UNIVERSITY OF MINNESOTA

CONTRIBUTIONS TO THE GEOLOGY OF WABASHA COUNTY, MINNESOTA

A.C. Runkel, *Project Manager*

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Minnesota Geological Survey
2642 University Avenue West
Saint Paul, Minnesota 55114-1057

Telephone: 612-627-4780
Fax: 612-627-4778
E-mail address: mgs@tc.umn.edu
Web site: http://www.geo.umn.edu/mgs

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Chapter 1

BEDROCK GEOLOGY OF WABASHA COUNTY, MINNESOTA

By
John H. Mossler

INTRODUCTION

Wabasha County lies in the scenic bluffland region of southeastern Minnesota. Unlike most of Minnesota, only a thin layer of Quaternary glacial deposits overlies the bedrock. The bedrock has been deeply cut by the Mississippi River and its tributaries to form the blufflands. The areas lying along the divides between tributaries stand as extensive level plateaus developed on resistant bedrock like dolostone and limestone.

Erosion has removed unconsolidated sediments and exposed underlying rock in ravines, bluffs, and cliffs along the valley of the Mississippi River and its tributaries. In addition to the many natural exposures in cliffs and ravines, there are excellent exposures—some spectacular—in numerous quarries and road cuts, where exposed rock formations that elsewhere in southern Minnesota and neighboring parts of the Upper Mississippi River valley lie deeply buried beneath glacial deposits and younger bedrock formations. The numerous outcrops afford geologists an opportunity to examine the bedrock in detail and decipher the geologic history for the region.

Formation of Sedimentary Rocks

The rocks that outcrop in Wabasha County are sedimentary rocks. Unlike igneous and metamorphic rocks, sedimentary rocks form through processes acting wholly at the surface of the earth. Sedimentary rocks form from waste products of older rocks that were broken down by the action of various agencies. These include the atmosphere, running water, and glaciers. They also form from precipitation of salts from solution and by the accumulation of organic remains. The particles (sediment) are commonly deposited in standing water, such as oceans, seas, or lakes, though deposition may also occur in streams and rivers or even on dry land. The particles accumulate and form layers that ultimately compact or are cemented to form rock.

A distinguishing feature of sedimentary rocks is *stratification*, a layering of different rock types that is a result of the varying environmental conditions under which the rocks formed. Two factors influence sedimentary rock formation: (1) the raw material available to form them and (2) the type and level of energy available in the environment where the sediments are being deposited. For example, if the only particles being supplied to a sea by surrounding land masses are silt and clay, no sandstone beds can form. In zones where wave and current energy are strong, such as beaches and stream channels, only the coarsest (heaviest) particles can accumulate and sandstone and conglomerate beds are preserved. In areas where sea water is clear, not turbid with silt and clay or other sediment from land sources, and sunlit because it is shallow (sunlight is a form of energy), marine life may flourish and the shells that accumulate will form carbonate rocks such as limestone or dolostone.

Stratigraphy and Stratigraphic Nomenclature

Layers of sedimentary rock are assigned relative ages based on their position in respect to one another. If undisturbed, younger beds overlie older beds in the sequence in which they formed. The geologic formations, groups, and members in the stratigraphic column (Fig. 1) are defined and formally named on the basis of their lithic characteristics (rock types) and stratigraphic position or age relative to other formally named units. A brief outline of the development of the nomenclature for Minnesota is given in Mossler (1987). The earth's geologic history encompasses a vast span of time (about 4.5 billion years) that is divided into many intervals arranged sequentially to make geologic history more understandable. To place the rock layers of Wabasha County into such a global framework, equivalency to rock in other regions must be established using methods that rely on fossils contained in the rocks—if they are sedimentary rocks—or on decay rates of radioactive elements found in minerals contained in the rock. It is not surprising that studies using these methods indicate that the rock in Wabasha County (Fig. 2) represents only a small part of earth history; no geologic record is preserved in the region for most of geologic time. Rocks in these missing time intervals either never formed or were deposited to be removed later by erosion.

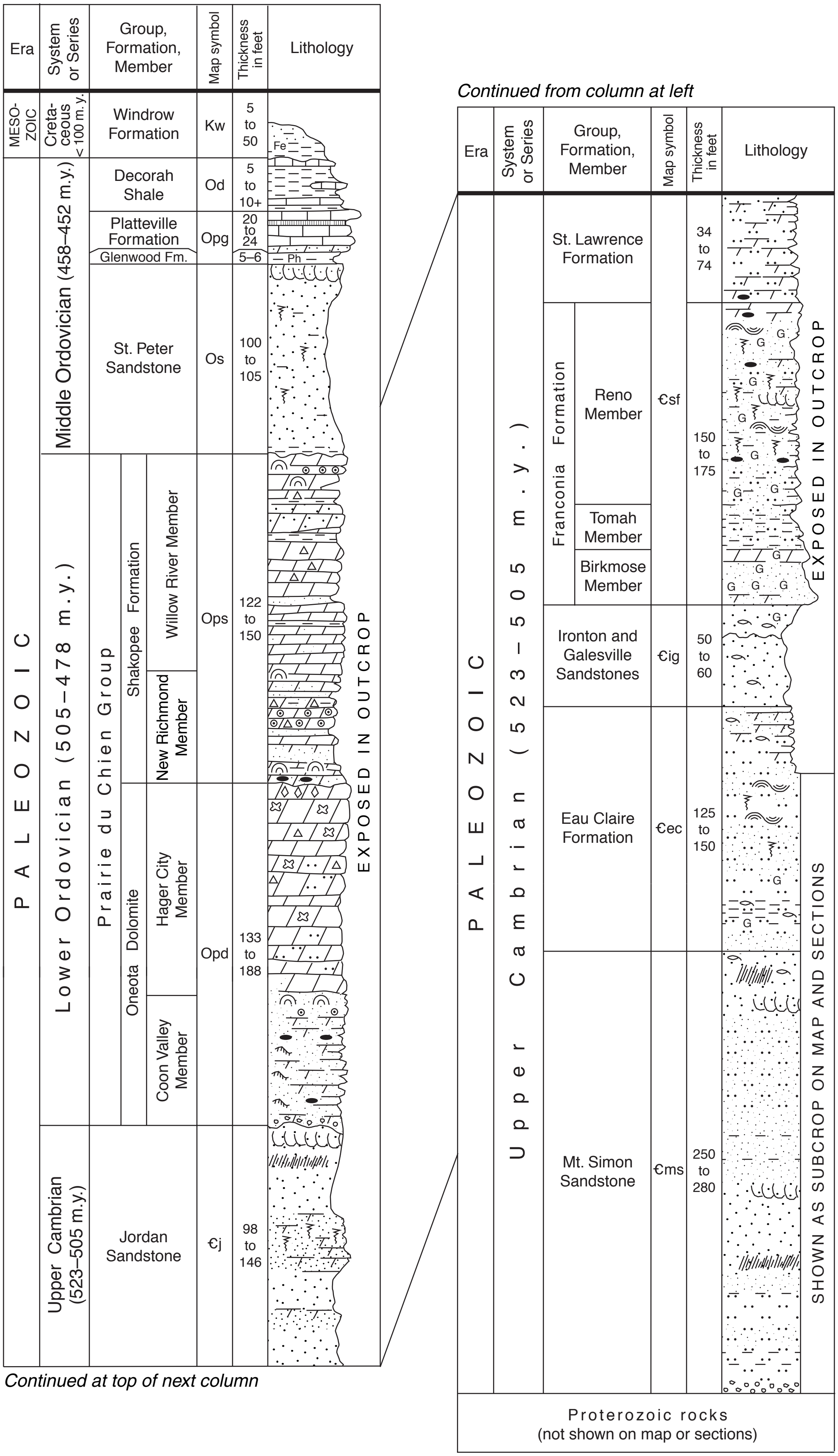


Figure 1. *(explanation of symbols on facing page)***.** Stratigraphic column showing formally defined Mesozoic and Paleozoic rock units of Wabasha County. Modified from Mossler (2001a).

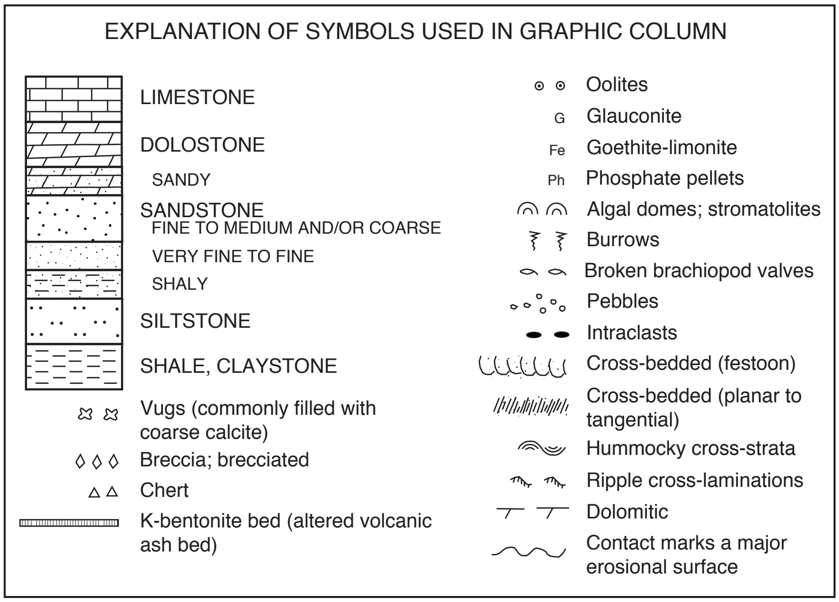


Figure 1 *continued from facing page.*

Most of the sedimentary rock in Wabasha County originated as sediment deposited from about 520 to 452 million years ago in shallow seas that covered the region at the time (Bunker and others, 1988). This was during the Late Cambrian and Early to Middle Ordovician Periods in the early part of the Paleozoic Era. No rock is preserved in Wabasha County for long intervals of time before and after these rocks formed. There are some thin beds of poorly consolidated, younger sedimentary rocks in western Wabasha County that probably date from the Cretaceous Period of the late Mesozoic Era, about 90–100 million years ago, but their age is not known with absolute certainty.

The Paleozoic rocks in Wabasha County consist mostly of well-indurated limestone, dolostone, sandstone, siltstone, and shale that are easily distinguished from overlying unconsolidated sand, gravel, silt, and clay of Quaternary age. However, the thin beds of Cretaceous rock consist mainly of poorly consolidated quartzose sandstone and conglomerate, siltstone, and soft claystone that superficially resemble overlying Quaternary glacial deposits, which makes them hard to distinguish, particularly in subsurface geologic records. Therefore, it is difficult to show their distribution accurately.

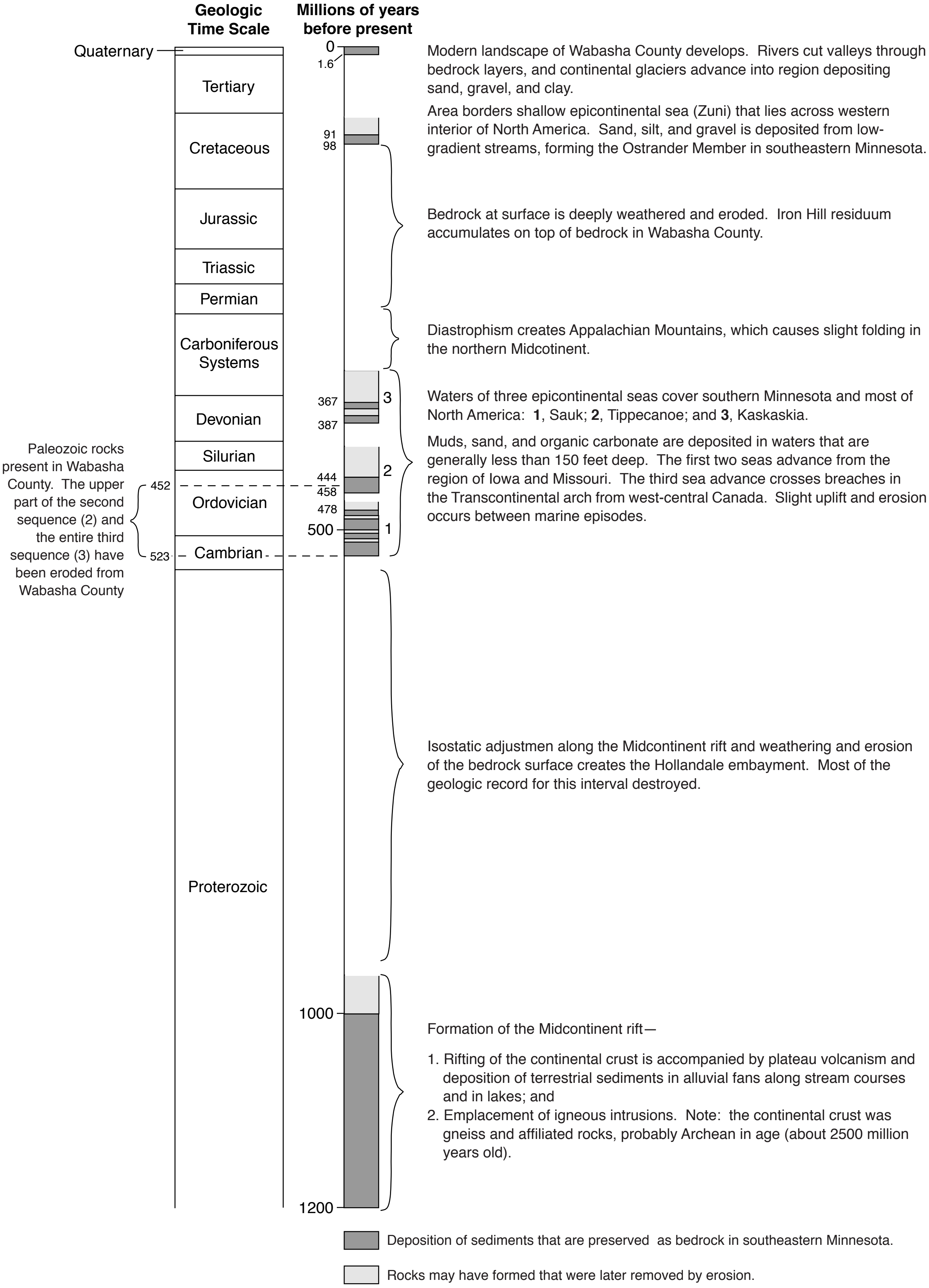
Mapping Bedrock Geology

To understand the distribution of Paleozoic rocks in Wabasha County as portrayed on the bedrock geologic map (Mossler, 2001a) it is useful to think of the rock in Wabasha County as flat-lying layers similar to those in a cake. The layers have retained their original depositional order without having been greatly disrupted or distorted by folding or faulting. The geologic sections (Mossler, 2001a) show views from the side of this layer-cake-like arrangement. The oldest rocks are at the bottom, the youngest at the top, although some of the youngest ones may be missing in places due to removal by erosion. The thickness of these layers must be exaggerated (by ten times) to show the details of the geology. The stratigraphic column on the Bedrock Geology plate (Mossler, 2001a) (Fig. 1) shows the complete sequence of rock strata known to be present in the map area. The bedrock geology map (Mossler, 2001a) shows the first (uppermost) bedrock encountered at the land surface or beneath unconsolidated Quaternary sediments. By referring to the stratigraphic column one can infer where many rock formations in the upper part of the pile are missing due to erosion, as, for example, along deeply entrenched stream valleys.

GEOLOGIC HISTORY

Proterozoic Era

Middle Proterozoic sedimentary rocks, which are approximately 1000–1200 million years old (Sims, 1990), form the basement to the Paleozoic rocks throughout most of Wabasha County. When these sedimentary rocks formed, the region that encompasses Wabasha County was located on the eastern margin of a large north–south-trending geologic feature known as the Midcontinent rift system. The rift system extends from Lake Superior on the north to Kansas on the



Paleozoic rocks present in Wabasha County. The upper part of the second sequence (2) and the entire third sequence (3) have been eroded from Wabasha County

Modern landscape of Wabasha County develops. Rivers cut valleys through bedrock layers, and continental glaciers advance into region depositing sand, gravel, and clay.

Area borders shallow epicontinental sea (Zuni) that lies across western interior of North America. Sand, silt, and gravel is deposited from low-gradient streams, forming the Ostrander Member in southeastern Minnesota.

Bedrock at surface is deeply weathered and eroded. Iron Hill residuum accumulates on top of bedrock in Wabasha County.

Diastrophism creates Appalachian Mountains, which causes slight folding in the northern Midcotinent.

Waters of three epicontinental seas cover southern Minnesota and most of North America: **1**, Sauk; **2**, Tippecanoe; and **3**, Kaskaskia.

Muds, sand, and organic carbonate are deposited in waters that are generally less than 150 feet deep. The first two seas advance from the region of Iowa and Missouri. The third sea advance crosses breaches in the Transcontinental arch from west-central Canada. Slight uplift and erosion occurs between marine episodes.

Isostatic adjustmen along the Midcontinent rift and weathering and erosion of the bedrock surface creates the Hollandale embayment. Most of the geologic record for this interval destroyed.

Formation of the Midcontinent rift—

1. Rifting of the continental crust is accompanied by plateau volcanism and deposition of terrestrial sediments in alluvial fans along stream courses and in lakes; and
2. Emplacement of igneous intrusions. Note: the continental crust was gneiss and affiliated rocks, probably Archean in age (about 2500 million years old).

■ Deposition of sediments that are preserved as bedrock in southeastern Minnesota.

□ Rocks may have formed that were later removed by erosion.

Figure 2. Time scale showing major geologic events in southern Minnesota. Modified from Mossler (2000).

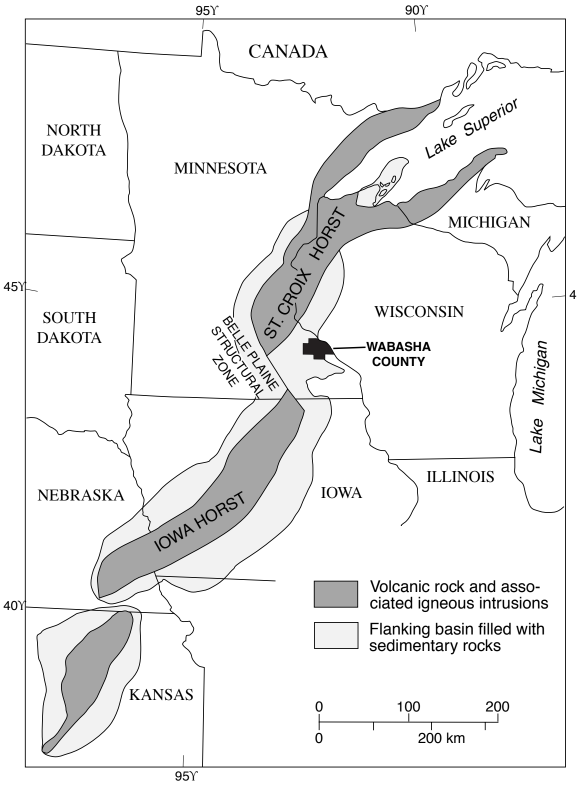


Figure 3. Generalized geology and structural features of the Midcontinent rift system. Modified from Sims (1990).

south (Fig. 3). The rift is the product of deep fracturing of older rocks that formed the earth's crust and concomitant volcanism as molten rock (magma) deep within the earth was forced to the land surface. Some of the older rock—gneiss and amphibolite that is more than 2,500 million years old—is located directly beneath the Paleozoic sedimentary rocks in extreme eastern Wabasha County (Sims, 1990). The rift widened considerably during the volcanism. From Belle Plaine in Scott County, to near Austin in Mower County, and onwards into adjoining northern Iowa, the rift is offset by large fractures, or faults, in a zone named the Belle Plaine structural zone (Fig. 3). The faults formed as the rift expanded and large slabs of the earth's crust slipped past one another. Basins formed along the axis of the rift as the rate of volcanism declined. Blocks composed of thick sequences of dense lava, which had been extruded earlier, subsided. In the absence of continued volcanism, these depressions filled with sedimentary detritus. Sand, silt and clay eroded from the flanks of the rift were carried to the depressions by streams. In places the streams flowed into large lakes occupying the basins (Morey, 1972; Tryhorn and Ojakangas, 1972). Some younger sandstone beds are interpreted to have been deposited subaerially as sand dunes (Beaster and others, 2000).

