UNIVERSITY OF MINNESOTA
MINNESOTA GEOLOGICAL SURVEY
Harvey Thorleifson, Director

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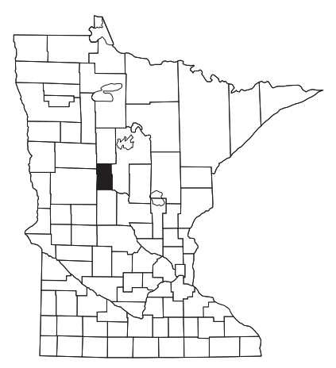
COUNTY ATLAS SERIES
ATLAS C-40, PART A
Wadena County
Plate 3—Surficial Geology

SURFICIAL GEOLOGY

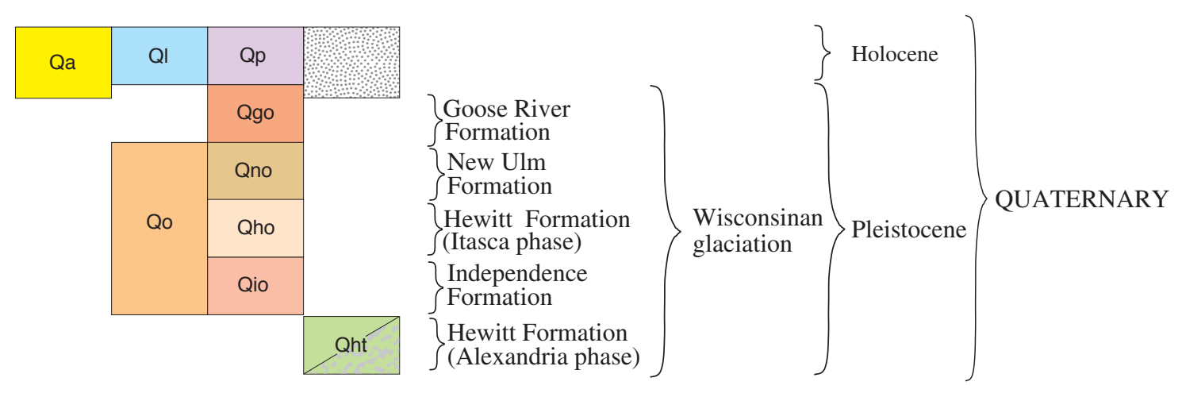
By

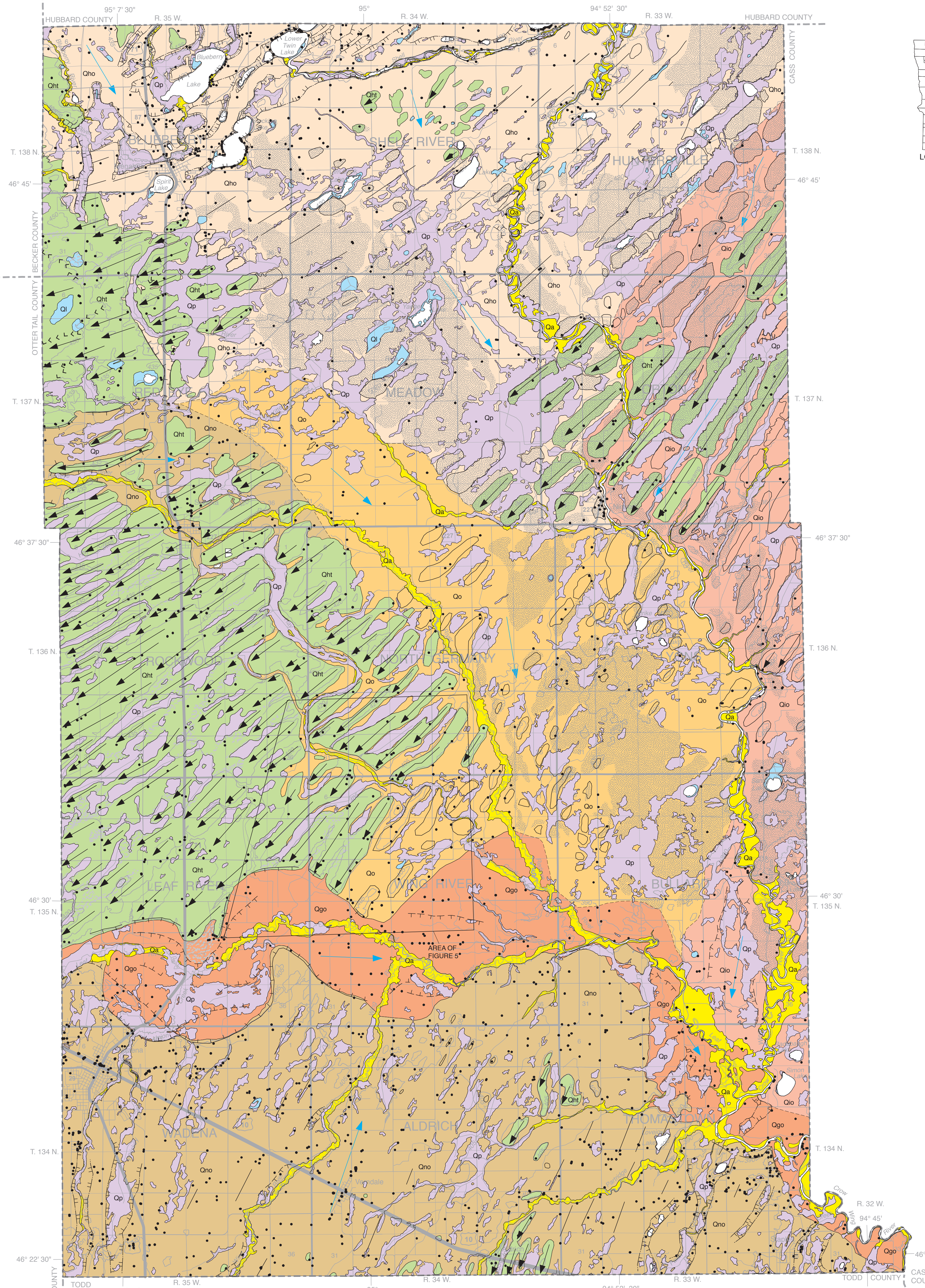
Barbara A. Lusardi and Katherine J. Marshall

