Geological mapping and 3D model of deposits that host ground-water systems in the Fargo-Moorhead region, Minnesota and North Dakota

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I. Executive Summary

The U.S. Department of the Interior, Bureau of Reclamation (Reclamation), and the State of North Dakota are jointly preparing an environmental impact statement (EIS) for the Red River Valley Water Supply Project, which is intended to ensure that the future comprehensive water quality and quantity needs of the Red River Valley are met. As part of current activity toward these objectives, it was recognized that there was a need to further compile consistent regional information on the capacity of known and potential ground-water sources. In particular, a need to synthesize published quantitative information on currently utilized ground-water sources in Minnesota was identified, to bring compilation of Minnesota data up to a standard similar to that already available for eastern North Dakota. Members of United States Geological Survey (USGS) staff therefore prepared a review on this topic. Concurrently, a need for a consistent, broad overview of all confirmed and potential ground-water sources that can presently be identified across the entire region also was recognized. The present report addresses the latter requirement in the form of geological maps, a 3D computer model, and accompanying documentation meant to facilitate subsequent ground-water-related assessment and planning. The USGS report and the current report were commissioned on a contract basis by Reclamation, and were completed in 2005 by a team of agencies coordinated by the Minnesota Geological Survey (MGS).

The present report and accompanying geologic maps and 3D model are thus meant to be an updated and enhanced depiction of the sediments and rocks that host ground-water systems across the Fargo-Moorhead region, for the purpose of supporting further assessment of currently utilized and potentially usable ground-water resources. The maps and model cover an area extending from 46 to 47.5 degrees north latitude and from 98 to 95 degrees west longitude – an area 142 miles (228 km) across west to east and about 103 miles (166 km) north to south.

A surficial geology map was prepared to depict the character and distribution of the uppermost geological materials, from the point of view of composition, processes of deposition, and history. The map shows deposits such as fine-grained Lake Agassiz clay along the Red River, the sandy Sheyenne Delta sediments southwest of Fargo, discontinuous sandy glacial outwash deposits, clay and silt-rich to gravelly tills deposited directly by glaciers, and Cretaceous sedimentary rocks such as shale. The surficial geology map is a basis for making predictions regarding subsurface geology, it can be used in combination with hydrologic information to outline aquifers that occur at the surface, and it can be used in assessments of ground-water recharge, ground-water protection, and engineering geology.

The Quaternary (Ice Age) sediments, consisting of strata related to multiple cycles of glacial advance, retreat, and shifts in ice flow were categorized using standard stratigraphic procedures. A lithostratigraphic database used for the project includes textural and lithologic information for 6,533 sediment samples collected from outcrops, soil-probe borings, power-auger test holes, and rotasonic cores. The textural data include percent sand, silt, and clay. The lithologic data are derived from microscopic examination of the coarse-sand fraction and are presented as percent igneous and metamorphic rocks, carbonate, and shale. Computer-assisted interpretation techniques were used to produce reproducible interpretations of the till datasets. Twenty-four Pleistocene lithostratigraphic units and eight Holocene and Lake Agassiz units were identified for the Fargo-Moorhead study area. A database of drillholes classified on the basis of this new scheme was prepared, as a guide for subsequent 3D modeling.

A bedrock geology map also was prepared. The map largely depicts Cretaceous shale and sandstone that are thick in the west to thin and discontinuous in the east. The Precambrian rocks that underlie the entire study area consist of igneous and metamorphic rocks, commonly altered to clay to a depth of tens of meters. Glacial erosion has stripped this weathering horizon off the Precambrian rocks to a variable degree, although the weathering profile is largely intact where Cretaceous cover is present.

A new compilation and interpretation of bedrock surface elevation as well as the elevation of the top of Precambrian rock was also completed, allowing glacial sediment and sedimentary rock thicknesses to be calculated. This mapping in the Minnesota portion of the study area was based on subsurface information from ~11,000 wells in the County Well Index (CWI) database, including 445 wells interpreted to penetrate bedrock. Mapping in North Dakota was based on data compiled by the North Dakota Geological Survey and the North Dakota State Water Commission, including 2,800 wells that terminate within the sediments, and about 1,300 that penetrate bedrock. In the North Dakota portion of the study area, Ordovician Red River Formation carbonate and sandstone of the Winnipeg Formation Black Island Member have previously been inferred to be present between Cretaceous strata and the Precambrian.

The surficial geology map, the stratigraphic classification, the bedrock geology map, and the bedrock elevation map provide a reference set of information that can be used by experts to make inferences regarding the deposits in the region, as well as a platform for prediction of subsurface materials and conditions. Currently available technology, however, also allows a more explicit and visual information system to be constructed in the form of a 3D model showing geometry of the strata. This model is a key requirement for subsequent hydrogeologic characterization and ground-water system analysis. The mapping therefore was merged with drillhole data, with the aid of current knowledge on geological processes and history, to produce a 3D depiction of the subsurface geology. The greatest level of detail in the 3D model was constructed for several areas where important aquifers were known to occur, including the Hankinson area in southeastern North Dakota, the Fargo area that straddles the North Dakota-Minnesota border, as well as the Pelican River and Pineland areas in Minnesota. In the detail areas, deposits approximately 0.6 mile (1 km) or larger in horizontal extent are depicted, while for the remainder of the area, geological features approximately 3 miles (5 km) across or greater are depicted.

Descriptions of sand bodies in the detail areas were derived. Current aquifer names were in some cases used, although the focus of this study was to best approximate the boundaries of the sand bodies. Over 130 sand deposits corresponding to known aquifers and potential aquifers were identified and mapped within the study area. Portions of twelve buried ice margins at various stratigraphic levels were mapped, suggesting trends that may be useful for future exploration and mapping. For several previously identified aquifers, revised geometry is presented. The work presented in this report thus will be an appropriate and essential basis for additional more site-specific work, as well as hydrogeologic characterization of the strata, and analysis of water resources.

II. Background

The U.S. Department of the Interior, Bureau of Reclamation, and the State of North Dakota are jointly preparing an environmental impact statement (EIS) for the Red River Valley Water Supply Project. The purpose of the project is to meet the comprehensive water quality and quantity needs of the Red River Valley, as directed by Dakota Water Resources Act Section (DWRA) 8(c)(2)(A). The needs as specified in DWRA are municipal, rural, and industrial supplies, as well as water quality, aquatic environment, recreation, and water conservation measures [DWRA Section 8(b)(2)]. The objective of the Red River Valley Water Supply Project is to meet the municipal, rural, and industrial water needs through year 2050 and to optimize water resources in an attempt to meet identified water quality, aquatic environment, and recreation needs.

It was recognized by Reclamation and their State partners that additional information on ground-water systems was required to facilitate further progress in preparation of the EIS. With respect to clarifying the capacity of ground-water sources within the region, a particular need to synthesize published quantitative information on currently utilized near-surface ground-water sources in Minnesota was identified, and a literature review on this topic was prepared by United States Geological Survey (USGS) staff (Reppe et al., 2005). The available information relates to ground-water systems within sand deposits at the earth surface, which are not buried by other deposits. Hence, these ground-water systems are referred to as being unconfined.

In addition to the USGS review of quantitative information on unconfined ground-water systems in the Minnesota portion of the region, it also was recognized that the EIS-development activity required a consistent, broad overview of all confirmed and potential ground-water sources that can presently be recognized across the entire region, within both the North Dakota and the Minnesota portions of the Fargo-Moorhead region. The present report addresses this need in the form of a surficial geological map that shows deposits at the earth surface, a bedrock geological map that describes the uppermost rocks in the region, a bedrock elevation map, a 3D computer model of all deposits that can readily be mapped using current knowledge and technology, digital files that document the model, and the present document, which describes and explains the maps and 3D model. Emphasis has been placed on mapping the geometry of sand deposits that host most currently or potentially utilized ground-water systems in the region. In addition, enclosing clay- and silt-rich strata were characterized, as their correlation facilitates identification of sand deposits that are much more difficult to correlate due to their more variable composition and geometry. These reports were commissioned on a contract basis by Reclamation, and were completed in 2005 by a team of agencies coordinated by the Minnesota Geological Survey, with consultations as required (Appendix A).

III. Purpose, scope, and method

The objective of the current project is to present an updated and enhanced depiction of the sediments and rocks within which ground-water systems occur across the Fargo-Moorhead region, to support further assessment of currently utilized and potentially usable ground-water resources in the region. To do so, existing geologic maps from North Dakota and Minnesota were compiled, interpreted, and integrated to produce two maps, one depicting the uppermost unconsolidated deposits (Surficial Geology; 1: 200,000), and the other depicting the uppermost rocks (Bedrock Geology; 1: 400,000). These maps were merged with a new interpretation of bedrock elevation and a compilation of readily available digital drillhole data for approximately 30,000 sites to produce a three-dimensional (3D) depiction of subsurface geology, extending from the land surface down to the top of the granites and other igneous and metamorphic basement rocks of Precambrian age that underlie the entire region.

IV. Study area

The study area (Figure 1) for the maps and model covers all or part of Barnes, Cass, Sargent, Steele, Traill, Ransom, and Richland Counties in North Dakota, and all or part of Norman, Clay, Wilkin, Traverse, Mahnomen, Becker, Otter Tail, Grant, Clearwater, Hubbard, Wadena, and Todd Counties in Minnesota. This area extends from 46 to 47.5 degrees north latitude and from 98 and to 95 degrees west longitude. The study area measures 142 miles (228 km) east to west and 103 miles (166 km) north to south, an area of 12,360 square miles (32,012 square kilometers).

V. Geology

A. Sediments

1. Surficial geology

Introduction: Ground water commonly is drawn from wells installed in deposits such as sand that are not buried by other deposits. Furthermore, the uppermost deposits are the first major layer that controls the rate at which ground-water resources are replenished, and determines their vulnerability to contamination. A surficial geology map that depicts the uppermost geological deposits, also known as soil parent materials, therefore is a key source of information required for ground-water management. Plan view geologic maps are prepared in a standard format by geological survey agencies, in order to convey the most detailed information available, and to serve as a basis for the interpretation of subsurface geology. A surficial geological map for the Fargo-Moorhead region therefore was compiled from previously published maps of varying format by developing a comprehensive set of map units that allowed a seamless reconciliation of the various maps. Surface geology in the region is dominated by fine-grained Lake Agassiz clay deposits along the Red River, the sandy Sheyenne Delta sediments southwest of Fargo, and discontinuous sandy outwash deposits that were deposited by glacial meltwater across much of the area. Between and beneath these clayey, silty, and sandy deposits, the entire area is underlain by multiple layers of clay and silt-rich to gravelly tills deposited by glacial ice, commonly separated by significant layers of sand and other sediments. Cretaceous sedimentary rocks such as shale are exposed locally in the western portion of the area. Older sedimentary rocks and the Precambrian igneous and metamorphic rocks that underlie the entire region are not exposed at the surface within the region. As such, they are not depicted on the surficial geology map.

Previous surficial geological mapping in the area (Figures 2 to 4) that was compiled as the surficial geology map that accompanies this report includes mapping of two North Dakota Geological Survey (NDGS) regional scale Atlas Series - geologic maps AS-14 (Harris and

Luther, 1991) and AS-15 (Harris, 1987), six NDGS County Bulletins - B-43 (Kelly and Bock, 1967), B-46 (Baker, 1967), B-47 (Klausing, 1968), B-49 (Bluemle, 1967), B-64 (Bluemle, 1975), and B-69 (Bluemle, 1979), two MGS/DNR Regional Assessments - RHA-3, Part A (Harris and others, 1995) and RHA-5, Part A (Harris and others, 1999), and five University of North Dakota theses and dissertations (Harris, 1973; Harris,1975; Sackreiter, 1975; Anderson, 1976; and Perkins, 1977). The NDGS County Bulletins report surface geology (Part I), ground water basic data available at the time of the study (Part II), and bedrock geology and hydrology (Part III). Appendix C presents a listing of previous work by agency and author, with a key to reference designations, author, and title. The surficial geology and other mapping were also supported by previous bedrock mapping (Figure 5), aeromagnetic mapping (Figure 6), and gravity mapping (Figure 7).

Methods: Previously published mapping in both the North Dakota and Minnesota portions of the study area was digitized and imported into a geographic information system (GIS). Unpublished material was compiled, digitized and combined with the previously published information. Map units, representing categories of sediments and rocks based on material, age, process of formation, and morphology, were developed that allowed the maps from various sources to be linked. The results were compiled as the GIS-based surficial geologic map at a scale 1:200,000 that accompanies this report. The map units are based primarily on compositional lithostratigraphic characteristics, and are organized in order of age and stratigraphic designation (Appendix D). Quaternary stratigraphic units in this area consist of unnamed, informally named, and formally named units of formation and group status. This map uses lithologic descriptions for the postglacial Holocene sediments, informal group designations for the Pleistocene sediments, and both unnamed and formal formation names for the Cretaceous deposits. Mapped lithostratigraphic units were reconciled with interpretations of the subsurface Quaternary stratigraphy.

Results: The 1:200,000 surficial geologic map that accompanies this report provides standardized information on the geological materials that occur at the earth surface. The youngest deposits shown on the map postdate the multiple glacial cycles that influenced the entire region over the past several hundred thousand years. These include clay, silt, and organic debris deposited in present-day ponds and sloughs (labeled Qho on the map and in Figure 8), gravel, sand, silt, clay, and disseminated organic debris deposited in channels and floodplains of present-day streams and rivers (Qha), gravel, sand, silt, clay, and disseminated organic debris deposited in abandoned channels and floodplains (Qaa), and pebbly sand, silt, and clay accumulated on steep slopes (Qht).

The next older generation of sediments was deposited in Lake Agassiz, the immense glacial lake that filled the Red River Valley due to blockage of northward drainage by the retreating continental glacier. These include sand and silt with gravel beach ridges deposited along Lake Agassiz shorelines (Qls), sand, silt, and clay deposited in shallow glacial lake waters (Qln), clay with thin silt laminae deposited in deep lake water (Qlo), sand, silt, and clay overlying sand and gravel deposited in shallow water (Qlg), as well as the sandy sediments of the Sheyenne Delta, which was deposited in an early phase of Lake Agassiz, and whose uppermost deposits have been reworked as dunes (Qw).

The uppermost sediments related directly to glaciation of the area (Qou) are sand and gravel deposited as outwash by glacial meltwater. Multiple generations of exposed outwash are present in the area, and an understanding of the history of these deposits allows predictions to be made regarding their geometry, texture, and composition. These multiple generations of outwash therefore have been categorized in this manner, including those labeled Qro, Quo, Qgo, Qoo, and Qcc. These deposits host important ground-water sources in the region, and are the subject of the accompanying USGS report (Reppe et al, 2005). The youngest till, sediments deposited directly from glacial ice, has been named the Forest River Group (Qfw). This clayey till occurs in the Red River Valley in the northernmost portion of the study area. The remaining till deposits are a succession of multiple strata that differ in composition and origin, and range in texture to the extent that their hydrogeological properties can be expected to differ. Also exposed at the surface in the Sheyenne River Valley are shales of Cretaceous age. The symbols and diagnostic criteria for these deposits are summarized in Figure 8, and are fully outlined in Appendix D and on the surficial geology map.

The surficial geology map was used to guide 3D mapping of subsurface geology, it can be used in combination with hydrologic information to outline aquifers that occur at surface, it is a basis for prediction of subsurface geology in some cases at a level of detail exceeding that depicted in the 3D model, and it can be used in assessments of ground-water recharge, ground-water protection, and engineering geology.

2. Quaternary stratigraphy:

Introduction: The Quaternary (Ice Age) sediment deposits in the area consist of multiple layers or strata related to multiple cycles of glacial advance, retreat, and shifts in ice flow (Figure 9). These strata have been categorized using standard stratigraphic procedures. For example, sediments postdating those associated with final glaciation in the area consist primarily of Lake Agassiz sediments, such as the clay deposits of the Red River Valley. In this case, drill hole descriptions and interpretations were based on Lake Agassiz stratigraphy defined by Arndt (1977). Other previous stratigraphic investigations in the Fargo-Moorhead study area have tended to be local in scope, and have been done in response to specific needs. For the purpose of the current study, it therefore was necessary to compile all available data, and assemble a new computer-assisted interpretation for the study area, within the context of knowledge available in a broader area.

Projects that previously developed interpretations of the Quaternary stratigraphy in the study area (Figure 3; Appendix C): NDGS County Bulletins B-43 (Kelly and Bock, 1967), B-46 (Baker, 1967), B-47 (Klausing, 1968), B-49 (Bluemle, 1967), B-64 (Bluemle, 1975), and B-69 (Bluemle, 1979); MGS Regional Assessments RHA-3, Part A (Harris and others, 1995) and RHA-5, Part A (Harris and others, 1999); NDGS Miscellaneous Series report addressing regional glacial stratigraphy (Harris, Moran, and Clayton, 1974); and a NDGS Report of Investigation describing offshore Lake Agassiz stratigraphy (Arndt, 1977). Several University of North Dakota (UND) theses and dissertations have also developed interpretations of the Quaternary stratigraphy in the study area (Figure 4; Harris, 1973; Harris, 1975; Sackreiter, 1975; Anderson, 1976; Perkins, 1977).

Data: The lithostratigraphic database used for the project includes textural and lithologic information for 6,533 sediment samples collected from outcrops, soil-probe borings, power-auger test holes, and rotasonic cores. These data were divided into two subsets based on sample depth. The near-surface file contains outcrop and soil-probe data for 3689 samples in the broader region, including 1999 samples from within the Fargo-Moorhead study area (Figure 10). The borehole file contains 2844 samples from greater depths collected from 112 test borings and rotasonic cores, including 1642 samples from within the study area (Figure 11). Among these, 24% of the samples were found to be unusable due to inadequate analyses; the remaining 76% have been defined and used as a basis for stratigraphic correlation. These data for the Red River Valley region were drawn from databases maintained by the Minnesota Geological Survey (QBASE) and North Dakota Geological Survey (N–File) and contain location, site and sample identification, geologist identification, textural, and lithological data on over 11,000 samples of glacial sediment collected over the past 35 years in North Dakota, Minnesota, and adjacent areas. The textural data include percent sand (SD), silt (SL), and clay (CL). The lithologic data are derived from microscopic examination of the coarse-sand fraction (1-2 mm) and are presented as percent igneous and metamorphic rocks (XT), carbonate (CO), and shale (SH). Additional data were obtained from analyses of Lake Agassiz stratigraphy along the Interstate Highway 29 corridor in North Dakota (Arndt, 1977) that dealt with engineering characteristics of Lake Agassiz offshore sediment, and include deeper test holes that provide information on the underlying tills. In the case of the near-surface data (Figure 12), textural data show a relatively constant clay/silt ratio, with significantly varying sand content and examples of clay-rich till, while the lithological data indicate that the greatest variability is displayed by shale content. In comparison, the subsurface textural data (Figure 13) show somewhat less variability in sand content, while the shale content is similarly variable.

Methods: Computer-assisted interpretation techniques (Harris, 1987; 1996; 1998) were used to produce reproducible interpretations of the till datasets. The location of sample sites was plotted by hand to verify computer location data. A sequential dataset was created by sorting the data by sample-site, location and sample depth. The near-surface data were divided into 5 working files and the borehole data were divided into 4 working files due to file size limitations. Each of these 9 datasets was interpreted for natural groupings using an iterative cluster analysis procedure. Clusters were refined, defined, and associated with till units. A till unit data subset was then created as a correlated dataset. The correlated data consist of the original sequential data with each sample of each till cluster labeled. This results in a listing of lithostratigraphic units in order of stratigraphic occurrence. Correlation charts were created to compare the results between data subsets (Figure 14). The correlated datasets provide a means to display and interpret the stratigraphic relationships between defined units. Stratigraphic interpretations were refined and GIS compatible data summaries were created for incorporation in the surficial geologic map compilation and drillhole database. These stratigraphic interpretations allow the surficial geologic map to be presented in a lithostratigraphic format, and provide a means of interpreting the drillhole cross sections.

Results: Twenty-four Pleistocene lithostratigraphic units (Figure 14) and eight Holocene and Lake Agassiz units (Figures 15 and 16) were identified in the Fargo-Moorhead study area. The tills have been characterized by average texture, textural classification, and average lithology of the coarse-sand fraction and assigned formation or group names. Pleistocene lithostratigraphic units 1 through 17 and unit 19 were known from previous studies in the Red River Valley, while unit 18 was previously only known in studies to the east. Units 20 through 24 are older tills poorly represented in the data, and not formally defined. These old tills are similar to units known elsewhere based on lithologic characteristics, but aspects of stratigraphic position and texture are unclear, although their provenance is similar to that of later tills. The stratigraphic column compiled for the project, summarized in Figure 16 and described in detail in Appendix E, shows the stratigraphic relationship and description of the Holocene and Pleistocene units encountered throughout the Fargo-Moorhead study area. A database of drillholes classified on the basis of this new scheme was prepared, as a guide for subsequent 3D modeling (Figure 17).

B. Sedimentary rocks

Sedimentary rocks in the area include Cretaceous shale and sandstone that are thick in the west to thin and discontinuous in the east, as well as a thin sequence of Ordovician carbonate and sandstone previously inferred to occur in the northwestern corner of the study area. The Cretaceous strata of North Dakota can largely be assigned to the Pierre Formation (Figure 16), consisting of dark gray shale, and the Niobrara Formation and underlying units, consisting of light brown to dark gray calcareous shale, both interpreted as having formed from marine offshore sediment. The older sedimentary rocks have been correlated by Anderson (1974) to the Red River Formation in the case of limestone, dolomitic limestone, and dolomite, and to the Winnipeg Formation in the case of the shale and underlying thicker quartzose sandstone that rests on the Precambrian rocks northwest of Fargo. The Cretaceous strata occurring in Minnesota have not been assigned formal stratigraphic names. Shale is the most common rock type in these deposits, but sandstone is also reported. The bedrock geology map indicates the extent of each of the Cretaceous strata, all of which intersect the bedrock surface, and differentiates areas underlain by Cretaceous sedimentary rocks from areas where Precambrian rock is the first bedrock encountered. The older, Ordovician-aged strata are completely buried by Cretaceous strata, so they do not appear on the bedrock geology map. A limited number of stratigraphic tests were also used to aid in the interpretation of Cretaceous stratigraphy in areas of North Dakota where the characterization could be improved.

C. Igneous and metamorphic rocks

The Precambrian rocks that underlie the entire study area consist of igneous and metamorphic rocks (Figure 16). These rocks are Archean (>2.5 billion years) in age, are largely arranged in belts with a west-southwest to east-northeast trend, and include rocks such as granite and other intrusive rocks, low-grade metamorphic rocks, including felsic to mafic metavolcanic rocks and metasedimentary rocks, as well as higher-grade metamorphic rocks such as schist and gneiss (Morey and Meints, 2000). These rocks underwent pre-Cretaceous chemical weathering that commonly has altered the rocks to clay to a depth of tens of meters, and the residuum is mapped as Precambrian rock. Where Cretaceous rocks are absent, post-Cretaceous erosion has typically removed all or part of the weathered Precambrian rock, although the weathering profile is largely intact where Cretaceous cover is present.

D. Bedrock surfaces

Introduction: A comprehensive new compilation and interpretation of bedrock surface elevation (topography) as well as the elevation of the top of Precambrian rock was completed for the study area. Both glacial sediment and sedimentary rock thicknesses were calculated from the results.

Data: Mapping of the bedrock topography in the Minnesota portion of the study area was based on subsurface information from the County Well Index (CWI) database. Nearly 11,000 wells in the database terminate within the glacial deposits and do not encounter bedrock. The elevation of the bottom of these wells was used to establish a maximum bedrock surface elevation. Most of these wells were drilled for domestic water supply and the descriptions of the materials encountered were recorded by well drilling contractors. Some 445 wells in the study area were interpreted to penetrate bedrock. Slightly more than 10% of those wells were drilled for mineral exploration or scientific purposes, and geologists recorded those descriptions. Of these 445 wells, 108 intersected deposits interpreted to be Cretaceous strata. All of the wells have field-verified locations. Mapping in the North Dakota portion of the study area was based on data compiled by the North Dakota Geological Survey and the North Dakota State Water Commission. Approximately 2,800 wells in the available database terminate within the glacial sediments, and slightly less than 1,300 penetrated bedrock. The North Dakota State Water Commission drilled most of the wells in this database as observation wells or test wells.

Method: The Minnesota well records were examined and interpreted on the basis of the driller's description, with principal reliance on wells logged by a geologist for scientific or exploration purposes as well as a few tens of downhole geophysical logs. Interpretation of the data and construction of the maps were done concurrently and iteratively. Patterns recognized in many drillers' logs were preferred to reliance on specific descriptive terms in a single log. The typical succession in the Minnesota portion of the area includes till, outwash, Cretaceous sandstone and shale, the saprolith (weathered Precambrian rock), and the unaltered Precambrian rock. Uncertainty results from the tills being commonly composed largely of reworked Cretaceous shale, the Cretaceous shales commonly containing debris derived from the weathered Precambrian rock, and poorly cemented Cretaceous sandstones being in contact with glacial sands of similar character. To distinguish these units, it was noted that the tills typically are described as sandy clay or clay and gravel, whereas the shales have no sand component. No gravels or conglomerates are known in the local Cretaceous section, so all deposits occurring above gravel likely are glacial deposits. Shales in the area were typically described by drillers as being sticky. Furthermore, Cretaceous sandstones in the area typically are described as white, while glacial sands as described as tan, although some drillers describe all sand as white. In the North Dakota portion of the study area, Ordovician Red River Formation carbonate and sandstone of the Winnipeg Formation Black Island Member have previously been inferred to be present between Cretaceous strata and the Precambrian (Anderson, 1974).

Results: For Minnesota data, initial age interpretations were entered in CWI and the well-bottom elevations or bedrock elevations were plotted at 1:100,000. An interpretation of bedrock topography was then hand-contoured at a 50-foot contour interval. Records were re-assessed during the contouring, and resulting changes were made to the database. Following this iteration, the data were again plotted on a stable base and final contours were drafted, scanned, vectorized, and gridded (Figure 18). Bedrock elevations were then subtracted from a surface topography to yield drift thickness, i.e. depth to bedrock.

After completion of the bedrock topography, the elevation of the Precambrian surface was labeled at the 108 locations in the Minnesota portion of the study area where well records indicated that Cretaceous strata were present. If the boring fully penetrated the Cretaceous section, the elevation of the underlying Precambrian rock was labeled. If the Cretaceous strata were not fully penetrated, the elevation of the bottom of the hole was labeled to indicate a maximum elevation of the sub-Cretaceous surface. The data were then contoured to yield a sub-Cretaceous bedrock topography at a 50-foot contour interval. These contours were then scanned and vectorized, and a grid of sub-Cretaceous topography elevations was generated. Subtracting the sub-Cretaceous topography grid from the bedrock topography grid yielded the thickness and extent of Cretaceous strata. This method was used to generate the contact between the two geologic units. These same grids were later used to generate 3D representations of the bedrock geology.

In the North Dakota portion of the study area, a data plot was created to show bottom hole elevations for wells that did not reach bedrock, and bedrock elevations for those wells that did. The same plot included an image of the bedrock topography as mapped by Bluemle (1983). This compilation of data was used to draft a new bedrock topography, slightly modified from the Bluemle map. In a similar manner, the Precambrian bedrock topography was modified from a scanned image of mapping done by Heck (1988). The available database did not indicate the age of bedrock encountered, so the Precambrian surface was delineated by the elevation of the contact as mapped by Bluemle in the small part of the North Dakota portion of the study area where the first bedrock is Precambrian, and by the Heck data for the remainder of the map. The geologic contact between post-Precambrian and Precambrian rocks was derived from the difference between the two topographic grids. Even though the topographic contours of the bedrock surface and the Precambrian surface are identical in areas where no Cretaceous strata were reported, the derived grid cell elevations can vary slightly. When the difference between the grids is calculated these small differences falsely infer negative values, or thin occurrences of Cretaceous strata. These small differences have been overridden using a minimum thickness criterion of 10’ (3 m), and this may cause the map to understate the extent of Cretaceous strata where they are very thin. For an accurate assessment users are encouraged to examine the well record database for reported thicknesses.

E. 3D Geological Model

Introduction: While the surficial geology map, the bedrock geology map, and the stratigraphic classification scheme provide a structure for analyzing the deposits in the region, as well as a platform for prediction of subsurface materials and conditions, a more readily usable information system for facilitating subsequent hydrogeologic characterization and ground water system analysis can be provided as a full 3D specification of the geometry of the strata. Construction of a 3D model can now be more readily achieved due to progress in computing power, so a 3D geological model therefore was constructed to optimally support future assessment of Fargo-Moorhead region ground-water resources. The bedrock surface and the Precambrian surface are important interfaces whose 3D geometry were mapped as the first priority. In order to subdivide the Quaternary sediment sequence into regional 3D strata, to the extent possible, it was necessary to correlate between stratigraphic reference sites. These correlations needed to be guided by all available subsurface data, consisting almost entirely of water wells of varying resolution and reliability. To do so, plans were made to subdivide the study area into 5-km wide strips (Figure 19), such that all drillhole data and stratigraphic reference sites could be plotted on charts and interpreted. It thus was anticipated that features approximately 5 km (3 miles) across or greater would be depicted in the model, a level of detail considered manageable in relation to computing power, and justified by the spatial distribution of available data.

It then was determined that a level of resolution higher than 5 km would be required for four areas where important aquifers were known to occur (Figure 20). A greater level of detail in the 3D model therefore was constructed for these four areas, referred to as the Hankinson, Fargo, Pelican River, and Pineland areas. These areas include the Pelican River Sand-Plain Aquifer (Miller, 1981), the Pineland Sands Area (Helgesen, 1977), the Becker-Ottertail Outwash Aquifer (Anderson, 1980), the Buffalo, Moorhead and West Fargo Aquifer systems (Ripley, 2000), the Hankinson, Brightwood, Sonora and Milnor Channel Aquifer systems of southeast North Dakota, a portion of the Spiritwood Aquifer in southeast Sargent County of North Dakota, and a portion of the Sheyenne Delta aquifer of eastern North Dakota. More closely spaced cross sections were planned for these areas, so deposits approximately 1 km (0.6 mile) or larger in horizontal extent would be depicted wherever it was possible to resolve their likely existence and prepare an interpretation of their geometry based on available drillhole data. Initial project plans had called for a 0.5 km horizontal resolution in the detailed areas, but it was found that the density of drillhole data only rarely supported a half-km cross-section spacing, while a 4-km spacing was determined to be the highest reasonable spacing for portions of the study area. Plans were made, however, to model the interpretations at a half-km or higher resolution in order to capture key features that would only have been roughly depicted at the 5-km level of resolution.

Methods: Digital drillhole data currently available in North Dakota State Water Commission and Minnesota Geological Survey databases (Figure 21) were reconciled and compiled as a project database and used as a basis for outlining the regional 3D geometry of strata formally defined at stratigraphic reference sites, within the constraints of surface topography, bathymetry, the surficial geology map, the bedrock topography map, Precambrian topography map, and current knowledge on geologic processes and history. The project water-well database consisted of about 30,000 drillers logs and about 60 Quaternary stratigraphic control sites. The regional base map with 34 east-west cross section lines (Figure 19) was used as a framework for interpreting regional 3D geology down to the Precambrian surface. The cross-section lines were split at the center of the study area, resulting in a total of 68 regional cross sections. Topographic profiles were extracted from USGS digital elevation models for each of the 68 cross sections. Wells were selected for the cross sections and required digital files were created. Drillhole lithological information was depicted on charts as borehole lithology graphs known as stick diagrams. Explanation files were created from the project drillhole database based on lithology and color. Each cross section was edited to eliminate overlapping wells. Wells projected to the cross section but located significantly off of the cross section line or at an elevation significantly different from that of the section line were noted to avoid misrepresentation of the geology along the line. Quaternary stratigraphic reference sites were then added to the cross section.

For the Hankinson area (Figure 22), 29 east-west detailed cross sections, with north-south spacing varying from of 1 to 4 km were plotted, interpreted, and digitized. In this area, revised thicknesses and extents were mapped for previously identified surficial and buried aquifer systems. For the Fargo area, 44 east-west detailed cross sections with north-south spacing of 0.5 to 3 km were used to produce an updated map of 4 buried aquifer systems. In the Pelican River area, 42 east-west detailed cross sections with a north-south spacing of 1 km were interpreted. Finally, for the Pineland area, 32 east-west detailed cross sections with a north-south spacing of 1 to 1.5 km were plotted, interpreted, and digitized to map two buried aquifer systems. Stratigraphy mapped in the four detail areas was then incorporated into the regional cross sections, and stratigraphic inconsistencies were reconciled.

Water-well cross sections were constructed in a 2D GIS environment using ArcView 3.3, ArcGIS 9.0, and custom extensions (Figure 23). Water-well logs and surface geology were displayed along the locus of each cross section, to aid interpretation. Creating these cross sections in a GIS environment allowed sand and till boundaries to be correlated by overlaying GIS files in the same view window. A series of points for each stratum were extracted from the lines and converted into X, Y, Z values using an ArcView script (Figure 24). These points were then used as control points for surface and solid construction using Gocad 3D GIS software (Figures 25 to 27). In addition, cross sections were scanned and registered in three-dimensional space in order to check surface locations and to add additional control points to constrain surface dimensions. Errors or inconsistencies between cross sections were easily identified and adjusted in 3D space. Visualization in 3D also provides for qualitative and quantitative assessment of the model uncertainty by showing or measuring the distance between portions of the model and control points used to construct it when depicted.

Descriptions and statistics related to sand bodies in the detail areas were derived from files exported from the Gocad 3D models. These files included 2D grid shape files, grouped by stratigraphic association, for thickness (feet), depth (feet), and elevation (feet). These files and polygon shapefiles of the sand unit outlines (border polygons) are included as attachments to this report. Using the zonal statistics function of the ArcGIS 9.1 spatial analyst extension, the statistical characteristics of these grids were calculated. Each of the detail area maps was given a reference number to the corresponding regional model layer (e.g. RL006). The sand bodies were labeled by a feature ID number from the grid files and border polygons, and standardized detail area maps were plotted at a scale of 1:300,000.

In some instances, especially for North Dakota, established aquifer names have been included for reference. The focus of this study was, however, to best approximate the boundaries of the sand units as physical geologic units with existing data. Many new sand bodies were mapped, although none have been evaluated for hydraulic continuity to determine if they represent discrete aquifers. The reported sand body statistics include bulk sand volume in cubic meters, which will have some relationship to available ground water. For purposes of water resource assessment, however, internal factors such as water quality, porosity, and permeability, and external factors such as recharge and connection to other aquifers or surface water may be more important considerations in many cases. In addition, the bulk volume estimates contain different levels of uncertainty since the bodies were mapped in 3D with well log information that often did not fully penetrate the sand body. In addition, since existing data were used, many of the sand body maps are approximations due to a general lack of drill hole data or geophysics.

Results: A total of 36 strata were mapped in 3D (Figure 28). These are numbered regional model layers 1 to 37, as layer 27 was merged with the adjoining stratum (Appendix F). Examination of the model in plan view (Figure 29) allows comparison with the surficial geology map to clarify the somewhat lesser level of detail that was achievable in 3D on the regional scale, a level of detail comparable to a 1: 500,000 map. Cross-sections (Figures 30 to 34) clarify the typical geometry of the strata. Over 130 sand deposits corresponding to known aquifers and potential aquifers were identified and mapped within the study area (Figures 35 and 36). The lateral extent of each layer is indicated in Figures 37 to 71.

The sand bodies (Figure 72) mapped from the well database using regional or detail area geologic cross sections may be used to infer probable ice margin positions as a basis for further exploration, as the sand bodies currently identified may prove to be more extensive than currently recognized along these trends. The major surficial sand units in the Hankinson, Pelican River, and Pineland areas were mapped from a combination of surficial mapping and well data. A much higher resolution of mapping was achieved in the four detail areas, shown in Figure 72 as black rectangles, since the cross section spacing in these areas ranged from 0.5 km to 3 km, with 1 km as the most common spacing. With such close cross section spacing, most of the wells within these detail areas were used in the mapping.

Outside the detail areas, where the cross section spacing was 5 km, buried sand bodies were only delineated if a sand layer occurring at a certain elevation and stratigraphic position could be found within close proximity on one or more adjoining cross sections at the same stratigraphic position and general elevation. Therefore, the sand bodies shown outside the detail area rectangles represent reconnaissance mapping designed to create a general understanding of where the large buried sand units may be. The buried sand units shown in these areas could serve as a guide for additional detail mapping and exploration.

A stationary glacier edge at the inferred buried ice margins (Figures 72 and 73) may have produced ice marginal fluvial deposits that were subsequently buried by a finer grained layer of till from later ice advances. These lines highlight areas where buried sand bodies at the same stratigraphic position and similar elevations seem to line up in a manner consistent with the probable outlines of former ice masses. Figure 73 shows only those sand bodies that seem to be linked in this manner. The western and eastern portions of the greater valley area seem to be dominated by moraine or marginal fluvial systems sand units. The central portion of the valley is dominated by tunnel valley deposits that formed perpendicular to the ice margins. Tunnel valleys are deep melt water channels that formed mostly beneath the ice as the glacier receded. These channels subsequently filled with sand and gravel deposited by the glacial melt water.

On Figure 73, the largest of the ice margin trend deposits is labeled as OT1, sand deposited on the top of the Otter tail group, indicating the highest elevation trend of stagnation moraine deposits associated with the Otter Tail group. Other successively lower elevation trends can be followed down into the valley, OT2, OT3, and OT4, possibly representing a recessional trend of an ice mass to the north. The OT3 trends of Minnesota and North Dakota may roughly outline both sides of a single ice mass. The A4 margins in Minnesota and North Dakota may represent unrelated recessional trends to the north and northeast. The narrow LT or Lake Tewaukon sand bodies in the south central portion of the project area probably represent a related set of tunnel valley deposits that includes the Wahpeton buried valley as the northern-most feature of this group.

F. Description of sands in the detailed areas

1. Hankinson area

Surficial sand units: The major surficial sand units in this area include the Milnor channel/Hankinson unit (1) and the Sheyenne delta (3) (Figure 74). Sand thickness values of approximately 30 to 40 feet are typical of the Milnor channel portion of the unit with some areas as thick as 70 feet. The Hankinson part of the unit is generally much thicker with typical values in the 60 to 100 foot range and maximum thickness values over 150 feet. The bulk sand volume of the Milnor channel/Hankinson unit is approximately 408 million m^3.

Sand units at the top of the Otter Tail River group: A relatively shallow and large sand body (unit 6) was delineated in the central portion of the study area (Figure 75) with typical depth range of 10 to 40 feet. This appears to be a relatively uniform sand body with a mean thickness of approximately 30 feet (Figure 76) and locally higher thickness values. This unit 6 appears to have many connections to both the overlying Milnor channel and the Sheyenne delta. The bulk sand volume of unit 6 is approximately 340 million m^3.

Another group of smaller and deeper sand units (0 through 5) exists in the valley area in the eastern portion of the area. The depths of these sand bodies range typically from 70 to 120 feet. The maximum thickness values range from approximately 30 to 60 feet (Figure 76). These units are not well defined by drilling or geophysics.

Sand units at the top of the Lake Tewaukon group: Typical depths to these units range from approximately 110 to 130 feet (Figures 77 and 78). Both units appear to be narrow and thick suggesting a tunnel valley origin and may be genetically related to the Wahpeton buried valley located a few miles north east of this detail study area. These units are not well defined by drilling or geophysics but maximum thickness values may range from approximately 140 to 150 feet with bulk sand volume values of approximately 70 to 110 million m^3.

Sand units at the top of the A3 (older unknown) till unit: The sand units within this group include the Gwinner aquifer (unit 0) at a depth of approximately 100 feet and several other small units (1, 2, 3, 4, 6 and 10) at approximately the same depth (Figure 79). The other smaller units are shallower due to local topographic variations. Unit 10 has the highest maximum thickness at 84 feet which is comparable the maximum thickness of the Gwinner unit with a value of 52 feet (Figure 80). Both units also have comparable bulk sand volumes of approximately 20 million m^3.

Sand unit at the top of the A4 (older unknown) till unit: This sand unit corresponds to the Spiritwood aquifer. The eastern portion of this sand body, near Hankinson, may also correspond to the Brightwood aquifer (Baker and Paulson, 1967). The elevation of this Spiritwood unit has a slight dip to the east but increases in depth to the west due to the subtle trough shape of the valley (Figure 81).

The thickness value distribution (Figure 82) and overall geometry suggests two coalesced stagnation outwash plains with northwest – southeast ice margin trends. The mean thickness value of this unit is 34 feet with maximum values over 100 feet in the central portions of the two sub-parallel trends. The bulk volume value of 633 million m^3 is the highest of any buried feature in any of the detail areas.

Sand unit at the top of the A5 (older unknown) till unit: The depths of these units typically range from 130 to 160 feet (Figure 83). Since these are the deepest mapped units in this area they are not well defined by drilling or geophysics. Unit 2 has the highest maximum thickness (62 feet) and bulk sand volume (48 million m^3) of the group and may also be related to the Brightwood aquifer (Figure 84).

2. Fargo area

Sand units at the top of the Red Lake River group: The shallowest and generally thickest group of sand bodies in this area is found at the top of the Red Lake River group. The Buffalo aquifer (6) was deposited along the edge of the basin and is, therefore, significantly shallower than the associated sand bodies to the west (Figure 85). With the exception of the southern end of the Horace aquifer (5) and unit 7, typical depths of these units range from approximately 70 to 110 feet. Most of the sand bodies in North Dakota were previously recognized by Ripley (2000) with the exception of units 2 and 7. In Minnesota, unit 3 appears to be a newly recognized unit.

The West Fargo North (8), Ponderosa (4), Horace (5), and Buffalo (6) units appear to be the thickest of this group (Figure 86) with maximum thickness ranging from 142 feet (Buffalo, unit 6) to 231 feet (Horace, unit 5). The deep narrow nature of these units suggests deposition in a tunnel valley setting. The maximum thickness of the other units in the group is not well known as they have not been adequately defined by drilling or geophysics. The three largest bulk sand volumes of this group belong to West Fargo North (180 million m^3), Horace (254 million m^3), and the Buffalo unit (258 million m^3). These are also the largest bulk volumes of all the units in this area.

Sand units at the top of the Goose River group: With the exception of units 0 and 4 along the eastern edge of the basin the depth to the top of these units ranges approximately from 110 to 150 feet (Figure 87). The units in North Dakota (94-10, unit 5, and West Fargo South, units 1 and 3) were previously recognized by Ripley (2000). The Border unit (2) in Minnesota appears to be a newly recognized unit. The deep narrow nature of these units suggests deposition in a tunnel valley setting.

The 94-10 (unit 5) and West Fargo South (unit 1, 3) are the thickest units with maximum values of 131 and 182 feet, respectively (Figure 88). However, the Border unit possibly has the largest bulk volume of the group at 159 million m^3, which is comparable to the largest sand units in this area. Much more delineation of the Border unit is needed to determine its actual size and potential.

Sand units at the top of the Otter Tail River group and an older unknown unit: Units along the eastern edge of the study area in Minnesota are relatively shallow and may be hydraulically connected to the overlying Buffalo unit. The depths to these shallower units (2, 3, 4, and 5) range from approximately 110 to 130 within the range of the deeper portions of the Buffalo aquifer (Figure 89). The deeper units, including unit 1 in Minnesota, and the Prosper aquifer in North Dakota (unit 6) occur at depths that range approximately from 160 to 180 feet.

The thickest units of this group are the Prosper (6) and unit 5 with maximum thickness values of 131 feet and 144 feet, respectively (Figure 90). The Proper aquifer has the highest bulk volume of this group at 82 million m^3, however units 3, 4, and 5 may have comparable values (40, 50, and 47 million m^3, respectively).

Another poorly defined sand unit exists at the top of an unnamed till south of Glyndon in the Minnesota portion of the study area. The average depth of this unit is about 200 feet (Figure 91) and may be as thick as approximately 60 feet (Figure 92).

3. Pelican River area

Surficial sand unit (Pelican River sand plain): The average thickness of the Pelican River sand plain (unit 0) is approximately 50 feet (Figure 93) with the thicker portions occurring in the western portion of the area where thickness values of 60 to 100 feet are common. The bulk sand volume of the Pelican River sand plain in this detail area is approximately 780 million m^3 which is the second largest bulk volume calculated for these detail area analyses.

Sand units at the top of the Upper Goose River group: Two sand units exist at this stratigraphic position in the western portion of the area. Unit 1 is relatively shallow at depths of 20 to 40 feet (Figure 94) and has an average thickness of about 40 feet (Figure 95). Unit 0 has a highly variable depth due to the complex local topography and may be thicker than unit 1. Unit 0 also appears to be the eastern extension of a larger unit west of the detail study area (Figure 72).

Sand units at the top of the Otter Tail River group: The sand units of this group seem to represent a highly diverse assemblage. Units 1 through 4, although poorly defined by subsurface data, appear to be long, narrow and deep features characteristic of tunnel valley features. The other features appear to have been deposited in a stagnation moraine setting or ice marginal fluvial environment. Units 5, 6, and 7 are part of the region-wide trend that extends across the larger regional study area (Figures 72 and 73). The depths to these units are generally shallower in the eastern and southern portions of this detail study area (Figure 96) but are also highly variable locally due to the complexity of the topography in this area. Unit 0 near Lake Park is the deepest of the units with a typical depth of approximately 200 feet.

Sand thickness values are typically 40 to 50 feet for these sand units (Figure 97). Units 0, 5, and 6 have the highest bulk sand volumes at 88, 88, and 189 million m^3, respectively.

4. Pineland area

Surficial sand unit (Pineland sand plain): The Pineland sand plain covers most of the northeastern portion of the study area with the thickest portion occurring in a zone from Park Rapids to Pine Point and beyond to the northwest (Figure 98). Sand thickness values of 60 to 100 feet are common along this trend. The thickest portions of this sand plain intersect and are connected to the underlying buried aquifers (A3 units) at several locations and completely merge with the A3 sand bodies in the eastern portion of the area. Unit 4 of this sand plain has a bulk sand volume within the study area of approximately 1,050 million m^3 which is the highest value of any sand body evaluated in the detail areas.

Sand units at the top of the Browerville (A3) group and Crow Wing River (A4) group: The orientations of the A3 sand units appear to have been controlled by northwest-southeast trending ice margins of glacial ice lobes that moved into the area from the northeast. The A3 units are relatively shallow sand bodies (50 to 80 feet) except where a somewhat anomalous topographic high exists in the west central portion of the area (Figure 99).

Thickness values are particularly hard to judge for the A3 units since most of the wells in the area only penetrate the upper 5 or 10 feet of these buried sand units. However, 30 to 40 foot thick sand may be a fairly common value (Figure 100). Unit 6 appears to have the highest bulk sand volume of approximately 106 million m^3.

The A4 sand units appear to have an origin similar to that of the A3 units. Typical depths range from approximately 70 to 120 feet (Figure 101) and thickness values of 30 to 40 feet may also be common (Figure 102). Unit 1 appears to have the highest bulk sand volume of this group at 203 million m^3.

5. Overview

The two largest buried sand bodies of all the evaluated detail areas occur in the Hankinson area. These sand bodies are the Spiritwood (Figure 82) and unit 6 at the top of the Otter Tail group (Figure 76) with bulk sand volumes of 633 and 340 million m^3, respectively. Substantial, buried sand units also exist in the other detail areas. In the Fargo detail area the Buffalo (6) and Horace (5) units (Figure F2) contain approximately the same bulk sand volume with values of approximately 250 million m^3. In the Pelican River detail area unit 6, at the top of the Ottertail River group, has the highest bulk sand volume of 189 million m^3 (Figure 97). In the Pineland detail area the unit 1 sand body at the top of the A4 unit (Figure 102) has the highest bulk volume of 203 million m^3.

Regionally, the most extensive buried sand body trend occurs at the top of the Otter Tail group (show as OT1 on Figure 73) and spans the entire north-south extent of the regional study area in Minnesota. If the lateral continuity of sand bodies along this trend within the Pelican River detail area is typical of other sand bodies along this trend within the region, this may represent one of the largest buried ground-water resources in the region.

VII. Summary

- New 3D mapping has revised the previously known extent (Figures 103-110) of aquifers in the Fargo-Moorhead region, and has drawn attention to several major sand deposits not previously recognized as named aquifers that may require further assessment in order to more fully clarify the capacity of potential ground-water resources in the region.

- New programs of data collection could readily be designed to clarify the characteristics and water resource potential of the deposits mapped in this study. Most important will be drill hole and geophysical data to further clarify thickness and extent of the major sand bodies, as well as clarification of the physical hydrogeologic and hydrogeochemical characteristics of these systems. In addition, clarification of the hydraulic continuity of these deposits and connections to other aquifers and surface water bodies will help determine how these resources can be best be protected, managed, and used. These analyses will be significantly aided if Quaternary stratigraphic data are enhanced, especially in the Minnesota portion of the study area. These data are essential for understanding the geologic history of the region, which in turn leads to a better understanding of aquifer distribution.

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VIII. Appendices

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Appendix B. Figures:

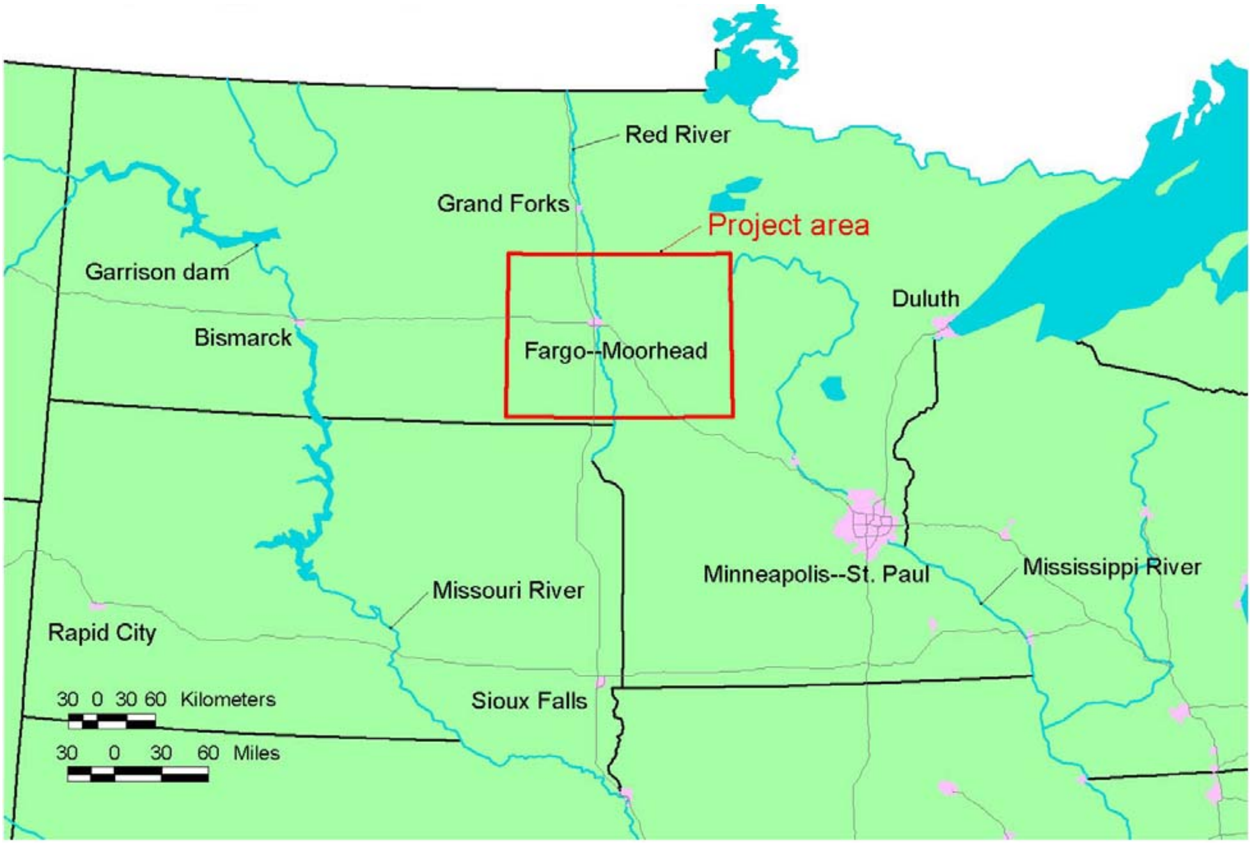


Figure 1 - Location of the Fargo-Moorhead study area

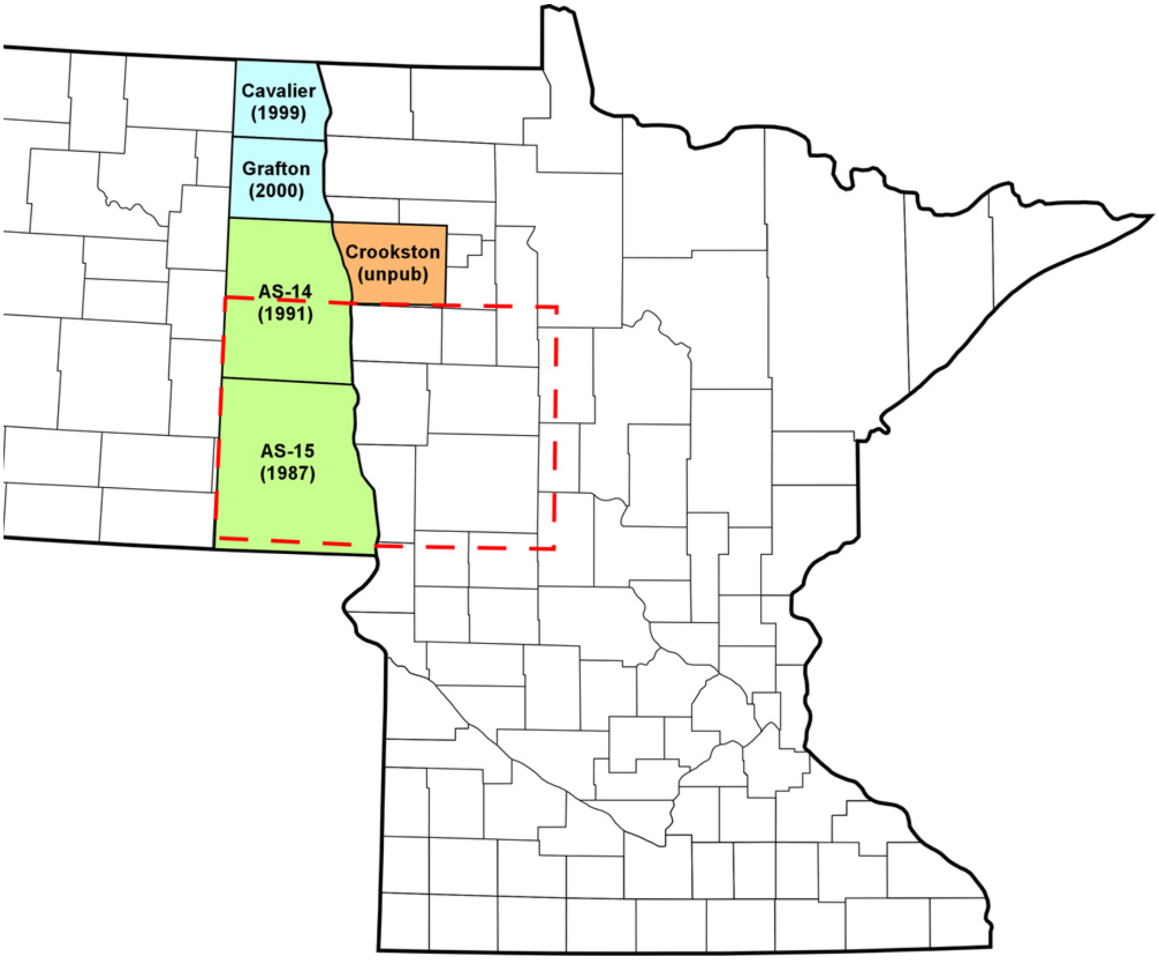


Figure 2 - Previous project areas in the Red River Valley that addressed surficial geology only; full reference information is provided in Appendix C.

