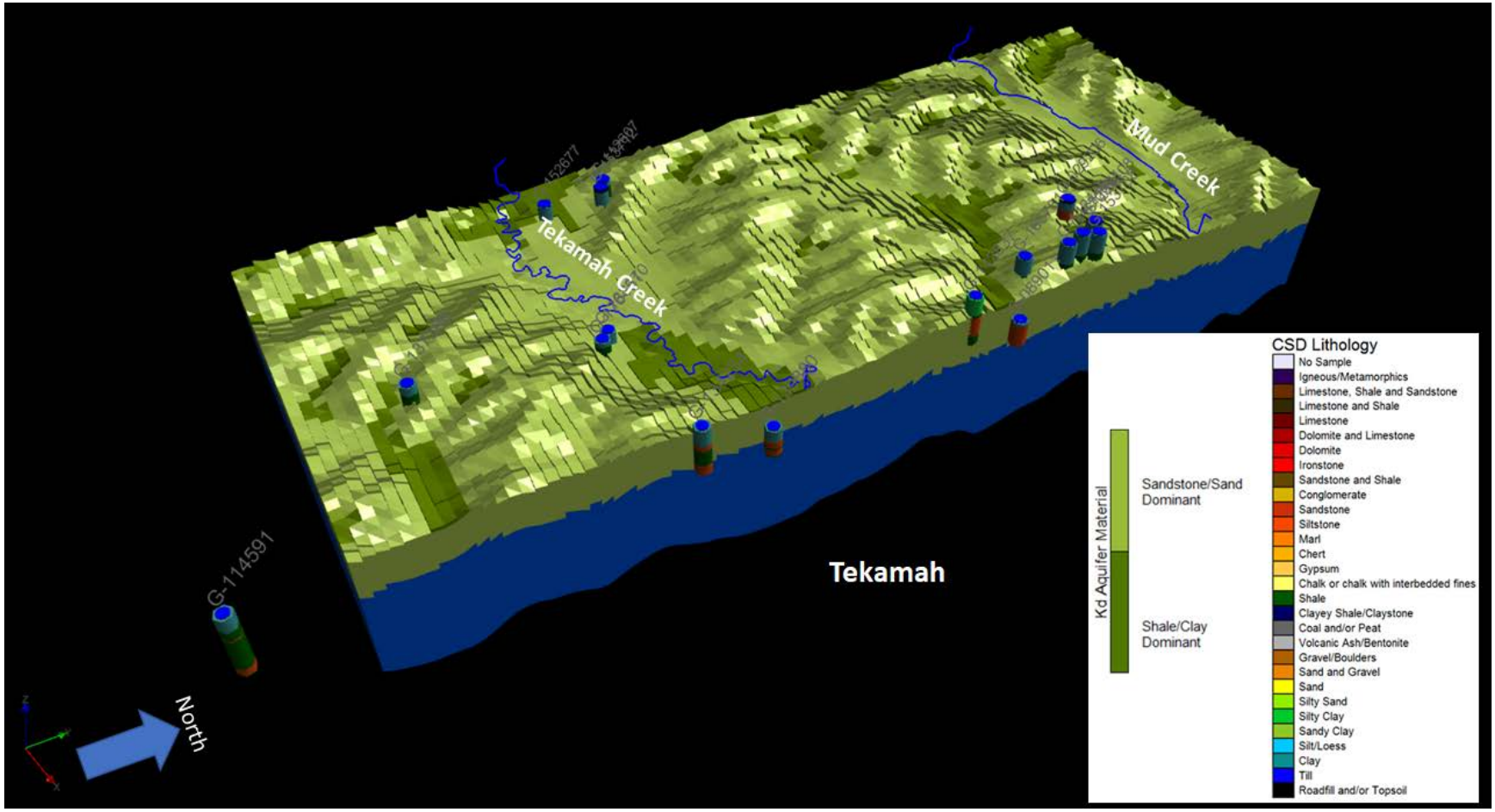


Figure 3-61. 3D voxel with of the Tekamah Block, looking to the west, with CSD borehole lithology logs, without the *Q* materials and the water table surface, and with all the *Kd* and *IP*. Interpretation of the undifferentiated Pennsylvanian (*IP*) is indicated by the blue area. VE = 15 x.

3.2.2.1 Tekamah Block Estimates of Aquifer Volumes and Yield

Three-dimensional digital representation of the subsurface resulting from the AEM method provides users the ability to more accurately estimate total unsaturated and saturated aquifer volume for ***Q*** and ***Kd*** materials. The saturated zones of the **Q** and ***Kd*** can be analyzed for an estimated amount of groundwater in storage and an amount of extractable water present. All aquifer materials within the ***Q*** sediments, including non-aquifer material, marginal aquifer material, and aquifer material are used for calculating the groundwater in storage volume and the extractable water volumes for the AEM survey area. Reported values of the average porosity for sand making up the aquifer material are based on values from Freeze and Cherry (1979). Clay ranges from 40%-70%, silt ranges from 35%-50%, and sand ranges from 25%-50%. Conservative estimates for the porosity values used in these calculations within the survey area are 40% for non-aquifer material, 35% for marginal aquifer material, 20% for the aquifer material, and 25% for the coarse aquifer material.

Specific yield values for ***Q*** materials were selected by estimating values from Olafsen-Lackey and Summerside (2005) and Summerside and Meyers (2005). No aquifer test information was available for this report from the 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 (Heath, 1983), 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 0.05 to 0.2 with an average of 0.10. The results are presented in Table 3-1.

Porosity and Specific Yield values for the ***Kd*** sandstone/sand dominant and the shale/clay dominant materials were taken from published values by Heath (1983) and O'Connor (1987). The values for sandstone are porosity is 0.11 of volume and specific yield is 0.06 of water in storage. The ***Q*** non-aquifer materials values, porosity = 0.40 and specific yield = 0.02, will be used for calculating groundwater storage/yield for the ***Kd*** shale/clay dominant materials. The results are contained in Table 3-2.

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

Table 3-1. Fully saturated Quaternary (*Q*) aquifer materials within the Tekamah Block area.

Aquifer Material Type	Aquifer Volume (ft^3)	Aquifer Volume (acre-ft)	Average Porosity	Groundwater in Storage Volume (acre-ft)	Average Specific Yield	Extractable Water Volume (acre-ft)
Non-Aquifer	184,444,746	4234	0.40	1,693	0.02	34
Marginal	622,917,754	14,300	0.35	5,005	0.05	250
Aquifer	746,709,902	17,142	0.20	3,428	0.10	343
TOTAL	1,554,072,402	35,676		10,126		627

Table 3-2. Fully saturated Cretaceous Dakota Group (*Kd*) aquifer materials within the Tekamah Block area.

Aquifer Material Type	Aquifer Volume (ft^3)	Aquifer Volume (acre-ft)	Average Porosity	Groundwater in Storage Volume (acre-ft)	Average Specific Yield	Extractable Water Volume (acre-ft)
Shale/clay	900,096,148	20,663	0.40	8,265	0.02	165
Sandstone/sand	20,267,523,876	465,279	0.11	51,180	0.06	3,071
TOTAL	21,824,464,402	485,942		59,445		3,236

3.3 Recharge Areas in the P-MRNRD AEM Survey Area

3D representations of the subsurface resulting from AEM investigations illustrate areas of aquifer materials from the bedrock up to the land surface. A new 40-layer model (previous work used a 30-layer model) was developed for the layer inversions and interpretations for the P-MRNRD. From these interpretations a new series of near-surface maps were constructed for the Tekamah Block AEM flight area that include the layer intervals from 0 to 3 ft, 7 to 11 ft, 15 to 20 ft, and 25 ft to 31 ft. These model layers are shown because they provide a visualization of whether the sediments are made up of aquifer material (brown - "good") to coarse aquifer material (blue - "very good"). From the discussion around Table 2-3, each model layer represents an average of the earth's resistivities within those depths, based on the physics of the electromagnetic exploration technique. The first layer through the seventh layer maps show aquifer materials and indicate the areas at the land surface and just below that can potentially transmit water to the groundwater aquifers in the area. The coarse aquifer material can transmit the largest volume of water. By viewing layers at depth an understanding of the heterogeneity of the aquifer materials and their distribution can be achieved. There is not always a direct path downwards to the aquifer from the land surface. Often there is no path available for the water to move through. Figure 3-62 shows the potential for recharge in layer 1, 0 to 3 ft as a range from blue representing very good recharge to brown which is good recharge. Figure 3-63 represents layer 3, 7 to 11 ft, Figure 3-64 represents layer 5, 15 to 20 ft, and Figure 3-65 represents layer 7, 25 ft to 31 ft. The layers below layer 31 ft tend to be poor for recharge in the Tekamah Block.