2015


LOCATION DIAGRAM

CORRELATION OF MAP UNITS





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

1 0 1 2 3 4 5 MILES

1 0 1 2 3 4 5 6 7 8 KILOMETERS

CONTOUR INTERVAL 15 METERS

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

INTRODUCTION

This map emphasizes the distribution and origin of surficial materials in Wadena County. The depiction of landform distribution was based on 1-meter resolution lidar elevation imagery (available from Minnesota Department of Natural Resources <http://deli.dnr.state.mn.us/>). The geologic interpretations were drawn in GIS on 1:24,000 U.S. Geological Survey topographic maps that were overlain on a 10-meter digital elevation model that covers the area (Fig. 1). These interpretations were compared to a soil map for Wadena County (Natural Resources Conservation Service, 2014) and to well logs included in the Minnesota Geological Survey County Well Index (CWI) and Quaternary Data Index (QDI), including bridge borings (Minnesota Department of Transportation) and U.S. Geological Survey scientific test holes (Lindholm, 1970; Helgesen, 1977). Fieldwork to verify and augment these interpretations was conducted in 2013 and 2014. Most described and sampled exposures consisted of excavations, including gravel pits, construction sites, and road cuts. These were supplemented with 71 auger borings drilled to an average depth of about 17 feet (5 meters), and 3 rotary-sonic drill cores drilled to an average depth of 350 feet (107 meters). Additional data from previous mapping (see Mapping Index) were included in the analyses and interpretation of map units. More than 400 samples were analyzed for texture and lithology.

GLACIAL HISTORY

The Pleistocene Epoch began about 2.6 million years ago. Between 2.6 million years ago and about 11,700 years ago, glaciers advanced and retreated across Minnesota many times. The glaciers advanced from different directions and left behind sediment of different colors and rock types indicative of the terrain over which they passed and the provenance from where they originated (Fig. 2; Table 1). The most recent glacial event in this area, known as the Wisconsinan glacial episode, extended from about 110,000 years ago to the start of the Holocene Epoch 11,700 years ago. The Holocene Epoch marks the end of the ice age in Minnesota and the transition to the warm conditions we have today.

Late Wisconsinan

The advance of the Wadena lobe from the north–northeast, or Rainy provenance (Fig. 2), is the earliest advance for which there is widespread evidence at the land surface. The Hewitt Formation (Johnson and others, in press) is the glacial sediment deposited by the Wadena lobe when the ice advanced to form the Alexandria moraine (Fig. 3A) during the Alexandria phase (Goldstein, 1998). Although Hewitt Formation deposits have not been directly dated, a minimum age of 20,500 ^{14}C yr BP (24,450 cal yr BP) was provided by a radiocarbon date on material from basal lake sediments overlying St. Croix phase Superior-lobe deposits (Wright, 1972). Clayton and Moran (1982) suggested a rough age of 30,000 ^{14}C yr BP (34,300 cal yr BP) based on five dates of wood collected in Wisconsin by Black and Rubin (1967), from a unit they tentatively correlated with the Hewitt Formation.

The till of the Hewitt Formation forms a radiating pattern of drumlins—elongate hills that are streamlined in the direction of ice flow (Fig. 1). Low areas between drumlins, called swales, are occupied by wetlands. In many places across the county the drumlins are buried by sand. Due to the sand cover, drumlins are not apparent everywhere, however, subtle inter-drumlin swales can be identified in many places by elongate depressions visible at the surface of the sand plain. These depressions form a continuous pattern parallel with the drumlin crests that rise above the sand plain (Fig. 1).

The mapped distribution of the Hewitt Formation indicates that as the Wadena lobe advanced and retreated, the Brainerd (Rainy provenance) and Superior (Superior provenance) lobes also advanced from the north–northeast and east, respectively, and were located somewhere to the east (Figs. 3A, B). The lack of Hewitt Formation deposits east of the modern Mississippi River (Knaeble and others, 2004; Lusardi and Adams, 2014; Johnson and others, in press) indicates that ice of the Brainerd and Superior lobes likely occupied this region, preventing eastward advance of the Wadena lobe.

Eventually, the Wadena lobe retreated northward, and the boundary between it and the Brainerd lobe became more distinct (Fig. 3C). While Wadena-lobe ice was forming the Itasca moraine to the north in Hubbard County (the Itasca Phase), the Brainerd (from the north) and Superior (from the south) ice lobes advanced westward, covering Wadena-lobe deposits, and forming the St. Croix moraine (the St. Croix Phase; Figs. 3C, D; Wright, 1972). At this time, meltwater from the Wadena lobe and meltwater from the Brainerd lobe flowed across Wadena County from the north and east, depositing sand and gravel outwash and burying the Hewitt phase drumlins in the central and southern portions of the county (Figs. 3C, D, 5). According to Norton (1982), the Brainerd lobe retreated before the Wadena lobe. Meltwater from the Wadena lobe then deposited outwash (unit Qho) on top of the Brainerd-lobe outwash (unit Qio) and behind the St. Croix moraine in Cass County (Fig. 3E).

In parts of Wadena County, both the drumlins and the swales are blanketed by fine- to medium-grained sand. Leverett (1932) proposed glacial Lake Wadena deposited this sand layer because he hypothesized glacial meltwater would have simply deposited outwash in the swales, leaving the drumlins exposed. Goldstein (1998) suggested instead that buried ice blocks between the drumlins allowed for deposition of outwash over both the swales and drumlins. The ice blocks then melted, leaving elongate, pitted lowlands that mark the inter-drumlin swales. Evidence compiled as part of our mapping indicates that post-glacial eolian processes may have played a role in diminishing the surface expression of the drumlins. Lidar imagery reveals that in some areas the drumlins are buried beneath lenticular and parabolic dunes consistent with an eolian origin. The dunes are composed of fine- and medium-grained sand that was apparently winnowed by wind from surrounding, unvegetated outwash deposits. The sand thickness varies over the surface of the drumlins but is no greater than 15 feet (3 meters). It tends to be thickest on the southeast side of the landforms, which is consistent with the postglacial prevailing wind direction from the northwest (Büdel, as cited in Flint, 1971). Additionally, this wind direction is supported by the morphology of sand dunes overlying outwash (units Qgo, Qho, and Qgo; Norton, 1982, and this study).

The final phases of glacial sedimentation in Wadena County originated from the northwest. The northwest-source Des Moines and Red River lobes did not reach Wadena County (Wright, 1972); however, meltwater from the Des Moines lobe flowed across the southern and western portions of the county (Figs. 3E, F). A final pulse of meltwater from the Red River lobe cut what is now the Leaf River valley, deposited sand and gravel outwash, and flowed east into the ancestral Mississippi River (Fig. 3F).

