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FIELD TRIP GUIDEBOOK FOR THE UPPER MISSISSIPPI VALLEY MINNESOTA, IOWA, AND WISCONSIN

PREPARED FOR THE 21ST ANNUAL MEETING OF
THE GEOLOGICAL SOCIETY OF AMERICA,
NORTH-CENTRAL SECTION
ST. PAUL, MINNESOTA, 1987

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Priscilla C. Grew, Director

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N.H. Balaban, Editor

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CONTENTS

KARST HYDROGEOLOGY OF SOUTHEASTERN MINNESOTA

by

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INTRODUCTION

This field trip will focus on the ground-water pollution problems in the well-developed fluvio-karst of the Upper Ordovician carbonates of Fillmore County, Minnesota. Interactions between karst hydrology and agricultural, domestic, and industrial pollutants have produced pervasive water-quality problems in the Upper Mississippi valley karst region. Cases involving each of the major classes of pollutants will be shown. We will examine and discuss the real-world "solutions" that are being adopted to deal with the various types of pollution problems. Only occasionally is the cure worse than the disease.

The trip will examine many of the classic karst topographic features--sinkholes, caves, disappearing rivers, blind valleys and big springs. We will see how quantitative dye-tracing work has begun to illuminate the often bizarre workings of the area's karst hydrology. The goal of the trip is to begin to acquaint you with complex workings of karst geology and hydrology. Yes Virginia, there are underground rivers-but you probably should not drink from them today.

ROADLOG AND STOP DESCRIPTIONS

Miles	
0.0	Start trip at junction of U.S. 52 and 14 next to Apache Plaza in Rochester, Minnesota (look for the large baby-blue water tower.) Drive south on U.S. 52. See Figure 1 for map.
0.8	Zumbro River bridge--continue south on U.S. 52.
1.2	Platteville outcrop on right.
1.5	Park.
STOP 1.	Roadcut on U.S. 52. Contact between the Decorah Shale and the overlying Cummingsville Formation of the Galena Group. See Figure 6, pages 78-79, this volume.
2.4	U.S. 63 South exits to right; continue south on U.S. 52.
8.2	Junction with I-90; continue south on U.S. 52.
8.9	Marion, Minnesota.

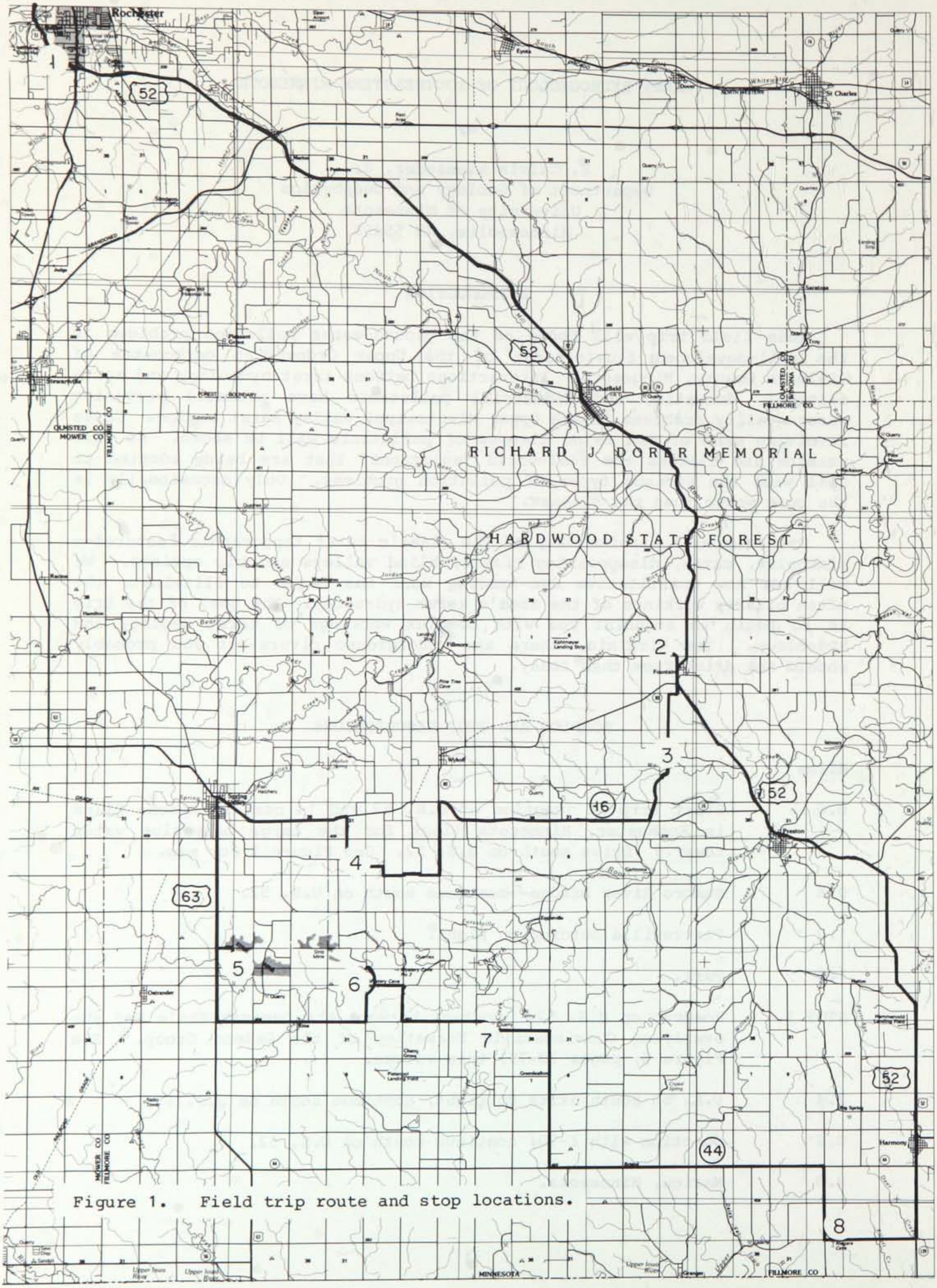


Figure 1. Field trip route and stop locations.

10.0 Topographic divide between Zumbro and Root River drainage basins. The bulk of the rest of the field trip is within the Root River drainage basin.

10.3 Predmore, Minnesota. Kinney Creek rises in a high, swampy area north of U.S. 52 and flows south to the North Branch of the Root River. The water table in this area is in the glacial deposits overlying the Galena Group.

12.3 The terrain here is a good example of the Rochester till plain (Wright, 1972) interfluve.

12.8 Sinkholes on right and left.

13.8 Begin descent into Mill Creek valley.

14.5 Outcrops of the Cummingsville Formation on left.

16.2 Outcrop of St. Peter Sandstone on right. Note the prominent joints visible on the outcrop. Although the joint control on karst development in the Paleozoic carbonates is well known, the prevalence in the sandstones is rarely appreciated. These joints are typically spaced 16 to 65 feet (5 to 20 m) apart and may be hydrologically significant.

17.4 St. Peter Sandstone outcrops on left. Again note the joints.

18.6 St. Peter outcrops on left--joints.

19.4 Entering Chatfield, Minnesota.

20.1 Fillmore County line in Chatfield.

22.7 Outcrops of Shakopee Formation on right and left for next mile.

23.6 Bridge over Middle Branch of Root River.

25.6 Bridge over Rice Creek. Rice Creek's headwaters are the springs around stop 2.

25.8 Township road to left. Tennis Shoes' Cave is about 1/8 mile southeast of U.S. 52 at this point. Figure 2 is a copy of the Tennis Shoes' Cave map. Tennis Shoes is typical of interstratal St. Peter Sandstone caves, which are fairly common in the Upper Mississippi karst (Hedges and Alexander, 1986).

26.0 As the road climbs the hill for the next 0.4 mile the Paleozoic section from the St. Peter up through the Galena is exposed.

27.6 Start of Fountain sinkhole plain. The land surface here is underlain by Galena Group.

28.7 Fountain, Minnesota.

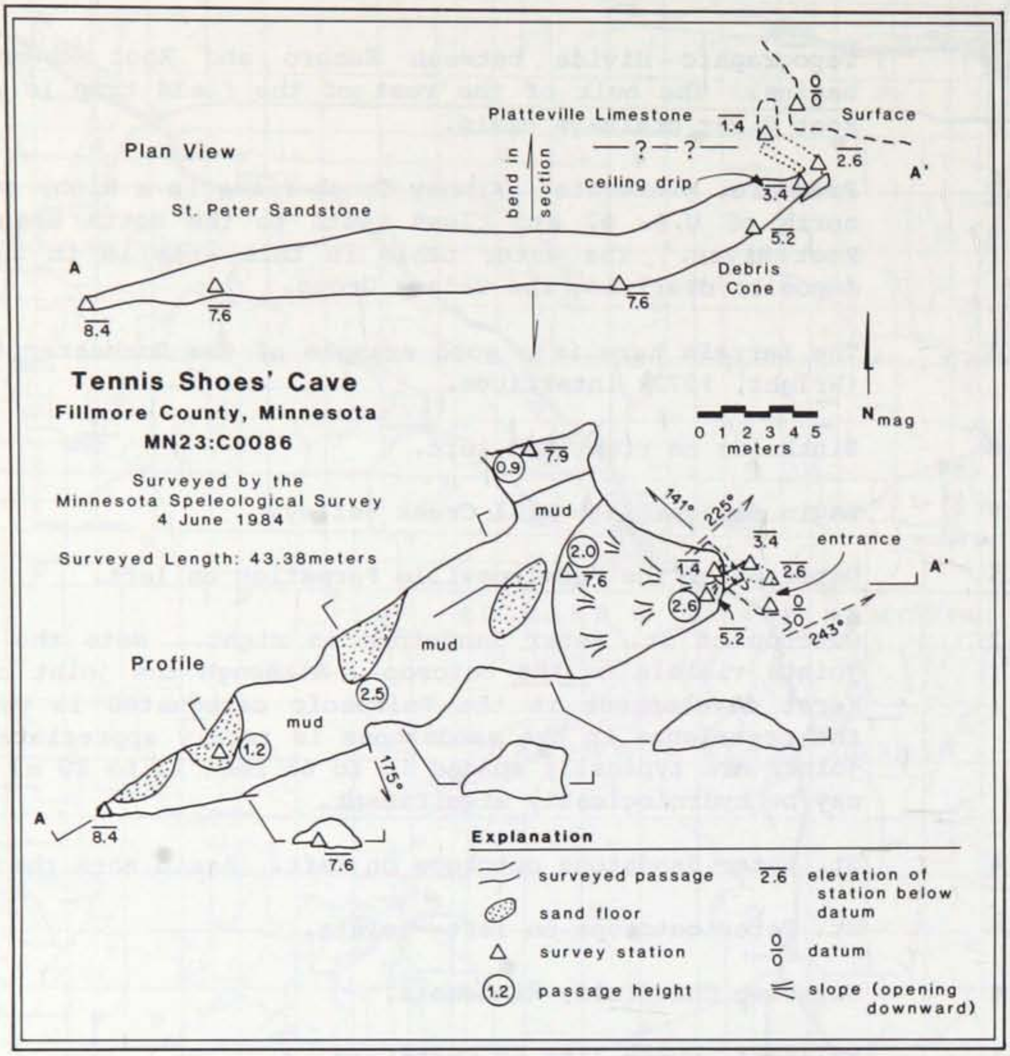


Figure 2. Tennis Shoes' Cave plan view and profile.

29.2	Junction of Fillmore County 8 with U.S. 52 in Fountain. Turn hard right back to the north on Fillmore County 8. Honey Well is about 1 block east of this intersection.
29.5	Fillmore County 8 turns left (west). Turn right onto township road.
30.8	Kappers Quarry on left. This active quarry mines and crushes lower Galena Group for gravel. Joints are very prominent in the quarry walls. Floor Drain and Sublime Caves are located in this quarry.
31.2	Park.
STOP 2.	Cave Spring on west side of road; Little Quarry Spring on east side of road (Figs. 3 and 4).

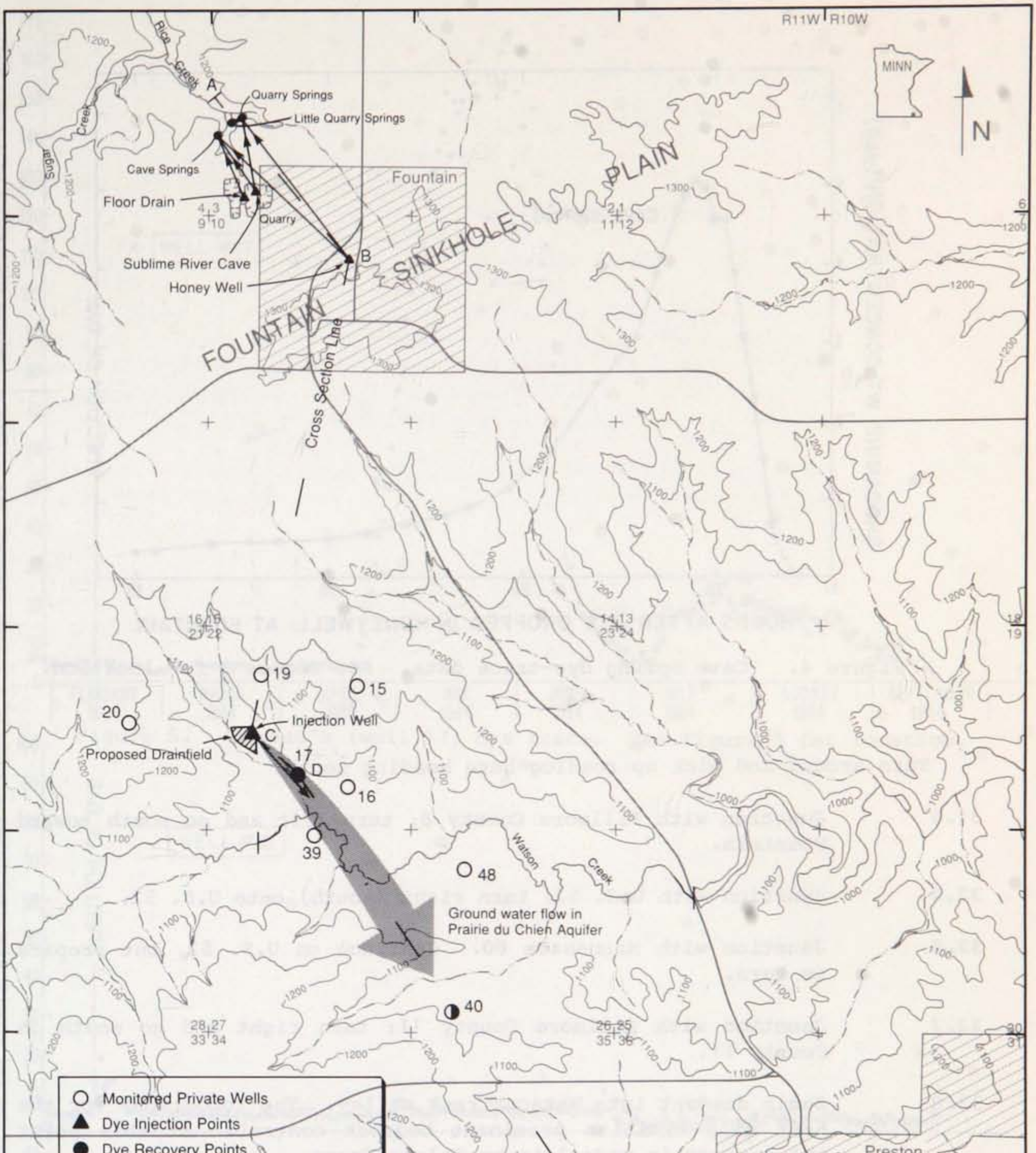


Figure 3. Fountain area karst features and Rhodamine dye-trace wells.

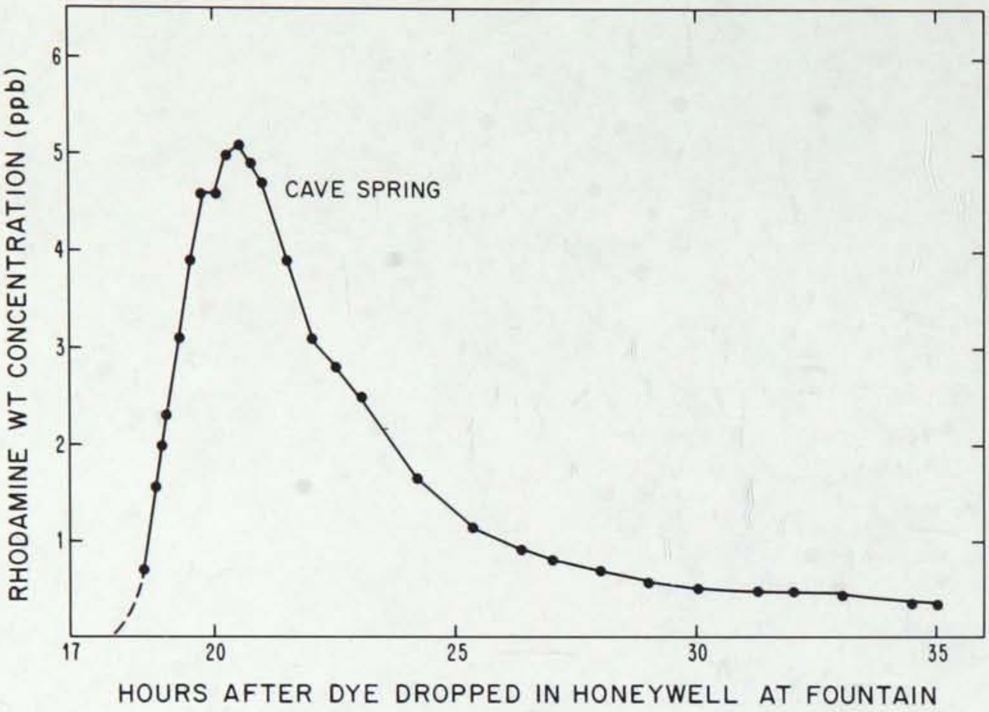


Figure 4. Cave Spring dye-trace data. See Figure 3 for location.

Turn around and pick up roadlog here heading south.

31.9	Junction with Fillmore County 8; turn left and go south toward Fountain.
32.2	Junction with U.S. 52; turn right (south) onto U.S. 52.
32.6	Junction with Minnesota 80. Continue on U.S. 52, but prepare to turn.
32.7	Junction with Fillmore County 11; turn right and go south on County 11.
33.8	Begin descent into Watson Creek valley. The topography for the next mile exhibits prominent bedrock control. At this point the surface is underlain by Galena Group.
34.3	Galena/Decorah contact--note break in topography.
34.5	Platteville bench.
34.6	St. Peter slope.
34.7	Park.
STOP 3.	Proposed site of Fountain Community Drain field. See Figures 3, 5, and 6.

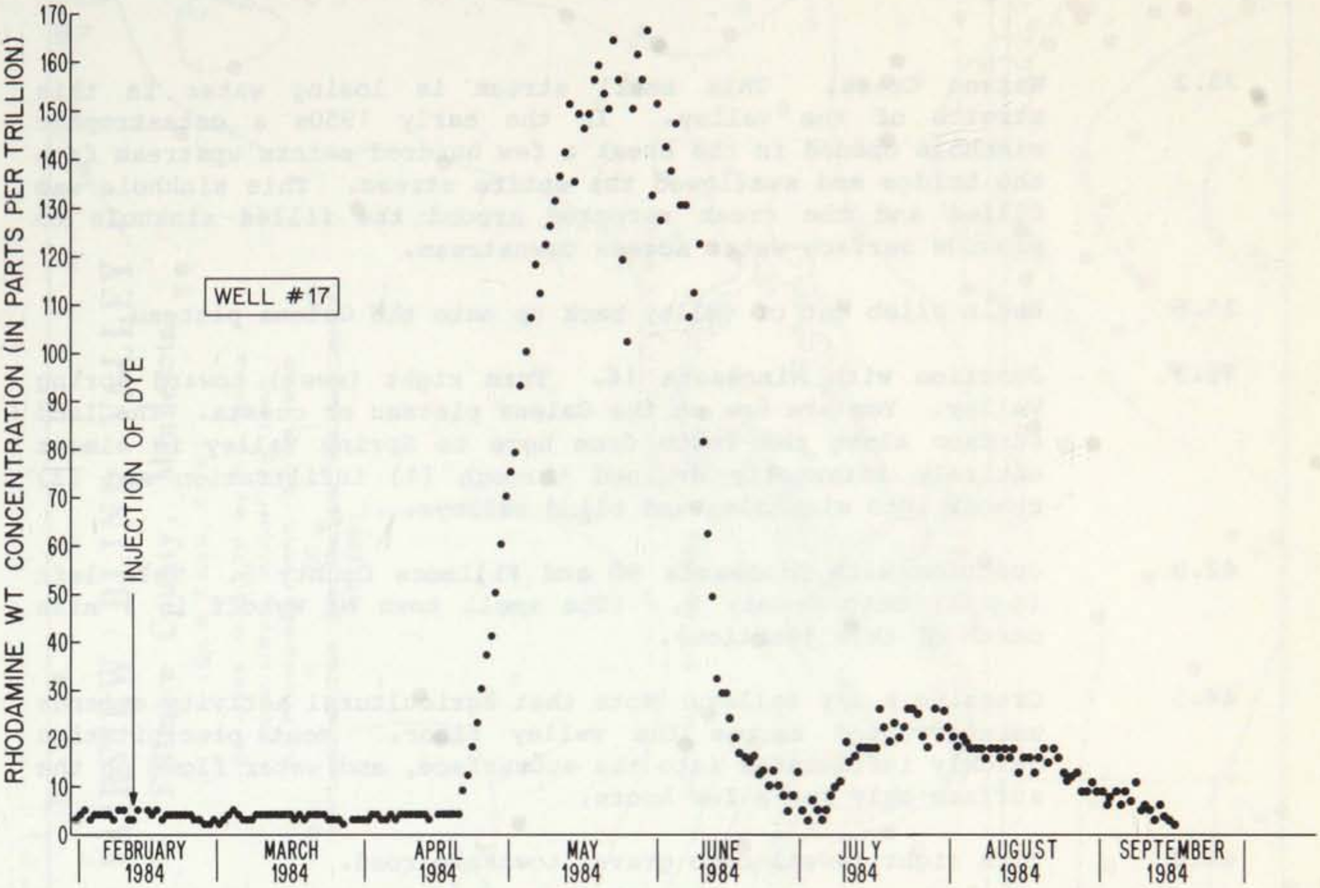


Figure 5. Bernau's (well 17) dye trace. See Figure 3 for location.

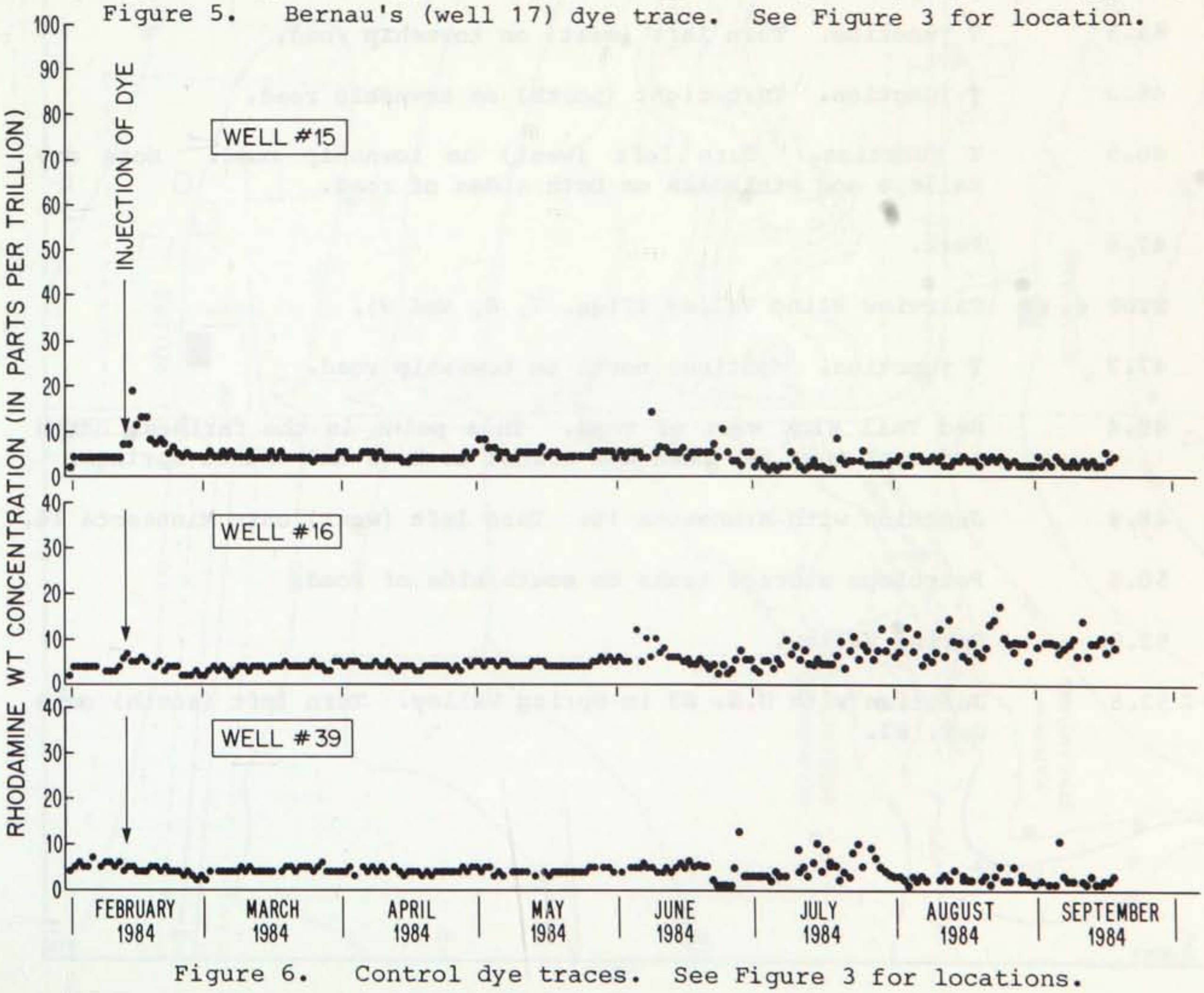


Figure 6. Control dye traces. See Figure 3 for locations.

35.2	Watson Creek. This small stream is losing water in this stretch of the valley. In the early 1950s a catastrophic sinkhole opened in the creek a few hundred meters upstream from the bridge and swallowed the entire stream. This sinkhole was filled and the creek rerouted around the filled sinkhole to provide surface-water access downstream.
35.6	Begin climb out of valley back up onto the Galena plateau.
36.9	Junction with Minnesota 16. Turn right (west) toward Spring Valley. You are now on the Galena plateau or cuesta. The land surface along the route from here to Spring Valley is almost entirely internally drained through (1) infiltration and (2) runoff into sinkholes and blind valleys.
42.8	Junction with Minnesota 80 and Fillmore County 5. Turn left (south) onto County 5. (The small town of Wykoff is 1 mile north of this junction).
44.5	Crossing a dry valley. Note that agricultural activity extends uninterrupted across the valley floor. Most precipitation quickly infiltrates into the subsurface, and water flows on the surface only for a few hours.
44.8	Turn right (west) onto gravel township road.
45.3	T junction. Turn left (west) on township road.
46.3	T junction. Turn right (north) on township road.
46.5	T junction. Turn left (west) on township road. Note dry valleys and sinkholes on both sides of road.
47.4	Park.
STOP 4.	Fairview Blind Valley (Figs. 7, 8, and 9).
47.7	T junction. continue north on township road.
48.4	Red Tail sink west of road. This point is the farthest north and west that has been dye traced to Moth and Grabau Springs.
48.9	Junction with Minnesota 16. Turn left (west) onto Minnesota 16.
50.9	Petroleum storage tanks on south side of road.
52.0	Spring Valley.
52.6	Junction with U.S. 63 in Spring Valley. Turn left (south) onto U.S. 63.

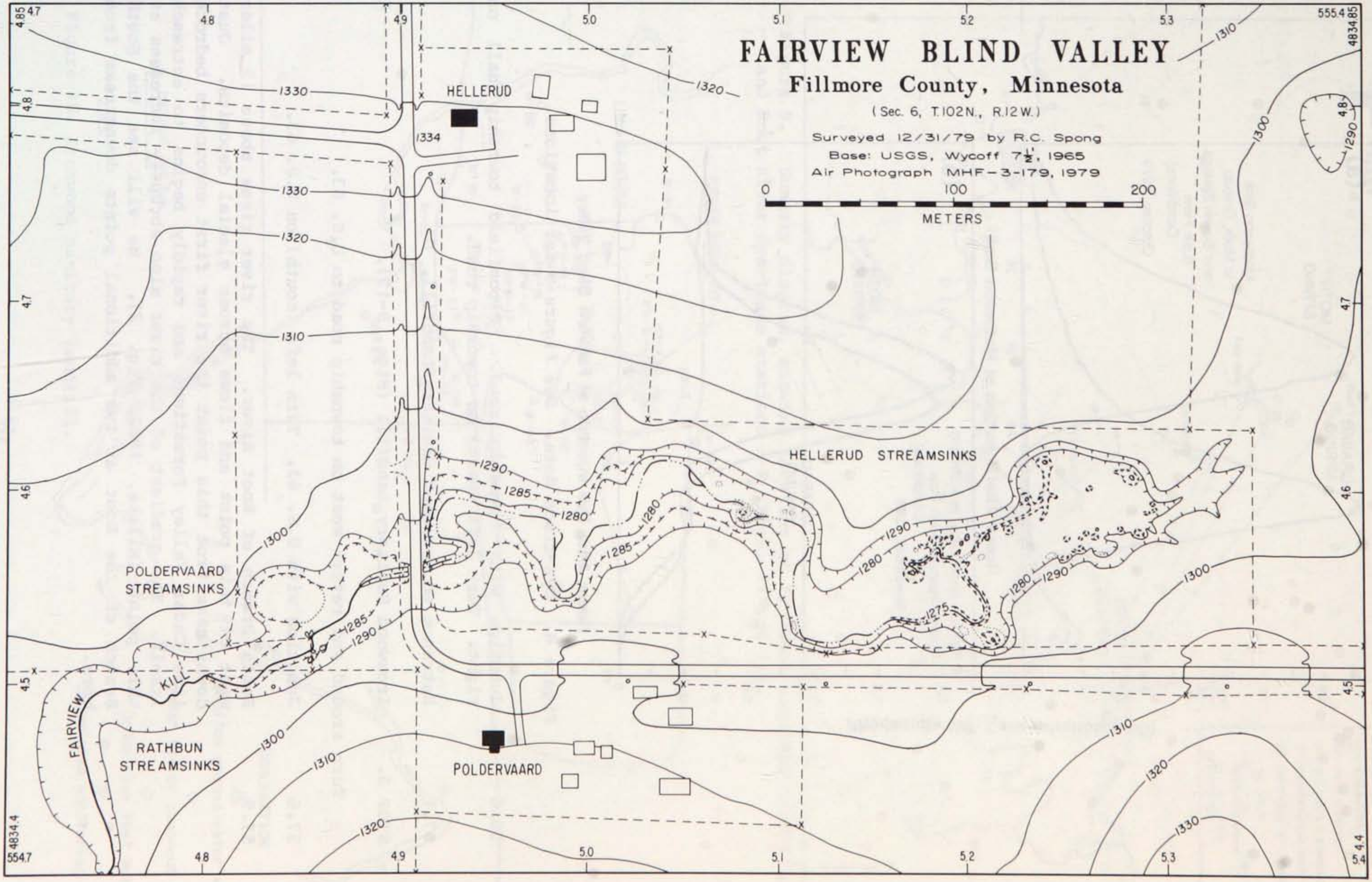


Figure 7. Fairview Blind Valley.

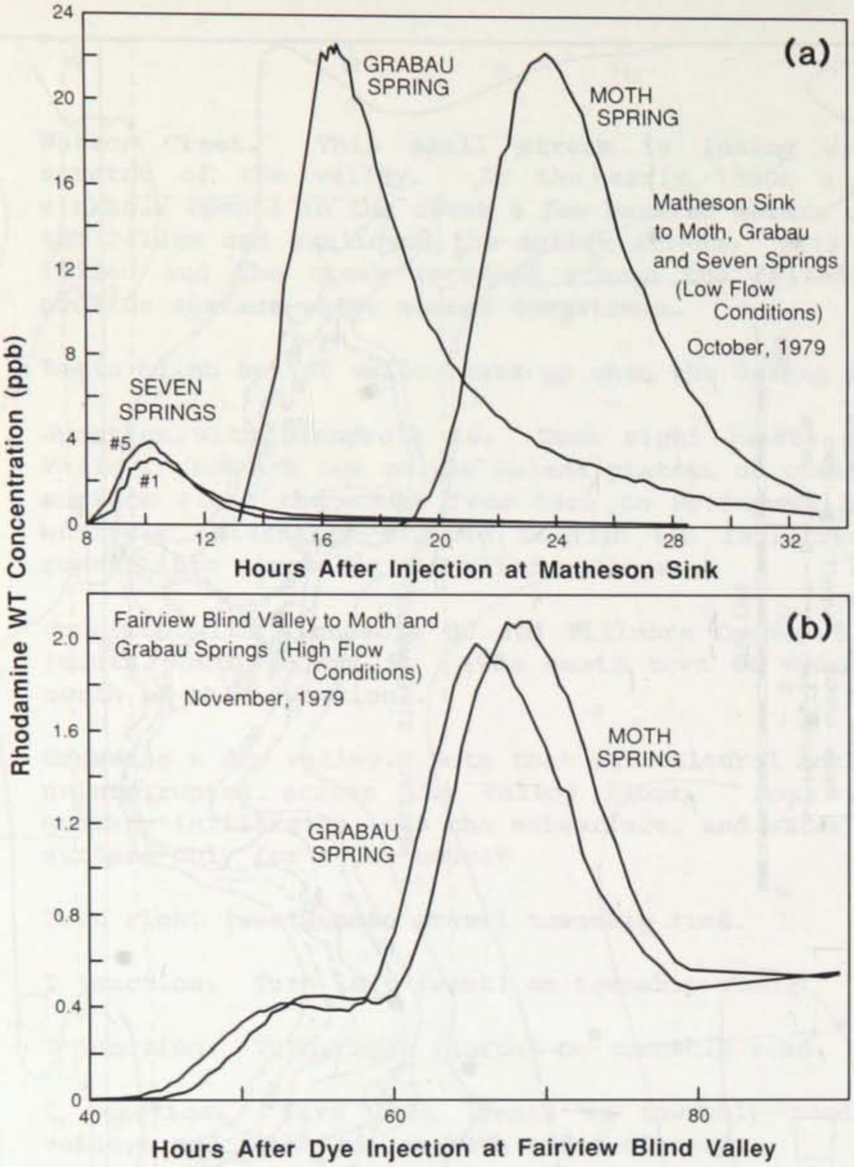


Figure 8. Dye-trace data. See Figure 9 for locations.

56.6 Junction with township road. Bloomfield township hall on right. Turn left (east) on township road.

57.1 Entrance to Ironwood Sanitary Landfill.

STOP 5. Ironwood Sanitary Landfill (Figs. 9-12).

Turn around and return west on township road to U.S. 63.

57.6 Junction with U.S. 63. Turn left (south) on U.S. 63.

57.9 South Branch of Root River. The river rises about 15 miles west of this point and flows across glacial deposits. Just downstream from this point the river first encounters bedrock (the Cedar Valley Formation) and rapidly begins to entrench itself. The gradient of the river also abruptly increases at this point (Milske, 1982, Fig. 2). We will see the South Branch of the Root at two additional points downstream from here.

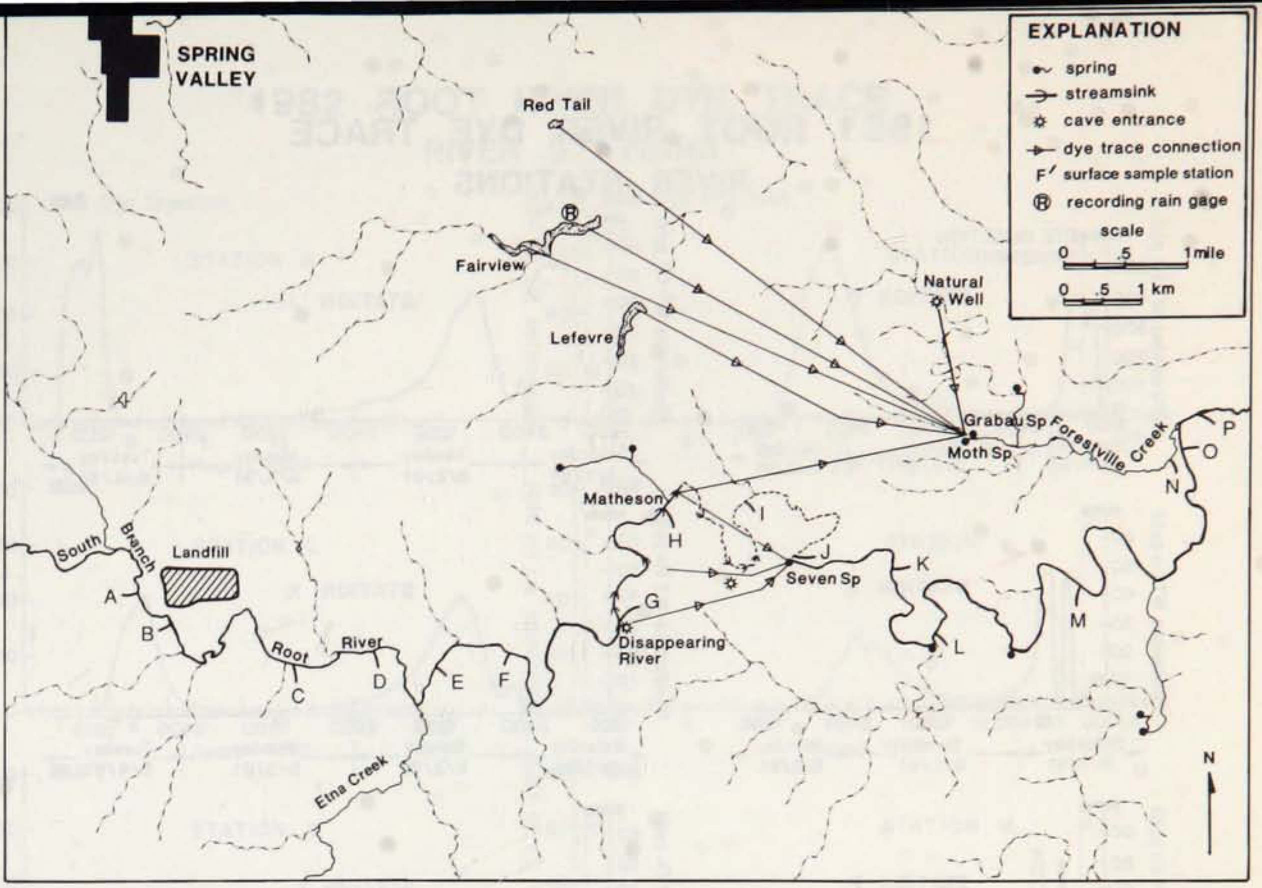


Figure 9. Summary diagram, showing location of Ironwood sanitary landfill and Root River dye-trace stations A-P (Figs. 11 and 12).

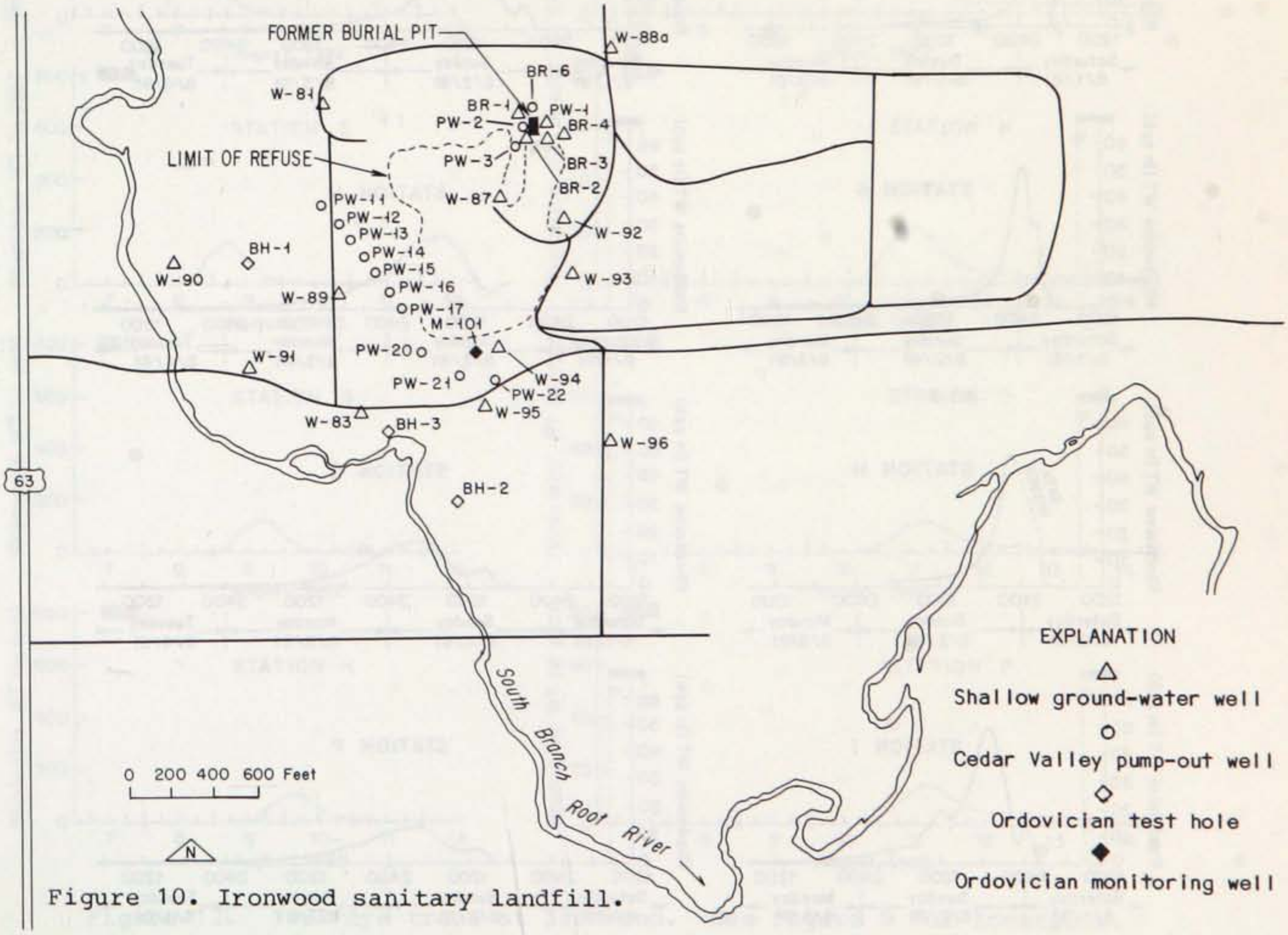


Figure 10. Ironwood sanitary landfill.

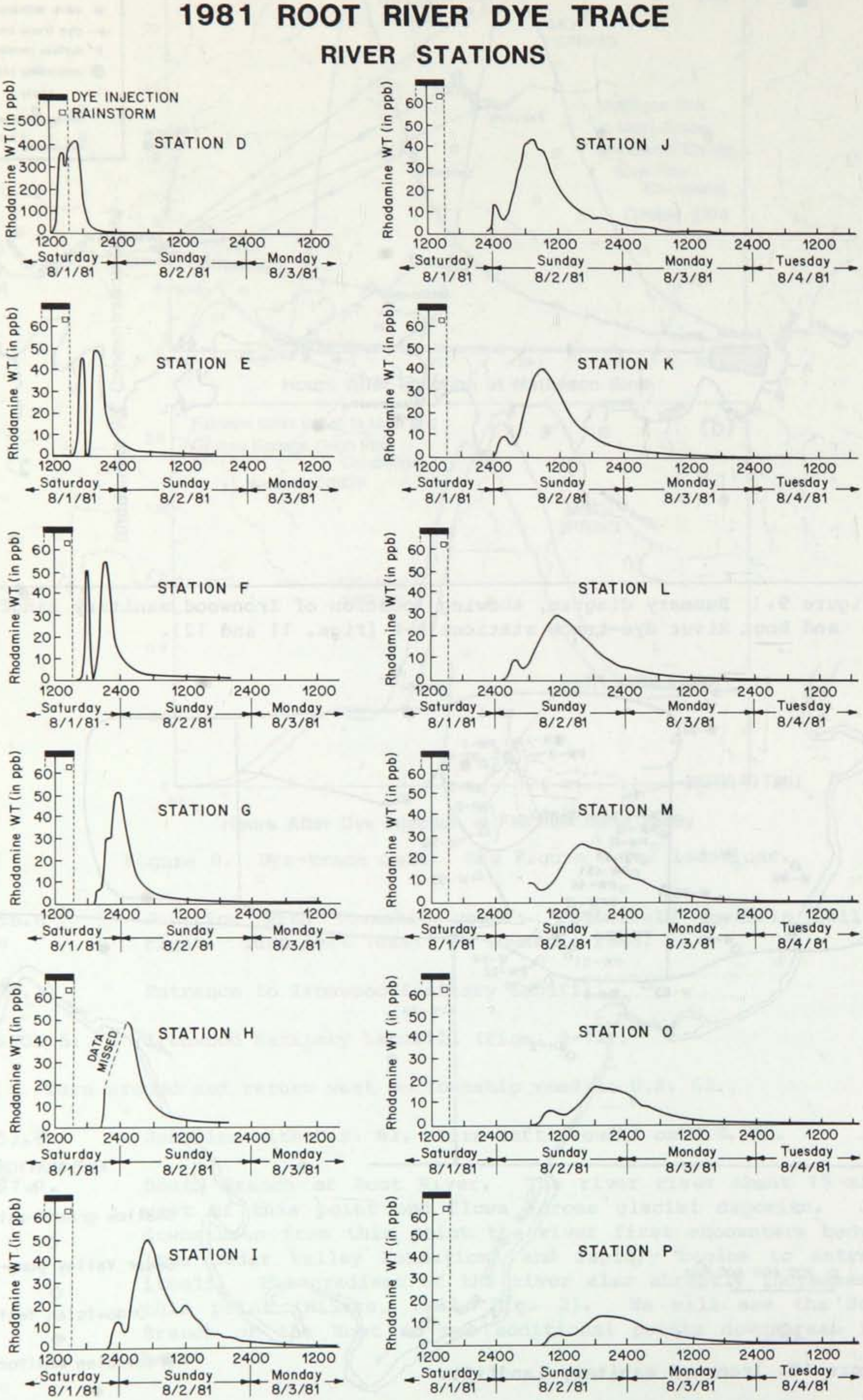


Figure 11. 1981 dye trace at Ironwood. See Figure 9 for locations.

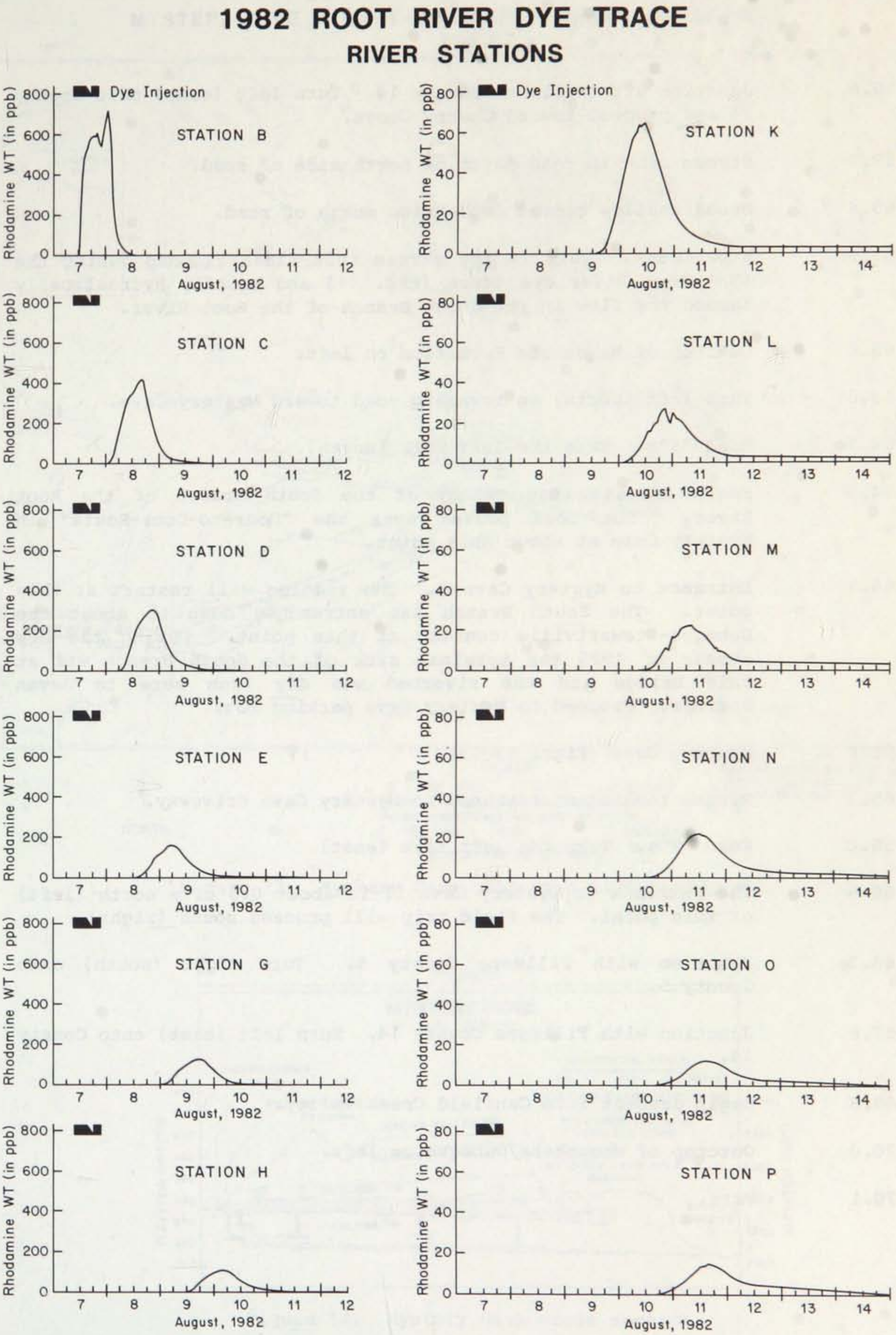


Figure 12. 1982 dye trace at Ironwood. See Figure 9 for locations.

59.6 Junction with Fillmore County 14. Turn left (east) onto County 14 and proceed toward Cherry Grove.

59.7 Stream sink in road ditch on north side of road.

60.4 Broad shallow closed depression north of road.

61.9 Etna Creek. This is the stream that flash flooded during the 1981 Root River dye trace (Fig. 11) and briefly hydraulically dammed the flow in the South Branch of the Root River.

63.0 Outcrop of Maquoketa Formation on left.

63.6 Turn left (north) on township road toward Mystery Cave.

64.7 Road "Y"s. Take the left fork (north).

64.9 Begin descent into valley of the South Branch of the Root River. The road passes over the "Door-to-Door-Route" in Mystery Cave at about this point.

65.3 Entrance to Mystery Cave I. The roadlog will restart at this point. The South Branch has entrenched down to about the Dubuque-Stewartville contact at this point. During the dry summer of 1985 the terminal sink of the South Branch was at this bridge and the riverbed was dry from here to Seven Springs. Proceed to Mystery Cave parking lot.

STOP 6. Mystery Cave (Figs. 13-18).

65.3 Resume roadlog at entrance to Mystery Cave driveway.

65.8 Road "Y"s. Take the left fork (east).

66.6 The entrance to Mystery Cave II is about 0.5 mile north (left) of this point. The field trip will proceed south (right).

66.7 Junction with Fillmore County 5. Turn right (south) onto County 5.

67.6 Junction with Fillmore County 14. Turn left (east) onto County 14.

69.8 Begin descent into Canfield Creek Valley.

70.0 Outcrop of Maquoketa/Dubuque on left.

70.1 Park.

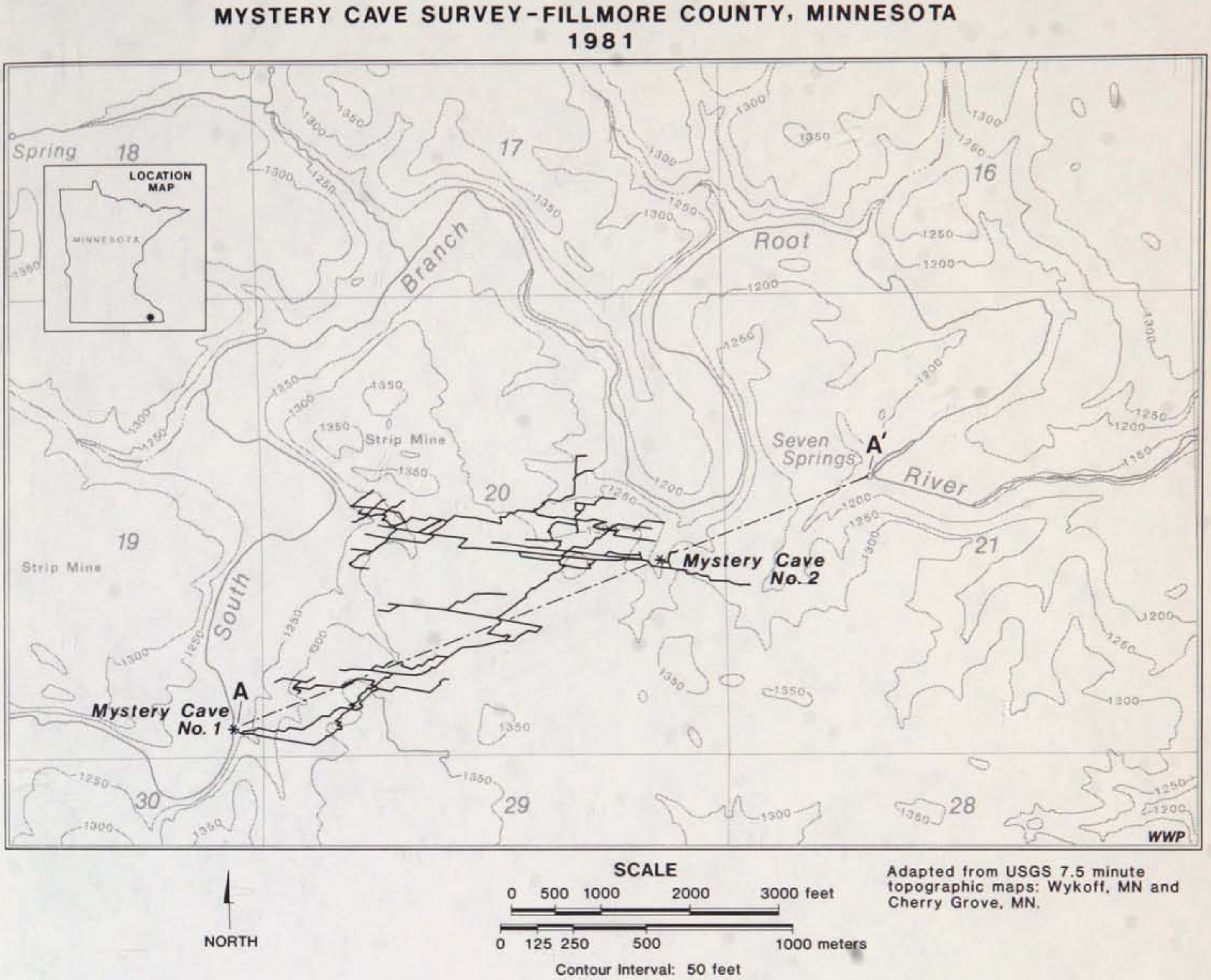


Figure 13. Mystery Cave plan view with topography.

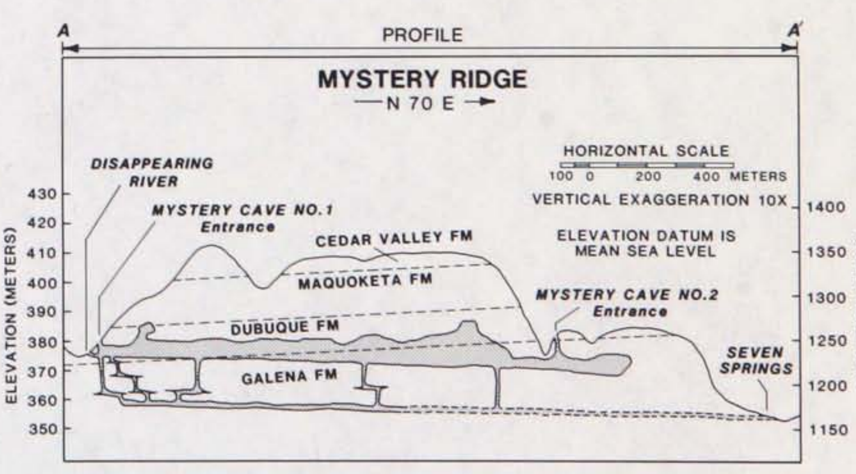
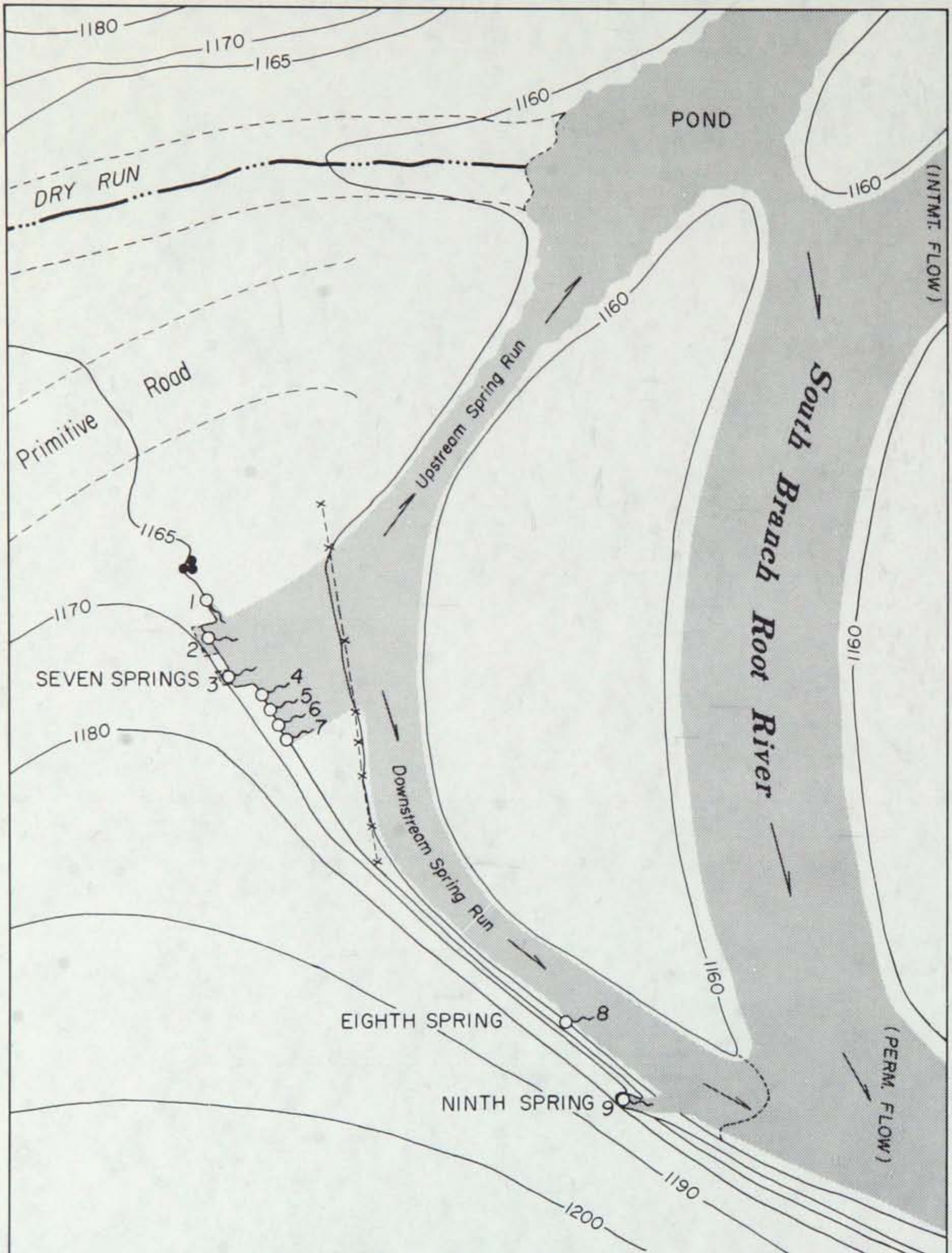


Figure 14. Mystery Cave cross section.



SEVEN SPRINGS & AREA

Fillmore County, Minnesota

(Sec. 21, T. 102N., R. 12W.)

Surveyed 2/8/80 by R.C. Spong
Base: USGS, Cherry Grove 7½', 1965
Contours ±5 feet
0 10
METERS

N
5°
1965 Mag. Declin.

Figure 15.

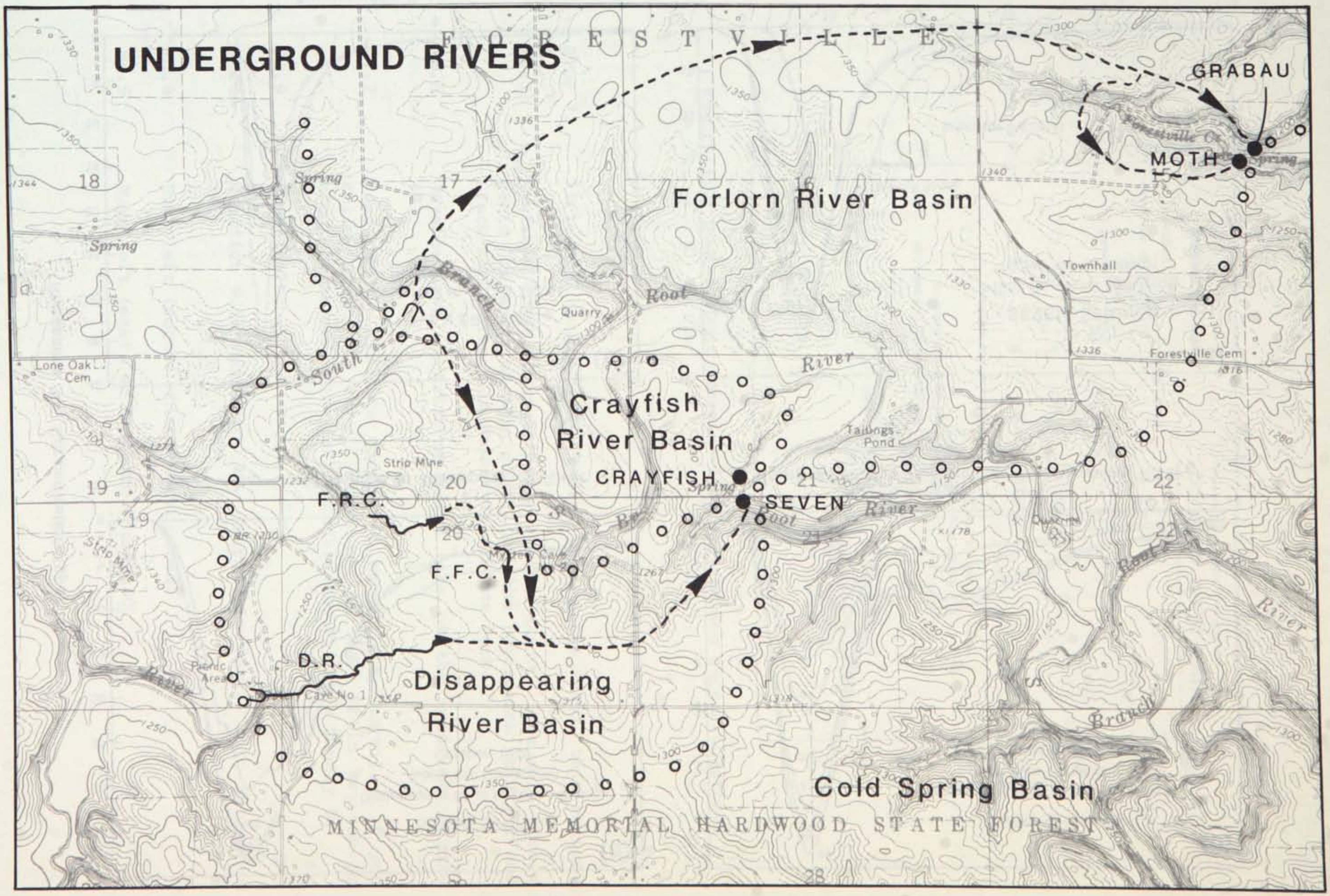


Figure 16. Underground basins and topography.

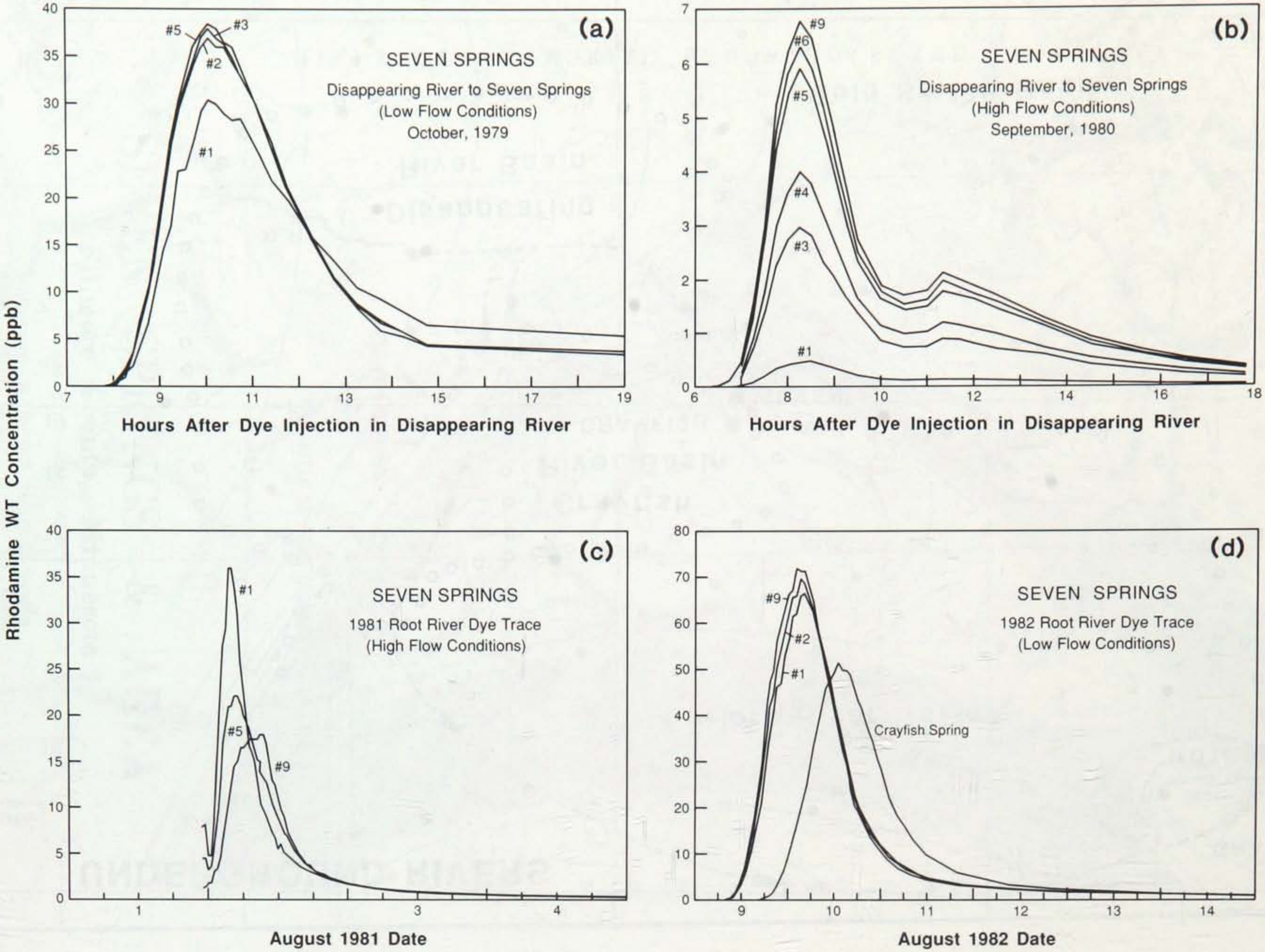


Figure 17. Dye-trace data. See Figures 15 and 16 for locations.