The P-MRNRD southern reconnaissance flight lines show an estimate of recharge near the flight lines only, they are not interpolated away from the line as the distance to be interpolated is too great and the only information for giving potential recharge is the resistivity interpretation of aquifer materials along the flight line. Only two model layers, layer 1, 0-3 ft (Figure 3-66), and Layer 7, 25 ft - 31 ft, (Figure 3-67) are shown. The layers below 31 ft are variable across the district depending on the materials present. Tills tend to be poor recharge areas and alluvial systems tend to be very good recharge. Note the very good potential recharge areas along the rivers in the southwest and across the reconnaissance flight lines in the far north, also along the river.

However, since the amount of slope of the land surface plays a large role in the amount of residence time that water will spend in an area, the greater the length of time spent at a location, the greater the amount of infiltration potential. The greatest possibility for recharge in the P-MRNRD AEM survey area is the alluvial valley floor and the creek beds that have aquifer and coarse aquifer materials near the land surface. On the table lands, the best possible location for recharge would be where there is a combination of aquifer and coarse aquifer materials at the land surface on the uplands with little relief in elevation with a pathway of similar materials down to the saturated aquifer at depth.

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

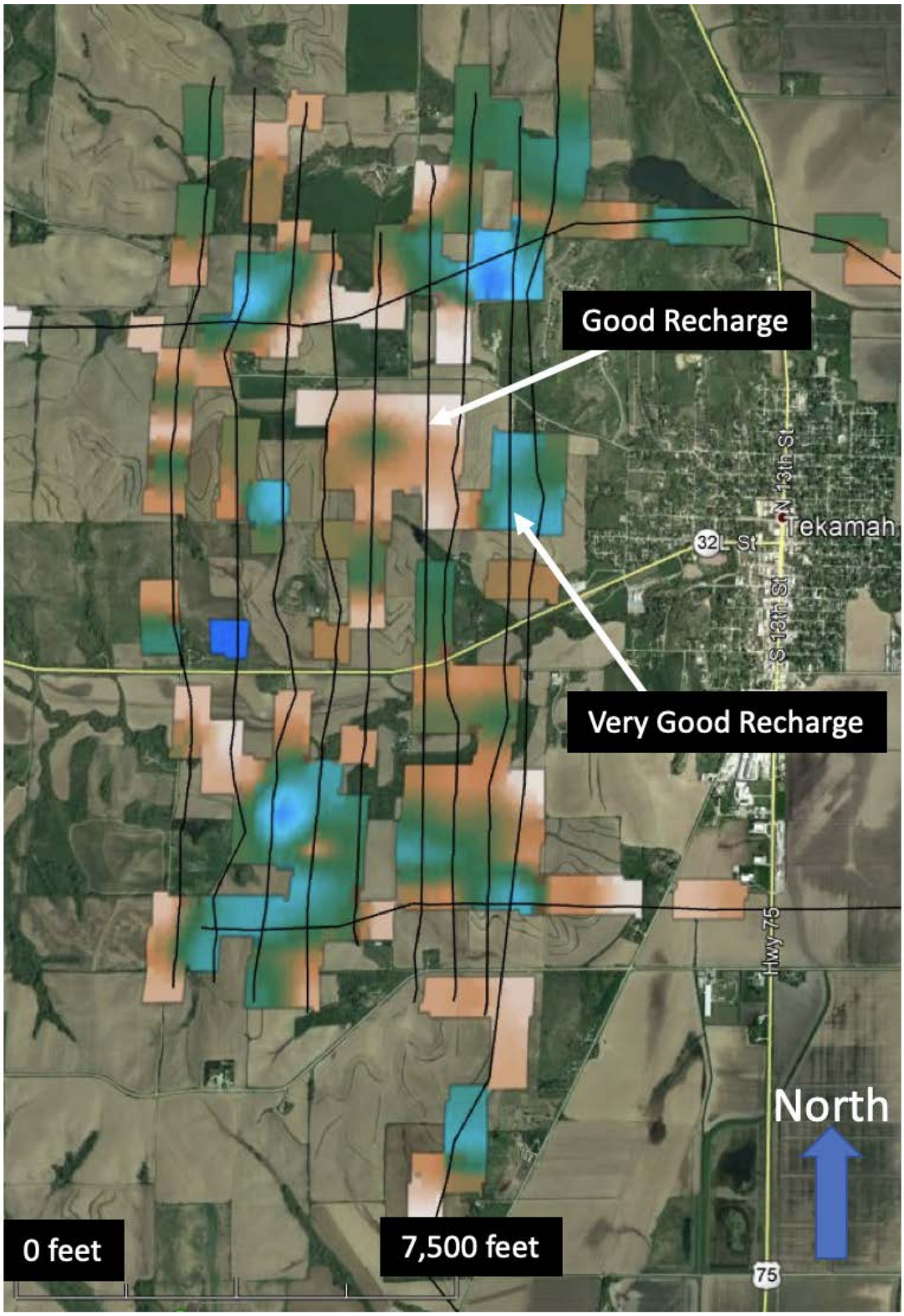


Figure 3-62. Google Earth image of potential recharge for the range 0-3 ft (AEM inversion model layer 1) for aquifer and coarse aquifer materials (resistivities greater than 20 ohm-m) within the 2018 Tekamah Block AEM flight area. Blue colors represent very good recharge and brown is good recharge. This kmz included in Appendix 3-Deliverables\KMZ\Recharge.

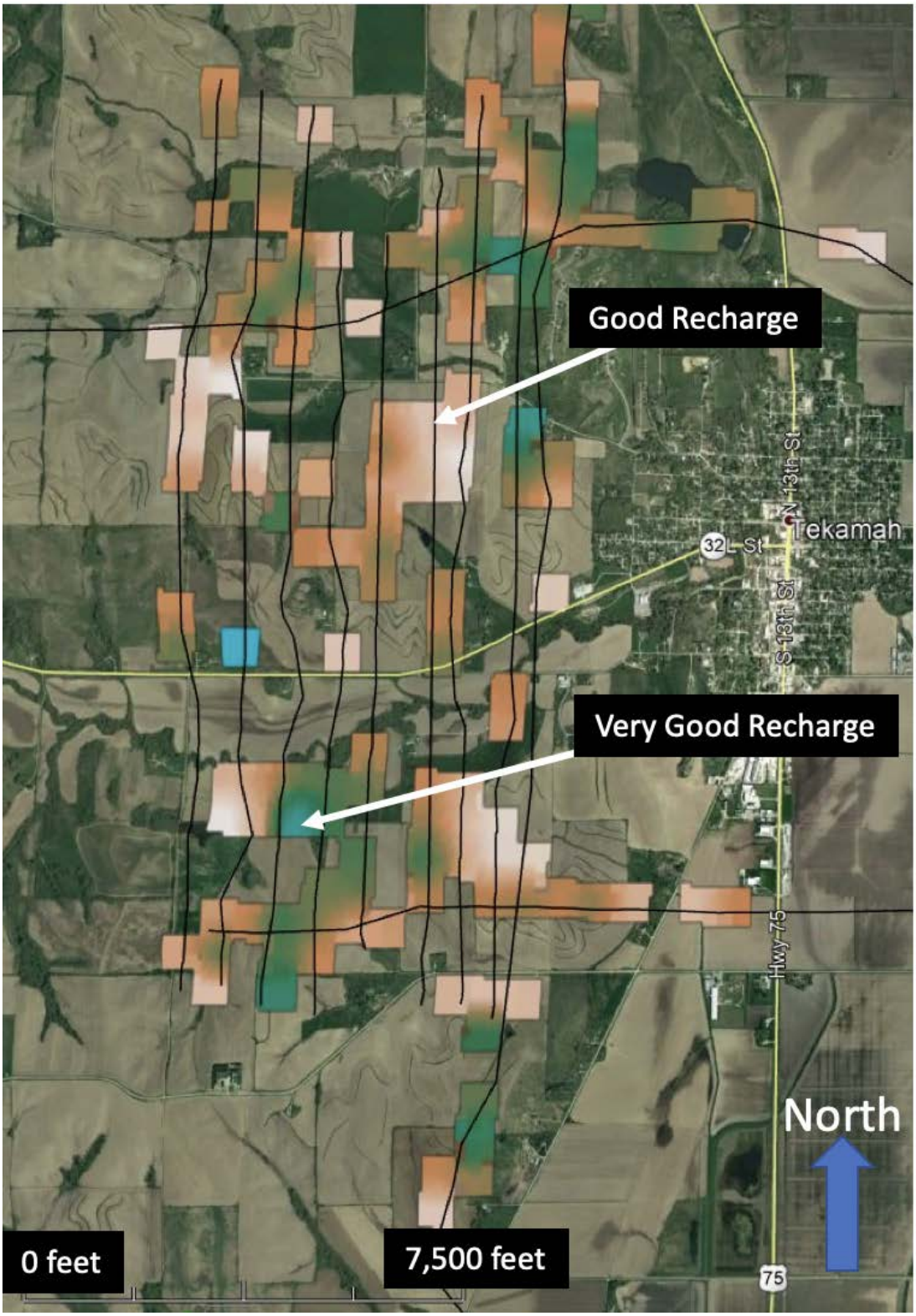


Figure 3-63. Google Earth image of potential recharge for the range 7-11 ft (AEM inversion model layer 3) for aquifer and coarse aquifer materials (resistivities greater than 20 ohm-m) within the 2018 Tekamah Block AEM flight area. Blue colors represent very good recharge and brown is good recharge. This kmz included in Appendix 3-Deliverables\KMZ\Recharge.