POSTGLACIAL HISTORY

During the Holocene Epoch, the landscape left by glaciers was modified by processes similar to what we experience today—wind and water. Meltwater established the channels of the Leaf and Crow Wing Rivers and their tributaries (unit Qa), and organic-rich deposits (units Qp, Ql) accumulated in low-lying areas including ice-block melt-out depressions and abandoned drainageways. In addition, wind winnowed sand and deposited it in dunes (eolian unit). Although many episodes of wind erosion, transportation, and deposition likely occurred during the glacial period, a study along the shore of Lake Winnibigoshish in Cass County (Grigal and others, 1976) suggested that there was an extended warm, dry period between 8,000 and 5,000 years ago during which winds from the northwest formed dunes across Minnesota. Changes in pollen assemblages and an increase in clastic sediments during this period, discovered in samples from Elk Lake, Clearwater County (Bradbury and Dean, 1993) and Lake Ann, Sherburne County (Keen and Shane, 1990), support this conclusion.

ACKNOWLEDGEMENTS

Stuart Orlowski, Vance Smith, and Alexander Gjorvad of the Minnesota Geological Survey assisted in drilling auger holes in Wadena County. Angela Gowan, Meagan Harold, Matthew Porter, Matthew Matko, Matthew Ettsen, Brittany Wagner, and Amy Radakovich of the Minnesota Geological Survey assisted with logistics and logging of the rotary-sonic drill core. Thanks to all of the landowners who allowed rotary-sonic drilling on their property, and to all gravel pit operators and landowners who gave permission to examine exposures on their property.

DESCRIPTION OF MAP UNITS

Holocene

Qp **Organic debris, clay, and silt**—Partially decomposed plant matter (peat) and fine-grained mineral sediment with disseminated organic matter deposited in marshes and ponded water. Organic content is greater than 50 percent. Includes minor alluvial deposits along streams, as well as beach deposits. Unit commonly occurs in buried inter-drumlin swales. Distribution of this unit has been modified from the Natural Resource Conservation Service (2014). *Peat and wetland sediment.*

Ql **Silt, clay, and loamy sand**—Locally includes organic-rich layers and typically overlies, or is overlain by, fine-grained organic matter or peat in some areas. Typically coarser-grained at the shoreline where waves erode the sediment and concentrate the sand; includes human-made beaches. The extent of exposure depends on the water level in the lake; includes lakes that have been drained. Deposited in post-glacial lakes. *Lake sediment.*

Qa **Sand and gravel, sandy loam to silt loam**—Generally coarse-grained sediment (sand and gravel) in channels, and finer-grained sediment (fine-grained sand and silt) on floodplains; coarsens with depth. Locally capped and/or interbedded with organic-rich layers. Low areas are typically filled with thick silty to clayey sediment. Sediment along smaller streams is generally finer-grained. Deposited by modern streams in channels and on floodplains. *Floodplain alluvium.*

▨ **Very fine- to medium-grained sand**—Well-sorted, rounded sand grains; forms dunes in places; dune relief locally exceeds 20 feet (6 meters). Pattern indicates regions where low- to moderate-relief dunes are apparent on lidar imagery. Where there is no pattern shown there is likely a thin mantle of windblown (eolian) sand covering outwash (units Qgo, Qho, Qio, Qno, and Qo). *Eolian sand.*

Pleistocene

As mentioned above, meltwater flowed into Wadena County from several ice margins, depositing sediment derived from multiple source regions, or provenances (Fig. 1). Although this map depicts the distribution of these sediments as separate units (units Qgo, Qho, Qio, Qno, and Qo), there is very little textural or mineralogic evidence to distinguish one unit from the other. The depiction here relies on drainage patterns and subtle clues in the topography (Fig. 1), and even more subtle compositional variations (Table 2). Figure 6 shows the combined extent of the various sand and gravel outwash units.

Goose River Formation (Harris, unpub. data)—Sediment deposited by ice of the Riding Mountain-provenance Red River lobe.

Qgo ***Sand to gravelly sand***—Poorly to well-sorted; coarsens with depth. This unit may include alluvium where it is adjacent to unit Qa in the upper 2 to 3 feet (1 meter) because there is very little gradient between the modern river channel and the surrounding outwash plain. Contains sediment from both the Riding Mountain and Rainy provenances (Tables 1, 2), including incorporated sediment from the underlying Hewitt Formation (unit Qho). Average composition of the very coarse-grained sand fraction of samples is shown in Table 2. Much of the sediment at the surface is leached of carbonate, making distinctions between units difficult. Depth of leaching ranges from 3 to 15 feet (1 to 3 meters). Carbonate content increases with depth, but so does the possibility of encountering outwash from an earlier event that contains higher amounts of carbonate. Deposited in meltwater streams sourced from the Red River-lobe ice margin (Fig. 3F). Channels leading away from the ice margin, as well as traces of gray shale in the sediment, help to identify these sediments as Riding Mountain provenance (Fig. 2). The scarcity of shale grains can be attributed to their lack of durability during fluvial transport. *Outwash.*

Undifferentiated—Sediment deposited by meltwater issuing from multiple ice lobes of Riding Mountain and Rainy provenance.

Qo ***Sand to gravelly sand***—Sand ranges from coarse- to fine-grained and is poorly to well-sorted in fining-upward layers. Predominantly contains sediment from the Rainy provenance (Itasca and St. Croix phase Wadena-lobe deposits; Tables 1, 2), including outwash from the underlying Hewitt Formation. Also includes an influx of Riding Mountain-provenance sand and gravel that flowed from the margin of the Des Moines lobe through the ancestral Redeye River in northwestern Wadena County (Fig. 3E). Average composition of the very coarse-grained sand fraction of samples is shown in Table 2. Much of the sediment at the surface is leached of carbonate, making distinctions between units difficult. Depth of leaching ranges from 3 to 15 feet (1 to 3 meters). Carbonate content increases with depth, but so does the possibility of encountering outwash from an earlier event that may also contain higher amounts of carbonate. Deposited in meltwater streams sourced from the Wadena- (unit Qho), Brainerd- (unit Qio), and Des Moines-lobe (unit Qno) ice margins (Figs. 1, 3E). Wadena- and Brainerd-lobe outwash sediments were deposited at roughly the same time, and outwash from the Des Moines lobe was deposited later. However, because these sediments are nearly identical, they are indistinguishable in areas where topographic features such as channels and scour marks are absent. Unit is covered by eolian sand in places. *Outwash.*

New Ulm Formation (Johnson and others, in press)—Sediment deposited by ice of the Riding Mountain-provenance Des Moines lobe.