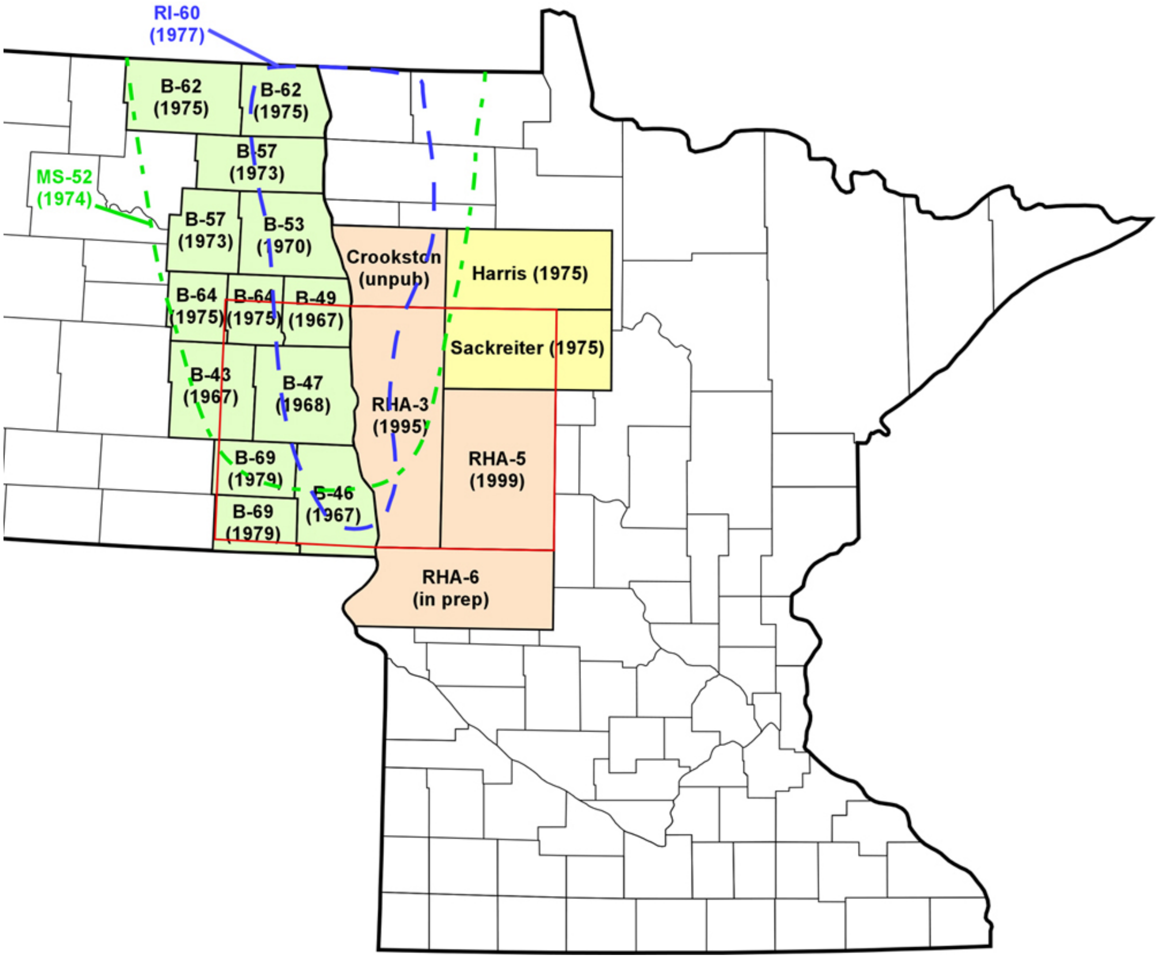


Figure 3 - Previous project areas in the Red River Valley that addressed surficial geology as well as Quaternary stratigraphy; full reference information is provided in Appendix C.

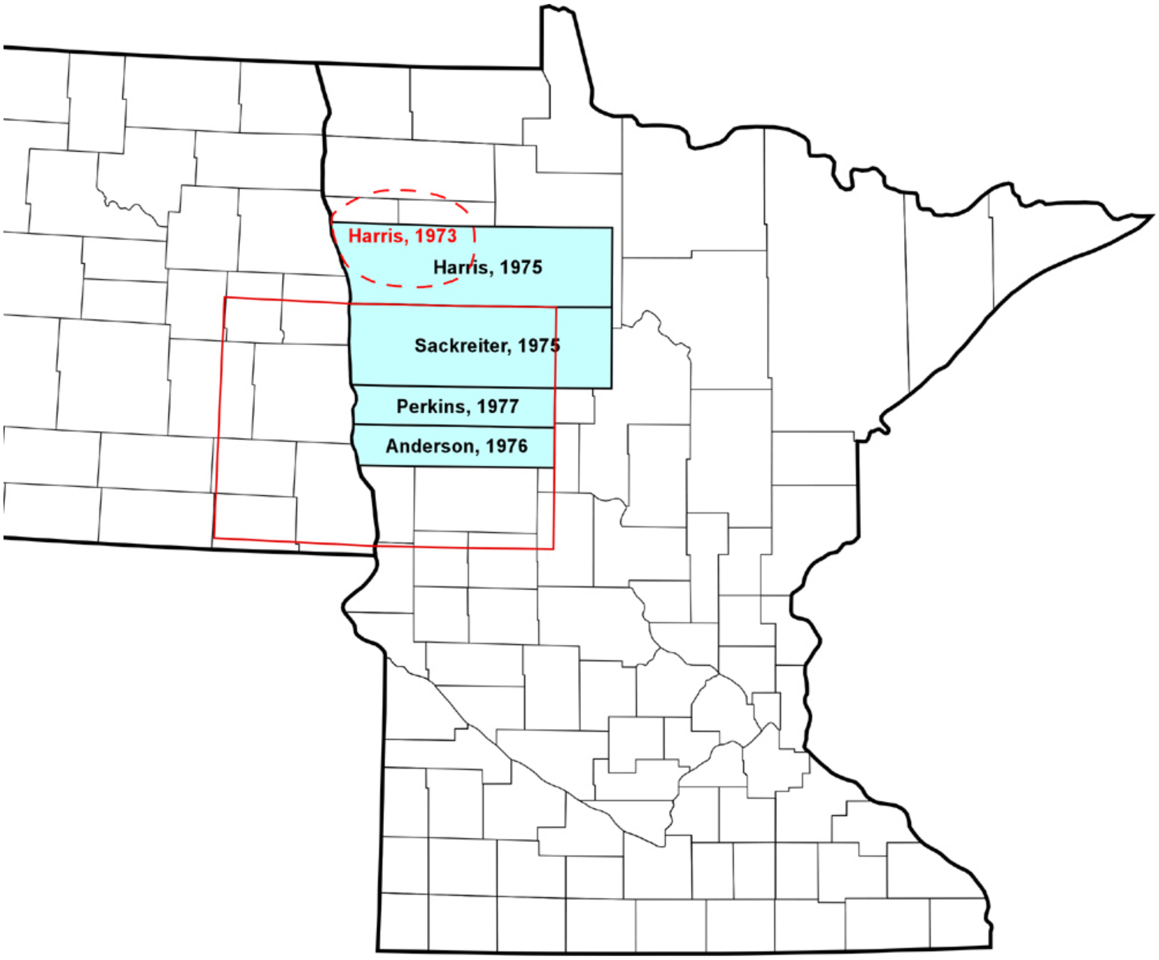


Figure 4 - Study areas for University of North Dakota theses that produced both surficial geology maps and Quaternary stratigraphy; full reference information is provided in Appendix C.

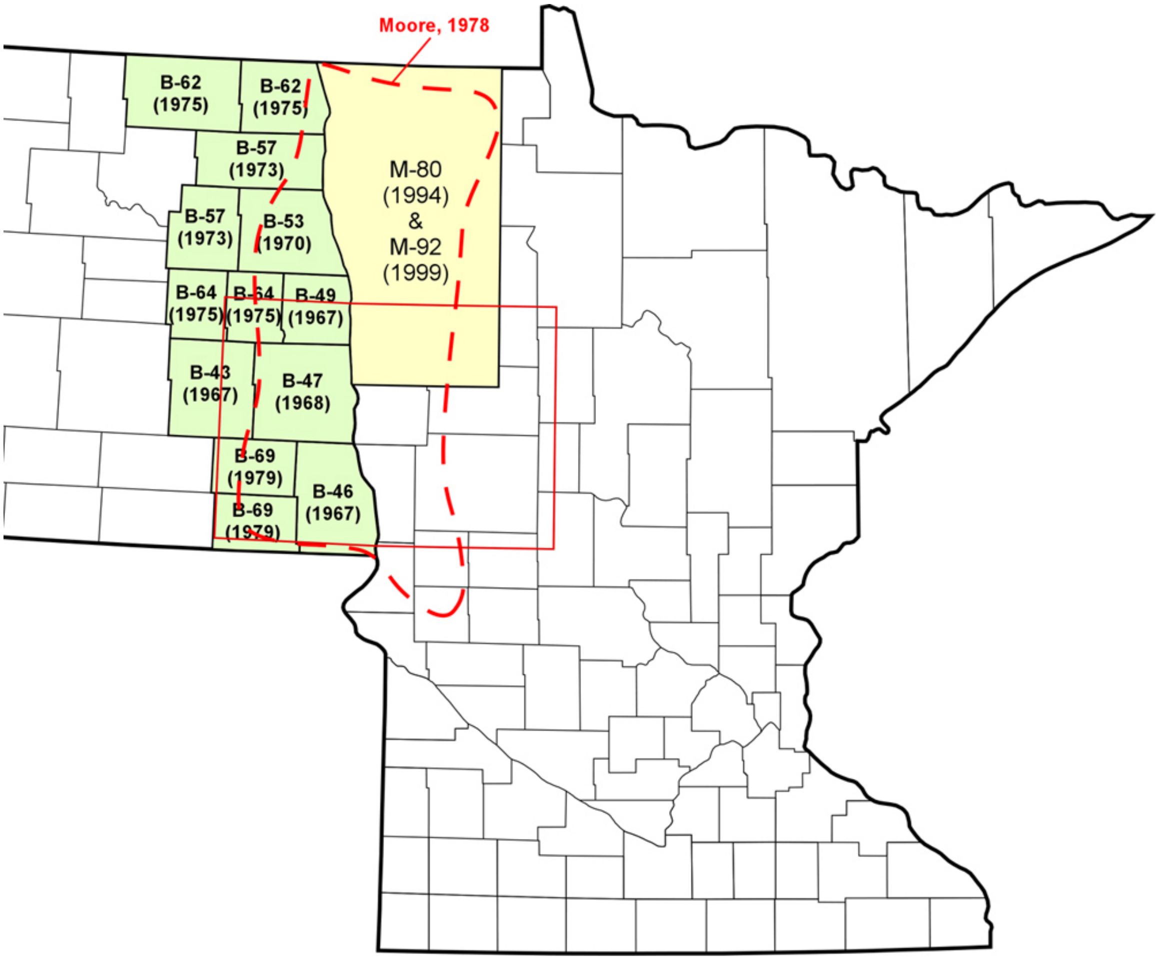


Figure 5 - Previous project areas in the Red River Valley that addressed bedrock geology and pre-Quaternary stratigraphy; full reference information is provided in Appendix C.

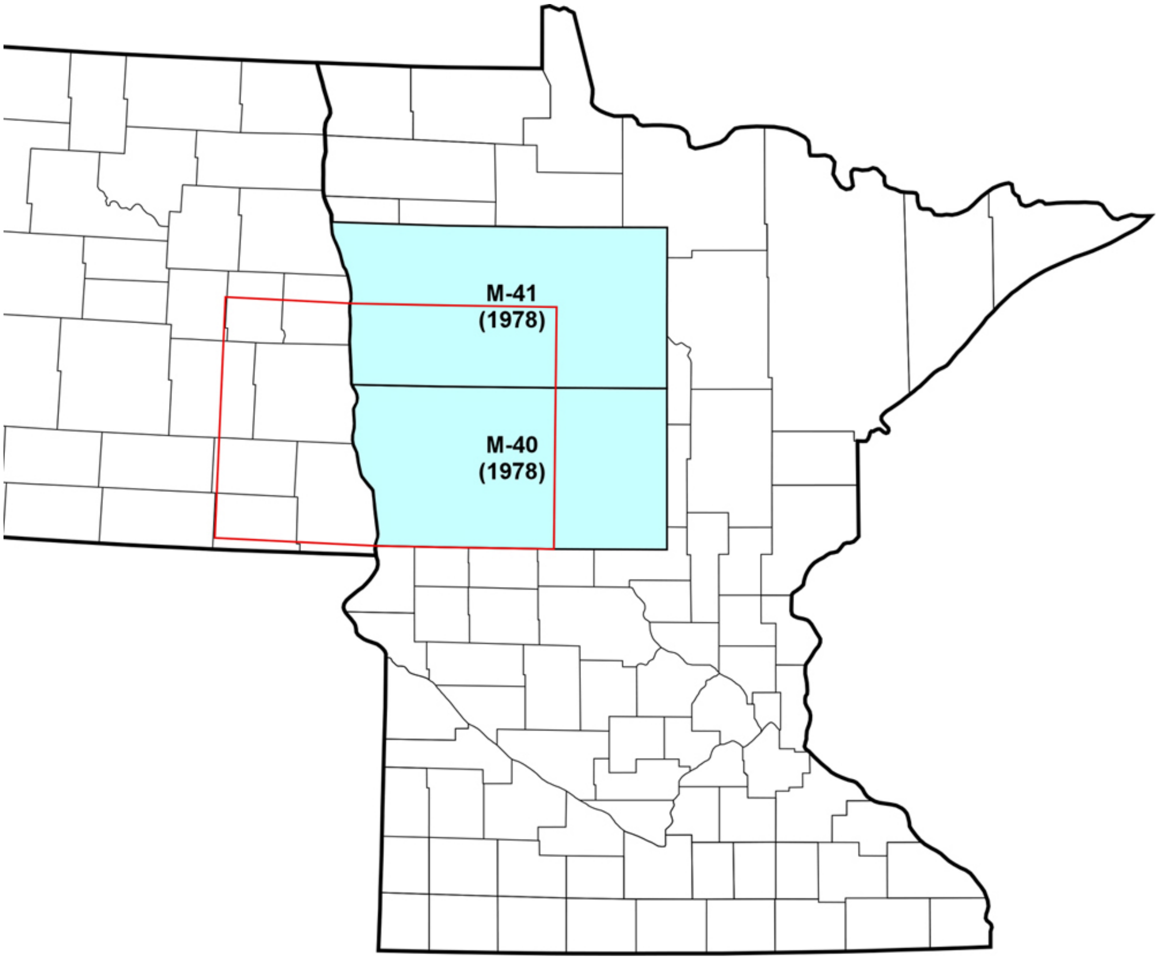


Figure 6 - Previous project areas in the Red River Valley that addressed aeromagnetic mapping; full reference information is provided in Appendix C.

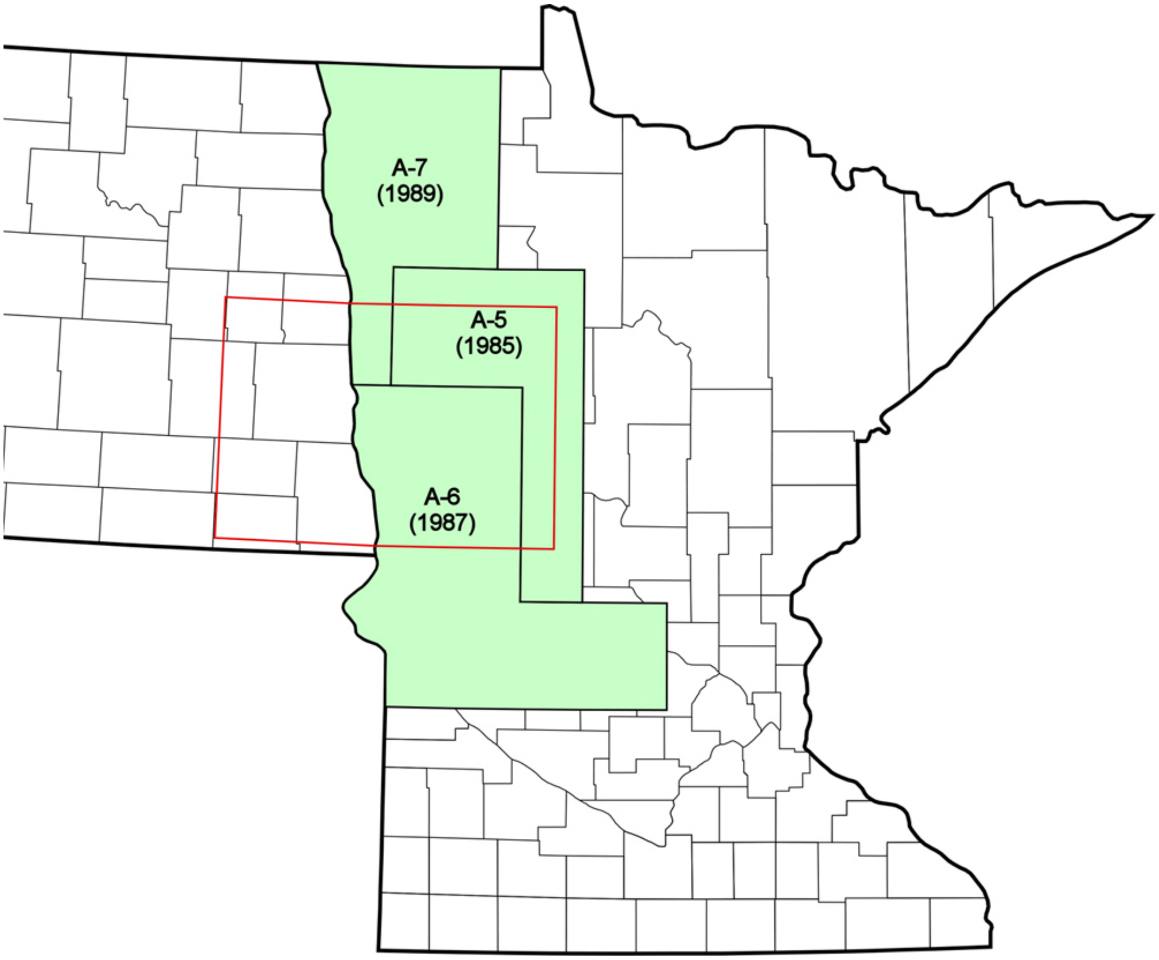


Figure 7 - Previous project areas in the Red River Valley that addressed gravity mapping; full reference information is provided in Appendix C.

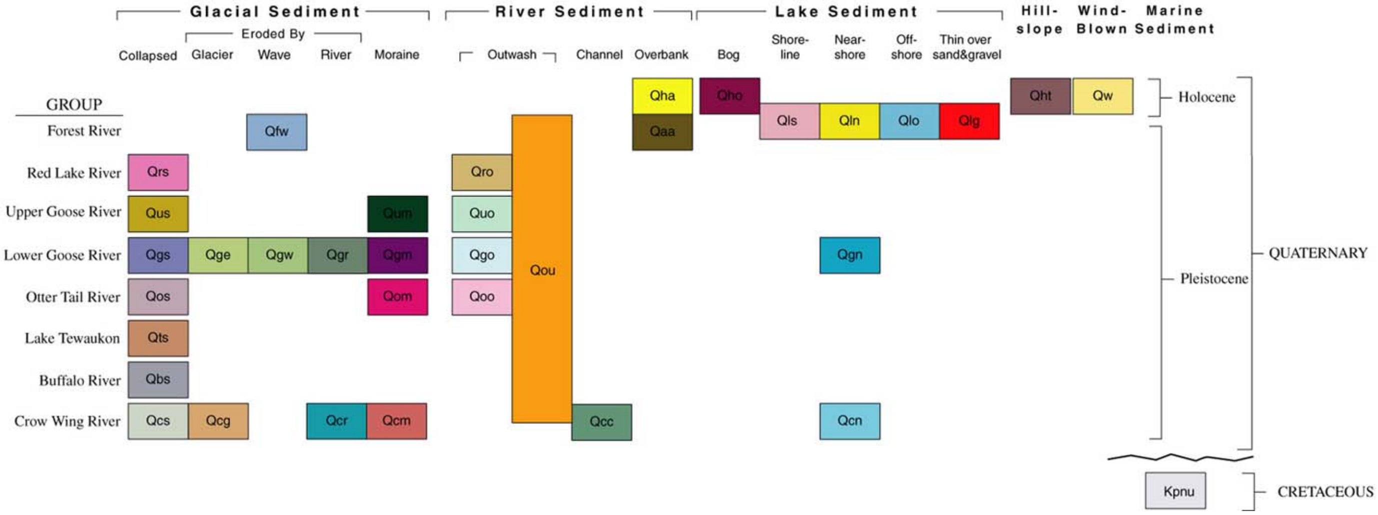


Figure 8 – Categorization of sediments in the Red River Valley as lithostratigraphic units at the group level, with subdivision of the groups and associated surficial geology map symbols according to depositional environment. No formal group name is assigned to the postglacial sediments of Holocene age

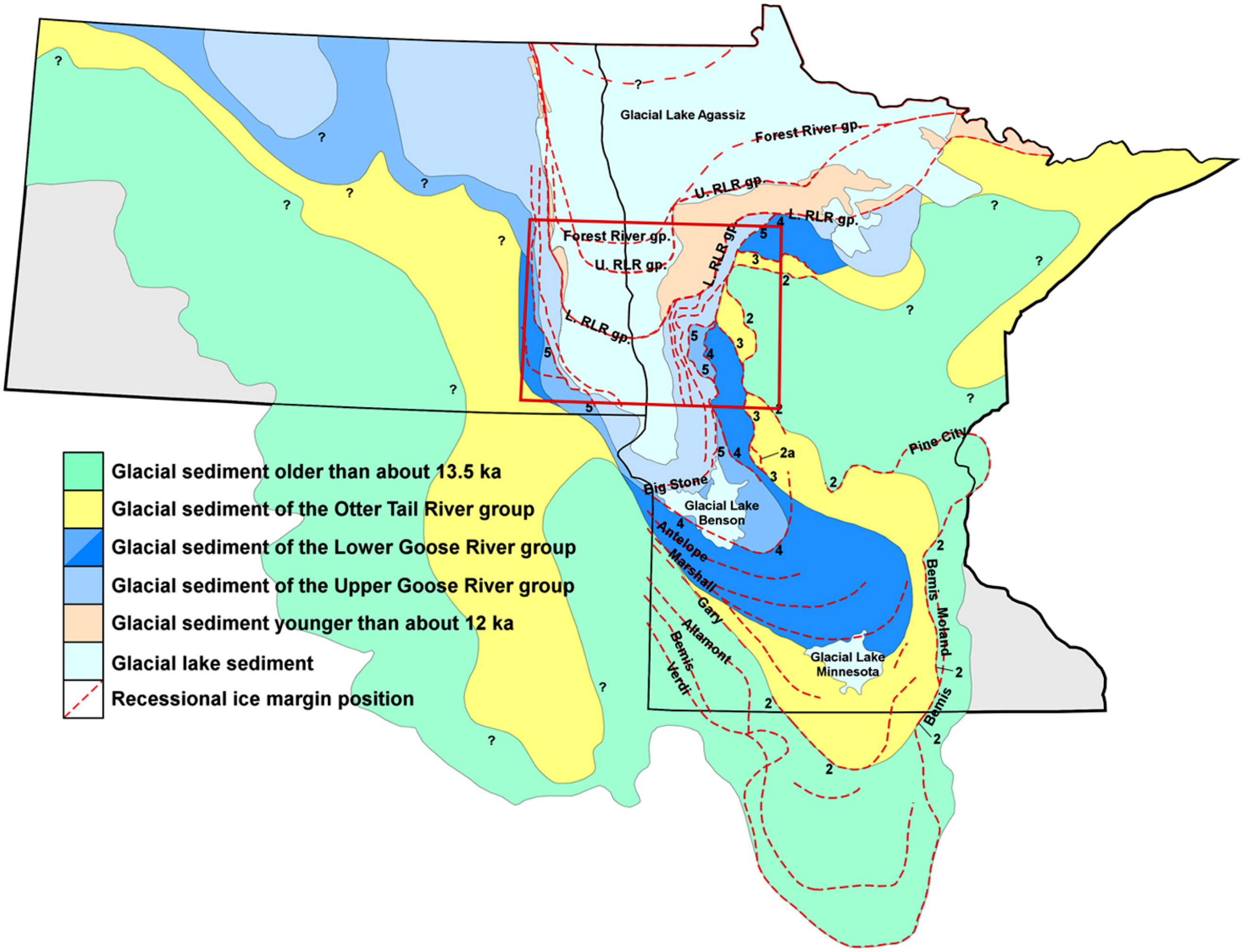
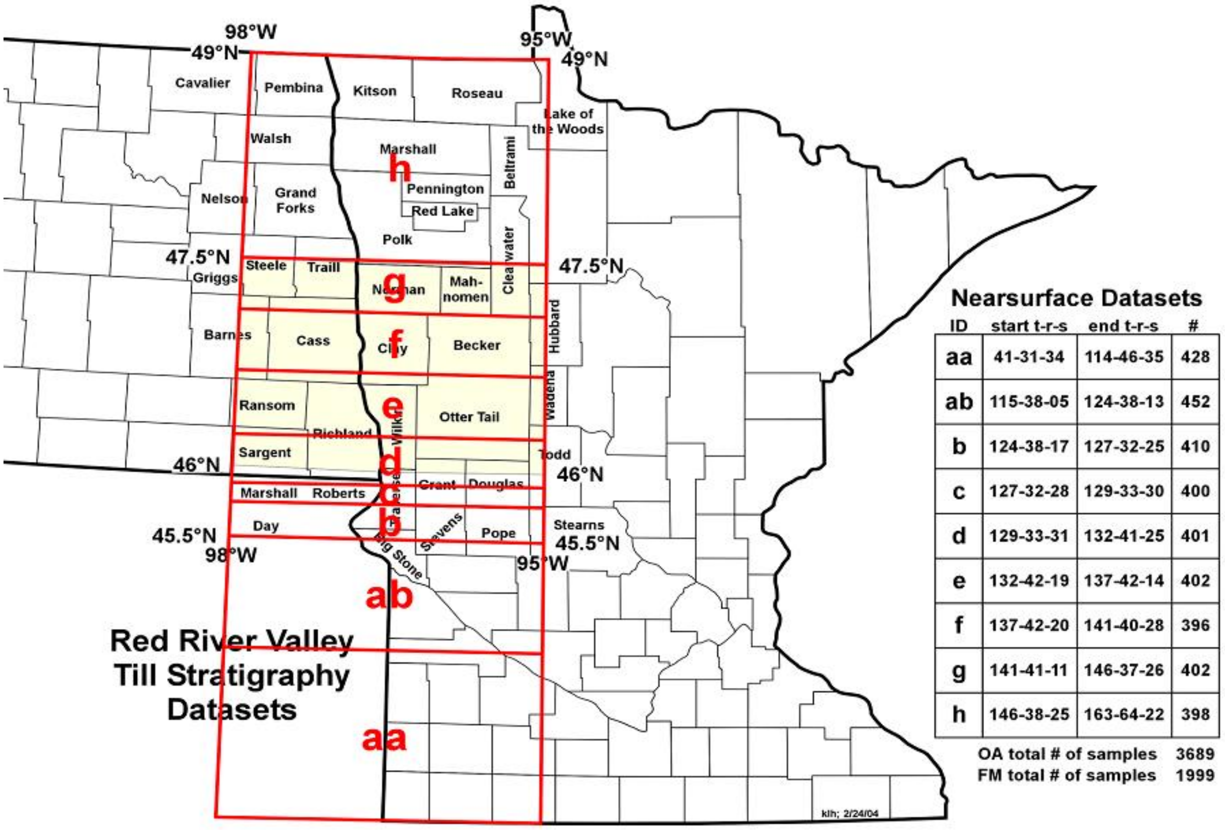


Figure 9 - Regional extent in the upper US Midwest of sediments associated with the final phase of glacial ice flow that largely emanated from the Canadian Prairie Provinces, following earlier ice flow largely derived from the northeast; showing maximum extent of this ice flow and sediment transport prior to 13.5 ka (13,5000 radiocarbon years ago), as well as extent of the younger glacial (till) and glacial lake sediment (clay and silt) strata that dominate the near-surface geology of the Red River Valley on the regional scale. Major sand deposits occur above, between, and beneath these tills and underlying the glacial lake sediment

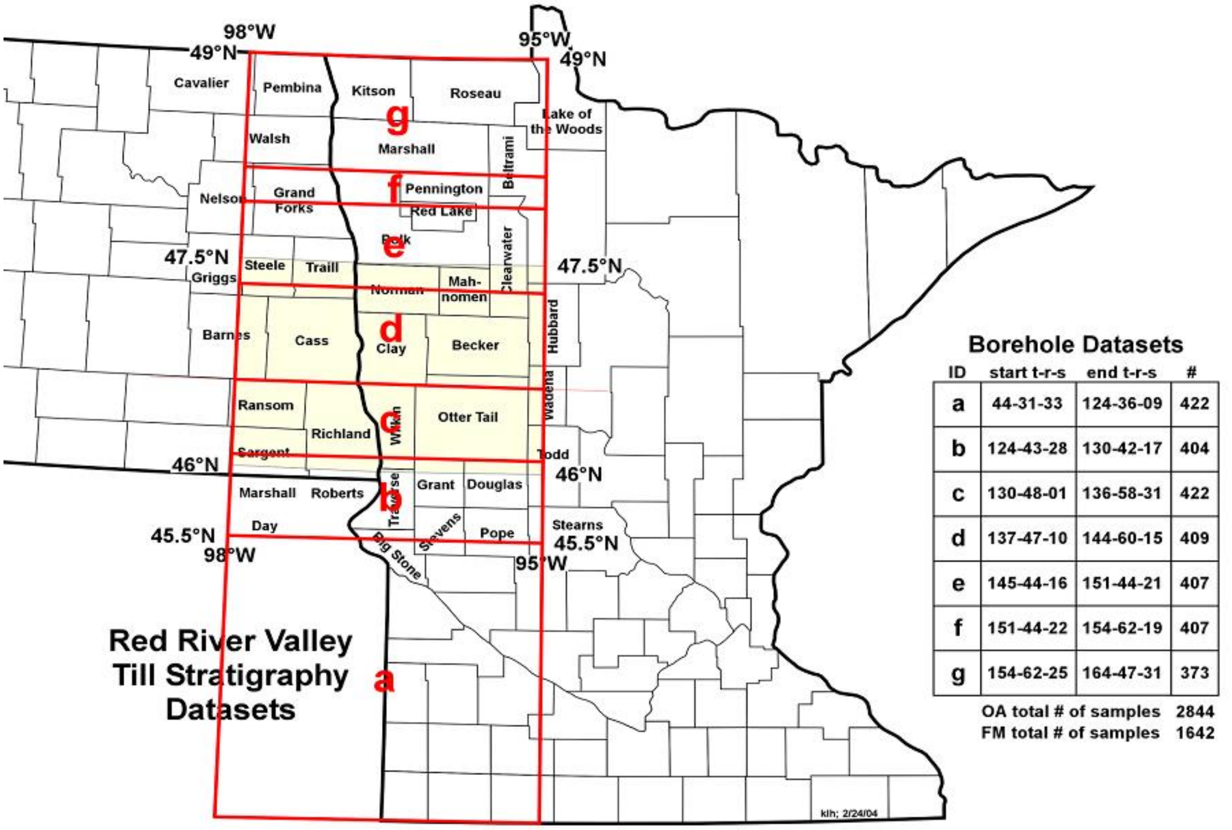


Nearsurface Datasets

ID	start t-r-s	end t-r-s	#
aa	41-31-34	114-46-35	428
ab	115-38-05	124-38-13	452
b	124-38-17	127-32-25	410
c	127-32-28	129-33-30	400
d	129-33-31	132-41-25	401
e	132-42-19	137-42-14	402
f	137-42-20	141-40-28	396
g	141-41-11	146-37-26	402
h	146-38-25	163-64-22	398

OA total # of samples	3689
FM total # of samples	1999

Figure 10 - Distribution in eastern North Dakota and western Minnesota of textural (grain-size) and lithological (rock-types in the very coarse sand or 1-2 mm fraction) data for till; these data are used to assess provenance and correlation of the strata, and in this case includes only sampling from surface such as shovel holes, rather than drilling, hence carbonate may have been at least partially removed by dissolution; data were subdivided into areas labeled aa to h, with range of locations according to township, range, and section (t-r-s) indicated; number of sediment samples in each area is indicated, as is overall (OA) total number of samples in the database and number of samples in the Fargo-Moorhead (FM) study area



Borehole Datasets

ID	start t-r-s	end t-r-s	#
a	44-31-33	124-36-09	422
b	124-43-28	130-42-17	404
c	130-48-01	136-58-31	422
d	137-47-10	144-60-15	409
e	145-44-16	151-44-21	407
f	151-44-22	154-62-19	407
g	154-62-25	164-47-31	373

OA total # of samples 2844
FM total # of samples 1642

Figure 11 - Distribution in eastern North Dakota and western Minnesota of textural (grain-size) and lithological (rock-types in the very coarse sand or 1-2 mm fraction) data for till; these data are used to assess provenance and correlation of the strata, in cases where the sampling was by drilling so carbonate is unlikely to have been removed by postglacial dissolution; data were subdivided into areas labeled a to g; range of locations according to township, range, and section (t-r-s), and number of sediment samples in each area, is indicated, as is overall (OA) number of samples in the database and number of samples in the Fargo-Moorhead (FM) study area

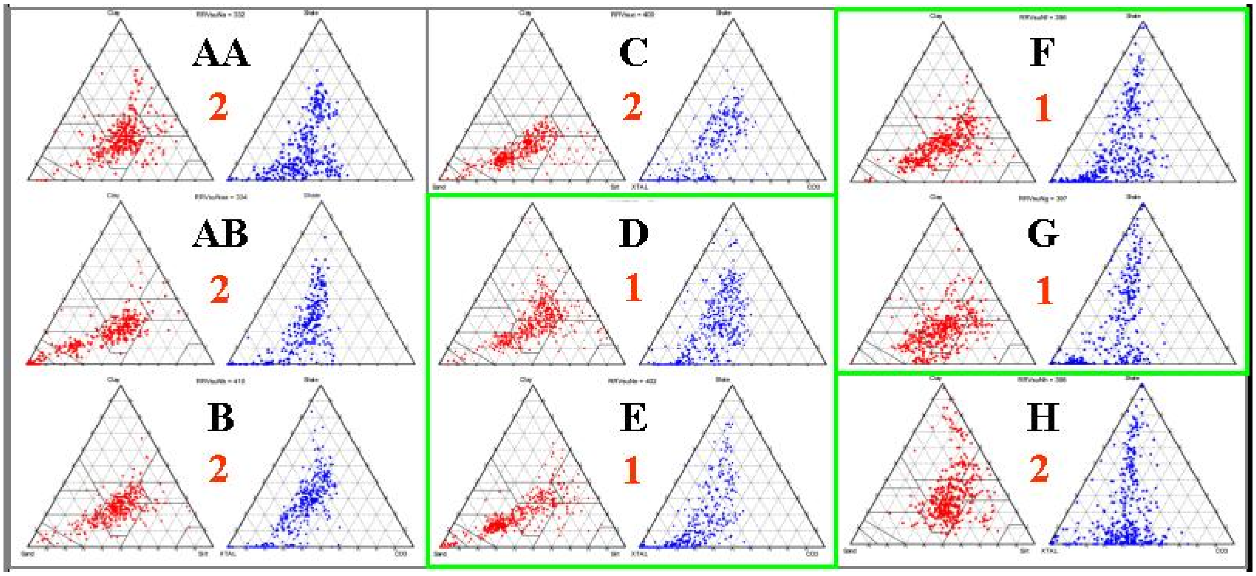


Figure 12 - For each area in the nearsurface Red River Valley till stratigraphy dataset, ternary plots showing till sample data for sand-silt-clay textural data at left and igneous/metamorphic-carbonate- shale data at right; areas within the Fargo-Moorhead study area are indicated (1).

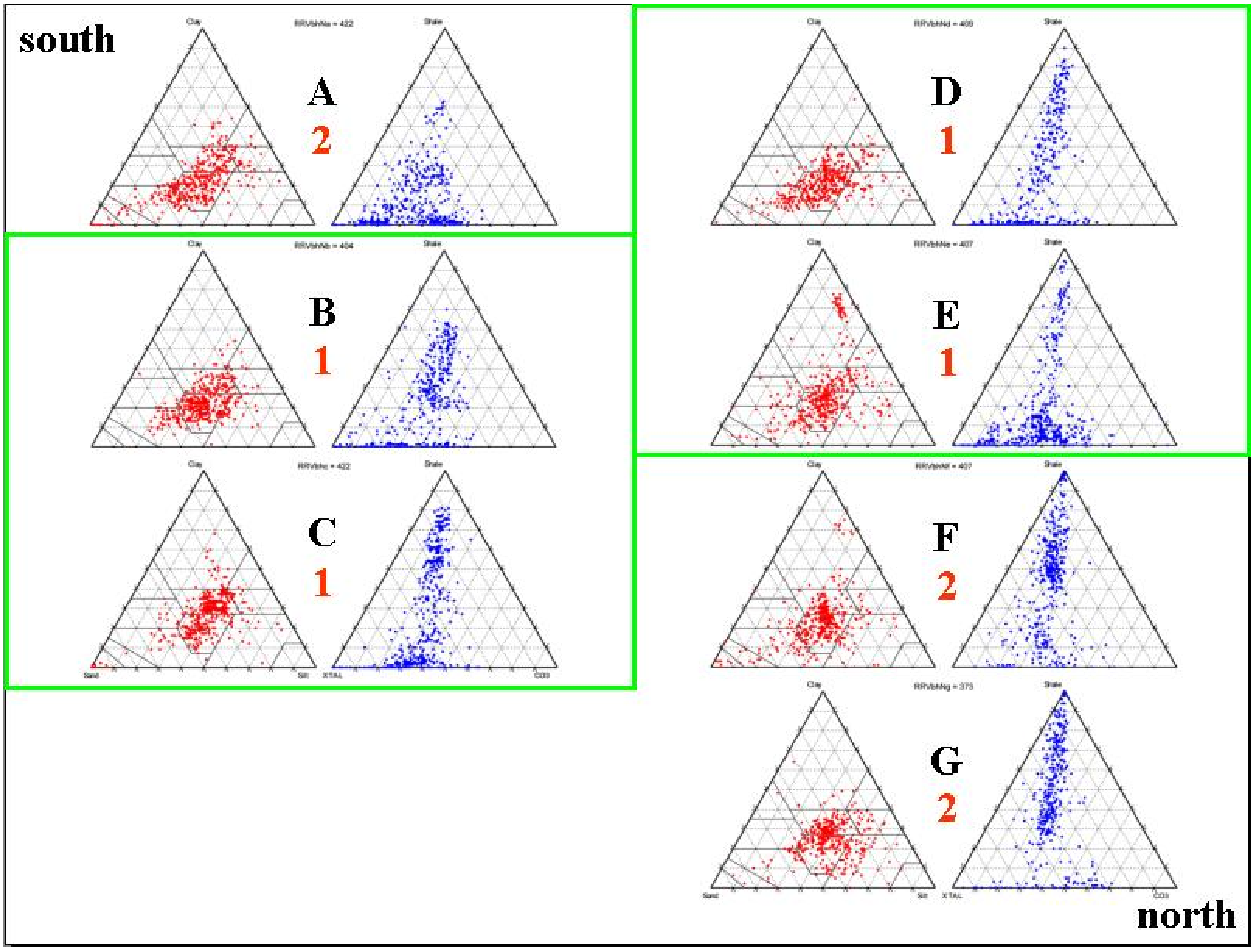
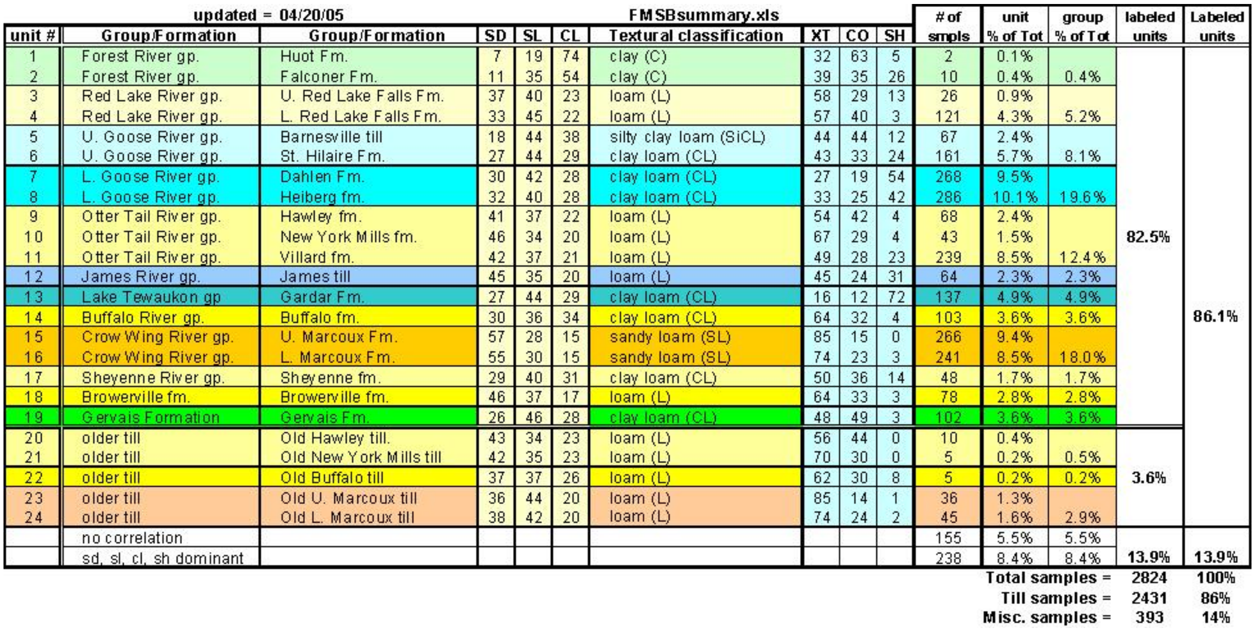


Figure 13 - For each area in the Red River Valley till stratigraphy borehole dataset, ternary plots showing till sample data for sand-silt-clay textural data at left and igneous/metamorphic-carbonate- shale data at right; areas within the Fargo-Moorhead study area are indicated (1).



updated = 04/20/05 FMSBsummary.xls

unit #	Group/Formation	Group/Formation	SD	SL	CL	Textural classification	XT	CO	SH	# of smpls	unit % of Tot	group % of Tot	labeled units	Labeled units
1	Forest River gp.	Huot Fm.	7	19	74	clay (C)	32	63	5	2	0.1%		82.5%	86.1%
2	Forest River gp.	Falconer Fm.	11	35	54	clay (C)	39	35	26	10	0.4%	0.4%		
3	Red Lake River gp.	U. Red Lake Falls Fm.	37	40	23	loam (L)	58	29	13	26	0.9%			
4	Red Lake River gp.	L. Red Lake Falls Fm.	33	45	22	loam (L)	57	40	3	121	4.3%	5.2%		
5	U. Goose River gp.	Barnesville till	18	44	38	silty clay loam (SiCL)	44	44	12	67	2.4%			
6	U. Goose River gp.	St. Hilaire Fm.	27	44	29	clay loam (CL)	43	33	24	161	5.7%	8.1%		
7	L. Goose River gp.	Dahlen Fm.	30	42	28	clay loam (CL)	27	19	54	268	9.5%			
8	L. Goose River gp.	Heiberg fm.	32	40	28	clay loam (CL)	33	25	42	286	10.1%	19.6%		
9	Otter Tail River gp.	Hawley fm.	41	37	22	loam (L)	54	42	4	68	2.4%			
10	Otter Tail River gp.	New York Mills fm.	46	34	20	loam (L)	67	29	4	43	1.5%			
11	Otter Tail River gp.	Villard fm.	42	37	21	loam (L)	49	28	23	239	8.5%	12.4%		
12	James River gp.	James till	45	35	20	loam (L)	45	24	31	64	2.3%	2.3%		
13	Lake Tewaukon gp	Gardar Fm.	27	44	29	clay loam (CL)	16	12	72	137	4.9%	4.9%		
14	Buffalo River gp.	Buffalo fm.	30	36	34	clay loam (CL)	64	32	4	103	3.6%	3.6%		
15	Crow Wing River gp.	U. Marcoux Fm.	57	28	15	sandy loam (SL)	85	15	0	266	9.4%			
16	Crow Wing River gp.	L. Marcoux Fm.	55	30	15	sandy loam (SL)	74	23	3	241	8.5%	18.0%		
17	Sheyenne River gp.	Sheyenne fm.	29	40	31	clay loam (CL)	50	36	14	48	1.7%	1.7%		
18	Browerville fm.	Browerville fm.	46	37	17	loam (L)	64	33	3	78	2.8%	2.8%		
19	Gervais Formation	Gervais Fm.	26	46	28	clay loam (CL)	48	49	3	102	3.6%	3.6%		
20	older till	Old Hawley till.	43	34	23	loam (L)	56	44	0	10	0.4%		3.6%	
21	older till	Old New York Mills till	42	35	23	loam (L)	70	30	0	5	0.2%	0.5%		
22	older till	Old Buffalo till	37	37	26	loam (L)	62	30	8	5	0.2%	0.2%		
23	older till	Old U. Marcoux till	36	44	20	loam (L)	85	14	1	36	1.3%			
24	older till	Old L. Marcoux till	38	42	20	loam (L)	74	24	2	45	1.6%	2.9%		
	no correlation									155	5.5%	5.5%	13.9%	13.9%
	sd, sl, cl, sh dominant									238	8.4%	8.4%		

Total samples = 2824 100%
Till samples = 2431 86%
Misc. samples = 393 14%

Figure 14 - Summary of the composition of till stratigraphic units in the Fargo-Moorhead area at the formation level, to which groups have been subdivided; the strata were identified on the basis of stratigraphic position, extent, and composition; compositional characterization is based on both near-surface and borehole data; average texture is indicated as percent sand (SD)-silt (SL) - clay (CL) and word characterization such as clay or loam; average very coarse sand (1-2 mm) lithology is indicated as igneous/metamorphic (XT) – carbonate (CO) – shale (SH); summary statistics indicate number of analyses for each formation, and proportion of the database that relate to each formation and group. Also indicated is the proportion of the data that relate to the relatively well-known upper strata, a count in number and proportion for analyses that do not conform to the clusters recognized to be distinctive of specific strata, and a count of analyses whose analysis indicate that the sampled sediment did not consist of or only partially consisted of till. These fine-grained till strata are regionally consistent across the region, and they typically act as confining layers in relation to ground water systems, so their correlation aids in 3D mapping of intervening subsurface sand deposits as well as the controls on the ground-water systems hosted by these sands

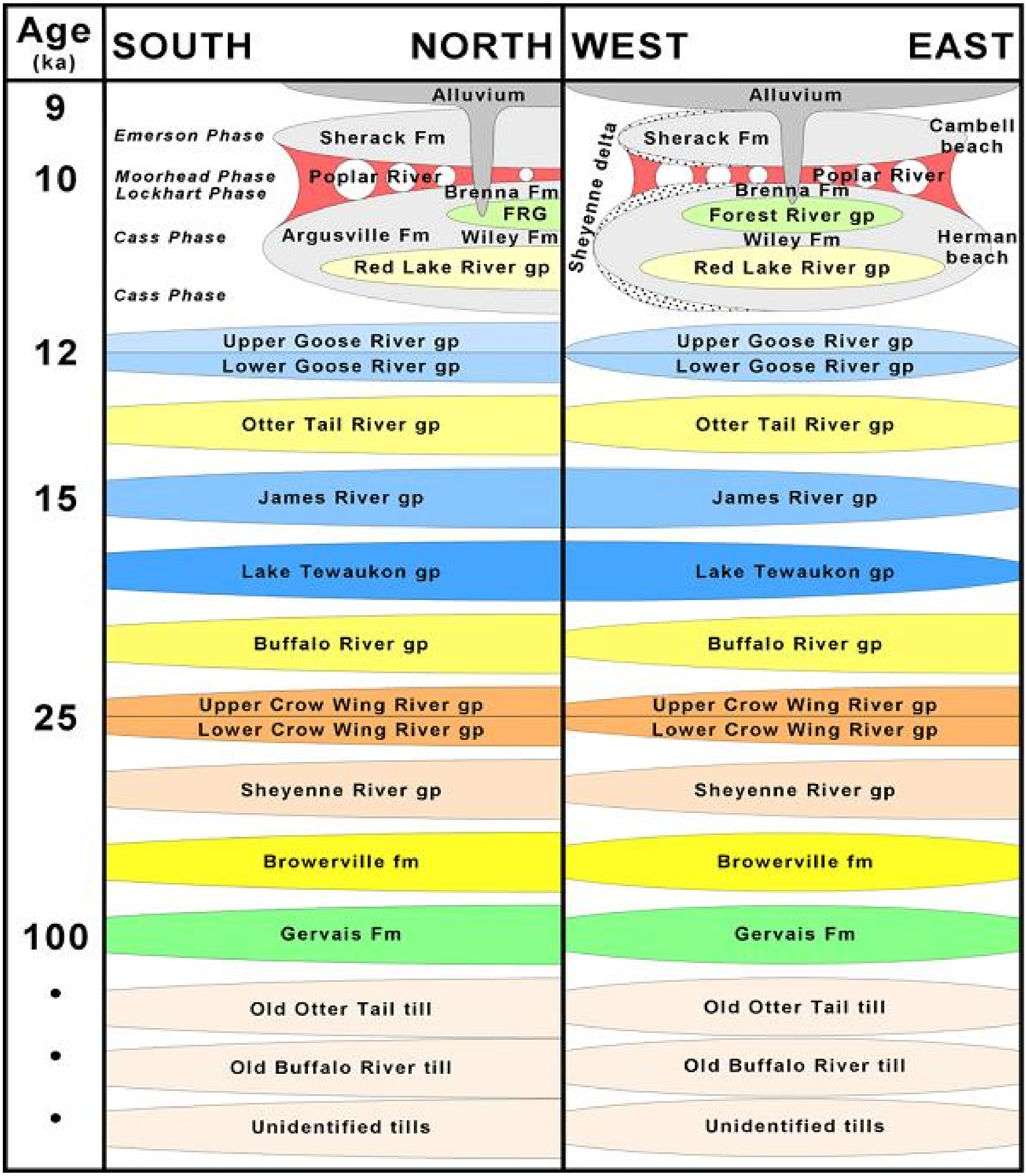
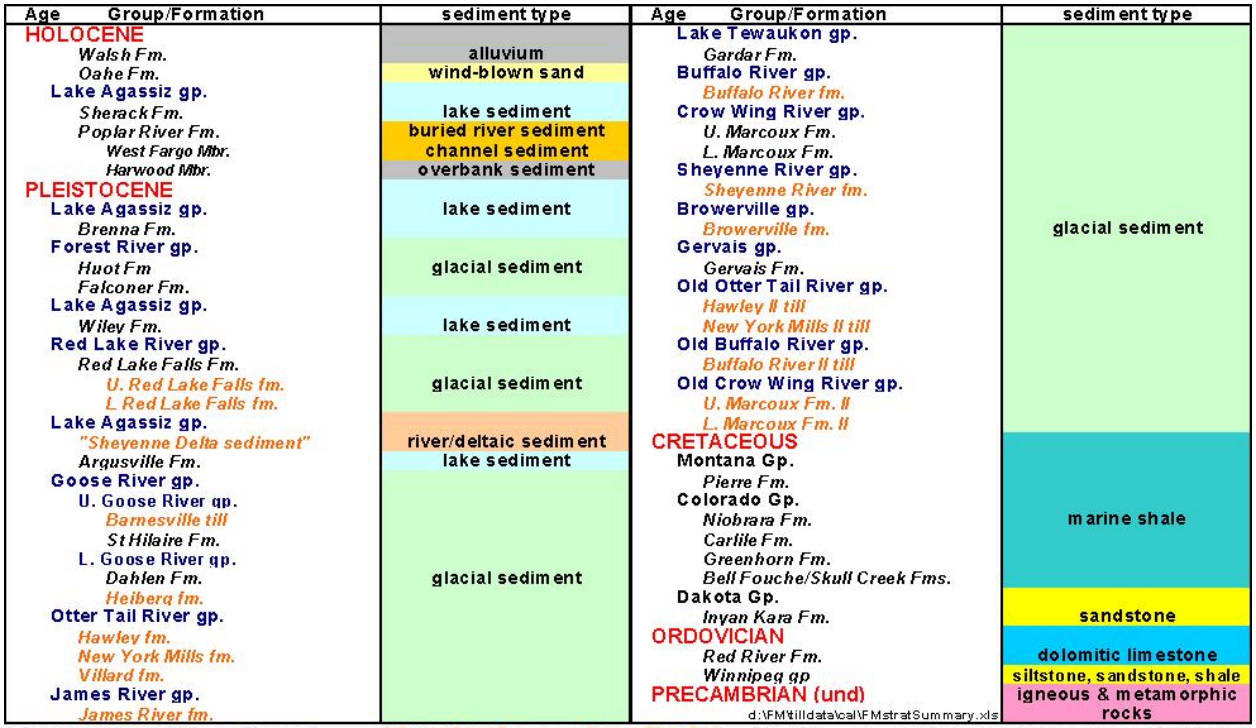


Figure 15 - Summary of the approximate distribution of Fargo-Moorhead Quaternary stratigraphic units in space and time, depicting stratigraphic position, regional thickness trends, and approximate age; in addition to tills, glacial lake sediment and postglacial alluvial sediments also are indicated; Lake Agassiz history (Fenton et al., 1983) is indicated as phases from the Cass Phase to the Emerson Phase; also indicated is linkage of the deposits to major Lake Agassiz features – the Sheyenne Delta, the Herman Beach, and the Campbell Beach



Age Group/Formation	sediment type
HOLOCENE	alluvium
Walsh Fm.	
Oahe Fm.	wind-blown sand
Lake Agassiz gp.	lake sediment
Sherack Fm.	
Poplar River Fm.	buried river sediment
West Fargo Mbr.	channel sediment
Harwood Mbr.	overbank sediment
PLEISTOCENE	lake sediment
Lake Agassiz gp.	
Brenna Fm.	
Forest River gp.	glacial sediment
Huot Fm	
Falconer Fm.	
Lake Agassiz gp.	lake sediment
Wiley Fm.	
Red Lake River gp.	glacial sediment
Red Lake Falls Fm.	
U. Red Lake Falls fm.	
L Red Lake Falls fm.	
Lake Agassiz gp.	river/deltaic sediment
"Sheyenne Delta sediment"	
Argusville Fm.	lake sediment
Goose River gp.	glacial sediment
U. Goose River gp.	
Barnesville till	
St Hilaire Fm.	
L. Goose River gp.	
Dahlen Fm.	
Heiberg fm.	
Otter Tail River gp.	
Hawley fm.	
New York Mills fm.	
Villard fm.	
James River gp.	
James River fm.	
Lake Tewaukon gp.	glacial sediment
Gardar Fm.	
Buffalo River gp.	
Buffalo River fm.	
Crow Wing River gp.	
U. Marcoux Fm.	
L. Marcoux Fm.	
Sheyenne River gp.	
Sheyenne River fm.	
Browerville gp.	
Browerville fm.	
Gervais gp.	
Gervais Fm.	
Old Otter Tail River gp.	
Hawley II till	
New York Mills II till	
Old Buffalo River gp.	
Buffalo River II till	
Old Crow Wing River gp.	
U. Marcoux Fm. II	
L. Marcoux Fm. II	
CRETACEOUS	marine shale
Montana Gp.	
Pierre Fm.	
Colorado Gp.	
Niobrara Fm.	
Carlile Fm.	
Greenhorn Fm.	
Bell Fouche/Skull Creek Fms.	
Dakota Gp.	sandstone
Inyan Kara Fm.	
ORDOVICIAN	dolomitic limestone
Red River Fm.	
Winnipeg gp	siltstone, sandstone, shale
PRECAMBRIAN (und)	igneous & metamorphic rocks

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Informal group names (James River gp.) *Informal fromation names (James River fm.)* Formal F*romation* and Group names (*Wiley Fm. and* Dakota Gp.)