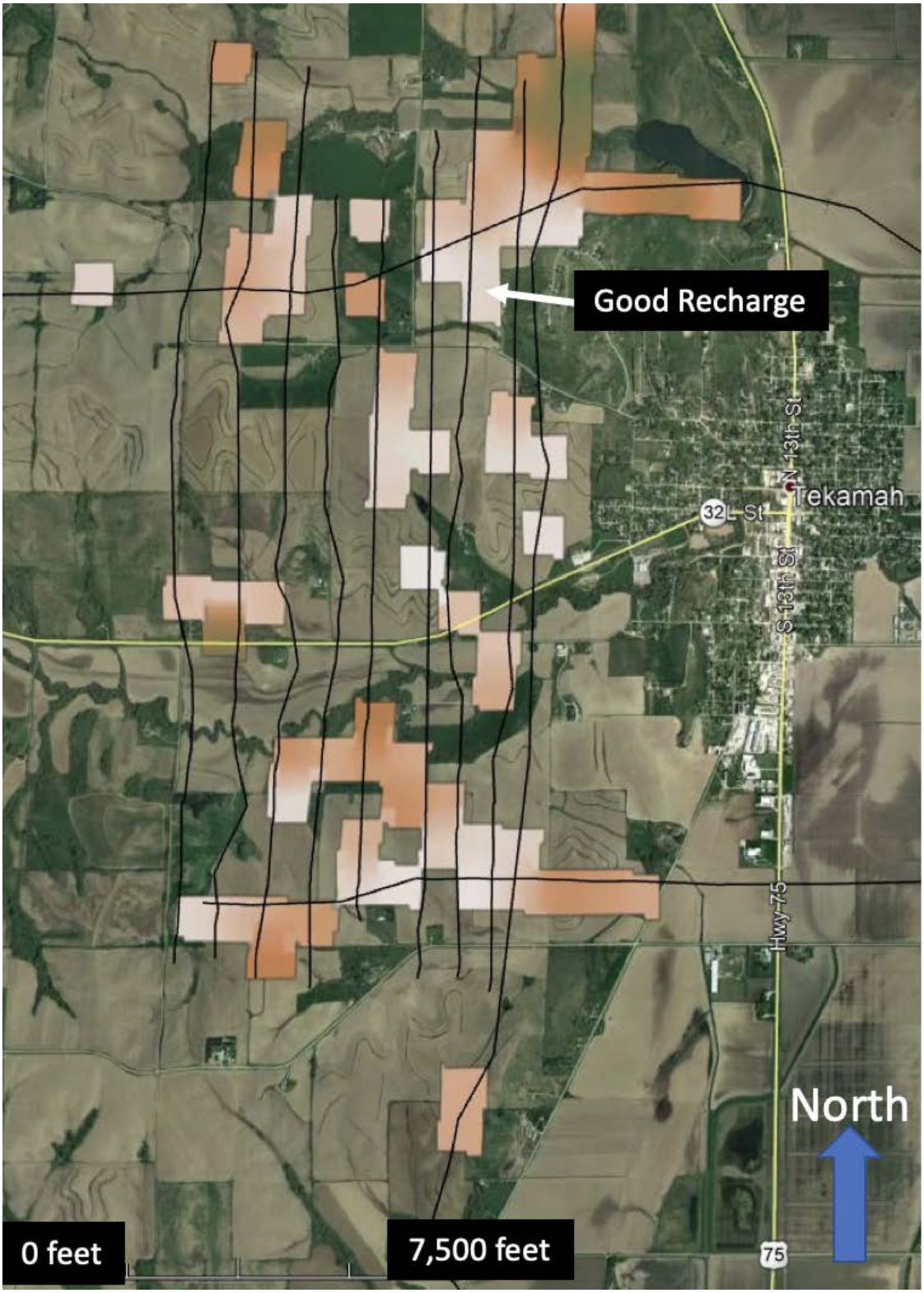


Figure 3-64. Google Earth image of potential recharge for the range 15-20 ft (AEM inversion model layer 5) for aquifer and coarse aquifer materials (resistivities greater than 20 ohm-m) within the 2018 Tekamah Block AEM flight area. Blue colors represent very good recharge and brown is good recharge. This kmz included in Appendix 3-Deliverables\KMZ\Recharge.

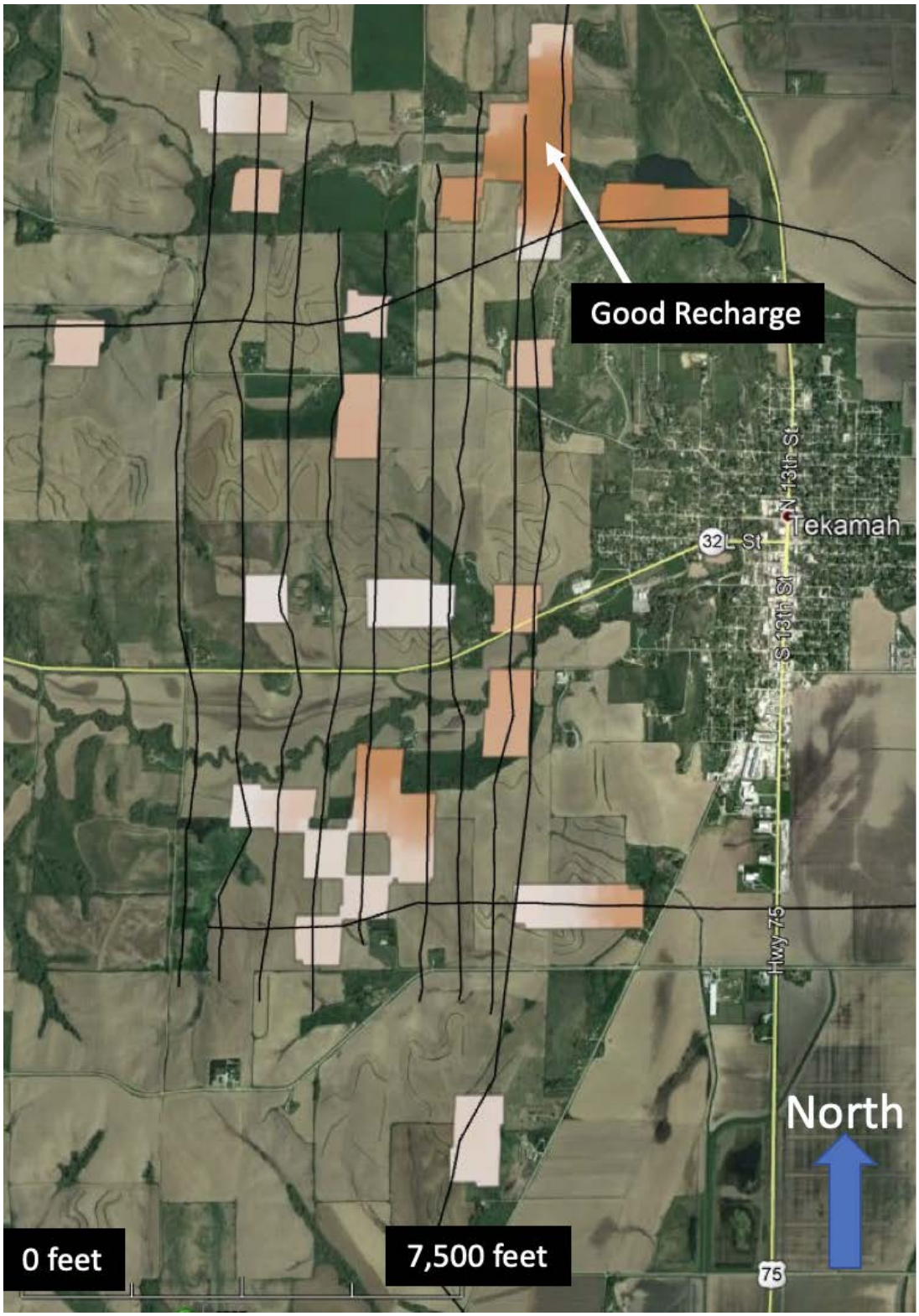


Figure 3-65. Google Earth image of potential recharge for the range 25-31 ft (AEM inversion model layer 7) for aquifer and coarse aquifer materials (resistivities greater than 20 ohm-m) within the 2018 Tekamah Block AEM flight area. Blue colors represent very good recharge and brown is good recharge. This kmz included in Appendix 3-Deliverables\KMZ\Recharge.

