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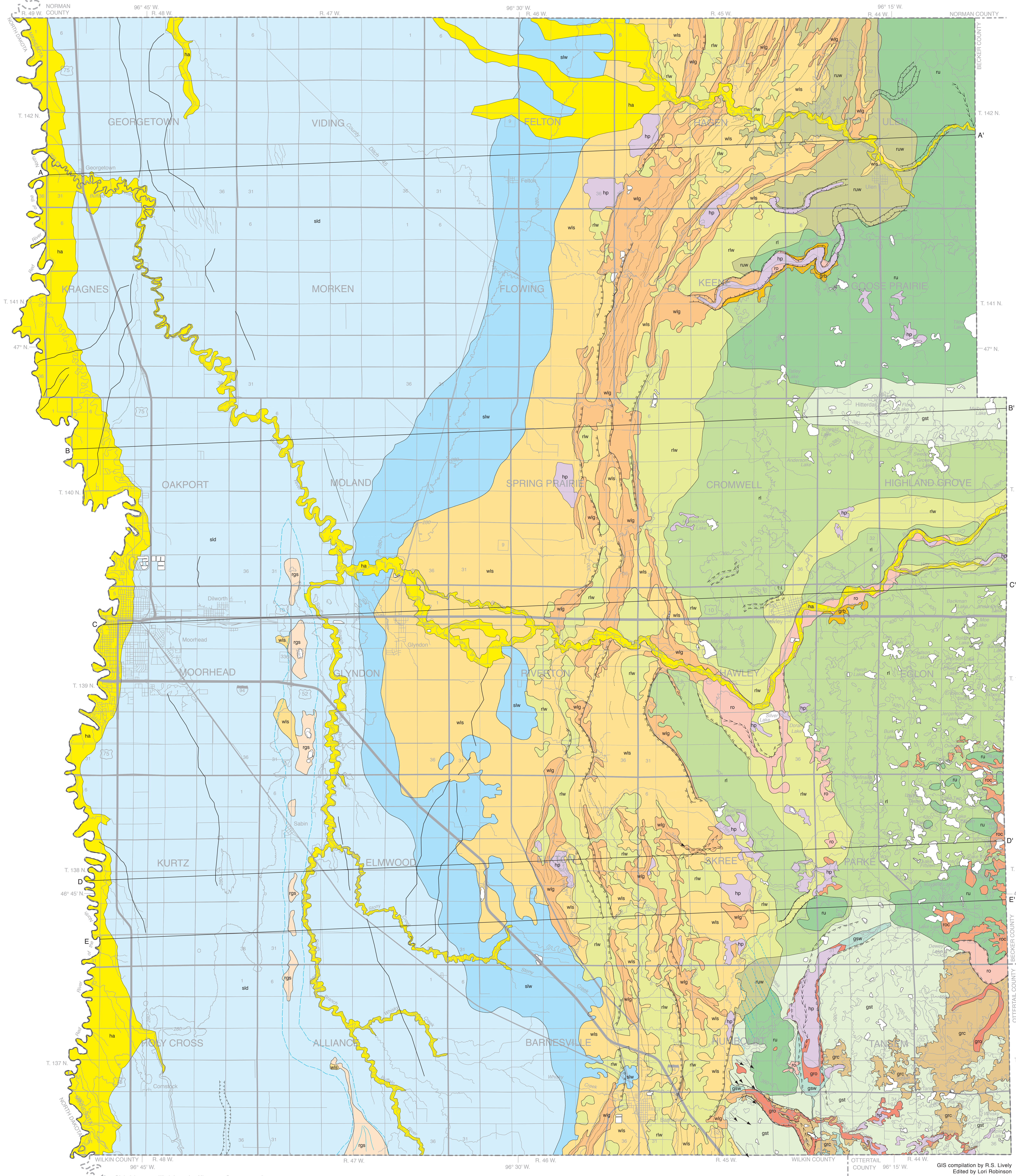
SURFICIAL GEOLOGY

By

Howard C. Hobbs and Angela S. Gowan

2014



Digital base modified from the Minnesota Department of Transportation BaseMap data; digital base annotation by the Minnesota Geological Survey.

Elevation contours were derived from the U.S. Geological Survey 30-meter Digital Elevation Model (DEM) by the Minnesota Geological Survey.