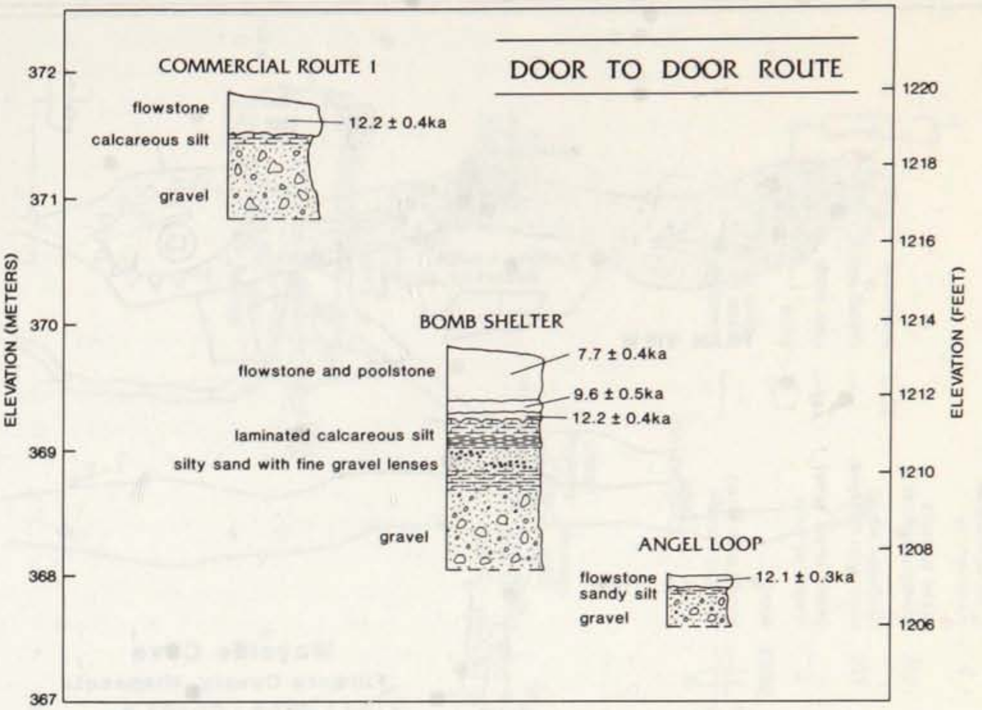


Figure 18. Door-to-Door gravels--sections showing dated flowstone.

STOP 7. Rifle Hill Quarry. See Figures 9-13, pages 84-92, this volume.

70.3 Canfield Creek is usually dry at this point. The main stream sinks are south of this point, and the resurgence is Trout and Black Rock Springs in Forestville State Park.

70.6 Wayside Cave in ditch on north side of the road--see Figure 19.

71.7 Road "Ts". Fillmore County 14 turns left (north). If you follow this road it will take you to U.S. 52 in Preston in about 11 miles. Turn left (south) onto Fillmore County 9.

72.9 Greenleafton.

75.4 Junction with Minnesota 44. Turn left (east) onto Minnesota 14.

82.9 Turn left (south) onto township road.

84.9 Turn left (east) on Fillmore County 30.

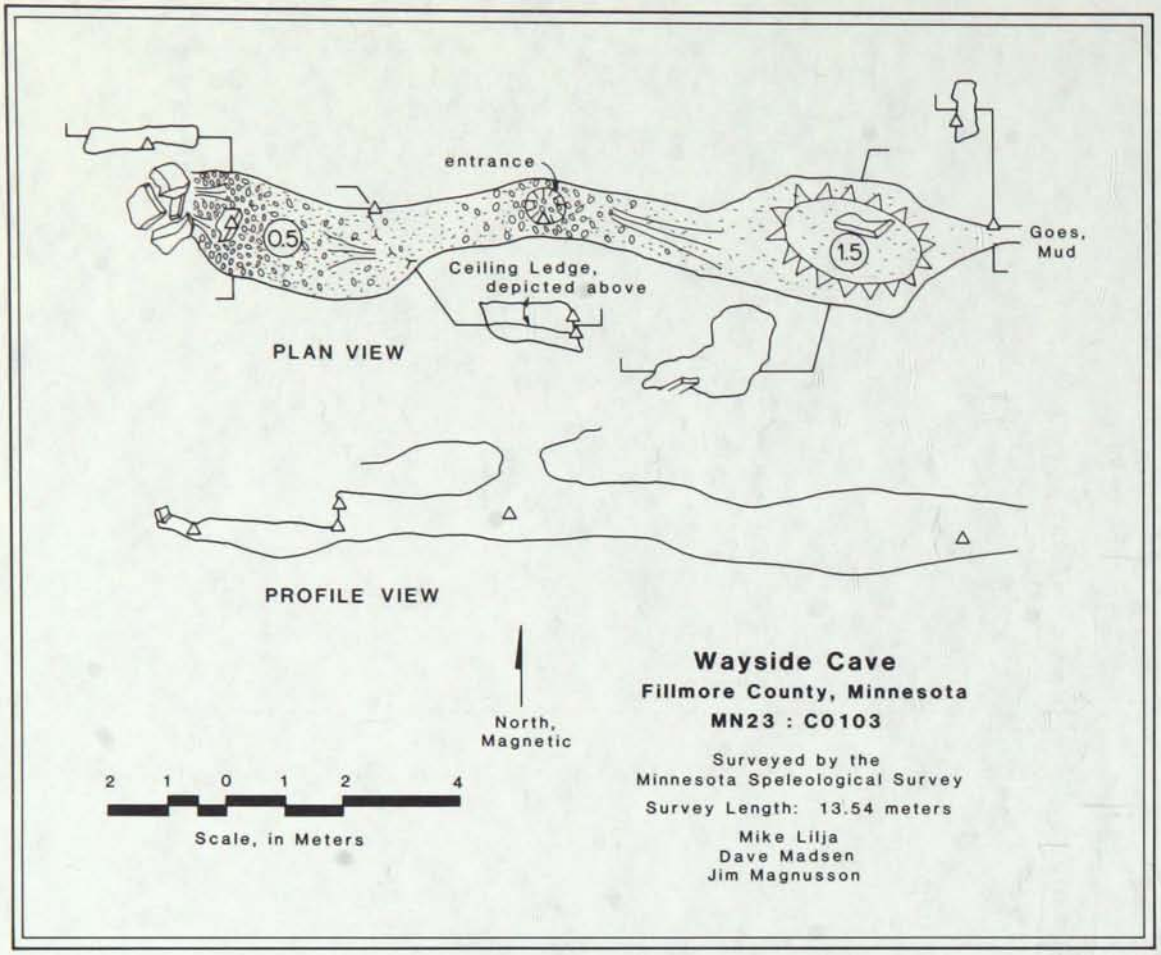


Figure 19. Wayside Cave plan view and profile.

STOP 8. Niagara Cave (Fig. 20).

Continue east on Fillmore 30.

87.4	Junction with Minnesota 139. Turn left (north) on Minnesota 139.
89.5	Harmony.
90.2	Junction with U.S. 52; Minnesota 139 ends. Continue north on U.S. 52.
91.6	Prominent sinkholes along both sides of highway for next 2.5 miles. U.S. 52 north is proceeding along a narrow ridge of Galena. Camp Creek flows in the valley west of the highway and Duschee Creek in the valley east. Both creeks have excavated their valleys down into the Prairie du Chien Group.
98.0	Junction with Minnesota 16. Continue on U.S. 52 toward Preston. As you descend into the valley of the South Branch of the Root River, the topography exhibits pronounced bedrock

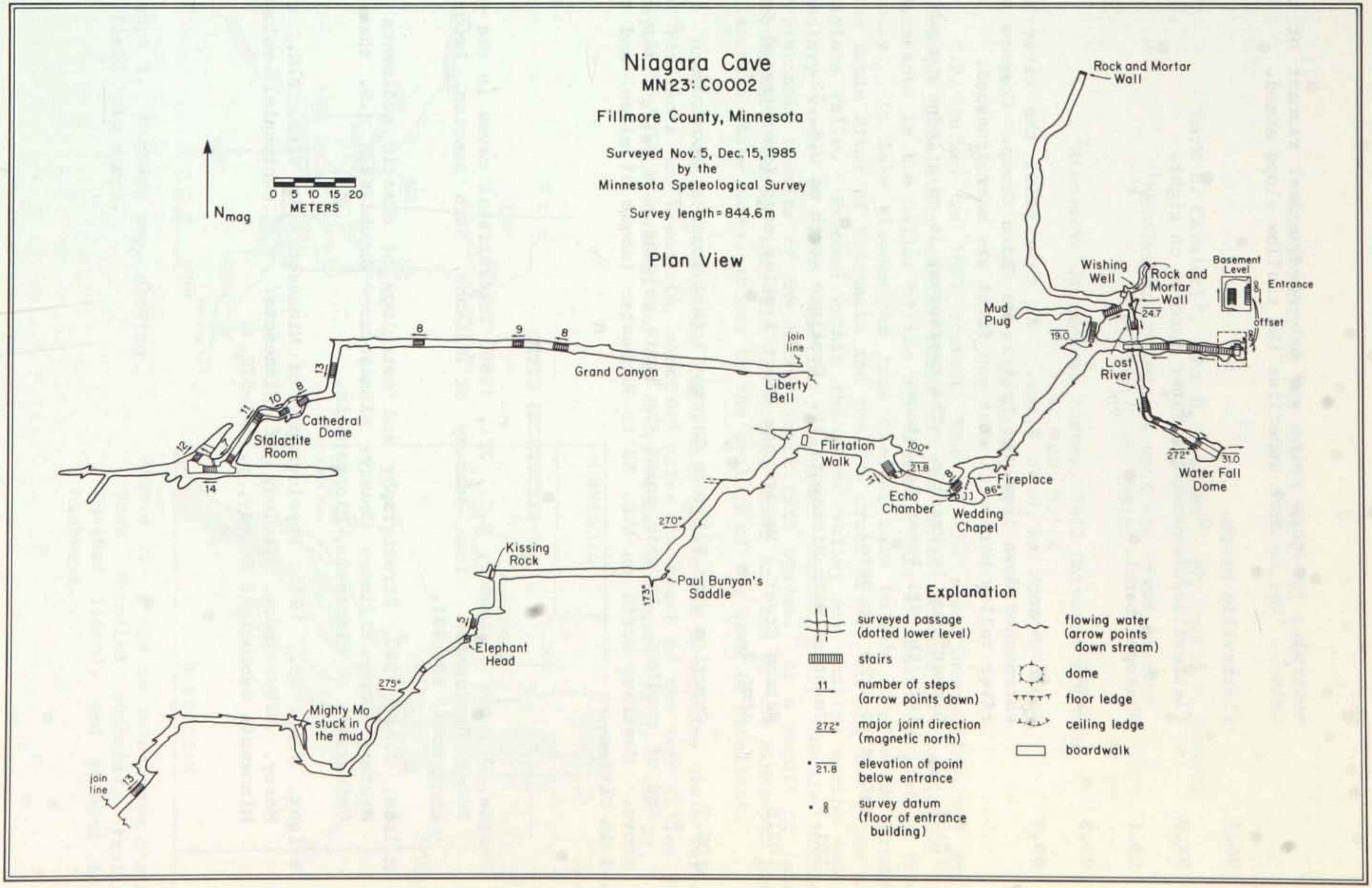


Figure 20. Niagara Cave plan view.

control. At this point you are on the last remnant of the Galena. The Decorah underlies the shallow slope ahead.

98.5 Platteville bench.

98.8 Platteville/Glenwood/St. Peter outcrop on right.

99.1 Shakopee bench.

99.5 Preston.

99.7 South Branch of Root River. At this point the river has entrenched down into the Prairie du Chien Group. Compare the river valley here with what you first saw near Ironwood.

101.1 Dinner stop in Preston. The restaurant is on a ledge excavated into the St. Peter Sandstone.

Return to trip log here.

101.7 Junction with Minnesota 16. Continue north on U.S. 52.

102.6 Watson Creek. We are now about 2 miles east (downstream) from stop 3.

105.7 Junction with Fillmore County 11 just south of Fountain.

End of roadlog. At this point the route rejoins mile 32.7 of the log above. Continue north on U.S. 52 to Rochester (about 31 miles) and the Twin Cities.

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THE GEOLOGY OF THE ST. CROIX RIVER VALLEY

by

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INTRODUCTION

C.P. Berkey in 1897 stated, "One of the most interesting and picturesque localities within reach of the chief centers of population of Minnesota is the Dalles of the St. Croix." This statement is just as true today. In late Wisconsinan time Glacial Lake Duluth overflowed through the Brule River of Wisconsin and the St. Croix River, carving the gorge at Taylors Falls. Exposed within the river valley are shallow marine sedimentary rocks of Late Cambrian age that unconformably overlie Middle Proterozoic basalts of the Midcontinent rift system. As a result of land acquisition through the Wild and Scenic River Act and by the Minnesota and Wisconsin state parks, access to the geology of the area is excellent.

Most of the stops for the field trip are in the Interstate State Parks of Minnesota and Wisconsin, about 40 miles northeast of the Twin Cities at Taylors Falls, Minnesota, and St. Croix Falls, Wisconsin (Figs. 1 and 2).

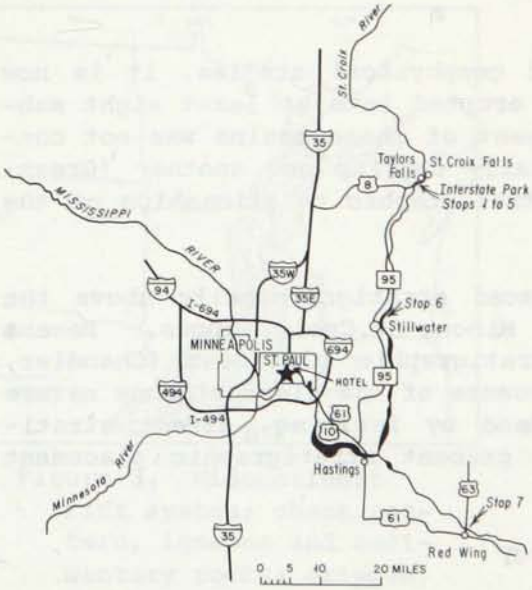

Figure 1. Highway map, showing field trip stops.

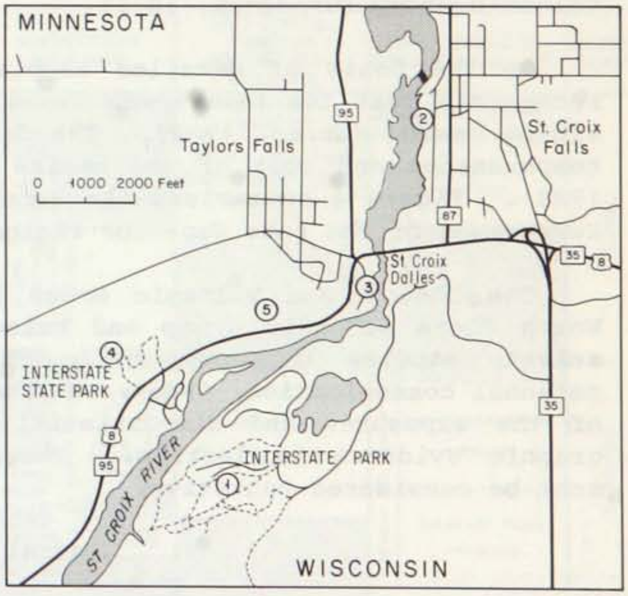

Figure 2. Stops in Interstate State Park (circled numbers), trails (dashed lines), and streets and highways.

KEWEENAWAN ROCKS

The rocks of the Keweenawan Supergroup accumulated at a time of extraordinary volcanic activity, during which the Midcontinent rift system (Fig. 3) was formed. Fissure eruptions of subaerial lavas into overlapping basins and intrusive activity along the length of the rift produced a 2.5-mile-thick (4 km) plateau basalt province covering more than 38,600 square miles (100,000 km^2) (BVSP, 1981). This province shows many similarities to other great plateau basalt provinces, such as the Deccan Traps and the Columbia River Plateau (Green, 1982).

Following the rifting event, the Keweenawan volcanics underwent metamorphism, folding, faulting, uplift, and erosion. These modifications were probably closely associated with the Grenville orogen (Van Schmus and Hinze, 1985). Today these rocks are exposed only in a narrow arcuate band through the Lake Superior region. The southernmost outcrops are the lavas, tuffs, and interflow sedimentary rocks of the Chengwatana Volcanic Group in the Taylors Falls-St. Croix Falls area.

Stratigraphy

Hall (1901) referred to the lavas in the St. Croix River valley as the "Chengwatana series," after the type locality on the Snake River east of Pine City, Minnesota. The early studies, such as those of Berkey (1897), Hall (1901), and Van Hise and Leith (1911), assumed the Keweenawan volcanism to have been of very short duration, and thus all of the Keweenawan volcanics of the Lake Superior region were presumed to be contemporaneous. As a result, as recently as 1972, the lava flows cropping out at Taylors Falls were thought to be the southernmost extension of the North Shore Volcanic Group (Craddock, 1972).

On the basis of detailed mapping and geophysical studies, it is now recognized that the Keweenawan lavas were erupted into at least eight subsiding basins (Green, 1982). The development of these basins was not contemporaneous and most of the basins partially overlap one another (Green, 1983). Figure 4 summarizes the general stratigraphic relationships of the Keweenawan of the Lake Superior region.

The Chengwatana Volcanic Group is placed stratigraphically above the North Shore Volcanic Group and below the Minong-St.Croix Ranges. Recent seismic studies lend support to this stratigraphic placement (Chandler, personal communication, 1986). However, because of the discontinuous nature of the exposures and discontinuities caused by faulting, direct stratigraphic evidence is lacking. Thus, the present stratigraphic placement must be considered tentative.

General Geology

The Chengwatana Volcanic Group accumulated in a rather elliptical northeast-trending basin (White, 1978). The group is bounded on the west by the Douglas and Pine faults and on the east by the Lake Owen and Cottage Grove faults (Fig. 5). Although it is clear the Chengwatana Volcanic Group of Pine and Chisago counties extends northeastward into Wisconsin, the northern boundary has not yet been established due to the lack of outcrop.

A series of faults in south-central Burnett County, Wisconsin, which cuts across the general trend, may mark the northern boundary. The southern boundary also has not been established because the southwestern extension from Taylors Falls is covered by Upper Cambrian sedimentary rocks.

The total stratigraphic thickness of the Chengwatana Volcanic Group is estimated to be 20,000 feet (6 km) (Hall, 1901). Within the area at Taylors Falls and St. Croix Falls, more than 1.2 miles (2 km) is represented (Cordua, 1980). A northeast-trending ridge, just north of Dresser, Wisconsin, provides almost continuous exposure of 0.75 mile (1.2 km) of the section. This sequence consists of more than 30 flows or flow units ranging in thickness from less than 6.5 to more than 115 feet (<2 to >35 m). In places the flow sequence is interrupted by thin layers of volcanic tuff and breccia (Berkey, 1897). Unlike the exposures along the Snake River in Pine County, interflow sedimentary material is scarce and confined to small depressions on the flow tops. The Chengwatana Volcanic Group lies within the Lake Superior (Ashland) syncline. The syncline is asymmetric with steep eastward dips in Pine County, while in the Taylors Falls area the dips are westward at 10° to 20°. The flows generally strike to the north at Taylors Falls with local variations from 15° west of north to 10° east of north.

Within the region are a series of east-northeast-trending high-angle faults (Dutton and Bradley, 1970). The faults have had a complex history. As noted by Cordua (1978), early dip-slip motions on some faults were followed at some later time by motions that were primarily strike-slip. In addition, these faults were reactivated after Late Cambrian time (Morey and Mudrey, 1972). This folding and faulting produced a series of east-north-

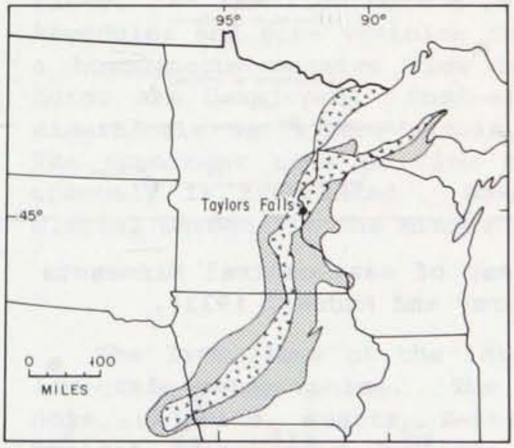

Figure 3. Midcontinent rift system; check pattern, igneous and sedimentary rocks; stipple, late Upper Keweenawan clastic rocks in basins flanking the main rift sequence (modified from Van Schmus and Hinze, 1985).

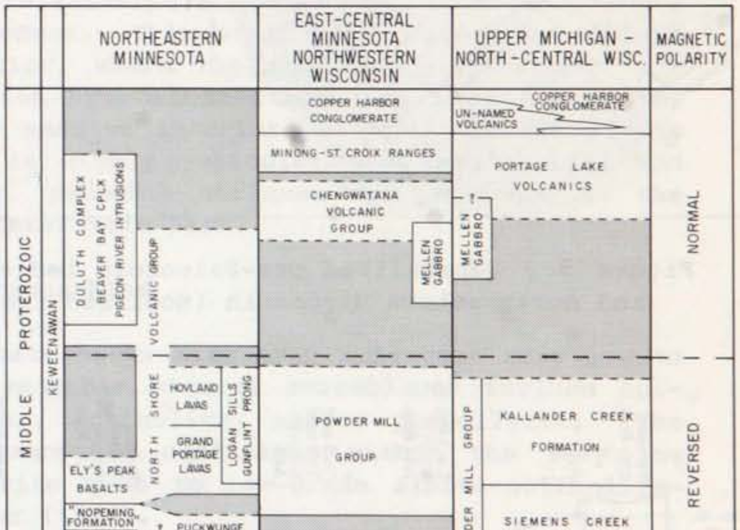

Figure 4. Generalized stratigraphic correlations of Keweenawan rocks in the Lake Superior basin (modified from Green, 1982).

east-trending ridges with steplike longitudinal profiles (Fig. 6). The east-facing slopes are very steep, and the shallow west-facing slopes have developed on the flow tops.

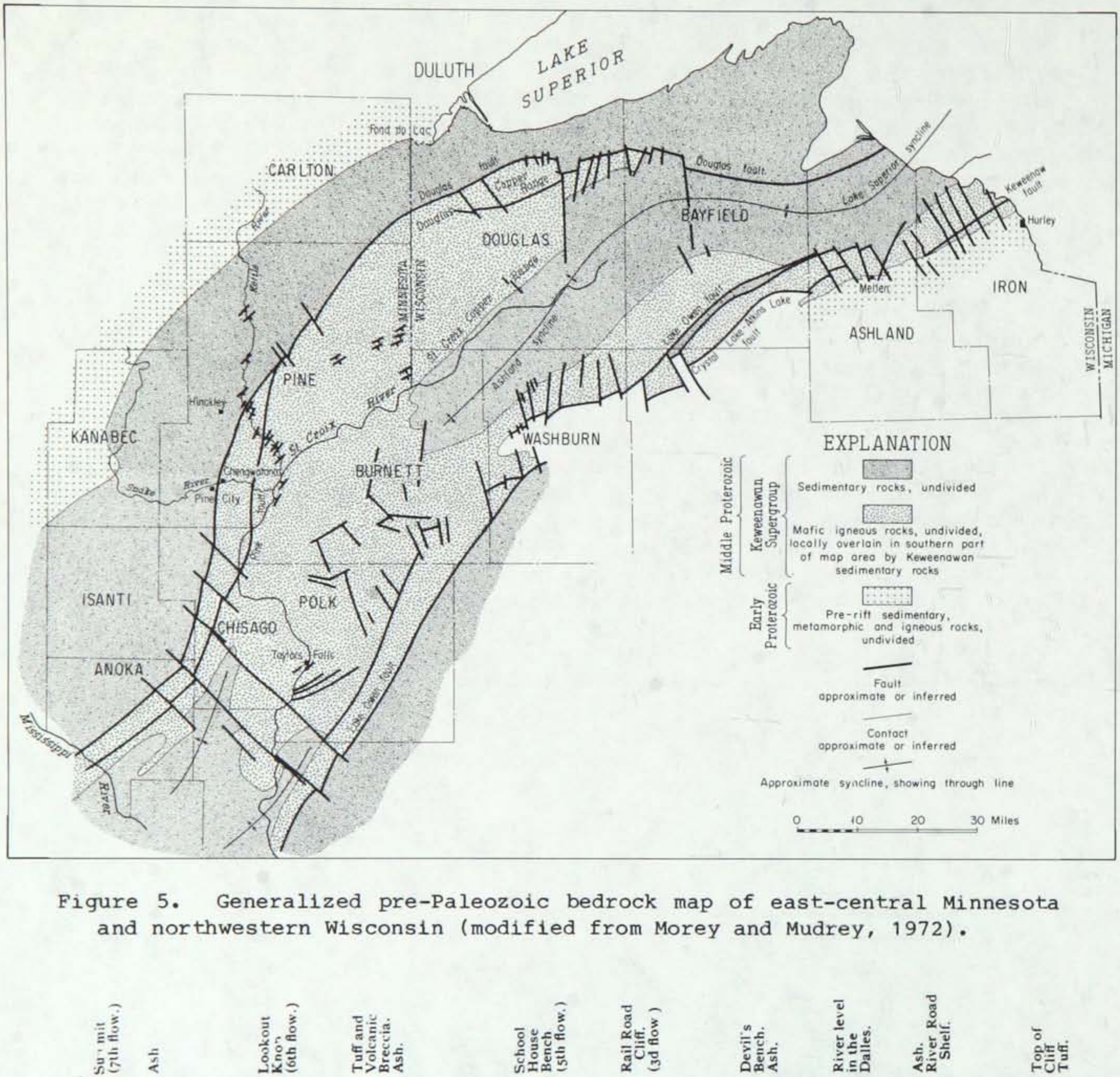

Figure 5. Generalized pre-Paleozoic bedrock map of east-central Minnesota and northwestern Wisconsin (modified from Morey and Mudrey, 1972).

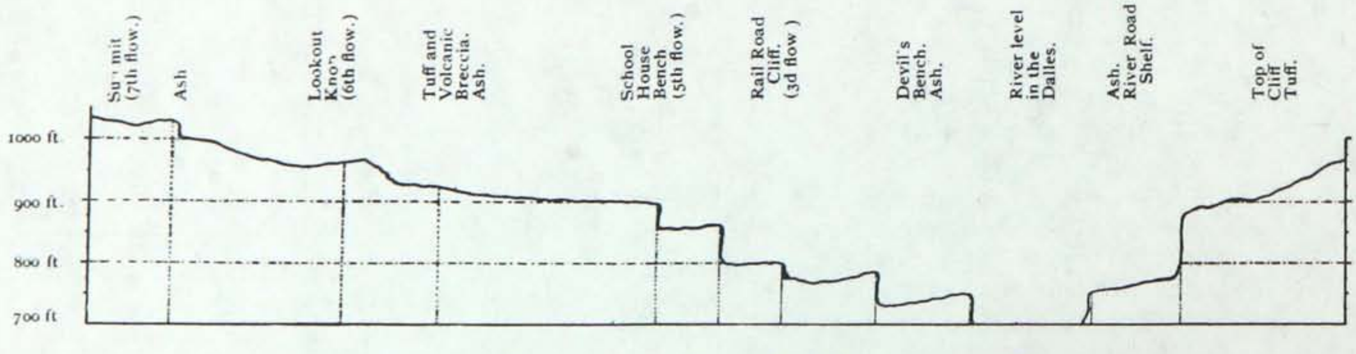

Figure 6. Topographic profile at Taylors Falls showing elevations in feet above sea level of the seven flows (from Berkey, 1897).

Petrography of the Flows

Within the Minnesota and Wisconsin interstate parks, three textural varieties of lava flows can be observed. These are (1) "luster mottled" or ophitic basalts, (2) plagioclase-phyric basalt, and (3) melaphyres or aphyric basalts.

The "luster mottled" or ophitic texture is most common in the area. It is characterized by medium to coarse, almost circular pyroxene oikocrysts, which partially or completely enclose laths of plagioclase. Pyroxene oikocrysts as large as 3 cm can be found in the interiors of the thickest flows. The pyroxenes on the fresh dark-greenish-gray fracture surfaces give the rock its "luster mottled" appearance. The weathered surfaces are pitted and grayish brown in color.

Although less common, plagioclase-phyric rocks can be found at several locations within the interstate parks. Large lath- to equant-shaped plagioclase phenocrysts, some as large as 5 cm, are abundant, and in places compose about half the rock. They are clear to gray, but weather to a milky white or pink to red color. This texture is well exposed along the Eagle Peak Trail in Wisconsin's Interstate Park.

Melaphyres or aphyric basalts, the least abundant of the flows, are very dark gray aphanitic rocks. Careful inspection of the outcrops does show that these rocks contain scattered large plagioclase crystals, and in thin section they display a subophitic texture. This rock type can be seen in a small quarry on the Eagle Peak Trail.

Individual flows exhibit textural variations typical of Keweenawan flows. At the flow bottom is a relatively thin aphanitic (quenched) zone. Amygdules and pipe vesicles are common. This basal zone grades upward into a homogeneous massive flow interior, where the previously described textures are developed. Post-eruption crystal fractionation is evidenced by mineralogic variations within the massive interiors of the thickest flows. The uppermost zone or flow top is highly vesicular and amygdaloidal and commonly is brecciated. However, pahoehoe surfaces can be found at the Glacial Gardens in the Minnesota Interstate Park.

Metamorphism

The lava flows of the interstate parks area have undergone very low to low-grade metamorphism. The metamorphic mineral assemblages include epidote, chlorite, quartz, K-feldspar, actinolite, and/or pumpellyite. The typical assemblages indicate metamorphic conditions within the very low grade pumpellyite-actinolite-chlorite zone to low-grade albite-actinolite-chlorite zone as defined by Winkler (1976).

The amygdaloidal flow tops and flow bases are the most pervasively metamorphosed, being almost completely epidotized. Microscopic examination of the amygdules shows clear evidence of multiple stages of hydrothermal activity. The amygdule mineral assemblages indicate hydrothermal temperature ranges from 130°C to 360°C (Ali, 1982). Cordua (1980) estimates a depth for burial metamorphism of at least 2 miles (3.5 km) and temperatures ranging from 255°C to 440°C.

Petrogenesis

The Chengwatana Volcanic Group exposed in the Taylors Falls area may be broadly classified as "transitional" or "Fe-Ti" basalts as defined by Green (BVSP, 1981). The Chengwatana basalts contain less than 52% (wt.) SiO_2, have Mg' values (Mg/(Mg+0.9Fe), atomic %) ranging from 49 to 34% and contain higher abundances of Ti, K, P, and other incompatible elements than most ocean floor (MORB) basalts (Cavaleri, 1987). All flows are tholeiitic (i.e., hypersthene normative), but the uppermost seven flows tend to be slightly quartz normative (<3%) and the lower eight flows are olivine normative (1.7-5% ol). The upper quartz tholeiites have more evolved (lower) Mg' values (0.36 ±0.02) than the lowermost olivine tholeiites (0.46 ±0.03).

The geochemical data provide evidence that at least two major eruptive cycles characterized by distinct magma compositions produced the lavas in the Taylors Falls area. The eight olivine tholeiite flows, which were produced during the first cycle, can be related by fractional crystallization of plagioclase and pyroxene. The second cycle produced the seven quartz tholeiite flows whose relative compositions cannot be explained simply by fractional crystallization, but may have involved magma mixing. The difference in incompatible element ratios between the two sequences of flows indicates distinct parent magma compositions. These compositional differences may have resulted from variable degrees of partial melting of a common source. Although generally similar in composition to transitional basalts from other Keweenawan basins, the Chengwatana Volcanic Group basalts define differention trends which are distinct from those of the North Shore Volcanic Group, Grandview-Minong area, and Portage Lake Volcanics (Cavaleri, 1987).

CAMBRIAN STRATA OF MINNESOTA

During Late Cambrian time, Minnesota was the site of a shallow epeiric sea that was generally confined to the southern and southeastern part of the state, with a shoreline trending southwestward from north of the Twin Cities to the southwestern part of the state. Sediments accumulated in a shallow depression, which shoaled to the north, between the northeast-trending Transcontinental Arch in Minnesota and the Wisconsin Dome and north-trending Wisconsin Arch (Fig. 7). This sedimentary basin, named the Hollandale embayment by Austin (1970), extended across Iowa to the Ozark basin of southern Missouri (Bunker and others, 1985, p. 77).

Although the position of the shoreline during Late Cambrian time undoubtedly varied, isopach maps of the Upper Cambrian strata (Berg and others, 1956; Ostrom, 1964; Austin, 1972; and Mossler, 1983) indicate that the maximum transgressive shoreline was roughly parallel to the present boundary of the Paleozoic rocks.

St. Croixan Series

Upper Cambrian sandstones, siltstones, and shale (Fig. 8), together with overlying Lower Ordovician dolostones of Minnesota, are part of the first of six broad marine transgressions, which crossed the North American craton during Phanerozoic time (Sloss, 1963). The rocks resulting from this transgression are named the Sauk sequence.

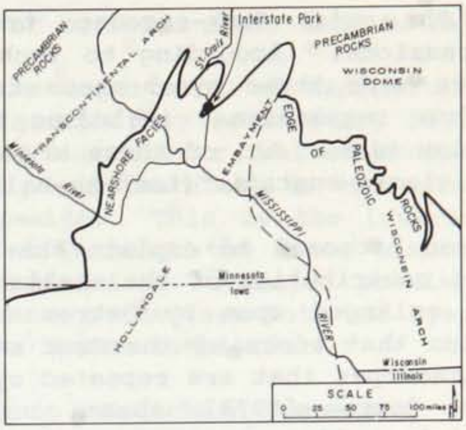

Figure 7. Large structural elements in southeastern Minnesota and adjacent states (modified from Austin, 1970).

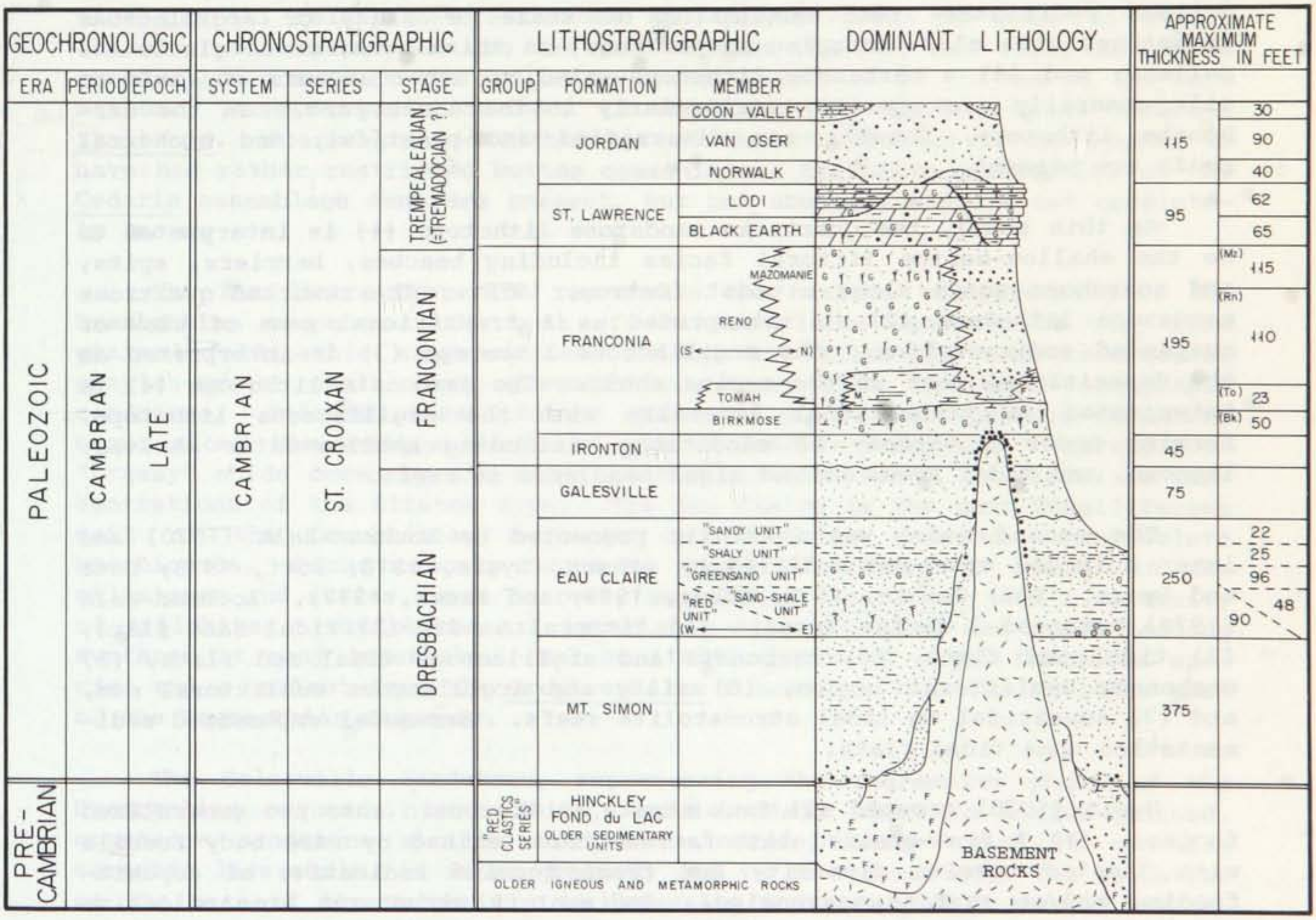

Figure 8. Stratigraphic column of Upper Cambrian rock units in Minnesota (from Mossler, in prep.).

Superimposed upon the major Sauk-sequence transgression are smaller regressions and transgressions. According to Lochman-Balk (1970), during Late Cambrian time there were three synchronous transgressions, including the initial one, and four regressions, including the one that marked the beginning of Late Cambrian time. All of these are ascribed to eustatic sea level changes, possibly glacio-eustatic (Lochman-Balk, 1970).

Two models have been proposed to explain the lithofacies of the Sauk sequence. The principal contribution of the earlier model proposed by Berg and others (1956) and enlarged upon by Ostrom (1964, 1978) and Austin (1970) is the recognition that rocks of the Sauk sequence could be grouped into several primary lithotopes that are repeated cyclically throughout the sequence. According to Ostrom (1978), these consist of (1) a quartzose sandstone lithotope--mainly well-sorted, clean, friable, medium- and fine-grained sandstone, with some coarser sand- to cobble-size material in the basal few feet; (2) a reworked quartzose sandstone lithotope--coarse-grained sandstones which commonly are interbedded with poorly sorted strata composed of materials ranging in size from clay to granules or interbedded with arenaceous carbonate strata; (3) an argillaceous lithotope--fine-grained sedimentary rock consisting of shale or silty or argillaceous sandstone, with clay occurring in partings, as thick beds, or as glauconite pellets; and (4) a carbonate lithotope--sand or minor amounts of shale or silt generally are present, particularly in the lower part. In the carbonate lithotope, fossils are diversified and plentiful, and biohermal reefs are present.

In this model, the quartzose sandstone lithotope (1) is interpreted to be the shallow-marine littoral facies including beaches, barriers, spits, and nearshore zones along a coast (Ostrom, 1978). The reworked quartzose sandstone lithotope (2) is interpreted as a transitional zone of slow or suspended sedimentation. The argillaceous lithotope (3) is interpreted as the depositional zone of the marine shelf. The carbonate lithotope (4) is interpreted as transitional laterally with the argillaceous lithotope, forming under a variety of conditions, including shallow-water shelves, lagoons, and tidal areas behind algal headlands or reefs.

The second model was initially presented by Lochman-Balk (1970) and later enlarged upon and modified by others (Byers, 1978; Dott, 1978; Dott and Byers, 1980; Driese, 1979; Huber, 1975; and James, 1977). Lochman-Balk (1970) proposed 7 facies types: (1) littoral sands, (2) tidal sand flats, (3) tidal mud flats, (4) carbonate and argillaceous tidal mud flats, (5) carbonate sublittoral lagoon, (6) silty and argillaceous sublittoral mud, and (7) supratidal to tidal stromatolite reefs. Her model emphasized sedimentation upon tidal flats.

Byers (1978) grouped all Sauk strata in Wisconsin into two generalized facies: (1) A fine-grained lithofacies characterized by rare body fossils with limited species diversity and trace fossils indicative of deposit-feeding and/or surface scavenging. Sedimentary structures are indicative of episodic or fluctuating energy levels; some are indicative of very shallow water or subaerial exposure. (2) A coarse-grained lithofacies dominated by quartzose sandstones with medium median grain sizes and well-rounded grain shapes and characterized by medium-scale trough cross-bedding. Body fossils are rare and trace fossils are dominated by Skolithos-type burrows. The tops of burrowed zones tend to be sharply truncated.

Byers emphasized the importance of sedimentary structures and trace fossil assemblages in interpreting sedimentary regimes. Byers (1978) and Driese (1979) interpreted the coarser grained sandstone units as representing subtidal sand shoals, and therefore as the offshore equivalents of the finer grained tidal deposits. This is the inverse of the interpretation made in the earlier model in which the finer grained facies are considered to represent offshore deposition. A major problem in applying the tidal flat model for Sauk sequence rocks (see Dott and Byers, 1980) is the absence of any deltaic or barrier lagoon complexes.

Dresbachian Sequence

As shallow epicontinental seas flooded Minnesota during Late Cambrian time, they crossed a land surface of low relief cut into mostly Middle Proterozoic clastic sedimentary rocks. The Mt. Simon Sandstone typically is white to light-gray, fine-, medium-, and coarse-grained, cross-bedded to massive, quartzose sandstone with very minor interbedded light-gray, very fine grained feldspathic sandstone and grayish-green to pale-red shale. Inarticulate brachiopods are the most common fossils, and their macerated remains are common in the medium to coarse sandstone at the top of the formation. Massive sandstone beds in the upper Mt. Simon contain numerous Skolithos. Coarse-grained lithotopes of the St. Croixan Series appear to have had rather restricted bottom communities; trilobite communities of the Cedaria assemblage zone are present, but not abundant and are not completely known.

The Eau Claire Formation represents the maximum transgression of the Dresbachian sequence. The bulk of the Eau Claire consists of very fine grained feldspathic sandstone and feldspathic siltstone with interbedded grayish-green shale and glauconitic, very fine grained feldspathic sandstone. Pale-red fossiliferous shale and silty, fine-grained sandstone occur along the western border of the Hollandale embayment. Ferruginous "brassy" ooids commonly are found in the red sandstones, in places in concentrations of the Clinton type. The Eau Claire is the most fossiliferous unit of the Dresbachian sequence and contains numerous inarticulate brachiopods, which commonly occur as coquinoid layers or lenses in the siltstones and shales; worm burrows, especially Planolites; and a diversity of trilobites. Trilobites are invariably disarticulated and crowd bedding surfaces at many intervals. Nelson (1951) described eight trilobite species and a variant from the Crepicephalus zone--more than in any other part of the Dresbachian sequence.

The Galesville Sandstone, representing the regressive phase of the Dresbachian sequence, is a white, cross-bedded, fine- to medium-grained, quartzose sandstone similar to the Mt. Simon, except that it contains somewhat less shale, is finer grained, and is better sorted. The sandstone at the base of the Galesville is generally moderately well sorted and becomes well sorted at the top (Austin, 1970). Fossils are sparse, but trilobites of the Aphelaspis zone are known from the top of the Eau Claire at two localities in the St. Croix valley (Nelson, 1951), and most of the Galesville is interpreted to be in this zone. The top of the zone probably coincides with the top of the Galesville, which is interpreted to be disconformable with the overlying Ironton Sandstone. Fragments of inarticulate brachiopods are sometimes observed along bedding surfaces in the cross-bedded sandstone. The Dunderbergia zone, described from a continuously evolving fauna in the western U.S., is absent in Minnesota. The disconformity between the Galesville and Eau Claire observed in outcrop in western Wisconsin (Ostrom, 1978) has not been observed in Minnesota, probably in part because this contact is not exposed in Minnesota and such contact relationships are more ambiguous in cores.

The basal half of the Mt. Simon Sandstone is interpreted to have formed principally along the marine foreshore and shoreface environment and in shallow marine shoals or sand bars (Driese, 1979). The upper Mt. Simon and Eau Claire are interpreted to be tidal flat facies (Driese, 1979; Huber, 1975), and they seem to provide the clearest examples of the tidal flat model in rocks of the St. Croixan Series. In the Wisconsin outcrop belt, the Eau Claire contains three lithofacies analogous to recognized sub-environments in recent North Sea tidal flats (Huber, 1975), and it contains many sedimentary structures recognized in recent tidal flats, including wavy, irregular to lenticular bedding, mud chips, flat-pebble conglomerates, mud cracks, and a shallow-water ichnofacies (Huber, 1975).

Although the Galesville Sandstone is marine sandstone in Minnesota, along the Wisconsin Arch it is interpreted to be eolian (Stenzel and others, 1983), and intermediate transitional facies have been recognized.

Franconian Sequence

A second Late Cambrian transgression marked the beginning of the Franconian sequence. A shallow epicontinental sea once again spread across an area of subdued relief and surrounded islands of the Chengwatana Volcanic Group at what is now Taylors Falls (Fig. 9). During this episode, the islands were eventually inundated.

The Ironton Sandstone, which disconformably overlies the Galesville, is the initial deposit of this transgression. It records a lower energy environment than its older analog, the lower part of the Mt. Simon Sandstone of the Dresbachian sequence. The Ironton is not as well sorted, and it contains a significantly larger proportion of silt. It is principally white, medium-grained, well- to poorly sorted quartzose sandstone that has a significant amount of admixed silt and a minor component of fine-grained feldspathic sandstone. The fauna is dominated by trilobites of the Elvinia zone (Berg, 1954), but is neither diverse nor abundant. Apparently life was sparse in the nearshore phase of sedimentation represented by the Ironton. In the Taylors Falls area, coarse conglomerates of Ironton age have yielded an uncommon molluscan fauna that includes monoplacophoran species. These fossils are found in sandstone pockets among coarse (as large as 3 feet in diameter) basalt boulders; the organisms lived in an intertidal environment at the shoreline.

The Franconia Formation is interpreted to represent sedimentary environments ranging from tidal flat (James, 1977) to shallow inner neritic marine (Odom, 1978). The Birkmose, the lowermost member, is a glauconitic, worm-burrowed, fine-grained feldspathic sandstone that is interpreted by

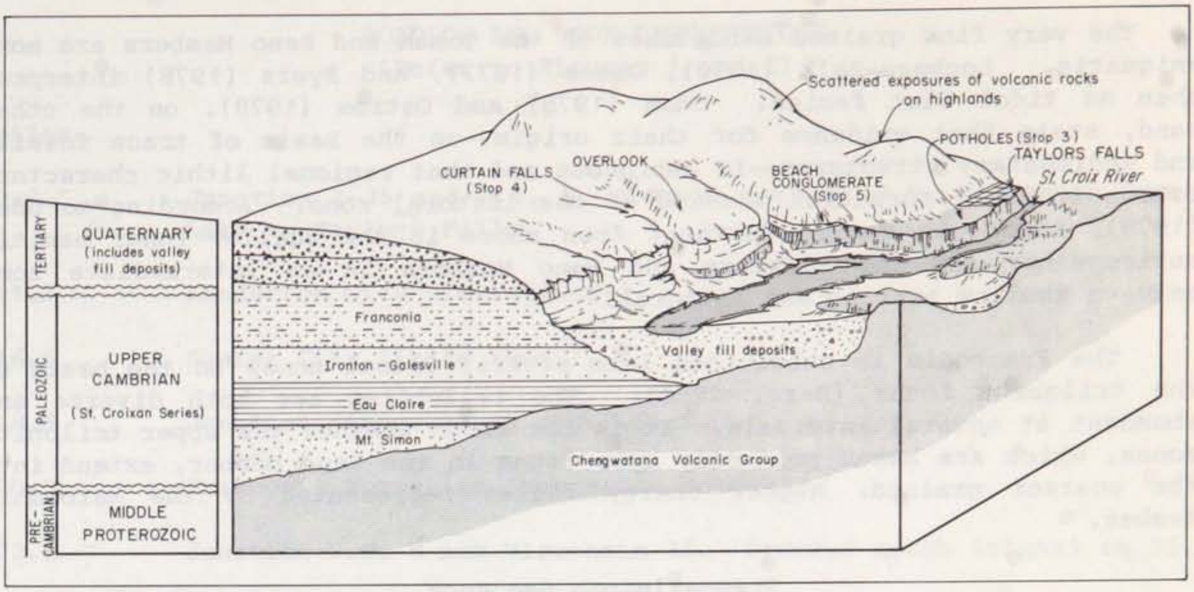

Figure 9. Schematic diagram showing onlap of Upper Cambrian sedimentary rocks onto Proterozoic Chengwatana volcanic rocks in the Taylors Falls area (after Olsen and Sloan, in press).

most investigators (Ostrom, 1964; James, 1977; Odom, 1978) to be a shallow offshore lithotope. It is characterized by trilobites of the Elvinia zone (Berg, 1954).

The Birkmose Member is overlain by the Tomah and Reno Members, and to the north and east by their lateral equivalent, the Mazomanie Member. Where they are found together in the same outcrop, the Reno overlies the Tomah (Austin, 1972; James, 1977). The Mazomanie Member, a thin-bedded or cross-bedded, dolomitic, nonglauconitic, fine- to coarse-grained sandstone, is quartzose in coarser grained facies and feldspathic in fine-grained facies (Odom, 1978); it is present in the northern part of the Hollandale embayment and along the Wisconsin Arch. It commonly intertongues with rocks of the Reno Member in the St. Croix valley (Berg, 1954).

The Tomah Member is interbedded micaceous, very fine grained, slightly glauconitic, feldspathic sandstone, and micaceous shale. The Reno is very fine grained, glauconitic, worm-burrowed to cross-bedded, feldspathic sandstone and interbedded intraclastic dolostone. Recent study of cores (Mossler, in progress) from the Hollandale embayment of southeastern Minnesota indicates that most of the Franconia in the subsurface of the embayment is lithically similar to the Reno Member. Earlier studies--based on a single core (Austin, 1970, 1972)--had equated much of the Franconia in the subsurface with the Tomah Member.

The coarser grained sandstones of the Mazomanie Member are interpreted to be littoral (beach and nearshore) deposits (Odom, 1978). They mark maximum regression during the third marine regression, which was much less extensive than the one at the end of the Dresbachian sequence (Lochman-Balk, 1970).

The very fine grained sandstones of the Tomah and Reno Members are more enigmatic. Lochman-Balk (1970), James (1977), and Byers (1978) interpret them as tidal flat facies. Odom (1978) and Ostrom (1978), on the other hand, state that evidence for their origin--on the basis of trace fossils and sedimentary structures--is ambiguous and that regional lithic characteristics indicate formation seaward of the littoral zone. According to Odom (1978), the Tomah formed farthest from shore in the shallow inner neritic environment, and the Birkmose and Reno Members in an intermediate zone between shallow neritic and littoral.

The Franconia is subdivided into several faunal zones on the basis of the trilobite fauna (Berg, 1954). The trilobites are both diverse and abundant at several intervals. It is not known whether the upper trilobite zones, which are based primarily upon fauna in the Reno Member, extend into the coarser grained, higher energy facies represented by the Mazomanie Member.

Trempealeauan Sequence

The St. Lawrence Formation, which overlies the Franconia, is composed of sandy dolomite, dolomitic siltstone, and fine-grained dolomitic sandstone. Dolomite content decreases, and clastic content and average grain size increase, as the formation thins toward the northeast (Berg and others, 1956). Trilobites of the Saukia zone (Berg and others, 1956) dominate the fauna; inarticulate brachiopods and dendritic graptolites comprise the remainder of the fauna. The Black Earth Member, the lower member of the formation in Minnesota, is composed almost entirely of slightly glauconitic dolostone. The overlying Lodi Member consists of dolomitic siltstone and very fine sandstone; it comprises the entire formation in the nearshore area to the north and east. Although the Black Earth Member along the Wisconsin Arch contains stromatolites (Byers, 1978) and is interpreted to be a tidal flat deposit, Black Earth dolostones in Minnesota, as well as the Lodi siltstones, are more enigmatic, and much of the St. Lawrence in Minnesota may have formed in a subtidal environment.

The Jordan Sandstone comprises three members. The basal Norwalk Member is white to light-gray, very fine to fine-grained, feldspathic sandstone that commonly is highly burrowed and massive. It is interpreted to have formed in a subtidal lagoonal environment (Odom and Ostrom, 1978), although it could also be sandy tidal flat sedimentary rock (see Byers, 1978). The medial Van Oser Member is white to yellow, fine- to coarse-grained quartzose sandstone that generally is trough cross-bedded and is unfossiliferous (Dott, 1978; Odom and Ostrom, 1978). It is interpreted to have formed in the littoral zone and in shallow marine shoals shoreward from the Norwalk (Dott, 1978).

The uppermost Jordan member, the Coon Valley, is very heterogeneous and contains dolomitic, fine- to medium-grained quartzose sandstone, sandy cherty oolitic dolostone, minor stromatolitic (algal mat) dolostone, and minor very fine grained feldspathic sandstone (Odom and Ostrom, 1978). There are some intraclasts. It has lithic characteristics of the subtidal carbonate shelf lithotope and, locally, of the intertidal lithotope (Odom and Ostrom, 1978). Bottom communities of the Saukia zone characterize the meager fauna.

ROADLOG AND STOP DESCRIPTIONS

(Refer to Figures 1 and 2)

Miles

0.0 Junction I-35 and U.S. 8, proceed east on U.S. 8 through Forest Lake to Taylors Falls.

11.1 Lindstrom City Limits (west).

16.5 Shafer City Limits (west).

18.8 Junction Minnesota 95 and U.S. 8.

20.3 Franconia Formation (Mazomanie Member).

22.8 Junction U.S. 8 and Wisconsin 35. Proceed south (right) on 35.

23.1 Wisconsin Interstate Park entrance. Turn west (right).

24.6 Follow park road to the group campground and the Eagle Peak Trail.

STOP 1. Eagle Peak Trail.

The Chengwatana Volcanic Group is well exposed in both the Minnesota and Wisconsin Interstate State Parks. The flows are part of 1.1-billion-year-old flood basalt plateau which is estimated to be 20,000 feet thick. At least three flows are exposed along the Eagle Peak Trail. Two flows, an aphyric flow overlying a feldsparphyric flow, are exposed in a small quarry along the trail.

26.1 Return to the park entrance and proceed north (left) on Wisconsin 35.

26.4 Junction Wisconsin 35 and U.S. 8. Proceed west (left) on 8.

26.7 Junction U.S. 8 and Wisconsin 87. Proceed north (right) on 87.

27.1 Junction Wisconsin 87 and Kentucky Street. Turn west (left).

27.2 Follow Kentucky Street to North River Street. Proceed south on North River Street to 107 North River Street.

STOP 2. St. Croix Falls. Contact, Chengwatana Volcanic Group and Upper Cambrian Eau Claire Formation.

About 13.5 feet of the Eau Claire Formation is exposed in lateral contact with the flood basalts of the Chengwatana Volcanic Group. Coarse basalt boulders occur in the shaly material at the contact. Primary dips are as much as 15° in the shale near the contact.

The section (Nelson, 1949, p. 85) is as follows:

Thickness	
5.0 feet	Shale, brown to buff, thinly laminated, soft and interbedded gray and brown sandy shale. Contains *Lonchocephalus chippewaensis*.
8.5 feet	Shale, gray to black, soft, with some sandy buff shale and resistant layers, in lateral contact with coarse basalt boulders. Contains *Lingulepis pinnaformis* and *Obolus matinalis*.

Trilobites are not abundant at this locality, but slab surfaces with abundant inarticulate brachiopods are found in the stream bed.

27.2 Return to Kentucky Street and Wisconsin 87. Proceed south (right) on 87.

27.6 Junction Wisconsin 87 and U.S. 8. Proceed west (right) on 8.

28.0 Turn left at entrance to Glacial Gardens in Interstate Park.

STOP 3. Taylors Falls.

At least ten flows are exposed at Taylors Falls. Here the nearly flat orientation of the flows, epidotized flow tops, and the steplike character of the topography (Fig. 6) can be observed. During Late Cambrian time, the flows formed bluffs much as they do today, and the sea gradually encroached from the south. For a time they formed islands with rather steep seacliffs, but they were gradually inundated toward the end of Cambrian time. The unconformity between the flows and the Cambrian sandstones can be seen at several localities around Taylors Falls.

Toward the end of the Wisconsinan Glaciation, ice dammed the Straits of Mackinac, and the meltwaters raised the level of the water in the Lake Superior basin more than 600 feet above its present level. This lake, known as Glacial Lake Duluth, overflowed to the south through the Brule River of Wisconsin and the St. Croix River, and cut a gorge through the resistant flow series at Taylors Falls. The tremendous discharge and the velocity of the water resulted in extensive pothole formation. More than 80 potholes are present, one as large as 60 feet deep and 15 feet in diameter.

Return to parking lot and proceed west (left) on U.S. 8.

28.8 Entrance to Interstate Park Campground (lunch).

STOP 4. Franconia Formation. Two stops are scheduled along Curtain Falls Trail.

The first stop is about 300 yards from the start of Curtain Falls Trail (Figs. 2 and 9). About 110 feet of Franconia sandstone is exposed at the site of Curtain Falls. The lower 30 feet consists of buff to green, fine-grained glauconitic sandstone of the Birkmose Member of the Franconia Formation. Only the upper few feet of this unit is well exposed at the falls. This is overlain by 80 feet of fine- to medium-grained sandstone of the Mazomanie Member of the Franconia Formation. Trilobites of the Elvinia and Conaspis zones are present, as well as inarticulate brachiopods and the problematic Pelagella. The Birkmose sandstone at this stop probably represents a nearshore sublittoral accumulation.

The second stop is 1000 yards from stop 1 at a small bridge about 300 yards from the end of the trail. Exposed where the trail meets a small stream are the basalts of the Chengwatana Volcanic Group. Upstream, the valley exhibits nearly continuous exposures of the flows, some of which show brecciated flow tops. An unconformity can be observed about 50 yards upstream from the bridge where buff, fine- to medium-grained sandstones of Franconian age overlie the flows. Abundant trilobites of the Conaspis zone can be found at the contact.

Return to U.S. 8 and proceed east (right).

28.9 Turn left into the Interstate Park maintenance area.

STOP 5. Mill Street Conglomerate (Fig. 9).

This exposure is one of the few in North America that shows a conglomerate at the base of the Upper Cambrian sandstone. A veneer of conglomerate covers the unconformable contact between the flows and the Cambrian sandstones at several localities. The conglomerate ranges in age from Dresbachian to Franconian. The conglomerate here is very coarse, consisting of angular basalt blocks as much as 2 feet in diameter surrounded by fine- to medium-grained, buff quartzose sandstone of Franconian age. The corners of the basalt blocks have been rounded by the surf action of the Late Cambrian seas.

Trilobites, inarticulate brachiopods, and monoplacophorans of the Elvinia zone have been collected at this locality. Inarticulate brachiopods are common. Included in the monoplacophorans are high-coned septate hypseloconids which are representative of the group from which cephalopods evolved.

Return to U.S. 8 and proceed west (right) on 8.

30.8 Junction U.S. 8 and Minnesota 95. Proceed south (left) on Minnesota 95.

35.8 Junction Minnesota 243.

41.5 Junction Minnesota 97.

43.0 Copas City Limits (north).

44.0 William O'Brien State Park.

45.8 Marine On St. Croix.

46.5 Junction Minnesota 7.

54.3 Cambrian sandstone exposure.

55.8 Stillwater city limits (north). Turn right into parking area just past intersection with Minnesota 95 and Elm Street (just past railroad tracks). Exposures are in roadcuts (Fig. 10) along Elm Street where it intersects Minnesota 95 (just north of the parking area).

STOP 6. Contact between the Cambrian Jordan Sandstone and the Ordovician Oneota Dolomite (Prairie du Chien Group).

The nature of the systemic contact between the Jordan Sandstone and the Prairie du Chien Group has long been a topic of debate (see Kraft, 1956). Early workers tended to regard it as an unconformity, but later workers tended to regard it as conformable; there has not been complete agreement at any one time. The change from a quartz sandstone to a dominantly dolomitic rock unit is gradational at many exposures in Minnesota over a considerable stratigraphic interval. In some sections this interval is as large as 30 feet. The change at Stillwater is exceptionally sharp, and the only gradation is in the abundance of quartz sand in the lower 2 feet of the Oneota and minor shale lenses just below the contact. One possible explanation for the sharp contact is that the Proterozoic St. Croix horst underlies Stillwater. The contact where Paleozoic rocks are underlain by the horst, for example at Nininger, Dakota County and near Copas north of Stillwater in Washington County, is commonly very sharp. Reactivation of this structure during Late Cambrian time could have resulted in the nondeposition or even erosion of the upper Jordan Sandstone beds. A generalized section is as follows:

	Covered
Thickness	
6.0 feet	Massive, buff dolomite, lower 2 feet sandy, contact sharp.
52.0 feet	Buff to white, medium-grained, cross-bedded, friable quartzose sandstone.
20.0 feet	Buff, fine-grained, thinly laminated, well-indurated quartzose sandstone; prominent worm burrows.
16.0 feet	Buff to yellow, medium-grained quartzose sandstone, some cross-bedding.
	Covered

Continue south on Minnesota 95.

57.1 Jordan Sandstone exposures.

59.1 Bayport City limits (north).

62.7 Lakeland City limits (north).

Figure 10. Outcrop of Jordan Sandstone in Stillwater at stop 6.

64.1	Intersection Minnesota 95 and U.S. 12. Continue south on Minnesota 95.
67.2	Afton City limits (north).
73.6	Cottage Grove City limits (north).
79.5	Junction with U.S. 61 and U.S. 10. Proceed south on U.S. 61 and 10.
80.6	Junction U.S. 61 and U.S. 10. Continue south on U.S. 61.
81.7	Hastings Bridge.
83.2	Junction U.S. 61 and Minnesota 291.
83.7	Junction U.S. 61 and Minnesota 316.
92.0	Junction U.S. 61 and Minnesota 20. Continue on U.S. 61 east through Miesville to Red Wing.
108.6	Red Wing City limits.
109.9	Junction U.S. 61 and Minnesota 63. Proceed south on 61-63.
110.2	Pull off onto right shoulder just past the underpass for stop 7.

STOP 7. Franconia and St. Lawrence Formations at Barn Bluff in Red Wing.

The Franconia and St. Lawrence Formations are here in fault contact. About 90 feet of the Reno Member of the Franconia Formation can be seen along the highway. The Reno is a green, mottled, fine-grained, highly glauconitic member of the Franconia Formation. Cross-bedding is developed in some beds; others are worm burrowed. The fault plane is nearly vertical, and highway excavation has reduced the Reno to a thin slice veneering the St. Lawrence Formation. The eastern fault contact on this slice of Reno is irregular because the plane of the fault nearly parallels the outcrop orientation. The western fault contact is very sharp. Slickensides can be found on some of the St. Lawrence surfaces at the fault, as well as a gouge zone of predominantly Reno material. About 30 feet of the St. Lawrence Formation is exposed on the western side of Barn Bluff. The material is predominantly a buff dolomitic siltstone. Unweathered beds maintain a blue color. Displacement on the fault is about 150 feet.

Trilobites of the Elvinia zone can be collected from the Reno Member, and trilobites of the Dikelocephalus zone can be collected from the lower part of the St. Lawrence Formation.

Overlying the St. Lawrence Formation at Barn Bluff is about 115 feet of Jordan Sandstone and about 75 feet of Oneota Dolomite of the Prairie du Chien Group.

Return to St. Paul via U.S. 61 to U.S. 10 and 61 to I-94, a distance of about 56 miles.

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INTRODUCTION TO THE MIDDLE AND LATE ORDOVICIAN FIELD TRIPS

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INTRODUCTION

This part of this guidebook grew from conversations between Dennis Kolata and Robert Sloan at various Geological Society of America conventions starting several years ago. It became very apparent to both of us that there was a wealth of unpublished and unorganized data on lithostratigraphy and biostratigraphy of the Middle and Late Ordovician rocks of the Upper Mississippi Valley region. It also became very apparent that organization of this data on a regional rather than state basis would lead to significant advances in understanding of these rocks, their faunas, and relationships to those of other areas. The large amount of long-distance bed tracing that has been done meant that available paleontological data could be pooled throughout the entire region, and that regional biofacies differences could be recognized on a very precise chronological basis. This guidebook and the accompanying Report of Investigations are the first fruit of this regional study. More are in progress.

We have included many graphic sections with as much detail as possible. All were drawn at a scale of 1:48, all are reproduced at a scale of 1:64. This scale is a useful one because architects' scales and model railroad scales (S scale) are readily available in this proportion. An ordinary fractional inch scale can also be used to scale off measurements; 1/16 inch on the drawing equals 4 inches on the outcrop.

The inclusion of Webers' (1966) conodont study in Sweet's (1984) Composite Standard Section, and Kunk and Sutter's (1984) date on the T-3 bentonite of Tennessee, and Kolata and others' (1986) precise correlation of the T-3 bentonite with the Deicke K-bentonite permit absolute dating of all events within this region to a degree of precision never before contemplated. Figure 1 summarizes all the bed tracing and terminology of the region. It permits estimation of absolute age to the precision of measurement of the most recent radioactive dates, ± 3 m.y. for an individual date, and ± 0.1 m.y. for the cluster of basal Rocklandian dates of Kunk and Sutter (1984).

