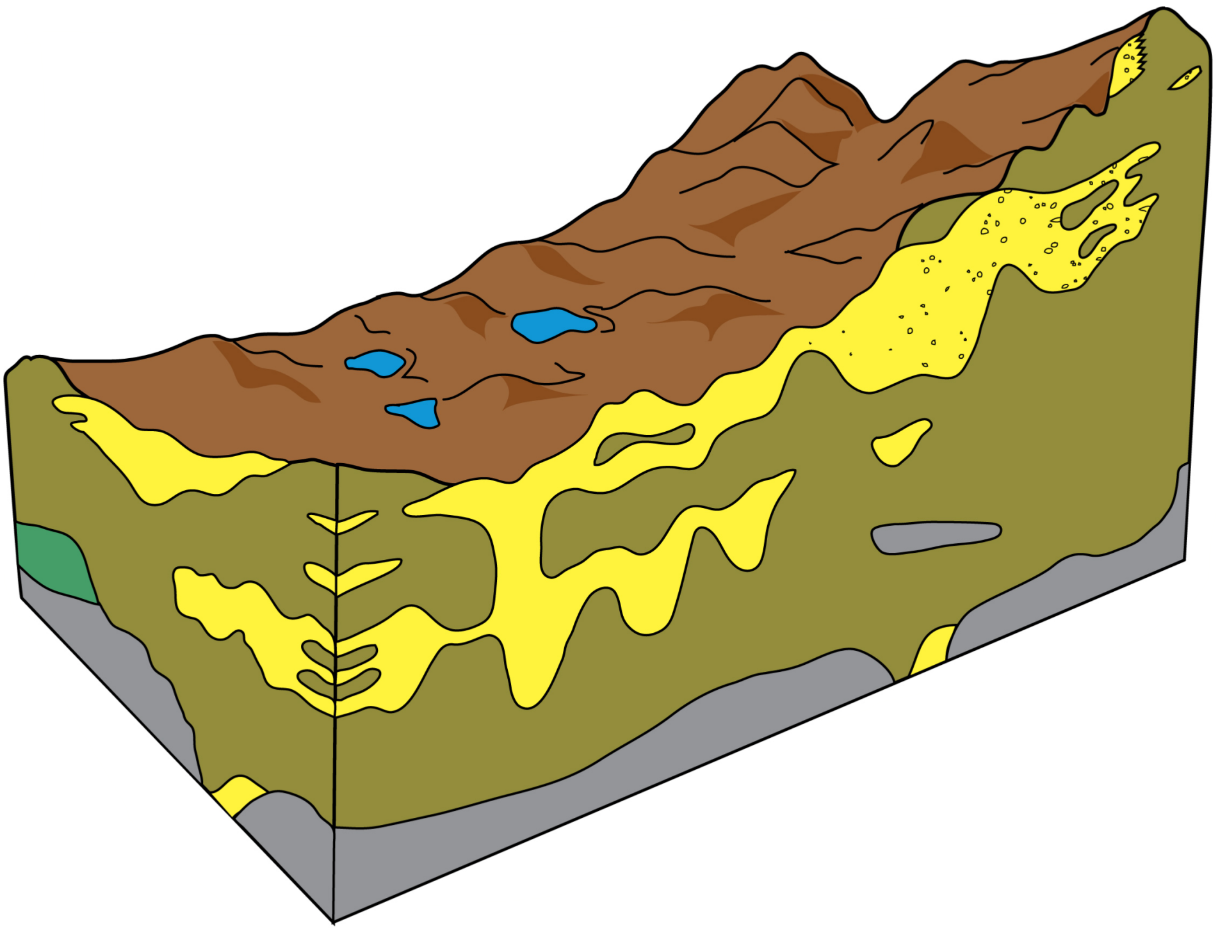
Hydrogeology and Groundwater Management in Northern Kidder and Northwestern Stutsman Counties



By
Gordon M. Sturgeon

Water Resource Investigation No. 52
North Dakota State Water Commission

2011

This report may be downloaded as a PDF file from the North Dakota State Water Commission website at http://swc.nd.gov.

- Click on “Reports and Publications”
- Then click on “Water Resource Investigations”
- Then scroll down to WRI No. 52

Hydrogeology and Groundwater Management in Northern Kidder and Northwestern Stutsman Counties

By
Gordon M. Sturgeon

Water Resource Investigation No. 52
North Dakota State Water Commission

2011

CONTENTS

LIST OF FIGURES

LIST OF FIGURES (continued)

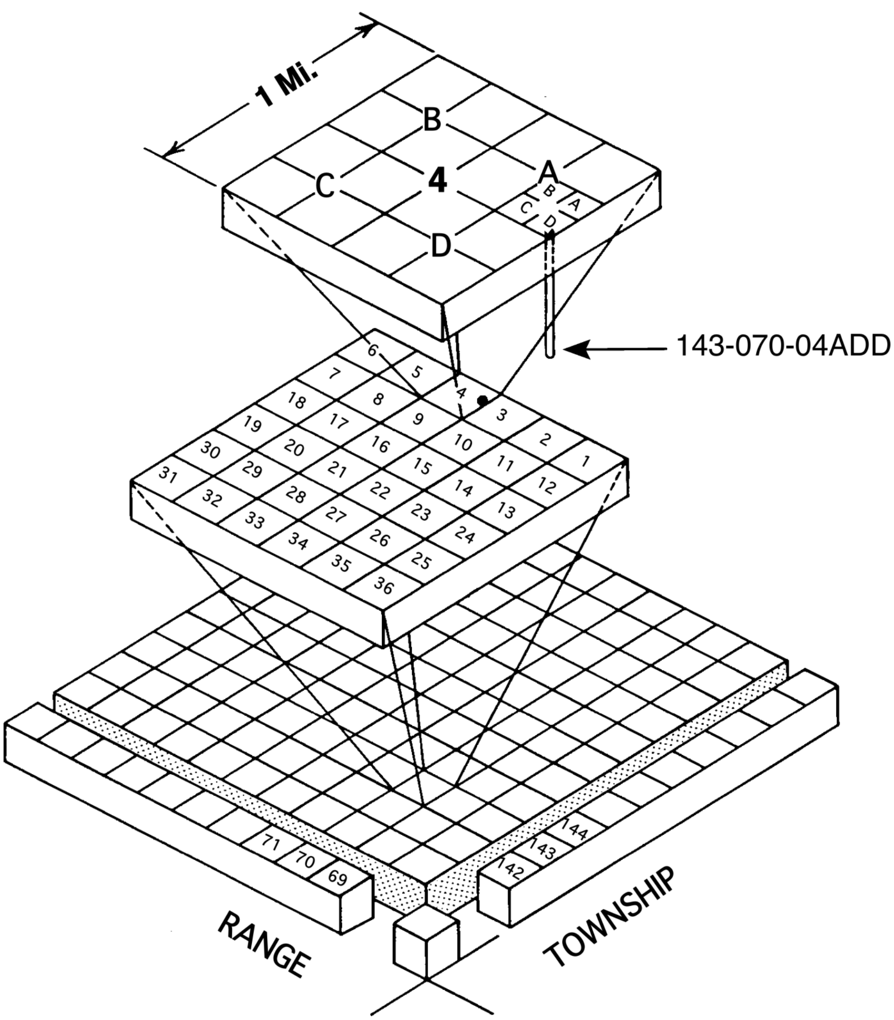
LIST OF FIGURES (continued)

LIST OF TABLES

LOCATION-NUMBERING SYSTEM FOR TEST HOLES AND WELLS

The location-numbering system is based on the public land survey system (PLSS) of the U.S. Government. The PLSS typically divides the land into 6-mile by 6-mile townships that are subdivided into 36 one-mile by one-mile sections, each containing 640 acres. The location of each township is identified by a township and range designation. The township designation indicates its location north or south of an east-west trending base line. The range designation indicates its location east or west of a north-south line called a Principal Meridian. For example, T143N R70W refers to the township that is in the 143rd row of townships north of a base line and the 70th column of townships west of a Principal Meridian.

The test hole and well location-numbering system is illustrated below. The first six numbers identify the township in terms of its township and range designation. The seventh and eighth numbers denote the section in the township, and the first letter A, B, C, or D indicates the northeast, northwest, southwest, or southeast quarter of the section, respectively. The second letter denotes the quarter of the quarter, and the third letter identifies the 10-acre tract within the quarter-quarter. Consecutive numbers follow the letters if more than one test hole or well is located within a 10-acre tract (e.g. 14307004ADD1 and 14307004ADD2).



Hydrogeology and Groundwater Management in Northern Kidder and Northwestern Stutsman Counties

INTRODUCTION

The overarching purpose of this study was to synthesize and interpret available information pertaining to the Central Dakota Aquifer System in northern Kidder and northwestern Stutsman Counties. Excellent descriptions of the geology and groundwater resources of Kidder and Stutsman Counties were published in the early 1960s (Rau et al., 1962; Winters, 1963). However, nearly 50 years of fieldwork have followed these county studies. Several hundred borings have been advanced, hundreds of water samples have been collected and analyzed, and thousands of water level measurements have been taken, so an update is warranted. Unlike the aforementioned county studies, the current investigation does not encompass the entire area of each county, because the Central Dakota Aquifer System only extends into the northwestern portion of Stutsman County, and it is managed separately in the southern half of Kidder County. Furthermore, the scope and purpose of the current investigation differ from the county studies. Specific objectives of this project were to advance our understanding of the local geology, and to develop a conceptual hydrogeologic model that could guide future resource investigations, support management decisions, and inform numerical hydrogeologic models. For a brief discussion of the local climate, soils, and vegetation see Rau et al. (1962) and Winters (1963).

Glacial Geology. Northern Kidder and northwestern Stutsman Counties lie within the Missouri Coteau physiographic province – an upland area of hummocky, glaciated plains with isolated drainages (Figure 1). The thick glacial deposits of the Coteau resulted from the large-scale stagnation and gradual wasting away of glacial ice, accompanied by the collapse of the glacial sediment that was carried by the ice. Areas in North Dakota that are characterized by collapsed glacial topography include the Missouri Coteau, the Turtle Mountains, and the Prairie Coteau. Hummocky collapsed topography formed in these three areas, because the glaciers were forced to advance up steep escarpments before they flowed onto the uplands.

When the glaciers advanced over these escarpments, the resulting internal stress in the ice caused shearing (Figure 2). Large amounts of sediment originally beneath the ice were forced upward into the glacier and onto its surface along shear planes. As the climate warmed, the glaciers stopped advancing and large masses of ice stagnated over the uplands. The ice became isolated and detached from the main body of the retreating glacier, because it was relatively thin and often covered by a thick blanket of rock debris. East of the escarpments the ice was more thick and less debris-rich, so the glaciers did not stagnate.

As the stagnant ice slowly wasted away, the ice surface topography became progressively more irregular. Ice covered with a lot of debris was well insulated and melted very slowly; ice with little debris melted more rapidly. The debris on top of the ice was unstable and prone to slumping and flowing into low areas.

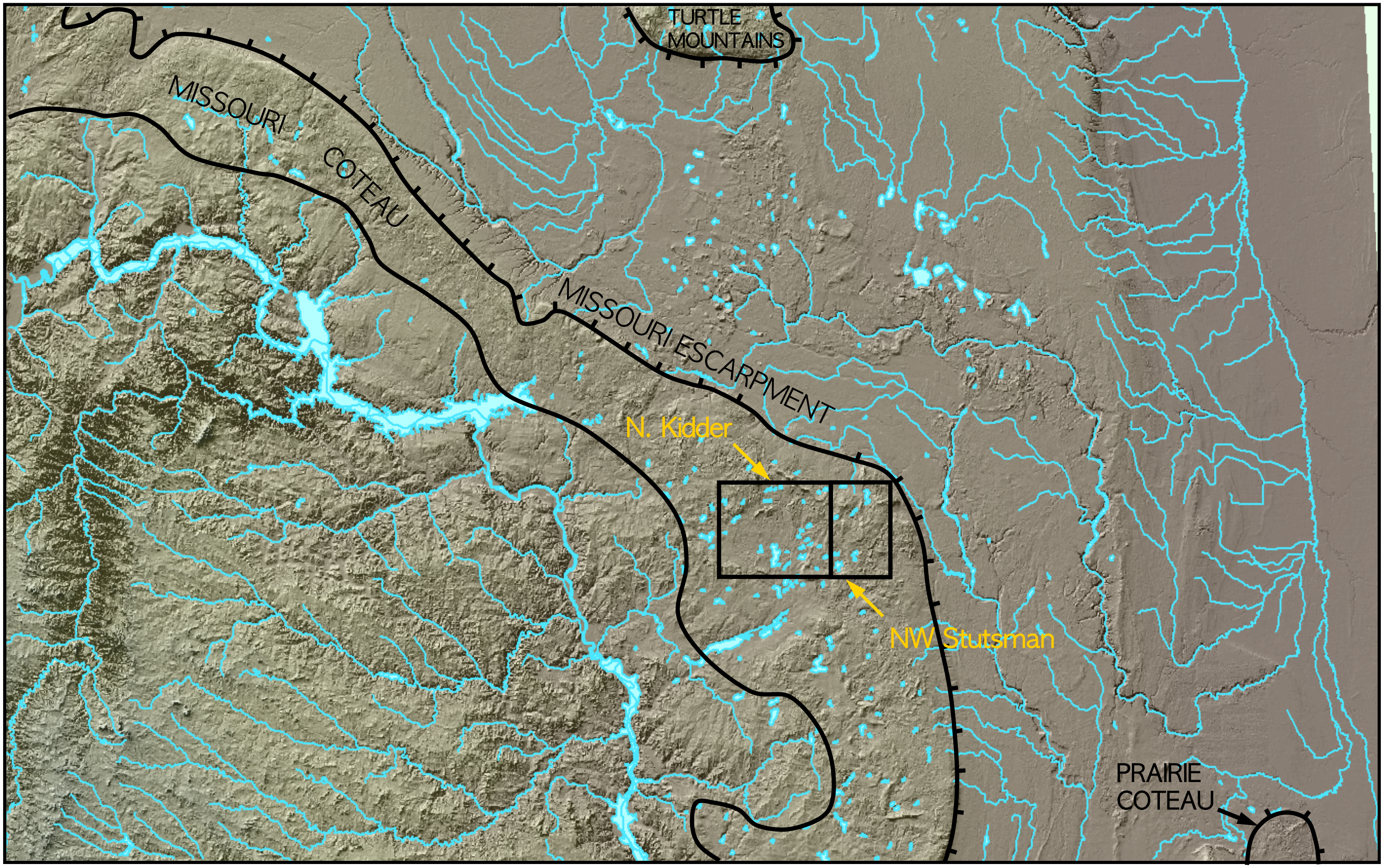


Figure 1. Physiography of North Dakota showing the three provinces that are characterized by collapsed glacial topography as well as the escarpments that bound these areas. Northern Kidder and northwestern Stutsman Counties are located within the Missouri Coteau province. The lack of an integrated drainage network in the couteau indicates that there has been little postglacial erosion of the landscape.

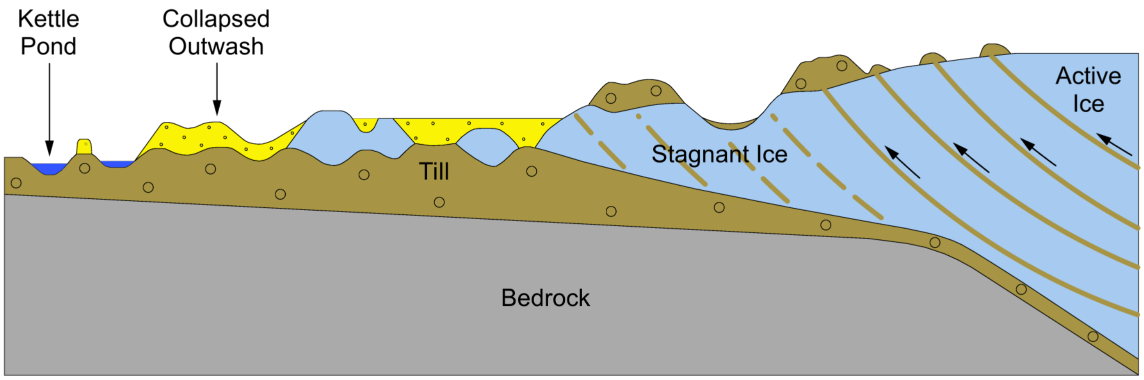


Figure 2. Cross section showing the collapsed glacial topography that arises from ice-sheet stagnation and wasting.

Rivers were common features on the irregular surface of the wasting ice. Consequently, test borings in ice-wasting depositional environments often encounter multiple layers of till, separated by layers of fluvial sand and gravel. This stratigraphic sequence is often misinterpreted to be the product of multiple glaciations, when in many cases it is the manifestation of a single episode of ice advance and retreat (Figure 3).

Rivers also extended beyond the margins of the melting ice. Most of the southern halves of northern Kidder and northwestern Stutsman Counties are covered by stratified sand and gravel that was "washed out" of the ice by meltwater streams (Figure 4). If the outwash was deposited on buried ice, melt out of the underlying ice caused the outwash to have a hummocky topography like the collapsed glacial till. Collapsed outwash has the same composition as uncollapsed river sediment, but its bedding is usually faulted and folded.

There is evidence of two Late Wisconsinan cycles of ice advance, stagnation, and wasting in the project area. Most of the land in the north half of Figure 4 is covered by hummocky stagnation moraine and tall, arc-shaped end moraines from the younger Streeter advance. The stagnation moraine, end moraines, and outwash associated with the Streeter advance partially bury the ground moraine and end moraines from the older Long Lake advance.

In the southern half of the study area, the most abundant surficial deposit is the outwash from the Streeter advance. The meltwater streams that formed this outwash plain generally flowed from the north, so the plain slopes to the south, and grain size decreases to the south. The outwash contains several closed depressions that were produced by the melting of isolated blocks of stagnant ice.

There is a long, narrow, northeast-southwest trending band of gravelly outwash at the eastern end of the project area (Qso in Figure 4). This glaciofluvial material was deposited in a valley between till-covered, ice-cored ridges. Over time, the ice beneath the ridges melted away, leaving the gravel train at a higher elevation than the surrounding till.

Bedrock Topography. The bedrock surface consists of a central, eastward-dipping plateau bounded by highlands to the north and west and bedrock valleys to the northeast and southeast (Figure 5). Maximum relief exceeds 1000 feet. The complex topography suggests a badlands-type preglacial landscape.

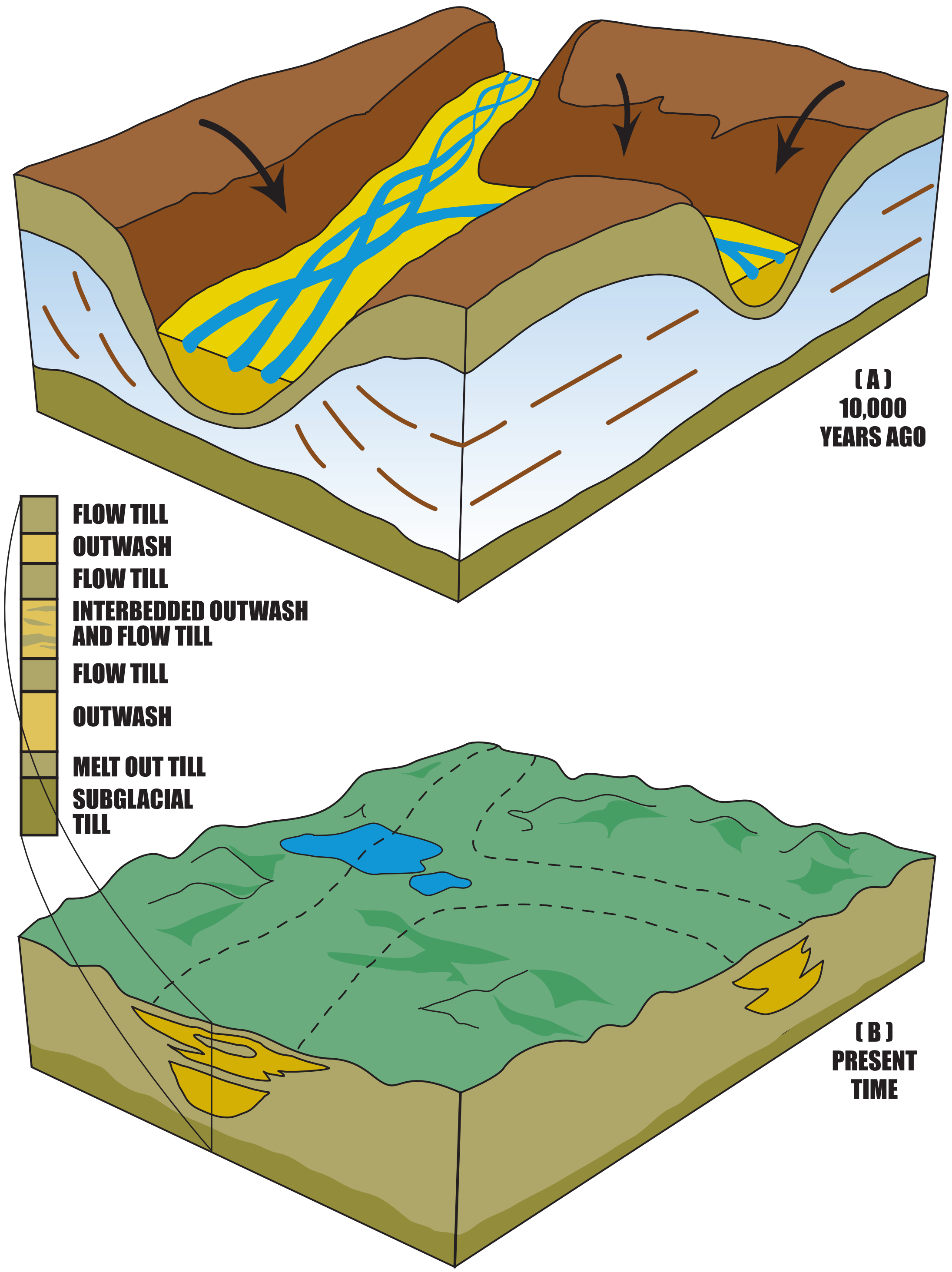


Figure 3. Formation of interbedded outwash and till from a single episode of glacial advance and retreat in an ice-wasting depositional environment. First, glacial ice advances over an area, depositing subglacial till. Later, as the ice retreats and stagnates, a series of ice-cored ridges develops (A). Glaciofluvial sands and gravels are deposited in the intervening valleys by meltwater streams. Till slumping and flowing off the adjacent ice-cored highlands occasionally buries the outwash. Eventually, the meltwater streams become abandoned and buried once and for all by till from the highlands (B). Illustration by Brenda Hove.

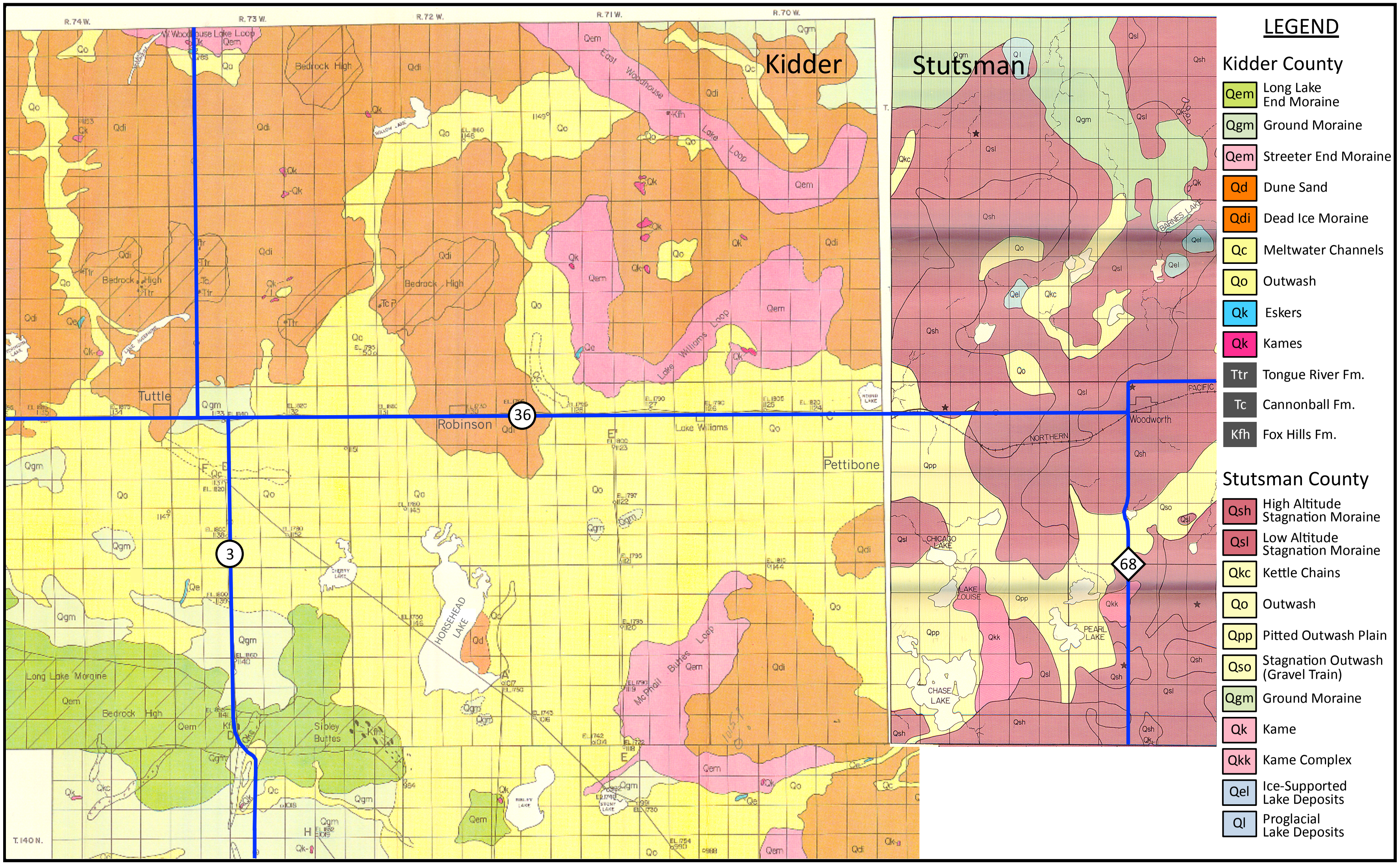


Figure 4. Surficial geology of northern Kidder and northwestern Stutsman Counties. Yellow is outwash. Orange and maroon are hummocky stagnation moraine. Pink and dark green in Kidder County are end moraines. Pink areas in Stutsman County are Kames. Light green is low relief ground moraine. Pale blue is lake sediment. Sources: Rau et al. (1962) and Winters (1963).

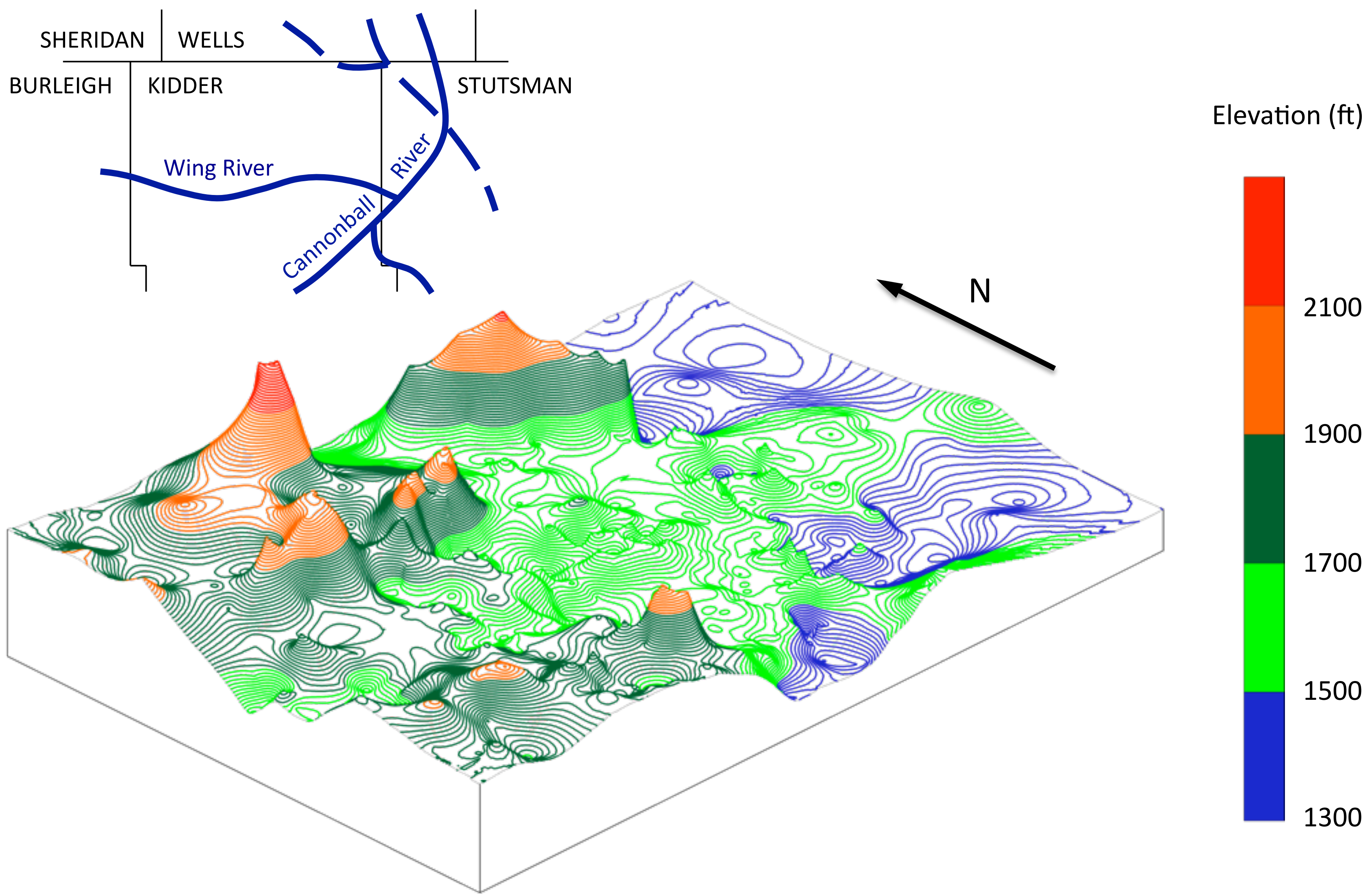


Figure 5. Block diagram of bedrock topography. Note the general increase in elevation from east to west and the bedrock highlands in the north and west. The complex bedrock topography in Kidder County suggests a badlands-type preglacial landscape. The inset shows Bluemle's (2000) interpretation of the courses of the major preglacial streams and glacial diversion channels. Segments of these ancestral river valleys are visible on the block diagram.

The inset at the top of Figure 5 shows Bluemle's interpretation of the courses of major preglacial streams and glacial diversion channels (Bluemle, 2000). Apparently, the Ancestral Wing River flowed to the east across northern Kidder County and emptied into the northerly flowing ancestral Cannonball River near the border between Kidder and Stutsman Counties. An unnamed tributary of the Cannonball entered from the southeast. Further north, a glacial diversion channel crosscut the Cannonball.

The unnamed tributary to the ancestral Cannonball is evident in the southeastern corner of the study area. However, only short segments of the northern diversion channel and the major preglacial river valleys are visible in Figure 5. A segment of the northern diversion channel lies immediately east of the highland in the north central portion of Figure 5. The valley of the ancestral Wing River can be seen where it enters the study area from Burleigh County, but its location is lost in the central portion of the map. Similarly, the valley of the ancestral Cannonball can be located at the southern edge of the study area, but it cannot be traced further north.

Perhaps we cannot trace these ancestral river valleys because their channels are narrow and were missed by the existing test hole and observation well network. Or perhaps, the locations of these valleys have been obscured by the occurrence of ice-shove blocks of bedrock that lie above the actual bedrock surface.

Large, intact blocks of bedrock can be incorporated into a moving glacier if the glacier has a mixed basal thermal regime, and the bedrock contains planes of weakness and layers of confined, permeable materials (Bennett and Glasser, 1996; Blumle, 2000). A glacier with a mixed basal thermal regime has regions of warm ice where the basal ice is constantly melting, and it has regions of cold ice where there is no basal meltwater and the ice is frozen to its bed. The great pressure of the overlying ice creates elevated pore pressures in the confined layers of bedrock. This forces groundwater in the confined units to move toward the margin of the glacier where the pressure is lower. If the migrating groundwater encounters an area where the overlying rock is weaker, it can force the overlying rock up and into the path of the moving glacier (Figure 6).

If the ice above the detached bedrock is warm, the rock will be subject to erosion by meltwater at the base of the glacier. However, if the ice above the detached bedrock is cold, and particularly if the ice had previously been warm and later turned cold, large rafts of previously saturated bedrock can become frozen to the bed of the glacier and entrained in the ice. The basal temperature can change from warm to cold near the edge of a glacier if the ice along the margin thins or the winter air temperatures are low enough to cool the peripheral ice.