After rifting ceased and flanking and axial basins along the rift had been filled by stream, lake, and sand-dune deposits, the region underwent a long period of subaerial weathering and erosion that may have lasted for most of the next 500 million years. This period of weathering and erosion, which separates the Proterozoic rocks from overlying Paleozoic rocks, is represented by an erosion surface that is referred to as an *unconformity*.

Paleozoic Era

The Paleozoic rocks that are so prominent in Wabasha County were created from sediment deposited in marine water of shallow epicontinental seas. The seas flooded low-lying parts of the North American craton from the deep oceans along its margins. In earliest Paleozoic time North America was positioned nearer the equator than it is now (Witzke, 1990), and Minnesota lay in tropical to subtropical latitudes. However, because higher plant forms had not yet evolved, the land surface was barren of vegetation barring, perhaps, some primitive algae and bacteria. Minnesota and Iowa were low lying and mostly flat and, except for the absence of higher plant forms, looked like the coastline of the Gulf of Mexico. The sediments transported into the sea were deposited in a broad topographical lowland named the Hollandale embayment by Austin (1969) for a small town in Freeborn County, Minnesota, near the axis of the embayment. The embayment (Fig. 4) was created in part by differential erosion. The Proterozoic shale and sandstone occupying the basins along the Midcontinent rift system were softer and less resistant to erosion than the quartzite of the Sioux Ridge in southwestern Minnesota**,** basalt and rhyolite beneath highlands along the Central Iowa arch on the west side of the Hollandale embayment, and the granite, gneiss, and quartzite beneath the Wisconsin dome and arch along its eastern side (Fig. 4). During the long period before flooding of the region by marine water during the Early Paleozoic, the region was subject to subaerial erosion by streams that removed more of the softer sedimentary rocks. Continued subsidence of dense, thick Proterozoic volcanic rock along the faults within the Midcontinent rift was another factor that may have caused the Hollandale embayment to be lower than the highlands that bordered it.

For nearly 200 million years, during early Paleozoic time, sediments accumulated in more or less flat layers in the seas that covered the region. They were then buried, compacted, and cemented to form sedimentary rocks. Deformation and subsidence of the embayment in the Paleozoic accommodated the accumulation of 1500 feet of rock at places within the embayment in Minnesota, and even more in Iowa.

Of the three major incursions of seas into southeastern Minnesota during Paleozoic time, Wabasha County contains records of the first two, the Cambrian to Early Ordovician Sauk transgression and the Late Ordovician-to-Silurian Tippecanoe transgression. Much of the sediment deposited in Minnesota during the Cambrian and Ordovician consisted of sand-, silt-, and clay-sized particles eroded by streams crossing the Wisconsin dome (Fig. 4). The Transcontinental arch became an important source for sediment during Mid to Late Ordovician time. Marine currents and waves subsequently sorted the sediments entering the sea and carried them across the texturally graded shelf (Fig. 5) underlying waters of the Hollandale embayment. Only the coarsest sand was deposited at the shoreface where current and wave activities were strongest. Finer sand-, silt-, and clay-sized particles were deposited in deeper water away from the shoreface, on the offshore shelf, with the finest silt and clay particles slowly settling from suspension in the deepest parts of the shelf, hundreds of miles from shore. The most distal areas were starved for land-derived detrital sediment, and in some places carbonate grains and the shells of indigenous marine organisms dominated deposition. The different layers (strata) of Paleozoic rocks that stretch across southern Minnesota formed because sea level changed, thereby changing the position of the shoreline through time. Large changes in relative sea level caused the shoreline to shift back and forth across southern Minnesota relative to the Wisconsin dome. Each time the sea shifted across southern Minnesota it left sandy shoreface deposits. When southern Minnesota was covered by deep water, fine sand, silt, and clay and carbonate sediment were deposited in the sea.

Unconformities developed on the surface of rocks after seas retreated entirely from Minnesota. *Unconformities* represent major gaps in the geologic record when the shallow seas receded and significant erosion occurred on an exposed land surface. In addition to the pre–Mt. Simon unconformity and the post-Devonian unconformity, at least eight widespread, major unconformities are evident in the Upper Cambrian, Ordovician, and Devonian marine sedimentary sequence of southern Minnesota. During the exceptionally long intervals in Middle Ordovician and Early Devonian time between major marine incursions most of the continent was exposed as dry land. Flooding of the region by shallow marine water, draining of the water from the

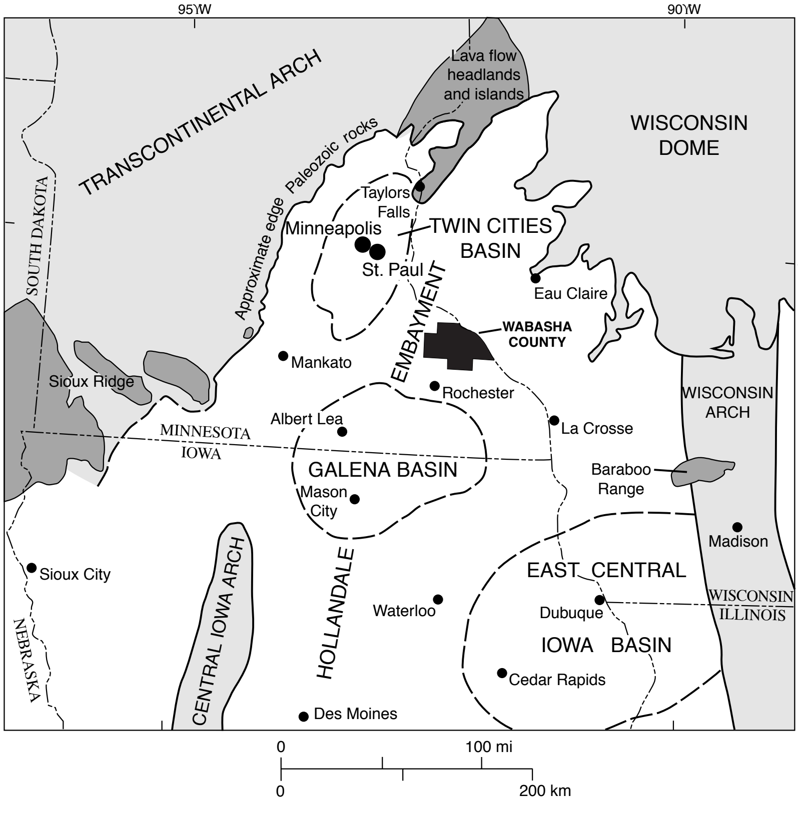


Figure 4. Paleogeography of the Hollandale embayment (unshaded area) during Early Paleozoic time. The Twin Cities, Galena, and east-central Iowa basins developed during late Ordovician time. Modified from Mossler (1995).

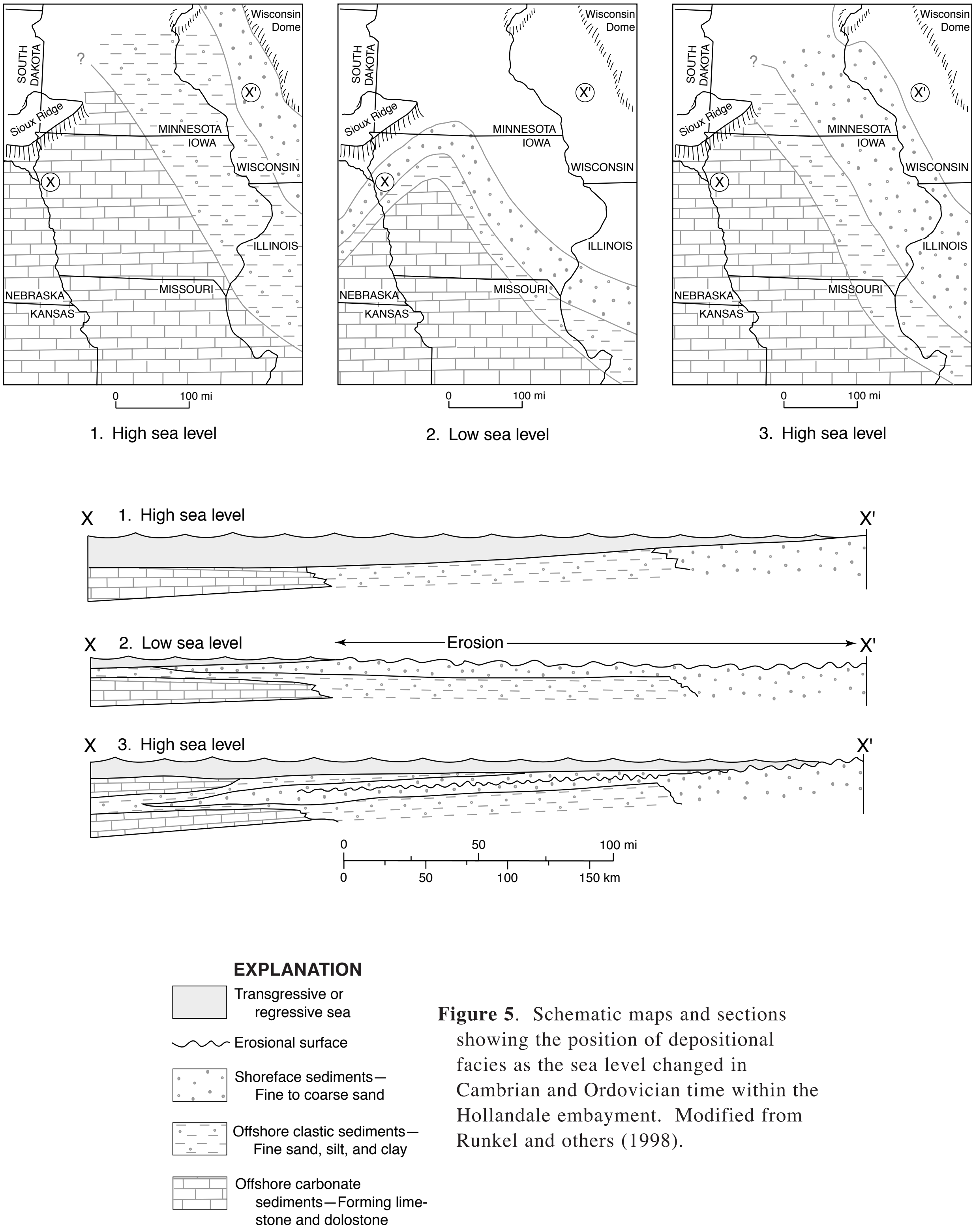


Figure 5. Schematic maps and sections showing the position of depositional facies as the sea level changed in Cambrian and Ordovician time within the Hollandale embayment. Modified from Runkel and others (1998).

region, emergence of the sea bottom and concomitant development of unconformities were probably related to far reaching effects of plate tectonics (Leighton, 1996).

The Upper Cambrian to Lower Ordovician Sauk sequence records the first incursion of epicontinental seas to flood the Hollandale embayment. The initial fluvial and braided delta-fan sediments within the embayment are today conglomerate and coarse sandstone of the basal Mt. Simon Sandstone (Mossler, 1992). Other coarse-grained sandstone in the basal and middle parts of the Mt. Simon accumulated as shoreface sand complexes during the initial marine flooding of Minnesota (Mossler, 1992). During this time the shoreface moved across southern Minnesota toward the Wisconsin dome. Younger coarse sandstone units, such as the Ironton–Galesville Sandstone and the Jordan Sandstone were also deposited during major changes in sea level. When sea level fell, the shoreline retreated out of Minnesota into Iowa, leaving behind a trail of sand (present-day Galesville Sandstone and basal Jordan Sandstone) (Runkel, 1994; Runkel and others, 1998). When the sea level rose, the shoreface moved across Minnesota toward the Wisconsin dome, leaving more sand (Ironton Sandstone, upper Jordan Sandstone) (Runkel, 1994; Runkel and others, 1998).

When sea level was relatively high, the sandy shoreface occupied high ground on the Wisconsin dome. Most of southern Minnesota at this time was part of a large offshore shelf covered by relatively deep water where clay, silt, and fine sand accumulated. The Eau Claire and Franconia Formations formed from these offshore shelf deposits (Runkel, 1994; Runkel and others, 1998).

Lengthy periods of high sea level, deep water, and the flooding of highlands that would otherwise supply detrital sedimentary particles resulted in little deposition of land-derived sediment. Under these conditions carbonate particles from marine organisms became an important constituent of the rock, as during deposition of the Upper Cambrian St. Lawrence Formation. However, during deposition of carbonate of the Lower Ordovician Oneota and Shakopee Formations (Prairie du Chien Group) at the end of the Sauk sequence, the supply of sand and other detrital material from the highlands decreased to the extent that carbonate derived from marine organisms dominated the entire depositional system, even shallow shoreline areas. Prairie du Chien rocks are interpreted to be tidal-flat (shoreline) and shallow subtidal deposits, except for some sandstone beds in the New Richmond Member of the Shakopee Formation that are interpreted as windblown (dune) sands that formed along the ancient shoreline (Smith and others, 1993).

Rocks from the second major marine incursion, the Upper Ordovician to Silurian Tippecanoe sequence, are present only in extreme northwestern and southern parts of Wabasha County. All that remains of the sequence are rocks of the lower part. Rocks of the upper part—Galena Group, Dubuque Formation, and Maquoketa Formation—have been eroded but are widely distributed in counties to the southwest and west, such as Olmsted and Goodhue Counties where a more complete sequence is preserved.

The Tippecanoe sea covered more of the continent than at any other time when North America was inundated. Widespread carbonate rocks (limestone and dolostone) formed in the sea because potential sources of detrital sand, silt, and clay were often flooded. When the sea was less extensive highlands like the Transcontinental arch emerged from the water and shed detrital sediment, principally clay and silt, into the sea. The Wisconsin dome and arch also continued to supply sediment to the depositional basin, although this contribution was masked by the contribution from the Transcontinental arch (Lively and others, 1997). The St. Peter Sandstone was deposited as shoreface sand accumulation (Fig. 5) during the initial marine flooding of the Tippecanoe sequence. As sea level continued to rise, clay-rich sediments and limy mud accumulated in relatively deep water, eventually forming the Glenwood, Platteville, and Decorah Formations (see Fig. 5). Abundant shale in the Glenwood–Decorah interval and in the basal part of the Galena Group (the Cummingsville Formation) indicates the great amounts of sediment being shed into the sea from the Transcontinental arch during the time these formations formed. Younger formations are found south of Wabasha County where they were not eroded. These are mainly carbonate rocks; limestone and dolostone that were deposited when the sea stood at higher levels.

Mesozoic Era

Following deposition of Devonian sediments to the south of Wabasha County, the seas withdrew from Minnesota for a long period of time, about 375–100 million years ago. Southern Minnesota was subject to much subaerial erosion (Fig. 1), following which the record of sediment deposition in southern Minnesota resumed with deposition of the Windrow Formation. Although most stratigraphers (Andrews, 1958; Sloan, 1964; Witzke and Ludvigsen, 1994) assign a Late Cretaceous age to the Windrow, it has been suggested by Bleifuss (1972) that both the Iron Hill residuum

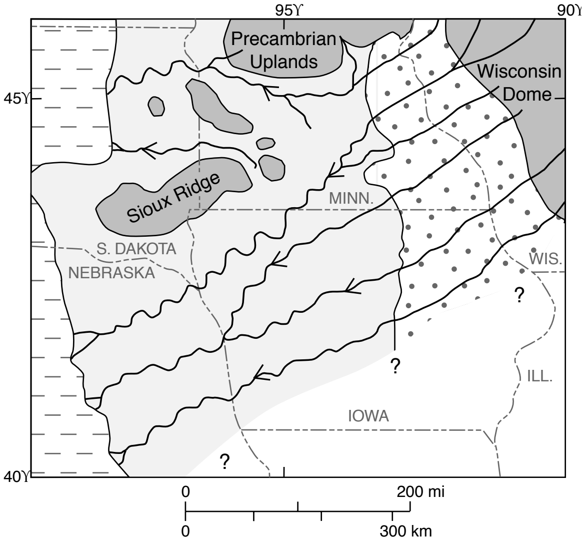


Figure 6. Inferred paleogeography during deposition of the Late Cretaceous Windrow Formation in the northern midcontinent of North America. Modified from Witzke and others (1983).

and Ostrander sand and gravel may be younger than Cretaceous in age. Therefore, age assignments are provisional.

The Cretaceous rocks of southeastern Minnesota were deposited on a low featureless plain that lay east of a large, shallow epicontinental sea (Fig. 6). Rocks formed from deposits in this sea are part of the Zuni sequence (Bunker and others, 1988). This sea covered the western interior of the North American continent east of the Rocky Mountains and extended at times into western and north central Minnesota. The basal part of the Windrow Formation—the Iron Hill Member—is a poorly dated residuum of unconsolidated, weathered material that formed on older Paleozoic rocks. In Wabasha County it is an iron-rich residuum that formed over a karsted surface of carbonate rocks. Today, most remnants of these residual deposits are on bedrock uplands, although some may be present along upper slopes of channels cut in bedrock. Austin (1963) describes ferruginous regolith composed of dolomite sand, chert, drusy quartz, limonite concretions, and ferruginous clay lying on Prairie du Chien dolostone. He observed that the residuum fills channels and enlarged joints; and that porous zones and clay-filled cavities extend down into the underlying dolostone. According to Austin (1963) the weathering probably occurred mainly during the Early Cretaceous; however, there is little evidence to support such an age assignment. In Wabasha County this residuum is found mainly in Mount Pleasant and Chester Townships (refer to plate in back pocket of Austin, 1963).

At some locations (most are outside Wabasha County) the Iron Hill Member is overlain by the Ostrander Member, a unit composed of sandstone, conglomerate, and claystone that was originally deposited as sediment in braided streams. The streams drained westward and southwestward into the shallow sea (Fig. 6) that covered the western interior of the United States at the time (Witzke and Ludvigson, 1994). The sediments accumulated either as sand and gravel bars within braided stream channels or as fine-grained (clay, silt) overbank deposits beside them (Andrews, 1958). Some claystone may have filled shallow depressions or sinkholes that formed through the dissolution of Prairie du Chien carbonate rock underlying the region. The sandstone and conglomerate in the Ostrander are composed almost entirely of quartz and chert clasts. Some of the clasts consist of silicified fossils derived from underlying Ordovician and Devonian formations and from Silurian formations in Wisconsin (Andrews, 1958). The sand grains and pebbles in the Windrow characteristically have highly polished surfaces and are well-rounded, indicative of transport long distances in shallow agitated water (Andrews, 1958).