Universal Transverse Mercator Projection, grid zone 15
1983 North American Datum

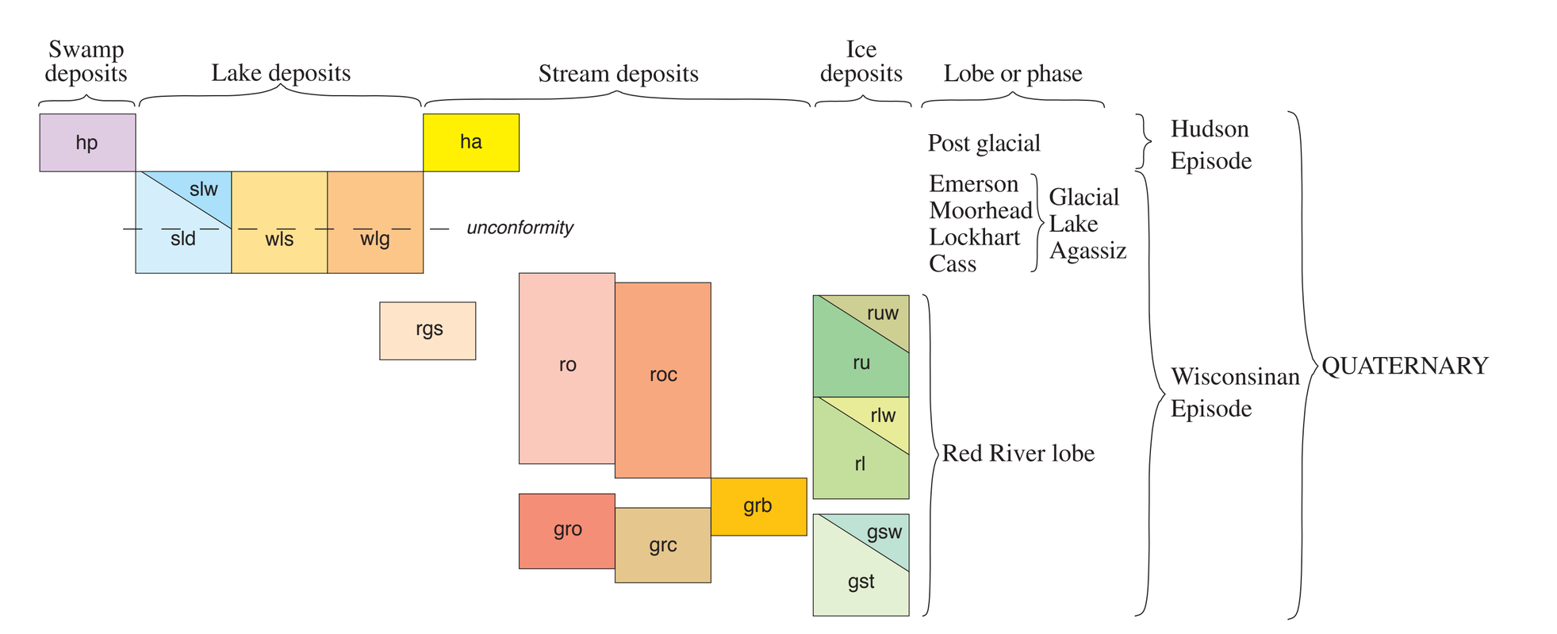
SCALE 1:100 000

CONTOUR INTERVAL 20 METERS

Every reasonable effort has been made to ensure the accuracy of the factual data on which this map interpretation is based; however, the Minnesota Geological Survey does not warrant or guarantee that there are no errors. Users may wish to verify critical information; sources include both the references listed here and information on file at the offices of the Minnesota Geological Survey in St. Paul. In addition, effort has been made to ensure that the interpretation conforms to sound geologic and cartographic principles. No claim is made that the interpretation shown is rigorously correct, however, and it should not be used to guide engineering-scale decisions without site-specific verification.

GIS compilation by R.S. Lively
Edited by Lori Robinson

CORRELATION OF MAP UNITS



MAP SYMBOLS

Geologic contact—Approximately located.

Glacial Lake Agassiz features

Beach ridge—Indicates the crest of a former beach of glacial Lake Agassiz. Includes wave-built features such as spits and bars. A given lake level may be marked by a beach in one place, and a wave-cut scarp in other places.

Wave-cut scarp—A scarp cut by waves at the shore of glacial Lake Agassiz. Ticks point downslope.

Buffalo aquifer compaction ridge—A wide, subtle ridge caused by differential compaction of aquifer sand vs. lake clay. The boundary was drawn from modern topography; it approximates the limit of underlying sand.

Fan of the Buffalo aquifer—Marks the spreading out of the deposit at a former ice margin.

Compaction ridge—A low, subtle ridge in the glacial Lake Agassiz plain caused by differential compaction of stream sediment that was deposited during the Moorhead low-water phase. Unlike the Buffalo aquifer, the sand coring these ridges is not exposed at the surface.

Post-lake drainage channel on lake plain—A shallow, wide channel eroded into lake sediment. Connects with the Red River south of Clay County. Only shown where clearly visible; it fades out to the north, possibly at a temporary shoreline. May be an early channel that formed as glacial Lake Agassiz drained for the last time, but was abandoned as the Red River in its current course eroded a deeper valley into the lake plain.

Glacial features

Drumloid feature—A surface lineation in till aligned north–northwest—south–southeast. Interpreted to be a streamlined form created by active ice.

Flute—A surface lineation interpreted to be a streamlined form created by active ice. Flutes are similar to drumloid features, but longer and more subtle.

Meltwater features

Esker—A narrow, linear body of sand and gravel deposited by a meltwater stream in a tunnel within or under the ice. Sand and gravel is covered by diamicton in most places. The direction of water flow (speculative) is shown by arrowheads.

Obscure meltwater channel—A long depression interpreted to be a segment of a meltwater channel partly obscured by deposits of a subsequent ice advance. Ticks point downslope.

Side of a meltwater channel—A scarp marking the edge of an area eroded by meltwater flow. Typically occurs in pairs, but locally only one side of the channel is clearly expressed. Ticks point downslope.

INTRODUCTION

This map of surficial geology shows the sediment expected to be encountered at the land surface in Clay County. Some very thin surface units are not mapped; these layers are described in the Clay County soil survey (Jacobson and others, 1982). For example, lake sand and outwash sand and gravel are commonly overlain by silty to loamy layers. In addition to the colored surficial units, map symbols show an interpretation of the surface morphology, which in some cases gives clues to the origin and content of deeper layers. Surficial sediments can be grouped into four main types based on texture: sand and gravel, sand, silt and clay, and an unsorted loamy mixture of sand, silt, clay, pebbles, and larger stones. Each type was deposited in a different environment: sand and gravel were deposited by flowing glacial meltwater and by waves in a glacial lake; sand was deposited in shallow water of a glacial lake; silt and clay were deposited in still, deep glacial lake waters; and mixed sediments were deposited by melting glacial ice, either directly by melting out of interstitial ice, or indirectly in the form of mudflows. The last sediment type is most common in hummocky areas, where ice melted out under a thick cover of supraglacial debris, forming a shifting pattern of depressions that locally filled with debris slumping or flowing from the steep sides. This type of sediment is called diamicton (defining its texture and material properties) or till (defining its mode of origin).