Qno ***Sand to gravelly sand***—Sand ranges from coarse- to fine-grained, poorly to well-sorted in fining-upward layers; the upper layer is predominantly fine-grained sand with minor gravel. Contains sediment from Riding Mountain and Rainy provenances (Tables 1, 2). Locally includes incorporated outwash from the underlying Hewitt Formation. Average composition of the very coarse-grained sand fraction of samples is shown in Table 2. Drill logs from U.S. Geological Survey borings south of the Leaf River (Lindholm, 1970) record two fining-upward sequences of sand and gravel. The uppermost sequence is about 20 feet (7 meters) thick. This upper layer is interpreted to have been deposited by meltwater streams sourced from the Des Moines-lobe ice margin to the west and makes up the Parkers Prairie outwash plain (Figs. 3E, F). The deeper sequence is as thick as 50 feet (17 meters) and overlies glacial till. Both the lower sand and gravel and the glacial till are interpreted to be part of the Hewitt Formation (see description below). Des Moines-lobe meltwater also flowed into the northwestern part of the county through what is now the Redeye River valley (Figs. 3E, F). Channels that lead away from the ice margin (Fig. 1), together with trace amounts of gray shale in the sand and gravel (Table 2), indicate these sediments have a Riding Mountain provenance (Fig. 2). Scour marks interpreted to indicate flow direction can be used locally to determine the meltwater path and therefore source area; however, if no additional evidence is available the sediment is mapped as undifferentiated (unit Qo). *Outwash.*

Hewitt Formation (Johnson and others, in press)—Itasca phase of the Wadena lobe—Sediment deposited by the Rainy-provenance Wadena ice lobe. The Itasca phase of the Wadena lobe is defined as the period when the Wadena lobe was depositing sediment in and around the Itasca moraine (Figs. 3C, D, E). The sand and gravel outwash described below was deposited by meltwater flowing from the Wadena lobe as it formed the Itasca moraine to the north (Figs. 3C, D). Although this sediment is defined as part of the Hewitt Formation, it was deposited during a later stage of glaciation than the Alexandria phase sediment that forms the drumlins to the south and west (Figs. 3A, B). Eventually, this Itasca-phase outwash may be defined as a separate member of the Hewitt Formation; however, at this time we are unable to distinguish between the older and younger deposits. Norton (1982) determined that the outwash of what he called the Park Rapids outwash plain (Fig. 3E) overlies, and is therefore younger than, the outwash of the Oshawa outwash plain (Fig. 3E) to the south and east (unit Qio).

Qho ***Sand to gravelly sand***—Sand ranges from coarse- to fine-grained and is poorly to well-sorted in fining-upward layers; the upper layer is predominantly fine-grained sand with minor gravel. Unit contains sediment predominantly from the north–northeast Rainy provenance including abundant crystalline rocks (basalt and granite; Tables 1, 2). Carbonate, predominantly dolostone attributed to the Winnipeg source area (Gowan and Thorleifson, 2011), is also common in the Hewitt Formation, although all of the surface samples collected for this study are leached of carbonate (to a depth of 20 feet [6 meters]). Either the carbonate was incorporated from the underlying Winnipeg-sourced tills, or the glacier that deposited the Hewitt Formation had a broad source area including elements of both the Winnipeg and Rainy regions. Average composition of the very coarse-grained sand fraction is shown in Table 2. This unit was deposited in meltwater streams that issued from the Wadena ice lobe as it retreated northward towards the Itasca moraine and while it was forming the Itasca moraine (Figs. 3C, D, E). This outwash composes the Park Rapids outwash plain (Norton, 1982). The unit is covered by eolian sand in places. *Outwash.*

Independence Formation—South Long Lake Member (Johnson and others, in press)—Sediment deposited by ice of the Rainy-provenance Brainerd lobe.

Qio ***Sand to gravelly sand***—Sand ranges from coarse- to fine-grained and is poorly to well-sorted in fining-upward layers; the upper layer is predominantly fine-grained sand with minor gravel. Contains Rainy-provenance sediment (Tables 1, 2). Average composition of the very coarse-grained sand fraction of samples is shown in Table 2. Unit was deposited in meltwater streams that issued from the Brainerd ice lobe while it was forming the St. Croix moraine and formed the Oshawa outwash plain (Figs. 3C, D, E; Norton, 1982). The unit is covered by eolian sand in places. *Outwash.*

Hewitt Formation (Johnson and others, in press)—Alexandria phase of the Wadena lobe—Sediment deposited by the Rainy-provenance Wadena ice lobe.

Qht ***Sandy loam to loamy sand diamicton***—Pebbly, unsorted; contains pockets of silt, sand, and gravel in places; generally yellow-brown (10YR 5/4) where oxidized and dark gray (10YR 4/1) where unoxidized; abundant pebbles, cobbles, and boulders; streamlined into drumlin landforms. Average composition of the very coarse-grained sand fraction is shown in Table 2. Inter-drumlin swales locally contain some outwash sand and gravel. Peat and wetland sediments (unit Qp) or standing water in these low areas make it difficult to sample and characterize underlying deposits. In broad, interconnected swales where meltwater flow was concentrated, the till is shown with a pattern to indicate the till was washed by meltwater and may be overlain by some thin sand and gravel (see "washed" map symbol). *Glacial till.*

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Numbers in parentheses correspond with those shown on the Mapping Index

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MAP SYMBOLS

Geologic contact—Approximately located. Contact is dashed where uncertain (as is the case between the various sand and gravel units).

Data point—Location of information used to prepare this map. Data include well logs recorded in the Minnesota Geological Survey County Well Index (CWI) and Quaternary Data Index (QDI), including bridge borings (Minnesota Department of Transportation), U.S. Geological Survey scientific test holes (Lindholm, 1970; Helgesen, 1977), and soil borings and outcrop samples by the Minnesota Geological Survey staff.

Drumlin—A streamlined hill or ridge composed mostly of glacial till; includes layers and lenses of sand and gravel in places. Arrow indicates the inferred direction of ice movement and the length of the arrow is approximately equivalent to drumlin length. Drumlins were formed at the base of moving ice and are commonly composed of subglacial sediment. In places, drumlins are partially or totally buried by fluvial and eolian deposits. Not all drumlins are marked with a symbol.

Buried drumlin—Drumlin landform, as described above, buried by sand and gravel of variable thickness. Sand typically is fine-grained and windblown but is only mapped as the eolian unit where dune landforms are apparent on lidar imagery. Not all buried drumlins are marked with a symbol.

Buried interdrumlin swale—A long, linear depression visible on outwash plains that has an orientation similar to the surrounding drumlins. Swales may have contained buried ice blocks, which melted following outwash deposition, forming the depressions in the outwash plains.