The only deposits younger than the Windrow are Quaternary glacial deposits, loess, and alluvium, which are less than two million years old. Most of the Quaternary Period belongs to the Pleistocene Epoch or Ice Age. The Holocene Epoch began about 10,000 years ago. During cold spells during the Pleistocene glaciers that formed in northern Canada flowed south into what is now Minnesota. As these glaciers advanced they scraped rock and soil from the landscape, mixed them, and then left them as unsorted material called till when the ice melted (Hobbs, 2001, 2002). Streams of water melting from the glaciers deposited sorted sand and gravel and silt as outwash deposits. During the cold, dry periods when there was little vegetation strong winds blowing off the glaciers picked up fine sand and silt from the outwash sediment and redeposited it in a thin blanket called loess.

Glacial deposits are not thick in Wabasha County and the rest of southeastern Minnesota because the area was free from ice during most of the Ice Age. The main influence of the glaciers on the area was from the large amounts of water released from the melting glaciers. The large volumes of water carved the deep valley of the ancient Mississippi. Then tributaries of the Mississippi, such as the Zumbro and Whitewater Rivers, cut deeply into their valleys to keep pace with the Mississippi, thereby creating the blufflands that we see today. The discussion of the glacial deposits in Wabasha County is covered in more detail in another chapter.

The uplands of Wabasha County are underlain by soluble carbonate rock. As ground water that contains carbonic acid moves through the rocks, it dissolves carbonate along the pathways formed by joints and fractures. The resulting landforms are characteristic of karst landscapes: caves, sinkholes, and large springs. The formation of the solution channelways increases the capability of rock formations to serve as sources for ground water. This capacity has also been enhanced by the erosion of the deep valleys in bedrock. As the rock in the valleys was removed, underlying rocks were relieved from the pressures confining them and fractured. In some instances the fractures may have been enhanced by the effects of mass movement, such as slumping, and of physical weathering, such as freeze–thaw. The formation of ice from water freezing in rock fractures expands them. These fractures now serve as conduits for ground water.

GEOLOGIC STRUCTURE

The consolidated sediment that forms the present-day bedrock formations was originally deposited in nearly horizontal layers. However, the bedrock layers are neither absolutely planar nor absolutely horizontal. They have deformed through compressive stresses in the crust that may be associated with mountain building on the east coast of the United States during the Paleozoic Era. The episodes of deformation warped the sedimentary rocks in the Hollandale embayment into a synclinal feature informally named the southern Minnesota syncline (Thiel and Schwartz, 1941). Several other smaller basins and synclines also exist, including the Galena basin in southern Minnesota and adjoining northern Iowa (Fig. 4), the Twin Cities basin of east-central Minnesota, and the River Falls syncline of east-central Minnesota and western Wisconsin.

The bedrock formations of Wabasha County have a gentle regional dip of 10–15 feet per mile toward the southwest. Contours drawn at the top of the Jordan Sandstone on the bedrock geology map (Mossler, 2001a) generally decrease in value (or altitude) toward the southwest. This regional dip is related to the synclinal folding of sedimentary rock layers along the axis of the Hollandale embayment shown on structural contour maps drawn by Mossler (1983). Smaller geologic structures that also influence local attitude or orientation of the rock layers probably formed when Proterozoic or older faults were reactivated during the Phanerozoic.

The most conspicuous faults are in western Wabasha County. They are related to the uplift, originally described by Crain (1957) and Cowie (1941), that has been informally referred to in the past as the Redwing–Rochester anticline. The longest fault, the Bellechester–Lake Zumbro fault, extends from east of the border city of Bellechester in northeastern Goodhue County south to Zumbro Lake near the southern border of Olmsted County. It has surface topographic expression because of the breaching of hard dolostone of the Shakopee and Oneota Formations and uncovering and erosion of underlying softer Jordan Sandstone. This has created an area of more subdued, gentler topography particularly along the Bear Valley, which is surrounded by areas where the topography is rougher and streams are bordered by bluffs incised into resistant dolostone beds of the Oneota and Shakopee Formations. This fault also has the most vertical displacement, as much as 150–175 feet in places. The other faults were inferred from subsurface geological data (and some outcrops), which indicate that values for the elevation of the top of the Jordan Sandstone deviate significantly (either higher or lower) from values that would be expected from the normal regional dip of 10–15 feet per mile. The evident alignment of wells possessing values that are either anomalously higher or lower than average along lines subparallel to the Bellechester–Lake Zumbro fault support the interpretation that subsidiary faults are present. These subsidiary faults show displacements of tens of feet over a mile or less.

GEOMORPHOLOGY

The present landscape in Wabasha County is largely the result of stream erosion acting on Paleozoic and Mesozoic bedrock during the Quaternary Period (approximately the last two million years). The broad, flat plateaus and intervening narrow valleys reflect the composition of underlying bedrock layers. Harder rock layers are more resistant to weathering and erosion; softer layers are more vulnerable to disintegration. Therefore, harder rock formations such as the Oneota Dolomite and the Shakopee Formation of the Prairie du Chien Group constitute a bedrock cap over large areas of the county beneath the plateaus and uplands. Formations composed of weaker, softer rock types, such as shale and sandstone, form bedrock surfaces within valleys and along lower parts of the bluffs. In Wabasha County, the tops of bluffs are capped by hard dolostone or limestone of the Prairie du Chien Group or Platteville Formation and the side slopes generally underlain by soft sandstone and siltstone (Fig. 7).

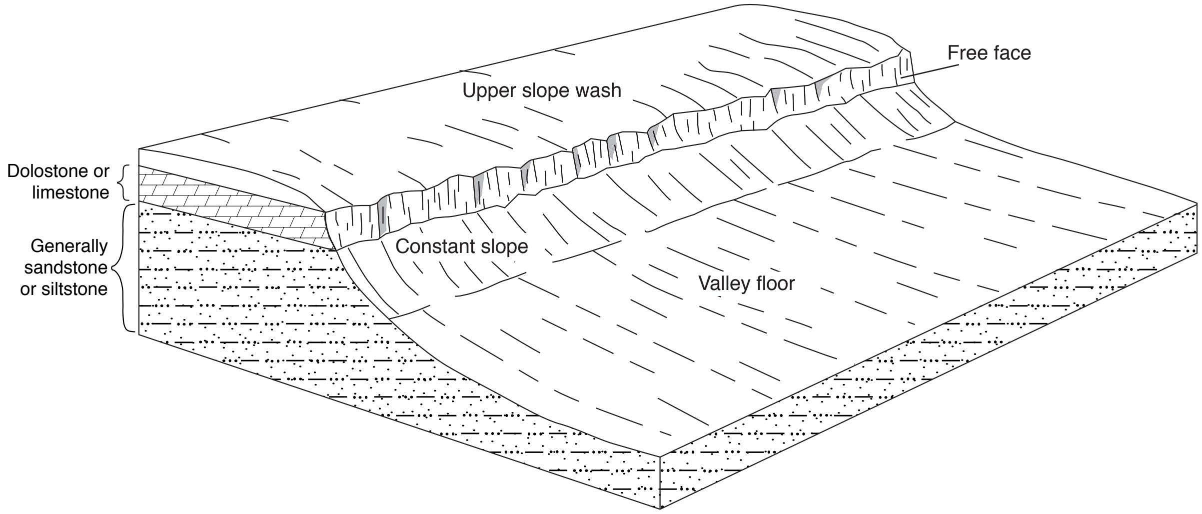


Figure 7. Slope formation in Wabasha County, Minnesota. Relatively hard dolostone or limestone caps the top of slopes, whereas more easily eroded sandstone and siltstone lie within the lower part of valleys. Modified from Holmes (1965). Slope types are

Upper or waxing wash slope—The upper surface tends to be rounded off into a convex shape at or near its edge with the free face. In Wabasha County this interval is generally underlain by unconsolidated Quaternary sediment and loess and poorly consolidated rock formations, such as the New Richmond Member of the Shakopee Formation and the Decorah Shale.

Free face—Outcrop of bare rock (scarp, bluff or cliff) that stands more steeply than the angle of repose of any scree or talus heap that may accumulate from its weathering products. In Wabasha County this interval is generally underlain by carbonate rock of the Prairie du Chien Group or the Platteville Formation.

Constant slope—Angle of rest of the scree debris or the bedrock surface on which a sprinkling of fragments may halt for a time. If a scree is present, the slope is commonly referred to as the talus or debris slope. This slope merges into the following:

Valley floor or waning slope—In Wabasha County this interval is commonly underlain by softer formations such as the Jordan and St. Lawrence Formations or the St. Peter Sandstone. The scree covering it is mostly fragments of more resistant formations, such as Prairie du Chien dolostone, Platteville limestone and St. Lawrence dolomitic siltstone.

Throughout most of the county these are sandstone and siltstone of the Jordan Sandstone and St. Lawrence and Franconia Formations. Along the deeply incised valley of the Mississippi River and neighboring deeply incised downstream parts of major tributaries that drain into it, sandstone and siltstone of the Ironton, Galesville, Eau Claire, and Mt. Simon Formations also subcrop (Mossler, 2001a). In lower reaches of tributaries and along the Mississippi valley these formations for the most part are deeply buried beneath thick layers of alluvium (Mossler, 2001b). Comparing the bedrock geology map (Mossler, 2001a) with the bedrock topography map (Mossler, 2001b) demonstrates how the pattern of outcrops is controlled by the erosion of the bedrock surface.

In western and southwestern parts of the county there are a few small mesas capped by resistant limestone of the Platteville Formation (Mossler, 2001a). The mesas have side slopes composed of less resistant Glenwood shale and St. Peter sandstone; they formed in a manner similar that described above for the more extensive Prairie du Chien plateau.

The Jordan Sandstone and St. Lawrence and Franconia siltstone and sandstone are the first (uppermost) bedrock beneath Quaternary sediments along the Bear Creek valley and in the Zumbro River valley two to three miles west of Zumbro Falls in western Wabasha County to the county line. The valleys are interpreted to have formed from dissolution and erosion of Prairie du Chien dolostone along the upthrown side of the extensive fault zone shown on the bedrock geology plate (see geologic map and sections A–A' and

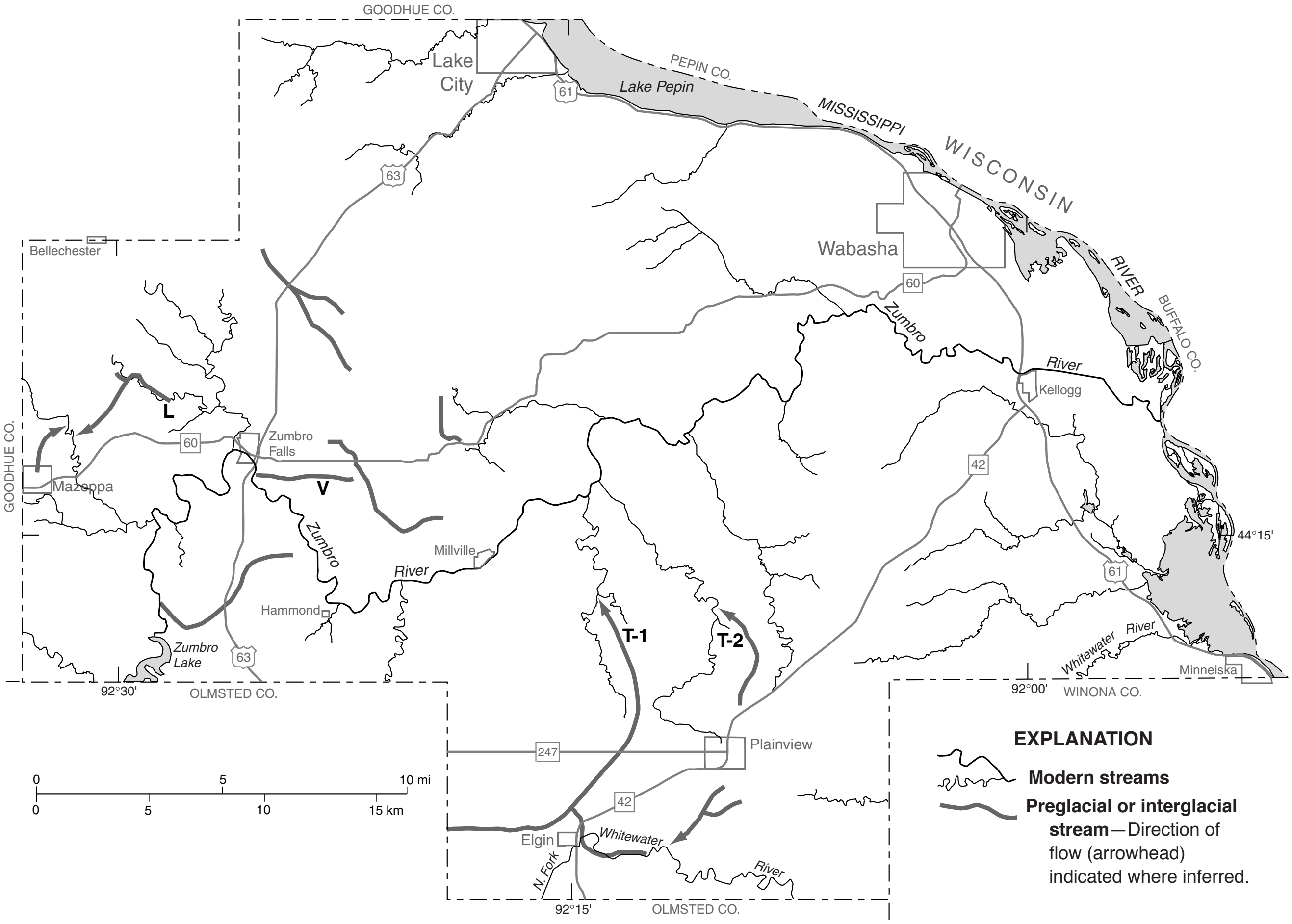


Figure 8. Location of pre-glacial stream segments in relation to present-day major drainage, Wabasha County, Minnesota. Modern lakes along the border with Wisconsin are indicated by light gray tone. Some stream segments discussed in text are labeled on the map using letters or letter-and-digit combinations, for example, **L** or **T-1**.

B–B' in Mossler 2001a). The valleys are much broader, and more of the Prairie du Chien dolostone has been removed there than along the Zumbro River east toward Zumbro Falls, Hammond, and Millville.

The present landscape of Wabasha County is relatively young in a geologic sense; it is largely the product of stream dissection during the Quaternary. However, fragments of older landscapes that date from preglacial time now lie buried beneath glacial till and loess on the uplands. Segments of pre-Quaternary valleys and possible early to mid-Quaternary valleys lie buried beneath Quaternary glacial till in parts of Elgin, Oakwood, Hyde, Gillford, Chester, and Zumbro Townships (Fig. 8). The areas underlain by these buried valleys contain the thickest glacial deposits preserved in Wabasha County. Because they are isolated fragments of valleys and may be of different ages (preglacial, interglacial), it is not possible to ascertain the original pattern of the former valley system.

Nearly all of the buried valleys were identified using subsurface geologic and geophysical methods, namely, the gravity–geologic method (Imbrahim and Hinze, 1972; Adams and Hinze, 1990; Chandler, 2000) and refraction seismic soundings. There also is evidence for the existence of buried valleys in the landscape today. The present-day lowland drained by Bear Creek sits over a partly exhumed lowland of pre-Quaternary age (**L** on Figure 8) mentioned above. A small valley tributary to the Zumbro River in sections 5 and 6 of Hyde Park Township (**V** on Figure 8) occupies a partially exhumed bedrock valley. The gradient of the stream flowing within it is not adjusted to the Zumbro River; it contains a waterfall over a bedrock lip before it enters the Zumbro. Other small tributaries in Oakwood and Highland Townships that are interpreted to flow in partially exhumed bedrock valleys are shown on Figure 8 (outcrop locations **T-1** and **T-2**).

One of the most prominent features on the landscape of Wabasha County is the well-integrated dendritic networks of stream valleys cut into bedrock that slope down toward the Mississippi River valley (Mossler, 2001b). At times when the base level of the Mississippi River was lower, the rivers incised their valleys. At other times glacial meltwater carried enormous amounts of sediment from glaciers into the region and partly filled them (Hobbs, 2002). These processes were repeated more than once. Many of the valleys contain a significant thickness of alluvium and once were much deeper than they presently are (see Depth to Bedrock map on Mossler, 2001b). Alluvium in the Mississippi River valley exceeds 350 feet in places, and it commonly is 100–150 feet or more thick throughout most of the Zumbro River valley.

HYDROSTRATIGRAPHY

The Paleozoic bedrock in Wabasha County is the chief source of potable water for its residents. An understanding of how water moves through the Paleozoic bedrock is therefore a matter of great importance for protecting this water supply for continued use. Geologic mapping provides critical information that is used in conjunction with additional hydrogeologic studies to characterize the ground-water system in the county. Hydrostratigraphy is the study of the porosity and permeability of rocks, which are the fundamental controls on ground-water movement. Ground water moves through openings in rock called pores. A rock of relatively high porosity can hold more water than an equal volume of rock with low porosity. The relative ease at which water can travel through a rock is expressed by the term *permeability*. Rocks that have high permeability transmit ground water relatively easily.

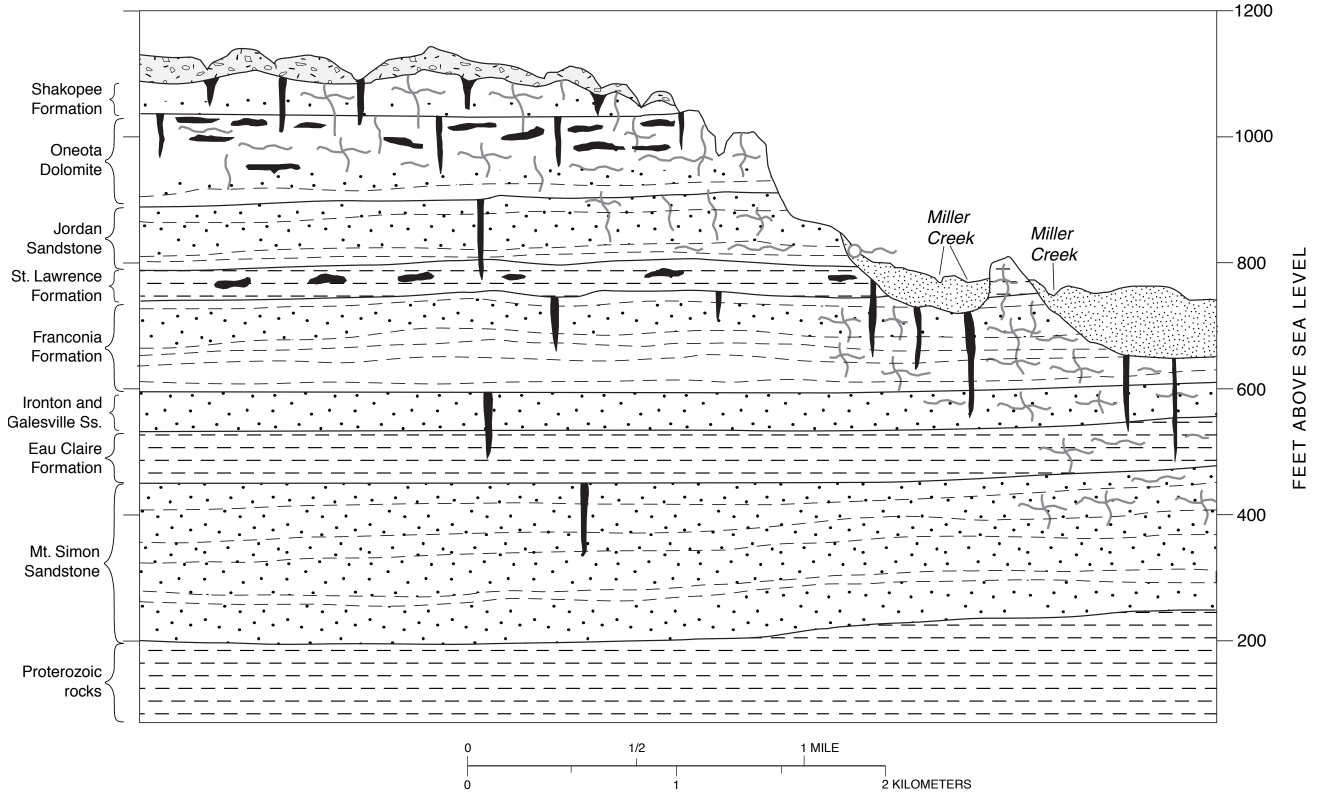
Hydrostratigraphic Components

The Paleozoic strata of southeastern Minnesota are divided into three distinct hydrostratigraphic components on the basis of the abundance and connectivity of small pores between the grains in the rock (Runkel and Tipping, 1998; Runkel, 1999). The components are (1) fine clastic, (2) coarse clastic, and (3) carbonate rock. The *fine clastic component* consists of very fine grained sandstone, siltstone, and shale in thin to medium beds that have moderate to low porosity and low to very low permeability. The *coarse clastic component* is a poorly cemented, moderately sorted to well-sorted, fine- to coarse-grained sandstone that has high porosity and permeability. The *carbonate rock component* consists of very fine grained to fine-grained dolostone and limestone that have variable amounts of silt, sand, and shale forming interbeds or admixed in the carbonate matrix. The carbonate rock component typically has both low primary permeability and porosity.