Figure 16 - Comprehensive summary of stratigraphic units in the Fargo-Moorhead study area, including postglacial and glacial lake sediments, defined till strata, as well as Cretaceous strata dominated by shale and sandstone, Ordovician strata consisting largely of carbonate and sandstone, and the Precambrian igneous and metamorphic rocks that underlie the entire region

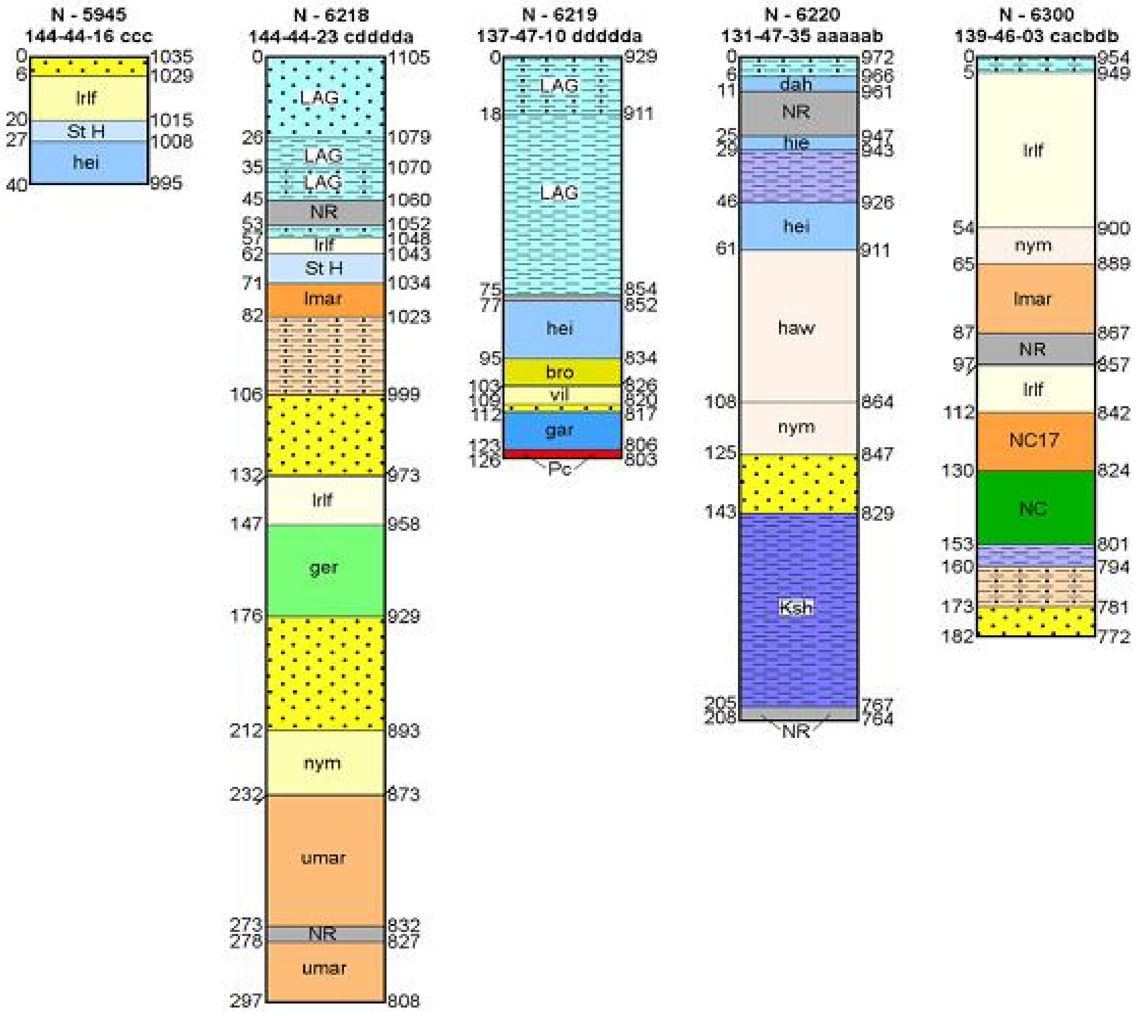


Figure 17 - Examples of stratigraphic reference sites used as controls on interpretation of 3D geology; stratigraphy defined at these sites was extrapolated laterally on cross sections with guidance from water well data as well as current understanding of geological processes and history; depth in feet is given to the left, while elevation in feet above sea level is given on the right

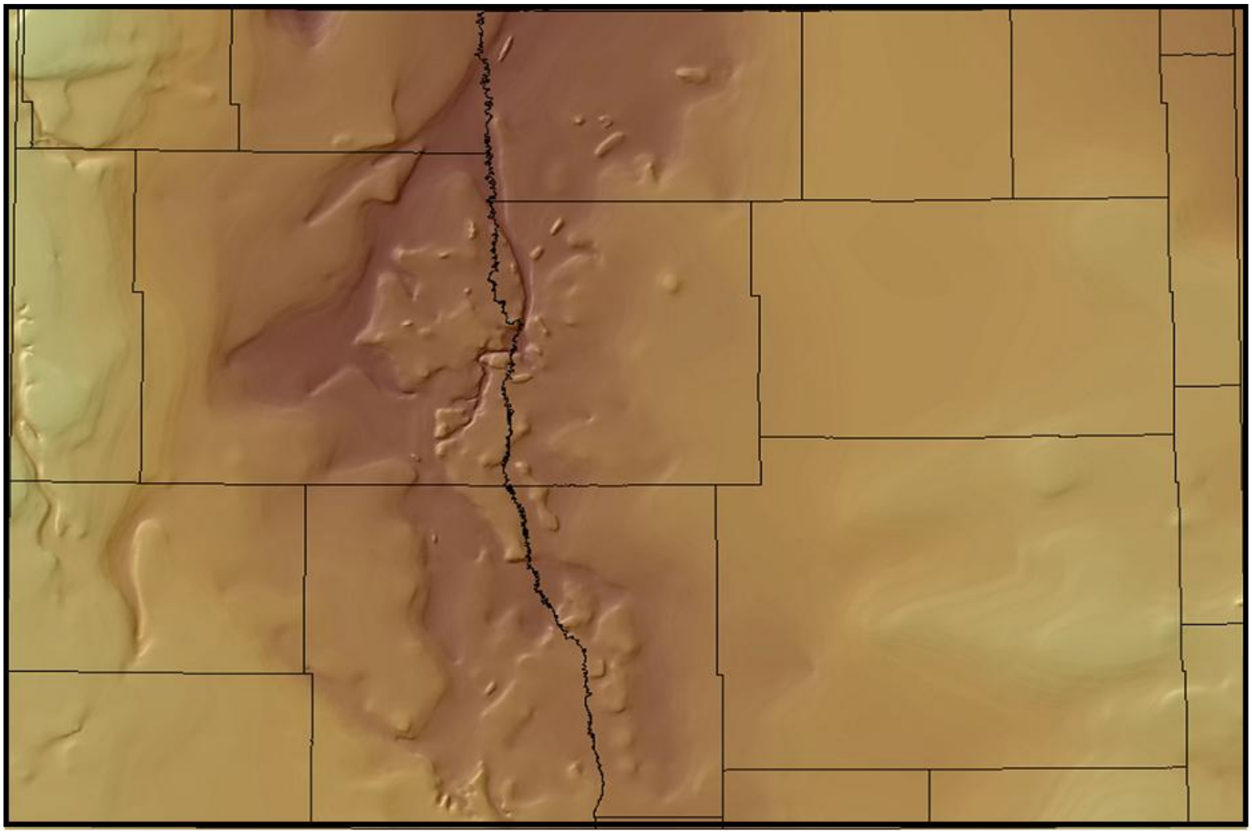
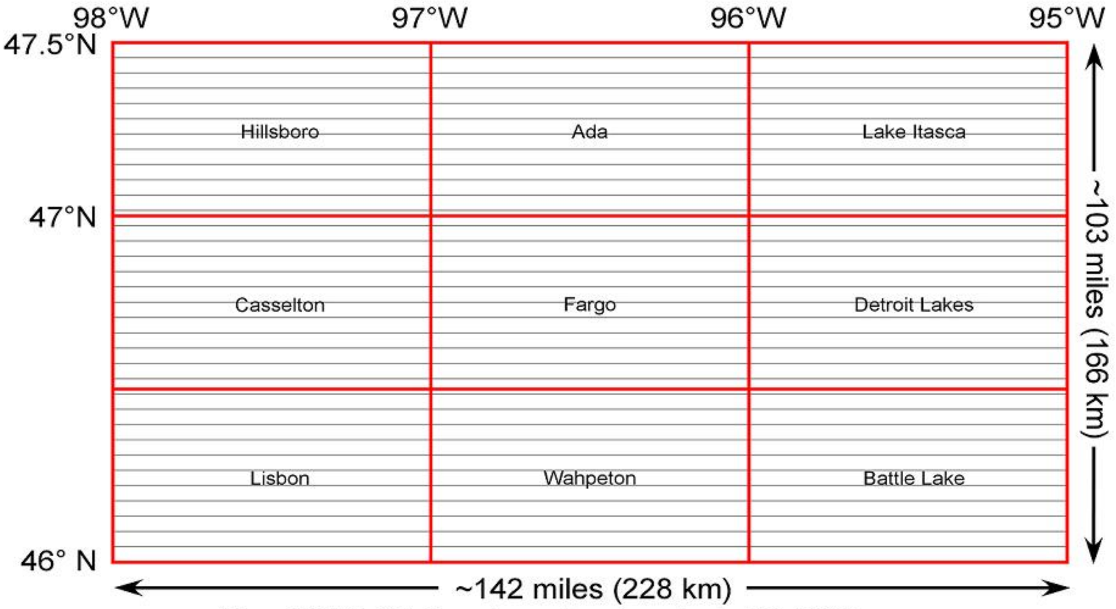


Figure 18 - Shaded relief depiction of bedrock surface morphology for the Fargo-Moorhead study area as compiled and interpreted from available data; elevations range from 386 to 1462 feet above sea level



- **Nine 30' X 60' Quadrangles (scale 1:100,000)**
- **142 mi by 103 mi (228 km by 166 km)**
- **14,626 square miles (37,848 square kilometers)**
- **5 km (~ 3 mi) grid spacing (34 E-W cross sections)**
- **1,625 grid points at a 5km grid spacing**

Figure 19 - Dimensions of the Fargo-Moorhead study area, and layout of the regional cross-sections at a 5-km interval, with map-area names indicated

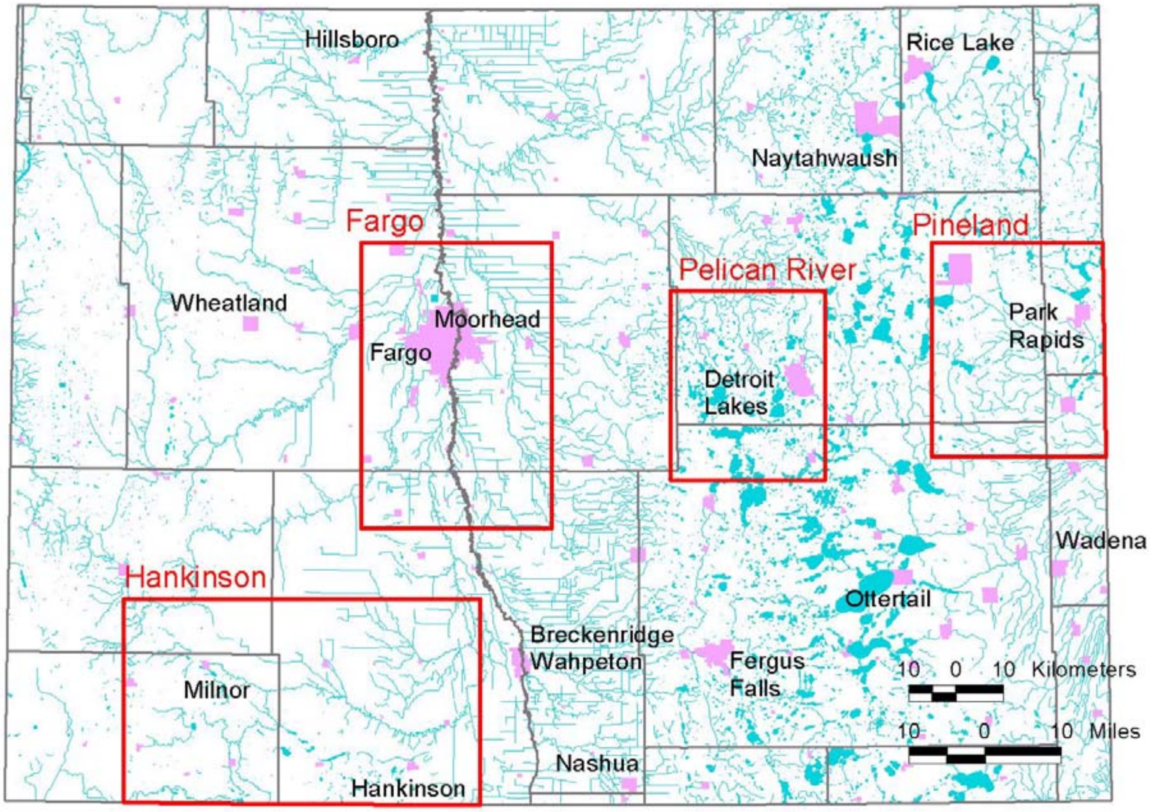


Figure 20 – Extent and naming of areas where a level of detail greater than the regional 5-km resolution was incorporated into the 3D model; in these areas, cross-section spacing ranged from 0.5 to 3 km

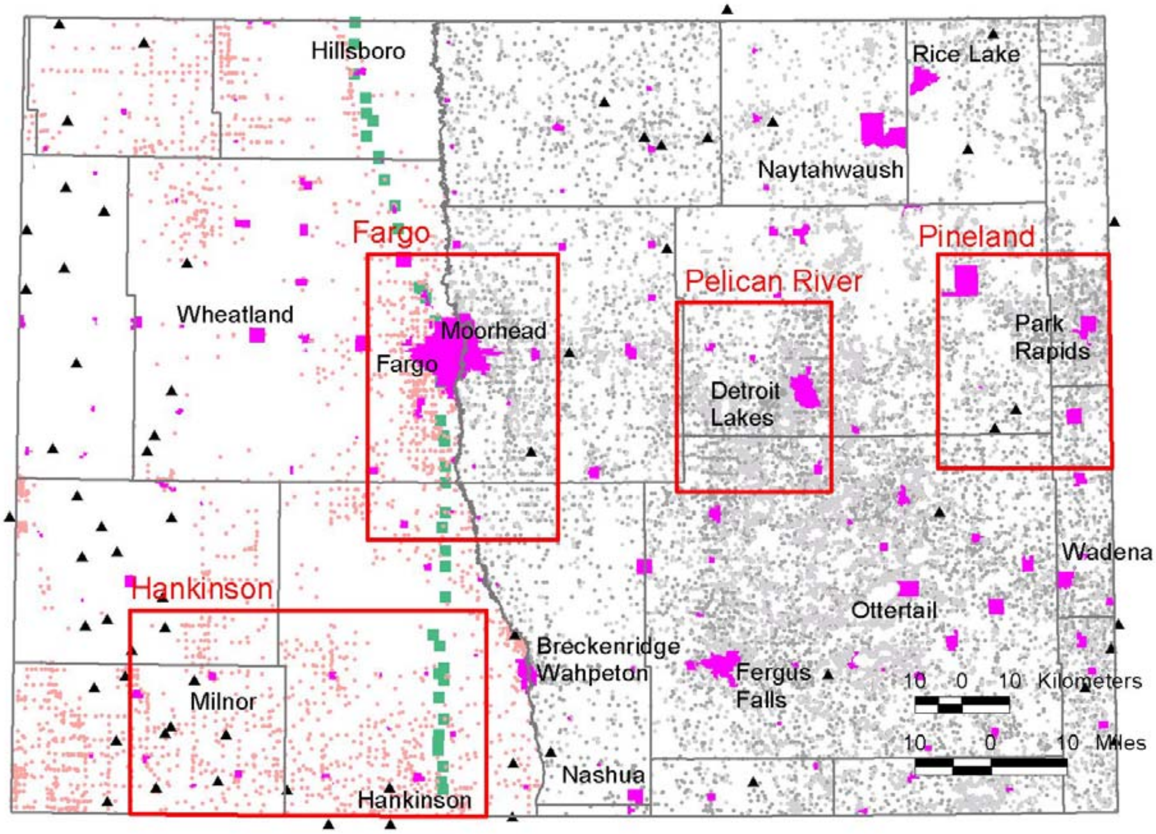


Figure 21 – Location of available digital drillhole data; triangles indicate stratigraphic reference sites, in most cases consisting of cores; well-documented engineering drillhole sites associated with the construction of Interstate Highway 29 are shown as green squares; North Dakota regional drillhole database sites, mostly water wells, are indicated in a pink color; for Minnesota, accurately located drillhole sites, mostly water wells, are shown in dark gray, while sites only located to legal survey polygon centroids are shown in light gray

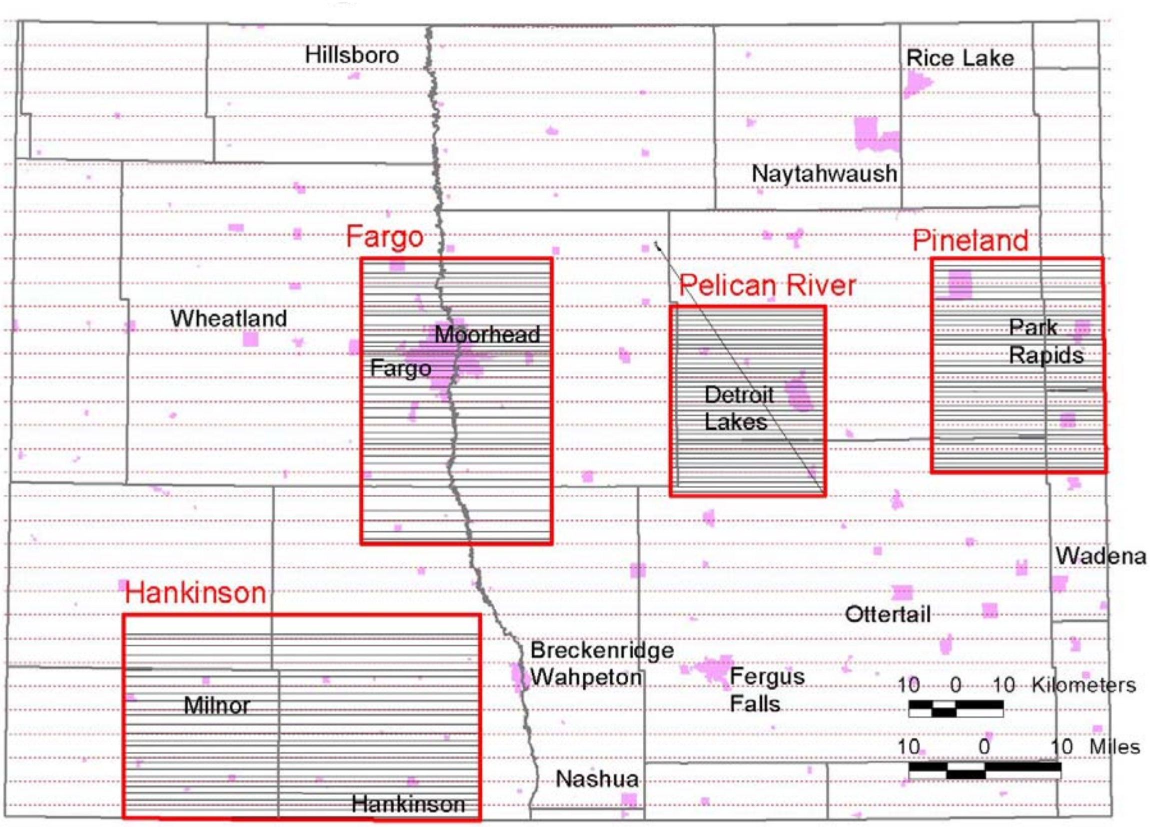


Figure 22 – Location of geologic cross sections; regional west to east cross sections constructed at a 5-km interval are shown as red dashed lines; cross sections in detail areas were constructed at 0.5 to 3 km intervals, depending on well control

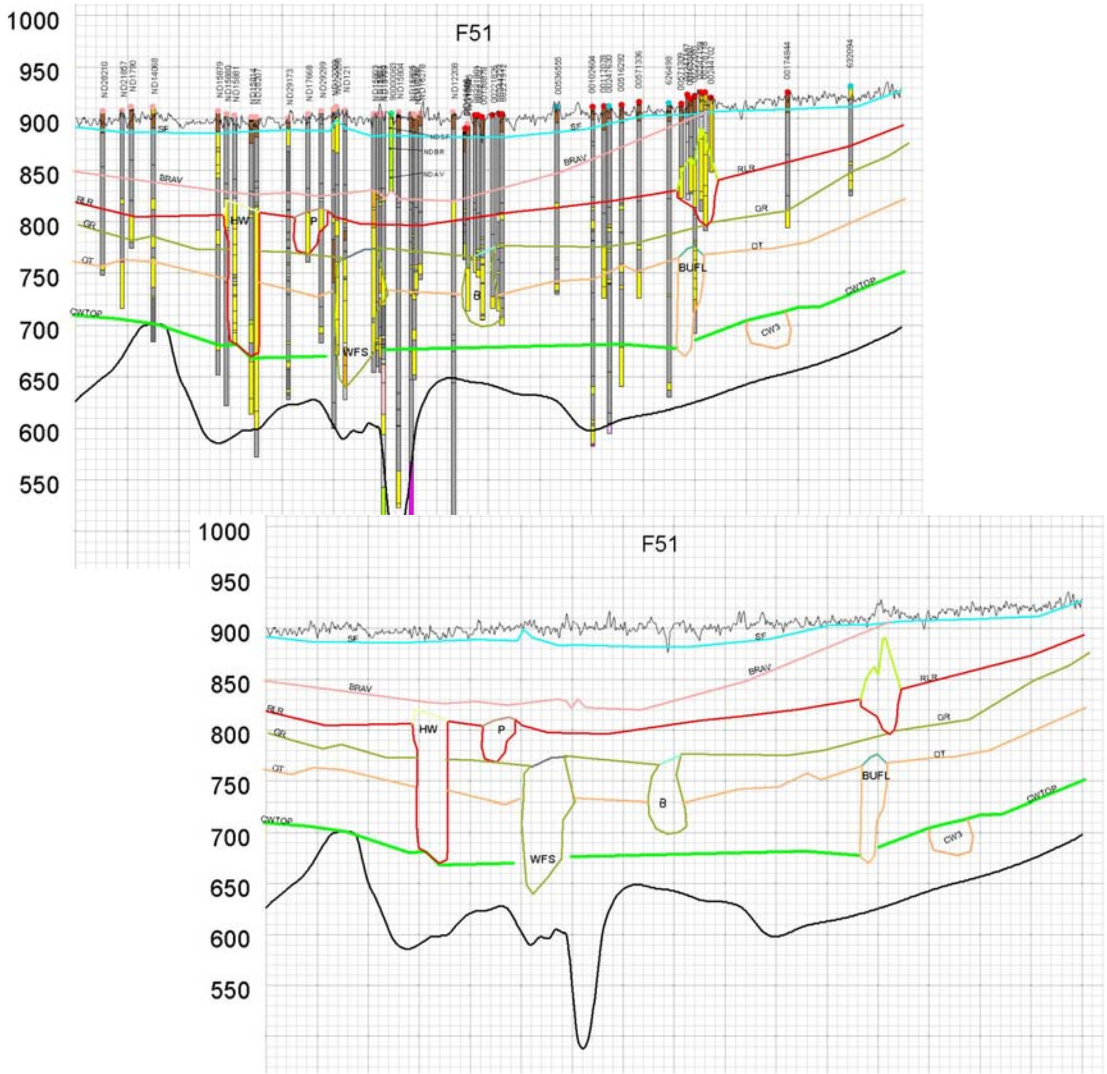


Figure 23 – Example of a portion of a drillhole data cross section (upper), and the resulting interpretation (lower); vertical scale is in feet above sea level; horizontal scale equals the east-west dimension of the Fargo detail area (40 km; 25 miles); correlations on all cross sections were refined based on comparison with adjacent cross sections; this example includes deposits that are lens-shaped in cross section and which are interpreted as tunnel valley sand and gravel deposits that are elongate north to south

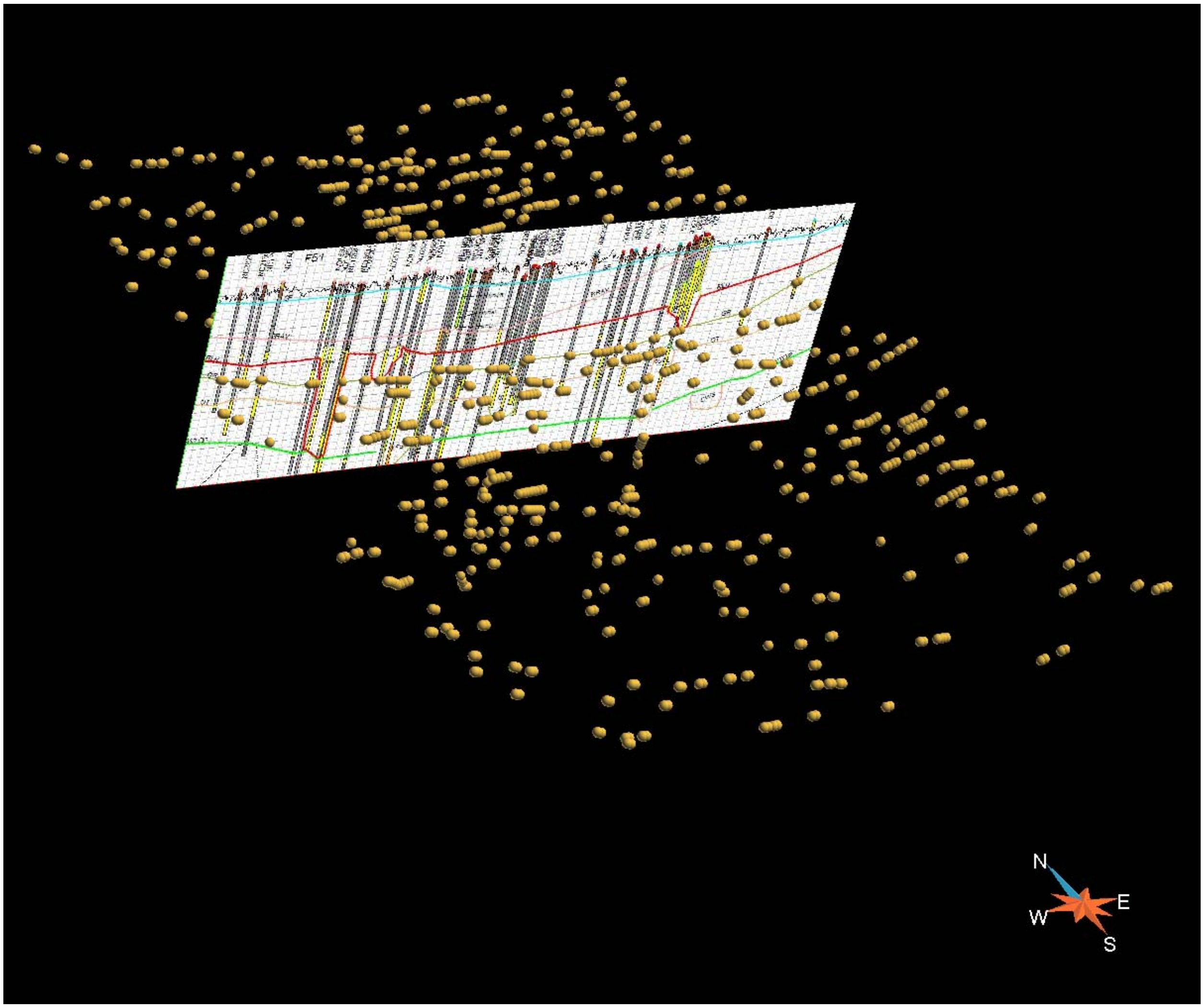


Figure 24 – Vertically exaggerated example of an interpreted cross section georeferenced in 3D space as a Gocad rectified image, with xyz points for one contact from all of the cross sections in the Fargo detail area; cross section images were made directly from ArcView layouts or from scanned paper copies prior to georeferencing; xyz points were captured in most cases using an ArcView 3.3 script that identified intersections of drillhole and interpreted stratigraphic unit contacts; point sets were also created interactively in Gocad on 3D georeferenced cross section images; xyz data in this example shows the top of the Otter Tail River group from all of the 43 cross sections in the Fargo detail area

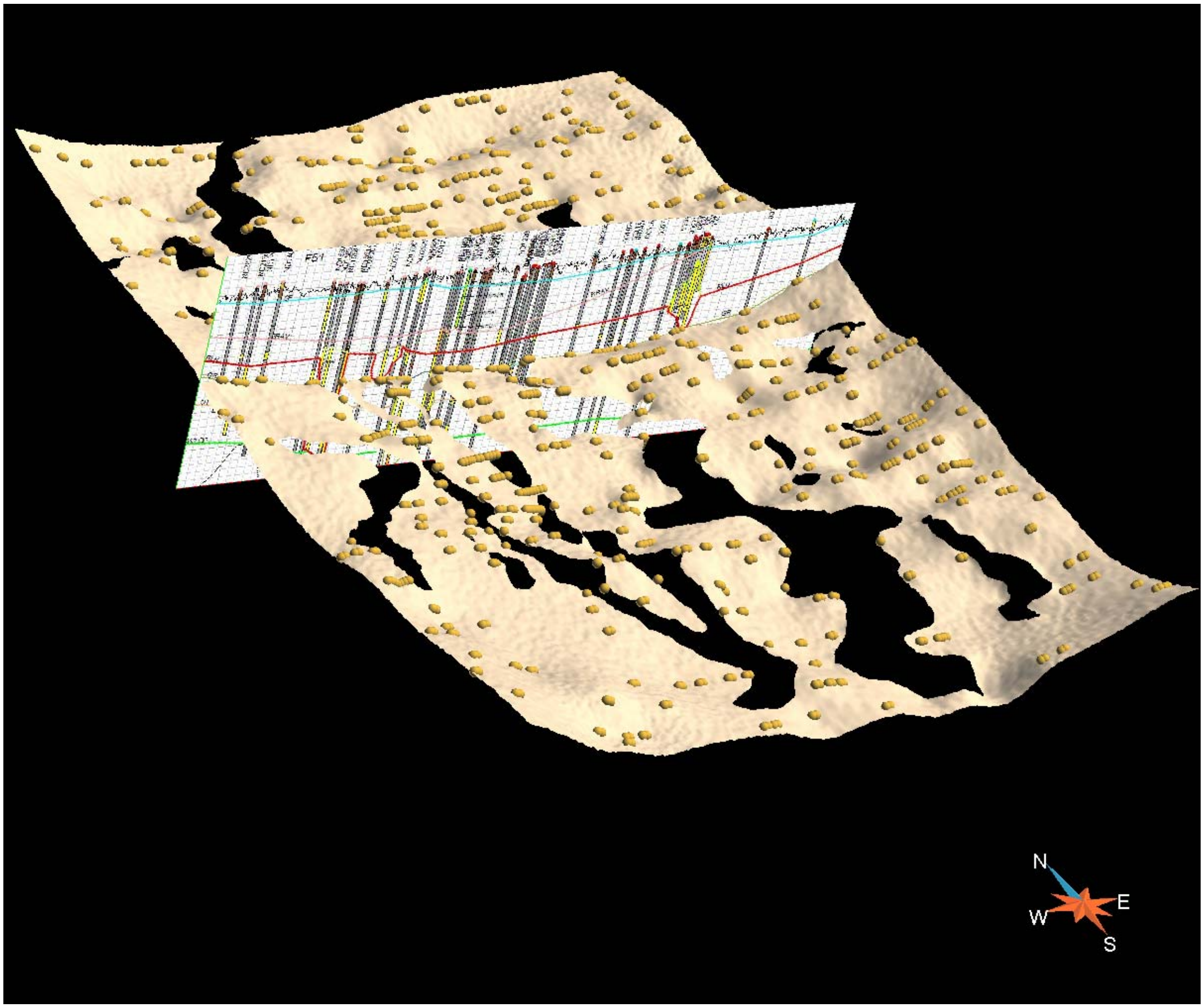


Figure 25 – Vertically exaggerated example of a surface modeled using xyz data derived from the cross sections; this example shows the top of the Otter Tail River group in the Fargo detail area; portions of the surface that had been eroded by younger tunnel valleys were cut out using a surface representing the lower contact of these sand and gravel deposits

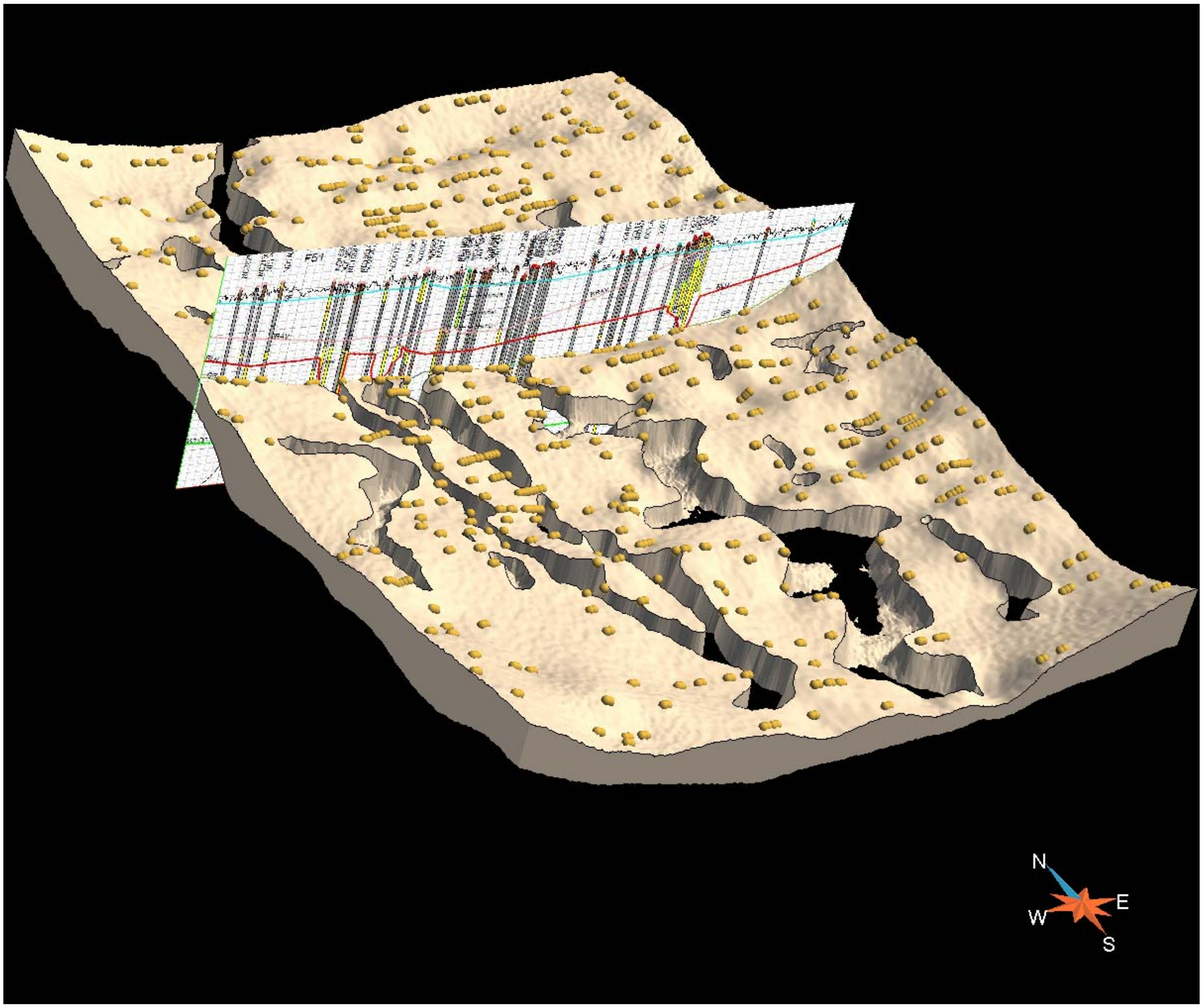


Figure 26 – Upon definition of surfaces representing the upper and lower contacts of a layer, a closed surface representing this solid stratum was generated to represent this volume

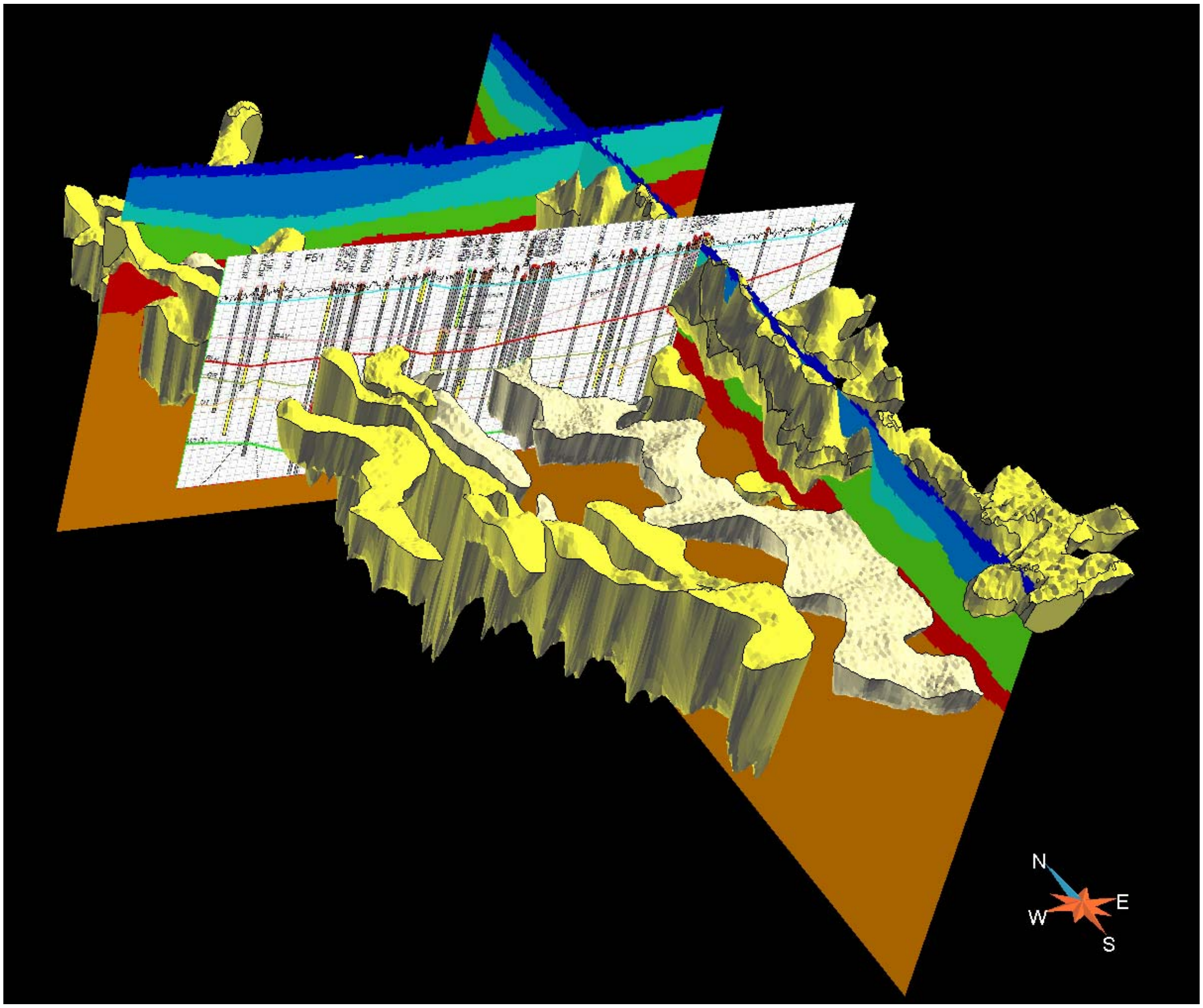


Figure 27 – Illustration of a scanned input cross section, several solids from the model that resulted from this and other cross sections, as well as output cross sections showing planar depiction of the entire 3D model; this example shows thick glacial lake clay in blue over the Fargo area, and a thinner clay cover above the Buffalo aquifer in the eastern portion of the area, to the right

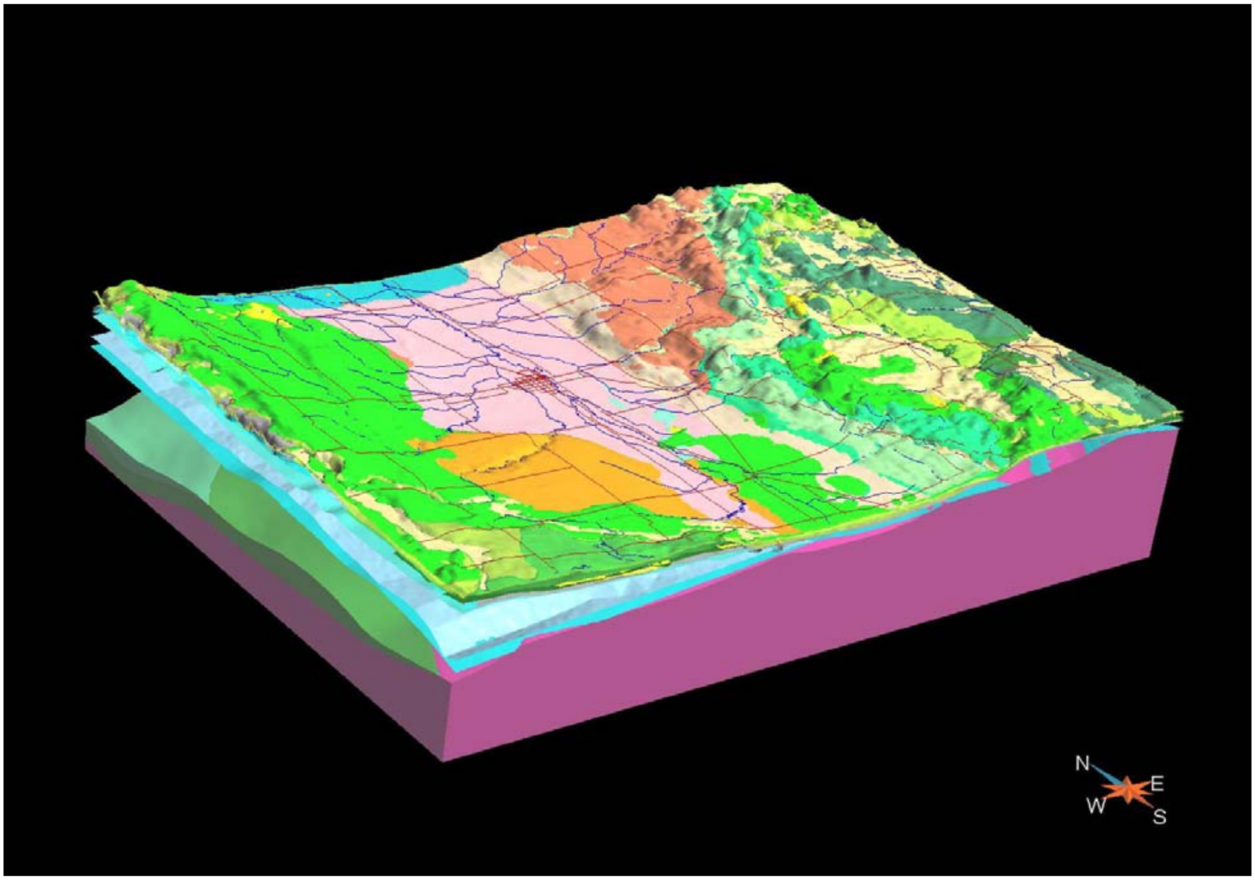


Figure 28 - Vertically exaggerated illustration of all strata defined in the Fargo-Moorhead regional 3D model, viewed in 3D from a viewpoint to the southwest

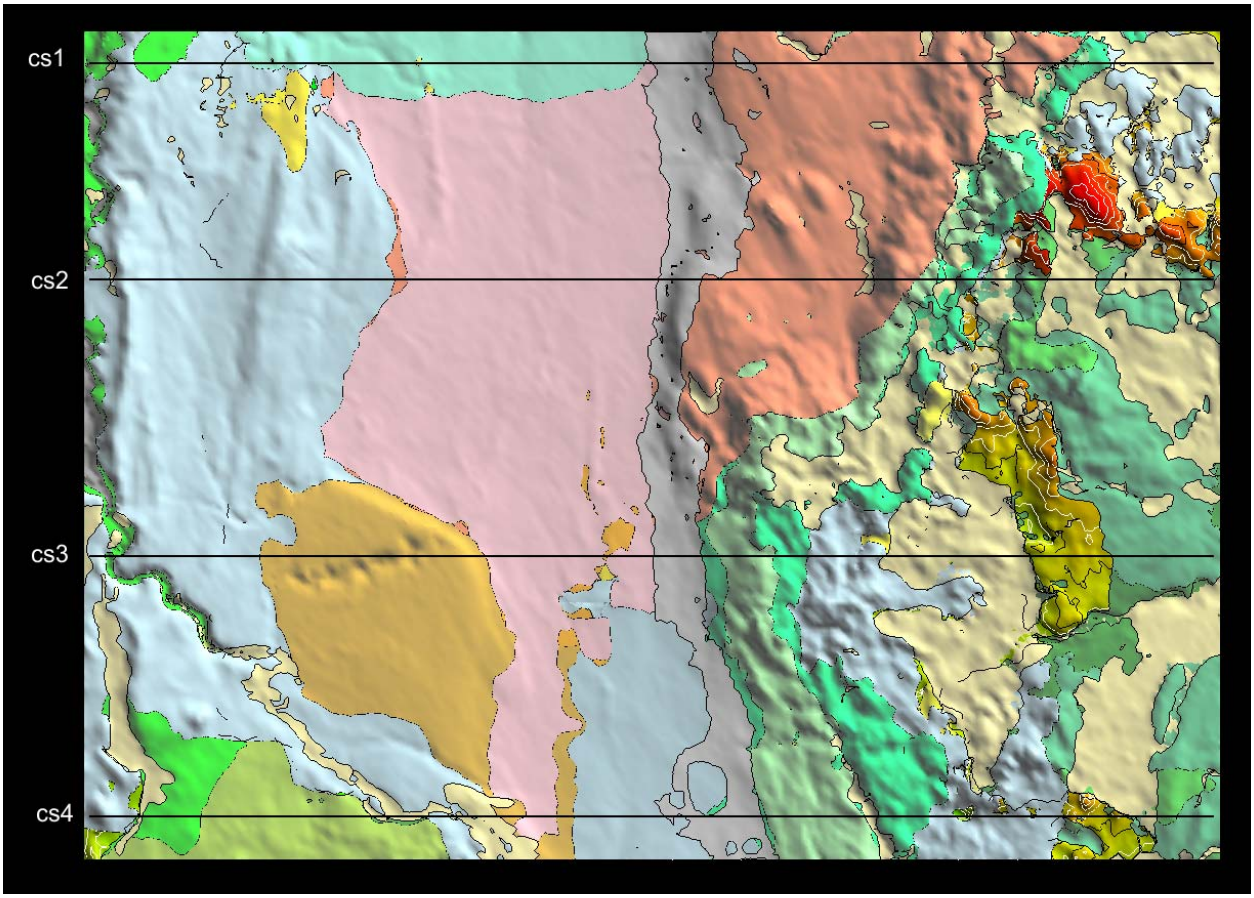


Figure 29 - Plan view of the Fargo-Moorhead regional 3D model, showing areas where strata are exposed at surface; this image can be compared to the 1: 200,000 surficial geology map to obtain an explanation for the various strata; in addition, comparison with the surficial geology map will clarify the somewhat lesser level of detail that was achievable in 3D on the regional scale – a level of detail comparable to a 1: 500,000 map; also indicated are the locations of cross sections shown in subsequent figures; for example, the Sheyenne Delta, located southwest of Fargo, is identified as a dark orange-colored area in the southwestern or lower left quarter of the study area

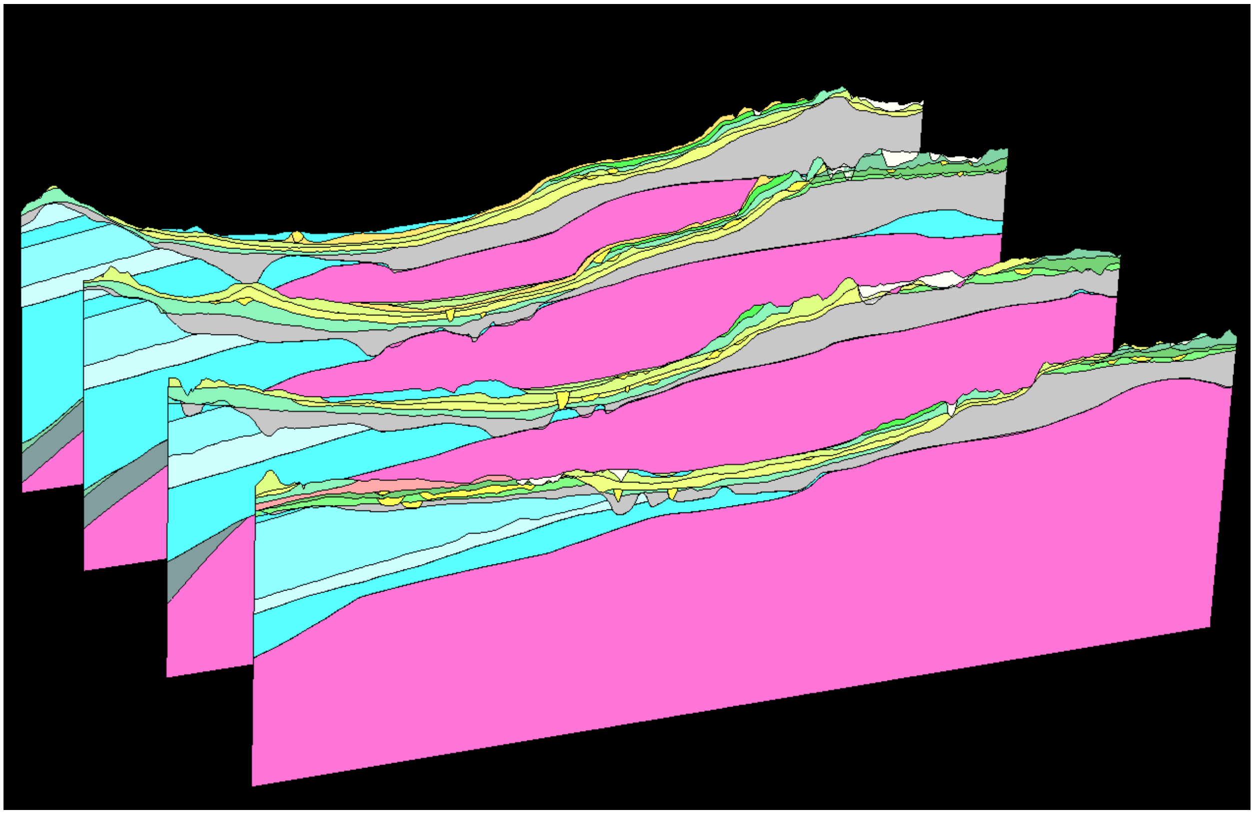


Figure 30 - Vertically exaggerated 3D depiction of four cross sections meant to indicate the typical geometry of the strata, ranging from cross section 1 in the north to cross section 4 in the south or the foreground of the view

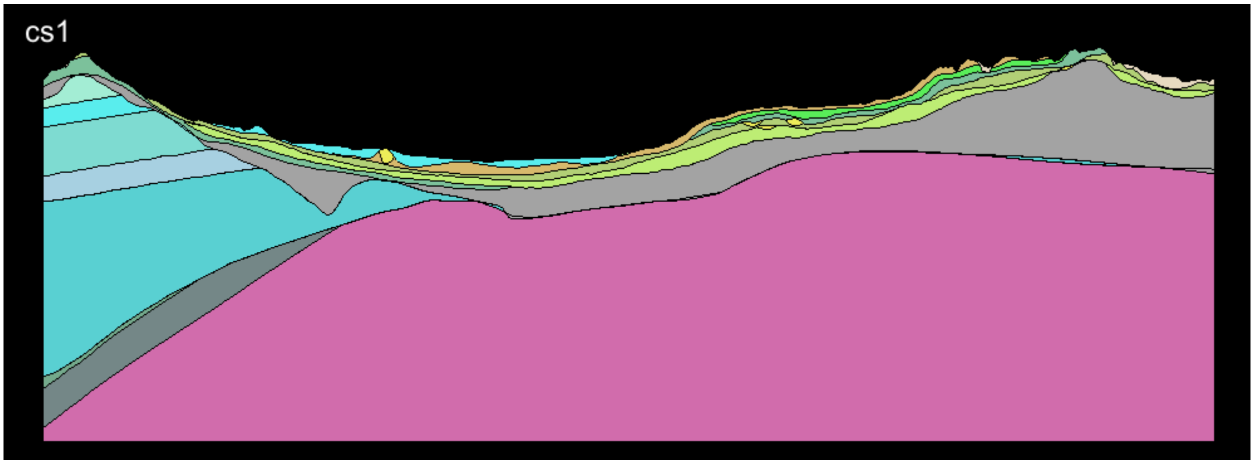


Figure 31 - Cross section 1, from west at left to east at right, depicting typical geometry of the strata modeled in the Fargo-Moorhead regional 3D model; pink represents the Precambrian igneous and metamorphic rocks that underlie the entire area, the thick strata to the west are sedimentary rocks of Ordovician to Cretaceous age, gray corresponds to the lower Quaternary sediment sequence for which there is insufficient data to permit subdivision into strata, and the layers above those depicted in gray are the mapped Quaternary strata, including the hosts of important ground-water sources in the region. Cross section 1 is the northernmost section

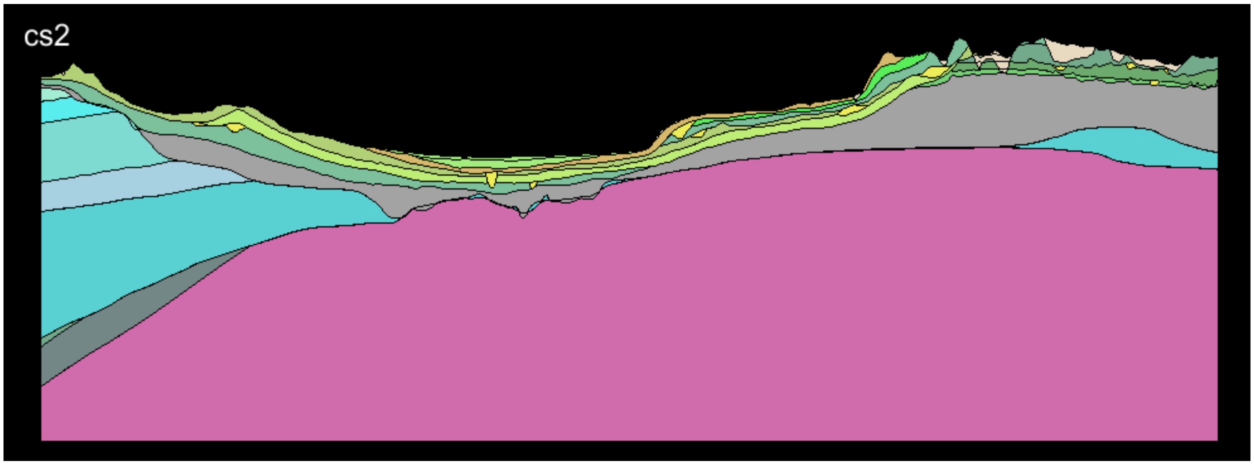


Figure 32 - Cross section 2, from west at left to east at right, depicting typical geometry of the strata modeled in the Fargo-Moorhead regional 3D model; colors are as explained for cross section 1

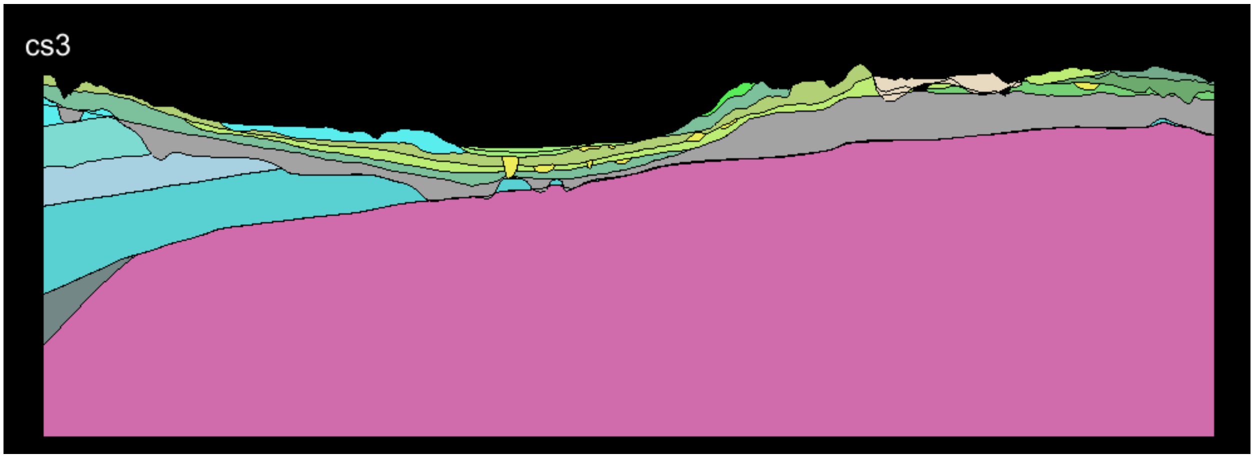


Figure 33 - Cross section 3, from west at left to east at right, depicting typical geometry of the strata modeled in the Fargo-Moorhead regional 3D model; colors are as explained for cross section 1; the Sheyenne Delta is apparent as the blue-colored area at surface in the upper left half of the section

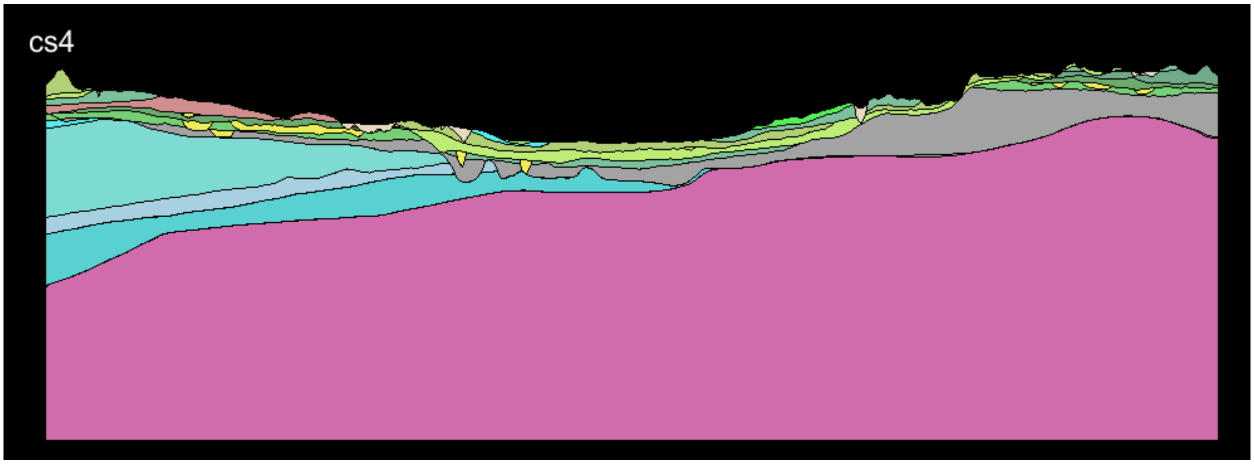


Figure 34 - Cross section 4, from west at left to east at right, depicting typical geometry of the strata modeled in the Fargo-Moorhead regional 3D model; colors are as explained for cross section 1; cross section 4 is the southernmost section

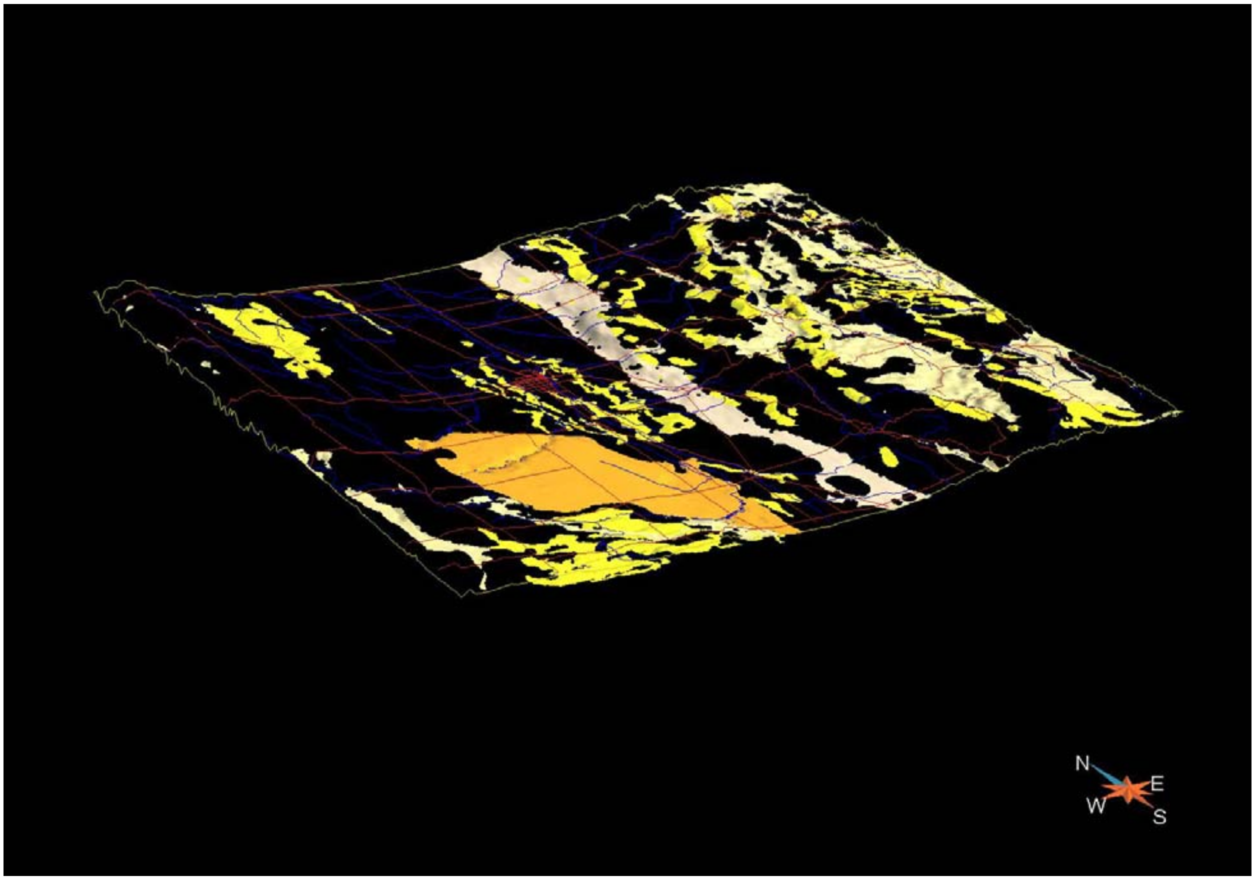


Figure 35 - Sand strata defined in the Fargo-Moorhead regional 3D model, viewed in vertically exaggerated 3D perspective, to provide an overview of the distribution of sand deposits adequately recognized by available drillhole data to be mapped; the Sheyenne Delta is the large orange-colored deposit in the foreground

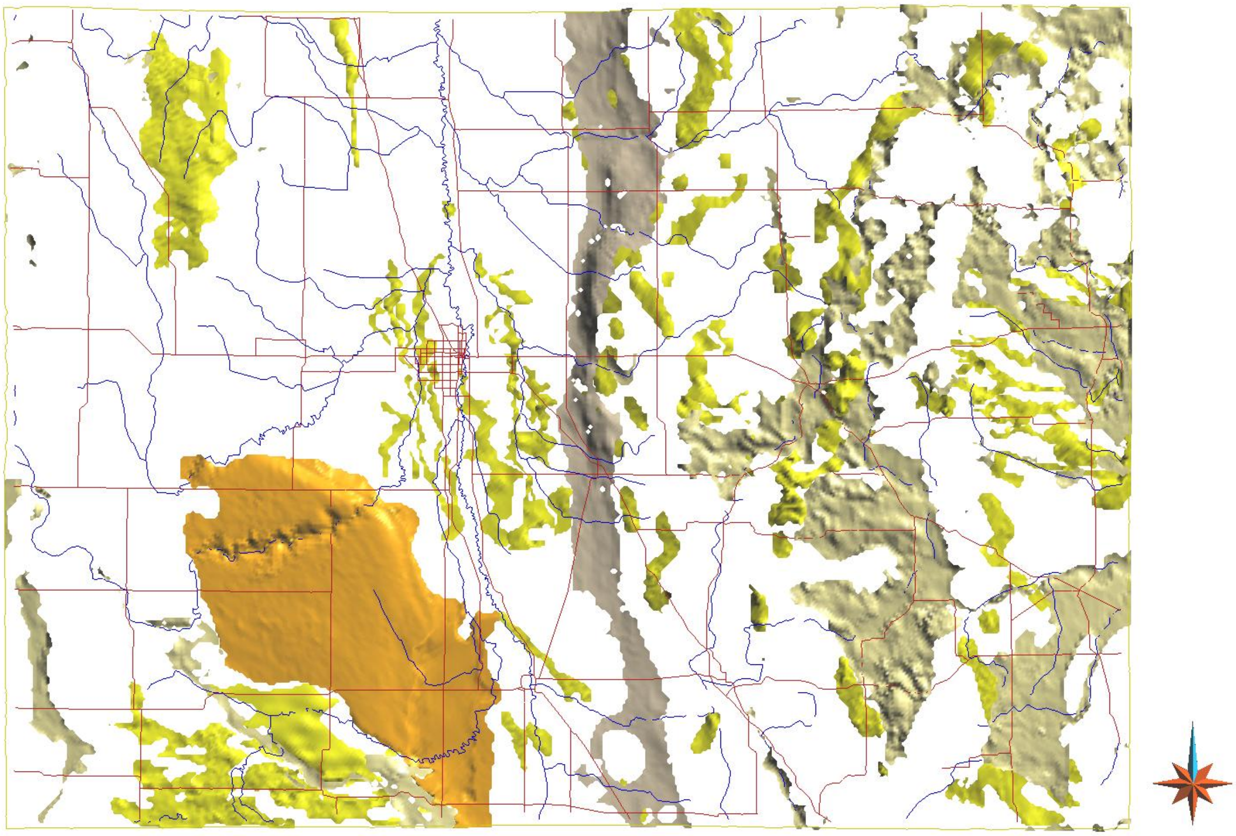


Figure 36 – Sand-dominated strata defined in the Fargo-Moorhead regional 3D model, viewed in 2D plan view perspective, to provide an overview of the distribution of sand deposits adequately recognized by available drillhole data to be mapped; for example, the Sheyenne Delta, located southwest of Fargo, is identified as a dark orange-colored area in the southwestern or lower left quarter of the study area. This depiction of the Sheyenne Delta, however, includes both the sandy core of the deposit, as well as finer sediments that extend to the southeast.

