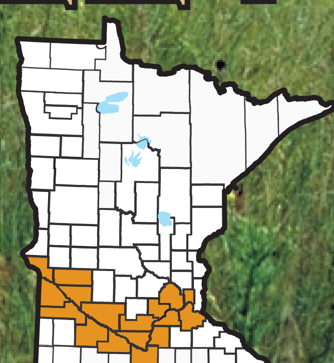
Native Plant Communities & Rare Species of the MINNESOTA RIVER VALLEY COUNTIES



Minnesota County Biological Survey
Division of Ecological Resources
Minnesota Department of Natural Resources

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The Minnesota River Valley Counties

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2. Overview of the Quaternary Geological History of the Minnesota River Watershed

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> *"The Minnesota River valley is truly the most striking and scenic feature of all south-central Minnesota. It is a narrow sliver of wooded hill slopes in the vast plains to north and south, and it holds within it a diversity of geologic features such as rugged granite knobs on the valley floor, boulder-gravel river bars, broad sandy terraces, gentle colluvial slopes – and a stream along the axis that is almost tiny in the context of these major features" (Wright 1972).*

THE WATERSHED—A GLACIAL TROUGH RUNS THROUGH IT

The Minnesota River flows down the centerline of the broad glacial trough formed by ice of the Des Moines lobe, which dominates the topography of the southern half of Minnesota (Fig. 2.1). This trough is so wide and gently-sloping that it is almost undetectable from the ground. The valley of the Minnesota River, on the other hand, is an arresting feature that was created abruptly after the Des Moines lobe retreated and is still affecting the evolution of the landscape today.

The ice lobe that formed this statewide trough was just the last of several that entered Minnesota during the last glaciation (and this last glaciation was just one of several that affected Minnesota during the last two million years). Ice lobes were dynamic tongues of ice that extended far south of the main ice sheet. Rather than being the slow inexorable movement of ice that is typically envisioned, the ice lobes advanced and stagnated quickly and repeatedly until they eventually drained the slower reservoir of ice that was feeding them. The lobes were directly controlled and fed by focused, fast-moving zones within the ice sheet called *ice streams* (Patterson 1996, 1997).

The Des Moines lobe, which extended south from the main Laurentide ice sheet that covered much of Canada and parts of the northern United States during the last ice age, had more than a dozen advances, driven by ice stream dynamics, between approximately 40,000 and 11,000 years ago (Clayton and Moran 1982, Patterson 1996). Each advance eroded a bit more from the land it covered and deposited it near the edge of the lobe, creating a suite of identifiable landforms at each ice margin. Geologists collectively refer to the sediment of all of these advances of the Des Moines lobe as the New Ulm Formation, even though each advance may have been subtly different in its composition. The sediment, or till, deposited by the ice was nearly an equal mixture of clay, silt and sand, with a predictable amount and assortment of pebbles in the fine-grained mud. Till was created as overridden sediment and rock fragments were either frozen into the glacier or dragged along by the moving ice and eventually conveyed towards the ice margin. This material was thoroughly ground up and mixed while in the shear zone at the bottom of the glacier.

The processes that occur beneath an ice sheet are difficult to study but drilling through and imaging the base of modern ice streams in West Antarctica have elucidated them. The boundaries of the subglacial shear zone change with the temperature of the bottom of the ice and these changes control whether material is eroded or deposited, frozen in or melted out. In areas of heat from friction, debris is released from the ice and left behind, forming a till sheet. Where the temperature is reduced at the glacier bed, sediment is frozen into the ice and carried away, resulting in erosion. The presence or absence of water also plays an important role in how these processes vary over time, so erosion and sedimentation vary with the temperature and melting point of the ice. Where the shearing force of the ice is reduced by lubricating water, sediment that was dragged along is left behind. Where subglacial water has drained away, the shearing force increases and a thicker pile of sediment is dragged along with the ice. Ice thickness also comes into play directly because thicker ice can drag along more sediment than thinner ice. Complicated though these processes may seem, we have evidence to show that these processes operated in the ancient ice lobes of the Laurentide ice sheet and effectively removed debris, mixed it thoroughly, moved it for hundreds of miles, and then spread a fairly uniform blanket of the end product over the region.