The hydrostratigraphic character of the three components is markedly affected by lateral and vertical variability in the abundance and interconnectivity of larger pores, such as fractures and dissolution cavities. Permeability is extremely high where such features are well developed and interconnected, and markedly lower where minimally developed. Paleozoic bedrock in southeastern Minnesota can be separated into two general categories based on the nature of these larger pores: (1) *shallow* bedrock conditions, and (2) *deep* bedrock conditions. Shallow bedrock conditions differ from deep conditions in having a relatively high density, large size and high degree of interconnectivity of fractures and cavities. In shallow bedrock conditions the fine clastic, coarse clastic, and carbonate rock components may be several orders of magnitude higher in permeability compared to deep conditions because of the greater development of the pores (Donahue and Associates, 1992; Gianniny and others, 1996; Wenck and Associates 1997). The carbonate rock component is especially well known for containing large, interconnected pores (Alexander and Lively 1995) because it is relatively easily dissolved in shallow bedrock conditions.

There is no precise boundary between shallow and deep bedrock conditions that is found at a consistent depth. Investigations by Runkel (1999, 2000) indicate that a 200-foot deep boundary between deep and shallow bedrock conditions is reasonable as a regional-scale generalization. The term *shallow bedrock conditions* in this report therefore refers to the upper 200 feet of Paleozoic bedrock regardless of the thickness and composition of overlying Quaternary deposits. This 200-foot boundary is chosen with the full understanding that the change from what we have characterized as shallow versus deep bedrock conditions is in reality transitional and will vary in depth from place to place.

An important component of hydrogeologic studies is defining and characterizing aquifers and confining units. Residents of Wabasha County extract water from *aquifers*, which are layers of bedrock that have sufficiently high permeability to yield economic quantities of water. Between aquifers are *confining units*, layers of relatively low permeability that retard the vertical movement of ground water. In deep bedrock settings the most widely used aquifers are layers of bedrock dominated by coarse clastic material, such as



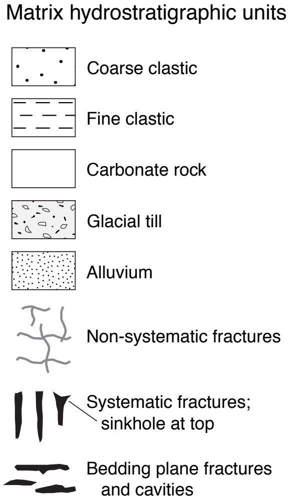


Figure 9. Schematic cross section of Paleozoic strata in Wabasha County, Minnesota, showing the distribution of the three rock-matrix hydrostratigraphic components (primary porosity), and fractures and dissolution features (secondary porosity). This figure is based on a segment of cross section B–B' from Plate 2 of the Wabasha geologic atlas (Mossler, 2001a) southwest of Lake City.

Under deep bedrock conditions major ground-water pathways are in the coarse clastic layers and along dissolution features in carbonate rock. These layers are used as aquifers. Fine clastic layers and carbonate rock lacking dissolution features can provide confinement (confining units). Under shallow bedrock conditions all layers have fractures or dissolution cavities, and ground-water flow may occur dominantly in such features. Layers that are of low conductivity in deep bedrock settings may be of much higher conductivity and may lose the ability to serve as confining units in a shallow bedrock setting.

This figure is highly generalized and individual hydrostratigraphic components are more complex than if shown at a local scale. Systematic joints in deep bedrock settings are not known to be common in Minnesota, but they are drawn in places on this cross section on the basis of their known presence in similar settings in Michigan (for example, Hurley and Swager, 1991).

the Jordan Sandstone, or by carbonate rock that has abundant cavities, such as the Shakopee Formation. Confining units are layers of bedrock dominated by the fine clastic or carbonate rock component that has few interconnected fractures and cavities.

Shallow bedrock conditions are hydrostratigraphically more complex than deep conditions because of the greater abundance, interconnectivity, and size of fractures and cavities. Permeabilty varies markedly from place to place within individual aquifers and confining units, and our understanding of ground-water flow is extremely limited in such a setting. The fine clastic, coarse clastic and carbonate rock components are all known to contain networks of large fractures and cavities that accommodate water flow at rates of hundreds of gallons per minute and speeds measured in hundreds of feet per day. They are separated by blocks of rock that have few fractures and cavities through which water moves markedly more slowly. Carbonate rock in shallow bedrock conditions forms karst systems (Tipping and others, 2001), which are characterized by relatively abundant, large secondary pores expressed at the land surface by caves, numerous springs, and many sinkholes in areas with only a thin cover of unconsolidated material. Fine clastic and carbonate rocks that serve as confining units in deep bedrock settings are known to be locally breached by interconnected secondary pores that allow relatively rapid vertical recharge to underlying aquifers.

Regional dip of bedrock layers and more localized bending, fracturing, and displacement of the layers have important implications for direction of ground-water flow. The configuration of aquifers and confining layers greatly influences direction of ground-water movement. Therefore, the bedrock map on Plate 2 of the Wabasha geologic atlas (Mossler, 2001a) includes structure contours on top of the Jordan Sandstone. The configuration of overlying and underlying formations are similar.

BEDROCK ENDOWMENT

Nearly all bedrock formations that are at or near the land surface in Wabasha County have historically had practical uses. Carbonate rocks like the Oneota and Platteville Formations have been used for building stone, as aggregate in concrete, for surfacing graveled roads, and as agricultural lime. Sandstone from the St. Peter has been used for backfill and, in other places in southeastern Minnesota, as foundry sand (Knapp, 1923), as a raw material in glass, and as sandblasting sand. In neighboring counties clay from the Windrow Formation was formerly used for ceramics and drain tile and shale from the Decorah was used for brick and tile (see, for example, Setterholm and Hobbs, 1998).

Today the bedrock resources extracted in Wabasha County are dolostone and sandstone, which are used chiefly for road building and related construction. The bedrock endowment map, Plate 6 of the Wabasha geologic atlas (Mossler and Hobbs, 2001), shows locations for active or intermittently active and abandoned dolostone and limestone quarries and sandstone pits. The locations are from (1) the Inventory of Industrial Minerals Pits and Quarries in Minnesota (Nelson and others, 1990); (2) the most current (March 2000) Minnesota Department of Transportation aggregate-resources map for Wabasha County; and (3) field mapping by the author.

The distribution of bedrock formations that form the bedrock endowment shown on Plate 6 of the Wabasha geologic atlas (Mossler and Hobbs, 2001) is based solely on geologic criteria derived from the bedrock geologic map (Mossler, 2000a) and the thickness of Quaternary sediments (Mossler, 2001b). Other important considerations in determining the feasibility for mining of natural resources are

1. Urban development,
2. Land-use restrictions and zoning,
3. Economic factors, such as demand for the re--source and haulage distances, *and*
4. Compliance with Minnesota Department of Transportation standards for bedrock aggregate, standards which also are used for roads constructed and maintained by the Wabasha County Highway Department and other counties in southeastern Minnesota.

Based on the preceding considerations, three formations are shown on the Wabasha County bedrock endowment map (Mossler and Hobbs, 2001) as principal sources for bedrock resources. They are the Oneota Dolomite, the Shakopee Formation, and the St. Peter Sandstone.

Some crushed Oneota dolostone from Wabasha County meets Minnesota Department of Transportation specifications for aggregate used in concrete and bituminous pavement. It has absorption and magnesium sulfate values low enough to meet the requirements of the Department (see Mossler and Hobbs, 2001). Quarries near Hammond are among the few in southeastern Minnesota that provide aggregate used in concrete pavement. The Oneota is also used for gravel-surfaced roads and shoulders, backfill, road-base materials, agricultural lime, and rip rap.

Chemical analyses by Niles and Mossler (1990) and Mossler and Hobbs (2001) indicate that some intervals of the Oneota dolostone are potential sources of high purity dolomite for metallurgical applications. They include manufacture of refractory bricks and fluxing additions to produce fluxed taconite pellets (Niles and Mossler, 1990, p. 81). Industrial minerals, including limestone and dolostone, are also widely used as fillers in products like adhesives and sealants (Niles and Mossler, 1990).

During the late nineteenth and early twentieth century bluffs of the Mississippi River at Lake City, Wabasha, and Reads Landing supplied dimension stone from the Oneota Dolomite and St. Lawrence Formation. Bowles (1918) reported that the stone was used in buildings (mostly for foundations) and for bridge piers. The Oneota also was quarried for building stone along the bluffs of the Zumbro River near Millville and Mazeppa, and is still quarried for dimension stone south of Wabasha County near Winona, and it could potentially be quarried for dimension stone in Wabasha

County.

The Shakopee Formation also is a source of crushed rock for gravel roads, highway shoulders, backfill, and base materials; it has also been used for agricultural lime and rip rap. However, it generally has not been used as aggregate for concrete or asphalt pavement because it has absorption and magnesium sulfate values that are too high to meet Minnesota Department of Transportation standards (Mossler and Hobbs, 2001).

The St. Peter Sandstone is mined for backfill, sandboxes, and other purposes at several pits in western and southwestern parts of Wabasha County. The Jordan Sandstone and other Cambrian formations are other likely sources for these uses.

The Platteville Formation is no longer used by the Minnesota Department of Transportation for road construction in southeastern Minnesota. Its high insoluble residue content in the clay-to-silt size fraction makes it unsuitable. Nonetheless, parts of the formation may be adequate for local needs. The Platteville Formation was not mapped as a mineral endowment because it failed to meet the criterion of thicknesses of 30 feet or greater in Wabasha County. The Platteville Formation formerly was quarried for building stone about three miles south of Plainview in the bluffs along the Whitewater River. Beds from the upper part of the Platteville from the same quarry were burned for lime (Bowles, 1918).

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Guide to Representative Bedrock Outcrops, Wabasha County and Adjacent Areas

INTRODUCTION

Wabasha County has many outcrops, most of which are formations composed of well-indurated (hardened) rock, primarily dolostone, that is resistant to weathering and erosion. Formations that have economic importance, such as the Oneota Dolomite and Shakopee Sandstone, are exposed in numerous quarries. Soft, less indurated formations, which commonly composed of shale, siltstone, and sandstone, are liable to weathering, erosion, and rapid overgrowth by vegetation. The Ordovician Decorah Shale and Cretaceous Ostrander Formation are rarely seen in outcrop. A comprehensive list of outcrops for the county is too lengthy to include in this report; however, locations of some of the better outcrops are described for readers who wish to familiarize themselves with local bedrock stratigraphy.

MIDDLE ORDOVICIAN ROCKS

Middle Ordovician rocks are part of the Tippecanoe sequence and were deposited during the second flooding of the continent by a sea in the Phanerozoic Era. Rocks of this age are limited to small outcrops southwest of Lake City, in the northwest part of the county, and outcrops near Elgin in southern Wabasha County. Only the lowermost formations in the sequence are present. This is because most rocks of the sequence were removed from the Wabasha County area by erosion prior to the Holocene (the period of time after the glaciers receded from the area and continuing to the present day). The lowermost rocks of the Tippecanoe sequence record the initial transgression of marine water across the region during the second flooding of the continent. They are predominantly detrital rocks such as sandstone (St. Peter Sandstone) and shale (Glenwood Formation and Decorah Shale) because widespread areas on highlands, such as the Transcontinental arch, shed detrital sediments (fragments of rock) into the sea during the earliest stages of the transgression. Rocks of the later Tippecanoe sequence, present farther south in Minnesota, are predominantly carbonate rocks (limestone, dolostone) that formed *after* the highlands flooded and the influx of detrital sediment into the sea was greatly reduced.

The uppermost part of the St. Peter Sandstone, the Glenwood Formation and the Platteville Formation, crop out in roadcuts along State Highway 42 one-eighth mile south of the border of Wabasha and Olmsted County line in NE1/4 sec. 3, Viola Township, Olmsted County (**outcrop 1a**[1]). To the east of this outcrop, St. Peter Sandstone roadcuts are along the road on the county line on the south edge of section 35, Elgin Township (**outcrop 1b**).

St. Peter Sandstone crops out in a large borrow pit near the county line with Olmsted County on County State Aid Highway 2 in SE1/4 sec. 33, Elgin Township (**outcrop 2**). The Glenwood Formation and thin beds of Platteville limestone are present at the top of the pit but are not very accessible. There is another pit one-half mile south along the same road, across the county line in Olmsted County.

LOWER ORDOVICIAN AND UPPER CAMBRIAN ROCKS

Rocks of the Lower Ordovician Prairie du Chien Group constitute the upper part of the Sauk sequence, the rock sequence that formed during the first incursion of marine waters across the continent. Rocks of the Prairie du Chien Group formed at the end of that marine inundation when most highlands were flooded and detrital sand influx into the sea was low. Carbonate sediments derived from marine organisms dominated the depositional system even in shallow shoreline areas.

The dolostone in the Prairie du Chien outcrops exhibit numerous features that result from surficial weathering and from dissolution by ground water. They include sinkholes, solution-enlarged fractures and bedding planes, and caves.

Rocks beneath the Prairie du Chien in the Sauk sequence are principally detrital sandstone and siltstone. The coarse, cross-stratified sandstone in formations such as the Jordan Sandstone and Ironton and Galesville Sandstones was deposited along the shoreface either as the sea receded or as it advanced across the Hollandale embayment during changes of relative sea level.

When sea levels were deeper in southern Minnesota and the shoreline nearer the Wisconsin dome, fine to very fine grained sand, silt, clay, and carbonate sediment were deposited. The fine-grained sandstone of the Jordan Sandstone and the St. Lawrence, Franconia,

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[1] The locations of all numbered outcrops (for example, **outcrop 1a**) are shown on Figure 10, p. 20.

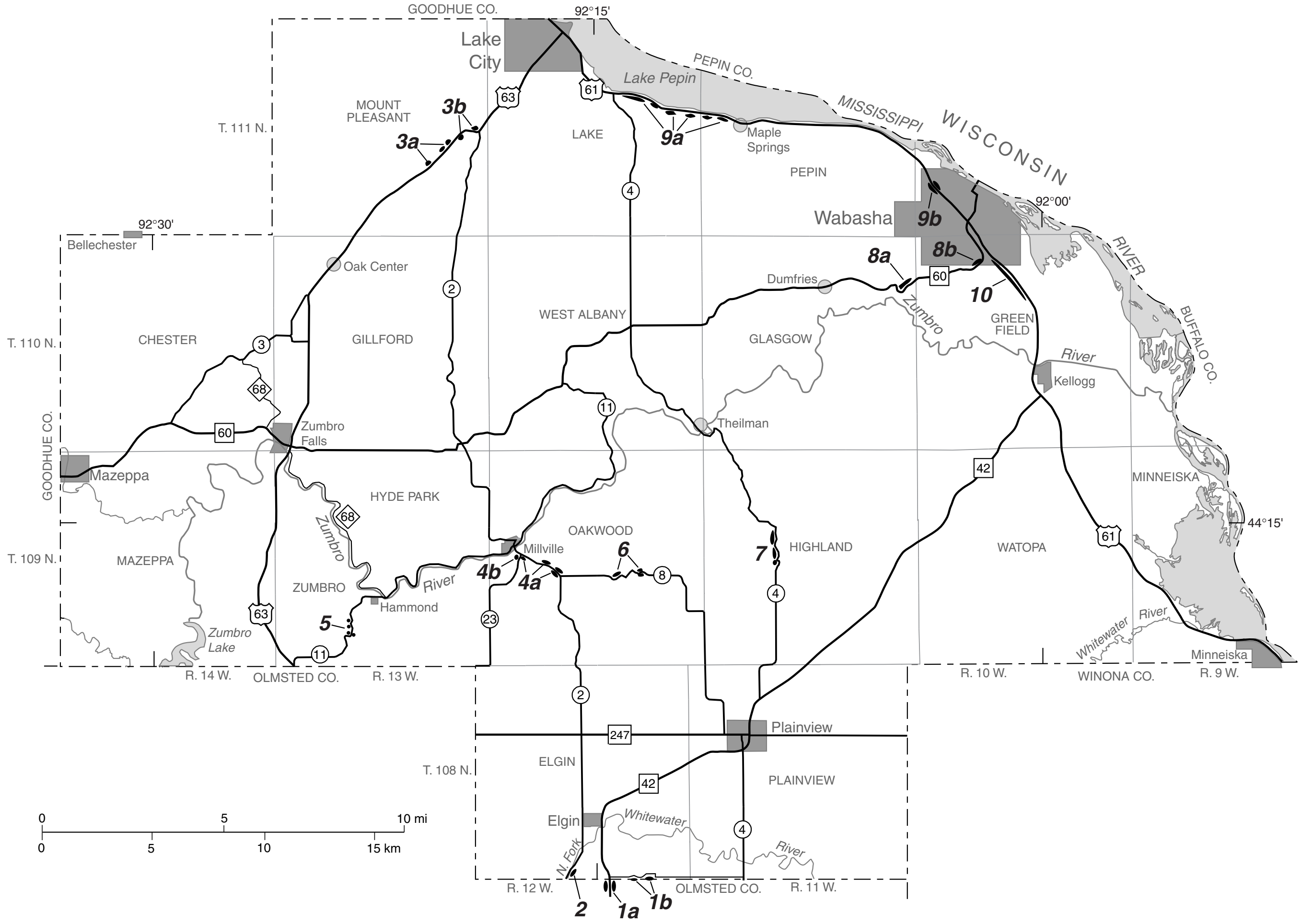


Figure 10. The locations of representative outcrops of bedrock units found in Wabasha County (and one, 1a, located in adjacent Olmsted County), Minnesota. Major towns and unincorporated communities referred to in the text are shown on the map, as are roads and highways by which outcrops are found.

and Eau Claire Formations are the products of these episodes. The St. Lawrence has a large carbonate (dolomite) component that is probably due to its distance from the shoreline, which reduced the influx of detrital sediment. The Franconia contains sand-size pellets of the green mineral glauconite This mineral is diagnostic for slow or reduced sedimentation. Slow sedimentation occurs on marine shelves in deep waters when there is little influx of detrital sediment.