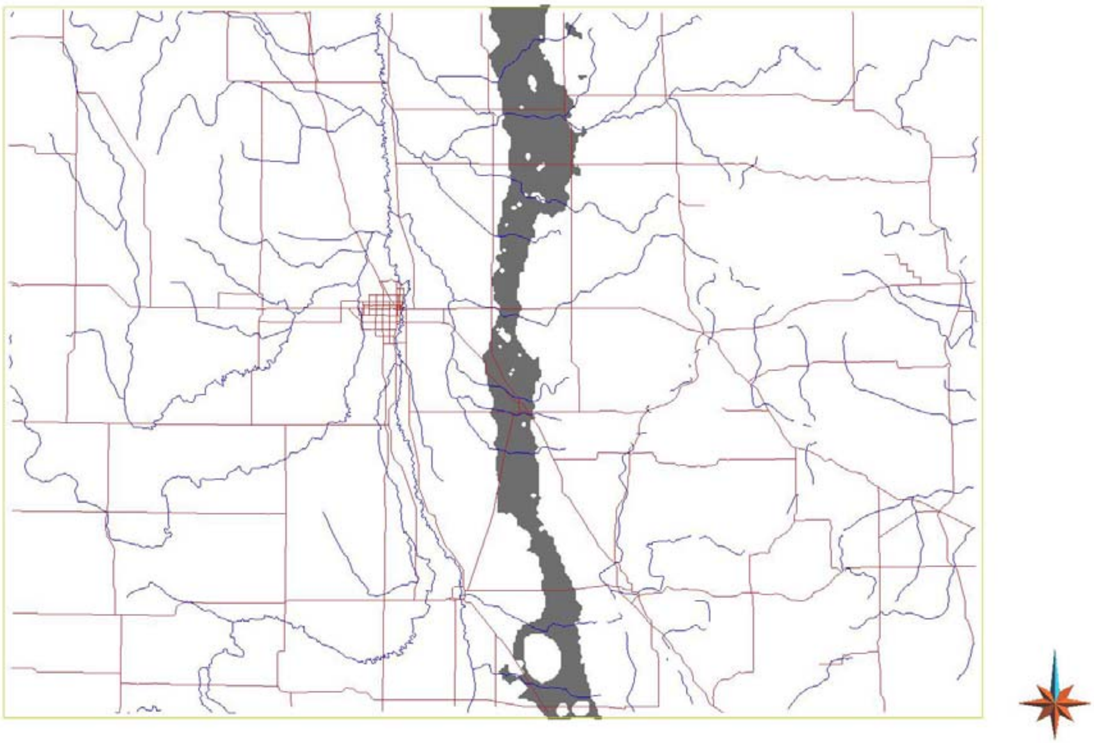


Figure 37 - Extent of regional 3D model layer 001: Lake Agassiz beach sands

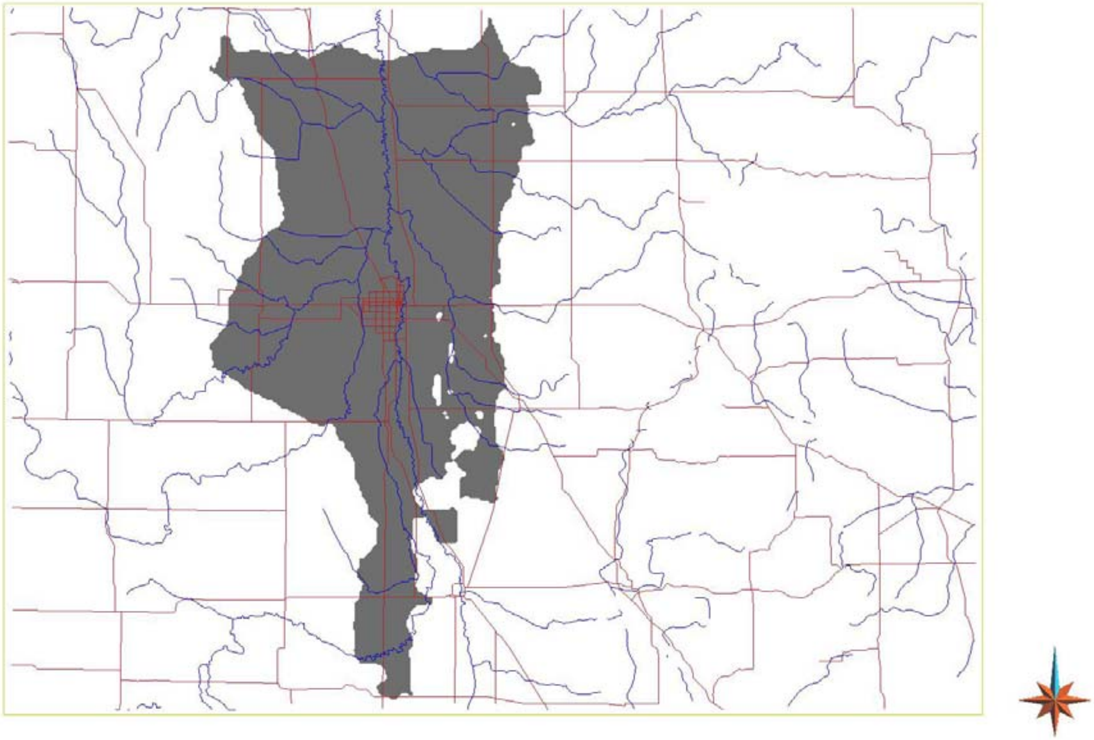


Figure 38 - Extent of regional 3D model layer 002: Sherack Formation glacial lake sediment

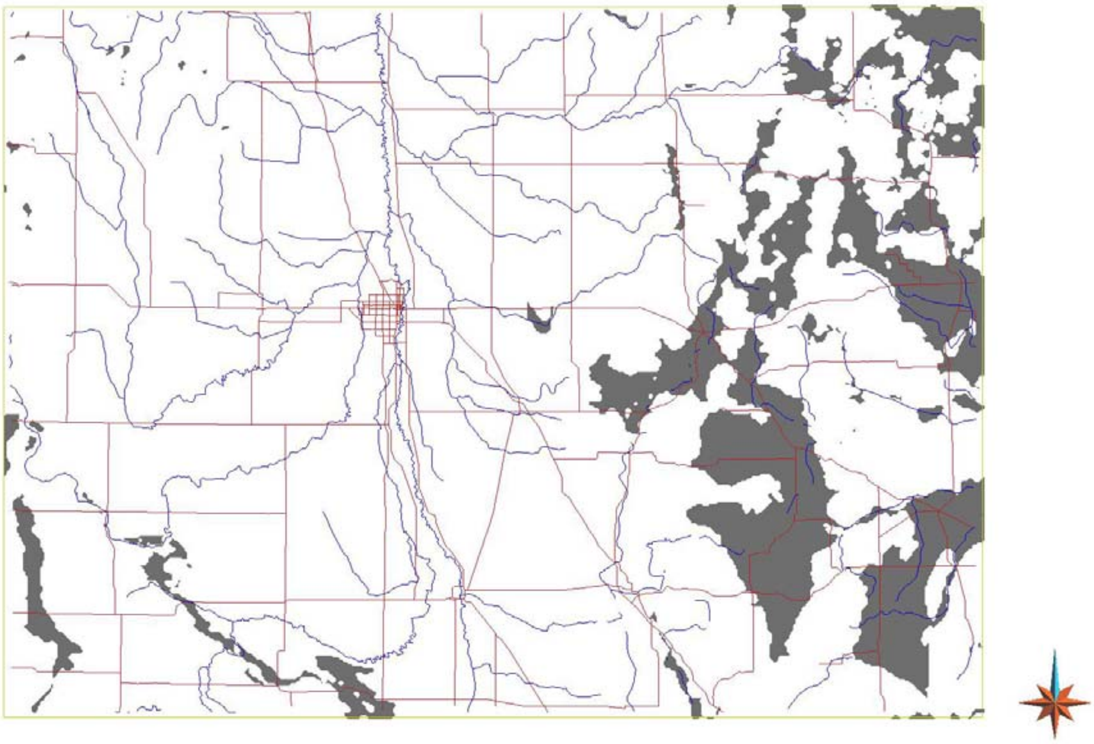


Figure 39 - Extent of regional 3D model layer 003: surficial outwash sand and gravel; includes aquifers such as the Milnor Channel, the Hankinson aquifer, as well as the Pelican, Ottertail, and Pineland outwash

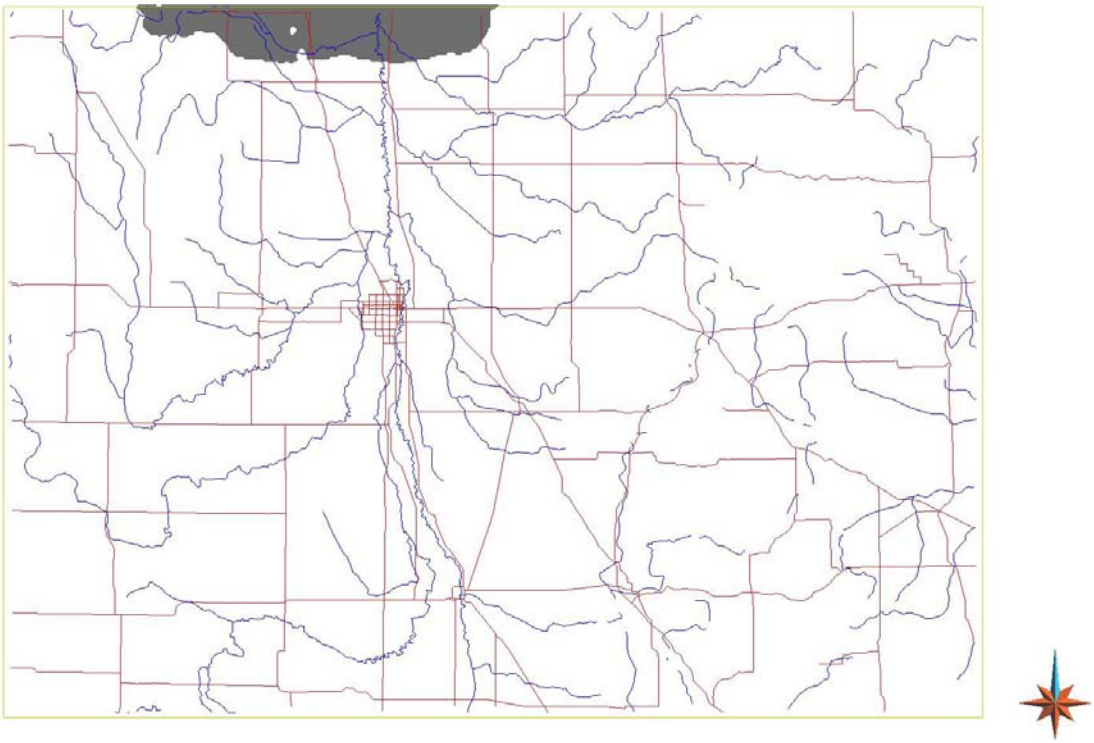


Figure 40 - Extent of regional 3D model layer 004: Forest River Group clay-rich till

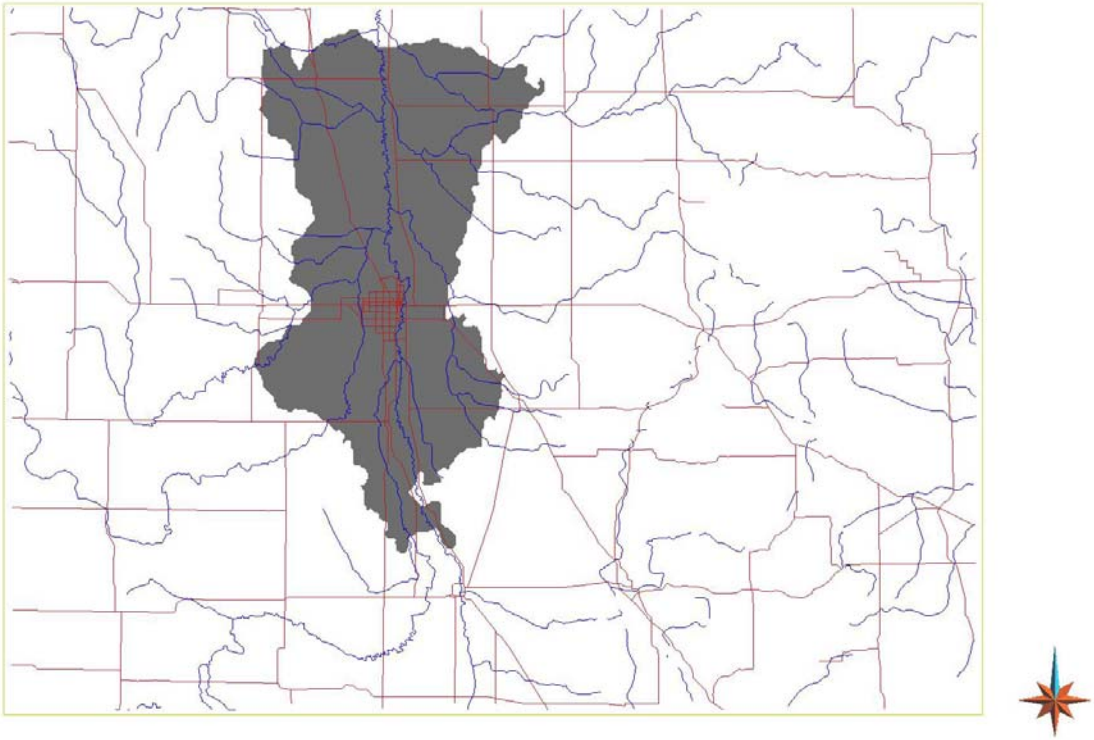


Figure 41 - Extent of regional 3D model layer 005: Brenna/Argusville Formation glacial lake sediment

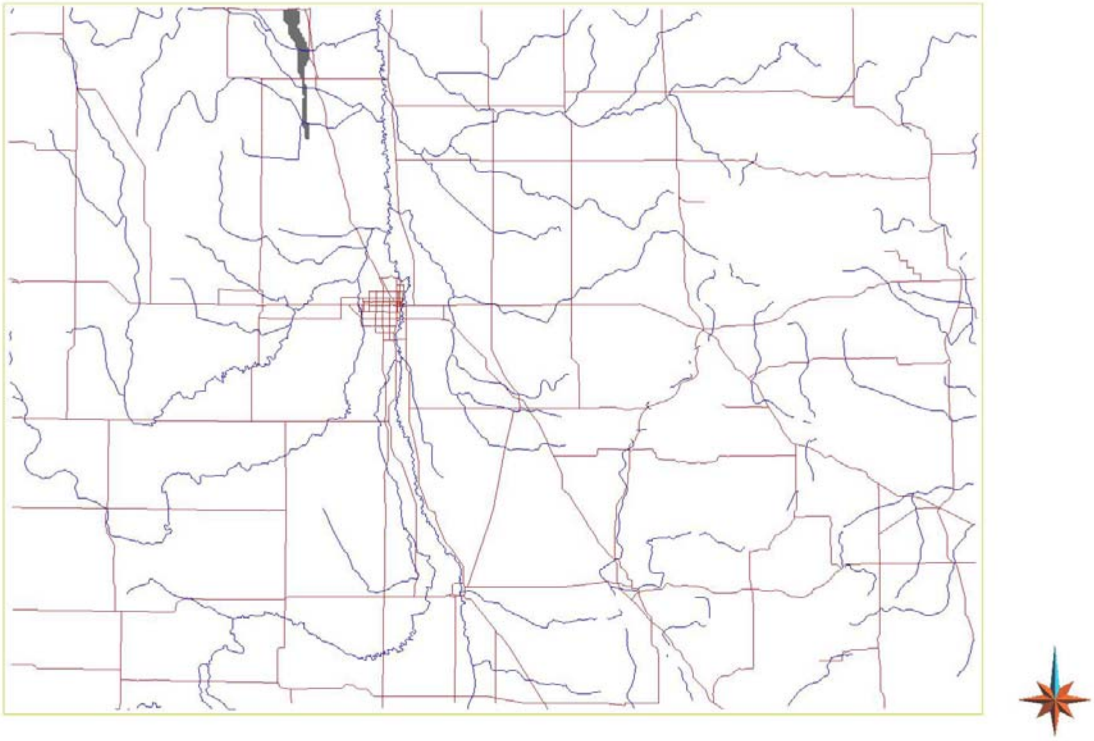


Figure 42 - Extent of regional 3D model layer 006: Red Lake River Group sand and gravel; known as the Hillsboro aquifer

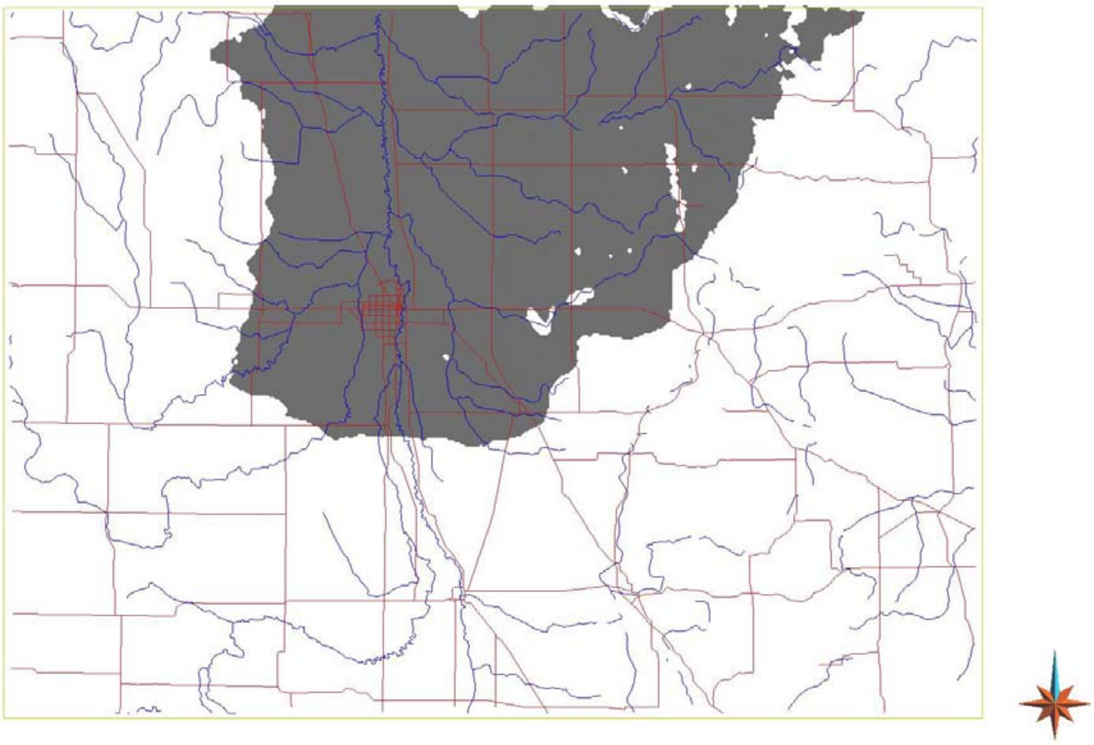


Figure 43 - Extent of regional 3D model layer 007: Red Lake River Group till

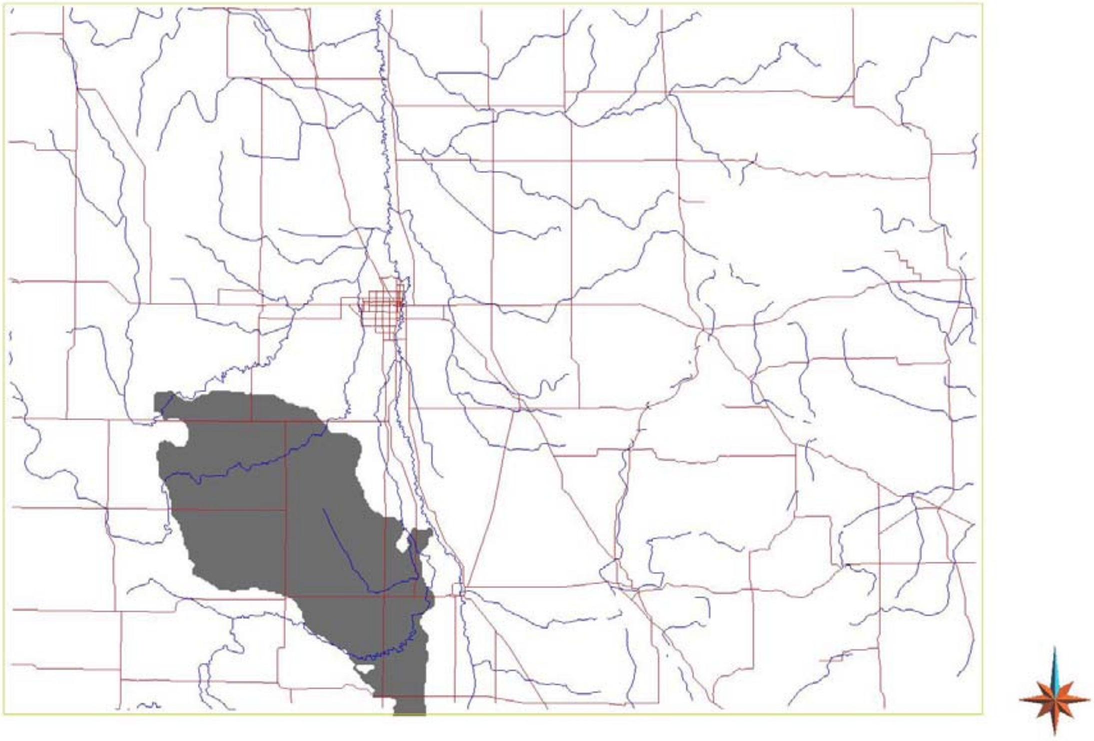


Figure 44 - Extent of regional 3D model layer 008: Sheyenne Delta, along with associated Red Lake River Group lacustrine and other sediments. This deposit includes a core of sand known as the Sheyenne Delta aquifer, as depicted by, for example, Reclamation (2005)

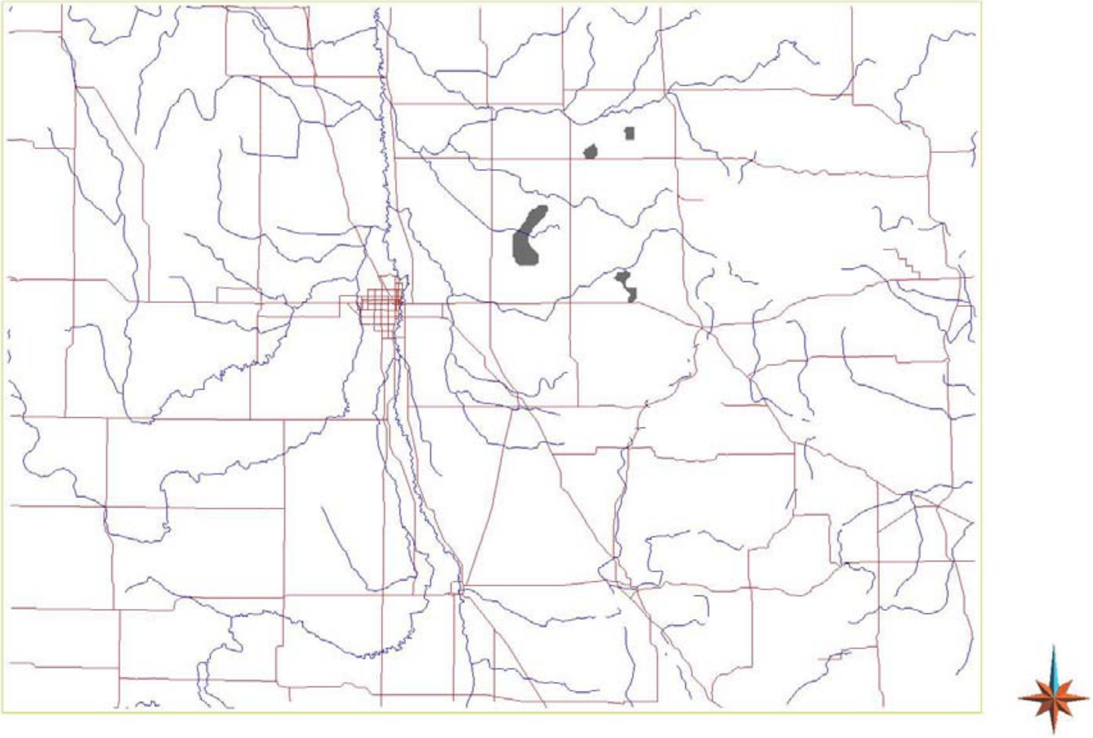


Figure 45 - Extent of regional 3D model layer 009: Upper Goose River Group unit 1 sand and gravel

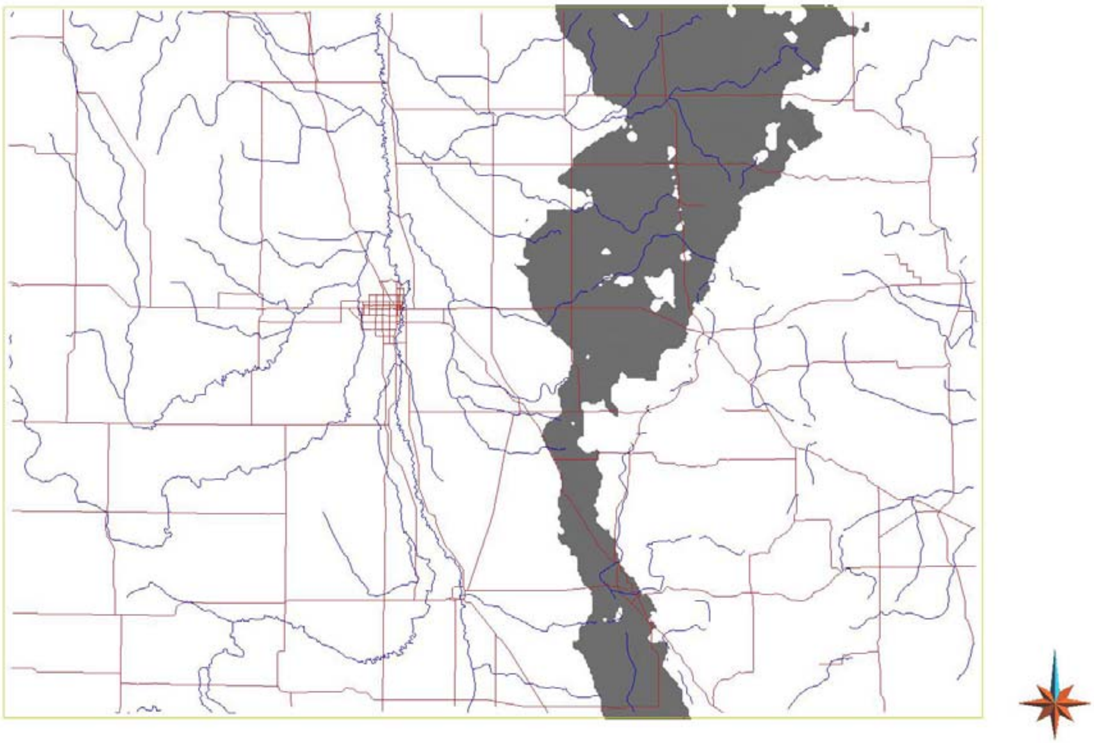


Figure 46 - Extent of regional 3D model layer 010: Upper Goose River Group unit 1 till

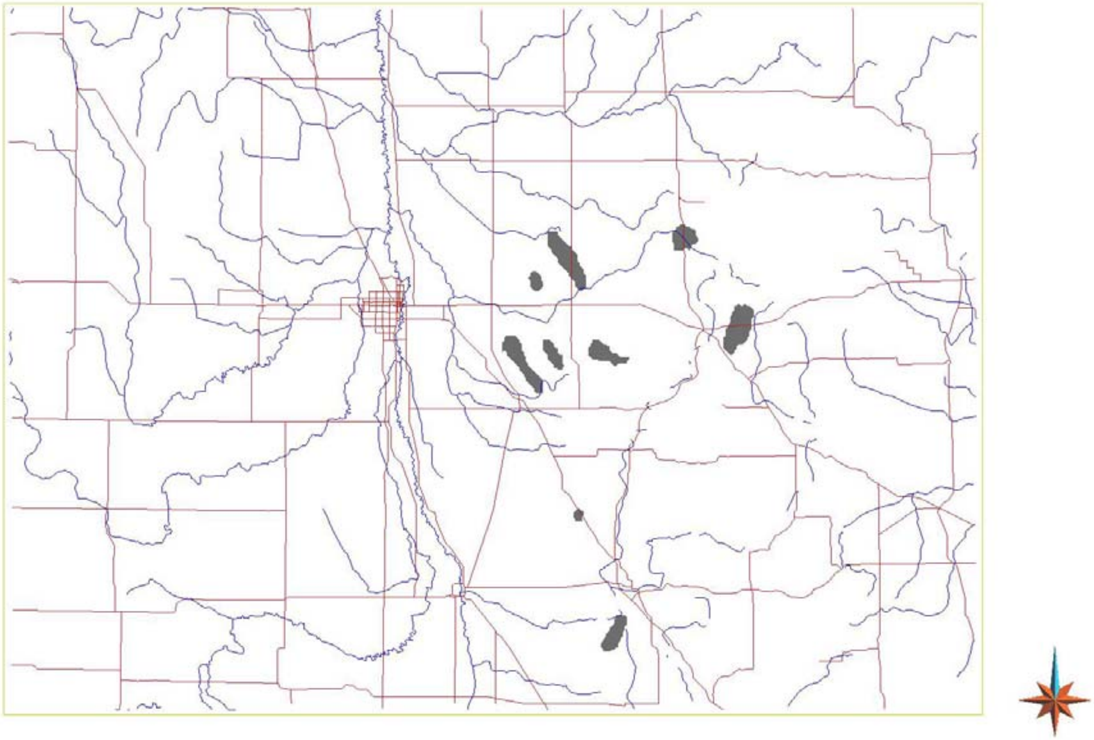


Figure 47 - Extent of regional 3D model layer 011: Upper Goose River Group unit 2 sand and gravel

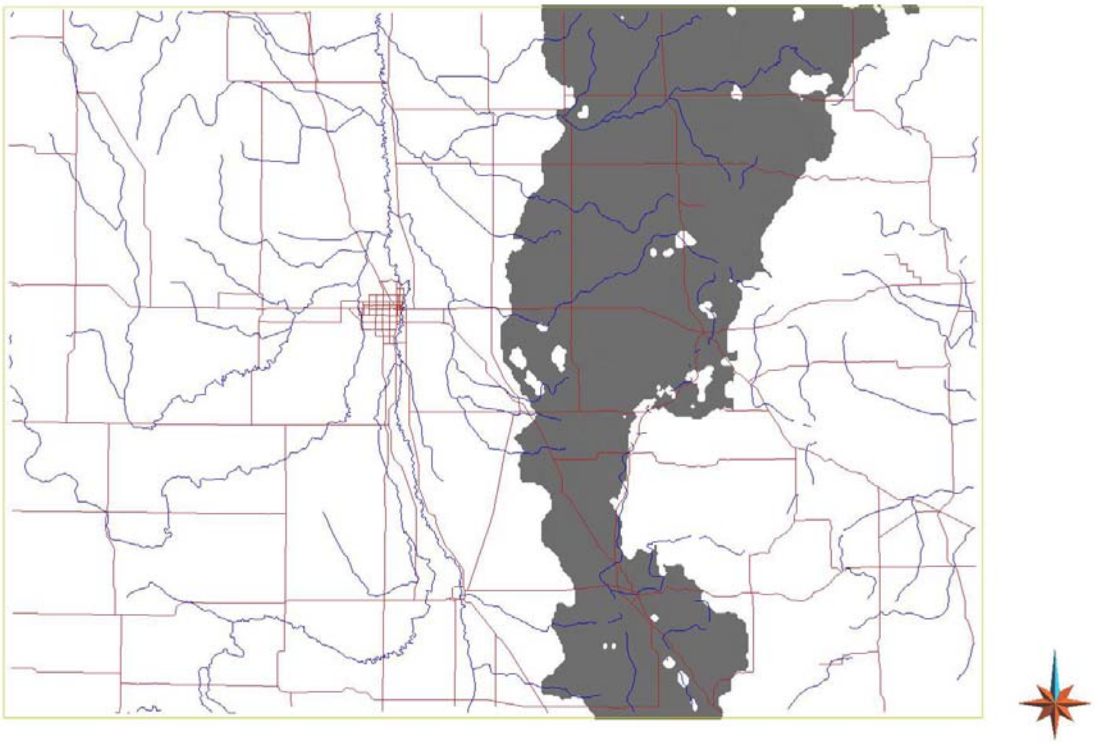


Figure 48 - Extent of regional 3D model layer 012: Upper Goose River Group unit 2 till

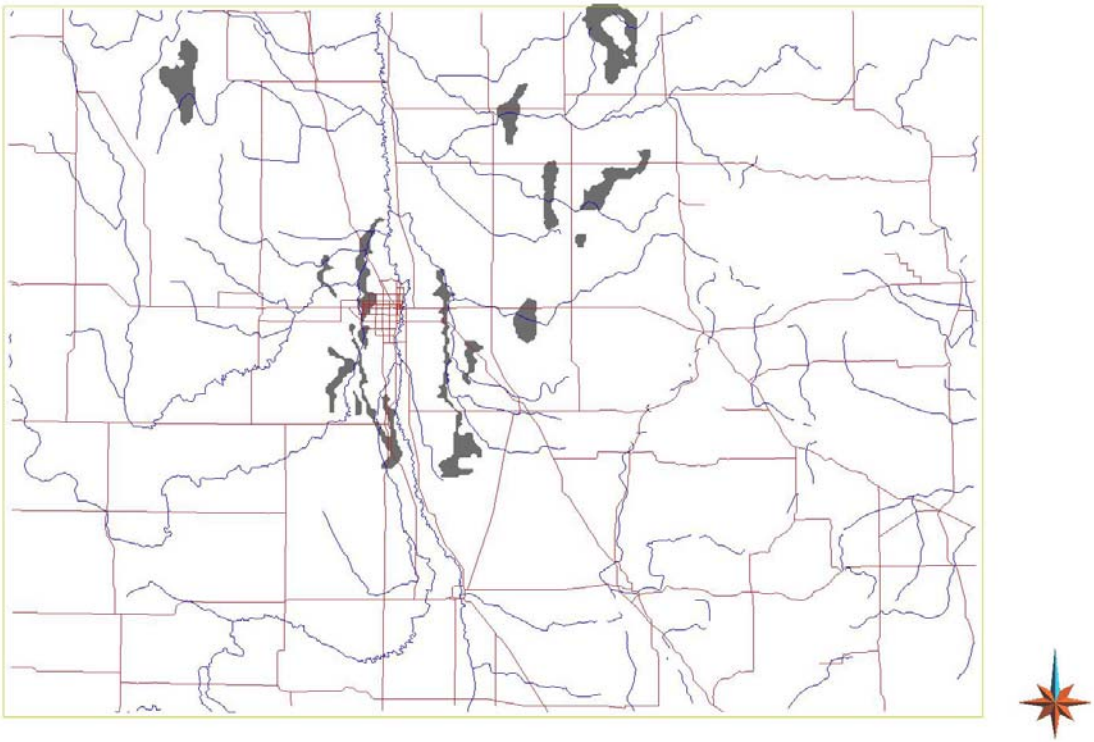


Figure 49 - Extent of regional 3D model layer 013: Lower Goose River Group sand and gravel; this layer includes, for example, the Buffalo aquifer, the West Fargo aquifer, and the Horace aquifer

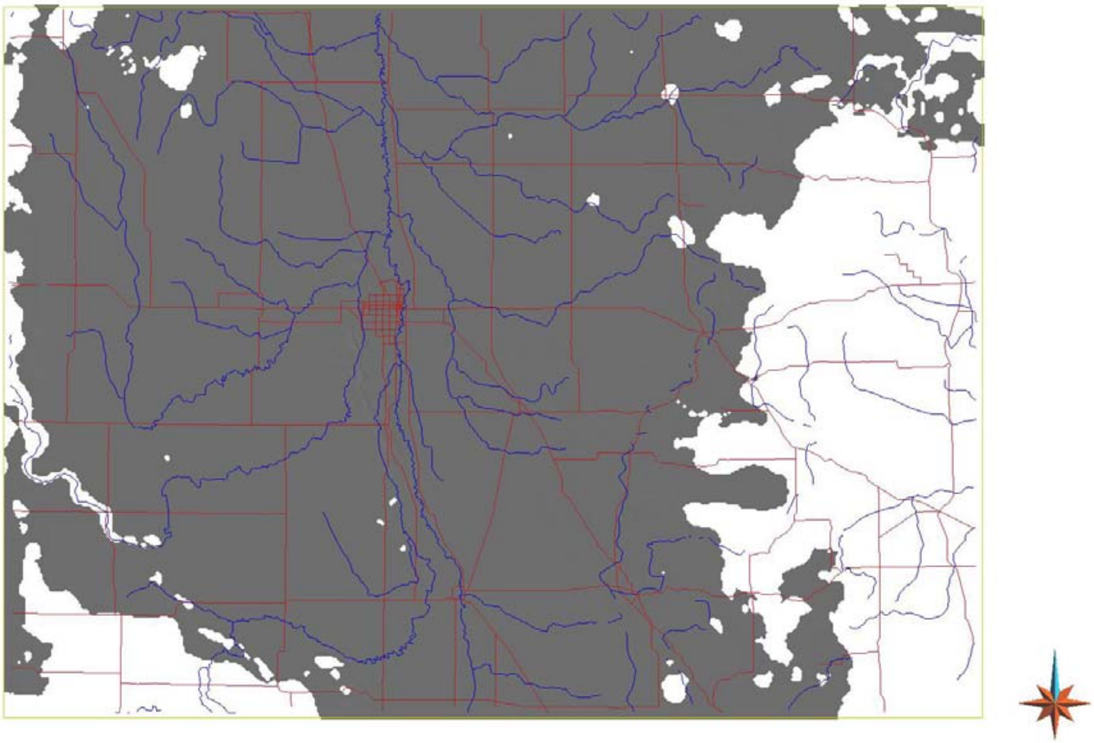


Figure 50 - Extent of regional 3D model layer 014: Lower Goose River Group till

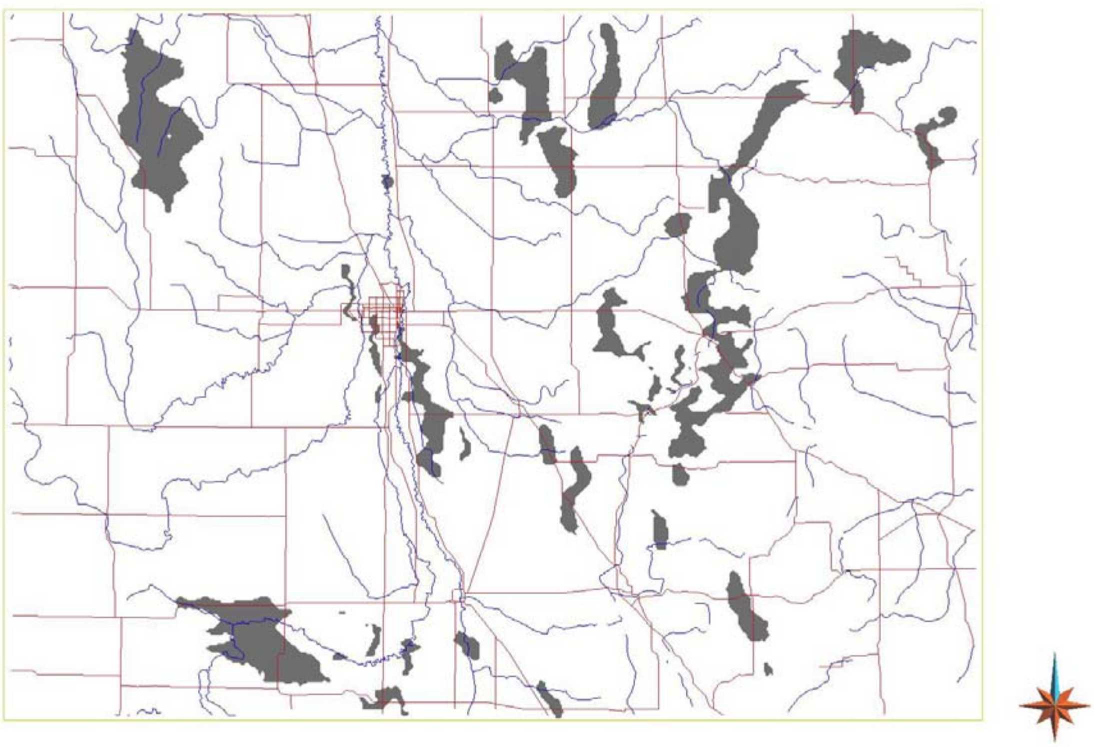


Figure 51 - Extent of regional 3D model layer 015: Otter Tail River Group sand and gravel. This mapping includes a new depiction of elongate sand lenses at this level in the Moorhead area, as well as an extensive, but apparently not previously recognized, sand deposit in southeastern North Dakota. These deposits as well as those occurring more deeply in southeastern-most North Dakota possibly encompass what has been known as the Sonora aquifer

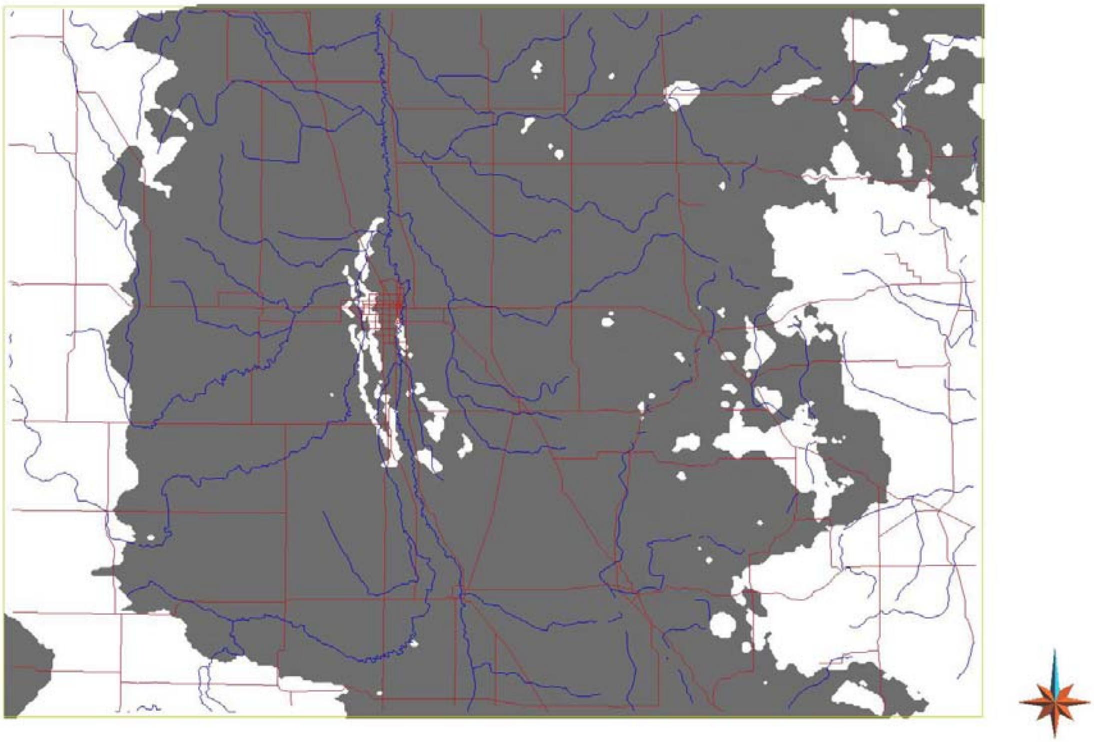


Figure 52 - Extent of regional 3D model layer 016: Otter Tail River Group till

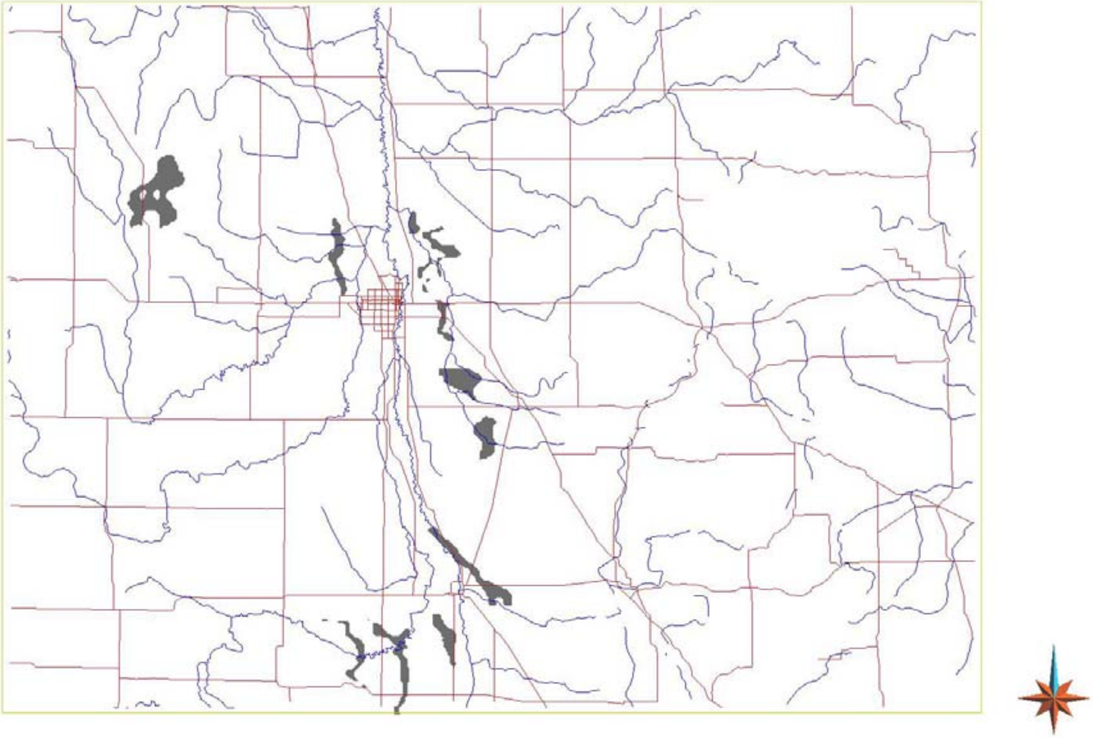


Figure 53 - Extent of regional 3D model layer 017: Lake Tewaukon Group sand and gravel