Unit contact lines and descriptions were determined by observation and sampling during the 2010 field season, both from surface exposures and shallow soil borings, by boring descriptions in the County Well Index, by soil parent material (Jacobson and others, 1982), and by characteristic landforms visible on topographic maps and lidar (Light Detection and Ranging). Line symbols were drawn mainly with the assistance of lidar. Lidar is analogous to radar, except it uses light rather than radio waves. A laser light beam is rapidly scanned from a moving airplane, and the delay in return is measured to give a model of surface topography. Depending on the resolution, this can be much more precise than a topographic map made by traditional methods, and the information can be processed to make a shaded-relief map that looks like a low sun shining on the landscape. Figure 1 shows a reduced version of the surficial map units superimposed on a 33-foot (10-meter) lidar image. Lidar images are available from the Minnesota Department of Natural Resources (http://deli.dnr.state.mn.us/). The Minnesota Department of Natural Resources title for this dataset is *High Resolution Digital Elevation Model (DEM).*

Clay County has been included in earlier surficial maps compiled at smaller scales. The North Dakota Geological Survey published a map of Cass County, North Dakota and Clay County, Minnesota at a scale of 1:250,000 (Arndt and Moran, 1974). Clay County is in the center of a regional 1:200,000 surficial map (Harris, 1995), and a 1:750,000 stratigraphic compilation (Harris and others, 1995) of the southern Red River valley. Most of Clay County is included in two surficial mapping and stratigraphy theses (Anderson, 1976; Perkins, 1977), both at the scale of 1:250,000. This map at 1:100,000 scale shows more detail and is based on additional data.

LOBES AND PROVENANCE

Continental ice sheets entered Minnesota from the northwest, north, and northeast at different times. In order to facilitate the interpretation of deposits and define glacial history, lobes have been recognized in the ice mass, each of which deposited a more or less distinct suite of rocks and pebbles (Wright, 1972a). The shape and direction of movement of the ice defines the lobes; some are long and narrow, and others bulge out only slightly from the main ice mass, the Laurentide Ice Sheet. Provenance is defined as the suite of rocks, pebbles, and sand deposited by the ice, which is controlled by the bedrock and sediment in the source area of the ice. Figure 2 shows a simplified bedrock map, and the general source of four provenance types. From west to east they are: Riding Mountain provenance, typified by common to abundant gray shale; Winnipeg provenance, which is rich in carbonate rocks; Rainy provenance, which is rich in crystalline rocks such as granite, greenstone, and graywacke (though all provenances contain some crystalline rocks); and Superior provenance, which is rich in red and dark gray mafic rocks and red sandstone. All provenances are mixed to some extent, but some are mixed enough to be given hybrid names, such as Rainy–Winnipeg.

The Rainy and Superior lobes deposited material of Rainy and Superior provenance, respectively. Sediment of Rainy–Winnipeg provenance was deposited by the Wadena lobe; relatively pure Winnipeg provenance sediment was deposited by the Red River lobe. The only lobe in Minnesota to deposit Riding Mountain provenance material was the Des Moines lobe, which entered Minnesota from the northwest and extended south to Des Moines, Iowa.

GLACIAL AND POST-GLACIAL HISTORY

Clay County was glaciated many times during the Quaternary period. However, the surficial geology map portrays only the most recent deposits, which can be seen at the surface and in excavations. Plate 4, Quaternary Stratigraphy, contains cross sections from the surface to bedrock. The earliest ice advance with a surficial expression (though draped with younger sediment) was of the Wadena lobe, which deposited thick sand and gravel and sandy diamicton of the Hewitt Formation (Wright, 1972a; Knaeble, in press). The general extent of thick Hewitt Formation sediment is shown in Figure 3A, but a thinner fringe underlies much of the county. Thick Hewitt Formation sediment in Clay County may be a northern and western extension of the Alexandria moraine complex (Wright, 1972b), believed to have been formed by the same advance that formed the Wadena drumlin field in central Minnesota. The general direction of this advance was from the northeast, but it fans considerably near the margin so that some of the flow lines trend northwest (Fig. 3A). The Itasca moraine is a recessional ice margin also depicted in Figure 3A; the flow lines behind this margin do not fan appreciably. The overall provenance of the Hewitt Formation is Rainy (Fig. 2), but it contains some carbonate, so it can be described as Rainy–Winnipeg. Sand, gravel, and till of the Alexandria moraine complex is mostly buried in the county, but may be exposed in places on the western side of the moraine southwest of Hawley, especially where the overlying material may have been eroded by waves of glacial Lake Agassiz.

Following retreat of the Wadena lobe, Clay County was covered by several ice advances from the northwest, carrying shale-rich debris from the Pierre Shale uplands of North Dakota and Manitoba (Fig. 2). This tongue of ice, called the Des Moines lobe, covered much of southern Minnesota with till of the New Ulm Formation (Lusardi, in press), whose mode of deposition was by ice streams (Patterson, 1998). Harris and others (in prep.) included deposits correlative to the Des Moines lobe in the Goose River and Otter Tail River Formations in the southern Red River valley; Figure 3B shows the maximum extent of the Des Moines lobe in the area, with generalized flow lines. Flow lines change with the extent of the lobe; these flow lines represent more extensive phases.