Sibley Buttes in west central Kidder County consists of ice-shove blocks of Cretaceous Fox Hills Formation (Figure 4). Similarly, the "Bedrock High" that straddles the border between T143N R73W and T143N R74W on Figure 4 is comprised of ice-shove blocks of Fort Union group sediments. Evidence that these highlands are not bedrock-cored includes the boring log for 14307308CBBA and the chaotic strikes and dips in outcrops (Rau et al., 1962).

Bedrock Geology. The oldest bedrock in the study area that is either exposed at the land surface or is in direct contact with the base of the glacial overburden is the Cretaceous Pierre Formation. In the subsurface, the Pierre Formation is a soft to hard, friable, dark gray to olive black, non-calcareous siltstone, claystone, mudstone, or shale that drills tight and often contains off-white bentonite laminae. The Pierre Formation is effectively impermeable, except where its upper surface is fractured, and it is more than 900 feet thick in west-central Stutsman County (Winters, 1963).

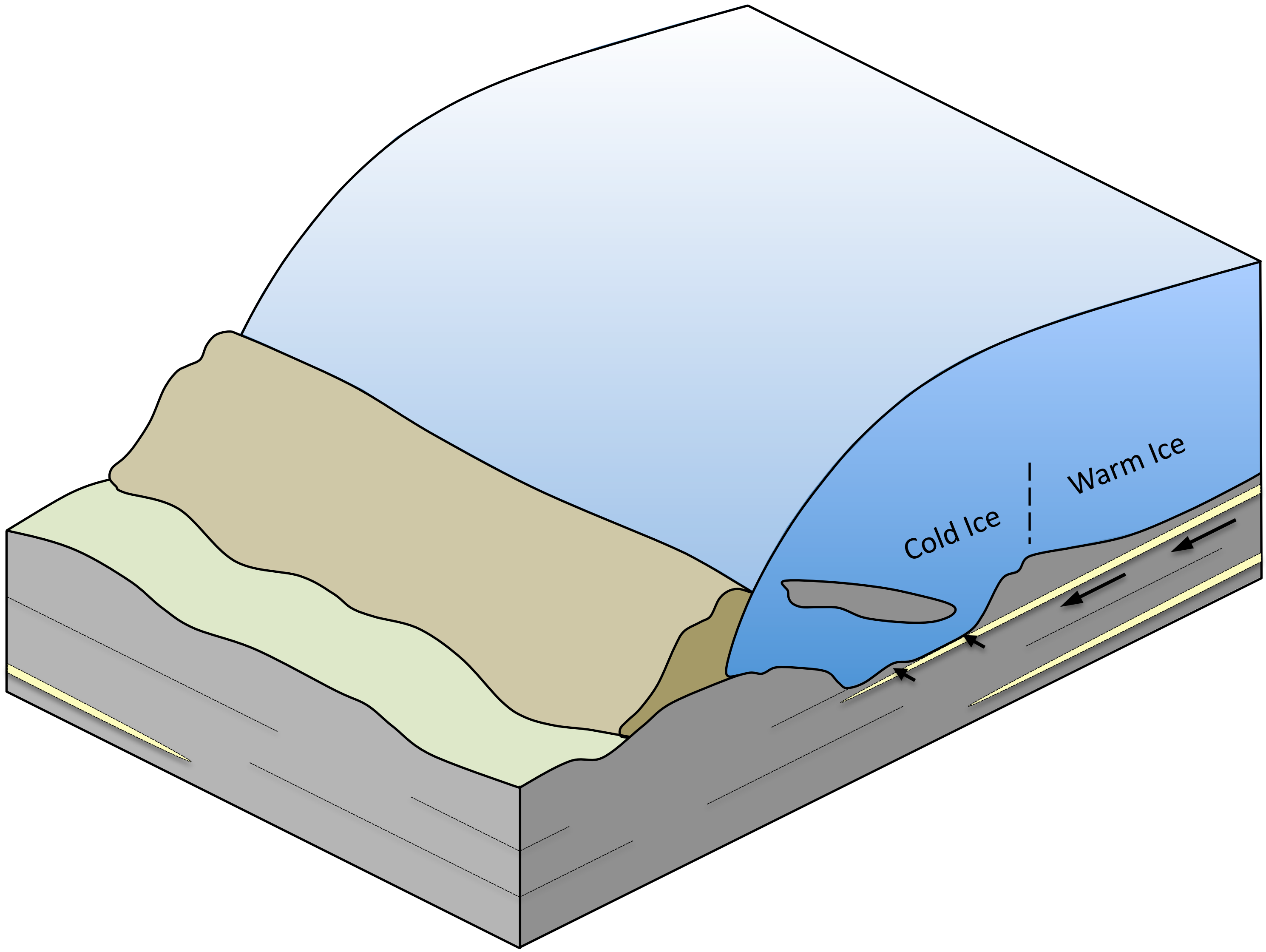


Figure 6. Formation of an ice-shove block. Arrows indicate the direction of groundwater flow.

The Cretaceous Fox Hills Formation overlies the Pierre in southwestern Stutsman County and most of southern and western Kidder County. The Fox Hills Formation consists of greenish-gray to grayish-yellow, fine- to medium-grained, generally friable sandstones interbedded with dark greenish-gray, brownish-gray, and gray siltstones and shales with occasional thin beds of carbonaceous material or bentonite. The Fox Hills is up to 300 feet thick in Stutsman County (Winters, 1963). In Kidder County, several domestic wells and stock wells are screened in the sandstones and sandy siltstones of the Fox Hills Formation, and many of these wells are artesian.

The Fox Hills Formation is the youngest bedrock in Stutsman County (Winters 1963). In Kidder County, the middle unit of the Tertiary (Paleocene) Fort Union Group, the Cannonball Formation, lies directly above the Fox Hills (Rau et al., 1962). The Cannonball Formation consists of olive, greenish-black, and brownish-gray sandstones, siltstones and shales, and lenticular limestones. The sandstones are friable and non-calcareous, unless cemented, and have a "salt and pepper" appearance. The siltstones and shales are non-calcareous, fossiliferous, carbonaceous, and frequently sandy.

The upper unit of the Fort Union Group, Tongue River Formation, is the youngest bedrock in Kidder County. It is a terrestrial formation that consists of a yellowish- to olive-gray basal sandstone with a basal pebble lag and an erosion-resistant limy cap that is overlain by yellowish-brown, olive gray, and brownish-black claystones, shales, and siltstones that are soft, calcareous, and interbedded with lignite (Kume and Hansen, 1965). Known occurrences of Fort Union Group sediments are restricted to highland areas in northwestern Kidder County.

Figure 7 shows the lithology of the bedrock surface at several hundred locations in northern Kidder and northwestern Stutsman Counties. Bedrock lithology is uncertain at many of these locations, because boring log descriptions of bedrock are terse. In numerous logs, the bedrock is simply described as gray shale or siltstone when both the Fox Hills and Pierre Formations contain gray shales and siltstones. In order to differentiate between these two units, more detailed observations of a dark green or olive black color, sandy texture, greasy luster, or calcareous character are needed. Similar problems are encountered when trying to distinguish between the Fox Hills and Fort Union Group sediments, since both units include brownish clays and greenish sands. Defining characteristics for the Fort Union Group include limestone layers and thick sequences of lignite, blackish shale, siltstone, or sandstone, or brown clay.

Since the bedding in most of the Fox Hills outcrops is very nearly horizontal (Rau et al., 1962), elevation data was used in conjunction with boring log data to distinguish between bedrock units. At elevations below 1535 feet, the bedrock was assumed to be Pierre Formation, because the contact between the Fox Hills and Pierre Formations was observed in three widely spaced borings (14207235CCDA1, 14307127AAA, and 14507133CBB) at elevations ranging from 1534-1551 feet. Between 1635 feet and 1770 feet, the bedrock was assumed to be Fox Hills, because the highest observed elevation for the Pierre was 1636 feet in 14007124BBB, and the lowest elevation for the Fort Union Group was 1770 feet in 14007416CCC. Above 1830 feet, the bedrock was assumed to be Fort Union, because the highest observed elevation for the Fox Hills in a State Water Commission (SWC) boring was 1827 feet in 14107433DDD. The outcrop of Fox Hills at 14407123ADA is probably part of an ice-shove block.

Several factors can explain the occasional occurrence of the Pierre Formation at elevations above its observed contact with the Fox Hills. First of all, the regional dip of the bedrock is approximately 2 to 3 degrees to the northwest (Rau et al., 1962), so the Pierre Formation would be expected at higher elevations in the easternmost portions of the study area (e.g., at

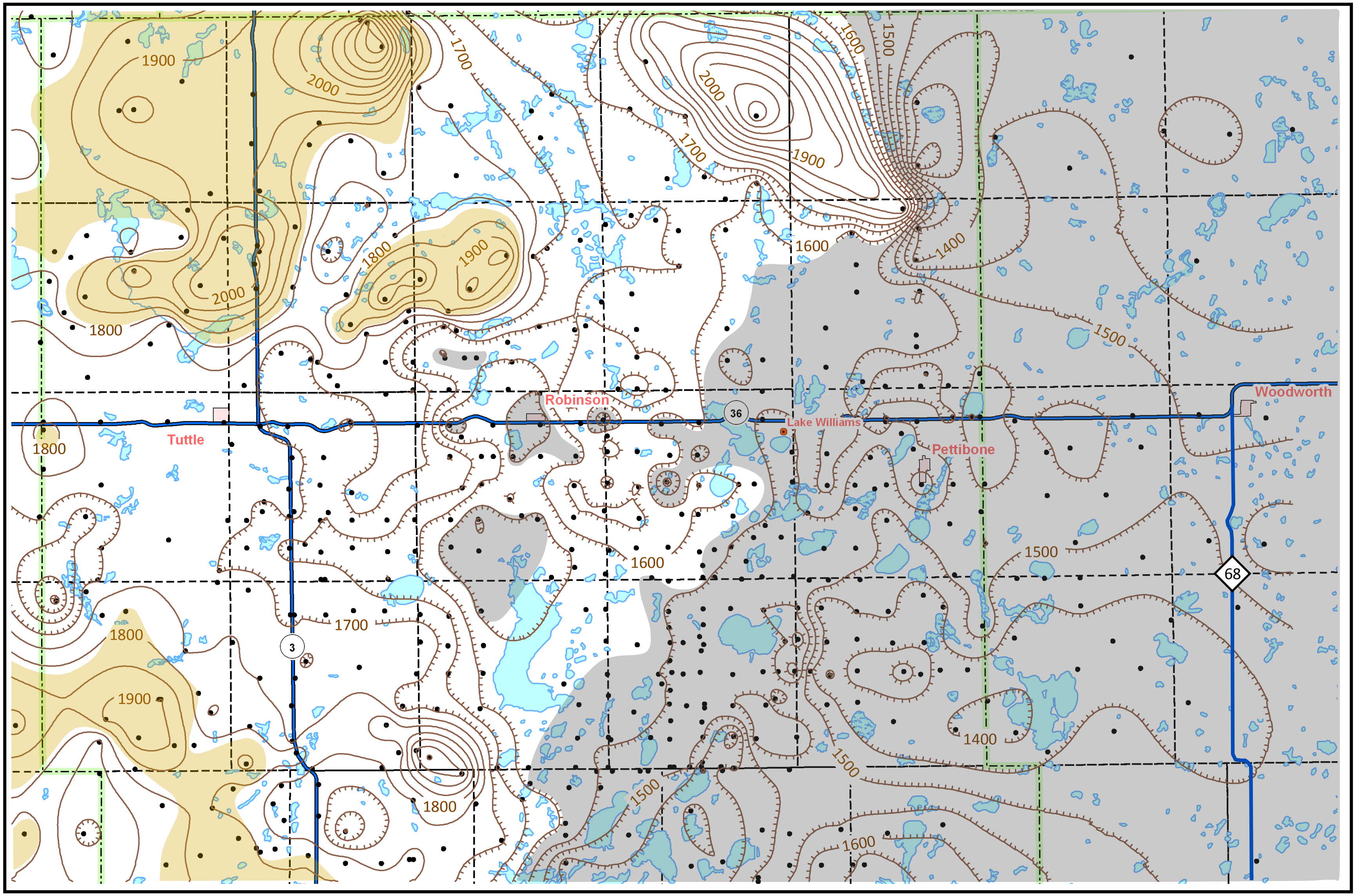


Figure 7. Topography and lithology of the bedrock surface in northern Kidder and northwestern Stutsman Counties. Gray area is the Cretaceous Pierre Formation, white is the Cretaceous Fox Hills Formation, and tan is the Tertiary Fort Union Group. Black dots represent data locations.

14206833AAA). Second, the contact between the two formations is gradational and can be difficult to recognize (Kume and Hansen, 1965). And finally, the Pierre Formation can occur as ice-shove blocks suspended in the glacial overburden.

The author recently encountered several ice-shove blocks of Pierre Shale in borings advanced near Chase Lake (Figure 8). The blocks ranged from 7 to 74 feet thick, and 4 of the blocks concealed sand and gravel deposits ranging from 17 to 110 feet thick. The occurrence of thick sequences of outwash beneath the blocks suggests that personnel working in this area should not automatically terminate drilling as soon as bedrock is encountered in a borehole. Instead, the hydrologist should carefully consider the objective of the drilling program, the elevation of the bedrock in the boring, and the elevations of the aquifers in the surrounding area in his or her decision to cease drilling.

Given the presence of ice-shove blocks near Chase Lake, it is likely that the valley of the ancestral Cannonball River in northeastern Kidder County is hidden beneath a combination of shove blocks and surface water bodies, and possibly exits the county beneath Round Lake (Figure 8). Its course through northwestern Stutsman County is ill defined, but probably follows the northeasterly trending chain of lakes and sloughs in T143N R68W and T143N R69W. The valley reappears in T145N R69W where it follows a northerly route through Wells County (Bluemle et al., 1967).

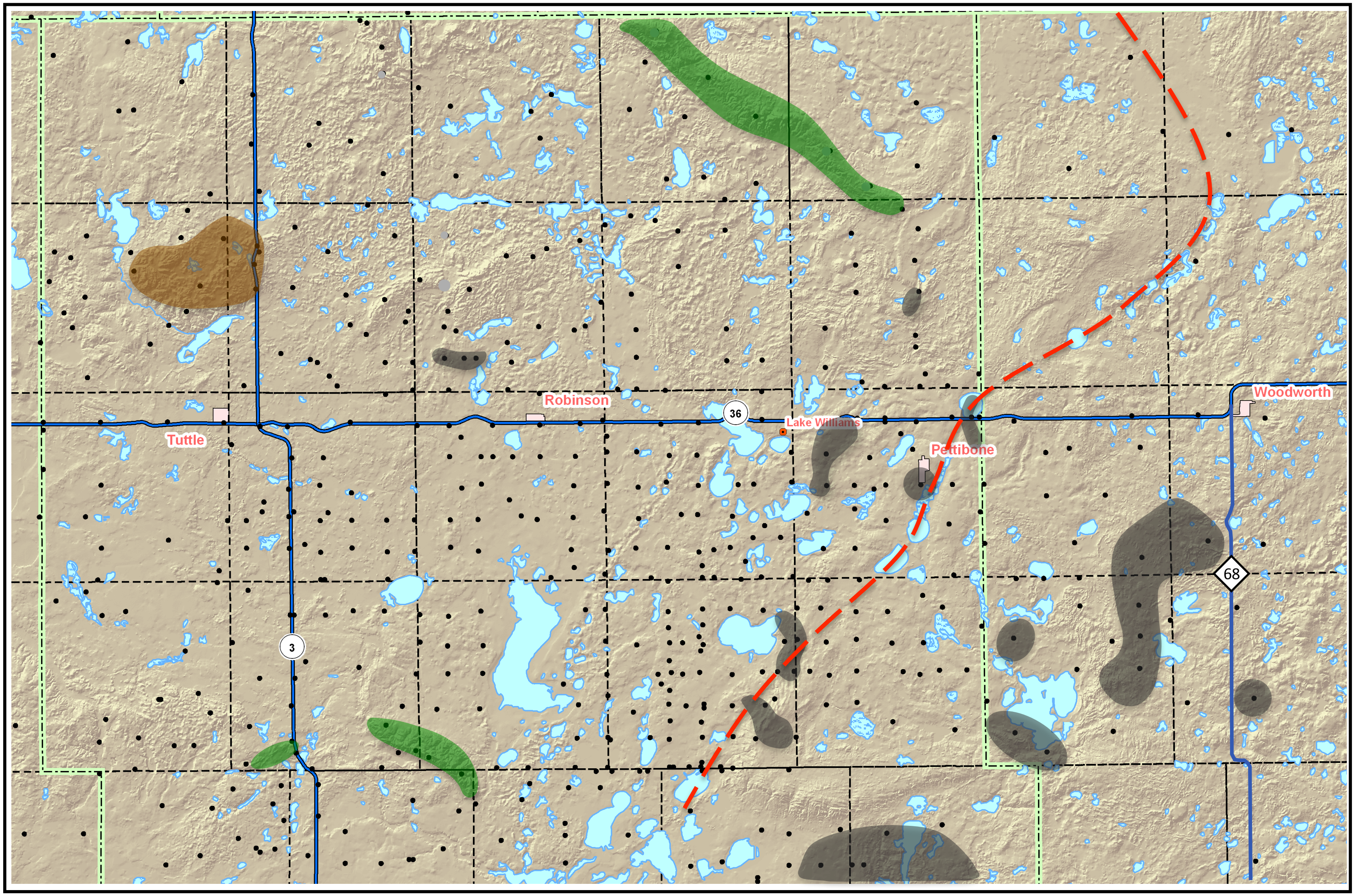


Figure 8. Locations of confirmed and suspected ice-shove blocks. Gray zones contain blocks of the Cretaceous Pierre Formation, green zones contain blocks of the Cretaceous Fox Hills Formation, and the brown zone contains blocks of the Tertiary Fort Union Group. Black dots represent data locations. Red line is the approximate location of the ancestral Cannonball River valley.

CONCEPTUAL HYDROGEOLOGIC MODEL

Glacial Hydrostratigraphy. Detailed subsurface characterization was limited to 14 townships in northeast Kidder and northwest Stutsman Counties where SWC boring log data are plentiful. Initially, more than 100 lithofacies maps were constructed to visualize the lateral distribution of geologic materials at 5 to 10 foot elevation increments. The maps were based on boring log descriptions of lithologic units for 400 SWC test holes. The maps included a few borings in southern Kidder and Stutsman Counties to provide a clearer picture of the hydrostratigraphy along the southern boundary of the study area.

Later, 50 cross sections were created from a larger set of 834 boring logs in order to interpret the lateral and vertical connectedness of lithologic units and delineate hydrostratigraphic units (Figure 9 and Appendix A). The cross sections were based primarily on SWC boring logs and irrigation well logs. Domestic well and stock well logs were consulted in areas lacking sufficient SWC and irrigation well data. Private contractor test hole logs were seldom considered, because it is rarely possible to verify the locations of the borings.

In general, the lithofacies maps and cross sections reveal: 1) a large, collapsed, surficial outwash plain derived from the Streeter drift that occurs at elevations between 1700 feet and 1900 feet; 2) an underlying clay-rich aquitard typically found between 1650 feet and 1700 feet; 3) a narrower, north-south trending body of collapsed outwash that lies at 1580-1650 feet (Figure 10); and 4) several deeper, isolated, sand and gravel bodies that lie in ancestral river channels (Figure 11). The surficial outwash and north-south trending buried outwash constitute the upper and lower members of the Central Dakota Aquifer System, respectively. The deeper, isolated sand and gravel deposits are not considered a part of the aquifer system – their small size, presumably poor water quality, and great depth below the land surface render them poor appropriation targets.

Rau et al. (1962) described the surficial outwash plain as “variable in texture, depending on the proximity of its source area, and becoming especially coarse close to the border of the … drift from which it was derived”. Accordingly, the upper aquifer consists of coarse sands and bouldery gravels near the till highlands north of Highway 36 and southwest of Woodworth. Grain size and aquifer thickness generally decrease to the south with increasing distance from the highland source area, and the outwash tends to be dominated by fine to medium sand and silt near the southern end of the study area.

Cross sections show that the lower aquifer is strongly heterogeneous (e.g., Figures A15 and A16). Lithologic units range from fine sands, muddy sands, and interbedded clays and sands to coarse sands and gravels, and all of these units may occur in a single stratigraphic section. The heterogeneous lithology and collapsed nature of the buried outwash produce a spatially variable transmissivity. The direction of maximum continuity for aquifer thickness coincides with the longitudinal (north-south trending) axis of the lower aquifer.

Figure 12 is a block diagram that summarizes the information contained in the cross sections and lithofacies maps. Obviously, deviations from this idealized representation occur throughout the study area. A few of these deviations are discussed below.

The hydrostratigraphy in Marstonmoor Township (T142N R69W) resembles Figure 12 with the exception of the lower aquifer, which is absent (Figure 13). Saturated thickness in the upper aquifer can exceed 100 feet (Figures 14 and 15), and the aquifer is often buried beneath the till in the local highlands. To the south, in Chase Lake and Iosco Counties, there appear to be

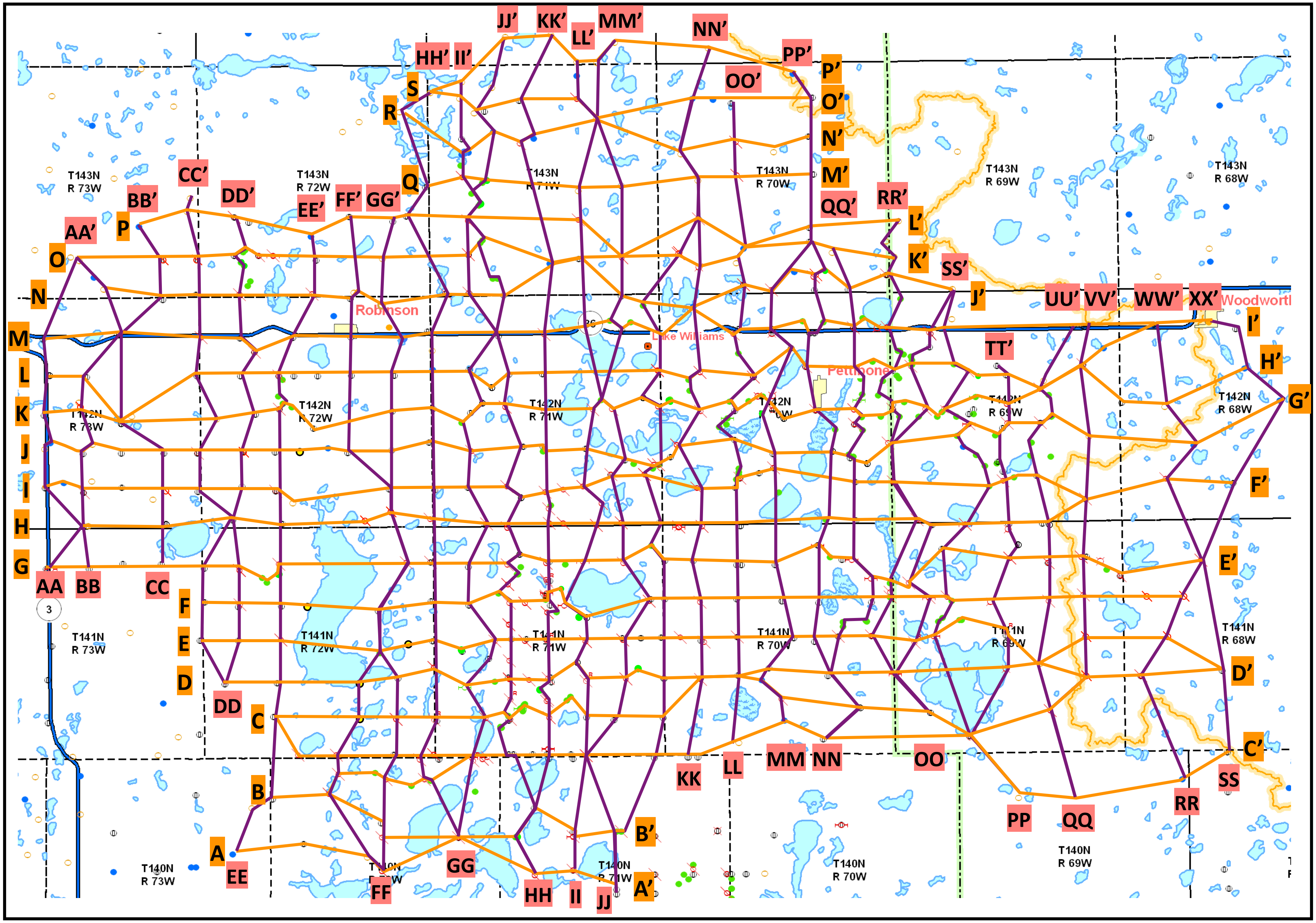


Figure 9. Locations of geologic cross sections. Cross sections extend a short distance into the southern halves of Kidder and Stutsman Counties to better describe the southern boundary of the study area. Yellow line is the eastern boundary of the Apple Creek Watershed.

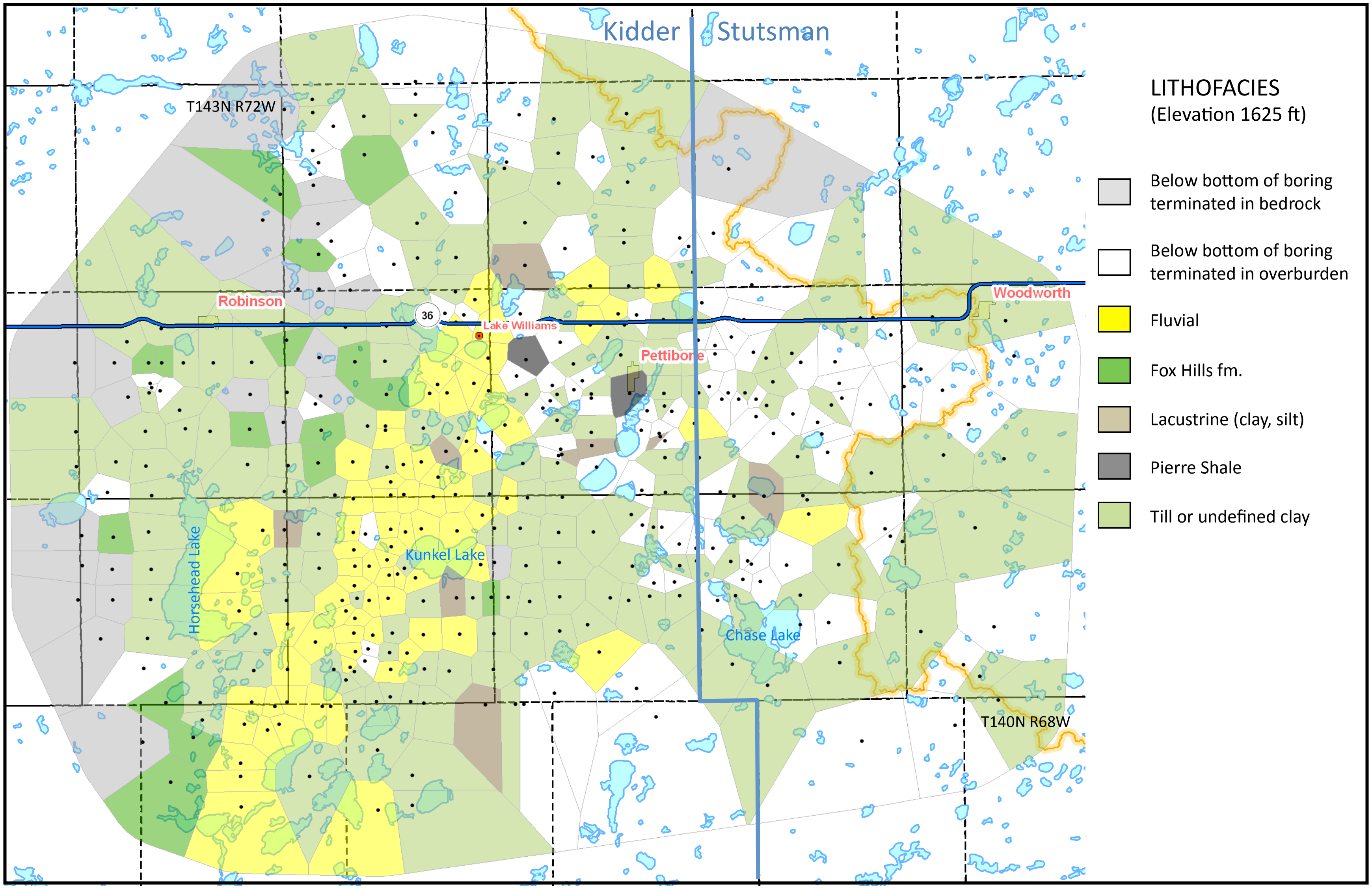


Figure 10. Lithologic units at an elevation of 1625 ft. Polygon size and shape are a function of the locations of the nearest neighboring borings, such that polygons are large where borings are sparse. This image, which was created in 2007, reveals a north-south trending confined aquifer that originates north of Pettibone and extends into southern Kidder County. More recent test drilling has revealed another confined aquifer at this elevation east and northeast of Chase Lake.

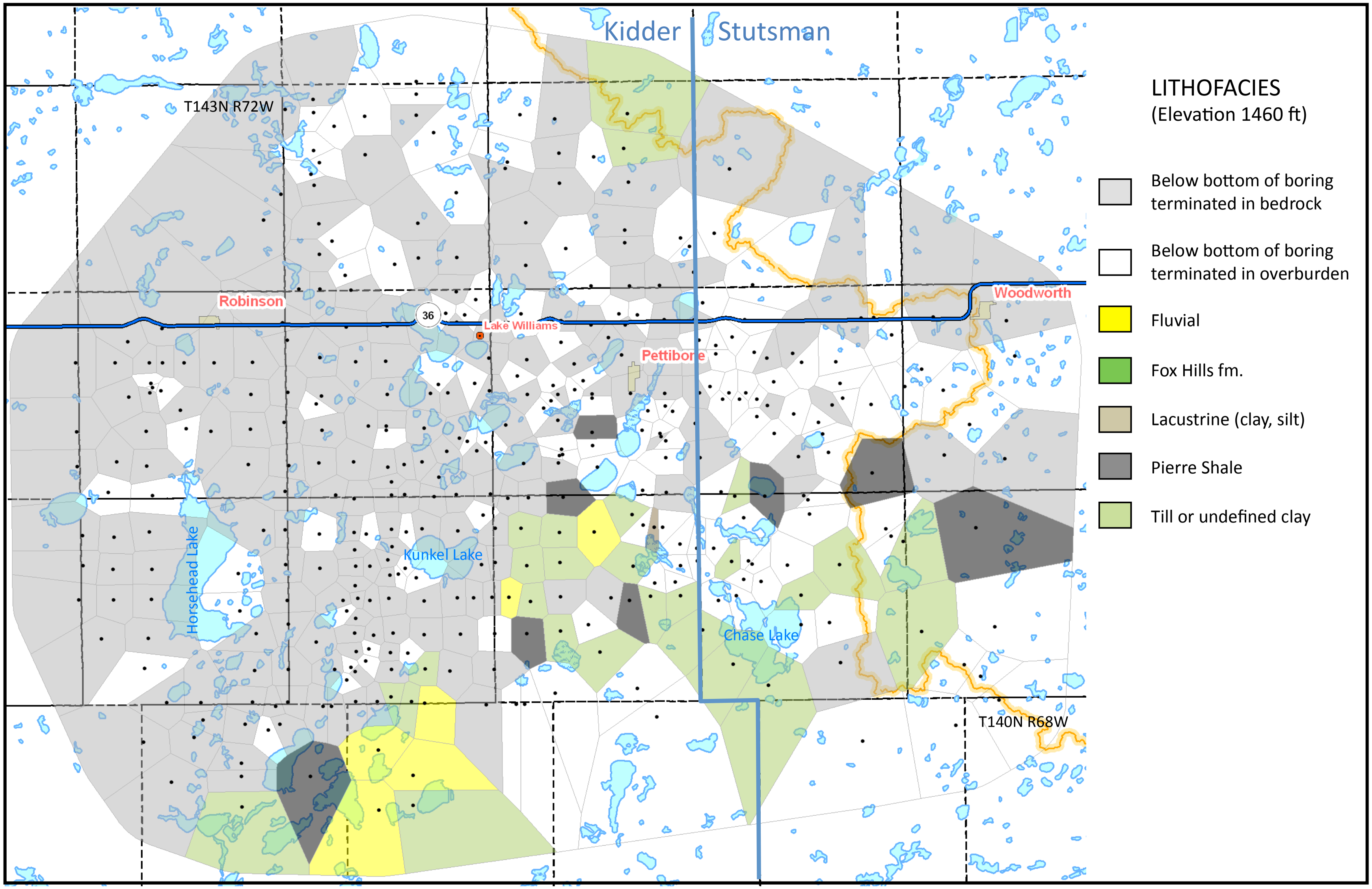


Figure 11. Lithologic units at an elevation of 1460 ft. Note the fluvial deposits deep in the valley of the ancestral Cannonball River.