Esker—A sinuous ridge of sand and gravel deposited in an ice-walled, or subglacial, stream channel; covered locally by 10 feet (3 meters) or more of till. Arrowheads indicate inferred flow direction. Esker ridges were removed locally by aggregate mining. In those localities, the esker positions were inferred from the presence of narrow, elongate lakes and from aerial photographs taken prior to excavation.

General flow direction of glacial meltwater—Arrow points downstream in the direction of glacial meltwater flow.

Irregular trough—Hachures point downslope; locally occupied by aligned depressions and lakes. The trough, called a tunnel valley, is interpreted to be a subglacial drainage channel of the Wadena lobe that was subsequently filled by outwash as the ice retreated northward.

Stream-cut scarp—Hachures point down scarp. Scarp marks the banks of former fluvial channels. Where paired, scarps bound stream-scoured areas. Dashed where obscure.

Washed—Pattern indicates where drumlinized glacial till (unit Qht) has been washed by meltwater. These areas typically are lower in elevation and display scoured surfaces that may include a cap of fine-grained sand to gravel.

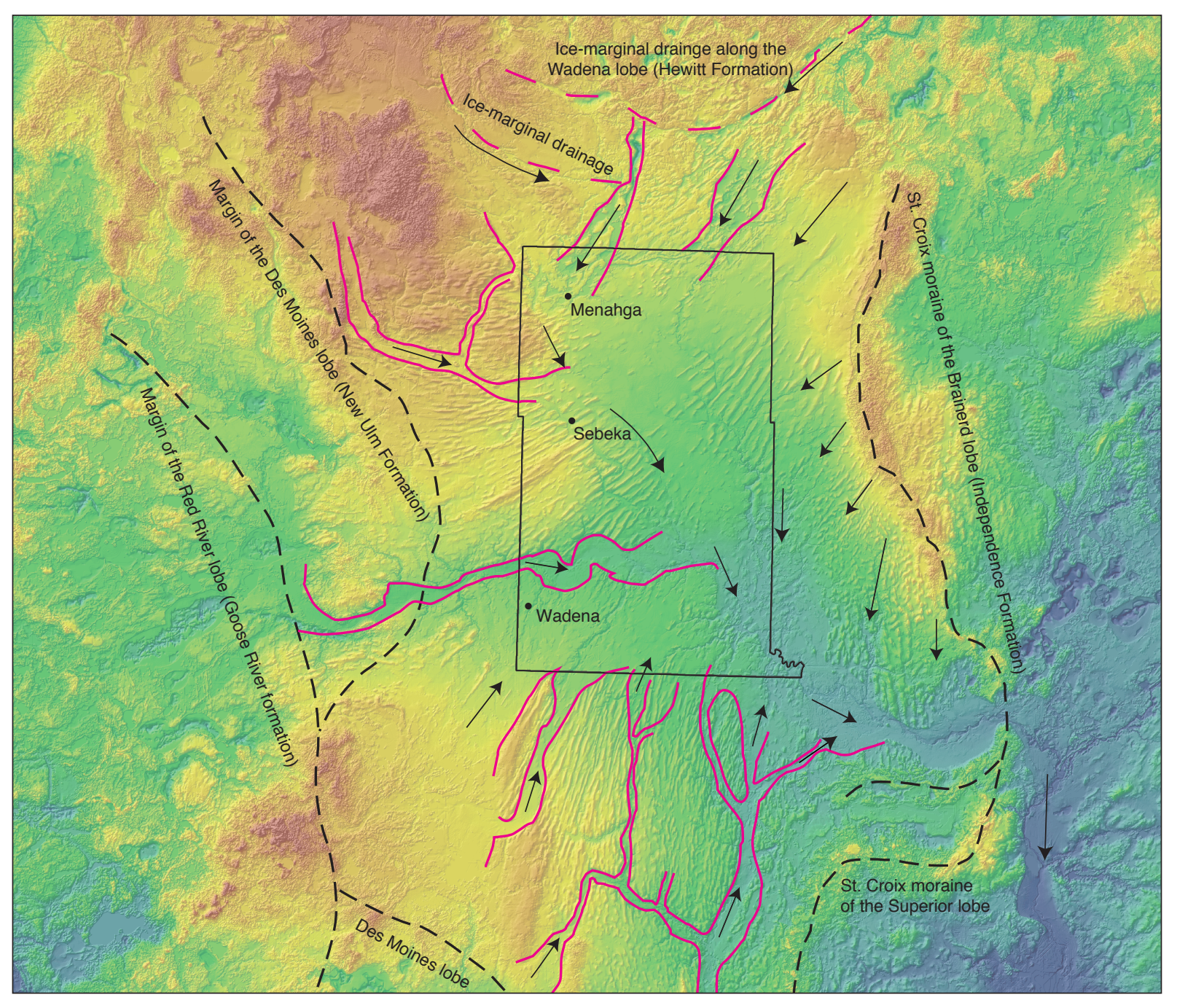


Figure 1. Physical relief of the land surface in central Minnesota (vertically exaggerated 7.5x). Wadena County is outlined. Elevation is shown by color: red-orange (higher elevation) grading to blue (lower elevation). Elevation ranges from about 1,224 to 1,524 feet (373 to 465 meters) above sea level. A false sun illumination at an elevation of 30° from the northwest (315°) provides contrast to accent landform details. Interpreted late Wisconsinan ice margins are shown by dashed lines, meltwater channels are magenta, and the direction of meltwater flow into Wadena County is indicated by arrows. This map was created using the U.S. Geological Survey's digital elevation model with a 10-meter grid; scale 1:400,000.