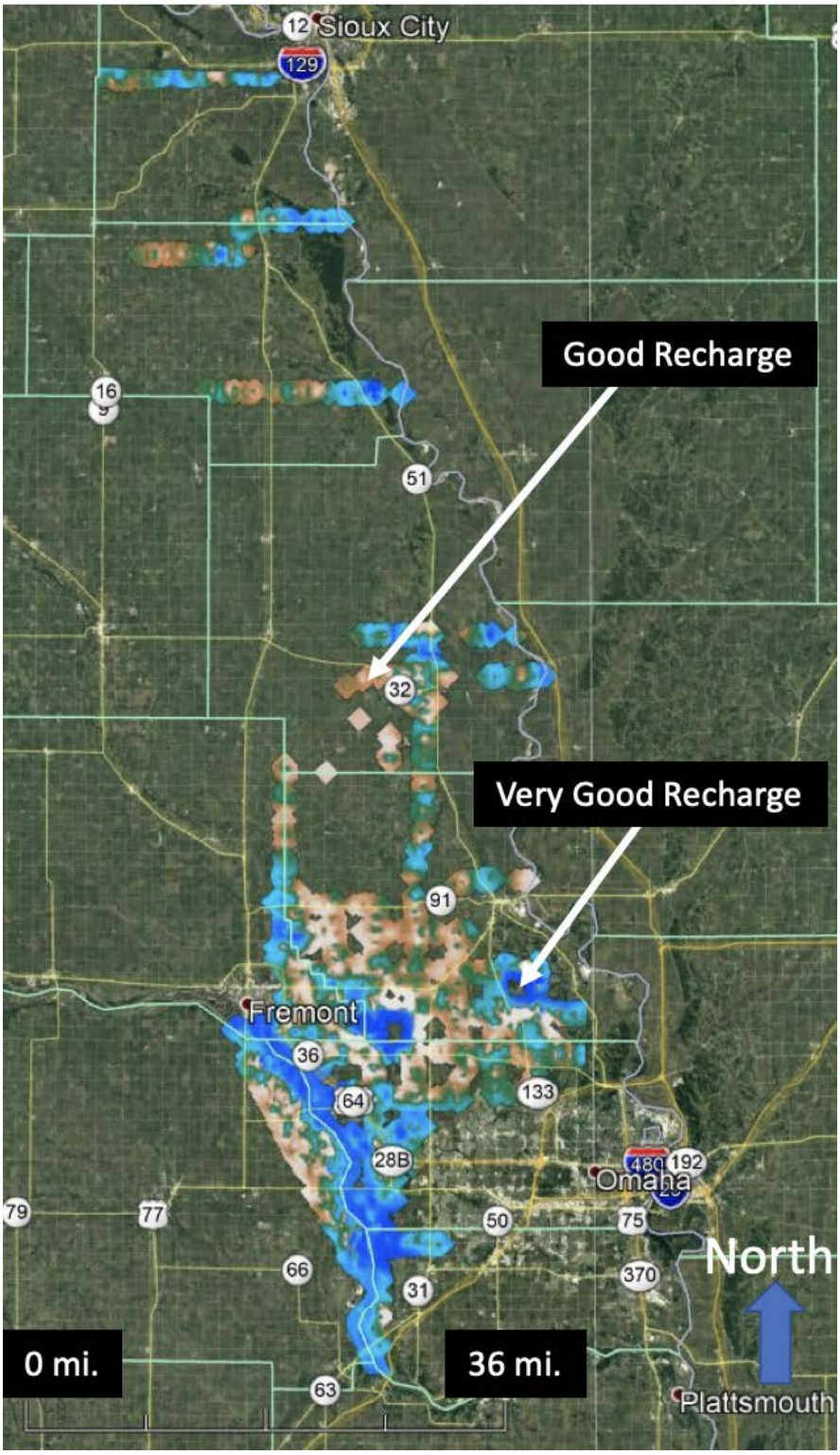


Figure 3-66. Google Earth image of potential recharge for the range 0-3 ft (AEM inversion model layer 1) for aquifer and coarse aquifer materials (resistivities greater than 20 ohm-m) along the reconnaissance flight lines within the 2018 P-MRNRD AEM flight area. Blue colors represent very good recharge and brown is good recharge. This kmz included in Appendix 3-Deliverables\KMZ\Recharge.

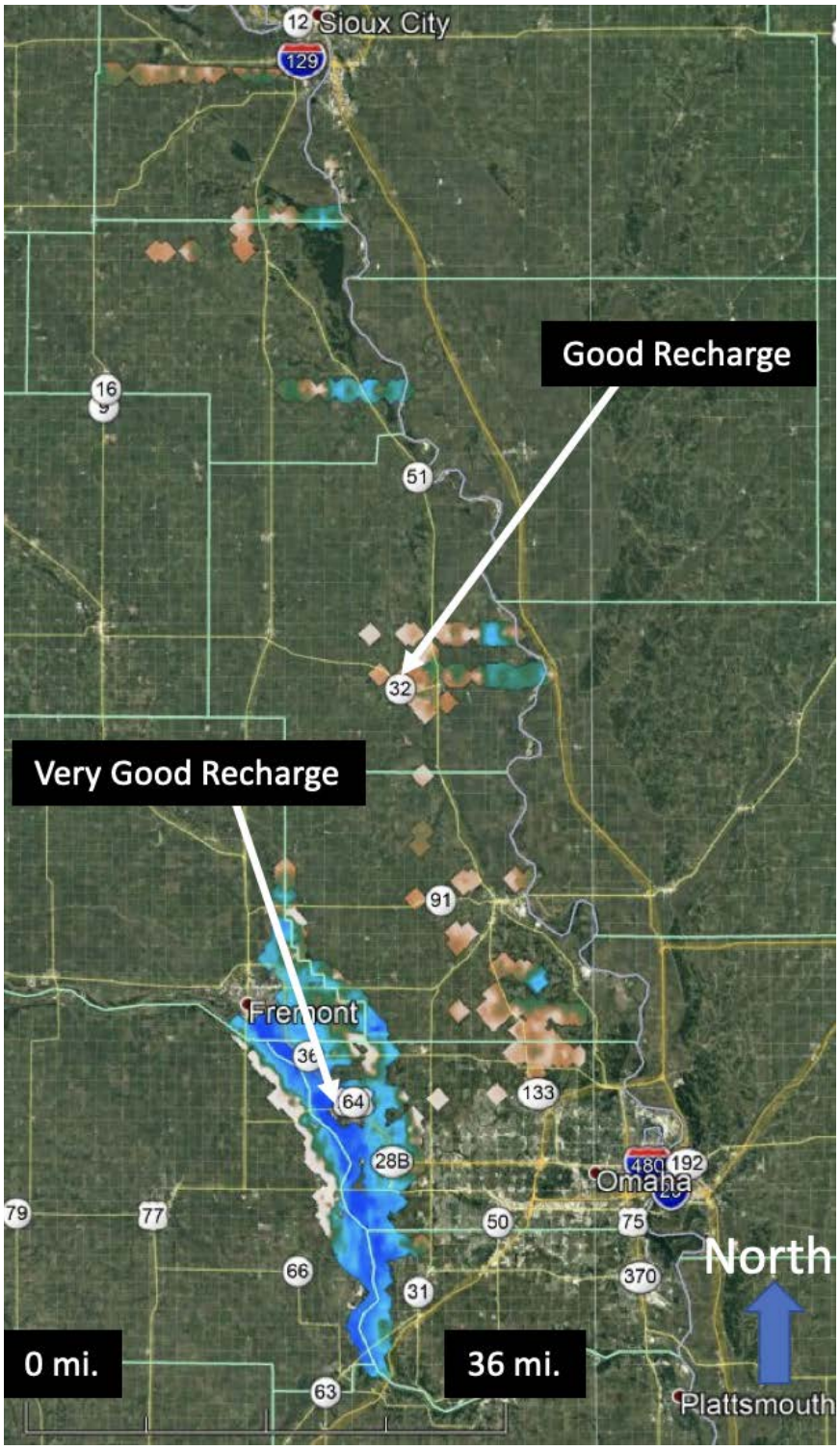


Figure 3-67. Google Earth image of potential recharge for the range 25-31 ft (AEM inversion model layer 7) for aquifer and coarse aquifer materials (resistivities greater than 20 ohm-m) along the reconnaissance flight lines within the 2018 P-MRNRD AEM flight area. Blue colors represent very good recharge and brown is good recharge. Note the good degree of recharge still available along the river in the southwest and up in the northeast of the AEM flight area. This kmz included in Appendix 3-Deliverables\KMZ\Recharge.