DEDICATION

The Middle and Late Ordovician part of this guidebook is fondly dedicated to the four amateur paleontologists who have given most to the study of the Middle and Late Ordovician of the Upper Mississippi valley.

The first was Wilbur H. Scofield, 1840-1895, pharmacist, teacher, and postmaster of Cannon Falls, Minnesota, who led Winchell, Clarke, Schuchert,

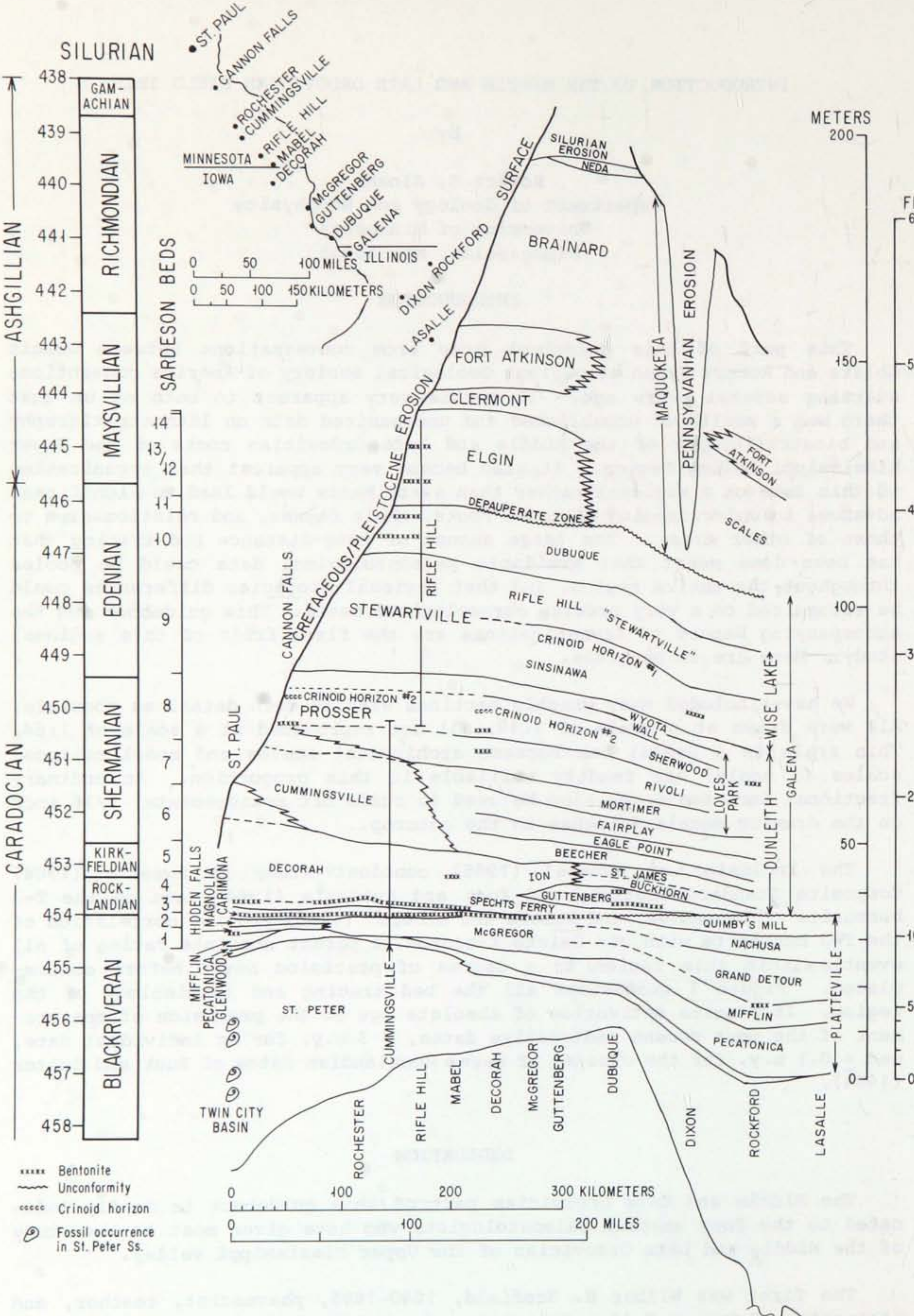

Figure 1. Stratigraphic cross section of Middle and Late Ordovician rocks between St. Paul, Minnesota, and LaSalle, Illinois, with correlations, zones, and absolute ages.

and Ulrich to the major fossil localities in southern Minnesota, and with Ulrich wrote the major monograph on snails of this age.

The next was Frederick William Sardeson, of Minneapolis, 1866-1959 (Fig. 2). He graduated from the University of Minnesota in 1891, Phi Beta Kappa, discovered the St. Peter fossils and zoned the Ordovician of Minnesota that year, and received a Master's degree in 1892 (1892a,b,c). He received a Ph.D. degree from Freiburg in 1895, returned to the University of Minnesota as a Scholar in Paleontology, then Instructor, and rose to be Assistant Professor, but was fired after several personality conflicts with W.H. Emmons in 1914. He then continued to work as an amateur on Ordovician problems until 1940. He published 50 papers between 1891 and 1914, and at least 95 more as an amateur. He amassed a large and very important personal collection of over 200,000 specimens, which was purchased for the University of Minnesota in 1947. His papers are still worth reading, and we are by no means through working up the fruits of his collecting, as you will see in reading this guidebook.

The latest pair, for they must be considered together, are Calvin O. Levorson of Riceville, Iowa, and Arthur J. Gerk of Mason City, Iowa (Fig. 2). Cal and Art decided to collect fossils as a serious hobby in 1969. By the summer of 1971, they found they needed to know the stratigraphic succession of the Galena Group in order to locate the best localities for the crinoids and trilobites that they were finding. They found to their disappointment that publications on the Galena in Iowa were sparse, and that Weiss's publications on Minnesota, and Templeton and Willman's on Illinois did not fully apply to Iowa. They traced the detailed classification of the Galena Group of Illinois into Iowa, and in the next 2 years measured some 80 sections in Iowa at a high degree of precision, bed tracing all the way into Minnesota. They produced a corpus of detailed measured sections and notes that is superior to most Ph.D. theses. These notes total 600 pages on the Galena of Iowa, and another 200 pages on the Galena of Minnesota, and the Platteville and the Maquoketa of Iowa. The fossils they collected are the subject of many professional papers, and they have shared their fossils and knowledge freely. They have written six very important stratigraphic papers. Their important notes have been copied with their permission, and

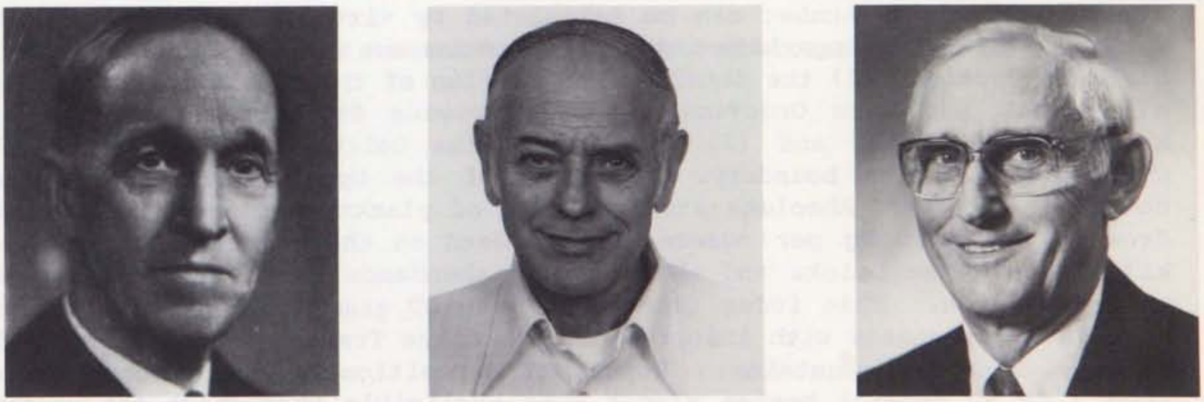

Figure 2. Portraits of Frederick W. Sardeson, Calvin O. Levorson, and Arthur J. Gerk.

have been deposited in the Department of Geology and Geophysics, and in the Minnesota Geological Survey, both at the University of Minnesota, at the University of Iowa, and at the Illinois Geological Survey. We have freely used copies of their graphic sections throughout this guidebook. You will see the quality of their work as you visit these localities. I hope your students will use these sections as a model for their own studies, they could do not better!

I think you will agree that these four gifted amateurs deserve all the praise that we can give them.

TECTONICS, BIOSTRATIGRAPHY, AND LITHOSTRATIGRAPHY OF THE MIDDLE AND LATE ORDOVICIAN OF THE UPPER MISSISSIPPI VALLEY

The history of development of the nomenclature of the Ordovician of the Upper Mississippi valley is summarized in Winchell and Ulrich (1895), Weiss (1957), Templeton and Willman (1963), and Willman and Kolata (1978). It will not be repeated here in total, except in the form of Figure 3, which shows in tabular form the development of the Minnesota classification of these rocks and the relationship of these units to those of Illinois. The two major classifications occur because of significant facies differences due to proximity of the Minnesota rocks to the Transcontinental Arch in central Minnesota. Iowa classification is more similar to that of Illinois.

The Deicke K-bentonite, by correlation with the T-3 ash bed of Tennessee is 454.2 Ma in age (Kunk and Sutter, 1984; Kolata and others, 1986; Samson 1986). The Deicke K-bentonite is a major provincial extinction event at the species level--the conodont extinction was 10%; the gastropod extinction was 80%; trilobite extinction was 90%; and the echinoderm extinction was 100%. This appears to be the Black River-Trenton boundary. The level of generic extinction is much lower. A second major extinction at a level of about 90 percent took place during deposition of the lower part of the Stewartville dolomite (Sinsinawa strata) during about 0.8 m.y., as a result of shoaling from 50 meters depth to about 5 meters depth.

Absolute ages of the regional Middle and Late Ordovician and all other strata with a CSS number can be calculated by virtue of (1) inclusion of Webers' (1966) Cummingsville-Rifle Hill section in Sweet's (1984) Composite Standard Section, (2) the detailed bed tracing of the past three decades of all Middle and Late Ordovician strata between St. Paul, Minnesota and Rockford, Illinois, and (3) the age of the Deicke and the age of the Ordovician/Silurian boundary. Duration of the Upper Mississippi valley column is 17 m.y. Absolute standing crop of plankton of these seas ranged from 0.1 to 12.5 kg per square meter, based on the quantitative plankton kill beneath the Deicke and the conodont abundance index measured for the entire section. This index (conodonts per 100 grams of sediment) in turn correlates precisely with inferred height of the Transcontinental Arch, the 1.8-b.y.-Penokean mountains. Depths of deposition of these rocks varied from 2 to 50 meters; bottom slopes were negligible throughout the region. Abundant clams, bryozoans, and *Isotelus* represent the shallow end,

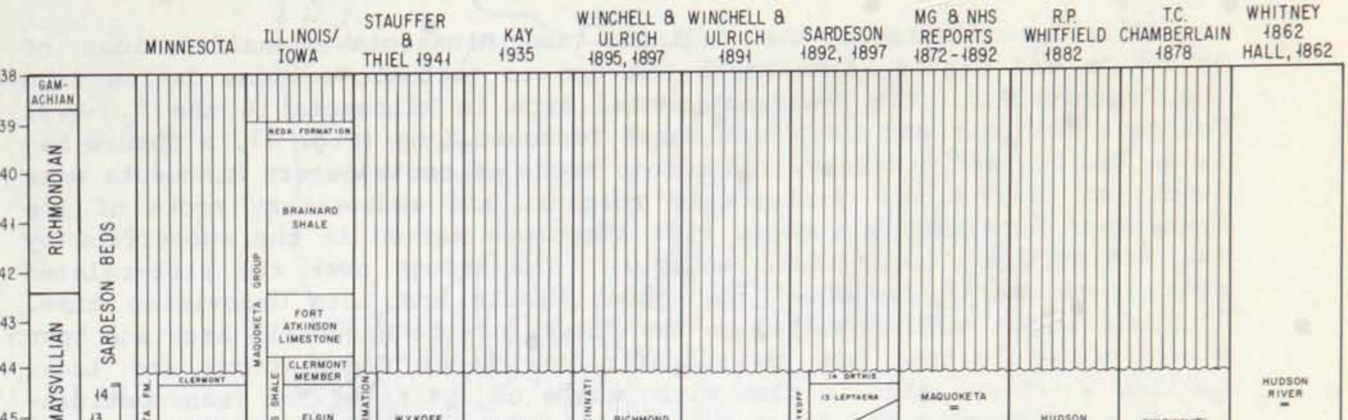

Figure 3. History of nomenclature for the Ordovician strata of the Upper Mississippi valley.

Ischadites and Dolichoharpes the deeper end of this spectrum. Rate of deposition averaged 12.6 mm per 1000 years.

Differences between the Illinois and Minnesota classifications of Mohawkian and Cincinnatian rocks are due to tectonic reasons dating from the Proterozoic. The Transcontinental Arch in Minnesota is the 1.8-b.y. Penokean foldbelt and the Great Lakes Tectonic Zone (Fig. 4), a suture between two Archean terranes. Paleozoic rocks of southeastern Minnesota were deposited over Middle Proterozoic volcanic and sedimentary rocks of the Keweenawan Supergroup, a major rift structure marked in the subsurface by the Midcontinent geophysical anomaly. The trough over the rift-related rocks persistently subsided throughout Middle and Late Ordovician time. Illinois rocks were deposited on the flanks of the Wisconsin Arch and have minor unconformities due to eustatic sea level fluctuations and local uplifts which coincide in time with pulses of uplift of the Transcontinental Arch. Detailed bed tracing over the 540 km between St. Paul, Minnesota and LaSalle, Illinois permits precise extension of local zones based on conodonts, ostracods, bryozoans, brachiopods, mollusks, echinoderms and trilobites over the entire region. By virtue of Sweet's (1984) CSS, this zonal synthesis can be extended to the rest of the continent with a high degree of precision. Croixan sandstones stripped off the Transcontinental Arch were the source of the Black Riveran St. Peter Sandstone and basal Winnipeg Formation. The Decorah and Cummingsville formations came from the underlying Proterozoic shales and were deposited 40 percent faster in the Twin Cities than at the Iowa-Minnesota state line. A 300-m uplift of the Transcontinental Arch at the beginning of the Rocklandian produced the Decorah Shale-Cummingsville Formation wedge in Iowa and Minnesota simultaneously with a 0.8-m.y. unconformity in northern Illinois, and with the upper part of the Winnipeg Formation in the Williston basin. The Prosser to Fort Atkinson formations correlate precisely with the Red River Formation of the Williston basin. The Transcontinental Arch was completely submerged during the deposition of the Prosser and Stewartville formations, but was reuplifted to form the source of the clastics of the Dubuque Formation and at least some of those of the Maquoketa Formation. During this uplift, the 0.09-m.y. unconformity beneath the depauperate zone was produced in Illinois and Iowa. Uplift of the Transcontinental Arch appears to have had a short periodicity of from 35,000 to 70,000 years based on the cyclicity of clay content in the Cummingsville Formation, and a longer cycle of mean period of 0.30 m.y., ranging from 0.20 to 0.37 m.y., based on the cyclicity of conodont abundance.

The detailed result of the bed tracing is shown in Figure 1. Details of timing of the tectonic events, depth changes, conodont abundance, and other events are shown in Figure 5. Using Figure 1, the horizon of any fossil or event in the Middle and Late Ordovician rocks of the region can be traced with great precision into the Rifle Hill and Cummingsville sections and related directly to the Composite Standard Section of Sweet (1984).

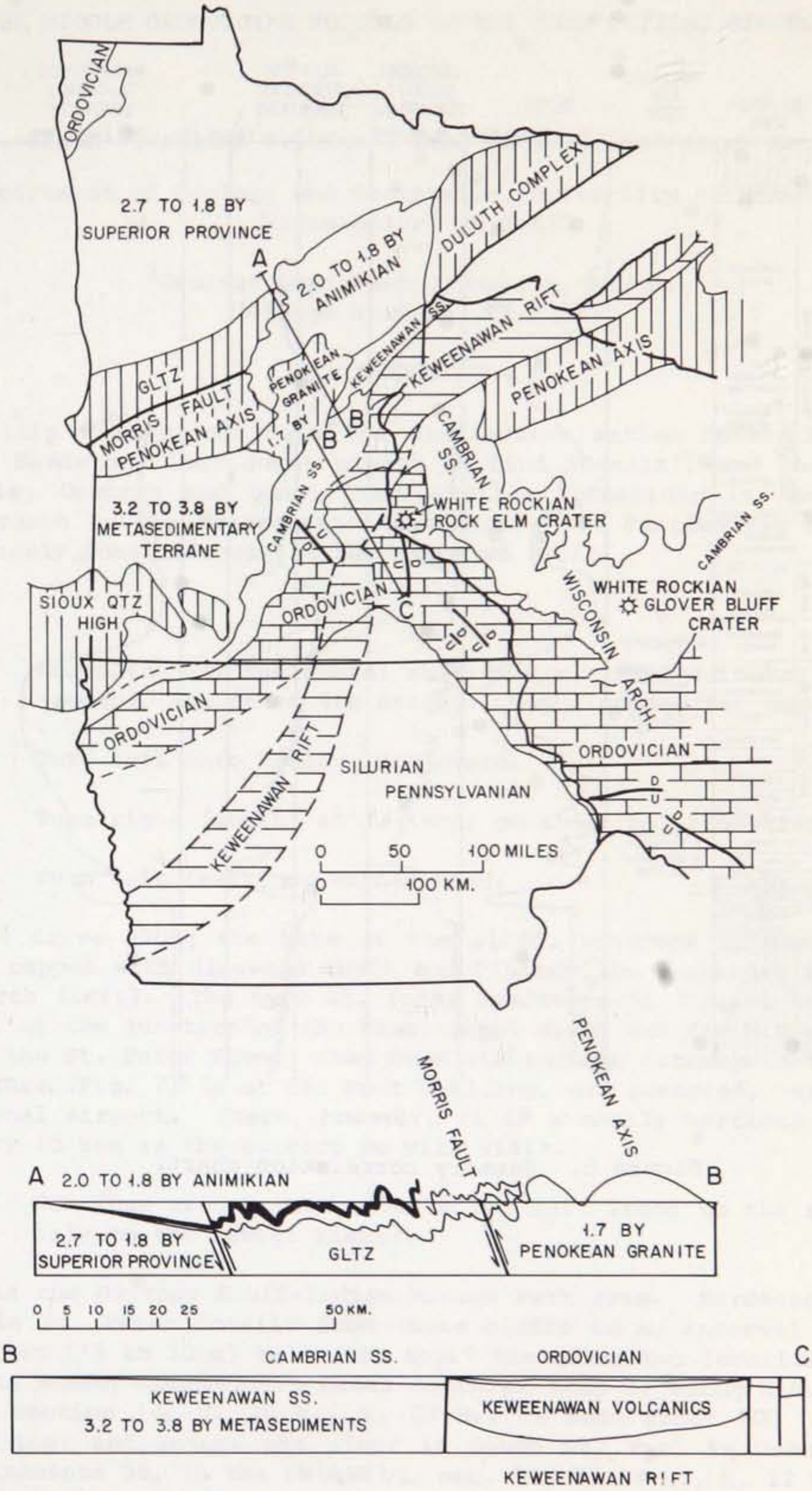

Figure 4. Tectonic map and cross sections of the Lake Superior and Upper Mississippi valley regions. Transcontinental Arch shown in vertical lines, Keweenawan rift in horizontal lines, Ordovician rocks in brick pattern. Adapted from Sims and others (1980).

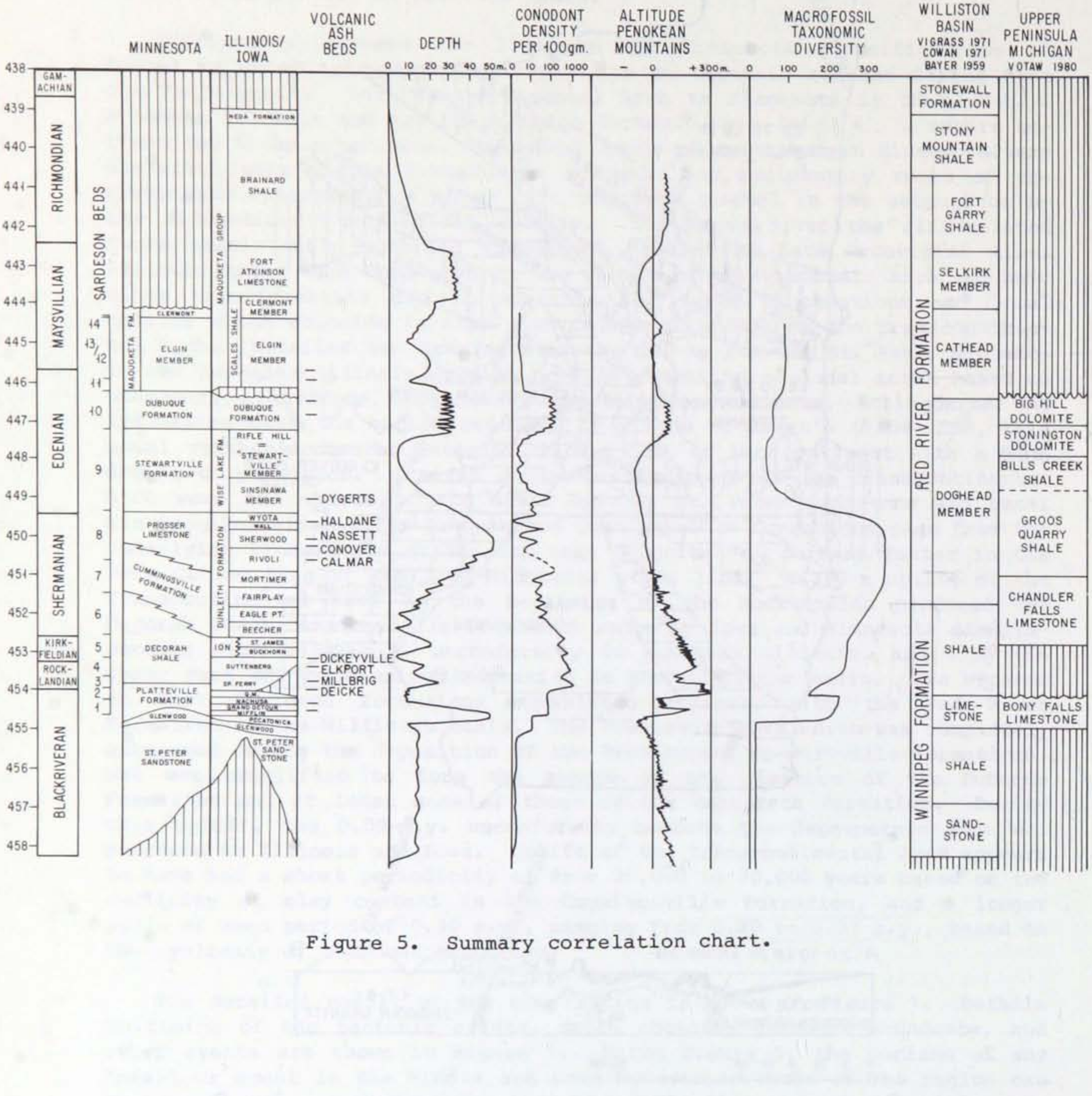

Figure 5. Summary correlation chart.

THE MIDDLE ORDOVICIAN FOSSILS OF THE TWIN CITIES, MINNESOTA

by

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INTRODUCTION

This trip will demonstrate the distinctive marine fossiliferous type St. Peter Sandstone (but don't expect to find fossils), and the Glenwood, Platteville, Decorah and basal Cummingsville formations in their closest known approach to the Transcontinental Arch. The Platteville and Decorah are abundantly fossiliferous at the stops we visit.

Miles	
0.0	Leave the St. Paul Hotel at 8:00 a.m. Exit driveway, turn left (south), and cross 4th street. See Figure 6 for map.
0.1	Turn left onto Kellogg Boulevard.
0.6	Turn right (south) at Jackson; go under railroad tracks.
0.7	Turn left (east) on Warner Road.

As you drive along the base of the cliff, outcrops of the St. Peter Sandstone capped with Glenwood shale and Platteville limestone are visible to the north (left). The type St. Peter Sandstone is 7 miles southwest of the hotel, at the junction of the Mississippi River and the Minnesota River (formerly the St. Peter River, when Owen visited the outcrop in 1852). The type exposure (Fig. 7) is at old Fort Snelling, now restored, very near the international airport. There, however, it is a nearly vertical cliff, and not as easy to see as the outcrop we will visit.

2.3	Continue around the curve to the left (road to the right leads only to the sewage plant).

This is the Daytons Bluff-Indian Mounds Park area. Sardeson collected many of his St. Peter fossils from these bluffs in an interval from about 50 to 70 feet (15 to 20 m) below the top. His other two localities were at Highwood in Ramsey County, 1.5 miles south of stop 1, along U.S. 61 in the center of section 14, T. 28 N., R. 22 W., in beds about 100 feet (30 m) below the top; and across the river in South St. Paul in Dakota County, next to Minnesota 56, in the SW1/4NW1/4, sec. 22, T. 28 N., R. 22 W., in beds about 80 feet (24 m) below the top. As best as we can determine, all of the St. Peter fossils collected by Sardeson and Stauffer came from the middle third of the 155-foot-thick (47 m) formation. The fauna is chiefly

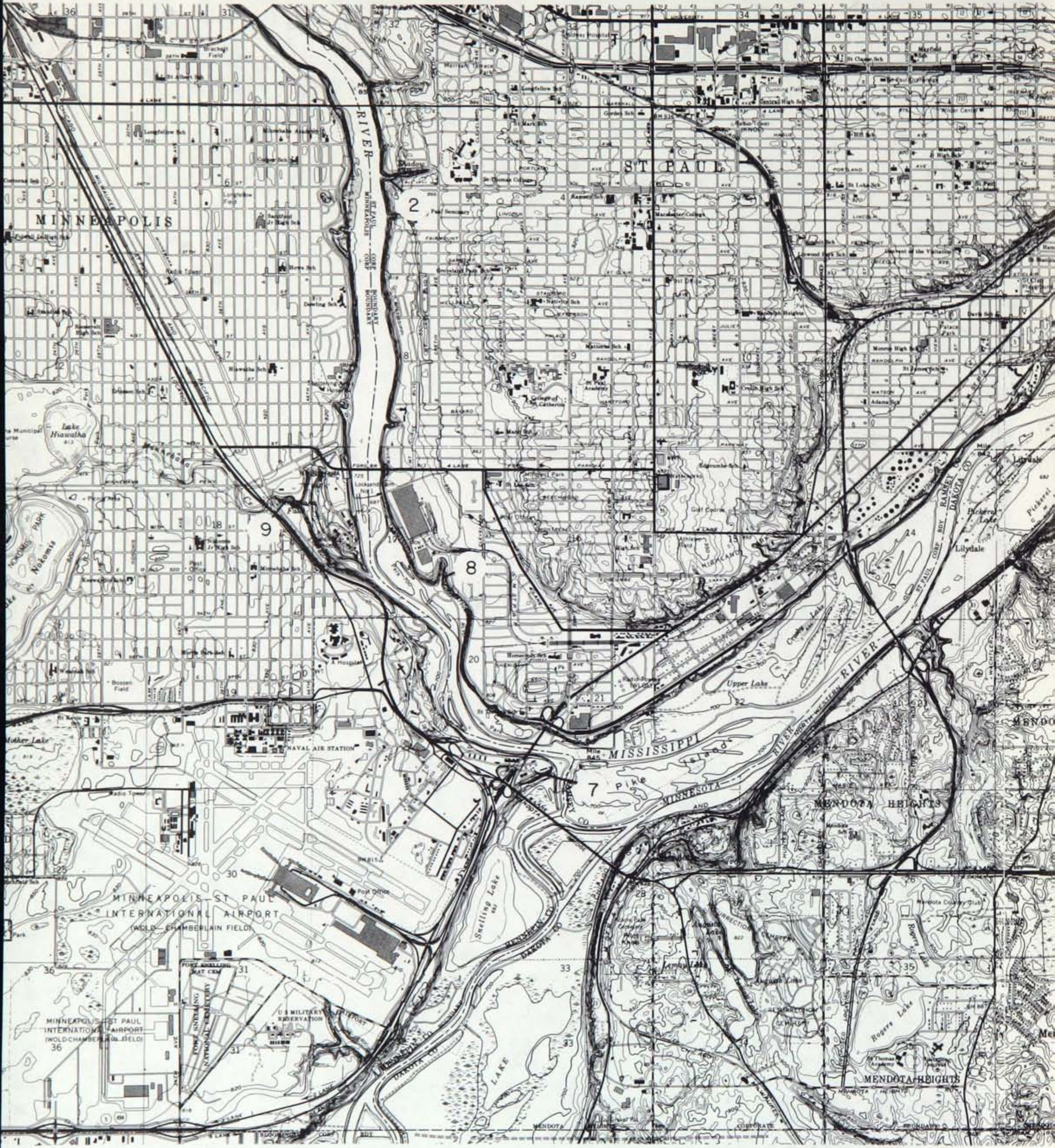

Figure 6. St. Paul and environs.
(1) Battle Creek Park (stop 1).
(2) Shadow Falls (stop 2).
(3) Twin City Brick Co. Clay Pit and Ravine (stop 3).
(4) Daytons Bluff-Indian Mounds Park, one of Sardeson's St. Peter fossil localities.
(5) South St. Paul, another of Sardeson's St. Peter fossil localities.

(6) Highwood, the last and lowest of Sardeson's St. Peter fossil localities.
(7) Fort Snelling, type locality of the St. Peter Sandstone. D.D. Owen chose this as the type because it was closest to the Fort, not because it was the best exposure.
(8) Hidden Falls Park, type locality of the Hidden Falls Member of the Platteville Formation.
(9) Minnehaha Falls, scenic waterfall and retreat gorge.

Figure 7. Fort Snelling and the type section of the St. Peter Sandstone as seen from across the Mississippi River.

clams, together with a few snails and rare other elements. All are molds; there are no shell remains. It represents deposition in very shallow water, perhaps 15 feet deep.

Witzke (1980) mentions conodonts from the middle of the St. Peter at 68 feet (20 m) below the top, from a well in downtown St. Paul, close to the St. Paul Hotel. They include the form-genera *Microcoelodus*, *Ptiloconus*, *Multioistodus*, *Stereoconus*, *Mixoconus*, *Neocoleodus*, *Chirognathus*, and *Oneotodus*. He interpreted them as Chazyan, because they are comparable to the Glenwood fauna, but they fit as well in the Ashbyan or lower Black Riveran according to Sweet's ranges in his (1984) CSS paper.

A quick census of Sardeson's St. Peter fauna (Fig. 8), with clams revised by Edward J. Cushing when he was a graduate student some years ago and the rest revised by Sloan, is as follows. Localities are H for Highwood, D for Daytons Bluff, and S for South St. Paul. A small collection from Fountain in Fillmore County, Minnesota, at the top of the formation at the contact with the Glenwood Shale, is labeled F, but not included in the counts.

BRYOZOA:		
Ptilodictya? sp.	1 specimen	H
BRACHIOPODA:		
"*Crania*" *reversa* Sardeson	2 specimens	H
"*Lingula*" *morsei* N.H. Winchell		F
Doleroides pervetus (Conrad)		F
MONOPLACOPHORA:		
Cyrtonellopsis vetulum (Sardeson)	10 specimens	S
GASTROPODA:		
Horiostomella aiens (Sardeson)	23 specimens	S
Lophospira tricarinata (Hall)	1 specimen	H, F

Hormotoma gracilis Hall	17 specimens	H, F
Holopea obliqua Hall	1 specimen	S, F
Holopea paludinaeformis Hall	1 specimen	S, F
"*Ophileta*" *fausta* Sardeson	5 specimens	H, S
CEPHALOPODA:		
"*Orthoceras*" *minnesotense* Sardeson	1 specimen	S
Cameroceras sp.	2 specimens	H, S
Kionoceras sp.	1 specimen	H
BIVALVIA:		
Orthodesma litoralis (Sardeson)	30 specimens	D, S
Ctenodonta novicia (Sardeson)	27 specimens	D, S
Cyrtodonta descriptus (Sardeson)	14 specimens	D, S
Cyrtodonta dignus (Sardeson)	34 specimens	D, S
Modiolopsis gregalis Sardeson	244 specimens	D, S
Modiolopsis contigua Sardeson	6 specimens	S
Modiolopsis fountainensis Sardeson	1 specimen	H
Vanuxemia dixonensis Meek and Worthen (= *V. fragosa* Sardeson)	8 specimens	H
Goniophora absimilis (Sardeson)	2 specimens	H
Total Specimens	431 specimens	

There are comparable molluscs in the Rock Elm shale, a basin-fill unit in the Rock Elm disturbance (Cordua, 1985, this volume) near the town of Rock Elm in Pierce County, Wisconsin. We suspect the Rock Elm shale and Washington Road sandstone are local facies of the St. Peter Sandstone within the crater.

Mazzullo and Ehrlich (1980, 1983) have demonstrated a twofold source of St. Peter sand grains: (1) irregular, less-rounded, immature grains inherited directly from the Late Cambrian Croixan sandstones and (2) well-rounded, mature grains that had been eroded and transported by wind. These alternate in abundance with cycles of about 1 foot (0.3 m) and larger rounding-upward cycles of about 10 to 30 feet (3 to 9 m). In many ways they correspond to the cycles of clay in the Cummingsville, and the cycles of conodont abundance in the Decorah and Cummingsville. We interpret all of these to imply tectonic influence on types of sand grains by Ordovician uplift of the Transcontinental Arch (the Penokean highlands), with less-processed sand grains being delivered to the sea by streams during and immediately after uplift, reworked in the sea by tidal currents, and delivered by wind as more rounded grains during times of flatter gradients on land.

3.1 Junction with U.S. 61 and U.S. 10, turn right and follow 61-10.

4.1 Entrance to Battle Creek Park; turn left and park.

STOP 1. St. Peter Sandstone in Battle Creek Park. SE1/4SE1/4 sec. 3 and NW1/4 SW1/4 sec. 2, T. 28 N., R. 22 W. This (Fig. 9) is one of the most complete and accessible exposures of St. Peter Sandstone in the Twin Cities. It shows the top 47 feet (14.3 m) of the total 155-foot (47 m) thickness. Discussion will be led by James Mazzullo.

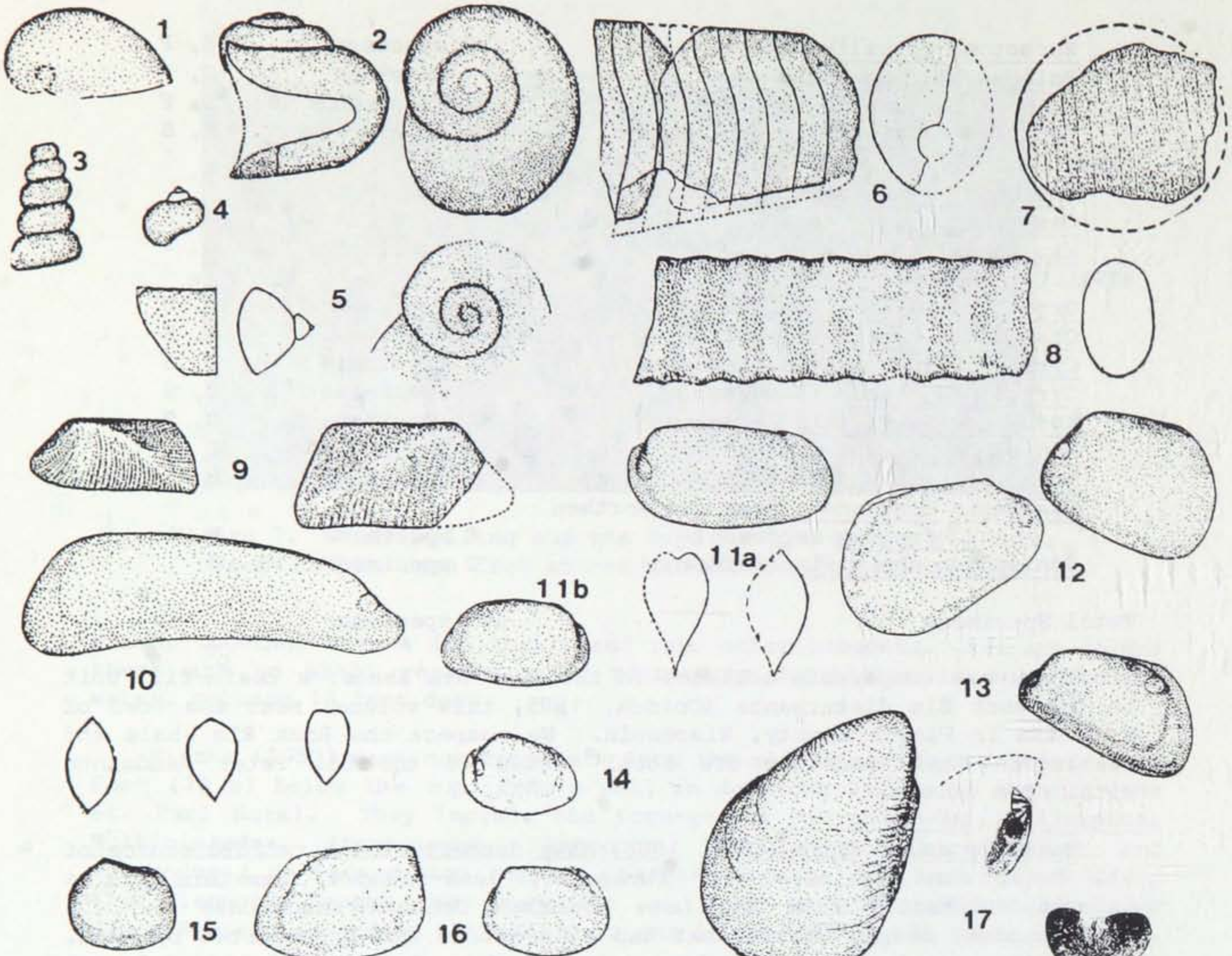

Figure 8. St. Peter fossils (from Sardeson, 1892a, 1896).

1. Cyrtonellopsis vetulum (Sardeson).
2. Horiostomella aiens (Sardeson) lateral and apical view.
3. Hormotoma gracilis (Hall).
4. Holopea obliqua Hall.
5. "Ophileta" fausta Sardeson, lip, cross section, and apical view.
6. "Orthoceras" minnesotense Sardeson, lateral and cameral view.
7. Kionoceras sp., lateral view and restored diameter.
8. Cameroceras sp., lateral view and cross section of siphuncle.
9. Goniophora absimilis (Sardeson), two individuals.
10. Orthodesma litoralis (Sardeson), lateral view and three cross sections.
11. Modiolopsis gregalis Sardeson; a, type lateral view and two cross sections; b, a second specimen, type of M. affinis.
12. Modiolopsis fountainensis Sardeson, type on left.
13. Modiolopsis contigua Sardeson.
14. Ctenodonta novicia (Sardeson).
15. Cyrtodonta descriptus (Sardeson).
16. Cyrtodonta dignus (Sardeson).
17. Vanuxemia dixonensis Meek and Worthen, lateral view and two views of teeth.

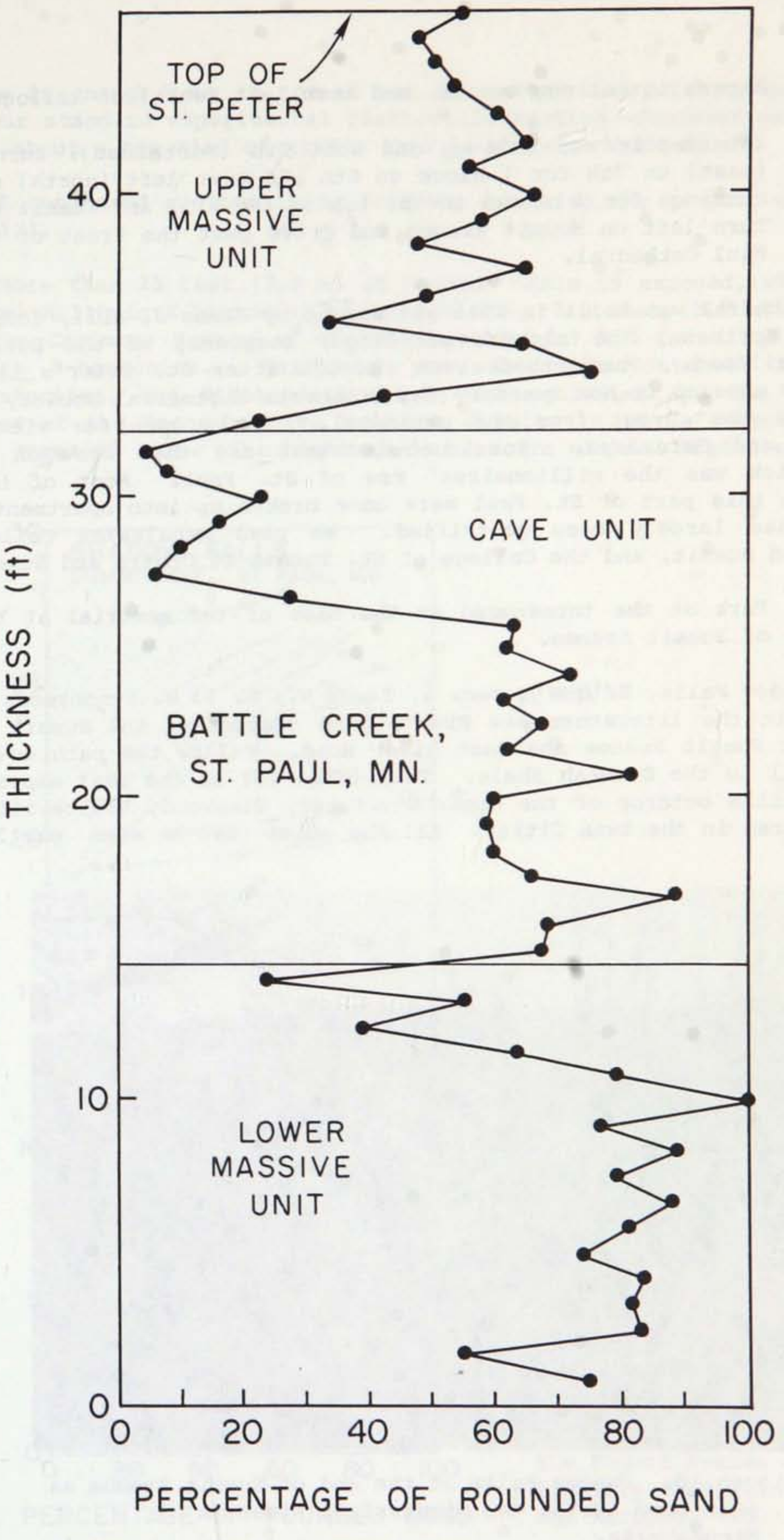

Figure 9. The St. Peter Sandstone measured section and roundness data at Battle Creek Park, St. Paul.

7.6 Return to Kellogg Avenue, and turn left (west) on Kellogg.

8.5 Intersection of Kellogg and West 7th (Fort Road); turn right (east) on 7th for 1 block to 6th and turn left (north) on 6th; continue for 3 blocks to the top of the hill and Summit Avenue. Turn left on Summit Avenue and drive past the front of the St. Paul Cathedral.

The Cathedral was built in 1915 and funded by James J. Hill, founder of the Great Northern, the richest pre-merger component of the Burlington Northern Railroad. The cathedral is modeled after St. Peter's in Rome. Hill's 1890 mansion is now owned by the Minnesota Historical Society and is just across the street from the cathedral. It is open for viewing on Wednesdays and Saturdays. Continue southwest and then west on Summit Avenue, which was the millionaires' row of St. Paul. Most of the old mansions in this part of St. Paul were once broken up into apartments, but the area has largely been gentrified. We pass Macalester College at Snelling and Summit, and the College of St. Thomas at Cretin and Summit.

13.5 Park at the turnaround at the base of the memorial at the end of Summit Avenue.

STOP 2. Shadow Falls, SE1/4NW1/4 sec. 5, T. 28 N., R. 23 W. Synonymous locality names in the literature are Finn's Glen (Sardeson) and Summit Avenue (Kolata) at Summit Avenue and East River Road. Follow the path down over glacial till to the Decorah Shale. This (Fig. 10) is the best exposed and most accessible outcrop of the upper St. Peter, Glenwood, Platteville, and lower Decorah in the Twin Cities. All the units can be seen easily, and

Figure 10. Shadow Falls at the end of Summit Avenue as seen from across the Mississippi River in Minneapolis.

there is enough room to spread out the entire crew without crowding. This is our standard experimental Platteville section--whenever we get a bright idea about a new kind of study, this is where we come first.

A condensed section is as follows, see also the graphic section (Figs. 11, 12).

More than 25 feet (7.6 m) of Decorah Shale is exposed, with the 1-inch (3 cm) Millbrig K-bentonite clearly visible 7.3 feet (2.2 m) above the top of the Carimona Member of the Platteville and 9.4 feet (2.9 m) above the Deicke K-bentonite. Sardeson's bed 3 is the interval between these K-bentonites, the Stictoporella bed, and equivalent to the Spechts Ferry Member of the Decorah. The conodont density in it is as much as 300 per 100 grams of rock. The higher beds here are within Sardeson's bed 4, the

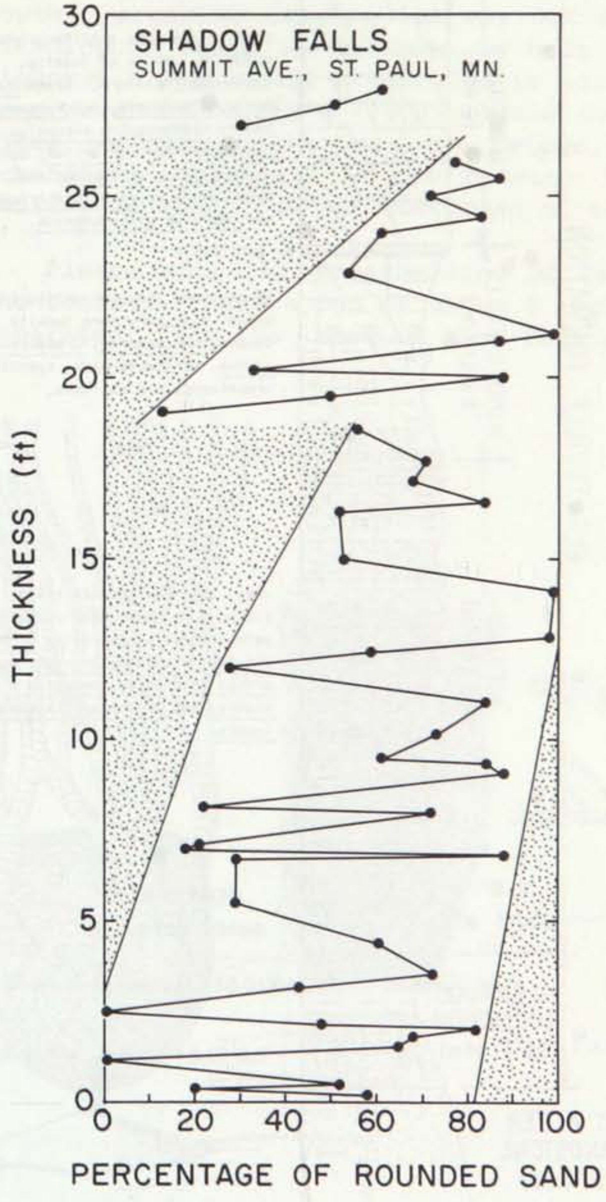

Figure 11. Graphic section of the St. Peter Sandstone at the Shadow Falls locality, also known as the Summit Avenue or Finn's Glen locality (modified from Mazzullo and Ehrlich, 1980).

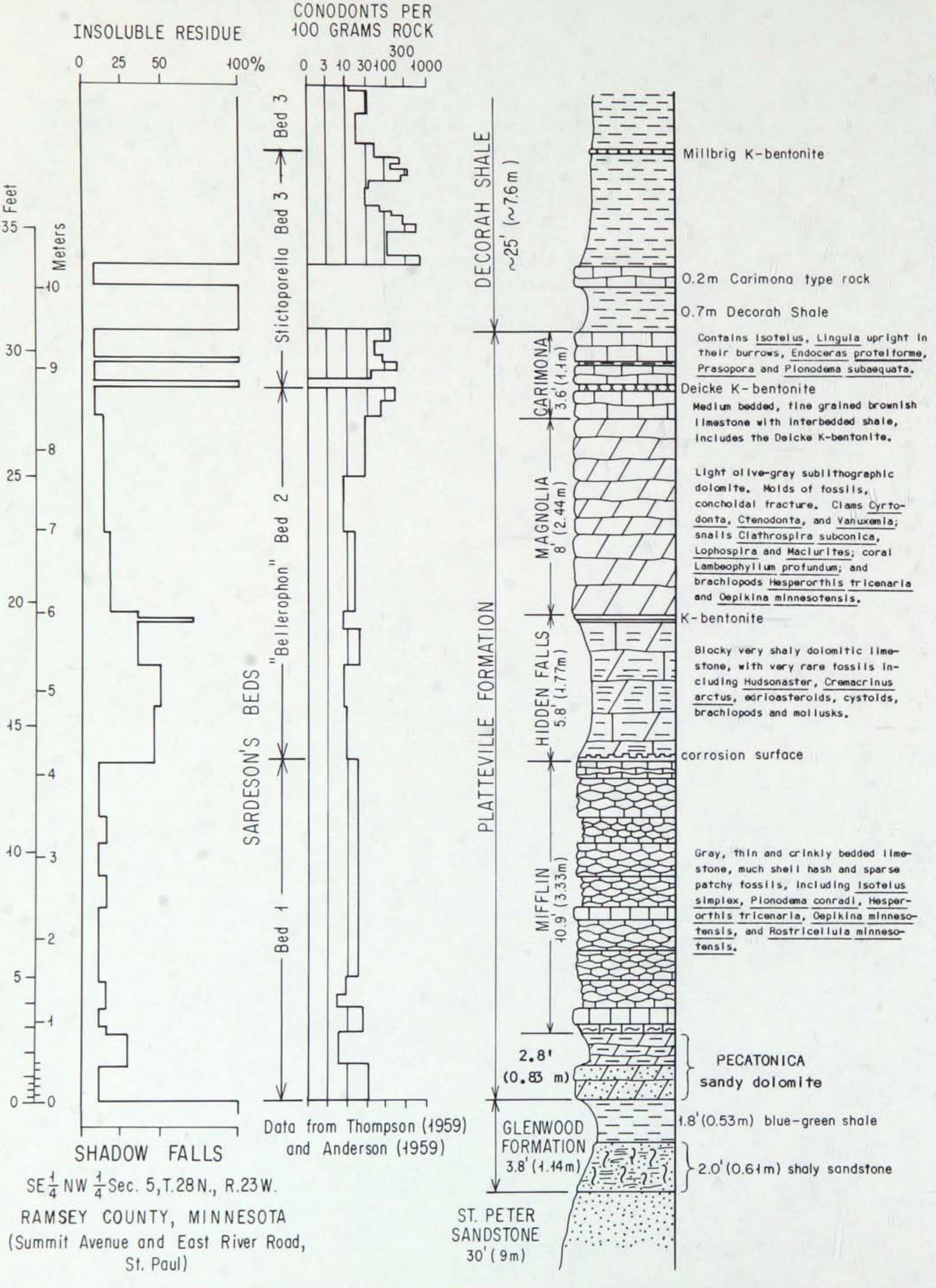

Figure 12. Graphic section of the Glenwood, Platteville, and Decorah Formations of Shadow Falls, with conodont and insoluble residue logs.

Stictopora or *Rhinidictya* beds, in which the conodont density is 30 per 100 grams. The type of the weird crinoid *Cremacrinus punctatus* Ulrich came from bed 4 at this locality (Fig. 13).

The Carimona Member of the Platteville Formation is 3.6 feet (1.1 m) thick here. It consists of richly fossiliferous, massive beds of limestone. *Isotelus* is common, suggesting that this unit represents a shallower facies than the other Platteville members. The 10-cm-thick Deicke K-bentonite is 1.2 feet (0.36 m) above the base of the Carimona Member here, always in a deep slot due to geologists digging in for a sample. The fall of the Deicke ash killed everything in eastern North America, and many species, such as the conodont *Scyphiodus primus*, terminate at this horizon. As best as we can determine on the basis of trilobites and conodonts, the Deicke is the boundary between the Black Riveran and Rocklandian (the basal Trentonian). In all the exposures Sloan has seen (100 or more) of this horizon, he has never seen evidence of a benthic organism digging its way out of this ash fall. Of 20 species of brachiopods found by Sardeson in beds 1 and 2, only 14 occur in bed 3 or higher. A 30-percent extinction is not small. The trilobite extinction is more severe. DeMott's (1963) thesis shows 9 of 10 upper Platteville trilobites becoming extinct at the Deicke, an extinction of 90 percent. The echinoderm extinction at the species level is 100 percent. The conodont density is about 100 per 100 grams of rock in the limestone beds.

Please note the interbedding of Decorah and Carimona rock types near the contact. Here a bed of about 8 inches (20 cm) of Carimona-type rock is separated from the rest of the Carimona by about 28 inches (70 cm) of

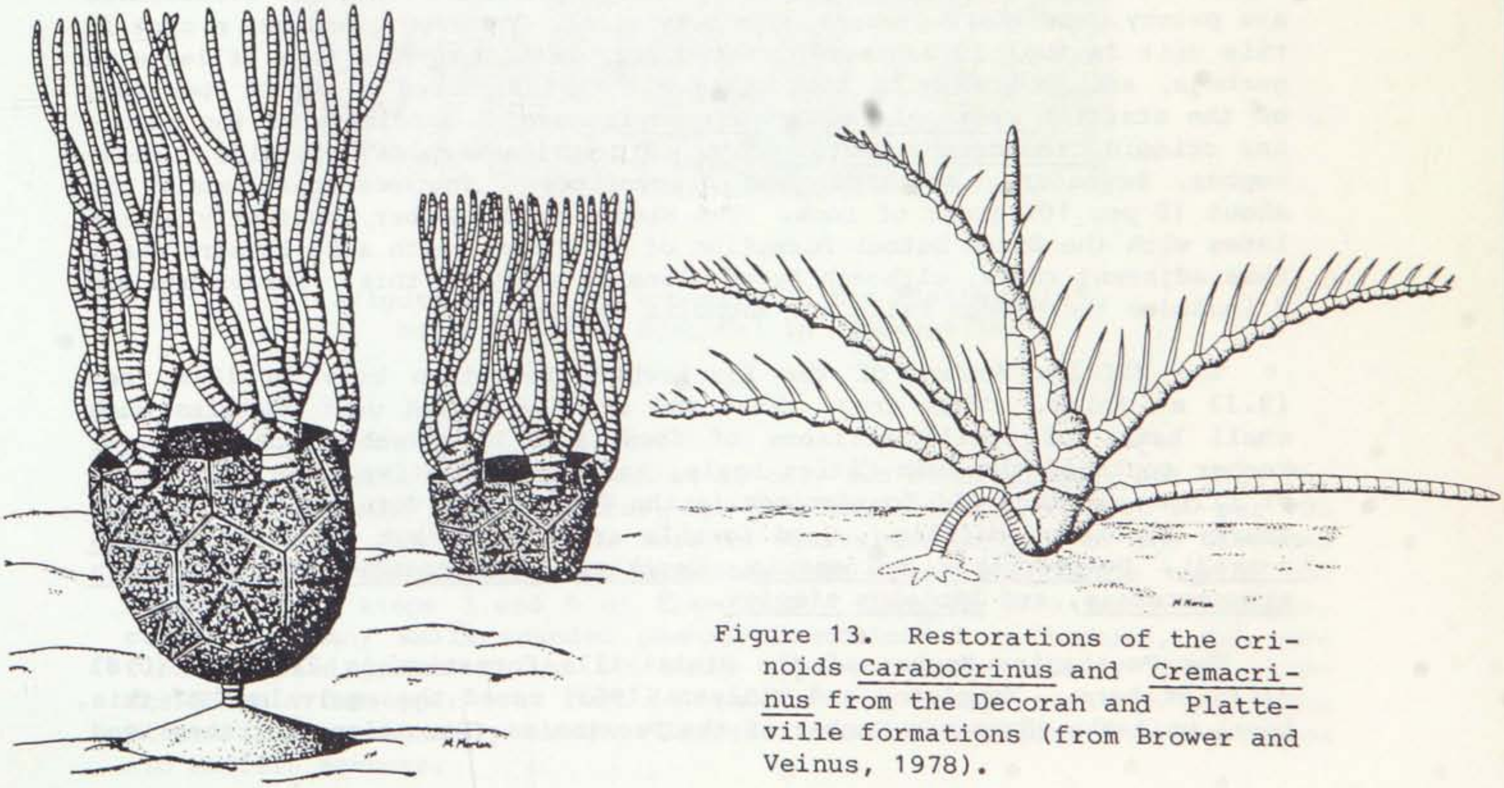

Figure 13. Restorations of the crinoids *Carabocrinus* and *Cremacrinus* from the Decorah and Platteville formations (from Brower and Veinus, 1978).

typical Decorah Shale. At Sogn, Minnesota (stop 1 of the southeastern Minnesota trip), this bed is part of the Platteville. Minnesota practice is to draw the boundary between the Platteville and Decorah at the point where the Decorah interbeds are thinner than the Carimona interbeds. This means, of necessity, that the formation boundary is diachronous, but always within the interval between the Deicke and Millbrig K-bentonites. The base of the Carimona is similarly diachronous, and depends on local lithofacies, depths, and biofacies. The lower Carimona is laterally equivalent to the Quimbys Mill Formation of Illinois, as well as to parts of the Magnolia and McGregor Members of Minnesota. The upper Carimona is laterally equivalent to the lower Spechts Ferry Formation of Illinois.

The Magnolia Member (Fig. 14) of the Platteville Formation here is about 8 feet (2.44 m) thick. It has a conchoidal fracture, is sublithographic in character, and contains a rich fauna dominated by the clams *Cyrtodonta*, *Ctenodonta*, and *Vanuxemia*; the snails *Clathrospira subconica*, *Maclurites*, and *Lophospira*; monoplacs; the coral *Lambeophyllum profundum*; and the brachiopods *Hesperorthis tricenaria* and *Oepikina minnesotensis*. All the fossils are preserved as dolomite rhomb-lined molds. The conodont density is about 10 per 100 grams of rock. The Magnolia Member apparently correlates with the Nachusa Formation of Illinois, although it more closely resembles the Quimbys Mill in lithology.

The 5.8-foot (1.77 m) thickness of the Hidden Falls Member of the Platteville Formation reflects an early epeirogenic uplift of the Transcontinental Arch just before the big uplift that produced the Decorah Shale. The insoluble residue of this member is as high as 45 percent. It is utterly worthless for any purpose except for filling holes. A 1-inch (2 cm) orange clay layer at the top may be a K-bentonite. Fossil occurrences are patchy, but where present, are very rich. Sardeson mined out a spot in this unit in the old Johnson Street Quarry in Minneapolis (now filled with garbage, and covered with Interstate 35) that produced about 20 specimens of the starfish *Protopalaeaster narrawayi*, several specimens of the peculiar crinoid *Cremacrinus arctus* (Fig. 13), edrioasteroids, cystoids, brachiopods, bryozoans, molluscs, and graptolites. The conodont density is about 10 per 100 grams of rock. The Hidden Falls Member apparently correlates with the Grand Detour Formation of Illinois, which also is more shaly than adjacent rocks, although by no means as shaly as this. Sardeson's bed 2 includes the Hidden Falls and Magnolia Members.

The Mifflin Member of the Platteville Formation here is 10.9 feet (3.33 m) thick. This gray, thin- and crinkly bedded unit contains much shell hash and spotty horizons of fossils. It resembles the McGregor Member south of the Twin Cities basin, and is correlative with the Mifflin of Illinois. Many old foundations in the Twin Cities were built of typical quarry blocks of Mifflin. Good fossils are sparse, but include *Pionodema conradi*, *Hesperorthis tricenaria*, *Oepikina minnesotensis*, *Rostricellula minnesotensis*, and *Isotelus simplex*.

The Pecatonica Member of the Platteville Formation is 2.7 feet (0.83 m) thick here. Templeton and Willman (1963) named the equivalent of this local unit the Hennepin Member of the Pecatonica Formation, but they used

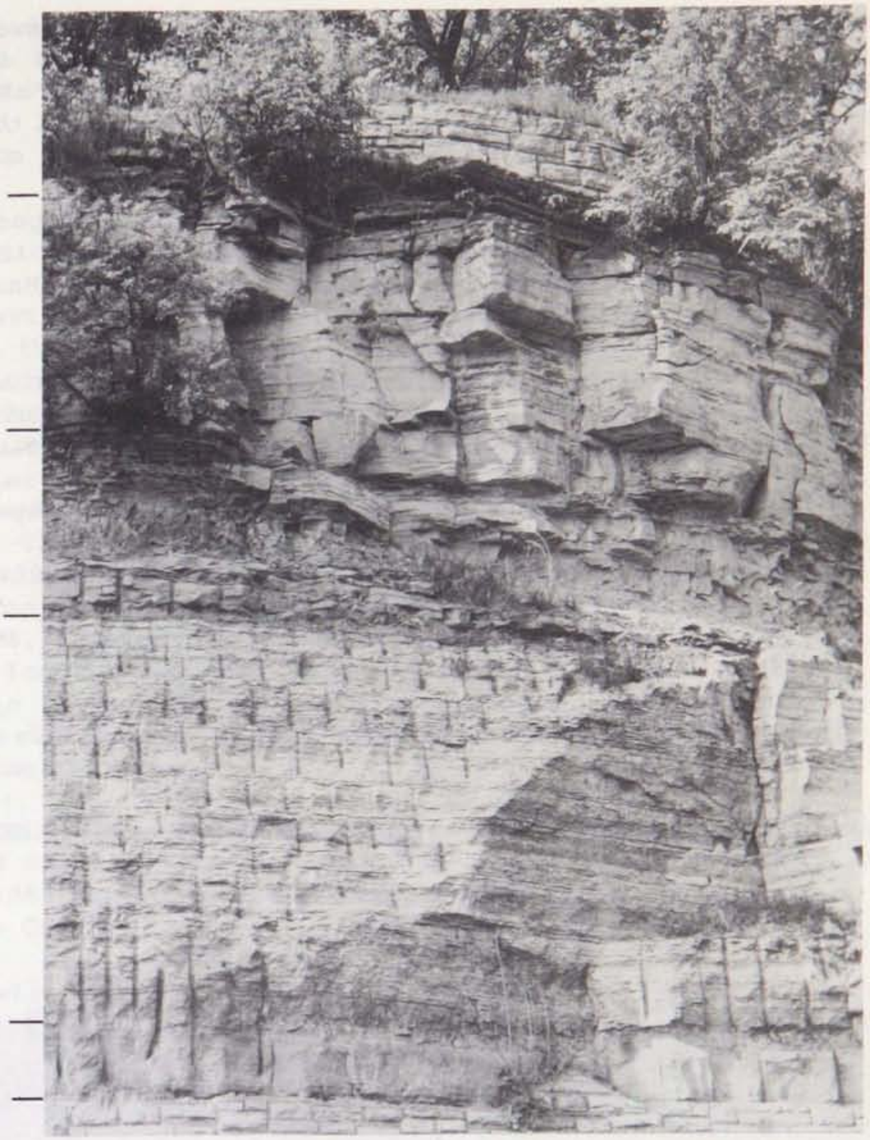

Figure 14. Cliff exposure of the Platteville below Fairview Hospital in Minneapolis.

the name for parts of the Pecatonica at only two other places, and then for rocks quite unlike this exposure. The conodont density is about 30 per 100 grams of rock. The Pecatonica here is equivalent to part of the Glenwood at stop 2 on the southeastern Minnesota-Iowa trip, and to the top of the Pecatonica at stops 3 and 5 of that trip. Here it is a rusty dolomite, containing many small rounded phosphate nodules of collophane, and some floating sand grains of the St. Peter type that were clearly blown in by the wind. The upper 1.33 feet (41 cm) is very shaly, although the basal Platteville is commonly sandy. Sardeson's bed 1 includes the Pecatonica and Mifflin Members.

The underlying 1.8 feet (53 cm) of blue-green Glenwood shale, containing the Chirognathus zone conodonts and a very few small macrofossils, is underlain by 2 feet (61 cm) of shaly sand, showing much bioturbation. This transition from the St. Peter Sandstone to the Glenwood shale is usually included in the Glenwood Formation.

At the base of the exposure is 30 feet (9 m) of typical upper St. Peter Sandstone (Fig. 11), measured from the river level. It shows three of the large rounding-upward cycles of deposition described by Mazzullo and Ehrlich (1980).

After leaving this stop at noon, we will stop for lunch along Grand Avenue, 1 block south of Summit, where several restaurants of different ethnic persuasion are available. Return to the bus by 1:30 p.m.

19.0	Return to the Cathedral and turn right on Kellogg Avenue.
20.0	Turn right on Wabasha Street, in front of the Radisson Hotel; cross the bridge to Fillmore Street (0.4 mile). Turn right on Fillmore Street which becomes Water Street. Continue on Water Street for 1.5 miles.
21.9	Park at the gate to the old Twin City Brick and Tile quarry and clay pit (Fig. 15).

STOP 3. Old Twin City Brick and Tile pit; now Lilydale Park, SE1/4 sec. 12, T. 28 N., R. 23 W.

Figure 15. Twin City brickyard clay pit seen from across the Mississippi River.

This is the richest place for Decorah fossils in the Twin Cities and is also the thickest known section of Decorah Shale. BE VERY CAREFUL IN THE BIG OPEN PIT! This is the locality where J.S. (Steve) Templeton was killed on April 21, 1953. He was hit by a slab of Cummingsville limestone that fell from the top of the pit.

Our collecting will be in a gully in the extreme southeast quarter of the section, where nearly the entire 89.2 feet (27.2 m) of the Decorah Shale is exposed, as well as the bottom 18 inches (45 cm) of the Cummingsville Formation, with Fisherites (= Receptaculites). The lower part of the type Cummingsville is here replaced by the upper part of the Decorah Shale. The Platteville is also exposed and much good collecting can be had in the loose blocks near the base of the section. By this time you should be able to recognize to which of the five Platteville members a particular block belongs, or ask one of us. We have driven stakes in the section every 10 feet (3 m) so you may keep your collections separated by level. These rocks have been zoned in detail for ostracods (Swain and others, 1961), bryozoans (Karklins, 1969), brachiopods (Rice, 1985), and trilobites (Hedblom, in prep). We anticipate that more zonation will be done here. For convenience in collecting we have provided plastic bags and printed locality labels. Rice's detailed graphic section (Fig. 16), broken down into 10-foot (3 m) units, is printed on the next page. We suggest you mark the horizons of your collections on the graphic section for ease in recovering the data.

This is not only the thickest Decorah section known--it also was deposited 1.4 times as fast as the Decorah in Fillmore County (on the basis of Rice's 1985 Shaw analysis comparing this section with Weiss's samples from Fillmore County), and is the section closest to the Transcontinental Arch.