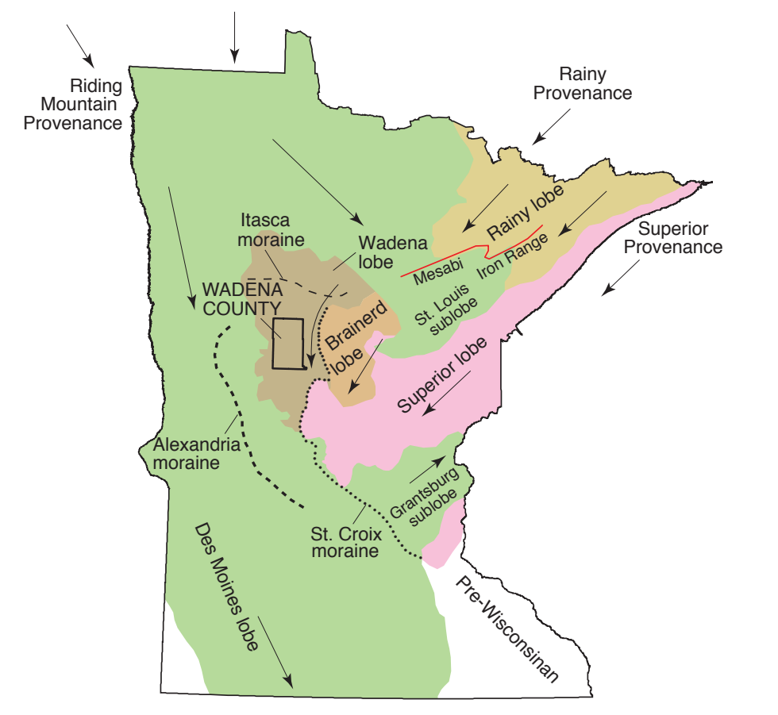


Figure 2. Location of major provenances and the distribution of ice-lobe materials at the land surface. Glacial sediments derive their distinct material content from bedrock and sediment found in the region of these source areas. The extent of Des Moines-lobe (Riding Mountain provenance) deposits is shown in green. The surface extent of the Wadena- and Rainy-lobe (Rainy provenance) deposits are shown in brown, Brainerd-lobe (Rainy provenance) deposits in tan, and Superior-lobe deposits in pink. Moraines are indicated by the labeled dotted or dashed lines.

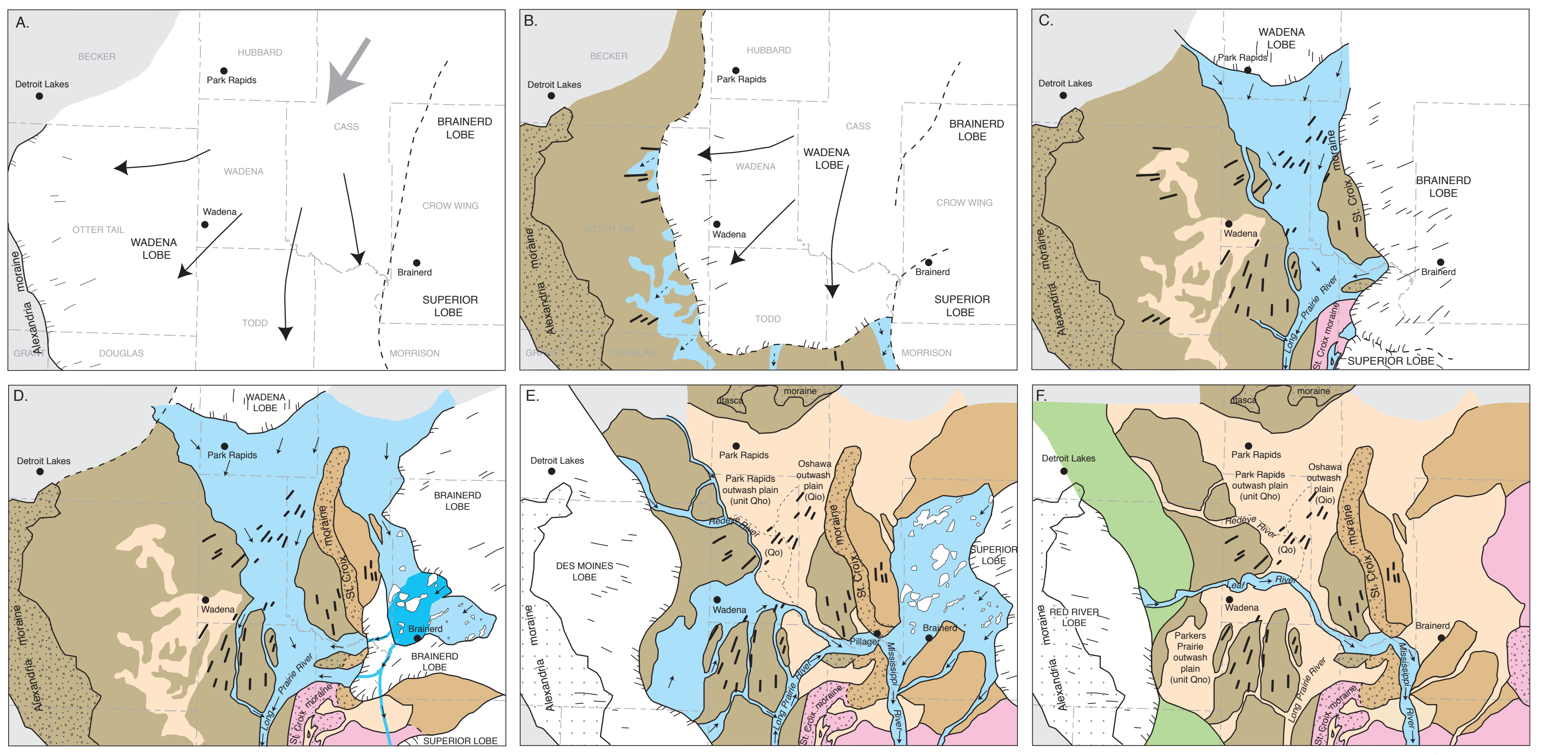


Figure 3. A schematic depiction of the late Wisconsinan glacial history of Wadena County and surrounding areas.

A. The Wadena lobe advanced from the north–northeast Rainy provenance and deposited sediment of the Hewitt Formation (unit Qht). As it advanced, ice fanned outward to the south and west. The Alexandria moraine marks an ice margin of this advance (Fig. 2), hence it is called the Alexandria phase of the Wadena lobe. Ice flow direction is indicated by the large gray arrow and the trend of ice is shown by thin arrows based on drumlins. The dashed line indicates the known easternmost extent of Wadena-lobe deposits of the Hewitt Formation. Ice of the Brainerd and/or Superior lobes was likely present somewhere in the eastern part of this region at the same time the Wadena lobe was advancing.

B. The Wadena lobe retreated from the Alexandria moraine. Dashed lines indicate the possible position of the Brainerd and Superior lobes at this time. Drainage from the retreating Wadena lobe (blue) is schematic because these older deposits were buried by sediment of subsequent ice advances. Hewitt Formation till is shown in brown; drumlins are represented by short, bold lines.

C. As the Wadena lobe retreated generally northward, it eventually formed the Itasca moraine in Hubbard County (see Fig. 2). To the east, the Brainerd lobe advanced and formed the northern section of the St. Croix moraine. Confluent with the Brainerd lobe, the Superior lobe also advanced at about the same time from the southeast to form the southern section of the St. Croix moraine. Meltwater flowed from these ice fronts and deposited outwash sand and gravel that partially buried the drumlins laid down by the Alexandria phase of the Wadena-lobe advance.