Beneath the till of the Des Moines lobe lie layers of older glacial units from previous glaciations; these layers vary in thickness and completeness of preservation (Gilbertson 1990, Patterson et al. 1995). The truncated stack of older tills that remains in the Minnesota River valley is exposed in the valley walls and forms the competent (indurated) gray-brown to yellow bluffs along the lower reaches of tributary streams to the Minnesota River. More than a million years worth of glacial advances is preserved in the banks of the Yellow Medicine River in Upper Sioux Agency State Park.

Over two million years worth of sediment is layered in the better-preserved stack of old debris

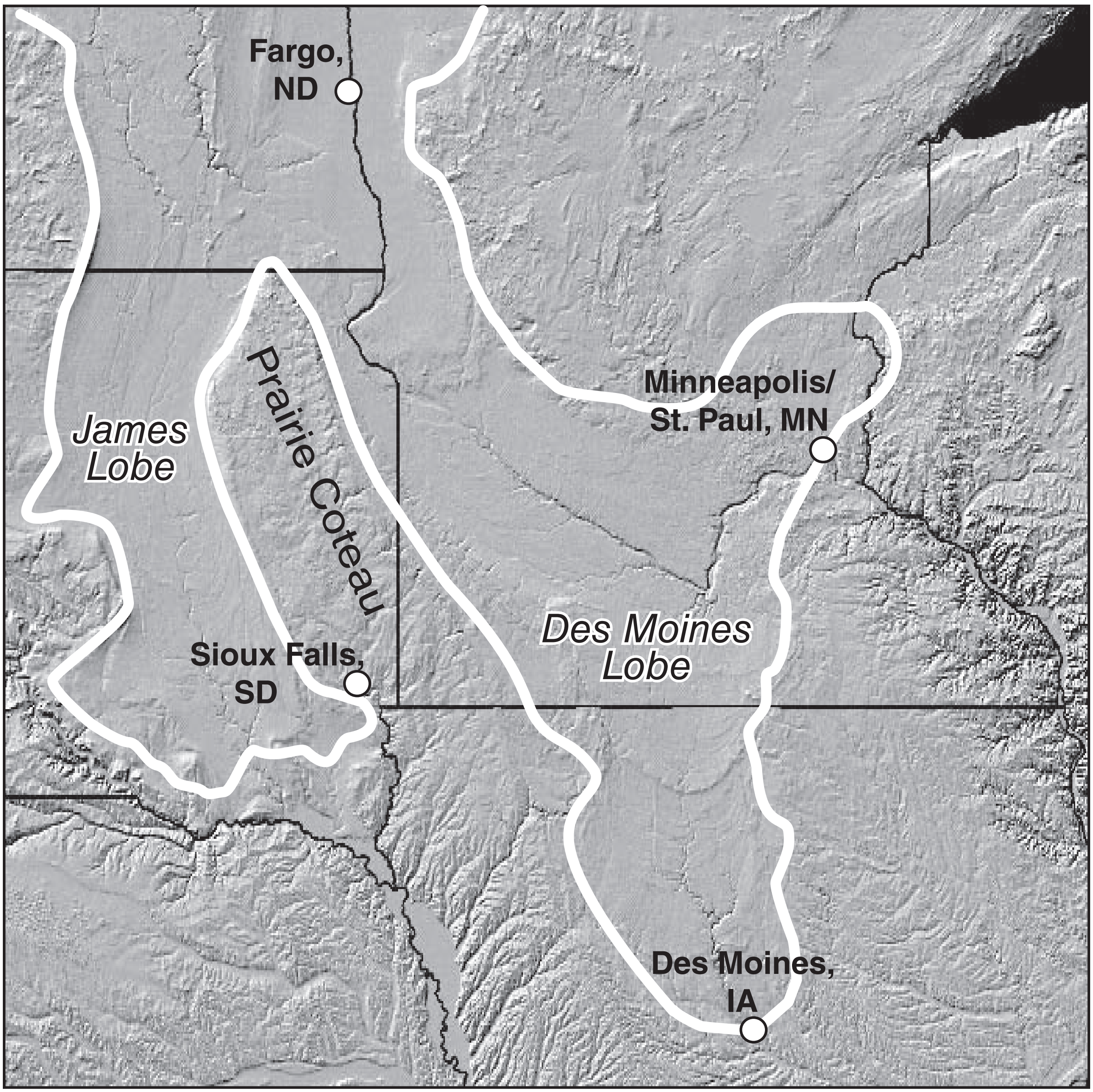

Figure 2.1: *Location of the Des Moines and James Lobes at their maximum extents.*