3.4 Key AEM Findings

3.4.1 Boreholes

Information from boreholes was used to analyze the AEM inversion results and was important for all areas in the P-MRNRD. The top of the undifferentiated Pennsylvanian (***IP***)was a challenging unit to interpret due to the highly variable resistivity of the ***IP.*** Top of the bedrock for the area was developed by inspection of the borehole logs that included consolidated geologic units and CSD (Nebraska Conservation and Survey Division) bedrock contacts. The Cretaceous Carlile (***Kc***) and the Cretaceous Greenhorn Limestone and Graneros Shale ***(Kgg)*** only occurred in the northern reconnaissance lines. The CSD stratigraphic control was utilized to distinguish the ***Q*** from the underlying ***Kc*** and ***Kgg***. Contacts between the Quaternary (***Q***) and Cretaceous Dakota Group (***Kd***) often had limited or no contrast in the electrical resistivity between the different geologic formations. Use of CSD stratigraphy calls and the presence of sandstone and shale in the NE- DNR (Nebraska Department of Natural Resources) registered wells were used to pick the **Q/Kd** contact when no resistivity contrast was present. The dependence on just boreholes for geologic interpretation also has its limitations because sometimes the boreholes are wrong, improperly located, have improper stratigraphic/lithology picks, and/or other errors. These errors in the boreholes are usually encountered in the NE-DNR registered wells. Very rarely inconsistencies are encountered in the oldest of the NE- CSD wells. The limited errors in the CSD wells may very well be due to poor positioning from a time before GPS and modern survey methods. As a guide in the interpretation of the AEM a bedrock surface was prepared using the of CSD and NE-DNR borehole logs. This work was conducted by Mike Plante and Roscoe Sopiwnik of WSP. As in all surveys of this nature the use of boreholes with AEM needs to be approached in a thoughtful and considered manner as to the value of information from an individual borehole.

3.4.2 Digitizing Interpreted Geological Contacts

Characterization and interpretation of the subsurface was performed in cross-section and derived surface grid formats. Contacts between the geologic units were digitized in 2D including: Quaternary (***Q),*** Cretaceous Dakota Group (***Kd***), and undifferentiated Pennsylvanian (***IP***). For the three northernmost flight lines the Cretaceous Carlile (***Kc***) and the Cretaceous Greenhorn Limestone and Graneros Shale ***(Kgg)*** were picked in a similar manner. The interpretive process benefited from the use of CSD, Nebraska Oil and Gas Conservation Commission (NEOGCC), and NE-DNR borehole logs. Surface grids of the interpreted geologic formations were then produced. Each flight line profile with interpretation including the Quaternary aquifer material mapping are included in the appendices as well as interpretative surface grids. Given the known differences between the parameters of the 2015 and 2018 AEM surveys, it has become apparent that there needs to be integration work done to bring the results of all the years together in one package using the same parameters such as projection, model layer parameters, and lithologic nomenclature.

3.4.3 Resistivity/Lithology Relationship

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

3.4.4 Hydrogeological Framework of the P-MRNRD

The 2018 P-MRNRD AEM survey reveals variability in the Quaternary (***Q***) and Cretaceous Dakota Group (***Kd***) deposits across the P-MRNRD AEM survey area that make up the aquifer materials. The ***Q*** make up the aquifer materials overlying the ***Kd*** bedrock units of which the ***Kd*** sandstone/sand dominant material are aquifers. In the north and south parts of the AEM survey area, the aquifer material and coarse aquifer material exist in paleochannels that are separated by ***Q*** deposits which consist of predominantly marginal to non-aquifer materials that are glacial till and loess and that can be more than 400 ft thick. ***Q*** aquifer and coarse aquifer materials are thick in the western part of the survey area near the Platte and Elkhorn Rivers. The Tekamah Block AEM flight area has very little aquifer and coarse aquifer material. Estimates of the groundwater in storage within the Tekamah Block of aquifer material below the 1995 CSD water table elevation is 3,428 acre-ft. The amount of extractable groundwater from aquifer material is 343 acre-ft. The main aquifer material type in the Tekamah Block is ***Kd*** sandstone/sand dominant material. While these materials will produce water, the yields and specific capacity will be reduced. The total estimate of the groundwater in storage for all materials for the ***Q*** and ***Kd*** below the 1995 water table is 69,571 acre-ft with 3,863 acre-ft extractable, demonstrating the impact of the fine-grained materials on the overall extractable groundwater.

3.4.5 Potential Recharge Zones within the P-MRNRD AEM Survey Area

The use of block flights in Tekamah area illustrates the preferred method of using AEM to identify areas where the potential for recharge to the aquifer can be high and low. Locations where the flight lines are closely spaced showing either aquifer or coarse aquifer material at the land surface should be considered as locations for higher likelihood for recharge because of the 2D and 3D spatial nature of the aquifer material distribution. The opposite is also true where AEM data analysis shows non-aquifer or marginal aquifer material; Those areas will likely not be optimal recharge locations. The area throughout the Tekamah Block has potential recharge that is limited in extent due to depth. The layers below layer about 31 ft are mostly poor aquifer materials for recharge transmission downward.

Within the reconnaissance AEM flight area of the P-MRNRD, the highest rate of recharge can be expected along the river and stream valleys due to the presence of aquifer and coarse aquifer

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

3.5 Recommendations

Recommendations provided to the P-MRNRD 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 P-MRNRD about their management challenges.

3.5.1 Integration of 2007-2018 AEM Hydrogeological Investigations

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

3.5.2 Additional AEM Mapping

The hydrogeologic maps provided in this report represent the completed hydrogeologic framework developed for the P-MRNRD at reconnaissance level with approximately 3-mile spacing between flight lines. The Tekamah Block flight area is the only exception to this flight line spacing which is about 700-800 feet. The first AEM project for the District was done in 2007 in the Ashland Block that was collected with dense flight lines over a limited area. In 2015 AEM data was collected at an approximately 20-mile grid spacing. The interpretations match well with the CSD and NE-DNR test holes. The 2016 AEM project was a combination of reconnaissance lines near Gretna, NE and a block flight around Springfield, NE. The 2018 AEM

project for P-MRNRD selected areas for a hydrogeologic framework map to support groundwater models, selection of rural water supply well locations, locating water quality monitoring wells, determining the potential for areas make decisions about irrigation development and management policy, and selecting MAR or ASR locations. It is highly recommended that additional AEM data be collected and analyzed within the area of the Platte and Elkhorn River basins near the town of Fremont, NE and additional block flight lines near Tekamah and the surrounding area for water quality efforts by further defining recharge and internal features of the Quaternary (***Q)*** sediments and Cretaceous Dakota Group (***Kd)***. Additional analysis of the ***Kd*** and ***Q*** internal features will shed important light on groundwater movement and groundwater in storage with delineation of flow paths related to water quality. This information will strengthen the knowledge base of the important aquifer areas of the district. Most importantly it will provide information including the geographic distribution of amount of groundwater in storage, recharge areas, susceptibility to groundwater contamination, and hydrologic connection to the streams in the block flight areas within the P-MRNRD that can be selected for current and future water development impacts.