As the volume and thickness of the Laurentide Ice Sheet gradually decreased by melting and rapid outflow, the ice became more confined to the Red River valley lowland, and the main direction of flow shifted from southeast to south, through the Winnipeg area. When the ice had retreated to the Red River valley and its dominant provenance was Winnipeg and Winnipeg–Riding Mountain, it is referred to as the Red River lobe, the maximum extent of which is shown in Figure 3B. The St. Hilaire Member of the Goose River Formation, which is exposed in the southeastern part of Clay County, extends to the middle of the Big Stone moraine (Fig. 3C). The Red Lake Falls Formation was deposited by an advance that extended to the Comstock ice margin. Till of the Red Lake Falls Formation is much lower in shale (10 to 20 percent) than the St. Hilaire Member till. Two ice marginal positions of the Red Lake Falls Formation are shown in Figure 3C; they are not marked by moraines, but by subtle geomorphic breaks. In its type area, the upper part of the Red Lake Falls Formation is richer in shale than the lower part. Harris and others (1974) divided the formation into two members on the basis of shale content, but the two are similar, and rarely separated by a clear stratigraphic break.

The lake that formed in the Red River valley before, between, and after these northern-source ice advances is called glacial Lake Agassiz. Its complex history has been studied for over 150 years, and continues today. The most recent comprehensive compilation of studies is by Teller and Clayton (1983). The known history of glacial Lake Agassiz begins with the withdrawal of ice from the Big Stone moraine. There is evidence of an earlier glacial lake in the Red River valley, and there must have been a lake any time the ice melted in the valley, because the normal drainage to the north was still blocked by ice. A north–south cross section based on bridge borings for Interstate 29 in North Dakota shows thin lake sediment under "unit B" of Arndt (1977), which underlies the great bulk of lake sediment in the southernmost Red River valley. A very thick sequence of glacial lake sediment is present in Clay County, as represented by the log of rotary-sonic drill hole CYR-1 near Rollag, where it occurs beneath diamicton of the St. Hilaire Member of the Goose River Formation (see Plate 4). This sequence, though very thick, is not extensive, indicating it was a small ice-marginal lake that was quickly filled with sediment, prior to glacial Lake Agassiz proper.

The most recent incarnation of glacial Lake Agassiz began in its southern end, as glacial ice melted back from the Big Stone moraine. Most of the Red River valley was still occupied by ice at this time. The initial outlets were at the southern end. As the lake enlarged from melting ice, and as large meltwater channels from other parts of the ice margin began funneling vast amounts of meltwater into the lake, the main outlet enlarged into a giant stream called glacial River Warren (Wright, 1972a). The width of glacial River Warren is approximated by the width of Lake Traverse and Big Stone Lake, which now occupy its channel. The present Minnesota River is a shrunken remnant of glacial River Warren.

As the main outlet was eroded deeper in stages, the water level dropped and earlier beaches were abandoned. The highest well-developed beach is named the Herman, after the town of that name, and the lowest one in this area is named the Campbell, also after a town; these levels were controlled by different stages of erosion of the southern outlet. These and other named levels have been traced to the north, but such correlations are difficult (Teller and Leverington, 2004). All formerly flat surfaces have been warped upwards to the north by differential glacial rebound, the result of land rising once the weight of ice is removed. Weller and Fisher (2009) revisited this effort. They showed that it is feasible to extend water planes a significant distance across the basin with confidence. They were able to recognize seven water planes over an extensive region, four of which could be traced to the towns for which they were named.

In general, fine-grained sediment accumulated under deep, still water. The depth is not known, but it can be estimated. The elevation of the deepest part of the lake plain is about 150 feet (46 meters) below the lowest well-developed strandline, the Campbell. This is the maximum depth at the end of deepwater sedimentation. The depth was greater during earlier phases, both because the water level was higher and the depositional surface was lower. Sand and silt accumulated in shallower water, and gravelly coarse-grained sand was transported and deposited by waves along the shoreline. Most of the deepwater lake sediment that accumulated in Clay County during this phase is referred to as the Brenna Formation (Arndt, 1977). It is chiefly massive, very soft, gray, calcareous clay. The contemporary beach and shallow-water sediment is not included in the Brenna Formation, but neither is it included in any other formal stratigraphic unit. Because the water level dropped over time, the trend is for shallow-water sediment to overlie deeper-water sediment.

As the ice that deposited the Red Lake Falls Formation was retreating, it was fronted by the waters of glacial Lake Agassiz. An outburst of glacial meltwater carved a large tunnel at the base of the ice and built a subaqueous fan of sand and gravel into the lake, creating what is now known as the Buffalo aquifer (Harris and others, 1998). At the time of formation, the ice margin must have been close to the southern boundary of Clay County, because there the narrow deposit of sand in the tunnel widens into a fan, no longer confined by the ice (Fig. 3C). A further recessional position is shown as the Erskine ice margin on Figure 3C. Further retreat of the ice margin was interrupted by an ice advance that deposited till greatly enriched in clay derived from the lake sediment. This readvance was the Caledonia advance (margin shown on Fig. 3C; Harris and others, 1995), which deposited the Huot and Falconer Formations (Harris and others, 1974). This advance did not reach Clay County.

When ice retreated far enough to allow northeastward flow into the Great Lakes and the St. Lawrence River, glacial Lake Agassiz dropped to the Moorhead low-water level (Clayton, 1983; Thorleifson, 1996) and no longer drained to the south. At this time the entire bed of glacial Lake Agassiz was dry in Clay County, though a shallow lake persisted farther north, where the surface elevation is lower. This Moorhead level is shown as an unconformity in the correlation chart. During the Moorhead low-water phase, streams entering the basin on their way to the north eroded valleys into the lake sediment, and deposited sand in their channels. When the northeastern outlets were blocked by renewed glacial activity, the lake rose to its southern outlet, and deepwater sediment of the Sherack Formation (units sld and slw) was deposited over the fluvial and deltaic sediment and peat that had accumulated. The trace of the Moorhead phase stream valleys can still be discerned where they cross the fine-grained lake sediment, as low, subtle "compaction" ridges in the lake plain (see Map Symbols). After deposition, the sand in the channels compacted less than the clay that they were eroded into, inverting the former topography (Arndt and Moran, 1974). Some of this channel sediment can be seen in cross sections (Plate 4, *Quaternary Stratigraphy*). The lake level went down again in stages as northern ice melted back and lower outlets opened.