PRAIRIE DU CHIEN GROUP AND JORDAN SANDSTONE

The Oneota and Shakopee Formations crop out as high road cuts on U.S. Highway 63 south of Lake City in sections 23 and 26, Mount Pleasant Township (**outcrop 3a**). The outcrop farthest north is the Hager City Member of the Oneota Dolomite overlain by New Richmond Member of the Shakopee Formation. There is a sharp disconformity between the two units, and some beds of Oneota dolostone are truncated by erosion. The outcrops to the southwest on Highway 63 are New Richmond and Willow River Members of the Shakopee Formation.

Farther north on U.S. Highway 63, past the rest area, there are outcrops of Jordan Sandstone. The one next to the rest area in NW1/4 sec. 24, Mount Pleasant Township (T. 111 N., R. 13 W.) contains the contact of the Jordan Sandstone and Coon Valley Member of the Oneota Dolomite. The high (50–60 feet) outcrop farther east in NW1/4 sec. 24 contains sandstone beds representative of the coarse facies of the Jordan Sandstone (**outcrop 3b**).

The Coon Valley (poorly exposed) and Hager City Members of the Oneota Dolomite, as well as the

New Richmond and Willow River Members of the Shakopee Formation crop out in a series of roadcuts and an old quarry along County State Aid Highway 2 southeast of Millville (**outcrop 4a**). The cuts are in the northern half of section 20, Oakwood Township from just east of the junction with CSAH 23 to just southeast of the junction with County Road 74. The Coon Valley is better exposed along CSAH 23 just southwest of its junction with CSAH 2 (**outcrop 4b**). (There are additional roadcuts in the Hager City and New Richmond farther southwest on CSAH 23.)

The Hager City of the Oneota Dolomite crops out in roadcuts, quarries, and stream exposures south of Hammond along CSAH 11 for 1.5–1.75 miles (**outcrop 5**). Most of the outcrops are in the SW1/4 sec. 28, NE1/4 sec. 32, and NW1/4 sec. 33, Zumbro Township. The New Richmond Member of the Shakopee crops out above the Hager City in many of the roadcuts and quarries. There are small caves and solution cavities just below the contact in the upper Hager City Member.

The Hager City Member of the Oneota Dolomite and New Richmond Member of the Shakopee Formation crop out in a series of roadcuts and a large quarry on County State Aid Highway 8 about five and one-half miles north of Plainview in sections 22 and 23 of Oakwood Township (**outcrop 6**). The quarry is in the thick- to massive-bedded dolostone of the Hager City Member. There is a cave in the uppermost Hager City just below the New Richmond, and sinkholes have developed in the New Richmond in the outcrops east of Long Creek. This locality is a good place to see many of the features found in the New Richmond Member, such as stromatolite layers, silicified oolites, and intraclasts.

A series of road cuts along County State Aid Highway 4 about three miles south of Theilman expose Jordan Sandstone and both the Coon Valley and the Hager City Members of the Oneota Dolomite (**outcrop 7**). The outcrops lie along the boundary between sections 16 and 17 and within the northwest corner of section 21, Highland Township (T. 108 N., R. 11 W.). Massive sandstone of the quartzose facies of the Jordan is exposed in the larger of the northern outcrops beneath the Coon Valley Member of the Oneota. Thick dolostone beds of the Hager City Member of the Oneota overlie the Coon Valley in the lowest of the southern outcrops. The highest outcrop by the junction with the west-trending road in the center of section 20 contains the contact of the Hager City with the overlying New Richmond Member of the Shakopee.

JORDAN SANDSTONE AND LOWERMOST ONEOTA DOLOMITE

The upper part of the St. Lawrence Formation, most of the Jordan Sandstone, and the basal Oneota Dolomite (Coon Valley Member) crop out along State Highway 60 just east of the junction with County Road 81 in the eastern half of section 12, Glasgow Township (**outcrop 8a**).

The same stratigraphic interval is exposed along State Highway 60 as it ascends Coffee Mill Bluff in section 5, Greenfield Township (T. 110 N., R. 11 W.) (**outcrop 8b**). The St. Lawrence is thin-bedded, flaggy dolomitic siltstone that is in the lowest part of the roadcuts. Some of the Jordan Sandstone is fine-grained, feldspathic sandstone of the offshore facies; most of it, however, is coarse-grained, trough cross-bedded, quartz sandstone of the shoreface facies. The lowermost part of the Oneota Dolomite (Coon Valley Member) contains sandy dolostone, sandstone, and thin, green shale beds. Some of the dolomitic beds contain oolitic chert and stromatolites.

FRANCONIA FORMATION

The Franconia Formation is exposed in numerous outcrops in ravines and roadcuts along U.S. Highway 61 from the eastern city limits of Lake City to Maple Springs in section 18, Pepin Township and sections 13, 14, and 15 of Lake Township (**outcrop 9a**). The outcrop immediately east of Riley Coulee in NW1/4SW1/4 sec. 13, Lake Township, is the largest. Another good roadcut is located on U.S. Highway 61 within the city limits of Wabasha in SE1/4 sec. 30, Wabasha Township (**outcrop 9b**). Many of the outcrops contain abundant glauconite, indicative of slow sedimentation.

IRONTON–GALESVILLE SANDSTONE AND THE EAU CLAIRE FORMATION

The Ironton and Galesville Sandstones and the Eau Claire Formation crop out in road cuts along U.S. Highway 61 between State Highway 60 and County Road 81 in sections 4, 9, and 10 of Greenfield Township (**outcrop 10**). The Eau Claire Formation along this series of outcrops is interbedded with Galesville Sandstone. The Eau Claire Formation is composed of very fine grained, thin-bedded, feldspathic sandstone, siltstone, and shale. Interbedded Galesville Sandstone is fine- to coarse-grained, swaley to trough cross-stratified, quartz sandstone.

Chapter 2

QUATERNARY GEOLOGY OF WABASHA COUNTY, MINNESOTA

By
Howard C. Hobbs

INTRODUCTION

Wabasha County lies within the Paleozoic Plateau (Fig. 1), an area where bedrock of Paleozoic age is present at relatively high elevation. The plateau is characterized by steep-sided, deep bedrock valleys of the Mississippi River and its tributaries, which separate broad uplands developed on flat-lying carbonate strata. Wabasha County is also part of the pseudo-driftless area (Fig. 1) where tills are present only as thin, erosional remnants beneath loess on the uplands and filling some bedrock valleys (Hobbs, 1999). To the east of Wabasha County, across the Mississippi River in Wisconsin, lies a physiographically similar region referred to as the Driftless Area because it contains no tills. The Driftless Area was apparently never covered by glacial ice. To the west and north of Wabasha County glacial activity was much more pronounced and occurred more frequently; as a result, the landscape is dominated by tills and associated deposits.

This report supplements the map of surficial deposits of Wabasha County (Hobbs, 2001). Sedimentary units are shown in a third dimension through geologic cross sections (Fig. 2), which show the stratigraphic relationships among geologic units. It also provides greater detail about the origin of the landforms and surficial deposits mapped on the surficial geology map (Hobbs, 2001) by providing an account of the Quaternary geologic history of the area (Fig. 3). The history for this area is divided into informal time periods of unequal length: (1) the preglacial landscape, which developed over tens of millions of years prior to late Cenozoic glaciations; (2) early glaciations, from roughly two million to one million years ago; (3) middle glaciations, from roughly one million to 300,000 years ago; (4) later glaciations, from roughly 300,000 to 10,000 years ago, and (5) postglacial history, which continues to the present.

PREGLACIAL LANDSCAPE

The preglacial landscape of Wabasha County and surrounding areas can not be described in great detail because little evidence remains. Before the first glaciation, the landscape was probably flatter than that of today; the Mississippi valley had not yet been deepened by repeated flows of glacial meltwater. The valleys that empty into the Mississippi were also relatively shallow. The bedrock was exposed and weathered for tens of millions of years prior to glaciation, and, as a result, residues of clay, sand, and chert accumulated on the land surface. This weathering residuum is most commonly oxidized to reddish brown. A clay- and chert-rich residuum that is particularly common on carbonate rocks is called *terra rossa* (Italian for red earth). Most weathering residuum in Wabasha County has been removed by erosion, but remnants are preserved as patches on bedrock uplands and the upper parts of bedrock valleys (shown schematically in Figure 2). Most occurrences are too small to map; larger occurrences are mapped as the Iron Hill Member of the Windrow Formation on the bedrock geologic map of Wabasha County (Mossler, 2001).

Carbonate bedrock across the Paleozoic Plateau contains a complex system of sinkholes and dissolution cavities that are referred to as karst (Tipping and others, 2001; Tipping, 2002). Karst systems are dynamic; new cavities are continually formed and enlarged, and existing cavities are periodically filled with unconsolidated sediment that collapses or infiltrates from above. Many cavities are filled with sediment that provides clues to the antiquity of the karst landscape. Solution cavities that contain only *terra rossa* may have been filled millions of years ago, prior to the first glaciation. Other cavities contain a mixture of *terra rossa* and Precambrian rock fragments that must have been brought into the area by glaciers.

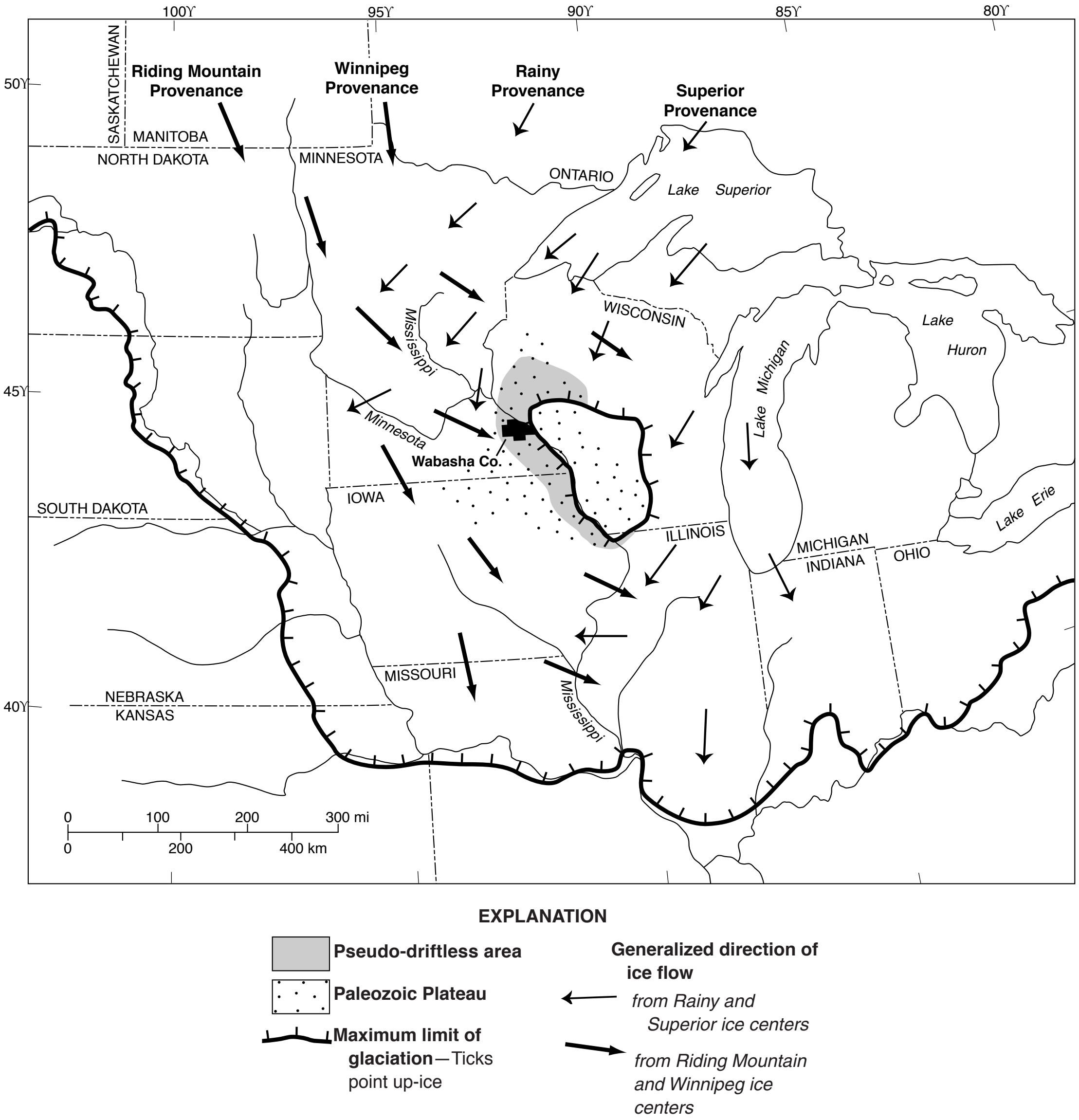


Figure 1. Map of the midcontinent region of North America showing the maximum extent of late Cenozoic glaciation and the location of the pseudo-driftless area and Paleozoic Plateau. Ice flow lines indicate general direction of flow for several different glaciations. The labels Riding Mountain, Winnipeg, Rainy, and Superior refer to areas of origin of glacial advances. Modified from Hobbs (1999),

EARLY GLACIATIONS

Scattered deposits of one or more very old glaciations are present in the pseudo-driftless area of Wisconsin and Minnesota, including Wabasha County (Fig. 1). The precise age of these deposits is not known, but they potentially could be as old as the earliest known glaciation to reach the Midwestern states, which began more than 2.2 million years ago (Boellsdorf, 1978). The deposits are unsorted, like glacial till, but some of them may not be original deposits from ice; they may instead have been reworked by slope processes. Deposits are exposed in scattered, thin patches and could represent the deposits of more than one glacial advance.

I have informally named these oldest glacial deposits *residual till*, because they contain reddish-brown residuum from weathered bedrock, and because the deposits themselves are the residue of a long period of post-depositional weathering. The residual till is equivalent to the till component of map unit rtl (loess-covered till and bedrock residuum) in Winona County (Hobbs, 1984). It is not mapped in Wabasha County (Hobbs, 2001), however, because it exists as thin, scattered patches above bedrock and beneath till of the Pierce Formation or the Peoria loess. Residual till is known only from the northern and easternmost portions of Wabasha County; it is shown schematically on the cross sections (Fig. 2).

The coarse-sand component of the residual till is dominated by quartz, granite, graywacke, and oxides of iron and manganese. Chert, basalt, rhyolite and iron formation are less common. Feldspar in the granite grains is milky, in places etched, and, in some grains, may be completely weathered away. Graywacke grains are commonly "bleached" by the weathering away of the matrix, which exposes the quartz grains to better view. Basalt grains are commonly coated with iron oxides. The absence of carbonate rock and the relative scarcity of feldspar may reflect weathering of the till after it was deposited. It may also in part reflect the character of the source area for the glacial sediments, an indication that the earliest glaciers passed over a great thickness of weathered bedrock as they moved into Minnesota. Setterholm and Morey (1995) describe a number of these weathering profiles, which were believed to be once much more extensive before they were eroded and incorporated into old glacial sediments.

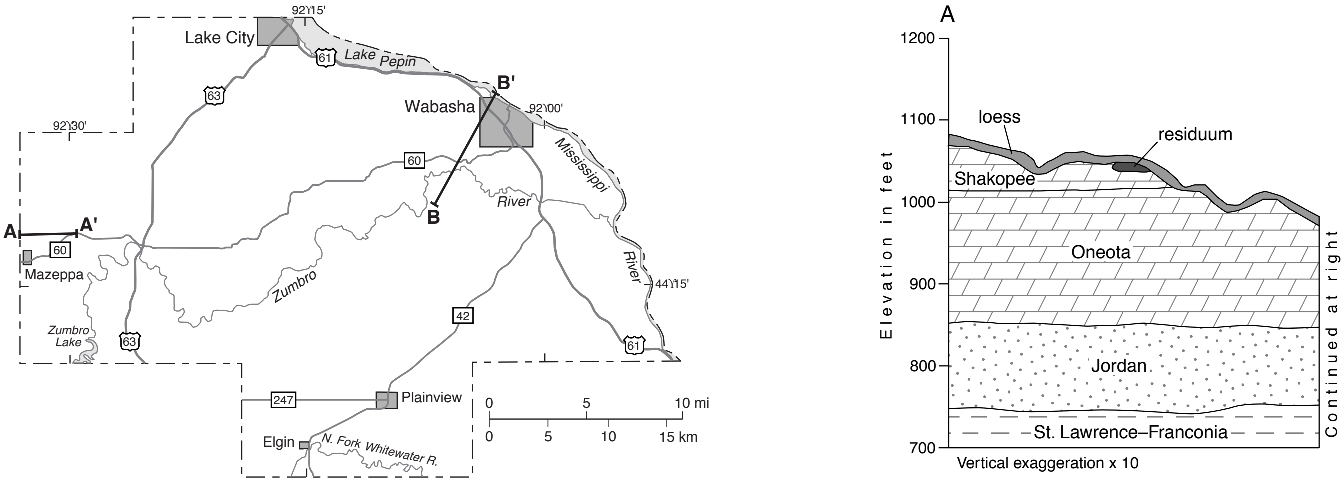
MIDDLE GLACIATIONS

The upper part of the till of the middle glaciations is also weathered, but not to such a great degree as that of the earlier glaciations, and the weathered material is commonly underlain by unaltered till. Till of the middle glaciations is correlated to the Pierce Formation of Wisconsin (Mickelson and others, 1984) by similarity in color, texture, grain assemblage, and general stratigraphic position. By its original definition, the Pierce Formation only includes tills of reversed magnetism, which indicates they were deposited before the Matayama–Brunhes magnetic reversal at about 790,000 B.P. (Richmond and Fullerton, 1986). No normally magnetized tills of Winnipeg provenance have been recognized in Wisconsin. Paleomagnetic work has not been done on the tills of Wabasha County, and some of the Pierce Formation sediment here may be younger. The till is mapped as a single unit (Pierce Formation till; map unit Qpt in Hobbs [2001] and section A–A' in Figure 3), but, based on previous investigations in nearby Goodhue County (Hobbs, 1998a), it may internally consist of four or more individual tills, each representing a discrete glacial advance.

Pierce Formation tills were sampled and subjected to textural and compositional analyses to determine provenance and to correlate the formation to other parts of southeastern Minnesota (Hobbs, 1998b). Pierce tills have an average texture of loam (Fig. 4); they differ from the residual tills chiefly in containing a higher proportion of silt. Grain composition, or rock type, in the Pierce Formation (Fig. 5) was determined from unweathered samples where possible. The grain assemblage indicates that the sediment is largely of Winnipeg provenance (Fig. 1) and includes (1) Precambrian grains dominated by granite; (2) carbonate, and chert grains of Paleozoic age; and (3) small amounts of limestone and calcareous shale of Cretaceous age. A large but unknown proportion of the grains was not eroded directly from bedrock but was picked up from older glacial sediments along the glacial flowpath. Because all the tills share a similar provenance, it is not possible to quantify this distinction.

Pierce Formation tills are a record of large lobes that entered Minnesota from the northwest and extended as far south as northern Missouri (Fig. 1). Till of the Pierce Formation was probably deposited over all of the bedrock surface of Wabasha County, but much of it has been removed by erosion over the past several hundred thousand years, and it now covers less than one-third of the county (Hobbs, 2001). Its most extensive preservation is on the highest, flattest bedrock surfaces farthest from major streams. In this landscape position the till is relatively thin, typically less than 50 feet thick (see, for example, the eastern part of cross section A–A' in Figure 2). Pierce tills are also preserved in low areas and valleys in the bedrock surface that are not now occupied by major streams (for example, the central part of cross section A–A' in Figure 2). By contrast, Pierce tills were entirely removed by erosion in areas close to relatively deep bedrock valleys, such as along the present day Zumbro and the Mississippi Rivers.