3.5.3 Update the Water Table map

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

3.5.4 Siting new test holes and production wells

The AEM hydrogeological framework profiles, maps, and surfaces provided in this report provide great insight in 3D on the relationship between current test holes and production groundwater wells. At the time of this report, the currently available lithology data for the P-MRNRD area was used in building the framework maps and profiles. Additional information from previous groundwater reports were helpful in this work. It is recommended that the results from this report be used to site new test holes and monitoring wells. Often test holes are sited based on previous work that is regional in nature. By utilizing the maps in this report new drilling locations can be sited in more optimal locations. The location of new water supply wells for communities can also use the results in this report to guide development of new water supply wells. Planners should locate wells in areas of greatest saturated thickness with the least potential for non-point source pollution. A good example of this would be confined aquifers with large volumes of coarse aquifer and aquifer material with minimal sedimentary boundary conditions. The previous AEM studies have already found use by CSD and local well drillers to locate test wells and production wells within the P-MRNRD.

3.5.5 *Aquifer testing and borehole logging*

Aquifer tests are recommended to improve estimates of aquifer characteristics. Limited aquifer properties from previous reports were available outside the larger cities in the survey area. A robust aquifer characterization program is highly recommended at the state, regional (NRD's), and smaller municipal levels. Aquifer tests can be designed based on the results of AEM surveys and existing production wells could be used in conjunction with three or more installed water level observation wells.

Additional test holes with detailed, functional, and well calibrated geophysical logging for aquifer characteristics are highly recommended. Examples of additional logging would be flow meter logs and geophysical logs including gamma, neutron, electrical, and induction logs. Detailing aquifer characteristics can be accomplished with nuclear magnetic resonance logging (NMR) at a reduced cost when compared to traditional aquifer tests. This is a quick and effective way to characterize porosity and water content, estimates of permeability, mobile/bound water fraction, and pore-size distributions with depth.

3.5.6 *Recharge Zones*

The P-MRNRD hydrogeologic framework in this report provides areas of recharge from the ground surface to the groundwater aquifer in Tekamah Block. This area has water quality concerns, but not enough AEM data around Tekamah was acquired nor a detailed analysis of the ***Kd*** and the ***Q*** sediments was conducted to be definitive in this report and thus additional work in this area is recommended. 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 similar to the Tekamah Block which utilized closely-spaced flight lines using an AEM system that has good near-surface resolution in areas identified by the P-MRNRD that are of priority importance for management purposes. It is further recommended that future work integrate new soils and land use maps with the results of this study to provide details on soil permeability, slope, and water retention to provide a more complete understanding of the transport of water from the land surface to the groundwater aquifer. A potential solution to water quality, quantity, and stream depletions is adding additional fresh surface water as recharge to select areas of rangeland or other areas. Additional work can be done to identify where the best locations are for these type of management efforts. This information can and has been used in Nebraska to improve Well Head Protection Areas by refining the estimated travel time estimates and the boundary areas.

3.5.7 *Managed Aquifer Recharge*

The areas which may have potential for managed aquifer recharge (MAR) can be approximately located by the interpreted results from AEM reconnaissance line interpretations. Detailed analysis for this purpose would need to be done to determine where viable opportunities for the P-MRNRD exist and what additional information would be required for final selections of MAR sites. Additional AEM mapping in new block flight locations and along the streams in the P-

MRNRD would also be beneficial in locating potential MAR locations. A detailed plan for locating and developing MAR sites would be beneficial to the P-MRNRD for storage and release of water for stream flow and other uses.

3.5.8 Updating previous groundwater reports and Groundwater Management Plans

The groundwater reports and management plans should be updated with the AEM information which make it more comprehensive publications. Should future AEM work be completed the results from that effort will help guide the future groundwater management plans for the district. The addition of estimates of groundwater in storage, recharge areas, hydrologic connection to streams and consideration of managed aquifer recharge sites will greatly improve and groundwater management plan.

4 Description of Data Delivered

4.1 Tables Describing Included Data Files

Table 4-1 describes the raw data files included in Appendix 3_Deliverables \Raw_Data. As discussed above, eighteen (18) flights were required to acquire the P-MRNRD AEM data (Figure 2-5). Grouped by flight date, there are four (4) data flies included in Appendix 3\Raw_Data for each flight. These files have extensions of "*.sps" and "*.skb". The "*.sps" files include navigation and DGPS location data and the "*.skb" files include the raw AEM data that have been PFC-corrections (discussed in Section 2.4.1). Two additional files are used for all the flights. These are the system description and specifications file (with the extension "*.gex") in the GEO subdirectory and the 'mask' file (with the extension "*.lin"), in the MASK subdirectory, which correlates the flight dates, flight numbers, and assigned line numbers.

Table 4-2 describes the data columns in the ASCII *.xyz file PMRNRD2018_EM_MAG_AUX.xyz. This file contains the electromagnetic data, plus the magnetic and navigational data, as supplied directly from SkyTEM.

The result of the SCI is included in PMRNRD2018_AEM_SCI_INV_v1.xyz and the data columns of these databases are described in Table 4-3.

The interpretation results are included in the data file PMRNRD2018_InterpSurfaces.xyz in ASCII format. Table 4-4 describes the data columns of those files.

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

ESRI Arc View Binary grids of the surfaces that were used in the interpretation (DEM, water table) and derived from the interpretation (top of geological units) of the AEM and borehole are listed in Table 4-6. And stored in Appendix 3_Deliverables\Grids.

The format of the voxel grid that has been created from the AEM data in the Tekamah Block is described in Table 4-7. The voxel grid is presented as an xyz file, *VoxelTekamah.xyz*.

In summary, the following are included as deliverables:

- Raw Data Files - SkyTEM files *.gex, *skb, *.lin
- Raw EM Mag data as ASCII *.xyz
- SCI inversion as ASCII *.xyz in array and an individual column format by model layer.
- Interpretations as ASCII *.xyz
- ESRI ArcView files – surface, topo, etc
- Voxel Grid of the Shubert Block ***Q*** *.csv
- 2D profiles and 3D fence diagrams of the AEM survey inversion results

KMZs for P-MRNRD AEM flight lines (Discussed in Section 4.2).

Table 4-1. Raw SkyTEM data files

Folder	File Name	Description
Data	..NavSys.sps, …PaPc.sps, ...RawData_PFC.skb, …DPGS.sps	Raw data files included for each flight used in importing to Aarhus Workbench
Geo	20180823_304_DualWaveform_60Hz_skb.gex 20181002_304_446_Nebraska_skb_SR2.gex 20181002_304_446_Nebraska_skb_SR2.sr2	304M System Description
Mask	20180613_446_NE304_PMRNRD.lin	Production file listing dates, flights, and assigned line numbers

Table 4-2: Channel name, description, and units for PMRNRD2018_EM_MAG_AUX.xyz with DEM, magnetic, DGPS, Inclinometer, altitude, and associated data.

Parameter	Description	Unit
Fid	Unique Fiducial Number	
Line	Line Number	
Flight	Name of Flight	yyyymmdd.ff
DateTime	DateTime Format	Decimal days
Date	DateTime Format	yyyymmdd
Time	Time UTC	hhmmss.sss
AngleX	Angle (in flight direction)	Degrees
AngleY	Angle (perpendicular to flight direction)	Degrees
Height	Filtered Height Measurement	Meters [m]
Lon	Longitude, WGS84	Decimal Degrees
Lat	Latitude, WGS84	Decimal Degrees
E_UTM14N_m	Easting, NAD83 UTM Zone 14N	Meters [m]
N_UTM14N m	Northing, NAD83 UTM Zone 14N	Meters [m]
E_NESP83_ft	Easting, NAD83 Nebraska State Plane	Feet [ft]
N_NESP83N_ft	Northing, NAD83 Nebraska State Plane	Feet [ft]
DEM	Digital Elevation	Meters [m]
Alt	DGPS Altitude above sea level	Meters [m]
GDSpeedL	Ground Speed	Kilometers/hour [km/h]
Curr_LM	Current, Low Moment	Amps [A]
Curr_HM	Current, High Moment	Amps [A]
LMZ_G01	Normalized (PFC-Corrected) Low Moment Z-RxCoil values array	$pV/(m^4*A)$
HMZ_G01	Normalized (PFC-Corrected) High Moment Z-RxCoil values array	$pV/(m^4*A)$
HMX_G01	Normalized (PFC-Corrected) High Moment X-RxCoil values array	$pV/(m^4*A)$
PLNI	Power Line Noise Intensity monitor	V/m^2
Bmag	Raw Base Station Mag Data filtered	nanoTesla [nT]
MAG_Raw	Raw Mag Data	nanoTesla [nT]
Mag_ED	Mag filtered	nanoTesla [nT]
Diurnal	Diurnal Mag Data	nanoTesla [nT]
Mag_Cor	Mag Data Corrected for Diurnal Drift	nanoTesla [nT]
RMF	Residual Magnetic Field	nanoTesla [nT]

TMI	Total Magnetic Intensity	nanoTesla [nT]

Table 4-3. Channel name, description, and units for PMRNRD2018_AEM_SCI_INV_v1.xyz with EM inversion results.