beneath the Coteau des Prairies (Prairie Coteau) farther west (Fig. 2.1) (Balco et al. 2005). Near the prow of the Coteau, along the North Dakota-South Dakota line, drill holes penetrate 800 feet of glacial sediment before reaching the bedrock beneath (Beissel and Gilbertson 1987). This highland, while dramatic, is not especially erosion resistant; it was simply bypassed this last time around by ice lobes on either side of it and thereby preserves a thick stack of older glacial sediment (Gilbertson 1990, Lineburg 1993, Patterson et al. 1995).

We do not know exactly what the land looked like before the advances of the Des Moines lobe and previous ice advances, but expect that it originally looked a lot like the unglaciated areas of North Dakota, west of the Missouri River (Bluemle 1991). Earlier ice lobes from older glaciations most likely initiated the path later followed by the Des Moines lobe, which was the last in a long line of ice advances from the northwest as indicated by the similar composition of the tills. Perhaps the early ice advances initially exploited a small river valley. The direct evidence for this has been removed, smeared out across Minnesota and Iowa, and deposited as far away as the Gulf of Mexico by continent-spanning meltwater streams. So we can only make an educated guess based on the nature of the unglaciated landscapes nearby.

As global climate warmed about 14,000 years ago, bringing an end to a 100,000-year-long ice age, the Des Moines lobe, rather than simply slipping back into Canada, began the long, stuttering process of advancing and stagnating in fits and starts, eventually leaving Minnesota about 11,000 years ago. The warming climate had actually created the conditions for this style of ice lobe advance by lubricating the base of the ice streams and lobes.

Today, it is this record of ice stagnation that is best preserved (Patterson 1997). Each indecisive margin is marked by an area where debris accumulated in a hilly band. In some cases, the stagnation of the lobe—which had become heavily crevassed as it wasted—was marked farther from the main margin by faint, crisscrossing pattern of debris that settled into the crevasses, forming low intersecting ridges. (Kemmis et al. 1981 and references therein, Patterson 1996). Beyond the ice, arcuate braided streams carried meltwater around the front of the melting ice but were not erosive enough to carve deep valleys (Leverett 1932, Patterson et al. 1999). Rather, they were debris-choked, shallow, and broad. After circumscribing the lobe, they flowed southeast down the regional slope, most likely near the present location of the Minnesota River, but prior to its formation. Some of the former, ice-marginal stream channels are still occupied by lazy reaches of modern rivers such as the Redwood, Cottonwood, and Watonwan (Map 1 [inside cover], Fig. 2.1). These rivers still take the long way around, looping around the margin of the phantom ice lobe. In other cases, modern streams have taken short cuts to the more recently formed Minnesota River, with courses that are more in line with the modern gradient. For example, the Yellow Medicine River begins in one former ice-marginal stream channel, then cuts across the broad, level till plain in an east-northeasterly direction until it intersects a younger ice-marginal stream, thereby taking a more direct route to the master stream, the Minnesota.

In areas away from the low-gradient braided streams, the ice lobe trough was not shaped to allow water to drain readily, and pooled water, from small puddles to large lakes, formed as the lobe melted. Most of the large lakes of glacial meltwater eventually drained, but shallow depressions that held water after rains persisted. The ten to twenty feet of fine-grained, dense, gray, clayey till deposited in the trough by the Des Moines lobe did not allow rainwater and snow melt to percolate into the substrate very quickly (Patterson et al. 1999). As seasonal water perched, wetlands formed, covering about half of the area of the trough. Most of these wet areas have been intentionally and progressively drained for farmland.