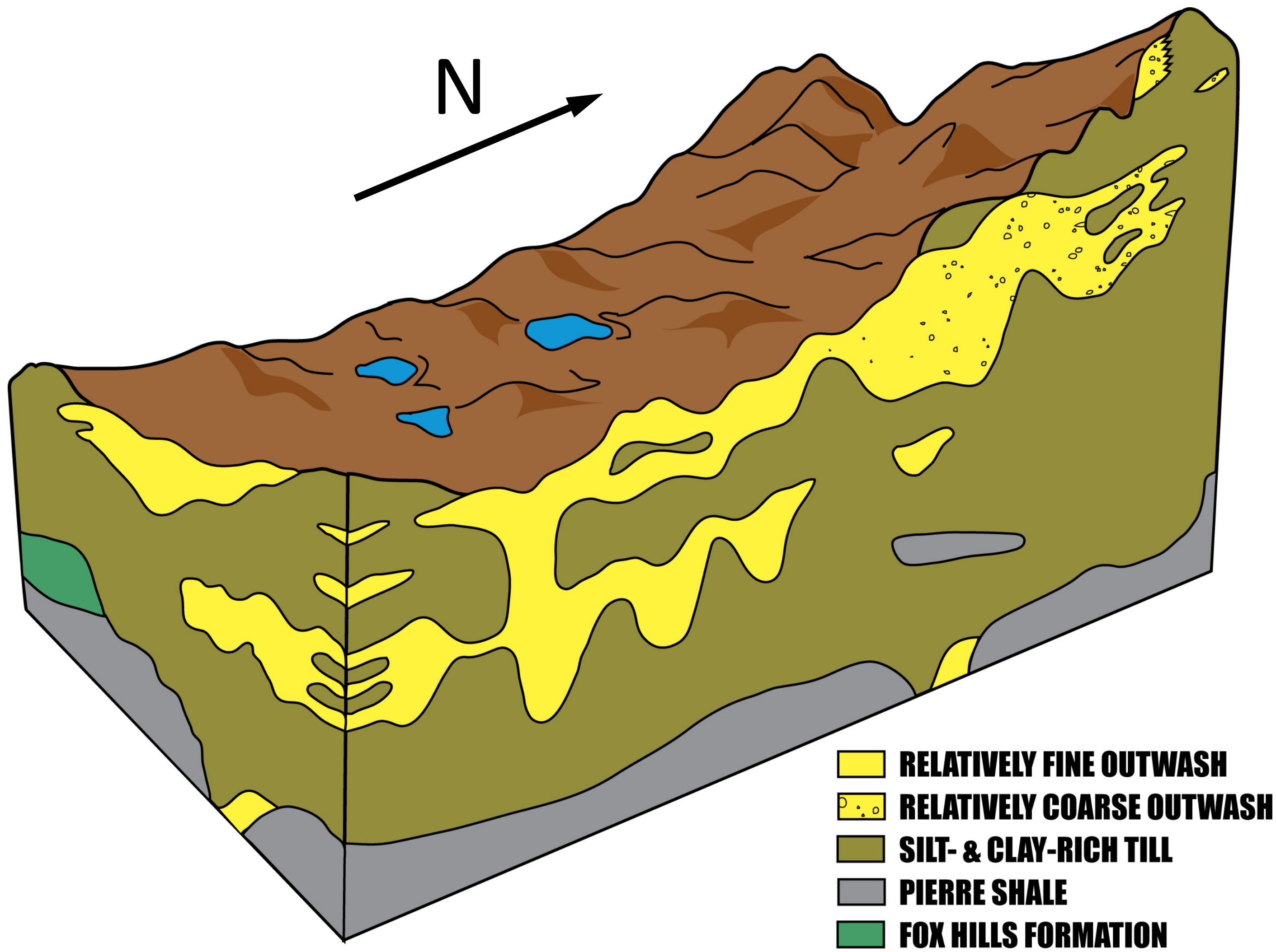


Figure 12. Conceptual block diagram of the hydrogeology of northeastern Kidder and northwestern Stutsman Counties showing: upper and lower aquifers composed of collapsed outwash, isolated sand and gravel deposits in deep bedrock valleys, and ice-shove blocks of bedrock that occasionally conceal lower-lying sands and gravels. Notice that the northern boundary of the upper aquifer is buried beneath the till highlands, and the aquifer fines and thins to the south. The block diagram also shows the presence of isolated recharge areas in the till highlands, direct connections between the upper and lower aquifers, and discontinuous layers of till within the aquifers. Illustration by Brenda Hove.

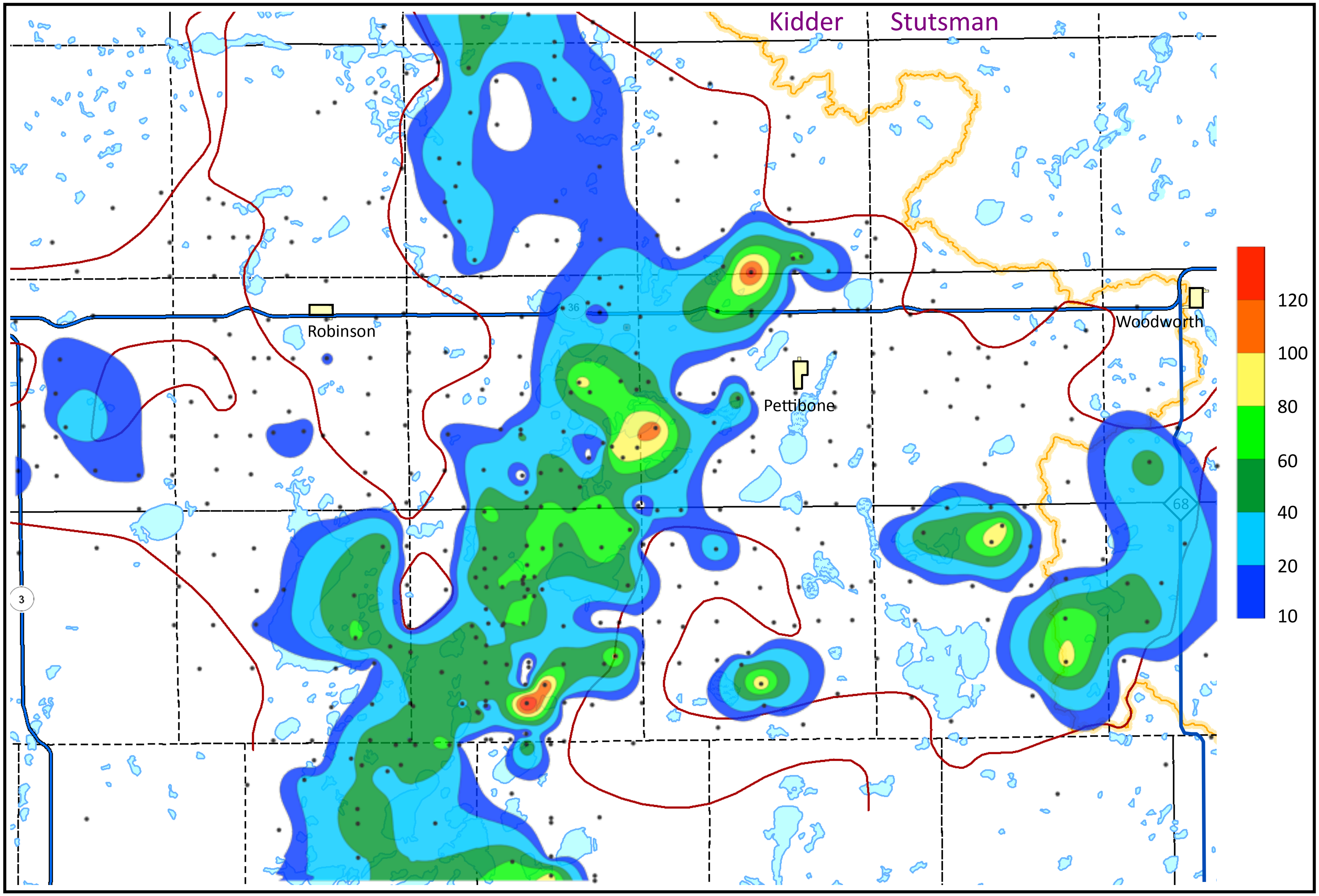


Figure 13. Thickness of sand and gravel (ft) in the lower aquifer. Yellow line is the eastern boundary of the Apple Creek Watershed. Red lines are the approximate boundaries of the Central Dakota Aquifer System.

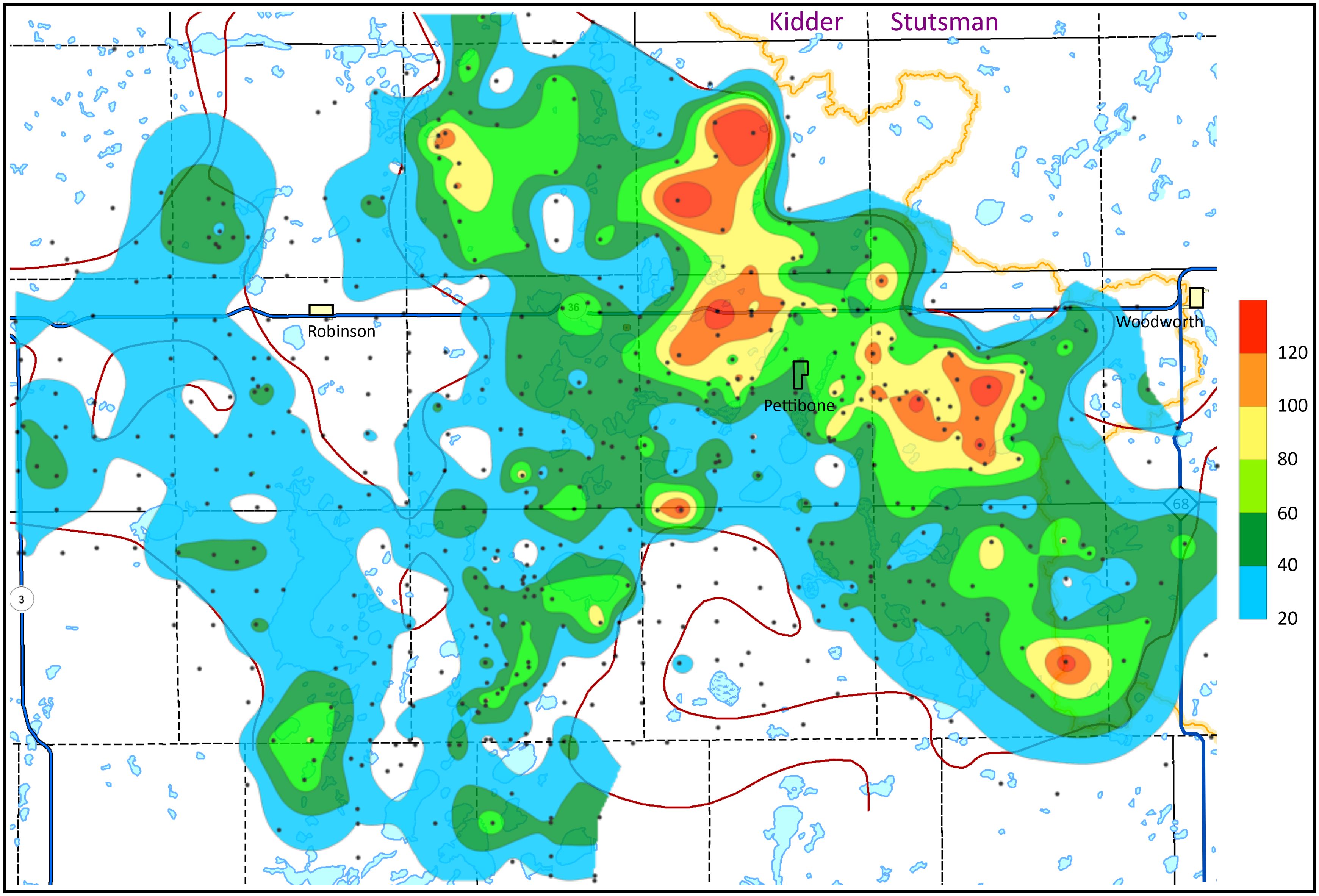


Figure 14. Thickness of sand and gravel (ft) in the upper aquifer. The map includes sand and gravel deposits that lie between the upper and lower aquifers.

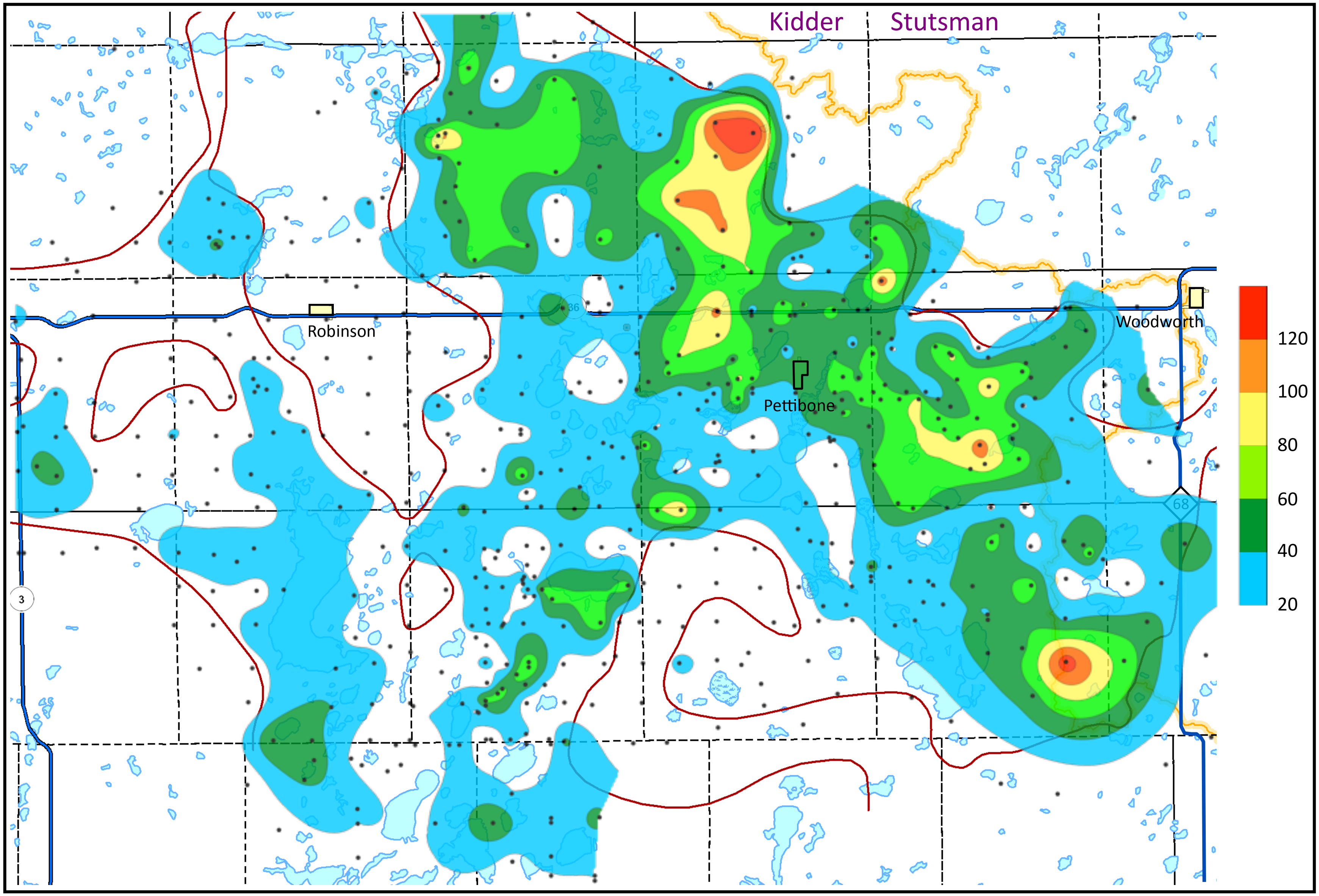


Figure 15. Saturated thickness of sand and gravel (ft) in the upper aquifer. Comparison with Figure 14 reveals thick sequences of sand and gravel above the water table in many areas.

three aquifers east of Chase Lake: an unconfined aquifer, an upper confined aquifer, and a lower confined aquifer (far right on cross sections ED', FE', and GE' in Figures A4 and A5). The associations of these three aquifers with the upper and lower members of the Central Dakota Aquifer System north and west of Chase Lake will be discussed in more detail in the section on groundwater flow.

The permeable hydrostratigraphic units in the Horsehead Lake area include the upper aquifer and two, buried, meandering, sand and gravel bodies (Figures 16, A4, and A5). The shallow buried channel system lies at an elevation of approximately 1650-1710 feet. One branch of this system trends west to east and may follow the course of the ancestral Wing River; the other two branches trend north to south. The three branches coalesce beneath Horsehead Lake (Figure 16). South of the lake, the channel system merges with the upper aquifer (cross section FFFF' in Figure A12).

The deeper channel system lies at an elevation of 1560-1650 feet. This deeper system may also follow the course of the ancestral Wing River west of Horsehead Lake (Figure 16). At the lake, the system trends to the south and merges with the main body of the lower aquifer near the southeast terminus of the lake (Figure 13).

South of the study area the Central Dakota Aquifer System consists of a surficial aquifer, a shallow semi-confined aquifer, and a deeper confined aquifer. The surficial aquifer lies in the distal, and therefore relatively thin and fine-textured portion of the Streeter outwash plain. The shallow semi-confined aquifer is the southern extension of the shallow buried channel system, and the deeper confined aquifer is the southern continuation of the lower aquifer.

Groundwater Flow. Potentiometric contour maps were generated from water level measurements taken by SWC staff in April 2010. The upper aquifer dataset was supplemented by information from two other sources: boring log observations of redox boundaries in test holes along the flanks of till highlands, and lake elevations posted on USGS 7.5 minute topographic quadrangle maps. Redox boundaries (i.e., boundaries between reduced and oxidized sediments) were used to estimate the position of the water table along the flanks of till highlands where water level measurements were lacking. Posted lake elevations were used in areas where outwash was exposed at the land surface and the lakes were not gauged. These lake level measurements constrained the height of the water table in depressional areas where contours based on SWC data alone would have placed the water table far above the lakes and surrounding land surface. In most cases, five feet were added to the non-gauged lake elevations posted on the USGS maps, because water levels at the gauged lakes were approximately five feet higher in April 2010 than they were on the USGS maps.

According to the potentiometric contour maps, groundwater in the upper aquifer moves from the highlands in the northern, eastern, and south-central portions of the study area to four terminal lakes: Sink Lake, Horsehead Lake, Kunkel Lake, and Chase Lake (Figure 17). Groundwater flow is fastest where the land surface elevation changes rapidly. In all probability, the pitted outwash contains smaller-scale groundwater flow systems (Toth, 1963; Freeze and Witherspoon, 1967) that are not visible on the map.

In the lower aquifer, groundwater generally flows from north to south (Figure 18). Flow appears to be westerly in Stutsman County; however, additional test drilling is needed to improve our understanding of the geometry of the lower aquifer and the direction of groundwater flow in this part of the study area. Based on available information, it appears that the lower aquifer in Stutsman County is not connected to the lower aquifer in Kidder County (see Figure 13).

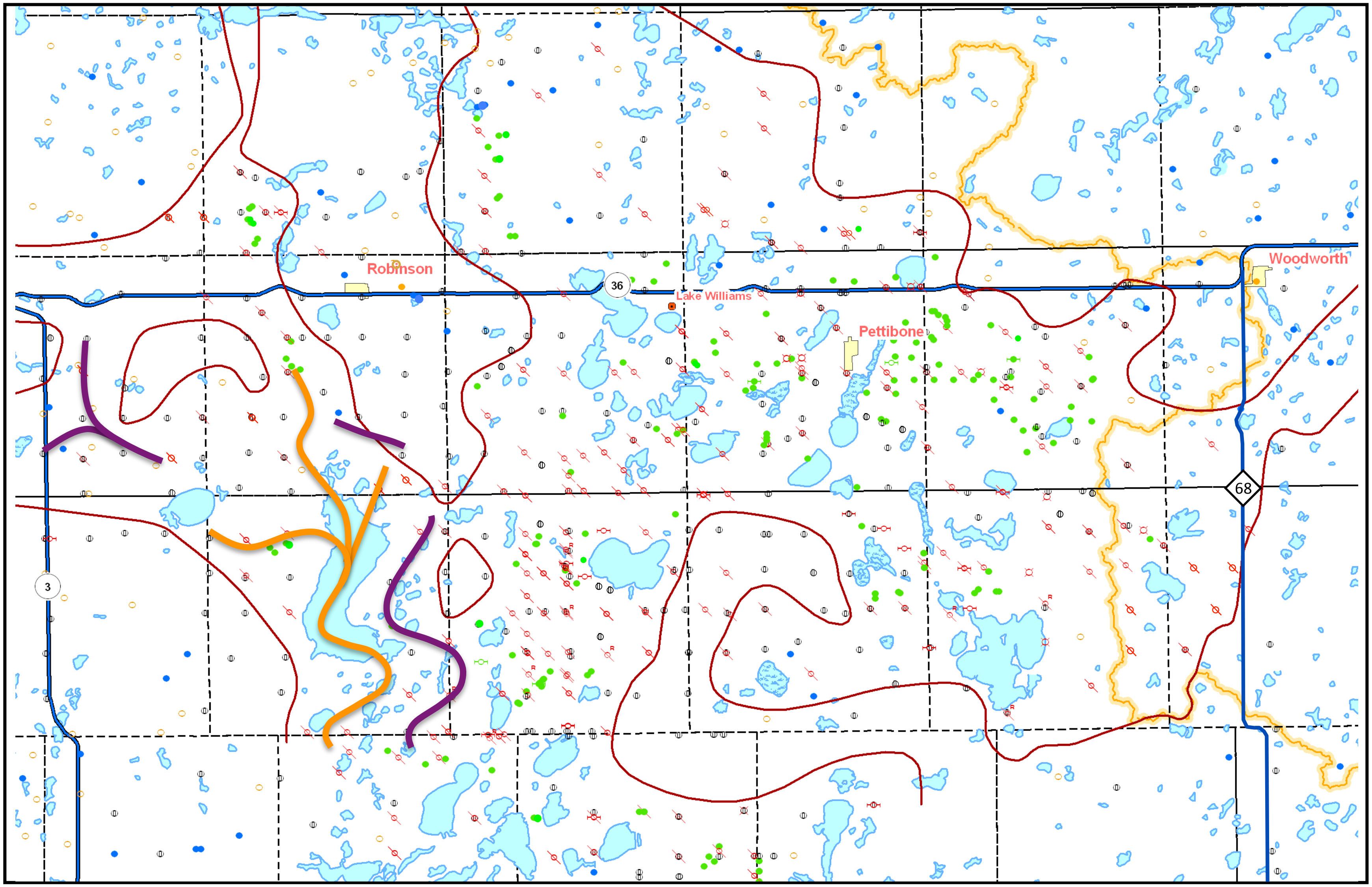


Figure 16. Approximate longitudinal axes of buried outwash channels in the Horsehead Lake area. The shallow buried channel system (shown in orange) lies at an elevation of approximately 1650-1710 ft and merges with the upper aquifer south of Horsehead Lake. The deeper channel system (shown in purple) lies at an elevation of 1560-1650 ft. This deeper system merges with the lower aquifer near the southeast shore of Horsehead Lake. Notice that Horsehead Lake follows the meanders in these buried channel deposits.

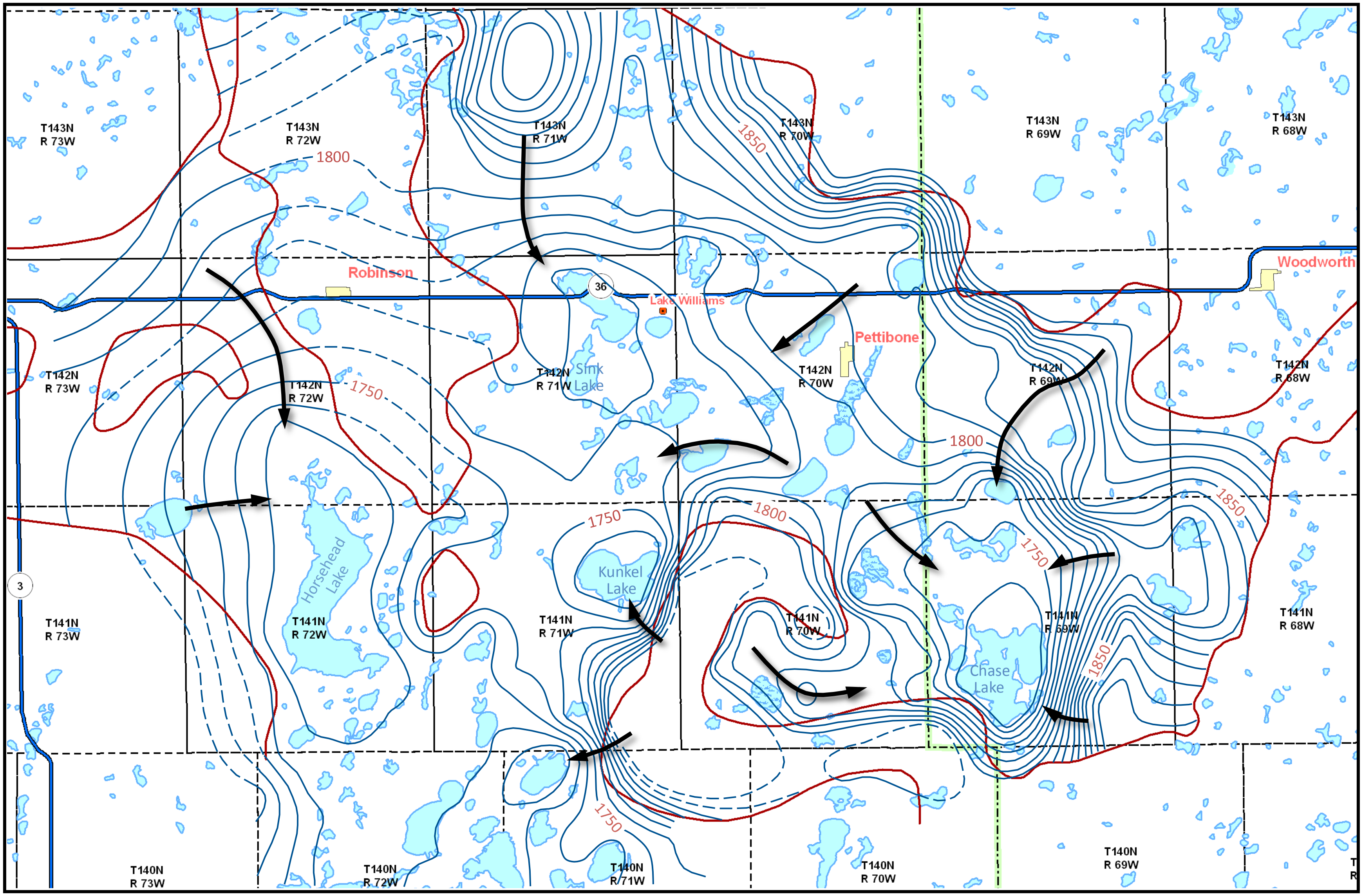


Figure 17. Potentiometric surface for the upper aquifer (April 2010). Black arrows indicate the direction of groundwater flow. Note the northeast-southwest trending hydrologic divide that runs through T142N R70W and T141N R70W and separates the Chase Lake area from the rest of the study area. The groundwater divide appears to be caused by the recessional moraine west of Chase Lake.

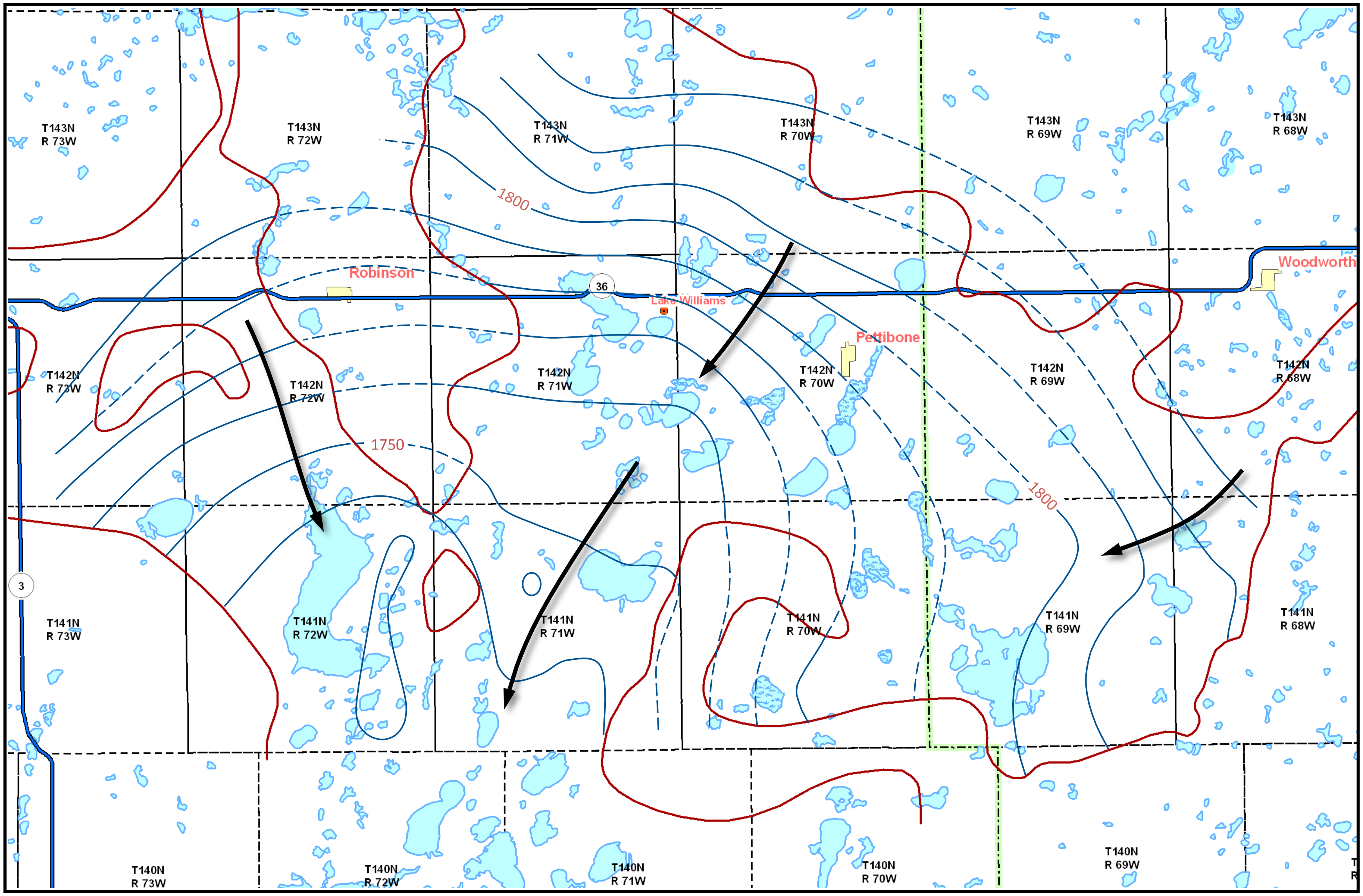


Figure 18. Potentiometric surface for the lower aquifer (April 2010). The lower aquifer in Stutsman County appears to be physically isolated from the lower aquifer in Kidder County (see Figure 13).

Instead, the lower aquifer in Stutsman County merges with the upper aquifer just north of Chase Lake and ultimately discharges to the lake. This interpretation is based on water level responses in several upper aquifer wells to the capping and uncapping of the artesian, lower aquifer well at 14106903CABA.

East of Chase Lake, there are three aquifers: an unconfined aquifer and two confined aquifers (far right on cross sections ED', FE', and GE' in Figures A4 and A5). The lower confined aquifer occurs at roughly the same elevation as the lower aquifer in Kidder County and was discussed in the previous paragraph. The upper confined aquifer occurs at the same elevation as the upper aquifer north and west of Chase Lake. Figure A3 reveals a possible connection between the upper confined aquifer and the upper aquifer at Chase Lake; however, the connection is south of Pearl Lake, and there is a hydrologic divide south of Pearl Lake that causes the upper confined groundwater east of the divide to flow toward Pearl Lake rather than Chase Lake (Figure 19).

Near Pearl Lake, the upper confined groundwater may merge with the unconfined groundwater and discharge to the lake (far right on cross section GE' in Figure A5). Alternatively, the upper confined groundwater may flow beneath Pearl Lake and pass to the north of 14106914DDD en route to Chase Lake (Figure 19). Available evidence favors the former scenario; the latter scenario requires not only that the upper confined and unconfined aquifers are disconnected, but also that the upper confined aquifer extends north and west of 14106914DDD and connects with the upper aquifer north of Chase Lake.