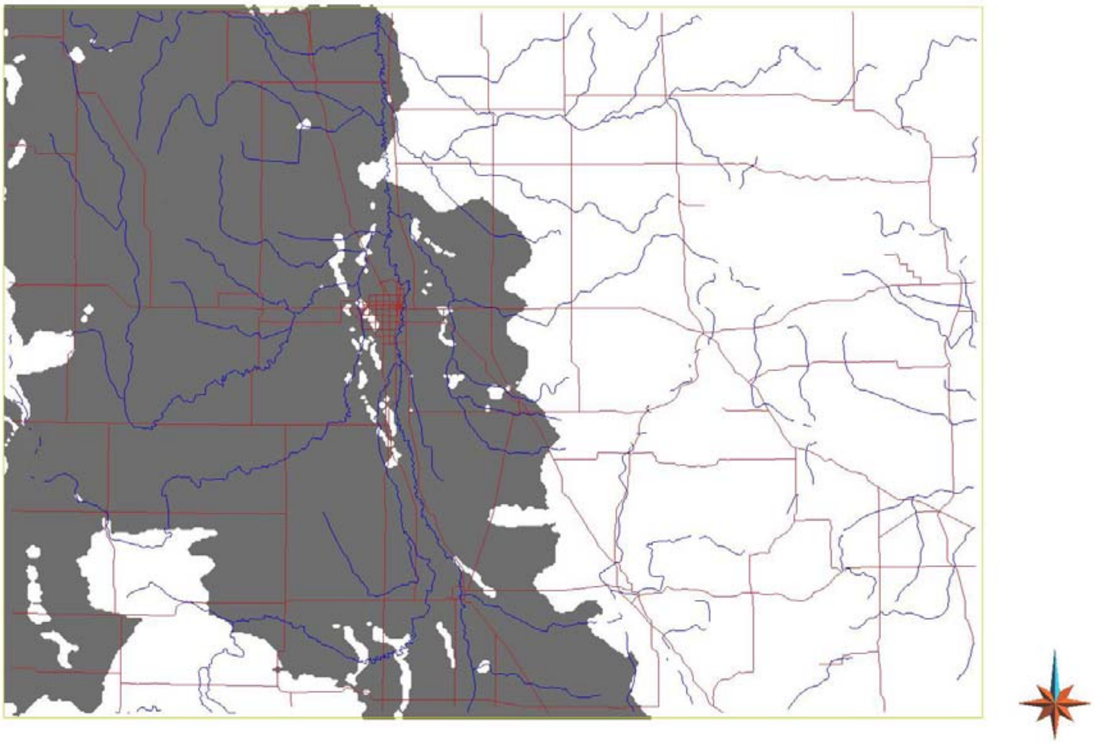


Figure 54 - Extent of regional 3D model layer 018: Lake Tewaukon Group till

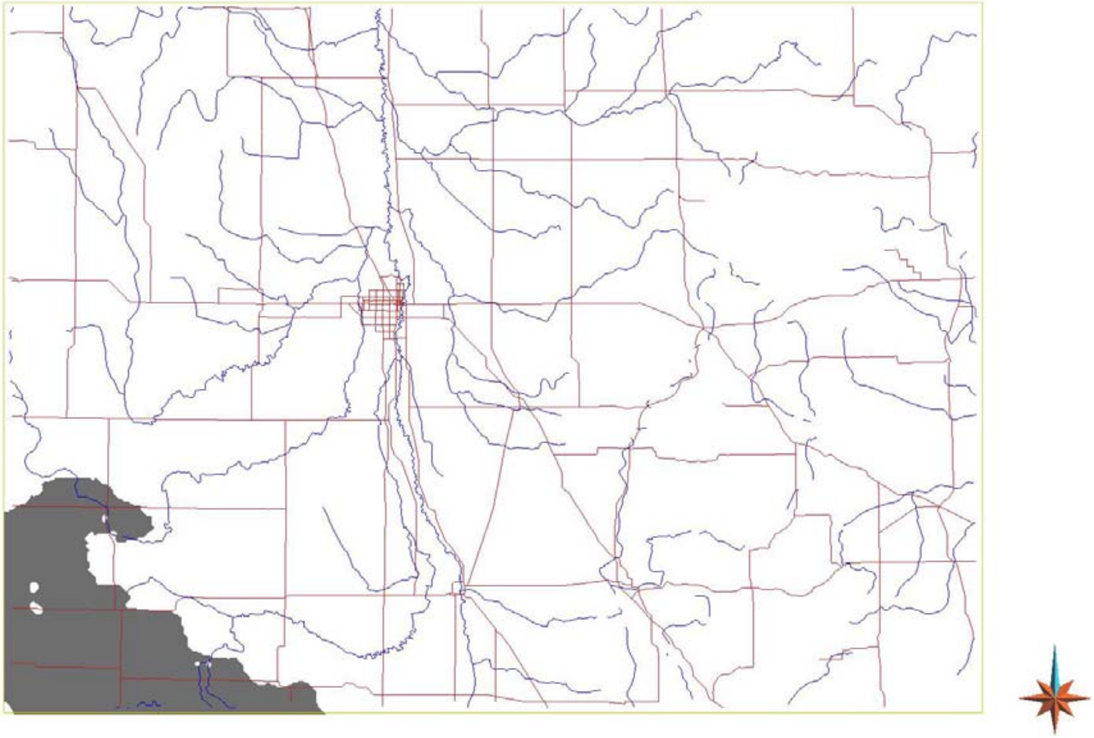


Figure 55 - Extent of regional 3D model layer 019: Buffalo River Group till

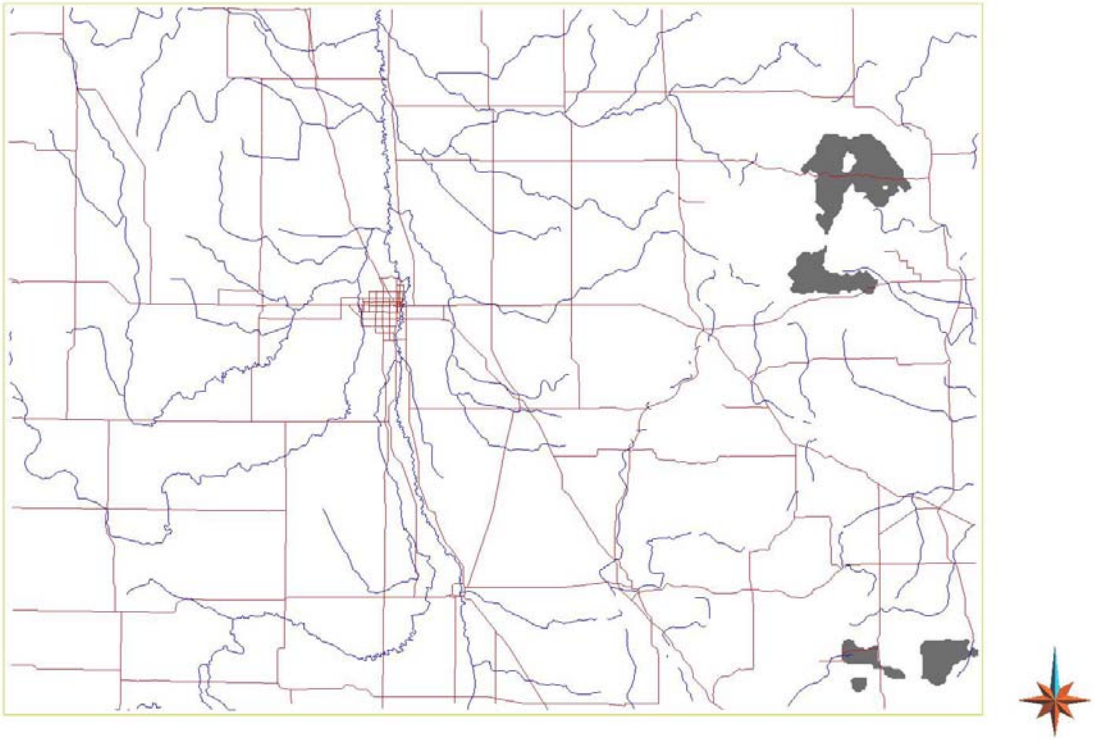


Figure 56 - Extent of regional 3D model layer 020: Crow Wing River Group unit 1 till

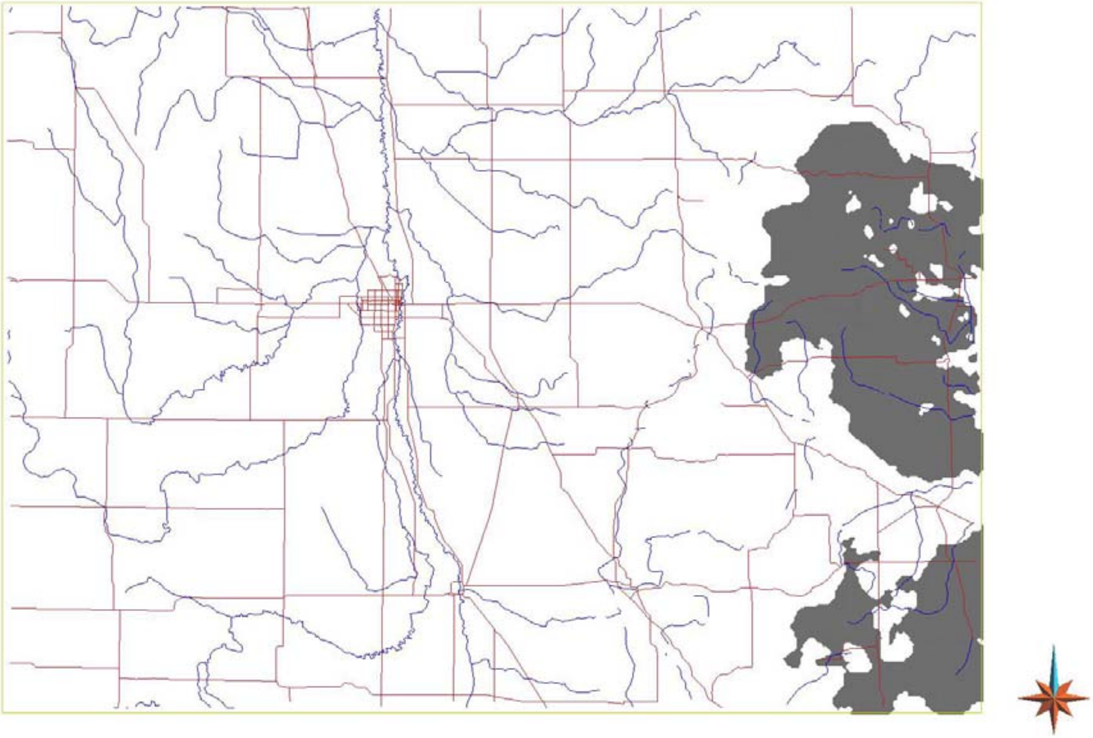


Figure 57 - Extent of regional 3D model layer 021: Crow Wing River Group unit 2 till

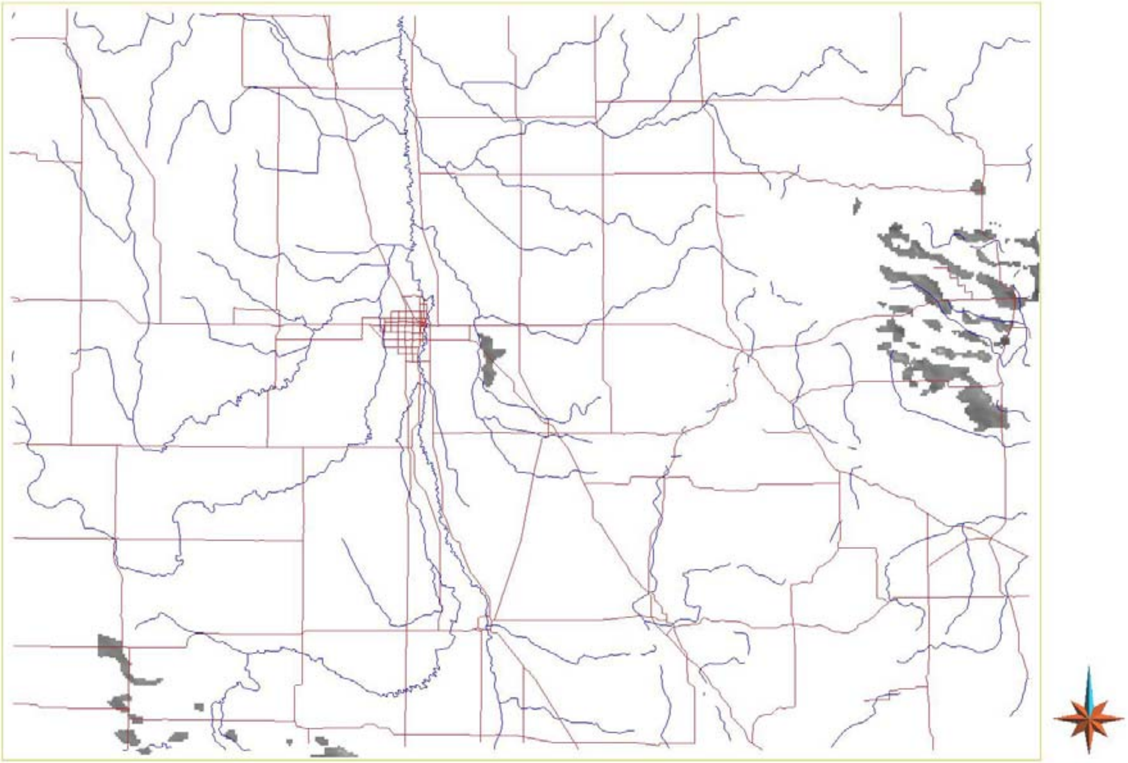


Figure 58 - Extent of regional 3D model layer 022: Browerville Formation sand and gravel, including deposits that have been known as the Gwinner aquifer

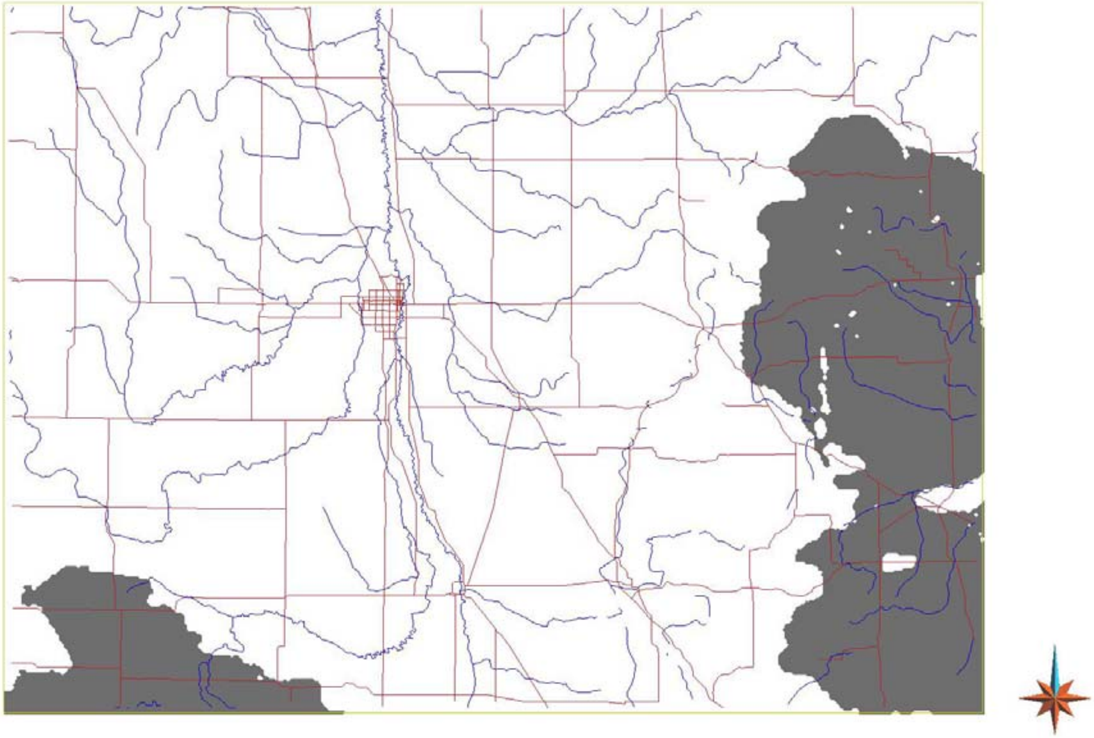


Figure 59 - Extent of regional 3D model layer 023: Browerville Formation till

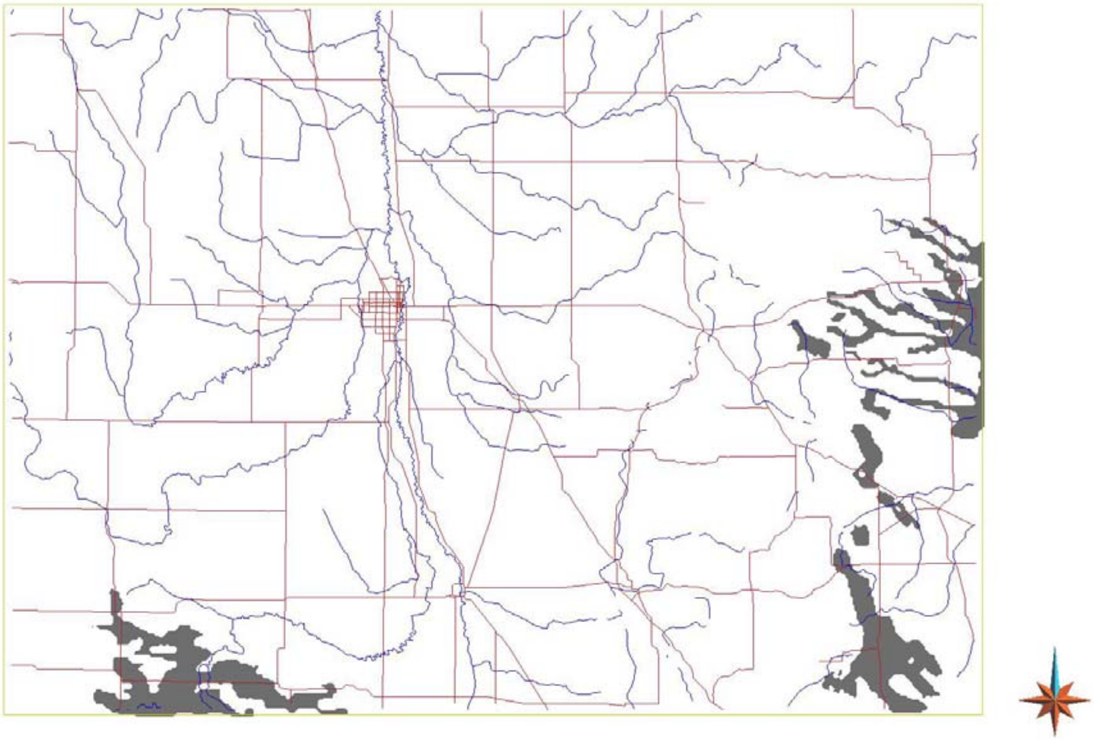


Figure 60 - Extent of regional 3D model layer 024: Older unknown unit a4 sand and gravel, including the upper portion of what has been known as the Spiritwood-Brightwood aquifer complex in southeastern North Dakota

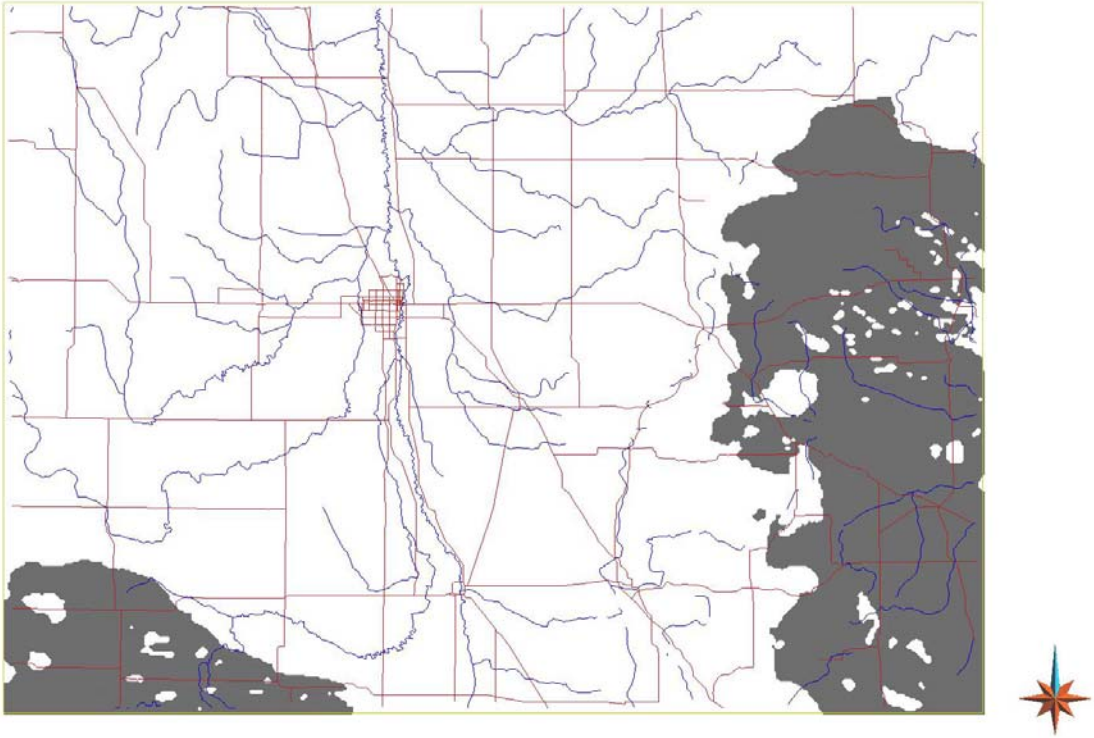


Figure 61 - Extent of regional 3D model layer 025: Older unknown unit a4 till

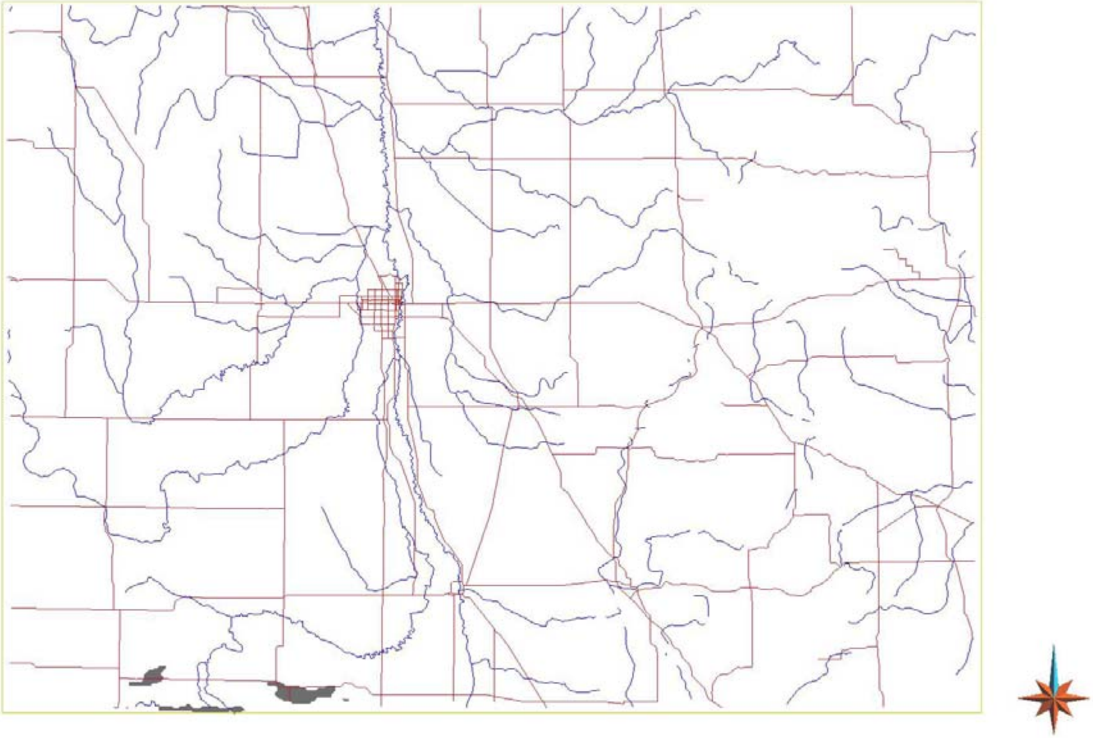


Figure 62 - Extent of regional 3D model layer 026: Older unknown unit a5 sand and gravel, including the lower portion of what has been known as the Spiritwood-Brightwood aquifer complex in southeastern North Dakota

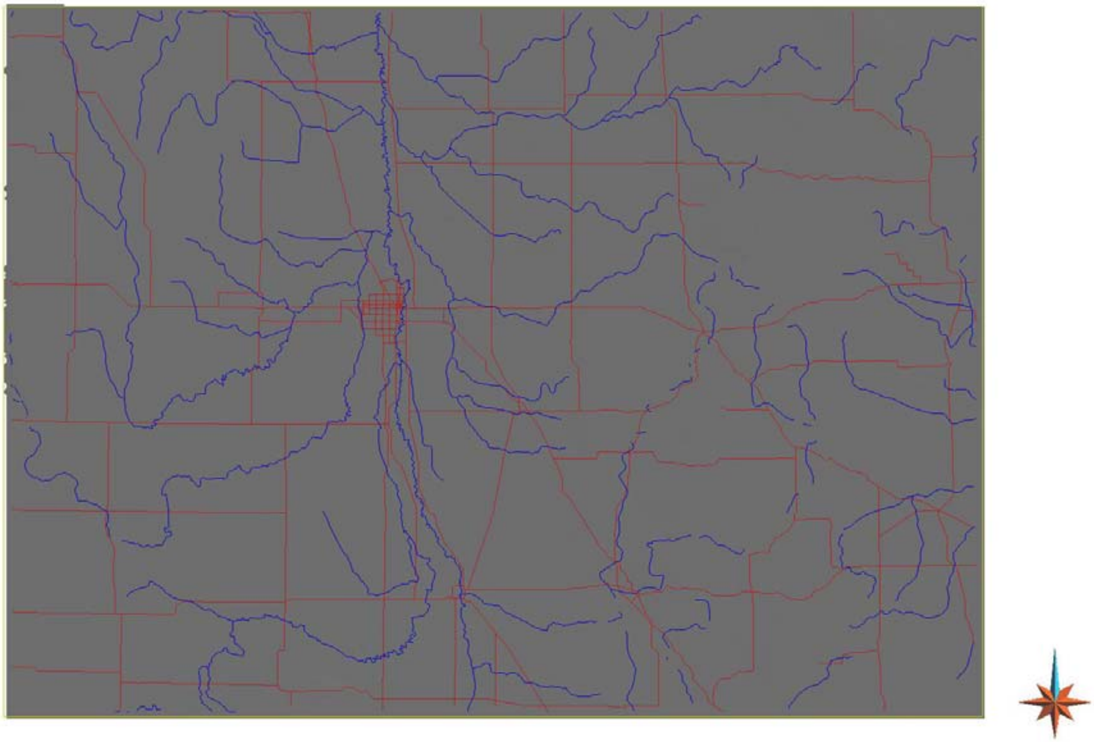


Figure 63 - Extent of regional 3D model layer 028: Quaternary undifferentiated

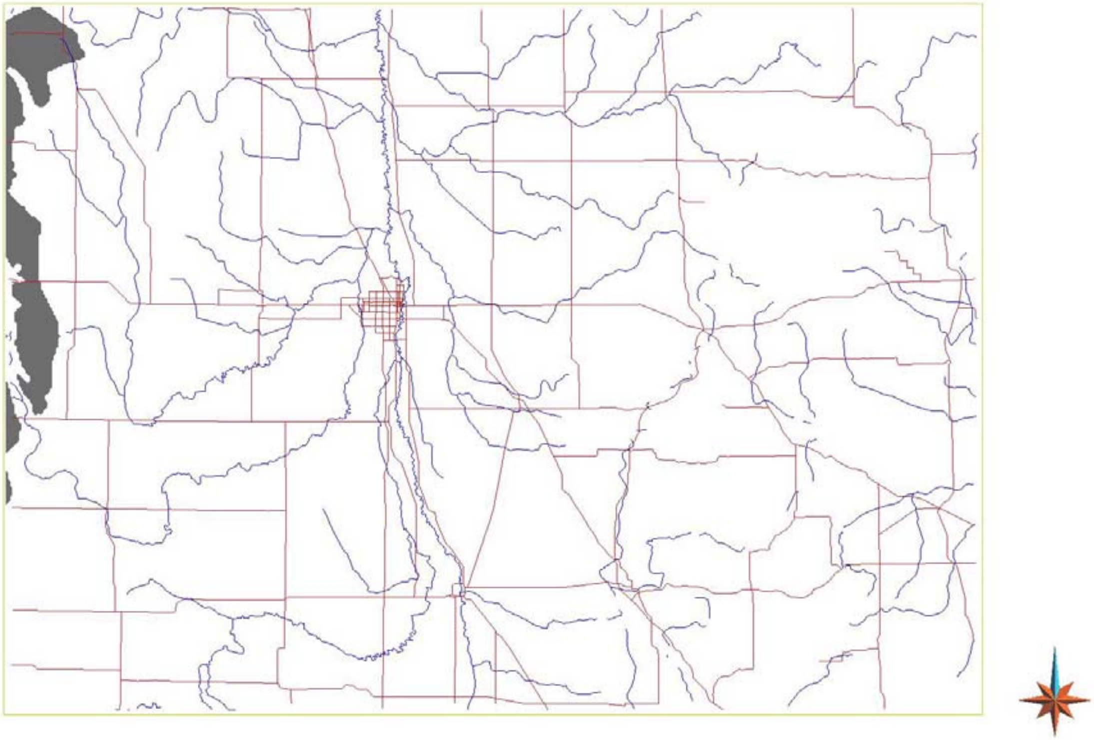


Figure 64 - Extent of regional 3D model layer 030: Cretaceous Pierre Formation

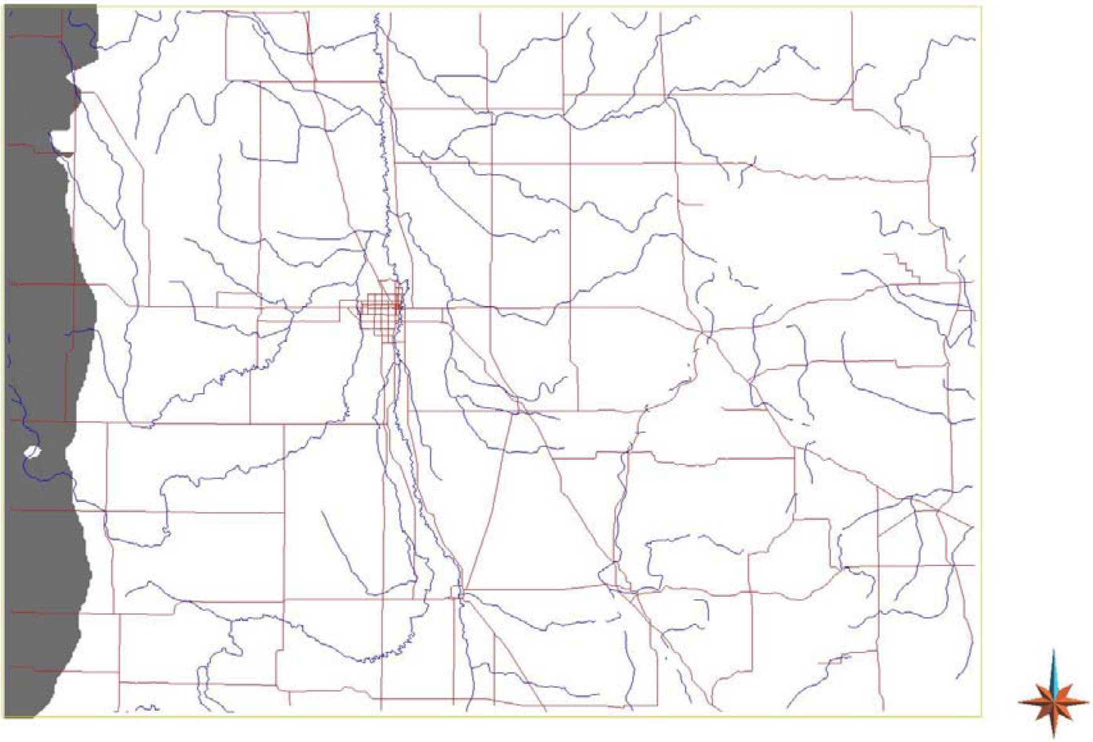


Figure 65 - Extent of regional 3D model layer 031: Cretaceous Niobrara Formation

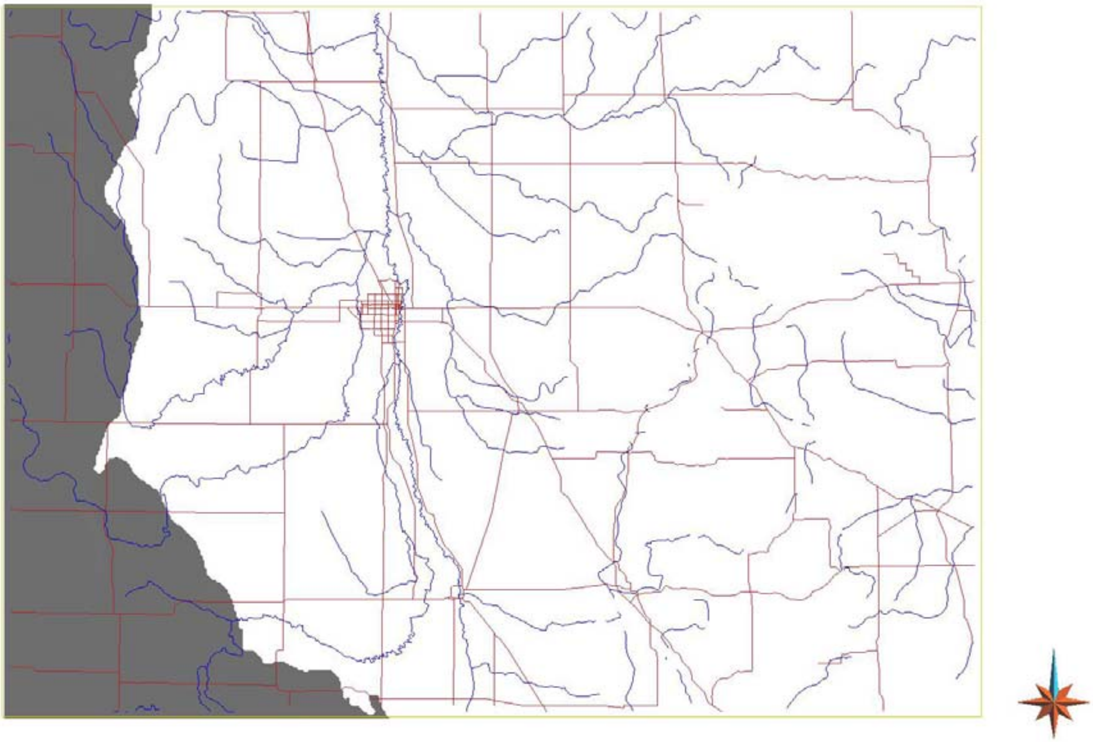


Figure 66 - Extent of regional 3D model layer 032: Cretaceous Carlile Formation

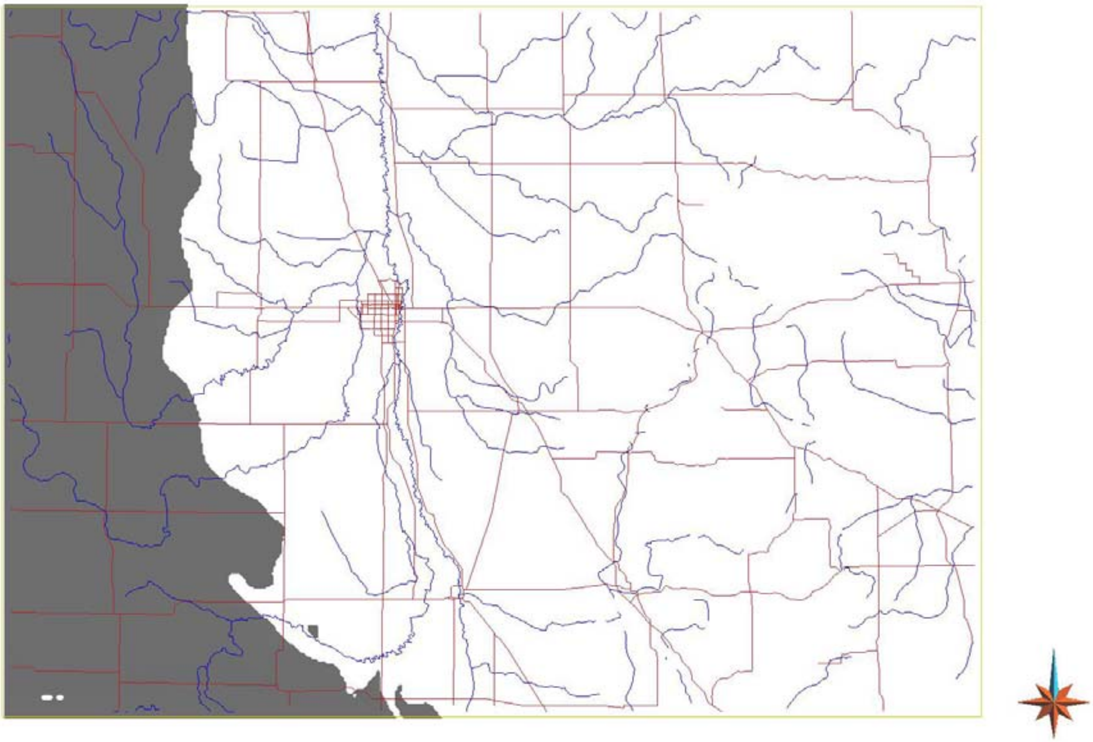


Figure 67 - Extent of regional 3D model layer 033: Cretaceous Greenhorn Formation

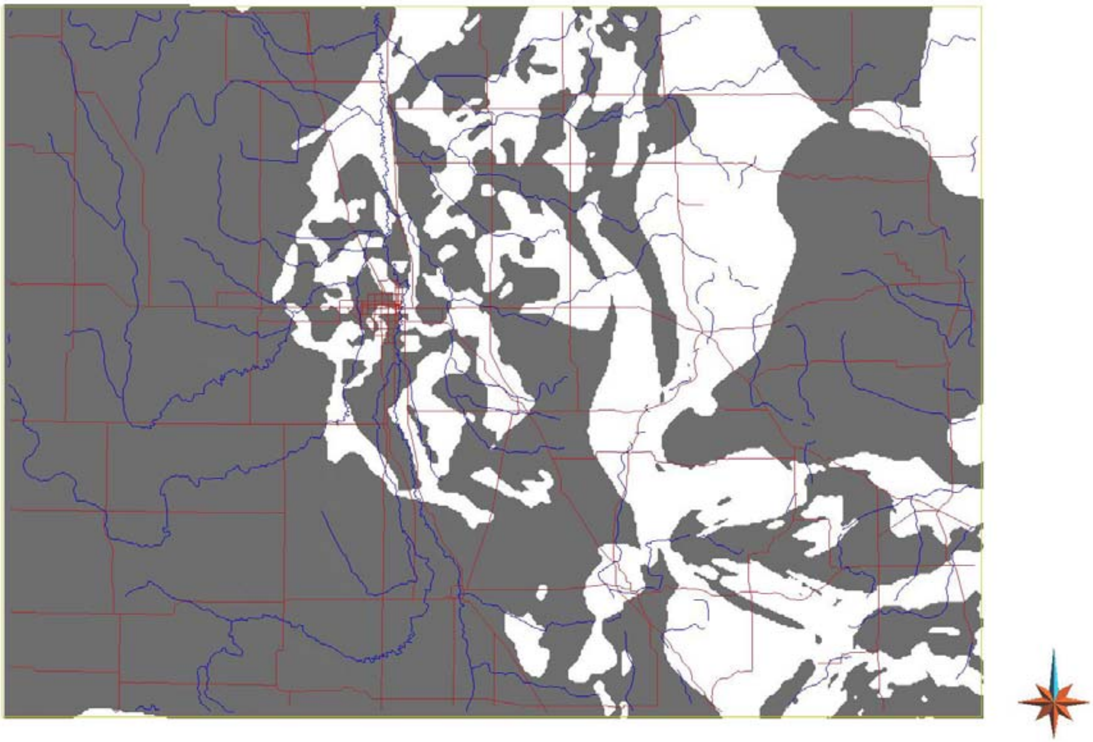


Figure 68 - Extent of regional 3D model layer 034: Cretaceous undifferentiated

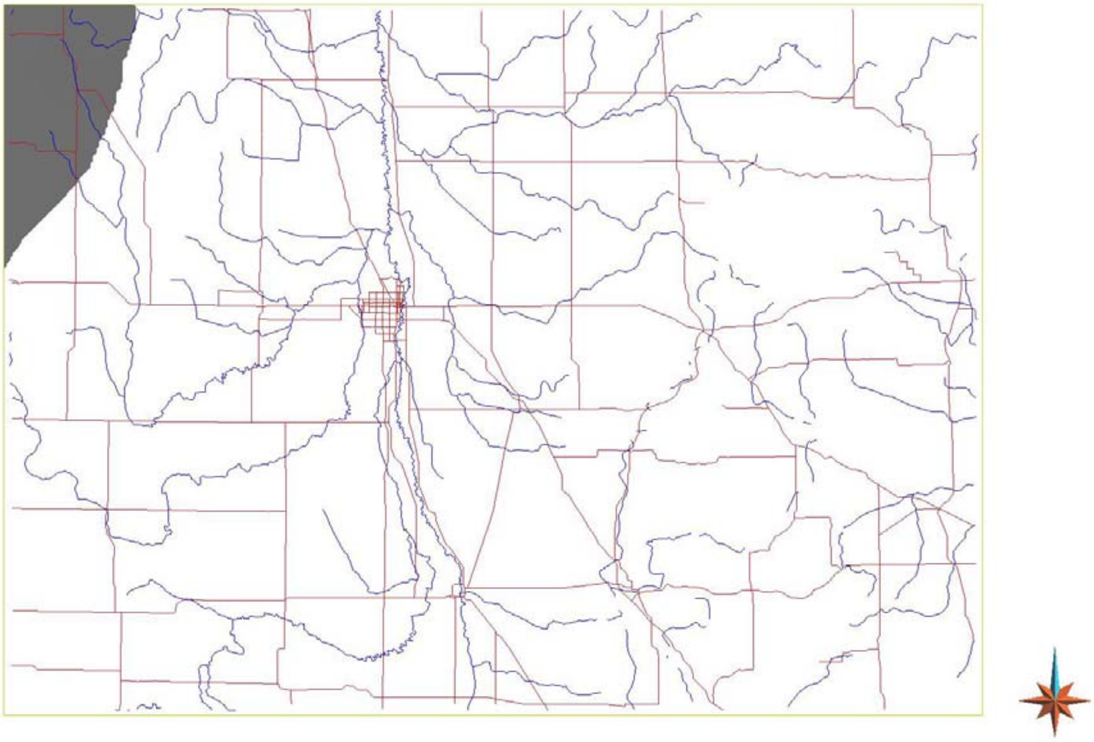


Figure 69 - Extent of regional 3D model layer 035: Ordovician Red River Formation carbonate

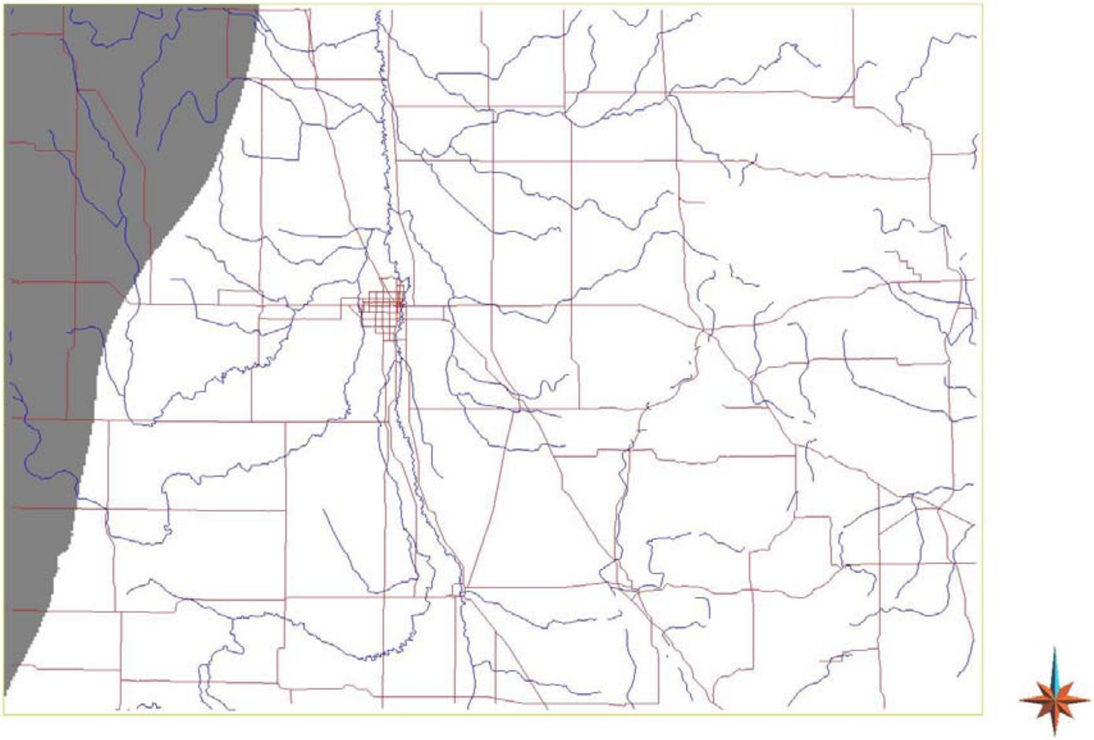


Figure 70 - Extent of regional 3D model layer 036: Ordovician Winnipeg Formation sandstone

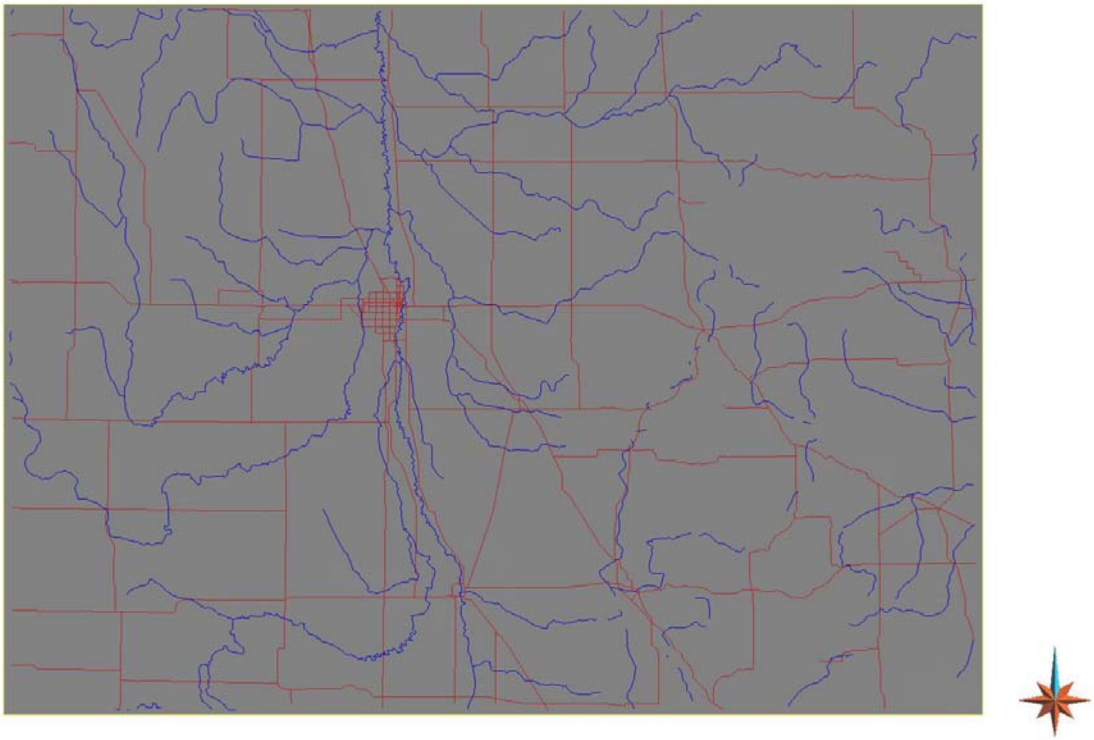


Figure 71 - Extent of regional 3D model layer 037: Precambrian igneous and metamorphic rock

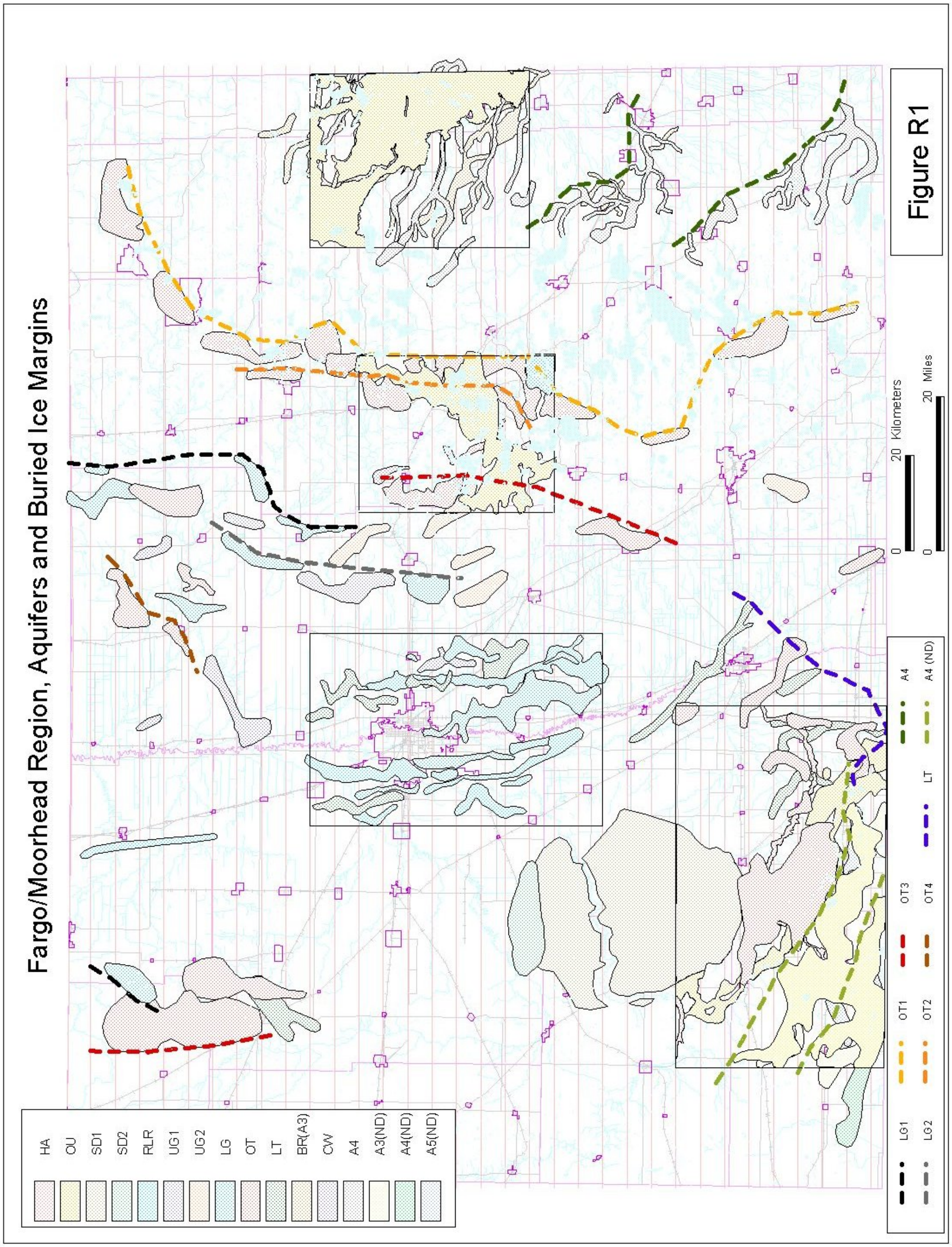


Figure 72 – Fargo-Moorhead region mapped sand deposits and inferred buried ice margins

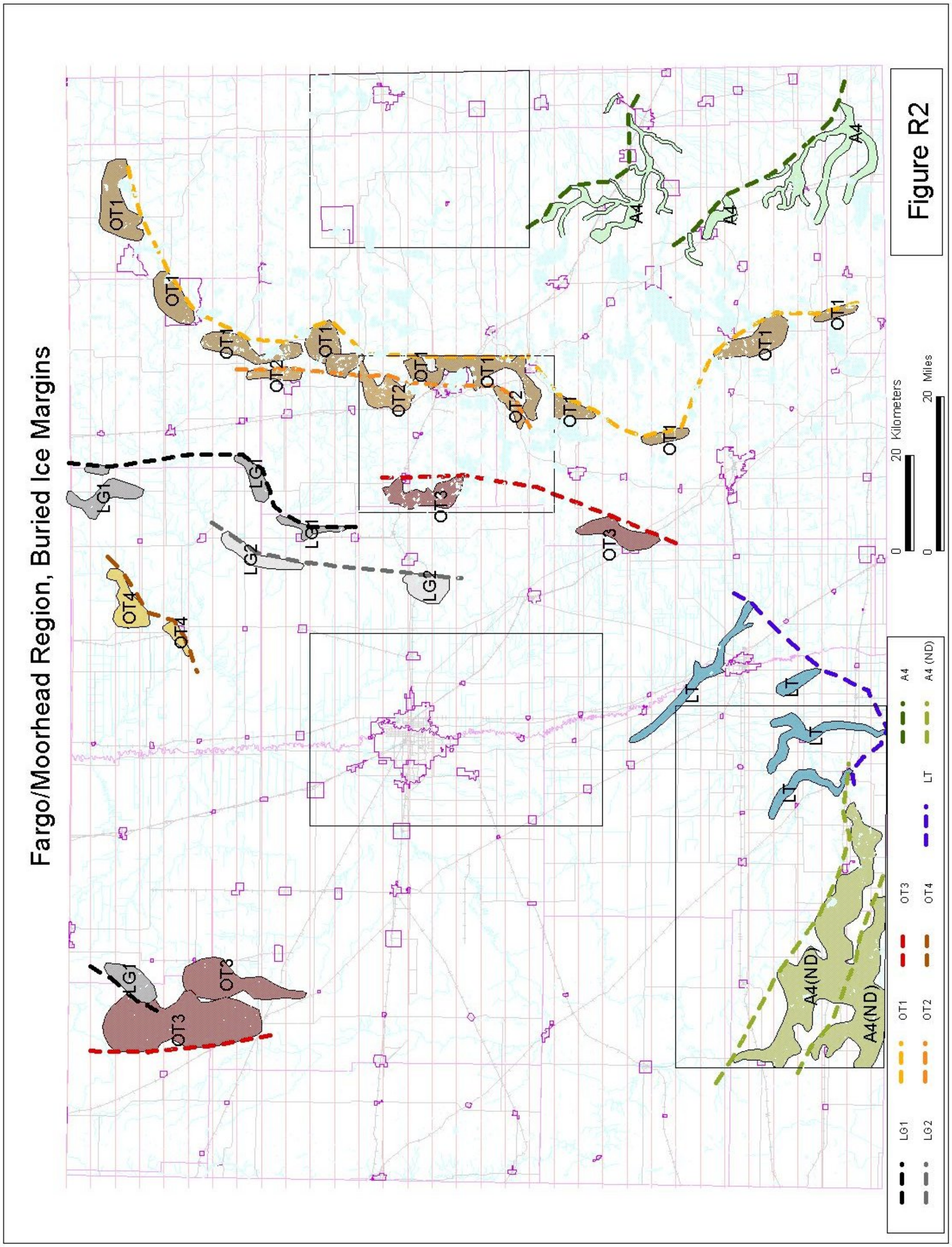


Figure 73 – Fargo-Moorhead region inferred buried ice margins

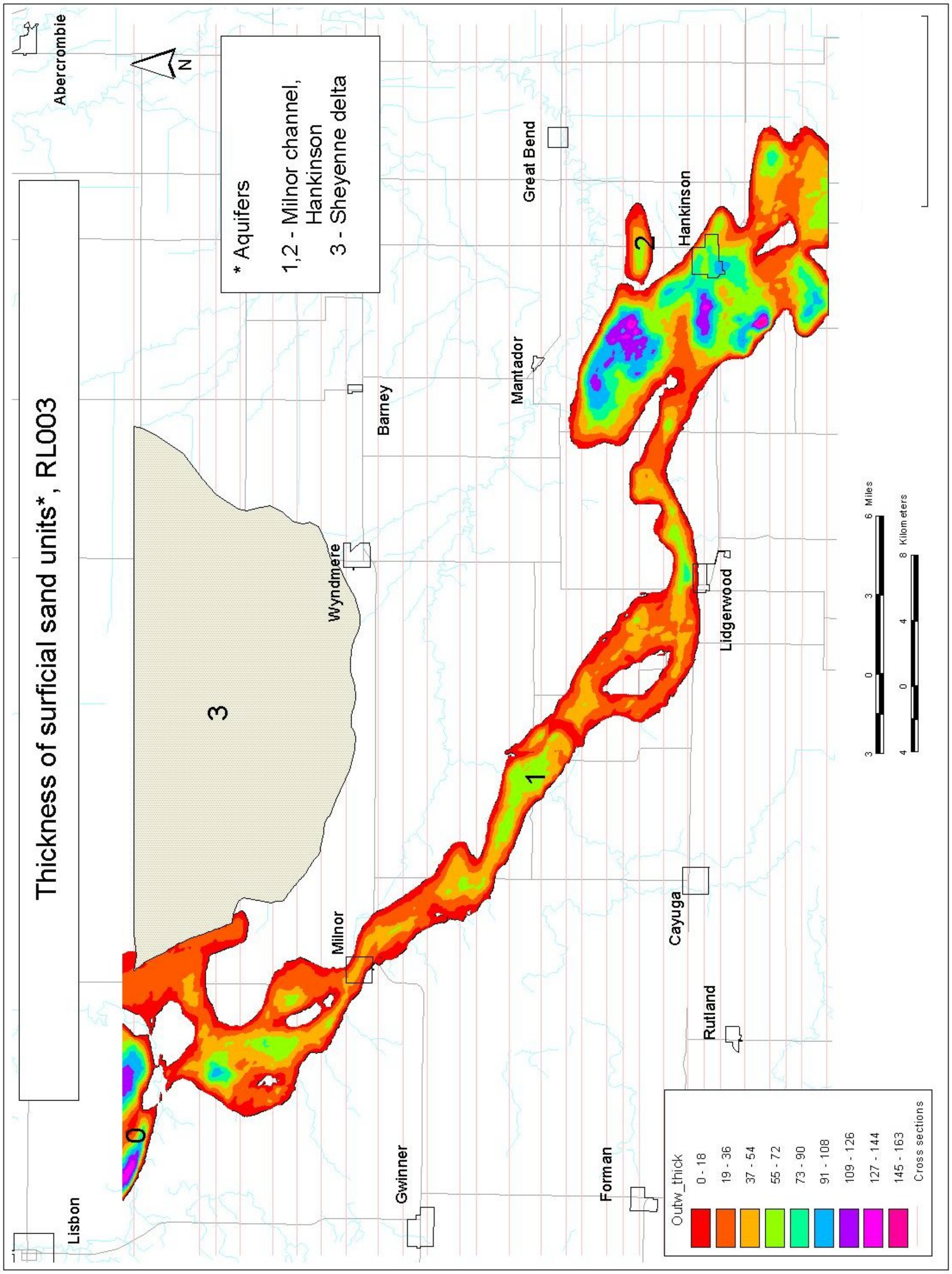


Figure 74 – Thickness in feet of surficial sand units in the Hankinson detail area, regional model layer 3