After the Des Moines lobe's final retreat into North Dakota, another lobe, the Red River lobe—fed by a different ice-stream source—took advantage of the newly vacated lowland, advancing south from the area we now know as Lake Winnipeg. It created a series of broad stagnation moraines north of Ortonville, Minnesota, collectively named for the county they lie in, Big Stone.

ICE MARGINAL LANDSCAPES—HUMMOCKS AND HILLOCKS

The thin ice of the punctuated advances of the Des Moines lobe moved a lot farther than one might have predicted—splintering into a spruce forest in Des Moines—the stumps are there to prove it (Clayton and Moran 1982, Bettis et al. 1996). The advances were most likely encouraged by pressurized water beneath the ice that allowed it to glide by reducing friction. Advances probably ended in stagnation when the water making the long glide possible was siphoned off through subglacial valleys. These tunnel valleys formed at the ice margin and worked their way up into the ice lobe, draining a large portion of it and causing it to skid to a halt (Patterson 1996). Today these valleys are marked by mile-wide depressions up to 10 miles long and frequently contain long lakes (e.g., Lake Benton) or chains of lakes (e.g., the lakes near Fairmont, see Map 1). The lobe advanced and stagnated again and again, at least thirteen times, with each advance a little less extensive than the previous one. This was because the lobe was progressively drawing down the reservoir of ice.

Each advance also eroded the ice-lobe trough a bit more, conveyed that material closer to the ice margin, and piled it near ice and debris from the previous advance. In this way, the margins of the lobe—especially those along the east and west sides, which received more total advances—accumulated thick stacks of dirt and stagnant ice. The slow decay of dirt-covered ice piles created the complex hilly areas that now mark the former limits of the ice (Clayton 1967, Patterson 1996). The western margins are marked by rolling hills that cross diagonally across Jackson, Murray, southwestern Lyon, Lincoln, and western Yellow Medicine counties (Map 1). The eastern margins are marked by the oak-dotted hillocks and hummocks, specked with lakes and wetlands, in Freeborn, Waseca, Steele, Le Sueur, Rice, Scott, Carver, and Hennepin counties (Map 1). These eastern hills fringed the former expanses of prairie (now corn and soybean fields) that occupied the flat, central trough of the lobe; they formed effective firebreaks against the windswept blazes that moved from west to east across prairie regions of the state, enabling the development of woodland and forest vegetation along the margins of the prairie.

Slightly impractical farming areas, the hummocky zones were probably the second choices of homesteaders and were more likely settled by homesick immigrants for nostalgic reasons because they looked like a left-behind "home" in Ireland, Czechoslovakia, or central Germany. The hummocks and swales formed as repeated advances of ice buckled the debris-covered, stagnant ice, which then wasted slowly and irregularly. The dirt and ice mix lasted a long time—long enough for trees to establish themselves in the wet debris. Ducks may have swum in the pools of water that developed on the ice. The dirt on top of the stagnant ice was wetted from below by melting ice, making it unstable and causing dirt, rocks, trees, and ducks to be rearranged for centuries on the ever-changing surface of the buried ice. Ultimately, all of the ice melted. The hills we see today represent the final resting place of the glacial sediment in the very last holes in the stagnant ice surface.

In some areas, water associated with melting ice, or simply gravity, sorted the till into better-organized layers of like-sized grains. Sand and gravel were carried away from the ice by flowing rivers. Silt and clay moved even farther, though it also settled out in the still waters of proglacial lakes formed by ice or moraine dams near the ice. Silt and sand became airborne with the persistent and strong glacial winds. Sand particles stay lower to the ground and saltate (bounce), continuing to dislodge particles that have settled out. The windblown silt settled out in a blanket of loess that thickens towards the Mississippi River (Mason et al. 1999). Most of this sorting occurred before vegetation became established on the landscape.

We are a state of imported dirt. Everywhere where there is sediment in Minnesota, it is likely to be the long-traveled deposits of an ice lobe or the re-sorted material described above. Pick up any rock; it was most likely imported from Manitoba or Ontario, as was the gray clay or red sand of the till matrix. Our rivers proceed to expose and erode this glacial sediment and deposit it in the nearest slackwater area, either in the streambed or floodplains or maybe a lake along the way. Some sediment might make it all the way to the Gulf of Mexico, or at least Lake Pepin.