The flow situation in the unconfined aquifer east of Chase Lake is similar to the upper confined aquifer. The surficial sands and gravels east of Chase Lake are physically connected to the upper aquifer sediments north and west of the lake (Figures 4 and A5). However, the Apple Creek watershed divide just east of Chase Lake appears to be a hydrologic divide for the unconfined groundwater, such that the unconfined groundwater east of the divide discharges to Pearl Lake rather than Chase Lake (Figure 20). A less likely situation is that after converging at Pearl Lake, the unconfined groundwater flows to the west, crosses the surface water divide south of 14106902DDD, and discharges to Chase Lake (Figure 20). Water level data are inconclusive, because there are no observation wells in the unconfined aquifer north of 14106914DDD2 (where the water level is much higher than Pearl Lake) or south of 14106902DDD2 (where the water level is slightly higher than Pearl Lake). Water chemistry data are also inconclusive, because Pearl Lake has roughly the same salinity as both Horsehead Lake (a terminal lake) and Des Moines Lake (a flow through lake). In 2001, the concentrations of dissolved solids in Pearl, Horsehead, and Des Moines Lakes were 1920, 2020, and 2460 milligrams per liter, respectively. In three other terminal lakes (Kunkel Lake, Sink Lake, and Chase Lake) the water was much more saline, with concentrations of dissolved solids ranging from 5300-13,700 milligrams per liter.

Aquifer Recharge. The upper aquifer is recharged primarily by precipitation that falls in late autumn through early spring (Figure 21; Sloan, 1972; Winter and Rosenberry, 1995). Although recharge is areally distributed on the pitted outwash plain, it may be more significant in depressional areas within the plain (Lissey, 1971; Freeze and Cherry, 1979; Labaugh et al., 1987). In the till highlands, recharge appears to occur at discrete locations where the upper aquifer extends to the land surface; for example, at 14307015BCBC, 14307029BBB, 14307124BBC, 14407133BCBA, and several locations in eastern Marstonmoor Township.

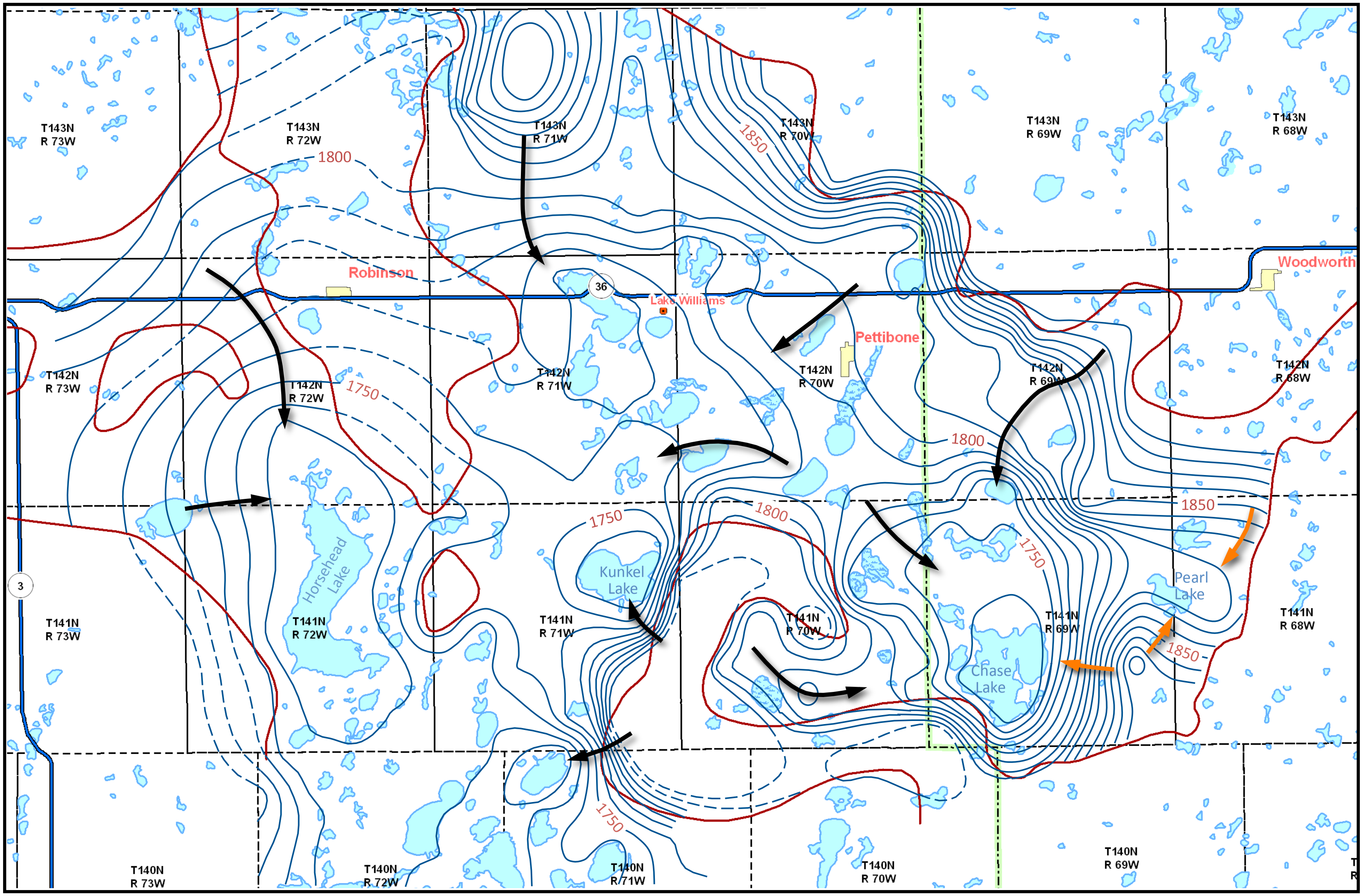


Figure 19. Potentiometric surface for the upper aquifer (April 2010) north and west of Chase Lake and the upper confined aquifer east of Chase Lake. (Figure 16 is based on water levels in the unconfined aquifer east of Chase Lake.) Orange arrows indicate flow paths in the upper confined aquifer.

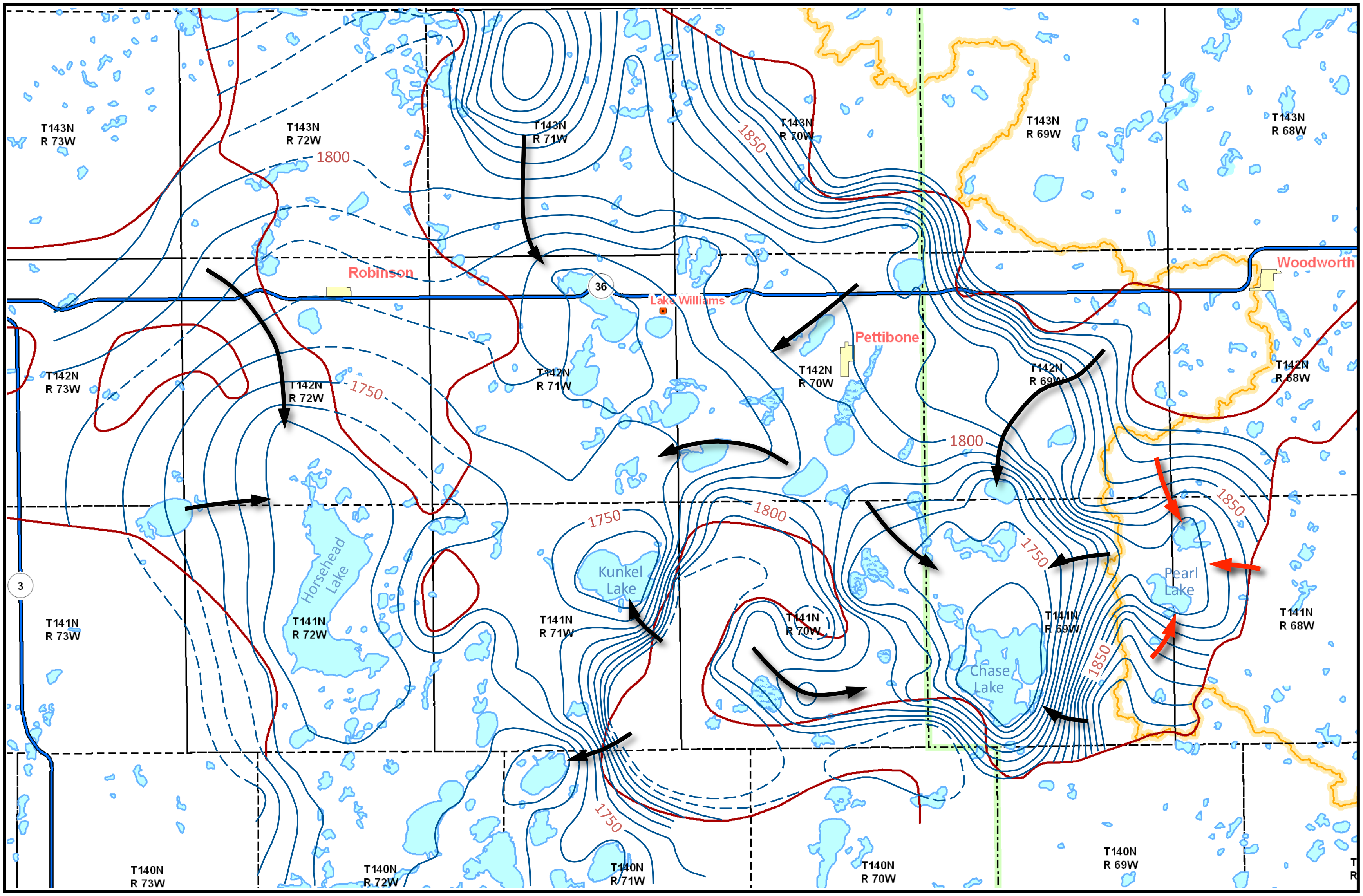


Figure 20. Potentiometric surface for the upper aquifer (April 2010) showing that groundwater in the unconfined aquifer east of the Apple Creek watershed divide discharges to Pearl Lake (red arrows). It is possible, but less likely, that Pearl Lake is a flow through lake rather than a terminal lake and that after converging at the lake, the unconfined groundwater flows west beneath the divide and ultimately discharges to Chase Lake.

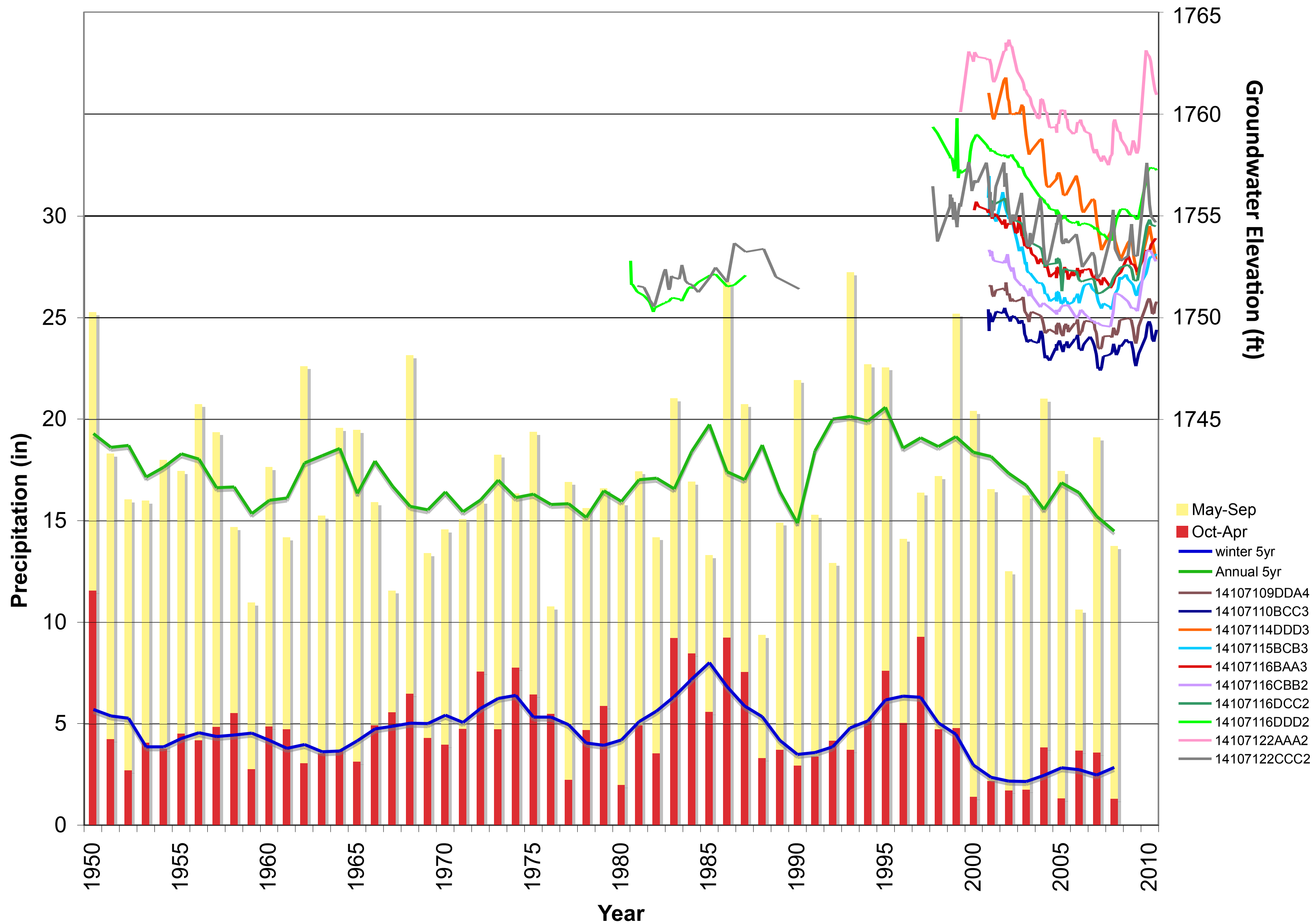


Figure 21. Hydrographs for ten upper aquifer wells in Buckeye Township (T141N R71W) superimposed on precipitation data from the Pettibone weather station. Note the dearth of winter precipitation from 2000 to 2008 and the concomitant decline in upper aquifer water levels.

Recharge to the lower aquifer most likely occurs by several mechanisms, including direct connections between the upper and lower aquifers. Lithologic information suggests that direct connections exist near 14106820BBB, 14106830ABB, 14106914BBB, 14106926AAA, 14106912ACBA, 14107115BAA, 14107134BBB, 14207004CCC, 14307118DA, and 14307132D (Figures A2, A3, A5, A8, A14, A15, and A21). Extremely low concentrations of sodium, sulfate, and dissolved solids in the deep groundwater at 14107122AAA suggest there is a direct connection nearby. Water level responses to the capping and uncapping of flowing well 14106903CABA indicate a direct connection north of Chase Lake near 14106914BBB. Indeed, direct connections may be commonplace given the rapid, post-irrigation recovery of water levels in lower aquifer wells. Hydrographs show that by May of any given year, lower aquifer water levels throughout the study area have recovered to within one foot of the previous May levels, even though the head may have dropped more than 60 feet during the intervening growing season (Figure 22). If the fall and winter following irrigation were relatively dry, the subsequent May water levels were approximately one foot lower; if the fall and winter were relatively wet, the May water levels were about one foot higher.

Water Quality. Rain and melted snow are extremely dilute and saturated with atmospheric oxygen and carbon dioxide. Since carbon dioxide and water combine to form carbonic acid, rain and melted snow are not only dilute and oxidizing, they are also acidic, and they react with the minerals and organic matter they encounter as they infiltrate and flow through the subsurface. As the groundwater moves from recharge to discharge areas, its major ion chemistry is largely controlled by mineral availability and solubility. Consequently, shallow groundwater in recharge areas tends to have low concentrations of dissolved solids, and the dominant cations and anions are often calcium and bicarbonate, respectively, from the dissolution of relatively abundant and moderately soluble carbonate minerals. As travel time and distance increase, the concentrations of dissolved solids increase, and the dominant anion may change from bicarbonate to sulfate and then perhaps to chloride as the groundwater has more opportunity to encounter less abundant but more soluble minerals such as gypsum and halite. Deviations from this evolutionary sequence may occur due to oxidation-reduction reactions, cation exchange reactions, and variations in mineral availability.

Figure 23 is a Piper diagram depicting the relative abundances of major ions in water samples collected from the upper aquifer within the past five years. Calcium was the dominant cation and bicarbonate the dominant anion at the majority of sampling locations. Concentrations of dissolved solids were less than 500 milligrams per liter in 62 percent of the samples, and with very few exceptions, the relative abundances of potassium and chloride were extremely low. The calcium-bicarbonate dominated chemistry, low to moderate abundance of sulfate, and low concentrations of dissolved solids indicate that the shallow groundwater is generally young and has not traveled far from its point of infiltration. The few samples with high concentrations of dissolved solids tended to be sodium-rich and were often found beneath or adjacent to till highlands where travel distances tended to be greater and opportunities for dilution by infiltrating precipitation were few and far between.

The major ion chemistry in the lower aquifer was similar to the upper aquifer (Figure 24). Bicarbonate was the dominant anion in all but three of the samples, and calcium was often the dominant cation. However, concentrations of dissolved solids were higher (only 7 percent of the samples had less than 500 mg/l), a larger proportion of samples had sodium as the dominant cation, and the relative abundance of chloride tended to be higher. These findings suggest that water in the lower aquifer is older and has traveled longer distances than water in the upper aquifer.

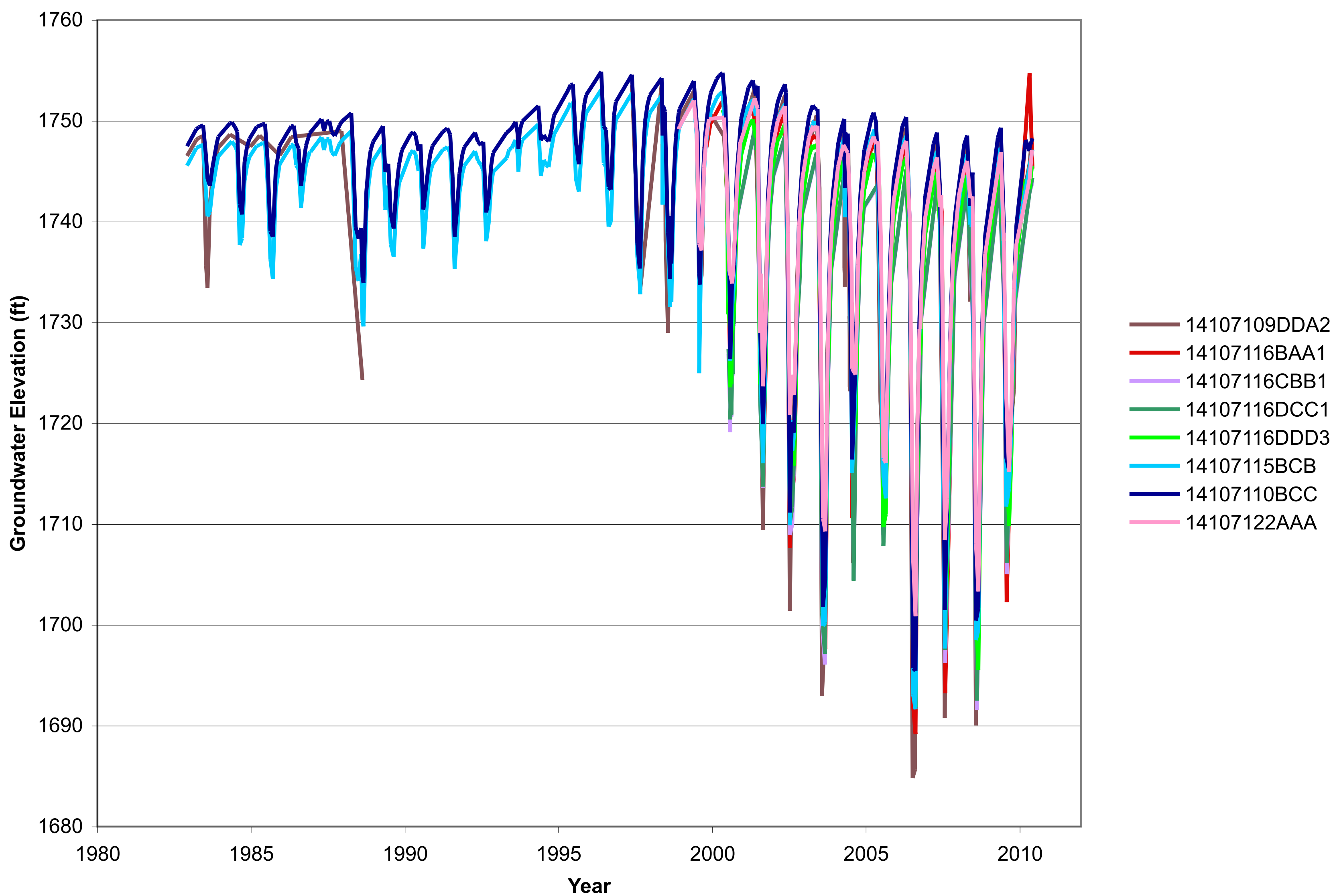


Figure 22. Hydrographs for eight lower aquifer wells in Buckeye Township (T141N R71W). The chart shows that: 1) annual changes in springtime water levels are generally less than one foot per year, 2) aquifer water levels are currently recovering from eight years of below average October through April precipitation, and 3) springtime water levels in 2009 were essentially the same as water levels twenty years ago.

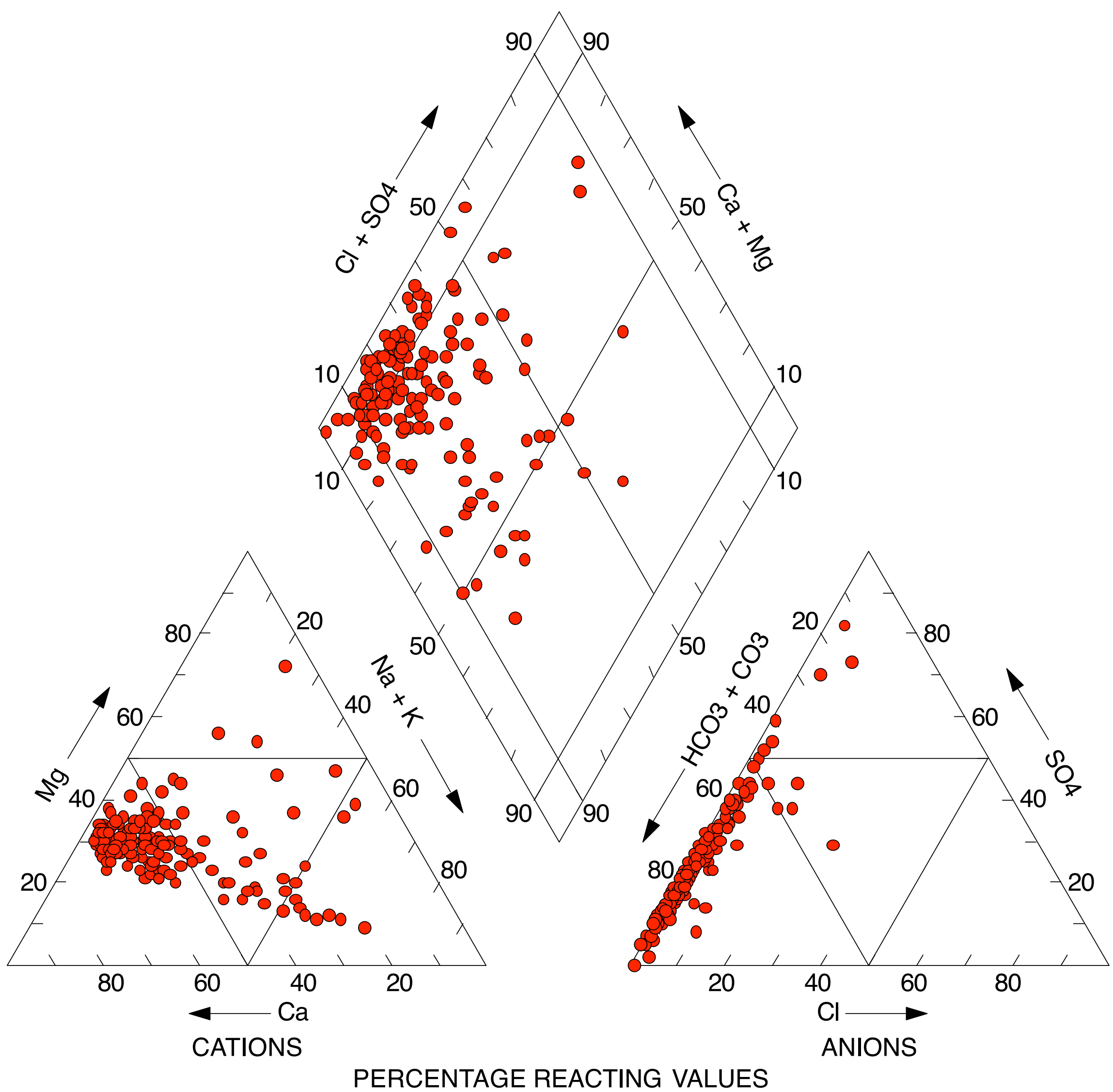


Figure 23. Major ion chemistry of water samples collected from upper aquifer wells in the past five years. Relative abundances of Na^+, K^+, Ca^{2+}, and Mg^{2+} are plotted on the cation triangle. Relative abundances of Cl^-, SO_4^{2-}, HCO_3^-, and CO_3^{2-} are plotted on the anion triangle. Straight lines projected from the two triangles define a point on the central quadrilateral.

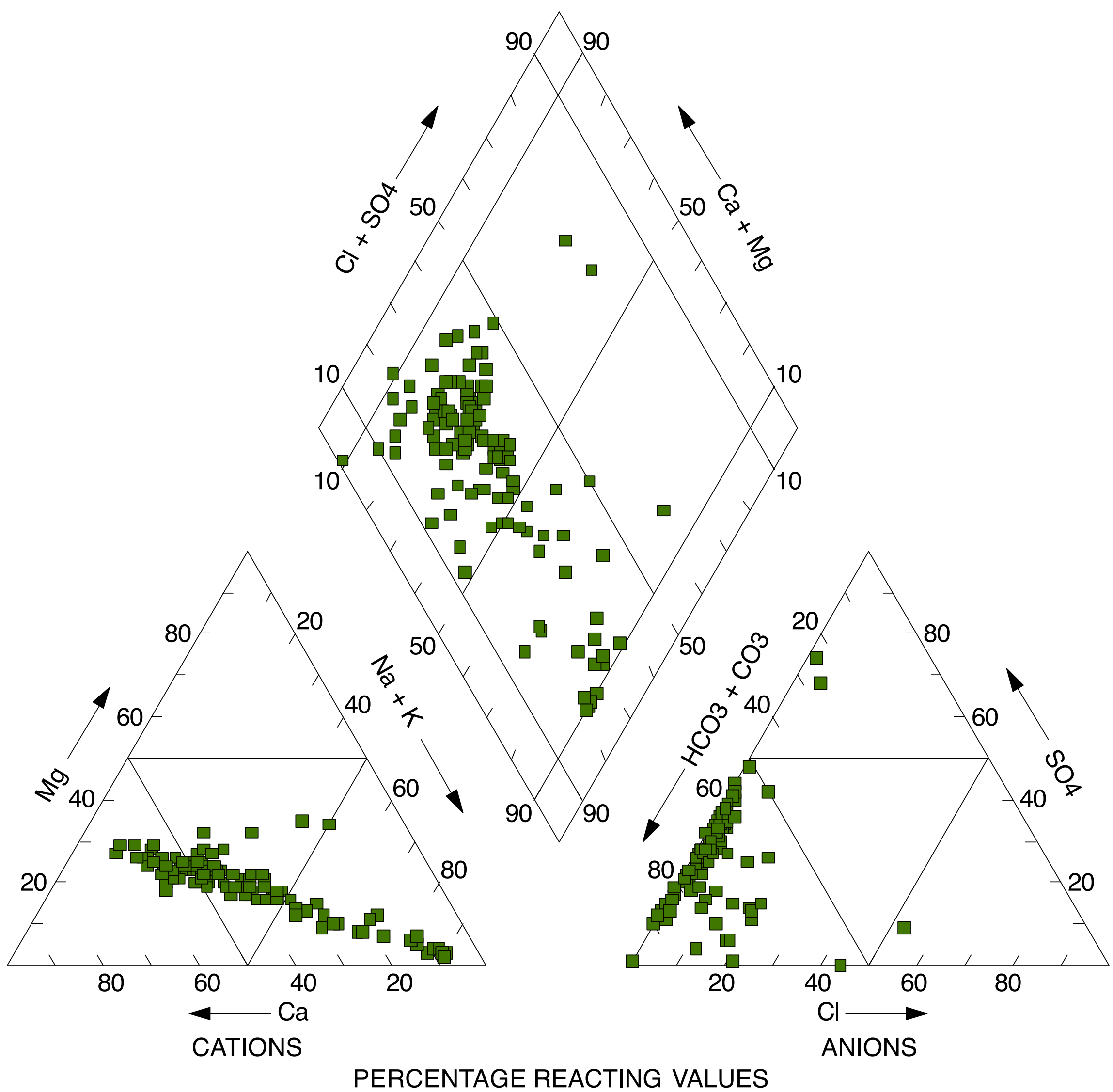


Figure 24. Major ion chemistry of water samples collected from lower aquifer wells in the past five years. Relative abundances of Na^+, K^+, Ca^{2+}, and Mg^{2+} are plotted on the cation triangle. Relative abundances of Cl^-, SO_4^{2-}, HCO_3^-, and CO_3^{2-} are plotted on the anion triangle. Straight lines projected from the two triangles define a point on the central quadrilateral.

The USDA classifies the suitability of water for irrigation in terms of its electrical conductivity and sodium adsorption ratio. The upper aquifer samples had conductivities ranging from 340 to 3740 micromhos per centimeter, and sodium adsorption ratios were 0.1 to 7.5. According to the USDA classification scheme, the shallow groundwater typically has a low sodium hazard and a medium to high salinity hazard (Figure 25). The deep groundwater also tends to have a low sodium hazard; however, it generally has a high salinity hazard, and several lower aquifer samples had very high salinity or sodium hazards (Figure 25). Waters with a low to medium sodium hazard and a medium to high salinity hazard are suitable for irrigation in settings with adequate drainage (U.S. Salinity Laboratory Staff, 1954). Waters with very high sodium or salinity are generally inappropriate for irrigation.

Hydraulic Properties. The SWC conducted a pumping test in the lower aquifer, approximately 0.5 miles west of Kunkel Lake (Krogstad, 2004). Aquifer transmissivity and storativity were estimated at four locations within a 0.5-mile radius of the production well. Transmissivities ranged from 5650-7440 ft^2/d and storativities varied between 0.00018 and 0.00083. Hydraulic conductivities calculated from aquifer transmissivity and thickness were 75 ft/d to 270 ft/d; these values fall within the expected range for sandy aquifers (Freeze and Cherry, 1979).

Two years later, a second pumping test was conducted in the lower aquifer approximately 14 miles south of Kunkel Lake (Parkin, 2006). Once again, aquifer parameters were estimated at four locations, but this time the locations fell within a 0.3-mile radius of the production well. Transmissivities ranged from 14,000-16,200 ft^2/d, and storativities ranged from 0.00037 to 0.00064. Hydraulic conductivities calculated from aquifer transmissivity and thickness estimates varied between 210 ft/d and 380 ft/d.

In the Kunkel Lake test area, aquifer thickness and lithology vary greatly over short distances. At the four parameter-estimation locations, aquifer thickness varies between 23 ft and 75 ft and lithologies range from clean sand and gravel to complex assemblages of clay, sand, and gravel units. At one location (14107115BCB), two borings were advanced through the lower aquifer. In one boring, the lower aquifer was 23 ft thick and consisted of 14 ft of silty sand, 6 ft of clean sand, and 3 ft of gravel; in the other, it was 59 ft thick and contained 53 ft of sand and 6 ft of gravel. The two borings were only 20 ft apart from one another.

Compared to the Kunkel Lake area, the lower aquifer in the southern test area is more thick, coarse-textured, and homogeneous. Aquifer thickness ranges from 41-66 ft and lithologies are invariably clean sand and gravel with 0-2 ft of clay. The relatively uniform aquifer thickness and texture is reflected in relatively uniform estimates of aquifer hydraulic properties.

Lower aquifer hydraulic properties were also estimated for the eight pumping test observation locations using boring log descriptions of lithologic units and published hydraulic property values (Table 1). The mean hydraulic conductivity and specific storage calculated from the tabulated data are 220 ft/d and 1.4×10^{-5} ft^{-1}, respectively, while the means for these locations determined by the pumping tests are 220 ft/d and 8.0×10^{-6} ft^{-1}, respectively. Since there is good agreement between the two methods, aquifer hydraulic properties were calculated for every boring location in the study area using the data in Table 1. Transmissivity maps for the upper and lower aquifers are presented in Figures 26 and 27. Figure 28 is a composite image of total transmissivity for the Central Dakota aquifer system.