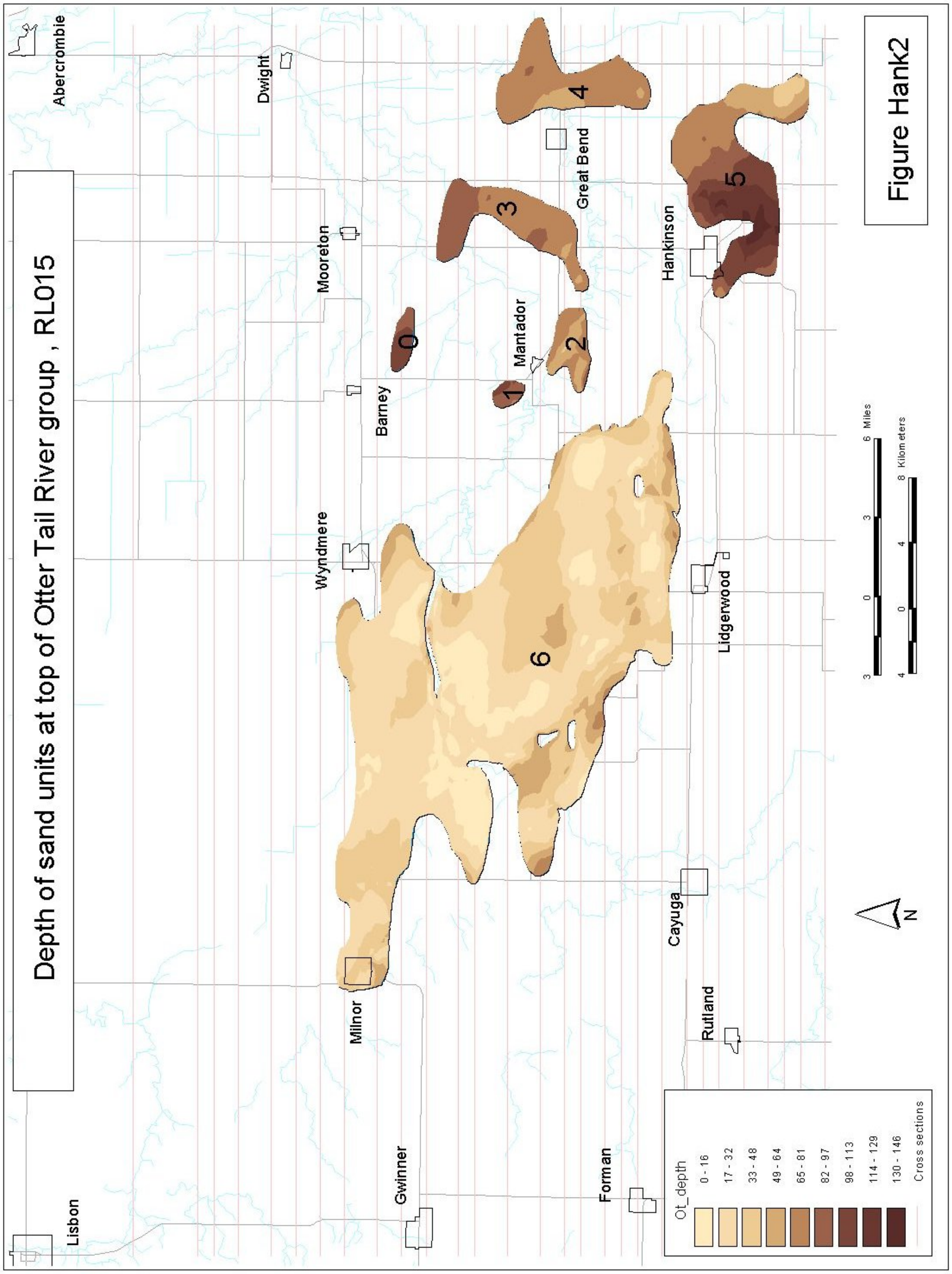


Figure 75 – Depth in feet to top of sand units at top of Otter Tail Group in the Hankinson detail area, regional model layer 15

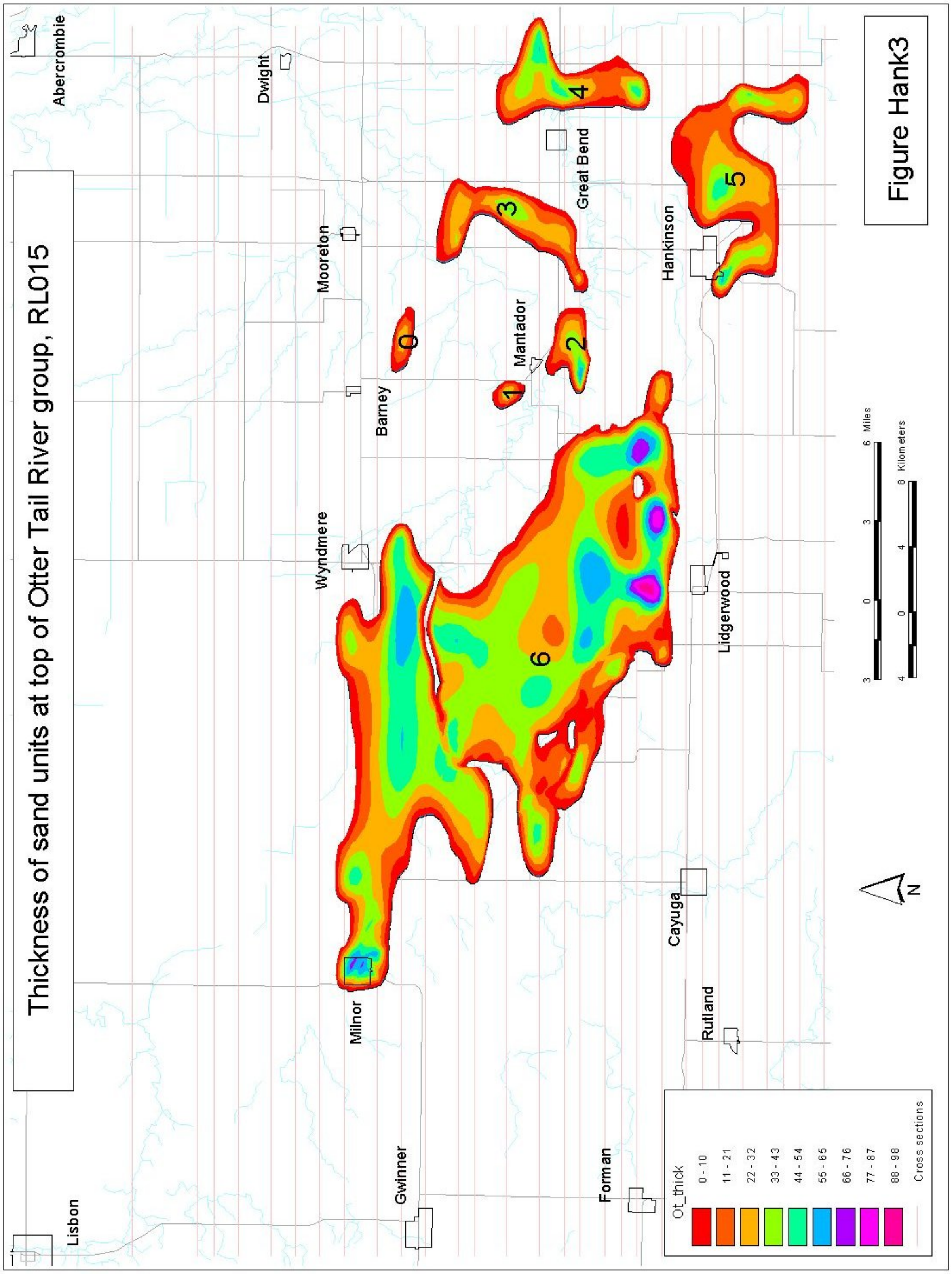


Figure 76 – Thickness in feet to top of sand units at top of Otter Tail Group in the Hankinson detail area, regional model layer 15

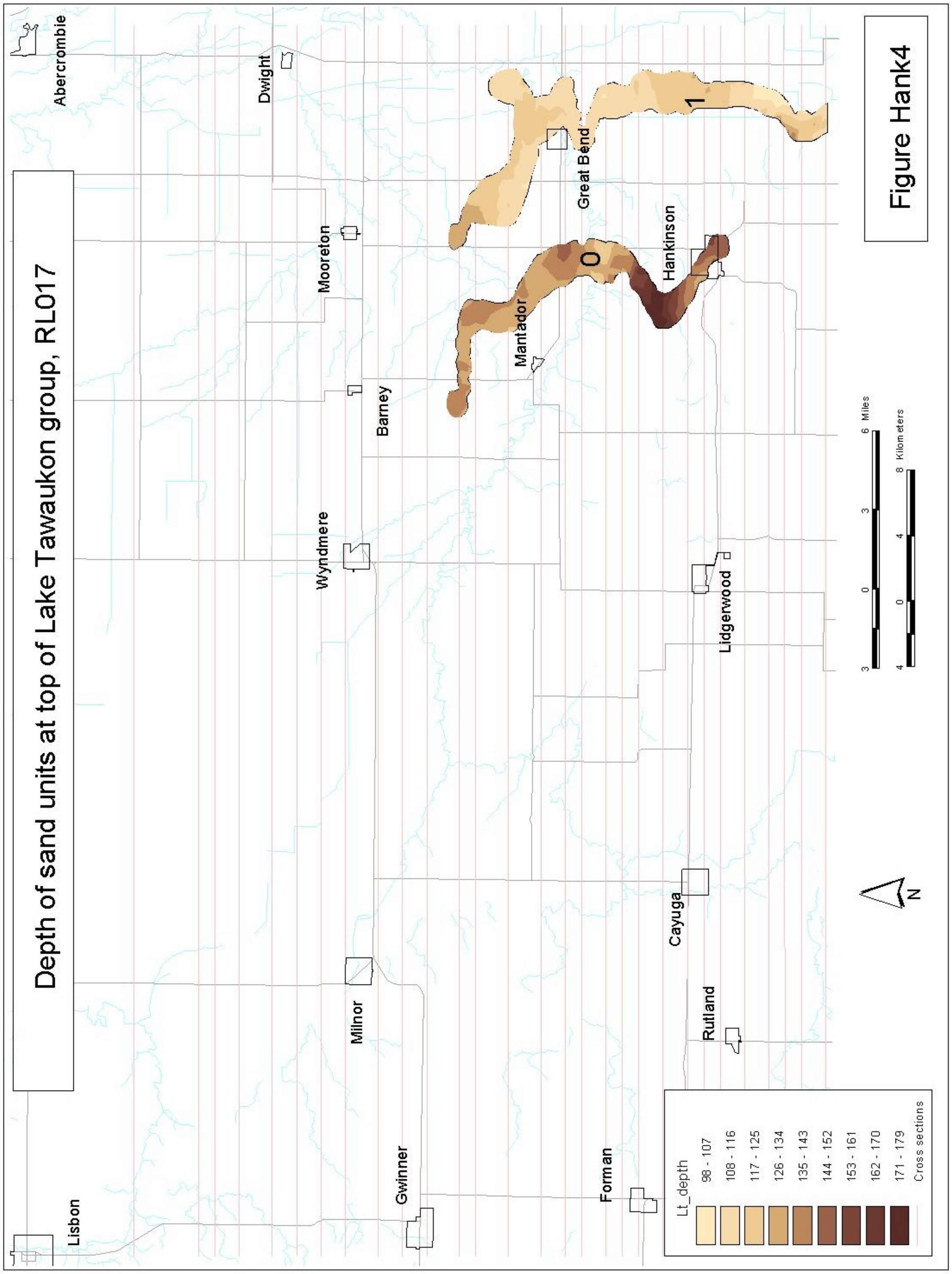


Figure 77 – Depth in feet to top of sand units at top of Lake Tewaukon Group in the Hankinson detail area, regional model layer 17

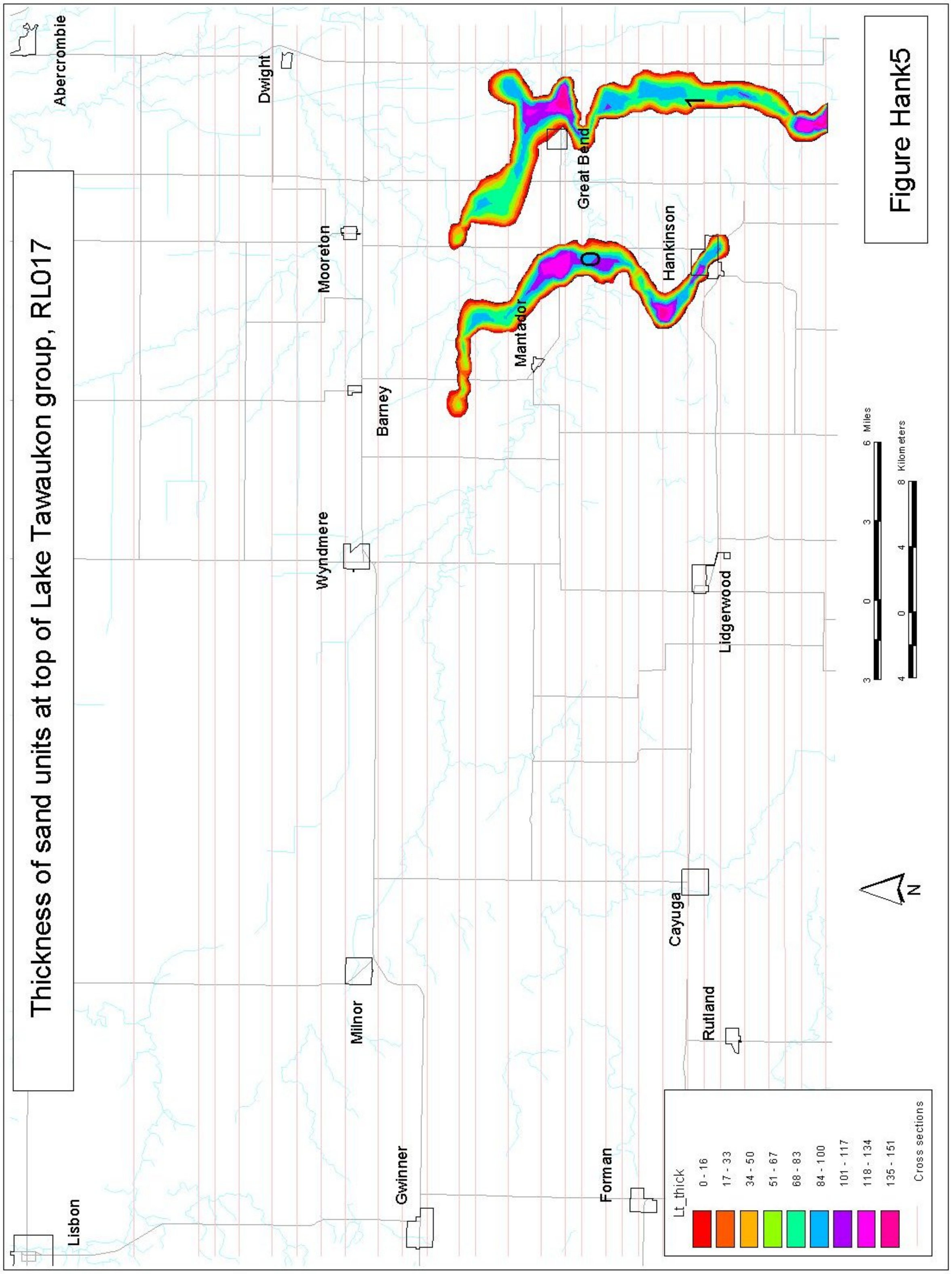


Figure 78 – Thickness in feet to top of sand units at top of Lake Tewaukon Group in the Hankinson detail area, regional model layer 17

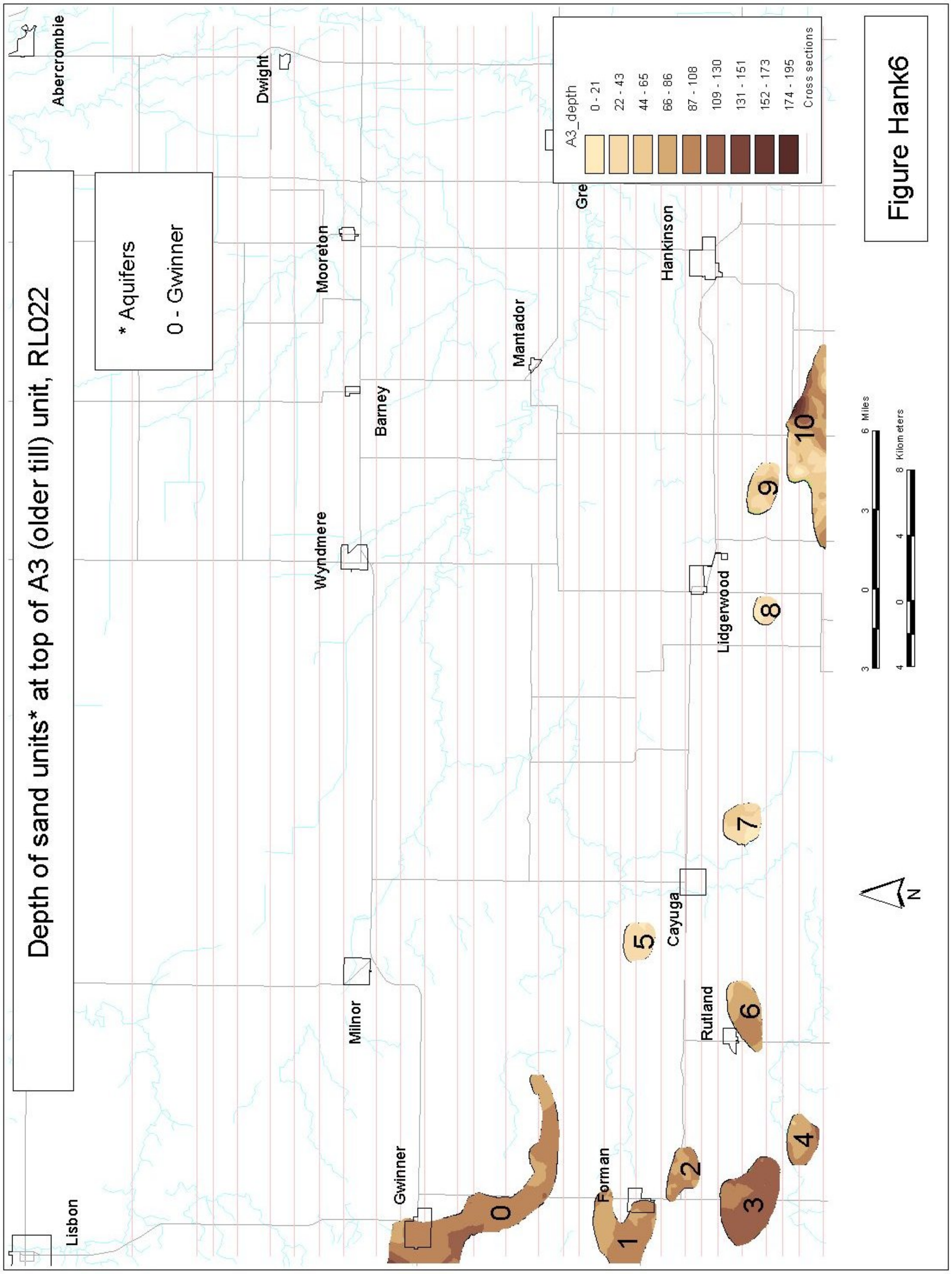


Figure 79 – Depth in feet to top of sand units at top of A3 (older till) unit in the Hankinson detail area, regional model layer 22

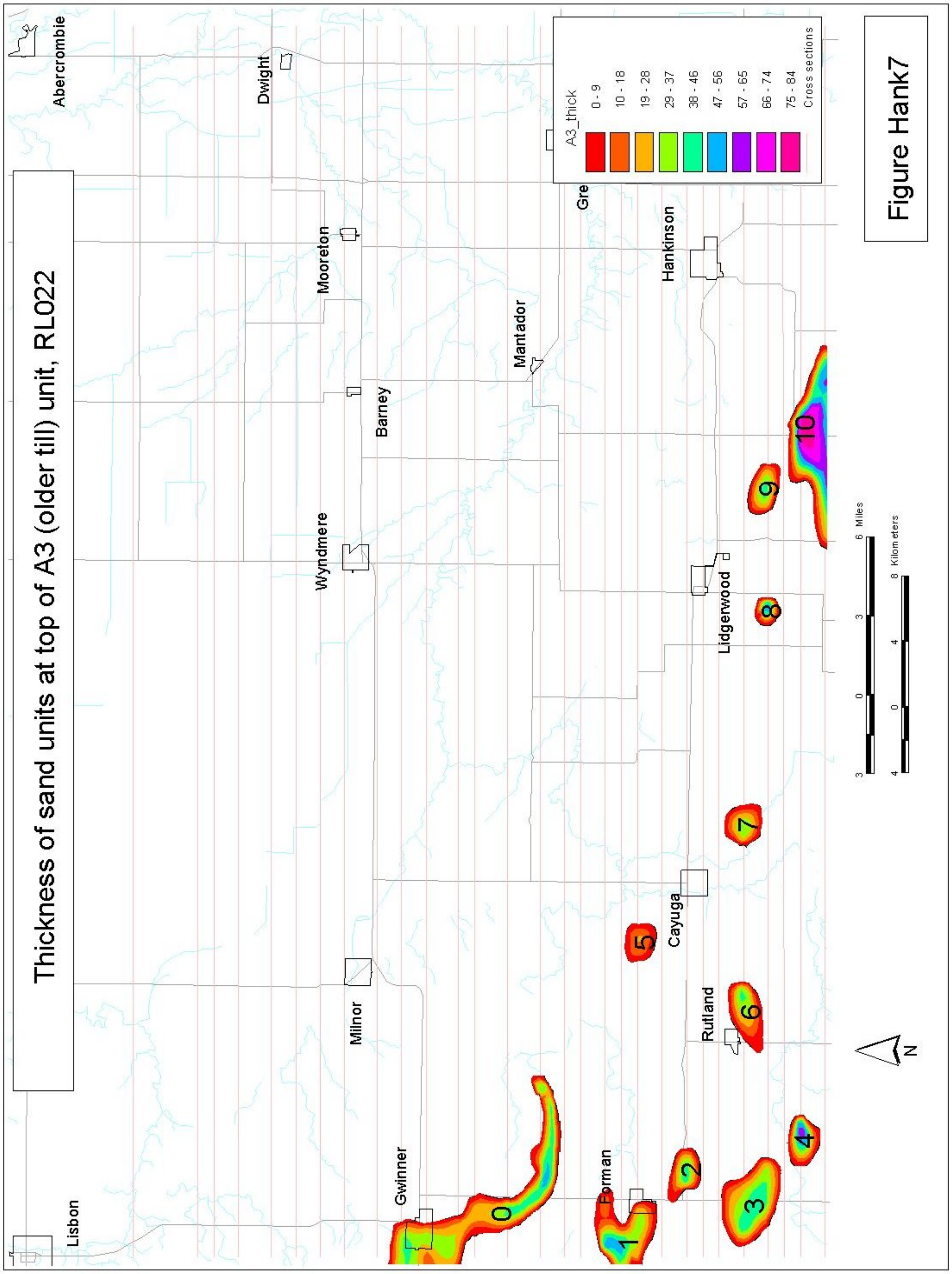


Figure 80 – Thickness in feet to top of sand units at top of A3 (older till) unit in the Hankinson detail area, regional model layer 22

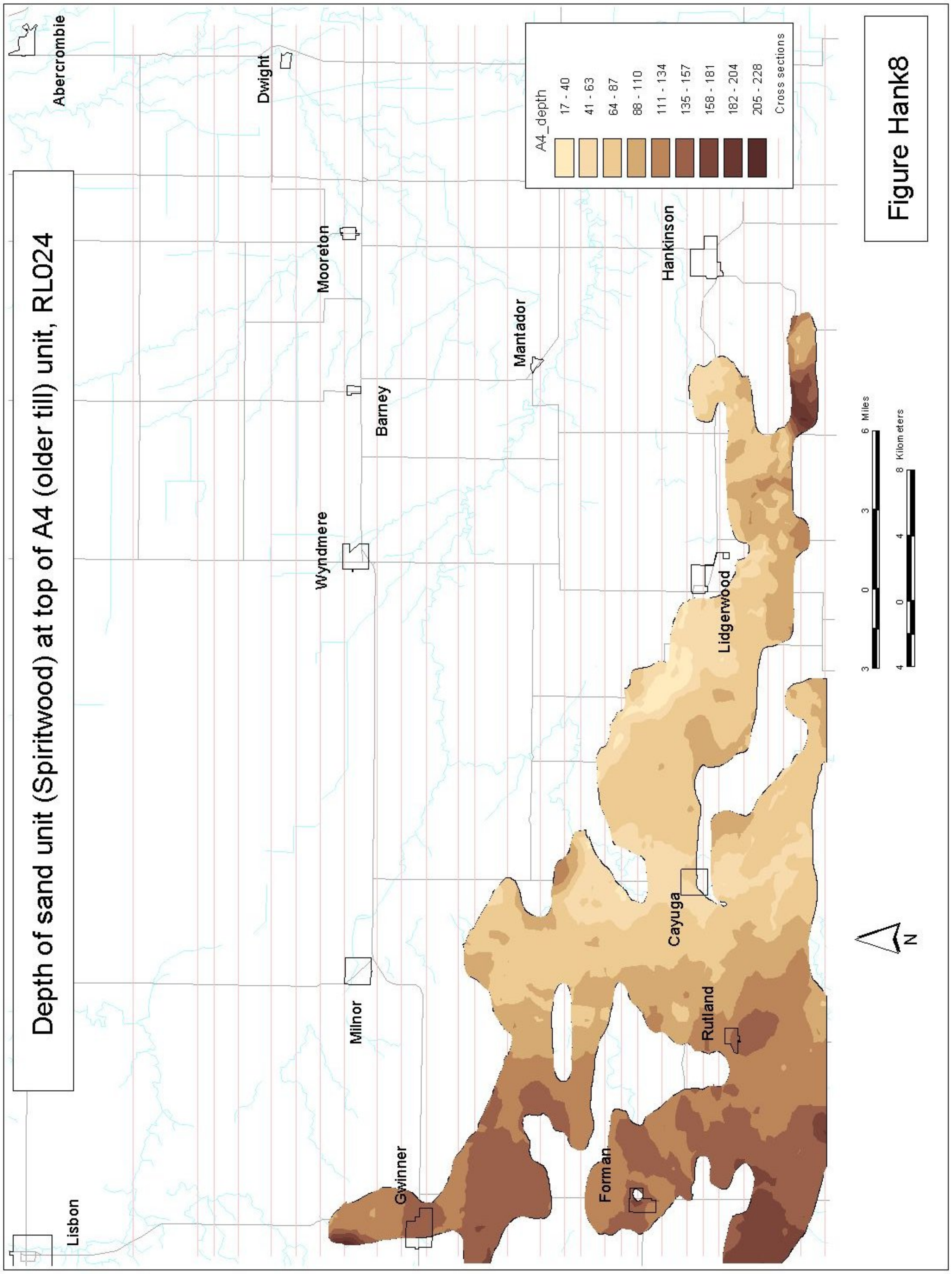


Figure 81 – Depth in feet to top of sand unit (Spiritwood) at top of A4 (older till) unit in the Hankinson detail area, regional model layer 24

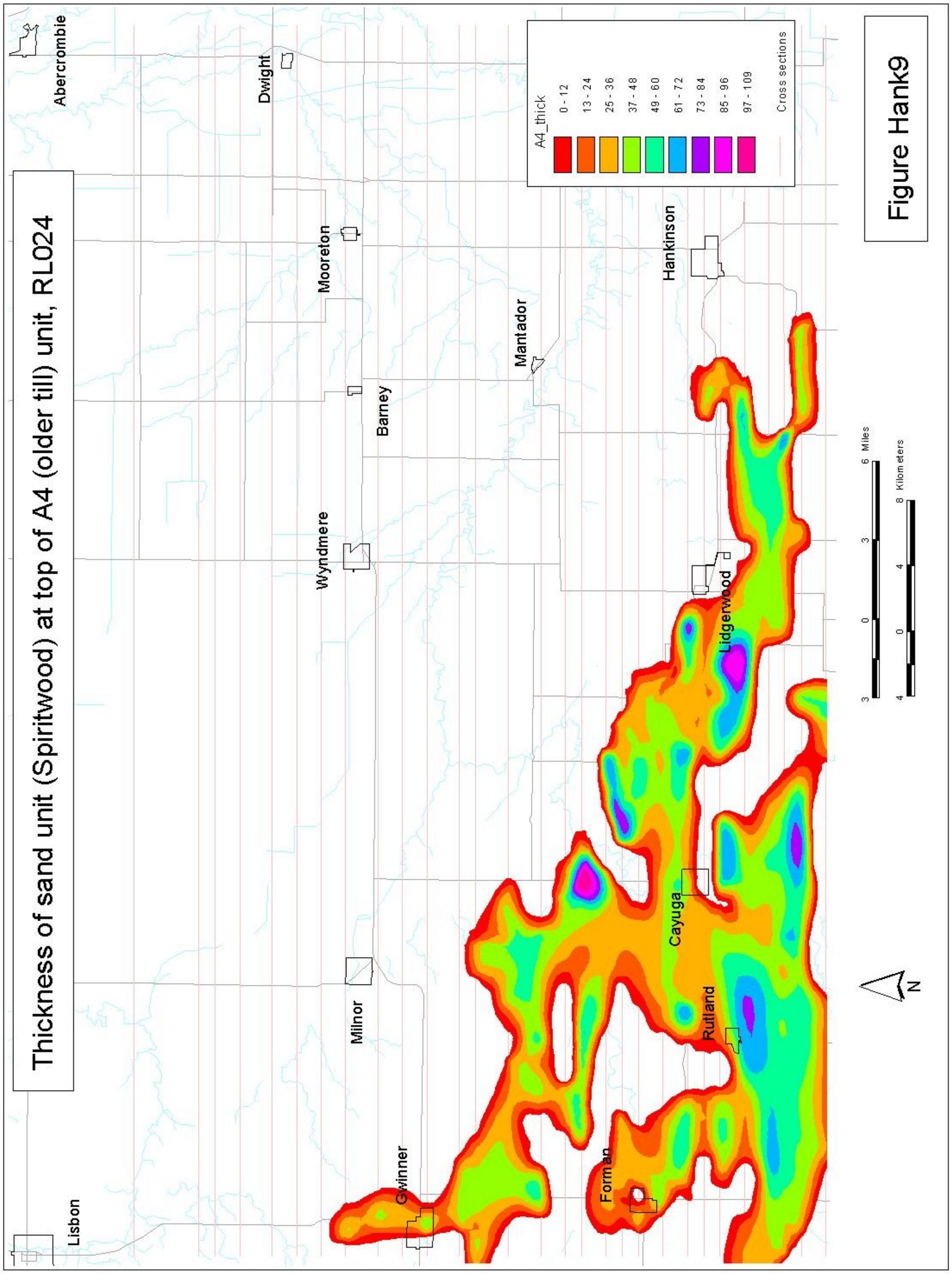


Figure 82 – Thickness in feet to top of sand unit (Spiritwood) at top of A4 (older till) unit in the Hankinson detail area, regional model layer 24

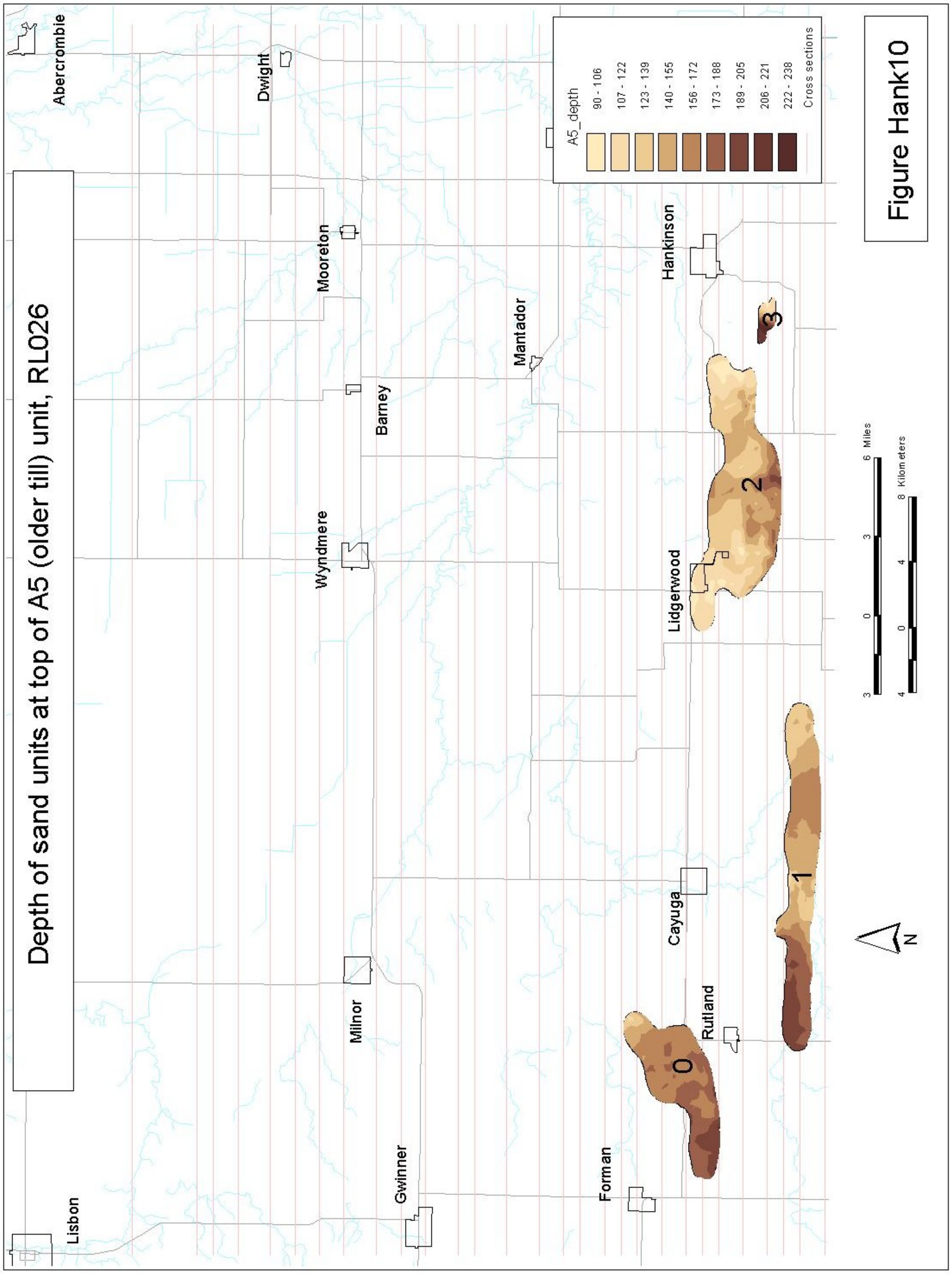


Figure 83 – Depth in feet to top of sand units at top of A5 (older till) unit in the Hankinson detail area, regional model layer 26

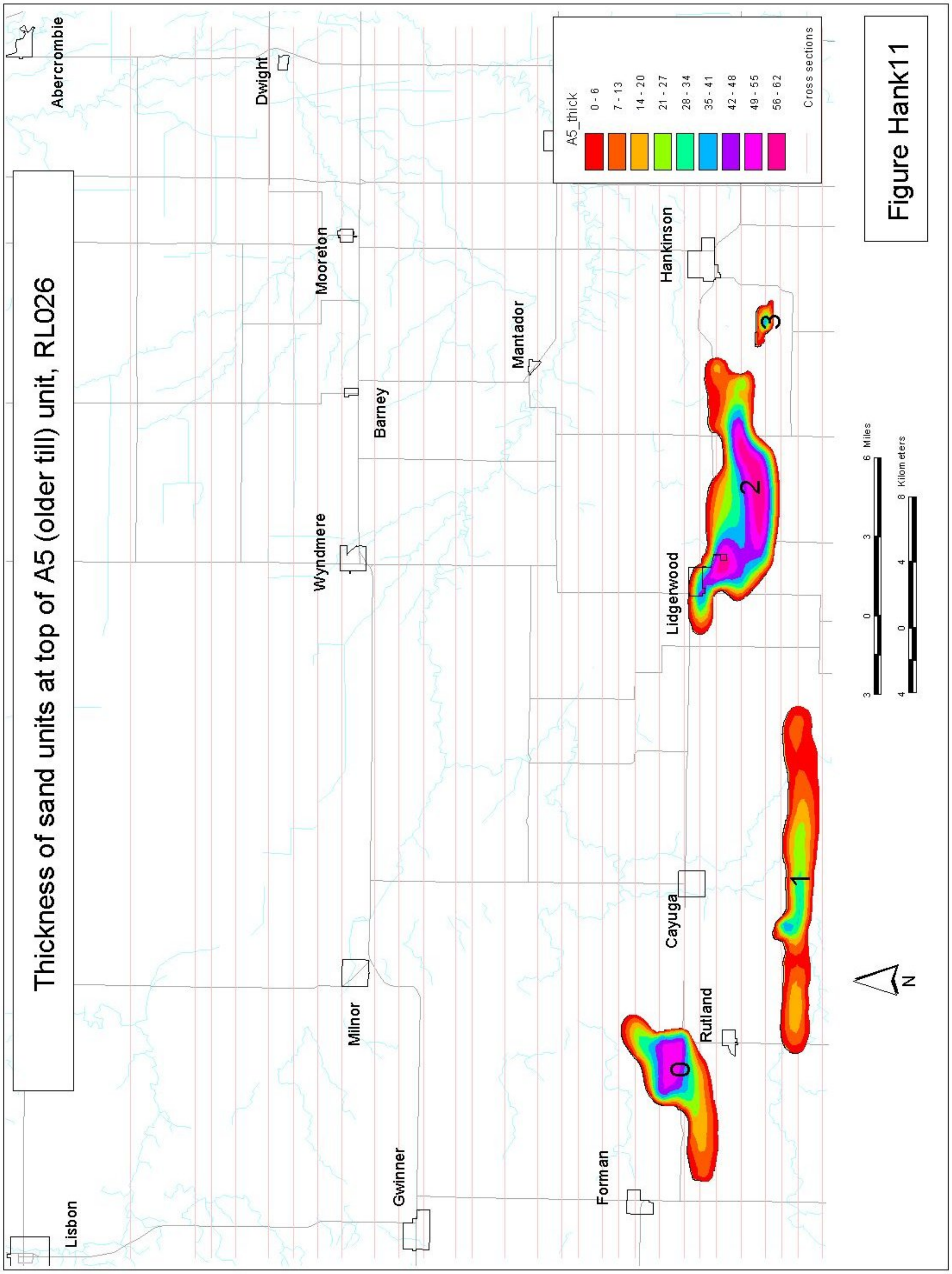


Figure 84 – Thickness in feet to top of sand units at top of A5 (older till) unit in the Hankinson detail area, regional model layer 26

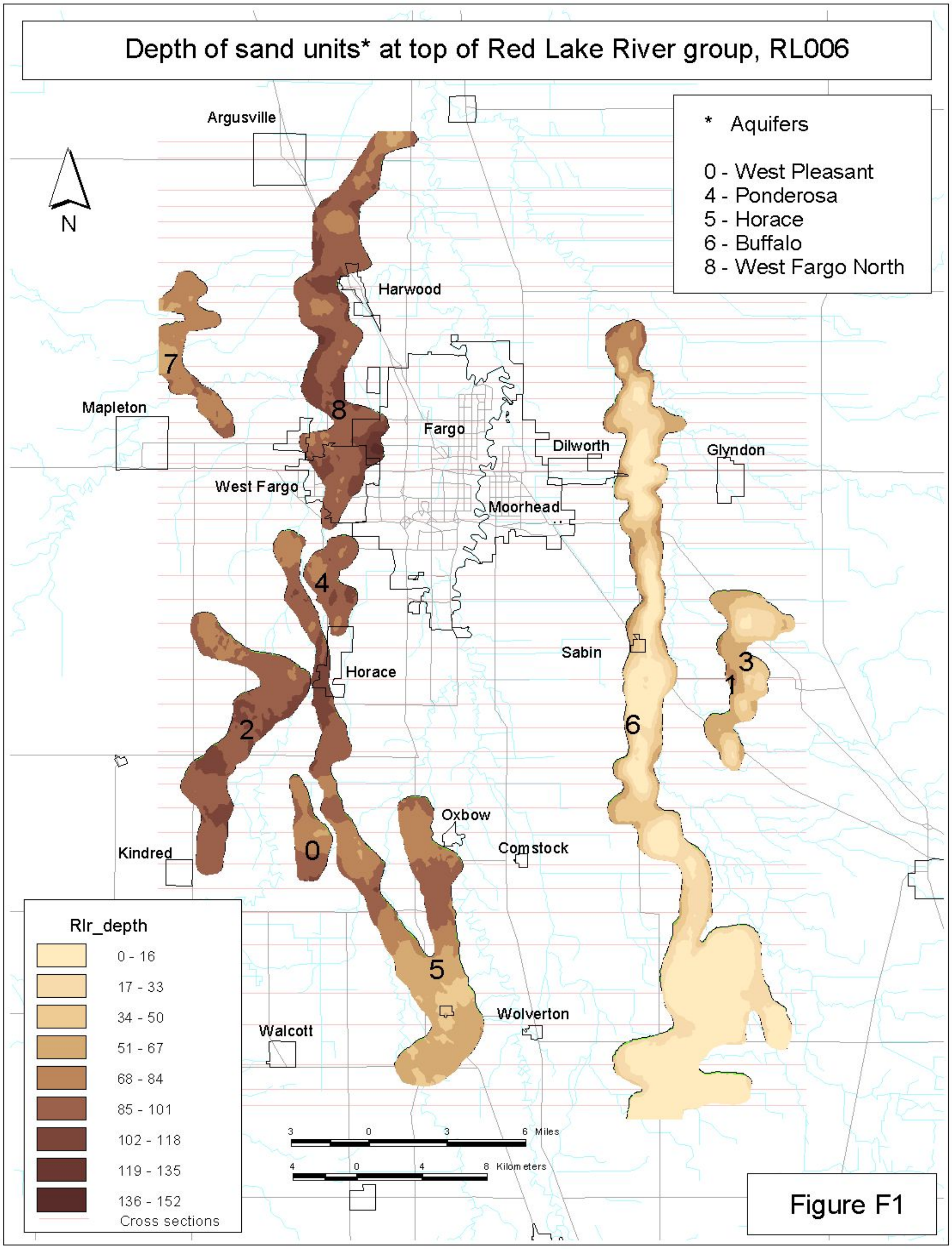


Figure 85 – Depth in feet to top of sand units at base of Red Lake River Group in the Fargo detail area, regional model layer 6

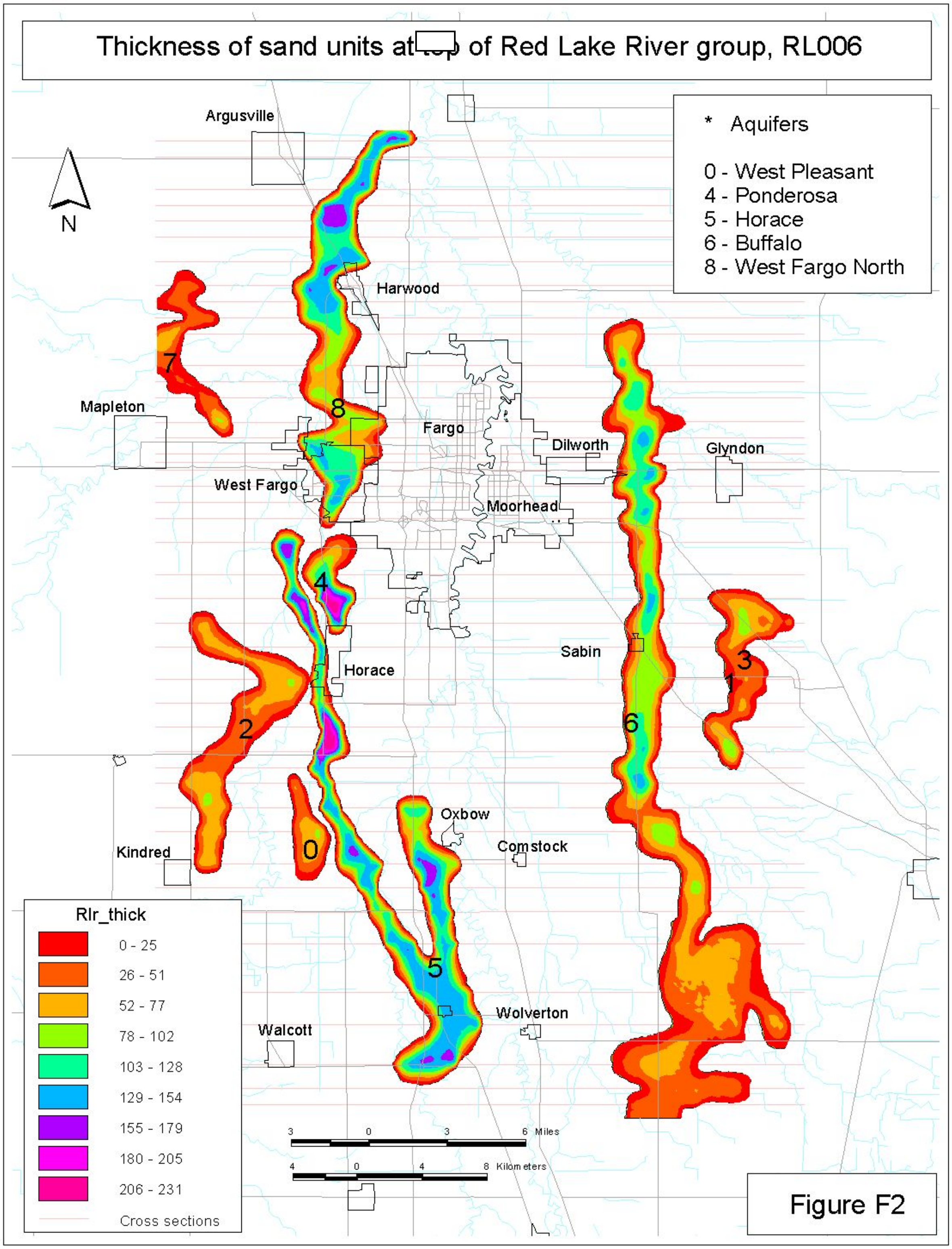


Figure 86 – Thickness in feet to top of sand units at base of Red Lake River Group in the Fargo detail area, regional model layer 6

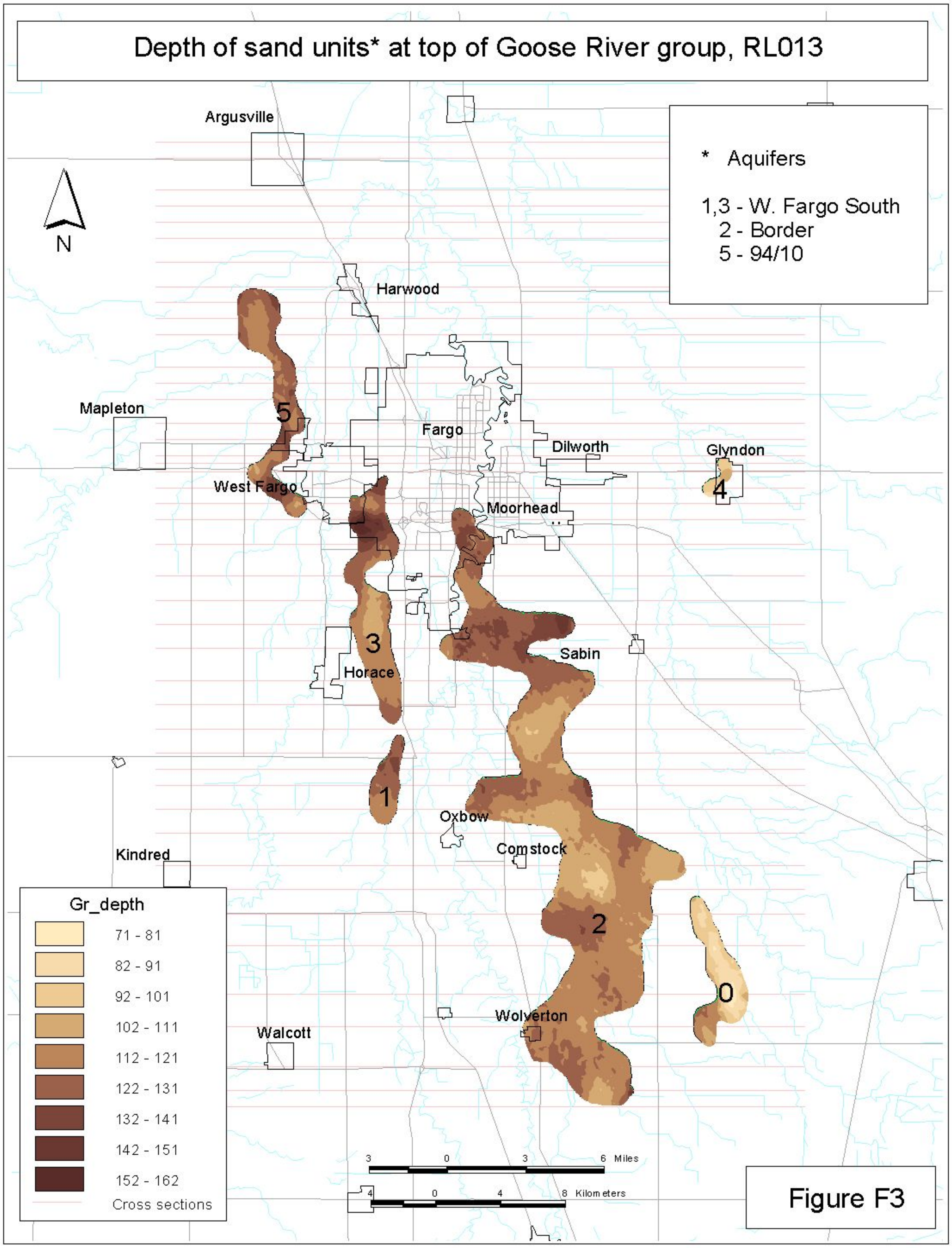


Figure 87 – Depth in feet to top of sand units at top of Goose River Group in the Fargo detail area, regional model layer 13

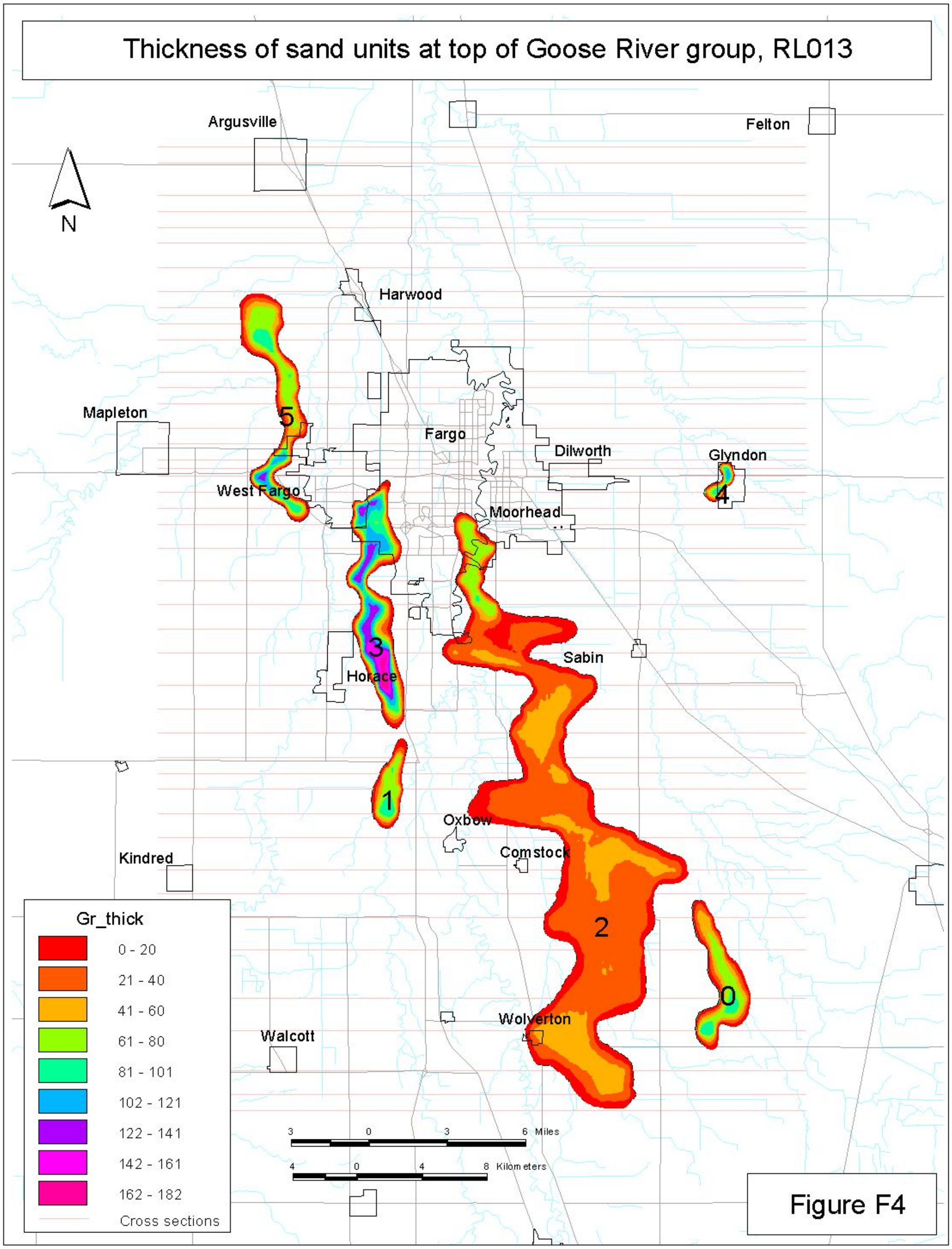


Figure 88 – Thickness in feet to top of sand units at top of Goose River Group in the Fargo detail area, regional model layer 13

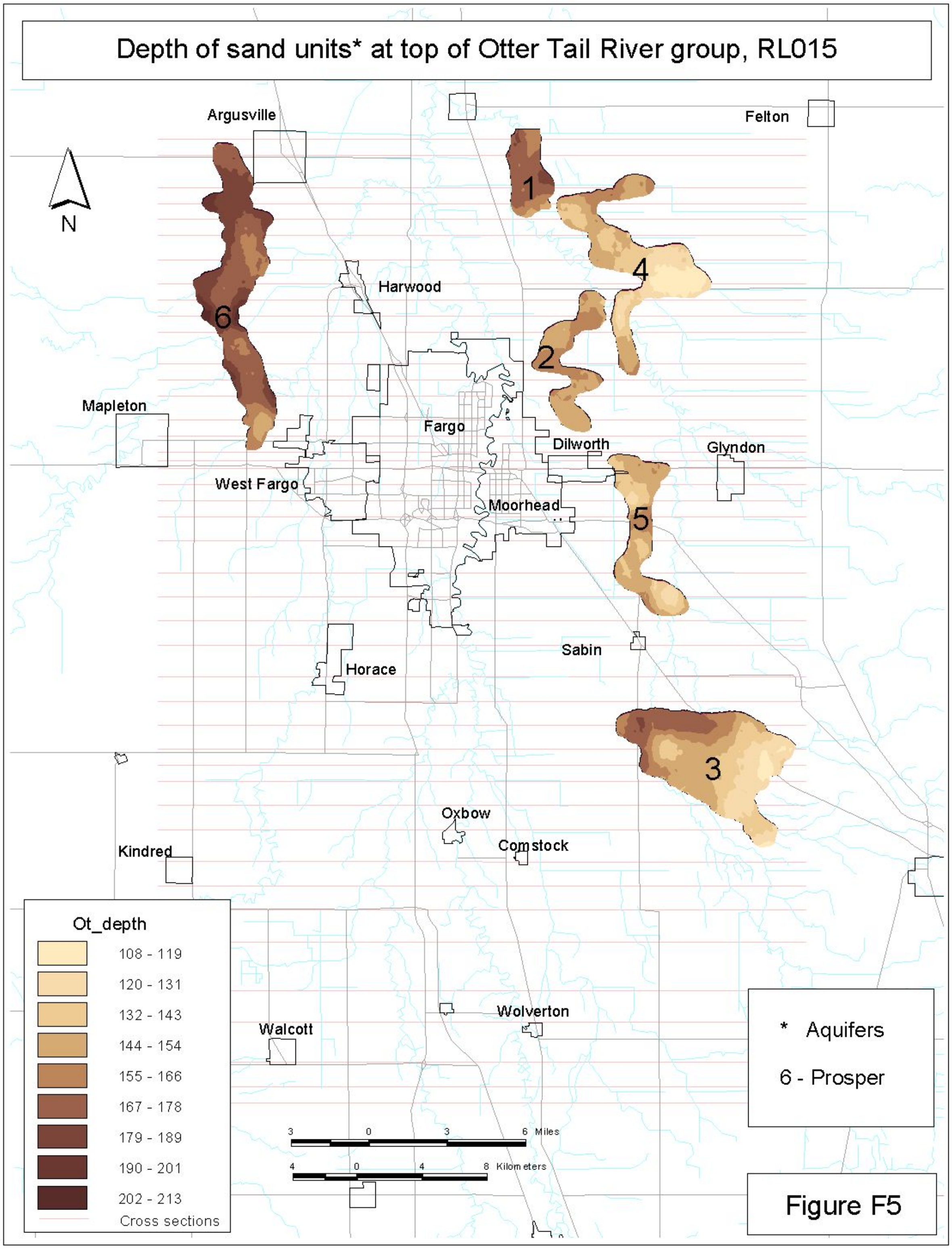


Figure 89 – Depth in feet to top of sand units at top of Otter Tail Group in the Fargo detail area, regional model layer 15