Surface alluvium and peat began to accumulate as soon as ice melted out of the glacial areas, and as soon as the water receded in glacial Lake Agassiz. They continue to accumulate today. Postglacial differential rebound continues today. Its effect is to decrease the gradients of north-flowing streams such as the Red River, because the more recently ice-covered land to the north is rising faster than the land in the south.

DESCRIPTION OF MAP UNITS

HUDSON EPISODE

Episode terminology is adopted from Johnson and others (1997). This system was designed as an alternative to the traditional system of named glaciations and interglaciations. Glaciations and interglaciations begin and end simultaneously worldwide. Episodes begin and end locally at different times in different places, depending on the local climate and geologic processes. The two episodes present at the surface in Clay County are the Wisconsinan Episode (Wisconsinan Glaciation) and the Hudson Episode (Holocene Period). The Hudson Episode is the most recent episode in the geologic history of the area. Hudson Episode sediments were deposited in nonglacial environments, not deposited by glacial ice or meltwater, or in glacial lakes. In addition to sediments, soils formed during the Hudson Episode.

ha **Alluvium**—Sediment deposited by streams. Unit is comprised of channel and overbank sediments; the former is too narrow to map at this scale. Channel sediment is generally sand, with some gravel. It is moderately well sorted and typically cross-bedded. The organic component is chiefly large, woody debris. Overbank sediment consists of material deposited outside of the channel by floods. Close to the channel, overbank sediment is typically fine-grained sand; farther away, it is mostly silt. During major floods, the Red River spills far out of its valley onto the lower part of the glacial Lake Agassiz plain. This distant alluvium is silty clay and clayey silt, similar to deepwater glacial Lake Agassiz sediment. The alluvium is only mapped where thick enough to obscure the natural micro-topography of the lake plain. Along higher-gradient streams at the edge of and out of the Red River valley, overbank sediment is chiefly fine-grained sand and silt. Overbank sediment is obscurely bedded, and contains interbedded, partially decomposed organic material ranging in size from coarse to fine. Fine-grained sand was deposited in several old courses of the South Branch of the Wild Rice River, where it spread out onto the flat lake plain.

hp **Peat**—Organic sediment deposited in low, saturated areas. Chiefly composed of partially decomposed reeds, grass, and brushwood. Includes some silt and clay-sized mineral matter, especially where transected by streams. Peat occurs in ice-block meltout depressions, former meltwater channels, depressions between beach ridges, and in sloping areas of ground-water discharge. The sloping areas remain saturated because the water that runs off is constantly replenished by seepage from below.

WISCONSINAN EPISODE

The most recent glaciation of the region took place during the Wisconsinan Episode. Older glacial deposits are known in the subsurface, but they cannot be assigned to named episodes in this area because of dating uncertainties.

Deepwater lake sediment

Sherack and Brenna Formations—Deepwater glacial Lake Agassiz sediment. The Sherack and Brenna Formations are separated by an unconformity formed during the Moorhead low-water phase (Plate 4). Comprised of two surficial mapping units in Clay County: sld and slw. Almost all of the deepwater lake sediment exposed at the surface is Sherack Formation, but Brenna Formation sediment is exposed in a few places, such as cutbanks of the Red River.

sld ***Fine-grained lake sediment***—Clay, silty clay, and silt; calcareous. Unoxidized color—dark to very dark gray (5Y 4/1 to 3/1); oxidized color—olive-gray to light olive-brown (5Y 5/2 to 2.5Y 5/3). Mostly massive, but laminated in places, especially in the upper part (the Sherack Formation). The upper few feet are more silty than below. Contains scattered pebbles and larger clasts, apparently dropped from melting icebergs. Deposited in deep water of glacial Lake Agassiz when its level rose to the Campbell level after the Moorhead low-water phase.

slw ***Washed fine-grained lake sediment***—Same as unit sld, but its surface is overlain by a layer of fine-grained sand and silt up to 5 feet (1.5 meters) thick. The surface layer is interpreted to have formed as the glacial Lake Agassiz water level lowered for the last time and the fine-grained lake sediment was washed by waves.

Shallow-water and shoreline sediment—These sediments are lateral equivalents of the deepwater Sherack and Brenna Formations, but are not currently included in a formal lithostratigraphic unit.

wls **Lake sand**—Very fine- to coarse-grained sand, calcareous, silty in places. No bedding is visible. Oxidized color—light olive-brown to light yellowish-brown (2.5Y 6/3 to 5/3); unoxidized color—gray to light brownish-gray (2.5Y 5/1 to 6/2). Generally fine-grained in the flat lake plain; grades down vertically and downslope laterally through silt to unit sld (similar sand less than 5 feet [1.5 meters] thick over lake clay is mapped as unit slw). In the beach areas adjacent to units wlg and rtw, lake sand is typically coarser-grained and generally overlies washed till. Interpreted to be relatively shallow-water sediment of glacial Lake Agassiz, from shoreline to perhaps 100 feet (30 meters) depth. Some of the sand was derived from meltwater streams entering the lake, especially the ancestral Buffalo River. Also derived from backwash of waves eroding the shore, especially where the shoreline sediment was sandy. In places, the upper part of this unit may be composed of thin, windblown silty sand, but the eolian sediment is generally within the soil horizons, and the distinction has been obscured by soil-forming processes.

wlg **Shoreline sediment**—Gravelly sand and sandy gravel, some beds of non-gravelly sand; calcareous. Contains cobbles and boulders in places. Well to moderately well sorted. Bedding is typically flat to shallowly dipping; cross beds are common in places. Oxidized color is typically light olive-brown (2.5Y 5/3), but it is difficult to specify because individual grains have different colors. Unoxidized color was not observed. Unit is commonly overlain by a thin (1 to 3 feet [0.3 to 1 meter]) layer of unbedded eolian fine-grained sand and silt, with a concentration of pebbles and larger stones at the contact. This stone concentration is interpreted to be a lag of coarser-grained material left behind by wind erosion of the finer-grained sand.