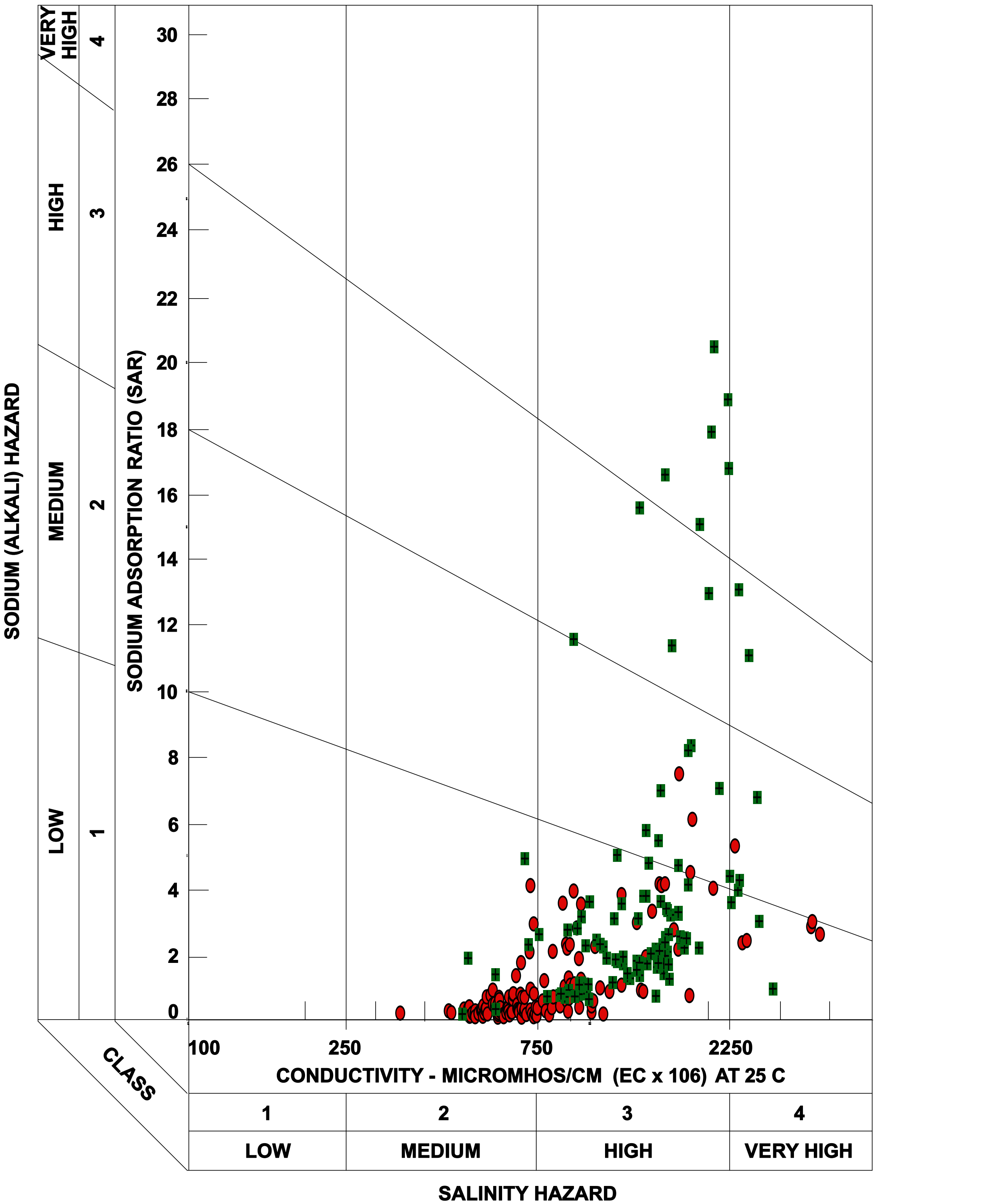


Figure 25. USDA classification of irrigation waters for upper and lower aquifer water samples collected in the past five years. Red circles and green squares represent upper and lower aquifer samples, respectively.

Table 1. Hydraulic properties for various sediments and rocks (Sources: Freeze and Cherry, 1979; Shaver, 1994; Spitz and Moreno, 1996; Domenico and Schwartz, 1998; Shaver, 1998; Wiedemeier et al., 1998)

Lithology	Hydraulic Conductivity (ft/d)	Anisotropy Ratio (Kv/Kh)	Specific Yield ( )	Specific Storage (ft^{-1})
Clay	0.014	0.1	0.05	1.70E-04
Clay, silty	0.014	0.1	0.05	1.70E-04
Clay, sandy	0.014	0.1	0.05	1.70E-04
Silt	0.028	0.1	0.08	1.70E-04
Silt, clayey	0.014	0.1	0.05	1.70E-04
Silt, sandy	0.014	0.1	0.05	1.70E-04
Sand	100	0.1	0.25	1.00E-05
Sand, clayey	1	0.1	0.15	1.00E-05
Sand, silty	1	0.1	0.15	1.00E-05
Sand, gravelly	300	0.1	0.25	1.00E-05
Gravel	1000	0.1	0.25	1.00E-05
Gravel, clayey	100	0.1	0.15	1.00E-05
Gravel, silty	100	0.1	0.15	1.00E-05
Gravel, sandy	600	0.1	0.25	1.00E-05
Cobbles+	10000	0.1	0.25	1.00E-05
Clay-silt interbedded	0.021	0.1	0.07	1.70E-04
Clay/interbedded sand (till)	0.34	0.1	0.08	1.17E-04
Clay/interbedded sand (fluvial)	33	0.1	0.12	1.17E-04
Silt/interbedded sand	0.35	0.1	0.10	1.17E-04
Sand/interbedded silt/clay	67	0.1	0.19	6.28E-05
Claystone	8.5E-06	0.1	0.05	1.50E-05
Siltstone (Pierre)	8.5E-05	0.1	0.05	1.50E-05
Siltstone (Fox Hills)	0.010	0.1	0.05	1.50E-05
Mudstone	8.5E-05	0.1	0.05	1.50E-05
Sandstone	0.010	0.5	0.05	1.50E-05
Gravel/interbedded silt/clay	670	0.1	0.19	6.28E-05
Clay/interbedded gravel (till)	33	0.1	0.08	1.17E-04
Clay/interbedded gravel (fluvial)	330	0.1	0.12	1.17E-04
Silt/interbedded gravel	33	0.1	0.10	1.17E-04
Silt, gravelly	0.014	0.1	0.05	1.70E-04
Clay, gravelly	0.014	0.1	0.05	1.70E-04
Sand, very fine	10	0.1	0.20	1.00E-05
Sand, fine	50	0.1	0.25	1.00E-05
Sand, medium	100	0.1	0.25	1.00E-05
Sand, coarse	500	0.1	0.25	1.00E-05
Sand, very coarse	1000	0.1	0.25	1.00E-05

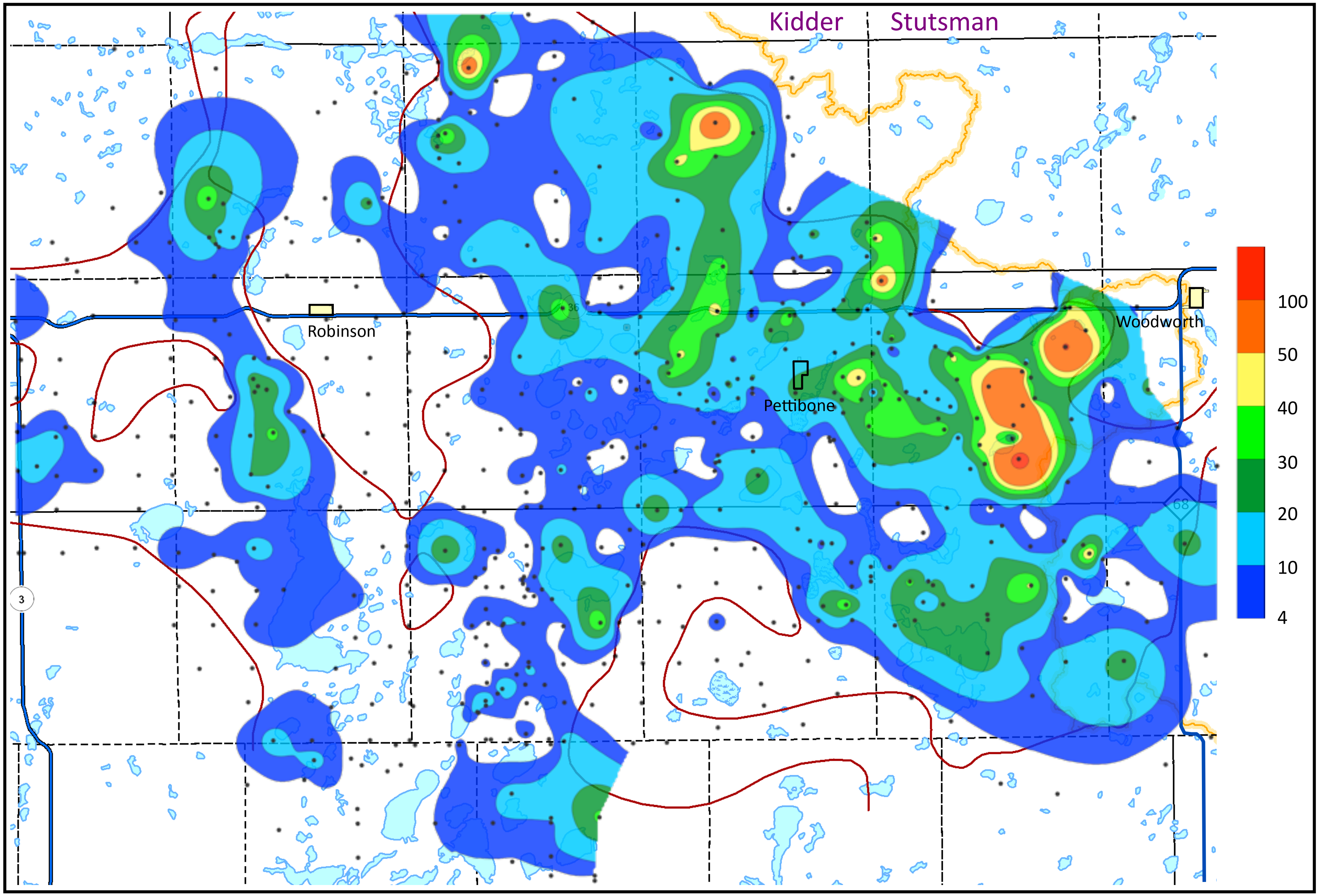


Figure 26. Estimated transmissivity (1000 ft^2/d) of sand and gravel in the upper aquifer.

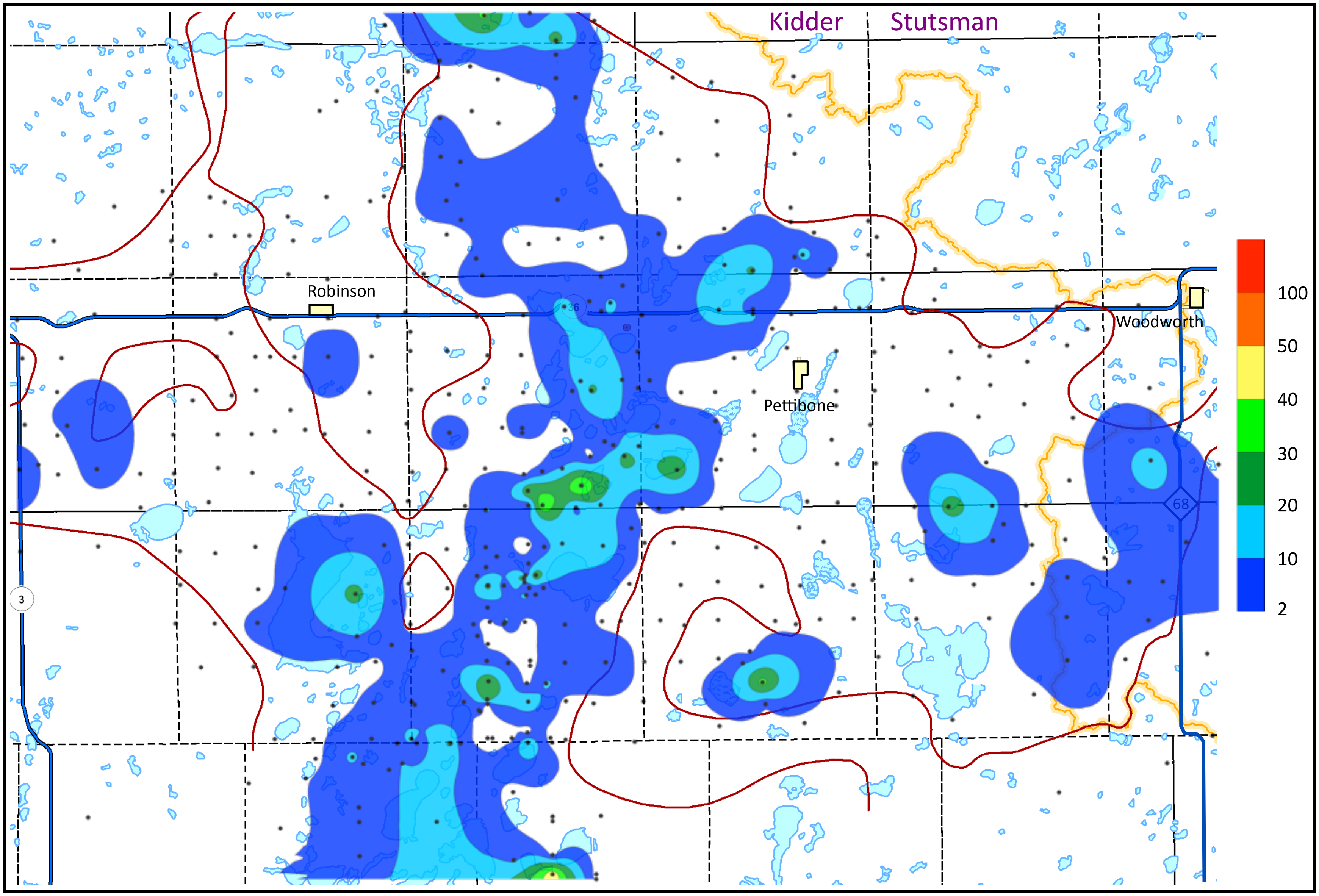


Figure 27. Estimated transmissivity (1000 ft^2/d) of sand and gravel in the lower aquifer.

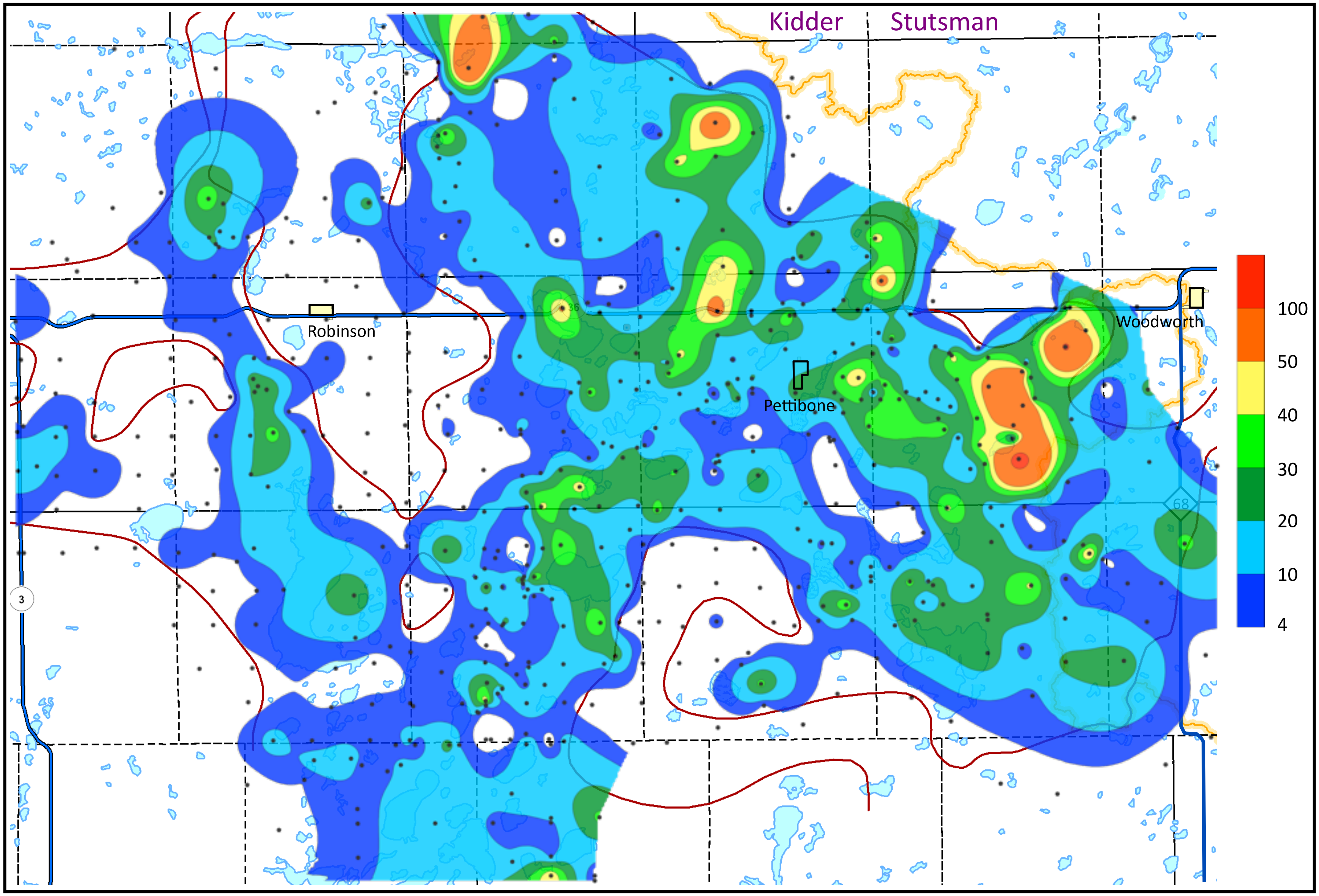


Figure 28. Estimated total transmissivity (1000 ft^2/d) of sand and gravel in the Central Dakota Aquifer System. The map does not include the isolated sand and gravel deposits that lie beneath the lower member of the aquifer system.

GROUNDWATER MANAGEMENT

Appropriation. Approved and pending appropriation are shown on Figure 29. The potential for additional development is poor throughout most of the study area, because the aquifer system is either fully appropriated or its members are too thin or fine textured. Areas that have the best potential for development are shaded green or brown on Figure 30.

Western Area: The brown-shaded region west of Horsehead Lake is largely unexplored. The soils in this area are deep, coarse textured, and excessively drained, but the thickness and lateral extent of the aquifer system beneath these soils are not well known. Most of the domestic wells and stock wells in this area are artesian wells completed in the Fox Hills Formation. Drilling logs often list a thick sequence of surficial sand and/or gravel, but there is usually no information pertaining to its saturated thickness.

The few SWC borings in this area indicate that upper aquifer grain size decreases in a southerly direction. All of the SWC boring logs for the northern half of the area describe the upper aquifer sediments as predominantly gravel or sand and gravel, while less than half of the SWC logs for the southern half of the area describe the upper aquifer as gravelly. The remaining SWC logs for the southern half of the area list the dominant grain size as fine to coarse sand. Saturated thickness, based on the eight observation wells in the area, ranges from 7 to 48 feet (Figure 15).

Five borings suggest that there may be a long, narrow, east-west trending, sand and gravel aquifer roughly 130 feet below the land surface that follows the course of the ancestral Wing River (Figures 13 and 16). However, the presence of a large, confined aquifer within the glacial overburden has not been confirmed. Additional test drilling is needed to characterize the saturated thickness of the upper aquifer and confirm the presence or absence of a significant lower aquifer.

Northern Area: The north central portion of the study area is another relatively unknown and undeveloped region of the aquifer system that has the potential for additional groundwater development (Figure 30). Nevertheless, only a small portion of this area is covered with soils that are suited for irrigated agriculture (Figure 4). Six borings in the northern area encountered 95 to 245 feet of saturated sands and gravels. At present, it is believed that the sands and gravels are concentrated in discrete channels. The deeper channel deposits constitute the northern reaches of the lower aquifer (Figure 13). The shallow channels are part of the upper aquifer and coalesce to the south as they merge to form the Streeter outwash plain (Figures 15, A14, A16, and A17).

Most of the land surface in the northern area is covered with collapsed till, and there are too few borings to accurately map the locations of the buried channels. The boring logs for this area show that the upper aquifer channels tend to be gravelly with till interbeds. Upper aquifer thickness is highly variable, ranging from less than 10 feet to more than 100 feet, and it appears that aquifer thickness is greatest in T143N R70W (Figure 15).

The lower aquifer stretches from north to south across T143N R71W (Figure 13). There is also a narrow, east-west trending branch that runs along the southern boundary of T143N R70W. The upper surface of the lower aquifer lies approximately 170 to 220 feet below the land surface. The main body of the lower aquifer is 15 to 25 feet thick and consists of fine to coarse sand. The east-west trending offshoot is up to 170 feet thick and includes interbedded till, sand, and gravel; muddy sands and gravels; and thick sequences of clean sands and cobbly sands and gravels.

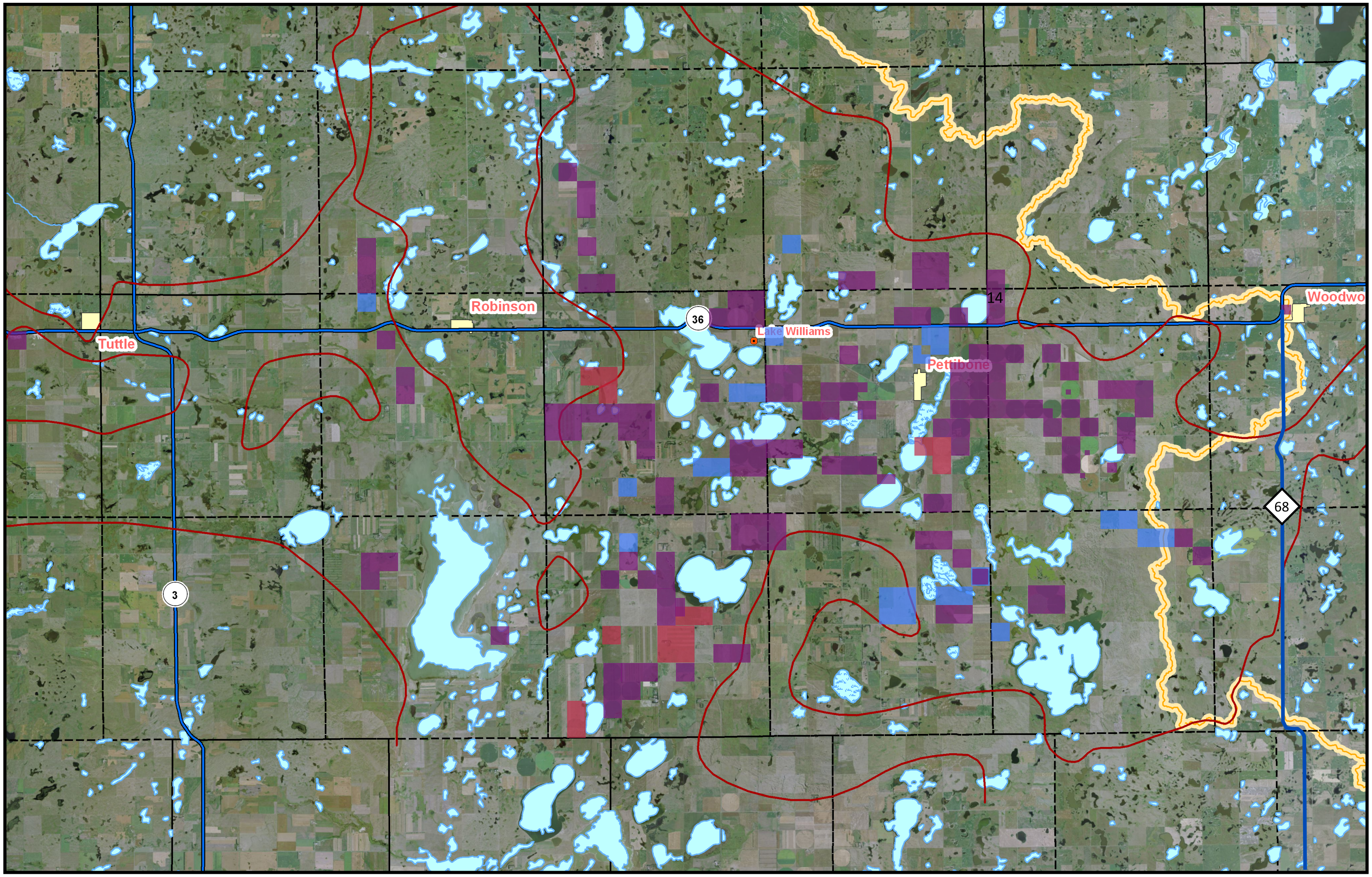


Figure 29. Groundwater appropriation in northern Kidder and northwestern Stutsman Counties as of June 2010.

Permit Status	Acre-Feet	Acres
Conditional or perfected	20220	13590
Deferred or acreage held in abeyance	2387	1737
Application in processing	3422	2271

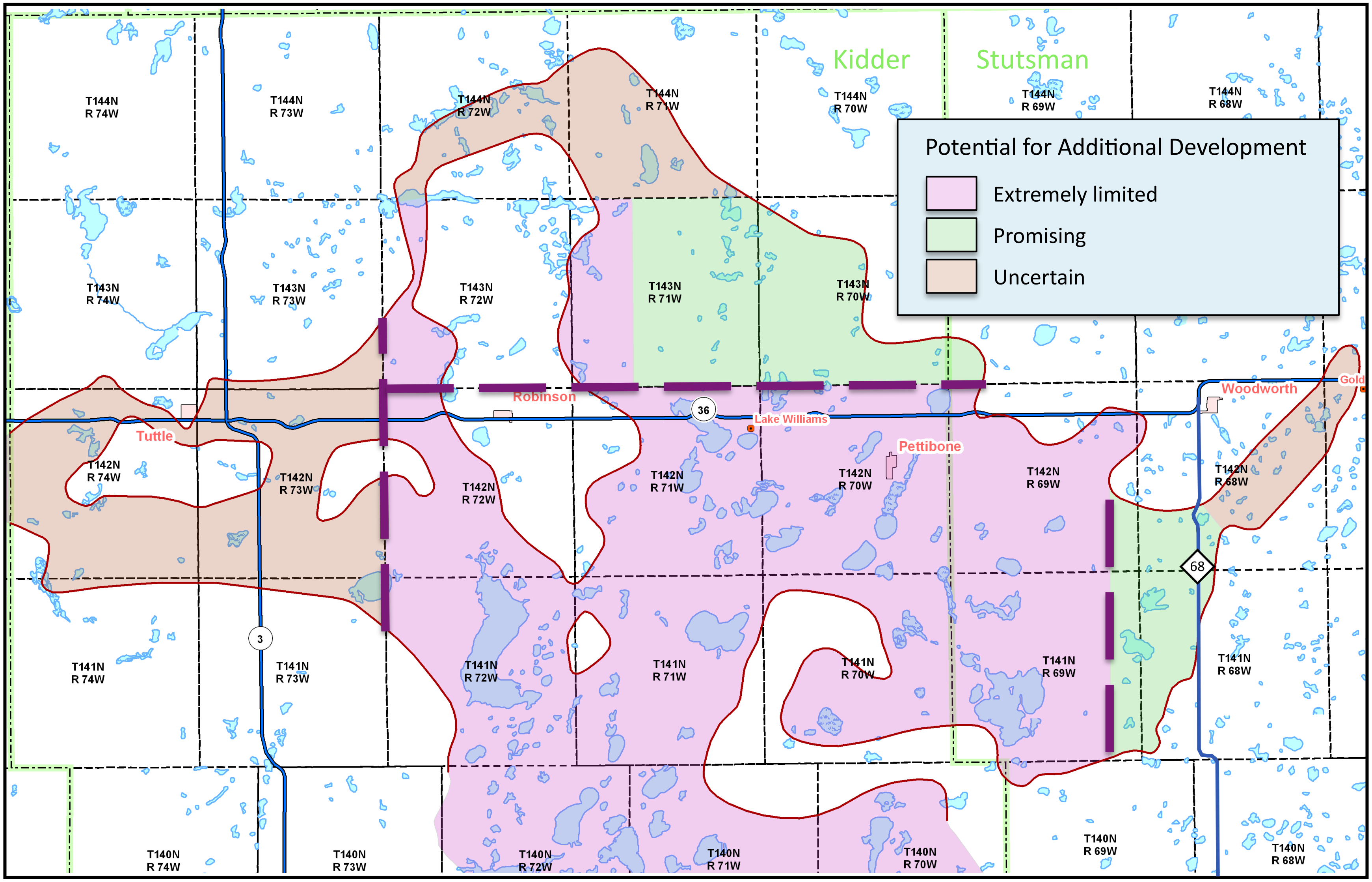


Figure 30. Groundwater development potential in northern Kidder and northwestern Stutsman Counties. Purple dashed lines delimit the western, northern, and eastern areas discussed on pages 39 and 42.

Eastern Area: The far eastern end of the study area also has the potential for additional development (Figure 30). Test drilling has revealed three significant aquifers west of Highway 68 (Figures A4, A5, and A21). East of Highway 68, there is a long, narrow, northeast-southwest trending band of gravelly outwash that was deposited in a valley between till-covered, ice-cored ridges. Over time, the ice beneath the ridges melted away, leaving the gravel train at a higher elevation than the surrounding till. The saturated thickness of this topographic inversion feature is not known, and test holes at 14206812CDD and 14206814CCD suggest there may be a significant confined aquifer below this feature.

There are only 13 SWC drill sites in the eastern area. As with the northern area, the upper aquifer is not always exposed at the land surface, aquifer geometries are not well known, and aquifer thicknesses are highly variable. Total thickness ranges from less than 20 feet to nearly 230 feet, and appears to be greatest in the southeast quarter of T141N R69W (Figure 31). Lithologies in the two upper aquifers are fairly uniform, consisting of clean sands and gravels. Lithologies in the lower aquifer are more variable and include muddy fine sand, clean sand and gravel, and interbedded sand, gravel, and clay.

Aquifer Yield. There are no field measurements of aquifer yield in the western, northern, and eastern areas apart from four, poorly-controlled, single well pumping tests conducted by private well drillers. In the western area, a test well at 14207432DDC was pumped for an unknown length of time at 50 gallons per minute, and the water level dropped 3.5 feet. In the northern area, a test well at 14307035CBAAD was pumped for one hour at 44 gpm, and the water level dropped 0.9 ft. In the eastern area, the irrigation well at 14106912ACC was pumped for 5 hours at 1600 gpm, and the water level dropped 8 ft; its replacement well (14106912ACBA) was pumped for one hour at 1500 gpm, and the water level dropped 53 ft.

Table 2 presents estimates of aquifer transmissivity for the three areas of interest. In the western area, mean transmissivities are less than the mean determined from the SWC pumping test near Kunkel Lake (Krogstad, 2004), because the aquifers are thinner in the western area borings. In the northern and eastern areas, mean transmissivities for the lower aquifer are in good agreement with the mean determined from the pumping test. In contrast, the means for the upper aquifer are higher and reflect the greater thicknesses and coarser textures of the upper aquifer sediments in these two regions of the aquifer system.