D. The Rainy-source Wadena and Brainerd lobes retreated north and eastward. Meltwater from the Wadena lobe drained southward. In places, water pooled on top of stagnant ice, forming glacial lake Brainerd (dark blue; Knaeble and others, 2004). When the blocks of buried ice (white) melted, they left round kettle lakes across the pitted outwash/lake plain. The Brainerd lobe separated from the Superior lobe along its confluent southern boundary. At this time, most of the drainage was still southward through what is now the Long Prairie River channel. Some drainage (blue lines) was likely across and through the stagnant ice to the south along the retreating Superior-lobe ice front, based on channels interpreted from the regional digital elevation model (Fig. 1).

E. Des Moines-lobe ice advanced from the west and overlaid the Alexandria moraine in places. After the breach of the St. Croix moraine at Pillager, Des Moines-lobe meltwater flowed to the north from the ice front, reversing the flow in the Long Prairie River channel. The meltwater now flowed east through the gap in the moraine, and then south, establishing the course of the modern Mississippi River.

F. The Red River lobe, the final ice advance into the region, is similar to the Des Moines lobe in that it occupied the Red River valley to the west. However, the Red River lobe advanced later and from a more northerly direction (mixed Riding Mountain/Winnipeg provenance). Meltwater from this ice flowed eastward through what is now the Leaf River, down the Crow Wing River, and eventually southward through the Mississippi River.

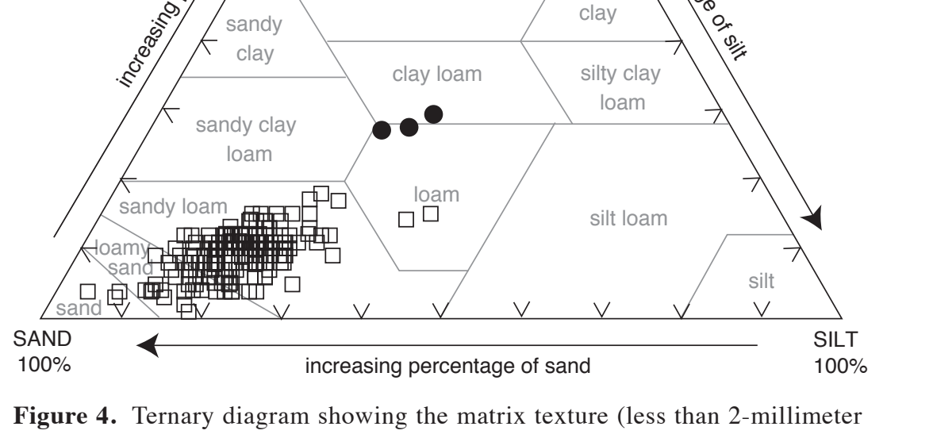


Figure 4. Ternary diagram showing the matrix texture (less than 2-millimeter grain-size fraction) of Hewitt Formation till samples mapped at the surface in Wadena County. Samples that plot as loam to clay-loam (circles) are interpreted to be an unnamed older till that occurs just below the Hewitt Formation till in at least two locations in the western part of the county.

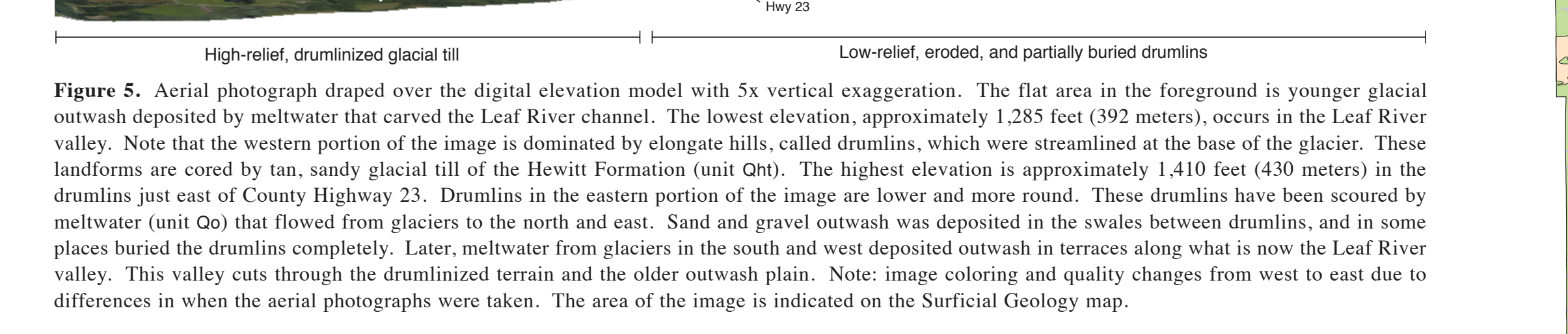


Figure 5. Aerial photograph draped over the digital elevation model with 5x vertical exaggeration. The flat area in the foreground is younger glacial outwash deposited by meltwater that carved the Leaf River channel. The lowest elevation, approximately 1,285 feet (392 meters), occurs in the Leaf River valley. Note that the western portion of the image is dominated by elongate hills, called drumlins, which were streamlined at the base of the glacier. These landforms are cored by tan, sandy glacial till of the Hewitt Formation (unit Qht). The highest elevation is approximately 1,410 feet (430 meters) in the drumlins just east of County Highway 23. Drumlins in the eastern portion of the image are lower and more round. These drumlins have been scoured by meltwater (unit Qo) that flowed from glaciers to the north and east. Sand and gravel outwash was deposited in the swales between drumlins, and in some places buried the drumlins completely. Later, meltwater from glaciers in the south and west deposited outwash in terraces along what is now the Leaf River valley. This valley cuts through the drumlinized terrain and the older outwash plain. Note: image coloring and quality changes from west to east due to differences in when the aerial photographs were taken. The area of the image is indicated on the Surficial Geology map.