The glacial till and the reworked byproducts of glaciation form the base for the rich soils of Minnesota. These soils were created over the past 10,000 years as the minerals in the glacial sediment were broken down. The slow movement of water through the till dissolved certain minerals and deposited them deeper in the soil profile. The mineral soil was amended with decaying organics from the succession of plants that occupied the land surface. Ten-thousand years worth of root activity, frost, fire, burrowing, and acid leaching from leaf litter have all played a role in forming the soils we depend on in the Minnesota River watershed.

THE GREATEST LAKE

In places, meltwater from the wasting ice was temporarily trapped—for at least a dozen years in the basin of glacial Lake Minnesota, which covered most of Blue Earth County in addition to parts of other contiguous counties (Patterson and Hobbs 1995), and for at least half a century in the basin of glacial Lake Benson, which covered large portions of Swift, Lac Qui Parle, and Chippewa counties (Rittenour et al. 1998) (Fig. 2.2). As the Red River lobe retreated, meltwater ponded behind the Big Stone moraine for about a millennium. The resulting glacial Lake Agassiz (Upham 1890, 1895) was one of the largest freshwater lakes in the world, eventually occupying 200,000 square miles, an area greater than all of the Great Lakes combined, covering much of what are now western Minnesota, eastern North Dakota, Manitoba, and western Ontario (Fig. 2.2) (Thorleifson 1996). The Red River lobe dammed the water to the north and the only outlet to the lake for much of this time was to the south, through the Big Stone moraine. This overflow from glacial Lake Agassiz made the initial incision into the newly vacated glacial trough, starting the process of formation of what eventually became known as the Minnesota River valley. The early river that spilled south from the vast, cold, iceberg-filled waters of glacial Lake Agassiz is referred to as glacial River Warren.

Overflowing water from glacial Lake Agassiz created glacial River Warren some time around 11,500 radiocarbon years before present (Clayton and Moran 1982, Matsch 1983) and the glacial River Warren outlet was occupied until about 10,900 radiocarbon years before present. Two other outlets were intermittently used by Lake Agassiz, one to the east, through Lake Nipigon and thence into Lake Superior, active between 10,900 to 10,300 (Thorleifson 1996), and one to the northwest in the Fort McMurray area of Canada through the Mackenzie River and thence to the Arctic Ocean between 10,000 and 9,600 radiocarbon years before present (Lowell et al. 2005). When Lake Agassiz drained through these other two outlets, the southern outlet was not used. River Warren was probably reoccupied after 9,600 but finally lost glacial lake discharge forever by 8,200 radiocarbon years before present.

The retreat of an ice sheet is not always a steady affair, however, and so the reign of Lake Agassiz was somewhat complicated. The lake did not successively take lower and lower outlets that were exposed as the ice sheet withdrew to the north. The ice lobes, driven by the independent ice streams, behaved erratically and shot out from the ice front at various times, rerouting and even blocking meltwater discharge. It appears that a late readvance of ice in the Lake Superior basin blocked the eastern outlet of Lake Agassiz through Lake Superior for a long enough interval to allow Lake Agassiz levels to rise to the elevation of the southern outlet a second time. The ever-changing part of the lake shore represented by the oscillating ice front was not the only factor complicating the drainage history of Lake Agassiz. The land had also

Fig 2.2: *Locations of glacial lakes Agassiz (after Teller et al. 1983), Benson, and Minnesota (after Hobbs and Goebel 1982) at their maximum extents. Note: these lakes were present at different times.*

been rebounding gradually as the weight of the ice sheet was lessened, more so in places where the ice was thicker. So the northern part of the basin was rising more than the southern part and that too has played a part in the occupation of the various outlets of Lake Agassiz (Thorleifson 1996).