Table 2. Estimated transmissivity (ft^2/d)[1] for areas with potential for additional development

		Minimum	**Maximum**	**Mean**	**n[2]**
Western Area	Upper Aquifer	900	13300	4700	20
	Lower Aquifer	1000	5500	2900	6
Northern Area	Upper Aquifer	1400	70100	14400	28
	Lower Aquifer	1500	21800	6400	11
Eastern Area	Upper Aquifer	2700	25500	11700	10
	Lower Aquifer	2600	14000	6900	8

1 Calculated from the information in Table 1 along with boring log observations of particle size and aquifer thickness

2 SWC borings that lie within the water level interpolation domain and contain at least ten feet of saturated sand and/or gravel

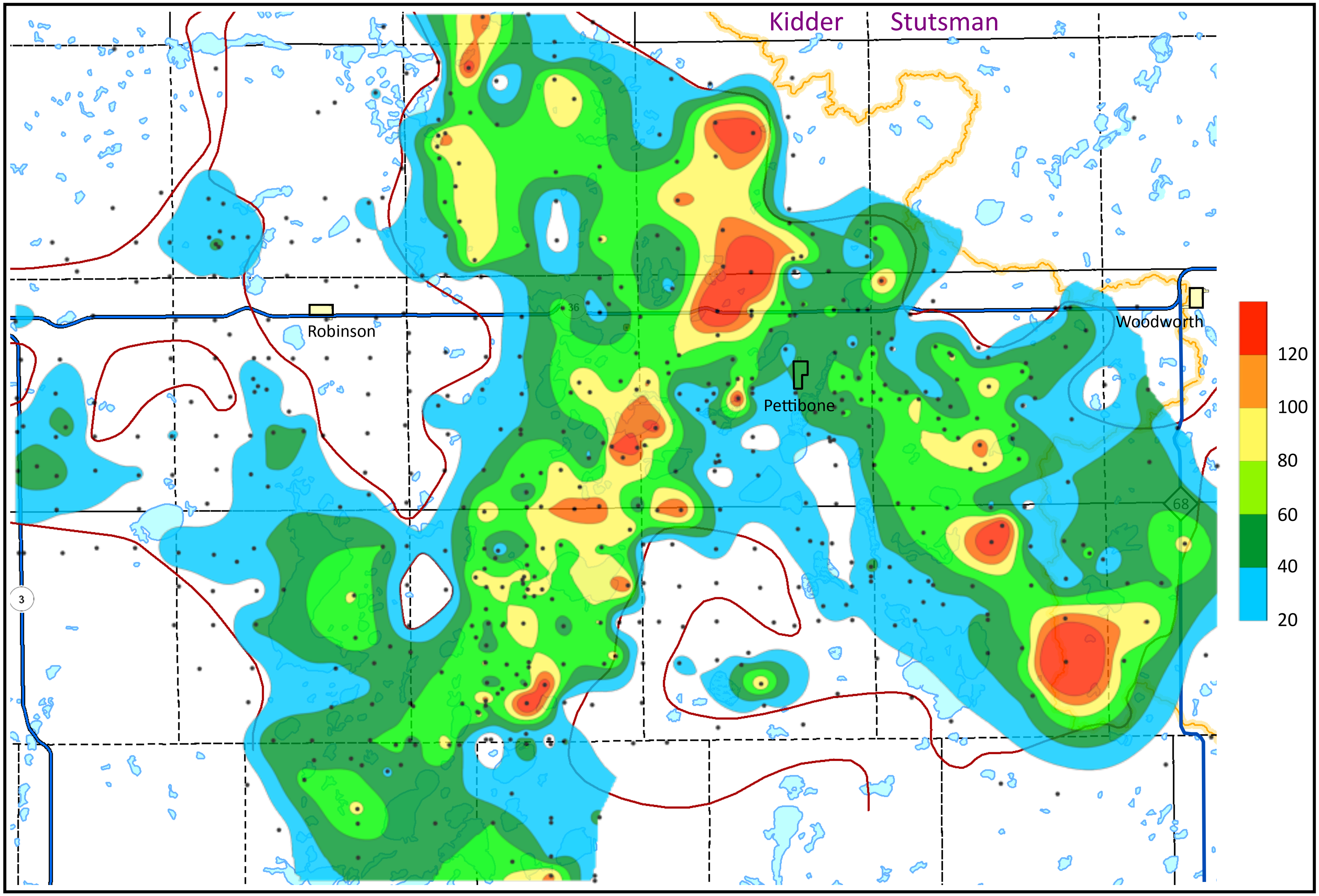


Figure 31. Total thickness of saturated sand and gravel (ft) in the Central Dakota Aquifer System.

Intentionally left blank

FUTURE RESEARCH

Field Studies. Additional test drilling and aquifer testing are needed in the three areas with the best potential for groundwater development (Figure 30). Additional drilling is needed in the western area to characterize the lateral extent and saturated thickness of the upper aquifer and to confirm the presence or absence of a significant lower aquifer. Test drilling and aquifer testing are needed in the northern area to delineate the buried sand and gravel channels. And, test drilling and aquifer testing are needed in the eastern area to better understand the geometries and hydraulic properties of the aquifers east of the Apple Creek watershed divide and to determine the relationships between the aquifers on both sides of the divide.

Laboratory Analyses. A deuterium and oxygen-18 isotope study of the groundwater in the upper and lower aquifers would greatly enhance our understanding of the nature and extent of connections between the upper and lower aquifers.

Regional Scale Numerical Modeling. An ongoing task of the Water Appropriations Division of the SWC is to develop regional scale models for its major aquifer systems. There are several challenges to developing a regional scale (approximately 14 township) model of the Central Dakota Aquifer System in northern Kidder and northwestern Stutsman Counties that could be used to make site-specific management decisions. The first challenge, of course, is the issue of scale. In general, regional scale models are best suited to answering regional scale, rather than site scale questions. One approach to dealing with this scale discrepancy is to imbed one or more site models within the domain of the regional model. Then the primary purpose of the regional model is to define the boundary conditions for the imbedded site models.

Remaining challenges to developing a regional scale model arise primarily from the complex nature of the ice-wasting depositional environment, the uneven distribution of available data, and the limitations of deterministic, finite difference modeling. These challenges include:

1) how to model the highly irregular land surface topography and assign topographically sensitive variables such as recharge and evapotranspiration when land surface elevation often varies more than 100 feet within a section;
2) how to deal with uncertainty regarding the horizontal and vertical connectedness of the collapsed and buried outwash in large areas with relatively few borings and no pumping data;
3) how to represent Chase Lake, given its importance in water management decisions and the lack of information regarding lakebed properties and lake-aquifer connectivity; and
4) how to deterministically model the extreme aquifer heterogeneity visible on many cross sections in Appendix A.

Sub-regional Scale Numerical Modeling. There are two important and unanswered water management questions in northern Kidder and northwestern Stutsman Counties that could be evaluated with numerical models: 1) is the lower aquifer in the Kunkel Lake area fully appropriated, and 2) what is the impact of irrigation on water levels in Chase Lake? The Kunkel Lake and Chase Lake area models could be imbedded in a 14 township regional model, but the regional model would not be *required* to address these questions. Both areas could be modeled separately, and model boundaries that were neither physical nor hydrologic could be placed far enough from their respective areas of interest that they would not affect the simulation results in the areas of interest.

In the Kunkel Lake area, there are two pending or deferred groundwater permit applications and two permits with groundwater held in abeyance. The upper aquifer is generally too thin to support irrigation, so abstraction from the lower aquifer is the only viable option. Unfortunately, existing appropriation from the lower aquifer is causing drawdowns in excess of 60 feet in observation wells, and drawdowns in production wells are significantly greater. Consequently, it is not clear whether or not there is additional room for development. The large number of existing irrigation wells and the complexity of the aquifer system near Kunkel Lake call for a numerical rather than analytical approach to the problem. Since the land surface is relatively flat and there are many observation wells in the area, the only significant obstacle to developing a numerical model is the complexity of the aquifer system near Kunkel Lake. The best way to deal with the heterogeneity may be to model it stochastically rather than deterministically.

The situation at Chase Lake is very different from Kunkel Lake. There is ample groundwater to support additional irrigation, but the US Fish and Wildlife Service (USFWS) is understandably concerned about the effects of current and future development on water levels in Chase Lake. The Chase Lake National Wildlife Refuge was established in 1908 by President Theodore Roosevelt to protect the American White Pelican. In 2006, 34,604 breeding pelicans were tallied at the refuge. The birds nest on islands in the large and shallow lake, and small changes in the lake level can cause significant changes in the area available for nesting and the ability of predators to access the islands.

Any assessment of the inflow to Chase Lake will be encumbered by uncertainty regarding: 1) the nature and extent of the aquifer system east of the lake and whether or not it is hydraulically connected to the lake, 2) the geometry of the lower aquifer north of the lake and whether or not the lower aquifer groundwater discharges to the lake, and 3) the hydrogeologic properties of the sediments that lie beneath the lake. Additional fieldwork in and around the refuge could reduce the uncertainty, but the USFWS prohibits vehicle access to the refuge for test drilling and well installation. Perhaps the most significant obstacle to developing a *useful* model of the Chase Lake area is the nature of the wildlife management problem. Numerical models of complex hydrologic systems are not capable of accurately predicting small changes in water levels due to the many simplifying assumptions required to construct the models. Since small changes in the lake level can have significant impacts on the area available for nesting and the ability of predators to access the islands, model forecasts would be too uncertain to serve as the basis for management decisions. Consequently, water allocation decisions for the Chase Lake area should be based on simple analytical assessments, incremental development, careful observation, and policies that consider the relative values of local irrigation and refuge protection.

REFERENCES CITED

Bennett, M. R. and N. F. Glasser. 1996. *Glacial Geology: Ice Sheets and Landforms.* John Wiley & Sons, New York, NY.

Bluemle, J. P. 2000. *The Face of North Dakota*, 3rd ed. Educational Series 26. North Dakota Geological Survey, Grand Forks, ND.

Bluemle, J. P., G. A. Faigle, R. J. Kresl, and J. R. Reid. 1967. *Geology and ground water resources of Wells County, part 1, geology.* North Dakota Geological Survey Bulletin 51. North Dakota Geological Survey, Grand Forks, ND.

Domenico, P. A. and F. W. Schwartz. 1998. *Physical and Chemical Hydrogeology,* 2nd ed. John Wiley & Sons, New York, NY.

Freeze, R. A. and J. A. Cherry. 1979. *Groundwater*. Prentice-Hall, Englewood Cliffs, NJ.

Freeze, R. A. and P. A. Witherspoon. 1967. Theoretical analysis of regional groundwater flow II: Effect of water table configuration and subsurface permeability variations. *Water Resources Research* 3: 623-634.

Krogstad, K. 2004. *Kidder County Aquifer Pumping Test*. Water Appropriations Division Memorandum. North Dakota State Water Commission, Bismarck, ND.

Kume, J. and D. E. Hansen. 1965. *Geology and ground water resources of Burleigh County, North Dakota, part 1, geology*. North Dakota Geological Survey Bulletin 42. North Dakota Geological Survey, Grand Forks, ND.

Labaugh, J. W., T. C. Winter, V. A. Adomaitis, and G. A. Swanson. 1987. *Hydrology and chemistry of selected prairie wetlands in the Cottonwood Lake area, Stutsman County, North Dakota, 1979-82*. USGS Professional Paper 1431. U.S. Geological Survey, Reston, VA.

Lissey, A. 1971. Depression-focused transient ground-water flow patterns in Manitoba. In *Geological Association of Canada Special Paper 9*, 333-341. Ottawa, Ontario, Canada: The Queen's Printer.

Parkin, S. 2006. *Aquifer Test: Kidder County Aquifer System*. Water Appropriations Division Memorandum. North Dakota State Water Commission, Bismarck, ND.

Rau, J. L., W. E. Bakken, J. Chmelik, and B. J. Williams. 1962. *Geology and ground water resources of Kidder County, North Dakota, part 1, geology.* North Dakota Geological Survey Bulletin 36. North Dakota Geological Survey, Grand Forks, ND.

Shaver, R. B. 1994. *An analysis and conceptual hydrogeologic model of a till aquitard overlying the Spiritwood Aquifer in southeastern North Dakota*. Water Resource Investigation No. 17. North Dakota State Water Commission, Bismarck, ND.

Shaver, R. B. 1998. The determination of glacial till specific storage in North Dakota. *Ground Water* 26(4): 552-557.

Sloan, C. E. 1972. *Ground-water hydrology of prairie potholes in North Dakota*. USGS Professional Paper 585-C. U.S. Geological Survey, Reston, VA.

Spitz, K. and J. Moreno. 1996. *A Practical Guide to Groundwater and Solute Transport Modeling*. John Wiley & Sons, New York, NY.

Toth, J. 1963. A theoretical analysis of groundwater flow in small drainage basins. *Journal of Geophysical Research* 68: 4795-4812.

Wiedemeier, T. H., M. A. Swanson, D. E. Moutoux, E. K. Gordon, J. T. Wilson, B. H. Wilson, D. H. Kampbell, P. E. Haas, R. N. Miller, J. E. Hansen, and F. H. Chapelle. 1998. Technical protocol for evaluating natural attenuation of chlorinated solvents in ground water. EPA/600/R-98/128. USEPA, Office of Research and Development, Washington, DC.

Winter, C. W. and D. O. Rosenberry. 1995. The interaction of ground water with prairie pothole wetlands in the Cottonwood Lake area, east-central North Dakota, 1979-1990. *Wetlands* 15(3): 193-211.

Winters, H. A. 1963. *Geology and ground water resources of Stutsman County, North Dakota, part 1, geology*. North Dakota Geological Survey Bulletin 41. North Dakota Geological Survey, Grand Forks, ND.

APPENDIX A

Geologic Cross Sections

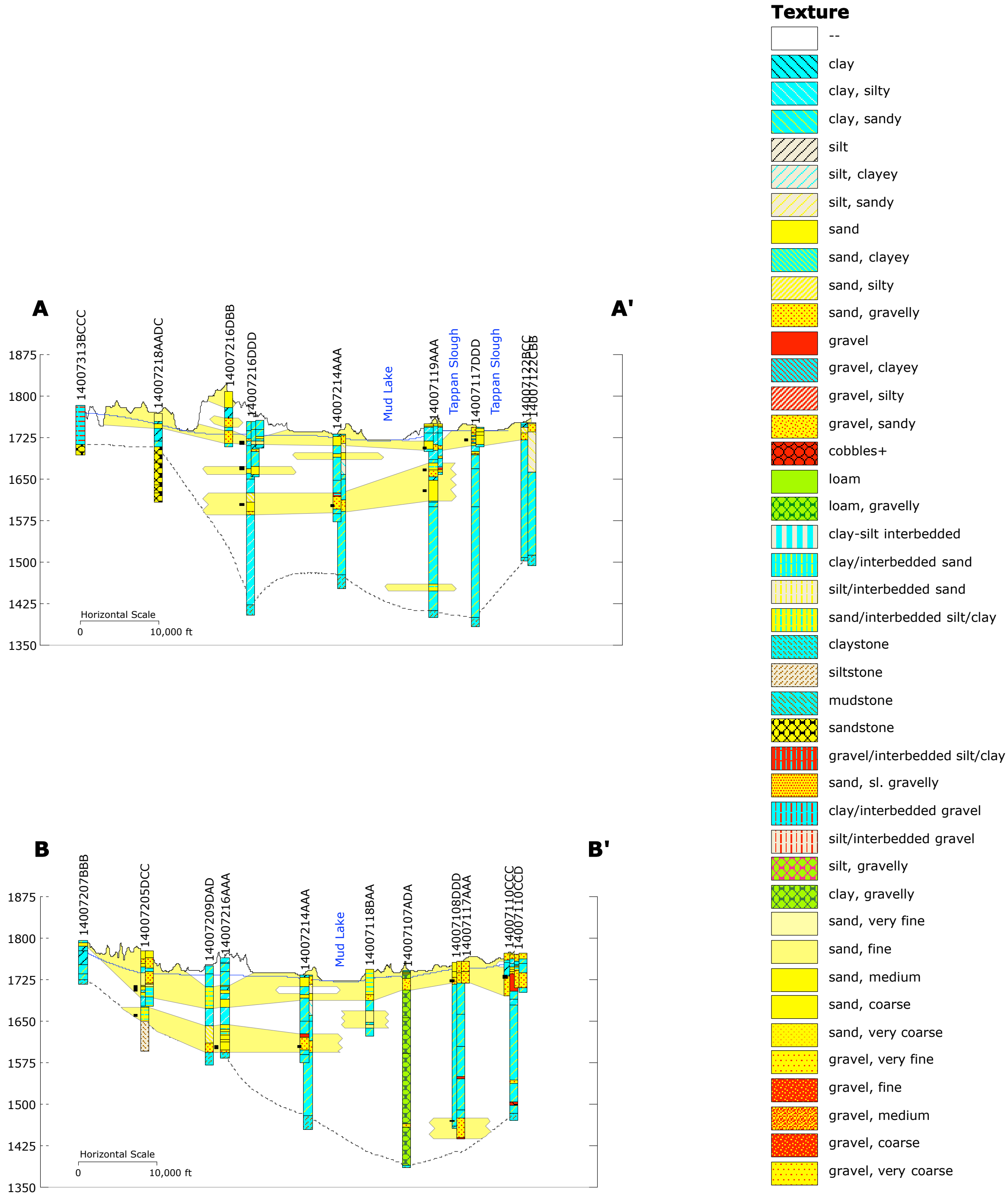


Figure A1. Geologic cross sections approximately 5 miles (BC') and 6 miles (CC') north of T139N. See Figure 9 for cross section locations and Figure A1 for map unit descriptions. Blue line represents the water table; dashed line represents the bedrock surface. Yellow fill indicates areas with significant sand and gravel. Horizontal scale: 1 inch = 4 miles.

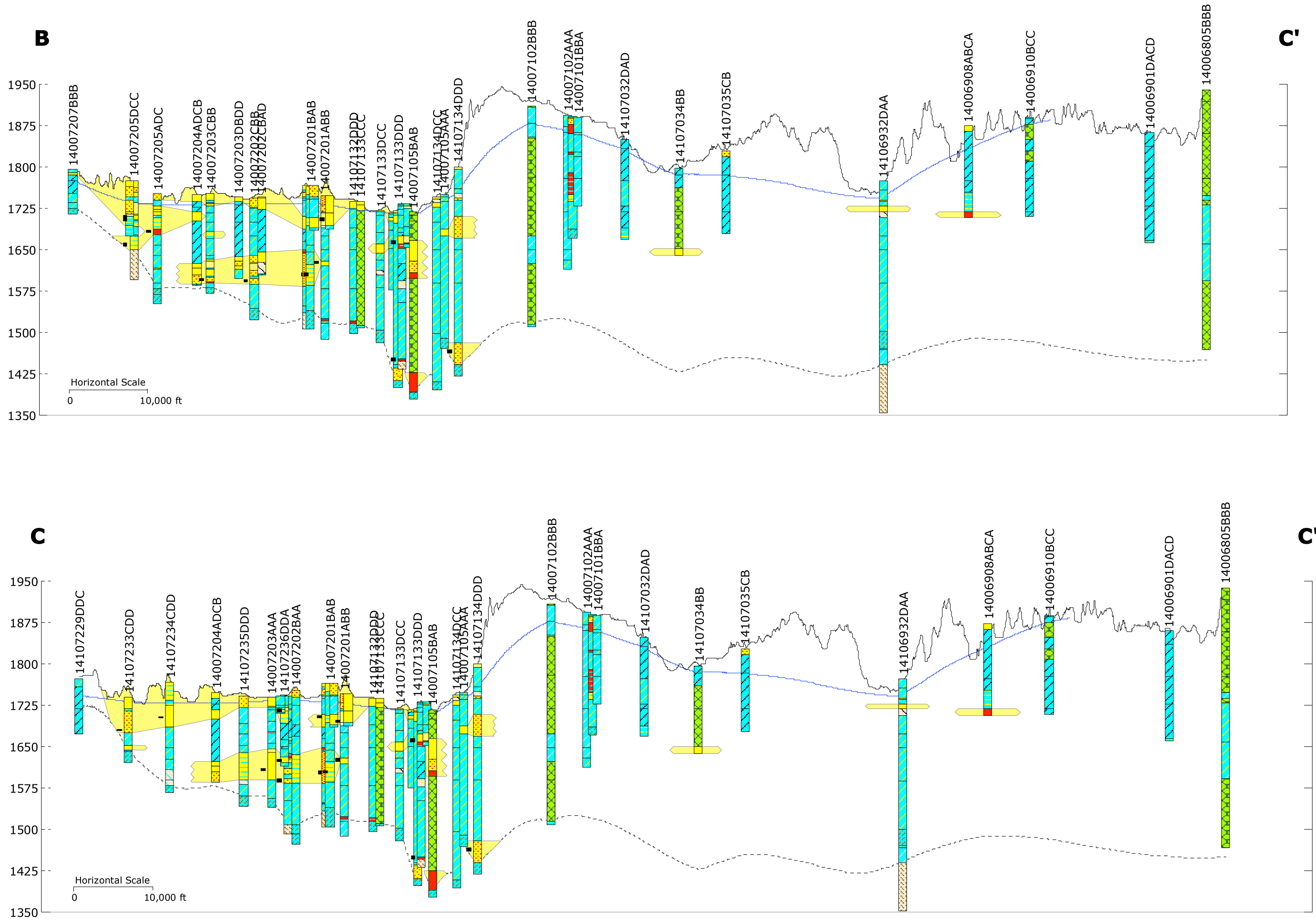


Figure A2. Geologic cross sections approximately 5 miles (BC') and 6 miles (CC') north of T139N. See Figure 9 for cross section locations and Figure A1 for map unit descriptions. Blue line represents the water table; dashed line represents the bedrock surface. Yellow fill indicates areas with significant sand and gravel. Horizontal scale: 1 inch = 4 miles.

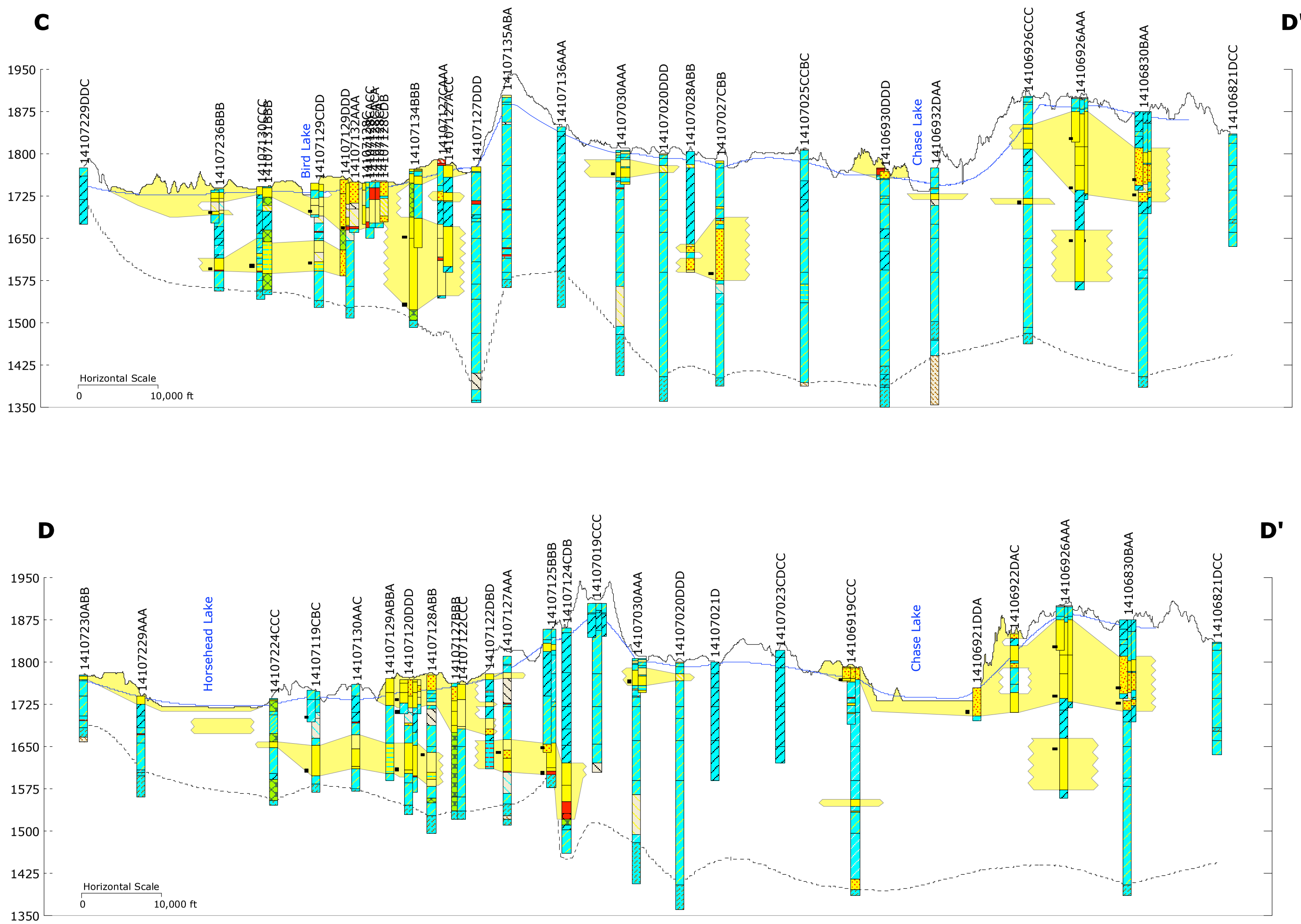


Figure A3. Geologic cross sections approximately 1 mile (CD') and 2 miles (DD') north of T140N. See Figure 9 for cross section locations and Figure A1 for map unit descriptions. Blue line represents the water table; dashed line represents the bedrock surface. Yellow fill indicates areas with significant sand and gravel. Horizontal scale: 1 inch = 4 miles.

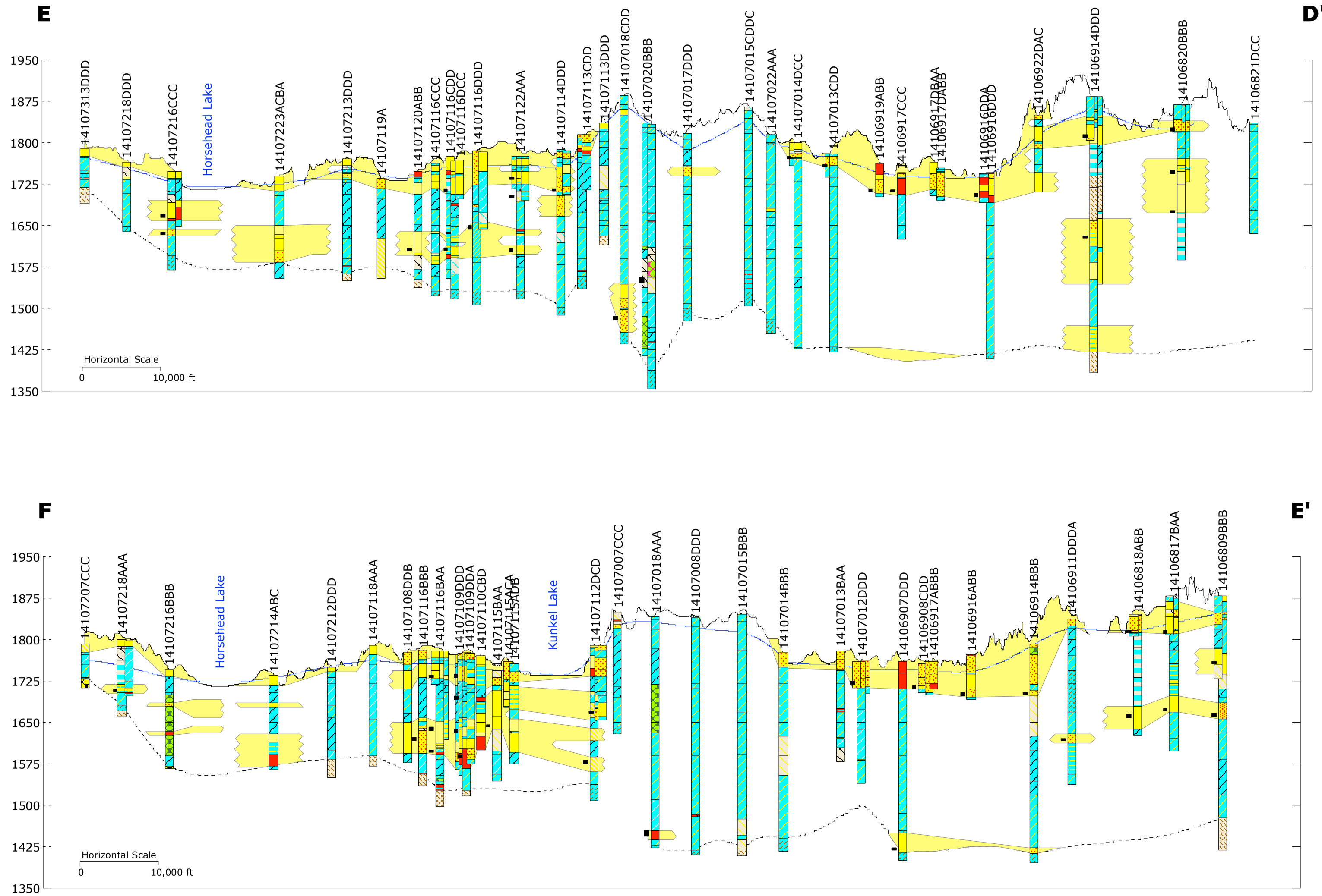
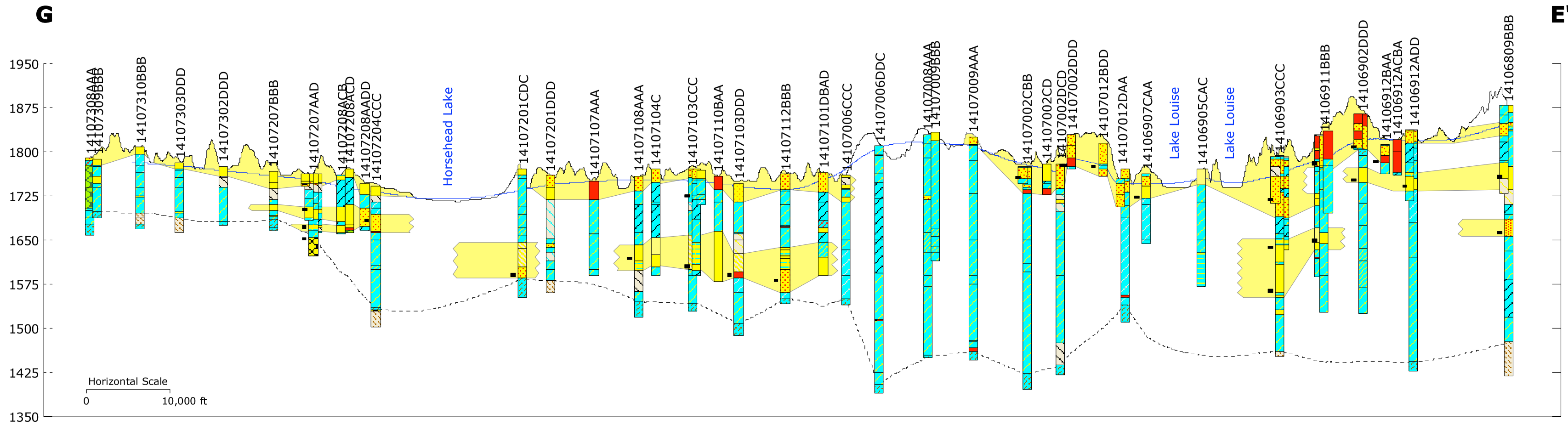


Figure A4. Geologic cross sections approximately 3 miles (ED') and 4 miles (FE') north of T140N. See Figure 9 for cross section locations and Figure A1 for map unit descriptions. Blue line represents the water table; dashed line represents the bedrock surface. Yellow fill indicates areas with significant sand and gravel. Horizontal scale: 1 inch = 4 miles. Bedrock surface is not shown beneath 14107113DDD and 14107007CCC, because both borings were probably terminated in ice-shove blocks.