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

Table 4-4. Channel name description and units for the interpretation results files PMRNRD2018_InterpSurfaces.xyz.

Parameter	Description	Unit
LINE	Line Number	
East_M	Easting NAD83, UTM Zone 14N	Meters (m)
North_M	Northing NAD83, UTM Zone 14N	Meters (m)
East_ft	Easting NAD83, Nebraska State Plane	Feet [ft]
North_ft	Northing NAD83, Nebraska State Plane	Feet [ft]
DEM_ft	Topography at 100ft sampling (NAVD 1988)	Feet [ft]
RHO [0] through RHO [38]	Array of Inverted model resistivities of each layer	Ohm-m
RHO_STD [0] through RHO_STD [38]	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 [38]	Depth to the top of 39 individual layers	Feet [ft]
DEP_BOT_FT [0] through DEP_BOT_FT [38]	Depth to the bottom of 39 individual layers	Feet [ft]
DOI_UPPER_FT	More conservative estimate of DOI from Workbench	Feet [ft]
DOI_LOWER_FT	Less conservative estimate of DOI from Workbench	Feet [ft]
WaterTable1995	Elevation of the top of the water table from the Nebraska School of Natural Resources Configuration Report, 1995.	Feet [ft]
AquiferTyp[0] through AquiferTyp[38]	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_NonAq1	Elevation of top of Non-Aquifer Material (<12 ohm-m)	Feet [ft]
Bot_NonAq1	Elevation of bottom of Non-Aquifer Material (<12 ohm-m)	Feet [ft]
Thk_NonAq1	Thickness of Non-Aquifer Material (<12 ohm-m)	Feet [ft]
Top_MargAq1	Elevation of top of upper Marginal-Aquifer Material (12 - 20 ohm-m)	Feet [ft]
Bot_MargAq1	Elevation of bottom of upper Marginal-Aquifer Material (12 - 20 ohm-m)	Feet [ft]
Thk_Marg1Aq1	Thickness of upper Marginal-Aquifer Material (12 - 20 ohm-m)	Feet [ft]
Top_MargAq2	Elevation of top of lower Marginal-Aquifer Material (12 - 20 ohm-m)	Feet [ft]
Bot_MargAq2	Elevation of bottom of lower Marginal-Aquifer Material (12 - 20 ohm-m)	Feet [ft]
Thk_Marg1Aq2	Thickness of lower Marginal-Aquifer Material (12 - 20 ohm-m)	Feet [ft]
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]
Thk_AqMat1	Thickness of upper Aquifer Material (20 - 50 ohm-m)	Feet [ft]
Top_AqMat2	Elevation of top of middle Aquifer Material (20 - 50 ohm-m), if present	Feet [ft]
Bot_AqMat2	Elevation of bottom of middle Aquifer Material (20 - 50 ohm-m), if present	Feet [ft]
Thk_AqMat2	Thickness of middle Aquifer Material (20 - 50 ohm-m), if present	Feet [ft]
Top_AqMat3	Elevation of top of lower Aquifer Material (20 - 50 ohm-m), if present	Feet [ft]
Bot_AqMat3	Elevation of bottom of lower Aquifer Material (20 - 50 ohm-m), if present	Feet [ft]
Thk_AqMat3	Thickness of lower Aquifer Material (20 - 50 ohm-m), if present	Feet [ft]

Top_Coarse_AqMat1	Elevation of top of Upper Coarse Aquifer Material (>50 ohm-m)	Feet [ft]
Bot_Coarse_AqMat1	Elevation of bottom of Upper Coarse Aquifer Material (>50 ohm-m)	Feet [ft]
Thk_Coarse_AqMat1	Thickness of Upper Coarse Aquifer Material (>50 ohm-m)	Feet [ft]
Top_Coarse_AqMat2	Elevation of top of Lower Coarse Aquifer Material (>50 ohm-m)	Feet [ft]
Bot_Coarse_AqMat2	Elevation of bottom of Lower Coarse Aquifer Material (>50 ohm-m)	Feet [ft]
Thk_Coarse_AqMat2	Thickness of Lower Coarse Aquifer Material (>50 ohm-m)	Feet [ft]
Bedrock	Elevation of interpreted bedrock surface	Feet [ft]
Kc	Elevation of the top of the Cretaceous Carlile Shale.	Feet [ft]
Kgg	Elevation of the top of the Cretaceous Greenhorn Limestone and Graneros Shale	Feet [ft]
Kd	Elevation of the top of the Cretaceous Dakota Group	Feet [ft]
IP	Elevation of the top of the Undifferentiated Pennsylvanian.	Feet [ft]

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

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

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

Grid File Name	Description	Grid Cell Size (feet)
PMRNRD_DEM_ft	Digital Elevation Model (ground surface elevation) (NAVD88 feet) of the 2018 P-MRNRD survey area, NAD83/State Plane Nebraska, feet	100
PMRNRD_WT_1995	Elevation (NAVD88 feet) of water table (1995) for the 2018 P-MRNRD survey area, NAD83/State Plane Nebraska, feet	1000
PMRNRD_Top_Kd	Elevation (NAVD88 feet) of top of Dakota Formation for the 2018 P-MRNRD survey area, NAD83/State Plane Nebraska, feet	1000
PMRNRD_Top_IP	Elevation (NAVD88 feet) of top of Upper Pennsylvanian for the 2018 P-MRNRD survey area, NAD83/State Plane Nebraska, feet	1000
PMRNRD_Top_Bedrock	Elevation (NAVD88 feet) of top of bedrock for the 2018 P-MRNRD survey area, NAD83/State Plane Nebraska, feet	1000
PMRNRD_Thickness_Q	Thickness (feet) of Quaternary deposits for the 2018 P-MRNRD survey area, NAD83/State Plane Nebraska, feet	1000
PMRNRD_Thickness_Kd	Thickness (feet) of Dakota Formation for the 2018 P-MRNRD survey area, NAD83/State Plane Nebraska, feet	1000
PMRNRD_SatThick_Q	Saturated thickness (feet) of Quaternary deposits for the 2018 P-MRNRD survey area, NAD83/State Plane Nebraska, feet	1000
PMRNRD_SatThick_Kd	Saturated thickness (feet) of Dakota Formation for the 2018 P-MRNRD survey area, NAD83/State Plane Nebraska, feet	1000
Tekamah_Top_Kd	Elevation (NAVD88 feet) of top of Dakota Formation for the 2018 Tekamah block survey area, NAD83/State Plane Nebraska, feet	200
Tekamah_Top_IP	Elevation (NAVD88 feet) of top of Upper Pennsylvanian for the 2018 Tekamah block survey area, NAD83/State Plane Nebraska, feet	200
Tekamah_Thickness_Q	Thickness (feet) of Quaternary deposits for the 2018 Tekamah block survey area, NAD83/State Plane Nebraska, feet	200
Tekamah_Thickness_Kd	Thickness (feet) of Dakota Formation for the 2018 Tekamah block survey area, NAD83/State Plane Nebraska, feet	200
Tekamah_SatThick_Q	Saturated thickness (feet) of Quaternary deposits for the 2018 Tekamah block survey area, NAD83/State Plane Nebraska, feet	200
Tekamah_SatThick_Kd	Saturated thickness (feet) of Dakota Formation for the 2018 Tekamah block survey area, NAD83/State Plane Nebraska, feet	200

Table 4-7. Channel name, description, and units for VoxelTekamah.xyz.

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

4.2 Description of Included Google Earth KMZ Data and Profiles

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

Unique KMZ files were created for each individual flight line in 10-mile segments or shorter. Within these specialized KMZ files, the AEM flight line is shown as well as place marks at each location where there are interpreted geologic results. The attribute data for each unique place mark contains location information as well as bedrock and the 1995 water table. These KMZ files are located within the "*Appendix_3_Deliverables\KMZ\Interpretation\PMRNRD18_Profiles*" folder. In this folder is a "*GoogleE_Readme.pdf*" file that provides instructions regarding the "*Settings*" changes that need to be made in Google Earth, and how to use the KMZ files in Google Earth including a legend of what attributes are displayed when an AEM sounding location is clicked. This P-MRNRD GoogleE_Readme.pdf file is repeated below as a convenience. The P-MRNRD interpretation KMZ is presented in Figure 4-1 and with the interpretation dialogue box in Figure 4-2.