River Warren easily cut through the stack of older tills and saprolite (weathered bedrock) that lay in the trough of the Des Moines lobe. In places it reached harder rock and could not erode deeper. It exposed old, pink quartzites near New Ulm; very old granitic rocks on terraces near Ortonville, Odessa, and Granite Falls; and the even older gneisses between Redwood Falls and Morton. These resistant rocks were local base levels that constrained the depth of erosion of River Warren (Matsch 1983) and required it to become wider to accommodate the flow. They are still the sites of rapids or waterfalls—collectively called nick points—as can be inferred from the names of some of the towns.

As the river swept the clay and grit of the weathered rock away it exposed the strange knobby bedrock surface that lay beneath the saprolite. In a few places, pebbles swirling in River Warren eddies scoured potholes. But in most places the river just removed the loose material leaving a strange but wonderful undulating surface. This landscape is well exposed on the route through the Big Stone National Wildlife Refuge near Odessa. This chemical weathering front may have never seen the light of day were it not for River Warren, and presents a very odd landscape for us to explore. The rocky outcrop area in Granite Falls stretches for miles and is a disorganized, lumpy moon-like landscape (Johnson et al. 1998, Patterson et al. 1999, Patterson and Boerboom 1999). The river stripped most of the saprolite from a bedrock surface that was shaped by the slow chemical weathering of hard rock in a tropical setting, with the partially dissolved rock blanketing it during this process. This is the way that rock turns to mush in places like Brazil today. The undulation of the rock surface is a result of the weathering front proceeding unevenly, going deeper along fractures and joints than over intact surfaces. In some places completely isolated rounded remnants of rock called corestones remained in the saprolite. These remnants formed as the rock around them dissolved. When the saprolite was swept away by glacial River Warren it left the large rounded rocks in place (Patterson and Boerboom 1999). The saprolite still remains in a few patches near the surface and has been mined near Redwood Falls and Sacred Heart for its unique clay mineral, kaolinite. Kaolinite is the stable end-product of long-term chemical weathering and is valued for its purity. It is used in porcelain and coated color paper, among other things.

There are waterfalls or rapids (nick points) on all of the tributary streams to the modern Minnesota River. The tributaries instantly developed waterfalls when glacial River Warren was incised below the levels of its tributaries. These waterfalls gradually moved upstream or became a series of rapids or nick points. In this way the lower reaches of all of the tributaries to glacial River Warren are adjusting their gradients to meet the new level of River Warren, a journey they are still on today even though River Warren ceased to flow millennia ago. Even now, only the lower 5–10 miles of each major stream is adjusted to the elevation of the valley floor of the Minnesota River. Look again at the location of the waterfalls, towns or dams on these tributary rivers. Their names and locations reveal the progress of nick point migration during the last 10,000 years.

The process does not stop just because we live here now. The nick points will continue to move up the tributaries and the tributaries to the tributaries, and so on, until the entire watershed of the Minnesota River valley has adjusted. Given the progress over the last 10,000 years, one might expect another glaciation to occur before the result is achieved. However, changes we have made to the drainage system have accelerated the rate at which this process would typically take place.

Upriver from Mankato, glacial River Warren was primarily a down-cutting stream (Johnson et al.

1998 and references therein). This means that terraces there are controlled by the depth of erosion of the river, usually to a level of resistant rock, and that surfaces along the valley are not related to stable lake levels and beaches of Lake Agassiz (Johnson et al. 1998). Some are channels that were briefly occupied before the erosive water became focused in one main channel—for example, Watson Sag (map 1) (Kehew and Lord 1986, Patterson et al. 1999). So depositional sand and gravel terraces are not a common feature of glacial River Warren in its upstream reaches. Where one does see sand or gravel flanking the upper Minnesota River valley, it is most likely remnants of braided glacial outwash streams or deltas that had formed in the wide, slower parts of the River Warren. There is a broad and complicated area of deltaic and outwash sand in the area near Appleton. It predates the formation of the glacial River Warren trench and is linked to glacial Lake Benson, which formed during ice lobe retreat (Patterson et al. 1999).