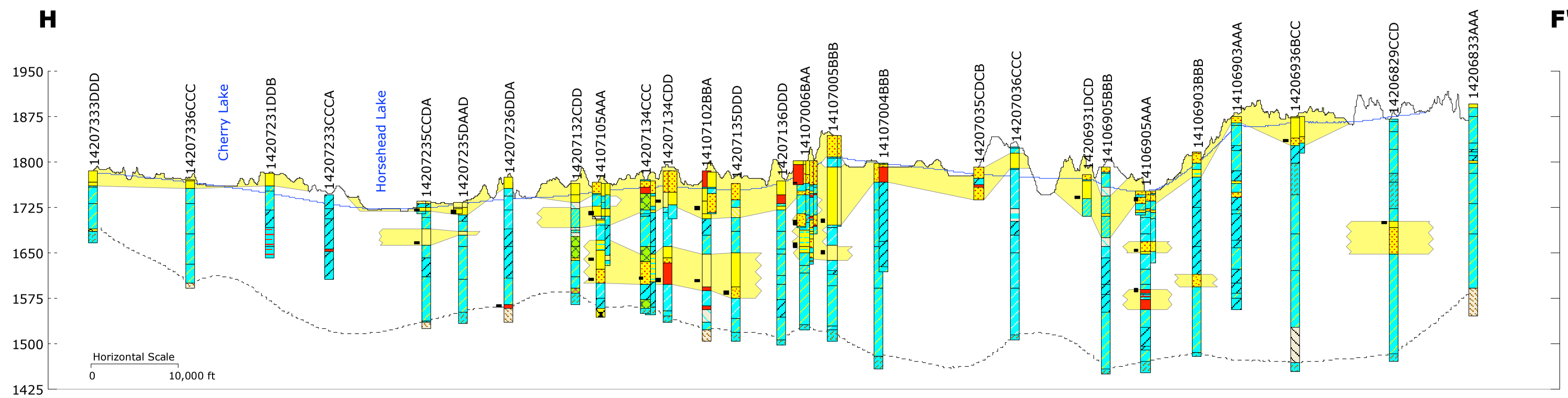
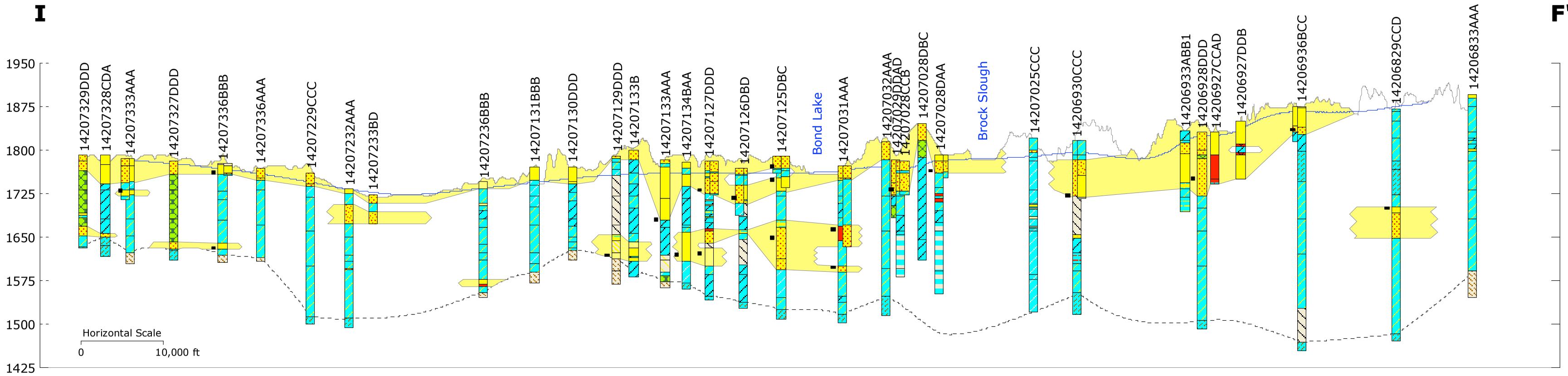


Figure A5. Geologic cross sections approximately 5 miles (GE') and 6 miles (HF') north of T140N. See Figure 9 for cross section locations and Figure A1 for map unit descriptions. Blue line represents the water table; dashed line represents the bedrock surface. Yellow fill indicates areas with significant sand and gravel. Horizontal scale: 1 inch = 4 miles.



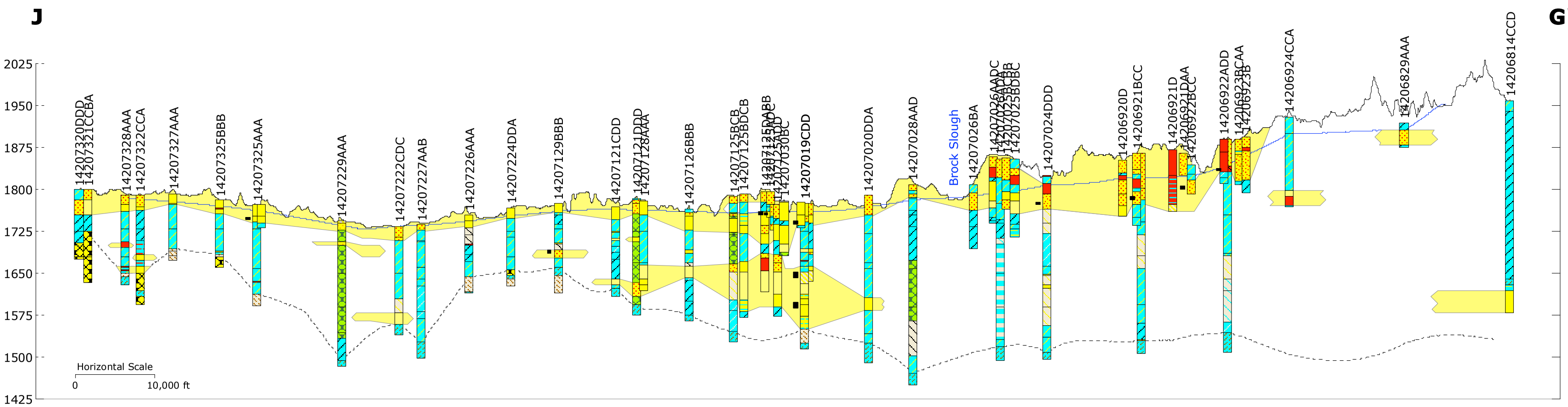


Figure A6. Geologic cross sections approximately 1 mile (IF’) and 2 miles (JG’) north of T141N. See Figure 9 for cross section locations and Figure A1 for map unit descriptions. Blue line represents the water table; dashed line represents the bedrock surface. Yellow fill indicates areas with significant sand and gravel. Horizontal scale: 1 inch = 4 miles.

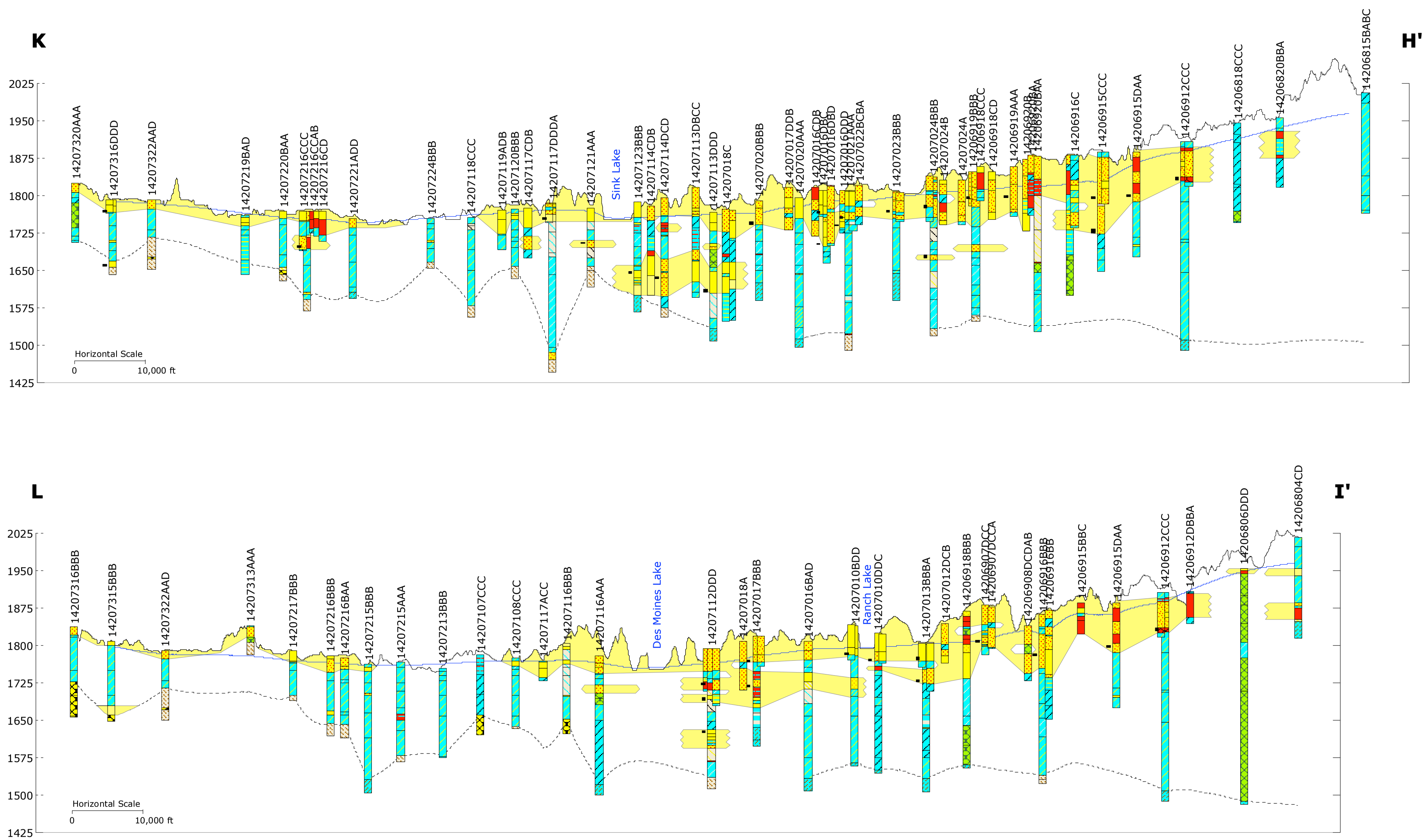


Figure A7. Geologic cross sections approximately 3 miles (KH') and 4 miles (LI') north of T141N). See Figure 9 for cross section locations and Figure A1 for map unit descriptions. Blue line represents the water table; dashed line represents the bedrock surface. Yellow fill indicates areas with significant sand and gravel. Horizontal scale: 1 inch = 4 miles. Bedrock surface is not shown beneath 14207017BBB, 14207020BBB, and 14207023BBB, because borings were probably terminated in ice-shove blocks.

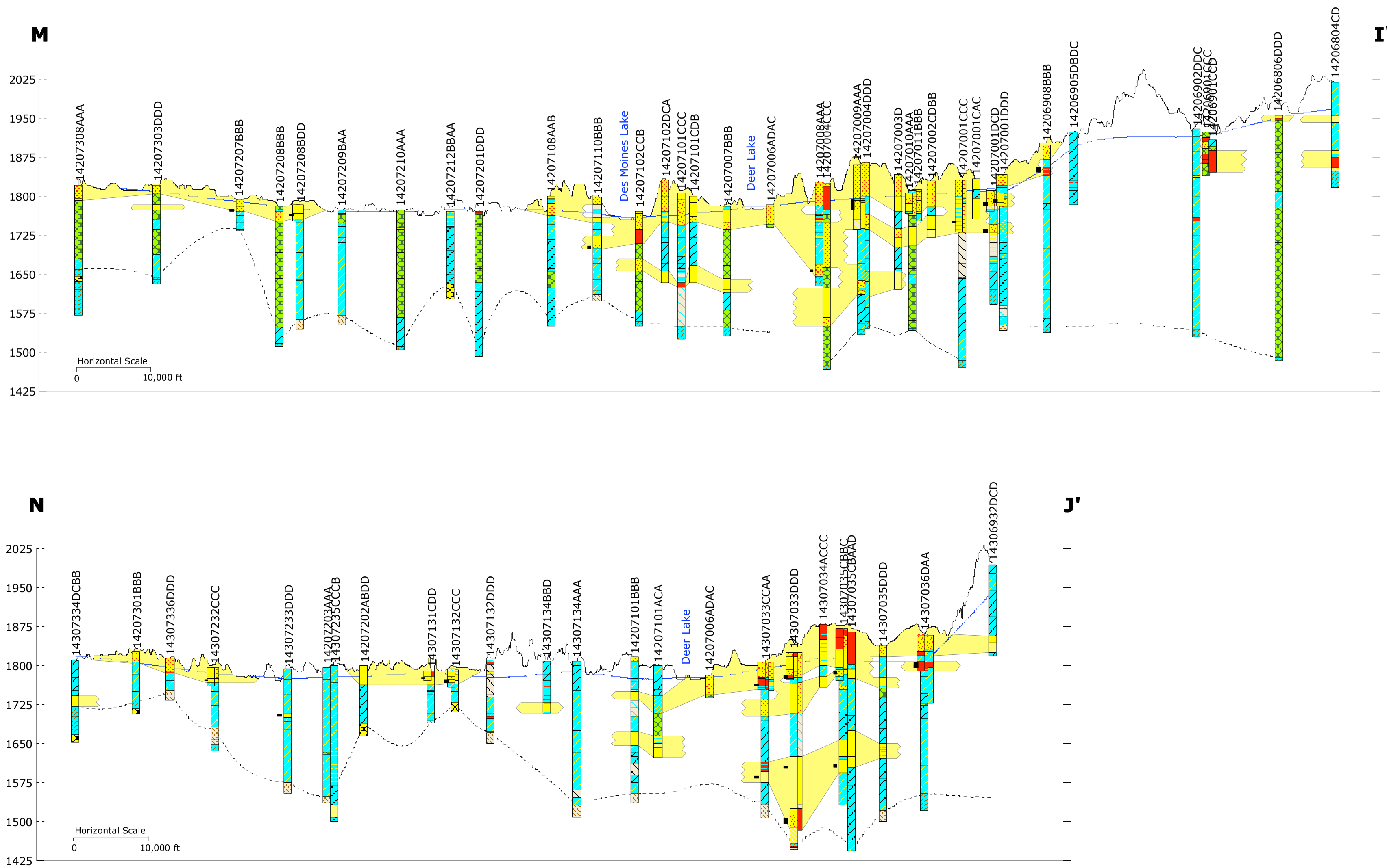


Figure A8. Geologic cross sections approximately 5 miles (MI') and 6 miles (NJ') north of T141N. See Figure 9 for cross section locations and Figure A1 for map unit descriptions. Blue line represents the water table; dashed line represents the bedrock surface. Yellow fill indicates areas with significant sand and gravel. Horizontal scale: 1 inch = 4 miles. Bedrock surface is not shown beneath 14207008AAA, 14207001DCD, and 14206804CD, because borings were probably terminated in ice-shove blocks.

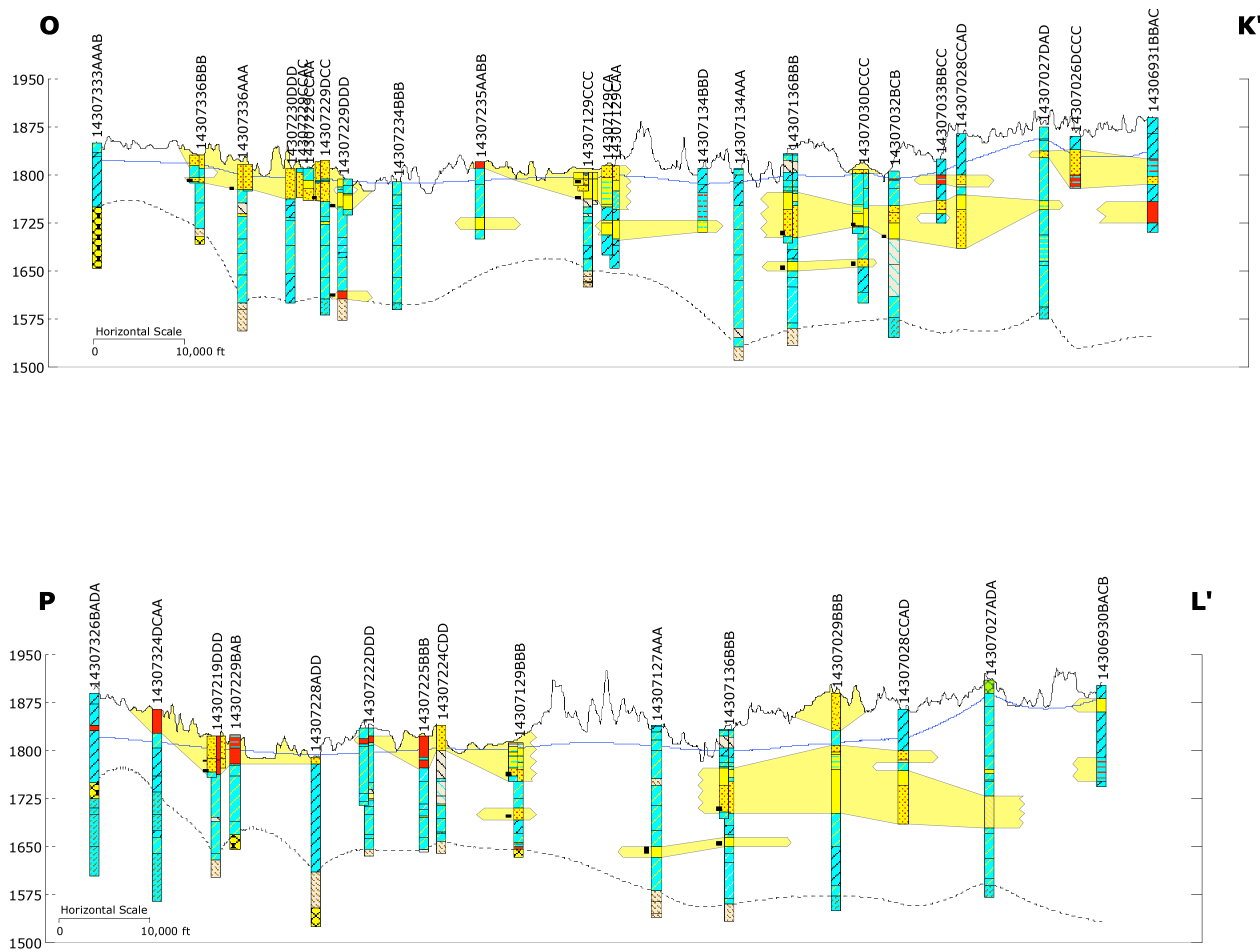


Figure A9. Geologic cross sections approximately 1 mile (OK') and 2 miles (PL') north of T142N. See Figure 9 for cross section locations and Figure A1 for map unit descriptions. Blue line represents the water table; dashed line represents the bedrock surface. Yellow fill indicates areas with significant sand and gravel. Horizontal scale: 1 inch = 4 miles.

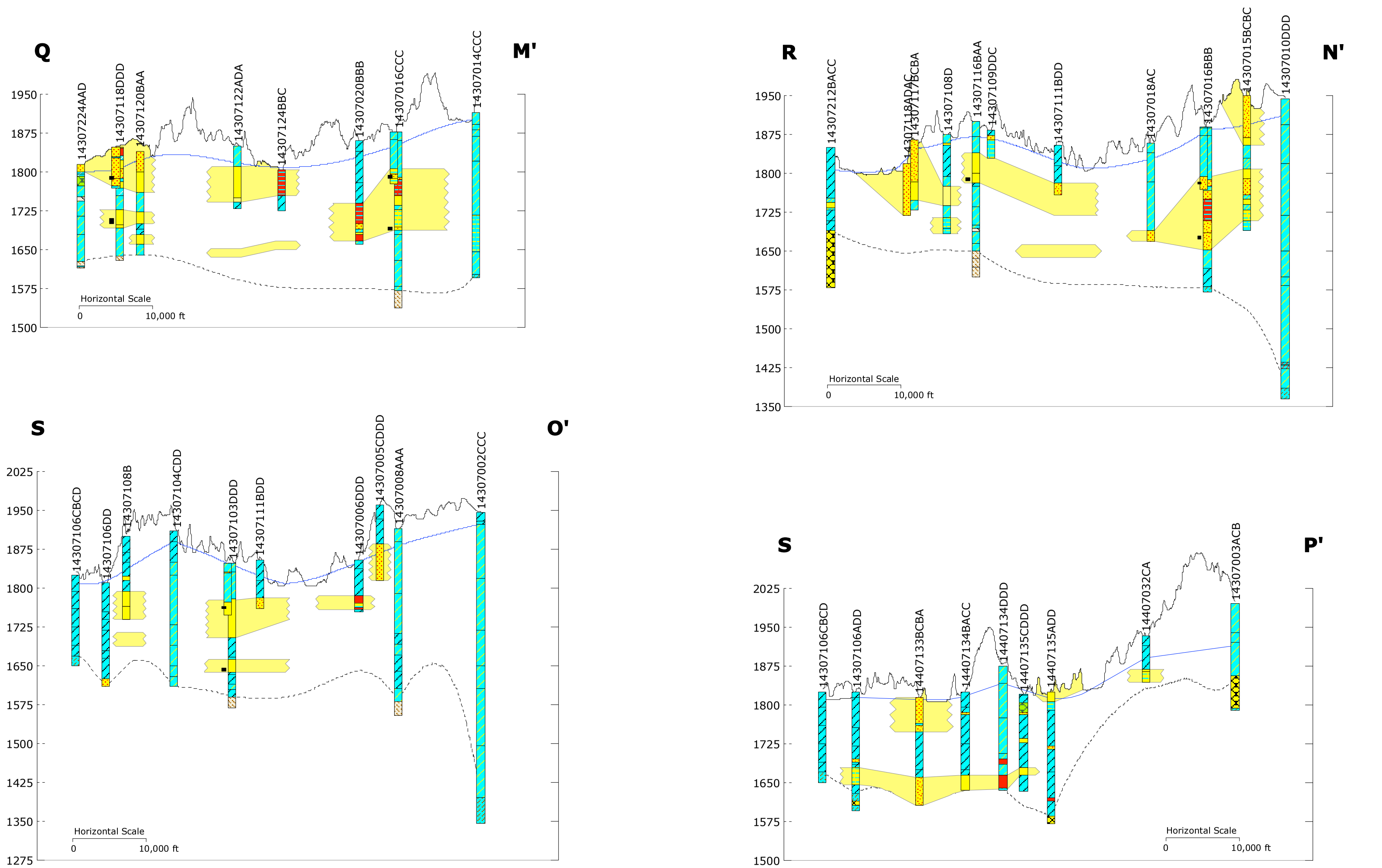


Figure A10. Geologic cross sections approximately 3 miles (QM'), 4 miles (RN'), 5 miles (SO'), and 6 miles (SP') north of T142N. See Figure 9 for cross section locations and Figure A1 for map unit descriptions. Blue line represents the water table; dashed line represents the bedrock surface. Yellow fill indicates areas with significant sand and gravel. Horizontal scale: 1 inch = 4 miles.

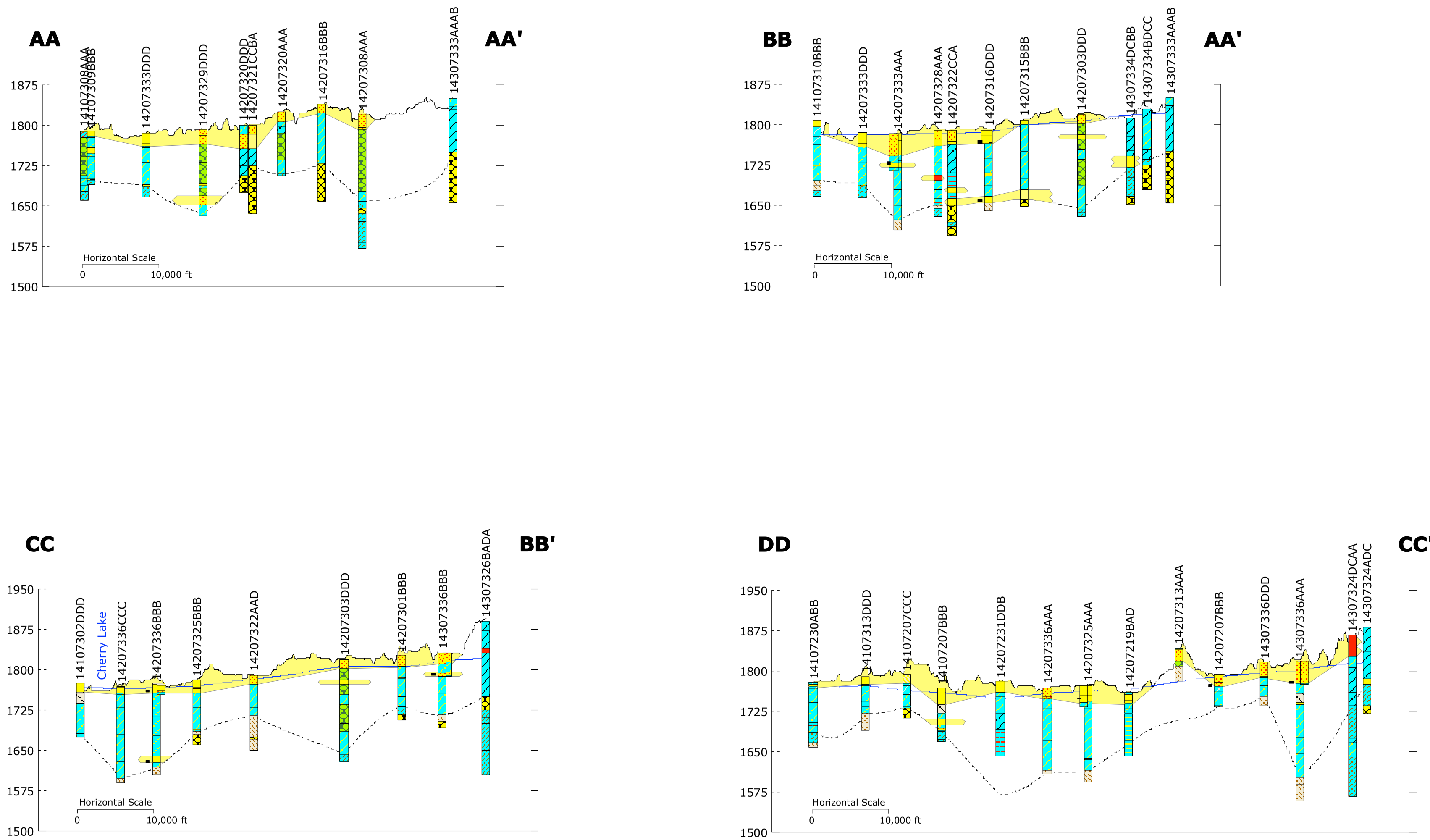


Figure A11. Geologic cross sections approximately 2 miles (AAAA'), 3 miles (BBAA'), 5 miles (CCBB'), and 6 miles (DDCC') east of R74W. See Figure 9 for cross section locations and Figure A1 for map unit descriptions. Blue line represents the water table; dashed line represents the bedrock surface. Yellow fill indicates areas with significant sand and gravel. Horizontal scale: 1 inch = 4 miles.

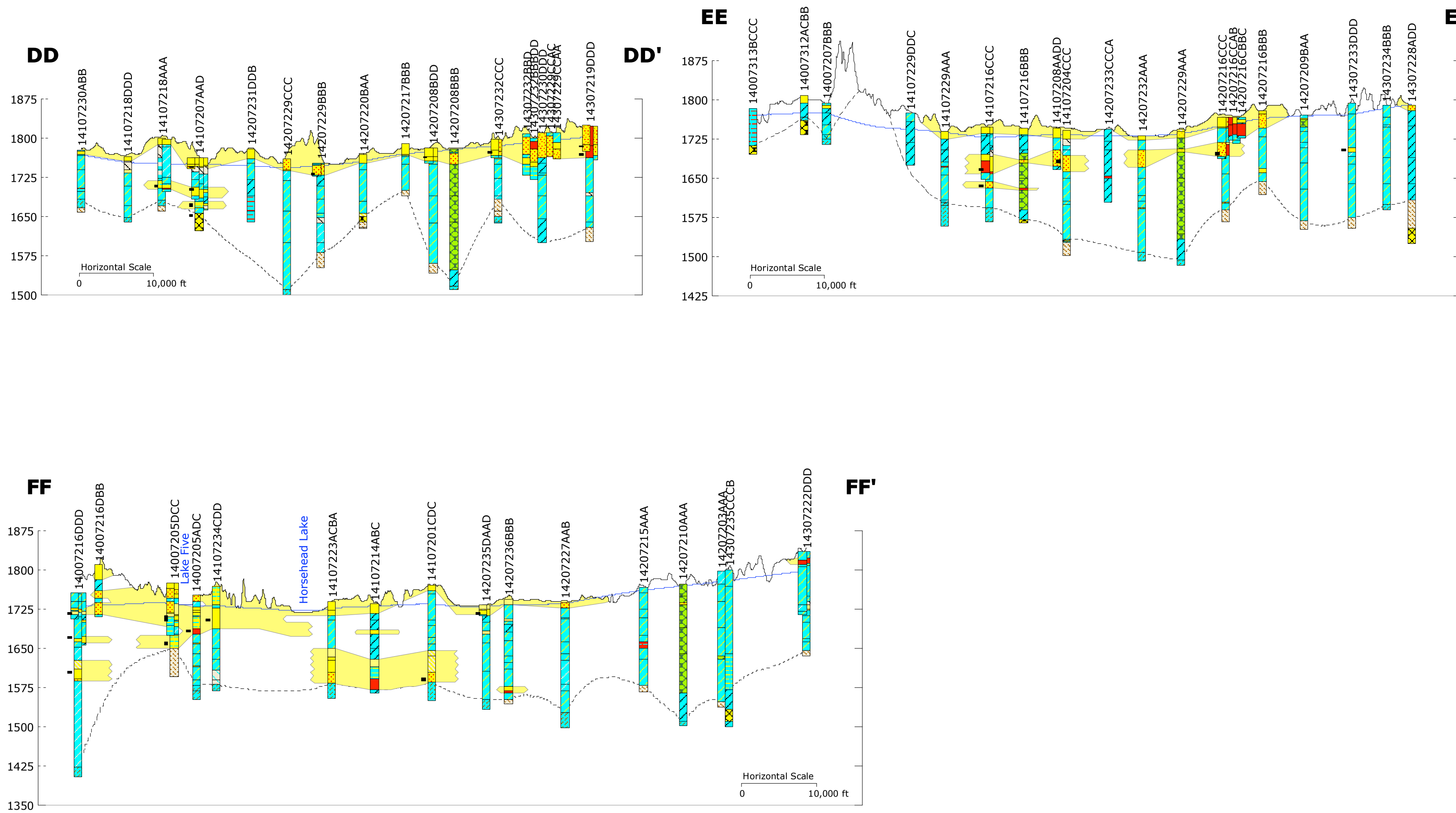


Figure A12. Geologic cross sections approximately 1 mile (DDDD'), 2 miles (EEEE'), and 4 miles (FFFF') east of R73W. See Figure 9 for cross section locations and Figure A1 for map unit descriptions. Blue line represents the water table; dashed line represents the bedrock surface. Yellow fill indicates areas with significant sand and gravel. Horizontal scale: 1 inch = 4 miles.

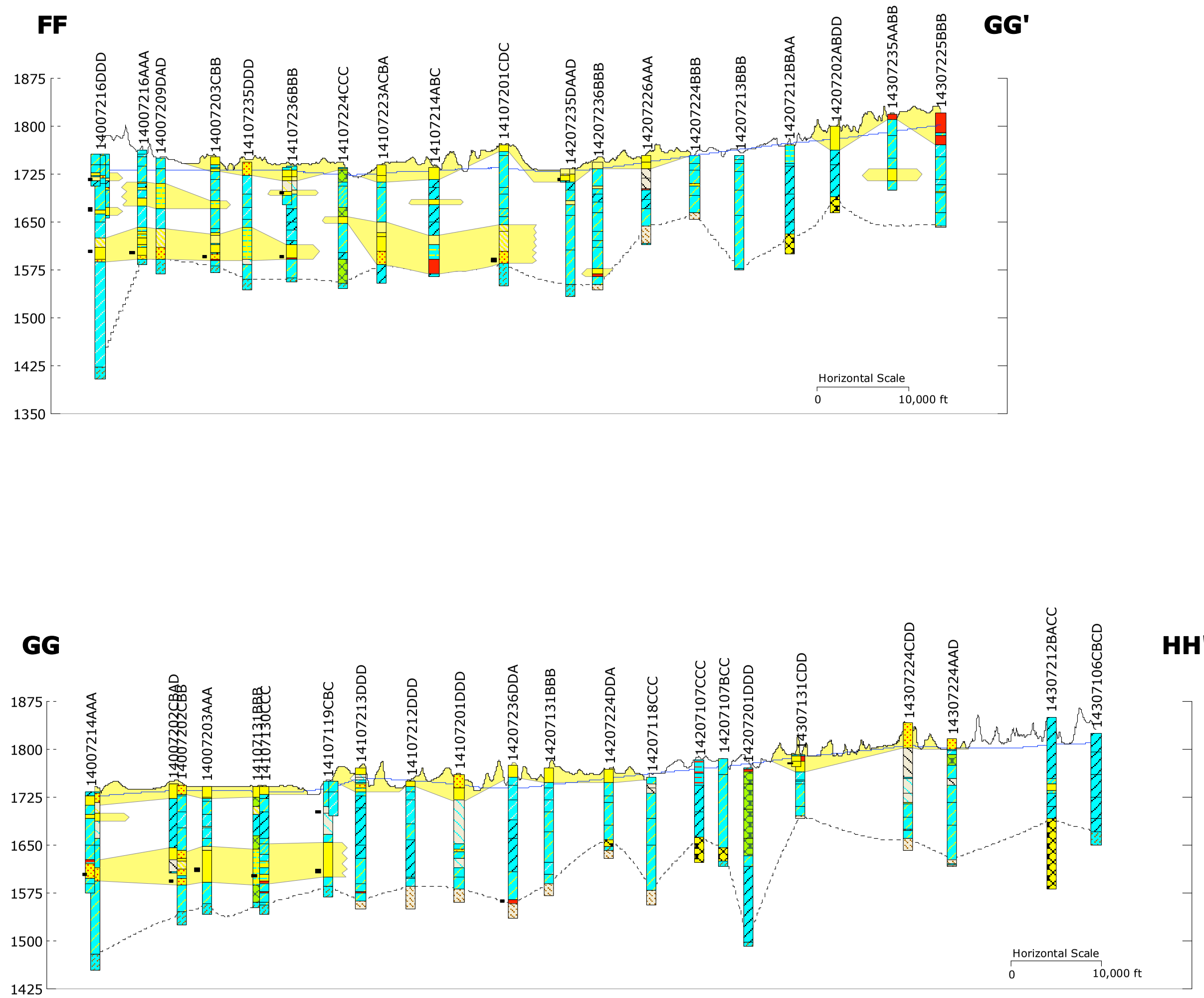


Figure A13. Geologic cross sections approximately 5 miles (FFGG') and 6 miles (GGHH') east of R73W. See Figure 9 for cross section locations and Figure A1 for map unit descriptions. Blue line represents the water table; dashed line represents the bedrock surface. Yellow fill indicates areas with significant sand and gravel. Horizontal scale: 1 inch = 4 miles.