The sand and gravel is interpreted to be beach and shallow water sediment of glacial Lake Agassiz. For the most part, the beaches are composed of this unit, and the interbeach swales are underlain by lake sand (unit wls). A small part of this unit is mapped where the Buffalo River outwash enters the lake plain. The sand and gravel were chiefly derived from large waves eroding the shoreline, which was composed mainly of Red Lake Falls Formation diamicton, and may have included some sand and gravel of the Hewitt Formation exposed by erosion that were too small to map. The overlying fine-grained silty sand is interpreted to be windblown sediment, deposited after the water level had lowered enough to expose broad sand flats (units wls and slw) to the west. The beach and interbeach deposits are less than 15 feet (5 meters) thick in most places, and are interspersed with thin sand deposits over washed till (unit rtw).

Red Lake Falls Formation—Diamicton and associated sand and gravel of the most recent glacial advance to enter the county. The ice advanced south, up the axis of the Red River valley, and spread eastward out of the valley. The provenance is mixed Riding Mountain–Winnipeg. Two members, the Upper and the Lower, have been defined (Harris and others, 1974), but the complexity of deposits in Clay County indicates there may have been more than two glacial pulses. Even in the type area near the town of Red Lake Falls, the contact between the Upper and Lower member is difficult to discern in many places. The distinction is made mainly on the shale content; diamicton of the Upper member contains more shale than the Lower member. This distinction is not seen everywhere in Clay County, and in places the formation is divided into members solely based on sand layers seen in the cross sections (Plate 4). Surficial outwash deposits of sand and gravel are undivided as to member. The Red Lake Falls Formation also includes a sandy subglacial stream deposit, referred to as the Buffalo aquifer, that has since been mostly covered over with glacial Lake Agassiz deposits.

ro ***Outwash***—Sand and gravel with some larger clasts; calcareous. Moderately well sorted, crossbedded. The oxidized color is typically light olive-brown or light yellowish-brown overall (2.5Y 5/3, 6/3), but it is difficult to specify in coarser-grained beds. Unit occurs in former meltwater channels leading to glacial Lake Agassiz. Unit has a generally smooth surface, implying that the underlying buried ice had melted before deposition was complete.

roc ***Collapsed outwash***—Sand and gravel as in unit ro, but some beds are offset by faults. The surface contains numerous undrained depressions. Unit occurs in the southeastern part of the county. Interpreted to be the deposits of braided meltwater streams washing debris off the melting glacier, generally towards the southeast. The sediment was deposited on a surface that contained considerable buried glacial ice from earlier events, and the surface collapsed as this ice melted. The timing of ice meltout indicates that this unit is older than unit ro.

rgs ***Buffalo aquifer***—Chiefly clean, fine-grained sand; calcareous. The upper 10 feet (3 meters) or so is coarse-grained silt in many places. Typically massive. The unoxidized color is dark gray (5Y 4/1). Coarsens to gravelly sand and sandy gravel at depth. Overlain by a variable thickness of glacial Lake Agassiz clay (unit sld), but unit rgs is mapped only where clay cover is less than 5 feet (1.5 meters) thick. Thus the surface exposure is discontinuous but the subsurface extent is continuous. Unit is interpreted to be a deposit of rapidly flowing water confined in a subglacial tunnel at the base of the ice. The wider part of the unit near the southern boundary of the county is interpreted to be a subaqueous fan deposited beyond the ice margin.

ru ***Upper member, glacial till***—Loamy diamicton with pebbles and larger clasts. Mostly unsorted, but includes scattered beds of silt and sand and gravel, containing an average of 13 percent shale grains (in the coarse-grained sand fraction). Calcareous under a leached zone several feet thick. The oxidized color is typically light olive-brown to olive-brown (2.5Y 5/4, 4/4); the unoxidized color is dark gray to dark grayish-brown (2.5Y 4/1 to 4/2). Overlain in places within a few miles of the glacial Lake Agassiz plain by thin, unbedded, silty, fine-grained sand interpreted to have been windblown. Surface topography ranges from hummocky to undulating, with subtle streamlining in places (Fig. 1). Interpreted to be glacial till of an ice advance that covered stagnant ice from earlier ice advances. Melting of the underlying ice from all advances created a chaotic topography with many closed depressions, but in places streamlined forms are visible.

ruw ***Upper member, washed till***—Loamy diamicton as above, having a smoother surface and overlain in places by thin sand and gravel. Interpreted to be areas where the diamicton was washed by water, either by the waves of glacial Lake Agassiz or by meltwater flow in channels. The boundary between units ru and ruw is vague and transitional in places. Although this unit is included in the Red Lake Falls Formation, some of it may be composed of older diamicton in small areas where the Red Lake Falls Formation has been removed by erosion.

rl ***Lower member, glacial till***—Loamy diamicton with pebbles and larger clasts. Very similar to the Upper member except the very coarse-grained sand fraction only averages 3 percent shale.

rlw ***Lower member, washed till***—Loamy diamicton as above, having a smoother surface and overlain in places by thin sand and gravel. The boundary between units rl and rlw is vague and transitional in places. Although this unit is included in the Red Lake Falls Formation, some of it may be composed of older diamicton in small areas where the Red Lake Falls Formation has been removed by erosion.