A right-angle bend exists in the Minnesota River valley at Mankato. It is likely that this bend was inherited from the course of an earlier stream that developed while the Des Moines lobe was in retreat. This stream appears to have started as an ice-marginal stream that was then used to drain glacial Lake Minnesota. There is no really good reason for a river to make a sharp left-hand turn otherwise and river courses tend to get reused. Glacial Lake Minnesota formed when the Des Moines lobe margin lay in North Mankato.The lake spread south almost to the Iowa border and deposited a fairly continuous blanket of silt and clay that buried the till in much of the Blue Earth watershed. The lake was initially deep enough to spill south through Union Slough into Iowa. Then a lower outlet to the east opened and the lake drained through what are now Waseca and Steele counties. The channel occupied by the chain of lakes that starts in Le Sueur County and trends northeast through Rice County and includes Cannon and Sakatah lakes is another presumed outlet for this lake (Patterson and Hobbs 1995). When the ice lobe receded from North Mankato, even lower ground was revealed and the lake *must have* suddenly and completely drained through a valley trending north. We see no direct evidence of that valley now; it has been completely obscured by the later drainage events of glacial River Warren. However, we do see the evidence for a proglacial lake, the outlets for which were progressively moving north towards lower ground. Some things can never be definitively proven, but other explanations for the bend in the river, such as a change in bedrock near the area of the bend (Wright 1972), don't seem to explain the existence of the bend as comprehensively.

Whatever the cause, the bend in the river at Mankato must have set up a mighty eddy. No civil engineer would deliberately create a channel of that shape for fear of erosion along the valley wall and the flotsam and jetsam that would accumulate in a giant, backward circling eddy. The effort of getting the water through here might have even created a hydraulic dam, backing water up in the channel as the river worked its way through the extreme bend, perhaps flooding the newly formed mouth of the Blue Earth River as evidenced by deposits of sand and gravel that are currently being mined several miles up from the mouth of the river.

The river encountered even more engineering problems downstream of Mankato: buried valleys that had been filled by deposits of earlier glacial episodes. The valleys were relatively easy to ream out and reoccupy but the river course was also interspersed with resistant, bedrock-reinforced areas. These sedimentary rock layers of sandstone and limestone thus created local nick points that would have migrated up a river (Johnson et al. 1998) already complicated by large flows of water and strange hydraulics. Some of this history is recorded in the walls of a sand and gravel mine on the broad terrace near Kasota. Fifty-foot high angled beds of sand—foresets—are evidence for a very deep, pooled part of the river valley that filled with sand as a bar or delta migrated across to fill it. The river lies far below this terrace now so it was eventually able to cut through the rock that is also mined here (Kasota stone is the local name given the rock) and form a narrower channel.

With the cessation of lake water discharge from glacial Lake Agassiz, the River Warren valley became grossly oversized for the regional precipitation brought to it by its tributaries. Tributaries to the Minnesota River, the successor to glacial River Warren, were in the process of adjustment to the level of the deeply incised valley and therefore were carrying as much sediment as they could handle, which they delivered to the valley. The Minnesota River was not effective at carrying this sediment away and the tributaries built fans at their mouths. Lakes formed behind these fans and long reaches of the Minnesota River were dammed (Zumberge 1952) to create river lakes that include Big Stone Lake (at the fan of the Whetstone River), Lac Qui Parle Lake (at the fan of the Lac Qui Parle River), and Marsh Lake (at the fan of the Pomme de Terre River) (Wright et al 1998). Much farther south, but in a similar fashion, Lake Pepin was created by a tributary fan from the Chippewa River of Wisconsin (Wright 1990, Wright et al. 1998). Water in Lake Pepin was initially backed up all the way to downtown St. Paul (Zumberge 1952, Wright et al. 1998).

River lakes age in the same way that an artificially dammed river does: they fill with sediment carried by the river. All of the river lakes in the state are gradually filling in as sediment is delivered to these shallow pools. The Minnesota River valley is filling in, or aggrading, everywhere; it is just more obvious in these river lakes. It is also more obvious to us now because modifications we have made to the landscape and drainage network have sped up the rate of sediment delivery (Wright et al. 1998).