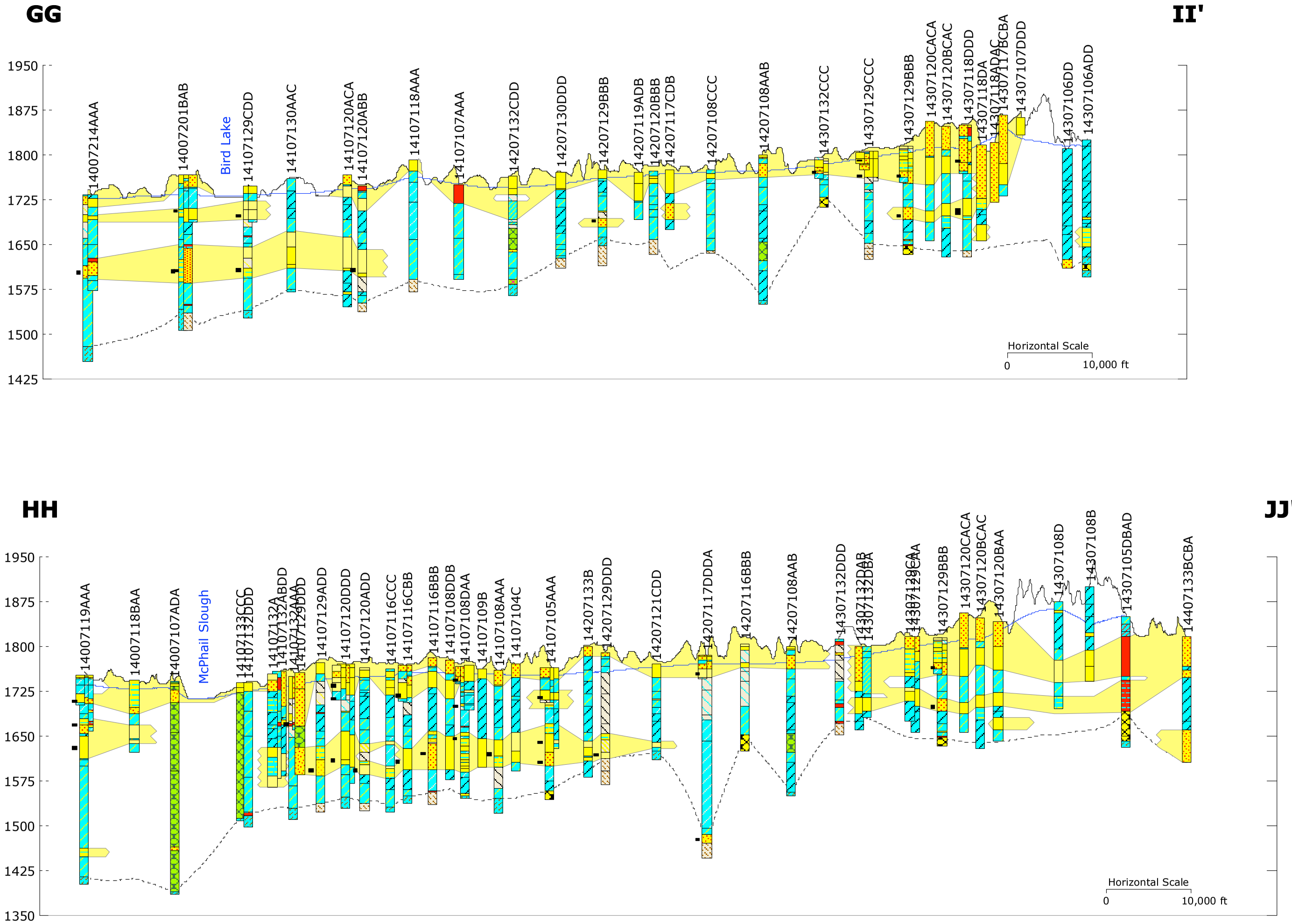


Figure A14. Geologic cross sections approximately 1 mile (GGII') and 2 miles (HHJJ') east of R72W. See Figure 9 for cross section locations and Figure A1 for map unit descriptions. Blue line represents the water table; dashed line represents the bedrock surface. Yellow fill indicates areas with significant sand and gravel. Horizontal scale: 1 inch = 4 miles.

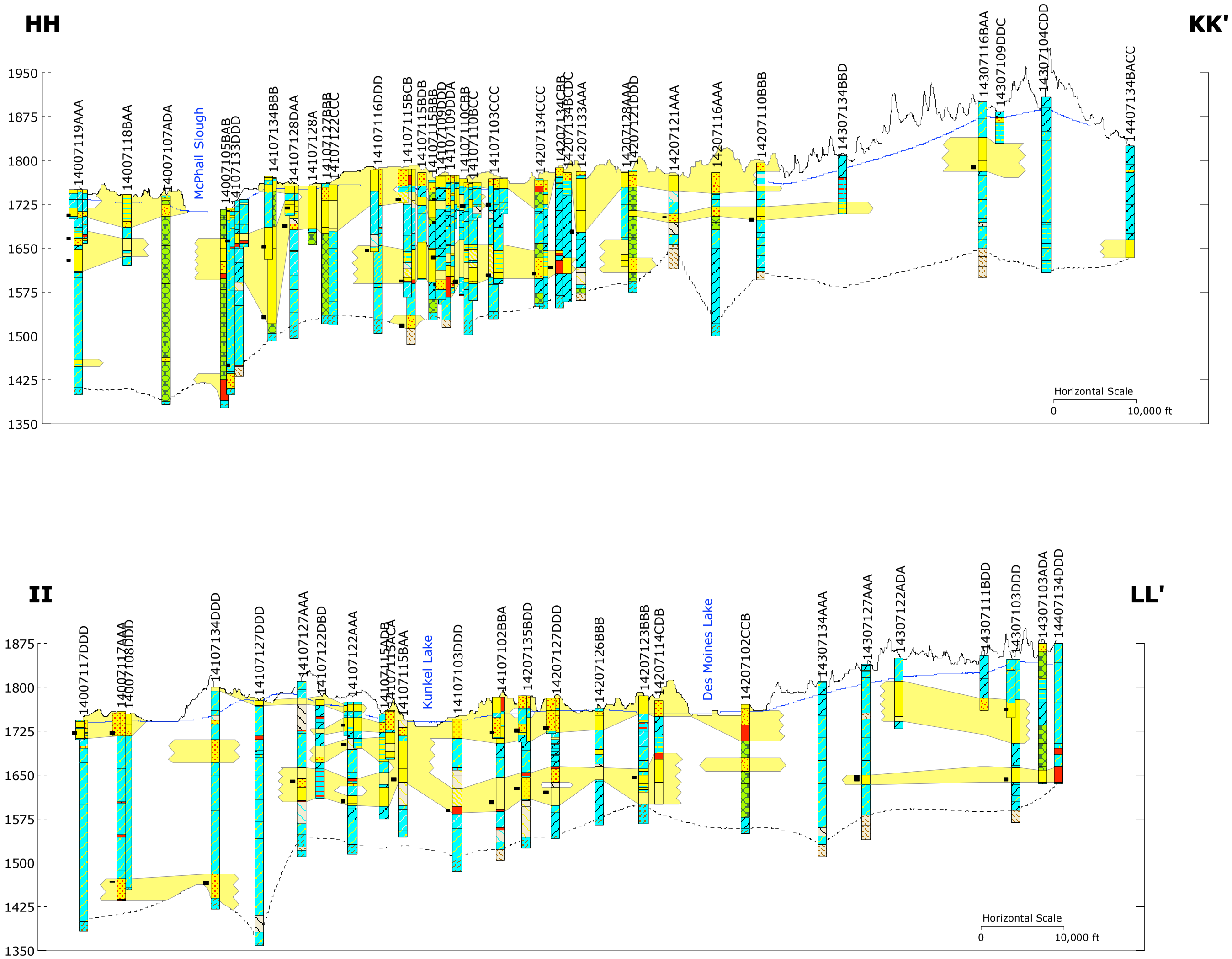


Figure A15. Geologic cross sections approximately 3 miles (HHKK') and 4 miles (IILL') east of R72W. See Figure 9 for cross section locations and Figure A1 for map unit descriptions. Blue line represents the water table; dashed line represents the bedrock surface. Yellow fill indicates areas with significant sand and gravel. Horizontal scale: 1 inch = 4 miles.

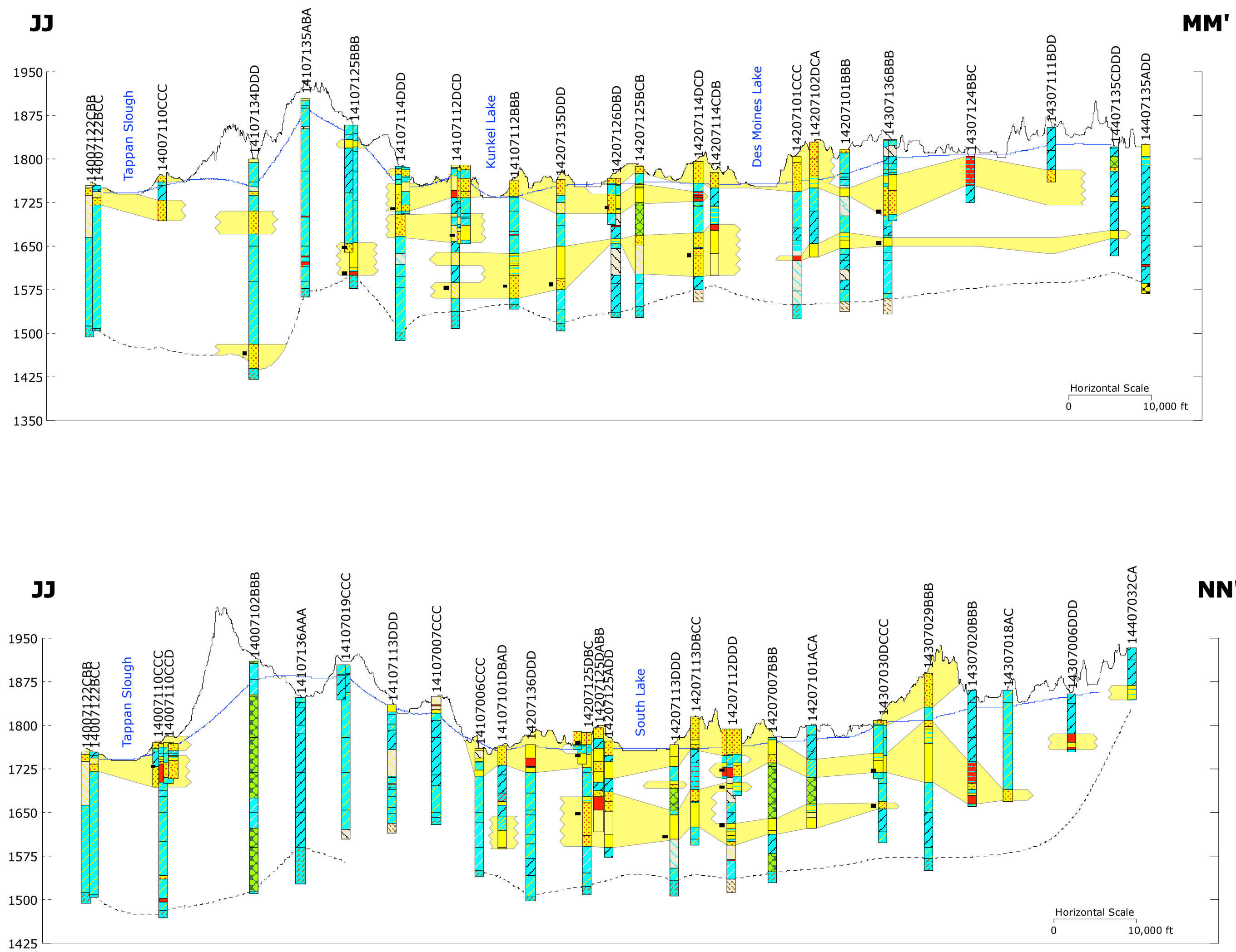


Figure A16. Geologic cross sections approximately 5 miles (JJMM') and 6 miles (JJNN') east of R72W. See Figure 9 for cross section locations and Figure A1 for map unit descriptions. Blue line represents the water table; dashed line represents the bedrock surface. Yellow fill indicates areas with significant sand and gravel. Horizontal scale: 1 inch = 4 miles. Bedrock surface is not shown beneath 14107007CCC and 14107113DDD, because borings were probably terminated in ice-shove blocks.

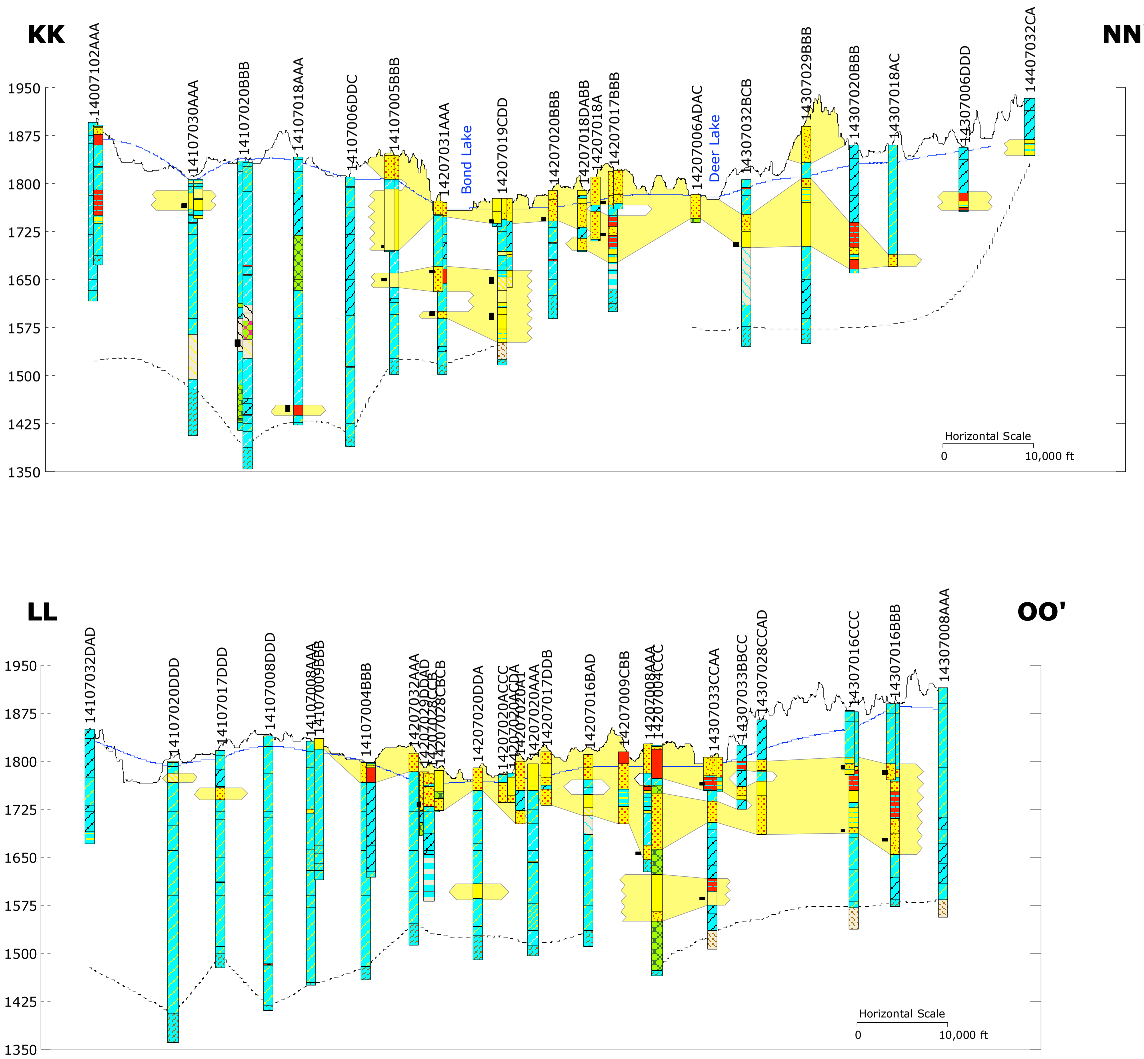


Figure A17. Geologic cross sections approximately 1 mile (KKNN') and 2 miles (LLOO') east of R71W. See Figure 9 for cross section locations and Figure A1 for map unit descriptions. Blue line represents the water table; dashed line represents the bedrock surface. Yellow fill indicates areas with significant sand and gravel. Horizontal scale: 1 inch = 4 miles. Bedrock surface is not shown beneath 14207008AAA, 14207020BBB, and 14207017BBB, because borings were probably terminated in ice-shove blocks.

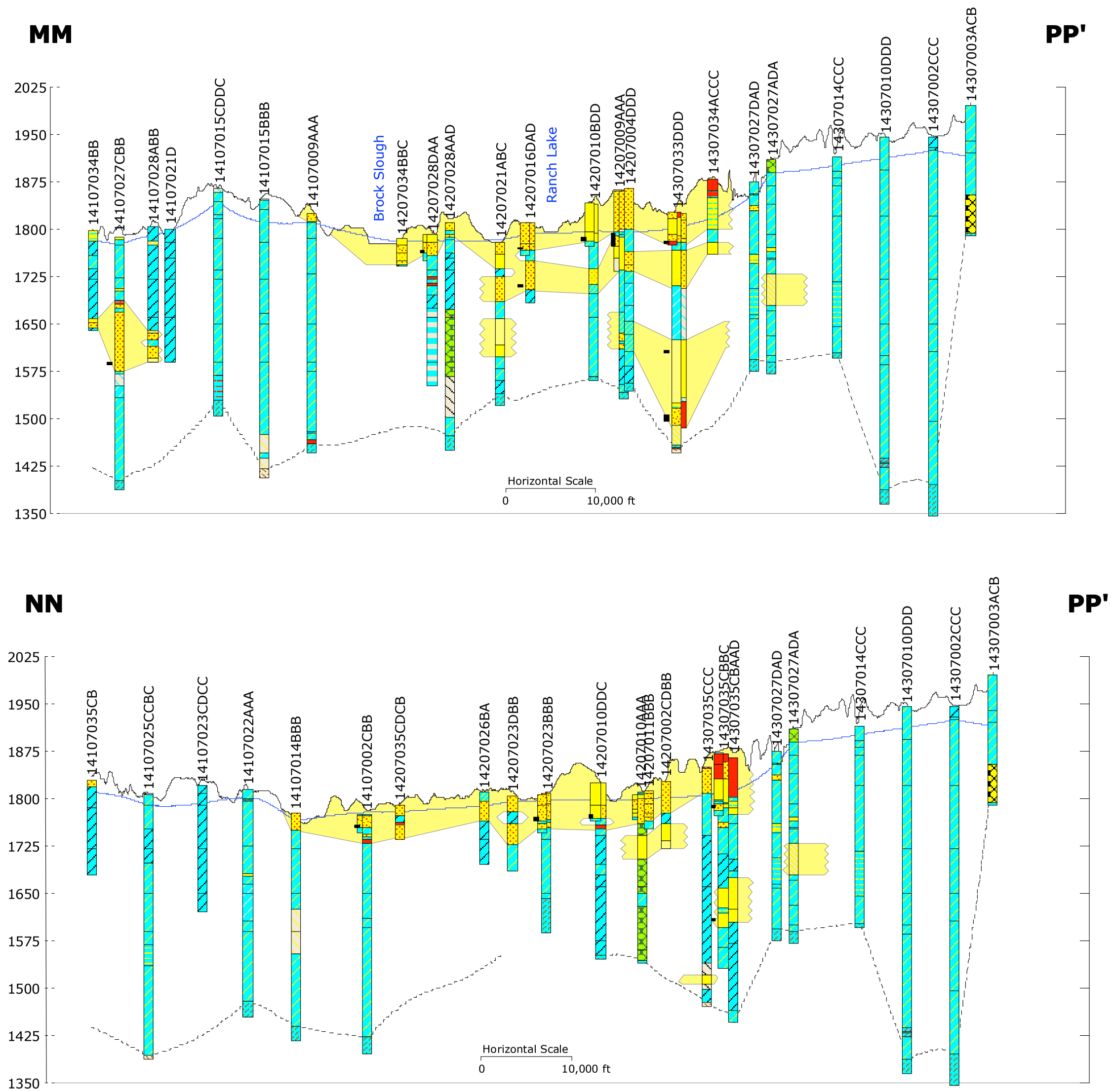


Figure A18. Geologic cross sections approximately 3 miles (MMPP') and 4 miles (NNPP') east of R71W. See Figure 9 for cross section locations and Figure A1 for map unit descriptions. Blue line represents the water table; dashed line represents the bedrock surface. Yellow fill indicates areas with significant sand and gravel. Horizontal scale: 1 inch = 4 miles. Bedrock surface is not shown beneath 14207023BBB, because boring was probably terminated in an ice-shove block.

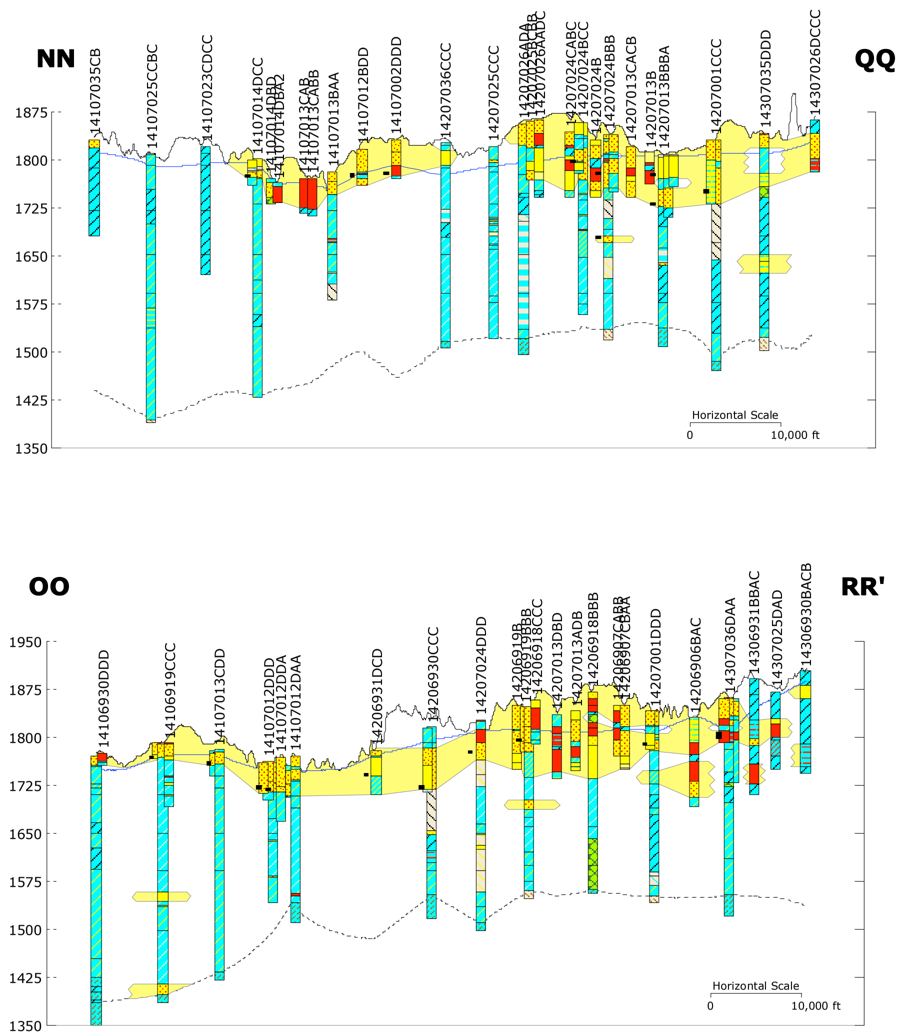


Figure A19. Geologic cross sections approximately 5 miles (NNQQ') and 6 miles (OORR') east of R71W. See Figure 9 for cross section locations and Figure A1 for map unit descriptions. Blue line represents the water table; dashed line represents the bedrock surface. Yellow fill indicates areas with significant sand and gravel. Horizontal scale: 1 inch = 4 miles.

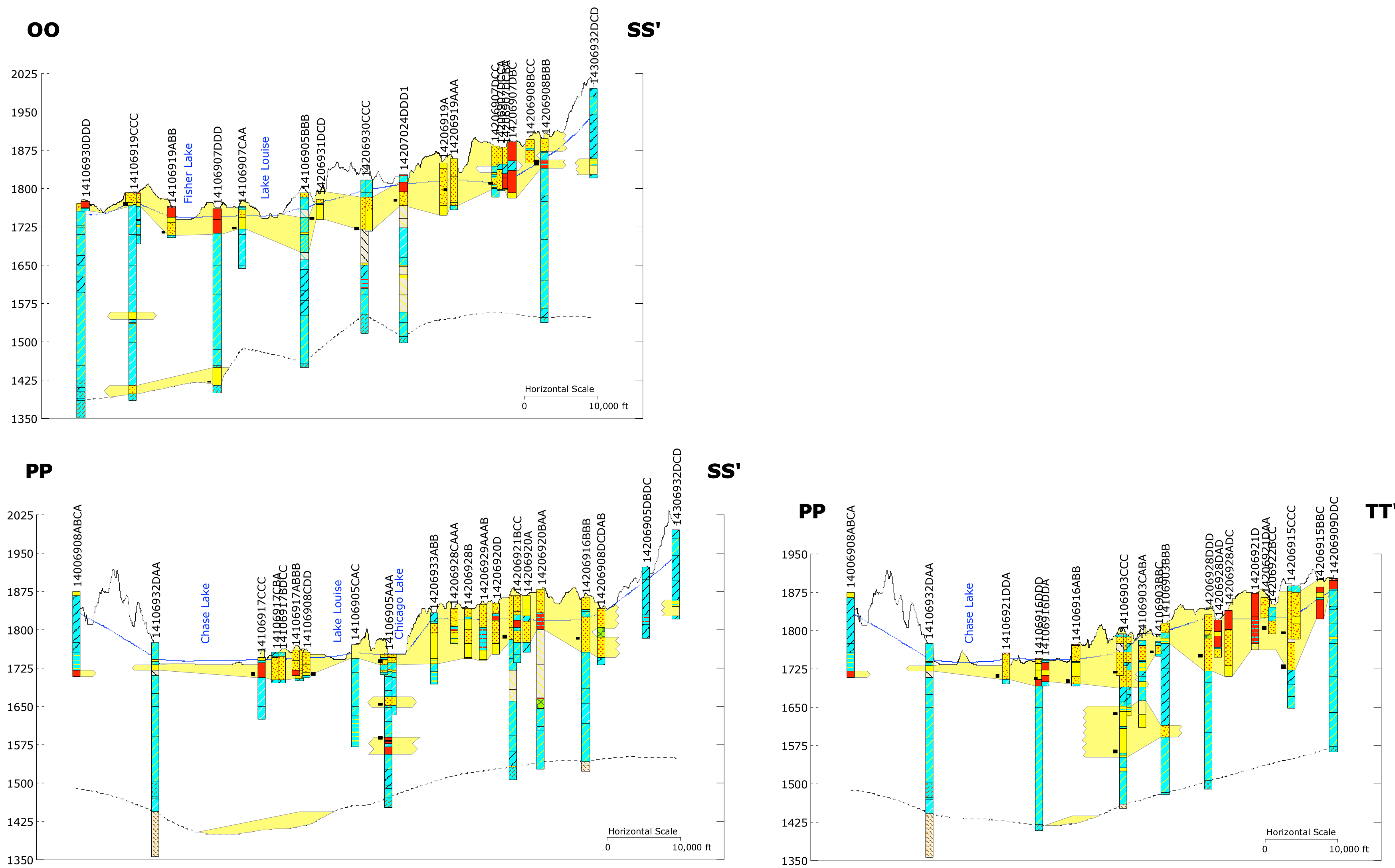


Figure A20. Geologic cross sections approximately 1 mile (OOSS'), 2 miles (PPSS'), and 3 miles (PPTT') east of R70W. See Figure 9 for cross section locations and Figure A1 for map unit descriptions. Blue line represents the water table; dashed line represents the bedrock surface. Yellow fill indicates areas with significant sand and gravel. Horizontal scale: 1 inch = 4 miles.

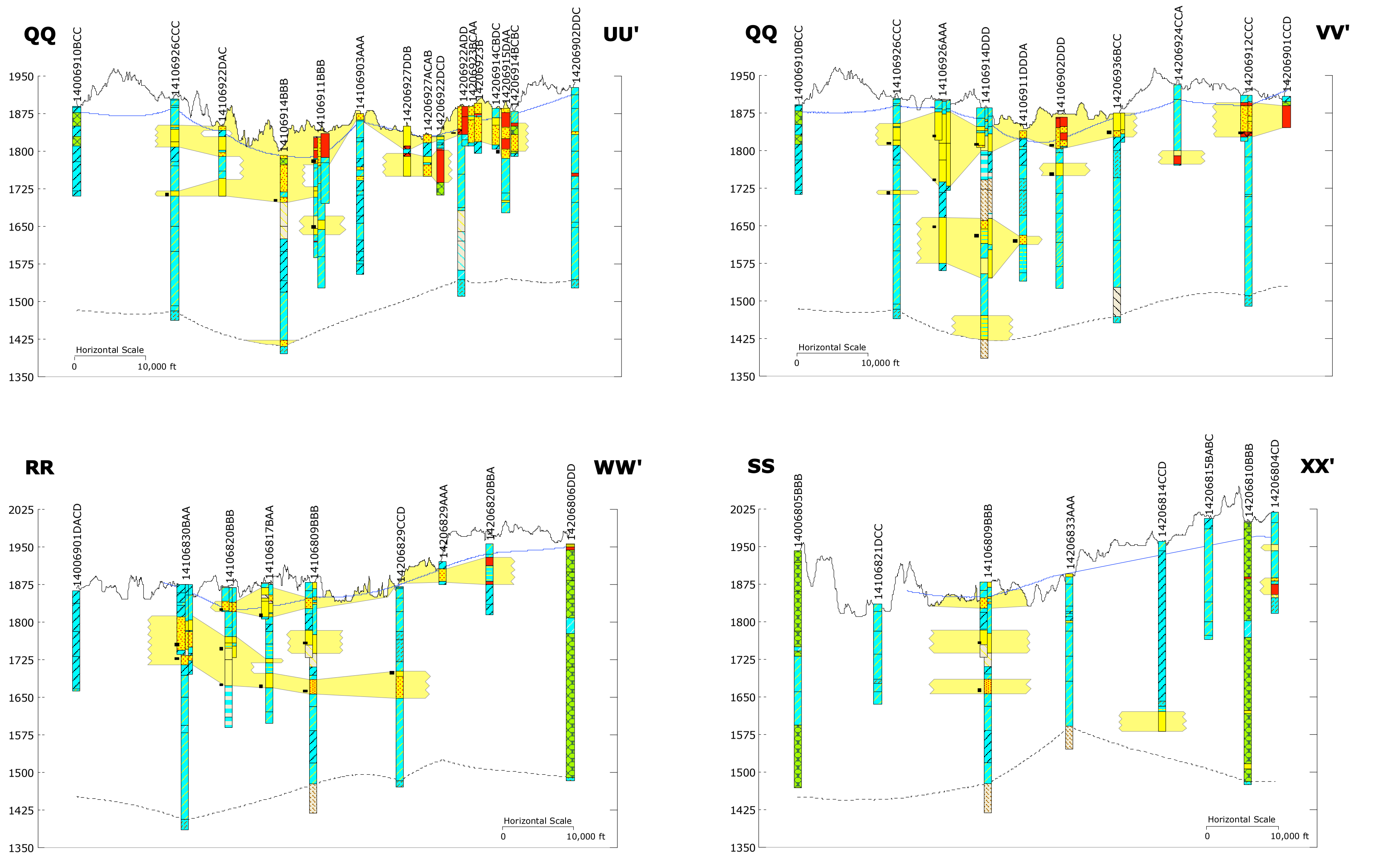


Figure A21. Geologic cross sections approximately 4 miles (QQUU') and 5 miles (QQVV') east of R70W, and 1 mile (RRWW') and 3 miles (SSXX') east of R69W. See Figure 9 for cross section locations and Figure A1 for map unit descriptions. Blue line represents the water table; dashed line represents the bedrock surface. Yellow fill indicates areas with significant sand and gravel. Horizontal scale: 1 inch = 4 miles.