4.2.1 Included README for the P-MRNRD Interpretation KMZ's

README for:

2018_PMRNRD_Interpretation.kmz

Data Files - Please copy the folder *PMRNRD_Profiles* to your C:\ drive. Do not rename any of the images within the folder.

Google Earth Instructions:

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

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

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

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

STEP 5: The *2018_PMRNRD_Interpretation.kmz* file within the folder named *PMRNRD_Profiles* can now be opened and viewed in Google Earth.

Data:

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

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

East (ft) – Easting coordinate in NAD83, Nebraska State Plane, in feet

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

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

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

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

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

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

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

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

Profile – Link to Interpreted AEM profile images

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

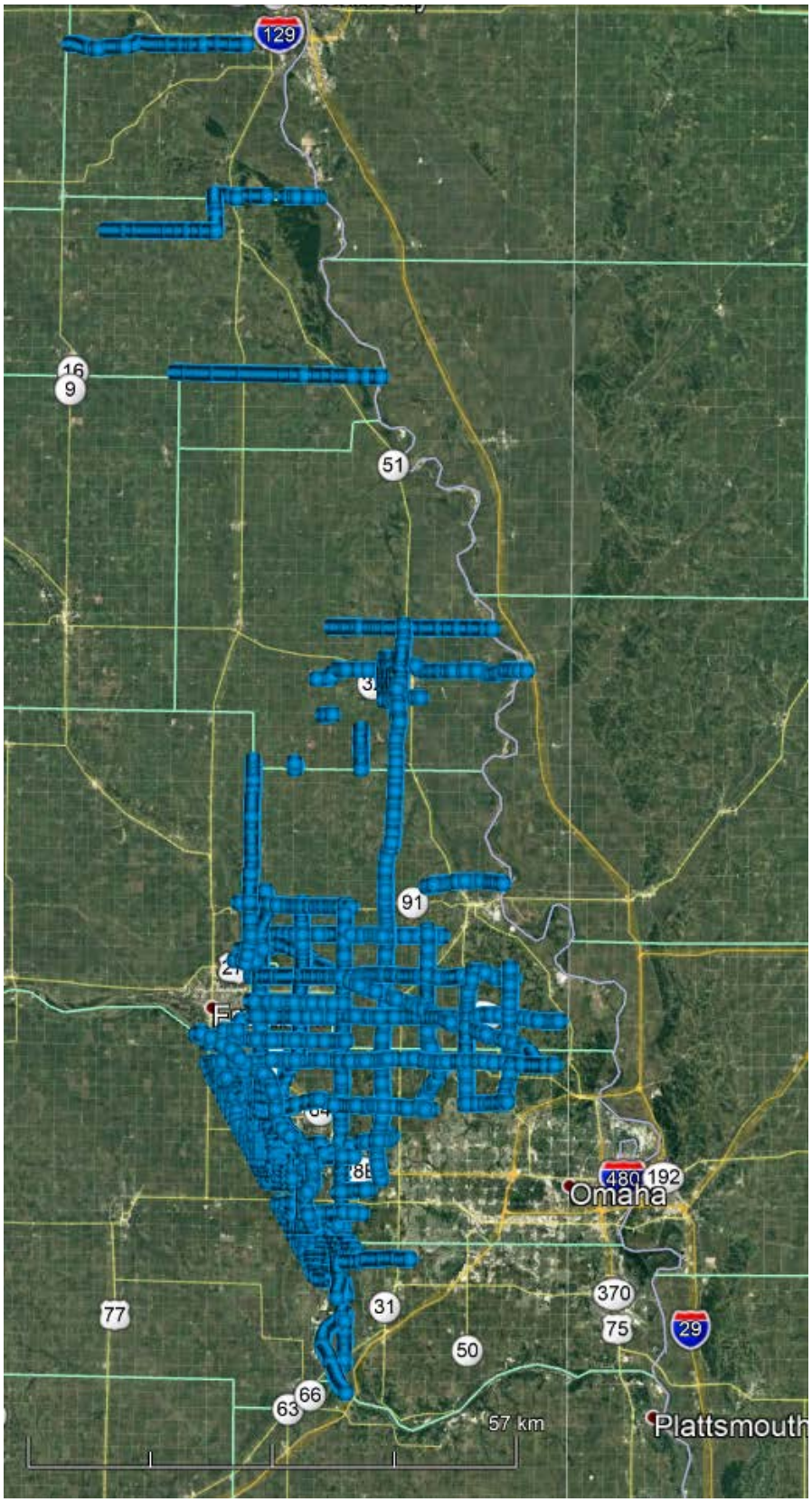


Figure 4-1. Example Google Earth image for the 2018 P-MRNRD Interpretation kmz.

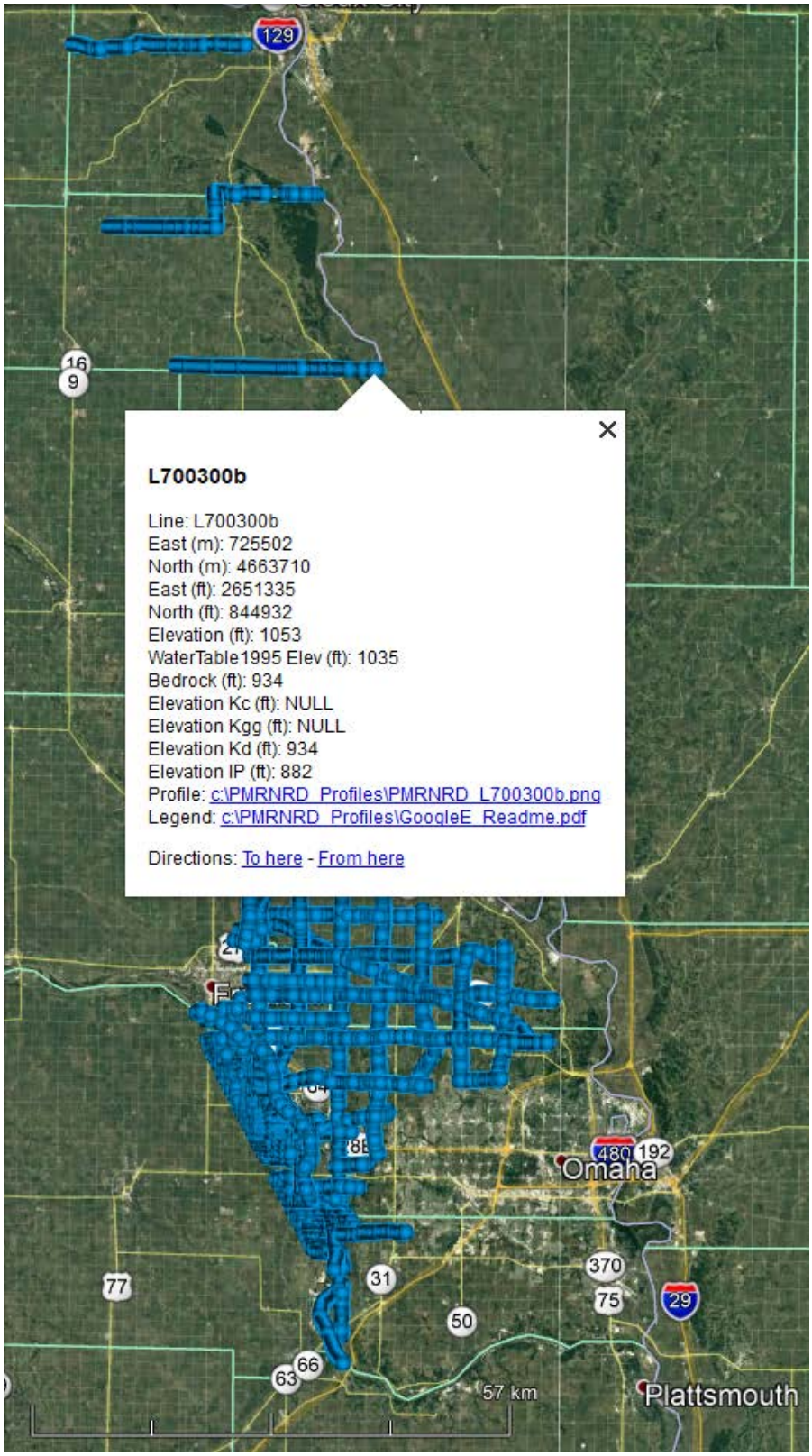


Figure 4-2. Example Google Earth image for the 2018 P-MRNRD Interpretation kmz showing location attributes.

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