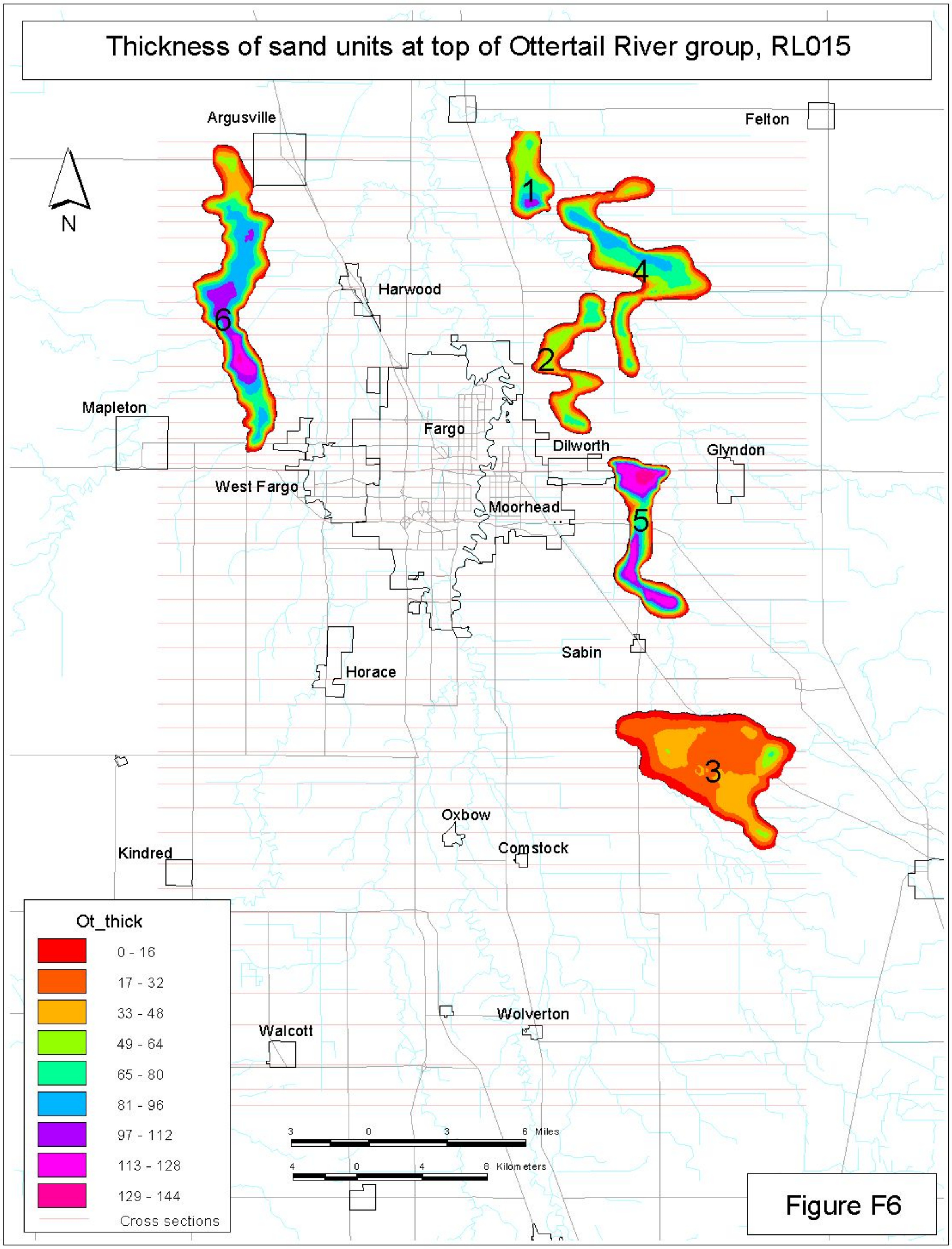


Figure 90 – Thickness in feet to top of sand units at top of Otter Tail Group in the Fargo detail area, regional model layer 15

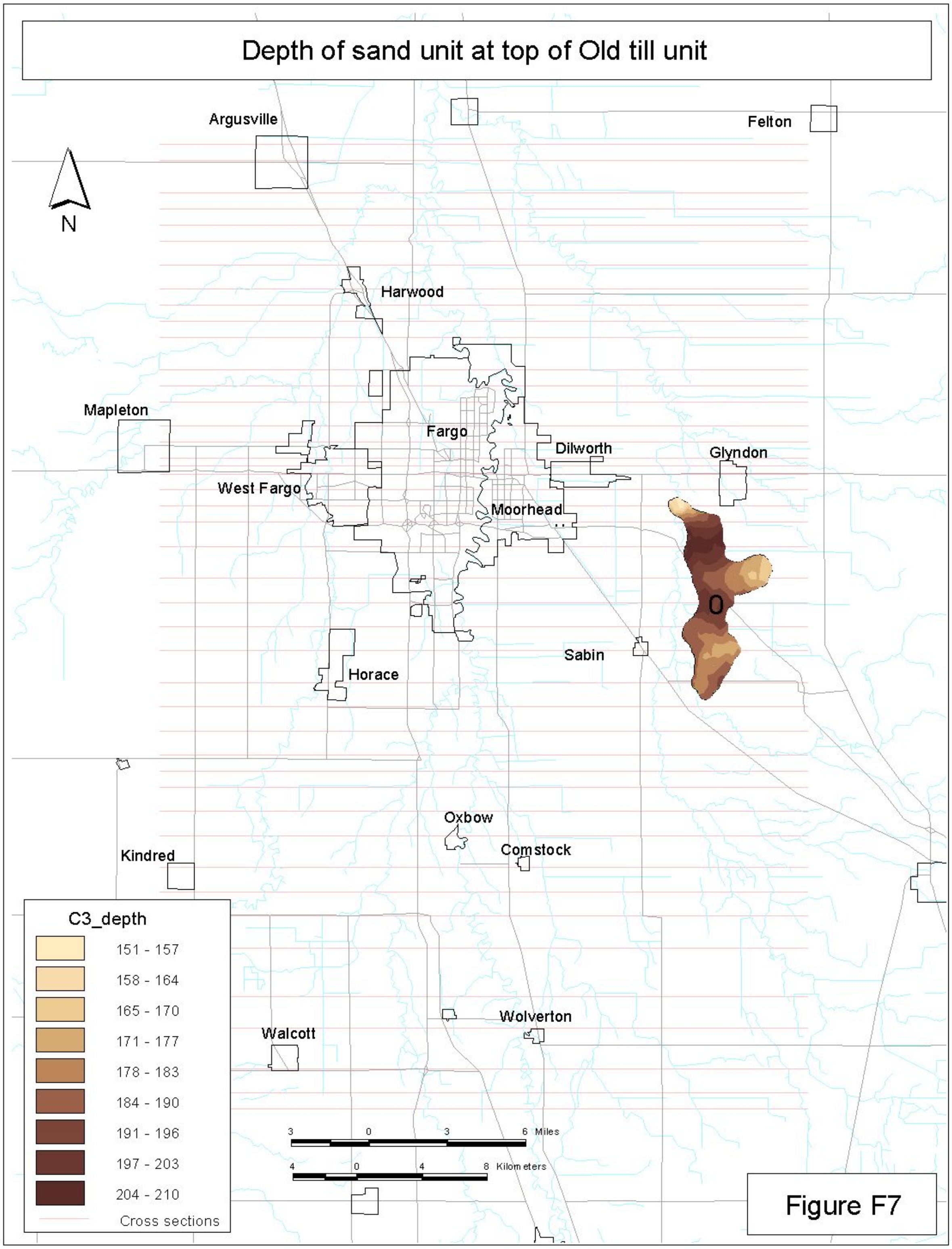


Figure 91 – Depth in feet to top of sand unit at top of old till unit in the Fargo detail area, regional model layer 22

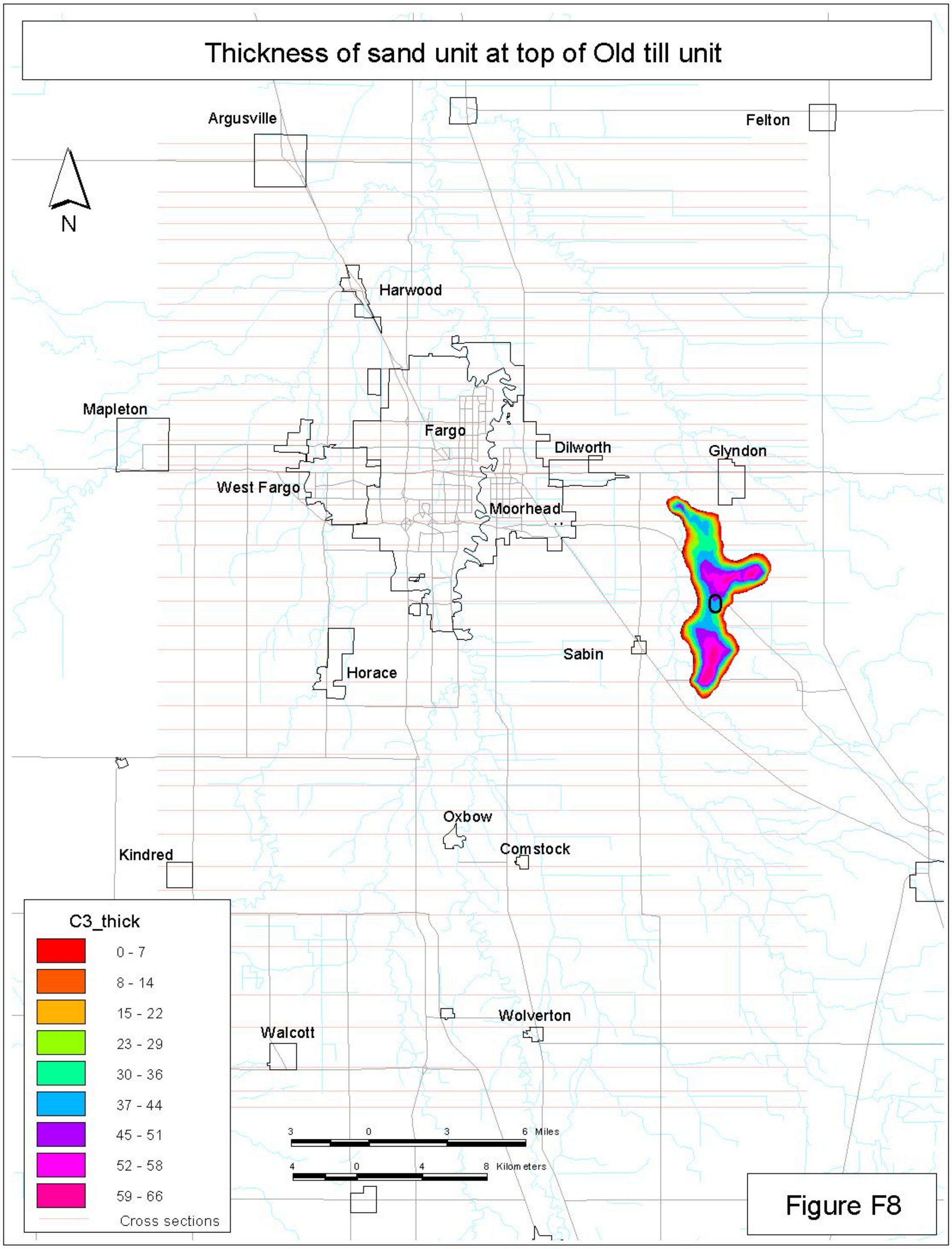


Figure 92 – Thickness in feet to top of sand unit at top of old till unit in the Fargo detail area, regional model layer 22

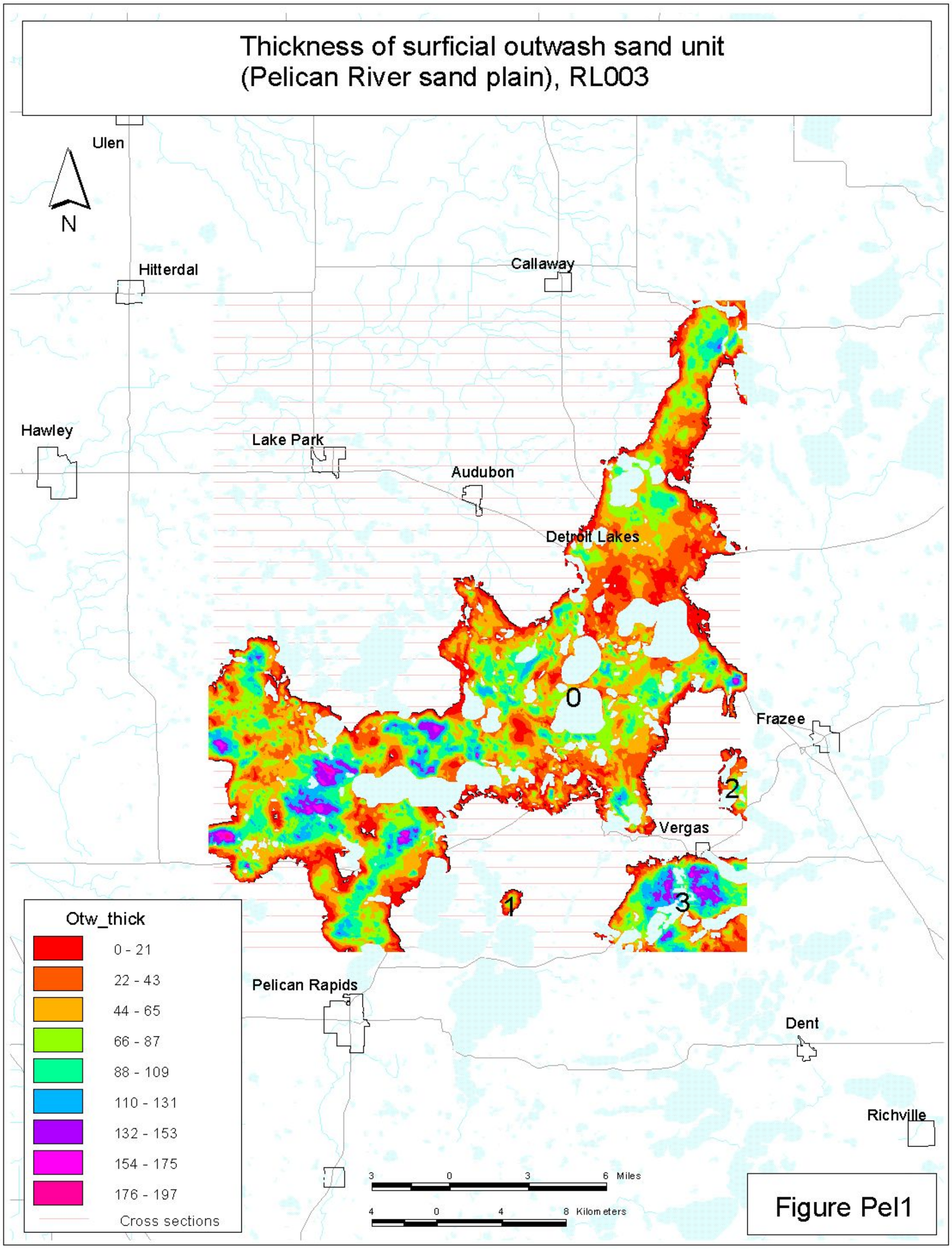


Figure 93 – Thickness in feet to top of surficial outwash sand unit (Pelican River sand plain) in the Pelican detail area, regional model layer 3

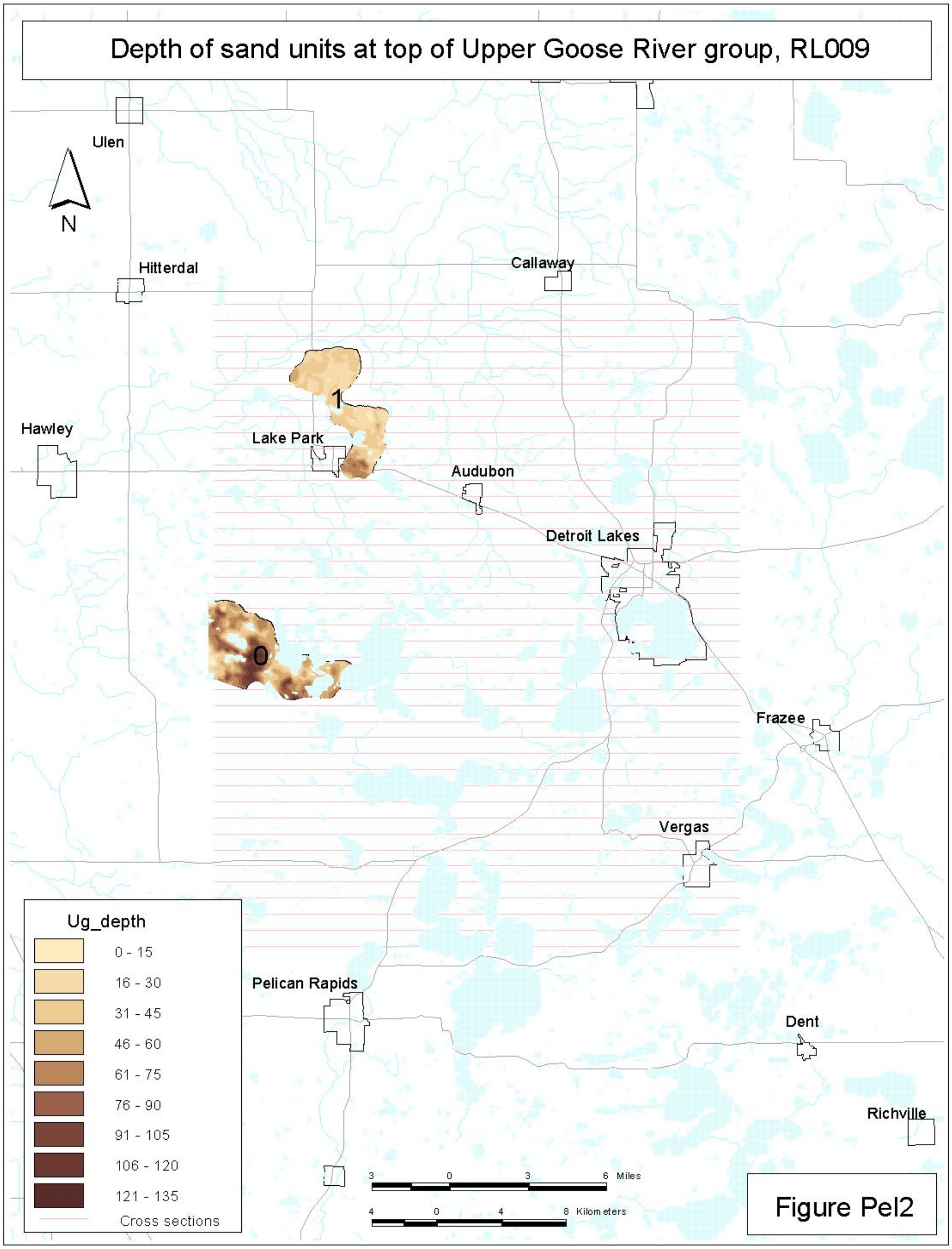


Figure 94 – Depth in feet to top of sand units at top of Upper Goose River group in the Pelican detail area, regional model layer 9

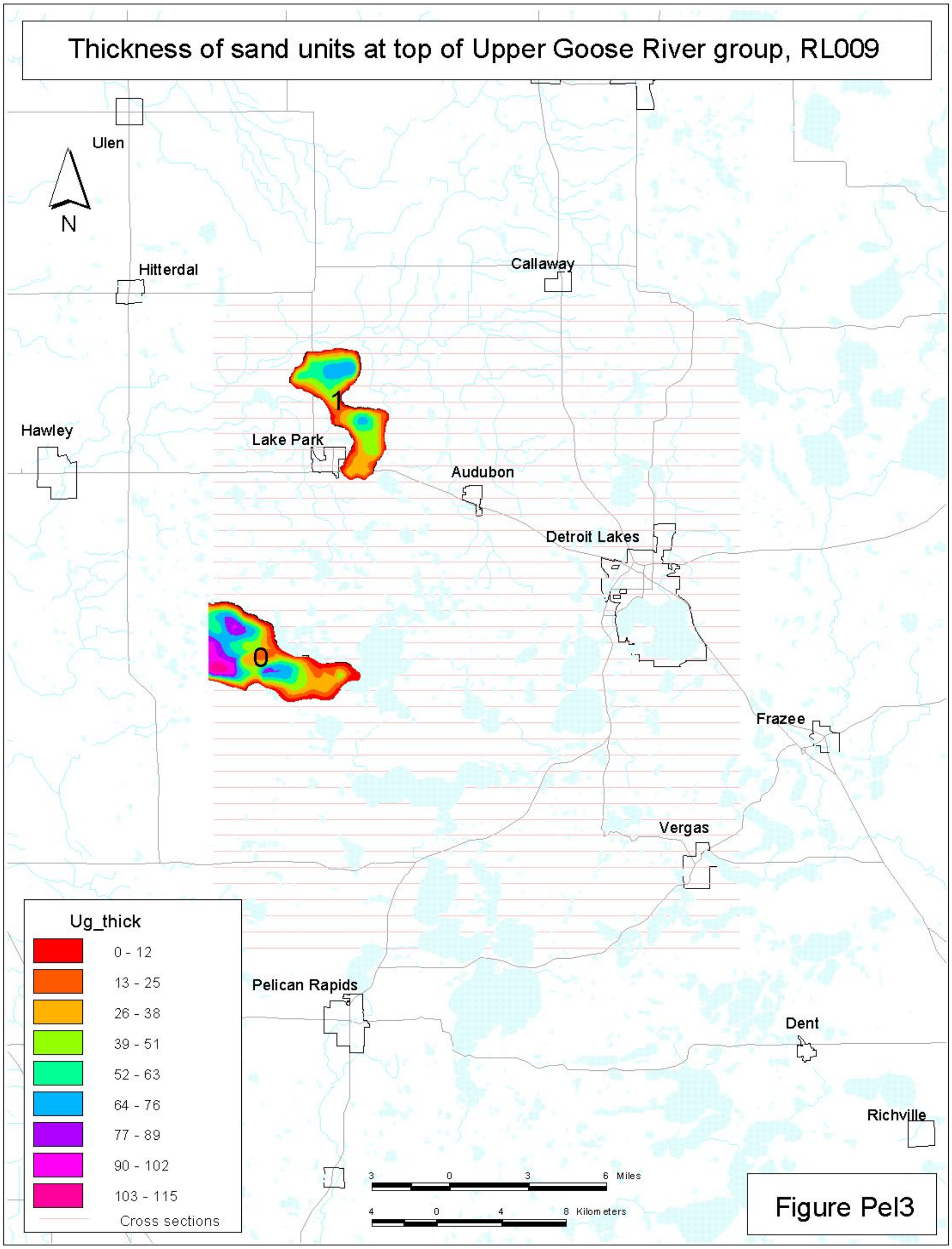


Figure 95 – Thickness in feet to top of sand units at top of Upper Goose River group in the Pelican detail area, regional model layer 9

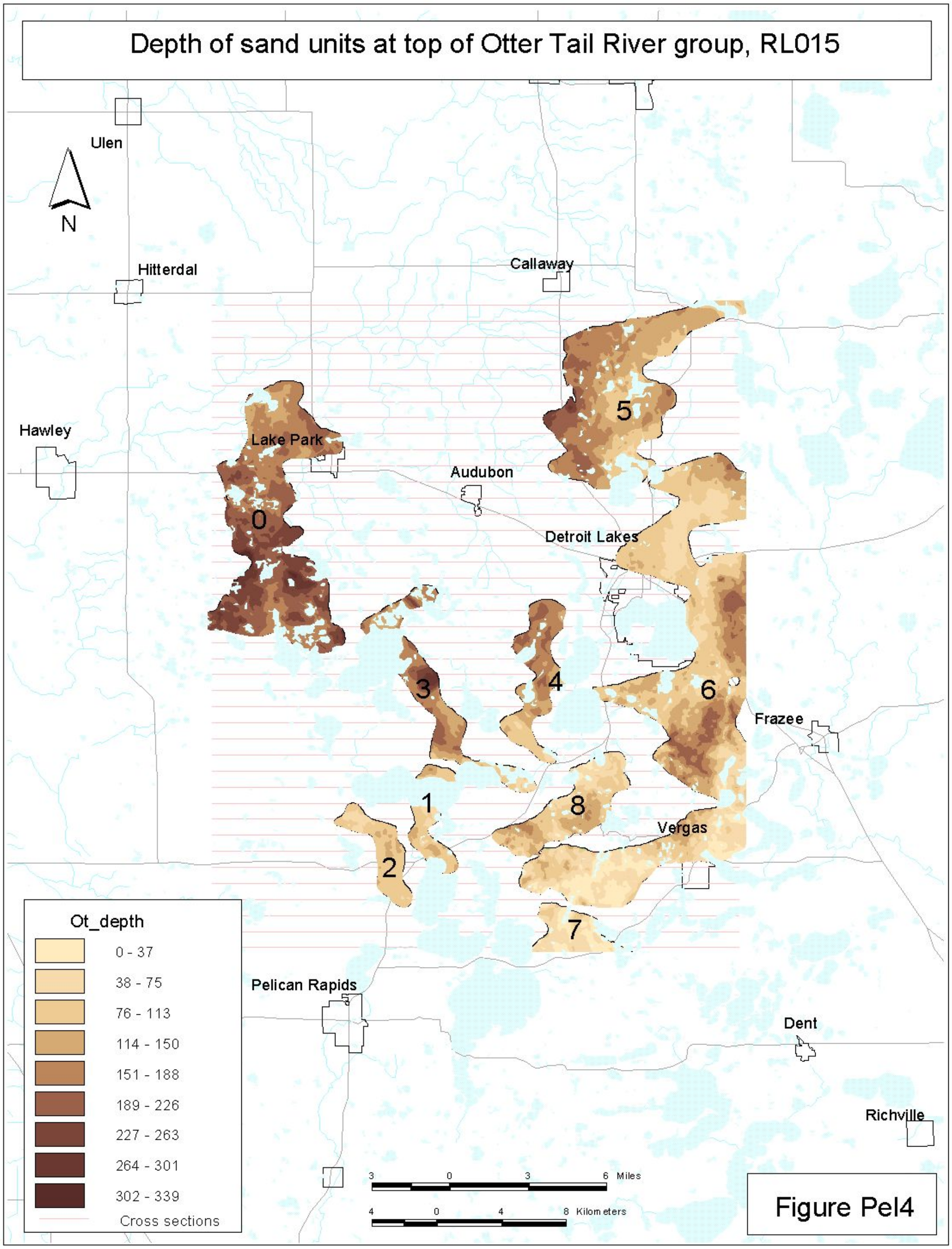


Figure 96 – Depth in feet to top of sand units at top of Otter Tail River group in the Pelican detail area, regional model layer 15

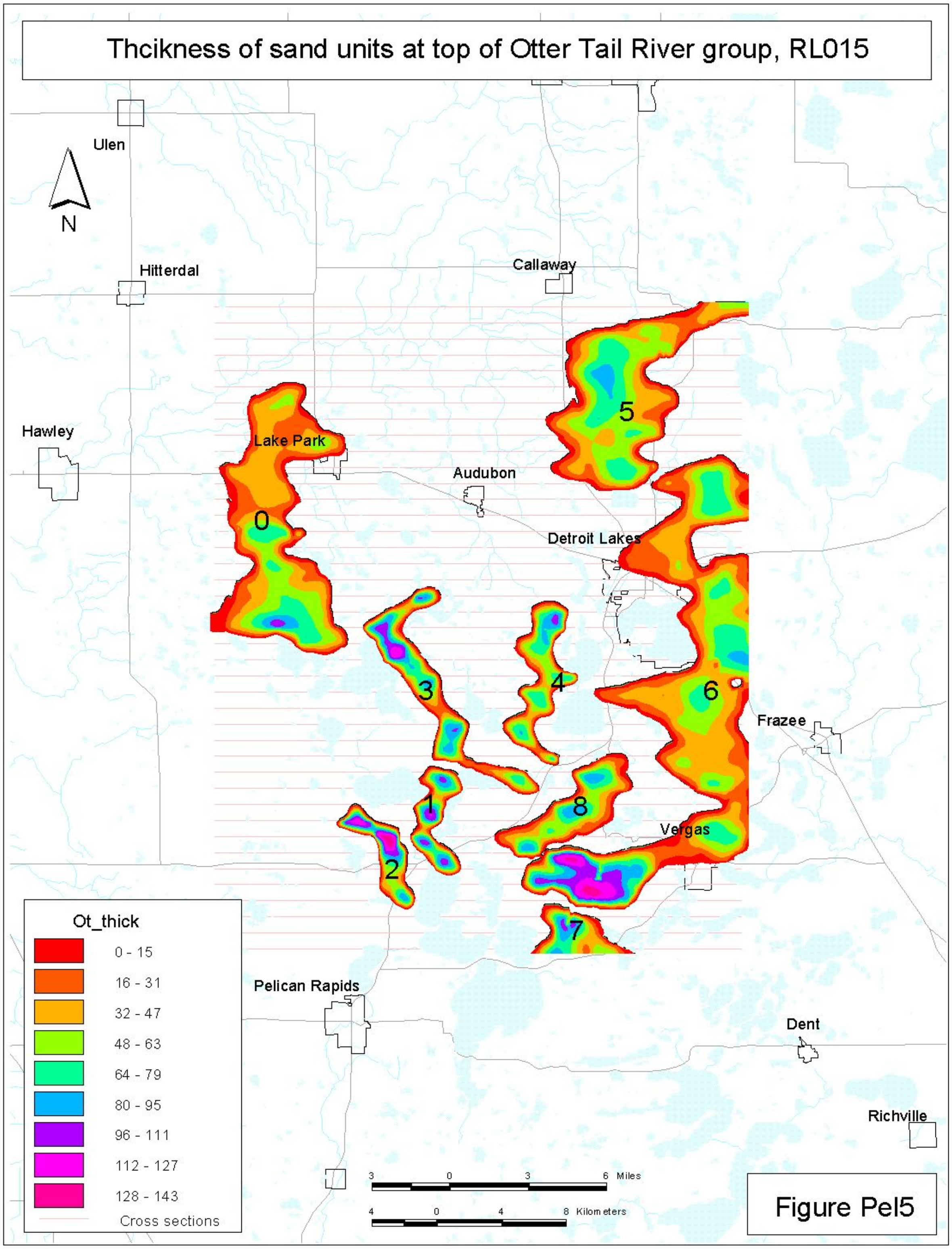


Figure 97 – Thickness in feet to top of sand units at top of Otter Tail River group in the Pelican detail area, regional model layer 15

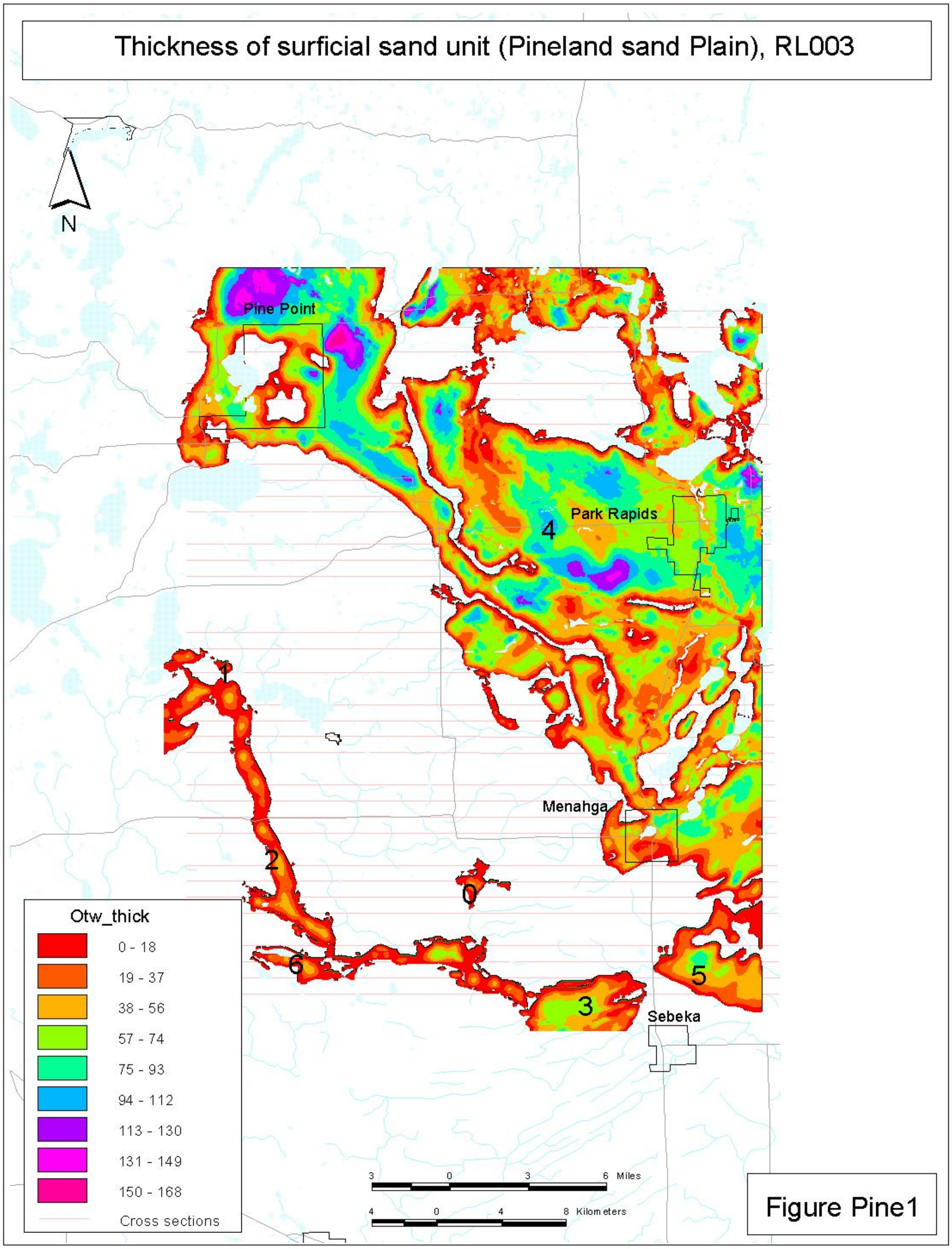


Figure 98 – Thickness in feet to top of surficial outwash sand unit (Pineland sand plain) in the Pineland detail area, regional model layer 3

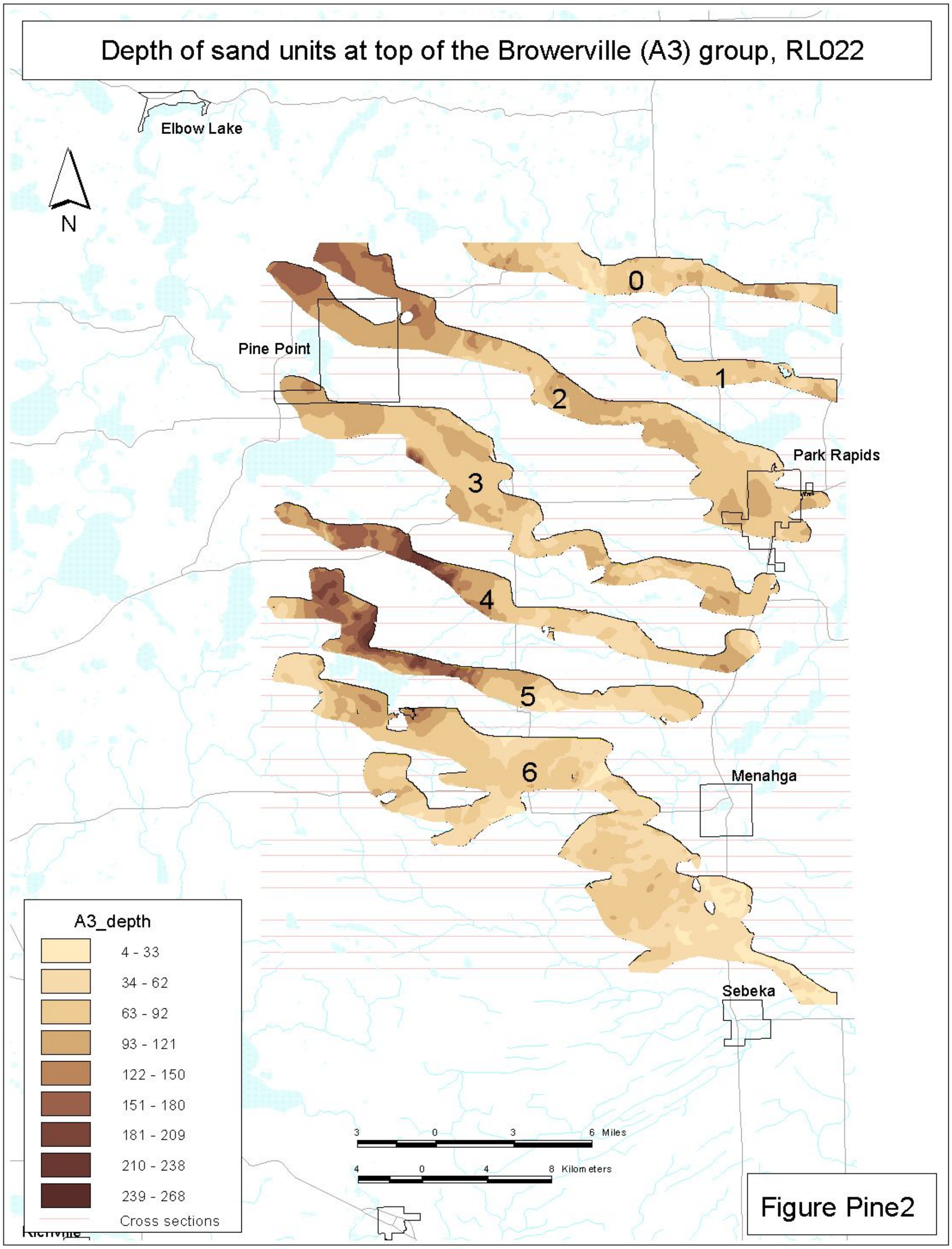


Figure 99 – Depth in feet to top of sand units at top of the Browerville (A3) group in the Pineland detail area, regional model layer 22

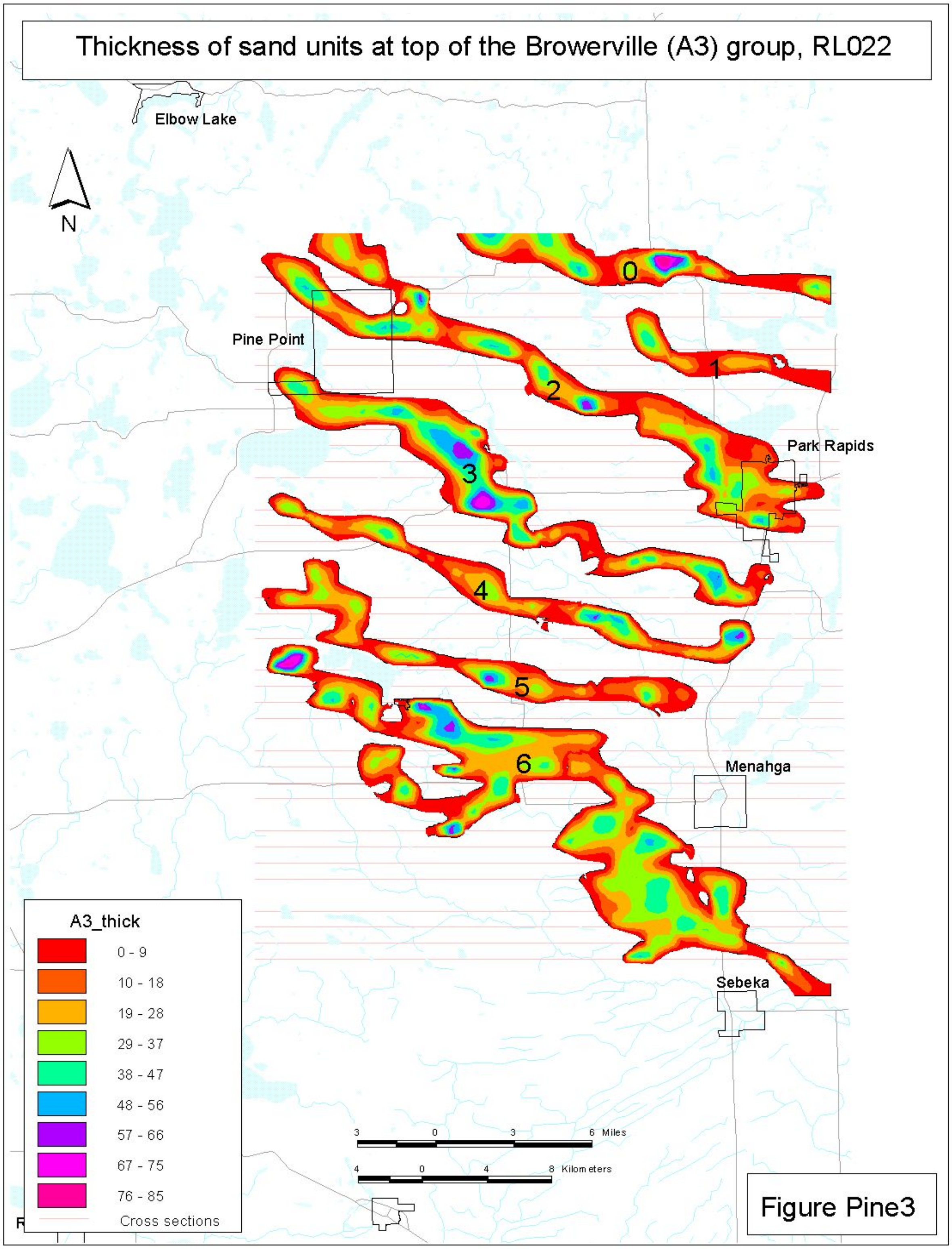


Figure 100 – Thickness in feet to top of sand units at top of the Browerville (A3) group in the Pineland detail area, regional model layer 22

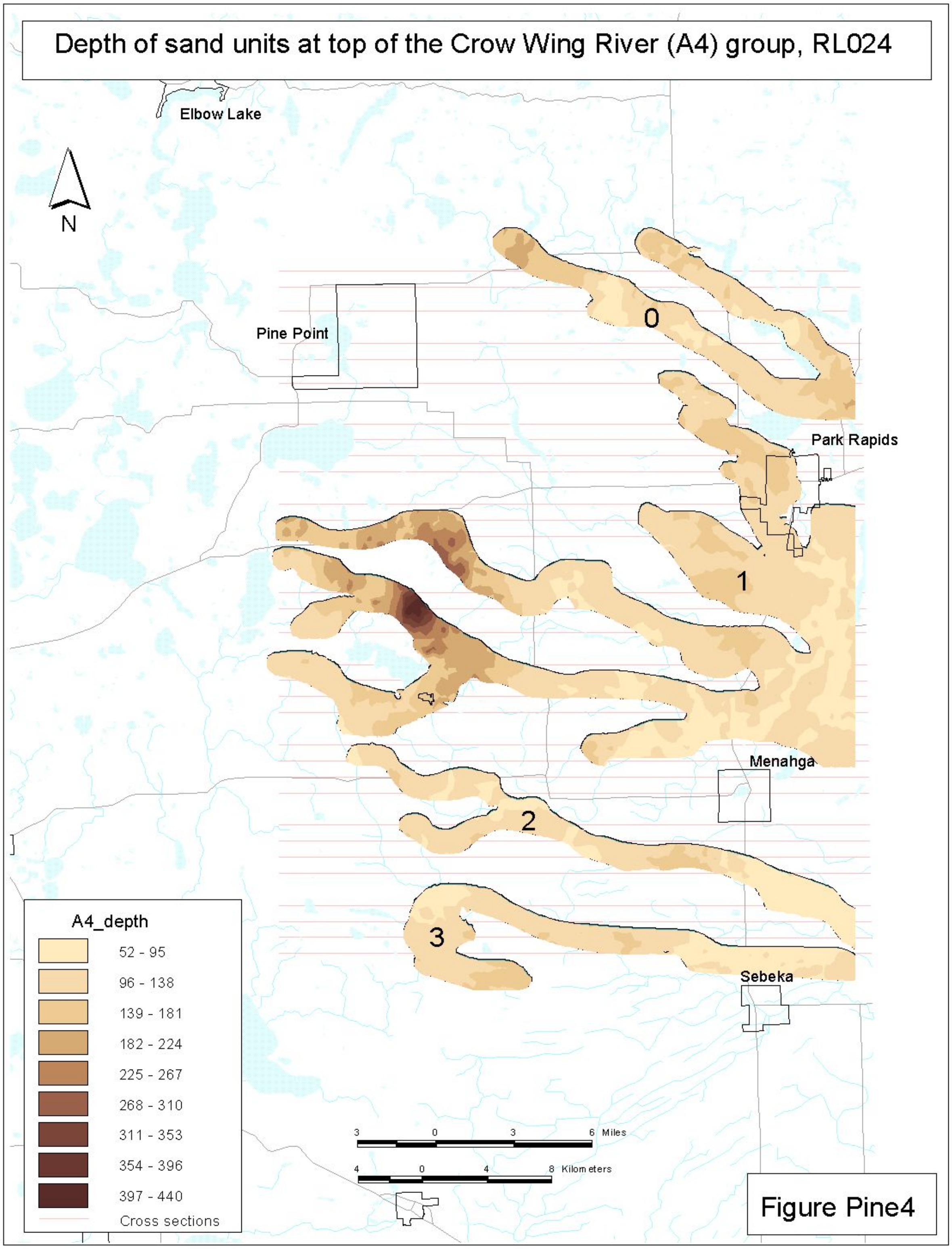


Figure 101 – Depth in feet to top of sand units at top of the Crow Wing (A4) group in the Pineland detail area, regional model layer 24

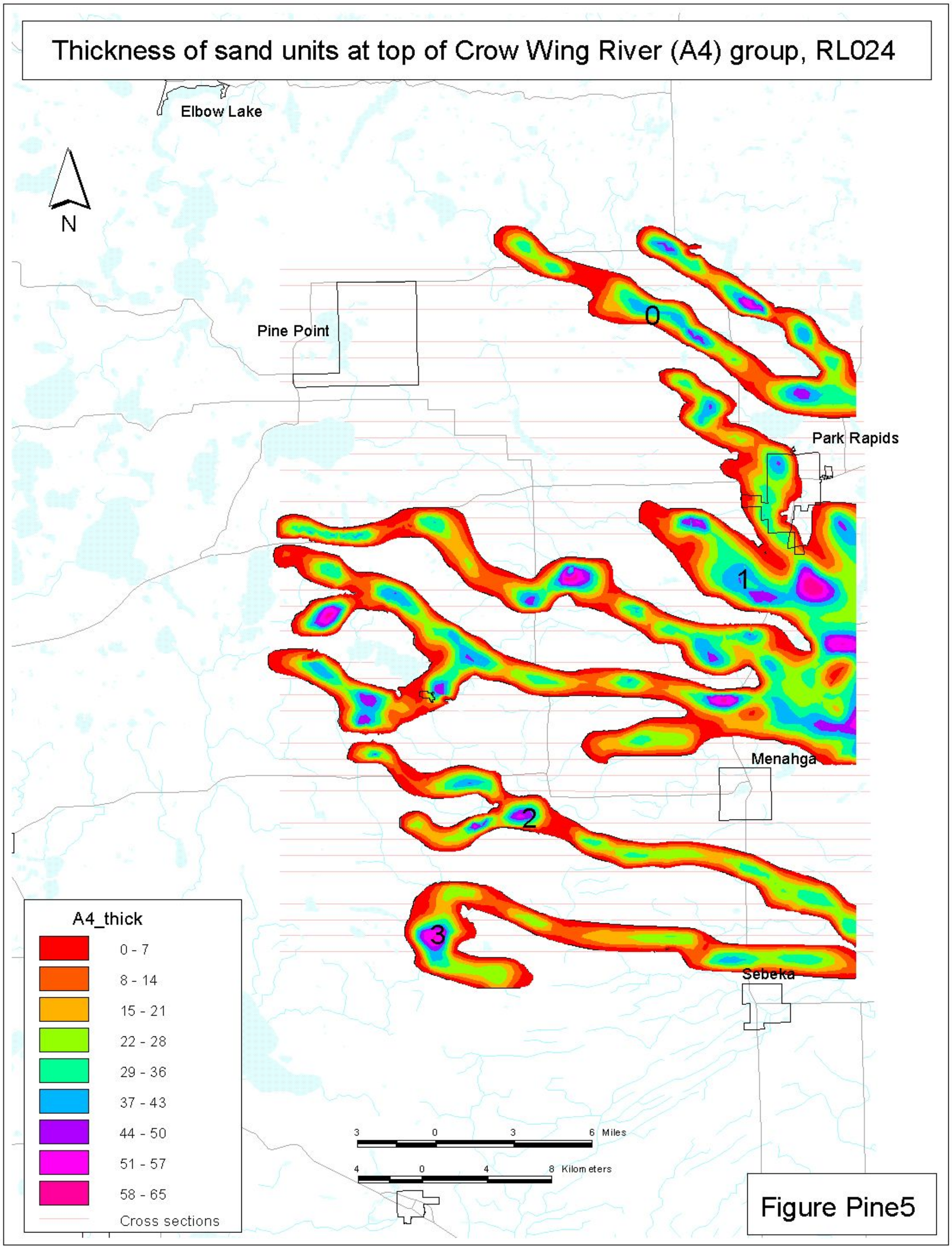


Figure 102 – Thickness of sand units at top of the Crow Wing (A4) group in the Pineland detail area, regional model layer 24

Figure 103 – Previously named aquifers in the Red River Valley investigated by Reclamation (2005)

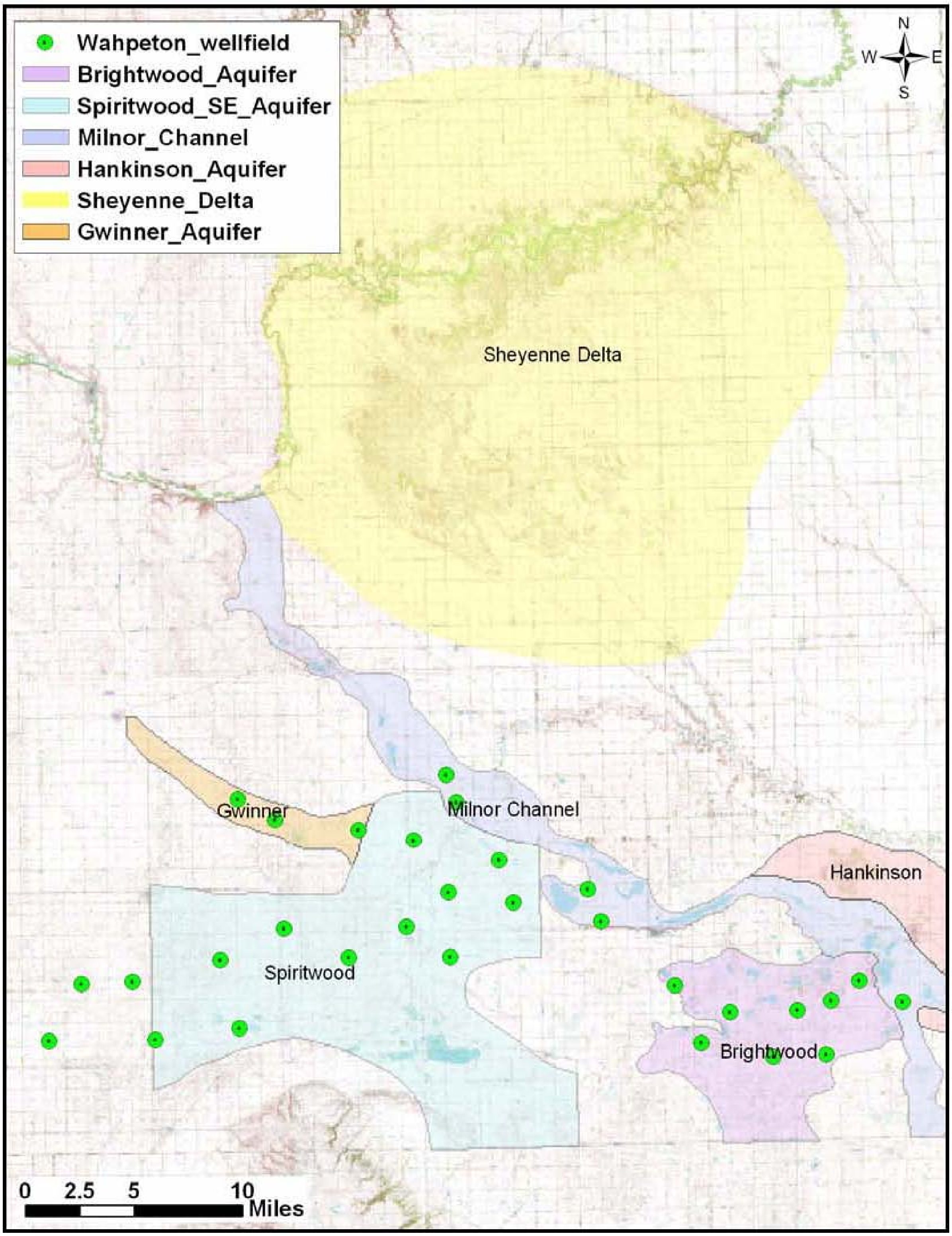


Figure 104 – Previously named aquifers in southeastern North Dakota, as summarized by Reclamation (2005)

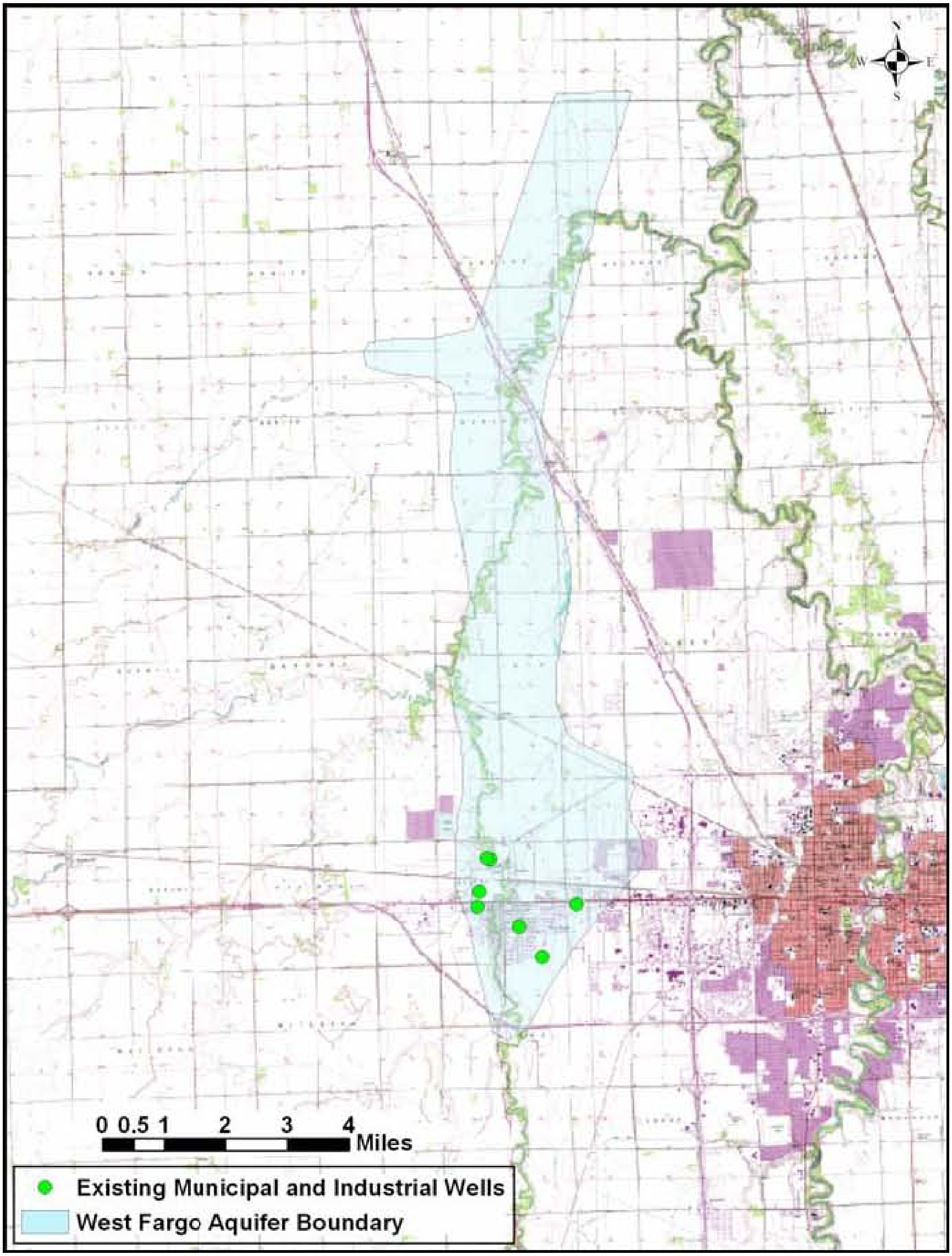


Figure 105 – Location of the West Fargo North Aquifer (Reclamation, 2005)