Landscapes that avoided the most recent glaciation, but were glaciated previously (Fig. 2.1, southeastern and southwestern regions of Minnesota), are veined with complexly branching tributaries of river systems. Natural lakes simply do not exist in these corners of the state. Here, rivers have effectively drained any formerly flat, wetland- and lake-dotted areas in the hundreds of thousands of years they've had to get the job done. The development of this kind of dendritic drainage

Bedrock of the Minnesota River Valley

Fred S. Harris

The knobs of ancient granite-like bedrock exposed in the Minnesota River valley upstream from New Ulm include some of the oldest rocks discovered at the earth's surface. Several geologists estimate that many of these "crystalline" rocks first formed as igneous rocks from molten magma that cooled very slowly deep below the earth's surface as long as 3.6 billion years ago (Grant 1972), when the core of North America was being formed. Once formed, these early rocks underwent extreme heat and pressure over the next 1 to 1.5 billion years, which altered their crystalline structure and transformed them into metamorphic rock. These rocks include many variants of gneisses and diorites that may be found today in several parts of the valley, such as the Morton Gneiss, which is exposed in the town of Morton.

Other crystalline bedrocks exposed in the valley are far younger in age. These include igneous rocks, such as granite and gabbro, which flowed into (or "intruded") cracks in the older gneisses. Examples include the Sacred Heart Granite, which formed about 2.6 billion years ago, and the Cedar Mountain Complex near Franklin, which dates to 1.8 billion years ago (Grant 1972). Cedar Mountain is a classic example of an igneous intrusion, in which magma flowed into cracks in older rocks. This complex includes an outer ring of gray rock (the Cedar Mountain Gabbro), which encircles an inner zone of pinkish crystalline rock (Cedar Mountain Granodiorite) (Bury 1958, Grant 1972). Today, the Cedar Mountain complex forms the highest point of relief within the Minnesota River valley (Schwartz and Theil 1954).

Sioux Quartzite is a younger bedrock layer exposed in the Minnesota River valley only near New Ulm. Many more exposures of it are located farther south and west. This is a pink-to-purplish rock that formed from sandstone deposited in a shallow sea (Ojakangas and Matsch 1982). The sandstone (composed of quartz grains) was then transformed into a metamorphic rock (quartzite) by heat and pressure, possibly due to severe compression from tectonic plate movement, which cemented the sand grains into much harder rock. Its dark, purplish color comes from iron oxide coatings on the quartz grains (Austin 1972).

In the eastern part of the Minnesota River valley, sedimentary rocks are exposed that originated as sediments in shallow seas that occupied much of the North American interior 500 million to 430 million years ago (Ojakangas and Matsch 1982). These marine environments contained a rich diversity and abundance of plants and animals, which remain embedded in some of the rocks as fossils. The Canadian Shield, which underlies northern, central, and western Minnesota, was not inundated by these shallow seas; thus these sedimentary rocks are absent from the western part of the Minnesota valley (Ojakangas and Matsch 1982). Major sedimentary rock units exposed in the lower Minnesota valley in order from youngest (400 million years old) to oldest (over 500 million years old) include the following:

- Platteville Limestone: a 35-foot thick layer of hard, fossil-rich limestone on top of the St Peter Sandstone. This is visible along the upper edges of the steep rock clifs along the Mississippi River valley in the Twin Cities.
- St. Peter Sandstone: a 155-foot thick layer of mostly white sandstone that makes up most of the exposed cliffs along the Mississippi River in the Twin Cities.
- Prairie du Chien Group (Shakopee and Oneota Dolomite): a 410-foot thick layer mostly composed of dolomitic limestone. Oneota Dolomite is the locally known Kasota Stone being mined from a glacial river terrace near Kasota, as described above.
- Jordan Sandstone: a 1 15-foot thick layer of whitish to yellowish sandstone exposed near Mankato and Jordan.

network is something that is just getting started in the recently deglaciated landscape of the Des Moines lobe. Eventually, the Des Moines lobe trough should be drained by a dendritic network every bit as complex as what we see in the southeastern and southwestern parts of the state. We can see it happening. The rate and style of drainage development, however, have been altered by the creation of new, artif cial tributaries such as farm tiles and ditches. Geologists are trying to understand the complex responses of the Minnesota River, its river lakes, and its tributaries to these changes.

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