We will collect at this locality until 4:30 p.m. or when people get tired, whichever comes first. We will then return to the St. Paul Hotel.

We thank you for your attention, and hope your collections are large enough to require an extra box on your trip home.

REFERENCES CITED

References cited in this road log are listed at the end of the Iowa field trip in this guidebook on page

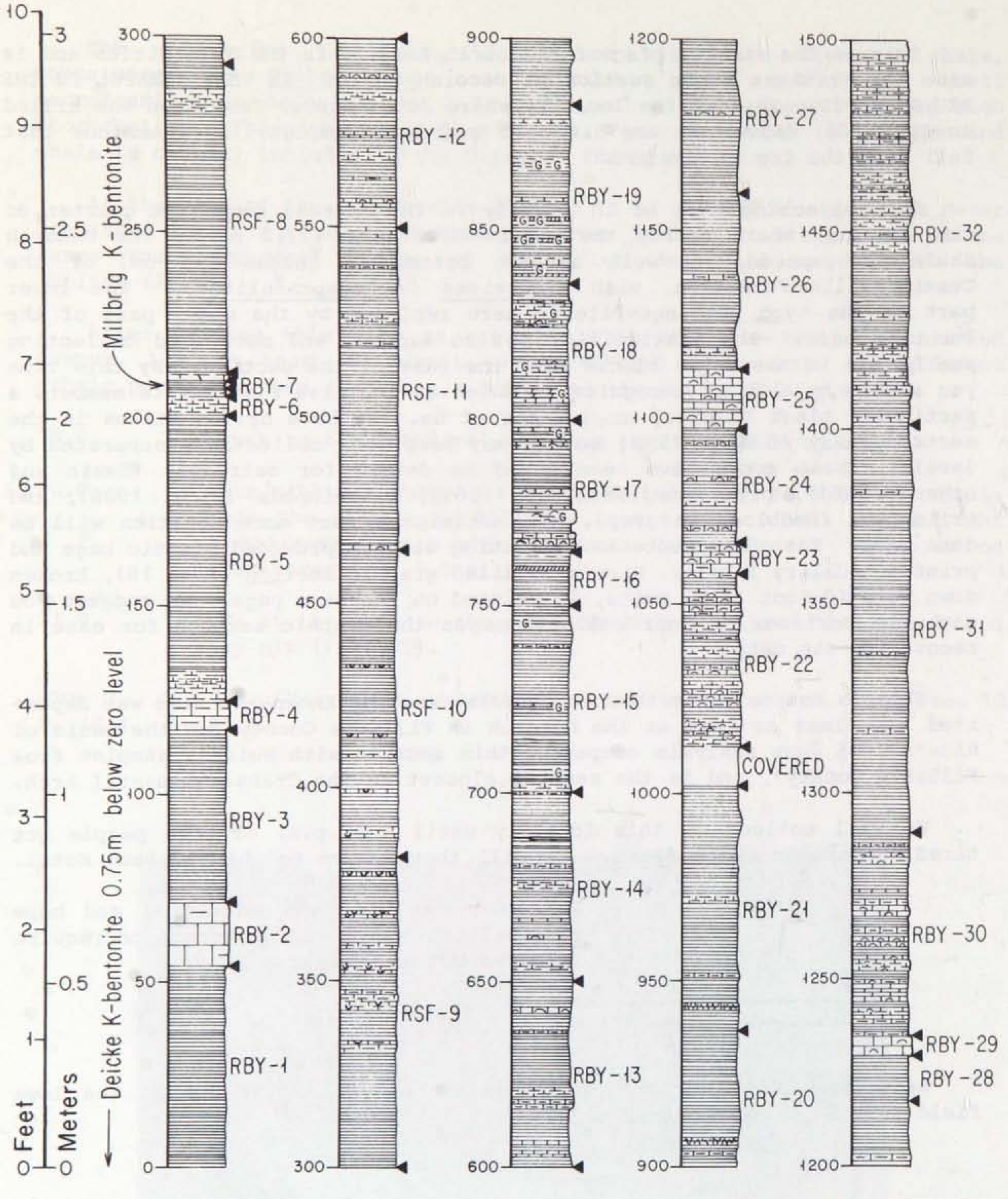

Figure 16. Detailed bed by bed graphic section of the Decorah Shale and basal Cummingsville Formation in the St. Paul brickyard.

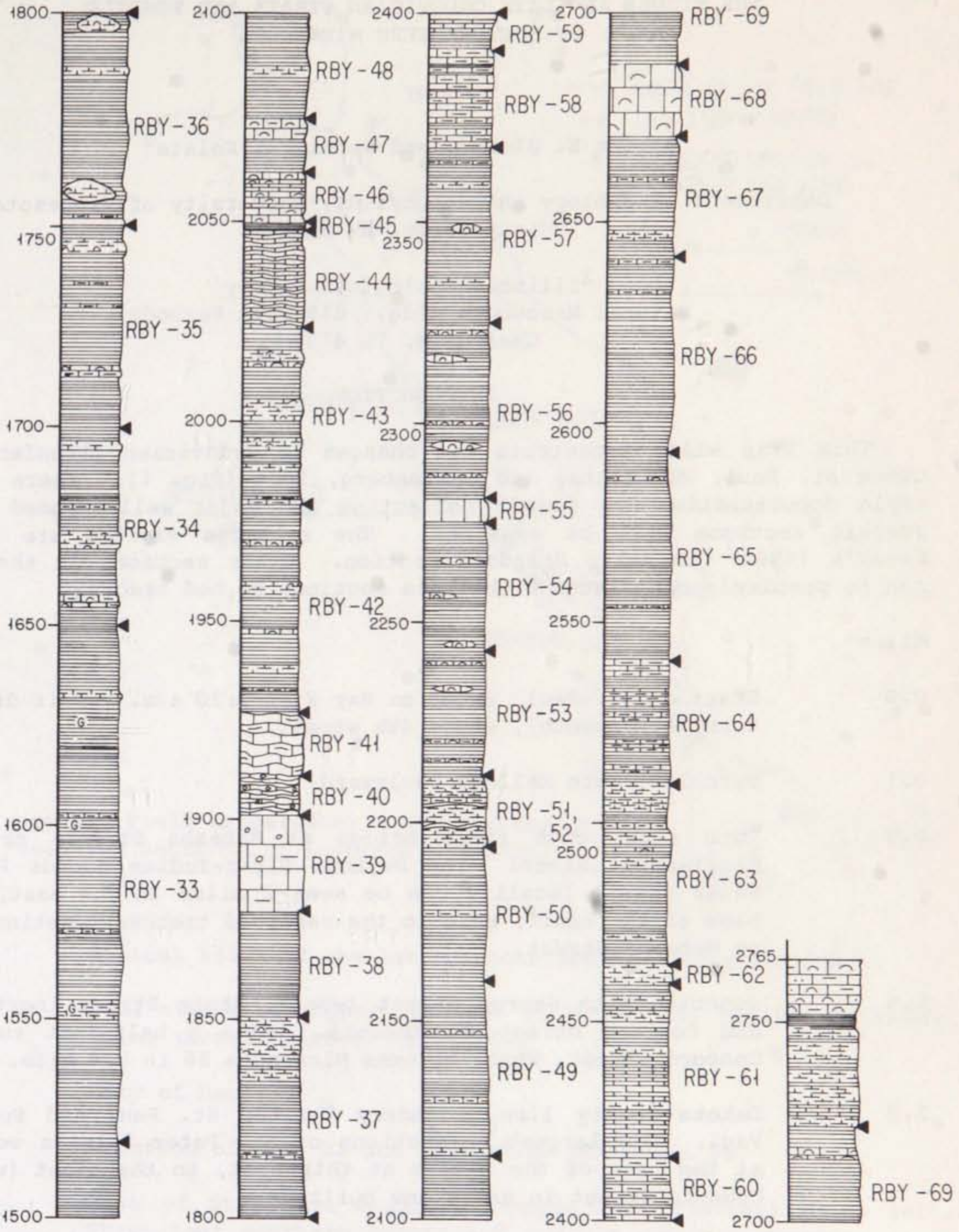

Figure 16 continued.

THE MIDDLE AND LATE ORDOVICIAN STRATA AND FOSSILS OF SOUTHEASTERN MINNESOTA

by

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INTRODUCTION

This trip will demonstrate the changes in Ordovician lithofacies between St. Paul, Minnesota, and Guttenberg, Iowa (Fig. 1). There will be ample opportunities for fossil collecting and major well-exposed stratigraphic sections will be examined. The sections visited are part of Sweet's (1984) Composite Standard Section. Other sections in the region can be precisely correlated with these sections by bed tracing!

Miles	
0.0	Start at St. Paul Hotel on May 2 at 7:30 a.m. Exit driveway, turn left (south), cross 4th street.
0.1	Turn left onto Kellogg Boulevard.
0.3	Turn right onto first bridge at Wabasha Street; cross the Mississippi River. The Daytons Bluff-Indian Mounds Park St. Peter fossil locality can be seen 2 miles to the east, at the base of the bluff, next to the railroad tracks. Continue south on Wabasha Street.
1.6	Junction with George Street (west), State Street (northeast), and Concord Street (southeast). Make a half-left turn onto Concord Street, which becomes Minnesota 56 in 0.4 mile.
2.8	Dakota County line, boundary between St. Paul and South St. Paul. The largest collections of St. Peter fossils were made at the base of the bluffs at this spot, to the right (west) of Concord Street in areas now built up.
6.0	Intersection with I-494, continue south on Minnesota 56.
11.1	Intersection with U.S. 52 and U.S. 55, continue south on combined roads.
13.6	Pine Bend oil refinery on right.
14.7	Junction of U.S. 55 with 52-56, continue south on Minnesota 56.

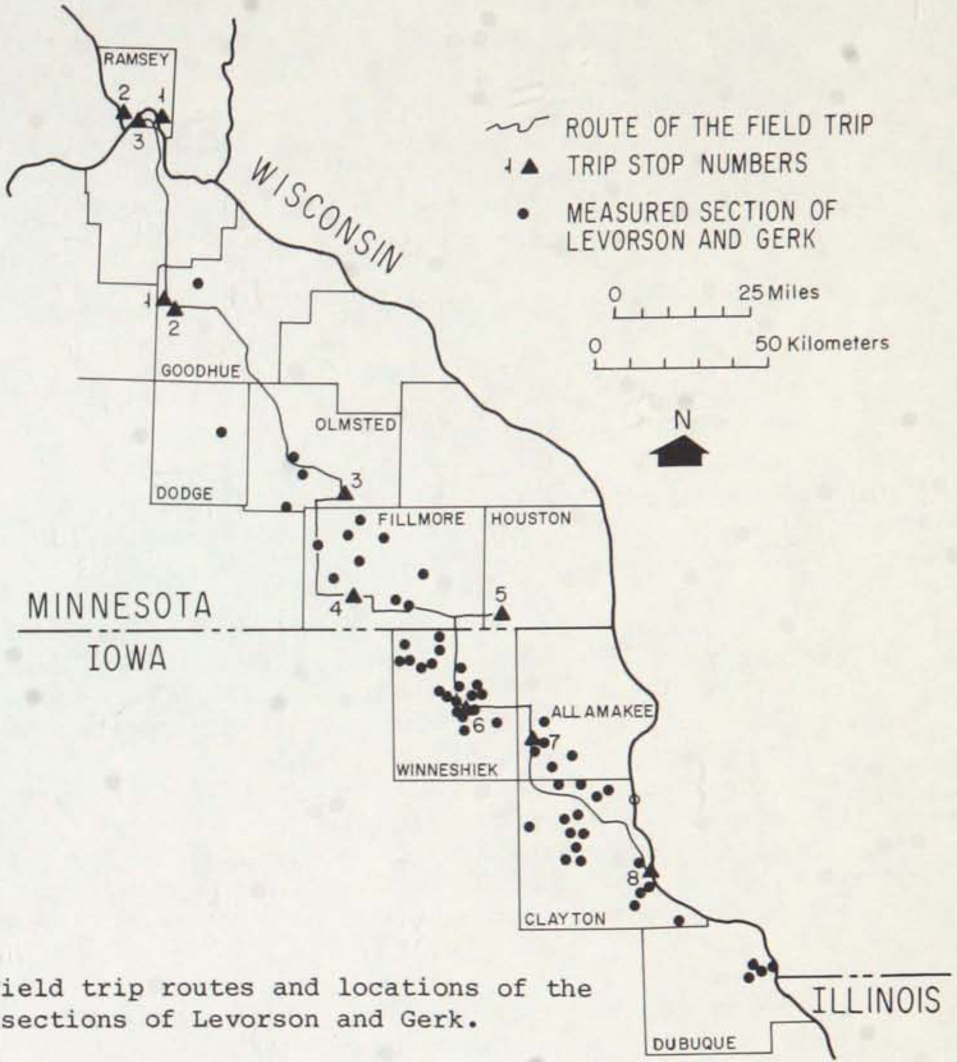


Figure 1. Field trip routes and locations of the measured sections of Levorson and Gerk.

16.1 Typical hills of the late-Wisconsinan St. Croix moraine.

17.1 Tall stacks of Gopher Ordnance Works (WW II) visible to right, going through Coates, Minnesota.

25.8 City of Hampton.

26.0 Junction of U.S. 52 and 56; follow Minnesota 56.

28.2 Mesa of St. Peter Sandstone capped with Platteville on left. Throughout southern Dakota and Goodhue and Rice Counties these landforms are very typical (Ernst, 1954).

32.7 Bridge over Cannon River; enter Goodhue County. Cannon Falls is 5 miles east; it was the home of the noted amateur paleontologist W.H. Scofield, who described the Minnesota Ordovician gastropods with Ulrich in 1896 in a classic monograph. (We suspect that Scofield did most of the work and Ulrich got the credit.)

34.8 Junction with Minnesota 19. One of the rare outcrops of the base of the St. Peter Sandstone is 0.8 mile east along a meander cut of Prairie Creek on the north side of the road. Another is located in the SW1/4 sec. 25, T. 112 N., R. 17 W., along a meander bend of the Little Cannon River at a bridge about 2.5 miles south of Minnesota 19 on Old Oxford Mill road. Continue south on Minnesota 56.

35.8 Junction with Minnesota 19. Continue south on Minnesota 56.

39.3 St. Peter outcrop east of road.

40.0 Park by roadside.

STOP 1. Wangs roadcut (1.2 miles north of Wangs), center sec. 16, T. 111 N., R. 17 W., Goodhue County; 1 hour will be spent in collecting fossils from the Decorah Shale here (Fig. 2).

This is one of the better exposures of the top of the Platteville, the full thickness of the Decorah, and the base of the Cummingsville Formation of the Galena Group. The Decorah Shale rapidly grows over and is best exposed in roadcuts. There are excellent exposures on U.S. 52, 5 miles east, but it is not possible to collect there with a large party. The upper Platteville, Carimona Member and the Deicke K-bentonite, and the base of the Decorah are exposed in the ditch to the west. The complete Decorah and the base of the Cummingsville can be seen in the cuts on the east side of the road for the next 0.7 mile. These outcrops are richly fossiliferous. Karklins (1969) discussed the cryptostome bryozoans from this locality.

You might want to collect a pair of fist-size samples of Carimona from the beds just above and below the Deicke K-bentonite either here or at stops 2, 3, or 5 for solution in dilute formic or acetic acid, because the conodonts are extremely abundant and well preserved. The most convenient reference for identification is Webers (1966).

The Cummingsville Formation is about 60 feet thick in Goodhue County, but only the lower 20 feet or so is exposed here, a rubbly, white, nodular shaly limestone. Expect to find *Vellamo*, *Platystrophia*, *Rafinesquina*, *Paucicrura*, *Sowerbyella*, *Ischadites*, and *Fisherites*.

The Decorah Shale in Goodhue County is about 61 feet (18.6 m) thick. It is a yellowish-green shale with fossiliferous, lenticular, and persistent thin interbeds of limestone. It is moderately to abundantly fossiliferous throughout. *Pionodema subaequata* is abundant 4 to 5 feet above the base and in the upper 10 feet. The *Prasopora conoidea* faunule with *Rhynchotrema*, *Sowerbyella*, *Paucicrura*, *Dinorthis*, and *Hesperorthis* is present in the upper 10 feet (3 m). The lower 14 feet (4.3 m) has the *Stictoporella angularis* zone of Karklins (1969) and the *Eurychilina subradiata* zone of Swain and others (1961). The top of the *Stictopora mutabilis* zone of Karklins and the *Byrsolopsina planilateralis* zone of Swain and others are about 45 feet (14 m) above the base. The *Stictopora minima* and the *Bollia simplex* zones range to the top of the Decorah and into the Cummingsville.

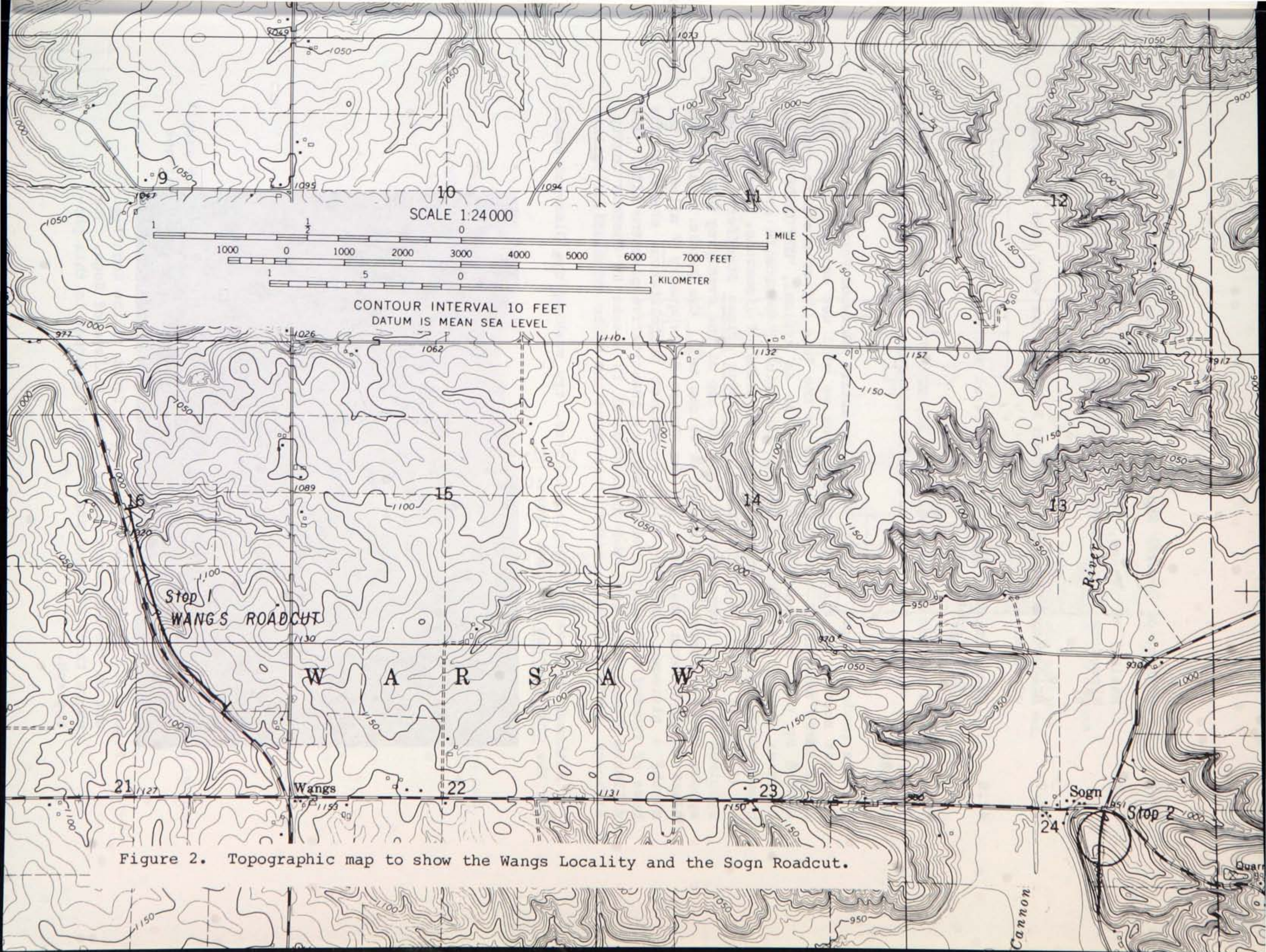


Figure 2. Topographic map to show the Wangs Locality and the Sogn Roadcut.

40.8 Contact of Decorah Shale and Cummingsville Formation.

41.2 Hamlet of Wangs, although no sign remains; junction of Minnesota 56 and Goodhue County 9. Turn left (east) on County 9.

43.7 Bridge over the Little Cannon River at the west edge of village of Sogn.

43.9 Junction with Goodhue County 14 at the east edge of Sogn, turn right (south) and stop.

STOP 2. Sogn roadcut. NE1/4SE1/4 sec. 24, T. 111 N., R. 18 W., Goodhue County. We will be here 45 minutes for collecting and stratigraphic discussion.

The roadcut (Figs. 2, 3, 4) shows the entire Glenwood Formation and the thinnest section of Platteville Formation we will see on this trip. The lower three members of the Platteville in the Twin Cities are here represented by part of the Glenwood shale. As is typical, the beds of the Carimona Member just above and below the Deicke K-bentonite are rich in conodonts, here about 300 conodonts per 100 grams of limestone. The Deicke is the upper limit of the conodont <u>Scyphiodus primus</u> Stauffer; the type specimen and other rare specimens from the top of the overlying Decorah all appear to be reworked. As closely as we can tell, the Deicke is also the Black River-Trenton boundary. At the Cannon Falls quarry 7 miles to the north, a nitrogen analysis of the 1-cm-thick petroliferous shale at the base of the Deicke K-bentonite indicates a quantitative plankton kill. The Millbrig K-bentonite from the lower Decorah is absent in Goodhue County, although it is generally present throughout the Upper Mississippi valley.

Although we have not sampled it here, try washing the Glenwood shale for the <u>Chirognathus</u> conodont fauna.

Figure 3. Dennis Kolata standing in front of the Sogn roadcut on the southeast corner of the village of Sogn. The extra thick Glenwood Shale is very apparent in this photograph.

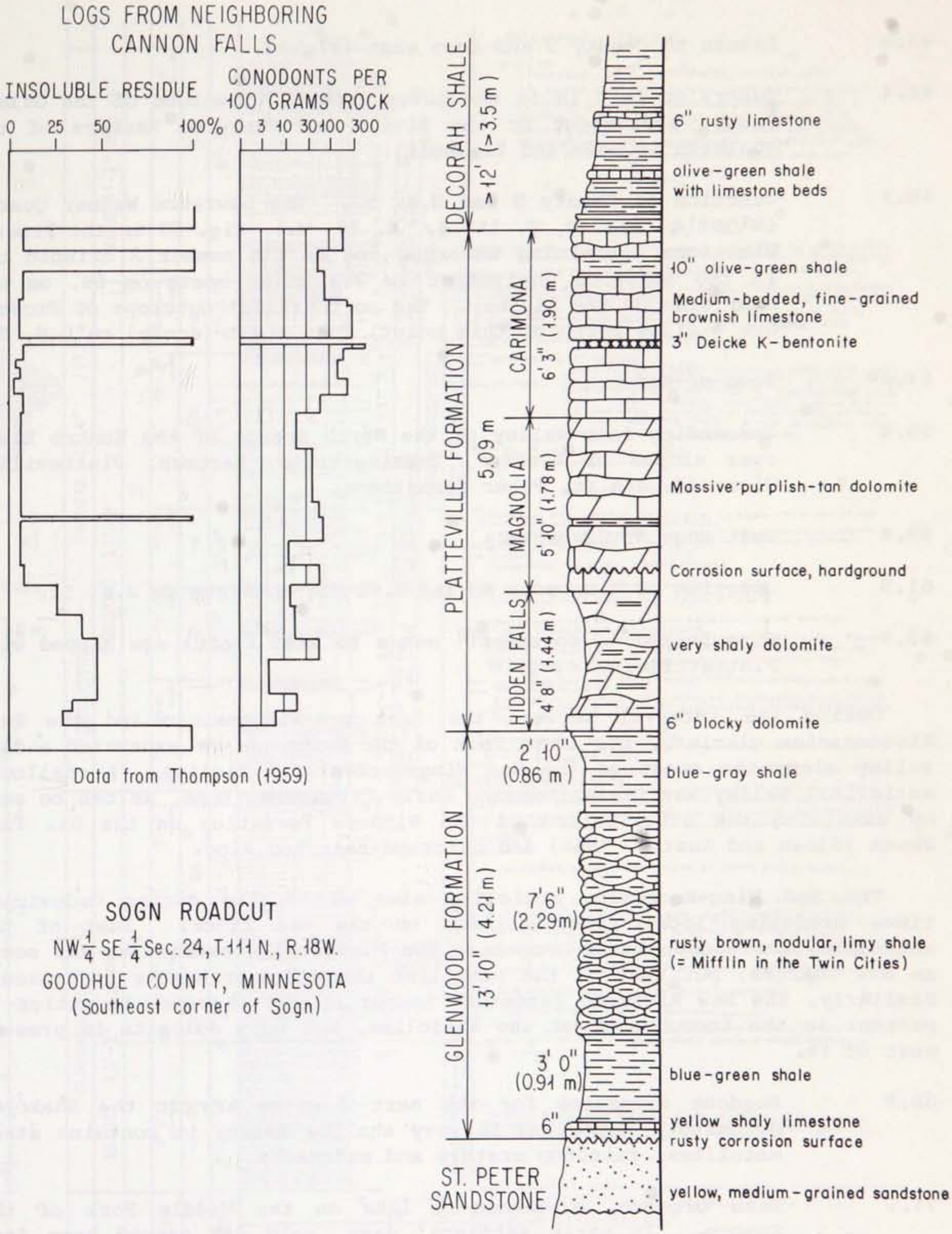


Figure 4. Graphic section of the Sogn roadcut, 0.1 mile south of the intersection of Goodhue county roads 9 and 14.

43.9 Return to County 9 and turn east (right).

44.4 Quarry on left is in the lower Prosser Limestone of the Galena Group, equivalent to the Rivoli and Sherwood Members of the Dunleith in Iowa and Illinois.

48.3 Junction of County 9 and U.S. 52. The Lawrence Wagner Quarry ($\mathrm{W}^1/_2\mathrm{SE}^1/_4$ sec. 8, T. 111 N., R. 17 W.; Fig. 5) in the Prosser Limestone containing Levorson and Gerk's number 2 crinoid bed in the Sherwood equivalent is 3.5 miles north on 52, on the east side of the highway. The northernmost outcrops of Prosser are 6 miles north of this point. Turn right (south) on U.S. 52.

51.4 Town of Hader.

56.4 Descending into valley of the North Branch of the Zumbro River over slopes of Prosser, Cummingsville, Decorah, Platteville, Glenwood, and St. Peter formations.

59.9 West edge of Zumbrota.

61.9 Junction of Minnesota 60 and U.S. 52, continue on U.S. 52.

65.9 Pine Island to southwest; mesas to east (left) are capped with Platteville.

During the interval between the last pre-Wisconsinan and the late Wisconsinian glaciers, the south Fork of the Zumbro River excavated a deep valley along the crest of the Red Wing-Rochester anticline. A shallower anticlinal valley was present during early Cretaceous time, as can be seen by examining the distribution of the Windrow Formation on the St. Paul Sheet (Sloan and Austin, 1966) and outcrops near Red Wing.

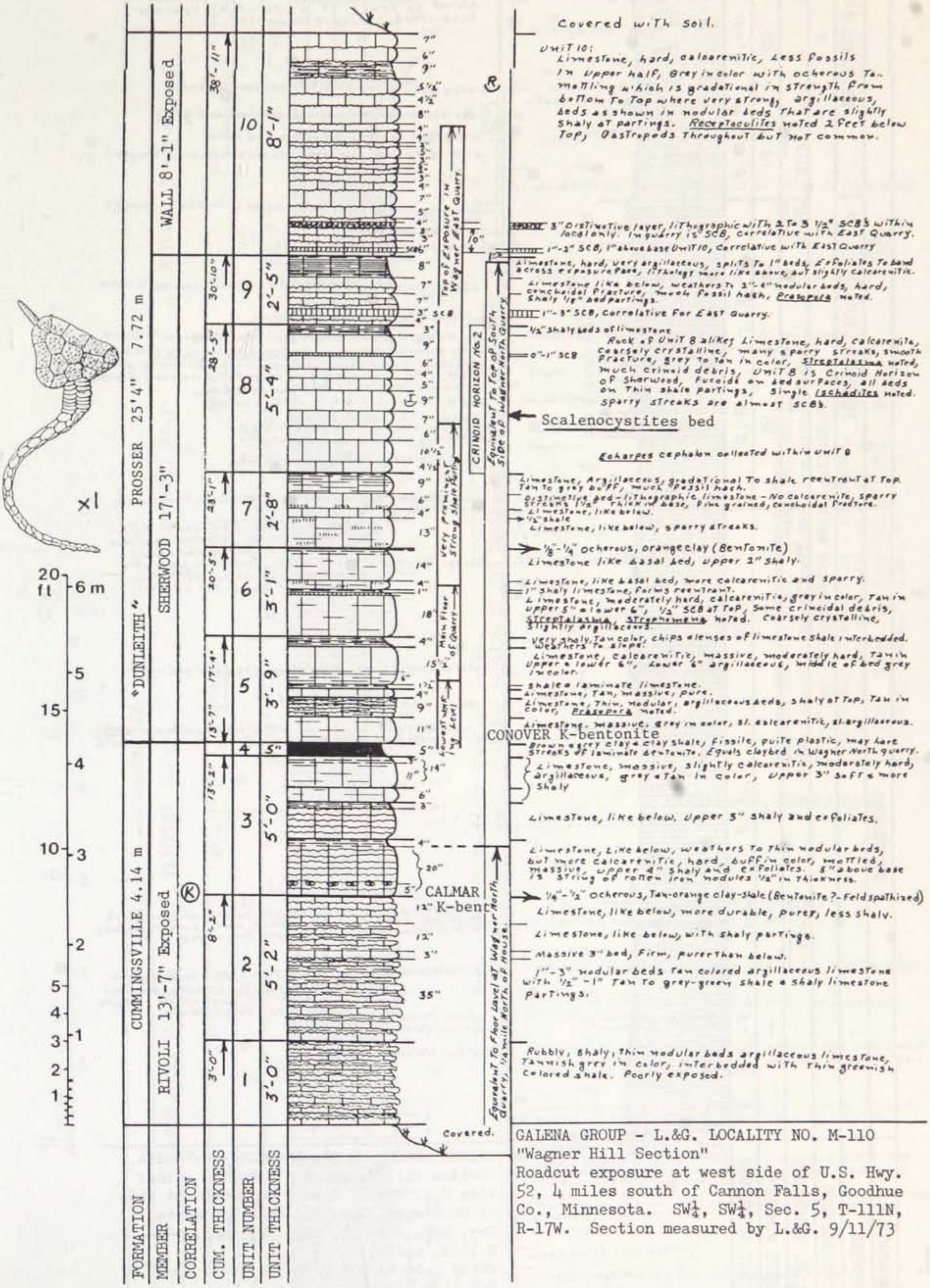
The Red Wing-Rochester anticline also was active during Ordovician time, producing local irregularities on the sea floor. East of the anticline, the Hidden Falls Member of the Platteville extends as far south as St. Charles, but west of the anticline the McGregor Member is present. Similarly, the New Richmond Sandstone Member of the Shakopee Formation is present in the trough east of the anticline, but only dolomite is present west of it.

66.9 Roadcut exposures for the next 7 miles are in the Shakopee dolomite. Deposited in very shallow water, it contains stromatolites, raindrop craters and mudcracks.

71.9 Lake Oronoco, a dammed-up lake on the Middle Fork of the Zumbro. In early settlers' days, gold was panned here from Pleistocene gravels at a rate of 50¢ per day. Allowing for inflation, that was worth doing.

83.3 First junction U.S. 14 and U.S. 52 at 5th Street NW in Rochester. Continue on 52.

86.3 Golden Hill section of Levorson and Gerk (Fig. 6). Excellent



Covered with soil.

UNIT 10:
Limestone, hard, calcarenitic, Less fossils in upper half, Grey in color with ocherous Tan mottling which is gradational in strength from bottom to Top where very strong, argillaceous, beds as shown in nodular beds that are slightly shaly at partings. *Receptaculites* noted 2 feet below Top; Gastropods Throughout but not common.

3" Distinctive layer, lithographic with 2 To 3 ½" SCB's within locally only. In quarry is SCB, correlative with East Quarry.

1"-2" SCB, 1" above base Unit 10, Correlative with East Quarry

Limestone, hard, very argillaceous, splits To 1" beds, Exfoliates To band across exposure face, lithology more like above, but slightly calcarenitic.

Limestone like below, weathers to 2"-4" nodular beds, hard, conchoidal fracture, much fossil hash, *Prasopora* noted. Shaly ⅛" bed partings.

1"-3" SCB, Correlative For East Quarry.

½" shaly beds of limestone

0"-1" SCB

Rock of Unit 8 alike; Limestone, hard, calcarenite, coarsely crystalline, many sparry streaks, smooth fracture, grey to tan in color, *Streptelasma* noted, much crinoid debris, Unit 8 is Crinoid Horizon of Sherwood, Fucoids on bed surfaces, all beds on Thin shale partings, Single *Ischadites* noted. Sparry streaks are almost SCB's.

Scalenocystites bed

Eoharpes cephalon collected within Unit 8

Limestone, Argillaceous, gradational To shale reentrant at Top. Tan to grey buff, much fossil hash.

Distinctive bed - lithographic limestone - No calcarenite, sparry streaks 1½" Thick in base, Fine grained, conchoidal fracture.

Limestone, like below.

½" shale

Limestone, like below, sparry streaks.

⅛"-¼" ocherous, orange clay (Bentonite)

Limestone like basal bed, upper 2" shaly.

Limestone, like basal bed, more calcarenitic and sparry.

1" shaly limestone, forms reentrant.

Limestone, moderately hard, calcarenitic, grey in color, Tan in upper 5" & lower 6", ½" SCB at Top, Some crinoidal debris, *Streptelasma*, *Strophomena* noted. Coarsely crystalline, slightly argillaceous.

Very shaly, Tan color, chips & lenses of limestone shale interbedded. Weathers to slope.

Limestone, calcarenitic, massive, moderately hard, Tan in upper & lower 6", Lower 6" argillaceous, middle of bed grey in color.

Shale & laminate limestone.

Limestone, Tan, massive, pure.

Limestone, Thin, nodular, argillaceous beds, shaly at Top, Tan in color, *Prasopora* noted.

Limestone, massive, grey in color, sl. calcarenitic, sl. argillaceous.

CONOVER K-bentonite

Brown & grey clay & clay shale, Fissile, quite plastic, may have streaks of laminate bentonite. Equals claybed in Wagner North quarry.

Limestone, massive, slightly calcarenitic, moderately hard, argillaceous, grey & Tan in color, upper 3" soft & more shaly

Limestone, like below, upper 5" shaly and exfoliates.

Limestone, Like below, weathers To Thin nodular beds, but more calcarenitic, hard, buff in color, mottled, massive, upper 4" shaly and exfoliates. 5" above base is string of rotten iron nodules ½" in Thickness.

CALMAR K-bent

¼"-½" ocherous, Tan-orange clay-shale (Bentonite ?- Feldspathized)

Limestone, like below, more durable, purer, less shaly.

Limestone, like below, with shaly partings.

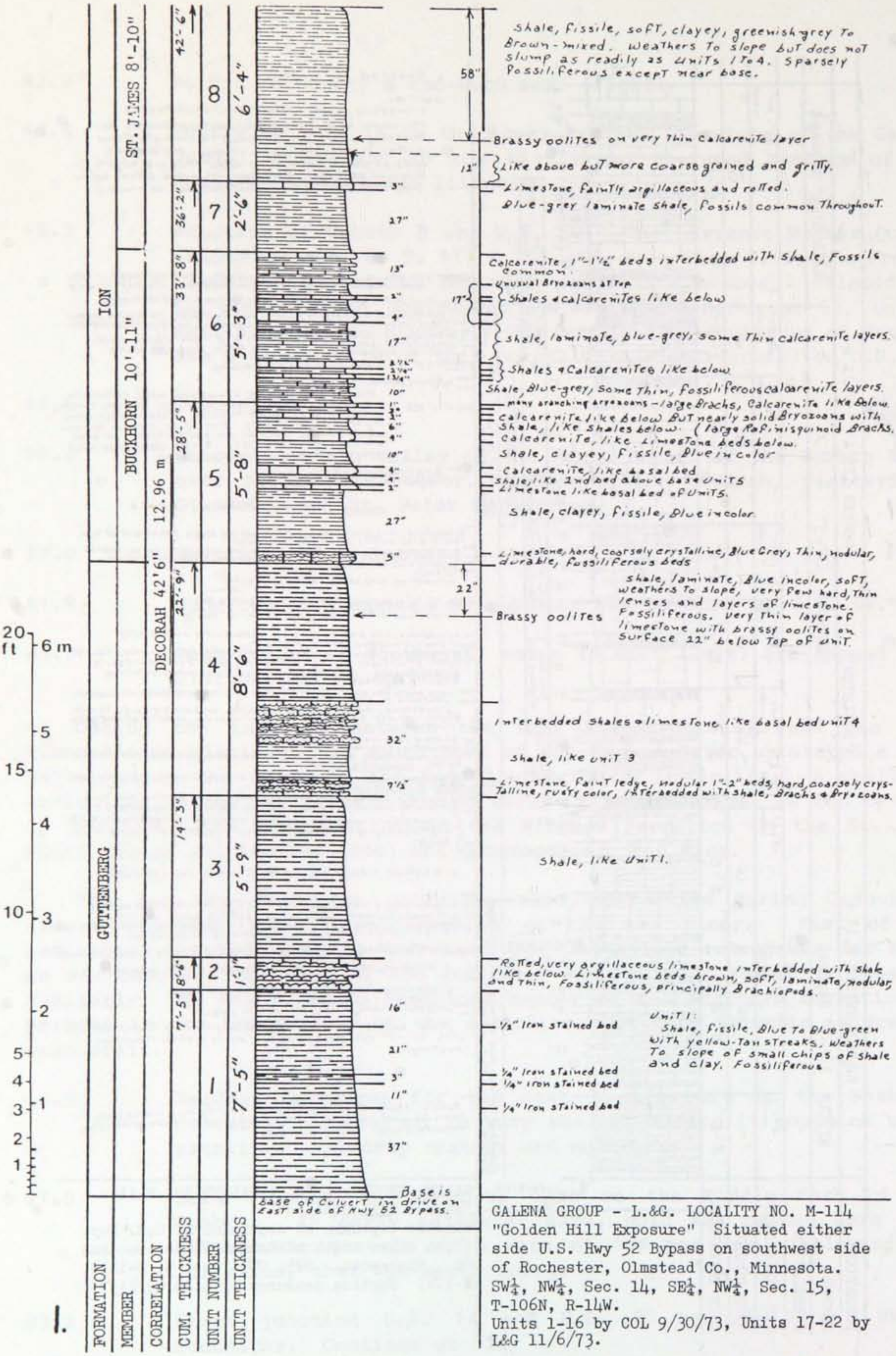
Massive 3" bed, Firm, purer than below.

1"-3" nodular beds Tan colored argillaceous limestone with ½"-1" Tan to grey-green shale & shaly limestone partings.

Rubbly, shaly, Thin nodular beds argillaceous limestone, Tannish grey in color, interbedded with Thin greenish colored shale. Poorly exposed.

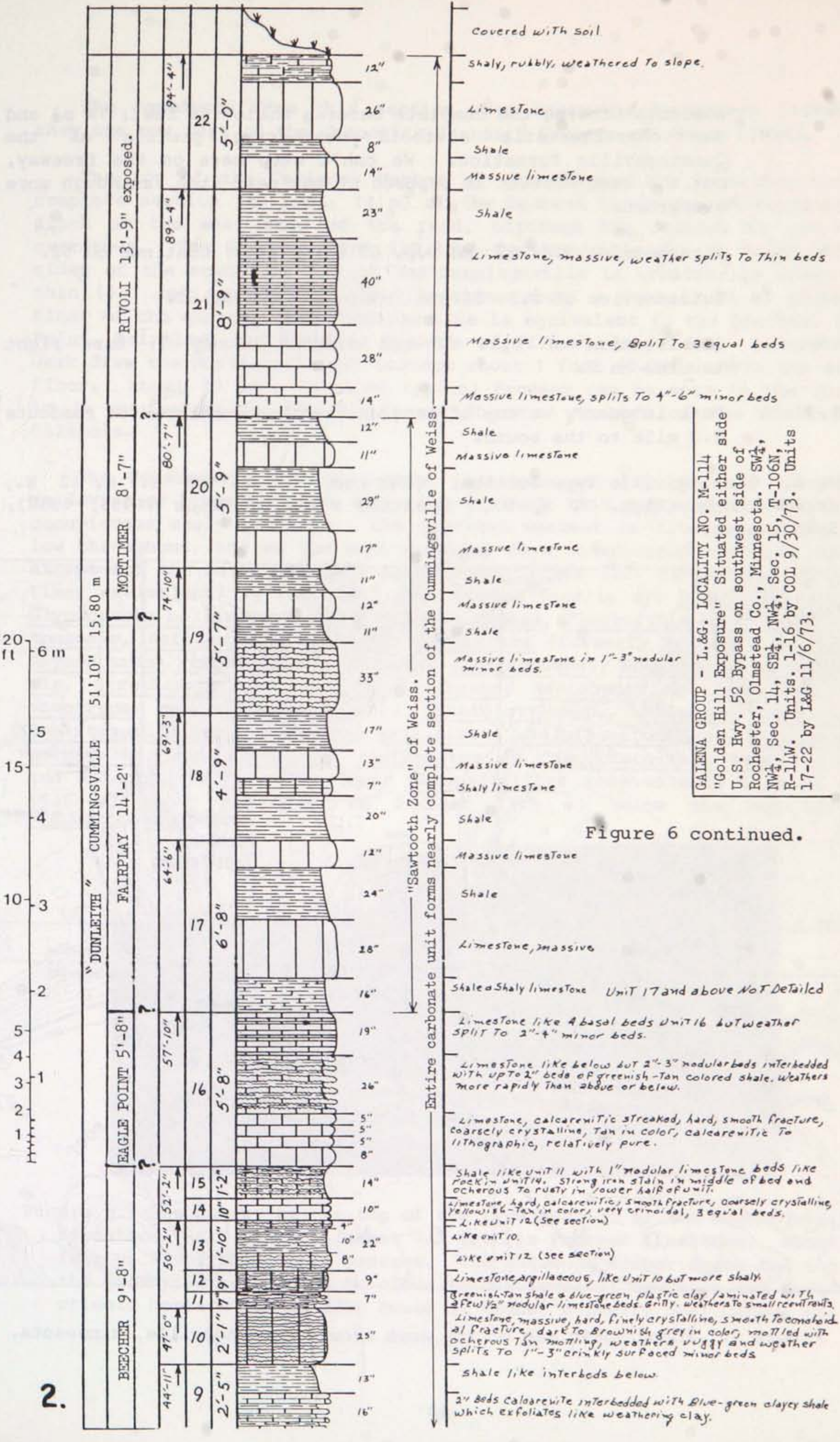
GALENA GROUP - L.&G. LOCALITY NO. M-110
"Wagner Hill Section"
Roadcut exposure at west side of U.S. Hwy. 52, 4 miles south of Cannon Falls, Goodhue Co., Minnesota. SW¼, SW¼, Sec. 5, T-111N, R-17W. Section measured by L.&G. 9/11/73

Figure 5. Graphic section of the roadcut near the Lawrence Wagner Quarry.



GALENA GROUP - L.&G. LOCALITY NO. M-114
"Golden Hill Exposure" Situated either side U.S. Hwy 52 Bypass on southwest side of Rochester, Olmstead Co., Minnesota.
SW¼, NW¼, Sec. 14, SE¼, NW¼, Sec. 15, T-106N, R-14W.
Units 1-16 by COL 9/30/73, Units 17-22 by L&G 11/6/73.

Figure 6. Levorson and Gerk's graphic section of the Decorah and Cummingsville formations of the Golden Hill section along U.S. 52 in southwestern Rochester, Minnesota.



GALENA GROUP - L.&G. LOCALITY NO. M-114 "Golden Hill Exposure" Situated either side U.S. Hwy. 52 Bypass on southwest side of Rochester, Olmstead Co., Minnesota. SW$\frac{1}{4}$, NW$\frac{1}{4}$, Sec. 14, SE$\frac{1}{4}$, NW$\frac{1}{4}$, Sec. 15, T-106N, R-14W. Units 1-16 by COL 9/30/73. Units 17-22 by L&G 11/6/73.

Figure 6 continued.

roadcuts showing the complete Decorah Shale (46 feet; 14 m) and the characteristic sawtooth weathering profile of the Cummingsville Formation. We can't stop here on the freeway, but the same section is exposed at our next stop, although more overgrown.

87.5 Intersection U.S. 52 and U.S. 63 (Broadway); continue on 52.

92.3 Intersection of U.S. 52 and I-90; continue on 52.

99.3 Intersection of U.S. 52 and Olmsted County 7; turn right (south) on 7.

101.2 Park in quarry at top of section; section continues in roadcuts 0.3 mile to the south.

STOP 3. Cummingsville Type Section, SE1/4 sec. 21, T. 105 N., R. 12 W., Olmsted County (Figs. 7, 8, 9). Location F-164 of Weiss (1955, 1957); 1.5-hour stop.

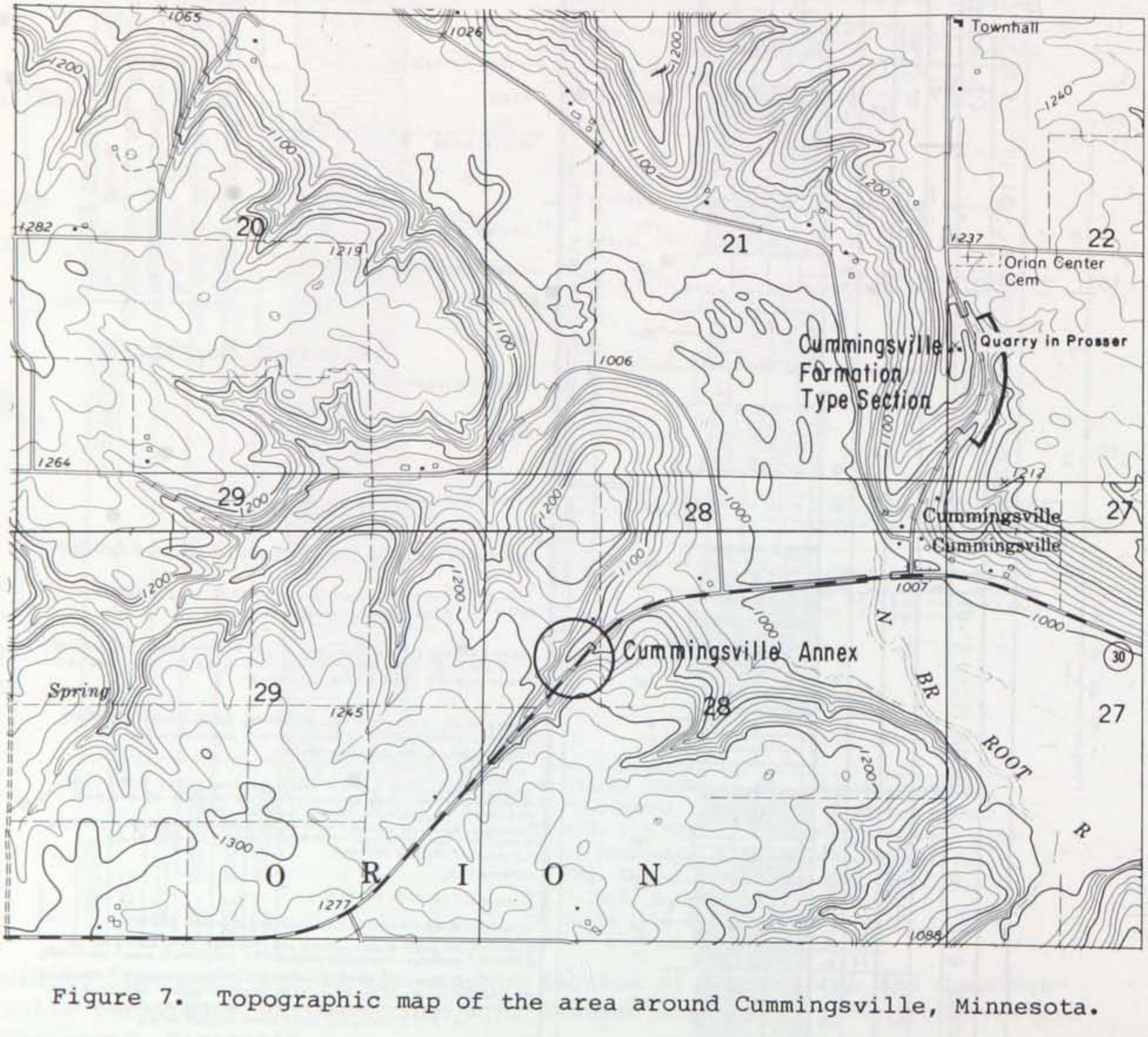


Figure 7. Topographic map of the area around Cummingsville, Minnesota.

The conodonts from this section were described by Webers (1966) and they are now part of the Composite Standard Section of Sweet (1984).

The top of the Carimona Member of the Platteville Formation and the complete section (46 feet; 14 m) of the Decorah Shale can be found in the ditch on the west side of the road, although the Decorah is now badly overgrown. The 63-foot-thick (19.2 m) Cummingsville can be found on both sides of the road; the top of the Cummingsville is arbitrarily drawn at a thin (5-7 cm) sandy phosphatic limestone about 4 feet (1.20 m) above the floor of the quarry. The Cummingsville is equivalent to the Beecher, Eagle Point, Fairplay, and Mortimer Members of Illinois and Iowa. Levorson and Gerk draw the Mortimer/Rivoli contact about 1 foot (0.3 m) above the quarry floor. About 30 feet (9 m) of typical Prosser can be seen in the quarry; it is equivalent to the Rivoli and Sherwood Members of the Dunleith in Illinois.

The Cummingsville Formation is limestone and argillaceous limestone, yellowish or brownish gray, very fine grained, thin and wrinkly bedded with conspicuous shaly partings. The detrital content is alternately high and low throughout, and so the unit weathers to a conspicuous sawtooth profile except for the basal (Beecher equivalent) 7 feet (2.1 m) and the top (Mortimer equivalent) 16 feet (4.9 m). Common fossils are *Dinorthis sweenyi*, *Glyptorthis bellarugosa*, *Platystrophia amoena*, *Plectorthis plicatella trentonensis*, *Rafinesquina camerata*, *Paucicrura* (formerly *Resserella*) *rogata*, *Rhynchotrema wisconsinense* (formerly *increbescens*), *Sowerbyella minnesotensis*, *Strophomena* sp., *Vellamo americana*, *Aspidopora* sp. *Batostoma* sp., *Monotrypa* sp., *Prasopora* sp., *Rhinidictya* sp., *Illaenus americanus*, *Bumastus billingsi*, *Hormotoma bellicincta*, *Salpingostoma* sp., *Streptelasma corniculum*, and *Fisherites reticulatus* (= "*Receptaculites oweni*" Finney and Nitecki, 1979). The lower *Receptaculites* zone extends from 18 feet (5.5 m) above the base to 5 feet (1.5 m) below the top of the Cummingsville.

Figure 8. The quarry at the top of the type section of the Cummingsville Formation. All but the lowest 2.5 feet is Prosser Limestone. About 21 feet of Rivoli Member is present. The Sherwood Member forms the top of the quarry, which should be close to the level of Levorson and Gerk's crinoid horizon no. 2, also found at Wagner's Quarry near Cannon Falls.

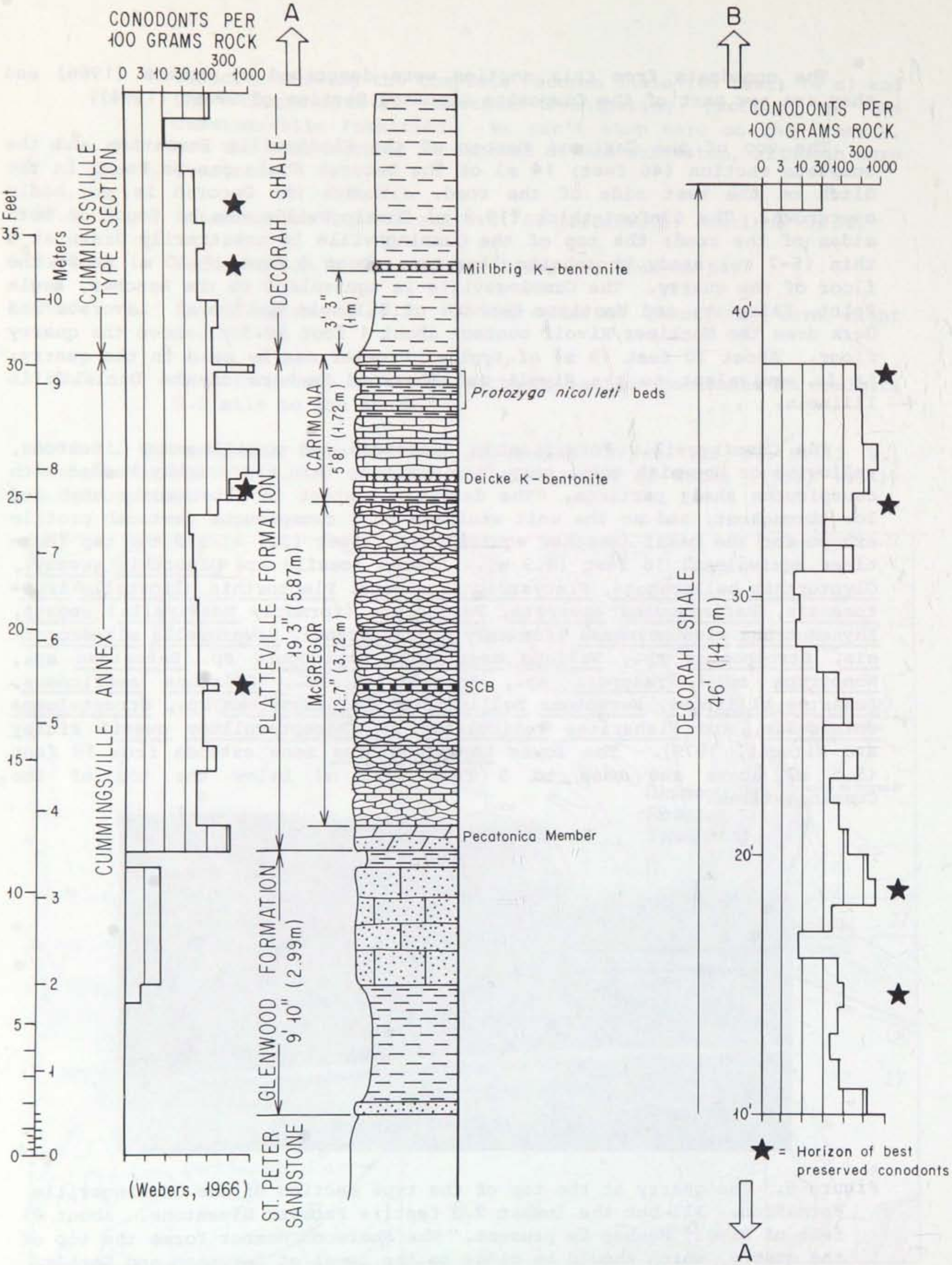


Figure 9. Graphic section of the Platteville Limestone at Cummingsville Annex and the Decorah through Prosser formations at the type locality for the Cummingsville Formation.

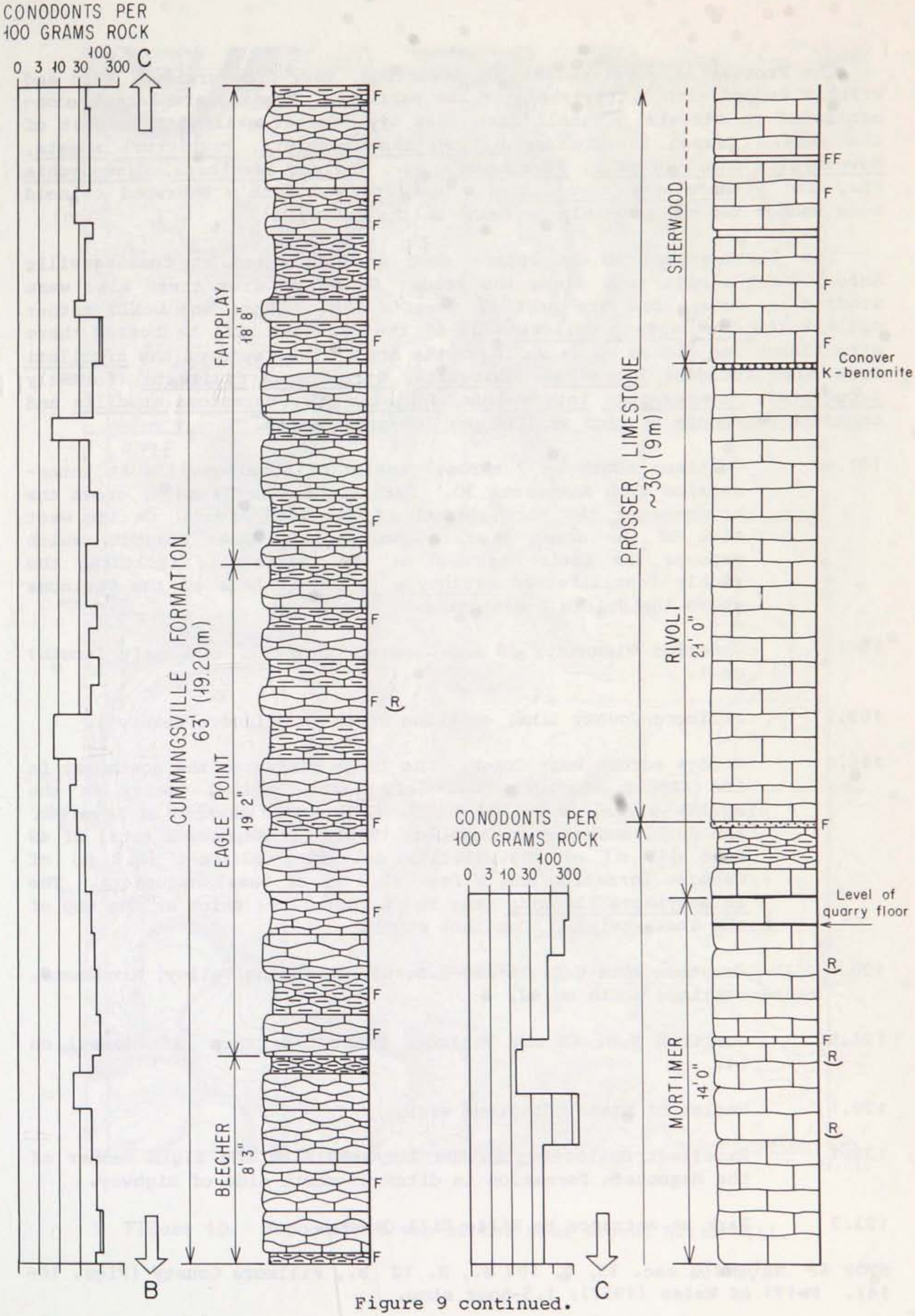


Figure 9 continued.

The Prosser is a yellowish-gray limestone, very fine grained, thin and wrinkly bedded with little shale in the partings. Fossils are largely concentrated in streaks of shell hash that are coarser grained than most of the unit. Common fossils are *Rafinesquina camerata*, *Paucicrura rogata*, *Sowerbyella minnesotensis*, *Strophomena* sp., *Vellamo americana*, *Byssonychia* sp., and *Streptelasma corniculum*. Levorson and Gerk's Sherwood crinoid zone number two can probably be found in the quarry.

The Platteville can be better seen and collected at Cummingsville Annex, half a mile away along the road. Conodonts from there also were studied by Webers and are part of Sweet's CSS. Those who would rather collect the *Protozyga nicolleti* beds of the Carimona will be bussed there after lunch and picked up as we leave the area. The fauna of the *nicolleti* beds also includes *Pionodema subaequata*, *Strophomena filitexta* (formerly *incurvata*), *Eomonorachus intermedius*, *Isotelus* sp., *Hormotoma gracilis* and abundant conodonts as rich as 1200 per 100-gram sample.

101.6 Continue south on 7 through hamlet of Cummingsville at intersection with Minnesota 30. Turn right (west) on 30, cross the bridge over the North Branch of the Root River. On the west side of the creek is the Cummingsville Annex roadcut, which exposes the entire section of the Platteville including the richly fossiliferous *Protozyga nicolleti* beds of the Carimona above the Deicke K-bentonite.

108.7 Junction Minnesota 30 and Olmsted County 1, turn left (south) on 1.

109.2 Fillmore County line, continue south on Fillmore County 1.

116.0 Bridge across Bear Creek. The large quarry to the southwest is the Kapper Aggregate Co. (of Spring Valley) Quarry in the NW1/4NW1/4 sec. 3, T. 103 N., R. 13 W. (M110 section of Levorson and Gerk, measured in November 1973). It exposes a total of 49 feet (15 m) of Stewartville dolomite, 32 feet (9.8 m) of Dubuque Formation and 5 feet (1.5 m) of basal Maquoketa. The *Paleosynapta flaccida* zone is 10 feet (3 m) thick at the top of the Stewartville. Continue south.

120.9 Junction with U.S. 16 and U.S. 63, in Spring Valley, Minnesota, continue south on 63.

126.9 Junction U.S. 63 and Fillmore County 14, turn left (east) on 14.

129.1 Hamlet of Etna. Continue east.

133.1 Excellent collecting in the limy shale of the Elgin Member of the Maquoketa Formation in ditch on north side of highway.

133.7 Park at entrance to Rifle Hill Quarry.

STOP 4. NE1/4NW1/4 sec. 35, T. 102 N., R. 12 W., Fillmore County (Figs. 10-14). F-171 of Weiss (1957); 1.5-hour stop.

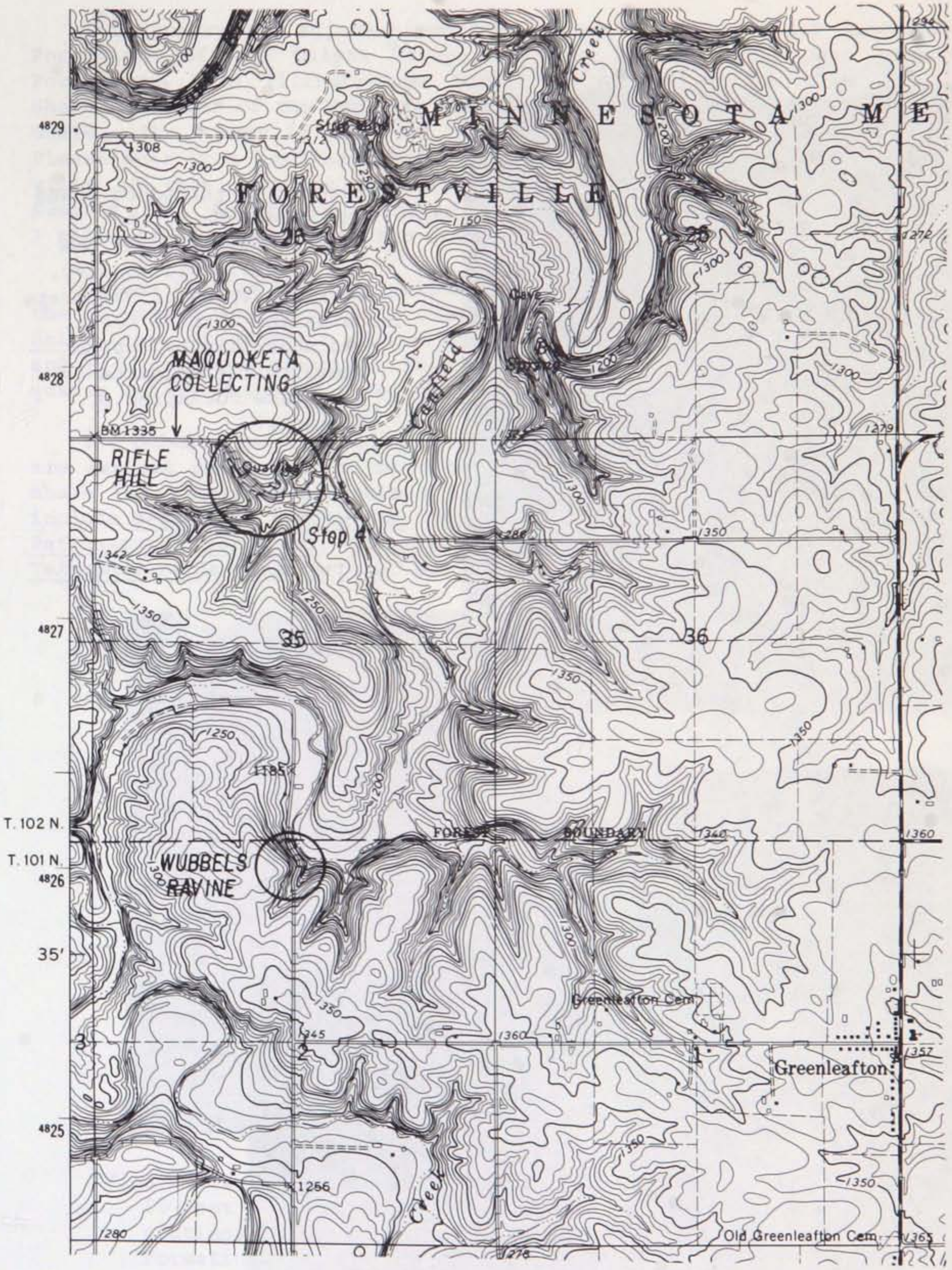


Figure 10. Topographic map of the area around Rifle Hill.

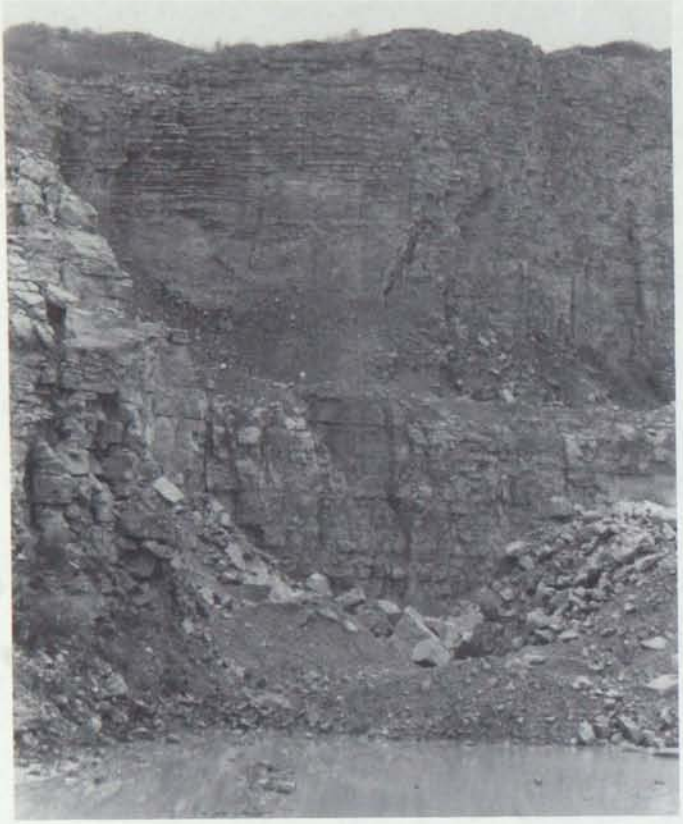


Figure 11. Interbedded shale and limestone of the Dubuque Formation at the top of Rifle Hill Quarry, overlain by basal Maquoketa Formation with no break, and underlain by typical Stewartville dolomite (= Wise Lake Formation of Illinois).