Goose River Formation, St. Hilaire Member—Diamicton and associated meltwater sediment similar to the Red Lake Falls Formation, but darker in color and richer in shale (averaging 23 percent). Some of the surface diamicton mapped as Red Lake Falls Formation may be St. Hilaire Member sediment exposed by erosion or non-deposition of the Red Lake Falls Formation. Underlies the Red Lake Falls Formation in most of the county, but two areas are mapped at the surface: one in the very southeastern corner of the county, the other in the east-central part of the county, around Hitterdal.

gro ***Outwash***—Sand and gravel with some larger clasts; calcareous. Moderately well sorted, crossbedded. The oxidized color is typically light olive-brown or light yellowish-brown overall (2.5Y 5/3, 6/3), but it is difficult to specify in coarser-grained beds. Unit occurs in former meltwater channels. Unit has a generally smooth surface, implying that the underlying buried ice had melted before deposition was complete.

grc ***Collapsed outwash***—Sand and gravel as in unit gro, but having a more irregular surface characterized by numerous undrained depressions. Unit occurs in the southeastern part of the county. Interpreted to be the deposits of braided meltwater streams washing debris off the melting glacier. The sediment was deposited on a surface that contained considerable buried glacial ice from earlier events, and the surface collapsed as this ice melted. The timing of ice meltout indicates that this unit is older than unit gro.

grb ***Buried outwash***—Sand and gravel with some larger clasts; calcareous. Moderately well sorted, crossbedded. The oxidized color is typically light olive-brown or light yellowish-brown overall (2.5Y 5/3, 6/3). Buried by diamicton of the Red Lake Falls Formation. Mapped where exposed by erosion on the sides of meltwater channels. Also mapped as "windows" of sand and gravel, where overlying till is less than 5 feet (1.5 meters) thick. This unit is listed under the Goose River Formation, but may include outwash derived from and buried by the till of the Red Lake Falls Formation.

gst ***Till***—Clay loam diamicton with pebbles and larger clasts. Mostly unsorted, but includes scattered beds of silt or sand and gravel. Calcareous under a leached zone several feet thick. The oxidized color is typically light olive-brown to olive-brown (2.5Y 5/4, 4/4); unoxidized color is dark gray to dark grayish-brown (2.5Y 4/1 to 4/2).

gsw ***Washed till***—Clay loam diamicton as above, having a smoother surface and overlain in places by thin sand and gravel. The boundary between units gst and gsw is vague and transitional in places. Although this unit is included in the Goose River Formation, some of it may be composed of older diamicton in small areas where the Goose River Formation has been removed by erosion.

Figure 1. Topography of surficial geologic map units; scale 1:300,000. Alluvium and peat are not shown.

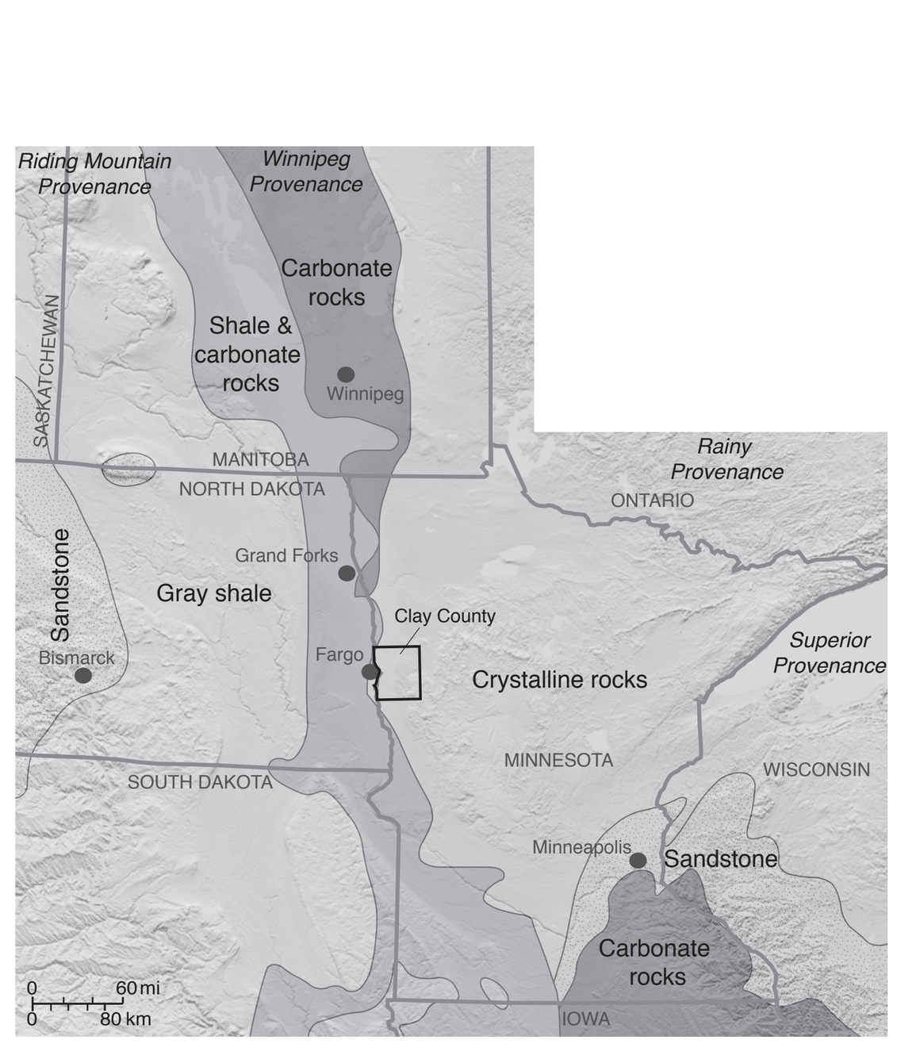


Figure 2. Bedrock source areas for glacial deposits in Minnesota (modified from Lusardi and others, 2011). Provenance refers to the source areas for glacial sediments. Riding Mountain provenance is rich in fragments of the Cretaceous period Pierre Shale Formation; Winnipeg provenance is rich in fragments of Paleozoic era limestone and dolomite (carbonate rocks); Rainy provenance is rich in fragments of Precambrian age igneous and metamorphic (crystalline) rocks; Superior provenance includes Precambrian age sedimentary and crystalline rocks, and is especially rich in fragments of mafic igneous rocks and red sandstone.