Sand and gravel bodies mapped as Pierce Formation were deposited by glacial meltwater. They commonly contain remnants of paleosols near the surface, which consist chiefly of leached material that has strong brown clay coatings on the grains. Stratigraphic relationships observed in the field indicate that they are most closely associated with Pierce Formation tills. Two units of Pierce Formation sands and gravels are recognized on the basis of landscape position: glaciofluvial deposits (map unit Qpg in Hobbs, 2001) are present on the uplands adjacent to Pierce tills, whereas Pierce outwash (map unit Qpo in Hobbs, 2001) is restricted to bedrock valleys. Glaciofluvial



LOCATION OF SECTIONS A–A' AND B–B' IN WABASHA COUNTY

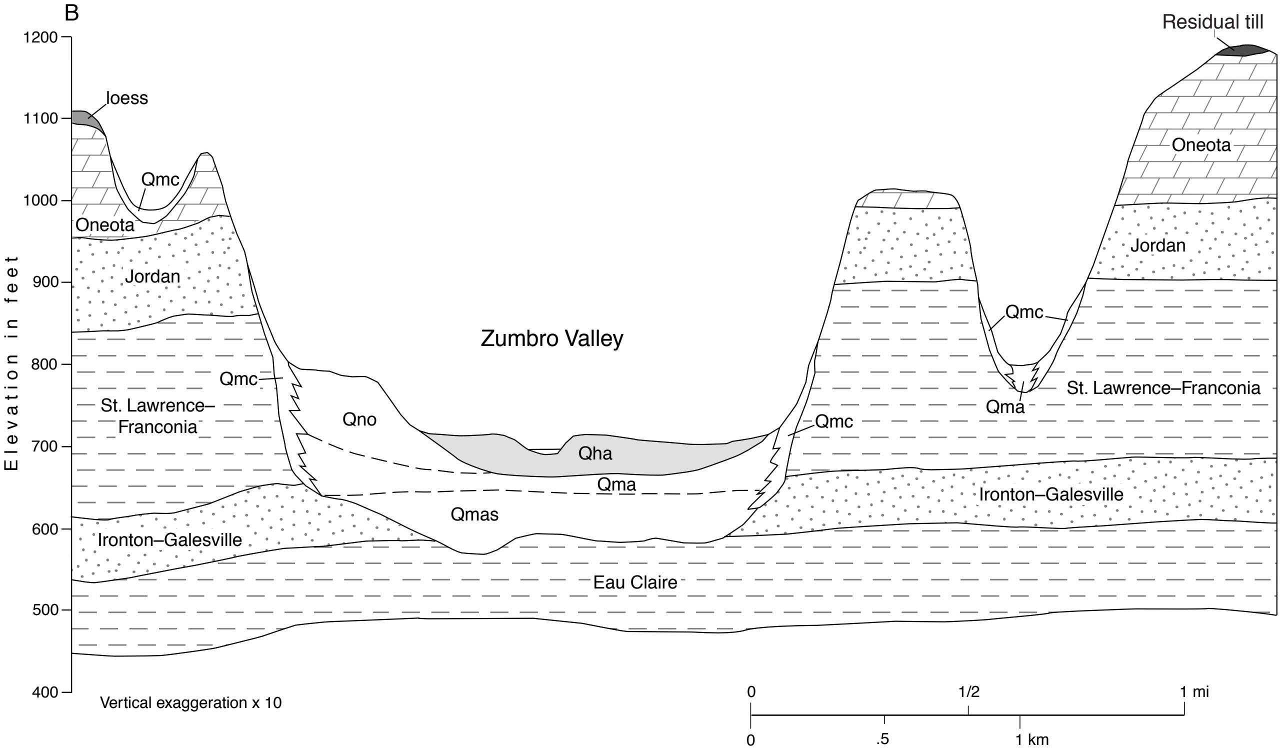
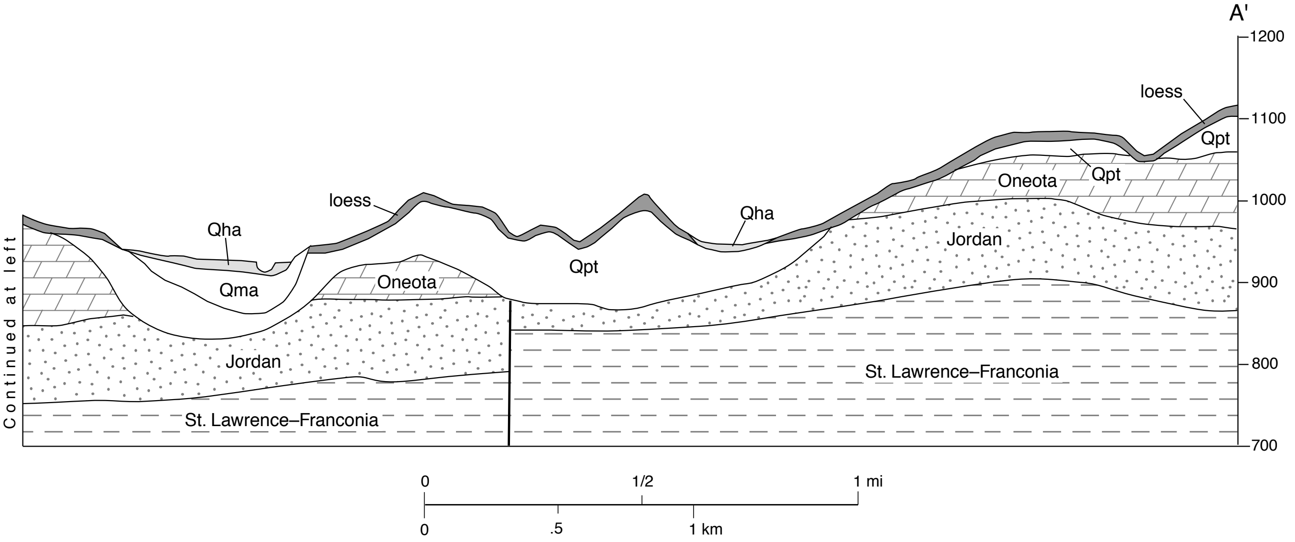
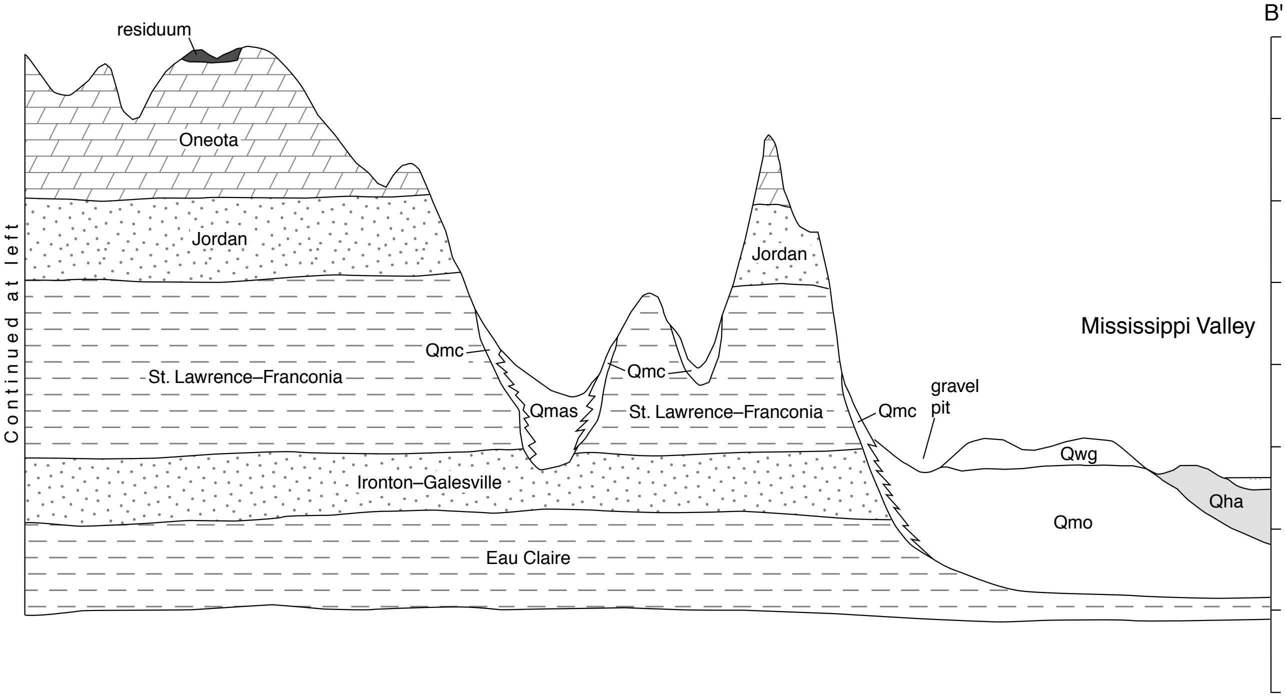


Figure 2 *(this and facing page)*. Two geologic cross sections in Wabasha County showing typical subsurface relationships between bedrock and various surficial units. Residuum and residual till are not known to occur precisely on the lines of section but are shown schematically in stratigraphic positions where they typically are present. On the sections, the Quaternary units are identified using the map-unit labels from Plate 3 of the Wabasha County geologic atlas, for example, Qho and Qmc. Additional information on the geologic units is given in Plates 2, Bedrock Geology (Mossler, 2001) and Plate 3, Surficial Geology (Hobbs, 2001).





BRIEF EXPLANATION OF UNITS AND SYMBOLS USED ON CROSS SECTIONS A–A' AND B–B'

Unconsolidated Surficial Deposits

(See Hobbs, 2001, for further information)

Qmc	Colluvium (slope deposits)—May include loess in places
Qno	Outwash of the New Ulm Formation
Qha	Postglacial alluvium
Qma	Sandy alluvium and slopewash
Qmas	Slackwater sediment
Qwg	Sand and gravel of Grey Cloud terrace
Qmo	Sand, gravelly sand, and gravel of the Mississippi valley train

Bedrock Geologic Units

(See Mossler, 2001, for further information)

Shakopee	Shakopee Formation
Oneota	Oneota Dolomite
Jordan	Jordan Sandstone
St. Lawrence–Franconia	Undivided St. Lawrence and Franconia Formations
Ironton–Galesville	Undivided Ironton and Galesville Sandstones
Eau Claire	Eau Claire Formation

Symbols

—	Contact
– – –	Inferred contact
|	Fault

YEARS BEFORE PRESENT	INFORMAL EVENTS	FORMAL EPISODES AND INTERGLACIAL	PHASES AND SUBEPISODES	GEOLOGIC HISTORY
10,000	Postglacial	Hudson Episode		• Soil erosion increases due to agricultural tilling (about 1850 to 1950) • Smaller volume of glacial meltwater as glaciers recede from area • **Sandy and silty alluvium** (map unit **Qha**) accumulates in valleys, causing water level in the Mississippi River to rise; Lake Pepin forms in consequence
11,500	Late glaciations	Wisconsin Episode	River Warren Phase of Wisconsin Episode	• Downcutting of River Warren (the ancestral Minnesota River) • **Formation of terraces along the Mississippi River: Langdon** (map unit **Qwl**), **Grey Cloud** (map unit **Qwg**), and **St. Mary's** (map unit **Qws**)
35,000			Michigan Subepisode of Wisconsin Episode	• Major advances and retreats of ice, ending with the last advance of the Des Moines lobe • Colluvium (map unit **Qmc**) accumulates on valley sides • Windblown silt (**Peoria Formation loess**) accumulates on uplands • Valleys fill with **meltwater sediment** (map units **Qmo and Qno**) and with **sediments eroded from uplands and valley sides** (map units **Qma** and **Qmas**)
80,000				• Little is known of this time period • Downcutting of Mississippi River valley removes most Illinoian outwash
130,000		Sangamon Interglacial		• Warm interglacial period (a long span of time during which glaciers are absent from the region), allowing soil to form on older glacial sediments
300,000		Illinois Episode		• Some **outwash** (map unit **Qpo**) may have been deposited in valleys by glaciers
1,000,000?	Middle glaciations	"pre–Illinois"?		• One or more advances of glacial ice moved over the county, depositing **till** (map unit **Qpt**) and **meltwater sandy gravel** (map unit **Qpg**). The most recent outwash was deposited in valleys (map unit **Qpo**) as the last glacier retreated • Erosion of older tills
More than 2.2 million	Early glaciations			• Deposition and erosion of **residual tills**
	Development of preglacial landscape			•Subdued topography and weathering of bedrock for tens of millions of years forms ***terra rossa*** on carbonate bedrock (not shown on Surficial Geology map) • Karstification of carbonate rock

Figure 3. Summary of Quaternary geologic history of Wabasha County, with emphasis on the formal and informal names used to describe Quaternary events, absolute ages, and geologic units mapped on Plate 3, Surficial Geology (Hobbs, 2001) and discussed in the text.

Figure 4. Matrix texture of samples of Pierce Formation till and so-called residual till using particles less than two millimeters in diameter, Wababsha County, Minnesota.

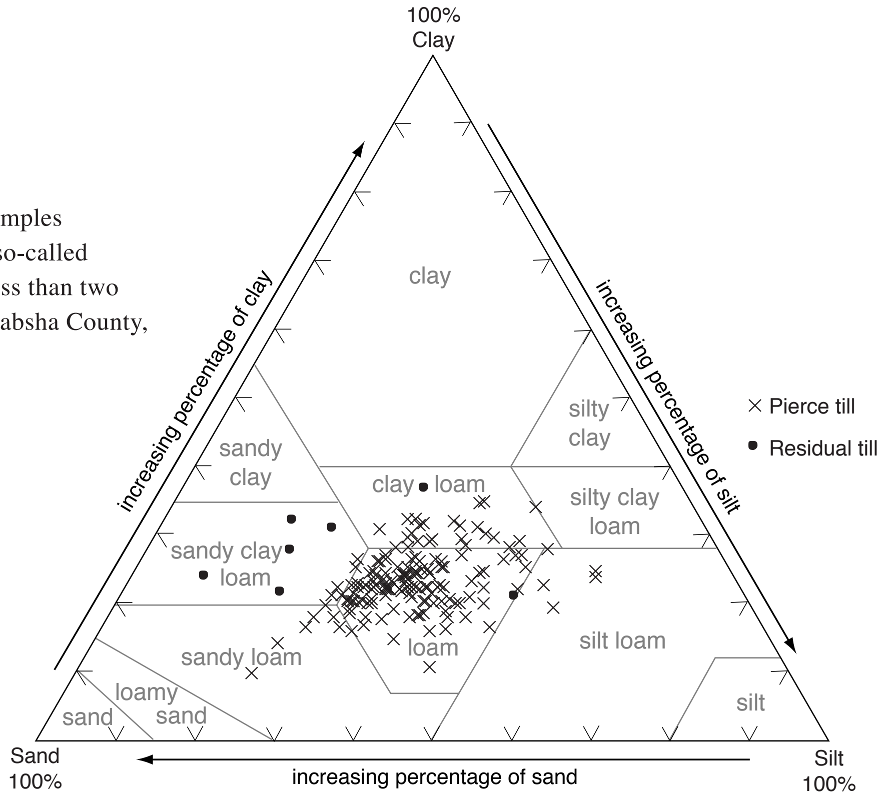
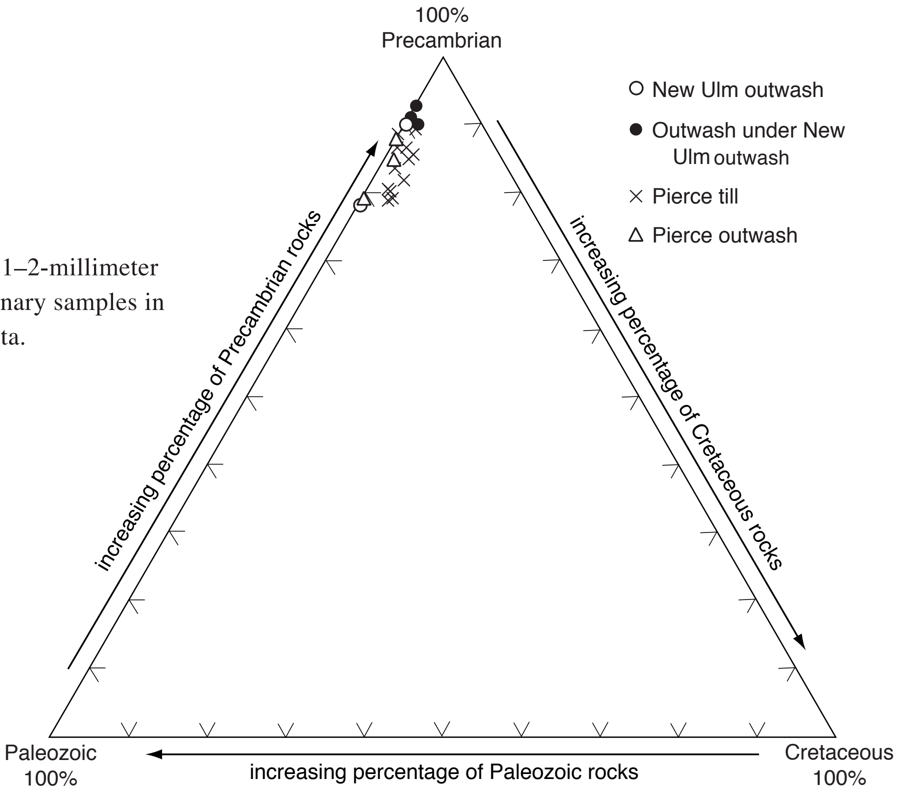


Figure 5. Rock types of the 1–2-millimeter fraction of selected Quaternary samples in Wabasha County, Minnesota.



deposits accumulated near the ice that deposited Pierce tills. In contrast, the outwash was deposited at a later time by meltwater from ice that had receded from the county. It is possible that some parts of the outwash were deposited during younger glacial advances that did not enter the county. Pierce outwash exists today as discontinuous terraces high above terraces deposited during the Wisconsin Episode. Most of the original deposit has been eroded and replaced with younger glaciofluvial deposits.

LATER GLACIATIONS

Following deposition of the Pierce Formation, two or more glaciations occurred in the northern midcontinent from roughly 300,000 to 130,000 years before present (Johnson, 1986, p. 19). This period, the Illinois Episode, was defined in Illinois, and our understanding of the events that occurred in Minnesota at this time is limited. The major difference between the middle glaciations and the later glaciations is that ice of the later glaciations was less extensive and apparently did not reach Wabasha County. However, the meltwater may have carried outwash across the county on its way to the Mississippi River. Small patches of sand and gravel on the boundary of Wabasha and Goodhue Counties near Bellechester contain clasts of Superior provenance and may have been derived from an Illinois Episode ice margin in northern Goodhue County.

Probably the most significant geologic occurrences during the Illinois Episode were erosion of Pierce Formation deposits and deepening of the valley system. A particularly extended period of warm climate followed the final retreat of Illinoian glaciers. Prolonged weathering of exposed sediments during this time led to the development of a thick, well-developed soil, the Sangamon Geosol, over the landscape.