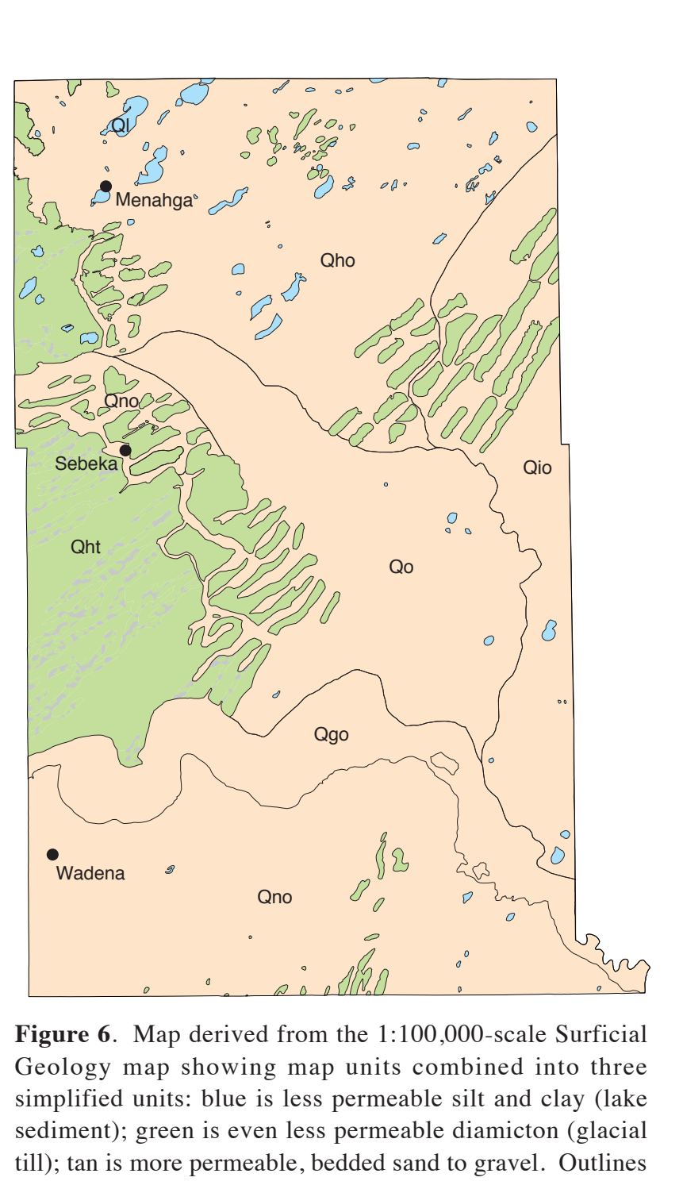
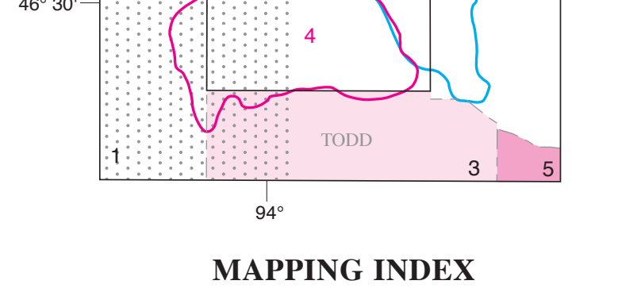


Figure 6. Map derived from the 1:100,000-scale Surficial Geology map showing map units combined into three simplified units: blue is less permeable silt and clay (lake sediment); green is even less permeable diamicton (glacial till); tan is more permeable, bedded sand to gravel. Outlines of individual mapped units are shown.



MAPPING INDEX

Marshall mapped the northern portion of the county (gray); Lusardi mapped the southern portion (white). Numbers for previous mapping projects correspond with those listed in the references.

Table 1. Physical characteristics of glacial deposits in Wadena County. Only deposits of the Wadena lobe (bold) are present at the surface. Other deposits occur in the subsurface only.

SOURCE AREA PROVENANCE	NORTHWEST RIDING MOUNTAIN	NORTH–NORTHWEST WINNIPEG	**NORTH–NORTHEAST RAINY**	NORTHEAST SUPERIOR
LOBE (Formation)	Des Moines (New Ulm) Red River (Goose River)	Pre-Wisconsinan	**Wadena (Hewitt)** Brainerd (Independence)	Superior Pre-Wisconsinan
TILL TEXTURE	Sandy loam to clay loam	Loam to silt loam to clay loam	**Sandy loam to loamy sand**	Sandy loam to loamy sand
TILL COLOR				
Oxidized	Light olive-brown	Light olive-brown	**Yellow-brown to brown**	Brown to red-brown
Unoxidized	Gray to dark gray	Gray to dark gray	**Gray to brown-gray**	Gray to red-gray
PEBBLE TYPE				
Carbonate	Common	Common to abundant	**Rare to common**	Rare to common
Gray-green rock	Uncommon to common	Uncommon to common	**Uncommon to common**	Common to abundant
Red felsite	Absent to rare	Absent to uncommon	**Rare to uncommon**	Common to abundant
Gray shale	Uncommon to abundant	Absent to uncommon	**Absent**	Absent
Clear quartz	Common	Common to abundant	**Common**	Common

Table 2. Average values for the texture and composition of outwash and till units recognized at the surface (and near surface) in Wadena County. Matrix texture (less than 2-millimeter grain-size fraction) is expressed as relative proportions of sand, silt, and clay in percent. The lithologic composition of the very coarse-grained sand fraction (1-2 millimeter) is expressed in percent as relative proportions of crystalline rock, carbonate rock, and shale fragments. The crystalline fraction is further subdivided by rock type—light (granite and gneiss), red (rhyolite, agate, and sandstone), dark (mafic-rich igneous [such as basalt] and metamorphic rocks), and clear quartz. These lithologic distinctions are one of the tools used to distinguish between glacial sediments and identify provenance (Hobbs, 1998).

		MATRIX TEXTURE				CLAST TYPE						
			percentage of the less than 2 millimeter sand fraction			percentage of total grains counted of the 1-2 millimeter fraction			percentage of total crystalline grains counted			
	Total number of samples	Gravel (percentage of total sample weight)	Sand	Silt	Clay	Crystalline	Carbonate	Shale	Light	Red	Dark	Clear quartz
OUTWASH												
Goose River formation (unit Qgo)	11	5	93	5	2	96	4	trace	86	13	1	18
unleached	7	3	93	5	2	85	14	1	84	15	1	20
New Ulm Formation (unit Qno)	19	9	91	7	2	95	5	trace	85	14	1	18
unleached	37	7	92	7	1	85	15	trace	85	14	1	19
Independence Formation (unit Qio)	8	7	93	4	3	98	2	0	85	13	2	19
unleached	4	5	95	3	2	86	14	0	85	14	1	16
Hewitt Formation (unit Qho)	11	2	95	3	2	97	3	0	84	14	2	24
Outwash (undifferentiated)	24	6	88	9	3	97	3	0	84	14	2	20
unleached	4	9	93	6	1	85	15	0	83	15	2	22
TILL												
Hewitt Formation (unit Qht)	132	4	71	20	9	97	3	0	84	14	2	21
unleached	22	9	73	18	8	85	15	0	81	16	2	21
Older till	4	4	41	34	25	82	18	0	85	13	2	23

GEOLOGIC ATLAS OF WADENA COUNTY, MINNESOTA