Figure 12. The Prosser part of the Rifle Hill Quarry, showing the cherty, wavy-bedded massive limestone of the lower 37 feet (10.9 m) of the quarry.

This quarry and adjacent roadcuts expose the Prosser and Stewartville Formations of the Galena Group, and the Dubuque and lower Maquoketa Formations. In Illinois-Iowa terms the exposed rocks range from the Sherwood Member of the Dunleith Formation to the Elgin Member of the Scales Shale. The quarry is owned by the Kapper Aggregate Co. of Spring Valley. Please wear your hard hats here! Conodonts from the Prosser and Stewartville of this locality were studied by Webers (1966) and are part of Sweet's CSS. Webers also studied the Dubuque conodonts at Wubbels Ravine, 1 mile south of here; they too are part of the CSS.

Common fossils from the yellowish, argillaceous, dolomitic limestone of the Maquoketa are Paucicrura (formerly Resserella) corpulenta, Megamyonia unicostata, Thaerodonta (formerly Sowerbyella) recedens, Isotelus gigas, and Flexicalymene senaria. They can be found at the road bend above the quarry and 50 yards (45 m) to the west.

The Dubuque is interbedded gray limestone and gray shale. Its fossils are easiest collected in the ditch above the quarry, where feldspathized shale (an altered K-bentonite) 5 inches (12 cm) thick is exposed. They include Megamyonia unicostata, Paucicrura (formerly Resserella) corpulenta, Rafinesquina sardesoni, Sowerbyella minnesotensis, Thaerodonta recedens, Tetraphalerella planodorsata, and Flexicalymene senaria.

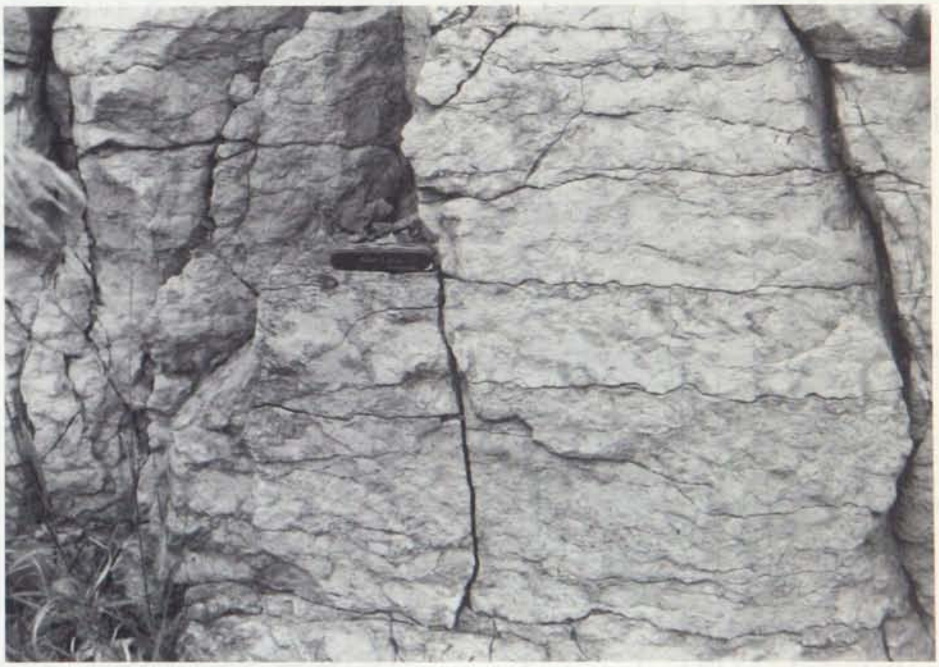
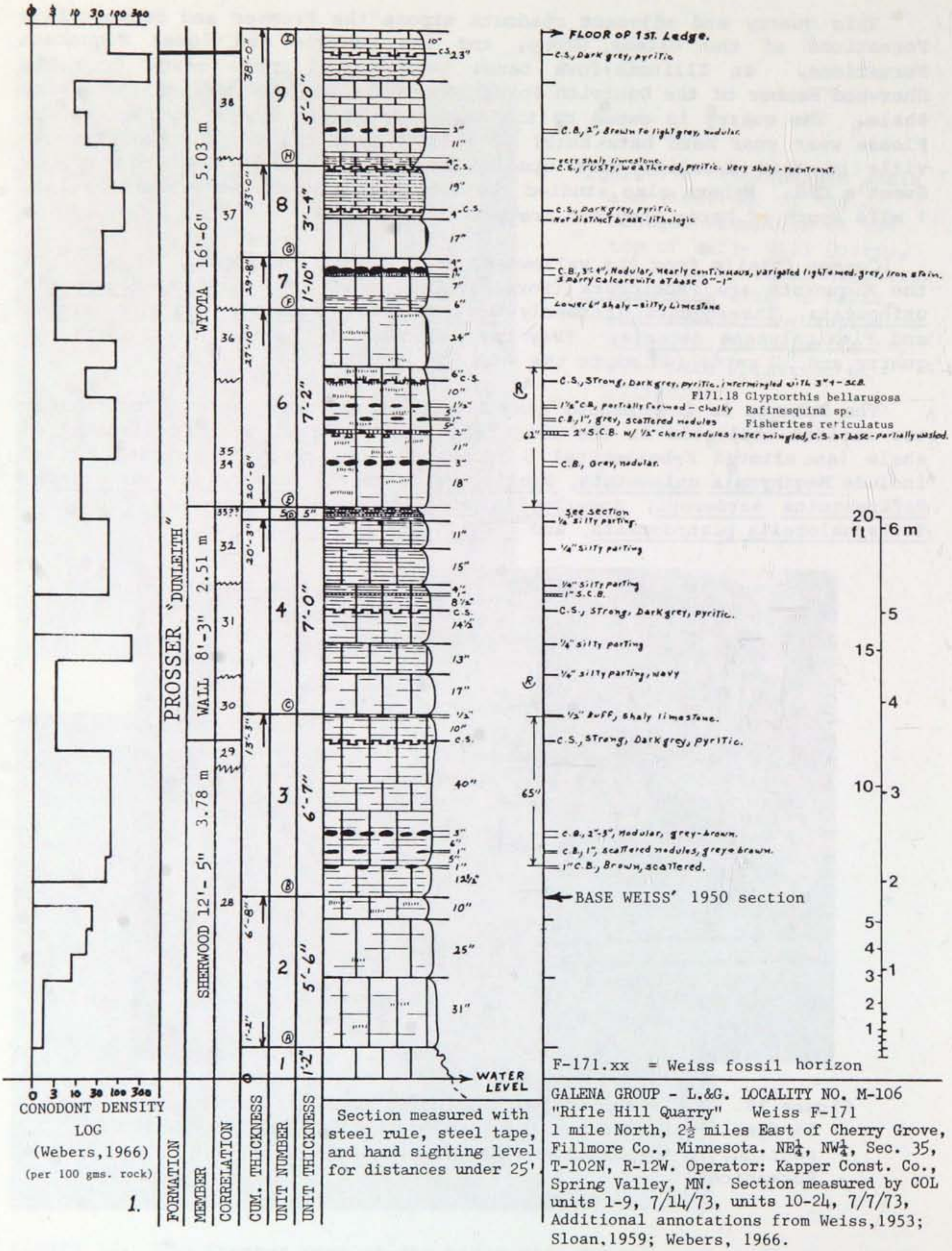


Figure 13. A cluster of four corrosion zones or hardgrounds 55 feet (16.8 m) above the base of the Rifle Hill Quarry section, in the Sinsinawa Member of the Stewartville Formation.



F171.18 Glyptorthis bellarugosa
Rafinesquina sp.
Fisherites reticulatus

BASE WEISS' 1950 section

F-171.xx = Weiss fossil horizon

Section measured with steel rule, steel tape, and hand sighting level for distances under 25'.

GALENA GROUP - L.&G. LOCALITY NO. M-106
"Rifle Hill Quarry" Weiss F-171
1 mile North, 2½ miles East of Cherry Grove, Fillmore Co., Minnesota. NE¼, NW¼, Sec. 35, T-102N, R-12W. Operator: Kapper Const. Co., Spring Valley, MN. Section measured by COL units 1-9, 7/14/73, units 10-24, 7/7/73, Additional annotations from Weiss,1953; Sloan,1959; Webers, 1966.

Figure 14. Graphic section of Rifle Hill Quarry by Levorson and Gerk, with additional annotations from Weiss (1953), Webers (1966), and Sloan (1959).

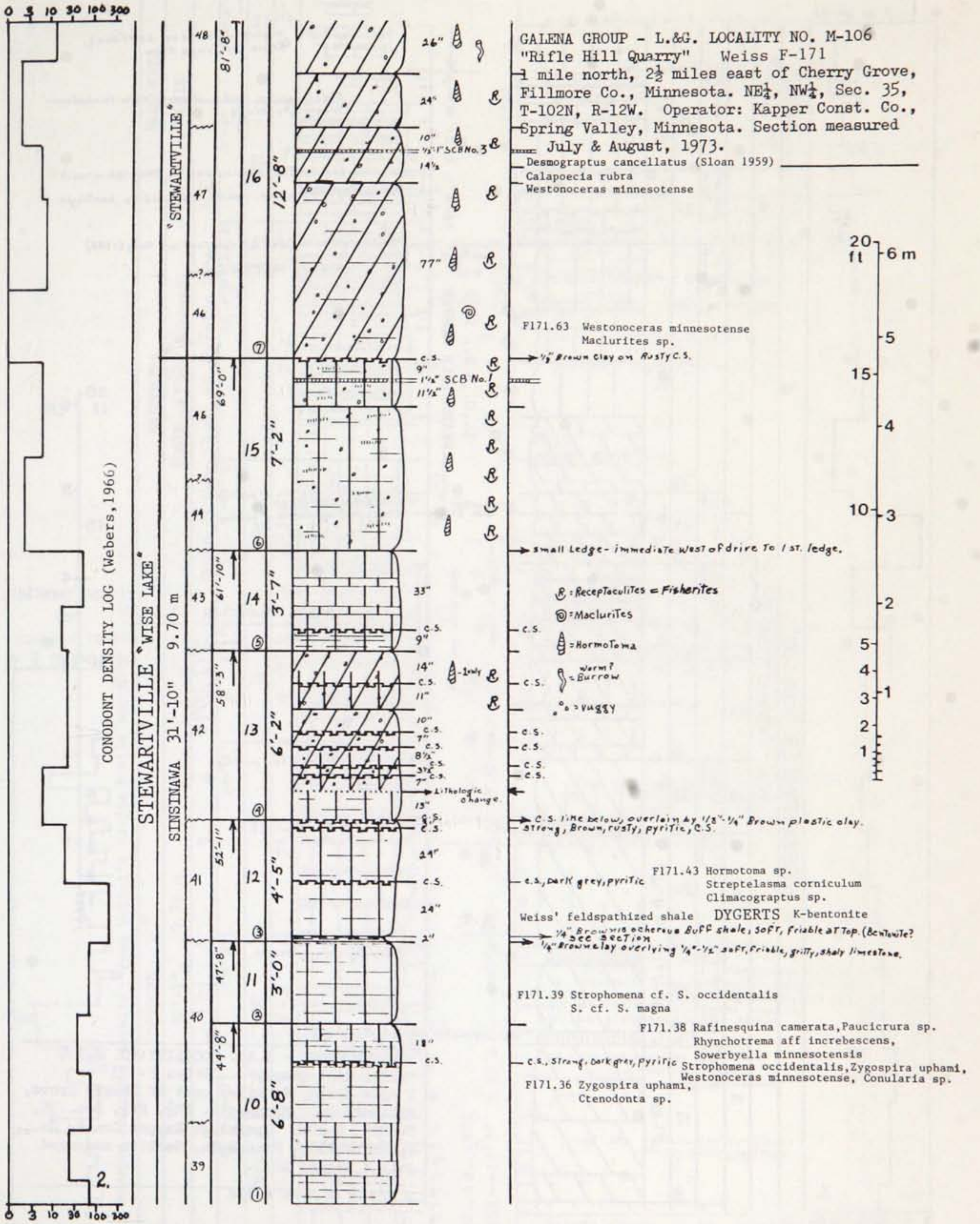
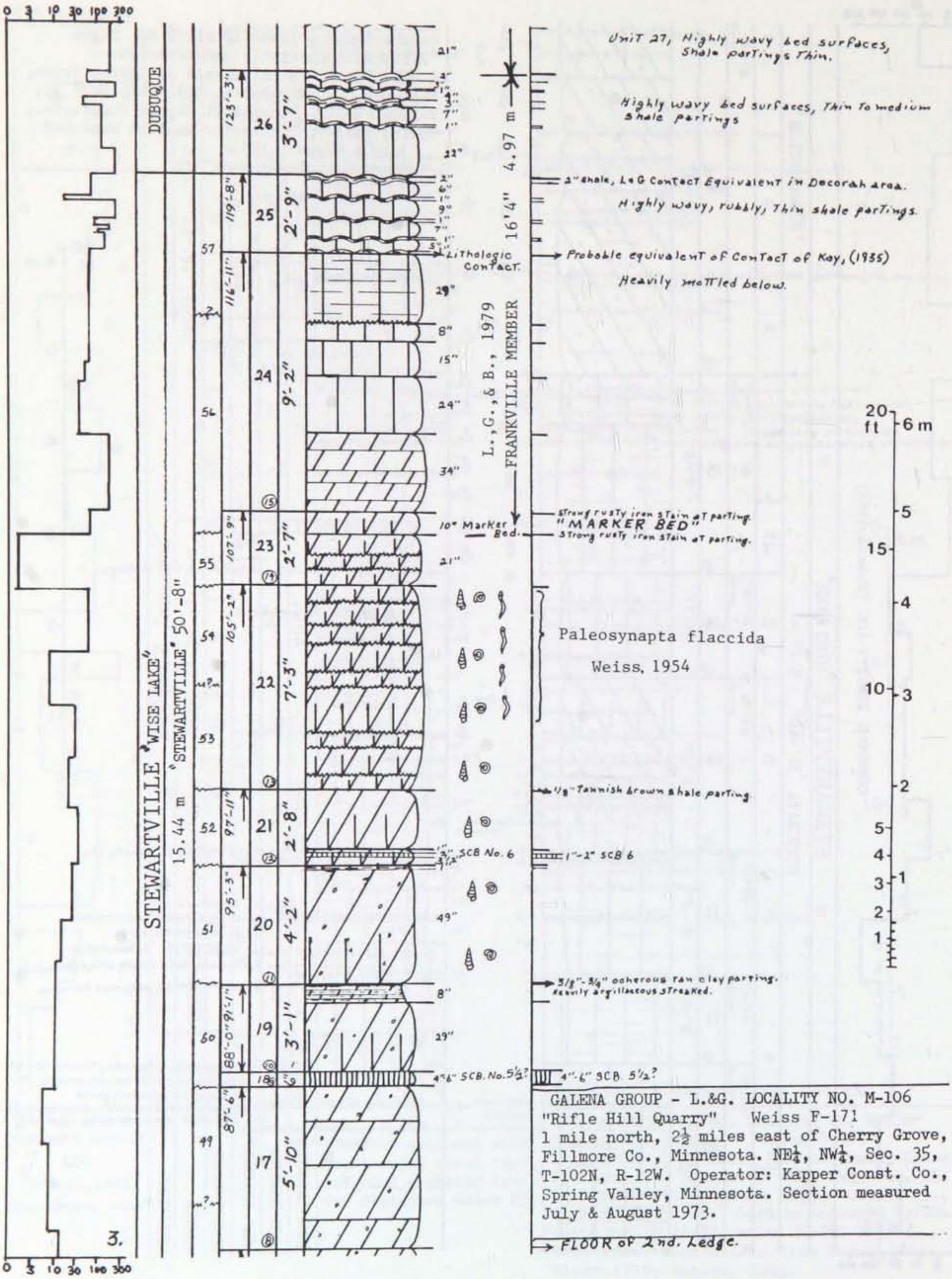
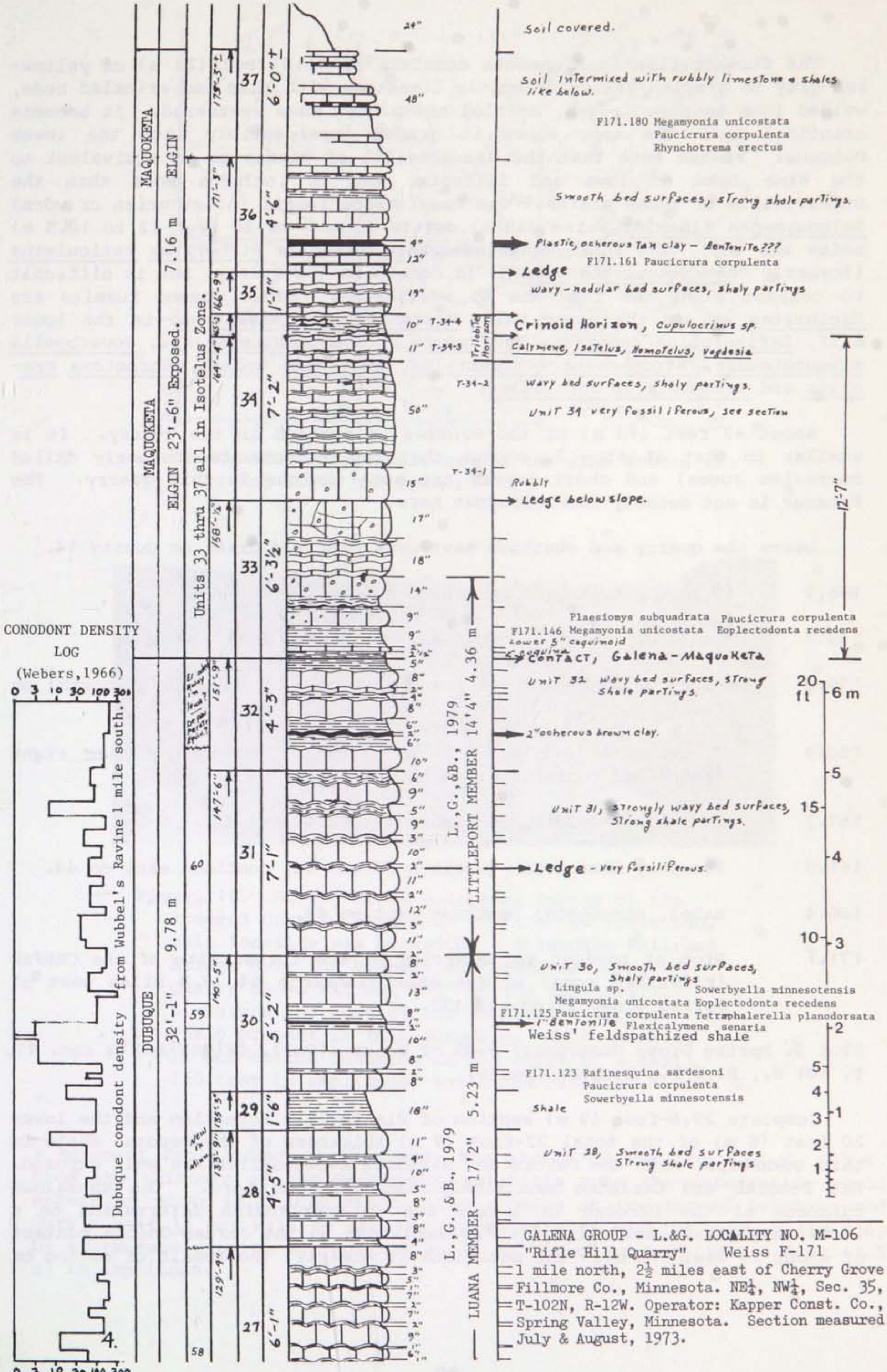


Figure 14 continued.



GALENA GROUP - L.&G. LOCALITY NO. M-106
"Rifle Hill Quarry" Weiss F-171
1 mile north, 2½ miles east of Cherry Grove, Fillmore Co., Minnesota. NE¼, NW¼, Sec. 35, T-102N, R-12W. Operator: Kapper Const. Co., Spring Valley, Minnesota. Section measured July & August 1973.

Figure 14 continued.



GALENA GROUP - L.&G. LOCALITY NO. M-106
"Rifle Hill Quarry" Weiss F-171
1 mile north, 2½ miles east of Cherry Grove
Fillmore Co., Minnesota. NE¼, NW¼, Sec. 35,
T-102N, R-12W. Operator: Kapper Const. Co.,
Spring Valley, Minnesota. Section measured
July & August, 1973.

Figure 14 continued.

The Stewartville in Minnesota consists of 75.5 feet (23 m) of yellowish-gray to grayish-orange dolomitic limestone with thin and wrinkled beds, welded into massive ledges, mottled and pitted when weathered. It becomes crinoidal near the top, where it grades imperceptibly into the lower Dubuque. Please note that the Stewartville of Minnesota is equivalent to the Wise Lake of Iowa and Illinois, and it includes more than the Stewartville of those states. The zonal trace fossil (holothurian or worm) *Paleosynapta flaccida* Weiss (1954) occurs from 6 to 35 feet (2 to 10.5 m) below the top. The zonal dasycladacean green alga *Fisherites reticulatus* (formerly "*Receptaculites oweni*") is common in the quarry, but is difficult to collect along the road due to weathering. Other common fossils are *Maclurites* sp. in the upper half, *Westonoceras minnesotense* in the lower half, *Rafinesquina camerata*, *Paucicrura* sp., *Rhynchotrema* sp., *Sowerbyella minnesotensis*, *Strophomena occidentalis*, *Zygospira uphami*, *Hormotoma gracilis* and *Streptelasma corniculum*.

About 43 feet (13 m) of the Prosser is exposed in the quarry. It is similar to that at stop 3, except that the hardgrounds (formerly called corrosion zones) and chert layers are more obvious in this quarry. The Prosser is not notably fossiliferous here.

Leave the quarry and continue east over Canfield Creek on County 14.

135.9	Turn right (south) on Fillmore County 9.
139.7	Junction 9 and Minnesota 44. Turn left (east) on 44.
150.0	Junction Minnesota 44 and Minnesota 139, turn left (north) on 44.
150.9	Junction 44 and U.S. 52 in Harmony, Minnesota, turn right (east) and continue on 44 and 52.
157.7	Canton, Minnesota; continue east on 44 and 52.
161.2	Prosper, Minnesota; junction 52 and 44, continue east on 44.
166.4	Mabel, Minnesota; continue east on 44.
171.1	Stop at roadcut and quarries at the former site of the CMSP&P (Milwaukee road) bridge over Minnesota 44, 3.2 miles west of Spring Grove (Figs. 15-17).

STOP 5. Spring Grove Underpass; F-85 of Weiss (1957). SW1/4SW1/4SE1/4 sec. 17, T. 101 N., R. 7 W., Houston County.

Complete 29.6-foot (9 m) section of Platteville Formation and the lower 20 feet (6 m) of the total 23-foot (7 m) thickness of the Decorah Shale in this township. Both the Deicke and Millbrig K-bentonites are well exposed. The Decorah and Carimona are richly fossiliferous here. The anomalous thinness of the Decorah is likely due to Rocklandian deformation on a local, asymmetric anticline with an amplitude on the Jordan-Oneota contact of about 50 feet (15 m). The anticline is clearly the result of motion on

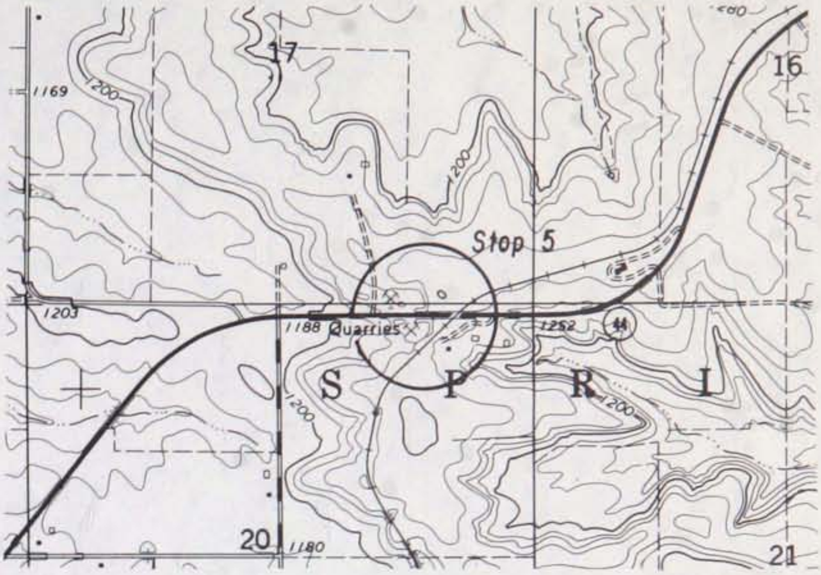
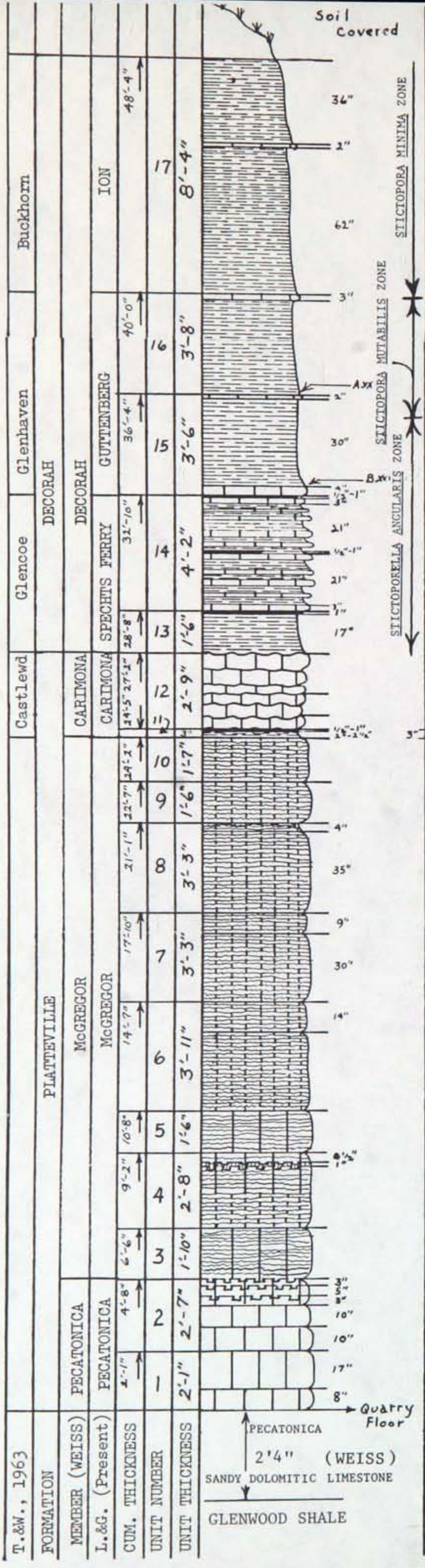


Figure 15. Topographic map of the area around the Spring Grove underpass.

Figure 16. Spring Grove Underpass Quarry of the Roverud Construction Co. Until a few years ago, this locality was marked by a Milwaukee Railroad bridge over the highway and hence the name. Quarry shows all but 2'4" of the Platteville Limestone and most of the 23 feet of Decorah Shale present in this township. This thinning is due to the location on the crest of a small (50 feet in amplitude) anticline oriented N. 40° W.

a basement fault, down to the east; the strike of the fault is N. 40° W. From the thinness of the Stictopora mutabilis zone the deformation would appear to occur in that horizon. The coquina at the top of Levorson and Gerk's unit 15 may well be the lag concentrate of washing away of the clay by storm-wave erosion during that small uplift of no more than 5 feet (1.5 m) in amplitude.



F-85.46 Idiospira panderi, Pionodema subaequata, Protozyga nicolleti, Sowerbyella curdsvillensis, Strophomena trentonensis, Schizotreta (?), Favositella sp. Ceraurus sp. Eomonorachus intermedius, Doleroides pervetus, Fascifera sp. Rhynchotrema ainsliei, Rostricellula minnesotensis, Strophomena filitexta, and Stictoporella frondifera.

F-85.45.5 Doleroides pervetus, Hesperorthis tricenaria, petrocrania sp. Pionodema subaequata, Rafinesquina trentonensis, Rostricellula minnesotensis, Sowerbyella curdsvillensis, Strophomena filitexta, Escharopora sp. Ceraurus sp., Eomonorachus intermedius, Dimeropyge galenensis.

F-85.44 Pionodema subaequata, Sowerbyella curdsvillensis, Strophomena filitexta, Doleroides pervetus, Hesperorthis tricenaria, Rostricellula minnesotensis, Batostoma sp., Stictoporella cribrosa, Stictoporella frondifera, Ceraurus sp., Eomonorachus intermedius, Streptelasma cf. corniculum, Raufella.

F-85.44B Idiospira panderi, Doleroides pervetus, Fascifera sp., Hesperorthis tricenaria, Petrocrania sp., Pionodema subaequata, Rhynchotrema ainsliei, Rostricellula minnesotensis, Sowerbyella curdsvillensis, Strophomena filitexta, Batostoma sp., Rhynidictya sp., Stictoporella frondifera, Loxoplocus sp., Phragmolites sp., Tetranota sp., Lambeophyllum profundum.

A. xx = Coquina of Bryozoans in basal 2" - Distinctive

F-85.37 Idiospira panderi, Hesperorthis tricenaria, Doleroides pervetus, Pionodema subaequata, Rhynchotrema ainsliei, Rostricellula minnesotensis, Strophomena filitexta, Petrocrania sp., Batostoma sp., Escharopora sp., Rhinidictya sp., Homotrypa sp., Hallopora sp., Stictoporella frondifera, Eomonorachus intermedius, Streptelasma cf. corniculum.

B. xx = Coquina of large Strophomenid Brachiopods in Basal Bed.

Bentonite, Sample No. 120-5

F-85.35 Doleroides pervetus, Pionodema subaequata, Strophomena filitexta.

Intermittent Bentonite (Local only) Sample No. 120-4

F-85.33.5 Doleroides pervetus, Pionodema subaequata, Rostricellula minnesotensis, Strophomena filitexta.

MILLBRIG K-bentonite

Bentonite, Sample No. 120-3

F-85.30 Doleroides pervetus, Pionodema subaequata, Strophomena sp., Sowerbyella curdsvillensis, Phyllodictya sp., Rhinidictya sp.

Schmidtella sp.

F-85.28 Doleroides pervetus, Pionodema subaequata, Protozyga nicolleti, Primitia sp., Conularia sp.

DEICKE K-bentonite

Bentonite, Sample No. 120-2

F-85.27 Pionodema conradi.

Bentonite, Sample No. 120-1 (See Section)

1/4" grey & brown clay.
Shaly in upper 4"

F-85.20 Oepikina minnesoetensis, Pionodema conradi, Protozyga nicolleti, Rostricellula minnesotensis, Sowerbyella curdsvillensis Rhinidictya sp., Isotelus sp., Hormotoma gracilis, Liospira sp., Lambeophyllum profundum, Leperditia sp.

1/4"-1/2" Brown Clay

2 C.S.'s, Lower Strong, Dark grey, pyritic, Upper weaker, Sparry Between

F-85.12 Oepikina minnesotensis

1/4" Shale parting

Snails and "Lingula"

C.S. weak.
C.S.
C.S., Strong, deeply pitted, pyritic, dark grey.

1/4"-1/2" Black & Dark Brown shale.

Weiss F-85

GALENA GROUP - L.&G. LOCALITY NO. M-120 "Spring Grove Underpass Quarry" Situated on north side of MN State Hwy. 44, 3.2 miles west of Spring Grove, Houston Co., MN, in SW¼, SE¼, Sec. 17, T-101N, R-7W. Section measured by Gerk 10/3/73, beds described COL 4/6/74. Roverud Const. Co., Operator. Additional annotations from Weiss (1953), Karklins (1969).

Decorah fossils collected here include: *Idiospira* (formerly *Camarella*) *panderi*, *Pionodema subaequata*, *Protozyga nicolleti*, *Sowerbyella curdsvillensis* (formerly *punctostriata*), *Strophomena trentonensis*, *Strophomena filitexta* (formerly *incurvata*), *Rafinesquina trentonense* (formerly *alternata*), *Hesperorthis tricenaria*, *Doleroides pervetus*, *Fascifera* sp. ("*hamburgensis*"), *Rhynchotrema ainsliei*, *Rostricellula minnesotensis*, *Schizotreta* sp., *Petrocrania* sp., *Loxoplocus* sp., *Phragmolites* sp., *Tetranota* sp., *Ceraurus* sp., *Eomonorachus intermedius*, *Dimeropyge galenensis*, *Escharopora* sp., *Hallopora* sp., *Homotrypa* sp., *Rhinidictya* sp., *Stictoporella frondifera*, *S. cribrosa*, *Batostoma* sp., *Streptelasma* cf. *corniculum* (high), *Lambeophyllum profundum* (low), *Favositella* sp., *Raufella filosa* and *fucoids*. The *Stictoporella angularis* zone occupies the lower 8 feet (2.4 m), the *Stictopora mutabilis* zone runs from 8 to 12 feet (2.4 to 3.6 m), and the *Stictopora minima* zone occupies the balance of the Decorah (Karklins, 1969).

181.0 Return (west) to the junction of 44 and U.S. 52 in Prosper and turn left (south) on U.S. 52.

182.0 Iowa state line. See Figure 18 for locations in Iowa.

194.6 Exposures of Dunleith and Wise Lake Formations on the left (east) side of U.S. 52.

195.1 Descend long hill into Decorah.

195.6 Intermittent exposures of Dunleith limestone on both sides of U.S. 52 all the way to intersection with Iowa 9.

198.2 Junction of U.S. 52 with Iowa 9 at the southwest edge of Decorah, turn left (east) on 9.

198.5 Turn right to Cliff House Motel where we will have supper and spend the night. Dunleith limestone is exposed in roadcut on Iowa 9 below the motel parking lot.

Figure 17. (opposite page) Levorson and Gerk's graphic section of the Spring Grove Underpass section, with additional annotations from Weiss (1953) and Karklins (1969).

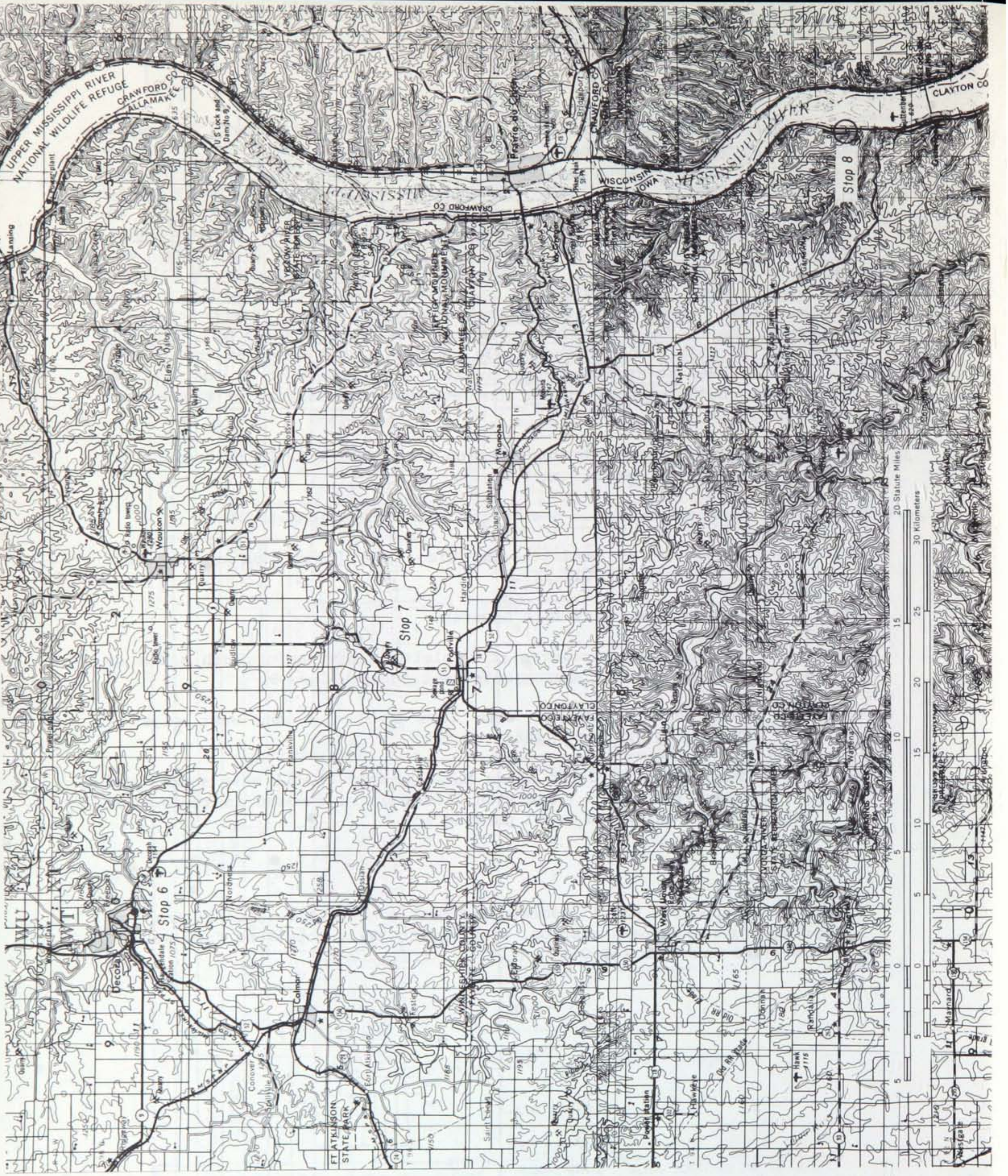


Figure 18. Topographic map showing locations of field trip stops in Iowa.

THE MIDDLE AND LATE ORDOVICIAN STRATA AND FOSSILS OF IOWA

Second Day, May 3, 1987

Dennis R. Kolata and Robert E. Sloan

0.0	Bus will leave parking lot of Cliff House at 8:00 a.m. Turn right (east) on Iowa 9.
0.6	Beginning of roadcut through Dunleith limestone extending to top of hill.
1.1	Exposure of Dunleith limestone on right (south) side of Iowa 9.
1.6	Dunleith limestone on right. Members of the Dunleith are equivalents of the Cummingsville and Prosser Formations of the Galena Group in Minnesota terminology. Due to facies changes, the Illinois and Iowa Geological Surveys include the Decorah and Dubuque in the dominantly carbonate Galena Group consisting in order of Decorah (Spechts Ferry and Guttenberg), Dunleith, Wise Lake, and Dubuque Formations.
1.8	Turn right into gravel road and park behind barn on megarippled limestone surface of the Carimona Member of the Platteville.

STOP 6. Decorah Shale, NE1/4NE1/4SE1/4 sec. 22, T. 98 N., R. 8 W., Winnesheik County; 45-minute stop (Figs. 18-21).

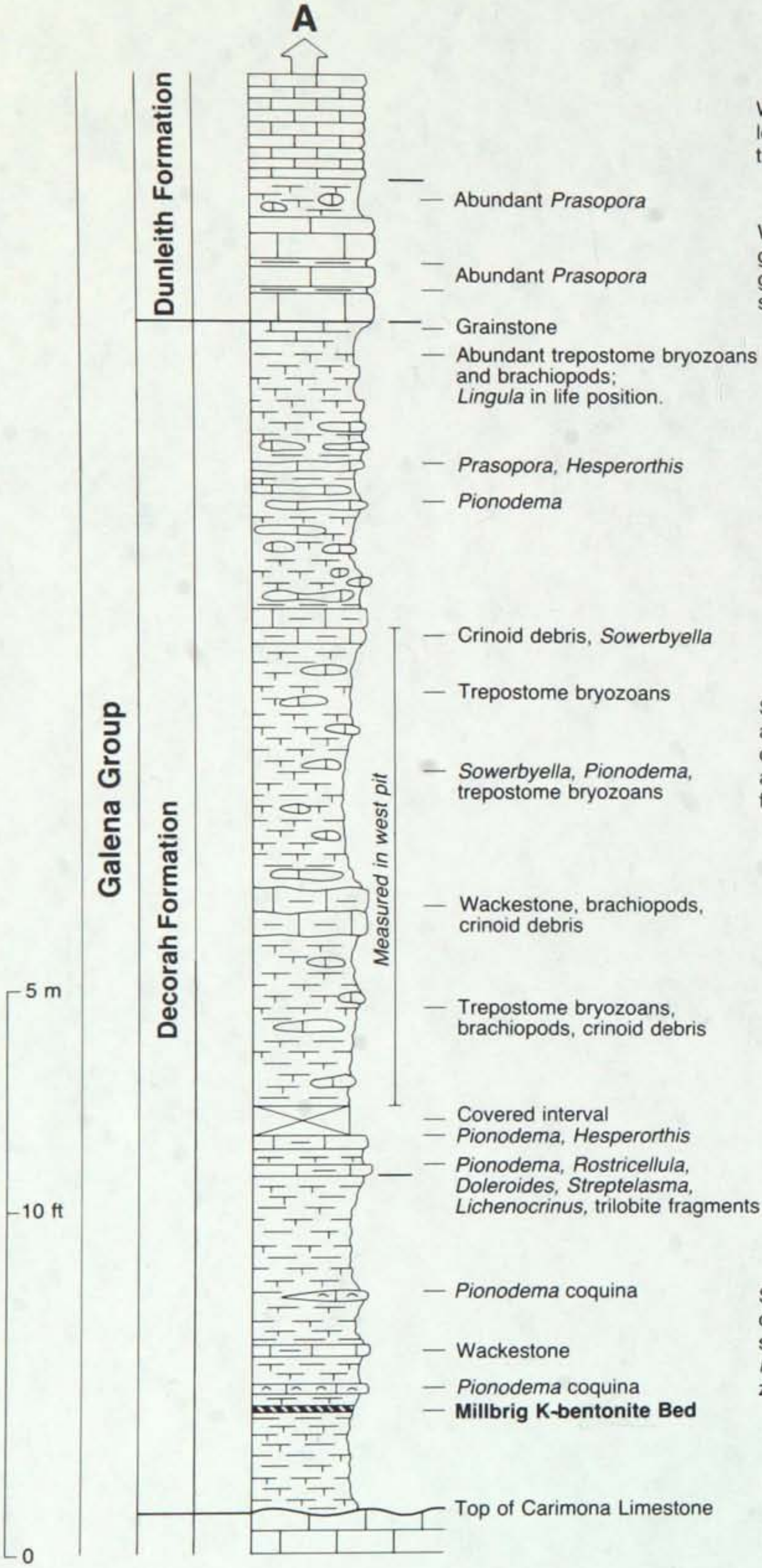
This is the best current outcrop of Decorah Shale in the type region. Such outcrops routinely grow over in a decade.

A composite section, measured and described by Witzke, Ludvigson, and Kolata, was compiled from exposures behind the barn and about 300 feet (100 m) west behind the house. At this locality the Decorah Formation is 35 feet (10.6 m) thick and consists primarily of interbedded shale and nodular limestone (see stratigraphic column). The thickness and lithology are very close to Calvin's (1906) original description of the Decorah, which was based mainly on outcrops along the Upper Iowa River on the west side of town. Calvin's (1906) Figure 7 (p. 85) shows an outcrop of the Decorah at the Dugway west of town that is very similar to the outcrop at this locality. The Decorah is partially exposed now in a roadcut on the north side of the Upper Iowa River at Ice Cave Hill Park on the north side of town.

Approximately 15 miles south of Decorah, Iowa, the middle part of the Decorah grades abruptly to lithographic limestone of the Guttenberg Formation (Fig. 24). The Guttenberg is locally overlain by shaly strata assigned to the Ion Member (Kay, 1928) and underlain throughout a wide area of the Mississippi valley by shale of the Spechts Ferry Formation (Kay, 1928). The Ion grades southward to carbonate of the Buckhorn and St. James Members of the Dunleith Formation (Templeton and Willman, 1963) in the area between McGregor and Guttenberg, Iowa. The Decorah was raised to subgroup rank by Templeton and Willman (1963) because of its heterogeneity throughout most of the Mississippi valley.

Near Decorah, Iowa, and northwestward through southeastern Minnesota, the Decorah-Dunleith boundary is a diachronous facies transition marked by

STOP 6 Bruening Quarry, Route 9, Decorah, Iowa



Wackestone, relatively pure, light gray; contains thin lenses of packstone and grainstone; brachiopods, trepostome bryozoans, and crinoid debris abundant.

Wackestone, argillaceous, pale yellowish brown to greenish gray; contains thin lenses of packstone and grainstone; forms three prominent ledges that are separated by greenish gray shale.

Shale, calcareous, greenish gray; abundant, very argillaceous, wackestone nodules 8–10 cm long; contains thin lenses and nodules of skeletal packstone and grainstone; brachiopod-bryozoan dominated fauna.

Shale, calcareous, greenish gray, blocky fractures; contains thin beds and lenses of wackestone, packstone and grainstone; fossiliferous, contains lenses of *Pionodema* coquina; brachiopods, trepostome bryozoans, trilobites, and crinoid debris.

Figure 19. Graphic section of stop 6, Decorah Shale, Decorah, Iowa.

STOP 6 Bruening Quarry, Route 9, Decorah, Iowa (continued)

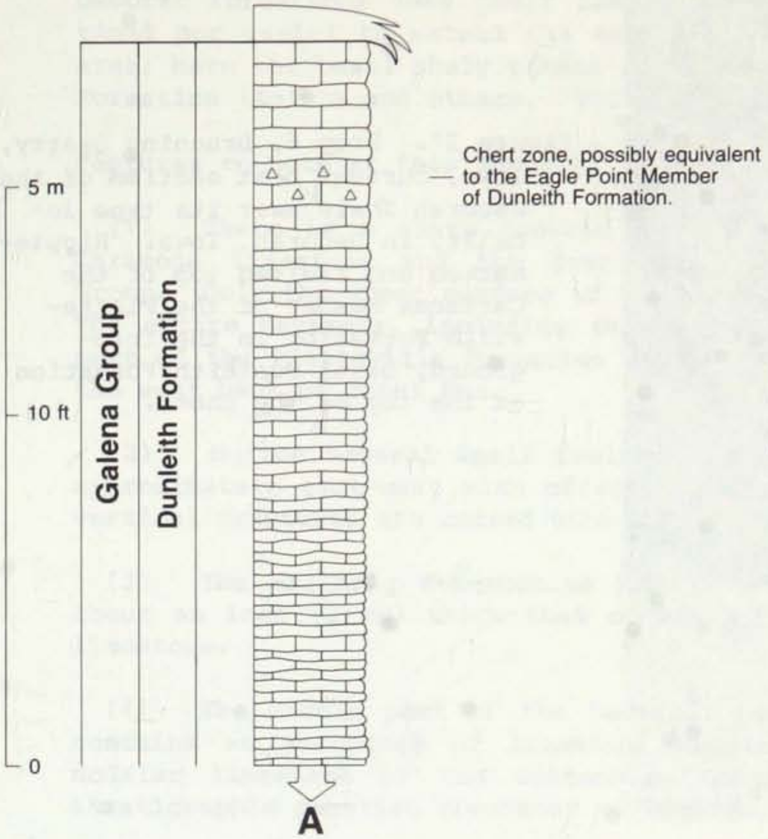


Figure 19 continued.

Figure 20. Detail photograph of the Prasopora simulatrix zone near the top of the Decorah Shale, stop 6.

Figure 21. Stop 6, Bruening Quarry, Iowa, current best section of the Decorah Shale near its type locality in Decorah, Iowa. Ripple-marked and faulted top of the Carimona Member of the Platteville Formation in the foreground, basal Dunleith Formation at the top of the photo.

Figure 22. More complete exposure of the Decorah Shale 100 yards west of Figure 21.

a gradual increase in shale in the basal part of the Dunleith. Because the Decorah formations lose their identity in this area, it is neither practical nor useful to extend the subgroup level of classification into this area; here the basal shaly strata of the Galena are assigned to the Decorah Formation (Kolata and others, 1986).

Features to note at this locality:

(1) There is a sharp contact between the Decorah and the underlying Carimona limestone and the overlying Dunleith limestone of the Galena Group. Only the upper surface of the Carimona is exposed at this locality. The entire Carimona, including the Deicke K-bentonite bed, and the upper part of the Platteville Formation are exposed 0.25 mile east of here along the west bank of Trout Run.

(2) Notice several small faults in the Carimona limestone that strike approximately east-west with offsets of 2 to 6 inches (5 to 15 cm). Some vertical fractures are coated with dripstone.

(3) The Millbrig K-bentonite bed is a very pale orange plastic clay about an inch (2 cm) thick that occurs 3 feet (90 cm) above the Carimona limestone.

(4) The middle part of the Decorah, best exposed in the western pit, contains an abundance of limestone nodules that are suggestive of the nodular limestone of the Guttenberg Formation which occupies the same stratigraphic position southeast of Decorah, Iowa.

(5) The orthid brachiopod Pionodema subaequata is one of the most abundant fossils throughout the Decorah. It is commonly the primary constituent in coquinas, especially in the lower part of the formation. Trepostome bryozoans become increasingly more abundant toward the top, Prasopora being particularly abundant in the uppermost beds. Southeast of Decorah, Iowa, the Prasopora zonule occurs in the Buckhorn and St. James Members of the Dunleith Formation. Both members are thought to be a facies of the upper part of the type Decorah (Templeton and Willman, 1963).

(6) The occurence of chert nodules in the uppermost limestone of the Dunleith Formation suggests that this part of the section is equivalent to the Eagle Point Member.

Exit driveway and continue east on Iowa 9.

2.1 Platteville limestone on right along ridge above Trout Run. Decorah Shale at top of outcrop is covered by vegetation.

2.9 Ascending hill, Dunleith limestone in roadcut on both sides of Iowa 9. Exposed hardground surface in Rivoli Member at prominent bench on right (south) side of Iowa 9. This is stop 6 of Delgado (1983). The paleoecology of this hardground has been described by Palmer and Palmer (1977) and Palmer (1978). Sorry! We will not have time to stop.

7.6 Roadcuts on both sides of a valley, stop 5 of Delgado (1983), showing complete Dubuque capped by a hardground and the depauperate zone of the Maquoketa, which is not present in Minnesota. Note how much thinner the shale beds are than at Rifle Hill; they become even thinner to the southeast, implying a rejuvenation of the Transcontinental Arch in Minnesota after its complete submergence during the deposition of the Prosser/Stewartville or Dunleith/Wise Lake.

11.3 Allamakee County line, continue east on Iowa 9.

13.6 Junction with Iowa 51, turn right (east) on 51.

17.2 Outcrops of the Wise Lake Formation on both sides of Iowa 51. Cross tributary of Yellow River.

19.4 Descending hill, Wise Lake limestone on both sides of road.

21.7 Park at roadcut exposing the upper part of the Wise Lake Formation and most of the Dubuque Formation.

STOP 7. Postville North Section, SW1/4SW1/4 sec. 16, T. 96 N., R. 6 W., Allamakee County; 2-hour stop for collecting and lunch (Figs. 23, 24). The quarry on the east side of Iowa 51 exposes the same section, as well as the hardground at the top of the Dubuque, and the lower part of the Elgin Member (Scales Shale equivalent) of the Maquoketa Formation. The upper part of the Elgin Member is exposed on both sides of Iowa 51 half a mile south, within walking distance of this stop.

Figure 23. Postville North Quarry, stop 7, uppermost Wise Lake Formation overlain by complete Dubuque Formation, which is much less shaly than at Rifle Hill, and in turn overlain by the depauperate zone hardground and the basal Elgin Member of the Maquoketa Formation.

The roadcut on Iowa 51 was measured and described by Witzke, Ludvigson, and Kolata. The Maquoketa section in the quarry on the east side of Route 51 was measured and described by Witzke and Ludvigson.

About 35 feet (10.7 m) of Dubuque and 4 feet (1.2 m) of Wise Lake limestone are exposed in the roadcut on the west side of Iowa 51. Judging from the thickness of the Dubuque strata in the quarry, the Dubuque-Maquoketa contact probably occurs at the uppermost bench in the roadcut. The hardground appears to have been covered by soil and vegetation.

The Dubuque Formation has been subdivided into the Frankville, Luana, and Littleport beds (Levorson and others, 1979) on the basis of bedding plane surface topography ranging from nearly planar beds in the Frankville upward to highly undulose surfaces in the Littleport beds. These features are quite prominent at this locality. The base of the Dubuque Formation is picked at the bottom of a remarkably uniform and widespread limestone or dolomite bed 8 inches (20 cm) thick that is separated off by thin shaly partings (Levorson and others, 1979).

One of the finest exposures of the hardground at the top of the Galena Group can be seen on the upper bench within the quarry. Here, like many other localities in the Upper Mississippi valley region, the hardground is characterized by a pitted surface at the top of the Dubuque limestone that is encrusted with iron sulfide and overlain by phosphorite as thick as 6 inches (15 cm). The phosphorite is separated into two layers by silty shale that contains a moderately diverse assemblage of invertebrates dominated by molluscs. The most abundant fossils are *Michelinoceras sociale*, *Hindia* sp., *Palaeoneilo fecunda* and *Nuculites neglectus*. Brown (1974) suggested that the basal phosphorite of the Elgin Member (Scales Formation equivalent) in Iowa originated from "an upwelling of deep cold nutrient-rich waters into the warm shallow environment of a carbonate shelf." The hardground can be traced in outcrop and subsurface cores through Wisconsin, Iowa, Illinois, Missouri, Indiana, and Michigan. Throughout this area there is no evidence of subaerial exposure of the Galena before deposition of the Maquoketa. The pitted, planar, upper surface of the Galena carbonates probably was formed by submarine solution. Near the Iowa-Minnesota state line the hardground is less well developed, and in Minnesota (compare to stop 4, Rifle Hill Quarry), the Dubuque is gradational with the overlying Maquoketa shale, and the hardground is not present.

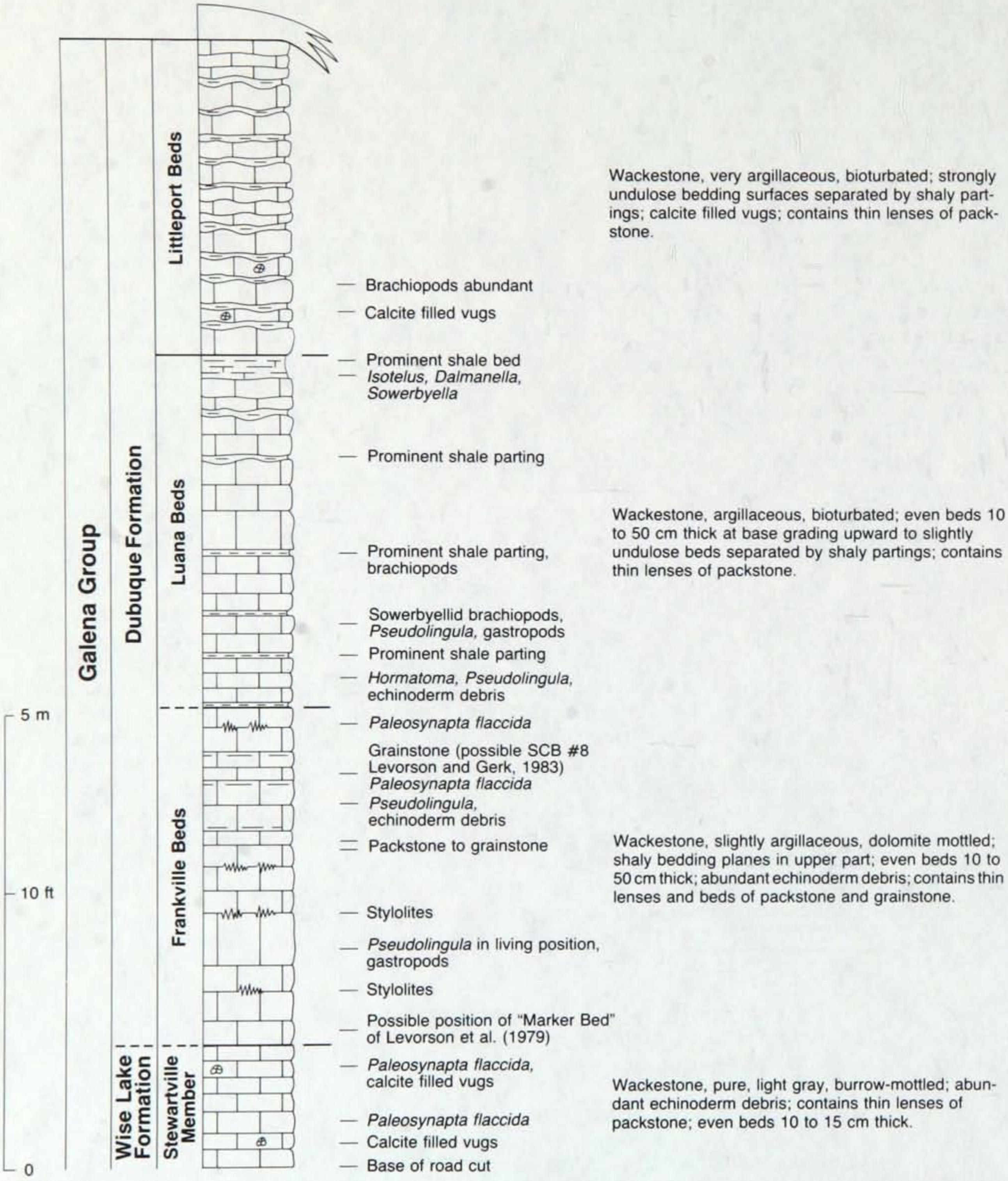
About 10 miles southeast of this locality the Dubuque and Wise Lake grade to dolomite which extends southeastward throughout southern Wisconsin, northern Illinois and adjacent parts of Iowa.

Features to note in the roadcut:

(1) Although not well developed at this locality, the base of the Dubuque Formation is marked by a 9.5-inch-thick (24 cm) bed with thin shaly partings at top and bottom ("marker bed" of Levorson and others, 1979).

(2) *Paleosynapta flaccida*, a vertical tube-like fossil of unknown affinities, is common in the Stewartville Member of the Wise Lake Formation and the Frankville beds of the Dubuque Formation. Also notable in these

STOP 7 Postville North Road Cut, Highway 51



Wackestone, very argillaceous, bioturbated; strongly undulose bedding surfaces separated by shaly partings; calcite filled vugs; contains thin lenses of packstone.

Wackestone, argillaceous, bioturbated; even beds 10 to 50 cm thick at base grading upward to slightly undulose beds separated by shaly partings; contains thin lenses of packstone.

Wackestone, slightly argillaceous, dolomite mottled; shaly bedding planes in upper part; even beds 10 to 50 cm thick; abundant echinoderm debris; contains thin lenses and beds of packstone and grainstone.

Wackestone, pure, light gray, burrow-mottled; abundant echinoderm debris; contains thin lenses of packstone; even beds 10 to 15 cm thick.

Figure 24. Graphic section of the Postville North roadcut and quarry, stop 7.

Postville North Quarry
SWSW sec. 16, T96N, R6W Allamakee Co., Iowa
(Maquoketa section)

B. Witzke, G. Ludvigson

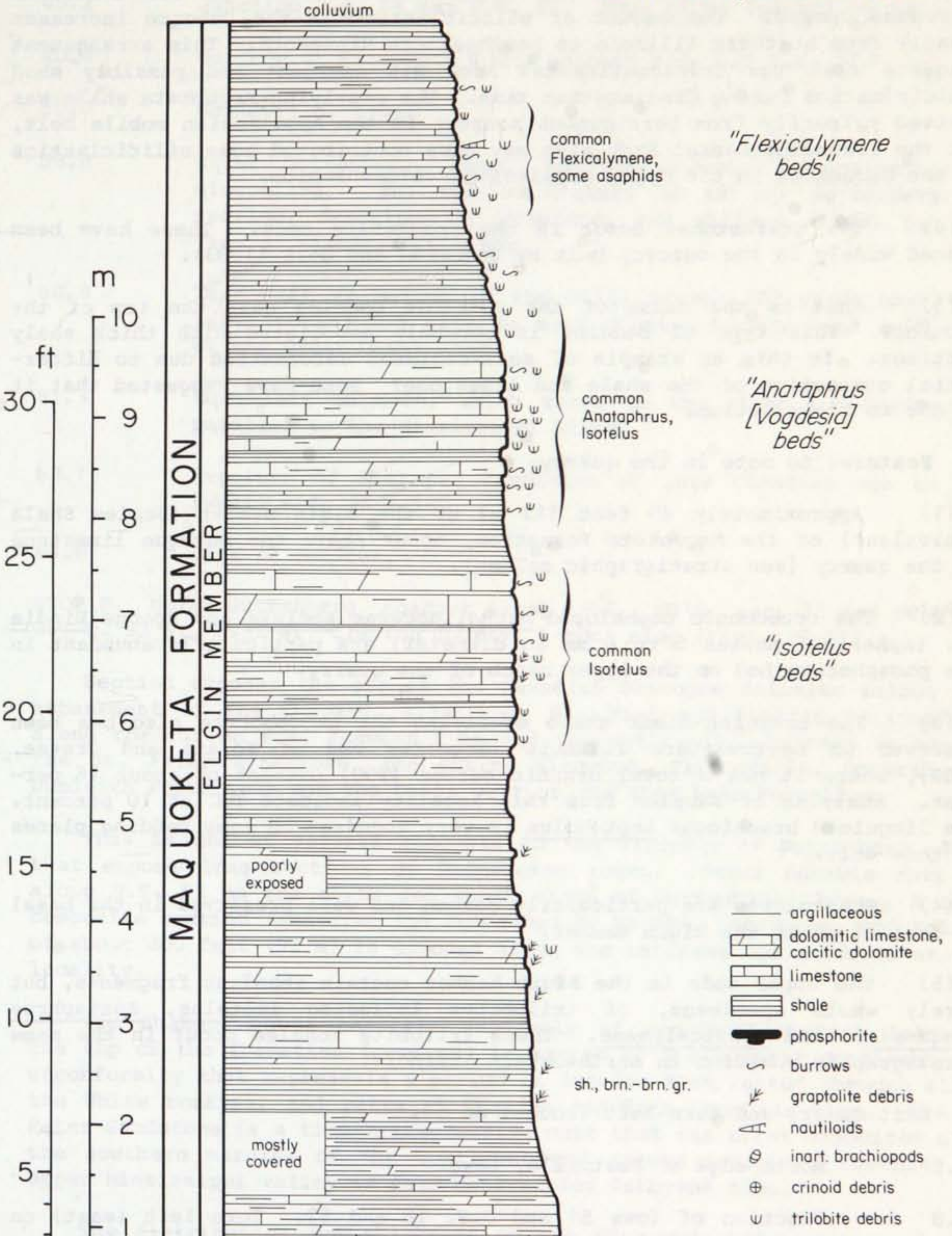


Figure 24 continued.

strata is the linguloid brachiopod Pseudolingula iowensis which is commonly found in life position.

(3) The amount of shale and argillaceous content of the limestone increases upward. The amount of siliciclastics in the Dubuque increases greatly from northern Illinois to southeastern Minnesota. This arrangement suggests that the Transcontinental Arch was emergent and possibly shed siliciclastics during Cincinnatian time. The overlying Maquoketa shale was derived primarily from terrigenous sources in the Appalachian mobile belt, but the Transcontinental Arch also may have contributed some siliciclastics to the Maquoketa in the Upper Mississippi valley region.

(4) Two grainstones occur in the Frankville beds. These have been traced widely in the outcrop belt by Levorson and Gerk (1983).

(5) What is the cause of the undulose bedding near the top of the section? This type of bedding is commonly associated with thick shaly partings. Is this an example of soft-sediment deformation due to differential compaction of the shale and limestone? Some have suggested that it is due to bioturbation.

Features to note in the quarry:

(1) Approximately 43 feet (13 m) of the Elgin Member (Scales Shale equivalent) of the Maquoketa Formation, occur above the Dubuque limestone in the quarry (see stratigraphic column).

(2) The orthoconic cephalopod Michelinoceras sociale and sponge Hindia sp. (spherical masses 5 to 8 mm in diameter) are particularly abundant in the phosphorite bed on the upper bench of the quarry.

(3) The brownish-black shale overlying the phosphorite also has been observed in northwestern Illinois (Argo-Fay bed of Kolata and Graese, 1983), where it has a total organic carbon (TOC) content of about 16 percent. Analyses of samples from this locality indicate TOC of 10 percent. The linguloid brachiopod Leptobolus is very abundant on some bedding planes in this unit.

(4) Graptolites are particularly common and well preserved in the basal 15 feet (5 m) of the Elgin Member.

(5) The upper beds in the Elgin Member contain abundant fragments, but rarely whole specimens, of trilobites including Isotelus, Anataphrus (Vogdesia), and Flexicalymene. These trilobite zonules occur in the same stratigraphic position in northwestern Illinois.

Exit quarry and turn left (south) on 51.

24.2	North edge of Postville, Iowa.
24.8	Junction of Iowa 51 and U.S. 18 and 52. Turn left (east) on U.S. 18 and 52.

39.8	Roadcut on left (north) side of U.S. 52 showing the Wise Lake-Dubuque contact.
40.2	Junction U.S. 18 and U.S. 52. Turn right (south) on 52.
40.4	Outcrop of Maquoketa Group on both sides of U.S. 52.
50.0	Garnavillo, Iowa.
58.8	Enter Guttenberg, named for the inventor of printing, but misspelled. The top of Highway 52 is the Guttenberg Iowa section, described by Templeton and Willman (1963, p. 236). View of Mississippi River.
60.8	Turn left at bottom of the hill, travel 200 yards east, then left (north) 0.5 mile to meet Clayton County Road X-56, part of the Great River Road.
61.3	Turn left on X-56, which turns to the right and heads north parallel to the Mississippi River.
63.1	Exposure of Shakopee Formation of late Canadian age on left (west) side of X-56.
63.6	Park at roadcut.

STOP 8. North Guttenberg Roadcut along X-56. NW1/4 sec. 32 and SW1/4 sec. 29, T. 93 N., R. 2 W., Clayton County, 1-hour stop (Figs. 25-27).

Section exposes the top of the Canadian Shakopee dolomite (along west embankment of the Chicago, Milwaukee, St. Paul and Pacific Railroad and along roadcut on road between X-56 and the railroad). Exposed is most of the St. Peter Sandstone, the entire Glenwood, Platteville, Decorah, and Dunleith Formations and the basal part of the Wise Lake Formation.