The final glacial advance to have a significant impact on Wabasha County was part of the Wisconsin Episode. The most prominent feature of that episode in southern Minnesota was a glacial lobe of ice called the Des Moines lobe, which extended from the Riding Mountain province (Fig. 1) south to central Iowa. The Des Moines lobe did not advance over Wabasha County, but at times its meltwater crossed the county about 35,000 to 11,500 years ago. Deposits laid down in Iowa at this time contain fossils that indicate the climate was periglacial during major glacial advances (Baker and others, 1986). Wabasha County likely had a cold tundra setting adjacent to nearby ice sheets. Climatic conditions varied from relatively wet to very dry, resulting in numerous episodes of erosion and deposition.

During wetter conditions in southeastern Minnesota, which appear to have been particularly prevalent early in the Michigan Subepisode of the Wisconsinan, the combination of extreme cold and abundant water led to extensive mass wasting along slopes. Colluvium (map unit Qmc in Hobbs, 2001) is a poorly sorted bedrock rubble mixed with sand and silt that mantles steep slopes. It formed when near-surface bedrock along the margins of bluffs was shattered by intense and repeated freezing and thawing. The resulting rock rubble slid and fell to accumulate at the bottom of slopes (Fig. 2). In areas of more subdued topography, water-laden, soupy soils flowed down gentle slopes along an underlying base of frozen sediment (permafrost) in a process called *solifluction*. A large quantity of soil was probably transported to streams in this manner, and eventually most of the Sangamon Geosol was removed.

The presence of loess across much of Wabasha county (see, for example, section A–A' in Figure 2; also Hobbs, 2001) indicates that the climate apparently became dry later in Michigan time. Loess is a deposit of windblown silt that typically accumulates in cold, dry conditions where the scarcity of vegetation allows strong winds to contact the land surface. Wind from the northwest (Mason and others, 1994) swept sand along the surface of older deposits of glacial outwash and till, scouring loose material. Silt- and clay-sized particles were carried higher and transported many miles downwind to be eventually deposited as loess in southeastern Minnesota and adjacent parts of Wisconsin.

Bedrock valleys of the Mississippi River and its tributaries were filling with sediment at the same time many of the events described above were occurring. The sediment delivered to the valleys included soils moved by solifluction, colluvium along valley walls, and remobilized loess. This material was deposited chiefly as sandy alluvium on floodplains and as aprons along bedrock escarpments (map unit Qma in Hobbs, 2001), and silty alluvium (map unit Qmas in Hobbs, 2001) in ponded waters along tributaries to the Mississippi River (Fig. 2). Meltwater from the Des Moines lobe also transported large quantities of sand and gravel, depositing the New Ulm outwash (map unit Qno in Hobbs, 2001) in the Zumbro River valley (see section B–B' in Figure 2), and contributing to the Mississippi valley train (map unit Qmo in Hobbs, 2001; also, section B–B' in Figure 2) in the Mississippi River valley. Radiocarbon dates for wood collected from deep within outwash deposits indicate that filling of the major bedrock valleys began over 27,000 years ago. By 11,500 years ago over 200 feet of sediment had accumulated in parts of the Mississippi River valley and in the lower parts of some tributary valleys, such as the Zumbro River valley.

At about 11,500 years ago conditions in southeastern Minnesota changed markedly as the Des Moines lobe retreated from Minnesota, passing north of the divide that separates the drainages of the Gulf of Mexico and the Arctic Ocean. Water north of the divide was prevented from reaching the Arctic Ocean by the retreating ice, which acted as a dam. As a result, a large glacial lake called Lake Agassiz formed in northwest Minnesota and adjacent parts of North Dakota and Canada. As the level of the lake exceeded the elevation of the divide, the overflow spilled to the south, draining to the Minnesota and Mississippi Rivers. This water was highly erosive, and downcut the unconsolidated sediment that had filled much of the Mississippi River valley earlier in Wisconsin time. Tributaries like the Zumbro River also downcut to keep pace with the falling base level of the Mississippi River. The downcutting formed terraces, which are flat-topped remnants of old stream deposits that stand considerably higher than present-day river levels. Three terrace levels are mapped in Wabasha County along the Mississippi River, each representing a distinct stage of downcutting. The highest, the Langdon terrace (map unit Qwl in Hobbs, 2001), was the first to form, followed in succession by progressively lower terraces called the Grey Cloud (map unit Qwg in Hobbs, 2001) and St. Mary's (map unit Qws in Hobbs, 2001) terraces. Younger terraces below St. Mary's may be present beneath the alluvium of the present-day Mississippi River.

POSTGLACIAL HISTORY

When glaciers in Canada retreated far enough to allow Lake Agassiz to drain to the east, River Warren shrank to the size of the Minnesota and Mississippi Rivers that we see today. This marks the beginning of the Hudson Episode, a time when glaciers no longer affected Wabasha County either directly or indirectly. The reduction in meltwater to the Mississippi River made it unable to transport all the sediment that was being delivered by its tributaries, and alluvial sediments (map unit Qha in Hobbs, 2001) began to accumulate (Fig. 2). The most notable result of this phenomenon is the formation of Lake Pepin. The lake is dammed by a sand delta where the Chippewa River flows from Wisconsin into the Mississippi valley. The base level has been rising for most of postglacial time, and alluvium and lake sediment is very thick (about 80 feet) in the Mississippi valley and the lower reaches of its tributary valleys. Tributary valleys also began to fill with sediment (map unit Qha in Hobbs, 2001) as the base level in the Mississippi valley was increased.

Except for the gradual filling of valleys, there were no major changes in the landscape during the Hudson Episode (Fig. 3). Soil erosion was slow, and loess deposition had ceased. Modern soil formation was able to outpace both erosion and deposition. There was a period of enhanced soil erosion during roughly the century from 1850 to 1950 that was largely caused by tilled soils in upland areas and limited soil-conservation practices at that time. Several feet of alluvium was laid down in floodplains, burying the pre-settlement soil and raising elevations of streams. Soil erosion has now been reduced through conservation practices, although not to pre-settlement rates, and the streams are returning to their former levels.

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Chapter 3

KARST FEATURES OF WABASHA COUNTY, MINNESOTA

By
Robert G. Tipping

INTRODUCTION

Karst processes are responsible for the sinkholes, springs, caves, and related features found in Wabasha County. As precipitation enters the ground, carbon dioxide from the soil zone dissolves into the water and makes it mildly acidic. The acidic water in turn dissolves carbonate rock, such as limestone and dolostone, particularly along existing cracks, creating conduits that can readily transmit large volumes of water. Eventually, the water emerges on the land surface as a spring after traveling through a system of interconnected bedrock conduits. Thus, drainage of precipitation in Wabasha County is intimately tied to surface and subsurface features that are a result of karst processes.

This report expands on information in the karst features plate (Tipping and others, 2001), which describes the relationship between drainage and karst processes through time. The carbonate rocks of the Prairie du Chien Group in Wabasha County were deposited during the Ordovician Period and are more than 450 million years old. They have been subjected to many different climates and groundwater flow systems, each of which has left a record of dissolution on the rocks in the form of conduits and caves that continue to be modified or re-activated as drainage patterns change. The present karst-dominated system of drainage within the county can only be understood by looking at the development of dissolution features over time.

PALEODRAINAGE

Early to Middle Ordovician Time

(480 to 440 million years ago)

Karst processes active early in the history of the Prairie du Chien Group initiated the development of a regionally extensive zone of high permeability near the contact of the Shakopee Formation and Oneota Dolomite. The two units of the Prairie du Chien Group were deposited in a shallow continental sea that extended over most of the North American continent during Early Ordovician time, about 480 million years ago (Fig. 1). Calcareous sediment that accumulated on the sea floor was eventually lithified (became rock), forming the Prairie du Chien Group and similar carbonate rock layers that exist today from Texas

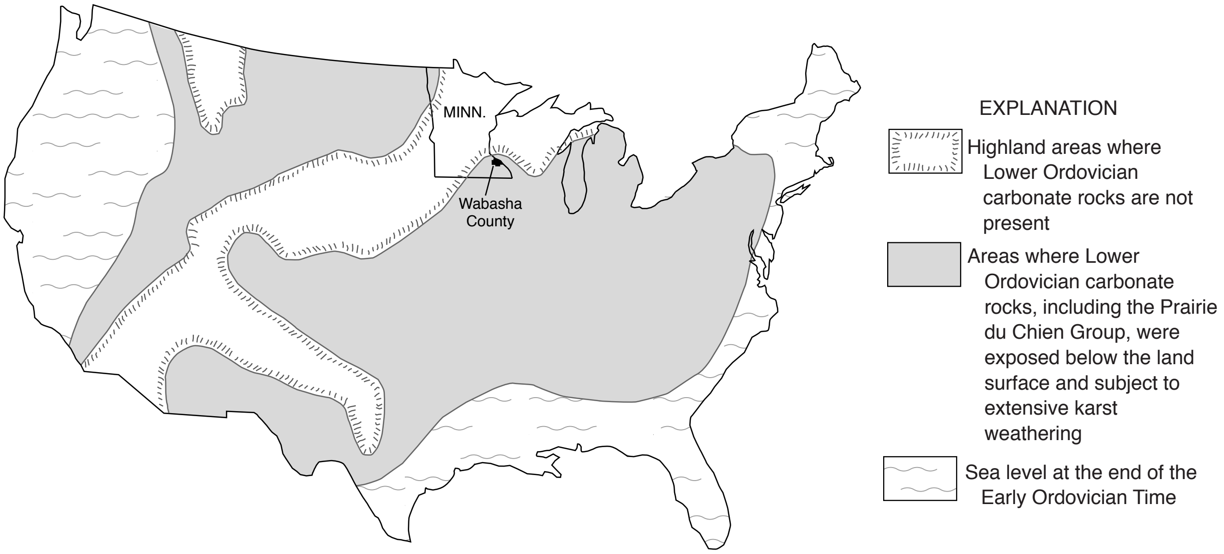


Figure 1. Map of the contiguous United States showing the extensive area of carbonate rocks that were subject to prolonged subsurface karst weathering at the end of the Early Ordovician time. Modified from Palmer and Palmer (1989).

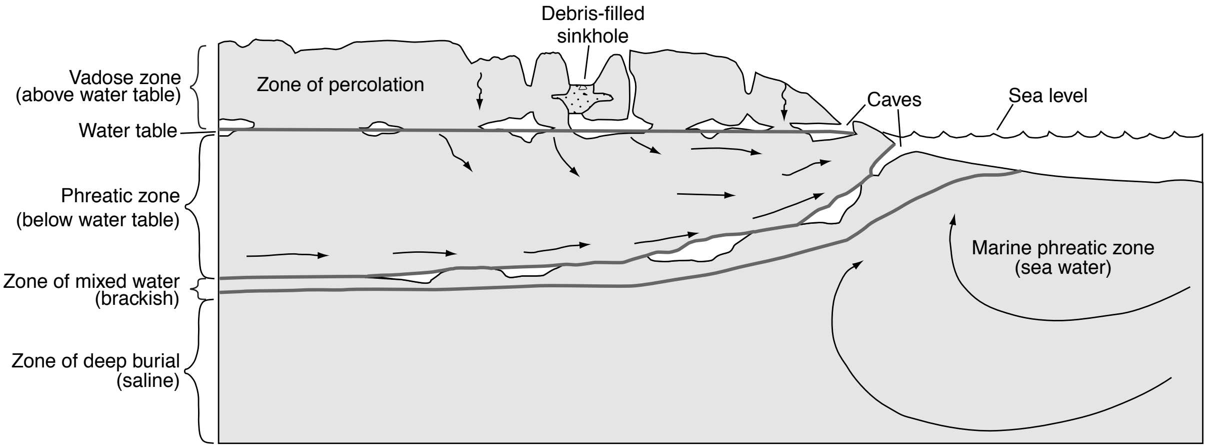
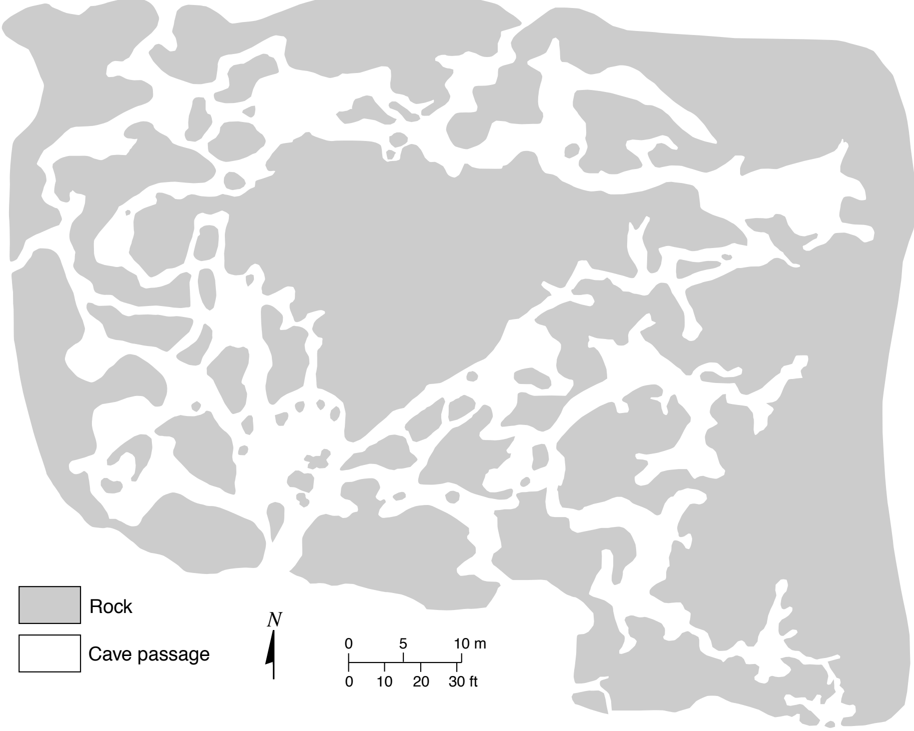


Figure 2. Typical development of karst features along a subaerially exposed carbonate platform. Similar prolonged exposure of the Prairie du Chien Group during Ordovician time created a regionally extensive zone of high permeability near the contact of Shakopee Formation and underlying Oneota Dolomite in Wabasha County. Dissolution preferentially occurs at the water table and at the interface of freshwater and sea water. Arrows indicate the general direction of ground-water flow. See Figure 3 for a plan view of the type of dissolution features that are in this figure viewed in cross section. Modified from Choquette and James, 1988; Mazzulo and Chilingarian, 1996.

to Canada (Mossler, 2002).

After the Oneota sediments were deposited and began to lithify into rock, there was a long period of time during which sea level dropped and the sediments were exposed to weathering and dissolution (Smith and others, 1996). In a general model of karst development along an exposed carbonate platform (Fig. 2), dissolution can occur both at the water table and at the freshwater–saltwater interface. The Oneota was subjected to these processes for a few million years before the sea level rose again, and the deposition of Shakopee sediments began. At the end of the deposition of the Shakopee, a still longer period passed during which sea levels dropped. Many of the conduits formed previously were reactivated and expanded. Because these karst

Figure 3. Plan view of Kruger's Cave, Plainview area, Wabasha County, Minnesota, showing the mazelike, anastomosing nature of the high-permeability zone. Note that bedrock continues east of the area shown. Plan depicts known passages as of November 1983. From a drawing by David Gerboth, Minnesota Speleological Survey.



processes began millions of years ago, and under different conditions of ground-water flow and drainage, the record of dissolution and weathering visible in the rocks today is known as *paleokarst*.

Weathering and dissolution during the Ordovician Period took place at or below the water table over a very large area and under relatively stable geologic conditions, thereby giving the paleokarst zone its distinct character and stratigraphic position within the Prairie du Chien Group in Wabasha County and elsewhere. One such cave in the paleokarst horizon exhibits the mazelike, anastomosing (branching and rejoining) morphology of passages characteristic of caves that form in exposed carbonate platforms (Fig. 3). Similar caves are found in the Yucatan Peninsula of Central America and other exposed carbonate platforms, where large cavities have developed at or just below either the present-day, or earlier Pleistocene water tables (Frank and others, 1998; Mylroie and Carew, 2000). This water-table to sub-water-table cave network is distinctly different from vadose (above the water table), joint-controlled karst cave systems (Fig. 4). Elsewhere in the county, cavities within the paleokarst horizon are filled with angular boulders of collapsed dolostone in a matrix of cemented sandstone; others contain soft clay, silt and sand. Still others are open, for example, Echo Chamber (Fig. 5). Similar paleokarst horizons in Lower Ordovician

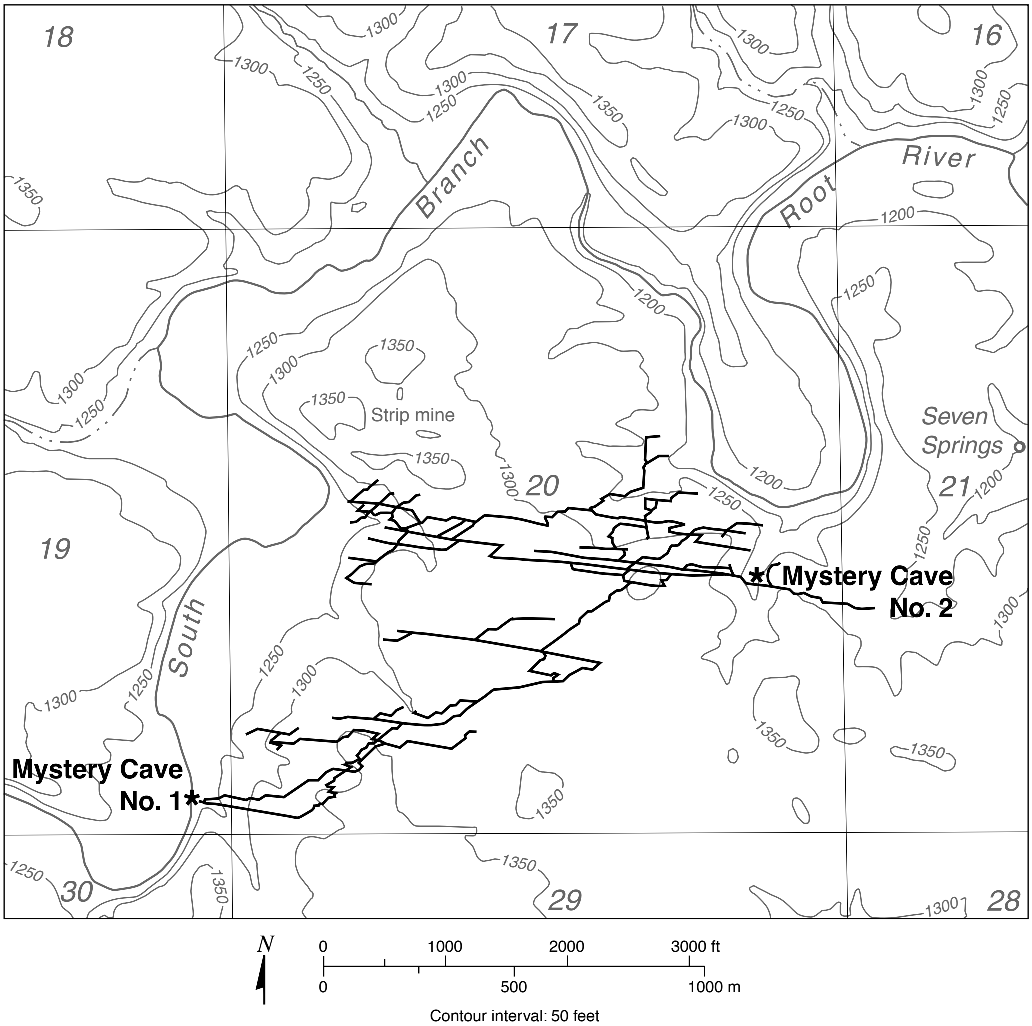


Figure 4. Plan view of Mystery Cave, west-central Fillmore County, Minnesota. The nearly straight paths and right-angled turns of the passages are due to dissolution of carbonate along joints in the rock. The plan depicts known passages circa 1981.The two asterisk-like symbols indicate the entrances to Mystery Cave One and Mystery Cave Two. Base modified from U.S. Geological Survey 7.5-minute topographic map for Cherry Grove, Minnesota–Iowa, 1965. Figure modified from Milske, 1982; Milske and others, 1983.