Glacial deposits commonly contain sediment from more than one source area because each successive advance incorporates material from earlier advances, which in some cases followed different flowpaths. The boundaries are gradational, and a compound such as Rainy–Winnipeg provenance may be used for transitional compositions.

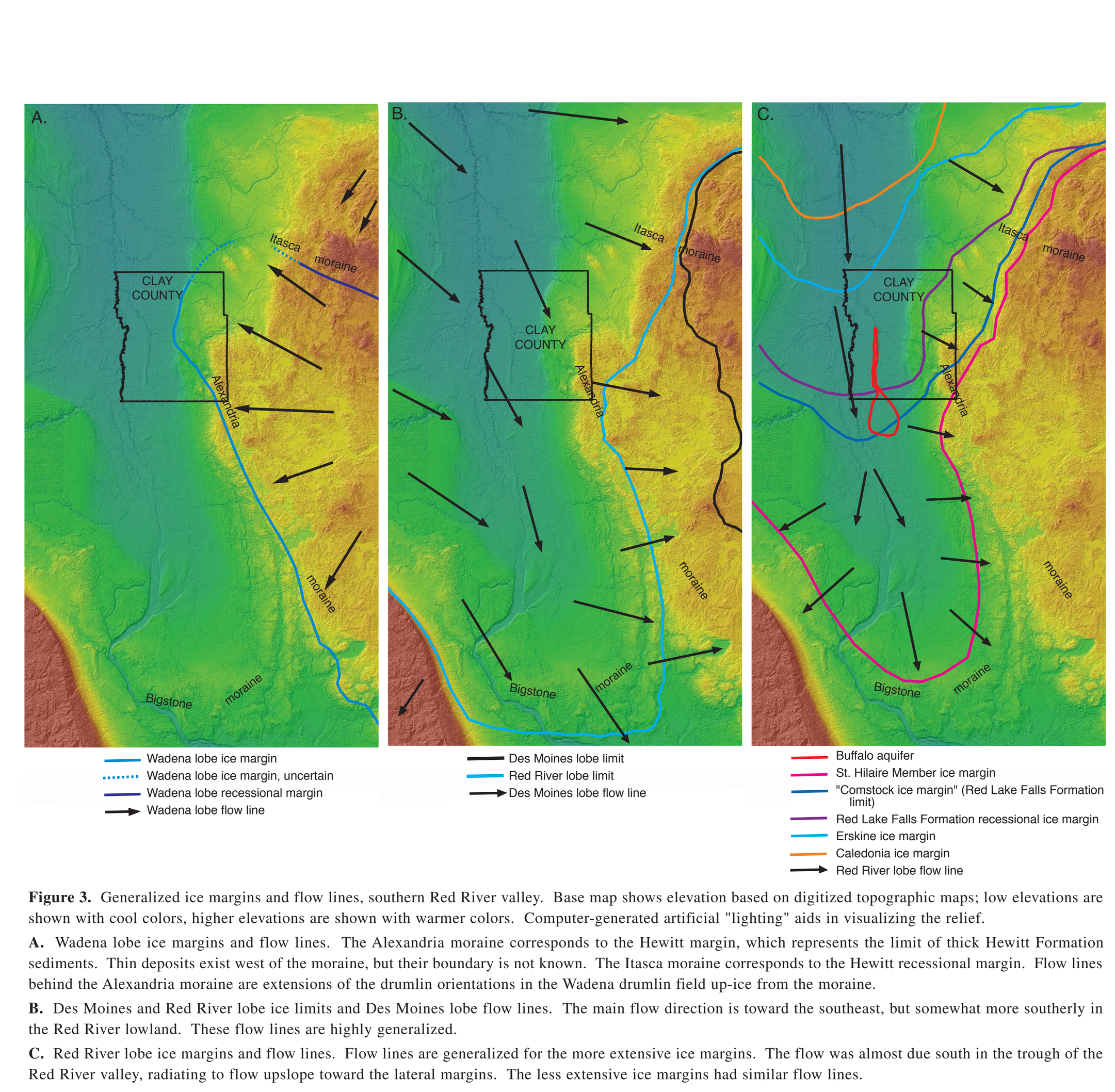


Figure 3. Generalized ice margins and flow lines, southern Red River valley. Base map shows elevation based on digitized topographic maps; low elevations are shown with cool colors, higher elevations are shown with warmer colors. Computer-generated artificial "lighting" aids in visualizing the relief.

A. Wadena lobe ice margins and flow lines. The Alexandria moraine corresponds to the Hewitt margin, which represents the limit of thick Hewitt Formation sediments. Thin deposits exist west of the moraine, but their boundary is not known. The Itasca moraine corresponds to the Hewitt recessional margin. Flow lines behind the Alexandria moraine are extensions of the drumlin orientations in the Wadena drumlin field up-ice from the moraine.

B. Des Moines and Red River lobe ice limits and Des Moines lobe flow lines. The main flow direction is toward the southeast, but somewhat more southerly in the Red River lowland. These flow lines are highly generalized.

C. Red River lobe ice margins and flow lines. Flow lines are generalized for the more extensive ice margins. The flow was almost due south in the trough of the Red River valley, radiating to flow upslope toward the lateral margins. The less extensive ice margins had similar flow lines.

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