This is one of several roadcuts in the vicinity of Guttenberg, Iowa, that expose long sections of Ordovician rocks. Other notable cuts are along U.S. 52 on the north and south sides of Guttenberg, Iowa. A total composite section (measured and described by Witzke, Ludvigson, and Kolata) of about 300 feet (93 m) is exposed along the railroad and roadcuts at this locality.

The Shakopee here consists generally of non-fossiliferous dolomite. The top of the formation (covered) is marked by a prominent continent-wide unconformity that represents a period of erosion that lasted through all of the White rockian, and parts of Chazyan and late Canadian time. The St. Peter Sandstone is a time-transgressive unit that was first deposited along the southern margins of the continent and spread northward reaching the Upper Mississippi valley in late Chazyan (or Ashbyan) time.

The distribution and thickness of the Glenwood shale suggest that it was probably derived from the Transcontinental Arch. The shaly partings and disseminated clay in the overlying Platteville carbonates also appear to have originated from the arch.

STOP 8 Highway X-56 Road Cut, Guttenberg, Iowa

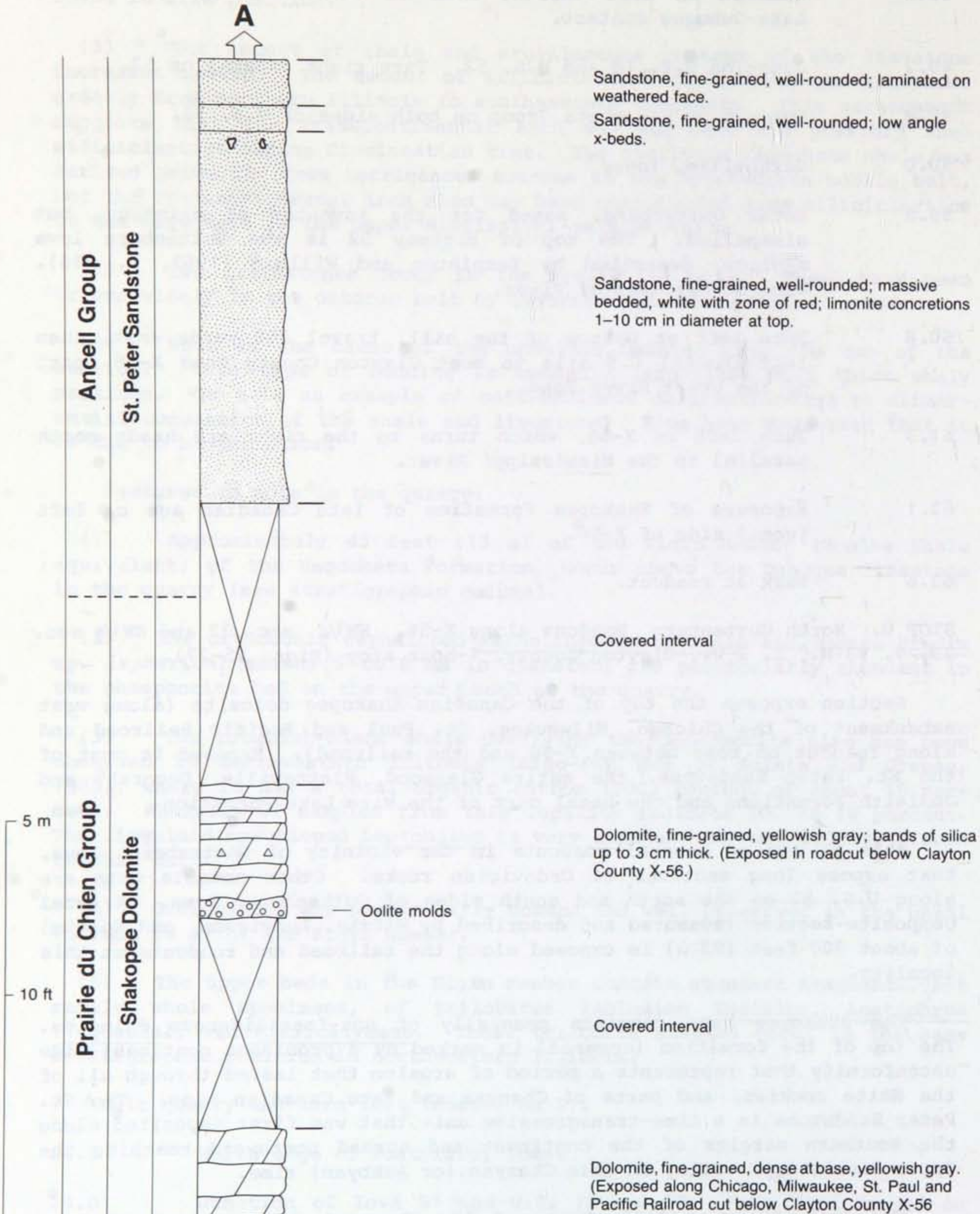
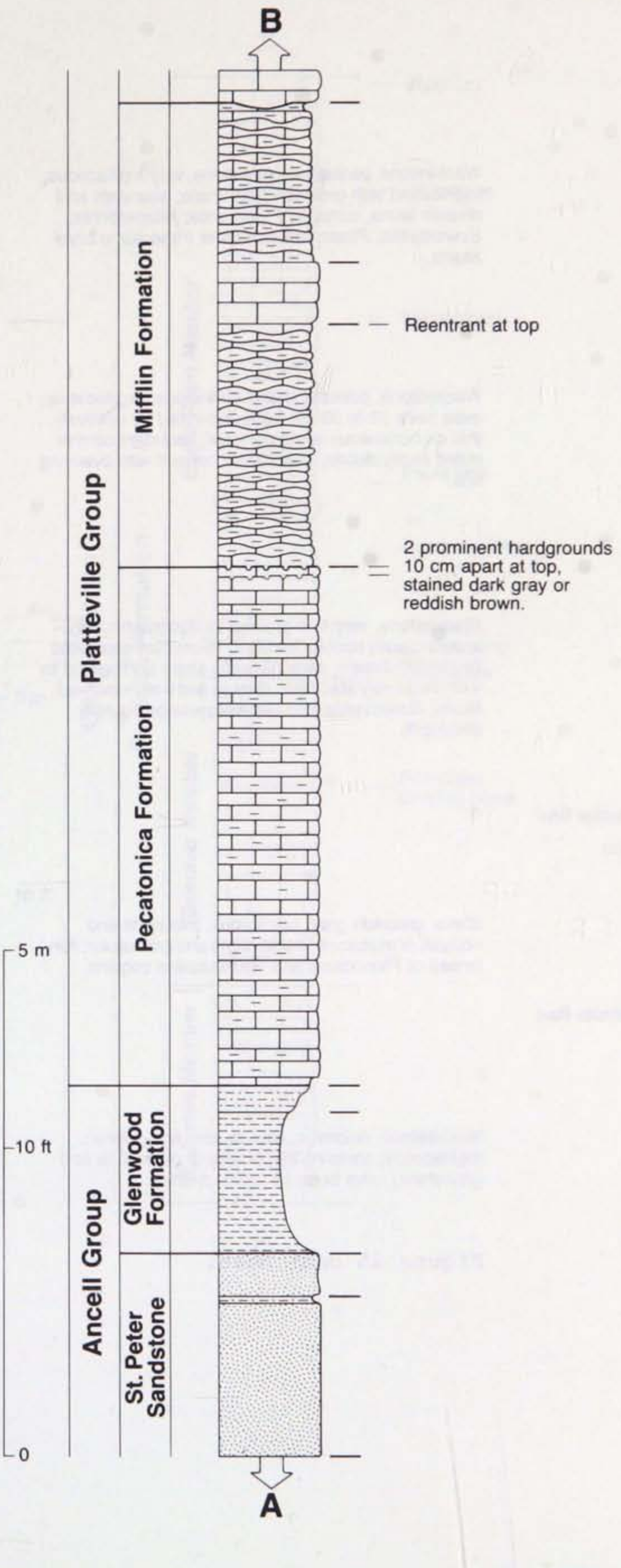


Figure 25. Graphic section of the Highway X-56 roadcut, Guttenberg, Iowa, stop 8.

STOP 8 Highway X-56 Road Cut, Guttenberg, Iowa (continued)



Wackestone, very fine-grained to lithographic, very argillaceous; contains thin lenses of packstone and grainstone; wavy nodular beds 5 to 7 cm thick; clay bed up to 7 cm thick at top, forms prominent reentrant; abundant and diverse fauna.

Wackestone, very fine-grained; even beds 15 to 20 cm thick.

Wackestone, very fine-grained to lithographic, very argillaceous; contains thin lenses of packstone and grainstone; wavy nodular beds 5 to 7 cm thick separated by shale partings up to 4 cm thick; bedding more even near base; abundant and diverse fauna, *Opikina minnesotensis* abundant.

Wackestone, very fine-grained, argillaceous, dolomitic, yellowish gray to light gray; even beds 8 to 30 cm thick; thin wispy shale partings; abundant and diverse fauna; abundant comminuted shelly debris.

Siltstone, very argillaceous, pale yellowish brown.

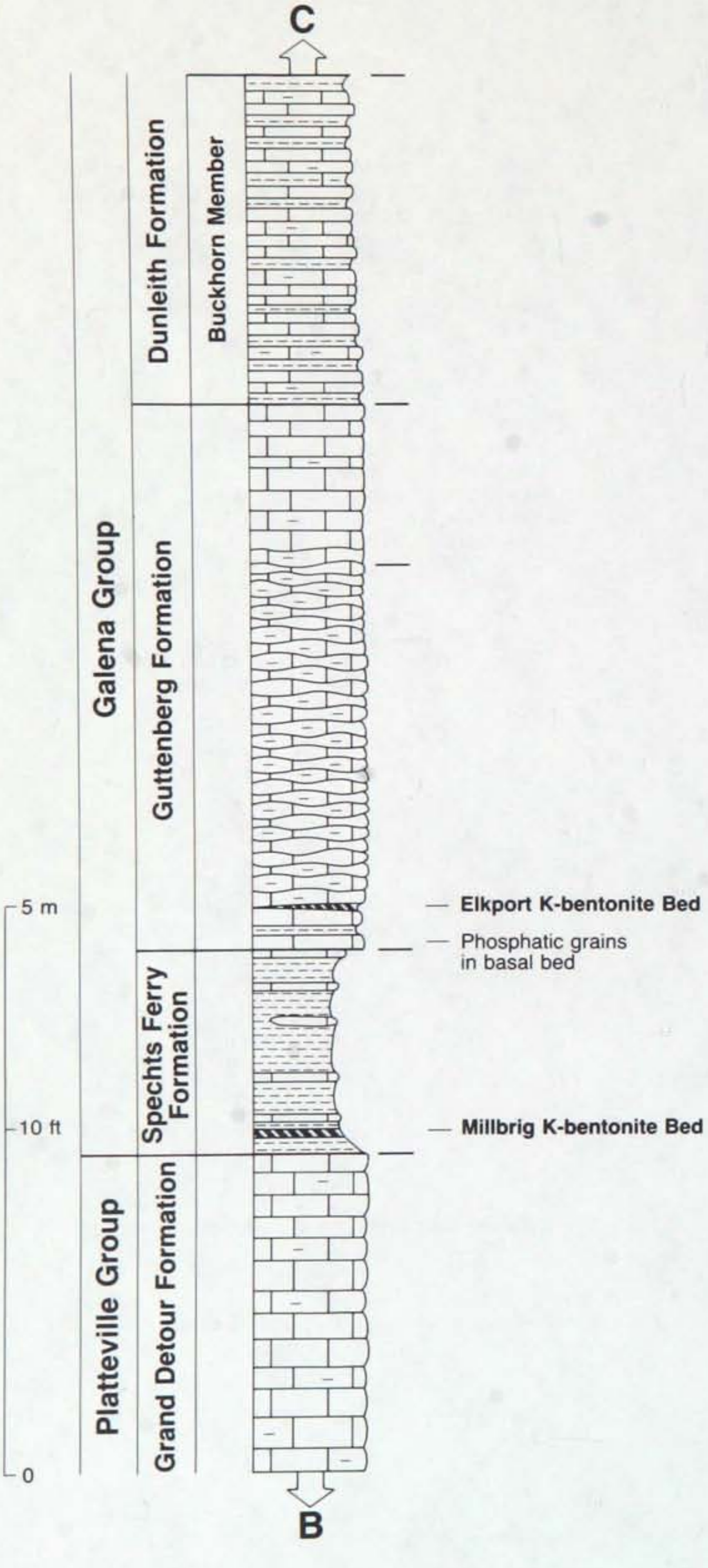
Shale, greenish-gray; light gray in basal 10 cm.

Sandstone, fine-grained, massive.

Sandstone, fine-grained, massive-bedded; 3–4 cm bed of clayey bimodal unconsolidated sand at top.

Figure 25 continued.

STOP 8 Highway X-56 Road Cut, Guttenberg, Iowa (continued)



Wackestone, packstone, grainstone, very argillaceous; intebedded with greenish gray shale; abundant and diverse fauna, contains *Pionodema, Hesperorthis, Sowerbyella, Prasopora* and other trepostome bryozoans.

Wackestone, packstone and grainstone, argillaceous; even beds 20 to 30 cm thick separated by relatively thin carbonaceous shale partings; abundant comminuted shelly debris; gradational contact with overlying unit.

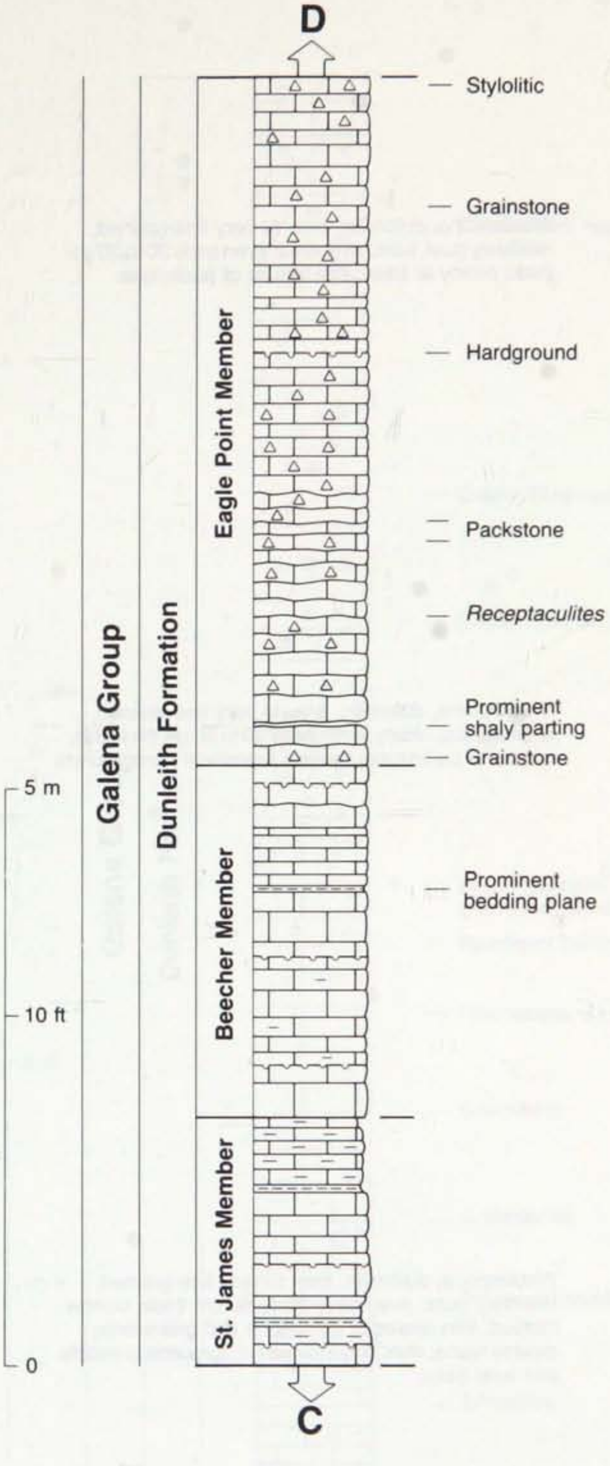
Wackestone, very fine-grained to lithographic, argillaceous; wavy nodular beds 8 to 15 cm thick separated by reddish brown, carbonaceous shale partings up to 4 cm thick; very abundant, diverse and well preserved fauna, *Sowerbyella* and *Rafinesquina* particularly abundant.

Shale, greenish gray, calcareous; thin beds and nodules of mudstone, wackestone and grainstone; thin lenses of *Pionodema* and *Rafinesquina* coquina.

Wackestone, dolomitic, fine- to very fine-grained, argillaceous; contains thin lenses of packstone and grainstone; even beds 10 to 30 cm thick.

Figure 25 continued.

STOP 8 Highway X-56 Road Cut, Guttenberg, Iowa (continued)



Wackestone, dolomitic, cherty, fine-grained, relatively pure; thin lenses of packstone; irregular beds in lower part; contains *Prasopora, Streptelasma,* and *Receptaculites.*

Wackestone, dolomite-mottled, fine-grained, relatively pure; even beds 20 to 50 cm thick separated by thin greenish gray shale partings; thin lenses of packstone; contains brachiopods, gastropods and echinoderms; hardgrounds near top, middle and base.

Wackestone, fine- to very fine-grained, argillaceous; even beds 30 to 50 cm thick separated by greenish gray shale partings; upper part is shaly and contains abundant *Prasopora* ; two prominent dark gray hardgrounds near base.

Figure 25 continued.

STOP 8 Highway X-56 Road Cut, Guttenberg, Iowa (continued)

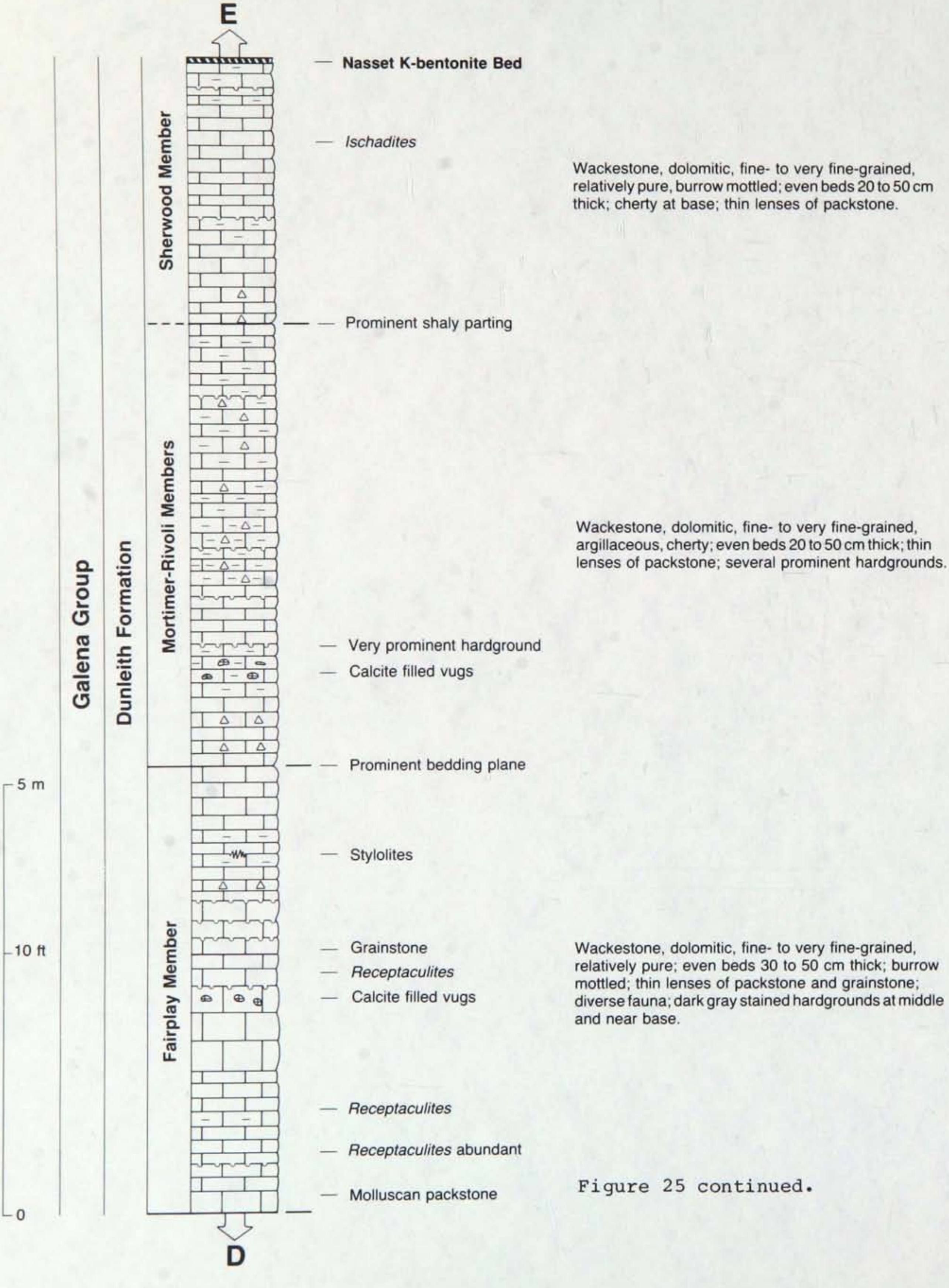
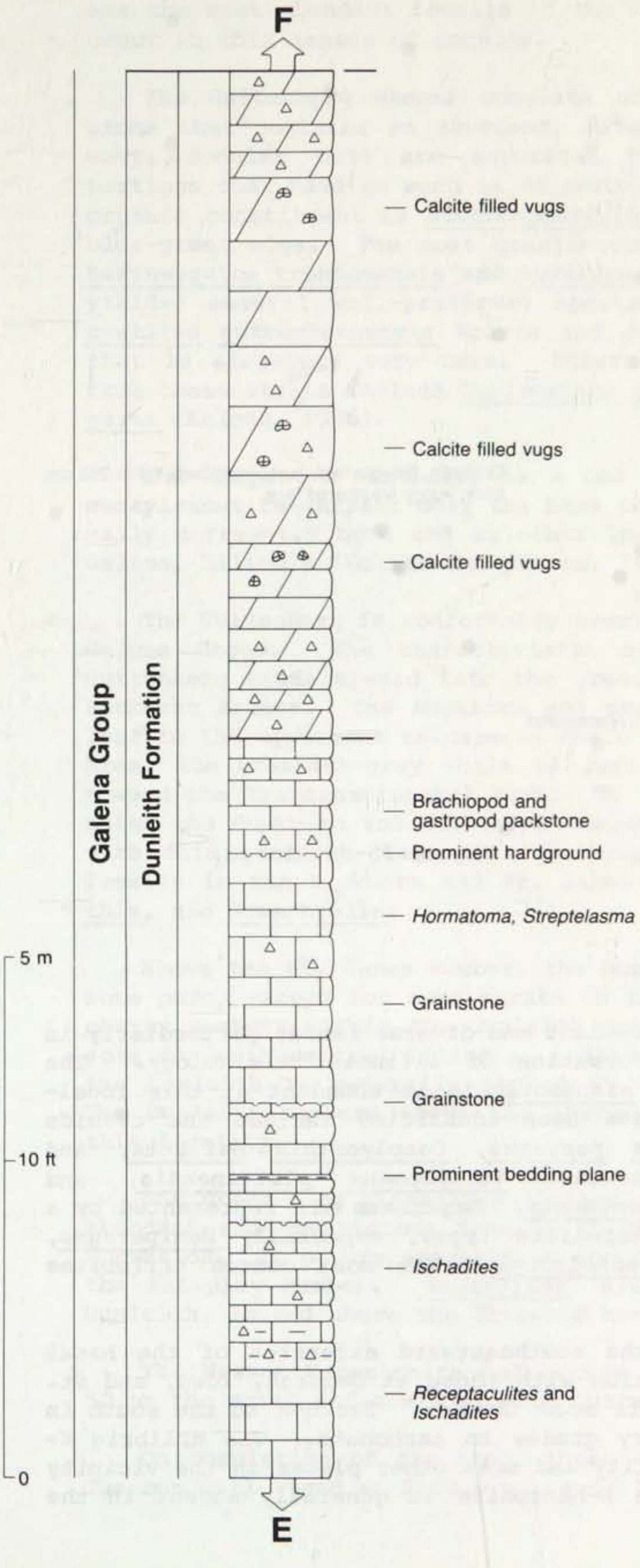


Figure 25 continued.

STOP 8 Highway X-56 Road Cut, Guttenberg, Iowa (continued)



Dolomite, fine-grained, pure, cherty; even beds 50 to 250 cm thick; molds and casts of primarily molluscan fauna; very vuggy weathered face.

Wackestone, dolomitic, fine- to very fine-grained, pure, cherty; even beds 30 to 60 cm thick; burrow mottled; thin lenses of bioclastic packstone and grainstone.

Figure 25 continued.

STOP 8 Highway X-56 Road Cut, Guttenberg, Iowa (continued)

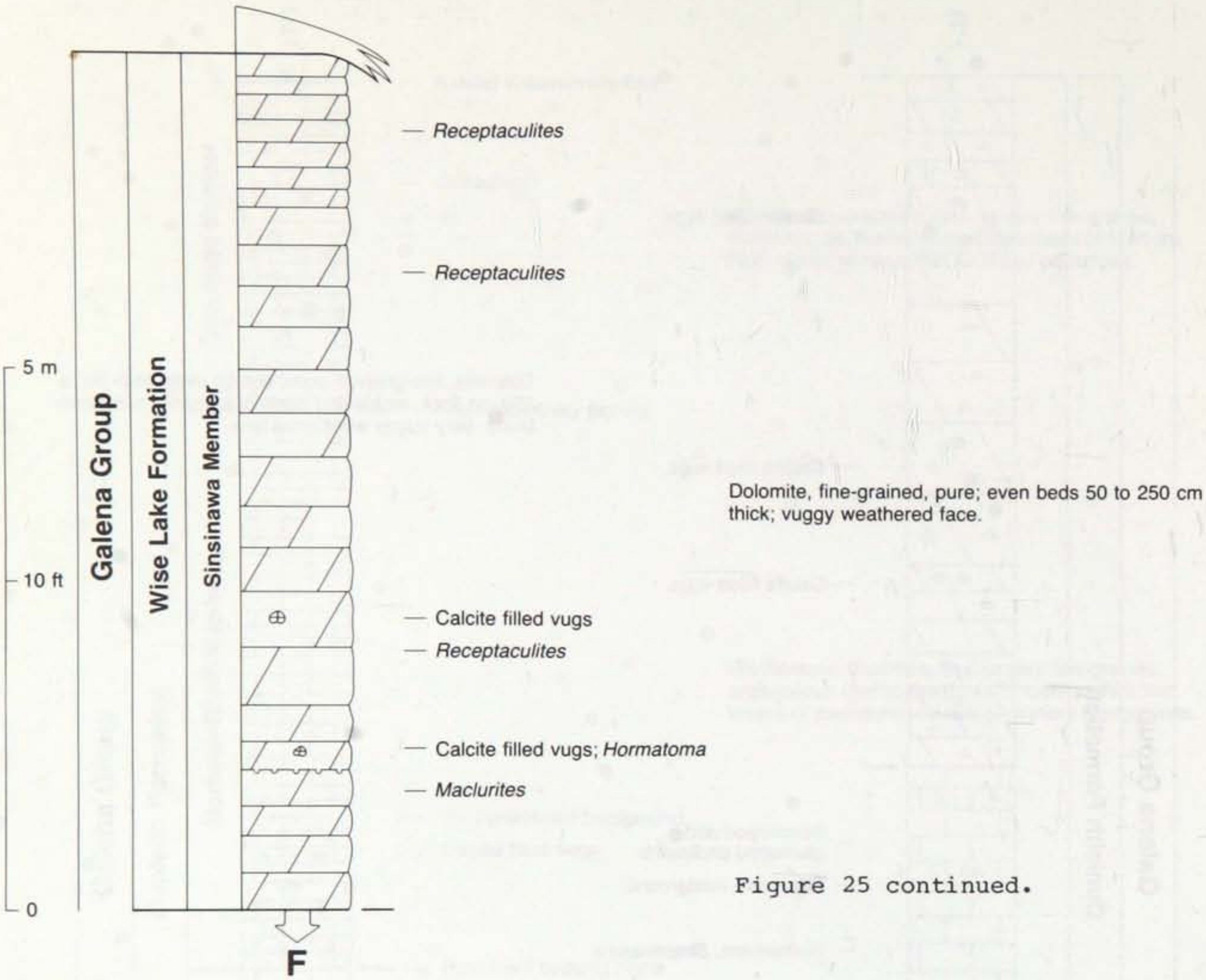


Figure 25 continued.

The Platteville contains an abundant and diverse fauna, particularly in the equivalent of the Mifflin Formation of Illinois terminology. The strophomenid brachiopod *Oepikina minnesotensis* is abundant at this locality. Other brachiopods that have been identified include the orthids *Hesperorthis concava*, *Doleroides pervetus*, *Camplyorthis deflecta*, and *Pionodema conradi*, the strophomenid *Strophomena plattinensis*, and rhynchonellid *Rostricellula minnesotensis*. Bryozoans are represented by a diversity of small ramose and bifoliate types, especially *Hemiphragma*, *Eridotrypa*, *Stictopora*, and *Astreptodictya*. The most common trilobites are *Ceraurus* and *Thaleops*.

The Spechts Ferry shale is the southeastward extension of the basal Decorah Shale. Compare this section with those at Decorah, Iowa, and St. Paul, Minnesota, where the shale is much thicker. Farther to the south in western Illinois the Spechts Ferry grades to carbonate. The Millbrig K-bentonite is present at this locality and most other places in the vicinity of Guttenberg, Iowa. The Deicke K-bentonite is generally absent in the immediate area.

Pionodema subaequata and, to a lesser extent, *Rafinesquina trentonensis* are the most abundant fossils in the Spechts Ferry here. Both brachiopods occur in thin lenses of coquina.

The Guttenberg Member consists of lithographic to fine-grained limestone that contains an abundant, diverse, and well-preserved fauna. The wavy, nodular beds are separated by reddish-brown carbonaceous shale partings that have as much as 40 percent total organic carbon. The primary organic constituent is *Gloeocapsamorpha prisca*, a microscopic single-cell, blue-green alga. The most conspicuous macrofossils are the strophomenids *Rafinesquina trentonensis* and *Sowerbyella punctostriata*. This locality has yielded several well-preserved specimens of the mitrate carpoid *Ateleocystites guttenbergensis* Kolata and Jollie (1982), a primitive echinoderm that is elsewhere very rare. Other echinoderms that have been reported from these strata include *Cuplocrinus levorsoni*, *C. jewetti* and *Pycnocrinus gerki* (Kolata, 1986).

The Elkport K-bentonite is a bed 1 to 5 cm thick that occurs at the conspicuous re-entrant near the base of the Guttenberg. It has been chemically correlated here and at other localities between McGregor, Iowa, and Galena, Illinois (Kolata and others, 1986).

The Guttenberg is conformably overlain by the Dunleith Formation of the Galena Group. The characteristic reddish-brown shale partings of the Guttenberg grade upward into the greenish-gray shale and limestone of the Buckhorn Member. The Buckhorn and overlying St. James Member are equivalent to the uppermost calcareous shale at Decorah, Iowa. In the Guttenberg area, the greenish-gray shale is less prominent than it is northwestward toward the Transcontinental Arch. To the southeast in north-central Illinois, the Buckhorn and St. James consist of slightly argillaceous dolomite with thin greenish-gray shale partings. At this stop the most abundant fossils in the Buckhorn and St. James are *Prasopora*, *Pionodema*, *Hesperorthis*, and *Sowerbyella*.

Above the St. James Member, the Dunleith Formation becomes increasingly more pure, except for some strata in the Mortimer and Rivoli Members. The cherty members within the Dunleith can be traced from southeastern Minnesota to north-central Illinois, a distance of about 250 miles. The top of the Dunleith is generally picked at the uppermost bed of chert nodules. The Dunleith members above the Sherwood are not easy to differentiate at this locality.

The green alga *Fisherites* (formerly *Receptaculites*) is one of the most abundant and conspicuous fossils in the Dunleith and overlying Wise Lake Formation. It occurs sparsely in the Eagle Point Member and is abundant in the Fairplay Member. *Ischadites*, also a green alga, is abundant in the Dunleith, in and above the Sherwood Member.

The Nasset K-bentonite bed occurs here and at nearby outcrops on U.S. 52 on the north and south side of Guttenberg, Iowa.

On completion of the stop, those driving their own cars are released. The bus will load at 2:00 p.m., and leave for the Twin Cities. We expect

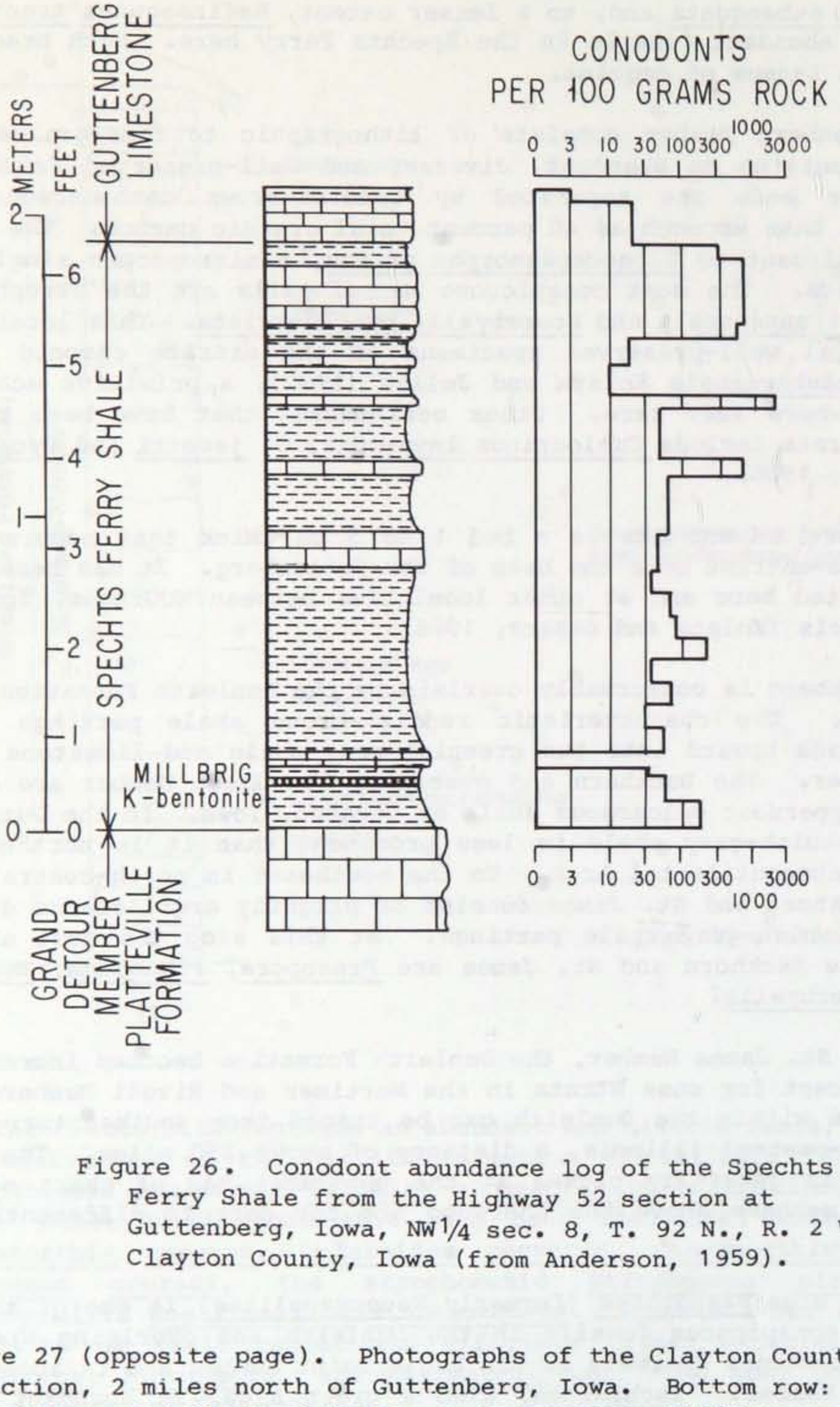


Figure 26. Conodont abundance log of the Spechts Ferry Shale from the Highway 52 section at Guttenberg, Iowa, NW1/4 sec. 8, T. 92 N., R. 2 W., Clayton County, Iowa (from Anderson, 1959).

Figure 27 (opposite page). Photographs of the Clayton County Highway X-56 section, 2 miles north of Guttenberg, Iowa. Bottom row: 1, St. Peter Sandstone and Glenwood Shale; 2, Pecatonica, Mifflin, and base of Grand Detour Members of the Platteville Formation; 3, Mifflin and Grand Detour Members overlain by Spechts Ferry Shale. Middle row: 1, Spechts Ferry Shale and Guttenberg limestone, Decorah Group; 2, Guttenberg limestone overlain by Buckhorn and St. James Members of the basal Dunleith Formation, correlative with the Ion Formation of the Decorah Group; 3, lower Dunleith Formation. Top row; 1, middle Dunleith Formation; 2, upper Dunleith Formation; 3, Wise Lake Formation. Tick marks on right edge of photos indicate contacts.

to reach the Minneapolis-St. Paul International Airport by about 6:00, after which we will return to St. Paul to offload the remaining passengers.

We thank you for your attention, and hope your collections are large enough to require an extra box on your trip home.

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THE ROCK ELM DISTURBANCE, PIERCE COUNTY, WISCONSIN

by

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INTRODUCTION

The Rock Elm disturbance is a nearly circular region of anomalous rocks and structures in west-central Wisconsin (lat 44°43'N., long 92°14'W.) that is surrounded by little-deformed, essentially flat-lying shallow marine sedimentary rocks of Cambrian and Ordovician age. The disturbance has a diameter of 4 miles and is centered about 1.5 miles south-southwest of the small town of Rock Elm, Wisconsin (Fig. 1). It is indicated by arcuate topographic ridges in the northwestern part of the Plum City 7.5-minute quadrangle (Fig. 2). The geology (Fig. 3) was partially mapped by Nelson (1942) and later by Cordua (1983, 1985). John Ladd did additional detailed mapping in the area in 1985, which has not been published.

Figure 1. Field trip route, stops 1-3, and the Rock Elm disturbance.

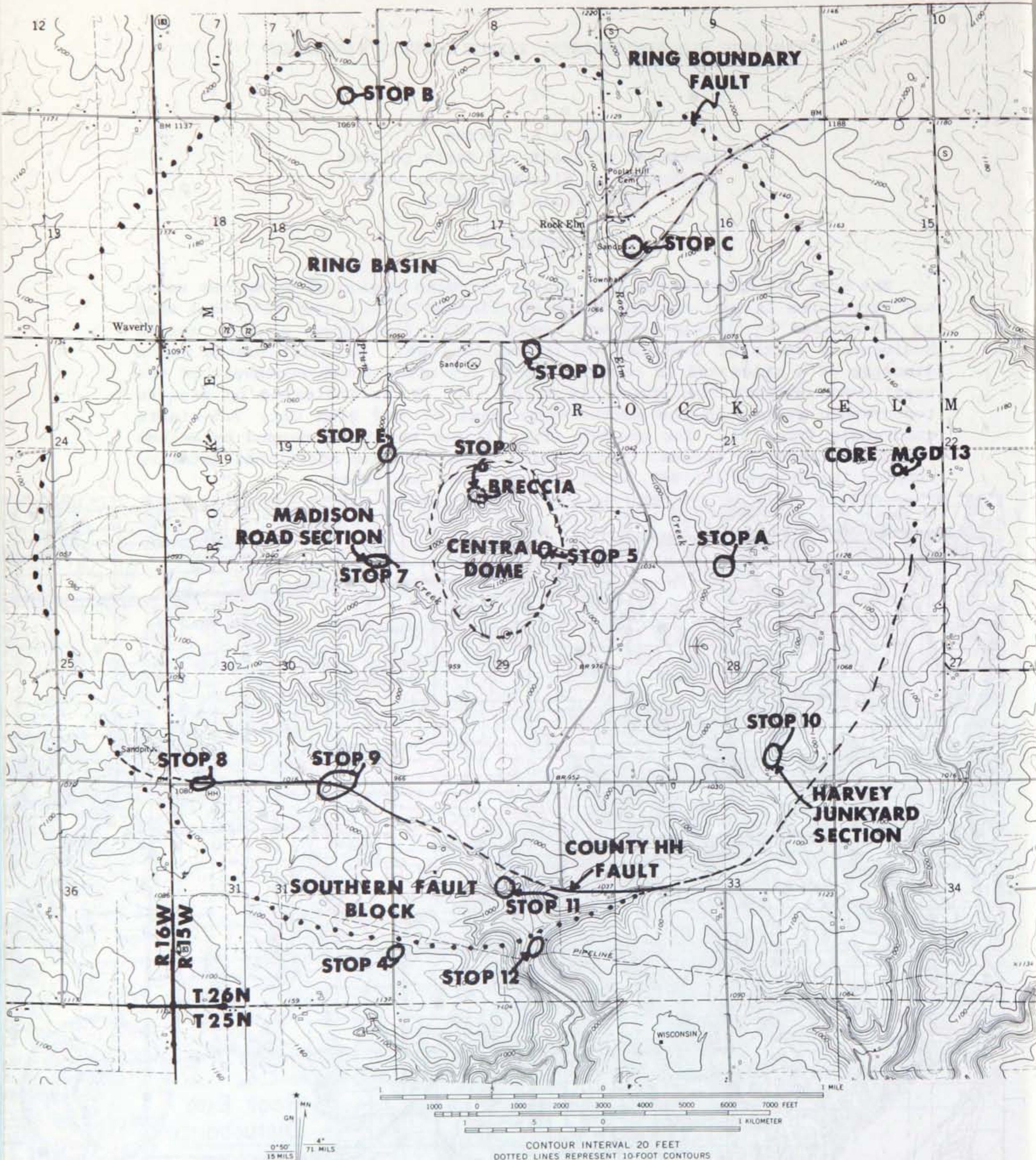

Figure 2. Topography and locations of cores and sections (Fig. 4) and stops 4-12. Lettered stops are supplemental.

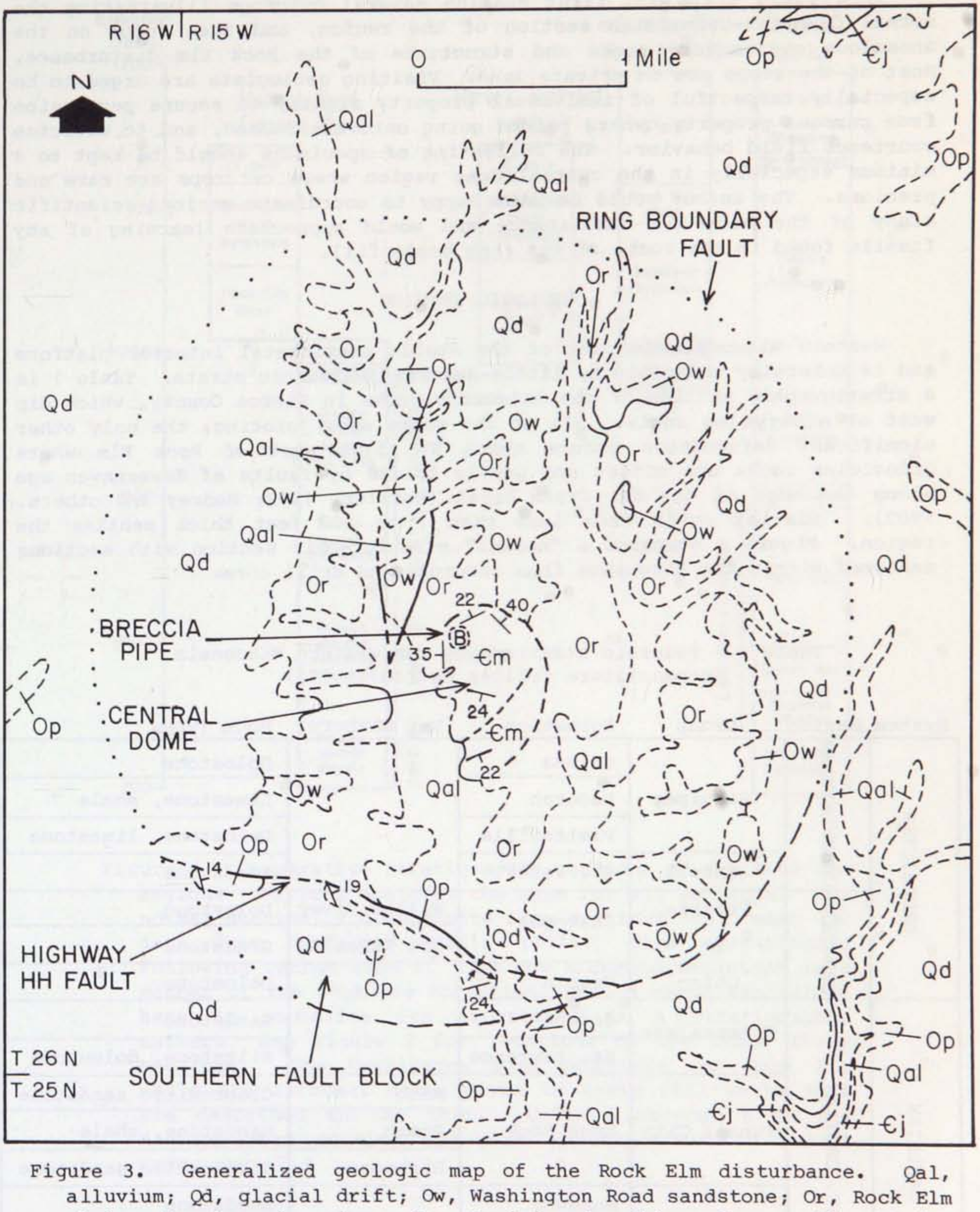

Figure 3. Generalized geologic map of the Rock Elm disturbance. Qal, alluvium; Qd, glacial drift; Ow, Washington Road sandstone; Or, Rock Elm shale; B, breccia pipe; Op, Prairie du Chien Group; Cj, Jordan Formation; Cm, Mt. Simon Formation. In the south-central part of the central dome, the strike and dip symbol is on the flank of a small anticline that cannot be shown at this scale.

This field trip will first examine several outcrops illustrating the normal Cambrian-Ordovician section of the region, and then focus on the anomalous sedimentary rocks and structures of the Rock Elm disturbance. Most of the stops are on private land. Visiting geologists are urged to be especially respectful of individual property rights, to secure permission from current property owners before going onto their land, and to exercise courteous field behavior. The collecting of specimens should be kept to a minimum especially in the central dome region where outcrops are rare and precious. The author would be most happy to coordinate serious scientific study of the Rock Elm disturbance and would appreciate learning of any fossils found in the rocks of the ring basin fill.

GEOLOGIC SETTING

Western Wisconsin is part of the stable continental interior platform and is generally underlain by little-deformed Paleozoic strata. Table 1 is a stratigraphic section of the Paleozoic rocks in Pierce County, which dip west at a very low angle. All of the rocks show jointing; the only other significant deformation occurs about 31 miles west of Rock Elm where Ordovician rocks are offset and gently folded by faults of Keweenawan age along the edge of the St. Croix horst (Mossler, 1972; Mudrey and others, 1982). Glacial drift from less than 1 to 100 feet thick mantles the region. Figure 4 compares a "normal" stratigraphic section with sections measured within the structure from outcrops and drill core.

Table 1. Palezoic stratigraphy for western Wisconsin
[Nomenclature follows Ostrom (1967)]

System	Series	Group	Formation	Key Members	Rock Types
ORDOVICIAN	CHAMPLAINIAN	Sinnipee	Galena		Dolostone
			Decorah		Limestone, shale
			Platteville		Dolostone, limestone
		Ancell	St. Peter		Sandstone
	CANADIAN	Prairie du Chien	Shakopee	Willow River	Dolostone
				New Richmond	Sandstone
			Oneota		Dolostone
CAMBRIAN	ST. CROIXAN	Trempealeau	Jordan		Sandstone
			St. Lawrence		Siltstone, dolostone
		Tunnel City	Lone Rock	Reno	Glauconitic sandstone
				Tomah	Sandstone, shale
				Birkmose	Glauconitic sandstone
		Elk Mound	Wonewoc		Sandstone
			Eau Claire		Sandstone, shale
			Mt. Simon		Sandstone

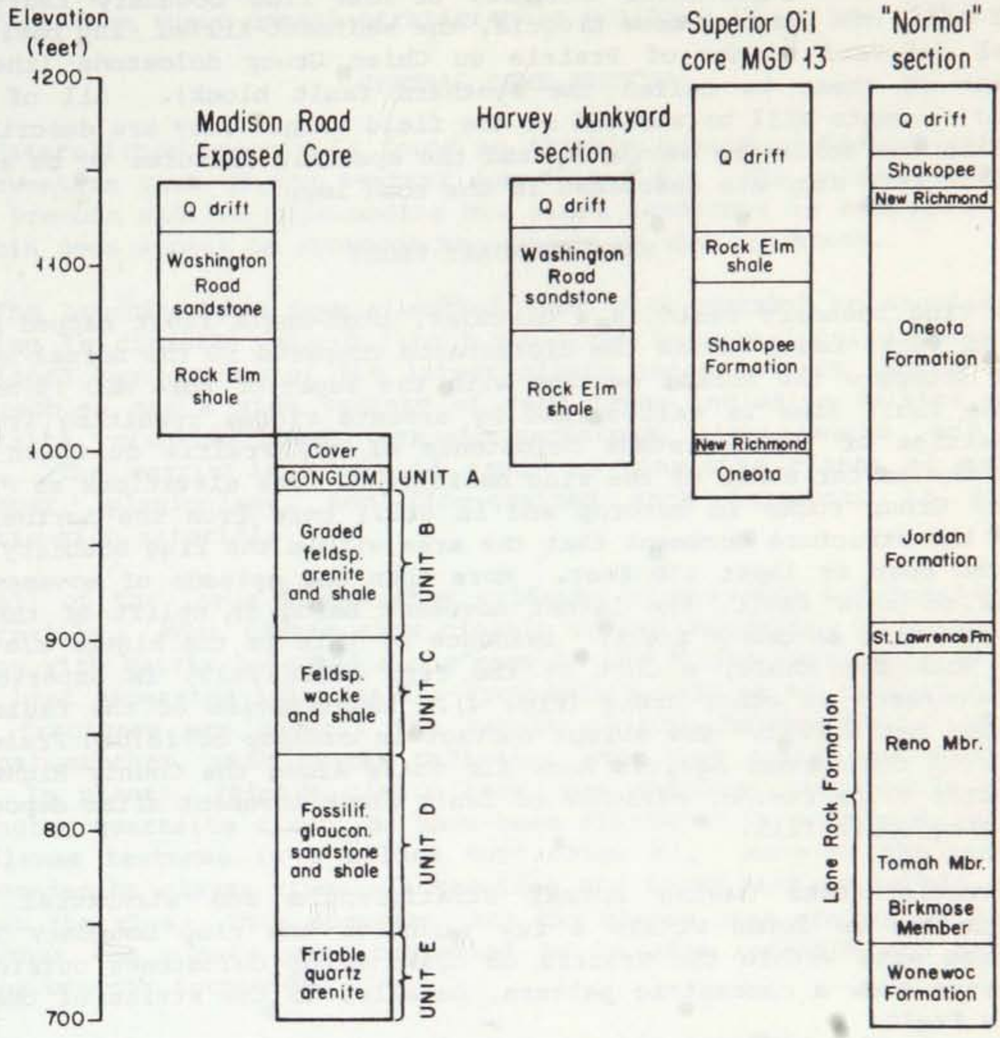

Figure 4. Comparative stratigraphic sections of the Rock Elm region. Vertical scale is the same for all sections. The normal section is a composite from original field work and data from Kopf and Willis (1974), with nomenclature following Ostrom (1967). The New Richmond sandstone is a member of the Shakopee Formation, but is shown separately here to emphasize its importance as a stratigraphic marker. See Figure 2 for locations of the other three sections. The Washington Road sandstone and Rock Elm shale are informal names given to basin fill units that are described in the text. Units A through E in the Madison Road section and core are described in detail under stop 7.

The Rock Elm disturbance consists of the ring boundary fault, the central dome, the central dome breccia, the sediment-filled ring basin, and marginal deformed blocks of Prairie du Chien Group dolostone (the most prominent of these is called the southern fault block). All of these geologic elements will be visited on the field trip. They are described in general in the following sections, and the specific features to be seen at each field trip stop are described in the road log.

RING BOUNDARY FAULT

The ring boundary fault is a circular, high-angle fault mapped by the offset of rocks found within the disturbance compared to the normal section outside (compare the normal section with the Superior core MGD 13 on Fig. 4). The fault line is well marked by arcuate ridges resulting from the juxtaposition of the resistant dolostones of the Prairie du Chien Group against the softer shale of the ring basin fill. The elevations of Prairie du Chien Group rocks in outcrop and in drill core from the northeastern part of the structure document that the area within the ring boundary fault has moved down at least 130 feet. More than one episode of movement has occurred on this fault, the latest movement being an uplift of the area within the ring boundary fault. Evidence of this is the higher elevation of the Rock Elm shale, a unit of the ring basin fill, in Superior Oil MGD 13 compared to other areas (Fig. 4). Reactivation of the fault thus post-dated basin fill. The abrupt contact in outcrop of folded Prairie du Chien Group dolostones against Rock Elm shale along the County Highway HH fault (stop 9) is further evidence of fault block movement after deposition of the ring basin fill.

Paleozoic rocks having normal stratigraphic and structural relationships can be found within a few yards of the ring boundary fault. Some joint sets within the Prairie du Chien Group dolostones outside the disturbance show a concentric pattern, parallel to the strike of the ring boundary fault.

CENTRAL DOME

The central dome is an oval area about half a mile wide and about 1 mile long, containing outcrops of conglomerate sandstone that generally dip 20° to 40° away from the center of the structure. The feature shows up prominently on topographic maps as an arcuate ridge breached by stream erosion on the southwestern side (Fig. 2).

The sandstone consists primarily of moderately sorted, medium to coarse, subangular to rounded sand with about 15 percent clastic K-feldspar. It contains up to 10 percent matrix, and is only weakly cemented. Conglomerate beds, which range in thickness from a single pebble to as much as 10 cm, contain rounded to subrounded pebbles of quartz, quartzite, chert and iron-formation. A few poorly preserved brachiopod molds and casts have been found in the sandstone.

On the basis of the presence of brachiopods and Precambrian clasts and the absence of Paleozoic clasts, the conglomerate sandstone is tentatively identified as the Upper Cambrian Mt. Simon Formation. If this correlation is correct, then the rocks of the central dome have been uplifted more than 750 feet from their normal stratigraphic position (Thwaites, 1957).

CENTRAL DOME BRECCIA

Heterolithic breccia is found as thickly scattered float blocks in the northwestern part of the central dome (stop 6). The relationship between this breccia and the surrounding Mt. Simon sandstone is ambiguous, but the breccia does appear to crosscut the trends of the sandstone.

The breccia is a poorly sorted rock with rounded to angular pebbles ranging in diameter from 0.2 to 5 cm. The breccia locally shows a well-developed segregation of the larger clasts into distinct layers (Fig. 5). The pebbles are a wide variety of rock types including felsite porphyry, quartzite, granite, chert, arkosic sandstone, lithic wacke, and amphibolite. The matrix is a mix of sand- to clay-size clasts of quartz, K-feldspar, plagioclase, and fine-grained rock fragments in a clayey, apatite-rich material.

All of the large clasts show evidence of shearing and locally plastic deformation. Most clasts show closely spaced fractures of varying orientation with matrix injected along many of the cracks (Fig. 6). Some clasts have been separated into smaller fragments separated by "veins" of matrix. Some fractures are clearly the result of the compression of one pebble against another, with cracks radiating away from points of contact (Fig. 7). In places, felsite clasts have been deformed plastically around an impinging quartzite clast, or have been flattened in a fashion reminiscent of fiamme textures in a welded tuff (Fig. 8). Many of the pebbles are surrounded by clayey rims; slickensides are found both on pebble exteriors and in the rims. This suggests that the clayey rims are pulverized matrix and that the clasts were subjected to in situ rotation and deformation during breccia formation.

Several interpretations of the breccia are possible. The breccia could represent an intrusive pipelike mass in which the pebbles and small clasts were rounded and broken during tectonic emplacement possibly in a fluidized system (McCallum, 1985). Another interpretation is that the breccia is a fault-bounded block of sedimentary conglomerate, possibly a basal Cambrian conglomerate, but this does not explain the deformation seen in the breccia. Read (1985) suggested that the felsite clasts could be bombs of impact-generated melt, and that the breccia is part of an ejecta blanket. However, the presence of subhedral K-feldspar phenocrysts as large as several centimeters in diameter in the felsite does not appear to support the hypothesis that the clasts are bombs. On the main, the author thinks that a breccia pipe is the best hypothesis that fits the currently available data.

RING BASIN FILL

A ring basin surrounding the central dome has been filled with a section of sedimentary rocks unlike any seen elsewhere in the region. The basin fill is at least 144 feet thick and can be subdivided into two mappable units. The lower unit is informally named the Rock Elm shale and the upper unit is informally named the Washington Road sandstone (stops 7, 9, and 10). These units overlie Prairie du Chien Group dolostones and rocks of the central dome with an angular unconformity. The rocks of the ring basin fill are generally flat lying but have locally been affected by significant faulting and tilting.

The Rock Elm shale is best exposed in an abandoned clay pit in the NE1/4NE1/4NW1/4 sec. 28, T. 26 N., R. 15 W. (supplemental stop A). This unit is a minimum of 100 feet thick and consists of gray, green and brown shale interbedded with fine-grained silty feldspathic wacke. The shales are noncalcareous and have local pyrite and oxidized concretions up to 5 cm across. The sandstone interbeds average 2 to 4 cm in thickness, are weakly cemented with silica and authigenic K-feldspar, and are massive to internally laminated. Conspicuous crawling tracks mark bedding plane surfaces. Nelson (1942) reports the find of two archeogastropods (genera Lophospira and Propilina) in the concretions, indicating an Early to Middle Ordovician age for the Rock Elm shale.

The Washington Road sandstone conformably overlies and grades into the Rock Elm shale. It is best exposed in the small quarry overlooking Harvey's Junkyard in the SE1/4SW1/4SE1/4 sec. 28, T. 26 N., R. 15 W. (stop 10). This sandstone is at least 45 feet thick and can be readily subdivided into three distinct subunits. These are, from oldest to youngest: a medium-bedded very fine feldspathic wacke with thin clay selvages along bedding planes; a very friable, massive, white feldspathic arenite; and a medium-grained ferruginous feldspathic arenite. Crawling tracks and feeding burrows along bedding planes in the oldest subunit are common. The beds tend to be internally laminated and lack cross-bedding. Phosphatic brachiopod fragments (Orbiculoidea?) and rare gastropod molds have been found in this subunit. Its conformable contact with the Rock Elm shale suggests that both are of Ordovician age.

DEFORMED BLOCKS OF PRAIRIE DU CHIEN DOLOSTONE

Along the edges of the Rock Elm disturbance are several apparently fault-bounded blocks of folded and faulted Prairie du Chien Group dolostone. The largest of these, the southern fault block (stops 8, 9, and 11), is a crescent-shaped block between the ring boundary fault and the Highway HH fault. This block consists of Shakopee Formation folded into a series of tight anticlines and synclines. Brecciation is locally prominent. The folds are open and upright and the dips on the limbs range from 20° to 70°. The folds trend north-northwest and plunge gently south-southeast.

The southern fault block has had a complex history. The block has dropped at least 130 feet relative to the normal section outside the ring boundary fault and then later was uplifted along the Highway HH fault, putting it against the Rock Elm shale (stop 9).

Other small outcrops of deformed Prairie du Chien Group rocks occur along the northern edge of the disturbance where the folded dolostones are unconformably overlain by flat-lying Rock Elm shale (supplemental stop B).

Figure 5. Hand sample from the central dome breccia showing the general size and degree of rounding of the clasts. Notice the large vug (black) in the white felsite clast at lower left. The scale is in centimeters.

Figure 6. Hand sample from the central dome breccia showing a fractured clast with matrix separating the fragments. The scale is in centimeters.

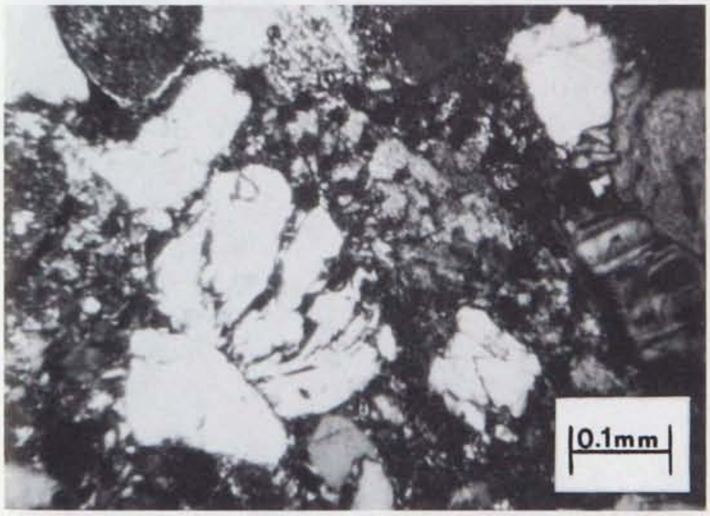

Figure 7. Photomicrograph of the central dome breccia. Notice the fractures resulting from the apparent in situ compression of two quartz clasts. Crossed nicols.

Figure 8. Hand sample from the central dome breccia showing the plastic deformation of a felsite clast due to impingement of a quartzite clast. The scale is in centimeters.

UNITS UNDERLYING THE RING BASIN FILL

Scattered water wells and drill cores provide some data on the rock underlying the Rock Elm shale. At the edges of the Rock Elm disturbance, the shale unconformably overlies or is in fault contact with rocks of Prairie du Chien Group. Nearer to the central dome, however, the shale apparently rests on Cambrian sandstone. The best section through these sandstones is at Madison Road (Fig. 4; stop 7) where a 300-foot-long core was drilled in January 1985 by the Superior Oil Company. In this core, the sandstones are tentatively correlated with the Lone Rock and Wonewoc Formations, although they differ in thickness and have structures, such as slump folds and graded beds, that are uncommon in the Cambrian rocks of western Wisconsin. See the stop 10 description for more details on this core.

This apparent distribution of rocks in the subsurface suggests an annular distribution of rocks perhaps due to concentric faults or a domal uplift extending beyond the exposed limits of the central dome.

GEOPHYSICAL DATA

At present, few geophysical data are available for the Rock Elm area. Regional gravity data (Wisconsin Geological and Natural History Survey, unpublished) show a distinct negative Bouguer anomaly of about 5 mgal associated with the central dome. A reconnaissance survey with a proton precession magnetometer did not indicate an anomaly associated with the central dome, but did delineate a general positive anomaly associated with the ring boundary fault, especially along the northwestern segment. An aeromagnetic study (Ruenger, 1986) indicates that the Rock Elm structure is at the intersection of several major faults in the Precambrian basement.

ECONOMIC GEOLOGY

Both gold and diamonds have been reported within the limits of the Rock Elm disturbance in the alluvium of streams whose headwaters also lie within the disturbance. Flour gold was mined near Rock Elm using rockers and sluicing in the late 1880s (River Falls Journal, 1887, 1888). During gold mining operations, at least ten small diamonds were reportedly found (Kunz, 1891; Cannon and Mudrey, 1981). Kunz described the diamonds as pale yellow to blue and weighing as much as 2 kt. Although the gold and diamonds may derive from the glacial drift, neither resource has been reported elsewhere in western Wisconsin.

In 1983-85, the Superior Oil Company explored the area for gold and verified the occurrence of placer gold. The exploration culminated in a series of cores drilled, including the Madison Road core. Traces of copper sulfides were reported in the Prairie du Chien Group dolomites in one core from the northeastern edge of the structure; otherwise no bedrock mineralization was found. Residents of the area report that other companies have periodically explored the Rock Elm area for diamonds.

GEOLOGIC HISTORY OF THE ROCK ELM DISTURBANCE

Field investigation has established several relationships which must be considered in any hypothesis offered to explain the origin of the Rock Elm disturbance. The earliest recognizable event is indicated by the unusual stratigraphic thickness and sedimentary features--such as graded beds and soft sediment deformation--in sedimentary rocks of inferred Cambrian age in the Madison Road drill core (stop 7). After deposition of the Shakopee dolomite in Early or Middle Ordovician time, the area was affected by an intense multiphase deformation that resulted in formation of the ring boundary fault, the central dome, the intervening ring-shaped basin, and the folding of the Paleozoic rocks. Later in Ordovician time, the ring basin filled with a coarsening-upward sedimentary sequence preserved as the Rock Elm shale and the Washington Road sandstone. After deposition of the basin fill, faulting offset rocks of the basin fill against the southern fault block. It is still unclear which event formed the central dome breccia.

Origin of the Structure

The Rock Elm disturbance satisfies many of the criteria of the so-called "cryptoexplosion structure" as defined by Dietz (1959). It occurs in a region not otherwise typified by deformation, has a distinct circular symmetry, a central dome, a ring basin, high-angle faulting, folding, and brecciation. It is also important to note the apparent absence of certain features. So far, no shattercones, high-pressure polymorphs, shock lamellae or diaplectic glasses have been found. No outcrops of igneous rocks or areas of recrystallized Paleozoic rocks have been found.

Anomalous circular structures of this kind have been the subject of spirited debate through the years as to whether or not their origin is due to an exogenous cause, such as a bolide impact, or an endogenous event, such as a cryptovolcanic explosion, or a nonviolent hydrotectonic event (Bucher, 1963; McCall, 1979; Kopf, 1982; Drake, 1985). Major hypotheses for the origin of the Rock Elm disturbance can be summarized as follows:

(1) The astrobleme model (Dietz, 1959). The disturbance resulted from the impact in Early or Middle Ordovician time of a bolide, forming a crater and producing the deformation seen in the Shakopee and older rocks. The central dome formed by rebound. Subsequent collapse of fault-bounded blocks around the dome produced the ring basin. This basin filled with sediments. Later readjustments, possibly isostatic in nature, reactivated the faults. In this hypothesis, the Madison Road core does not penetrate Cambrian rocks, but rather samples lower levels in the Ordovician basin fill.

(2) The cryptovolcanic model (Bucher, 1963). The disturbance resulted from the emplacement of a volatile-rich magma in Early or Middle Ordovician time. Sudden crystallization or decrease of pressure on a supercooled water-rich magma produced a volatile-rich fluid system which burst upward, likely erupting onto the surface. The stress accompanying this event produced the deformation seen in the Shakopee and older rocks and formed a crater or ring basin by explosion or collapse of overlying layers. Resurgence formed the central dome. Later readjustments reactivated many

of the faults after the depression filled with sediments. The location of this activity was controlled by the intersection of major Precambrian faults in the subsurface. The zone of weakness had also been active in Cambrian time, producing the anomalies seen in the sediments in the Madison Road core.