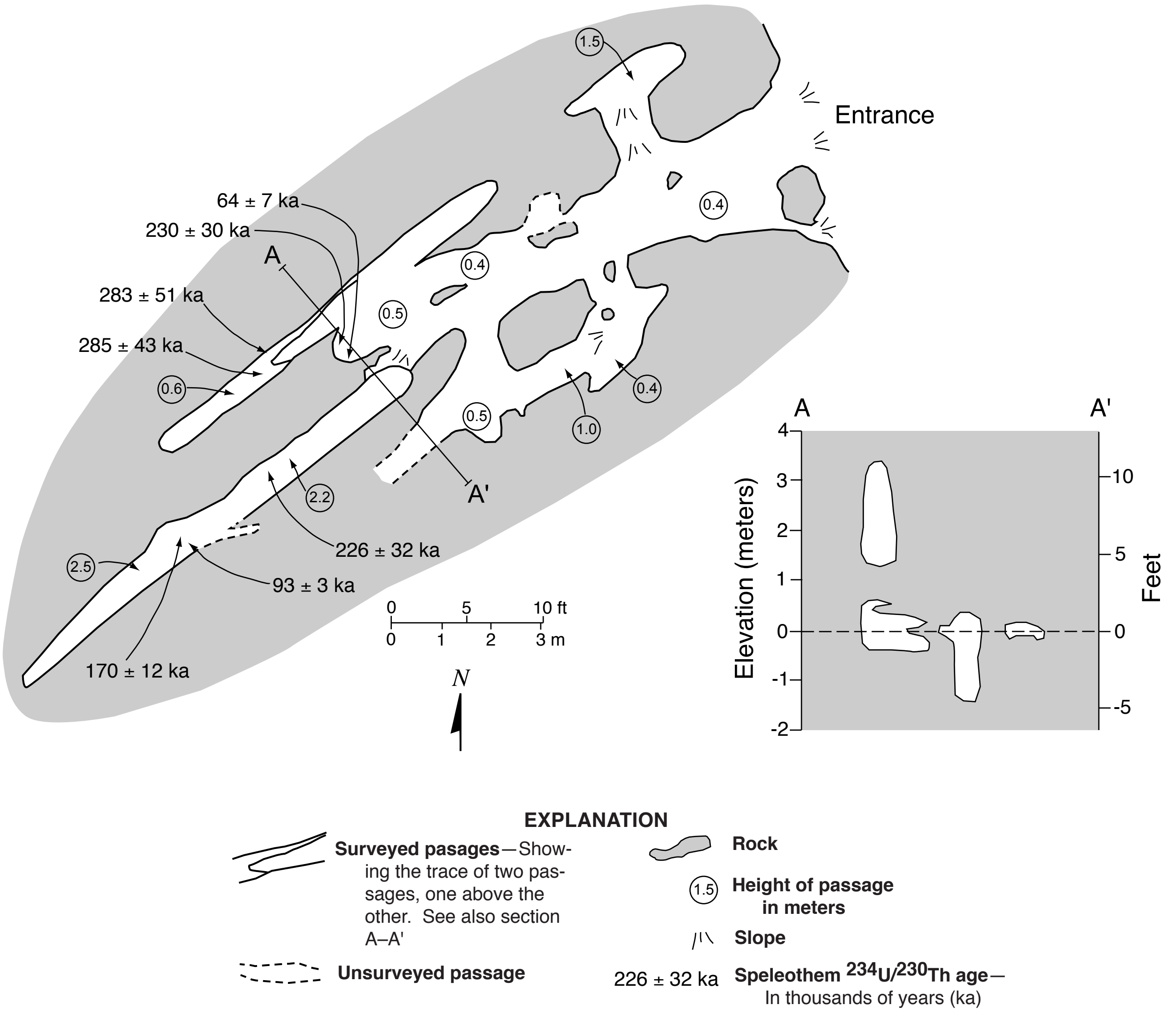


Figure 5. Plan view and cross section of Echo Chamber, Wabasha County, Minnesota, showing the general morphology of the cave and the distribution of speleothem $^{234}U/^{230}Th$ ages within it (Lively, 1983). Modified from Minnesota Speleological Survey plan.

dolostones have been recognized elsewhere (Kerans, 1988; Palmer and Palmer, 1989; Wilson and others, 1992), affirming the regionally extensive nature of this horizon and its ubiquitous position within the Prairie du Chien Group.

Late Ordovician–Tertiary Time

(440 to 2 million years ago)

Rocks of Late Ordovician through Tertiary age are generally absent from Wabasha County. As a result, much of the record of water movement is also missing. Scattered thin patches and pockets of Iron Hill residuum sitting on the eroded tops of older sediments are a fragmentary record of this long period of erosion (Mossler, 2002). Iron-rich clays, silt, and fine sand, which are thought to be associated with this residuum, have been found in joints, fractures, and cavities within the Prairie du Chien Group. When these sediments entered bedrock conduits is unclear. However, it can be reasonably assumed that karst processes were active during this period, and that new conduits were forming, and old ones reactivating.

Quaternary Time

(2 million to 10,000 years ago)

The effect of karst processes on bedrock in Wabasha County during the last two million years is clearer than for earlier periods. The development of conduits within the Prairie du Chien was impacted by events during the Quaternary and have left a record in the rocks. The Quaternary Period was dominated by a series of continental glaciations and retreats. Although only a limited number advanced over Wabasha County (Hobbs, 2002), the glaciers left distinctive deposits, and the abundant meltwater associated with them enhanced karstification of the bedrock by periodically supplying large volumes of cold, dilute water to the ground-water system. Massive amounts of meltwater also reactivated some of the paleokarst conduits, which may have been relatively inert prior to glaciation. The presence of sand-sized to boulder-sized igneous and metamorphic rocks that are unrelated in rock type to the surface bedrock of southeastern Minnesota is strong evidence for Quaternary activity in some paleokarst deposits. The complete absence of glacial sediments in many of the paleokarst deposits is strong evidence of karst activity preceding the Quaternary.

Meltwater from the glaciers downcut the Mississippi River valley, causing entrenchment of the Zumbro River valley and its tributaries. Downcutting of bedrock valleys during the Quaternary also enhanced the permeability of joints and fractures in the lower Oneota Dolomite by dropping the water table into or below the Prairie du Chien Group. In western Wabasha County, the lower Oneota has not been incised by bedrock valleys, and it is relatively free of dissolution cavities. When valley entrenchment began, joints—either pre-existing or induced by stress release—became pathways for water to move from the Shakopee Formation through the Oneota Dolomite to the Jordan Sandstone in the valley bottoms. Well-developed dissolution cavities, which are thought to have formed in the lower part of the Oneota following bedrock-valley downcutting, are visible in the Boston Coulee roadcut on U.S. Highway 63 (section 24, T. 111 N., R. 13 W.). Old phreatic (below the water table) dissolution cavities associated with the upper Oneota paleokarst horizon now can be found high along the cliff faces of this outcrop and elsewhere in eastern Wabasha County.

Clues to the timing of Quaternary events come from speleothem dating. The dates for Echo Chamber in Wabasha County range from 64,000 to 284,000 years before present (Fig. 5). The passages likely formed during several different interglacial climates (Lively, 1983; Hobbs, 2002). The cave also has the characteristic tubelike shape associated with phreatic dissolution cavities. It is thought to have formed below the water table and then reactivated as a vadose (above the water table) cave during the time of speleothem deposition.

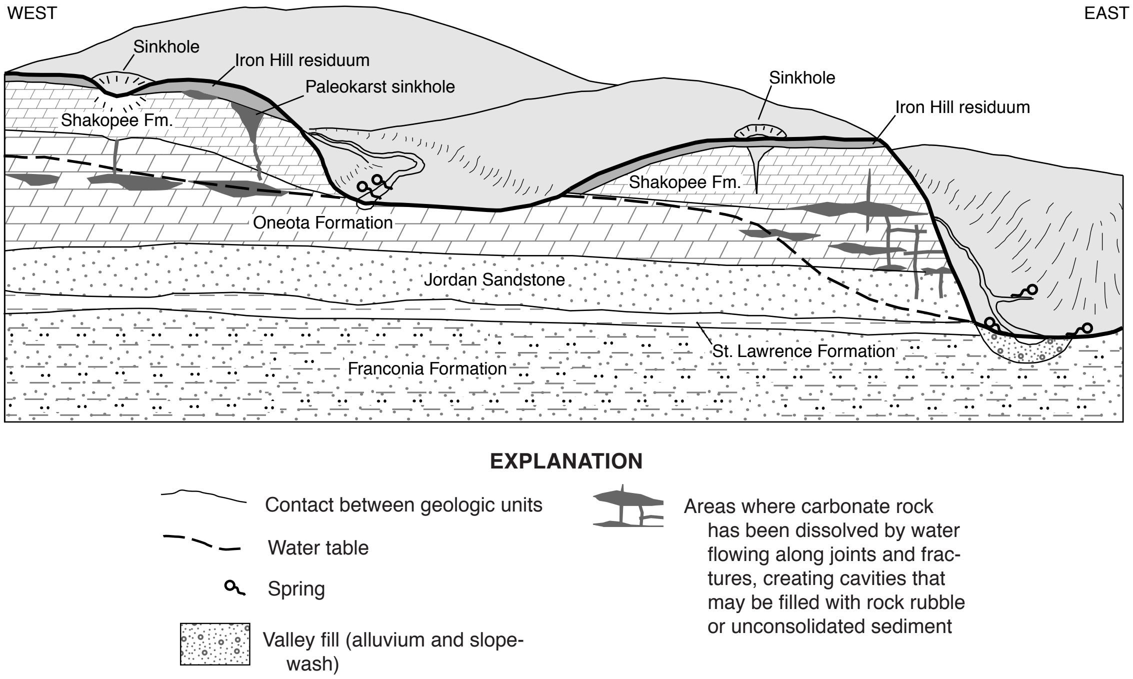


Figure 6. Schematic cross section through Wabasha County, showing the relationship between drainage, dissolution features, and geology in western versus eastern Wabasha County.

Modern Drainage

The past history of ground-water flow systems, drainage, and karst processes manifests itself in the present-day hydrology of the county through rates of infiltration, susceptibility to flooding, stream morphology, and the location of sinkholes and springs. A schematic west–to–east section through Wabasha County (Fig. 6) shows the relationships among drainage, dissolution features, and geology. To the west in the county, the water table is higher up in the stratigraphic section. Springs and headwaters of streams are located near the Shakopee–Oneota contact. Dissolution features in the Oneota are chiefly limited to the upper part of the formation, within the paleokarst horizon. To the east in Wabasha County, the water table moves below the Prairie du Chien Group. Weathering and dissolution in the lower Oneota Dolomite is more developed, and springs are present at the base of the bluffs, commonly near the contact of the Jordan Sandstone and St. Lawrence Formation.

Under normal rainfall conditions, west-central Wabasha County drains relatively quickly; fields may dry out within days of rainfall events. If rainfall is prolonged, subsurface conduits will flow at capacity, i.e., they are fully flooded. Under these conditions, stream levels can rise extremely rapidly as surface water, which normally infiltrates, flows directly to streams. Large-scale flash flooding occurred in the county in late June, 1998, after as many as eight inches of rain fell on parts of the county over a five-day period (Minn. Dept. of Natural Resources, State Climatology Office, 1998).

The impact of geology, karst dissolution, and weathering is also apparent in stream morphology. A widening in the stream bank and broadening of the river valley is typical near the intersection of the streambed and the paleokarst zone. After the stream cuts into the less permeable lower part of the Oneota Dolomite, the course of the river is controlled by the presence of joints and systematic fractures. As a result, the stream valleys are steep-sided and run in straight reaches, which in many places are perpendicular to the general direction of drainage. The headwaters of West Indian Creek near Plainview, south-central Wabasha County, is an example of this type of control, where the stream disappears under conditions of low flow near the top of the contact of the Oneota Dolomite with the overlying Shakopee Formation, only to reappear at or near the contact with the Oneota Dolomite and underlying Jordan Sandstone (Fig. 7).

The position of the paleokarst horizon relative to the land surface is a factor in sinkhole development. Cross-section A–A' on the karst features plate of the Wabasha atlas (Tipping and others, 2001) shows the position of the paleokarst zone relative to the land surface. The position of the zone is closest to the land surface in Chester Township in the northwestern part of the county. The proximity of the paleokarst zone to the land surface, and the existence of a high water table provide the means to transport sediment and water through the subsurface at high rates, prompting the formation of more sinkholes here than elsewhere in the county. Sinkholes are also found near the Shakopee–Oneota contact in Oakwood and Highland Townships in central Wabasha County, and Plainview Township in southern Wabasha County (Tipping and others, 2001).

Springs in the Prairie du Chien Group are uncommon. Notable exceptions are near the headwaters of Cold Creek near Zumbro Falls in west-central Wabasha County (see Karst Features section in Runkel, 2001).

Springs typically are present at the contact between geologic units of contrasting rock types; for example, sandstone and shale, or carbonate and shale. In Wabasha County springs of this type are found at the contact of the Jordan Sandstone and St. Lawrence Formation, and within the Franconia Formation (see Figure 4 in Tipping and others, 2001). Tritium dates indicate that the springs contain water that entered the ground within the last 50 years, some of it possibly much more recently.

IMPACT OF KARST ON GROUND WATER

The paleokarst horizon within the Prairie du Chien Group is an important factor in the current movement of ground water and in the formation of sinkholes. The zone has high permeability relative to the rocks above and below it; in consequence, ground-water flow is focused within it. Water can move quickly through this zone; measured rates are hundreds of feet to several miles per day (Donahue and Associates, 1992; Wheeler, 1993). Rapidly moving water carries sediment. When the high-permeability zone is close to the land surface, sediment can be transported to the subsurface, causing the formation of sinkholes.

Where surface runoff enters bedrock aquifers through karst conduits, it bypasses the natural filtering capacity of the soil. In this way, bedrock aquifers in karst terranes are highly susceptible to surface contamination, as are the springs and streams that drain them. Sediment-choked karst conduits in the bedrock of Wabasha County form

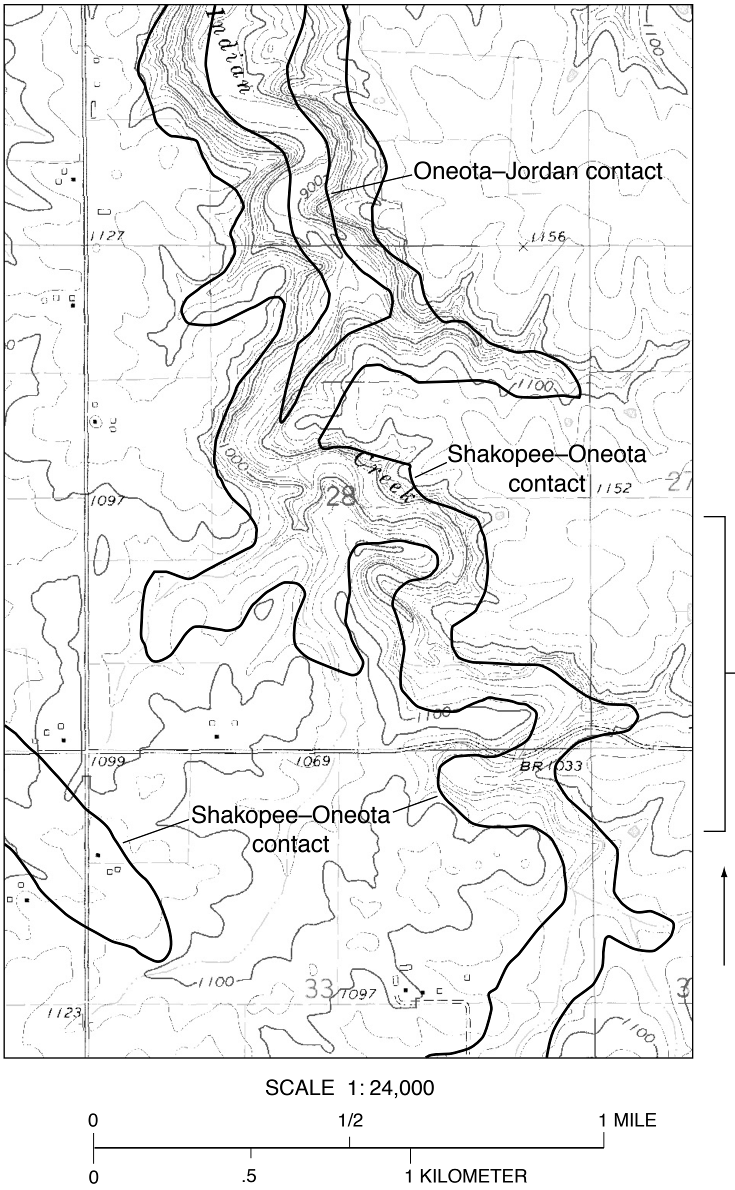


Figure 7. The effect of joints in the lower Oneota Dolomite (Prairie du Chien Group) on stream morphology within West Indian Creek. Stream flow in the area indicated by brackets is perpendicular to the general direction of stream flow, which is north. The segment of the creek shown is about three miles northeast of Plainview, south-central Wabasha County, Minnesota. Base modified from U.S. Geological Survey Plainview 7.5-minute topographic quadrangle, 1972.

a complex subsurface network of clogged plumbing. Conduits in this network can become unclogged due to changes in drainage, or in response to heavy rainfall. As a consequence, new sinkholes typically form when there is a temporary or long-term change in drainage patterns, either natural or induced by human activities.

In the spring of 1992, six sinkholes were discovered to have drained the number two pond of the City of Bellechester's wastewater stabilization pond treatment facility (Alexander and others, 1993). The sinkholes are interpreted to have formed in or near the paleokarst horizon of the Prairie du Chien Group, presumably in response to increased hydraulic head of the ponds reactivating previously clogged bedrock conduits. Similar failures have happened in the same stratigraphic position within the Prairie du Chien Group in Winona County at Lewiston (Jannik and others, 1991), and Altura (Alexander and Book, 1984). Sinkholes in Wabasha County and elsewhere in southeastern Minnesota commonly develop at the edges of retention ponds; they are interpreted to have formed because of geologic and hydrologic condi-tions similar to the wastewater-pond failures. Many of the sinkholes in Wabasha County were reported to have formed after heavy rains.

Rapid infiltration of surface water into bedrock aquifers is not limited to sinkholes. As previously noted, much of the county landscape dries out quickly after rainfall. In addition, most of the upland valleys are dry except under conditions of heavy rains. Areas that remain wet several days after rainfall are typically where the depth to bedrock is greater than 50 feet, which is limited to a small portion of the county (see depth-to-bedrock map in Mossler, 2001). In areas that are less than 50 feet from the land surface to bedrock, water infiltrates rapidly into bedrock conduits within the Prairie du Chien Group, where it moves—depending on gradient—either to discharge in springs and streams, or down into lower aquifers. The entire landscape is directly connected to the ground water.

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