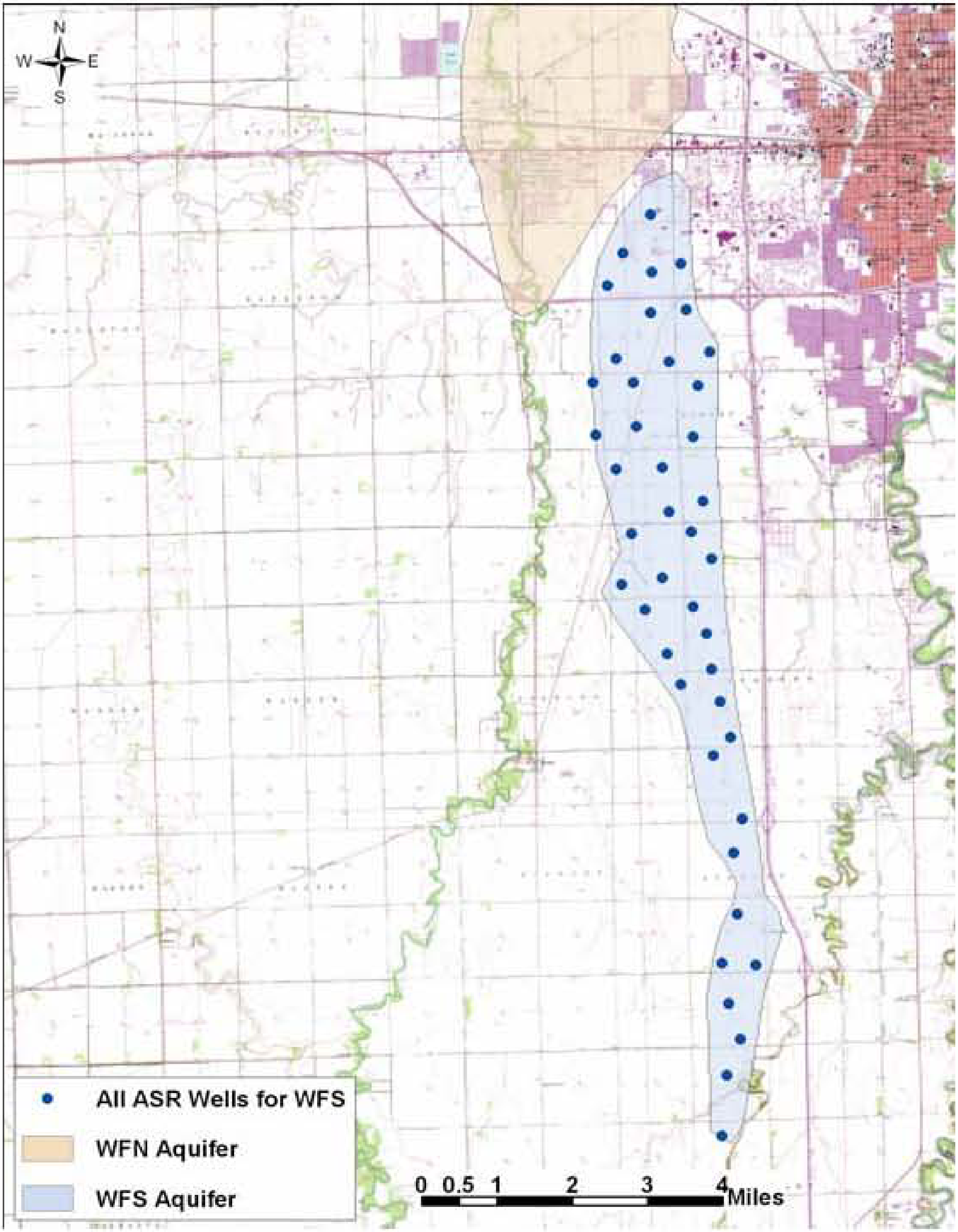


Figure 106 – Location of the West Fargo South Aquifer (Reclamation, 2005)

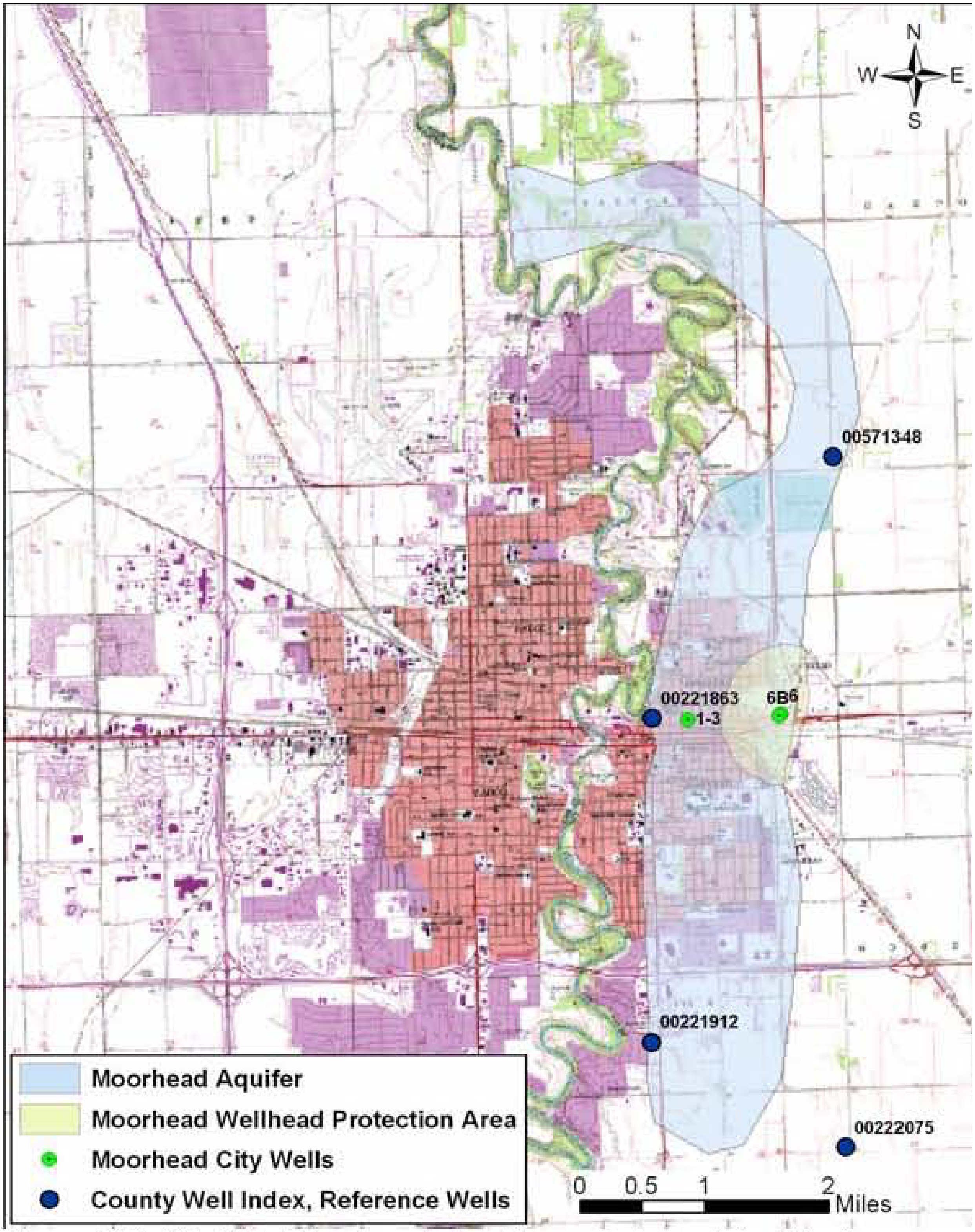


Figure 107 – Location of the Moorhead Aquifer (Reclamation, 2005)

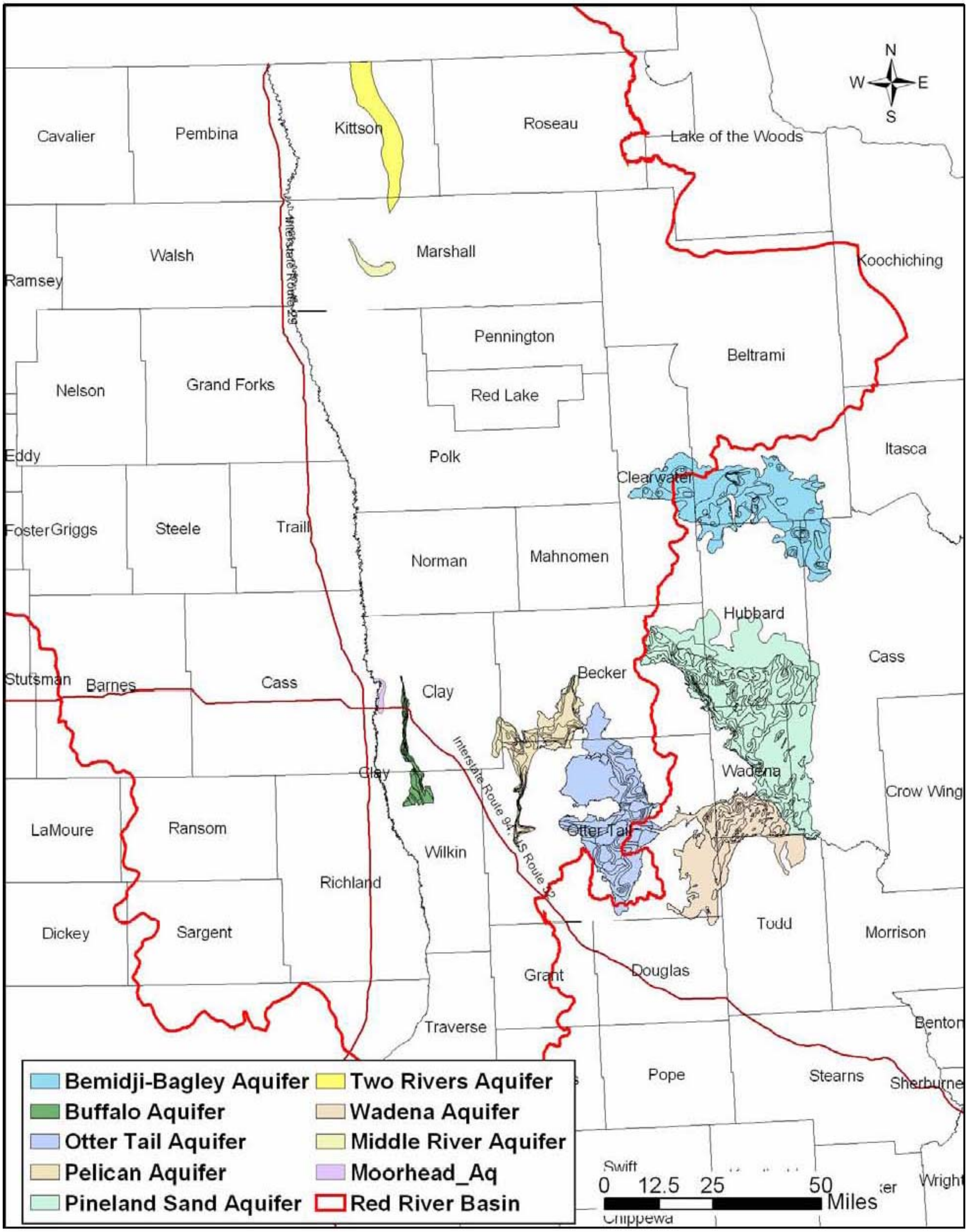


Figure 108 – Location of major Minnesota aquifers in the Red River Valley region, as investigated by Reclamation (2005)

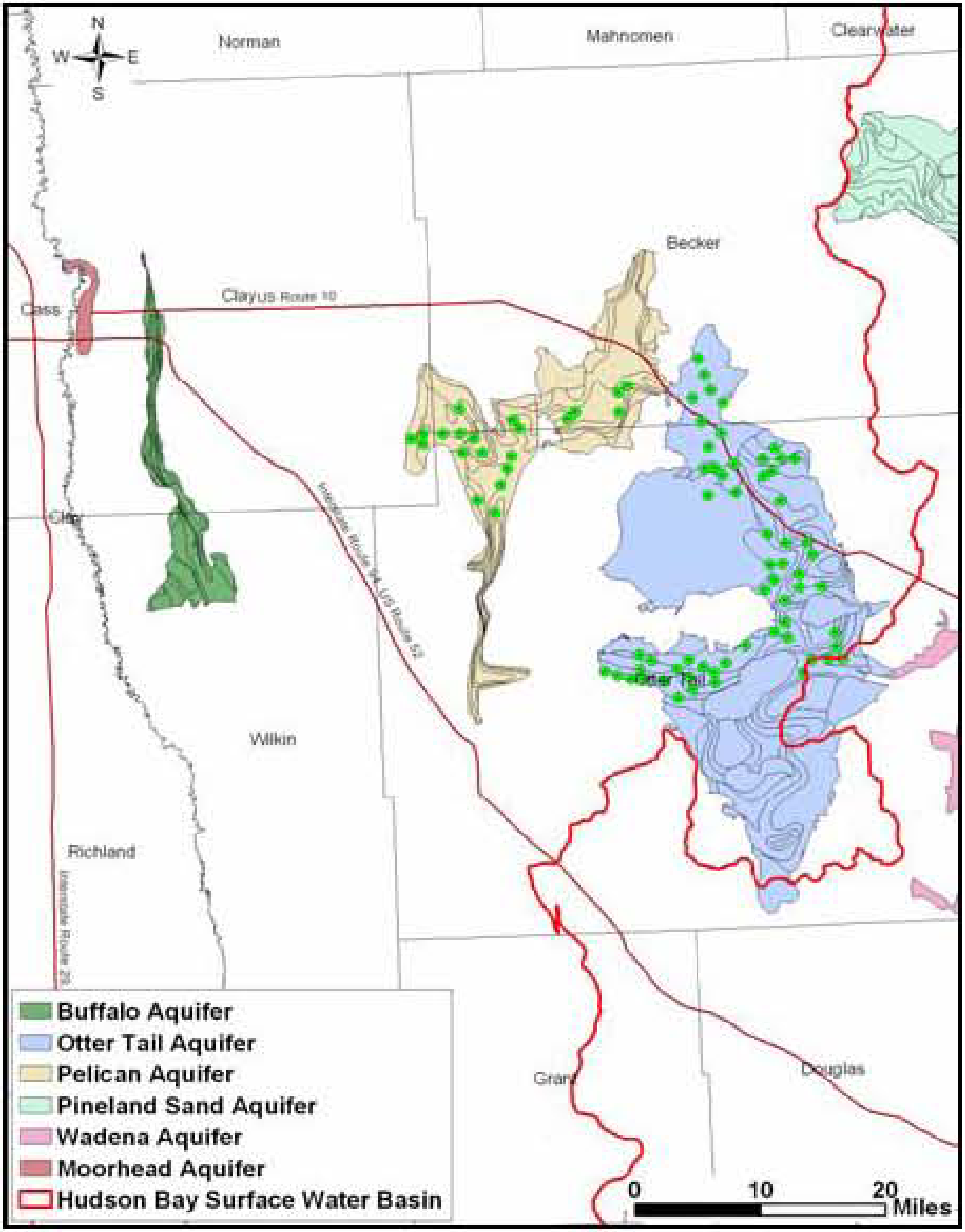


Figure 109 – Location of Minnesota aquifers in the Fargo-Moorhead region (Reclamation, 2005)

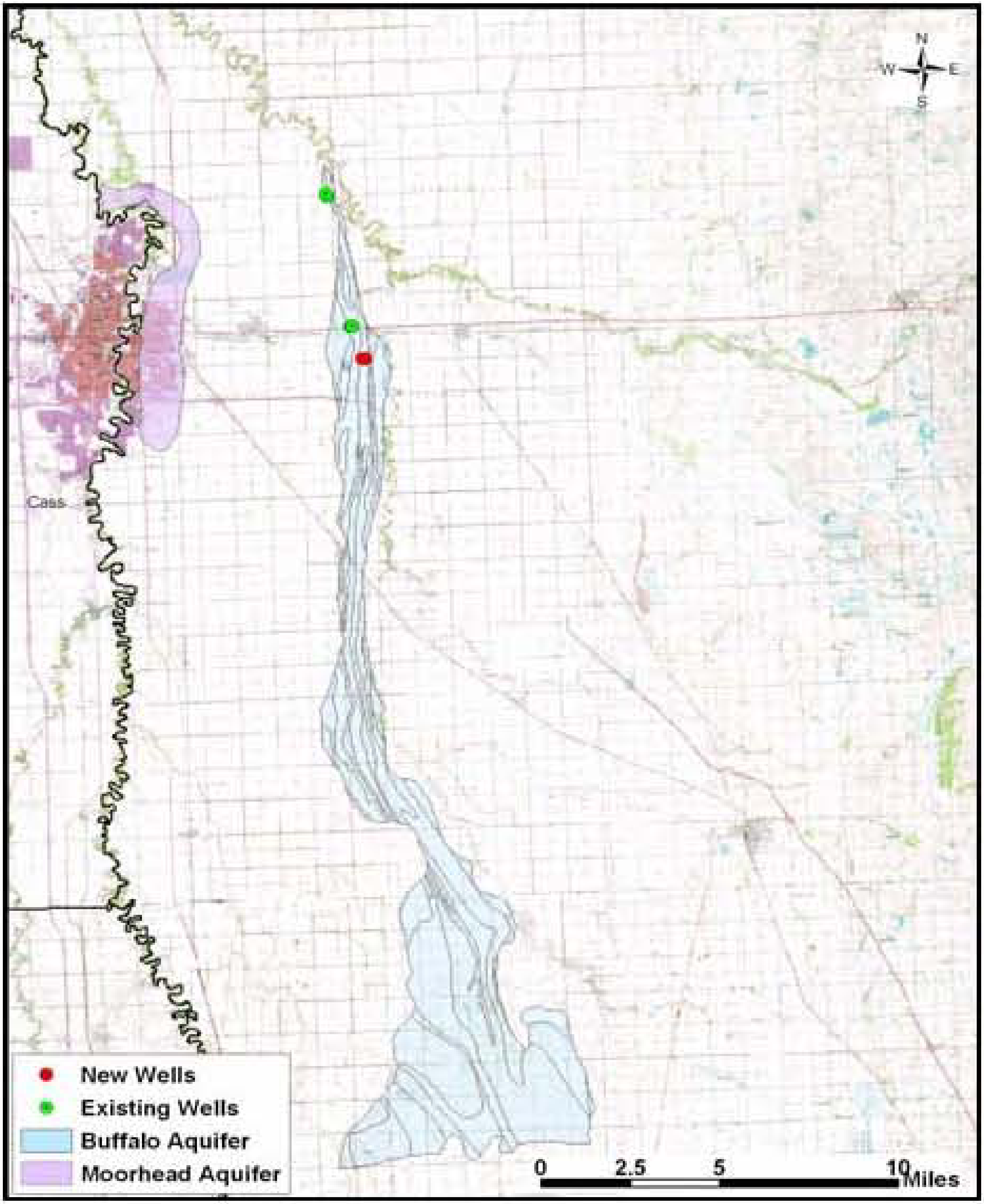


Figure 110 – location of the Buffalo Aquifer, as depicted by Reclamation (2005)

Appendix C. Previous publications:

1) Minnesota Department of Natural Resources -Waters Division Publications:

- RHA 3, Part B, Falteisek and others, 2000, Regional hydrogeologic assessment: Quaternary geology-southern Red River Valley, Minnesota
- RHA-5, Part B, Eckman and Berg, 2002, Regional hydrogeologic assessment: Quaternary geology-Otter Tail Area, west-central Minnesota

2) Minnesota Geological Survey Publications:

a) Regional Assessments:

- RHA-3, Part A, Harris and others, 1995, Regional hydrogeologic assessment: Quaternary geology- southern Red River Valley, Minnesota
- RHA-5, Part A, Harris and others, 1999, Regional hydrogeologic assessment: Quaternary geology-Otter Tail Area, west-central Minnesota
- RHA-6, Part A, Harris and others, in preparation, Regional hydrogeologic assessment: Quaternary geology—west-central Minnesota

b) Miscellaneous Map Series:

1) Surficial geology:

- Preliminary geologic map, Harris, in prep., Surficial Geology of the Crookston 30 X 60 Minute Quadrangle

(2) Bouguer gravity maps:

- M-40, McGinnis, Jackson, and Ervin, 1978, Simple Bouguer gravity map of Minnesota, Brainerd Sheet
- M-41, McGinnis, Steffy, and Ervin, 1978, Simple Bouguer gravity map of Minnesota, Bemidji Sheet

(3) Bedrock geology maps:

- M-80, Jirsa and others, 1994, Bedrock geologic map of northwestern Minnesota (map scale 1:250,000)
- M-92, Jirsa and others, 1999, Bedrock geologic map of northwestern Minnesota (map scale 1:200,000)

(4) Aeromagnetic Maps Series:

- A-6, Chandler, 1987, West-central region
- A-5, Chandler, 1985, Central region
- A-7, Chandler, 1989, Northwestern region

3) North Dakota Geological Survey Publications:

a) Atlas Series Maps:

- AS-13, Harris, 1987, Surface geology of the Sheyenne River Map Area
- AS-14, Harris and Luther, 1991, Surface Geology of the Goose River Map Area

b) County Bulletins:

- B-43, Kelley and Bock, 1967, Part I—Geology and ground-water resources of Barnes County North Dakota, Geology
- B-46, Baker, 1967, Part I—Geology and ground-water resources of Richland County North Dakota, Geology
- B-47, Klausing, 1968, Part I—Geology and ground-water resources of Cass County North Dakota, Geology
- B-49, Bluemle, 1967, Part I—Geology and ground-water resources of Traill County North Dakota, Geology
- B-64, Bluemle, 1975, Part I—Geology of Griggs and Steele Counties, North Dakota
- B-69, Bluemle, 1979), Part I—Geology of Ransom and Sargent Counties, North Dakota

c) Miscellaneous Series:

- MS-52, Harris and others, 1974, Late Quaternary stratigraphic nomenclature, Red River Valley, North Dakota and Minnesota

d) Report of Investigation:

- RI-60, Arndt, 1977, Stratigraphy of offshore sediment Lake Agassiz—North Dakota

e) State-wide Maps:

- MM-30, Heck,1998, Precambrian structure map of North Dakota
- MM-27, Moore and others,1987, Isopach map of the Inyan Kara Fm.
- MM-26, Bluemle, 1986, Depth to bedrock in North Dakota
- MM-25, Bluemle, 1983, Geologic topographic bedrock map of North Dakota
- MM-24, Teller and Bluemle, 1983, Bedrock geology of the Lake Agassiz region
- MM-23, Carlson, 1982, Structure map of the Pierre Fm.
- MM-17, Anderson, 1974, Pre-Mesozoic paleogeologic map of North Dakota

f) State Map Series:

- Preliminary geologic map, 1998, Cavalier 30 X 60 Minute Quadrangle
- Preliminary geologic map, 1998, Grafton 30 X 60 Minute Quadrangle

4) North Dakota State Water Commission:

- City Studies Series, Report 106-4, Ripley, 2000, Water Resource Characteristics of the West Fargo Aquifer System

5) USGS Publications:

a) Water Resources Investigations:

- Report 77-102, Helgesen, 1977, Ground water appraisal of the Pineland Sands area, central Minnesota
- Report 97-4084, Schoenberg, 1998, Hydrogeology and sources of recharge to the Buffalo and Wahpeton aquifers in the southern part of the Red River of the North Drainage Basin, west-central Minnesota and southeastern North Dakota
- Report 94-4009, Stark, Armstrong, and Zwilling, 1994, Stream-aquifer interactions in the Straight River area, Becker and Hubbard Counties, Minnesota
- 89-4136, Stark, Busch, and Deters, 1991, Hydrogeology and water quality of glacial-drift aquifers in the
- Bemidji-Bagley area, Beltrami, Clearwater, Cass, and Hubbard Counties, Minnesota

b) Water Resources Research Bulletin:

- Volume 29, Number 4, Stoner, Lorenz, Wiche, and Goldstein, 1993, Red River of the North Basin, Minnesota, North Dakota, and South Dakota

c) Open-File Report:

- OFR 82-347 Miller, 1981, Appraisal of the Pelican River Sand-Plain aquifer, western Minnesota

d) Unpublished Data:

- Anderson, 1980, Hydrogeological Reconnaissance of Selected Sand-Plain Aquifers in Central Minnesota

6) University of North Dakota published faculty research and unpublished theses and dissertations:

- Harris, 1973, Pleistocene stratigraphy of the Red Lake Falls area, Minnesota
- Harris, 1975, Pleistocene geology of the Grand Forks-Bemidji area, northwestern Minnesota
- Sackreiter, 1975, Quaternary geology of the southern part of the Grand Forks and Bemidji Quadrangles
- Anderson, 1976, Pleistocene geology of the Comstock-Sebeka area, west-central Minnesota
- Perkins, 1977, The Late Cenozoic geology of west central Minnesota from Moorhead to Park Rapids
- Moore (1978), A preliminary report on the Red River Valley drilling project, eastern North Dakota and northwestern Minnesota.

Appendix D. Description of sediments and rocks at the land surface:

QUATERNARY PERIOD

HOLOCENE EPOCH

Qho **Clay, silt, and organic debris**—Dark, obscurely bedded; generally more than one meter (3 feet) thick. *Peat and bog sediment deposited in modern ponds and sloughs.*

Qha **Gravel, sand, silt, clay, and disseminated organic debris**—Dark, obscurely bedded; associated in places with sand and gravel of older river-channel sediment; commonly more than one meter (3 feet) thick. In places, eroded glacial sediment is exposed in channel. *Alluvium and overbank sediment deposited in channels and floodplains of modern streams and rivers.*

Qaa **Gravel, sand, silt, clay, and disseminated organic debris**—Dark, obscurely bedded; associated in places with sand and gravel of older river-channel sediment; commonly more than one meter (3 feet) thick. *Alluvium and overbank sediment deposited in channels and floodplains of ancient rivers and on the Lake Agassiz plain.*

Qht **Sand, silt, and clay—**pebbly; unsorted; unbedded; the surface of the eroded glacial sediment forms steep banks along the present-day river channel. *Glacial sediment that has been eroded by mass movement, soil creep, and other hillslope processes.*

Qls **Sand and silt with gravel ridges—**Moderately to well sorted; plane bedded to crossbedded; as much as 5 meters (15 feet) thick. *Sediment deposited along the shoreline of a lake, commonly on eroded till; beach ridges and offshore bars are shown as line symbols.*

Qln **Sand, silt, and clay—**Moderately to well sorted; flat bedded to crossbedded; as much as 5 meters (15 feet) thick. *Nearshore sediment deposited in shallow water.*

Qlo **Clay with thin silt laminae—**flat bedded, commonly laminated; as much as 60 meters (200 feet) thick. *Offshore sediment deposited in deep, quiet water of a lake.*

Qlg **Sand, silt, and clay—**moderately to well sorted; flat bedded to crossbedded; as much as one meter (3 feet) thick; overlying sand and gravel. *Thin lake sediment over sand and gravel; deposited in shallow water; offshore bars and beaches are shown as line symbols.*

Qw **Sand and silty sand—**medium to fine grained; well sorted; obscurely bedded; associated with older lake and river deposits. *Windblown sediments that form wind-scoured surfaces. Low-relief and high-relief dunes are shown by pattern.*

PLEISTOCENE EPOCH

Qou **Sand and gravel—**Moderately to poorly sorted, cross-bedded to flat-bedded; as thick as 30 meters (98 feet). In places, relatively thin outwash covers but does not obscure pre-existing topography; buried meltwater channels common; draped (palimpsest) features visible on aerial photographs *Outwash sediment, no differentiated by source area, deposited by meltwater streams; areas of collapse (pits) due to melting of buried ice blocks.*

FOREST RIVER GROUP—Deposits of the Red River lobe; ice that flowed from a northern source area.

Qfw **Sand, Silt, and clay—**pebbly; unsorted; unbedded; the surface of the eroded glacial sediment is flat to undulating; a veneer of shoreline, nearshore, or offshore sediment is commonly present. *Glacial sediment that has been eroded (washed) by the action of waves in a lake; beach ridges and offshore bars are shown as line symbols.*

RED LAKE RIVER GROUP—Deposits of the Wadena/Rainy lobe; ice that flowed from a north-northeastern source area.

Qrs **Loam to clay loam—**Pebbly, unsorted, unbedded; abundant cobbles and boulders; more than 10 meters (33 feet) thick; 3–10 meters (10–33 feet) of overall relief on undulating to rolling surface; in places, relatively thin glacial sediment covers but does not obscure pre-existing topography; buried meltwater channels common. Draped (palimpsest) features visible on aerial photographs. *Medium-relief glacial sediment deposited by glacial ice on ice-cored glaciated landscape that later collapsed.*

Qro **Sand and gravel—**Moderately to poorly sorted, cross-bedded to flat-bedded; as thick as 30 meters (98 feet). In places, relatively thin outwash covers but does not obscure pre-existing topography; buried meltwater channels common; draped (palimpsest) features visible on aerial photographs *Outwash sediment deposited by meltwater streams; areas of collapse (pits) due to melting of buried ice blocks.*

UPPER GOOSE RIVER GROUP—Deposits of the Des Moines (Red River) lobe; ice that flowed from a source area to the north-northwest.

Qus **Loam to clay loam—**Pebbly, unsorted, unbedded; abundant cobbles and boulders; more than 10 meters (33 feet) thick; 3–10 meters (10–33 feet) of overall relief on undulating to rolling surface; in places, relatively thin glacial sediment covers but does not obscure pre-existing topography; buried meltwater channels common. Draped (palimpsest) features visible on aerial photographs. *Medium-relief glacial sediment deposited by glacial ice on ice-cored glaciated landscape that later collapsed.*

Qum **Loam to clay loam—**Pebbly, unsorted, unbedded; inclusions of sand and gravel and older stratigraphic units (variable lithology, sorting, and bedding); abundant cobbles and boulders. Overall relief of hummocky surface generally more than 10 meters (33 feet); palimpsest and collapse features visible on aerial photographs; longitudinal lineations apparent on aerial photographs interpreted to indicate strike of thrust faults. *Thrust-faulted, high-relief glacial sediment deposited along margin of glacial ice that later collapsed.*

Quo **Sand and gravel—**Moderately to poorly sorted, cross-bedded to flat-bedded; as thick as 30 meters (98 feet). In places, relatively thin outwash covers but does not obscure pre-existing topography; buried meltwater channels common; draped (palimpsest) features visible on aerial photographs *Outwash sediment deposited by meltwater streams; areas of collapse (pits) due to melting of buried ice blocks.*

LOWER GOOSE RIVER GROUP—Deposits of the Des Moines (Red River) lobe; ice that flowed from a source area to the north-northwest.

Qgs **Loam to clay loam—**Pebbly, unsorted, unbedded; abundant cobbles and boulders; thicker than 10 meters (33 feet); 3–10 meters (10–33 feet) of overall relief on undulating to rolling surface; in places, relatively thin glacial sediment covers but does not obscure pre-existing topography; buried meltwater channels common. Draped (palimpsest) features visible on aerial photographs. *Medium-relief glacial sediment deposited by ice on ice-cored, glaciated landscape that later collapsed.*

Qgm **Loam to clay loam—**Pebbly, unsorted, unbedded; abundant cobbles and boulders, inclusions of sand and gravel, and older stratigraphic units (variable lithology, sorting and bedding). Overall relief of hummocky surface generally more than 10 meters (33 feet); many palimpsest and collapse features visible on aerial photographs; longitudinal lineations apparent on aerial photographs interpreted to indicate strike of thrust faults. *Thrust-faulted, high-relief glacial sediment deposited along margin of glacial ice that later collapsed.*

Qge **Loam to clay loam—**Pebbly, unsorted, unbedded; abundant cobbles and boulders, inclusions of sand and gravel, and older stratigraphic units (variable lithology, sorting and bedding). *Eroded glacial sediment scoured by advancing ice to expose patches of older stratigraphic units.*

Qgw **Sand, silt, and clay—**pebbly; unsorted; unbedded; the surface of the eroded glacial sediment is flat to undulating; a veneer of shoreline, nearshore, or offshore sediment is commonly present. *Glacial sediment that has been eroded (washed) by the action of waves in a lake; beach ridges and offshore bars are shown as line symbols.*

Qgr **Loam to clay loam—**Pebbly, unsorted, unbedded; eroded undulating to rolling surface; veneer of outwash sand and gravel commonly present. *Glacial sediment that has been scoured (or washed) by running water.*

Qgo **Sand and gravel—**Moderately to poorly sorted, cross-bedded to flat-bedded; as thick as 30 meters (98 feet). *Outwash sediment deposited by coalescing, anastomosing meltwater streams; areas of collapse (pits) due to melting of buried ice blocks.*

Qgn **Sand, silt, and clay—**Moderately to well-sorted, flat-bedded to cross-bedded; as thick as 5 meters (16 feet). Forms flat-topped hills that stand above the surrounding topography. *Sediment deposited in ice-walled lakes.*

OTTER TAIL RIVER GROUP—Deposits of the Des Moines (Red River) lobe; ice that flowed from a source area to the north-northwest.

Qos **Loam—**Pebbly, unsorted, unbedded; abundant cobbles and boulders; 10 meters (33 feet) or more thick; 3–10 meters (10–33 feet) of overall relief on undulating to rolling surface; in places, relatively thin glacial sediment covers but does not obscure pre-existing topography; buried meltwater channels common. Draped (palimpsest) features visible on aerial photographs. *Deposited by glacial ice on ice-cored glaciated landscape.*

Qom **Loam—**Pebbly, unsorted, unbedded; inclusions of sand and gravel and older stratigraphic units (variable lithology, sorting, and bedding); abundant cobbles and boulders. Generally more than 10 meters (33 feet) of overall relief on hummocky surface. Many palimpsest and collapse features visible on aerial photographs; longitudinal lineations (apparent on aerial photographs) interpreted to indicate strike of thrust faults. *Thrust-faulted, high-relief glacial sediment that was deposited along margin of glacial ice that later collapsed.*

Qoo **Sand and gravel—**Moderately to poorly sorted, cross-bedded to flat-bedded; as thick as 30 meters (98 feet). in places, relatively thin outwash covers but does not obscure pre-existing topography buried meltwater channels common; draped (palimpsest) features visible on aerial photographs. *Outwash sediment deposited by meltwater streams. Sediment of undulating outwash plain deposited by coalescing, anastomosing meltwater streams; areas of collapse (pits) due to melting of buried ice blocks.*

LAKE TEWAUKON GROUP—Deposits of the Des Moines (Red River) lobe; ice that flowed from a source area to the north-northwest.

Qts **Loam—**Pebbly, unsorted, unbedded; abundant cobbles and boulders; 10 meters (33 feet) or more thick; 3–10 meters (10–33 feet) of overall relief on undulating to rolling surface; in places, relatively thin glacial sediment covers but does not obscure pre-existing topography; buried meltwater channels common. Draped (palimpsest) features visible on aerial photographs. *Deposited by glacial ice on ice-cored glaciated landscape.*

BUFFALO RIVER GROUP—Deposits of the Des Moines (Red River) lobe; ice that flowed from a source area to the north-northwest.

Qbs **Loam—**Pebbly, unsorted, unbedded; abundant cobbles and boulders; 10 meters (33 feet) or more thick; 3–10 meters (10–33 feet) of overall relief on undulating to rolling surface; in places, relatively thin glacial sediment covers but does not obscure pre-existing topography; buried meltwater channels common. Draped (palimpsest) features visible on aerial photographs. *Deposited by glacial ice on ice-cored glaciated landscape.*

CROW WING RIVER GROUP—Deposits of the Rainy lobe; ice that flowed from a source area to the north-northeast.

Qcs **Sandy loam—**Pebbly, unsorted, unbedded; abundant cobbles and boulders; thicker than 10 meters (33 feet); multiple-event deposits may be as thick as 200 meters (650 feet); 3–10 meters (10–33 feet) of overall relief on undulating to rolling surface; in places, relatively thin glacial sediment covers but does not obscure pre-existing topography; buried meltwater channels common. Draped (palimpsest) features visible on aerial photographs. *Deposited by glacial ice on ice-cored glaciated landscape.*

Qcg **Sandy loam—**Pebbly, unsorted, unbedded; eroded undulating to rolling surface; elongate, streamlined hills (drumlins) common. Veneer of outwash sand and gravel and alluvium common in low areas between drumlins. *Glacial sediment eroded (drumlinized) by overriding glacial ice.*

Qcr **Sandy loam—**Pebbly, unsorted, unbedded; eroded undulating to rolling surface; veneer of outwash sand and gravel commonly present. *Glacial sediment that has been scoured (or washed) by running water.*

Qcm **Sandy loam—**Pebbly, unsorted, unbedded; inclusions of sand and gravel, older stratigraphic units (variable lithology, sorting, and bedding), and abundant cobbles and boulders; generally more than 10 meters (33 feet) of overall relief on hummocky surface; many palimpsest and collapse features visible on aerial photographs; longitudinal lineations apparent on aerial photographs interpreted to indicate strike of thrust faults. *Thrust-faulted, high-relief glacial sediment deposited along margin of glacial ice that later collapsed.*

Qcc **Sand and gravel—**Moderately to poorly sorted, cross-bedded to flat-bedded; as thick as 30 meters (98 feet). *Outwash sediment deposited by meltwater streams.*

Qcn **Sand, silt, and clay—**Moderately to well-sorted, flat-bedded to cross-bedded; as thick as 5 meters (16 feet); forms flat-topped hills that stand above the surrounding topography. *Sediment deposited in ice-walled lakes.*

Cretaceous

Kpnu **Pierre and Niobrara Formations; undifferentiated, North Dakota—**shale, dark gray to brown. *Sediment deposited in marine and marginal marine environments.*

DESCRIPTION OF SURFICIAL GEOLOGY MAP SYMBOLS

Confident map unit boundary—Judged to be within 0.4 kilometers (0.25 miles) of the true boundary along most of its length

Approximate map unit boundary—Judged to be 0.4 kilometers (0.25 miles) to 0.8 kilometers (0.5 miles) from the true boundary along most of its length

Uncertain map unit boundary—Judged likely to be more than 0.8 kilometers (0.5 miles) from the true boundary

Ice margin—Position established from aerial photographs, topographic cross sections, and analysis of sediment samples; paired ticks point toward the glacier; line dashed where the margin is buried. Interpreted to be the approximate position of a glacial margin; may mark a glacial maximum or recessional position; margins are numbered from earliest to latest; generally discernible on topographical maps and on the ground

Sharp scarp—Established from aerial photographs; line indicates the crest of the scarp and ticks point downscarp; easily discernible on topographic maps and on the ground

Discontinuous scarp—Established from aerial photographs; line indicates the crest of the scarp and ticks point downscarp; apparent on topographic maps and on the ground

Sharp-walled channel—Established from aerial photographs; paired sharp scarps; lines indicate the crests of the scarps and ticks point downscarp. Interpreted to be meltwater channel; apparent on topographic maps and on the ground

Discontinuous channel—Established from aerial photographs; lines indicate the top of the slopes and ticks point down slope. Interpreted to be an eroded or collapsed meltwater channel; generally apparent on topographic maps and on the ground

Tunnel valley—Established from aerial photographs; lines indicate paired, very sharp scarps; saw teeth point downscarp. Interpreted to be subglacial meltwater channel

Palimpsest channel—Established from aerial photographs; lines indicate the top of the slopes; half-circles indicate the down slope direction. Interpreted to be an obscure meltwater channel; generally apparent on topographic maps; may not be apparent on the ground. Sediment may include thin channel deposits of sand and gravel over scoured diamicton

Channel scour—Established from aerial photographs; line marks the scour; arrowhead indicates probable direction of water flow; interpreted to be anastomosing stream channel eroded during episodes of overland flow; generally not apparent on topographic maps or on the ground

Beach ridge—Established from aerial photographs; line indicates the crest of the ridge; interpreted to be beach ridge deposited along the margin of a lake or temporary high water level; discernible on topographic maps and on the ground

Esker—Established from aerial photographs; line indicates the crest of a sinuous ridge; generally located in areas mapped as glacial sediment. Interpreted to mark the location of a stream channel that formed on top of, in, or under glacial ice. Apparent on topographic maps; generally apparent on the ground

Drumlin—Established from aerial photographs; line indicates the crest of ridge; interpreted to be a streamlined ridge formed at the base of a moving glacier. Apparent on topographic maps; generally apparent on the ground

Thrust fault—Established from aerial photographs; line marks the upstream boundary of a thrust block. Saw teeth point toward up-thrown block. Commonly present in hill–hole combinations; a glacier, frozen to its bed, has "plucked" a block of sediment out of the basal material and moved it down glacier. The "holes" commonly are lakes

Lineations—Established from aerial photographs; lines mark the long axis of the feature. These are obscure lineations of unknown origin; they generally are not apparent on topographic maps or on the ground

Low-relief dunes—as much as 3 meters (10 feet) thick

High-relief dunes—as much as 10 meters (30 feet) thick

Appendix E. Description of the mapped strata: This is a complete stratigraphic column for the area; not all of these units are used in the stratigraphic interpretations or the geological maps.

HOLOCENE

Alluvium

Walsh Formation - sand, silt, clay, gravel, and organic debris; dark gray; generally dirty appearance; ALLUVIUM (Bluemle, 1973)

Lake Agassiz sediment

Sherack Formation - Clay, silty clay, and silt; laminated (mm to cm thick); clayey in the central part of the lake plain and silty toward the margins; light gray where unoxidized and yellowish gray to olive brown where oxidized; wood fragments common at the base ; OFFSHORE LAKE SEDIMENT (Harris, 1973, 1975, in prep.; Harris and others, 1974; Moran and others 1976; Arndt, 1977)

Poplar River Formation - Sand; fine to coarse grained; and associated silt and clay; crossbedded; significant thicknesses of gravel are present in some areas; RIVER SEDIMENT (Harris, in prep. Harris and others, 1974; Moran and others, 1976)

West Fargo member - Sand; fine to coarse grained; cross bedded; significant thicknesses of gravel are present in some areas; commonly contains peat, wood and other organic fragments; commonly expressed at the surface as a compaction ridge; RIVER CHANNEL SEDIMENT AND NEAR-CHANNEL OVERBANK SEDIMENT (Arndt,1977)

Harwood member - Clay, gray to dark grayish brown; mealy structure; stiff and brittle; usually not more than 2 meters (6 feet) thick; RIVER OVERBANK SEDIMENT (Arndt, 1977)

PLEISTOCENE

Lake Agassiz sediment

Brenna Formation - Clay; obscurely laminated to unbedded; dark gray to black; very high natural water content; very low shear strength; typically contains small, white, silty, calcareous fragments (1 mm to 30 mm); slump prone; not exposed at the land surface; OFFSHORE LAKE SEDIMENT (Harris and others, 1974; Moran and others 1976; Arndt, 1977; Harris, in prep.)

Forest River group (glacial sediment)

Huot Formation (RRV01) - Pebble-clay; very few pebbles; unbedded; unsorted; massive; gray to very dark grayish brown; high natural water content; low shear strength; slump prone; deposited in or very near Lake Agassiz basin; lateral equivalent of the Falconer Formation; calcareous; average texture (07-19-74); average coarse-sand lithology (32-63-05); GLACIAL SEDIMENT (Harris, 1973, 1975, in prep.; Harris and others, 1974; Moran and others, 1976; Arndt, 1977)

Falconer Formation (RRV02; glacial sediment) - Pebble-clay to pebble-loam; silty; clayey; unbedded; unsorted; massive; light gray; deposited along the margin of the Lake Agassiz basin; lateral equivalent of the Huot Formation; average texture (11-35-54); average coarse-sand lithology (39-35-26); GLACIAL SEDIMENT (Harris, in prep. Harris and others, 1974; Moran and others, 1976; Arndt, 1977)

Lake Agassiz sediment

Argusville Formation - Clay; unbedded; gray to dark gray; not exposed at the land surface; OFFSHORE LAKE SEDIMENT (Moran and others, 1976; Arndt, 1977)

Wiley Formation - Clay and silt; generally thinly laminated (millimeters to centimeters); olive-gray to dark gray clay; light-brownish-gray to olive-brown silt; not exposed at the land surface; OFFSHORE LAKE SEDIMENT (Harris, 1973, 1975, in prep.; Harris and others, 1974; Moran and others, 1976; Arndt, 1977)

Red Lake River group (glacial sediment)

Upper Red Lake Falls formation (RRV03) - Pebble-loam; unbedded; unsorted; conspicuous columnar jointing; brownish gray to olive brown calcareous; average texture (37-40-23); average coarse-sand lithology (58-29-13); GLACIAL SEDIMENT (Harris, 1973, 1975, in prep.; Harris and others, 1974; Moran and others, 1976; Arndt, 1977)

Lower Red Lake Falls formation (RRV04) - Pebble-loam; unbedded; unsorted; massive; brownish gray to olive brown; calcareous; average texture (33-45-22); average coarse-sand lithology (57-40-03); GLACIAL SEDIMENT (Harris, 1973, 1975, in prep.; Harris and others, 1974; Moran and others, 1976; Arndt, 1977)

Goose River group (glacial sediment)

Upper Goose River group

Barnesville formation (RRV06) - Pebble-loam; silty; clayey; unbedded; unsorted; massive; gray to very dark gray; calcareous; average texture (18-44-38); average coarse-sand lithology (44-44-12); GLACIAL SEDIMENT (Anderson, 1976; Perkins, 1977, Harris and others, 1995, 1999; Harris, in prep.)

St. Hilaire Formation (RRV07) - Pebble-loam; clayey; unbedded; unsorted; columnar structure or weak vertical jointing common; shale pebbles common; lignite fragments; gray to very dark gray; calcareous; average texture (27-44-29); average coarse-sand lithology (43-33-24); GLACIAL SEDIMENT (Harris, 1973, 1975, in prep.; Harris and others, 1974, 1999, 2003; Moran and others, 1976; Arndt, 1977)

Lower Goose River group (glacial sediment)

Dahlen Formation (RRV08) - Pebble-loam; clayey; unbedded; unsorted; massive; abundant shale pebbles; light yellowish brown to olive gray; calcareous; average texture (30-42-28); average coarse-sand lithology (27-19-54); GLACIAL SEDIMENT (Salomon, 1975; Hobbs, 1975; Moran and others, 1976, Harris and others, 1995, 1999; Harris, in prep.)

Heiberg formation (RRV09) - Pebble-loam; unbedded; unsorted; massive; shale pebbles abundant; Lignite fragments common; dark olive brown to very dark gray; lacustrine facies present south of Wahpeton; calcareous; average texture (32-40-28); average coarse-sand lithology (33-25-42); GLACIAL SEDIMENT AND LACUSTRINE FACIES; (Harris and others, 1995, 1999, 2003; Harris, in prep.)

Otter Tail River group (glacial sediment)

Hawley formation (RRV10) - Pebble-loam; unbedded; unsorted; massive; yellowish brown to very dark grayish brown; Lignite and wood fragments; calcareous; average texture (41-37-22); average coarse-sand lithology (54-42-04); GLACIAL SEDIMENT; (Anderson, 1976, Perkins, 1977, Harris and others, 1995; Harris, in prep.)

New York Mills formation (RRV11) - Pebble-loam; unbedded; unsorted; massive; dark grayish brown to very dark grayish brown; calcareous; average texture (46-34-20); average coarse-sand lithology (67-29-04); GLACIAL SEDIMENT (Harris and others, 1995, 1999, 2003; Harris, in prep.)

Villard formation (RRV12) - Pebble-loam; unbedded; unsorted; massive; Lignite and wood fragments; calcareous; average texture (42-37-21); average coarse-sand lithology (49-28-23); GLACIAL SEDIMENT; (Harris and others, 1995, 1999, 2003; Harris, in prep.)

James River group (glacial sediment)

James formation (RRV05) - Pebble-loam; unbedded; unsorted; massive; shale common; Lignite fragments present; calcareous; average texture (45-35-20); average coarse-sand lithology (45-24-31); GLACIAL SEDIMENT; (Biek, 1994; Harris and others, 1995, 1999, 2003; Harris, in prep.)

Lake Tewaukon group (glacial sediment)

Gardar Formation (RRV13) - Pebble-loam; unbedded; unsorted; massive; abundant shale pebbles; yellowish brown to dark gray; calcareous; average texture (27-44-29); average coarse-sand lithology (16-12-72); GLACIAL SEDIMENT (Hobbs, 1975; Solomon, 1975; Moran and others, 1976; Harris and others, 1995, 1999; Harris, in prep.)

Silty member (RRV14) - Pebble-loam; silty, clayey; unbedded; massive; yellowish brown to olive gray; probable silty, clayey alteration product of the Gardar Formation; GLACIAL SEDIMENT; (Harris and others, 1995; Harris, in prep.)

Buffalo River group (glacial sediment)

Buffalo formation (RRV15) - Pebble-loam; clayey; unbedded; unsorted; massive; olive brown; calcareous; project average texture (30-36-34); average coarse-sand lithology (64-32-04); GLACIAL SEDIMENT; (Harris and others, 1995; Harris, in prep.)

Crow Wing River group (glacial sediment)

Upper Marcoux formation (RRV16) - Pebble-loam; sandy; unbedded; unsorted; massive; dark grayish brown; calcareous; 26 feet of lacustrine sand and laminated silt and clay in Hawley area; average texture (57-28-15); average coarse-sand lithology (85-15-00); GLACIAL SEDIMENT; (Harris, 1973, 1975, in prep.; Harris and others, 1974, 1995, 1999, 2003; Moran and others, 1976)

Lower Marcoux formation (RRV17) - Pebble-loam; sandy; unbedded; unsorted; massive; abundant pebbles, cobbles, and boulders; light gray to grayish brown; very hard in outcrop; lignite and wood fragments in Hawley area; calcareous; average texture (55-30-15); average coarse-sand lithology (74-23-03); GLACIAL SEDIMENT; (Harris, 1973, 1975, in Prep; Harris and others, 1974, 1995, 1999, 2003; Moran and others, 1976)

Sheyenne River group (glacial sediment)

Sheyenne formation (RRV18) - Pebble-loam; clayey; unbedded; unsorted; massive; calcareous; average texture (29-40-31); average coarse-sand lithology (50-36-14); GLACIAL SEDIMENT; (Harris and others, 1995; Harris, in prep.)

Browerville formation - Pebble-loam, sandy; light yellowish brown (2.5Y 6/4) to very dark grayish-brown (2.5Y 3/2); unbedded; unsorted; massive; compact; and calcareous. Clasts are angular to rounded. They contain abundant igneous and metamorphic rock fragments, moderate carbonate rock fragments, and very few shale rock fragments; contains pebble-sized stones; average texture; average texture (46-37-17); average coarse-sand lithology (64-33-03); GLACIAL SEDIMENT; (Meyer, 1986, Meyer and others,1995; Meyer and Knaeble, 1996, Harris, in prep.)

Gervais Formation (RRV20)- Pebble-loam; clayey; silty; very slightly pebbly; unbedded; unsorted; massive; strongly jointed; light olive gray to dark gray; abundant wood chips, twigs, and logs; fragments of mollusk shells, insects, carbon flakes, and moss; calcareous; Carbon-14 dates: >39,900 B.P. (I-5317), >46,900 B.P. (BIRM 522); not exposed at the land surface; average texture (26-46-28); average coarse-sand lithology (48-49-03); GLACIAL SEDIMENT; (Harris, 1973, 1975, in prep.; Harris and others, 1974; Moran and others, 1976; Ashworth, 1980)

Older tills: These units are either 1) vary similar texture and coarse-sand lithology to previously described units, but occur much lower in the section or 2) distinctly similar to previously described units in coarse-sand lithology, have significantly different texture, and occur lower in the section

Old Hawley till - Pebble-loam; unbedded; unsorted; massive; very compact; calcareous; abundant carbonate clasts, very few shale fragments; contains "pebbles" of regolith south of the study area in Pope County, Minnesota; average texture (43-43-23); average coarse-sand lithology (56-44-00); GLACIAL SEDIMENT; (Harris, in prep.)

Old New York Mills till - Pebble-loam; unbedded; unsorted; massive; average texture (42-35-23); average coarse-sand lithology (70-30-00); GLACIAL SEDIMENT; (Harris, in prep.)

Old Buffalo till - Pebble-loam; unbedded; unsorted; massive; average texture (37-37-26); average coarse- sand lithology (62-30-08); GLACIAL SEDIMENT; (Harris, in prep.)

Old U. Marcoux till - Pebble-loam; silty; unbedded; unsorted; massive; dark grayish brown; compact; calcareous; abundant crystalline and metamorphic, moderate carbonate, and few shale rock fragments; average texture (36-44-20); average coarse-sand lithology (85-14-01); GLACIAL SEDIMENT; (Harris, in prep.)

Old L. Marcoux till - Pebble-loam; silty; unbedded; unsorted; massive; olive gray; compact; calcareous; abundant crystalline and metamorphic, moderate carbonate, and few shale rock fragments; average texture (38-42-20); average coarse-sand lithology (74-24-02); GLACIAL SEDIMENT; (Harris, in prep.)

CRETACEOUS

Pierre Formation – dark gray shale; marine offshore sediment

Niobrara Formation – light brown to dark gray calcareous shale; marine offshore sediment

ORDOVICIAN

Red River Formation – Limestone, dolomitic limestone, dolomite

Winnipeg Formation - Basal sandstone overlain by complex sequence of quartzose sandstone and shale

PRECAMBRIAN

Precambrian rocks – igneous and metamorphic rocks

Appendix F. List of attachments:

1) Surficial geologic map; full color with legend, scale 1: 200,000

- Fargo Moorhead surficial geology.pdf

2) Bedrock geologic map; full-color with legend, scale 1: 400,000

- Fargo Moorhead bedrock geology.pdf

3) Drill-hole database used to map 3D geology

- E.g. Fmsindex1212.dbf; FMSst_1212.DBF

4) GIS files depicting the extent of each mapped subsurface layer, scale 1:500,000 with inset areas of additional detail

- E.g. b_001.shp

5) Modeled surfaces for the top of each mapped subsurface layer; grid spacing ~ 0.5 km with inset areas of additional detail; Database of top elevations for each mapped subsurface layer; grid spacing ~5 km with inset areas of additional detail; numbers refer to stratigraphic order of units from youngest to oldest

- E.g. w001001.adf

Digital products

The digital products created in support of this project are arranged for delivery in a set of compressed archive ("zip") files organized by major elements of the project. Contained in each archive are "index.txt" files which list and document the individual files contained in that archive

archive files

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base.zip	all GIS layers used to generate the base used for the surficial and bedrock geologic maps.
database.zip	the point GIS layers and associated tables containing information from drill holes, geologic material samples, and other site information used in the geologic interpretations and 3D model generation.
surfgeol.zip	all GIS layers and supporting files used in the generation of the surficial geologic map.
bdrkgeol.zip	all GIS layers and supporting files used in the generation of the bedrock geologic map.
grids.zip	digital elevation models of units tops from the three-dimensional geologic model.

- Questions concerning regional geology may be directed to Ken Harris (harri015@umn.edu) or Barb Lusardi (lusar001@umn.edu), or Fred Anderson (fjanderson@state.nd.us)

- Questions concerning construction of the 3D model may be directed to Bob Tipping (tippi001@umn.edu) or Jim Berg (jim.berg@dnr.state.mn.us)

- Questions regarding GIS components may be directed to Tim Wahl (tewahl@umn.edu), Rich Lively (lively@umn.edu), or Bob Tipping (tippi001@umn.edu)

3D model layers:

Layer 001: Lake Agassiz beach sands
Layer 002: Sherack Formation
Layer 003: Surficial sand and gravel (undifferentiated)
Layer 004: Forest River Group
Layer 005: Brenna/Argusville Formations
Layer 006: Red Lake River Group sand and gravel
Layer 007: Red Lake River Group sediments
Layer 008: Red Lake River Group lacustrine/Sheyenne Delta sediment
Layer 009: Upper Goose River Group unit 1 sand and gravel
Layer 010: Upper Goose River Group unit 1 till
Layer 011: Upper Goose River Group unit 2 sand and gravel
Layer 012: Upper Goose River Group unit 2 till
Layer 013: Lower Goose River Group sand and gravel
Layer 014: Lower Goose River Group till
Layer 015: Otter Tail River Group sand and gravel
Layer 016: Otter Tail River Group till
Layer 017: Lake Tewaukon Group sand and gravel
Layer 018: Lake Tewaukon Group till
Layer 019: Buffalo River Group till
Layer 020: Crow Wing River Group unit 1 till
Layer 021: Crow Wing River Group unit 2 till
Layer 022: Browerville Formation sand and gravel
Layer 023: Browerville Formation till
Layer 024: Older unknown unit a4 sand and gravel
Layer 025: Older unknown unit a4 till
Layer 026: Older unknown unit a5 sand and gravel
Layer 027: no layer assigned
Layer 028: Quaternary undifferentiated
Layer 029: Bedrock undivided
Layer 030: Cretaceous Pierre Formation
Layer 031: Cretaceous Niobrara Formation
Layer 032: Cretaceous Carlile Formation
Layer 033: Cretaceous Greenhorn Formation
Layer 034: Cretaceous undifferentiated
Layer 035: Ordovician Red River Formation carbonate
Layer 036: Ordovician Winnipeg Formation sandstone
Layer 037: Precambrian igneous and metamorphic rock