(3) The hydrotectonic model (Kopf, 1982). The Rock Elm disturbance resulted from the emplacement of a fluid-rich tectonic breccia initially along irregularities along a low-angle fault within or at the base of the plate. Contraction of the irregularities pressurized this slurry, causing it to be injected upward into the overriding plate. Older high-angle faults controlled its movement. Renewed fault creep caused the material along the irregularities to fluctuate in volume, "converting it to a slow-moving but powerful, deep-seated reciprocating pump. A clastic pipe rooted in such pumps is converted to a surge tube whose top grows upward spasmodically and whose wallrocks are repeatedly deformed." (Kopf, 1986, personal communication). Variations in fluid pressure would cause the slurry to rise and subside at different times, accounting for the reversal of vertical motions during reactivation of the disturbance. The action of this hydrotectonic system would affect the deposition of the Cambrian strata seen in the Madison Road core, deform the Cambrian and Ordovician strata, uplift the central dome, cause the subsidence of the ring basin, and later fault the ring basin fill.

The purpose of this field guide is not to advocate one or another of these hypotheses, but rather to review the evidence now available and direct the interested geologist to the critical outcrops. It is, however, important to recall the method of multiple working hypotheses, especially when working in an area such as Rock Elm, where so many questions remain to be answered.

ROADLOG AND STOP DESCRIPTIONS

The field trip starts at the St. Paul Hotel in downtown St. Paul, Minnesota. Load onto the bus. Go south to Kellogg Boulevard and turn left (east) onto Kellogg. Follow Kellogg Boulevard through the city of St. Paul to the intersection with Mounds Boulevard. Bear right onto Mounds, then merge left onto I-94 eastbound. We will continue on I-94 about 15 miles to the Wisconsin border.

Our route takes us over a rolling terrace composed dominantly of drift of the St. Croix moraine, a stagnant ice complex produced by the last advance of the late Wisconsinan Superior lobe. A few remnants of Ordovician St. Peter Formation poke through the drift. Terraces of the St. Croix River become prominent about 12 miles east of St. Paul as we descend into the St. Croix valley near Lakeland, Minnesota.

The detailed roadlog begins at the west end of the I-94 highway bridge over the St. Croix River. Mileage is measured cumulatively from this point. The trip route and the locations of stops 1, 2, and 3 are marked on Figure 1. The locations of stops 4 through 12 appear on Figure 2.

Miles	
0.0	I-94 bridge over the St. Croix River. The lower St. Croix River is a designated U.S. Scenic Riverway.
0.5	Exit to the right on Highway 35 north into Hudson. Welcome to Wisconsin!
1.4	Turn right (south) onto Coulee Road, just north of the Dairy Queen.
1.5	Turn right into the parking area at Casanova's Liquor Store. This is STOP 1.

STOP 1. Cuts behind Casanova's Liquor Store on Coulee Road in Hudson, Wisconsin, NE1/4SW1/4 sec. 25, T. 29 N., R. 20 W.

Be careful of steep slopes and overhangs! Confine sampling to float material.

The purpose of this stop is to see a representative exposure of the Cambrian Lone Rock Formation. These cuts are good exposures of the Birkmose Member, a fine- to medium-grained glauconitic and feldspathic sandstone. The sandstone ranges from finely cross-laminated beds to more massive, highly burrowed "wormstone." Above the Birkmose is the Tomah Member, a yellow to buff, fine-grained, thin-bedded feldspathic sandstone with thin gray shale interbeds. Notice the absence in these members of coarse material, graded beds, and soft sediment slump structures. We will later compare these rocks to rocks in the Madison Road core in the Rock Elm disturbance (stop 7).

Some medium- to coarse-grained, white to yellow sandstone of the Cambrian Wonewoc Formation can be found at the base of this section and to the west of this stop.

We are in the middle of the Hudson-Afton horst, a fault block uplifted in post-Shakopee time along several steep reactivated faults of Keweenawan age at the edge of the Keweenawan rift.

	After stop 1, turn right (south) onto Coulee Road.
1.7	Birkmose Member of the Lone Rock Formation in cut at left.
1.8	Entrance to Birkmose Park on the right.
2.3	Stop sign at the intersection of Coulee Road and 11th Street. Turn right onto 11th Street, crossing over I-94.
2.4	Turn left onto Crestview Road.
3.0	Continue straight on Crestview Road. The tree-covered slope ahead is a scarp formed by the Hastings fault. The trees are

on downthrown resistant dolostones of the Prairie du Chien Group, and we are on the upthrown block, which is overlain by the softer Lone Rock Formation. The Hastings fault, which bounds the Hudson-Afton horst, is a high-angle structure that was active in Keweenawan time and was reactivated sometime after the deposition of the Ordovician Platteville Formation.

3.6 Stop sign. Continue straight ahead, merging with I-94 eastbound.

4.7 Exit I-94 onto Highway 35 southbound to River Falls. We will follow Route 35 all the way to River Falls.

6.1 A large kame with a gravel pit in it is visible on the left. This is part of the St. Croix moraine complex of late Wisconsinan age.

9.5 Roadcut in St. Peter Formation (Ordovician). Ahead we can see a mesa and butte topography controlled by the Ordovician bedrock. The hills are capped by resistant Platteville Formation and their slopes are in the St. Peter Formation. Deeper river gorges in the area cut into dolostones of the Prairie du Chien Group. The point where the streams pass from the St. Peter Formation into the Prairie du Chien Group is generally marked by waterfalls or rapids. The town of River Falls gets its name from such a waterfall.

12.5 Cross the Kinnickinnic River. Enter River Falls.

13.4 Stoplight. Go straight ahead.

13.6 Stoplight. Go straight ahead. Beware of the congestion in downtown River Falls.

14.0 Stop sign. Turn left, following signs for Highways 29 east and 35 south.

14.1 University of Wisconsin-River Falls campus on the right.

14.9 Stop sign. Bear right on Highway 35 south.

15.1 Cross the South Fork of the Kinnickinnic River.

16.7 Quarries on the left are in the St. Peter and Platteville Formations.

17.7 Outcrop of the St. Peter Formation on the left.

19.8 Outcrops of the St. Peter and Platteville Formations on both sides of the road. Pull over onto the right shoulder of the road. This is STOP 2.

BE EXTREMELY CAUTIOUS OF TRAFFIC, ROCK OVERHANGS, AND STEEP CLIFFS.

STOP 2. Roadcut along Wisconsin State Highway 35, about 5 miles southeast of River Falls, Wisconsin, SE^1/4NE^1/4 sec. 27, T. 27 N., R. 18 W.

These roadcuts show an excellent section of Middle Ordovician rocks including the Tonti and Glenwood Members of the St. Peter Formation and the Pecatonica Member of the Platteville Formation. The Tonti is a white, friable, fine- to medium-grained quartz arenite. It is massively bedded, has a few iron oxide concretions, and locally shows large-scale cross-bedding. The Glenwood consists of thin-bedded shale and silty dolomitic sandstone with scattered phosphate nodules. A major erosional unconformity (not visible here) separates the St. Peter from the underlying rocks of the Lower Ordovician Prairie du Chien Group. It will be important to compare the Tonti sandstone with the Washington Road sandstone in the ring basin fill of the Rock Elm disturbance (stop 10).

The Pecatonica Member of the Platteville Formation consists of thin-bedded fossiliferous dolostone. The Platteville is characteristically prominently jointed, with the joint orientations symmetrically related to the Hastings fault.

After stop 2, continue southbound on Highway 35.

20.0	Valley of the Trimbelle River. Again, notice the butte and mesa landscape. Broad valleys such as this in this region are commonly underlain by glacial lake clays.
21.1	Cross the Trimbelle River.
22.7	Enter Beldenville. Continue straight ahead on Highway 35.
23.9	Turn left onto Pierce County Highway J. Sharp turn!
24.3	Turn right onto Pierce County Highway N.
27.9	Stop sign. Intersection with Highway 63. Turn right (south) onto Highway 63.
30.7	Turn left onto Pierce County DD. Sharp turn!
30.9	Turn left (east) onto Highway 72.
35.4	Cross the Rush River.
35.5	Outcrops on left are the Jordan Formation (Cambrian) overlain by the Oneota Formation (Ordovician).
36.2	Jordan Formation outcrops are on the left. Bluffs on right expose Oneota Formation.
36.7	Jordan Formation overlain by Oneota Formation on left.
36.9	Cross Cave Creek.

37.3 Prominent roadcuts in Oneota Formation. Pull over onto the right shoulder for STOP 3.

STOP 3. Roadcut on the south side of Wisconsin State Highway 72, just east of the confluence of Cave Creek and Rush River, about 2 miles west of Waverly, Wisconsin, SE1/4SE1/4 sec. 15, T. 26 N., R. 16 W.

These roadcuts, less than 2 miles west of the edge of the Rock Elm disturbance, show an excellent section of the Oneota Formation of the Prairie du Chien Group. The lithological and structural features seen here are typical of this formation throughout western Wisconsin.

The rock is dominantly a medium- to thick-bedded, dense to vuggy, sugary to sparry dolostone. Common textural and structural features seen here include stratiform layers of laminated chert nodules, floating quartz sand grains, layers of intraformational conglomerate, and large algal stromatolites.

The Oneota Formation has many solution cavities of various sizes, some of which are filled with collapse breccia and red clays and sands. One cave is associated with a small collapse syncline, closely resembling the "pitch and flat" structures found in the Upper Mississippi valley lead-zinc mining district in southwestern Wisconsin. A number of the smaller cavities are partially filled with a thin chalcedonic rim and drusy quartz or dolomite crystals.

The bedding is essentially horizontal. Numerous vertical joints show a variety of orientations, with diffuse maxima at N. 45° W., N. 15° W. and N. 45° E. Many joints consist of zones of closely spaced fractures. There is little or no displacement along any of the fractures.

We will compare these rocks with dolostones of the Prairie du Chien Group inside the Rock Elm disturbance at stops 8, 9, and 11.

Continue straight (east) on Highway 72.

37.6 Oneota and Shakopee Formations in roadcuts on both sides of the road.

39.0 Cross the trace of the ring boundary fault of the Rock Elm disturbance. Drift obscures the exact location of the fault here.

39.5 Intersection of Highway 72 and Highway 183 in the little town of Waverly. Turn right (south) onto Highway 183.

41.5 Highway HH goes to the left (east) to Nugget Lake Park. Continue straight ahead on Highway 183. We are crossing the trace of the Highway HH fault.

42.0 Cross the trace of the ring boundary fault, again obscured by glacial drift.

42.5 Turn left (east) onto Chimney Rock Road. Chimney Rock, several miles to the west, is a pillar of Oneota Formation dolostone.

43.5 Turn left (north) onto Kennedy Road.

43.7 Pull over to the right side of the road. This is STOP 4.

STOP 4. Kennedy Road, facing north, about 2.5 miles south of Waverly, Wisconsin, NW1/4SW1/4SW1/4 sec. 32, T. 26 N., R. 15 W.

From this vantage point, we get the best view of the overall geographic and geologic features of the Rock Elm disturbance. Refer to Figures 2 and 3.

We are standing at the southern edge of the disturbance on drift-mantled Prairie du Chien Group dolostones such as those seen at stop 3. The break in slope immediately to our north is the trace of the ring boundary fault. It can be followed to the east and west along a topographic high forming the horizon. The northern extension of the ring boundary fault also forms the far horizon due north of us. The ridged lowland to the immediate north between the boundary fault and Highway HH is underlain by tightly folded rocks of the Prairie du Chien Group of the southern fault block (stops 8, 9, and 11). The Rock Elm shale of the ring basin fill is exposed north of Highway HH (stop 9) and along the valleys of Plum Creek to the northwest and Rock Elm Creek to the northeast. The basin fill to the west and northwest is covered by glacial drift. To the east and northeast, the flat-topped hills are capped by the resistant Washington Road sandstone of the ring basin fill. The cuts on the hill to the northeast at N. 60° E. are small quarries in this rock (stop 10). The wooded hill on the near skyline between due north and N. 30° E. is the central dome (stops 5 and 6), underlain primarily by what is interpreted to be Cambrian Mt. Simon Formation.

Continue straight ahead (north) on Kennedy Road after stop 4.

44.1 Outcrops of folded Prairie du Chien Group dolostones in the creek to the left.

44.3 Small knob to the right held up by dipping Prairie du Chien Group dolostone.

44.4 Cross trace of the Highway HH fault, covered by alluvium.

44.5 Intersection with Highway HH. Turn right (east).

44.9 Cross Plum Creek.

45.2 Turn left (north) onto Rock Elm Road. We will now follow the drainage of Rock Elm Creek, a valley developed on the Rock Elm shale. Hills to the right (east) are capped by the Washington Road sandstone. Hills to the left (west) are part of the central dome.

46.1 Rock Elm shale exposed in roadcut at left.

46.2 Rock Elm shale exposed in roadcut at left.

46.3 Stop sign at the intersection with Truman Road. Continue straight ahead on Rock Elm Road. Good outcrop of Rock Elm shale at left.

46.7 Tree-covered slope on the left is the dip slope of the Mt. Simon sandstone of the central dome.

46.9 Roadcut on right in Rock Elm shale.

47.6 Stop sign at intersection with Highway 72. Turn left (west) onto Highway 72.

47.7 Road to the right leads up to the Rock Elm landfill, which is in the Washington Road sandstone.

48.0 Turn left onto Madison Road (gravel).

48.1 Pit to the left is in the Washington Road sandstone.

48.3 Roadcuts and areas of poor drainage are underlain by the Rock Elm shale. Central dome is straight ahead.

48.5 Sharp bend to the right. Bear right, and park on the right side of the road.

Stops 5 and 6 illustrate the geology of the heavily wooded central dome (Fig. 9). The traverse to stops 5 and 6 will entail about 2 miles of hiking, round trip, with a relief of 140 feet.

The poorly drained area at the start of the trail is on clayey soil on the Rock Elm shale. We ascend the northern flank of the central dome, following a dip slope on the Mt. Simon Formation. Uphill, small outcrops and float are of the Mt. Simon Formation. Small glacial erratics of rocks, including granites, gneisses, iron-formation, quartzite, basalt and gabbro, may be found. Once on top, we will walk southeast along the strike of the Mt. Simon Formation to STOP 5.

STOP 5. Stream cut, NE$^1/4$NW$^1/4$NE$^1/4$ sec. 29, T. 26 N., R. 15 W.

This is a typical outcrop of the central dome bedrock, presumed to be Mt. Simon sandstone, as described earlier. The bedding here strikes about N. 60° E. and dips 25° to the southeast. The strike and dips of other bedrock outcrops elsewhere in the area describe, with few exceptions, a simple dome. The exceptions are interpreted either as slump blocks, minor folds, or blocks displaced along faults. The paucity of outcrop in the central dome makes a more definitive interpretation impossible. The sandstone here consists primarily of friable, moderately sorted, medium- to coarse-grained, subangular to rounded sands with as much as 15 percent K-feldspar clasts. Interbedded conglomerate layers, typically only one pebble thick, contain rounded clasts of quartz, quartzite, chert and iron-formation. No fossils have been found at this outcrop; however, poorly preserved brachiopod molds and casts have been found in nearby outcrops.

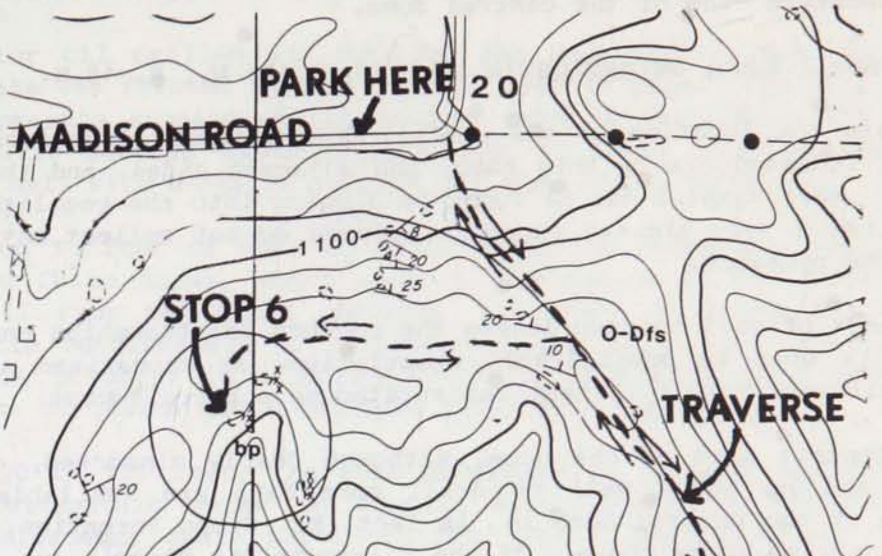

Figure 9. Detailed topographic map of part of the central dome showing the locations of outcrops and the recommended route of traverse to stops 5 and 6. The geology is modified from John Ladd (1985). ODfs is Ladd's symbol for the upper part of the Washington Road sandstone and Cms indicates Mt. Simon Formation. The symbol "bp" denotes "breccia pipe" and outlines the extent of the central dome breccia. The contour interval is 20 feet. Black circles in the northeastern part of the map are a powerline trace.

Retrace the route and follow paths as indicated on Figure 9 to the next outcrop. We are following the strike of the Mt. Simon Formation around to the northwestern side of the central dome.

STOP 6. Small knob, SW1/4NE1/4SW1/4 sec. 20, T. 26 N., R. 15 W.

This is the location of the central dome breccia. The rock occurs as scattered float blocks on this knob, the adjacent ridge, and the valley to the east. More samples can be found by digging into the regolith. Because the rock has a very limited exposure, please do not collect any unless you need it for research.

The lack of good outcrop leaves the contact relationships and origin of the breccia open to considerable speculation, as summarized above. The author believes that it is best interpreted as a breccia pipe.

The central part of the dome, although deeply dissected, contains no outcrop, and no water well or drill core data are available. If the sandstone of the central dome is, in fact, Mt. Simon Formation, one should find Precambrian rocks there. If the clasts in the breccia are any indication, a diverse Precambrian section with volcanics, arkosic sandstones, lithic wackes and granites would occur at depth.

Return to bus by retracing our path.

Continue straight ahead on Madison Road.

48.8 Sandstone outcrop on the right is likely Washington Road sandstone, dropped down along a post-basin-fill fault.

49.0 Plum Creek is to the right.

49.5 Bridge across Plum Creek.

49.6 Park on the right side of the road. This is STOP 7.

STOP 7. South side of Madison Road at NE1/4NE1/4NE1/4 sec. 30, T. 26 N., R. 15 W.

There is a small but fascinating outcrop in the ditch along Madison Road. In January 1985, the Superior Oil Company cored a 300-foot hole (Fig. 4) here. Segments of this core will be available for examination at this stop.

Small roadcuts to the west are typical Rock Elm shale with interbedded silty sandstone dominating the float. Greenish-brown, weathered shale can be found by digging through the colluvium.

The small ditch on the south side of the road where the road dips down toward the bridge over Plum Creek exposes several interbedded rock types including a quartz pebble conglomerate, a coarse quartzose sandstone, a yellow-brown siltstone, and a green claystone. The quartz pebbles in the conglomerate are fractured, and many disaggregate easily upon handling. The Rock Elm shale apparently overlies these materials.

Superior Oil drilled its hole on the possibility that the fractured conglomerate was related to some form of breccia pipe. The core shows that the conglomerate exposed at the surface here is stratiform and overlies a thick clastic section which extends down at least 280 feet and does not correlate well with sections outside the Rock Elm disturbance.

The top 10 feet of core is till containing dolostone clasts from the Prairie du Chien Group, which also is the source of the dolostone float just uphill from the ditch outcrop. It rests on a 10-foot section of heterolithic conglomerate of fractured clasts of quartz, green claystone, and felsite porphyry in a dolomitic-sericitic matrix with abundant sand-size clasts of quartz and K-feldspar (unit A on Fig. 4).

From 20 to 105 feet, the core penetrates a friable, medium- to fine-grained feldspathic wacke to arenite with spectacular graded beds and greenish micaceous shale partings (Fig. 10). The sandstone is commonly medium grained and contains clastic K-feldspar grains (Fig. 11). Authigenic K-feldspar as overgrowths and cement is also common. Clastic muscovite is common in both the sandstone and the shale layers. Scattered quartz-pebble conglomerate layers exist. This interval is unit B on Figure 4.

From 105 to 165 feet (unit C on Fig. 4), the rocks contain more and thicker shale beds and little conglomerate. The sandstones are similar to those in unit B but tend to be finer grained, containing more feldspathic wackes. Slump structures such as recumbent folds are common in the thicker shale intervals (Fig. 12). Load structures also are common at sandstone-shale contacts.

From 165 to 260 feet (unit D on Fig. 4), the rock consists of glauconitic sandstone and scattered layers of phosphatic shell hash. Some layers consist of as much as 50 percent glauconite. The sandstones are feldspathic wackes, again with authigenic K-feldspar cement, as well as some dolomite cement. The clasts are distinctly bimodal with medium-grained glauconite and quartz appearing in a matrix of fine sand and silt dominated by quartz and K-feldspar clasts (Fig. 13). Recumbent folds and load structures are again extremely common.

From 260 feet to the bottom of the core at 300 feet, the rock is a friable, medium-grained quartz arenite with some horizontal laminations and phosphatic shell hash (unit E on Fig. 4).

It is interesting to speculate that unit E may correlate with the Wonewoc Formation, unit D with the Birkmose Member of the Lone Rock Formation, and units B and C with the Tomah Member of the Lone Rock Formation. If this correlation is valid, it still raises many questions, because the units in the core would be anomalously thick, they contain highly uncommon sedimentary structures in the form of graded beds and slump folds, and the Prairie du Chien Group and Jordan Formation are absent. A possible explanation is that the Rock Elm region was an anomalously low area during Cambrian time. A deeper water facies accumulated in this low, accompanied by slumping and possibly contemporaneous local subsidence. Later deformation uplifted the section, causing the erosion of the Prairie du Chien Group and Upper Cambrian strata prior to the deposition of the Rock Elm shale. The origin of the conglomerate unit A is a major enigma. The clasts are similar to those in the breccia pipe. The conglomerate could represent an unroofing of central dome rocks, or, alternatively, could be part of an extrusive breccia at the margin of an unexposed breccia pipe to the north or east.

Another possibility is that the rocks in the core represent an earlier stage of basin fill, and hence, do not correlate with any formation found outside of the Rock Elm region. If so, the sedimentary rocks in the core would likely be Ordovician rather than Cambrian in age.

It is clear that this section represents an important, but still poorly understood, clue to the origin of the Rock Elm disturbance.

After stop 7, continue straight ahead on Madison Road.

49.7 Roadcut in Rock Elm shale on the left.

49.8 Roadcuts in Rock Elm shale on both sides of the road. Washington Road sandstone caps the hills.

49.9 Rock Elm shale exposed on the left.

50.5 Stop sign at Highway 183 intersection. Turn left (south) onto Highway 183.

51.5 Turn left (east) onto Highway HH.

51.6 Prairie du Chien Group dolostone in field at right. It strikes N. 20° W. and dips NE. 20°.

51.7 Pull off on right side of road for STOP 8.

STOP 8. Ditch on south side of Highway HH just east of the intersection with Highway 183, NW1/4NW1/4 sec. 31, T. 26 N., R. 15 W.

This outcrop lies along the trace of the Highway HH fault which forms a small escarpment just north of the road. The outcrops are a monolithic breccia consisting of fragments of Prairie du Chien Group dolostone in a dolomitic matrix. The quartz grains in the matrix are from the disaggregation of dolostone containing floating sand grains. This is interpreted as a fault breccia on the basis of its location along the trace of a fault and its dissimilarities to collapse breccias and intraformational conglomerates seen elsewhere in Prairie du Chien Group rocks.

The fields north of the fault are underlain by Rock Elm shale; the hills are capped by Washington Road sandstone and glacial drift. Just north of the road is a single float block of iron oxide-stained conglomerate that contains pebbles and cobbles of quartz, schist, gneiss, and

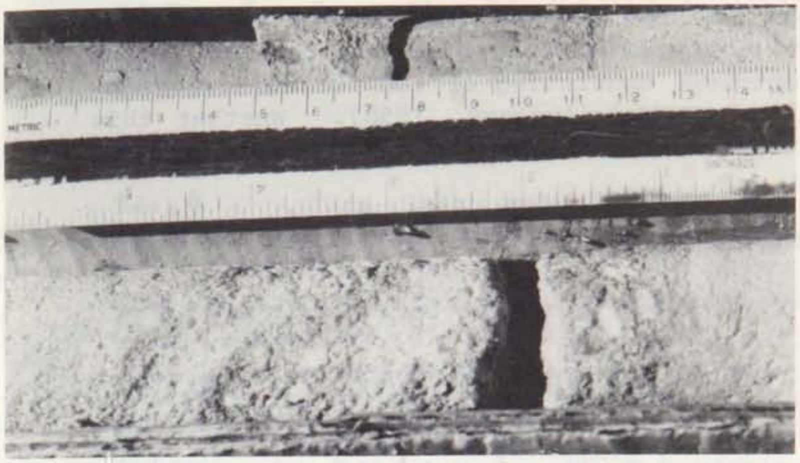

Figure 10. A sample from the Madison Road core showing graded bedding in unit B. Top is to the left.

Figure 11. Photomicrograph of a sample from unit B of the Madison Road core. Notice the K-feldspar clasts with authigenic overgrowths. Crossed nicols.

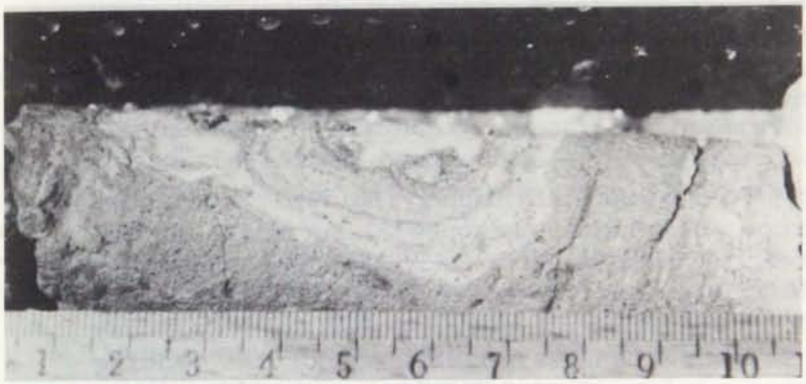

Figure 12. Sample from unit C of the Madison Road core showing the nose of a recumbent slump fold in sandstone and shale. Top is to the left. The scale is in centimeters.

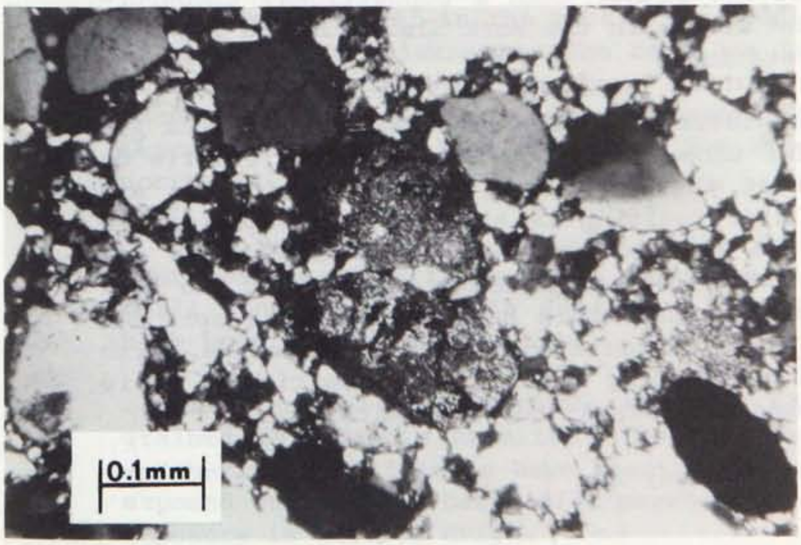

Figure 13. Photomicrograph of a sample from unit D of the Madison Road core. Notice the bimodal distribution of medium-grained quartz and glauconite in a finer grained matrix. Clastic K-feldspar occurs in the silty to fine sandy matrix. Crossed nicols.

granite. This float block does not resemble any clastics of the central dome or basin fill; it may be from the Cretaceous Windrow Formation, which in this region forms isolated outcrops consisting of the ferruginous regolith and continental floodplain deposits (Andrews, 1958). Whether this block was involved in the faulting or was transported to this spot by some other means is an open question.

Continue east on Highway HH.

52.1 Dipping Prairie du Chien Group dolostone on right (stop 9B).

52.2 Pull over to right side of the road. Roadcuts are in Rock Elm shale on both sides of the road.

STOP 9. Outcrops and roadcut within 0.2 mile of each other along Highway HH. Stop 9A is in the SW1/4SE1/4SE1/4 sec. 30 and stop 9B is in the NE1/4NW1/4 NE1/4 sec. 31. Both are in T. 26 N., R. 15 W.

Stop 9A is a roadcut in the Rock Elm shale, here a fissile light-gray paper shale with relatively few sandstone interbeds. It contains small iron oxide concretions with locally preserved pyritic cores. No macro- or microfossils have yet been found in the shale at this outcrop. The shale appears to be flat lying here.

Walking west along Highway HH we cross the Highway HH fault. At stop 9B we are on a cluster of outcrops of deformed Shakopee(?) Formation in the southern fault block. The rock is dominantly a medium-bedded sugary to sparry dolostone with some chert nodules. Monolithic dolostone breccia occurs as both stratiform and crosscutting layers. Solution vugs, many with drusy quartz lining, are common. Changes in attitude of the bedding from outcrop to outcrop reflect a series of tight folds, or alternatively blocks of various orientations separated by small faults. In the dolostones of the southern fault block, a number of tight folds have been mapped; they trend north-northwest and plunge gently south-southeast.

The abrupt transition from basin-fill Rock Elm shale to deformed dolostones suggests a fault contact rather than a depositional unconformity. The lack of any dolostone clasts in the Rock Elm shale and its fine grain size support this interpretation.

In the northern part of the disturbance (supplemental stop B) Rock Elm shale does seem to be in angular unconformity on top of folded Prairie du Chien Group dolostone. The fact that the shale post-dates folding and faulting but was involved in later faulting is also seen in Superior Oil core MGD 13 (Fig. 4), where the Prairie du Chien Group dolostones are downdropped relative to their expected stratigraphic position, and the Rock Elm shale is uplifted. This proves that there have been several episodes of vertical motion along the faults associated with the structure, with deformation both preceding and post-dating basin fill deposition. It is also significant to note the reversal in fault movement with time.

Continue eastbound on Highway HH.

52.8 Cross Plum Creek.

53.5 Cross Rock Elm Creek. Go straight ahead on Washington Road.

53.7 Rock Elm shale in roadcut on right.

54.2 Turn left and park by the entrance to Wallace Harvey's Junkyard. We will traverse north uphill for STOP 10.

STOP 10. Outcrops and small quarry north of Wallace Harvey Junkyard in the SW1/4SE1/4 sec. 28, T. 26 N., R. 15 W.

This is the most complete and best exposed section of the ring basin fill. Please obtain Mr. Harvey's permission before going up to the outcrop.

The base of the exposure consists of approximately 65 feet of Rock Elm shale. This rock is a light-grayish-green silty shale with thin interbeds of fine-grained silty sandstone. The shale is fissile, noncalcareous, and locally micaceous, and it contains small iron oxide concretions pseudomorphous after marcasite or pyrite. The sandstone interbeds contain significant silt-size K-feldspar and muscovite clasts, and they have a K-feldspar authigenic cement. Horizontal crawling burrows occur at sandstone-shale boundaries. The sandstone interbeds become more common toward the contact with the overlying Washington Road sandstone.

The sandpits higher on the slope show all of the major lithologies of the Washington Road sandstone. The contact with the underlying shale is not exposed, but the two seem gradational and conformable. The contact is taken at the point where the shale layers become mere partings along the sandstone bedding planes.

The lowermost subunit of the Washington Road sandstone is a resistant, medium-bedded, fine-grained feldspathic wacke. In thin section, fine quartz sand 0.1 to 0.2 mm in diameter floats in a clayey or silty matrix and shows small-scale normal graded bedding. K-feldspar overgrowths are common on the silt-size K-feldspar grains. Authigenic K-feldspar is also the cementing agent in the rock. The bedding is even and ranges from about 1 to 10 cm in thickness. The beds are internally laminated. Horizontal burrows more than 20 cm long occur along bedding planes. Several incomplete phosphatic shell fragments have been found, as has one impression of a small gastropod. The bedding dips about 5° to the north-northwest.

The next overlying subunit in the Washington Road sandstone is a 16-foot section of white, massive sandstone with iron oxide-stained layers and small concretions. This sandstone is a feldspathic arenite. No fossils have been found in this unit.

The upper exposed subunit consists of an iron oxide-stained, medium-grained feldspathic arenite. The unit is medium bedded and resistant to weathering. No fossils have been found in this unit. This is the highest exposed unit of the basin fill anywhere in the structure. Uphill from this exposure is glacial drift.

Crane (1986) did a detailed grain-size analysis of the Washington Road sandstone and documents a coarsening-upward sequence. The mean grain size at this exposure, for example, ranges from a ϕ of 3.48 at the base to a ϕ of 1.66 at the top. A coarsening-upward pattern also occurs in the underlying Rock Elm shale.

The picture that emerges from the basin fill is that of a calm, deep basin that was slowly filling with clastic debris. The absence of dolostone clasts indicate that rocks of the Prairie du Chien Group either were not exposed, were exposed at such low relief that they did not contribute clasts, or were subjected to such extreme chemical weathering that no clasts survived to be deposited in the basin.

The age of the Rock Elm shale is established as early as Middle Ordovician on the basis of paleontologic evidence (Nelson, 1942). The Washington Road sandstone is probably similar in age because of its conformable and gradational nature. One may speculate on possible correlation with the St. Peter Formation. It is also possible that the basin fill section was deposited during the hiatus represented elsewhere as an erosional unconformity between the St. Peter Formation and the Prairie du Chien Group.

Turn around and proceed back west on Washington Road.

55.2 Turn left (south) on Rock Elm Road toward Nugget Lake county park.

55.6 Turn right into Nugget Lake Park. A nominal entrance fee is charged. No digging or collecting is allowed in the park.

55.9 Drive past park office. After descending hill into the Plum Creek valley, pull over to the right side of the road. We will traverse to STOP 11.
Follow the "Adventure Trail" and signs to Blue Rock. Do not climb up to the overlook. The best vantage point is obtained by crossing Plum Creek and walking upstream to the prominent cliff at the meander bend. Your feet may get wet.

STOP 11. Blue Rock, on meander bend of Plum Creek at SE1/4SE1/4NW1/4 sec. 32, T. 26 N., R. 15 W.

Plum Creek has cut through an elegant syncline in the Prairie du Chien Group dolostone in the southern fault block. The north limb strikes N. 82° E. and dips 30° SE.; the south limb strikes N. 85° W. and dips 25° N. Joints here are not vertical but instead fan the fold. The gentle eastward plunge of the fold is visible. Visible rock types include massively bedded dolostone, dolostone with isolated vertical burrows, a thin-bedded sandstone resting on a conspicuously ripple-marked dolostone, and dolostones with some intraformational conglomerate. The sandstone beds may be the New Richmond Member; if so, both the Oneota and Shakopee Formations are present.

Retrace the path to the bus and continue straight ahead on the park road.

56.1 Cross Plum Creek.

56.2 Recross Plum Creek.

56.3 Enter the parking lot for the picnic area at Nugget Lake Park. This is STOP 12.

STOP 12. Nugget Lake Park picnic area at the NE$^{1}/_{4}$SW$^{1}/_{4}$SE$^{1}/_{4}$ sec. 32, T. 26 N., R. 15 W.

The trace of the ring boundary fault coincides with a small valley just north of the water well and restroom area. Outcrops surrounding the picnic area are flat-lying Oneota dolostone in its normal stratigraphic position. The well at the park is of interest. It was drilled in July 1973, when the park was being developed. The well log notes clay and "limerock" to 14 feet, "limerock" to 46 feet, and "sandrock" to 92 feet. The "limerock" is Oneota Formation; the "sandrock" is the underlying Jordan sandstone, an important local aquifer. At 92 feet, however, the driller reported "granite" and quit drilling the well. According to Thwaites (1957), Precambrian basement should be at an elevation of 350 feet in this area, about 650 feet below us. What is this "granite," then? A driller's error? Uplifted Precambrian basement? A pluton intruded along the ring boundary fault? Apparently no cuttings from this well were kept.

Return on the park road, past the office, to the intersection with Rock Elm Road.

57.1 Turn left (north) onto Rock Elm Road.

57.5 Turn left (west) onto Highway HH.

59.2 Stop sign. Turn right (north) onto Highway 183.

61.2 Stop sign at the intersection of Highways 183 and 72 in Waverly. Go straight ahead on Highway 183. Careful! Dangerous intersection.

62.8 Cross the trace of the ring boundary fault on the northern edge of the Rock Elm disturbance.

68.5 Stop sign. Intersection of Routes 183 and 29. Turn left (west) onto Route 29. The town of Spring Valley is about a mile to the right. Crystal Cave, which features commercial tours, is a few hundred feet to the right.

70.0 Sandpit in cross-bedded outwash on right.

74.4 Stop sign at intersection of Routes 29 and 63. Turn right (north) onto Route 63 and 29 west.

75.4 Route 29 west bears to the left. Continue straight ahead on Highway 63 north.

75.8	Large glacial erratics in field at right.
76.4	Cross St. Croix County line.
78.5	Gravel pit showing pre-Illinoian till of the Hersey Member of the Pierce Formation overlying related outwash sands and gravels.
81.6	Cross I-94. At north end of bridge, turn left onto I-94 westbound. This is the end of the detailed roadlog. It is a distance of 19 miles via I-94 to Hudson, Wisconsin, and 35 miles via I-94 to St. Paul, Minnesota.

SUPPLEMENTAL STOPS. These additional outcrops may be of interest to those undertaking a more detailed study of the Rock Elm disturbance.

Stop A. Clay pit on the south side of Truman Road, NE1/4NE1/4NW1/4 sec. 28, T. 26 N., R. 15 W. The best exposed section of Rock Elm shale in the area, demonstrating especially well the silty sandstone-shale interbeds.

Stop B. Small outcrops in Plum Creek, NW1/4SE1/4SE1/4 sec. 7, T. 26 N., R. 15 W. A small syncline in Prairie du Chien Group dolostone. Outcrops on adjacent stream banks suggest that the folded dolostones are overlain in angular unconformity by the Rock Elm shale.

Stop C. Sandpit just north of Highway 72 at the southeast edge of Rock Elm, NW1/4SW1/4 sec. 16, T. 26 N., R. 15 W. A good section of Washington Road sandstone is exposed.

Stop D. Sandpit just south of Highway 72 at Drum Hill Road, NE1/4NW1/4NE1/4 sec. 20, T. 26 N., R. 15 W. A good section of Washington Road sandstone is exposed.

Stop E. Stream cut on Plum Creek, NE1/4NE1/4SE1/4 sec. 19, T. 26 N., R. 15 W. An exceptionally thick section of sandstone here is inferred to be part of the Washington Road sandstone that has been dropped down along a small graben marginal to the central dome after deposition of basin fill.

Stop F. Quarry, SW1/4SE1/4 sec. 15, T. 26 N., R. 15 W. The quarry exposes a good section of Oneota dolostone, just outside and to the east of the Rock Elm disturbance. This exposure of normal rocks is one of the closest to the inferred location of the ring boundary fault.

Stop G. Roadcuts along County Highway S, NW1/4SE1/4 sec. 10, T. 26 N., R. 15 W. These cuts show an excellent and typical section of the Jordan Formation and overlying Oneota dolostone. This location is outside and southeast of the Rock Elm disturbance. These rocks show normal elevations, structures, and lithologies for this region.

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QUATERNARY GEOLOGY OF SOUTHEASTERN MINNESOTA

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INTRODUCTION

This trip primarily explores the Pleistocene geology of Winona and Olmsted Counties, where fieldwork has been carried out in recent years as part of the county geologic atlas program of the Minnesota Geological Survey. Little had been done in the last two generations on the Pleistocene geology of southeastern Minnesota outside the deposits of the last glaciation. The most recent synthesis of the whole area was by Leverett (1932). Since that time, concepts of the regional geology have changed, based largely on work done in Iowa. For example, the "Iowan Drift" is now recognized as an erosion surface, paleosols are better understood, and the surficial loess is known to be primarily a late-Wisconsinan deposit. The old distinction between "Kansan" and "Nebraskan" is now known to be arbitrary and inconsistent, and the emphasis now is to correlate tills as lithostratigraphic units rather than as time-stratigraphic units. New dating methods, such as uranium disequilibrium, offer the prospect of dating pre-Wisconsinan events.

However, the work done so far in this area has only begun to unravel the complexities of Quaternary history. I will welcome the input of field trip participants as we go along. A new synthesis of the area will require years of county-level mapping and sampling; however, some preliminary observations can be made now.

To begin with, most of the surficial deposits in southeastern Minnesota, other than till, are late Wisconsinan. This includes loess, colluvium, and terrace deposits, as well as outwash derived from the north and west. Even where older till and glaciofluvial sediment is at or near the surface, the effects of late-Wisconsinan erosion can be widely recognized.

These effects confounded the early geologists; the existence and age of the "Iowan Drift" was debated for years. It appeared that the Iowan till was younger than the Kansan, because of its thin oxidation and leaching zones, and younger than the bulk of the loess, because little loess occurs on "Iowan" deposits. Finally, Ruhe (1968) resolved the question by proving that the Iowan drift was actually older drift, from which much of the oxidized and leached material had been removed by erosion. Since then, "Iowan erosion surface" has been used in place of "Iowan drift."

Second, there does appear to be an unglaciated zone in southeastern Minnesota, although "Driftless area" never was really appropriate, because loess is a form of drift. The unglaciated zone is small--it encompasses only eastern Winona and Houston Counties. Leverett had mapped it pretty accurately with a dashed line back in 1932. I found a few erratics and patches of till east of his line, shrinking the area somewhat, but still an area remains in which no evidence of glaciation has been found. In the unglaciated zone (Fig. 1), the sediment under the loess on a karsted bedrock surface is highly oxidized cherty clay and sand, commonly called "residuum." Most of this sediment represents the insoluble fraction from the bedrock sandstone and dolomite. However, the term should not imply <u>in-place</u> residuum. Much of the sediment has been eroded and redeposited. It tends to fill local bedrock lows, and is thin on bedrock highs.

There is a much larger area west of the unglaciated zone in which glacial deposits are patchy and so thin that they cannot be recognized geomorphically; the landforms in this zone are eroded bedrock forms--primarily plateaus, escarpments and deep, steepsided bedrock valleys. This

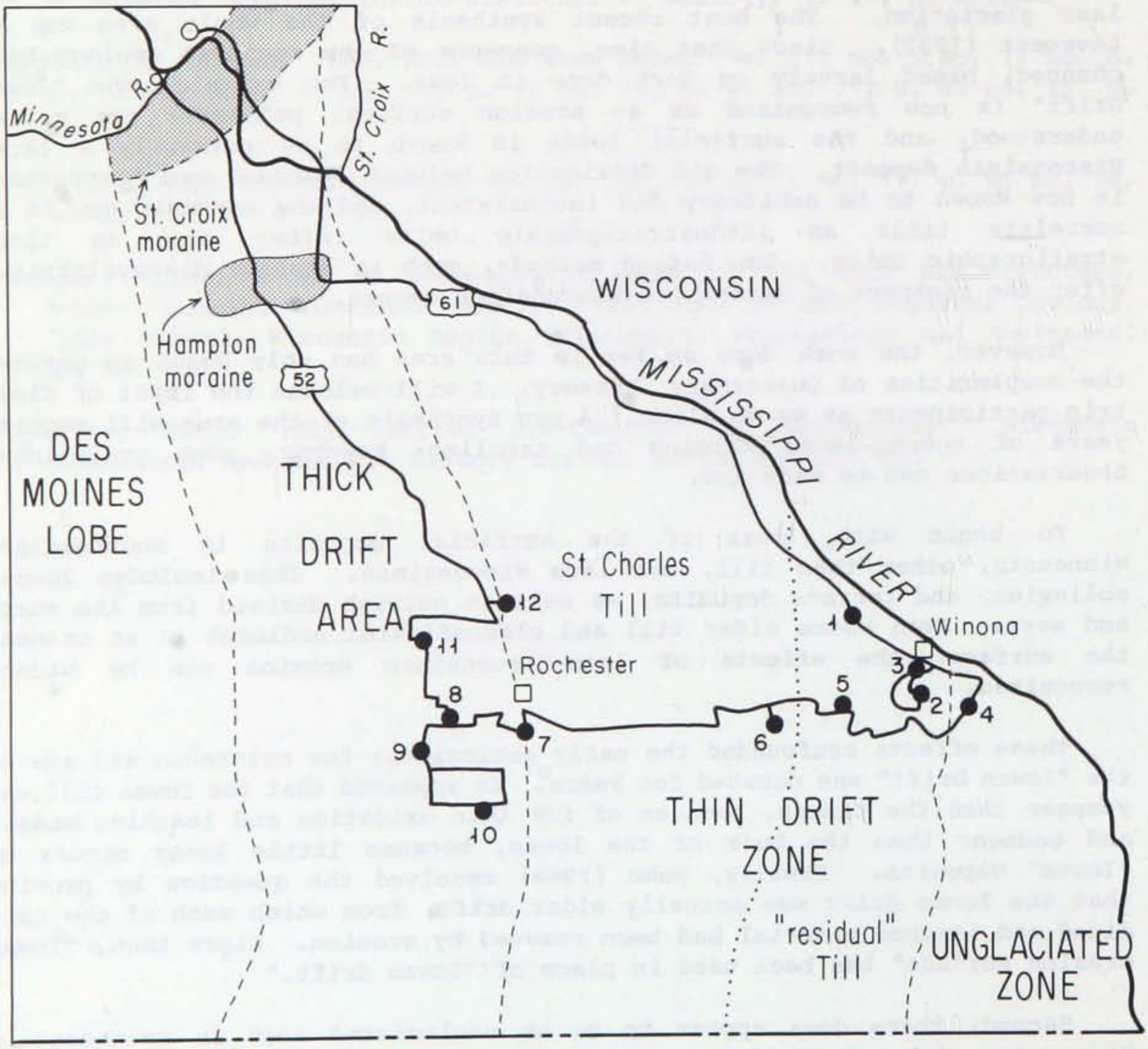

Figure 1. Field trip route, stops, and generalized Quaternary geology of southeastern Minnesota.

zone, or a part of it, was included in the "Driftless area" of some previous workers. In the eastern part of this thin-drift zone, the till is highly oxidized, completely leached, and very patchy in occurrence. In the western part, though still patchy, in some places it is unoxidized and unleached. Nowhere in the thin-drift zone have two tills been observed in the same section. I interpret the till in the eastern part of the thin-drift zone to be a remnant from a very old glaciation, which was the most extensive ever in this region. Stop 5 is in this area. Stop 2 is near the boundary between the thin-drift zone and the unglaciated zone, because erratics have never been found in place at the Winona County landfill, but till has been observed only a mile away.

Stop 6 is near the middle of the thin-drift zone, and stop 7 is near the boundary between the thin drift and thick drift zones. Both of these stops expose unoxidized and unleached till, though not necessarily the same till.

In the thick-drift zone, there is some evidence for multiple glaciation, including several exposures of unoxidized till over older oxidized till. There are also numerous buried bedrock valleys in a pattern that contrasts with the modern drainage network. Some old valleys are partly exhumed, or were never completely filled; others are completely invisible in the modern landscape. Stop 11 exhibits a remnant of an old till in a modern valley.

I am guessing that the thick-drift zone contains the deposits of one or more glaciations that did not extend into the thin-drift zone. But the timing and even the sequence of these events is not known. It seems reasonable that the relatively fresh till of the western part of the thin-drift zone (the St. Charles till) is the youngest pre-Illinoian drift in the area, and forms the youngest till in the thick-drift zone. But even the youngest till is near or beyond the limit for uranium disequilibrium dating (about 350,000 years).

The interval between the most recent pre-Illinoian glaciation and the Wisconsinan glaciations was presumably marked by alternate periods of erosion and soil formation, which are recorded in paleosols, and by episodes of downcutting and backfilling of valleys, which are recorded in high remnant terraces and the stratigraphy of the valley sediments. Someday it may be possible to put the two lines of investigation together in a chronology constrained by radiometric dates, but at present, investigations are just beginning.

I thank the landowners who have given us permission to visit their excavations. Let me remind you that I obtained permission for this particular group at this particular time. If you wish to revisit any of the sites (except those on highway right-of-way), it is up to you to obtain permission for your group.

The stops are listed below; private landowner names are in parentheses; and the major feature of each is noted.

1. Gravel pit (Modern Concrete Products), late-Wisconsinan outwash in the Mississippi valley.

2. Winona County landfill (Winona County), karsted bedrock surface and weathering residuum.

3. Garvin Heights city park, view of Mississippi valley.

4. Roadcut, late-Wisconsinan valleyside colluvium.

5. Roadcut, filled sinkhole.

6. Roadcut, St. Charles till over St. Peter Sandstone.

7. Gravel pit (Elcor Construction Co.), pre-Illinoian woody till and outwash.

8. Gravel pit (Jim Paulson), late-Wisconsinan stream terrace sediment.

9. Gravel pit (Duane Molde), pre-Illinoian stratified drift, highly weathered.

10. Quarry (Quarve-Anderson Co.), paleosol developed in pre-Illinoian till over limestone.

11. Quarry (Quarve-Anderson Co.), pre-Illinoian woody till, late-Wisconsinan colluvium and loess.

12. Olmsted County landfill, two pre-Illinoian tills.

ROADLOG AND STOP DESCRIPTIONS

Day 1 of the field trip starts at the St. Paul Hotel at Wabasha and St. Peter in downtown St. Paul; day 2 starts at the Roadstar Motel in Rochester.

Miles	
0.0	Take St. Peter southeast, toward the Mississippi.
0.1	Turn left on Kellogg Boulevard.
0.7	Pass under Lafayette Bridge; Kellogg becomes Third Street. Cross over rail yards on Third Street Bridge.
1.5	Turn right on freeway ramp to combined U.S. 10 and 61 and I-94E. Stay in right two lanes on freeway.
2.7	Exit onto U.S. 61 south, which quickly descends into the Mississippi River valley; we will travel along the east side of the valley for several miles.

9.8 St. Paul Park city limits. The bedrock wall of the valley swings east here, and we follow it along a channel cut into a high terrace. Over the next few miles we rise in steps up to the terrace (12.5) and onto the outwash plain (16.5) graded to the St. Croix moraine. The outwash plain is collapsed in places, and dissected by small streams that drain into the Mississippi.

18.3 We descend onto the terrace and into the valley again (19.7) and cross the Mississippi at Hastings (20.8). South of Hastings we pass over an outwash plain. The lower part south of town is outwash derived from the Des Moines lobe to the west; it is cut into the older outwash plain graded to the St. Croix moraine to the north and northwest.

26.3 Just south of the Bellwood Cemetery, we rise up a gentle scarp to the St. Croix outwash plain again.

We rise almost imperceptibly from the outwash plain to a loess-covered, pre-Wisconsinan highland. We pass between two mesas of St. Peter Sandstone capped by Platteville limestone (30.6) and turn east (31.2). The surface drift is "Old Red" drift of the Hampton "moraine," which has traditionally been considered Illinoian, underlain in places by pre-Illinoian "Old Gray" drift.

39.4 U.S. 61 turns southeast and follows a small tributary into the Cannon River valley. After crossing the floodplain, we rise onto a terrace composed of outwash derived from the Des Moines lobe to the west (42.9). We go generally east a few miles and descend a Mississippi River terrace (44.9) and so into Red Wing. Follow U.S. 61 through Red Wing.

48.9 Just past downtown Red Wing, we can see Barn Bluff ahead and to our left as we pass by it. Barn Bluff is a remnant of bedrock isolated from the main bedrock uplands by an abandoned channel of the Mississippi.

51.0 Just past the reform school we pass into an old Mississippi channel separated from the main valley by a bedrock highland. After skirting the main valley (54.4 to 55.6), we pass into another channel, emerging into the main valley at the town of Frontenac (59.3). These channels must have been used during the late Wisconsinan, because their sediment fill roughly corresponds with the late-Wisconsinan terrace levels, but they may have formed much earlier. Higher channel remnants occur in this area, which have floors more than 100 feet higher than U.S. 61. All of the channels may have originally formed at the high level, and some were subsequently downcut, but others were left behind at the level of their original formation. They may have been overflow channels formed when the valley was blocked by glacial ice; such a scenario requires that the ice advanced from the north and is consistent with an "Old Red" advance, but not with an "Old Gray," which advanced from the west or northwest. Alternatively, the channels could have started out when the main valley had filled with sediment up to the level of low divides between tributaries, and some of the flow was diverted to the side. However, no trace of such high valley fill can be seen in the valley today.

61.3 We are now traveling along the shore of Lake Pepin. This is a natural lake, unlike the other impoundments along the river which were created by the Corps of Engineers for navigation. Lake Pepin formed behind a sediment dam at the mouth of the Chippewa River, a major tributary on the opposite side of the river that joins the Mississippi near Wabasha, Minnesota. Sediment-dammed lakes have formed in the Minnesota and St. Croix River valleys, also. The whole system was overdeepened by glacial lake drainage during the waning stages of the last glaciation, and has gradually been filling in again. Thus, the system is vulnerable to damming where streams of unequal load come together.

68.4 Just past Lake City, the terrace that we have been traveling on disappears, as the channel switches to the Minnesota side of the valley. The terrace is now on the Wisconsin side. Our terrace reappears at Wabasha (77.7).

84.3 Just before Kellogg, we cross the Zumbro River and rise onto the high terrace south of the Zumbro. The Zumbro River is the southernmost Mississippi tributary in Minnesota to have carried outwash from the late-Wisconsinan Des Moines lobe. Farther south, the tributaries head in pre-Illinoian drift and in the small unglaciated area.

87.4 U.S. 61 follows the base of the bluff from a few miles south of Kellogg until it crosses the Mississippi near La Crosse. In places, the road is separated from the river by a wide terrace, but for most of the way the river is very close to the road.

99.9 Pass Lock and Dam No. 5.

105.5 Turn right onto gravel road and park at large gravel pit visible from U.S. 61.

STOP 1. Gravel pit near Minnesota City, Rollingstone quadrangle, SW1/4 SW1/4SW1/4 sec. 2, T. 107 N., R. 8 W. (Fig. 2).

This pit is developed in the late-Wisconsinan terrace of the Mississippi River. The top of this terrace here is about 30 feet below the top of the adjacent terrace of Rollingstone Creek, also of late-Wisconsinan age, and so presumably the Mississippi terrace here represents an early phase of downcutting by the river, rather than the highest terrace level.

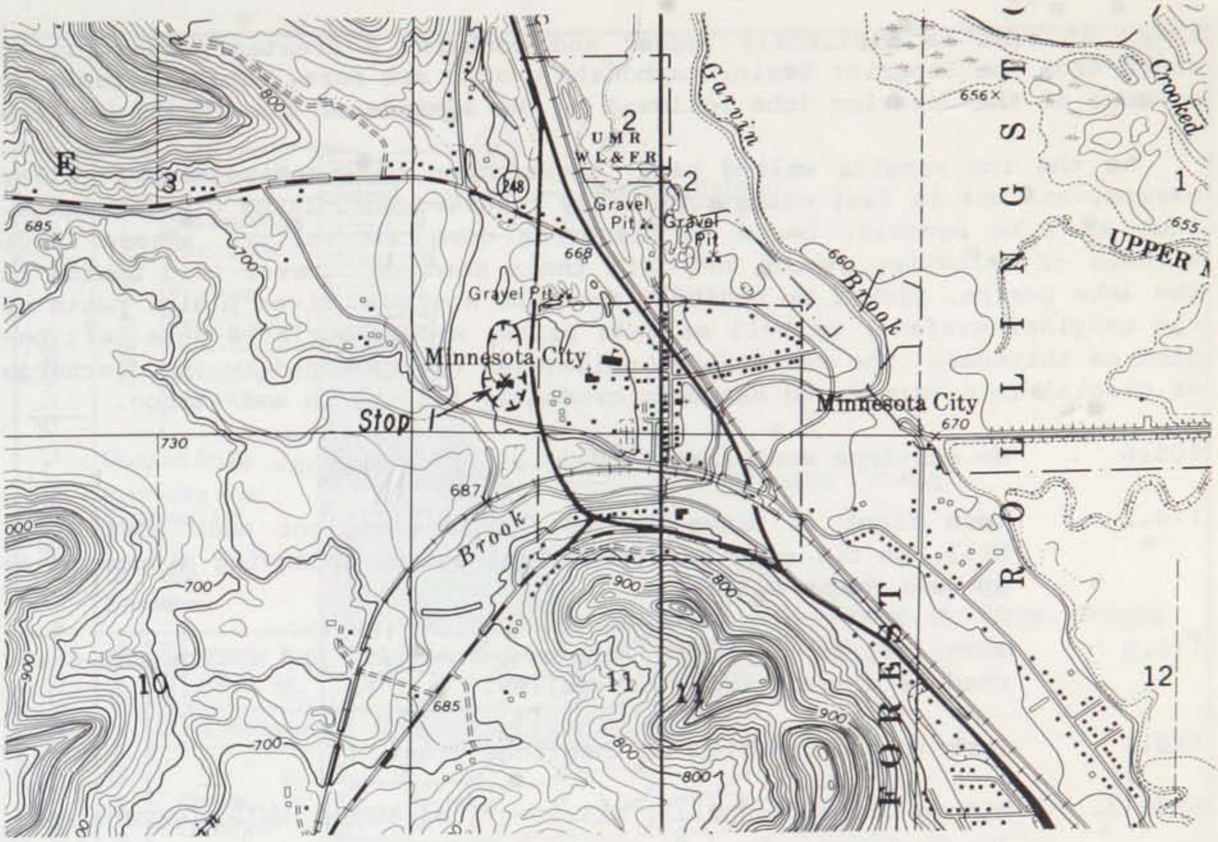

Figure 2. Stop 1--Terraces of Rollingstone creek and of the Mississippi River.

The section exposed comprises about 9 feet of very fine silty sand, overlying about 22 feet of clean, well-sorted, cross-bedded sand and some gravel. The clean sand and gravel represents the late-glacial valley fill of the Mississippi valley; the overlying silty sand was probably deposited by the postglacial river after it had cut down into the valley fill. The silty sand is brown (10YR 6/3 to 5/4), vaguely color-banded, and non-calcareous. The gravel in the clean sand and gravel unit includes many pebbles of basalt, felsite, and red sandstone derived from the Superior basin by means of the Superior lobe. Some gravel-size clasts of calcareous silt derived from loess also occur. Carbonate pebbles are probably derived from the Des Moines lobe. Cretaceous shale pebbles also should be expected from the Des Moines lobe, but they are not present, or are extremely rare. They must have disintegrated in transit.

The source for the material that makes up the terrace was outwash from ice margins upstream. The nature and thickness of these deposits is not known in much detail, but the bedrock floor of the valley is consistently more than 100 feet below modern river level. Where the valley fill has been sampled and described (admittedly only in a few places), the whole sequence appears to have been deposited in the late-Wisconsinan. For example, samples from a well at the Froedert Malt Corporation in Winona are clean sand and gravel down to bedrock at about 120 feet. In the upper 60 feet the glaciofluvial sediments are similar to what we see here. The lower 60 feet is distinctly redder and contains a greater proportion of rocks from the Superior basin; carbonate grains are rare. This reflects an advance of the Superior lobe followed by the advance of the Des Moines lobe.

As the ice margins melted back, aggradation of the Mississippi valley ceased, and was in fact catastrophically reversed when large glacial lakes, such as Lake Agassiz, began to discharge down the valley. These large volumes of meltwater, which had left their sand and gravel load behind in the lake basins, picked up sediment from the aggraded river plain; parts of the original surface, as well as some partly eroded surfaces were left behind as terraces. The rest of the valley was overdeepened by the discharge of glacial lake water, and has been gradually filling in ever since.

105.6 We continue southeast on U.S. 61, past Winona.

114.2 Turn right on Minnesota 43 at the stoplight near Sugar Loaf Hill, go 0.1 mile and turn right again, following Minnesota 43 up West Burns valley.

118.0 Turn left at the sign "Sanitary landfill" and follow the steep road up a small tributary valley.

118.7 Park in the landfill on the ridge crest.

STOP 2. Winona County landfill, Wilson quadrangle, NW1/4NW1/4SW1/4 sec. 10, T. 106 N., R. 7 W.

The landfill property provides an excellent view of the valley-and-ridge topography adjacent to the Mississippi River valley in southeastern Minnesota. Test drilling and excavations at the landfill give insight into relationships between local geologic conditions and geomorphology.

Steep valley walls stand in marked contrast to the relatively flat-topped ridges which extend from the broad upland plateau. An intricate dendritic stream drainage has cut into marine sedimentary rocks of Paleozoic age (Fig. 3). Lower Ordovician dolostones, which compose most of the Prairie du Chien Group, are much more resistant to erosion than the underlying sequence of Upper Cambrian sandstones, siltstones, and shales. Thus, the Prairie du Chien caps the ridges and forms a broad plateau throughout much of southeastern Minnesota.

Local bedrock structures. Bedrock jointing appears to have strongly influenced the orientation of local stream drainage. Compare the jointing directions at outcrops along the landfill ridge with topographic lineations (Fig. 4). It is logical to assume that stream erosion would be most aggressive along trends of highly fractured bedrock. In estimating the effects of bedrock jointing on the development of topographic lineation, outcrop orientations should be considered. If an outcrop locally parallels the trends of master joint sets, then only the face of an exposure remains to portray this relationship, and joints actually measured at any exposure will most likely be only secondary or less dominant directions of fracture.

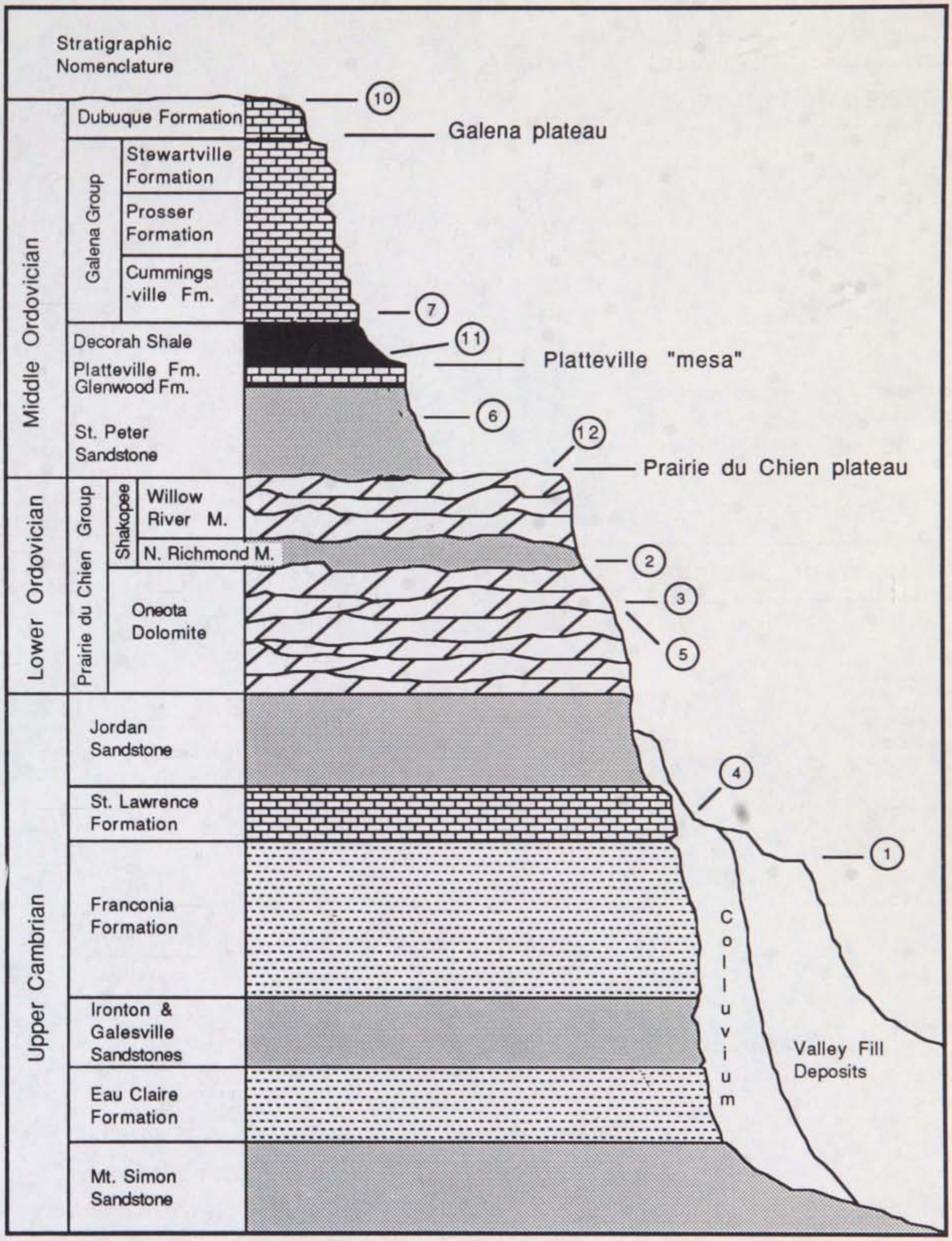

Figure 3. Generalized bedrock stratigraphy and relative positions of field stops.

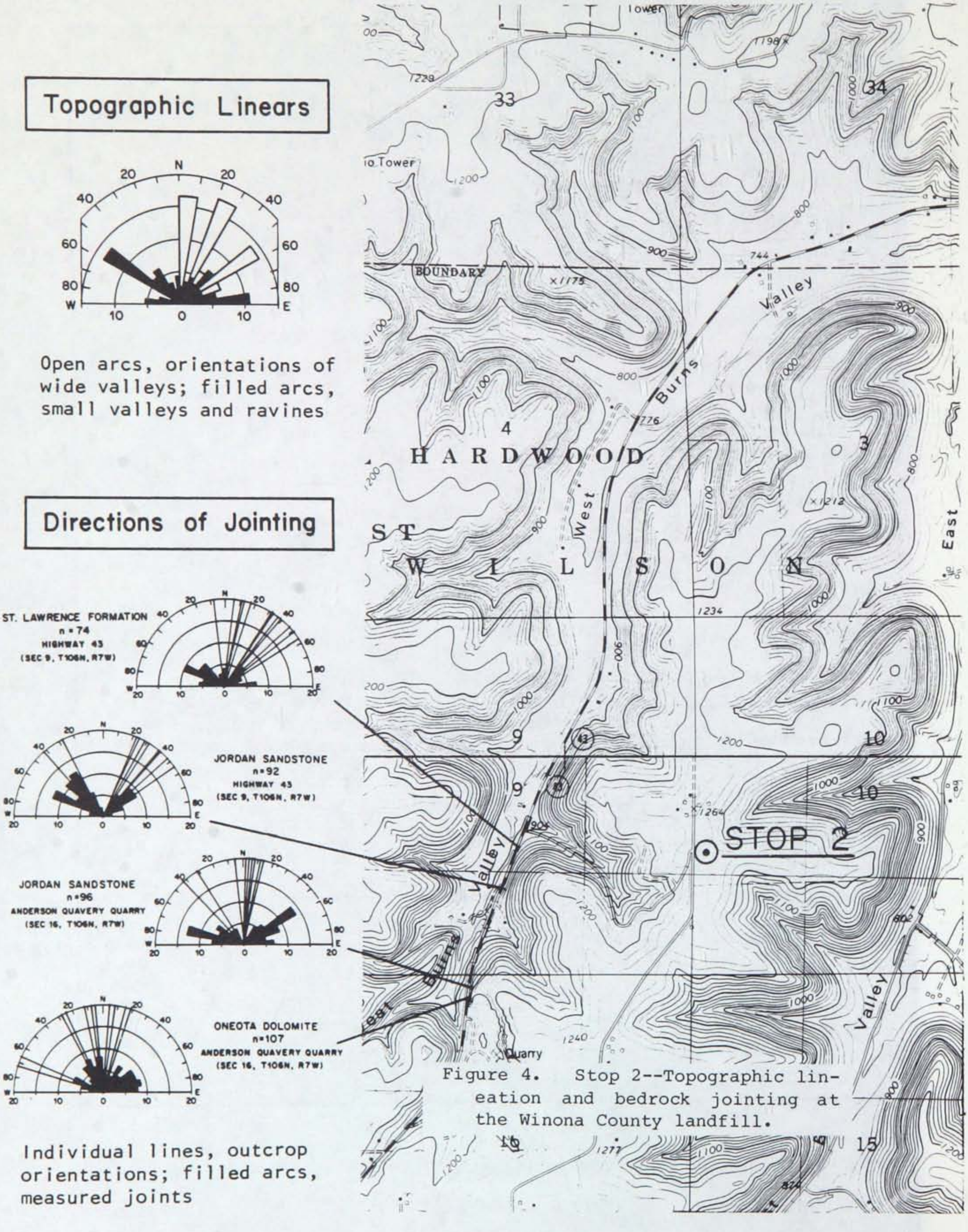

Figure 4. Stop 2--Topographic lineation and bedrock jointing at the Winona County landfill.

Open arcs, orientations of wide valleys; filled arcs, small valleys and ravines

Individual lines, outcrop orientations; filled arcs, measured joints

Topographic lineaments for the landfill ridge and adjacent valleys were determined from 1:24,000-scale topographic maps. The orientations of wide valley segments are shown on Figure 4 as open arcs while those of ravines and small valleys are shown as filled arcs. Clearly, the directions of measured joints and the trends of ravines and small valleys are related. Outcrop orientations are more closely parallel to large valleys than are the directions of measured joints. Master joint sets probably influenced the orientation of master stream drainages and still control the directions in which exposed bedrock will spall due to weathering.

The relationship between the orientations of large tributary valleys and the strike of local bedrock structures is not well understood. The landfill ridge is underlain by a local structural high which plunges into a small basin that extends at least to the Mississippi River valley (Fig. 5). Sugar Loaf Hill, which can be observed from the landfill, provides a reference for appreciating the small-scale nature of local bedrock flexure. The Witoka Dome is the best known structural feature in Winona County, but it too exhibits only a small displacement of about 100 feet.

There appears to be no direct relationship between geomorphology and bedrock flexure. Both valleys and ridges occur over structural highs and lows. As the top of the Prairie du Chien Group was exposed to weathering, closely spaced joints related to local flexure probably influenced stream positions. Also, prior to development of the present gently rolling plateau, the Prairie du Chien surface may have exhibited more relief due mostly to local flexure. Structurally low areas were probably topographically low and received runoff from structurally high areas such as the Witoka Dome. However, jointing was still the major factor controlling the rate and orientation of stream dissection.

Surficial materials. Soil borings data and excavations at the landfill show a great diversity in the lithology and thickness of the unconsolidated deposits covering the Prairie du Chien. Small isolated knobs of bedrock occur within a few feet of the land surface juxtaposed against unconsolidated materials tens of feet in thickness, which appear to be derived from local bedrock types. Glacial erratics have not been observed associated with these materials. Soil borings have penetrated as much as 40 feet of interlayered yellow-brown to red-brown sandy, silty clay, clayey sand, fat clay, and reworked sandstone (Fig. 6). Incorporated with these sediments are angular to rounded fragments of carbonate bedrock, ranging in size from cobbles to boulders more than 6 feet in diameter. The textures and rock types of the unconsolidated deposits at the landfill suggest a fluvial or colluvial origin.

As different parts of the landfill have been excavated for cover material, excellent (but temporary) exposures of surficial materials and the bedrock surface have been revealed. If we are lucky, we will be able to see the heavily weathered upper surface of the Oneota Dolomite, pocked with numerous sinkholes. Ripple-marked slabs of the New Richmond have collapsed into the sinkholes, overlying reddish-brown clay. In some places, the dolomite is sound; the only sign of weathering is a solution-etched surface. In other places, the crystal boundaries have dissolved,

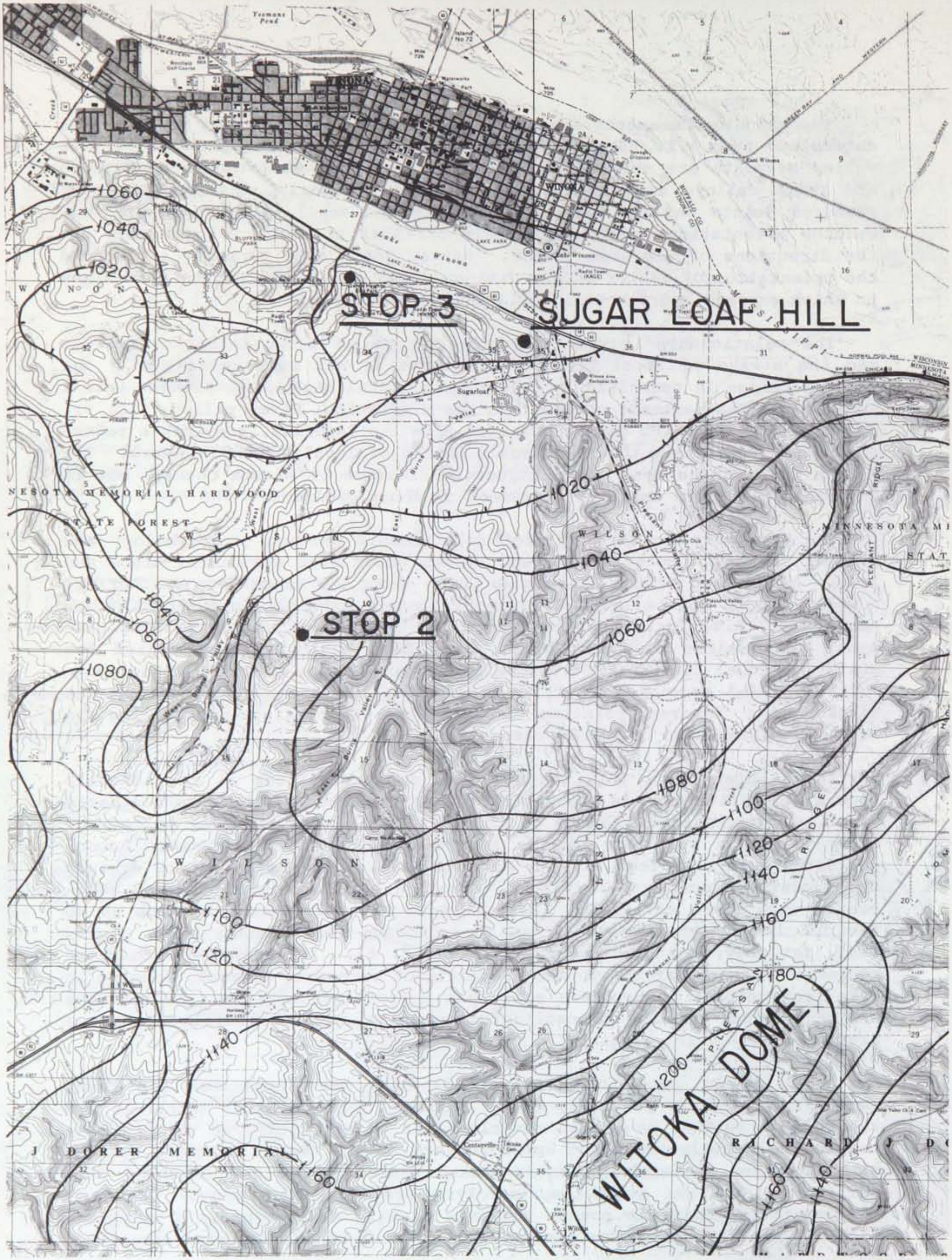

Figure 5. Stops 2 and 3--Structural contour mapping of the top of the Jordan Sandstone near the Winona County landfill. Contour interval=20 feet.

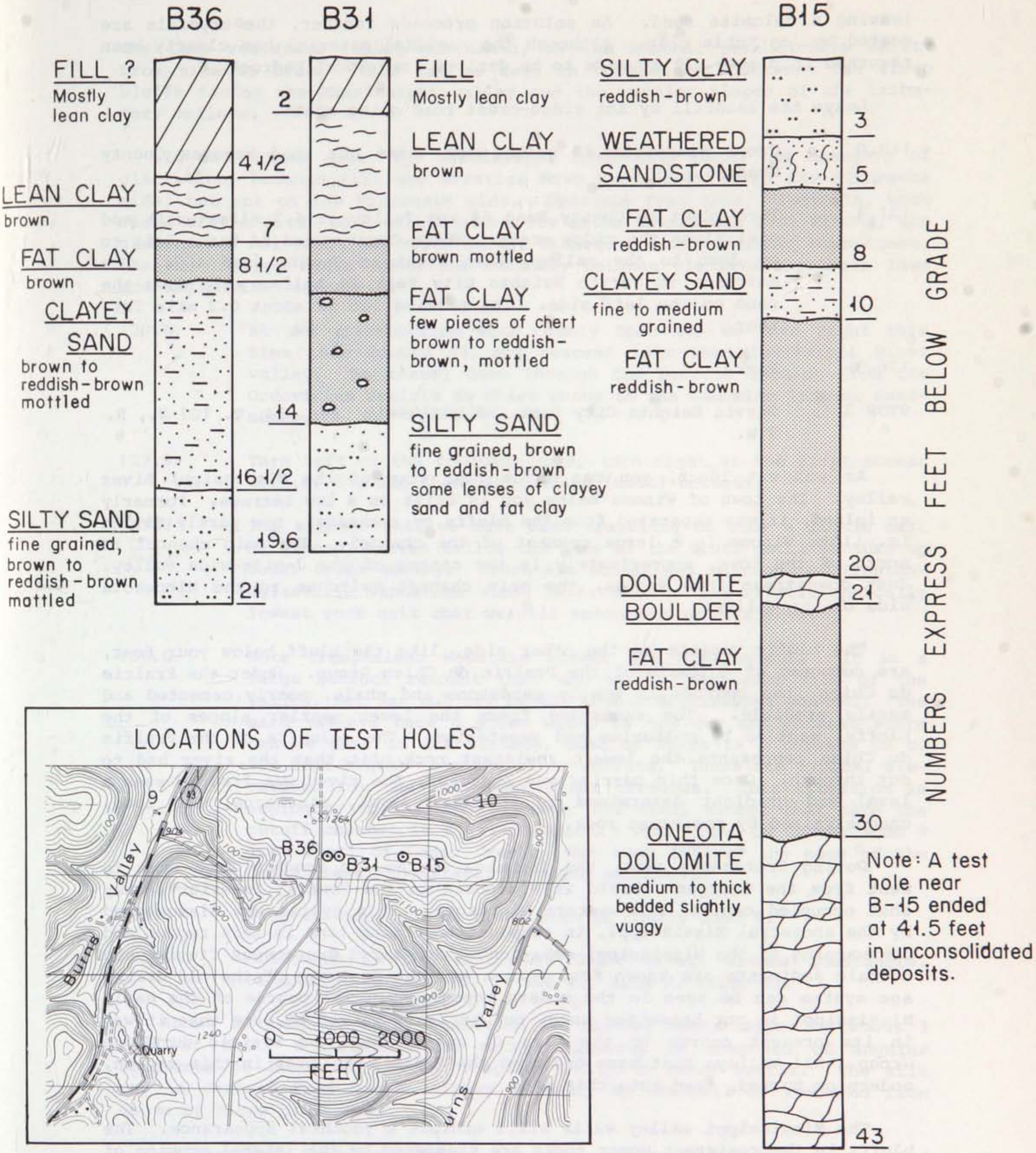

Figure 6. Variability of the unconsolidated deposits at the Winona County landfill.

leaving a dolomite sand. As solution proceeds farther, the crystals are coated by insoluble clay. Although the residual material has clearly been reworked in places. it appears to be derived from local bedrock.

Leave the landfill by the ridge-crest road going south.

119.0 Cross Minnesota 43 going west; here our road becomes County Road 21.

121.4 Turn right on County Road 44 and follow it 4.2 miles north and east along the ridge crest. Where County Road 44 turns left to go down to the valley, turn right on County Road 107. The entrance to Garvin Heights City Park is half a mile down the road on the left side. The parking lot is about 0.2 mile farther.

126.3 Park.

STOP 3. Garvin Heights City Park, NE1/4NE1/4NW1/4 sec. 34, T. 107 N., R. 7 W.

As you eat lunch, you can enjoy your view of the Mississippi River valley. The town of Winona below you is built on a low terrace. Formerly an island, it was separated from the bluffs by a channel, now partly filled in. Lake Winona is a large remnant of the channel. The main channel is north of the town, approximately in the center of the 3-mile-wide valley. Just downstream from Winona, the main channel switches to the Minnesota side of the valley.

The bluffs visible on the other side, like the bluff below your feet, are composed of dolomite of the Prairie du Chien Group. Under the Prairie du Chien, the bedrock is mostly sandstone and shale, poorly cemented and easily erodible. The sandstone forms the lower gentler slopes of the bluffs, mantled by colluvium and vegetation. The dolomite of the Prairie du Chien represents the lowest resistant rock unit that the river had to cut through. Once this barrier was breached, the river was free to seek a level and gradient determined by its base level, discharge, and load, unconstrained by resistant rock.

During Cretaceous time, the drainage system ran roughly from east to west from the emergent shield in Wisconsin to the Central Interior seaway that occupied central and western Minnesota. This system was dismembered by the ancestral Mississippi, in response to rising land in this region and downwarping in the Mississippi embayment. Scattered Cretaceous fluvial and deltaic sediments are known from this area, but no trace of the old drainage system can be seen in the modern topography. The course of the early Mississippi is not known for sure, but at least we can be sure that it was in its present course by the time it cut through the Prairie du Chien Group. All valleys that have breached the Prairie du Chien in this region, modern or buried, feed into this one.

The Mississippi valley walls still exhibit a youthful appearance. The bluffs in the resistant upper rocks are steepened by the lateral erosion of the less resistant rocks underneath, as the channel periodically shifts from side to side. This can be seen in the contrast between the steep bluffs facing the Mississippi valley and the gentler slopes of the tributary valleys.

In the Winona area, the Mississippi apparently marks the boundary of glaciation, because till and erratics have been observed on the Minnesota side, but not on the Wisconsin side. Upstream from Alma, Wisconsin, both sides of the river were glaciated; a few miles downstream from Winona, the glacier did not reach the river on the Minnesota side. Farther downstream, the Mississippi again marks the boundary between glaciated northern Iowa and unglaciated Wisconsin.

127.0 At the intersection with County Road 44, we turn right this time onto County 44, and descend into the Mississippi River valley. We travel down through the bedrock section from the Ordovician Prairie du Chien Group to the Cambrian Ironton Sandstone.

127.9 Turn left on the frontage road, turn right at the first access to U.S. 61, and then right again (east) onto 61.

131.7 The terrace that we have been traveling on ends a little east of Winona, and we follow the base of the bluff until we turn up Cedar Creek valley. There are occasional outcrops of Ironton-Galesville sandstone along here; this is the stratigraphically lowest rock unit that we will encounter in this area.

136.0 Note Trempealeau Mountain across the Mississippi. It is a large bedrock remnant that was on the Minnesota side of the valley, but was cut off by the modern Mississippi channel. The main valley, here 4 miles wide, is now dry and channel scars can be seen in its surface, most of which is a terrace 80 to 100 feet higher than the river surface. These are typical elevations for the late-Wisconsinan terraces. This situation is analogous to the channels near Red Wing, except that here the cutoff channel is still occupied. Turn right on County Road 9 just short of Cedar Creek. Our road follows the edge of the Cedar Creek floodplain, trending southwest.

138.5 Stop at wide spot on right side of County Road 9.

STOP 4. Colluvium in the valley at Cedar Creek, Witoka quadrangle, SE1/4NE1/4SE1/4 sec. 15, T. 106 N., R. 6 W. (Fig. 7).

About 20 feet of rocky colluvium is exposed here, capped by about 3 feet of silty sediment. The rocky colluvium is composed of angular fragments of local bedrock in a sparse silty to sandy matrix. The silt cap is derived from loess, either directly as dustfall or reworked from above by slope processes.

Silt-capped rocky colluvium is very common along the steep-sided valleys of this area. Roads commonly hug the valley sides, and so road-

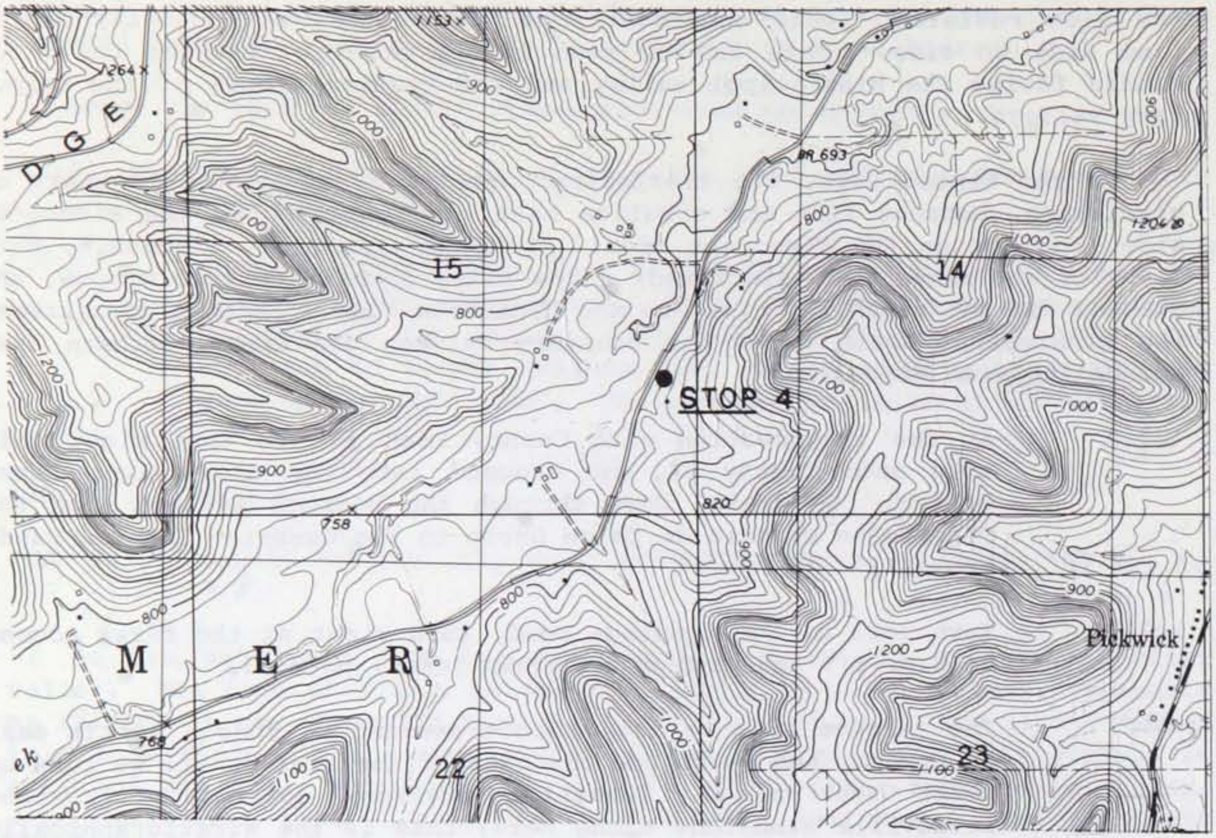

Figure 7. Stop 4--Part of the Cedar Creek valley and its bounding ridges in the unglaciated zone.

cuts in colluvium are fairly common. Rock type and matrix texture depend on the locality, but certain features are almost ubiquitous. Both the rocky and the silty material are unbedded, or nearly so. Also, rocky colluvium is overlain by silty material, separated by a sharp contact; the reverse stratigraphy was not observed, although the silt cap contains a few angular stones in places. In addition, post-depositional weathering is moderate and the silt is oxidized and leached to about the same degree as the loess on the uplands; no paleosols were observed. Finally, the rocks in the colluvium are not highly weathered, and the most that has been observed is a thin skin of clay on some carbonate fragments.

The lack of paleosols, together with the lack of reversed stratigraphy, suggests that the rocky colluvium accumulated during a single event of slope instability, followed by accumulation of the silt cap, and the slopes have remained fairly stable since then. A modern analog to the rocky colluvium is talus slopes in the mountains, fed by freeze-thaw activity on rock outcrops higher up the slope.

The degree of weathering suggests that the silt cap is correlated with the late-Wisconsinan Peoria Loess, and that the rocky colluvium is not much older. Presumably, the cold climate of the late Wisconsinan was responsible for the widespread production of talus from exposed bedrock on valley walls.

138.5 Continue upstream along Cedar Creek.

This valley is fairly typical of the valleys cut into the Prairie du Chien plateau. Bedrock, colluvium and terrace deposits are exposed in numerous roadcuts, now somewhat overgrown. Oneota Dolomite outcrops are common high on the valley sides. Many of the south- and west-facing slopes are "goat prairies"; they are too dry to support a forest, even in this humid climate. Much of the rainfall runs off, and the soil does not have much water-holding capacity. These factors are the same for all slopes, but in addition, the south- and west-facing slopes are exposed to the sun during the warmest part of the day.

142.3 Cedar Valley Church. This would make a good photo, if anyone is interested.

145.8 Town of Witoka. Turn right onto County Road 17 and then almost immediately left onto County Road 12. We have to parallel the interstate for several miles because there is no interchange at Witoka.

148.3 County Road 12 turns left here. We are on the divide between south-flowing tributaries of the Root River and north-flowing direct tributaries of the Mississippi. I-90 follows this major divide through eastern Winona County; it is the only flat passage through this highly-dissected landscape.

150.1 Turn left on Minnesota 43. Go south 0.2 mile and turn onto the westbound entrance ramp of I-90. Take the next exit, about 3 miles west.

153.1 Turn right from the exit ramp, and then almost immediately left onto County Road 12.

155.9 Wyattville. Turn right on County Road 25.

157.5 County Road 25 turns left. Keep going straight on County Road 23 for half a mile, then follow the road down into the upper reaches of Schoeniger valley.

158.8 Park.

STOP 5. Sinkhole Fill, Schoeniger valley, Lewiston quadrangle, SW$^{1}/_{4}$NW$^{1}/_{4}$ SW$^{1}/_{4}$ sec. 16, T. 106 N., R. 8 W. (Fig. 8).

About 10 feet of sinkhole fill is exposed here, capped by 3 feet of loess. The sinkhole is developed in the Oneota Dolomite of the Prairie du Chien Group.

The loess is oxidized and leached; the contact between the loess and the sinkhole fill is marked by a stone line. Most of the stones are angular pebbles and cobbles of sandstone and sedimentary quartzite from the New

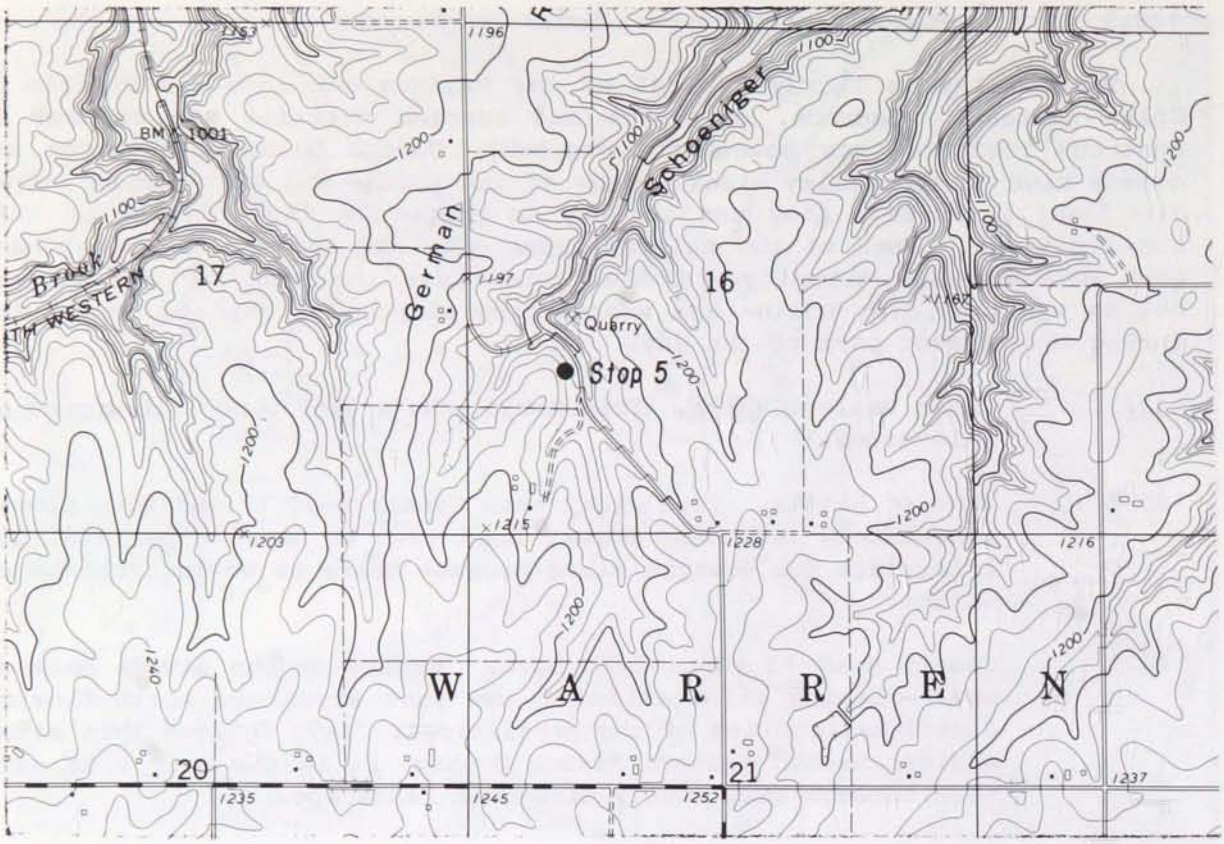

Figure 8. Stop 5--Dissected Prairie du Chien plateau.

Richmond Member of the Shakopee Formation, which overlies the Oneota Dolomite. An outcrop of the New Richmond can be seen about a third of a mile southeast along this road, about 75 feet higher than this sinkhole.

The texture of the sinkhole fill is variable: one sample is sandy loam, one silty clay loam and one clay. The uppermost zone, about 2 feet thick, is a pebbly clay loam. This "pebbly zone" was first interpreted as a till, informally called "residual" till, but it may not be a true till. Although it contains some erratic pebbles and sand grains, it may have been deposited by slope processes from material higher up the slope, rather than directly by glacial ice. The blocky structure in the pebbly zone may be a remnant of a paleo B horizon, which would probably be pre-Wisconsinan in age.

Most of the sand grains and coarse fragments in the sinkhole fill are derived from local bedrock and consist chiefly of rounded frosted grains of Paleozoic quartz sand, angular chert and lacy quartz from dolomite, and sandstone fragments. A few sand grains and pebbles are polished, and probably were derived from the Cretaceous Windrow Formation. Only a small proportion of the sand is definitely "erratic" in origin; it is mostly quartz from Precambrian rocks. These grains are angular to subrounded; they are not polished or frosted.

The entire sinkhole fill is leached and oxidized. Colors tend to be strong brown to reddish brown, typical of long weathering. Either the sinkhole fill is very old, or it is composed of sediment which had been weathering on the surface for a long time. Some of the clay along the sides of the fill may have accumulated in place after the sinkhole was filled.

160.0 Retrace the last mile, but then turn right and follow County Road 25 west. After about 3.5 miles, it bends north, and we follow it to its junction with U.S. 14.

164.7 Town of Lewiston. Turn left on U.S. 14 and proceed west to Utica. We are still traveling over the Prairie du Chien plateau, here undissected. We are gradually moving upsection in the Prairie du Chien.

169.9 Town of Utica. Turn left on County Road 33.

171.6 Park on field approach.

STOP 6. St. Charles till exposure south of Utica, Utica quadrangle, NW1/4 SE1/4SW1/4 sec. 19, T. 106 N., R. 9 W.

This stop is at the eastern edge of the St. Peter escarpment where an outlier of St. Peter Sandstone is capped by till informally named the St. Charles till. No loess is present at this stop; we have entered the late-Wisconsinan Iowan erosion surface. The edge of the Des Moines lobe ice advance (the Bemis moraine) lies about 55 miles to the west.

From this stop, the Prairie du Chien and stratigraphically higher plateaus (Fig. 9) are all visible. The flat-topped hill west of County Road 33 is an escarpment of St. Peter Sandstone capped by the Platteville limestone. The Platteville is about 20 feet thick and tends to form isolated mesas along the edge of the Galena plateau. A remnant of the much thicker Galena plateau is visible about 2 miles to the south.

At this stop the St. Charles till is a calcareous, pebbly loam or clay loam, approximately 8 feet thick. Only the upper 2 to 3 feet of it is leached. At the top, the till is a uniform yellowish brown (10YR 5/4), grading downward through a light gray (2.5Y 6/2) to the base, which is strongly iron stained (10YR 4/6, 4/8). Secondary carbonate deposits are common in the lower part of the exposure.

Grain counts of two samples showed Platteville limestone, probably locally derived, occurring in the till, along with iron oxide, quartz, basalt, and greenstone. Granite was not common in the pebble fraction, but made up about half of the 1- to 2-mm sand. The remainder of the sand fraction is mostly Paleozoic carbonate grains and metamorphic rock fragments. One sample contained about 10 percent limonite and limonite-cemented till fragments. Both samples had minor amounts of polished quartz and chert, believed to be from the Ostrander Member of the Cretaceous Windrow Formation.

Figure 9. Stop 6--St. Peter escarpment and undissected Prairie du Chien plateau.

The thin leached zone, the moderate degree of oxidation, and the relative soundness of the pebbles might imply that the St. Charles is a young till, although it is well beyond the known boundary of the late-Wisconsinan Des Moines lobe advance. It was mapped as "Kansan" by Leverett (1932). A probable explanation for its relatively fresh appearance is that much of the leached and oxidized till was removed by the same process which removed the loess. Where thick loess overlies the St. Charles till, the till is commonly leached and oxidized. Cuttings samples from a well about 7 miles southwest of this stop show 25 feet of St. Charles till overlain by 15 feet of loess. The upper 10 feet of the till is oxidized and leached, and the lower 15 feet is gray and unleached.

This is the easternmost good exposure of the St. Charles till. Erratics and remnants of a till farther to the east appear to be much older, possibly derived from a glaciation that extended almost to the Mississippi River. The St. Charles is the surface till (and only till) in western Winona County and eastern Olmsted County. The drift is thin, and the landscape is dominated by bedrock landforms: plateaus, escarpments, and steep-sided valleys.

Within this area, weathering residuum derived from bedrock is generally sparse. It is represented by brown, red, and reddish-brown clay in joints and solution cavities in carbonate rocks. Erratic pebbles are occasionally observed in the clay; they are presumably derived from the same older till that extends farther east. If a thick layer of residuum was once present, it has been removed by glaciation.

171.6	Return to Utica, and turn left (west) on U.S. 14.
175.8	St. Charles. Turn left (south) on Minnesota 74. Just south of town, the road rises on an escarpment composed of the St. Peter, Platteville, and Decorah Formations. The plateau is capped by the Galena Group.
177.1	Turn right onto the westbound entrance ramp of I-90. We will be traveling on the Galena plateau, only slightly dissected, almost all the way to Rochester. The drift cover is very thin; rock outcrops can be seen even in shallow roadcuts.
192.9	Exit on U.S. 52 toward Rochester. We have just come down off the Galena plateau, into a valley. We will cross two outliers of the plateau before we get to Rochester.
198.6	Exit onto U.S. 63 north toward Rochester.
200.0	Arrive at Roadstar Inn.

Day Two

0.0	Leave motel parking lot. Turn left twice and proceed south on U.S. 63.
3.3	Turn left on County Road 20 (southeast, bending to south).
3.8	Turn left into haul road at the sign "Elcor Construction."
STOP 7.	Elcor gravel pit, Simpson quadrangle, NE1/4NW1/4 sec. 36, T. 106 N., R. 14 W. (Fig. 10).

This pit was once a hill, and its top was about 30 feet higher than the flanks that remain. On the north side of the pit is a remnant of highly oxidized, leached and clayey sand and gravel that probably represents the upper, weathered zone, now mostly removed. Most of the remaining deposit is clean, moderately calcareous, cross-bedded sand and gravel, and beds of silt and fine sand. The fine-grained beds were probably deposited flat, but are highly contorted in places.

A drainage ditch has been cut from about the center of the pit through the west wall, passing under the haul road in a culvert. In the center of the pit, the east side of the ditch exposes bedrock: the upper part of the Decorah Shale overlain by the Cummingsville Formation, which is the lower-

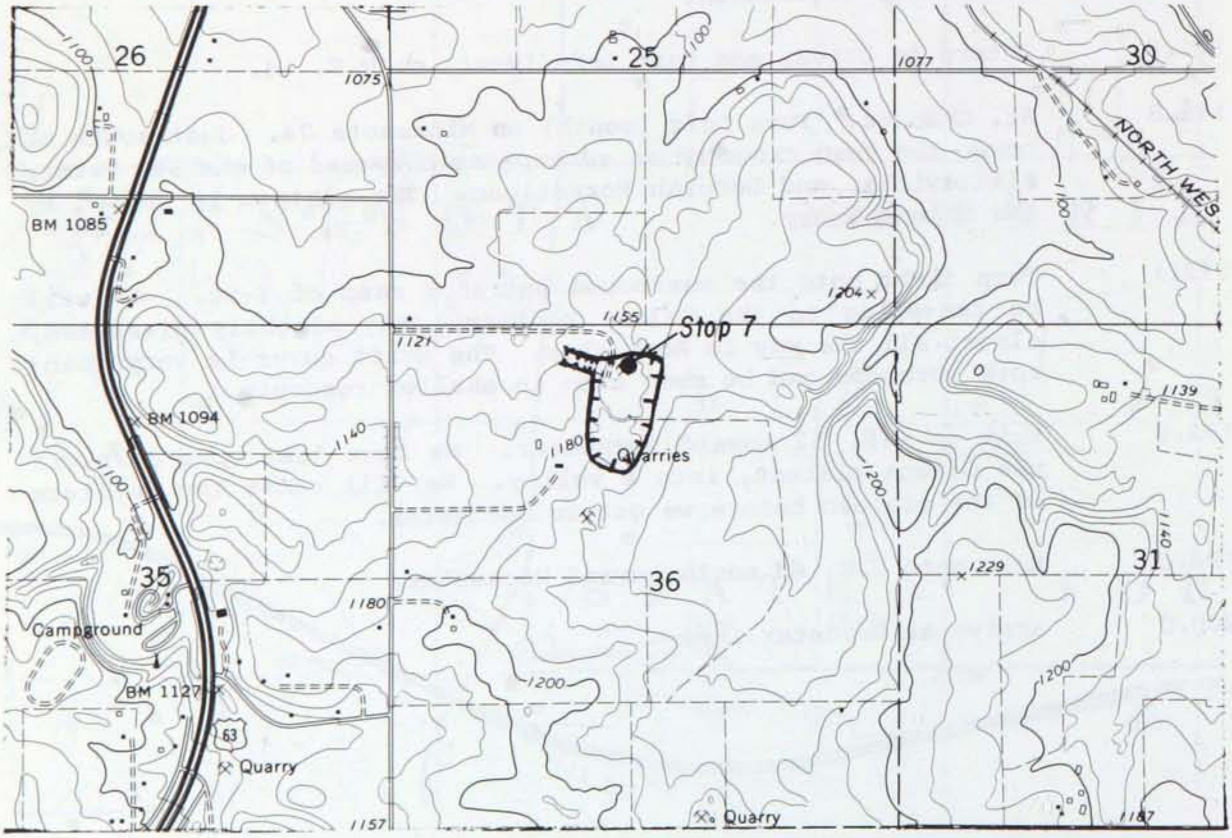

Figure 10. Stop 7--Area around Elcor gravel pit.

most unit of the Middle Ordovician Galena Group. The west side of the ditch exposes till. Both the bedrock and the till are overlain by sand and gravel; the contact in both cases is flat and sharp. The bedrock is unweathered. The till is slightly to moderately calcareous, pebbly loam, and contains some wood and some clasts of sorted sediment.

Along the west side of the pit, the sand and gravel is overlain by till. Both the till and the underlying sand and gravel were probably deposited on stagnant ice and collapsed when the ice melted out. The contact between them dips steeply to the west. The sand and gravel under the till is collapsed, but east of the contact is relatively uncollapsed. This contact is well exposed in the southwestern wall of the pit and in the side of the drainage ditch near the culvert.

Like the lower till, the upper till is calcareous and fairly rich in silt and clay. It contains wood and disseminated organic material. Colors are typically gleyed where not oxidized--dark greenish gray to very dark gray (5BG 4/1 to 2.5Y 3/2). It contains patches of anomalously brown to reddish-brown till. Despite the color, these patches do not contain more Superior basin rock types than does the rest of the till.

A layer of bedded organic silt dips west within the till. This and other features of the deposit, such as stumps in growth position and the generally loose texture of the sediments, indicate supraglacial accumulation. The sand and gravel of the pit contains balls of till, silt, and clay, indicating that it was deposited close to the ice front. The whole sequence probably formed in a single episode of advance and retreat near the edge of a glacier.

How does this event correlate with that of the St. Charles till at stop 6? No definite answer can yet be given, but several factors can be considered. If this stop represents a major ice margin, it must be old, because no geomorphic evidence of such an ice margin remains. No extensive outwash plain survives; the soils are predominantly shallow to bedrock east of this site. The general pattern in Olmsted County is thick drift and presumably multiple glaciations in the western part, and thin drift in the eastern part. There ought to be one or more ice margins in the center of the county where this pit is located.

If the glaciation represented at this stop is younger than that of the St. Charles till (stop 6), then the till here has undergone an inordinate amount of erosion for its age. It should be widely exposed at the surface to the west of here, but most of the surface till exposures in western Olmsted County are more similar to the St. Charles than to this till. Woody till is known only from one other place in the county (stop 11). If the St. Charles till is younger, however, it must have been deposited over this site, and completely eroded away. Alternatively, the woody till here could be just a local facies of the St. Charles, and have no stratigraphic significance. Texture, grain lithology, and clay mineralogy may resolve this problem, but the laboratory work has not been completed as of this writing.

On the west side of the central part of the pit, there is a paleosol under thin loess and dirty gravelly sand. The A horizon is missing; the B horizon is gray clay, exhibiting prismatic and angular blocky structure. Stripped sand grains were observed on the surfaces of some peds. This soil lacks many of the features displayed in the paleosol at stop 10, but is stratigraphically equivalent, in that it was truncated and buried during the late Wisconsinan.

4.5 Turn right on County Road 20 at the end of the haul road, proceed north a quarter mile, and turn left on a township road.

5.0 Cross U.S. 63 and continue west.

7.5 Road ends in a T. Turn right on County Road 8.

8.3 Turn left (west) on County Road 117. Follow 117 through a left turn at 10.3 and right turn at 10.8. The road makes a short jog on County Road 15 at 11.7.

13.4 Turn right on County Road 3. The gravel pit road is 1 mile north.

14.5 Turn right on gravel pit road and left into gravel pit.

STOP 8. Gravel pit near Salem Corners, Salem Corners quadrangle, SW1/4NE1/4 sec. 22, T. 106 N., R. 15 W. (Fig. 11).

This gravel pit exposes about 10 feet of sand and gravel, capped by thin loess. The sand and gravel is clean and relatively fine--cobbles and boulders are rare. Sorting is only moderate, although there are several beds of uniform sand.

Granite and fine-grained igneous and metamorphic rocks are the most common types in the gravel fraction. Carbonate rocks are considerably less abundant, and Superior-basin rocks are rare, although they catch the eye. Sand grains are predominantly quartz and carbonate.

The whole deposit is moderately oxidized, but only the upper few feet is leached, and weathering is minor. A few granite pebbles are grusified; there are almost no iron stains. This appears to be a young deposit, not much older than the loess.

The geomorphic setting is a terrace near the confluence of Salem Creek and its tributary. Although the South Fork of the Zumbro and its tributaries, including Salem Creek, are not connected to any late-Wisconsinan outwash, their terraces are similar in stratigraphic position (under loess) and in degree of weathering to terraces on the North and Middle Forks of the Zumbro River that can be traced upstream to outwash derived from the late-Wisconsinan Des Moines lobe.

I believe that the material in this terrace, as well as in similar terraces in the area, is derived from local erosion of the interfluves

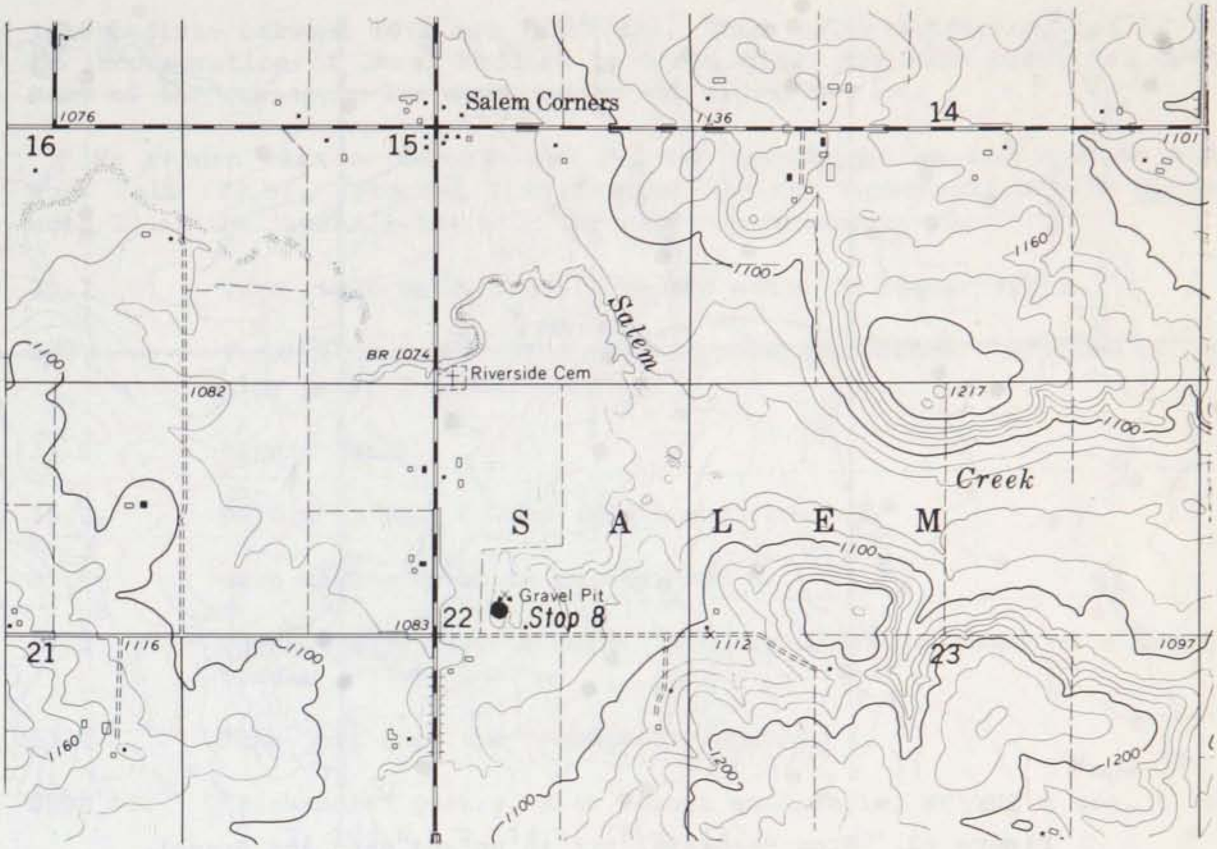

Figure 11. Stop 8--Terrace of Salem Creek and its tributary.

during the late-Wisconsinan time. In other words, the terrace is made up of debris from the Iowan erosion surface. The accumulation of deposits such as this may have been related to rising base level as the Mississippi trench filled with outwash, but was probably related more to the inability of the streams to move all the material that was supplied to them by the hillslopes.

Return south on County Road 3, this time following it around the corner to the west, and around another corner to the south, a mile beyond.

19.6	Rock Dell. Turn right on County Road 26, and proceed west.
21.1	Park at gravel pit on right side of road.
STOP 9.	Gravel pit near Rock Dell, Rock Dell quadrangle, SE1/4SE1/4SW1/4 sec. 6, T. 105 N., R. 15 W. (Fig. 12).

This pit is developed in pre-Illinoian outwash or ice-contact sand and gravel. (The distinction between outwash and ice-contact cannot easily be made in old deposits, where all the geomorphic clues, such as the original surface of the deposit, have been eroded away.) This site is typical of upland sand and gravel deposits in this area that were not protected from

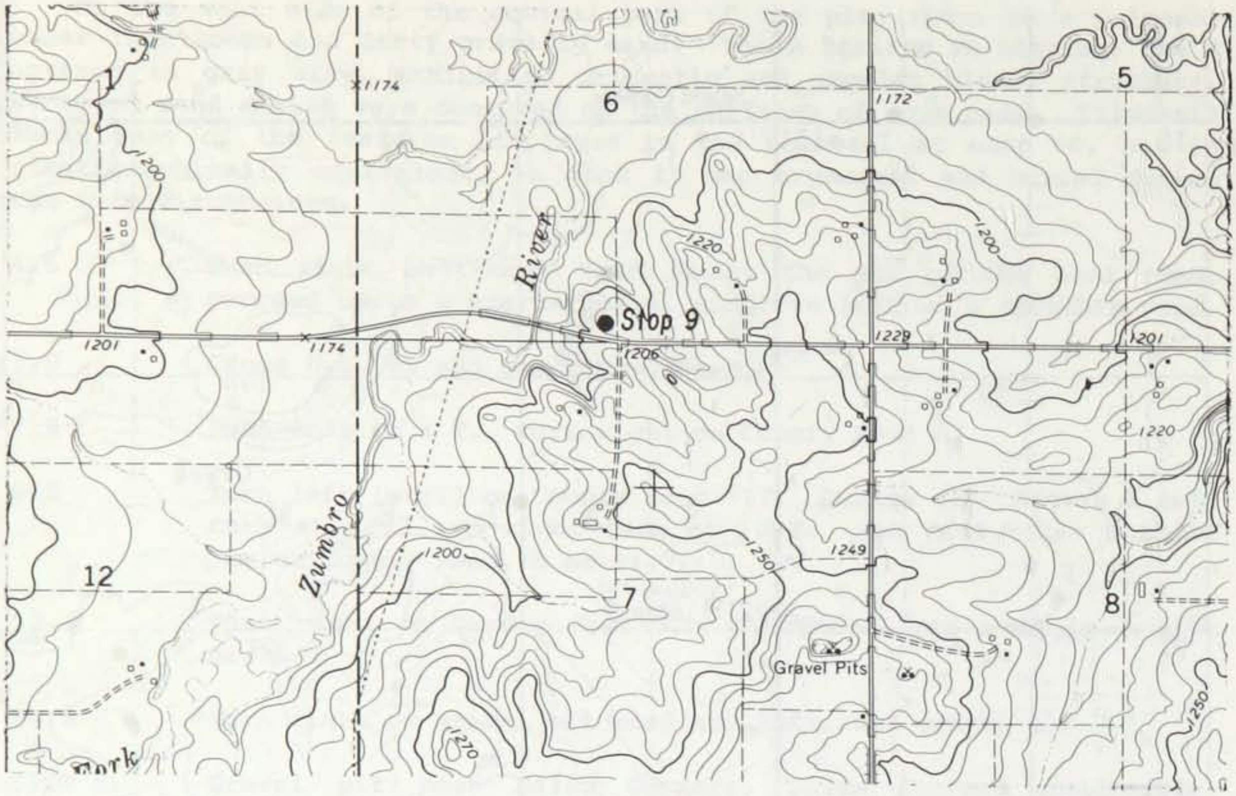

Figure 12. Stop 9--Gravel pit in upland sand and gravel.

weathering by a layer of till: They are highly oxidized, clayey, and completely leached. The large number of cobbles and boulders in the stone line on the south side of the pit implies that the deposit was once capped by till--most likely the same till which makes up the highest part of this ridge. Now only the large clasts remain. However, the sand and gravel at this stop must have been exposed for a long time to account for the observed degree of weathering, either before or after the deposition of the till.

Features of the Iowan erosion surface can be seen below the thin loess. The stone concentration at the top of the sand and gravel represents a lag from slope erosion. In some parts of the pit it is a simple stone line. On the south side there is a stone-line complex 2 or 3 feet thick, composed of rocky unbedded clayey sand and gravel. A depression cuts through this complex into the sand and gravel below. It is filled with clean sand at the bottom; the remainder is filled with loess containing a few stones. This may represent a filled ice wedge.

Bands of brown clay (7.5YR 4/6) occur below the stone line. Although they follow the bedding, I interpret them as pedogenic "beta" horizons. They may consist of clay translocated from the loess, or the remnants of a paleosol, otherwise completely eroded away.

The loess at this site is more clayey and redder than most loess in this area, which is typically 10YR 5/4 where oxidized. The loess here is intermediate between 10YR and 7.5YR 4/4. This color difference may be due to incorporation of local reddish to brown clay, the same clay that coats many of the grains in the sand and gravel deposit.

We return east on County Road 26, and turn right on County Road 3 at Rock Dell (22.5). Proceed 2 miles south to the intersection with Minnesota 30 at the townhall (24.6). Turn left on Minnesota 30.

32.2	Turn right on U.S. 63. Proceed south to Stewartville.
34.7	Turn right on the first street past the bridge. Proceed to the city park, 2 blocks west.
34.9	Picnic lunch.
35.0	Return to U.S. 63 and turn right (south).
35.6	Turn right (west) on County Road 6.
37.5	Where County Road 6 turns left, go straight ahead on a gravel road.
37.8	Turn left into the "Panhandle" Quarry.
STOP 10.	"Panhandle" Quarry, High Forest quadrangle, NE1/4NE1/4 sec. 5, T. 5, T. 104 N., R. 14 W. (Fig. 13).

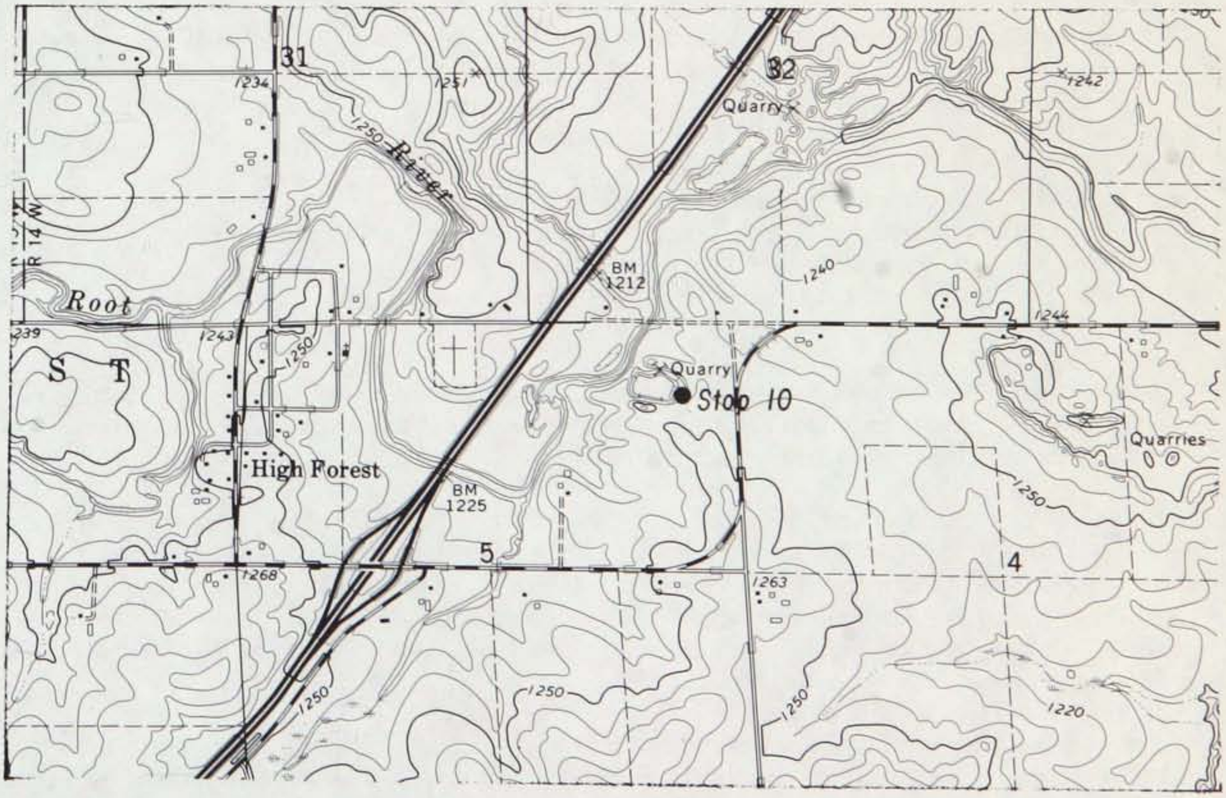

Figure 13. Stop 10--Exposure near the southeast corner of the "Panhandle" Quarry.

A considerable variety of sediment is exposed here, but we will concentrate on the south side of the quarry. A well-developed paleosol is exposed that is developed in a thin till which overlies the Middle Ordovician Dubuque Formation. The paleosol, overlain by a thin (1 to 2 feet) loess, consists of about 3 feet of grayish B horizon over about 4 feet of mottled B horizon over the weathered bedrock. There is considerable variation laterally.

The mottled B horizon is a gray (2.5YR 6/1) noncalcareous clay or silty clay, with mottles of strong brown (7.5YR 5/6) and yellowish brown (10YR 5/6). It contains erratic pebbles, and was probably a till before pedogenesis. The structure is fairly massive with only a few desiccation cracks. Thick clay skins and pore fillings are present and the interstices in the underlying rubble of weathered bedrock are filled with clay. Some erratic pebbles of resistant rock types occur in the rubble, whereas the rock types in the overlying till include less resistant varieties. Possibly the resistant pebbles in the cobble layer were derived from a much older glaciation.

The upper B horizon is dark brown (7.5YR 3/2, 4/2 and 3/3) noncalcareous clay or silty clay in which pebbles are rare. A fine angular blocky structure is formed by numerous desiccation cracks, and clay skins are common in places. White silans composed of silt and fine sand can be found in the upper 6 inches of this horizon. These silans are especially developed along vertical joints, and indicate a remnant of an E horizon not completely eroded away.

A stone line occurs at the contact between the loess and the upper B horizon. The clasts range in size from small pebbles to medium cobbles; a few boulders also are present. The clasts are a great variety of rock types--granite, gabbro, basalt, quartzite, rhyolite, iron-formation, rounded quartz from the Ostrander gravel, diorite, slate, greenstone, chert, and chalcedony. No carbonate rocks are present in the stone line or the underlying horizons; the whole sequence has been leached down to the bedrock rubble. The assemblage is a mixture of weatherable (granite, gabbro, etc.) and weathering-resistant (basalt, rhyolite, quartz, etc.) rock types.

Many of the stones in the stone line appear to be at least incipient ventifacts. Some are polished, and a few exhibit facets. The polish is especially evident on fine-grained resistant rocks such as basalt.

Irregular masses of yellowish-brown (10YR 5/6) clayey sand and gravel occur in the upper B horizon. The pebble assemblage is similar to that of the stone line. The form of the inclusions varies widely, from subhorizontal stringers to subvertical ice-wedge casts to diagonal bands. In a few places, clay skins that presumably were planar originally have been deformed around the inclusions.

I interpret this exposure as a paleosol developed in pre-Illinoian till, deformed and truncated by processes associated with the Iowan erosion episode. The sand and gravel inclusions indicate strong frost activity, and probably permafrost. The stone line indicates sheet erosion, and the ventifacts indicate strong wind activity. These processes need not all have gone on at the same time, but they could all be associated with a periglacial climate that was cold, dry, and windy.

37.9 Turn right from the quarry road onto County Road 6. Follow County Road 6 around a curve and continue westward to the junction with County Road 3.

43.6 Turn right (north) on County Road 3.

55.2 Salem Corners (again). Turn left on County Road 25.

55.9 Turn right on County Road 5.

59.8 Cross U.S. 14 and continue north on County Road 5 through Byron.

63.6 Turn right on quarry access road.

63.8 Park in the quarry.

STOP 11. Quarry north of Byron, Byron quadrangle, SW$^1/_4$SE$^1/_4$NE$^1/_4$ sec. 18, T. 107 N., R. 15 W. (Fig. 14).

Figure 14. Stop 11--Quarry in the valley of the South Branch, Middle Fork of the Zumbro River.

This quarry is developed in the Middle Ordovician Platteville limestone on the side of the valley of the South Branch, Middle Fork of the Zumbro River. The active part of the quarry on the east side exposes the Middle Ordovician Decorah Shale overlying the Platteville; such exposures are uncommon because the Decorah weathers rapidly on exposure. On the inactive west side, most of the Decorah has been removed and replaced with a thick drift sequence, which is probably a remnant of drift that filled the valley, but now is mostly removed.

The general stratigraphy is about 20 feet of till and stratified drift, overlain by about 7 feet of colluvium, overlain by about 10 feet of loess.

The till is a slightly pebbly clay loam, containing inclusions of clayey silt. The colors range from gray (7.5Y 5/1) and dark grayish brown (10YR 4/2) where unoxidized, to olive brown (2.5Y 4/4), dark yellowish brown (10YR 4/6), and dark brown (7.5YR 3/4) where oxidized, especially along joints. Wood is common in the till, and the variety of colors, which includes gleyed colors, may be caused by disseminated organic material.

A zone of stratified drift occurs near the center of the till. The stratified drift is highly oxidized and iron-stained sand and gravel, typically yellowish red (5YR 4/6) to dark reddish brown (2.5YR 3/4), underlain in places by grayish-brown (2.5Y 5/2) silt and very fine sand. The lower contact of the stratified drift sequence is flat, but the upper contact is wavy.

The colluvium above the till is composed of angular limestone clasts in a silt matrix. It is very similar to the colluvium that normally occurs on the sides of bedrock valleys, such as at stop 4. Galena Group limestone and shale make up the upper part of the slope.

The relatively thick loess at this site was not much affected by the Iowan erosion episode. The reason for the patchy occurrence of the erosion surface is not at all clear.

This branch of the Zumbro River served as a channel conducting meltwater from the Des Moines lobe ice margin about 20 miles west of here. This is certainly consistent with the morphology of the valley--the whole valley meanders, and its sides are steeper on the outside of the meanders. However, such morphology has also been observed in valleys that cannot be traced upstream to Wisconsinan ice margins.

Is the till at this stop the same as the till at the Elcor gravel pit (stop 7)? The main similarity is the abundant presence of wood. This could certainly be a local phenomenon at both places, and therefore, of no stratigraphic value. On the other hand, woody tills are not common in this area, and they might all be derived from only one glaciation. Either the glacier advanced over a boreal forest, or a boreal forest developed on the glacier as it was melting (or both). Wood from this quarry was submitted for dating by the Olmsted County Historical Society, and it produced a date of >40,000 years BP.

64.1 Turn right and continue on County Road 5 and follow it up out of the valley to the north, where the road coincides with the Olmsted-Dodge County line.

67.2 Turn right on County Road 14 and follow it more or less straight east to U.S. 52.

75.4 Turn left on U.S. 52, go north about a mile, and turn right on County Road 154 at the sign: "Sanitary landfill" (76.5). The entrance to the landfill is a mile east.

77.5 Park near the landfill entrance.

STOP 12. Olmsted County landfill, Rochester, Douglas, Oronoco, and Zumbro Lake quadrangles, mostly in the SE¼SE¼SE¼ sec. 28, T. 108 N., R. 14 W.

We will be looking in the eastern cut of the borrow area in the southeastern corner of section 28 (Fig. 15). Two tills are exposed; the upper one makes up the bulk of the exposure, and the lower one is poorly exposed in the bottom of the borrow pit. No loess is present--we are again in the

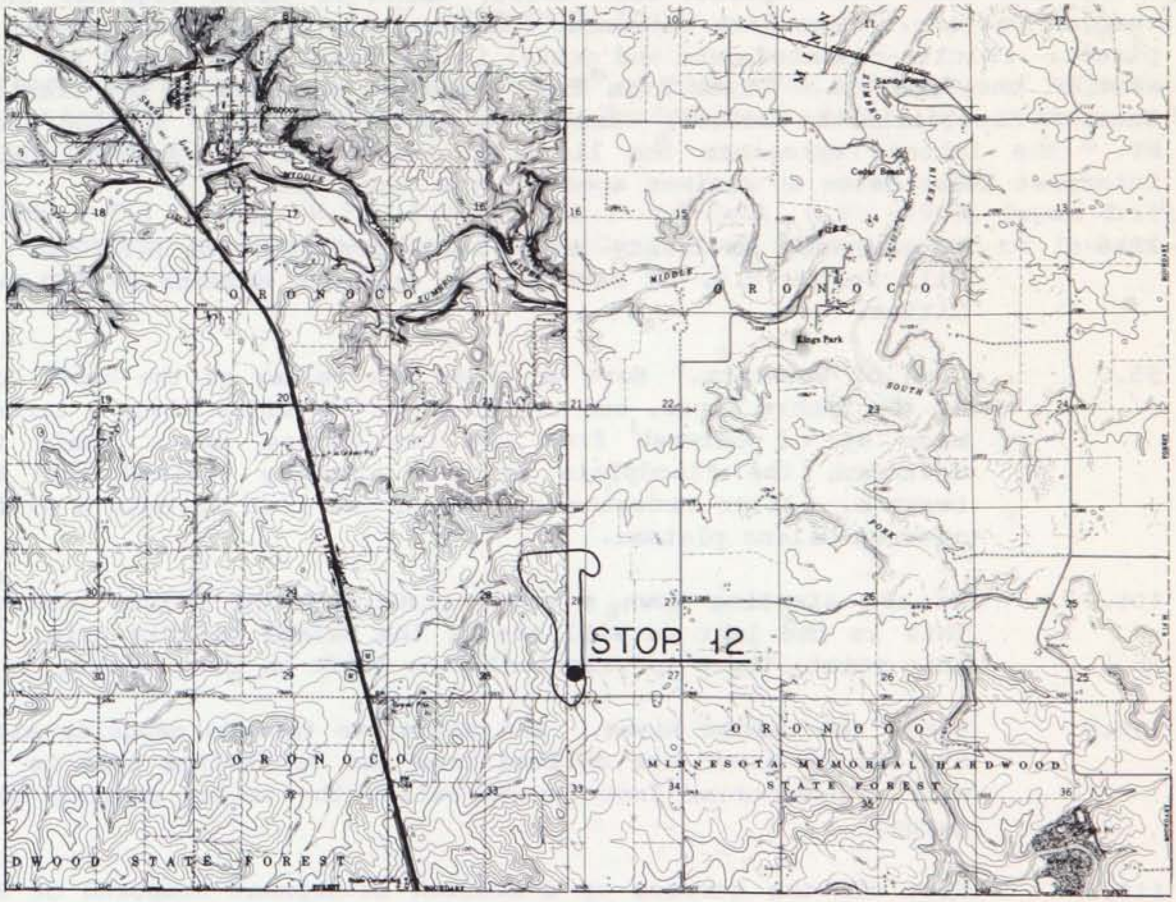

Figure 15. Stop 12--Area of the Olmsted County landfill.

Iowan erosion surface. A concentration of stones occurs at and near the top of the upper till.

This is one of the few till exposures that clearly records multiple glaciation. The oxidation of the lower till shows that a significant period of time occurred before deposition of the upper till. Although it is oxidized, the lower till is unleached. It is calcareous, and contains fragments of carbonate rock. The texture, based on one sample, is sandy loam, close to the boundary of loam. It has a platy structure which may be typical of subglacially deposited sandy till. In places it is cemented by calcite, presumably derived from the upper till.

The texture of the upper till ranges from loam to clay loam. Its unoxidized color is very dark gray and very dark grayish brown that grades upward through a mottled and partly oxidized zone to a dark yellowish brown (10YR 4/5) in the upper 3 feet. Only the upper 3 feet is leached; the rest of the exposure is calcareous. This degree of leaching is consistent with Holocene leaching, and so all of the former leached zone must have been removed during the Iowan erosion episode.

Farther north in the borrow area, the surface till overlies stratified drift and some red Superior-lobe drift, which is mixed together in a complex pattern. Secondary carbonate has cemented the sand and gravel in places. Calcite-cemented sand and gravel is abundant in the gravel pit just west of the landfill. Dates from these cements, obtained by the uranium-thorium disequilibrium method, range from about 300,000 to 350,000 years BP. The latter represents the limit of dating for the method, and I interpret these dates as minimum ages for the upper till.

78.5 Return west on County Road 154. Turn right on U.S. 52. We will follow U.S. 52 back to the southern suburbs of the Twin Cities.

95.0 Town of Zumbrota. Here we enter the valley of the North Fork of the Zumbro River, and travel for a few miles along a terrace made up of outwash from the Des Moines lobe. This far upstream, the floodplain is only slightly incised into the terrace. After crossing the river, we rise up onto a drift-covered Galena plateau.

108.9 We are starting down a major grade off the Galena plateau. This is the last we will see of the Galena on this trip. At this point, there is practically no drift on the plateau.

114.9 Cross the Cannon River. The extensive terrace deposits along the Cannon River are derived from the Des Moines lobe to the west. Downstream from Cannon Falls, the valley narrows to a gorge.

118.9 Rise off the terrace up a bedrock escarpment composed of St. Peter sandstone capped by Platteville limestone. This is within the area mapped as Old Red drift of the Hampton moraine by Leverett, but the area that we cross is mostly shallow to bedrock.

126.5 Cross the Vermillion River. The sandplain along the river is outwash derived from the Des Moines lobe, cut into an older outwash plain derived from the St. Croix moraine. We rise onto the St. Croix outwash a few tenths of a mile past the river. This is the same sequence of deposits that we crossed yesterday, downstream, near Hastings.

134.9 Pine Bend refinery. We are about to enter the St. Croix moraine, after having crossed outwash since the Vermillion River. Note the sudden profusion of lakes and swamps in closed depressions. Minnesota 55 joins U.S. 52 from the right. Follow 55 to the Minneapolis-St. Paul International Airport.

143.9 U.S. 52 diverges to the north. Stay on Minnesota 55.

149.7 Mendota Bridge over the Minnesota River. Follow the signs to the airport.

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